Application form

Gravitation
2013

NL-APP: Crossing the frontiers of astroparticle & particle physics

Flammarion engraving. *'If I came to be at the edge, for example at the heaven of the fixed stars, could I stretch my hand or my stick outside, or not?´*

Stephen Hawking: "Most sets of values would give rise to universes that, although they might be very beautiful, would contain no one able to wonder at that beauty."

General information

Main applicant (co-ordinating researcher)

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FTE dedicated to this programme	0.7 FTE
Pref. for correspondence	English

Brief summary of research over last 5 years

At the *HERA electron-proton collider* he was the first to determine the proton structure function F_2 and the gluon density. He invented the 'double-angle method' to reconstruct the kinematics in deep-inelastic scattering, which was essential in virtually all subsequent publications of the ZEUS and H1 collaborations.

At the *LEP electron-positron collider* (OPAL collaboration) he was, as CERN fellow and later as CERN staff, expert in multi-jet physics and characterisation of hadronic decays. He determined the strong coupling constant in electron-positron collisions as a function of the beam energy, showing its energy dependence and the validity of Quantum Chromo Dynamics.

Since 2000 he is a member of the ATLAS collaboration at the *LHC proton-proton collider* at CERN. He developed reconstruction software and initiated a number of performance studies. He was a pioneer in the phenomenology of top-quarks and became coordinator of the international top-quark studies in ATLAS. With his VICI grant of the Netherlands Organisation for Scientific Research (NWO) he initiated a team to obtain the first determination of the yield of top-quarks and their properties, testing the Standard Model in a subtle and completely new energy domain.

As leader of the ATLAS/FOM program he is the driving force of the Dutch contribution to the ATLAS collaboration. With this group of 18 staff physicists, 5 postdocs and approximately 20 PhD students his main focus is the harvest of physics results with ATLAS. Additionally the installation and commissioning of the Dutch contributions to the detector hardware, the development of software and performance studies also fall under his responsibility.

He coordinated the group efforts during the discovery of the Higgs particle. His group made essential contributions to two of the Higgs main decay channels and the statistical combinations of all obtained information.

In 2011, Prof. Bentvelsen co-founded the Centre of Excellence in Gravitation and Astroparticle Physics Amsterdam (**GRAPPA**), which brings together theoretical physicists, astronomers and particle physicists in order to answer some of the most profound questions in Particle Astrophysics and Cosmology. He is also well-known for his outreach activities. He was featured in the internationally renowned documentary "Higgs into the heart of imagination" and was awarded the Physica Prize of the Netherlands Physical Society in 2013 for his contribution to the Higgs discovery.

International visibility, activities, prizes, scholarships etc.

Prof. Bentvelsen previously held staff positions at CERN. He has currently a leading position in the Dutch particle physics research community and often represents this community in international collaborations, such as ATLAS. He organised the International Conference on High-Energy Physics (2002), the Belgian-Dutch-German graduate school in particle physics (2006) and the Amsterdam Particle Physics Symposium (2011).

Personal grants and prizes

- Physica Prize of the Netherlands Physical Society (NNV) (2013).
- VICI grant from the Netherlands Organisation for Scientific Research (NWO) (2006).
- CERN fellowship and CERN staff.

Key organizational roles

- Program leader 'Physics at the TeV scale: ATLAS' (since 2004).
- Secretary of the CERN Contact Committee at the Royal Netherlands Academy of Arts and Sciences (KNAW) (since 2010).
- Director of the Institute of High Energy Physics at UvA (since 2004).
- Board member of the FOM organization (since 2008).

Prof. Bentvelsen (co-)authored 440 scientific papers in peer reviewed journals with approximately 24,350 citations in total and he has an h-index of 71.

5 key publications main applicant

1. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC - ATLAS Collaboration (G. Aad *et al.*). Phys.Lett. **B716** (2012) 1. [768 citations]
2. Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s}$=7 TeV - ATLAS Collaboration (Aad, Georges *et al.*) Eur. Phys. J. **C71** (2011) 1577 [200 citations]
3. Measurement of the $W \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$ production cross sections in proton-proton collisions at $\sqrt{s}$=7 TeV with the ATLAS detector - ATLAS Collaboration (G. Aad *et al.*) JHEP **1012** (2010) 60. [221 citations]
4. Special supersymmetric features of large invariant mass unpolarized and polarized top-antitop production at CERN LHC - M. Beccaria, S. Bentvelsen, M. Cobal-Grassmann, F.M. Renard, C. Verzegnassi. Phys.Rev. **D71** (2005) 073003. [18 citations]
5. QCD studies with e^+e^- annihilation data at 161-GeV - OPAL Collaboration (K. Ackerstaff *et al.*). Z.Phys. **C75** (1997) 193-207. [107 citations]

Applying university (contact person on behalf of Executive Board)

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NWO subcommittee (Choose one)

Humanities and Social Sciences	
Natural and Technical Sciences	X
Biomedical and Life Sciences	

NWO Division (Choose one or more)

ALW	
CW	
EW	
GW	
MaGW	
ZonMw	
N	X
STW	

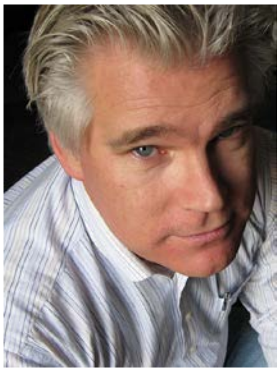
Main field of research

Code: 12.10.00	Field of research: Subatomic physics

If applicable: other fields of research, in order of relevance:

Code: 17.90.00	Field of research: Astronomy, astrophysics, other

Co-applicant 1



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FTE dedicated to this programme	0.6 FTE

Brief summary of research over last 5 years

Prof. dr. Sijbrand de Jong is professor of Experimental Physics at the Radboud University Nijmegen, and expert in particle physics and astroparticle physics.

At the *HERA electron-proton collider* (ZEUS experiment) he established a second level calorimeter trigger based on jet reconstruction within a millisecond using a large parallel transputer-based real-time computing system.

At the *LEP electron-positron collider* (OPAL experiment) he was involved in the construction of three generations of silicon vertex detectors, responsible for the slow control systems and the daily operation of these detectors.

At the *Tevatron collider* (DØ experiment) he was the Dutch group leader, he helped constructing the silicon microvertex detector and second level silicon track trigger and was responsible for the radiation detection system for the silicon microvertex detector.

From 1995 until 2012, Sijbrand de Jong was involved in the search for the Higgs boson. First in OPAL as convenor of the Higgs search group and subsequently in DØ with contributions to several search channels and in the development of essential tools, such as b-quark and tau-lepton identification, eventually leading to the 3σ hint that was published by the Tevatron experiments for observing a Standard Model Higgs decaying to b-quarks.

Since 2005 he is a member of the Pierre Auger collaboration and part of the leading Dutch effort to establish radio detection of cosmic rays as a new and complementary technique and to study interactions at centre-of-mass energies that are 20 times higher than the LHC energy.

In 2005 Prof. De Jong was appointed as the founding director of the Institute for Mathematics, Astrophysics and Particle Physics at the Radboud University Nijmegen, an at that time unique co-operation of mathematicians, astrophysicists and particle physicists to unravel the fundamentals of Nature at the smallest and largest distance scales.

Prof. De Jong is very active in outreach and education. He won the Academic Year Award in 2009 and is currently director of the Radboud Pre-University College of Science. For these activities he was honoured as Nijmegen citizen of the year 2009. He helped to shape the new national upper-level secondary school physics and Nature, and life and technology curriculum and wrote parts of teaching material for both these curricula.

International visibility, activities, prizes, scholarships etc.

Prof. De Jong previously held positions as CERN fellow and tenured associate professor at Indiana University. He has a leading position in the Dutch and international particle physics community, holding posts of major responsibility in the LHC committee, the CERN Council and the European Research Council Advanced Grant panel. He organised the International Vertex Workshop (1999), the International Conference on High-Energy Physics (2002), Fysica (2008), the Nijmegen Astroparticle Physics Summer School (2003, 2006, 2009) and will co-organise the International Conference on Cosmic Ray Physics in 2014.

Personal grants and prizes

- CERN fellowship.
- Academic Year Award 2009.
- Nijmegen Citizen of the Year 2009.

Key organizational roles

- Director Radboud University Nijmegen School of Physics (2000-2004).
- Director IMAPP (2005-2011).
- Director Radboud Pre-University College of Science (since 2011).
- Dutch national representative, Strategy Group European Particle Physics Strategy (2006 en 2013).
- CERN Council delegate (since 2010).
- LHC Committee member ad-personam (2005-2009).
- Member, European Committee for Future Accelerators (ECFA) (since 2003).
- ERC Advanced Grant panel member (since 2009).
- Associate Editor European Physics Journal C (since 2013).

Prof. De Jong (co-)authored more than 620 scientific papers in peer reviewed journals with approximately 31,000 citations in total and he has an h-index of 83.

5 key publications co-applicant

1. The upgraded DØ detector – DØ Collaboration. Nucl.Instrum.Meth. **A565** (2005) 463. [888 citations]
2. Search for neutral MSSM Higgs bosons at LEP – OPAL Collaboration. Eur.Phys.J. **C47** 547, 2006. [563 citations]
3. Correlations of the highest energy cosmic rays with nearby extragalactic objects – Pierre Auger Collaboration. Science **318** (2007) 938. [391 citations]
4. Measurement of B_s^0 mixing parameters from the flavor-tagged decay $B_s^0 \rightarrow J/\psi\varphi$ – DØ Collaboration. Phys.Rev.Lett. **101** (2008) 241801. [321 citations]
5. Combined search for the standard model Higgs boson decaying to bb using the DØ Run II data – DØ Collaboration. Phys.Rev.Lett. **109** (2012) 121802. [17 citations, but very proud of it!]

Co-applicant 2

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FTE dedicated to this programme	0.6 FTE

Brief summary of research over last 5 years

Raimond Snellings is professor of Heavy Ion Physics at Utrecht University and is an expert on collective effects and measurements of particle correlations. He is interested in understanding the properties of the Quark Gluon Plasma, a state of matter which we believe existed in the early Universe (about 10^{-6} s after the Big Bang).

In the STAR experiment at the *Relativistic Heavy Ion Collider* (RHIC) he was responsible during the startup of the experiment for the particle reconstruction software and he was the convenor of the largest physics working group. He was one of the first to point out the importance of measurements of anisotropic flow at RHIC, which resulted in many high impact publications. He, together with two colleagues, performed the first measurement of elliptic flow at RHIC. The corresponding paper (cited almost 500 times) provided the basis for the discovery of the perfect liquid behavior of the Quark Gluon Plasma. He was also a primary author for the experimental paper from STAR summarizing the evidence for Quark Gluon Plasma formation (cited more than 1500 times).

In 2002 he obtained a FOM *"springplank-positie"* and joined the ALICE collaboration at the LHC.

He was one of the editors of the ALICE Physics Performance Report and with his VIDI grant (2005) he built a team that played a leading role in the anisotropic flow analysis in ALICE. He and his team developed and implemented the sophisticated statistical techniques that are needed for a reliable measurement of anisotropic flow. This effort resulted in the first heavy-ion physics publication at the LHC, a few days after the data became available. This publication received an editor's selection in Physical Review Letters and was also selected by the American Physical Society for a commentary in Physics, a distinction that APS reserves for its most important papers. This paper is currently the most cited ALICE physics paper (already more than 250 times). He is a convenor of one of the ALICE physics working groups and a member of the ALICE physics board.

Since 2010 he is a professor at Utrecht University where, in addition to his scientific work, he is also the vice chair of the Institute of Subatomic Physics and the director of the Particle Physics Masters program. He received in 2011 a NWO VICI and recently the Centre for Science and Technology Studies (CWTS) listed him as the 7th highest-cited scientist in the Netherlands.

International visibility, activities, prizes, scholarships etc,

Prof. Snellings previously held staff positions at Lawrence Berkeley Laboratory and at Nikhef. He has a leading position in the Dutch and international heavy-ion physics community. He was a co-editor and co-author of the ALICE Physics performance report and a co-author of the 2010 NuPECC long range plan. He is a referee for various international journals and for international applications in the fields of Nuclear and Physical Science. He organized, and was a convenor at large international conferences: *e.g.* ECT*, ICHEP and Quark matter. He very frequently represents the heavy-ion community as a plenary speaker at international conferences and gives lectures at international summer schools.

Personal grants and prizes

- VICI grant from the Netherlands Organisation for Scientific Research (NWO) (2011).
- VIDI grant from the Netherlands Organisation for Scientific Research (NWO) (2005).
- Foundation for Fundamental Research on Matter FOM "springplank position" (2001).

Key organizational roles

- Member Nuclear Physics European Collaboration Committee (NuPECC) for the Netherlands (since 2012).
- Physics board member ALICE collaboration (since 2011).
- Vice chair Institute for Subatomic Physics Utrecht (since 2010).
- Group leader ALICE at Nikhef (since 2007).

Prof. Snellings (co-)authored 181 scientific papers in peer reviewed journals with approximately 19,600 citations in total, with an average of 108 citations per paper, and he has an h-index of 71.

5 key publications co-applicant

1. Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV – STAR Collaboration. Phys. Rev. Lett. **86** (2001) 402. [498 citations]
2. Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions – STAR Collaboration. Nucl. Phys. **A757** (2005) 102. [1576 citations]
3. Collective phenomena in non-central nuclear collisions, Landolt-Börnstein, Relativistic Heavy Ion Physics, Vol. **1/23** (Springer-Verlag, Berlin) 2010. [159 citations]
4. Flow analysis with cumulants: Direct calculations – ALICE Collaboration. Phys. Rev. **C83** (2010) 044913. [42 citations]
5. Elliptic flow of charged particles in Pb-Pb collisions in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV – ALICE Collaboration. Phys. Rev. Lett. **105** (2010) 252302. [273 citations]

Co-applicant 3

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FTE dedicated to this programme	0.7 FTE

Brief summary of research over last 5 years

Prof.dr. Jo van den Brand is director of the Subatomic Physics group at VU University Amsterdam and specializes in particle physics and gravitational physics.

In the early 1990s he was active in electron scattering experiments at SLAC concerning colour transparancy and virtual Compton scattering. He was spokesman of BLAST at MIT-Bates (with Prof. Milner, MIT), and carried out the world's first fully polarized internal target experiment (CE25) at the Indiana University Cooler Facility.

In the 1990s he was involved in the HERMES collaboration at DESY, an experiment at HERA to determine the contribution of the various quark flavours and gluons to the nucleon spin. He was the leader of the Dutch participation and he was spokesman of HERMES during start-up and first measurements (1994-1995).

Until 2000 he directed the Amsterdam Pulse Stretcher facility at Nikhef. AmPS was the first storage ring where longitudinal polarization of electrons was maintained by a Siberian snake and the stored electrons were scattered from polarized targets. He designed and constructed polarized hydrogen, deuterium and ^{3}He internal targets. The measurement of the charge form factor of the neutron is the best cited work carried out with Nikhef's local accelerator.

Since 2000 he is a member of the LHCb experiment at CERN to study CP violation in the decay of the B meson; to determine elements of the CKM matrix (relation between mass and electroweak eigenstates). As leader of the LHCb/FOM program he was the driving force of the Dutch contributions to the collaboration. He was LHCb project leader of the VELO vertex detector (2001–2005), one of the most advanced silicon vertex detectors worldwide.

His present research focuses on gravitational physics, the least understood interaction in physics. He coordinates all activities in the Netherlands for the Virgo experiment near Pisa, and has made substantial contributions to Einstein Telescope, a third generation gravitational observatory in the design stage. He leads the effort on the development of instrumentation for Advanced Virgo, a European project that should lead to the first detection of gravitational waves. His group has made a systematic study in a Bayesian framework of model independent tests of the validity of General Relativity by using gravitational-wave events. In this field, his group is the leading one in the world.

International visibility, activities, prizes, scholarships etc.

Prof. van den Brand previously held staff positions at MIT, University of Wisconsin-Madison, UvA, and Nikhef. He has a leading position in the Dutch and international gravitational-wave physics community. He was a co-editor and co-author of the Einstein Telescope conceptual design study for a third-generation gravitational-wave observatory. He is a referee for various international journals and for international applications in the fields of subatomic physics. He organized, and was a convenor at large international conferences: *e.g.* PANIC, Few Body, and GWADW. He very frequently represents the gravitational-wave community as a speaker at international conferences and gives lectures at international summer schools.

Personal grants and prizes
NWO-Large investment Advanced Virgo (since 2012).

Key organizational roles
- FOM Program leader "Gravitational physics - the dynamics of spacetime" (since 2010).
- Member of the Virgo Program Supervisory Boards IPRB, CCB, and VSC (since 2010).
- Einstein Telescope: Leader of Working Group 1 of the design study (2008–2011).
- Member of the CERN Contact Committee at the Royal Netherlands Academy of Arts and Sciences (KNAW) (2005–2010).
- FOM Program leader "To study CP violation in the decay of the B meson" (2001–2006).
- FOM Program leader "Spin-dependent electron scattering at AmPS" (1993–2000).
- FOM Program leader "Nucleon spin, flavour and glue" (1993–1995).
- Program Advisory Committee for the Los Alamos Meson Physics Facility (LAMPF), Los Alamos (1992–1995).

Prof. Van den Brand (co-)authored 210 scientific papers in peer reviewed journals with approximately 6,968 citations in total, with an average of 33 citations per paper, and he has an h-index of 43.

5 key publications co-applicant

1. An upper limit on the stochastic gravitational-wave background of cosmological origin, LIGO and Virgo Collaborations, Nature **460** (2009) 990. [136 citations]
2. The LHCb Detector at LHC, LHCb Collaboration, JINST **3** (2008) S08005 [404 citations].
3. Predictions for the rates of compact binary coalescences observable by ground-based GW detectors LIGO and Virgo Collaborations, Classical and Quantum Gravity **27** (2010) 173001. [202 citations]
4. Observation of a Single-Spin Azimuthal Asymmetry in Semi-Inclusive Pion Electro-Production, HERMES Collaboration, Phys. Rev. Lett. **84** (2000) 4047. [330 citations]
5. The Charge Form Factor of the Neutron from ^{2}H(e,e′n)p, I. Passchier, J.F.J. van den Brand *et al.*, Phys. Rev. Lett. **82** (1999) 4988. [145 citations]

Co-applicant 4

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Brief summary of research over last 5 years

Maarten de Jong has focussed his career on the study of cosmic neutrinos. The study of cosmic neutrinos is one of the key components in the field of astroparticle physics. In 2006, he has been appointed as professor in the Netherlands in the field of experimental astroparticle physics. The election as deputy spokesperson (2006–2009) of the ANTARES project and the spokesperson (2013) of the KM3NeT project speak for his leadership in this field.

He invented the 'All-data-to-shore' concept for the readout of the ANTARES deep-sea neutrino telescope. In this, the rare neutrino signal is filtered on shore from the background using a farm of commodity PCs and state-of-the-art software. This achievement is remarkable (few considered this possible) and changed the picture dramatically. Now, his idea has become a seminal part of the astrophysics program with the future KM3NeT research infrastructure.

For the Chorus experiment at CERN, he developed a new track-fit algorithm which improved the final measurement of $\nu_\mu \rightarrow \nu_\tau$ oscillations by such an amount that the most precise result ever was achieved. For neutrino astronomy, he developed a formalism for the probability density function of the detectable signal in a neutrino telescope and showed that the track-fit problem has a linear component. These insights significantly improved the reliability of the simulations and the performance of the analyses.

He initiated the measurements and supervised the analysis that has led to the publication *"Measurement of nucleon structure functions in neutrino scattering"*. At that time, there were only two measurements made worldwide which yielded contradicting results. This paper has been seminal in two ways. It resolved the long standing discrepancy and it is today the one and only measurement of all three structure functions of the nucleon known to exist.

His ideas led to new results (measurement of the size of a very short lived particle), others disproved an initial claim for a new theory (colour transparency). He coordinated the construction and operation of a new kind of particle detector (so-called 'Honeycomb chamber') which marked the first successful application of this kind of detector in a large scale experiment.

For the funding of scientific projects Maarten de Jong has (co-)written various proposals which provided so far a total amount of about 12.4 M€ for investments (more than 1 M€ per year) and about 4.8 M€ for personnel. Throughout his scientific career, he has been supervising Master and PhD students. About half of them continued careers in science, the others found jobs in industry. He regularly gives lectures to laymen and provides quotes to newspaper articles. He appeared multiple times on radio and local TV and appeared once in a theatre play.

International visibility, activities, prizes, scholarships etc.

Maarten de Jong is a leading scientist in the field of neutrino astronomy. He has been a member of various committees in the fields of astroparticle and particle physics and is frequently asked to present the field on various occasions, most notably as a summary speaker of the VLVnT workshop (2011).

Key organizational roles
- Spokesperson of KM3NeT (since 2013).
- Deputy spokesperson of ANTARES (2006–2009).

International committees
- Member of the AstroParticle Physics International Forum (APIF) (since 2008).
- Member of the Astroparticle Physics European Coordination (ApPEC) peer review committee (2002–2005).
- Member of the SPS committee at CERN, (2001–2004).

Prof. De Jong (co-)authored more than 118 scientific papers in peer reviewed journals with approximately 7,015 citations in total and he has an h-index of 41.

5 key publications co-applicant

1. Search for a diffuse flux of high-energy neutrinos with the ANTARES neutrino telescope – ANTARES Collaboration. Phys. Let. **B696** (2011) 16. [31 citations]
2. Measurement of the atmospheric muon flux with a 4 GeV threshold in the ANTARES neutrino telescope – ANTARES Collaboration. Astropart.Phys. **33** (2010) 86. [25 citation]
3. Final results on $\nu_\mu \rightarrow \nu_\tau$ oscillation from the CHORUS experiment – CHORUS Collaboration. Nucl. Phys. **B793** (2008) 326. [22 citations]
4. The data acquisition system for the ANTARES Neutrino Telescope – ANTARES Collaboration. Nucl. Instrum. Meth. **A570** (2007) 107. [82 citations]
5. Measurement of the nucleon structure functions in neutrino scattering – CHORUS Collaboration. Phys. Lett. **B632** (2006) 65. [59 citations]

Co-applicant 5

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Brief summary of research over last 5 years

Prof. dr. Ad van den Berg leads the Astroparticle Physics group at the Kernfysisch Versneller Instituut and is an expert in the detection of cosmic rays at the highest energies using radio-detection techniques. He is interested in understanding the origin of cosmic rays at ultra-high energies and their acceleration mechanisms.

His recent research focuses on the understanding of the origin of the highest energy cosmic rays and on the development of radio-detection techniques for the observation of extensive air showers. He is leading the radio-detection technique at the Pierre Auger Observatory and his group at the University of Groningen has developed the models for radio emission from air showers using a macroscopic approach. This work resulted in the disentanglement of different emission mechanisms which play a key role at MHz frequencies.

Ad van den Berg has focused in the recent years on the physics with and the origin of cosmic rays at extreme energies, which is one of the key science questions of astroparticle physics. In 2009 he has been appointed as professor at the University of Groningen in the field of experimental astroparticle physics. He and his group joined in 2005 the Pierre Auger Collaboration and was asked at that time by the collaboration to lead the development of the radio-detection technique for cosmic rays, recognizing his leadership. Under his leadership the first detection of cosmic rays at the Pierre Auger Collaboration was performed and a detailed comparison of experimental and theoretical data has been achieved. With these efforts he moved the radio-detection technique from small-scale experiments to the present medium-scale experiment through the deployment of more than 100 stations spread over an area of more than 10 km^2.

In mid-1990s he was active in the determination of the Gamow-Teller strength using charge-exchange reactions at at small momentum transfer values, which is extremely important for neutrino-less double-beta decay studies. He is an expert in the technique to perform experiments at very small scattering angles with very high energy resolution using magnetic spectrometers. He designed and constructed such a spectrometer for the AGOR facility of the University of Groningen.

International visibility, activities, prizes, scholarships etc.

Ad van den Berg is a leading scientist in the field of cosmic-ray physics. He has been member of various committees in the fields of astroparticle.

Key organizational role

- Leader of the R&D for radio detection of high-energy cosmic rays at the Pierre Auger Observatory (since 2005).
- Member of the Financial Board of the Pierre Auger Collaboration (since 2005).
- Member of the taskforce Auger2015 of the Pierre Auger Collaboration (since 2012).
- Country representative of the Netherlands and member of the Collaboration Board at the Pierre Auger Collaboration.
- Deputy Director Kernfysisch Versneller Instituut of the University of Groningen (2001–2009).
- Director of the International Summer School Nijmegen2012 (2012).

International committees

- Associate member of the IUPAP C4 (since 2012).
- Organizer of the International Cosmic Ray Conference (ICRC) in 2015 at The Hague, NL.
- Member of the ASPERA Scientific Advisory Committee (2010–2012).
- Co-author of the European Roadmap for Astroparticle Physics (2011).
- Member of FINUPHY (FP5 I3 on Frontiers in NUclear PHYsics) (1998–2005).

