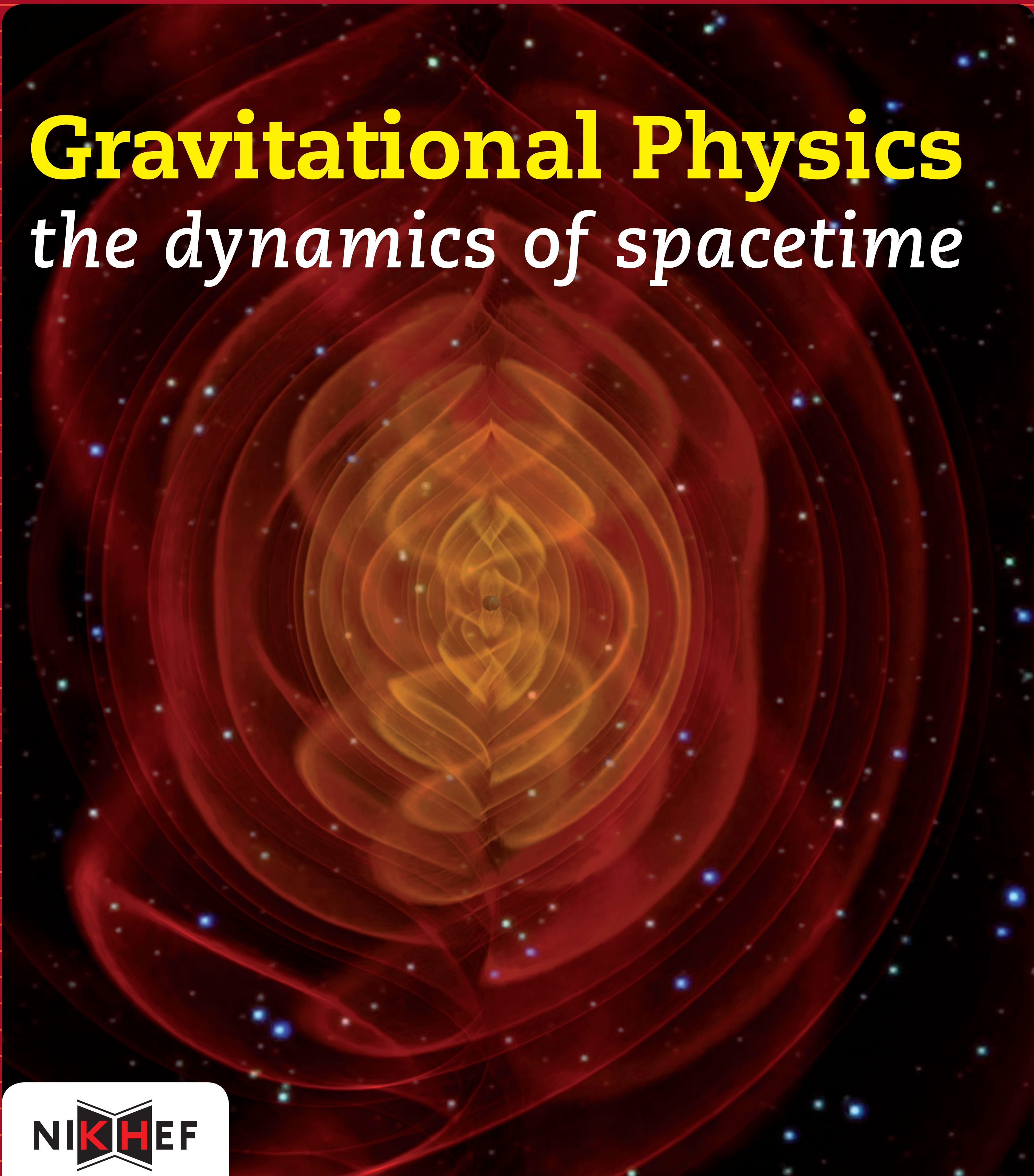
FOM program proposal 2009

Gravitational Physics

the dynamics of spacetime



NIKHEF

1 Gravitational Physics

the dynamics of spacetime

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Nikhef is the National institute for subatomic physics in the Netherlands, in which the Foundation for Fundamental Research on Matter (FOM), the Universiteit van Amsterdam (UvA), the Vrije Universiteit Amsterdam (VU), the Radboud Universiteit Nijmegen (RU) and the Universiteit Utrecht (UU) collaborate. Nikhef co-ordinates and supports activities in experimental and theoretical particle and astroparticle physics in the Netherlands.