Prof. Van den Berg (co-)authored more than 150 scientific papers in peer reviewed journals with approximately 3,700 citations in total and he has an h-index of 33.

5 key publications co-applicant

1. Correlation of the highest-energy cosmic rays with nearby extragalactic objects, Pierre Auger Collaboration, Science **318** (2007) 938. [360 citations]
2. Observation of the suppression of the flux of cosmic rays above $4x10^{19}$ eV, Pierre Auger Collaboration, Phys. Rev. Lett. **101** (2008) 061101. [227 citations]
3. Correlation of the highest-energy cosmic rays with the positions of nearby active galactic nuclei, Pierre Auger Collaboration, Astropart. Phys. **29** (2008) 188. [225 citations]
4. Measurement of the depth of maximum of extensive air showers above 10^{18} eV, Pierre Auger Collaboration Phys. Rev. Lett. **104** (2010) 091101. [146 citations]
5. Measurement of the energy spectrum of cosmic rays above 10^{18} eV using the Pierre Auger Collaboration, Phys. Lett. **B685** (2010) 239. [120 citations]

Other co-applicants

Name	Gender	Affiliation	Specialisation / group	Awards, grants, roles	h-index
Frank Linde, Prof.	Male	FOM-Nikhef	Nikhef Director	Physicaprijs 2013	71
Niels van Bakel	Male	FOM-Nikhef	Detector R&D	Nikhef program leader	44
Harry van der Graaf	Male	FOM-Nikhef	Detector R&D	ERC Advanced	34
David Groep	Male	FOM-Nikhef	Grid Computing		11
Els Koffeman, Prof.	Female	FOM-Nikhef	ATLAS		74
Marcel Merk, Prof.	Male	FOM-Nikhef	Flavour Physics	FOM program leader	50
Marieke Postma	Female	FOM-Nikhef	Theoretical Physics	VIDI	14
Wouter Verkerke	Male	FOM-Nikhef	ATLAS		89
Jos Vermaseren	Male	FOM-Nikhef	Theoretical Physics	ERC Advanced	41
Sytze Brandenburg, Prof.	Male	RUG	Accelerator Technology		17
Klaus Jungmann, Prof.	Male	RUG	Precision (Particle) Physics	FOM program leader	24
Mariano Mendez, Prof.	Male	RUG	Astroparticle Physics		41
Elisabetta Pallante, Prof.	Female	RUG	Theoretical Physics	R. Franklin Fellowship	23
Rob Timmermans, Prof.	Male	RUG	Theoretical Physics	KNAW Fellowship	21
Nicolo de Groot, Prof.	Male	RU	ATLAS	FOM program leader	88
Heino Falcke, Prof.	Male	RU	Cosmic Ray Physics	Spinoza, ERC Advanced	52
Ronald Kleiss, Prof.	Male	RU	Theoretical Physics		45
Klaas Landsman, Prof.	Male	RU	Mathematical Physics	NWO-TOP, Pionier	21
Gijs Nelemans, Prof.	Male	RU	Gravitational Physics	VIDI	34
Ana Achucarro, Prof.	Female	UL	Theoretical Physics	VICI	22
Alexey Boyarsky	Male	UL	Theoretical Physics		20
Dorothea Samtleben	Female	UL	Astroparticle Physics		9
Gleb Arutyunov	Male	UU	Theoretical Physics	VICI	73
Andre Mischke	Male	UU	Heavy Ion Physics	ERC Starting, VIDI, VENI	55
Thomas Peitzmann, Prof.	Male	UU	Heavy Ion Physics	FOM program leader	81
David Berge	Male	UvA	ATLAS / CTA		64
Patrick Decowski	Male	UvA	Dark Matter Physics	FOM program leader	51
Paul de Jong, Prof.	Male	UvA	ATLAS	VICI	73
Paul Kooijman, Prof.	Male	UvA	Astroparticle Physics / KM3NeT		74
Eric Laenen, Prof.	Male	UvA	Theoretical Physics	FOM program leader	30
Sera Markoff	Female	UvA	Astroparticle Physics / CTA	VIDI	30
Ralph Wijers, Prof.	Male	UvA	Astroparticle Physics	ERC Advanced, VICI, EU Prix Descartes	57
Kjeld Eikema, Prof.	Male	VU	Laser Precision Physics	VICI, VIDI	20
Davide Iannuzzi, Prof.	Male	VU	Optical Technology	ERC Starting, VIDI	14
Piet Mulders, Prof.	Male	VU	Theoretical Physics	ERC Advanced	43
Gerhard Raven, Prof.	Male	VU	Flavour Physics		79
Wim Ubachs, Prof.	Male	VU	Laser Precision Physics	FOM program leader	31

Co-applicants with an indication of their work field. The h-index is determined for published articles as specified by the SPIRES database and verified whenever possible with the ISI database.
The co-applicants are scientists who are committed to the research foci of this proposal. The full complement of astroparticle and particle physicists linked to this proposal is significantly larger, and includes people such as Prof. M.J.G. Veltman (Nobel prize 1999) and Prof. J.J. Engelen (presently chair of the NWO board).

Abstract

Study summary

In the past century immense progress has been made in unravelling the structure of elementary particles and fields - from the periodic table of elements to quarks and leptons and their antiparticles – culminating in the Standard Model of particle physics. Throughout, cosmic-ray and accelerator-based experiments played a decisive role, with the discovery of the Higgs particle as a recent highlight. The Standard Model not only explains a plethora of high-precision data from particle-physics experiments all around the world, but also allows a qualitative and quantitative description of the evolution of our Universe. It connects the sciences of the infinitely large (astronomy) and the infinitesimally small (particle physics).

Recent experiments, observations and theoretical speculations, however, point to a Universe far stranger than predicted by the Standard Model. Fundamental deficiencies in the model have emerged, for example concerning dark matter and dark energy, or different species of neutrinos transforming into one another. Fascinating, yet unproven, theories, such as supersymmetry, have been put forward. Addressing these far-stretching scientific questions is the domain of (astro)particle physicists. Nicknamed 'Big Science' because of long lead times and substantial investment costs, progress in (astro)particle physics requires strongly synergistic efforts by groups all over the world.

Dutch scientists play a disproportionally large role in these global developments. This is in part due to the fact that four Dutch universities have effectively bundled their activities into a national centre for particle physics, Nikhef. In this way, they achieve optimal synergy without losing the ability to respond to new developments quickly. Both internationally and nationally, the Nikhef organization model is invariably referred to as the exemplary way to nationally coordinate research in 'Big Science'.

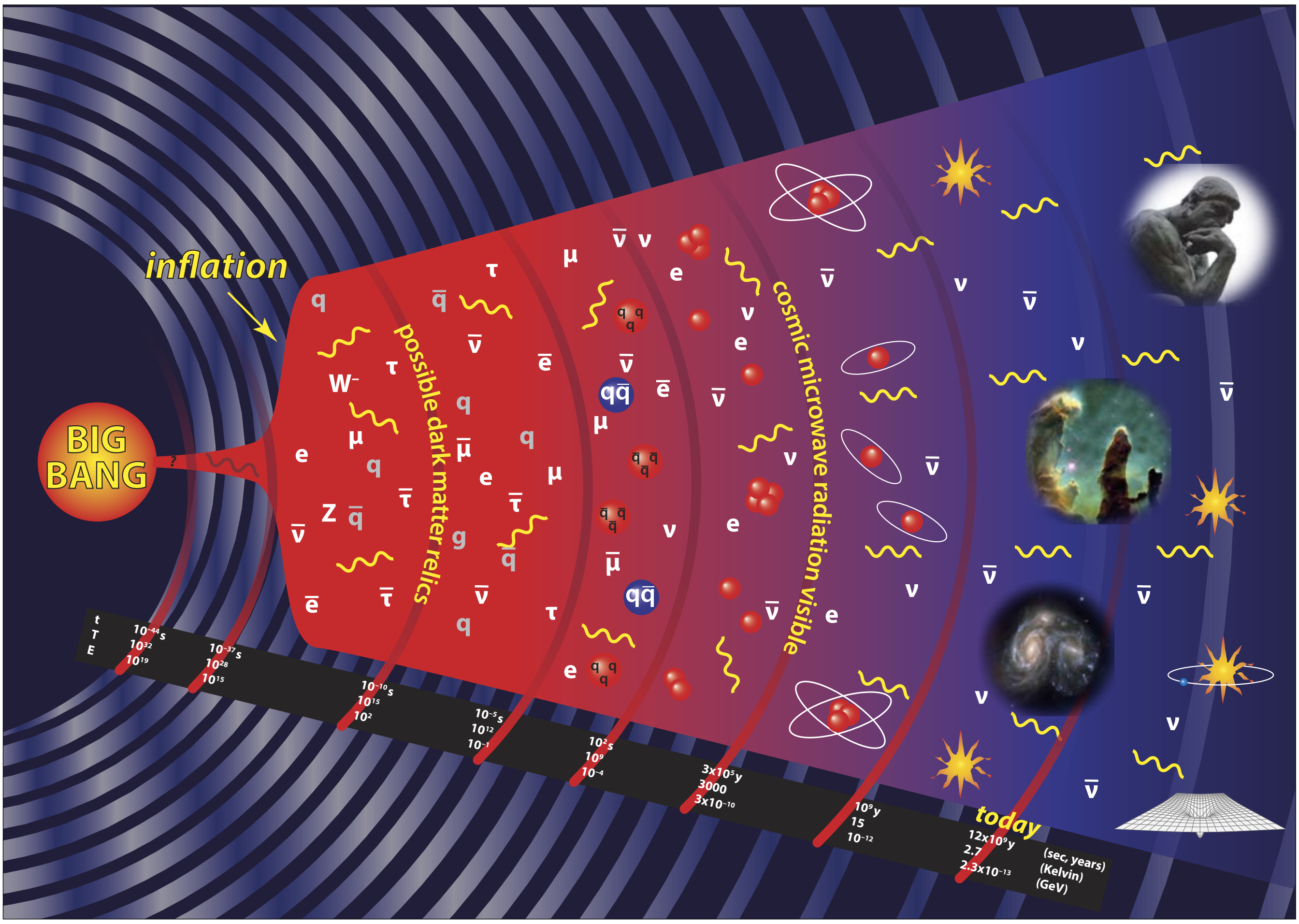
With this Gravitation proposal "NL-APP", we aim to leverage Nikhef's world-class knowledge infrastructure and harvest the strong potential of Dutch researchers in the field. Through NL-APP, we will establish an ambitious research program pushing the frontiers in (astro)particle physics and technology. The national consortium and organizational model as proposed in NL-APP will provide the astroparticle and particle physics research communities in the Netherlands the strongest possible position for the coming decades.

We will achieve our aims along two routes: First, we will roll out the very successful Nikhef model of collaboration to research groups in other Dutch universities, by funding high-profile new positions between these groups and Nikhef. By forging new strong links and extending the network, we can truly make the whole stronger than the sum of its parts. Second, through strategic hirings and associated funds, the consortium can engage in new experiments that are vital to answer the questions above, and which were hitherto not pursued.

The NL-APP program focuses on the main frontiers of the research field:

- **The Energy Frontier:** *Exploration of the limits and possible limitations of the Standard Model at the Large Hadron Collider (LHC) and the future International Linear Collider (ILC);*
- **The Cosmic Frontier:** *Search for answers about the origin of cosmic rays and the nature of dark matter, and investigation of General Relativity by studying gravitational waves;*
- **The Precision Frontier:** *Search for new phenomena by extremely accurate measurements of precisely calculable quantities;*
- **The Technology Frontier:** *Groundbreaking technology, such as detector technology, computational techniques and data handling and analysis, to enable groundbreaking experimentation at the leading edge in (astro)particle physics.*

The time to do so, is now: fundamental discoveries that will (re)define our understanding of the Universe are truly within reach, provided the right synergy and critical mass is achieved in (astro)particle physics research. With the Nikhef model having proven its strength as a platform of collaboration, and Dutch scientists at the forefront of research developments, the opportunity to take a leap forward is real.



The history of the Universe according to our standard model of cosmology.

Summary of the research proposal in layman's terms

The physics of the infinitely small (particle physics) and the infinitely large (astronomy) use a common and very successful theoretical framework. For the first time we have a quantitative description of the evolution from the Big Bang, 13.7 billion years ago, to our 'cool' Universe, today. However, this framework is shown to be incomplete.

In this proposal Dutch research groups from six universities will collaborate to explore unsolved mysteries of our Universe, using highly advanced experimental techniques.

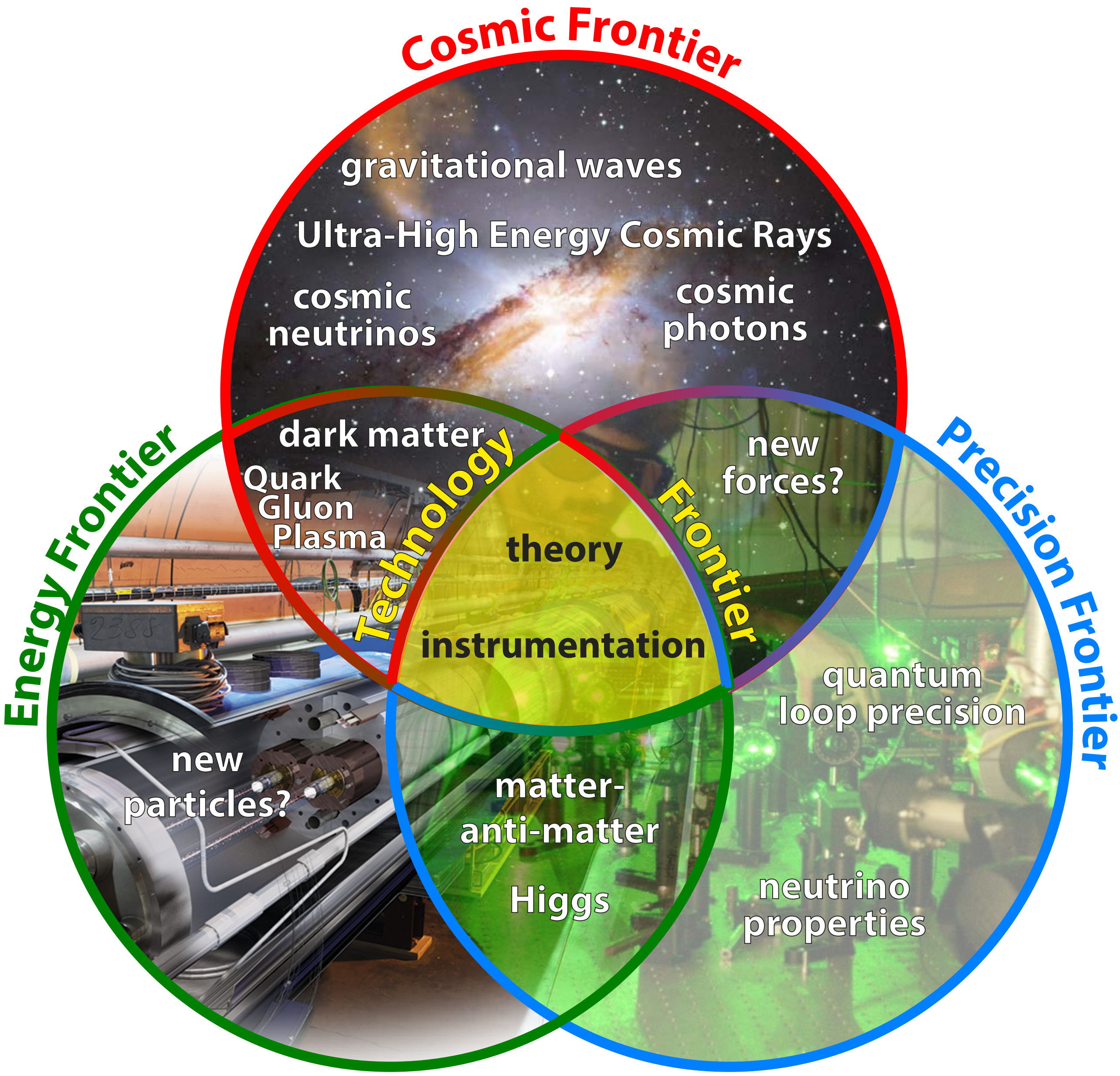
Key words

1. Elementary particles
2. Early Universe
3. Dark matter
4. Cosmic rays
5. Gravitational waves

Research proposal

NL-APP: Crossing the frontiers of astroparticle & particle physics

Contents



Executive summary

Our understanding of the physical processes driving our Universe has increased to the point where we can describe most phenomena within the framework of a single Standard Model. This model can not only explain the plethora of high-precision data from particle-physics experiments all around the world, but it also, together with Einstein's theory of General Relativity, allows for a quantitative description of our Universe's evolution from nanoseconds after the Big Bang until today, 13.7 billion years later. With more precise measurements and theoretical understanding has come a realization that our Universe is stranger, more wonderful and more complicated than anticipated. In addition to normal matter (and light), our Universe is filled with dark matter and dark energy. Every known particle may even be paired with a, so far undiscovered, supersymmetric partner particle. The properties of the lightest and least interacting Standard Model particle, the neutrino, may be responsible for the abundance of matter over antimatter and hence, in essence also for the mere existence of galaxies, stars, planets … and us.

The time has come to turn our attention to the Universe as a whole. The questions that come to the forefront are the themes of this proposal. Can we identify dark matter? What are the cosmic accelerators that provide particles with an energy beyond 10^{20} eV and how do they work? What is the origin of the widely different masses of the elementary particles? How were protons created out of the initial plasma of quarks and gluons? Is the neutrino its own antiparticle, and thereby of Majorana type? Do gravitational waves exist? If so, could these provide insights into limitations of General Relativity or even allow for us to literally hear the echo of the Big Bang? Answers to any of these questions will revolutionize the understanding of our Universe and of its evolution. As has often happened before, we may well end up with a view of our Universe that is quite different from the picture we have today. Our search for answers to these questions requires a diverse experimental program in particle physics and astronomy, fields in which The Netherlands has a long-standing, excellent reputation, witnessed by our high profile in flagship projects like the Large Hadron Collider and the LOFAR radio telescope, where we "punch above our weight".

The research plan

With this NWO Gravitation program the consortium intends to raise the pursuit of these questions to a world-leading level on all fronts. We will roll out the very successful Nikhef model of collaboration to research groups in other Dutch universities and fund high-profile new positions to form new collaborative working groups in key areas of astroparticle and particle physics research. The areas of research where concerted and coordinated efforts are most likely to lead to breakthroughs are: *Precision High- and Low-Energy Physics; Gravitational Waves; Search for the sources of Cosmic Rays; Search for Dark Matter; Technological Innovation*.

In the area of **Precision High- and Low-Energy Physics** the emphasis will be on ever more precise measurements of parameters within the Standard Model. A comprehensive determination of the properties of the Higgs particle, both at the LHC and a future linear collider (ILC) will provide strict limitations for any physics that does not fit in the Standard Model. The investigation of the strong interaction and the Quark Gluon Plasma, a matter state through which the Universe passed as it cooled from the Big Bang to its present state, will provide us insight on how present-day particles were formed. The investigation of properties of quarks and leptons is expected to shed light on the asymmetry between matter and antimatter in the Universe. The determination of the anomalous magnetic moment of the muon, the search for an electric dipole moment of the muon and for evidence of neutrinoless double beta-decay, provide an alternative to experiments at the energy frontier as a route towards establishing physics beyond the Standard Model.

Gravitational Waves research promises to open up an entirely new way of observing the Universe. Einstein's theory of General Relativity postulates that mass deforms spacetime. One of the more spectacular consequences of this theory is that a system with accelerated masses (*e.g.* the coalescence of compact binary systems) emits moving ripples of deformed spacetime, the so-called gravitational waves. A new generation of experiments that monitor the structure of spacetime on Earth will soon be sufficiently sensitive to detect the passage of such gravitational waves. The observation of gravitational waves from the coalescence of binary systems allows for a stringent test of the second theoretical ingredient required for the description of the evolution of the Universe, General Relativity. Additionally, they allow for an independent distance measurement in the Universe. In the future they may even be able to establish evidence for the ringing of spacetime from the effects of the Big Bang.

The **Search for the sources of Cosmic Rays** has yet to unveil the most powerful accelerators in the Universe and will then investigate their extreme physics. These quests will be pursued with a "multi-messenger" approach that the Dutch astroparticle physicists have adopted. Here, the search is performed using ultra-high-energy cosmic rays and high-energy neutrinos. Through this proposal the pursuit of the missing ingredient in the present Dutch effort, high-energy gamma rays, will as well become possible.

In the research area **Search for Dark Matter**, the collaborative effort proposed will allow a multi-pronged search for dark matter and its properties. In most dark matter theories the space around us is filled with weakly interacting dark-matter particles. Earth's movement through space thus results in a constant flux of such particles through the Earth. This flux might be detectable with specialized experiments. As dark matter in space is gravitationally attracted by massive objects, higher densities of dark matter are expected to accumulate in the core of massive celestial bodies such as the Sun and the centre of the Galaxy. Here, pairs of dark-matter particles might annihilate each other. Such annihilations leave a distinct signature in the form of high-energy neutrinos or gamma rays that can be detected on Earth. Finally, dark-matter particles might be produced at the LHC, which offers an opportunity for a detailed investigation of their properties, and link them to the, yet undiscovered, laws of Nature that govern their existence.

All these areas require contributions from the last research area, **Technological Innovation**. Here, the above fields find an additional link through the required cutting edge technology for detectors and accelerators. The areas of data acquisition, data handling and data integrity are also indispensable pillars on which the above research platform is built.

Embedding

The strength of the Dutch particle physics effort lies in the nationwide cooperation in a single well thought out and well coordinated science program. Herein, Nikhef plays a crucial role by providing continuity as well as critical mass in setting up new areas of research. From this platform the Dutch have been able to reach high. This paradigm of central organization and constructive dialogue between researchers in various universities and even various disciplines has made the Dutch particle physics the envy of the world. Where efforts from other countries are all too often fragmented into many university groups, the Nikhef model has allowed for the Netherlands to achieve a position and status much stronger than one would anticipate from numbers alone. The applicants of this proposal are known for their individual talents and have a proven track record of high-profile international collaboration in their respective fields, and with each other. They are fully prepared to take the lead in expanding the Nikhef model to incorporate more universities and more individual research groups. With collaborative and increased strength, we shall be a world-leading force in researching the questions above, and a centre of astroparticle and particle research in the world.

Talent plan

To reach this goal, we plan to provide a substantial injection of resources into each of the described research areas. For each area we envisage the appointment of a number of tenure-track positions together with a comprehensive package of associated postdoctoral appointments and PhD positions. This will provide a nation-wide research focus in the area of astroparticle and particle physics. The appointees will be respected (young) scientists with proven track record in research and leadership, will form a new network for the emerging topics in the research focus areas and will provide the necessary coherence in relation to the more established topics. Together, the appointees will constitute a pool of educators that will provide nationwide courses at the Master level in their research area. They are expected to enhance the program of outreach to the general public, which is already an established priority and success within the astroparticle and particle physics community in the Netherlands. The Nikhef institute will provide the technical and organizational focal point. This will position the appointees in a well-established framework providing international recognition and the continuation of the excellent links with industry and the general public at large.

The focus areas identified in this proposal are all newly emerging fields. Either because of recent breakthrough measurements (the Higgs), or because they are positioned in fields where the technology for the measurements has only recently become mature enough to expect significant results in the next decade (gravitational waves, ultra-high-energy cosmic-ray observatories, gamma-ray telescopes, neutrino telescopes and dark-matter detectors).

Now, the time is ideal to invest in these emerging research fields to reap maximum scientific return.

Quality of the researchers involved

Success in experimental astroparticle and particle physics *i.e.* 'Big Science' depends not only on the excellence of the individual scientists, but also on focus and critical mass. Moreover, in view of the often long lead times and substantial investment costs, an excellent governance and management structure is a *sine qua non*. Nikhef (Fig. 1), as a collaboration of the physics-funding agency FOM and four Dutch universities, offers all these aspects. Because of the 'Big Science' character and the position of Nikhef in the NL-APP proposal, we first comment on the qualities of Nikhef as a collective, before addressing the individual qualities of the researchers.

Figure 1. The Nikhef collaboration (dark grey) plus other Nikhef-associated Dutch universities and institutes. In Nikhef (National Institute for Subatomic Physics) collaborate: the Foundation FOM, the University of Amsterdam, the VU University Amsterdam, the Radboud University Nijmegen and Utrecht University. Nikhef coordinates and supports the (astro)particle activities in the Netherlands. Besides, the Nikhef consortium, other Dutch universities and institutes collaborating with Nikhef are indicated.

Nikhef research

The central and pivotal strength of our research community is Nikhef, established in 1976 to coordinate Dutch research at CERN. Dutch physicists (and government representatives) have played important roles throughout the history of CERN, as first Director General (Bakker), Scientific Director (Hoogland & Engelen) and members of the Scientific Policy Committee (Gaemers, 't Hooft and Veltman). Dutch scientists were also instrumental in CERN's major discoveries: the W and Z boson discovery in 1983 (relied upon stochastic cooling developed by Nobel prize winner van der Meer); the detailed tests of electroweak radiative corrections in the 1989-2000 period (Nobel prize winners 't Hooft and notably Veltman contributed in many ways to this success); the recent Higgs discovery (the number one scientific breakthrough in 2012 according to Science Magazine) required sophisticated tools like the FORM computer algebra program (Vermaseren) and the RooFit data modelling and fitting package (Verkerke). This crowning research required a vast coordinated experimental effort that in the Netherlands was coordinated by the main applicant (Bentvelsen). At CERN he and other members of the consortium, notably from the University of Amsterdam and the Radboud University Nijmegen, occupied key positions in the analysis organization and detector operations that led to the rapid discovery of the Higgs particle. Within the Netherlands, Nikhef pioneered astroparticle-physics research in 1999 with the ANTARES deep-sea neutrino telescope project. In 2004, Nikhef brought together particle and nuclear physicists, astronomers and theorists to form the Committee Astroparticle Physics Netherlands that defined and published the Dutch priorities in astroparticle physics research [1]. Following the strategy defined in this roadmap, we are now a major player in the next generation neutrino telescope project KM3NeT (spokesperson M. de Jong); we lead the radio detection studies for the Auger cosmic-ray observatory (coordinated by van den Berg); and we are a key player in the Virgo gravitational-wave interferometer (group of van den Brand). In addition we accepted major responsibilities in the construction of the next direct dark matter search: the noble-liquid XENON1T experiment (group of Decowski).

Organizational model

Both internationally and nationally, the Nikhef organization model is invariably referred to as the exemplary way to coordinate particle physics research nationally. An excellent example hereof is found in the conclusions of the international committee installed by NWO to review Nikhef in 2011:

- *The committee was very impressed by FOM-Nikhef and assess it as an outstanding centre of excellence. It is one of the leading laboratories in particle physics in the world, with outstanding achievements in detector and electronics design, construction and commissioning, physics analysis and advanced computing techniques, supported by a strong theory group.*

- *It is remarkable how the Netherlands, thanks to this unique organization, play a central role in particle- and astroparticle physics while the level of Dutch investments are just at the European average. Nikhef, with FOM-Nikhef in the centre, is a unique and very efficient model, giving the Dutch research a much larger international impact than if the corresponding resources were distributed among a set of independent university groups and institutes, as is the case in most other countries in the world.*

- *The success of Nikhef is also due to the strong leadership and active management within FOM-Nikhef. It has resulted in a restrictive set of programs covering the mission of the institute with experiments at the most competitive level. For each program, there are no experiments with a higher potential, than the ones in which Nikhef is engaged.*

NWO evaluation report Nikhef 2005-2010

To further corroborate the international standing of Nikhef, we compared the aggregate h-index of Nikhef with those of other leading large particle physics research institutes and laboratories. As can be concluded from the aggregate h-index (Table 1) and the h-indices of the individual applicants (see page 15), Nikhef sits in the top league.

Institute	Npub	mean citations per article	aggregate h-index
LAL-Orsay	3089	51	6.43
Nikhef	**4030**	**46**	**6.36**
MPI-Munich	5642	46	6.32
DESY-Hamburg	7466	52	6.21
LAPP-Annecy	2844	48	6.19
CPPM-Marseille	1495	51	6.12
LNF-Frascati	5953	40	5.90
KIT-Karlsruhe	4126	48	5.80

Table 1. The output of Nikhef compared to other leading large particle physics research institutes and laboratories. The aggregate h-index (h-index/Npub$^{0.4}$, see [2]) is an indicator designed to compare the scientific output of institutes that could be of disparate size. Npub is the number of publications in the HEP-SPIRES database.

The researchers

With the NL-APP proposal, experimental astroparticle and particle physics research will become a truly nationally organized endeavour putting together research groups in the six Dutch universities that are active in the field of (astro)particle physics (see Fig. 1). Four of these six are already part of the Nikhef collaboration. The new groups (Groningen and Leiden) come with important and often complementary expertise, for example in accelerator physics and low-energy precision experiments. In addition, by joining forces, a strong Dutch contribution to challenging and very promising projects, like the Cherenkov Telescope Array (CTA), becomes realistic. (Fig. 22 on page 49, shows the complementarity and collective strength of the NL-APP consortium for the selected research activities.)

Individual recognition (as opposed to excellence) is hard to achieve in 'Big Science' endeavours since it is often difficult to separate between personal and collaborative achievements. What is evident from the information provided for the applicants, is that many of them have very high h-indices. In addition to personal grants and awards, a recognized figure of merit is the responsibilities one has within large collaborations. Nikhef does very well in this respect according to its international scientific advisory committee:

Dutch scientists, after making important contributions to the hardware, have kept their prominent position in all –LHC– collaborations with a very significant (even outsized) role in producing the first physics results. They are very visible and well represented in a number of leadership and management positions, including the position of 'upgrade coordinator' in both ATLAS and ALICE.

Scientific Advisory Committee report Nikhef 2011

The applicants of NL-APP have a strong track record in the area of (astro)particle physics. To illustrate this, we list below some key accomplishments (detector hardware, data analysis and/or physics interpretation) achieved over the past decade:

- ATLAS: Design and construction of high-precision muon detectors covering a very large surface (2000–2008); Discovery of the Higgs boson with notable contributions to the observation of its decay into pairs of Z and W bosons; Exclusion of light strongly interacting supersymmetric particles (2009–2013);
- LHCb: Design & realization of the LHCb VELO silicon strip vertex detector (2001–2005); Innovative CO_2-cooling principle; First measurement of the extremely rare $B_s \rightarrow \mu\mu$ decay (2012);
- ALICE: Design & realization of the extremely low-mass ALICE Silicon Strip Detector (1998–2007); Discovery of large elliptic flow in heavy-ion collisions, (Snellings, 2010);
- Theory: Calculation of the 3-loop QCD splitting functions with FORM computer algebra, (Vermaseren, 2004);
- Computing: Foundations for LHC computing grid (2001-2004); International Grid Trust Federation (Groep, 2005). Realization of a national e-Infrastructure, including the Dutch LHC Tier1 site (2007–2012);
- Detector R&D: First recording of an ionizing track with the revolutionary GridPix detector: a drift cell on top of a silicon pixel chip (van der Graaf, 2007); RASNIK alignment system patent (van der Graaf, 2008);
- Knowledge utilisation: The development and first applications of hybrid pixel detectors for X-ray imaging outside high-energy physics. This resulted in a Nikhef startup company, Amsterdam Scientific Instruments (van Bakel, 2012);
- Neutrino telescope: ANTARES 'All data to shore' data acquisition concept (M. de Jong, 1997); KM3NeT multi-PMT optical module concept (2003); First observation of upgoing neutrinos in ANTARES (2006);
- Gravitational waves: Design & realization of compact vibration isolation systems for Advanced Virgo gravitational-wave search (2011→); Realisation of a dedicated "Test Infrastructure for General Relativity" data analysis pipeline for LIGO and Virgo;
- Cosmic rays: Development and proof of principle of the radio detection of cosmic rays at the Pierre Auger cosmic-ray Observatory (2006–2010); First quantitative decomposition of polarization components in radio signals of extensive air showers (2013).

Personal grants and awards by Nikhef staff include: one Spinoza award winner (Falcke); four ERC Advanced grant recipients (Mulders, van der Graaf, Vermaseren, de Wit); three VICI (Bentvelsen, P. de Jong, Snellings) and many VIDI recipients within the NWO Innovational Research Incentives Scheme; and one ERC Starting grant recipient (Mischke). Bentvelsen and Linde shared the 2013 Physicaprijs for their contributions in the discovery of the Higgs particle. The applicants of the 'new' groups include one ERC Advanced grant recipient (Wijers); four VICI (Achucarro, Arutyunov, Eikema, Weijers) and several VIDI recipients, and a Rosalind Franklin fellowship (Pallante).

Figure 2. Prof. Stan Bentvelsen discusses the ATLAS results pertaining to the Higgs boson with Prof. Peter Higgs (July 2012).

The main applicants, each representing one of the six partner universities in the NL-APP consortium, all have leading positions in large international collaborations. Some of them have been (van den Brand, HERMES) or are (M. de Jong, KM3NeT) the spokesperson, the highest leading position in an (astro)particle physics experiment. One received the prestigious (KNAW) Academische Jaarprijs (S. de Jong) and another one the equally prestigious (NNV) Physicaprijs (Bentvelsen).

Several of the (other) co-applicants are also involved in the Delta-Institute for Theoretical Physics (DITP), which has been granted a 'Gravity subsidy' in the previous round for their proposal *"Theoretical Physics of Matter at all Scales"*. Whilst this shows the excellence and relevance of this research in the Netherlands, we want to underline that there is ***no*** funding overlap between the DITP work and the predominantly experimental subatomic physics approach in this NL-APP proposal.

Quality of the scientific research programme

The discovery in 2012 of the Higgs particle (See Fig.3) at CERN [3] has opened a new chapter in particle physics, where the emphasis is toward the understanding of not only the world around us but also of the Universe as a whole. The very successful Standard Model of particle physics has been built over the last century by a close interplay between theory and experiment. Many theoretical extensions of this model, addressing insofar unresolved problems, point the way to new physics, as yet unfettered by experimental results. The present proposal will extend and strengthen experimentation in astroparticle and particle physics to provide evidence of the Universe beyond the Standard Model. The true nature of the Higgs particle will be sought by high statistics experiments at the LHC and the future linear collider. At the same time, these experiments will search for phenomena such as creation of new particles, with a particular emphasis on possible candidates for the dark matter that seems to outweigh normal matter in our Universe by five to one. In addition, high-precision low-energy experiments allow for the search for new interactions that manifest themselves as minute deviations from the predictions of our Standard Model. The nature of dark matter is investigated by searching for evidence of collisions by dark-matter particles with normal matter and through the search for signals from areas in the cosmos where they are expected to congregate and annihilate.

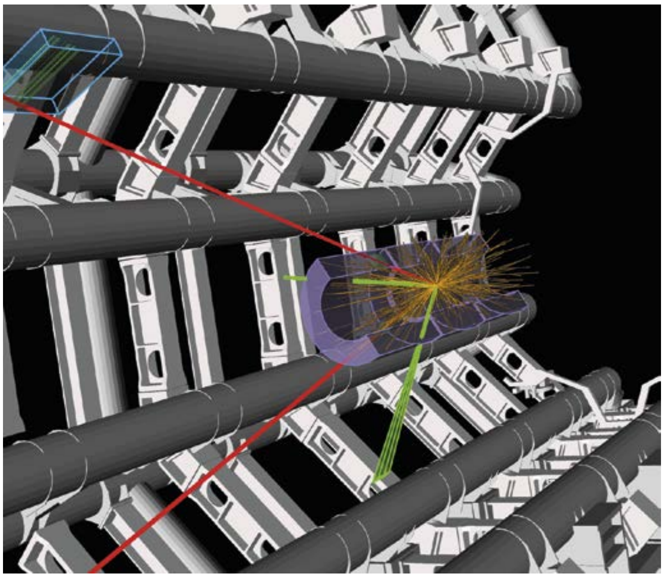


Figure 3. Observed decay of a Higgs particle into two muons (red) and two electrons (green) in the ATLAS detector.

The origin of the extremely high-energy particles that pervade the Universe remains a mystery. Searching for sources of these particles and investigating the mechanism through which they are accelerated is the goal of experiments that will detect ultra-high-energy cosmic rays, high-energy neutrinos and high-energy photons.

The investigation of the Universe would of course not be complete without a study of the force governing the large scale expansion of the Universe: gravitation. Detection of gravitational waves will provide stringent tests of General Relativity and promise, to even allow for a 'look' at the Big Bang itself.

All this experimentation is of course not possible without technology that keeps pace with experimental requirements. Detectors with extreme accuracy in position and time determination, data acquisition and handling, computation in triggering as well as physics modelling, and data access and security are all being pushed to the technological limit.

Finally, this experimental endeavour cannot be undertaken without positioning it clearly in society as a whole. Both outreach to the general public and dissemination of gained knowledge and technology are an integral part of this proposal.

I. Crossing the Particle Physics Frontier

With the spectacular discovery of the Higgs-like particle with the ATLAS and CMS detectors in 2012, the foundation of the Standard Model of elementary particles seems undisputed. All properties of elementary particles (their quantum numbers and interactions) are described by this Standard Model. At the same time, insofar as they can be predicted, all experimental data ranging from high-energy collisions at accelerators to high-precision measurements at low energy are described by this model. The Standard Model is the triumph of particle physics of the last 40 years.

The Standard Model (See Fig. 4) encompasses the fermions, the fundamental building blocks of all known matter: quarks and leptons, each in six types, organised in three families. The Standard Model describes three fundamental forces, each of which is carried by spin-1 bosons that act on the matter particles. The strong interaction is mediated by eight gluons, the weak nuclear interaction by W- and Z-bosons and the electromagnetic interaction by the photon. The fourth force, gravitation, is not included in the Standard Model, but is independently described very successfully by the theory of General Relativity.

There are, however, limitations to the Standard Model. It lacks, for instance, a deeper explanation for the number of particle generations, the hierarchy of particle masses, the origin of observed symmetry violations such as the matter-antimatter asymmetry in the Universe or even more intriguingly the nature of the dark matter known to pervade our Universe.

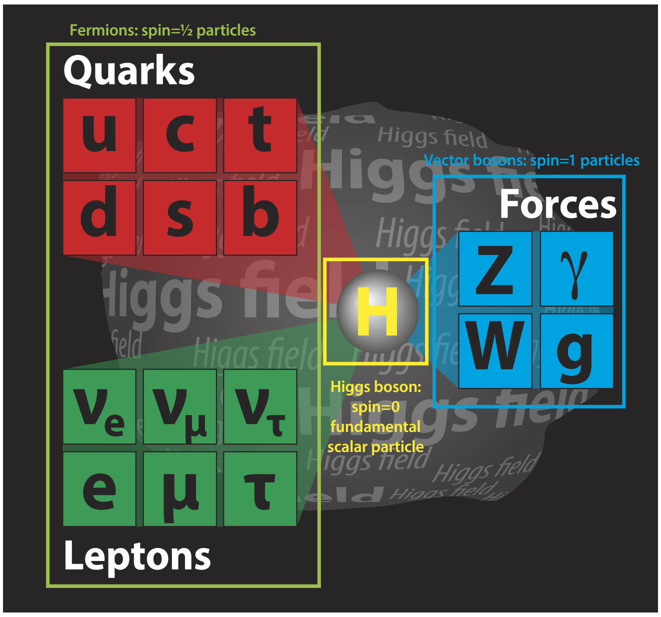


Figure 4. The Standard Model, comprising building blocks of matter (six quarks and six leptons), the messengers of forces (four vector bosons), and the Higgs particle.

The Higgs particle and beyond

All interactions described by the Standard Model are based on internal local gauge symmetries that form the heart of the model. Symmetries not only provide a very elegant guiding principle of Nature but also ensure a consistent mathematical description. Intrinsically, through their mass, the W- and Z-bosons do not obey the electroweak symmetry. The Higgs mechanism [4] provides a means of breaking the electroweak symmetry and generating particle masses in a dynamical way. The breakdown of the electroweak symmetry at low energy creates an omnipresent Higgs field in the vacuum of the Universe. Particles effectively acquire mass through interactions with this field. The Higgs particle is the inescapable consequence and is therefore rightly considered as the smoking gun evidence for this mechanism. In the Standard Model, the Higgs field not only imparts masses to the fundamental particles, but is also directly related to the origin of a matter versus antimatter asymmetry in the laws of Nature.

Advancing our knowledge beyond that of the Standard Model will require precise determination of the electroweak symmetry breaking and of the properties of the Higgs particle itself. The discovery of a Higgs-like particle is the start of the study of electroweak symmetry breaking. In the near future, the mass, width, spin and symmetry properties of the new particle will become clear. To know whether the particle is really a Standard Model Higgs boson requires precise determination of its couplings to fermions, to gauge bosons, and ultimately the measurement of the coupling to itself. Such measurements need a large sample of Higgs particle candidates and consequently a very large number of additional collisions at the LHC.

Research focus — Precision studies of the Standard Model and beyond

Phenomenology of the Higgs at the LHC, in connection with high precision Higgs physics at the future electron-positron International Linear Collider (ILC). Searches for deviations from the Standard Model predictions.

Even if the measurements favour the interpretation of this particle as a Higgs boson, it may not be the Standard Model Higgs boson and the electroweak symmetry breaking may be more complex and involve other elements:

- There may be more Higgs bosons than the Standard Model one;
- The discovered Higgs particle might be a composite particle instead of an elementary particle;
- The discovered particle may be a mix between a Higgs boson and another, non-Standard Model, state;
- The Higgs boson might decay into new, massive, weakly interacting particles;
- The Higgs boson may not be solely responsible for restoration of unitarity in high-energy gauge boson scattering.

At the LHC, large samples of events will be collected, providing answers to a number of these questions. Providing and collecting these samples requires a significant upgrade of the accelerator to enhance the production rate, and the detectors ATLAS, ALICE and LHCb to deal with these higher intensities. A future linear (electron-positron) collider, ILC, will explore the Higgs sector with even higher precision.

New symmetries beyond the Standard Model

As symmetry properties play a crucial role in our understanding of the structure of the subatomic world, the observations of new symmetries or new particles provide a direct and spectacular indication of physics beyond the Standard Model. New symmetries may only become apparent at very high energies, equivalent to going back further in the history of the Universe.

- *Grand Unification* is the idea that the gauge groups of the Standard Model are in fact subgroups of a more fundamental gauge group at higher energies, with unified couplings. The expectation is that such a unification could take place at energies of order 10^{16} GeV. At lower energy, the fundamental grand unified gauge group breaks down into the Standard Model groups and additional groups, giving rise to new gauge bosons. These may be observable at the LHC.
- *Supersymmetry* provides a link between fundamental matter and force particles. (See Fig. 5) Supersymmetry is a deep symmetry, connecting internal symmetries with spacetime symmetries. Supersymmetry transforms a boson into a fermion, and vice-versa, while keeping all other quantum numbers untouched. Supersymmetry predicts the existence of superpartners to every known Standard Model particle. Supersymmetry at the TeV-scale also provides stability of the Higgs boson mass, it enables unification of the gauge forces and it naturally provides a dark-matter candidate particle.

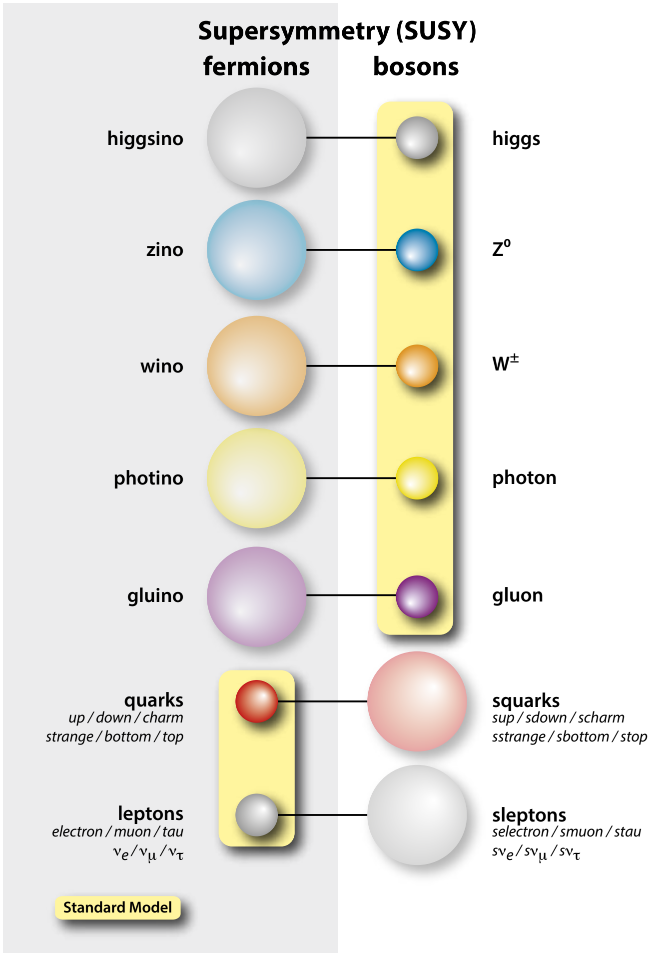


Figure 5. Supersymmetry; for every type of boson there exists a corresponding type of fermion and vice-versa.

Extensions of the Standard Model contain alternatives to the Higgs mechanism of electroweak symmetry breaking and predict new particles such as multiple Higgs and W and Z bosons.

Research focus — Creation of dark-matter particles

The use of high energy proton-proton collisions for the creation of new particles in the context of a search for dark matter. Phenomenology of Supersymmetry and other physics models beyond the Standard Model.

Symmetries of the strong interactions

Although the Higgs mechanism is seminal in the understanding of the mass of fundamental particles, it does not account for all the mass in the subatomic world. The formation and existence of composite objects like protons and neutrons, described by the strong interaction, is not understood in terms of its fundamental particle content. In fact, the largest fraction of the mass of these particles, and hence the mass in our known Universe, is generated dynamically by the strong interaction.

Quantum chromodynamics (QCD) is the underlying theory of strong interaction that differs from the other interactions by being a genuine multi-particle theory. QCD is well established even though the fundamental constituents of QCD, the quarks and gluons, cannot be observed as free particles. One of the key features of QCD is the self-coupling of the gauge bosons (gluons), which leads to the confinement of the quarks and gluons in bound states. This phase transition, thought to have occurred 10^{-5} s after the Big Bang at a temperature of 10^{12} K, is poorly understood from first principles. Some theoretical understanding of the complex features of the theory is provided by lattice QCD, where the QCD field equations are solved numerically on a discrete spacetime grid. Lattice QCD can provide quantitative information on the strong phase transition and on the equation of state of the matter, the so-called Quark Gluon Plasma (QGP, see Fig. 6).

The calculation of dynamical properties of the QGP (like transport coefficients) from lattice QCD is very difficult and currently only possible with very large uncertainties. An alternative approach, using the correspondence between strongly coupled conformal field theories (CFT) to classical gravitation in weakly curved spacetime geometries, has recently been successfully used to establish strong coupling limits for some of the transport coefficients.

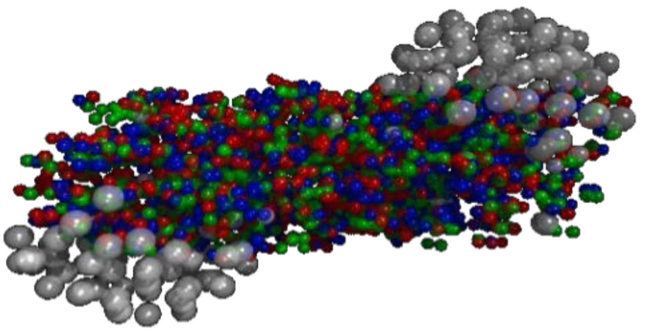


Figure 6. Simulation of the moment of impact of two lead ions in the ALICE detector, quarks in red, blue and green. Hadrons (protons, neutrons) in grey.

Collisions of heavy-ions at LHC energies produce matter with temperatures that are well above the strong phase transition temperature and provide a unique tool to create the QGP and study its properties. The properties of the QGP will teach us about the evolution of the early Universe, about the formation of normal matter and about the behaviour of the strong interaction under conditions of extreme temperature and density.

These same collisions can also reach another new limit of the strong interaction: the colour-glass condensate. The extremely high densities in the initial state of the collisions should allow for a description of the fundamental quantum fields of QCD (the gluons) in their classical field limit, which is very likely the only such opportunity for a subatomic interaction. The exact characterization of the QGP state of matter and the search for new phenomena are the future program with heavy-ion collisions at the LHC.

Research focus — Exploring the limits of the strong interaction
Investigation of QCD matter to further understand the strong interaction and its role in the early Universe. Exploit newly emerging theoretical approaches in the interpretation of the phenomenology of the Quark Gluon Plasma.

Violation of symmetries: matter versus antimatter
In our Universe, matter dominates over antimatter. For our Universe to exist, some fundamental symmetries such as baryon number conservation, charge conjugation and charge-parity (CP) conjugation must be broken. The Standard Model allows for a small amount of CP violation in the interactions of quarks, but this amount is insufficient to explain matter dominance. With the discovery of neutrino oscillations, that require neutrinos to have mass and mix between generations, an alternative mechanism to generate the matter-antimatter asymmetry, leptogenesis, becomes feasible.

Quarks versus leptons
Currently, experimental observations of CP violation are all consistent with complex couplings within the Standard Model, giving rise to subtle differences in the interactions of quarks and antiquarks. The recent measurements of neutrino oscillations indicate that also there CP violation would be possible due to the same mechanism. In particular, in the case of Grand Unified theories, the mechanisms become intertwined and for instance large mixing angles between ν_μ and ν_τ lead to measurable deviations from Standard Model predictions for decays of B-mesons.