Nikhef participates in the preparation of experiments at the Large Hadron Collider at CERN, notably ATLAS, LHCb and ALICE. Astroparticle physics activities at Nikhef are threefold: the ANTARES neutrino telescope in the Mediterranean Sea, the AUGER cosmic ray observatory in Argentina, and the Virgo gravitational-wave interferometer in Italy. Detector R&D, design and construction of detectors and the data analysis take place at the laboratory located at Science Park Amsterdam as well as at the participating universities. Nikhef has a theory group with both its own research program and close contacts with the experimental groups.

3 Objectives and focus

Albert Einstein's theory of general relativity, published in 1915, gave science a radically new way of understanding how space, time and gravity are related. Gravity is defined as the curvature of spacetime and is caused by the four-momentum of matter and radiation. Einstein predicted that accelerating objects will cause vibrations in the fabric of spacetime itself, so-called gravitational waves.

The detection of gravitational waves is the most important single discovery to be made in the physics of gravity. Gravitational waves exist in any theory of gravity that incorporates a dynamical gravitational field, be it a metric theory such as general relativity (or one of its generalizations), or a non-metric theory such as string theory. Observations of binary pulsars, whose orbital motion evolves in agreement with general relativity, revealed that gravitational radiation must exist. However, no direct observation of gravitational waves has been reported to date. Discovering gravitational waves would confirm once and for all that gravity is a fundamental dynamical phenomenon.

Historically, quantum theory was discovered as a result of the particle–wave duality in electromagnetic phenomena, leading to the concept of the photon. Quantum gravity might well arise out of a similar duality between gravitational waves and massless spin-2 particles: gravitons. The existence of gravitational waves would be the first step on the experimental road to quantum gravity.

Gravitational-wave detection opens up the possibility to test general relativity itself and to study questions about spacetime, cosmology and structure in the Universe. For instance, the hitherto experimentally untested strong-field regime of general relativity may be accessed. Can we do this by observing the gravitational waves generated when two black holes or neutron stars merge? These events in itself may provide the first experimental evidence of gravitational waves. When we do detect them directly, will it be found that there are deviations from Einstein's general relativity? Furthermore, it may be that gravitational waves were generated during inflation, in the earliest moments of the Big Bang. Can we detect these waves? If so, will we learn about particle energy scales vastly higher than those attainable in accelerators? Do atoms behave in unexpected ways when they are at the high temperatures and pressures associated with the strong gravitational field near a black hole? Shouldn't a more complete census of black holes be made? Furthermore, according to current understanding structure in the Universe itself is due to gravitation. What does the Universe look like in gravitational waves? Developing techniques for the detection and analysis of gravitational waves is the key to answering these questions.

We propose a FOM program that focuses on the direct observation of gravitational waves using modern developments at the frontier of laser-interferometry. This technique to search for gravitational waves is the one most forcefully pursued at present world-wide, with instruments in Europe (Virgo and GEO600), the USA (LIGO), and Japan (TAMA). The same technique is also proposed for the detection of low frequency waves by a space-born experiment (LISA), and for a large new Earth-based experiment, Einstein Telescope, which is part of the European roadmap for astroparticle physics and which has received substantial support from the European Union in their FP7 program.

The contribution of the proposed FOM program to this international effort will consist of *(a)* hardware contributions to Virgo (see Fig. 1), *(b)* the development of data analysis methods, and *(c)* the modeling of gravitational-wave signals of various sources. Our request to FOM is timely, since the proposed hardware projects are targeted to the Advanced Virgo upgrade. Decisions for this upgrade program are taken this year, while hardware installations will start in 2012. The second Virgo science run (VSR2) has started this summer simultaneously with the sixth LIGO science run (S6). Data analysis concentrates on procedures for all-sky searches for periodic and transient wave phenomena using laser interferometers. Closely related theoretical studies will provide model signals to search for in the data.

The quest for direct observation of gravitational waves requires understanding of how the various possible signals, be it from mergers of binary systems (black holes or neutron stars), periodic sources, or the early Universe, should be extracted from the background noise. This requires detailed theoretical modeling of signals and development of analysis techniques, combined with a thorough understanding of the instruments. The participants have the expertise in instrumentation, data handling and analysis, theoretical expertise and expertise in astrophysics to carry out the proposed program.

Figure 1. The Virgo experiment for detecting gravitational waves coming from any part of the Universe, consists of a Michelson laser interferometer made of two orthogonal arms being each 3 kilometers long. Multiple reflections between mirrors located at the ends of each arm extend the effective optical length of each arm up to hundreds of kilometers. Virgo is located within the site of EGO, the European Gravitational Observatory, near Pisa in Italy and is operated by a French-Italian-Dutch collaboration. (Source: Virgo)

Gravitational physics is part of Nikhef's strategic plan for 2007–2012. Nikhef became full member of Virgo in 2007. On July 2, 2009, Nikhef became associate member of the European Gravitional Observatory Council. Jo van den Brand is member of the Virgo Science Council. Moreover, he is member of the Governing Council and Executive Board for Einstein Telescope, and leads Working Group 1 for Site Selection and Infrastructure. Chris Van Den Broeck recently joined the Nikhef scientific staff. He has expertise on mathematical general relativity, gravitational-wave source modeling, the coalescence of binary neutron stars and black holes, and gravitational-wave data analysis. Henk Jan Bulten has expertise in computational physics and Grid computing. He works on the analysis of continuous gravitational waves from sources in binary systems, both in the analyses groups of LIGO and Virgo, and as member of Working Group 4 of Einstein Telescope. Jan Willem van Holten has expertise on theory of particles and fields, gravitation and cosmology. He models gravitational-wave sources such as EMRI, compact binaries and black holes while taking into account the effect of radiation reaction. He also has a considerable expertise in the construction and analysis of exact wave-solutions of general relativity. The RU–IMAPP is deeply involved in the scientific definition of LISA (see Fig. 2), as Gijs Nelemans is member of Working Group 1a of the science team and has been the lead author of the Galactic binary chapter of the Science Case and the white paper for the current US Decadal survey. He also is a member of ESA's fundamental physics advisory group. Jan Kuijpers started theoretical work in general relativity at the RU in 2001, in particular on the coupling of gravitational waves and magnetic fields in the environs of compact objects with Joachim Moortgat. Presently, he is a member of the Nikhef board. Until 2009 he has been *"werkgroepleider"* of the FOM working group on particle astrophysics N-18, and leader of the FOM project *"High energy cosmic rays and coherent radio emission"*. Until 2007 he has been co-chair of the Committee for Astroparticle physics in the Netherlands (CAN) and PI of the LOFAR key program Cosmic Rays. Thomas Bauer, Harry van der Graaf and Tjeerd Ketel are working on improving the sensitivity of Virgo (see Fig. 3). Bauer has experience in data acquisition and analysis, precision mechanics and electronics. He is responsible within Virgo for the upgrade of the Input Mode Cleaner. Van der Graaf has developed RASNIK, a now widely applied optical alignment system which can monitor minute variations in geometry. He is involved in the design of the front-end for Virgo's linear alignment system. Ketel is responsible for the upgrade of the linear alignment electronics required for Advanced Virgo.

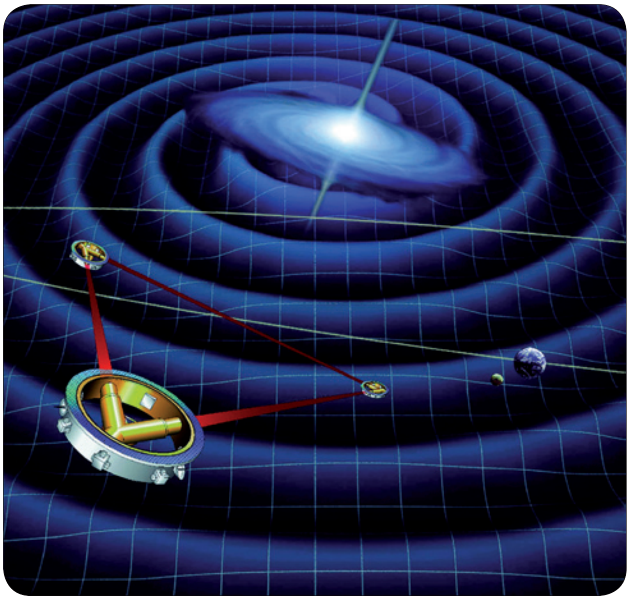

Figure 2. Laser Interferometer Space Antenna, LISA, is an interferometer in space. LISA does not suffer from unwanted vibrations that plague similar instruments on the ground. LISA will therefore be sensitive to the lower-frequency gravitational waves produced, for example, by massive black holes, binary white-dwarf stars and phase transitions in the early Universe. LISA, which is due to launch about 10 years from now, will contain gold-platinum alloy cubes that float inside cavities in three spacecrafts (i.e. where only gravitational forces act on them). Lasers will measure of order picometer differences between the position of each cube and similar cubes in the other two spacecrafts five million kilometers away induced by a passing gravitational wave. (Source: ESA)