Majorana and sterile neutrinos
Neutrinos are unique among the Standard Model fermions as they are neutral and only interact through the weak nuclear interaction. In the past decade, it has been established that neutrinos possess mass, be it very small. If neutrinos would be their own antiparticles, making them so-called Majorana particles, an extension of the Standard Model, called the seesaw mechanism, could give rise to an inverse relationship between the masses of new, heavy, right-handed neutrinos and the light neutrinos. The heavy neutrinos would have been produced abundantly at the high temperatures in the early Universe. In the presence of CP-violating phases their decays would result in a lepton-antilepton asymmetry that in turn could be converted into a baryon-antibaryon asymmetry.

It is important to establish the Majorana nature of neutrinos, as well as the existence of CP-violating phases in the neutrino mixing matrix. For the former aspect, neutrinoless double-beta decay experiments are the only practical method. The recent observation of a comparatively large neutrino mixing angle (θ_{13}) has opened up the possibility for measuring the latter. The issue of the neutrino mass hierarchy and the number of neutrino families, including the possibility of sterile neutrinos hinted at by recent experimental results, is also an exciting window on new physics.

Research focus — Flavour physics in the quark and lepton sector
Research to establish possibilities of matter-antimatter asymmetry through CP violation in both the quark and lepton sector.

LHC experiments
The Large Hadron Collider (LHC, see Fig. 7) has shown to be very successful and will dominate particle physics in the coming years. After a shutdown in 2013 and 2014, the LHC will provide proton-proton collisions at, or close to, the design energy of 14 TeV, as well as collisions between heavy ions. The energy increase allows to scan an even larger mass range for the existence of new (supersymmetric) particles. It also directly benefits Higgs physics, since the Higgs production cross section increases by a factor 2.6 in going from 8 to 14 TeV. Until approximately 2022, a total of at least 300 fb^{-1} of integrated luminosity will be delivered, 10 times what is available today. After a further upgrade, the LHC will operate until 2030 providing yet another full order of magnitude more data. Exploiting the scientific potential offered by this LHC program is clearly the priority in particle physics research. The Dutch community has made significant contributions to the ATLAS [5], LHCb [6] and ALICE [7] experiments, in terms of detector hardware and electronics, software, and data analysis. SARA/Nikhef also operates one of about ten worldwide Tier1 data centres for the LHC.

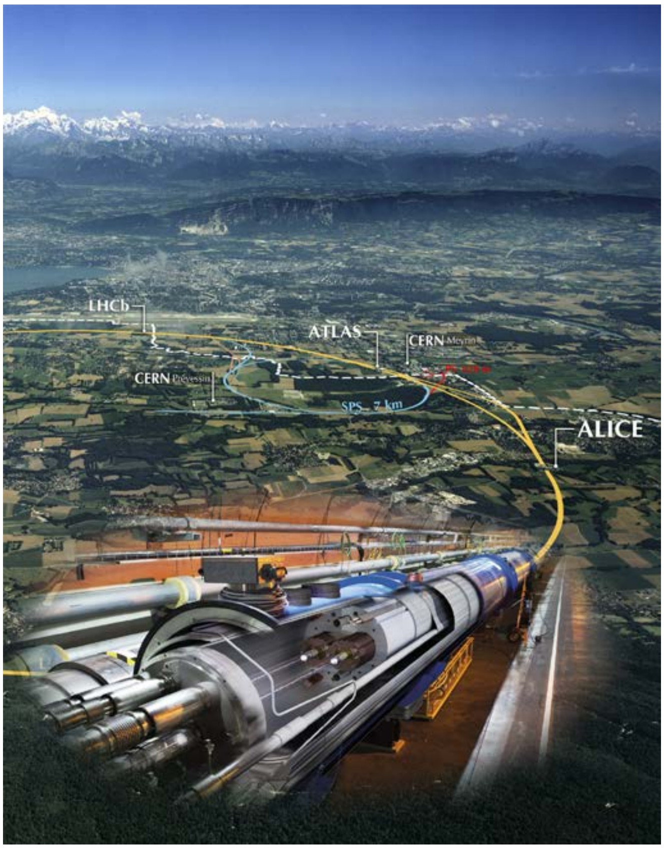


Figure 7. An aerial view of the CERN site, showing the location of the LHC experiments. The inset shows an artist's impression of the LHC accelerator underground.

In the first years of running, the ATLAS detector provided the evidence for the Higgs particle. The future program concentrates on high-precision measurements of the Higgs particle properties and the search for new particles, new symmetries or new phenomena. There are great challenges associated to future LHC running with ATLAS. Triggering will become increasingly difficult. Each event will be produced together with more than 100 other collisions. New, radiation-hard detectors need to be designed, constructed and installed. Large and powerful computing systems, and intelligent software, are needed to analyse the data. The ATLAS experiment foresees achieving its goals through a series of successive upgrades to the detector, the trigger, and the data acquisition system. Dutch physicists are actively involved in the inner tracker, the muon spectrometer, the trigger and data acquisition system, computing, and advanced software tools.

The ALICE experiment has demonstrated its excellent performance in the first years of operation, already producing results far beyond the capabilities of many years of data-taking with earlier, lower-energy experiments [8]. The new upgraded detector will, from 2019 onward enable ALICE to measure collisions at much higher rates. The agreed continuation of the heavy-ion program at the LHC up to at least 2025 will allow for the advance into precision measurements of the strong interaction and, in addition, investigate signatures of the colour-glass condensate.

The discovery potential of the LHCb experiment was proven by the observation of new CP-violation phenomena in charm and beauty mesons, as well as the discovery of one of the rarest particle decays measured to date [9]. In the lepton sector, the experiment will test lepton flavour violation in τ to μ decays and search for second and third generation GeV-scale sterile neutrinos, in particular in decays of charm and beauty mesons. The upgraded detector allows for a precise investigation of the question whether it is the specific interplay of the Higgs field and the weak interaction that is the sole source of the matter-antimatter asymmetry in Nature, or whether this picture is insufficient. The upgraded detector, scheduled to collect data from 2019 onward, allows for operation with ten times higher luminosity and implements a real-time reconstruction of the events at the 40 MHz LHC collision frequency. Dutch physicists have the ambition to build an improved detector system for charged particles and to design a real-time trigger-system based on GPU technology.

High Precision Particle Physics at Lower Energy

Whereas high-energy experiments aim at the direct observation of new particles, low-energy precision experiments search in a complementary way for deviations of measured parameters from the predictions of the most precise calculations within the Standard Model. Precision experiments allow in many cases for exploration of a parameter space not accessible in present direct searches at high energies.

Precision techniques probe phenomena normally associated with TeV-physics with measurements at the femto-eV level. Key ingredients in these measurements are ultra-stable lasers and cold and controlled samples of atoms and molecules. An example is the measurement of parity violation in atomic and molecular systems, where indications for new Z bosons or leptoquarks, predicted by Grand Unification, may appear. New physics may also reveal itself in a deviation of the Weinberg angle $\sin^2\theta_W$ from its predicted value as a function of momentum transfer.

Sensitive searches for electric dipole moment [10]

New sources of CP violation can manifest themselves in large permanent Electric Dipole Moments (EDMs) of fundamental particles. Although CP violation is included in the Standard Model, the predicted EDMs are strongly suppressed and are orders of magnitude smaller than present experimental sensitivities. The observation of a large EDM is an unambiguous sign of the existence of physics beyond the Standard Model. On the other hand, its absence can serve to rule out or constrain new theories.

Three systems can provide unique EDM sensitivities: the radium and xenon atoms and the muon. The enhancement of the electron EDM is largest in atoms. The atomic and nuclear structure of radium enhances the EDMs of its constituents by many orders of magnitude. Long spin coherence times, in excess of six hours, make sensitive measurements on xenon possible. The muon EDM offers the shortest route between experiment and fundamental theory.

Determination of the anomalous magnetic moment of the muon [11]

The anomalous magnetic moment of the muon (‘g–2’) is known to a relative precision of about ½ parts-per-million, both experimentally and theoretically. Currently, the predictions differ by a tantalising 3 to 4 standard deviations from the observations. New particles and interactions, not contained in the Standard Model, are able to provide an explanation for such a discrepancy. The theoretical uncertainty is dominated by the hadronic uncertainty. This can be reduced by employing new approaches such as lattice gauge theory. The experimental uncertainty will be reduced by a factor of five by a new set-up planned at Fermilab (Chicago, USA).

Research focus — Sensitive EDM, g–2 and neutrinoless double-beta decay

Precision determination of the EDMs, g–2 and neutrinoless double-beta decay as harbingers of new physics.

Variation of ’constants’ of Nature over cosmological time scales

The Standard Model neither provides an explanation for the values of the fundamental coupling constants, nor does it require their constancy over space and time. Observation of a varying constant may shed light on these fine-tuned values that underlie the complexity of the Universe. Theoretically, models for drifting constants invoke additional quantum fields such as a dilaton scalar field in the simplest scenario, which may be interpreted as evidence for a new force.

Experimentally, a promising target is the dimensionless proton-electron mass ratio $\mu=m_p/m_e$ [12], which, if variations occur, is anticipated to undergo a more rapid rate of change than the fine structure constant α_{EM}.

Precision measurements of transition frequencies (spectral lines) in atoms and molecules provide an ideal search-ground for spacetime varying constants. On a cosmological time scale, large numbers of spectral lines in the hydrogen molecule, the so-called Lyman and Werner band lines, probe the Universe looking back 10 billion years in cosmological history. These are detected via optical spectroscopy using the world's largest telescope; the Very Large Telescope of the European Southern Observatory, in Paranal, Chile. A comparison is then performed with laboratory laser spectroscopy. The goal is to significantly reduce the current constraint on a variation of the proton-electron mass ratio of $\Delta\mu/\mu<10^{-5}$, exploring more than 12 billion years back in time.

Search for new particles and forces in table-top experiments

Technological advances in lasers, in particular the frequency comb laser revolution, combined with the emerging capabilities of controlling and manipulating single photons, atoms, ions and molecules, have defined a new realm of precision. The possibility of performing frequency measurements of quantum systems to 17-digit accuracy brings the opportunity of testing theory into unexplored territory. Small quantum objects, like the hydrogen atom and the helium ion, are calculable to extreme precision. LaserLab VU aims at investigating the He-ion, for which a laser with an extremely short wave length is being developed, and the He-atom which is investigated at high precision from a Bose-Einstein condensate. Both are expected to provide crucial insights into the proton-size conundrum. The precision is such that new long-range hadronic interactions can be probed at the Å scale. The ultra-precise laser techniques will also be extended to search for drifting constants on a laboratory time scale, where some objects chosen are known to be very sensitive to the effect of a varying proton-electron mass ratio, and which is amenable by molecule manipulation by lasers and electromagnetic fields.

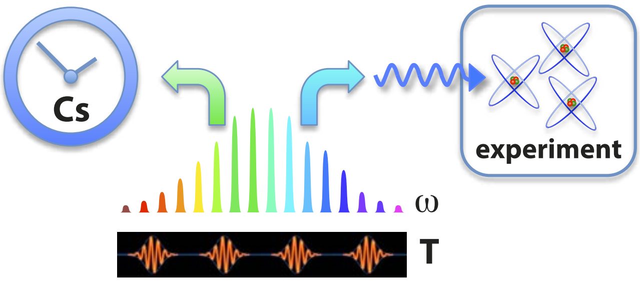


Figure 8. Frequency comb lasers enable unprecedented accuracy for optical precision measurements, by linking optical frequencies to the best atomic, such as cesium, clocks.

Research focus — Extreme precision table top experiments

A comprehensive research program focusing on extreme precision experiments to search for deviations from precise theoretical predictions and for drifting of fundamental constants on both a laboratory and a cosmological time scale. The latter requires a 0.6 M€ investment budget to build a sub-Hz frequency comb facility, attached to a state-of-the-art ion-trap atomic clock (See Fig. 8).

II. Crossing the Cosmic Frontier

Only a century ago, our information about the Universe came from visible light. It is now known that visible-light photons are but a minute fraction of the particles with which the cosmos can be investigated. Cosmic photons are now observed with energies ranging from much below empty space thermal values (neV) to high-energy gamma rays (up to 300 TeV). Nuclei of practically all elements are observed as charged cosmic rays with energies from GeV to many EeV (10^{18} eV), and have led to many particle physics discoveries in the early days of cosmic ray research. Neutrinos from the Sun and the nearby cosmos have told us about solar dynamics and supernova explosions, while they have also revealed some secrets of their own nature, *e.g.* that they have mass. The information from all these particles has coalesced in our understanding of a Universe originating from a Big Bang and evolving according to the laws of particle physics and General Relativity. But there are ingredients missing from our observations: known matter only constitutes 5% of the energy content of the Universe, the remaining 95% consisting of dark matter and dark energy of unknown composition and origin. Finally, one cosmic messenger, much anticipated, has remained unobserved so far: gravitational waves, travelling ripples in the fabric of spacetime itself.

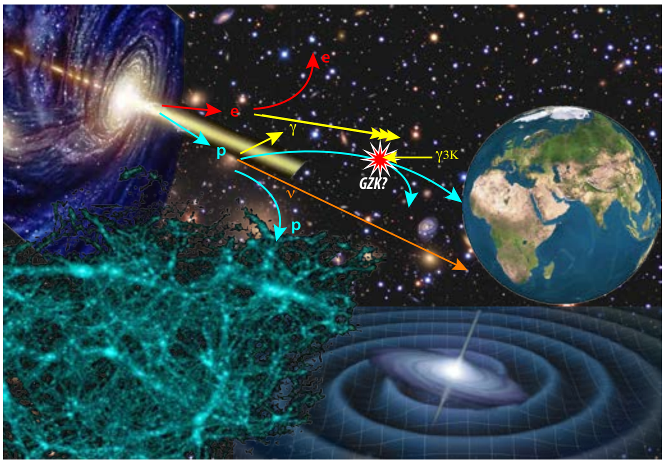


Figure 9. The multi-messenger approach to scientific studies at the cosmic frontier. Sources emit various species of cosmic particles, such as nuclei that can be detected in Auger, neutrinos that can be detected in KM3NeT, high-energy photons that can be detected in CTA, and gravitational waves that can be detected in Virgo. These different messengers involve sometimes the same, sometimes different physics processes at the source. They have different properties of propagation over large distances: photons travel via straight lines and have a short cosmic horizon due to their interaction with matter and background photons. Charged cosmic rays are bent by the galactic and intergalactic magnetic fields. At energies where they are hardly bent, their cosmic horizon is limited due to interactions with the cosmic microwave background. Neutrinos travel virtually unaffected over any distance in a straight line. Gravitational waves penetrate practically unaffected through the entirety of spacetime, back to times that are unreachable in any other way.

In a coherent approach together with astrophysics and high-energy physics, astroparticle physics investigates fundamental questions about the Universe with all possible tools at its disposal.

- *Where and how are cosmic rays accelerated?* The details of the acceleration mechanisms for the galactic sources of cosmic rays will be investigated. The detection and understanding of the sources of ultra-high-energy cosmic rays ($E>10^{18}$ eV) is still one of the most fundamental and unsolved questions in astroparticle physics. Both for the Galactic and extra-galactic sources, combined data sets from gamma-ray, cosmic-ray and neutrino observatories are needed to pinpoint their origins, and to unveil the spectacular physics processes that initiate such extreme acceleration (See Fig. 9).
- *What is the nature of dark matter?* Dark matter is a key ingredient in both particle-physics theories beyond the Standard Model and our understanding of cosmology. It is looked for in three ways: direct detection through the interaction of a dark matter particle with normal matter; indirect detection via signals of dark matter annihilation processes from massive object in the cosmos; and direct production in Earth-based accelerators such as the LHC.
- *What is the nature of spacetime itself?* The observation of gravitational waves would open the door to unparalleled precision measurements in the regime of strong and dynamical gravitational fields, and start the field of "cosmography". The Hubble constant can be measured directly, the nature of dark energy can be investigated and the very early Universe observed.

The NL-APP consortium will address all of these questions. The origin of the highest-energy particles in the Universe is studied through the measurements of cosmic rays, the detection of high-energy neutrinos, the measurement of GeV to PeV gamma rays, and the detection of gravitational waves. The properties of the dark-matter particles will be studied by the three detection methods. To understand the structure of the Universe, the detection of gravitational waves will be advanced.

Experimental astroparticle physicists in the Netherlands operate in large international collaborations such as Auger (cosmic rays), KM3NeT/ANTARES (neutrinos), XENON (dark matter) and Virgo (gravitational waves). Each of these, besides their astrophysical-oriented research, can also pursue particle-physics goals, providing both a connection to and an extension of the high-energy and precision frontiers. For example, interactions of incredibly high-energy cosmic rays in the upper-atmosphere may show evidence for new particles and open a window to the study of particle-particle interactions far beyond the TeV scale. Neutrino telescopes may discover long-sought magnetic monopoles. Dark matter detectors can be used to investigate the nature of neutrinos through neutrinoless double beta decay. Gravitational waves will test our understanding of spacetime structure in ways that are otherwise completely inaccessible.

The current line-up has one main missing core element: the detection of high-energy gamma rays from sources within and outside our Galaxy. There is much interest in this burgeoning field in the Netherlands, and this proposal would allow our participation as full partners in the international Cherenkov Telescope Array (CTA) project, currently in an advanced state of development. A small group of researchers in the Netherlands are already full members of the CTA collaboration and have been developing plans to contribute to part of the small telescope components, via a proposal to the Netherlands Research School for Astronomy (NOVA). If successful, this proposal will roughly match the funding requested here for CTA-related research, and lead to a significant role of the Netherlands in the world-wide collaboration.

The strength of our interdisciplinary approach is that we combine expertise in building and running experiments with expertise in data analysis and interpretation, as well as with expertise in theoretical modelling of astrophysical processes. This unified approach will allow for substantial advancement in questions like the mechanism of high-energy particle acceleration in the Universe. In a multi-messenger approach the same astrophysical objects will be investigated by means of cosmic-ray, neutrino, gamma-ray and gravitational-wave detectors. Via our connections with the astrophysics community, we will combine these data with radio through X-ray measurements of non-thermal emission processes that trace the same high-energy particle population at the source, and compare this complete experimental picture to theoretical models of acceleration, propagation and emission processes of high-energy particles. The NL-APP consortium is comprised of world-leading experts of particle-detection techniques, experimental astroparticle physics, astronomical data analysis and theoretical high-energy astrophysics, and it is therefore ideally positioned, by combining our expertise, to address those seminal questions of astroparticle physics mentioned above.

All techniques used in these detectors and telescopes are now so advanced that they form a perfect complement to the precise particle-physics methods in the previous section. Used together, breakthroughs in the understanding of our Universe are almost guaranteed in the next decade. The scale and scope of the questions above are grand indeed, so let us clarify them each further, starting with the most common and yet mysterious force of all: gravitation.

Gravitation and gravitational waves

Albert Einstein's 1915 theory of General Relativity revolutionized our understanding of the relationship between space, time and gravitation. No theory has had such an impact on our imagination. It is a classical theory and therefore must surely fail at the Planck scale, where quantum effects become important. However, there is as yet no complete quantum theory of gravitation, nor is gravitation unified with the other fundamental forces. Experiments to test gravitation are difficult, and progress has been slow. Meanwhile, another jolt to our understanding of gravitation came to us from astronomers who shocked the world with the discovery of dark energy. Times are changing, however, and new technology now provides the opportunity to study gravitation, and thereby the very nature of spacetime.

Figure 10. The Virgo interferometer near Pisa, Italy.

General Relativity has no adjustable parameters and therefore makes solid predictions. One of these is that gravitational waves, caused by mergers of black holes or neutron stars, must be traversing the Universe, and by all estimates are detectable. If they are detected they allow for high precision tests of General Relativity. Already exciting by itself, the detection of gravitational waves from the period of inflation of the Universe would be sensational. This will directly probe strong quantum gravitation effects.

The dynamics of spacetime

In 1974 Hulse and Taylor discovered a binary pulsar, two neutron stars in orbit around each other, a wonderful system to study the workings of gravitation. Its orbital properties change precisely in accordance with loss of energy and angular momentum caused by the emission of gravitational waves. Naturally, this has changed the emphasis of gravitation research from static to dynamical properties of General Relativity. The direct detection of gravitational waves on Earth would be a watershed event. For the first time, we could actually study strong-field dynamics of General Relativity and test the theory in the most extreme regimes, where effects of quantum gravitation may become manifest.

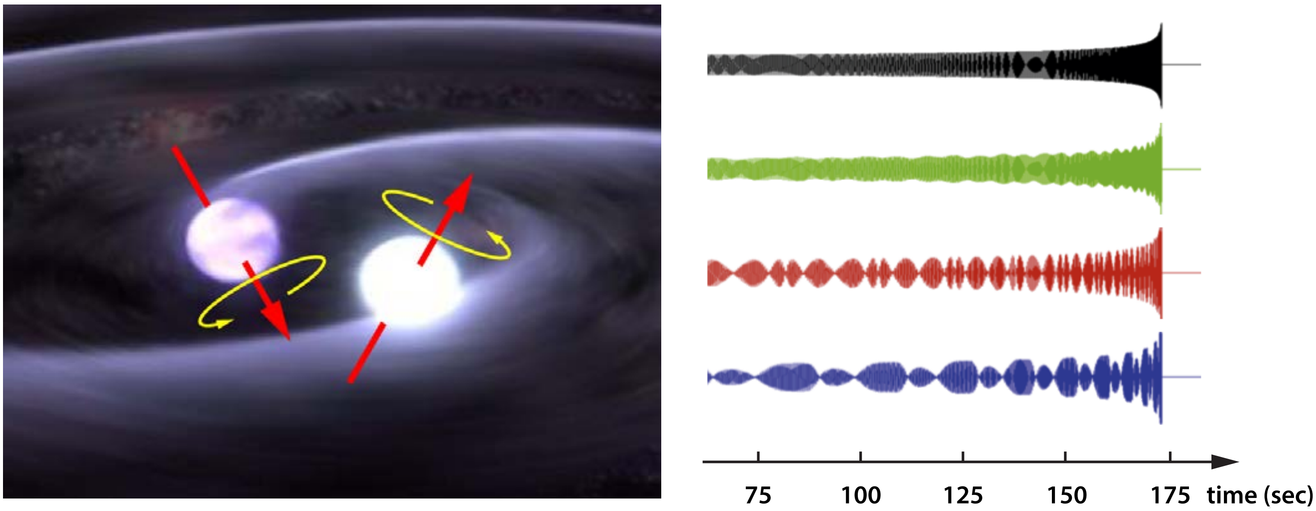


Figure 11. Without spins the amplitude and frequency of the gravitational-wave signal increase in a steady 'chirp' (top), while with spins, precession of the inspiral plane causes amplitude and frequency modulation. The rich dynamics appearing in this way can be exploited to dramatically improve parameter estimation. These effects will need to be included in waveforms used for data analysis, in order to disentangle the subtle behaviour of binary black holes and look for corrections to General Relativity.

The dynamics of binary coalescence is remarkably rich, especially for two merging black holes. Such black holes are predicted to spin fast, which affects their mutual revolution. If the two spin axes are not aligned the orientation of the orbital plane precesses, and a tumbling motion can result. This in turn modulates the phase and amplitude of the emitted waveform, as illustrated in Fig. 11. General Relativity predicts these effects precisely, so they can be tested in detail. Modifications to General Relativity have been suggested in the context of compact binary coalescence. These include scalar-tensor theories, a varying Newton's constant and parity violating theories. Also string theory suggests new effects that are in reach of gravitational-wave observations. General Relativity may even be shown invalid in a way that is not yet envisaged. The current Advanced Virgo/LIGO detectors (See Fig. 10) will provide the first strong field test [13], preparing for future ultra-high precision tests with the ground based Einstein Telescope and the eLISA gravitational-wave satellite mission. The tasks are clear: methods must be developed to detect deviations from General Relativity in a generic way, for which accurate predictions, including astrophysical effects, within the framework of General Relativity are important.

Research focus — Numerical relativity
Numerical relativity, which involves large-scale simulations of the spacetime around merging binary black holes or neutron stars. Connecting predictions of General Relativity with data from the LIGO and Virgo interferometers.

Cosmography
Among the purposes of cosmology is cosmography: mapping the geometry and evolution of the Universe from the Big Bang until now. Such a map would tell us about the composition of the Universe, including the dark energy that seems to drive its accelerated expansion, and could well reveal deviations from General Relativity, now at very large length scales. For this to work there is still too large an uncertainty on the fundamental Hubble constant (H_0), in terms of which the expansion of the Universe at the present time is measured. The current best value, H_0=70.2±1.4 km/(s Mpc), follows from combining data from the Wilkinson Microwave Anisotropy Probe (WMAP) with measurements of the Baryonic Acoustic Oscillations. If the assumption that the dark energy equation of state is constant in time is relaxed, the uncertainty on H_0 increases substantially and its value lies, at the 90% confidence level, somewhere in the range 61–84 km/(s Mpc).