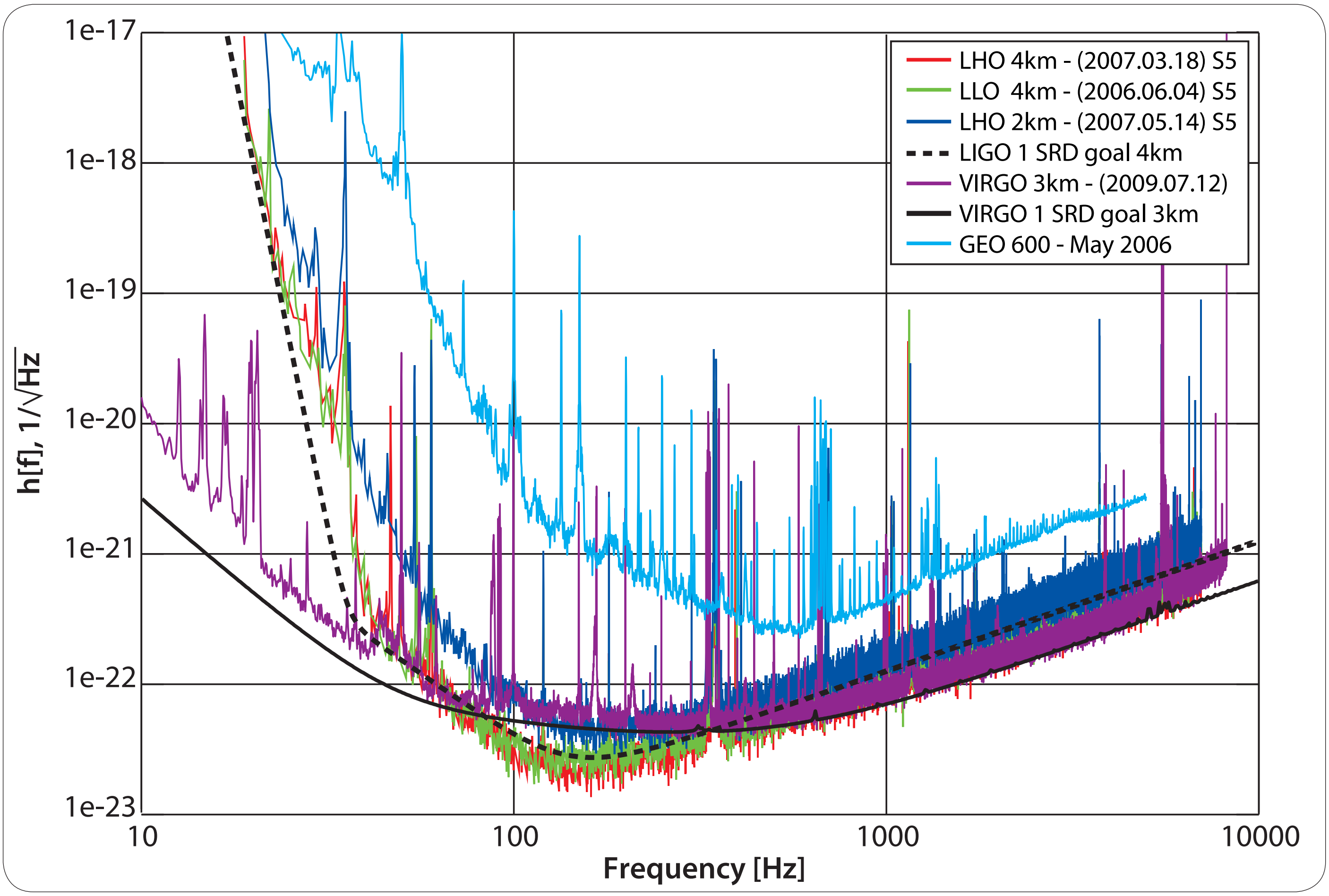

Figure 3. The sensitivity of the LIGO detectors (red, green and blue), the Virgo detector (purple) and the GEO600 detector (light blue), compared with the design sensitivity of LIGO (dashes) and of Virgo (solid black). Note the strain vertical scale. (Source: LIGO/Virgo/GEO600)

We believe that the scientific focus of our proposed program, together with ongoing activities in Astronomy and Theory, provides a strong starting position for the Netherlands in the growing field of gravitational-wave physics. In order to benefit and further exploit this position in Europe, programmatic funding of this part of astroparticle physics in the Netherlands is essential.