Gravitational-wave observations will provide an alternative, more direct method to determine this parameter, without the systematic uncertainties associated with the so-called cosmic distance ladder. Specifically, for gravitational waves emitted by coalescing binaries and merging super-massive black holes, the luminosity distance can be measured directly from the gravitational waveform itself. The redshifts of the gravitational-wave sources must then be determined from other measurements. If the binary coalescence involves at least one neutron star, then, based on numerical relativity calculations, an electromagnetic counterpart to the wave is expected that can identify the host galaxy. Dutch astronomers are actively developing facilities and methods to tackle the problem of finding these counterparts in the large gravitational-wave sky error boxes. The accuracy on H_0 would reach 1.3 km/(s Mpc) after only one year of running the LIGO–Virgo, Kagra and LIGO–India interferometer network.

The time dependence of the dark energy equation of state is highly interesting. Scientists at Nikhef have shown that the future Einstein Telescope would provide a handle on this through gravitational waves, albeit in competition with future supernova surveys, but with the benefit of being independent of the more uncertain cosmic distance ladder.

Primordial gravitational waves
The most spectacular discovery from gravitation research would be the identification of gravitational waves emitted immediately after the Big Bang (primordial gravitational waves), or of waves caused by so-called cosmic strings. This would truly be a window on the early Universe, because gravitational radiation propagates uninterrupted from cosmic events at the highest temperatures and distances, such as from the beginning of the Universe. Only redshift affects their journey to here and now. Primordial gravitational waves may also bear imprints from the Grand Unification scale of 10^{16} GeV. The detection of any such background would have consequences for fundamental physics that cannot be exaggerated. We would have a direct view on the mechanisms of inflation, of phase transitions in the early Universe or of the formation of topological defects, and possibly of much more.

Clearly, gravitational-wave research holds great promises: a direct view on the beginnings of our Universe, and many other exciting phenomena at the cosmic frontier and beyond. There is a growing, highly active group of Netherlands-based astronomers and physicists pursuing gravitational-wave detections, aided by a versatile theory community.

From such a base, building an interdisciplinary gravitational-physics program between particle physics, cosmology and astronomy is called for. The bridge will be a new initiative that combines input from the different disciplines to determine the experimental signatures of the gravitational-wave sources. The excitement in this community about the imminent first detections and the long-term future with ground and space detectors is palpable. Through the NL-APP consortium, and its highly connected network, this program would take off rapidly.

Research focus — Gravitational-wave sources
Modelling of experimental signatures of gravitational waves, including neutron star physics, quantum gravitation effects and Big Bang phenomenology.

Cosmic rays
Extremely high-energy cosmic rays are rare but they do manage to arrive sporadically at Earth. Exactly what sort of particles they are, however, as well as where and how they are created are still profound mysteries. This proposal will enable big steps in addressing these questions.

Figure 12. Artist's impression of a cosmic-ray shower development in air. The inset shows a Pierre Auger surface-detector station with a radio-detection station barely visible in the background.

Interactions at ultra-high energies
Ultra-high-energy cosmic rays with energies above 1 EeV (=10^{18} eV) are observed as air showers: particle cascades caused by their violent interactions high in the Earth's atmosphere. The first few interactions of an ultra-high-energy cosmic ray in air take place at centre-of-mass energies much higher than reached with man-made accelerators such as the LHC. This fact alone poses a challenge to understanding how to relate the observed cascade to the initial properties of the cosmic ray. At the same time, it is an opportunity to probe physics at energy scales not accessible at Earth-bound accelerators.

Beside this challenge at the demise of cosmic rays, there is challenge at their birth: ultra-high-energy cosmic rays must originate from the most powerful accelerators in the Universe. The maximum energy per particle a cosmic source can produce depends on its size, magnetic field and also on the particle's charge. The apparent end-point of the cosmic-ray energy spectrum, a steep drop at 60 EeV, is unexplained. At these energies the Universe becomes opaque for ultra-high-energy particles. For protons that interact with the cosmic microwave background this is known as the Greisen-Zatsepin-Kuz'min (GZK) cut-off. Alternatively, this end-point may be a consequence of the most powerful cosmic accelerators running out of steam, for instance if the source cannot contain the particles any longer, or cooling becomes too catastrophic to maintain higher energies. These most powerful cosmic accelerators are most likely active super-massive black holes in the centre of galaxies, but other proposed sites could be extreme cosmic explosions or enormous shocks traversing the extrema of clusters of galaxies.

While travelling from source to Earth, the paths of charged cosmic rays will be deflected by intervening galactic and extra-galactic magnetic fields, the latter of which are not very well constrained. Protons with energies above 50 EeV should point back to their extra-galactic sources to within about a degree, this would be less so for iron nuclei (10° or more). Thus, the electric charge of the incident cosmic-ray particle must be determined to assess its direction of origin [18]. Conversely, if its electric charge is known, its direction-energy relation may be used to find both the source and the cumulative magnetic field in this direction. To make progress the mass composition of ultra-high-energy cosmic rays must be determined. With the NL-APP consortium we can do so, using the Pierre Auger Observatory in Argentina.

Research focus — Composition and physics of Ultra-High-Energy Cosmic Rays (UHECR)
Measurement of interactions of ultra-high-energy cosmic rays with atmospheric nuclei using radio detection in conjunction with the other detectors at the Pierre Auger Observatory.

The Pierre Auger Observatory (see Fig. 12) is at present the largest facility to study these ultra-high-energy cosmic rays. It deploys two measurement techniques for the extensive air showers caused by cosmic rays. The first is a Surface Detector (SD) grid of about 1600 water Cherenkov tanks, spaced 1.5 km apart over an area of 3000 km^2. The second is a Fluorescence Detector (FD) of four stations each with six telescopes covering the same 3000 km^2 area. This design has been upgraded with an area that is more densely populated with water Cherenkov tanks and that is overseen by three more FD telescopes looking at higher elevation. In this "in-fill" area lower energy cosmic rays can be detected. Here the new Auger Engineering Radio Array (AERA) that allows for measurements of extensive air showers through their radio emission, is being deployed. This radio technique promises superior performance at lower cost. The development is led by the Dutch group that is part of the NL-APP consortium. The same group leads the cosmic-ray key-science project in LOFAR. The very ability to combine the expertise from both LOFAR and AERA, enhanced by theoretical developments, has brought this group to a position of leadership in the field of radio detection of cosmic rays.

Impressive though the scale may be, a detector area of at least ten times that of Auger is required to definitively find the sources of ultra-high-energy cosmic rays and to perform mass and energy spectroscopy on them. With such an observatory we would also have a ten times higher rate of ultra-high-energy cosmic ray collisions in the atmosphere. This would allow for the study of hadronic interactions at energies 40 times that of the LHC. For such an observatory, radio detection will provide an excellent technology for studying the electromagnetic part of the air showers in great detail. Our ambition is to develop radio detection to suit an extremely large surface area, and thereby guarantee our leadership position in this arena for a number of decades.

Research focus — Radio detection of Ultra-High-Energy Cosmic Rays (UHECR)
Development of radio detection technology for precise measurement of energy, direction and composition of ultra-high-energy cosmic rays.

High-energy photons

Besides cosmic rays, high-energy photons are fascinating messengers from the cosmos. With energies from a few tens of GeV to above 10 PeV they may tell us much about cosmic-ray particle acceleration in our own Galaxy and in extra-galactic objects, about gamma ray bursts and even about Lorentz invariance or the nature of dark matter. But, like cosmic rays at extreme energies, such high-energy photons are very rare, so collection areas of many tens of square metres are required, making space-based instruments too expensive. Ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) are the most successful instruments in this regime, detecting the Cherenkov light produced when energetic photons cause electromagnetic showers in the atmosphere, allowing for the reconstruction of the direction and energy of the incoming photons.

The present generation of IACTs measures photons with energies from about 50 GeV to 10 TeV. They are 2–4 telescope systems with a 3°–5° diameter field of view and about 0.1° angular resolution. To date, these experiments have detected more than 130 celestial objects of many types. They enabled a wide range of studies that deepened our knowledge of the high-energy Universe. However, the sensitivity, energy range, and angular resolution of the current instruments now limit further progress [19]. Planned upgrades to existing facilities will provide only modest improvements. Therefore the international community has come together to construct an ambitious next generation instrument, the Cherenkov Telescope Array (CTA, see Fig. 13). CTA will offer dramatically increased sensitivities, energy coverage, angular resolution and field of view [20]. Many tens of telescopes, of three different sizes, will be combined into one array that will detect gamma-ray-induced air showers over a large area. With CTA the number of detected gamma rays from any source would increase dramatically, while at the same time more telescopes will provide images of the same air shower resulting in improved geometric reconstruction and far better background suppression of air showers from charged cosmic rays mimicking gamma-ray showers. The NL-APP consortium is keen on participating strongly in this CTA endeavour. We will be focusing on three CTA science topics that are detailed in the following.

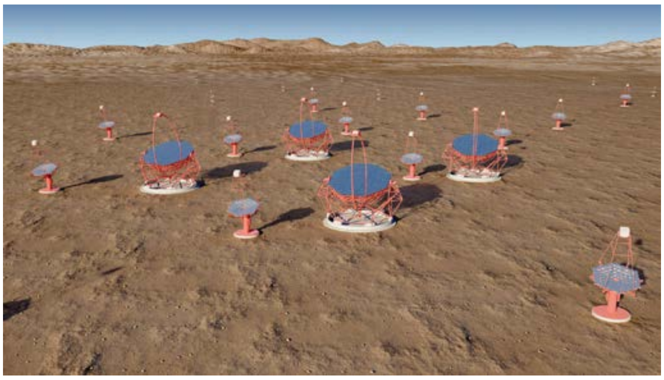


Figure 13. Artist's impression of the Cherenkov Telescope Array (CTA).

High-energy photons and cosmic rays

The most accepted theory for the brunt of hadronic cosmic-ray acceleration in our Galaxy invokes shock waves of supernova remnants as particle accelerators. During the acceleration and propagation, also gamma rays will be produced in interactions of accelerated hadrons (mostly protons) with ambient gas. Very recently, characteristic spectral features from neutral pions, produced in such interactions of cosmic-ray protons and decaying to lower energy gamma rays, have indeed been found in such objects [14]. CTA will measure higher-energy gamma-ray spectra of supernova remnants and establish a population of such very high-energy gamma-ray emitters, providing substantial insight into cosmic-ray acceleration and propagation in our Galaxy. CTA might even find "PeVatrons", young supernova remnants that can accelerate particles up to PeV (*i.e.* 10^{15} eV) energies. Such energies are believed to be the end-point of the galactic cosmic-ray spectrum, but these PeVatrons have so far gone undetected. Furthermore, galaxies beyond our own have been found to produce an observable gamma-ray flux from cosmic-ray interactions with interstellar gas. With CTA, many more such galaxies should be detected, thereby allowing for studies of the connection between cosmic rays and star-formation processes in galaxies.

High-energy photons from black holes, jets, and astrophysical shocks

Astrophysical systems, such as black holes, produce relativistic jets of plasma, which are thought to contain shocks where particles are accelerated to very high energies. The particles accelerated by such systems usually display a similar power-law energy spectrum as found in other cosmic accelerators such as supernova remnants, but the precise particle-acceleration mechanisms have not been established. The impact of these particles on their environments and on their parent systems can be dramatic. This is key to understanding the evolution of the building blocks of our Universe: star clusters, giant molecular clouds, galaxies and clusters of galaxies. Diffusive shock acceleration is at present perhaps the best candidate mechanism for the production of these particles, but this has not been demonstrated convincingly. CTA aims to measure large samples of active galaxies of various types as well as gamma-ray bursts, thereby allowing for the study of particle acceleration and gamma-ray emission processes. Some of these extra-galactic objects are thought to accelerate cosmic rays up to ultra-high-energies and these measurements will allow for probing combined models of particle acceleration and gamma-ray emission. In addition, very far away extra-galactic gamma-ray sources interact on their way to the Earth with stellar photons and are absorbed, hence they probe the amount and energy distribution of stellar light in the Universe. Measurements of gamma rays from far away galaxies will provide reliable estimates of this extragalactic background light. CTA, with its significantly increased sensitivity, will provide such measurements.

High-energy photons and Lorentz Invariance

Though perhaps not the main goal, CTA will make it possible to test the fundamental symmetry of spacetime: Lorentz invariance. Quantum gravitation theories allow for notable quantum effects on the structure of spacetime. Some quantum gravitation theories predict an effective refractive index of the vacuum and an energy-dependent speed of light. This effect would cause a measurable dispersion in the arrival time of photons from an astrophysical source that varies in time like a gamma-ray burst. CTA observations of such sources promise to improve the present limit dramatically and allow for disentanglement of intrinsic source physics effects from those induced by the propagation of gamma rays.

These are the science questions that drive the NL-APP consortium into joining CTA with significant efforts, both in terms of construction and physics contributions. Combining the experimental expertise of astroparticle and particle physicists with detailed knowledge of high-energy astrophysics from the astronomy faculty members of the NL-APP consortium promises to make the difference and will put us into a prime position to exploit the exciting science questions of the high-energy Universe.

Research focus — Cherenkov Telescope Array (CTA) physics and construction

CTA optimizations for the medium and high energy range, focusing on dark matter searches and cosmic particle acceleration mechanisms. Once CTA science operations commence, establish a significant data analysis effort. Make use of existing world-class expertise in the Netherlands in the areas of photo-sensors and readout electronics for the construction of CTA. For this we request a 2.0 M€ investment budget to allow a significant Dutch contribution to CTA.

Neutrinos

Having seen the benefits of detecting gravitational waves, cosmic rays, and high-energy photons, the vibrancy of the field of neutrino observations should not be surprising. The Dutch community plays a key role here. The ephemeral neutrinos are produced in many of the putative mechanisms of acceleration we study. Therefore, the detection of high-energy neutrinos will be an essential ingredient to study hadronic-acceleration mechanisms. These neutrinos appear for instance as decay products of charged pions produced by accelerated protons and nuclei colliding with the gas surrounding the acceleration site. Neutrinos unambiguously tag hadronic-acceleration sources. The neutrinos themselves travel through dense matter essentially unperturbed, which also makes their detection challenging, to say the least. Neutrino detectors must be huge, and several are now in operation. They are located in exotic places and have varying instrumented sizes: deep below the surface of lake Baikal, deep in the Antarctic ice (IceCube, 0.8 km^3), and in the Mediterranean Sea (ANTARES, 0.03 km^3, and in the near future KM3NeT, 4 km^3). All of them are arrays of light sensors placed in a large volume of a naturally transparent medium. Some

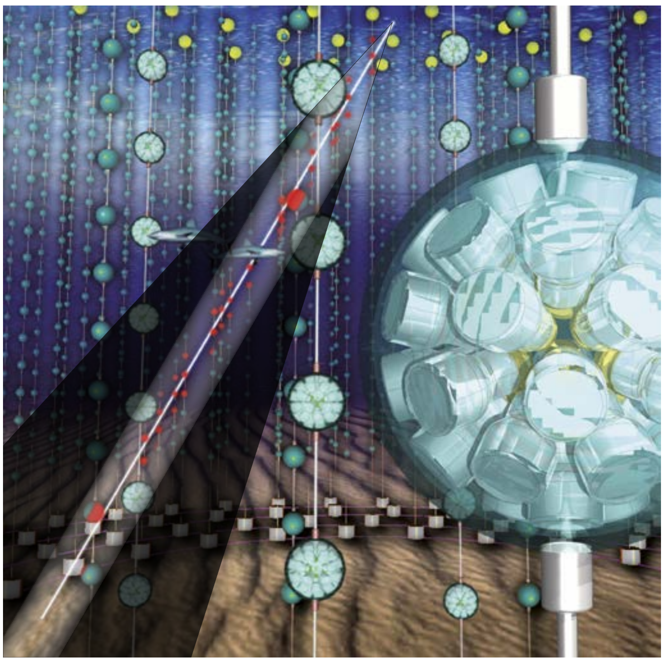


Figure 14. The KM3NeT telescope, consisting of hundreds of slender strings, each supporting dozens of sensors.

of the neutrinos will interact inside or near the detector. The charged particles produced in this interaction emit Cherenkov radiation and the detection of this light allows for the accurate reconstruction of the energy and direction of the neutrinos (See Fig. 14).

Neutrinos and cosmic rays
From the measurements done so far it is clear that the sources of cosmic rays do not give up their secrets easily. The most sensitive detector, IceCube, has yet to register a neutrino from outer space, although recently two very-high energy events hint at a possible cosmic signal. Located in the Antarctic, the IceCube detector only has very limited coverage of the centre of the Galaxy, where many potential cosmic accelerators reside. Because of the measured observational energy limits imposed by IACTs, this region of the sky cannot be accessed by neutrino detectors deployed at the South Pole. The next generation neutrino telescope KM3NeT is planned in the Mediterranean Sea; it has an optimal view of the galactic plane and is designed for neutrino detection with the energy spectrum predicted by the IACT data set. KM3NeT will be far better in angular resolution than present-day telescopes, leading to a significant reduction in background. KM3NeT will be able to unambiguously classify the long-sought sources of Galactic cosmic rays. It is clear that the combination of measurements from high-energy gamma rays and from neutrinos will lift the fog over our understanding of the acceleration processes and the conditions prevailing at the acceleration sites. Within five years of full KM3NeT running, firm conclusions will be drawn. The members of NL-APP have provided the design of all major components of KM3NeT and are therefore considered the drivers of KM3NeT; witness the spokesperson being Dutch. This proposal will help maintain this leading role.

Neutrino mass hierarchy
With these enormous water neutrino telescopes the characteristics of the tiny neutrinos themselves may also be studied, especially the ordering of their masses, known as the neutrino mass hierarchy. Neutrinos occur in three mass states that are in fact quantum super-positions of their weakly interacting states. This mixing leads to the well-known neutrino oscillations (Physics Nobel prize, 2002). Mixing measurements have provided us with the differences between the squares of the neutrino masses. From this information we can infer that two neutrino mass eigenstates are close in mass, while the mass difference with the third one is larger. It is unknown whether the two closely spaced mass eigenstates are more (inverted hierarchy) or less massive (normal hierarchy) than the third state. The KM3NeT collaboration is keen to study this; it might be technically feasible [15,16], but would require adjustments in detector spacing and software. The collaboration will soon decide whether to pursue this, and if so would add an exciting new physics program to KM3NeT.

Research focus — Search for galactic neutrino sources
Search for galactic neutrino sources and study of the neutrino mass hierarchy with the KM3NeT neutrino telescope.

Dark matter searches
Astronomical measurements have provided clear evidence for dark matter at macroscopic scales, but we have not yet observed dark-matter particles. All known matter is composed of the elementary Standard Model particles, but these do not make up dark matter (See Fig. 15). Dark matter cannot consist of neutrinos, because particles that are too light –less than about 1 keV in mass– would have prevented galaxies to form if they were produced in thermal equilibrium in the early Universe. Dark-matter particles cannot be electrically charged, because then they would be visible through electromagnetic interactions. They cannot be the known gauge particles, because the W and Z are unstable, the gluon cannot exist as free particle and photons, more or less by definition, would surely have been seen. Particles that follow from theories pro-

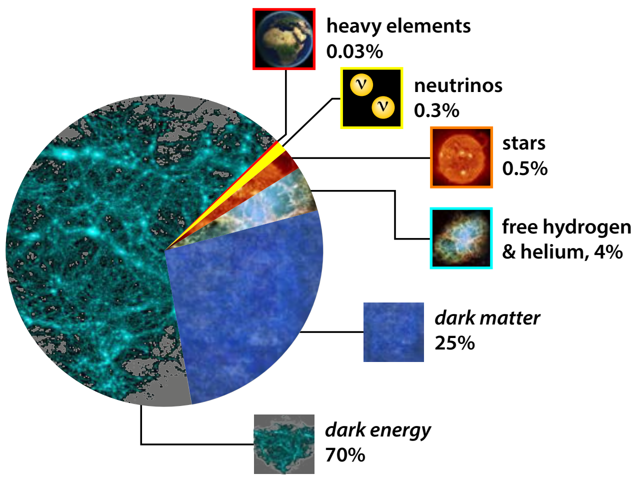


Figure 15. Energy and matter composition of the Universe.

posed to solve long-standing puzzles in the Standard Model, are seen as serious candidates for dark matter. Many such suggested dark-matter particles share the characteristics of being weakly interacting, massive particles: WIMPs. WIMPs would feel the weak nuclear force and have masses of the order of 100 GeV. Supersymmetric theories, theories with extra dimensions, and other extensions of the Standard Model involve WIMPs in a natural way. In most of these models, the WIMP cross section is sufficiently large, that WIMPs would have been produced and annihilated for some duration in the early Universe, bringing them into thermal equilibrium with our known matter. With this assumption we can predict the relic dark matter density. This predicted WIMP relic density, in standard cosmological models, is in fact compatible with astrophysical observations, such as data from the WMAP satellite. So the evidence mounts: the hypothetical WIMP is a prime suspect as dark-matter particle. Our main goal is to find this smoking gun. It is clear that should WIMPs be discovered not only will the riddle of the matter composition of the Universe be solved, but it will also be irrefutable evidence for physics beyond the Standard Model to boot.

It is important to pursue all types of dark-matter experiments. WIMP candidates can be produced at particle colliders, but, though fortuitous, this would not prove that they are stable enough to be dark matter. Such a proof would require consistent signals from collider experiments, such as ATLAS, direct-detection experiments, such as XENON, and indirect measurements such as those from CTA and KM3NeT. Our purpose is to engage in all three types of dark-matter searches with major, enhanced strength.

Direct dark-matter detection
If WIMPs fill our Galaxy, they will also pass through the Earth and occasionally scatter off nuclei. Direct detection experiments look for the telltale recoil energy of WIMPs as they interact with the target material. This is very difficult: the recoil energy is only a few tens of keV, and these scatterings are extremely rare. Extraordinarily sensitive detectors are needed with very low background. For this, the detectors must be placed deep underground to shield them from cosmic rays and be made of materials free of radioactive contamination. Any remaining gamma and beta emitters, which produce electron recoils, must be discriminated from the wanted nuclear recoils. With analysis methods from particle physics we can in fact suppress the background without loosing potential WIMP signal events. The most promising technique for direct dark-matter detection is the dual-phase xenon detector. Such an instrument aims to record the elastic scattering of WIMPs with xenon nuclei in a liquid-gas time projection chamber (TPC) filled with xenon. Xenon is a good dark-matter target because it is a heavy element and the (spin independent) WIMP-nucleus elastic scattering cross section is expected to scale with the atomic mass squared. The NL-APP consortium was requested by the other XENON partners to participate in the XENON-series of experiments in 2010. The XENON collaboration is currently operating the 100-kg-scale XENON100 detector and analysing the data [16]. At the same time the ton-scale XENON1T (See Fig. 16) experiment is being designed and prepared for commissioning in 2015. XENON100 is now the world's most sensitive dark matter detector and is making inroads into the theoretically favoured supersymmetric WIMP parameter space and is already excluding some models. Once XENON1T enters the arena, it will extend the limits by two orders of magnitude or, ideally, find a signal. In this happy case, a two year exposure to WIMPs with a mass of 100 GeV and an interaction cross section of the order of 10^{-45} cm^2 would result in approximately 100 dark-matter events, providing a robust dark-matter signal.

Figure 16. Illustration of the XENON1T dark-matter experiment currently being built in the Gran Sasso underground laboratory.

Research focus — Direct detection of dark-matter particles in our Galaxy
Use ultra-sensitive detectors installed underground to capture the collision of weakly interacting particles with normal matter. Analyse data from the XENON1T and develop new detection techniques for future detectors.

Point sources in dark-matter annihilation: gamma rays and neutrinos
The CTA observatory, discussed already above, will also address the dark matter question for both WIMPs and axion-like particles (ALPs). If WIMP annihilations occur in space, the resulting flux and spectrum of gamma rays depends on both particle physics (the annihilation cross-section as well as possible spectral signatures) and astrophysics (the dark-matter density distribution in the target). Various astrophysical systems whose WIMP annihilation signal is potentially observable have been suggested in the literature, including dwarf spheroidal galaxies, close to the Galactic centre and nearby galaxy clusters. The wide field of view of CTA is particularly important for an annihilation signal from the dark-matter halo of our own Galaxy. With the angular and energy resolution of CTA, different gamma-ray components detected towards the Galactic centre can be disentangled and spectral features identified in any detected signal and thereby constrain the dark-matter characteristics. In short, indirect dark-matter detection with CTA will reveal where dark matter is located, and what it is.

Neutrinos provide another powerful and complementary angle into the search for dark matter. With them we could see possible annihilations of dark-matter particles near or even inside astrophysical objects. The most promising sources for these are our Sun and the Galactic centre, and KM3NeT can look at both. In these dense regions the neutrino signal may well be the only signal of the dark-matter annihilation to escape. The neutrino energies from such annihilations are either relatively low (from the annihilation into bottom-quarks) or higher and thereby easier to measure (from annihilations into top quarks and Z- or W-bosons). Dark-matter particle masses up to several hundred GeV, and WIMP cross sections in the 10^{-41} cm^2 range are reachable with KM3NeT. Interestingly, and as remarked above, many supersymmetric models predict dark-matter particles with such properties. Ideas abound already about how to optimize the sensitivity of the neutrino telescope for such searches, many highly promising. The detector configuration of KM3NeT proposed for the mass hierarchy measurement would be much more sensitive to lower energies than the larger neutrino telescope, and allow studies of low-mass dark-matter annihilation. Restricting the model parameters to only those that predict a Higgs particle in the measured mass range seems to also be advantageous for detection of dark matter with neutrinos.