4 Scientific challenges

Scientific challenges

We have defined three scientific perspectives indicated as *Direct observation of gravitational waves*, *Gravitational-wave signals*, and *Gravitational-wave observatories*. Nikhef will lead the proposed activities related to first direct gravitational-wave detection. This ambition is the emphasis of the present proposal and the major part of the requested resources will be allocated to achieve this goal. Two components can be identified: data analysis to search for gravitational-wave signals and hardware improvements to Virgo to increase the sensitivity of the instrument. Some of the activities that will be carried out within this program are defined as 4-year PhD projects, while others are postdoc projects. Responsibility for each project is assigned to one of the senior scientists involved, depending on specific relevant expertise. These projects represent significant cross-institute collaboration.

Activity 1: Direct observation of gravitational waves

Nikhef scientists intend to be part of the team that makes the first direct detection of gravitational waves. Possible sources for which the current detectors are sensitive include supernova events, mergers of massive objects (black holes and/or neutron stars), primordial relics (see *activity* 2) and fast-spinning massive objects. Nikhef scientists (Bulten, van der Putten) perform an 'all-sky' search for periodic signals from fast-spinning neutron stars, including for the first time those in binary systems. Compared to supernovae or mergers, the expected signals from neutron stars are several orders of magnitude weaker. However, these sources are continuous such that signals can be integrated over long times, increasing the signal-to-noise ratio significantly. An all-sky analysis is extremely computing intensive (see *section* 5), and we take advantage of the excellent Grid infrastructure in Amsterdam. The same tools will be used to study the performance of Einstein Telescope and LISA and later to analyze LISA's verification binaries (see *activity* 3).

Nikhef will consolidate its involvement in the search for periodic signals, and use the requested funds to initiate analysis activities towards coalescing binaries (Van Den Broeck). Apart from the fact that these are prime sources for a first gravitational-wave detection, they will offer a first real test of the genuinely strong field dynamics of general relativity. Furthermore, mapping the mass distribution of black holes and neutron stars and its time evolution will give valuable insight into the evolution of star-formation rate. For coalescences involving a neutron star, the last stages of inspiral and the merger signal will yield information about the neutron star equation-of-state, about which little is currently known. There is also the possibility of using binary coalescences as self-calibrating 'standard sirens', with no need for a cosmic-distance ladder.

Activity 2: Gravitational-wave signals

Gravitational-wave observations open a window on processes in which gravity is the dominant driving force. In particular they provide access to phenomena which are difficult to study in electromagnetic or other windows. The most important of such phenomena include the physics of black holes, and of cosmological processes in the very early Universe.

Black holes: Observations show that giant black holes exist in many, if not all, galaxies of large or intermediate mass. Our own galaxy houses a central black hole of almost four million solar masses, but in some galaxies the central compact object exceeds a billion solar masses. Evidence for smaller black holes, ranging from a thousand to hundred thousand solar masses, has been found in studies of dwarf galaxies and star clusters. These extremely massive objects interact gravitationally with stars in their vicinity, disturbing their orbits. Occasionally, one of these stars will suffer fatal attraction and plunge into the horizon of the black hole. This process, and the following ring-down of the black hole, is accompanied by strong gravitational-wave emission. Study of these gravitational-wave signals will provide insight in the physics of black holes as well as the evolution of galaxies.

Stellar mass black holes are the end product of the collapse of massive stars, formed in supernovae or gamma-ray bursts. A population of stellar mass black holes is therefore expected in all galaxies, of which little is known at present. Gravitational-wave signals from these objects, in particular in binary systems, are an important source of information about this class of stars.

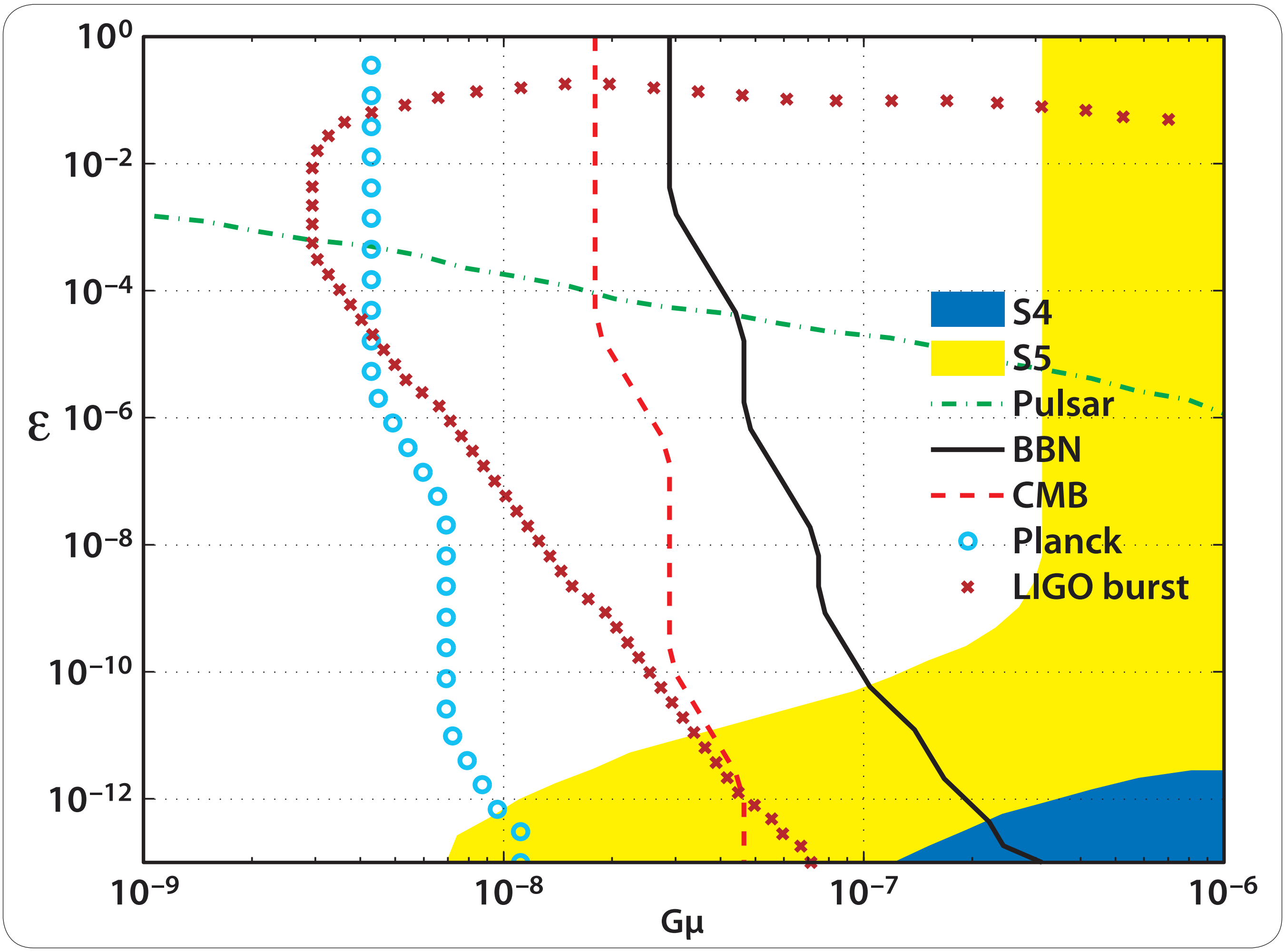

Figure 4. Cosmic strings have descriptions both in terms of string theory and quantum field theory and may have formed in the early Universe as defects at the end of the inflationary phase transition and then stretched to astronomical size by cosmic expansion. Detecting cosmic strings from their gravitational radiation would allow connecting these beautiful mathematical ideas with real experimental data. The new science of gravitational waves might therefore reveal signatures of new fundamental physics. The network of cosmic strings is usually parametrized by the string tension μ (multiplied by the Newton constant G), and reconnection probability p. The CMB observations limit $G\mu < 10^{-6}$. If the size of the cosmic string loops is determined by the gravitational back-reaction, the size of the loop can be parametrized by a parameter ε, which is essentially unconstrained. The mechanism for production of gravitational waves relies on cosmic string cusps: regions of string that move at speeds close to the speed of light. If the cusp motion points towards Earth, a detectable burst of gravitational radiation may be produced. The superposition of gravitational waves from all string cusps in the cosmic string network would produce a stochastic gravitational-wave background (SGWB). The figure is extracted from a recent publication by LIGO and Virgo on this topic and shows how different experiments probe the ε – Gμ plane for a typical value of $p = 10^{-3}$ (p is expected to be in the range 10^{-4}–1). The excluded regions (always to the right of the corresponding curves) correspond to the S4 LIGO result, S5 result, the BBN bound, the CMB bound, and the pulsar limit. In particular, the bound presented excludes a new region in this plane ($7\times10^{-9} < G\mu < 1.5\times10^{-7}$ and $\varepsilon < 8\times10^{-11}$), which is not accessible to any of the other measurements. Also shown is the expected sensitivity for the search for individual bursts from cosmic string cusps with LIGO S5 data. The region to the right of this curve is expected to produce at least one cosmic string burst event detectable by LIGO during the S5 run. Note that this search is complementary to the search for the SGWB as it probes a different part of the parameter space. Also shown is the region that will be probed by the Planck satellite measurements of the CMB. The entire plane shown here will be accessible to Advanced LIGO SGWB search. (Source: LIGO/Virgo; NATURE, Vol 460, 20 August 2009)