Research focus — Cosmic signals of dark-matter annihilations
Search for dark-matter particles with gamma-ray (CTA) and neutrino (KM3NeT) telescopes.

Dark-matter creation at the LHC
The full palette of experiments and observations to determine the properties of dark matter includes the LHC, because dark-matter particles may also be created in high-energy collisions. WIMPs, be they supersymmetric or not, with masses up to about 1 TeV could be produced and detected at the LHC. Because dark-matter particles interact so weakly, they are ghostlike, and will escape from the particle detectors of the LHC unnoticed. Their presence can be felt indirectly though from the apparent non-conservation of momentum. In these experiments the masses and couplings to normal matter can be determined.

Taken all together, physics of dark matter is extremely rich. Its very nature is fascinating and forebodes a rich palette of physics beyond the Standard Model. With the variety of approaches above, and the proposed NL-APP network, we expect to know, in the next few years, what it is and what it implies.

III. Pushing the Technology Frontier
Experiments in astroparticle and particle physics take technology to the limit, be it by the sheer size of the detectors, the volume of data transport, the speed and precision of measurement, the intricacy of model calculations or merely adaptation to hostile environments. Experimenting on this cutting edge requires a dedicated team of physicists, engineers, technicians and IT-specialists to lead the way in innovation and development of new technologies.

Significant parts of the current LHC experiments have been designed and constructed at Nikhef and are still being monitored by Nikhef physicists. In the particle physics community, the design and construction departments of Nikhef are considered to be among the absolute best in Europe. The Nikhef institute has an outstanding track record in the field of technological innovation which is exemplified by the ERC Advanced grant received by Jos Vermaseren for his pioneering work in algebraic manipulation used in calculating cross sections including intricate higher order corrections and by the ERC Advanced grant received by Harry van der Graaf for the development of a completely new method of photon detection.

Challenges for the next decade

The Large Hadron Collider has pushed the technology of high magnetic-field superconducting dipole-magnets to the limit. For the future linear electron-positron collider the technology of radio-frequency acceleration cavities has to be pushed beyond current limits, utilizing a metal surface-quality that is only possible through new fabrication technology. The next generation of neutrino beams require extremely high-power proton drivers or even the use of stored muon beams to obtain the necessary intensities, and this would be the premiere of acceleration and storage of unstable particles.

Collider experiments, like the ATLAS, LHCb and ALICE detectors, employ many millions of necessarily low-power readout channels, capable of withstanding the often harsh radiation environment and able to deal with MHz collision frequencies. The detectors are operated for several years without the possibility to access them and therefore reliability and quality control are key issues. In order not to disturb the trajectories of the charged particles, the tracking detectors must be built with minimal amounts of material. Decisions on the relevance of the recorded data must be taken within microseconds. Even after this real time data selection, the resulting data rates are many gigabits per second. To extract the signatures of interest from such huge data sets, requires data analysis (and simulation) tools that beggar belief. All this requires innovative computing concepts.

Low-energy experiments, although typically much smaller in size, are required to deliver levels of accuracy that exceed our imagination. Sensitivities in some cases have reached the quantum limit. Often a single electron or atom is trapped in a man-made quantum system. For example, to identify Majorana neutrinos tons of ultra-pure material are probed for years to find only a handful of relevant decays. Billions of muon decays are recorded to measure the anomalous moment of the muon with a precision of a part per million. Nanohertz frequency shifts are sought for in the various electric-dipole moment experiments, requiring femtotesla magnetic field stabilization and many megavolt-per-meter electric fields. Optical frequency standards, sensitive enough to detect millimetre height differences by their gravitational effect will soon be available and distributed across the country via the existing telecom/internet optical fibre network.

The technical challenges in astroparticle physics are different by the nature of the measurements. Huge areas or volumes must be instrumented to register the low rate of particles arriving from the cosmos. Here, the key concepts are cost effective sensors and efficient data transfer over large distances. For the efficient detection of air showers radio-frequency antennas are proving to be an interesting alternative to the present-day technology, but they need to be made cheap, reliable, while being completely self-supporting in power and communication, driving us to extremely low-power electronics. In the new deep-sea neutrino telescope, a fibre-optic network is required to provide time-synchronisation to better than a nanosecond over a volume of several cubic kilometres. New cost effective methods of high pressure feedthroughs and cabling are being developed. The extremely low-power high-voltage generation bases for photo-multipliers, developed at Nikhef, have made the present deep-sea sensor design possible. The direct dark-matter searches require purity of the detector material that gives less than a single background count per ton per year. In addition they need a low environmental background and hence a deep, well-shielded, underground location. Gravitational-wave detection requires measurement of kilometre-scale distances with an absolute precision significantly smaller than the size of the proton. Such measurements require isolation from environmental seismic noise of an unprecedented complexity. Cherenkov telescopes for measuring high-energy gamma rays require large-area photo sensors with excellent detection efficiencies and low-noise rates. Cost-effective fast-readout electronics are essential given the large numbers of telescopes of the currently planned facility.

Detector R&D

NL-APP has the ambition to embed detector R&D in order to enable ground breaking astroparticle and particle physics experiments. It merges current activities of the Nikhef detector R&D group and those at VU (LaserLab), RU (IMAPP) and RUG (KVI), with emphasis on:

- Miniaturisation, higher granularity and low-power electronics;
- Time measurement and synchronization;
- Extreme precision instruments.

These topics are among the expertise and fine reputation of the institutes, and therefore can play a central role in the future experimental devices.

Miniaturisation, higher granularity and low-power electronics

Miniaturization is driving the developments in the majority of novel detector concepts: sensor elements (*e.g.* pixels) get smaller while the electronics functionality increases. Each pixel is a stand-alone detection element with complete readout circuitry providing data processing and data reduction capabilities. Many of these new detector concepts rely on time-stamping with a resolution of 0.1 ns or better to measure the arrival time of a charged particle or photon.

The higher granularity (more pixels per unit area) and increased functionality per pixel (*e.g.* timing information) in combination with high interaction rates, significantly increase the overall data rate. The data acquisition systems will soon reach and in some cases have passed already the transport capacity of copper cables and therefore we are now active in the field of fibre-optic readout and photonic integrated circuits. In particular the radiation hardness of these new technologies is to be assessed.

Figure 17. Testing the ATLAS SemiConductor Tracker (SCT).

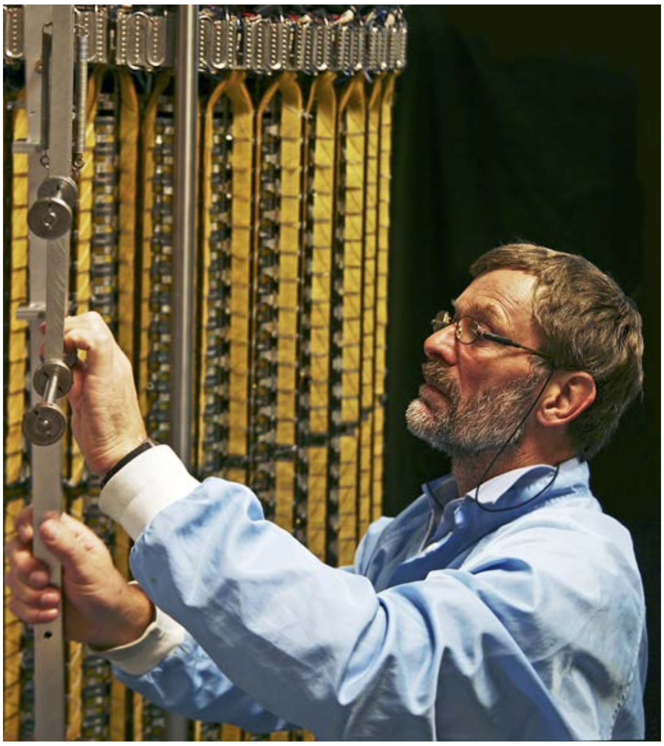


Figure 18. The ALICE Silicon Strip Detector during completion at Utrecht University.

In the past we played a major role in the design, construction and stable operation of the silicon tracking systems of the three LHC experiments ATLAS (See Fig. 17), LHCb and ALICE (See Fig. 18). It is therefore natural that R&D activities are focussed on improving tracking and vertexing technologies. Plenty of challenges must be addressed, bearing in mind the upcoming upgrade for these devices, which is required to cope with the planned luminosity upgrade of the LHC. Regarding experimentation at the future electron-positron linear collider (ILC), we are considering pixelated readout of a Time Projection Chamber (TPC). Both the upgraded trackers of the LHC experiments as well as the tracker for the ILC experiment require detectors with significantly improved spatial and time resolution. The work on these systems is presently underway, as experience has shown that many years are required to pass from a new detection concept, via a number of prototypes, to series production. We are developing a Micro Pattern Gas Detector (MPGD) for various applications. These pixelated gaseous detectors, coined GridPix (See Fig. 19), will be used to build a large TPC prototype for 3D tracking of charged particles and could also have applications in calorimetry and dark-matter searches. This requires performance demonstrations and developing large scale manufacturing techniques in nano-fabrication research laboratories as well as in industry.

Progress in the design of silicon detectors partially relies on industrial developments in Through-Silicon-Via and 3D-Vertical-Integration technologies, that lead to the integration of silicon pixel sensors and readout electronics. We are on the forefront of ASIC development, using a 65 nm CMOS design. The insensitive edges of planar semi-conductor sensors are presenting sources of efficiency-loss, that are impractical for medical or X-ray applications. We have started research into novel edgeless silicon sensors to make fully integrated large area X-ray imagers feasible.

The higher transistor density in CMOS circuits allows for additional on-chip data processing, albeit at the expense of a higher power consumption. This has sparked the development of modern cooling techniques and advanced materials research into for instance micro-channel cooling embedded in the detector design itself. This builds on the cutting-edge CO_2 cooling technology, that Nikhef pioneered for the AMS space experiment. This system is now up and running and installed on the International Space Station. A more complex system is used in the LHCb experiment.

Large scale application of radio detection of cosmic rays, requires autonomous detector stations that harvest their own (solar) power and communicate wirelessly. To make this cheaply and reliably, high-rate signal sampling and high-bandwidth communication have to be realised with the lowest possible power consumption, which can be achieved through a high level of component integration, preferably on a single chip. Such low-power chips, that digitize signals and wirelessly communicate them to the outside world, may well be suitable for much wider societal applications. Specifically, low-power technology also comes in very handy to minimize cooling needs in particle-collider experiments.

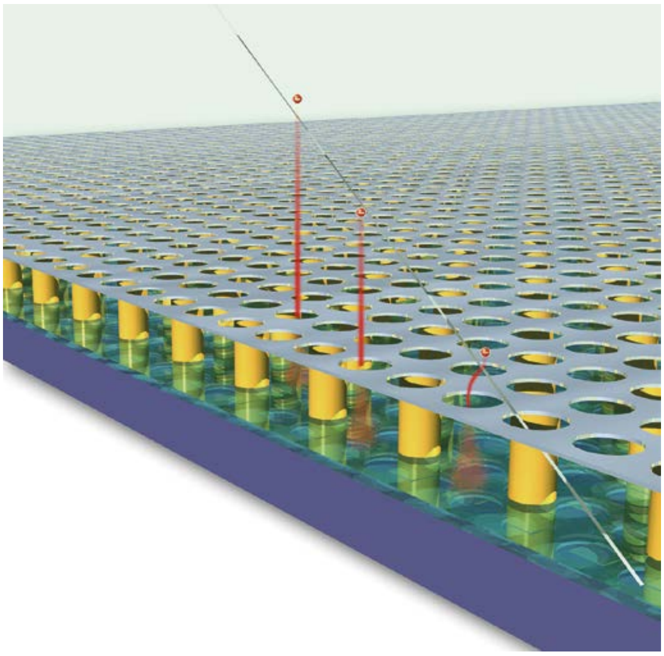


Figure 19. GridPix: MEMS made micromegas with a pixel chip as active anode readout [24].

Recently, Nikhef R&D staff scientist Harry van der Graaf proposed the development of a radically new and generic detector type for photons, electrons and energetic charged particles. In essence it consists of a stacked set of curved miniature dynodes in vacuum, created through Micro Electronic Mechanical Systems (MEMS) fabrication techniques, allowing miniaturized detector elements on top of a state-of-the-art CMOS pixel chip. This combination in itself is an extremely efficient electron detector. By capping the system with a traditional photocathode or with an Electron Emission Membrane, highly sensitive photon and charged particle detectors may be produced that provide unprecedented timing accuracy.

Time measurement and synchronization

Many of the new detector concepts rely on time-stamping with a resolution of 0.1 ns or better to measure the arrival time of a charged particle or photon. For these detectors we are developing sensitive low-noise readout ASICs with fast timing TDCs and circuitry to be shared between pixels to increase the pixel functionality and to reduce overall power consumption. The challenge is to develop CMOS circuitry that can process these signals and output data with the full potential in time resolution. Previously, we developed the Gromov Time-to-Digit Convertor (TDC) with a resolution of 1 ns in each individual pixel. This time resolution can be improved to about 50 ps, but for future detector concepts another order of magnitude improvement is needed.

In the context of time-synchronisation for astroparticle-physics experiments, Nikhef is working on a fully deterministic Ethernet-based network for general purpose data transfer and synchronisation. The aim is to be able to synchronise of the order of 1000 nodes with sub-ns accuracy over fibre and copper cable extending over tens of kilometres. A complementary effort takes place with a recently established optical fiber link between the LaserLaB VU and KVI by pushing the reach of these Ethernet-based networks to the scale of several 100 kilometres with sub-ns timing accuracy and with stable transfer of more than 17 digits accuracy in the frequency. Besides using such links for frequency comparisons of remote optical clocks in search for drifting fundamental constants, LaserLaB Vu and KVI aim to make such methods compatible with the existing optical telecommunication network, so that the network itself may serve as an optical 'SuperGPS' system for many novel applications, such as terrestrial optical-wireless navigation systems (*e.g.* for autonomously driving vehicles) which can be far more accurate and reliable than satellite navigation systems.

Extreme precision instruments, stable mechanics and precise positioning
The detection of gravitational waves relies on extremely high-precision laser interferometry requiring compact multi-stage vibration isolation systems to limit unwanted (seismic) vibrations of optical components (entire optical benches weighing up to 1000 kg). These vibration attenuation systems employ antispring technology through the use of inverted pendula and geometric antisprings. Such systems, together with other improvements, should boost the sensitivity of the Advanced Virgo detector in the 10–100 Hz range by an order of magnitude, which should allow the first direct detection of a gravitational wave on Earth. For real gravitational-wave astronomy *i.e.* future third-generation gravitational-wave observatories, gravity-gradient noise will limit the low-frequency sensitivity. We intend to overcome this fundamental noise source by installing a large network of very precise seismic sensors to directly measure and hence subtract the gravity-gradient noise. For this we are developing a revolutionary ultra-sensitive seismic sensor concept implementing for the first time novel antispring technology in MEMS-based accelerometers to lower their resonance frequency. Vacuum packaging needs to be developed to avoid squeezed film damping and to reach high quality factors. The design goal for these sensors is about 1 ng/√Hz between 1 and 100 Hz. Once achieved, we plan to employ a dense array of thousands of these sensors in the vicinity of the main optical components of Advanced Virgo to measure correlations with local seismic displacement fields and to develop strategies for subtracting gravity-gradient noise in preparation for real gravitational-wave astronomy.

Colliding the nanometre-sized beams of the future ILC head-on requires extreme precision in alignment and beam monitoring. In this context Nikhef is adapting the optical alignment system originally designed and presently used for the alignment of various detector layers in the ATLAS and LHCb experiments.

Research focus — Detector R&D
Advancing detector technology to enable fundamental discoveries in (astro)particle physics

Computing R&D
The increasing ambition and accuracy of present and future high-precision detectors presents a continuous series of new challenges for the processing and analysis of the recorded data. One aspect of these challenges is the sheer volume of data of modern particle-physics experiments, now measured in petabytes, that require dedicated large-scale computing facilities (*BiG Grid, NL-Tier1*). Another aspect is the required complexity of data analysis models: the search for rare physics processes, such as Higgs-boson production or the passage of a gravitational wave, requires analysis models of an unprecedented level of detail, simultaneously testing the consistency of hundreds of (control) measurements with a particular physics hypothesis (*RooFit*) [21]. A third aspect is the need for better theoretical models predicting the observed distribution for both signal and background (*FORM*) [22]. Nikhef and the NL-APP consortium are addressing the computing challenges along a two-pronged approach, *i.e.* making more processing power available through scale-out of the computing infrastructure and by improving the way mathematics and physics processes are mapped onto algorithms in computers, and on itself.

The development of large-scale distributed computing is addressed by designing software to securely share Peta-scale data processing facilities through grid technologies. The 28.8 M€ 'BiG Grid' NWO subsidy granted in 2006, has –in collaboration with SARA and other partners– resulted in the setup and operation of one of the about ten world-wide grid ('Tier1') centres for LHC data analysis at the Science Park Amsterdam. The infrastructure constructed, comprising over 10 petabyte of storage and 10,000 compute cores in the Netherlands alone, showed effective and stable operations, handling the first LHC run. However, the next generation data processing –dealing with inevitable massive multi-core systems and new 'trigger-less' detector data acquisition– necessitates a scale-up of the computing infrastructure as well as accompanying software frameworks and algorithms.

The second issue concerns the scaling challenges in the algorithms in the data analysis, which are due to the inherent complexity of combining data from the wide range of data sources, that together make up the most exciting (astro)particle physics results. We are now making the next steps in precision measurements, and developing data modelling environments like RooFit to efficiently exploit the massive multi-core systems that drive the next generation computing systems (See Fig. 20). This is essential to deal with more and more fit parameters and to control systematic uncertainties, which not only have a substantial computational cost but can also induce occasional numeric instabilities. These model scalability issues require a solution through improved numeric algorithms, but can also benefit from the increased computational power offered by massive multi-core systems such as Graphical Processor Units (GPUs). The experimental results then need to be compared to highly precise theoretical predictions. Fundamental new ideas are being developed, for example merging symbolic algebraic manipulation codes like FORM with concepts from computer game theory like Monte Carlo Tree Search. These new ideas bring a new level of computational intensity to symbol manipulation, pushing it towards the same compute-intensive multi-core domain as data acquisition, modelling and analysis.

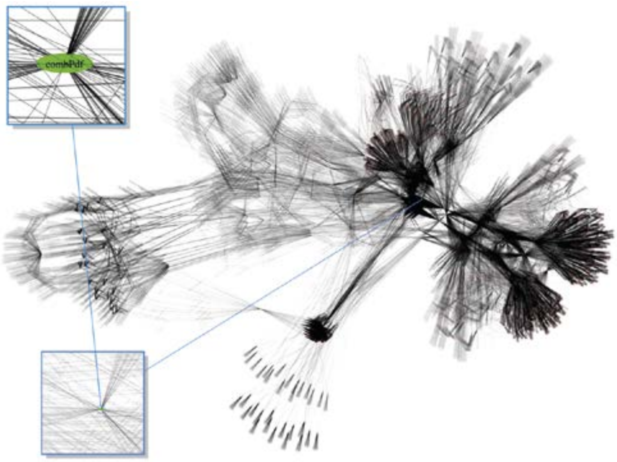


Figure 20. RooFit: Map of the detailed mathematical model used for the Higgs boson discovery, capable of simultaneously describing all involved signal and control measurements. In this map, nodes represent parameters or individual probability density functions, and lines represent relations between these.

These are the computing challenges that the NL-APP consortium is facing in the next decade. The grid computing systems research, supported by the developing computer engineering best practices, show that the necessary architectural innovations can only be demonstrated to be correct by practical application. This means that Nikhef, together with NL-APP, has to build the concrete research facility for all mentioned scaling tiers. This entails continuously revising the scaling validation facility to allow the conceptual R&D to be validated under production-level conditions — and leverage the data storage, processing, cloud and network systems that hold the physics data for such R&D. At the same time the infrastructure has to be effective as a physics research system and be independent enough to allow controlled experiments.

Accelerator R&D

The development of accelerator physics and technology has been one of the main enablers of progress in experimental subatomic physics for over 80 years already, starting with the first RF linear accelerator by Widerøe in 1928 and culminating today in the LHC and the concepts for future linear electron-positron colliders. Right from the beginning until the present day these developments have found their way into many other branches of science (including history and arts), healthcare (radiotherapy, isotope production) and technology (welding, material analysis, material modification *etc.*).

Today the development of new accelerators for frontier subatomic physics and for other applications are strongly intertwined. Ultrahigh gradient, energy-efficient and cost-effective acceleration techniques are essential for the realization of a next generation accelerator for particle physics. The performances required for future accelerators for particle physics are such that they can only be developed in a combined effort of accelerator physicists, material scientists and high-tech industry extending over a period of several decades, as exemplified by the development of LHC and currently the future linear electron-positron colliders. At the same time these requirements are also relevant for progress in the other branches of science and technology, where (smaller) accelerators play a crucial role. This synergy offers a solid justification for the efforts to be made and also provides an economic basis for the sustained effort requested from industry: in the course of the development substantial spin-off will be generated, which plays a crucial role in establishing the viability of the technology.

By combining the accelerator-related expertise at several Dutch universities and research institutes with the expertise on ultra-precise machining and high-power electronics of Dutch industry, we plan to make a focussed contribution to the further performance improvement of the technology for a next generation accelerator for particle physics. This R&D activity will be integrated in the international development effort for both the ILC and the CLIC, which in Europe are coordinated by DESY and CERN, respectively.

The planned R&D will initially focus on increasing the accelerating gradient that can reliably be achieved to still higher values, thus allowing for an even more compact accelerator, by optimization of the materials properties and the production technology for the accelerating structures. To this end a dedicated high-power test facility will be build, where the breakdown properties of both complete structures and materials can be assessed under well controlled conditions. Furthermore we plan to develop a facility to determine the performance of accelerating structures under realistic beam-loading conditions (0.5 M€ investment required). Such a facility is particularly important for the development of the spin-off applications.

In parallel we will develop the use of this technology in novel smaller accelerators for applications in science (*e.g.* compact FELs for XUV and soft X-rays), healthcare (radiotherapy) and technology (XUV-light sources for the semiconductor industry).

Research focus — Accelerator physics and technology
Accelerator physics for high-tech post-LHC particle-physics experiments. Multidisciplinary collaboration between accelerator physics, material science and with a keen eye on the possible applications of the newly created technology for other applications such as light sources and healthcare (radiotherapy).

National embedding
Technical advancements allow for the design and construction at the NL-APP consortium of major detector components and sub-systems for (upcoming) large-scale and high precision experiments. The NL-APP consortium will be a highly welcome participant in many scientific collaborations. In the past years, several key technologies from Nikhef, VU LaserLab and RUG have already resulted in start-up companies or joint ventures with industrial partners.

Forging tighter connections with other Dutch technology centres not (yet) formally part of the Nikhef but already collaborating in some areas (like KVI, NIOZ, SRON, ASTRON and the nano-technology centres in Delft and Twente) will further strengthen the Dutch (astro)particle physics community in general. In particular, it will also help to retain accelerator R&D as a viable activity in the Netherlands. A closer collaboration as envisaged in the NL-APP consortium with other research communities and notably with astronomers and with particle physicists at KVI will be essential in order to meet the world-wide expectations of the level of the Dutch instrumental contribution (typically 2–4%) to large research infrastructures.

Institutional embedding and organizational structure of the scientific research

The NL-APP proposal brings together a number of researchers at the cross roads of astroparticle and particle physics. The proposal aims to strengthen a number of key strategic areas where there is a strong synergy between groups or an outstanding potential for a scientific breakthrough in the near future. Traditionally the research has been organized along the following lines (see Fig. 21):

From the Big Bang to now

This theme centers on experimental astroparticle physics and the investigation of General Relativity. The ambitious aims of the experimental facilities are:

- First direct detection of a gravitational wave;
- Discovery of ultra-high-energy cosmic-ray point sources;
- Determination of the acceleration mechanisms for the highest-energy cosmic rays, neutrinos and gamma-rays;
- First direct detection of dark-matter particles.

From now to the Big Bang

This theme centers on high-energy and precision phenomena to better understand our Universe. The goals of the experimental facilities are:

- Discovery of new particles (including dark-matter particles) at the LHC and through quantum corrections in high-precision experiments;
- Discovery of new fundamental forces and interactions (including matter-antimatter asymmetry) at LHC and with high-precision measurements.