Cosmology: The detection of primordial gravitational waves would be one of the most exciting discoveries to be made in astrophysics. Nikhef's gravitational-physics program will contribute to the search for signals from the early Universe. The weakness of the gravitational interactions here becomes a benefit, as it allows gravitational-wave signals to propagate virtually undisturbed through the entire visible Universe. This makes it possible to look back in time to phases of the early Universe which are not accessible by observing either photons, of whatever energy, or even neutrinos. Clearly, such physics is at the heart of Nikhef's scientific mission.

There are various candidate sources for primordial gravitational waves; we mention a few:

Inflation. A period of rapid expansion of the early Universe explains very well some of its global properties, such as its smoothness and flatness, as well as the spectrum of primordial density fluctutations. The physical mechanism at the root of such an inflation period is highly uncertain. By observing the fluctuations in spacetime geometry caused by inflation, we learn more about the actual mechanism. Gravitational-waves detectors have the potential for providing such data, and may lead to a break-through in the field: interferometers can search for the gravitational waves directly, whereas PLANCK (by its excellent angular resolution and capability to measure the polarization of the CMB) may determine the spacetime fluctuations encoded in the CMB itself. With two independent ways of measurement, the interpretation of the data from each experiment can be verified and the correlation of the data sets may strongly improve the limits on various inflational models.

Thermal gravitational-wave background. If dynamical gravity was in thermal equilibrium with matter and radiation at some early epoch in the evolution of the Universe, there could exist a thermal background of gravitational waves, similar to the electromagnetic CMB. At a typical temperature of 1 K, the spectrum of these gravitational waves would peak at very high frequencies, of the order of 1 THz.

Phase transitions. It is possible that during the expansion and cooling of the early Universe it experienced one or more phase transitions, *e.g.* an electroweak, a QCD or a GUT (gauge unification) transition. The resulting change in the structure of the vacuum, being a dynamical process, will leave its mark on the spacetime geometry in the form of a spectrum of gravitational waves.

Topological defects. When large-scale domains of spacetime with a homogeneous vacuum structure are formed, topological effects like the formation of strings or domain walls can be produced at the boundaries. Such topological defects could decay under emission of gravitational radiation. An example of the sensitivity of LIGO and Virgo for cosmic (super)strings is shown in Fig. 4. These strings are topological defects that could form during phase transitions in the early Universe.

Pre-Big-Bang physics. In certain quantum gravity models like string theory, the standard Big Bang is a transition dominated by quantum effects between two different regimes of essentially classical spacetime geometry. In such a scenario it is possible that information about the pre-Big-Bang structure is transmitted in the gravitational-wave spectrum from the early Universe.

Interferometers are powerful tools for exploring gravitational activity up to vastly higher energy scales than can be reached by present-day accelerators. While other particle relics are absorbed and thermalized, this epoch is accessible to direct observation *only* by gravitational waves.

Activity 3: Gravitational-wave observatories

Virgo is located at the site of EGO, the European Gravitational Observatory near Cascina, Italy. The goal of Virgo and LIGO is to measure tiny fractional distortions of spacetime and these collaborations have achieved relative length sensitivities better than $10^{-22}/\sqrt{\text{Hz}}$. This corresponds to a measurement of the distance between the Sun and Alpha-Centauri with a length resolution better than the width of a human hair. Nevertheless, these interferometers are upgraded, and Nikhef participates in the Virgo upgrade programs. Nikhef has contributed to the first upgrade, termed Virgo+ (see the section on *milestones*). Virgo+ and the so-called Enhanced LIGO detectors, started their second common science run in Summer 2009. Although there is a significant chance for first detection of gravitational waves, additional upgrades (termed Advanced Virgo and LIGO) are foreseen. Nikhef will also contribute to the Advanced Virgo upgrade. The contributions include cryo-vacuum links in the interferometer arms to reduce optical path length fluctuations, seismic attenuation of external optical benches, payloads for both injection/detection benches and input-mode cleaner, and electronics for angular alignment of the interferometer. The Advanced Virgo (and LIGO) upgrades will be installed in 2013. In case no gravitational waves are discovered with the Virgo+ and Enhanced LIGO detectors, it is expected that the Advanced detectors should record gravitational-wave events within weeks, starting in 2014.