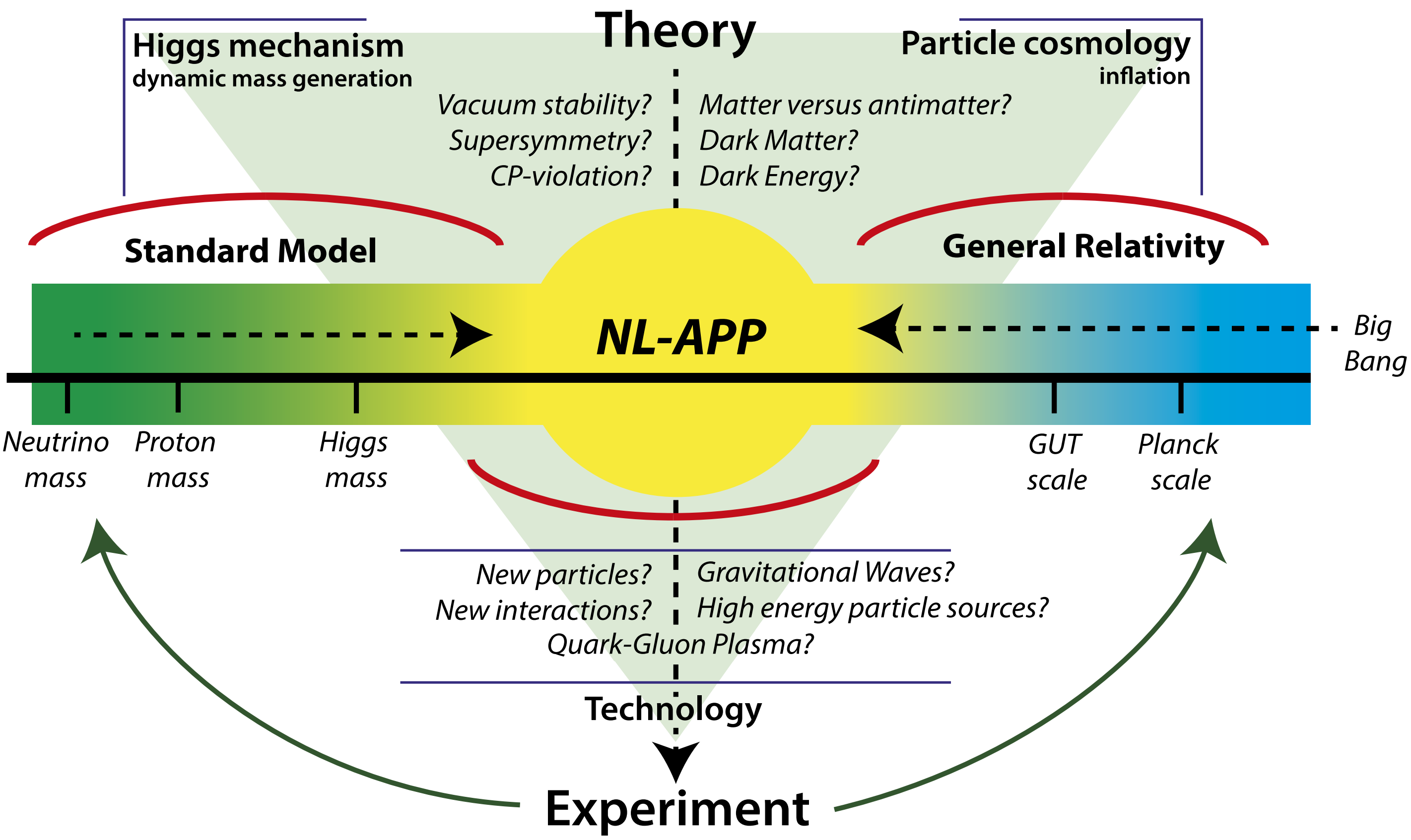


Figure 21. The challenges (top half) as addressed in the NL-APP proposal and how they link the two themes: "From the Big Bang to now" and "From now to the Big Bang". The bottom half indicates how experiments will shed light on these challenges, to further our understanding of the evolution and working of our Universe. The proposed NL-APP consortium will link all activities in the field.

These two research themes are becoming more and more closely interwoven. The crux of the NL-APP proposal is to bring the talent of both themes together to increase interdisciplinary collaboration and strengthen areas, that have the potential to become world leading. We identified three partially overlapping frontier areas in which Dutch science is already well represented by the applicants of this NL-APP consortium: the cosmic, the energy and the precision frontier, with at the centre the technology frontier: the fields of theory and instrumentation. All frontiers are present in each of the two themes (see Fig. 22).

I. Talent Plan

The (co- and other) applicants of this proposal are major players in astroparticle and particle physics research and will embed and provide the support structure of the new scientific staff to be hired. In total the NL-APP proposal requests funding for 86 scientific staff positions: 10 tenure-track positions, 32 postdoc positions and 44 PhD positions. The recruitment falls into three categories: tenure-track groups, NL-APP fellowships and thematic positions.

Scientific staff positions

Tenure-track groups (10)

The NL-APP proposal provides for ten new university based high-profile tenure-track faculty (or possibly tenured faculty) positions. These positions will have staged starting dates, spread over the first five years of the NL-APP program, in order to provide flexibility in the appointment strategy and to allow for adjustment in case of unforeseen scientific breakthroughs. To be able to attract the best candidates in an international competitive market, they will be offered a start-up package consisting of one 3-year postdoc (following the usual scheme of a 2-year appointment with a possible extension of another year) and two PhD students. It is expected that one of these PhD positions will be filled immediately after the appointment of the new faculty member and the second one approximately two years later. The selection of the tenure-track candidates will be done by a search committee consisting of members from the appointing university and other respected scientists from the NL-APP consortium in the relevant field. We will appoint outstanding young researchers with a proven track record of scientific excellence, and leadership qualities. This, together with our internationally renowned research infrastructure, will make the Netherlands a world leader in the chosen focus areas, well beyond the duration of this NL-APP Gravitation proposal.

The six universities applying for the NL-APP proposal, have committed to embed these 10 qualified tenure-track candidates: the University of Amsterdam (UvA, 2 positions); the VU University Amsterdam (VU, 1 position); the University of Groningen (RUG, 2 positions), Leiden University (UL, 1 position); the Radboud University Nijmegen (RU, 2 positions); and Utrecht University (UU, 2 positions).

NL-APP fellowships (10)

A total of 10 postdoc positions will be offered as prestigious 3-year NL-APP fellowships. These fellowships are targeted at young researchers that have demonstrated outstanding potential during their PhD or their first postdoc position. These positions will be internationally attractive as the successful candidate will have a free choice of the research area and will be given a yearly personal research budget of 10 k€.

Thematic positions (12 postdocs, 24 PhD students)

The NL-APP program provides for 12 postdoc positions (following the usual two plus one year appointment scheme) and 24 PhD student positions, to be assigned to concrete research projects emanating from the (sixteen) research topics, proposed by the (co- and other) applicants of the proposal. The evaluation of these proposals will follow the usual procedures within the Nikhef collaboration (see Governance, pages 51–52).

Research topics

Figure 22 gives the envisaged distribution of tenure-track appointments (√-symbol) and investments (€-symbol) over the frontier areas.

- *Cosmic frontier (4 tenure-track positions, thematic positions).* It is this area, where the emphasis of the NL-APP consortium is planned. We seek long term support of the current, relatively young initiatives. In these areas the NL-APP consortium is positioned to take a leading role, when granted the requested human resources. We plan to appoint four faculty tenure-track positions in gravitational waves, ultra-high-energy cosmic-rays, cosmic neutrinos and high-energy gamma rays.

- *Cosmic-energy frontier overlap (3 tenure-track positions, thematic positions).* This field, where high-energy and cosmic physics meet, contains the search for phenomena beyond the Standard Model, such as for dark matter, and the research into the Quark Gluon Plasma. The NL-APP consortium will appoint one faculty tenure track on direct searches of dark-matter particles. Another new faculty tenure track will concentrate on integrating searches for physics beyond the Standard Model at the LHC energy frontier with searches for new physics in astroparticle physics experiments. For the Quark Gluon Plasma research we seek one faculty tenure-track position to enhance the cross fertilization of this research in connection to cosmology.
- *Energy frontier (thematic positions).* This research area represents the present particle-physics component of Nikhef, which is leading in the international particle-physics community, as exemplified by the Dutch contributions to the recent discovery of the Higgs particle and its dissemination among the general public. The NL-APP consortium seeks to maintain its strength and leading role by adding a number of temporary scientists at PhD and post-doctoral level, and leverage their flexibility and expertise.
- *Energy-precision frontier overlap (1 tenure-track position, thematic positions).* The NL-APP consortium seeks for one faculty tenure-track position in the phenomenology of matter-antimatter, neutrino properties and Higgs precision-physics. This research is positioned to oversee the already existing research areas at Nikhef and to investigate the direction of future experiments.
- *Precision frontier (1 tenure-track position, thematic positions).* The level of participation in the precision frontier builds upon the experience of the physicists at the RUG. The NL-APP proposal connects these activities to the strength of Nikhef. NL-APP will open one faculty tenure position to expand these efforts. The combination of the efforts of RUG and Nikhef will strengthen this area significantly for the long term.
- *Precision-cosmic frontier overlap (thematic positions).* Positioning the research at the VU LaserLab (Amsterdam) on time variation of constants of nature within the context of the NL-APP consortium will provide the necessary synergy of these currently separate programs. Here the NL-APP consortium targets on dedicated investments (laser facility) and temporary scientific positions.
- *Technology frontier (1 tenure-track position, thematic positions).* For the instrumentation required in the cosmic frontiers and the energy frontier we seek for a faculty tenure-track position for a scientist with particular affinity with detector hardware or data handling infrastructure.

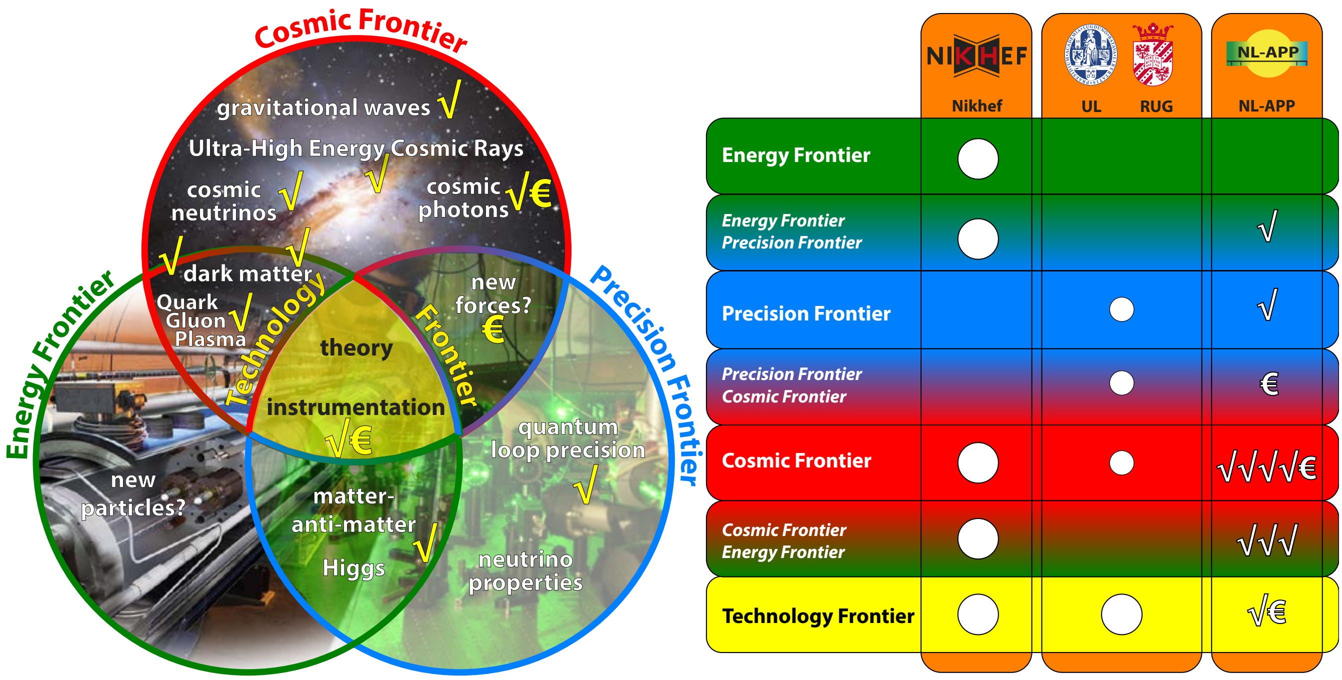


Figure 22. Participation of present and future Nikhef partners in experiments/research topics. The size of the circles denotes the relative strength. The √ symbols denote where we envisage to position the tenure trackers. The € symbols indicate the activities for which we request investment funding.

Training and supervision of PhD students

The Nikhef PhD students are all affiliated with research schools: experimentally oriented PhD students are enrolled in the *'Research School for Subatomic Physics'* (OSAF, coordinated by Radboud University Nijmegen) whereas the theoretically oriented students are enrolled in the *'Research School for Theoretical Physics'* (LOTN, coordinated by Utrecht University), but their program is in essence not different from that of OSAF, which is outlined below.

Training program

Students have to attend six topical lectures. These are three-day intensive courses, taught by scientists from NL-APP or international experts in the field. In the first two years PhD candidates working in experimental particle physics attend a two-week school that is jointly organized between Germany, Belgium and the Netherlands. For theoretical physics students, the LOTN organizes dedicated two-week schools in the area of high-energy physics and in the area of statistical physics and condensed matter physics. In the third year PhD students often will attend an international school. In principle candidates can choose the school themselves, provided it is a good match with the research program and at the appropriate level. Possibilities are *e.g.* the CERN European school of physics or the SLAC summer institute at the Stanford Linear Accelerator Center in California.

Besides the scientific training, students will be able to follow a number of other courses. FOM organizes a number of courses for PhD students that will be open to the NL-APP PhD students through the link to the FOM-institute Nikhef. Examples of such courses are: *Taking charge of your PhD project, The art of presenting science, Being successful in Dutch organizations, a Business Orientation Week* (offered by Nyenrode Business Universiteit), *Personal career planning, Write it right* (scientific writing skills) and *Teaching and Learning* (Universities' teaching and learning program).

As part of the research work many PhD-students are facilitated to spend a significant amount of time, up to twelve months, at CERN or another international research facility.

Supervision

Students will typically have a daily supervisor and a thesis advisor. The latter always is a professor at the university, that will award the PhD degree. At the beginning of the PhD a training and supervision plan will be prepared. This plan specifies, in which experiment the student will work, who are the thesis advisor and daily supervisor, how frequently the student meets with his advisors (with a minimum of twice a month) and which courses will be part of the PhD training. The training and supervision plan will be discussed with the student before it is signed. Progress is monitored in progress interviews. The student, the supervisor(s) and an independent member of the education committee of the OSAF research school meet and discuss the progress of the thesis work, training of the student, future plans and evaluate, whether the supervision is adequate. These interviews contain both a look at past performance and a discussion of future steps. Progress interviews will be held after 6, 12, 24 and 36 months. The independent member of the education committee reports at the meeting of the full committee on the progress of the student. When the 6 months interview leads to serious doubt about the students' ability to complete the PhD, progress can be monitored more closely and a go/no-go decision will be taken within the first 12 months. The independent member can also advise to replace the supervisor in case of problems with the supervision.

Recruitment

All positions will be widely advertised, through posting at international laboratories such as CERN and DESY, and on international websites for research positions in astroparticle and particle physics.

NL-APP researchers will encourage excellent candidates to apply for these positions, using their personal networks. Appointment of the tenure-track positions will be done first, such that the postdoctoral appointments and the appointments of the PhD students can be done in strong consultation with the relevant tenure-track appointee. To further increase the quality of the applicants, a number of measures will be taken:

- Active scouting of excellent foreign students at international laboratories;
- Master students will be encouraged to write their own research proposal as part of the application process;
- Annually, the PhD positions that are available will be advertised together.

Equal opportunity

The NL-APP consortium is aware of the gender imbalance in the research fields covered in this proposal. The faculty tenure-track positions will be specifically used to reduce this – which in practice means we will actively search for excellent female candidates to provide both an increase in quality and a reduction of the gender imbalance. In addition, we will make use of programs, present at most of the universities in the NL-APP consortium, specifically targeted at excellent female staff, such as MacGillavry (UvA), Rosalind Franklin (RUG) and Joliot-Curie (RU). Within the Nikhef collaboration such a dedicated policy, supported by the so-called *FOm/v* program, has already generated a marked improvement in the gender balance: from two tenured female post-graduate researchers in 2004 to eight in 2012.

Activities at MSc level

With the new faculty members, we plan to offer new advanced courses in the field to Master students in a national context. This will be either in the form of topical lectures at one of the partner universities or as video lectures. This will be an important step in the harmonization of the Master program at the different partner universities and eventually lead to the creation of a national Master program in astroparticle and particle physics. We further intend to promote summer internships at international research facilities like CERN and DESY. Through OSAF we already send a number of students to the *CERN summer student* program. They spend two to three months at the laboratory participating in a research project, preferably in a research group without direct NL-APP connection. While at CERN, students get a flavour of research at the frontiers of science. They invariably return inspired and often determined to pursue a PhD in subatomic physics.

II. Governance

Currently the Nikhef collaboration consists of the FOM-institute Nikhef, (FOM is the Dutch Foundation for Fundamental Research on Matter), and four universities: the VU University Amsterdam (VU); the University of Amsterdam (UvA); the Radboud University Nijmegen (RU); and Utrecht University (UU). The Nikhef Collaboration agreement, *i.e.* a joint venture between a national funding agency and several universities, is nationally and internationally regarded as exemplary as already outlined in the section on the 'Quality of the researchers involved' of this proposal (page 21-23). For the governance of the NL-APP project, we will build upon the proven Nikhef collaboration and organizational model (see Fig. 23).

Nikhef collaboration

The *Board* of the Nikhef collaboration consists of representatives of FOM and the partner universities. The Board is responsible for the approval of the scientific program and the corresponding (multiannual) budget, as proposed by the *Directorate*. Nikhef's external *Scientific Advisory Committee* (SAC), composed of renowned international experts in the field, yearly provides a report to the Board, covering the complete scientific program. New research initiatives are scrutinized on various levels. The internal *Scientific Council* (WAR) will be the first to advise the director regarding upcoming scientific opportunities. Once the director decides to pursue an option, he presents it to the SAC. If the SAC, taking into account scientific merit, manpower requirements and availability, and investment prospects, gives a positive recommendation, the director prepares a proposal to the Board as part of the scientific program and budget, and gets approval (or not). All this can take place on short notice and allows Nikhef to make swift decisions if needed. Technical contributions are realized in project teams consisting of physicists, engineers and technicians. If necessary, conflicts between projects are discussed and resolved in the regular *Project Planning* (OPP) meetings in which all project leaders, the heads of technical departments and the Directorate participate.

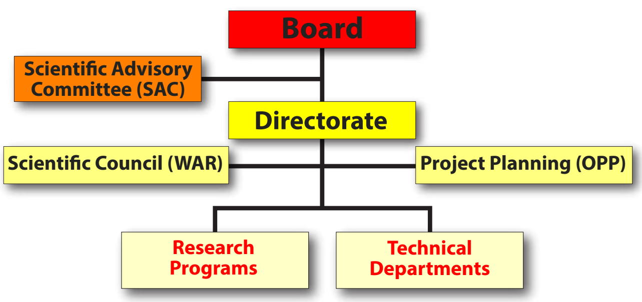


Figure 23. The Nikhef organigram.

Each main research activity or program is coordinated by a *Program leader* appointed by the director. The program leaders have, within budgetary constraints, significant autonomy. Each year each program leader discusses the details of his/her program with the directorate. In shaping the Nikhef collaboration there have always been opportunities for the university partners to choose a particular research profile. Each university partner therefore typically focuses on two experimental research activities (at present one in accelerator-based particle physics and one in astroparticle physics) and most of the programs are in fact led by a university professor.

Many links to activities outside the Nikhef collaboration
Nikhef started originally with only three partners (FOM, University of Amsterdam and Radboud University Nijmegen). VU University Amsterdam and Utrecht University joined Nikhef at a later stage. Already today, Nikhef staff, via professorships by special appointment and other affiliations, not only teach at the four partner universities, but at all nine Dutch universities with a physics department (six regular and three technical). These teaching activities provide a stable influx of Master- and PhD students. Another example: Nikhef's theory group has been very active in forming (and is leading) a national network for phenomology and cosmology. The UvA GRAPPA and RU IMAPP centres of excellence connect theoretical physics with experimental high-energy physics and astronomy. And as an indication of the reverse: a non-Nikhef staff member at the University of Groningen (RUG) leads one of Nikhef's research programs: the Pierre Auger cosmic-ray observatory.

NL-APP technical infrastructure
Collectively, the NL-APP consortium avails over an excellent and impressive technical infrastructure, both in terms of people as in terms of facilities. Key facilities include: a state-of-the-art laser centre; elaborate silicon characterization and handling equipment; precision machining equipment such as huge (and small) 5-axes milling machines, lathes; modern electronics design facilities; large clean rooms; fiber-optics and electronics laboratory; extensive computing facilities including an LHC Tier1 grid computing site (one of about 10 worldwide) and a GPU cluster. The NL-APP consortium employs about 100 engineers and technicians working in the three key instrumental areas relevant to our research interests: mechanics, electronics and computing (covering instrument design as well as realization and construction). These engineers and technicians work in close interaction with experienced detector, laser and accelerator R&D physicists.

The integrated technical infrastructure has in the past repeatedly resulted in innovative design ideas, many of which found their way into large construction (instruments, detector systems) projects, some for in-house experiments at notably KVI and the VU LaserLab and many others for large experiments at CERN's Large Hadron Collider or astroparticle-physics facilities elsewhere. This high-level of technical expertise has also attracted the interest of industrial partners, which has resulted in joint projects and start-up companies. More information can be found in the knowledge utilisation section (pages 53–57). The NL-APP consortium is committed to continue this excellent track record into the future.

NL-APP as catalyst for expanding the Nikhef collaboration
This NL-APP proposal, prepared by scientists from six universities and the FOM-institute Nikhef, will act as a catalyst for expanding the Nikhef collaboration. The University of Groningen (RUG) and Leiden University (UL) have expressed their wish to explore entering the collaboration. Running the NL-APP activities as part of the Nikhef collaboration will reduce overhead, since they benefit from the existing and well proven Nikhef organizational structures and excellent technical facilities and infrastructure. Representatives of the new partners will be included in the relevant bodies (Board, Scientific Council and Project Planning). All NL-APP appointed PhD students will enroll in, and benefit from, the long-standing research schools in subatomic physics or theoretical physics (see Talent plan, page 50). NL-APP will also further strengthen the collaboration with autonomous astronomy and theory groups not formally joining the Nikhef collaboration. Also this will yield additional synergies on top of the sole benefit of a financial stimulus to the field.

In summary, we are committed to embed the NL-APP activities seamlessly in the Nikhef organization.

Knowledge utilisation

The primary focus of the NL-APP proposal is curiosity driven research, in short: "*What is the Universe made of?"* and "*How does it work?"* Nevertheless, our research community has, long time ago, realized that it is vital to make the connection between our research activities and 'third parties', where third parties can be other research disciplines, industry, our youth and society at large. Thanks to CERN's Large Hadron Collider project and in particular the recent discovery of the Higgs particle, interest in our research is simply overwhelming. Collaboration with industry and the knowledge and technology transfer to other research disciplines, capitalize on the inherently high-tech and almost always cutting-edge technologies required in our experiments. Typical examples are radiation detectors, sensor networks and computing technologies like grid, cloud and hadoop. Some concepts pioneered in our research community have become so successful, with the *World Wide Web* as the prime example, that it is sometimes hard to imagine our society has ever managed without them.

Outreach to general public

Our researchers engage in many different manners with the general public. In addition to the standard public lectures and interviews in the usual media like newspapers, magazines, radio and television, our researchers now also perform in science cafés and pop temples like *Paradiso* and *Paard van Troje* throughout the Netherlands and even as lecturer on Rhine and Rhône river cruise ships. Even more adventurous are appearances in (physics oriented) theatre and movie projects with the highly acclaimed and prize winning movie titled "*HIGGS —into the heart of imagination"* (featured on Dutch television the same evening CERN announced the Higgs discovery) as the undisputed highlight. Another novelty was *Cosmic Sensation* —a multi-day silent disco in a large dome-shaped tent with the music and light show steered by and visualizing the passage of cosmic-rays. This last event was awarded the prestigious *Academische Jaarprijs* for the best science inspired outreach activity in 2009. During the *Kennismaand* (science month) our institutes open their doors to share the excitement of our research with the general public. Several of us also consult with (popular) science authors. An excellent example is *De deeltjesdierentuin* (The particle zoo) by Jean-Paul Keulen, covering in popular language elementary particle physics from the discovery of the electron in 1897 to the Higgs discovery in 2012 and beyond. We are determined to continue and wherever possible to extend these numerous public outreach activities to further raise public awareness of fundamental curiosity-driven scientific research.

Outreach to youth

Apart from the outreach activities aimed at the general public, we have special programs targeting children and high-school students (and sometimes their teachers). For kids we collaborate with the NEMO science museum in Amsterdam. We constructed a large spark chamber setup for the visualization of cosmic-rays and we donated a cloud chamber showing the presence of numerous ionizing particles in our everyday environment. Operated by people from NEMO, these detectors now form the main attraction in a hands-on cosmic-ray experience. NEMO also organizes the so-called monthly *Wakker Worden Kinderlezing* (Wakeup Lecture) for 8–12 year young children in which our researchers regularly appear with topics like: *What is the origin of lightning?; Can you measure what you cannot see?; Why do you float on the Dead Sea?* When science inspired movies (*e.g. The Fantastic 4; Angels & Demons*) have their first viewings, we are also frequently asked to separate fact from fiction herein. The annual *Techniektoernooi*, a technical competition (paper bridges; balloon cars; air-pressure rockets; *etc.*) for elementary school pupils, was long-time chaired by one of us and to date many of us still take part in this annual national event wearing our formal university gowns. We also have and will again collaborate with the makers of *Klokhuis*, a program aimed primarily at elementary school kids to explain all kinds of interesting phenomena. One episode featured the Nikhef director colliding head-on with the Klokhuis host on in-line skates inside the LHC tunnel. New episodes are being planned together with Nikhef scientists.

Figure 24. Illustrations of outreach activities of some of NL-APP consortium members.

To high-school students we offer various activities, including guest lessons at their premises, (CERN) master classes at our institutes, assistance with high-school projects that have a particle physics content like the measurement of the muon lifetime and guided tours to CERN. In addition, one of us chairs the organization responsible for the www.natuurkunde.nl and www.sciencespace.com websites, aimed at high-school students with the goal to stimulate interest in science. Nikhef initiated and runs the HiSPARC (High School Project on Astrophysics Research with Cosmics) project, in which high-schools install large scintillator slabs in ski-boxes on their school's rooftop. These detectors are connected to an (inter)national network, giving the students of the schools the opportunity to study high-energy cosmic-rays. At present, about 100 stations are installed in the Netherlands. Every year, about seven high-school teachers spend a stage (one day per week) at Nikhef to further expand HiSPARC's possibilities. High-school teachers are also sponsored by Nikhef to take part in high-school teacher events at CERN. Nikhef staff members were also involved in shaping the new physics high-school curriculum that is to start in September 2013 and in producing modules for the high-school curriculum on Nature, Life and Technology (NLT). One of the co-applicants is the director of the Radboud Pre-University College of Science, streamlining all activities of the Radboud University's faculty of science with high schools.

Links through the national e-Infrastructure

The data volumes and computing requirements of the LHC experiments have been the driving force in the development of the Dutch e-Infrastructure for data processing. BiG Grid is a project founded by Nikhef, NBIC (Netherlands Bio-informatics Centre) and NCF (National Computing Facilities), with SURFsara as an operational partner, for building the data-intensive computing infrastructure. It was expressly constructed as a multidisciplinary facility from its inception in 2006 and includes the Dutch LHC Tier1 grid computing facility in the Netherlands (See Fig. 25). Although the LHC experiments were (and still are) the largest consumers, it gives today thousands of researchers, from over 40 distinct communities including astroparticle physics, astronomy, the life sciences, the humanities, civil engineering, and econometric studies, access to grid, cloud and open-source software hadoop services. The BiG Grid facilities are now an integral part of the national e-Infrastructure, governed by SURF.

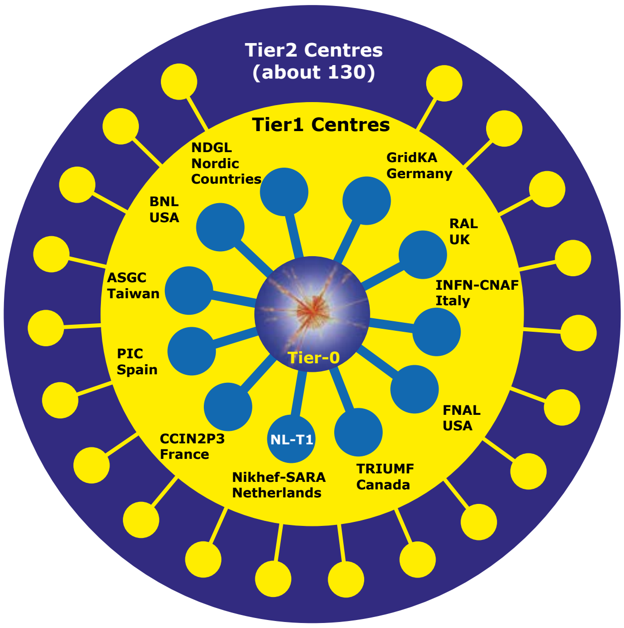


Figure 25. The Tier1 computing centres in the world, with Nikhef/SARA as one of them.

Having particle physics as an early adopter and primary driver of the e-Infrastructure has been crucial for its success in other domains. The methodology used in the preparation for the LHC data was one of 'data challenges' and 'service challenges' of continually increasing scope and size. This method has been re-used in preparing for the radio-astronomy data avalanche for the LOFAR archive. Data access and integrity processing developed at Nikhef for managing large volumes of data in long-term archives has been deployed for the DANS (*Data Archiving and Networked Services*) back-end storage, thus ensuring data stored there are verifiably correct. The security and authorization technologies developed to allow ten thousand physicists, spread across more than 150 particle-physics institutes and over 50 countries and economic regions, to cooperate in sharing data and computing capacity has been used as the basis for the authorization service in CLARIN, the ESFRI project on common language resources and technology infrastructure.

The BiG Grid infrastructure itself is a distributed system comprising resources at Nikhef, SURFsara, University of Groningen, Philips Research on the High-Tech Campus in Eindhoven, as well as 12 dedicated 'life science grid' nodes. Approximately half of the throughput-oriented data processing facility, is housed at Nikhef and is seamlessly integrated in both the national and global grid infrastructure. The infrastructure at Nikhef specifically caters for data-intensive computation, serving, besides the LHC communities, next-generation sequencing, medical imaging research, structural chemistry, molecular simulation and earth science research.

Working on the frontier of e-Infrastructure for science offers an excellent basis for joint development projects with all Dutch universities. Through internships at Nikhef and Masters' projects, a new generation of (applied) ICT professionals have contributed to the e-Infrastructure and to solving the data management challenges of the LHC. At the same time these challenges have extended the envelope of existing training and ensured new ideas are effectively disseminated in Dutch industry. Nikhef works with PDEng students of the Software Technology program (OOTI) at the Technical University of Eindhoven (TU/e), with the System and Network Engineering (SNE) master of the Institute of Informatics at the University of Amsterdam, and has a continuing collaboration with the Amsterdam University of Applied Sciences (HvA) on systems engineering and security software projects. One of us has also been appointed as e-science integrator at the recently founded *Netherlands eScience Center* (NLeSC), which supports and reinforces multidisciplinary and data-intensive research through creative and innovative use of ICT in all its manifestations.

Links with marine sciences
The KM3NeT project has led to intense cooperation with the National Institute for Sea Research (NIOZ). Initially, the expertise of NIOZ, as the world leader in deployment of mooring lines in the deep sea, was sought to aid in the development techniques for the neutrino telescope. The result has been an innovative design where the detector lines are deployed from the seafloor up, rather than the traditional deployment from the surface. This makes extremely lightweight construction of the lines possible, which reduces the hydrodynamic drag. This cooperation has grown into a more synergetic relationship with the telescope being used to house accurate temperature sensors distributed over the full volume. Oceanography has been limited to measurements using single mooring lines to measure properties of the internal waves, that are considered the most important elements in the redistribution of nutrients in the oceans. Using the neutrino telescope as host for the measurement devices will allow for the first time a 3-dimensional investigation of the ocean.

Links through FEL-like research facilities
In structural biology, (bio-)molecular physics and condensed matter physics research spatially and temporally coherent X-rays are in high demand. These are delivered at an rapidly increasing number of facilities worldwide, including the European XFEL (Germany), SwissFEL (Switzerland), FERMI@Elettra (Italy), LCLS (USA) and SACLA (Japan). High energy time-resolved electron diffraction with 10–100 femtosecond electron pulses, requiring significantly smaller scale infrastructure, offers complementary research possibilities. The high acceleration gradient X-band technology, in development at CERN for future high-energy electron-positron colliders, allows for a considerable reduction in size and cost of future research infrastructure in these fields. By optimizing design with ultra-precise dynamic alignment (Nikhef) and state-of-the-art electron sources (TU/e), the undulators can be made significantly shorter. This, in combination with the generation of higher harmonics in lasers (VU), can guarantee a high degree of reproducibility.

Figure 26. PANalytical PIXcel detector system, based on single-chip Medipix2 technology, developed in collaboration with Nikhef.

The detector and data acquisition systems for the experiments at FELs are very demanding due to the requirement in area, resolution, multiplicity and sensitivity to different types of particles. The same holds for the data analysis and interpretation. These are exactly the areas in which our community has much to offer.

Links to industry in general
Our detector R&D activities have demonstrated to be an extremely fruitful and proven breeding ground for valorisation activities, *i.e.* the translation of knowledge into technology in order to create commercially viable products or services. Nikhef has a long-standing collaboration with PANalytical, a company marketing X-ray diffraction systems

with pixel detectors originating from our detector R&D (See Fig. 26). For ASML, the world's largest manufacturer of semiconductor lithography equipment, Nikhef is investigating CO_2 cooling applications with very accurate temperature stabilisation.

A few years ago Nikhef founded, together with an investment firm, P2IP (*Particle Physics Inside Products*) as an umbrella organization for start-up companies. In 2011 P2IP launched Sensiflex to market a Nikhef patented alignment concept (RASNIK) for civil engineering applications (See Fig. 27). RASNIK systems are nowadays in use for monitoring movements in tunnels, shopping malls, bridges and driven piles. ASI (Amsterdam Scientific Instruments) was also launched in 2011 and markets custom applications for detector systems at FELs all over the world. With Royal Dutch Shell Nikhef is engaged in studies of a huge low-mass and low-power seismic sensor network with wireless readout to be deployed over a few hundred square kilometres for oil exploration. This is likely to result in another P2IP start-up.

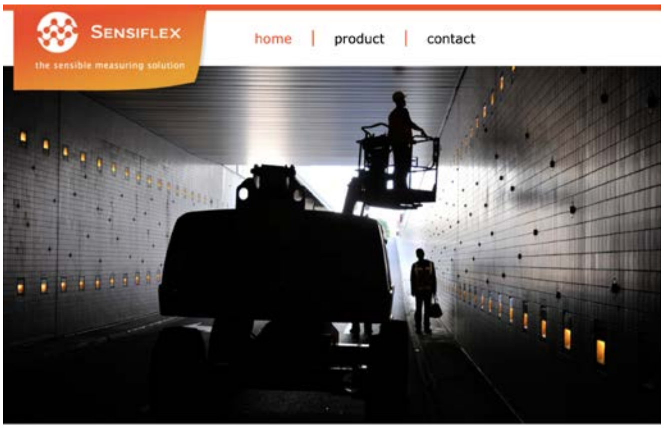


Figure 27. Installation of Sensiflex RASNIK systems in the Rotterdam Weena tunnel.

Nikhef has a long-standing tradition in cutting edge information technology, with internet involvement from the beginning in the early eighties. This resulted in the housing of AMS-IX, one of the World's largest internet exchanges, at Nikhef in the mid nineties. Today Nikhef is still one of the largest of the presently eight AMS-IX locations, as measured in number of customers (about 120 companies, representing a sizeable portion of the total public and private peering traffic in the Netherlands). The societal impact of this activity is unquestionable. The success of the Internet really took off, after CERN developed the WWW concept in the early nineties with the future LHC community in mind. The first three websites in the World were: www.cern.ch, www.slac.stanford.edu and www.nikhef.nl (in that order). One of the WWW cofounders still vividly remembers one of the very first innovative web applications: the *square root facility* launched by Nikhef collaborator Willem van Leeuwen. This illustrates that the enormous and often unexpected societal impact of the spin-off of curiosity driven research is hard to anticipate. The experience of providing a reliable data centre for AMS-IX at Nikhef has paid off enormously in setting up and running of the Dutch Tier1 grid computing facility.

Links to medical industry

The same pixel technology as marketed by our ASI start-up is being developed together with Philips to yield large area X-ray detectors that provide spectral (energy) information. This development is taking place in view of particle therapy, conventional X-ray therapy and cardiac angiography applications. With X-ray energy information specific features, such as K-edge imaging of iodine or gadolinium, when using contrast agents and the disentangling of density and elemental composition in radiotherapy, can be significantly enhanced.

Currently, PET camera count rates are limited by the coincidence logic that triggers the read-out. With the modern SiPMT technology, developed by Philips, a triggerless readout, with timestamp in combination with large scale parallel processing of the data will result in a higher statistical accuracy, whereas the better timing resolution translates in more precise 3D position information on the point of interaction in the detectors and hence better sensitivity and image contrast. This is relevant for dynamic metabolic studies (diagnostics), for which count rate capability is a key issue and for particle therapy (verification dose delivery), where sensitivity and image contrast are essential.

In particle radiotherapy of cancer conventional X-ray CT-imaging is often a limiting factor for the quality of the treatment. This applies in particular to cases with complex geometries (*e.g.* head and neck region) and/or with image distortions due to metal parts (like hip prosthesis and teeth implants) in the patient's body. These distortions are caused by the physics of X-ray absorption in matter. Imaging proton energy loss does not suffer from these problems but has a lower contrast than X-ray imaging. The detector technology developed for the LHC experiments is a key factor for a successful proton imaging system. By combining the information from both imaging modalities the quality of the information needed for treatment planning in radiotherapy can be strongly improved, thus leading to a better outcome.

Industrial networking

Besides the aforementioned activities, Nikhef interfaces in many more ways with the 'outside world'. Our industrial liaison officer informs Dutch industrial parties about upcoming CERN-tenders. He has also organized a successful *'Holland@CERN'* symposium, a 3-day long industry event at CERN, where 27 Dutch high-tech companies displayed their products to CERN users, engineers and technicians. The link to CERN and for that matter other accelerator laboratories provided by Nikhef provides pay-back to Dutch society in terms of industrial contracts that not only provide financial advantages but also, due to their high-tech nature, broaden the Dutch technology base. Furthermore, our technical groups (mechanics, electronics, computing) are in constant dialog with local and European industries. Industrial networking meetings are organized to inform each other on technological advances. Finally, Nikhef has an open policy with regard to giving external parties access to the Nikhef technical facilities, on a cost recovery basis. In this way, our *Silicon Alley* facilities for semiconductor detectors, containing equipment for probing, bonding, precision measurement and diagnostic EM, are used by several companies, most notably PANalytical.

Figure 28. Holland@CERN exhibition of 27 companies in 2010.

"Topsectoren"

A few years ago, the Dutch government identified nine areas (*'topsectoren'*) in which the Netherlands excels. *High-tech systems and advanced materials* (HTSM), matches well with our research. The recently added HTSM sub-chapter *advanced instrumentation* is a perfect match for many of our experiments. Through the imaging hardware and software development there is a strong tie to *Life Sciences and Health*. The view held by the Dutch government on innovation:

> *"Innovation is essential for companies that want to grow. The development of new technologies is expensive and requires specialist knowledge. Often it is uncertain whether the technology is successful. This requires a good strategy."*
>
> *http://www.rijksoverheid.nl/onderwerpen/ondernemersklimaat-en-innovatie/investeren-in-topsectoren*

applies equally well to our own activities in experimental astroparticle and particle physics. Particle physics has become the breeding ground for high-tech development in the areas of data handling, computational science and detection devices. Companies that have been involved with CERN invariably profit from an increase in revenue but maybe even more importantly of know-how. In 2005 CERN compiled an overview of best examples: *"CERN technology transfers to industry and society"* (including *e.g.* PANalytical). Both CERN and Nikhef actively promote and support technology transfer and spin-off activities. The emerging field of astroparticle physics will again provide an area in which innovative technology, be it in the deep sea or in seismic isolation, will come to the forefront. Nikhef will vigorously pursue the transfer of its technology to industry and it is convinced that with the in-house technology and with excellent links to CERN it offers a broad spectrum of opportunities.

Young, highly trained professionals

Finally, maybe the most important contribution from NL-APP activities to the 'knowledge economy' are the many well trained and educated PhD students. Career data from the OSAF Research school show, that while one third of PhDs continue in research, two thirds pursue a career in other sectors, notably in high-tech industries and ICT (*e.g.* the current consultancy group on 'big data' at KPMG is formed almost completely of former Nikhef-PhD students).

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Budget

Table A1: Requested Staff (period 2014-2018) *(in k€ incl. surcharge)*

Scientific staff (WP)	FTE	2014	2015	2016	2017	2018	TOTAL
Postdoc	22	170	481	759	850	930	**3,191**
PhD student	28	186	393	775	1,153	1,285	**3,792**
Tenure track	10	159	330	514	711	922	**2,636**
Total Scientific		**516**	**1,205**	**2,048**	**2,715**	**3,136**	**9,619**
Non-scientific staff (NWP)	**FTE**	**2014**	**2015**	**2016**	**2017**	**2018**	**TOTAL**
Coordinator	1	72	76	80	84	88	**399**
Total Non-scientific		**72**	**76**	**80**	**84**	**88**	**399**
TOTAL STAFF		**587**	**1,280**	**2,128**	**2,799**	**3,224**	**10,018**

Table A2: Requested Staff (period 2019-2023) *(in k€ incl. surcharge)*

Scientific staff (WP)	FTE	2019	2020	2021	2022	2023	TOTAL
Postdoc	10	819	848	713	521	311	**3,211**
PhD student	16	1,464	1,370	1,088	682	358	**4,961**
Tenure track (cont.)		968	1,016	843	656	454	**3,938**
Total Scientific		**3,251**	**3,234**	**2,644**	**1,859**	**1,123**	**12,111**
Non-scientific staff (NWP)	**FTE**	**2019**	**2020**	**2021**	**2022**	**2023**	**TOTAL**
Coordinator	1	92	97	102	106	112	509
Total Non-scientific		**92**	**97**	**102**	**106**	**112**	**509**
TOTAL STAFF		**3,343**	**3,331**	**2,746**	**1,965**	**1,235**	**12,620**

Table B1: Requested investment costs (period 2014-2018) *(in k€)*

Requested investment funding						
Description	**2014**	**2015**	**2016**	**2017**	**2018**	**Total**
LaserLab facility			600			**600**
RF Facility	100	250	150			**500**
Cherenkov Telescope Array				500	500	**1,000**
Total Investments						**2,100**

Table B2: Requested investment costs (period 2019-2023) *(in k€)*

Requested investment funding						
Description	**2019**	**2020**	**2021**	**2022**	**2023**	**Total**
Cherenkov Telescope Array	500	500				**1,000**
Total Investments						**1,000**

Table C1: Requested other costs (period 2014-2018) *(in k€ incl. surcharge)*

Requested other funding						
Description	**2014**	**2015**	**2016**	**2017**	**2018**	**Total**
Travel costs (3 k€/fte WP/year)	33	65	107	135	153	**492**
Membership fee (5 k€/fte tenure track & postdoc/year)	30	60	90	105	120	**405**
Secondments (15 k€/year)	37	87	139	174	191	**628**
Additional budget for fellows (7 k€/year)		14	28	35	35	**112**
MEMS lab fees	50	50	50	50	50	**250**
Coordination costs	20	20	20	20	20	**100**
Total other funding requested						**1,987**

Table C2: Requested other costs (period 2019-2023) *(in k€ incl. surcharge)*

Requested other funding						
Description	**2019**	**2020**	**2021**	**2022**	**2023**	**Total**
Travel costs (3 k€/fte WP/year)	153	146	116	75	42	**531**
Membership fee (5 k€/fte tenure track & postdoc/year)	115	110	90	65	40	**420**
Secondments (15 k€/year)	169	144	118	98	58	**587**
Additional budget for fellows (7 k€/year)	28	28	21	14	7	**98**
MEMS lab fees	50	50	50	50	50	**250**
Coordination costs	20	20	20	20	20	**100**
Total other funding requested						**1,986**

Total Staff (2014–2023)	***22,638***
Total Investment costs (2014–2023)	***3,100***
Total Other costs (2014–2023)	***3,973***
Overall total requested (2014–2023)	**29,711**

Case for the requested budget

The total requested budget in the NL-APP proposal amounts to 29.7 M€ and covers a ten-year period; 76.2% is devoted to personnel costs, 10.4% is requested for investment cost, and 13.4% for other cost. About 2.7% of the requested funding is budgeted for the coordination costs of the consortium.

Scientific and non-scientific staff (22.6 M€)

Following the Talent plan as detailed on pages 48–51 we request funding for 44 PhD positions, 32 (3 year) postdoc positions and ten tenure-track positions, in the course of the total ten year project duration. We request funding for ten tenure-track groups, of which in the first five years two will start each year. Each tenure-track groups consists of a tenure-track position (funded for on average seven years from NL-APP), two 4-year PhD positions and one 3-year postdoc position. Successful tenure-trackers will become university staff. For all ten positions we have received a commitment from the universities taking part in NL-APP. In addition, we request funding for ten NL-APP 'fellowship' positions (postdoc level, three years). Finally, we request funding for 24 PhD students and 12 postdoc positions to be attributed to the various research foci. Only one non-scientific position is requested: the coordinator of the NL-APP consortium (one fte for ten years). Staff personnel costs are based on standard gross-wages, including employers contributions, but excluding overhead. For the details of each of the tenure-track groups and other research groups, we refer to the Talent plan (pages 48–51).

Requested investments (3.1 M€)

The requested investment funding is inherent to the experimental focus of this proposal.

For the Cherenkov Telescope Array (CTA) experiment we request significant construction funds (2 M€), representing 1% of the total construction cost of 200 M€, which is the minimum contribution to become a regular consortium member with full data access rights. The contribution will be targeted at the area of advanced photo-sensors (where a common development with Philips Research is foreseen) and readout electronics.

We also request 0.5 M€ funding for our contribution to an RF-testing facility in order to be able to significantly strengthen accelerator physics in the Netherlands (see pages 45–46).

For the LaserLaB (VU-group) we request an investment of 0.6 M€ to build a sub-Hz frequency comb facility, attached to a state-of-the-art ion-trap atomic clock, to enable the extreme precision experiments on the atomic scale (page 30).

Requested other costs (4.0 M€)

Travel expenses (conferences, collaboration meetings, workshops, *etc.*) are inherent to working in an international field like astroparticle and particle physics research. We estimate these costs to average about 3 k€ per person per year *i.e.* about 1 M€ over the duration of NL-APP. For the (10) NL-APP fellows we reserve an additional annual budget of 7 k€, adding up to a total of 10 k€ personal research budget per year.

Taking part in large international collaborations implies sharing a fraction of the running costs of the experiment (power, consumables, *etc.*). To do so implies that each scientific author with a PhD-degree or equivalent (*i.e.* staff scientists and postdocs) typically pay an annual membership fee of on average 5 k€. For this we estimate, for those tenure-trackers and postdocs affiliated with large projects, in total about 0.8 M€.

Many junior scientists spend up to one year (PhD students) or two years (postdocs) stationed at location (CERN for the LHC experiments, Pisa for the Virgo gravitational-wave search, Gran Sasso for the direct dark matter search, *etc.*). During this time they receive an allowance ('secondment cost') on top of their usual salary (about 15 k€/year). We estimate that around 81 fte-years from PhD-students and postdocs will be spent abroad, amounting to almost 1.2 M€ on secondment costs over the project duration.

For the access to nano-fabrication laboratories for MEMS work (seismic sensors and Gossip) we request 50 k€ per annum (0.5 M€ for the duration of NL-APP).

For the consortium coordination and management activities we request a moderate running budget of 20 k€ per year, particularly devoted to double the frequency of the Nikhef collaboration meeting ('jamboree') to twice a year.

Co-funding

We have not specified co-funding in a separate table. The funding streams in the (current) Nikhef collaboration amount to about 26 M€ annually (excluding investments). From this around 14 M€ can be considered as basic funding (*i.e.* the mission budget from the FOM-institute Nikhef and the institutional funding from the four universities), the rest is acquired via national and international (European) grants and through activities for third parties. In the extended Nikhef collaboration the base funding will be around 16 M€, likely raising the total level of research funding from about 26 M€ to almost 30 M€ annually. The proposed activities in this NL-APP proposal (averaging 3 M€ per year) will therefore be backed up by a strong home base.

Duration of the project

Planned starting date:	1 January 2014
Expected completion date:	31 December 2023

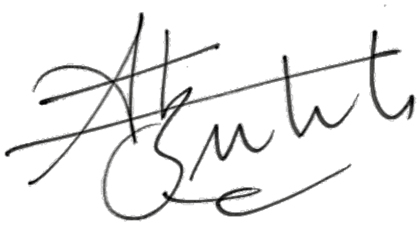
Declaration and signature (by main applicant)

Have you requested funding for this research elsewhere?

■ No

Declaration

By submitting this form through Iris, I declare that I have completed this form truthfully and completely.



The award-winning documentary about the discovery of the Higgs-boson with Nikhef involvement.