Figure 5. End-mirror of the input-mode cleaner of Virgo. The picture shows the new mirror and the reaction mass designed and constructed at Nikhef for controlling the mirror position with magnetic forces. The mirror and reaction mass are suspended with wires from a so-called marionette. (Source: Bruno van Wayenburg, NRC, July 2008)

As a next step on the roadmap, it is foreseen that by the end of the next decade gravitational-wave observatories will become operational which will detect thousands of sources. Such observatories are required to fully exploit this new window on the Universe. The proponents of the present proposal will contribute towards this development.

Einstein Telescope is the long-term future project of Earth-based gravitational-wave astronomy. It will record thousands of high-frequency (1 Hz–10 kHz) events per year and will have unprecedented sensitivity to the stochastic gravitational-wave background from the Big Bang due to its excellent performance at intermediate frequencies. In May 2008, Einstein Telescope received 3 M€ from the European Commission within the FP7 program to start a preliminary design study. This design study will define the specifications for the required site and infrastructure, the necessary technologies and the total budget needed, and can be considered an important step towards the third generation of gravitational-wave observatories. Nikhef leads the work package on site selection and infrastructure. Here, the minimization of gravity-gradient noise is of utmost importance in order to guarantee excellent low-frequency performance. These activities are carried out in an international context and in close collaboration with geoscientists and industry.

Europe also has a leading role in the space-based LISA and LISA-Pathfinder projects. LISA is a low-frequency gravitational-wave observatory that will study the mergers of supermassive black holes throughout the Universe, the inspiral of compact objects into supermassive black holes and thousands of Galactic ultra-compact binaries containing white dwarfs, neutron stars and black holes. The proper functioning of the instrument will be checked in the first weeks of operation with a number of known sources, the so called verification binaries. The richness of sources, all contributing to the same interferometer signal, provides a completely new challenge to data analysis. The Mock LISA Data Challenge (MLDC) is an international effort to develop the necessary data analysis techniques. The group at the Radboud University has already contributed significantly to this effort by providing the input for the Galactic sources. In order to maximally exploit LISA for studying astrophysics and fundamental physics, it is crucial to investigate the opportunities and challenges of complementary electromagnetic and gravitational-wave observations. At the Radboud University detailed study of the data analysis techniques and the scientific gain of including electromagnetic data will be performed, using the expertise of Nikhef in large scale (Grid) computing. The other challenge for the era of gravitational-wave observatories is the synergy of LISA with Einstein Telescope, in particular for intermediate mass/stellar mass black hole binaries that move from the LISA band into the Einstein Telescope band on human time scales.

Milestones

At present there are four collaborations with large interferometers operational: GEO600 in Germany (with 600 m arms), TAMA in Japan (300 m arms), LIGO in the USA (two 4 km arms and one 2 km arms), and Virgo in Italy (3 km arms). Realization of these instruments required sizable investments, *e.g.* LIGO represents the largest single enterprise undertaken by NSF, with capital investments of about 500 M$ and annual operating costs of more than 30 M$. In 2007, GEO, LIGO and Virgo have signed a Memorandum of Understanding (MoU) laying out the agreement to observe and analyze data together. On May 18, 2007, the first Virgo science run (VSR1) was started in coordination with LIGO's fifth science run (S5). The MoU gives Dutch physicists access to both Virgo and LIGO data, and resulted in joint data analysis and publications. Although the present devices are sensitive enough to detect signals from the occasional merger of a binary black hole system up to hundreds of million light years away, such a detection is not likely given the rarity of these processes. Consequently, the existing detectors are being upgraded.

In preparation for major upgrades for Advanced Virgo, the Virgo collaboration carried out in 2008 the interferometer upgrade program, called Virgo+. In this upgrade, the laser power was increased and thermal compensation systems installed. Nikhef took responsibility for the upgrade of front-end electronics for angular alignment of the various mirrors and for the input-mode cleaner (IMC). The IMC is a 144 m long high-finesse triangular cavity. Nikhef was responsible for the redesign, installation and testing of the end-mirror system (see Fig. 5). Currently, all Virgo+ subsystem upgrades have been installed, and commissioning of the improved interferometer has been completed. On July 7, 2009, Virgo started its second science run (VSR2) in joint operation with the Enhanced LIGO detectors (S6).

Further upgrades are planned, termed Advanced Virgo and Advanced LIGO. On April 1, 2008, the upgrade Advanced LIGO has been funded for 205.11 M$, while the corresponding operations from FY2009–FY2013 have been funded for 150 M$ by the US National Science Board. These second-generation gravitational-wave detectors will cover a cosmic volume about a thousand times larger than

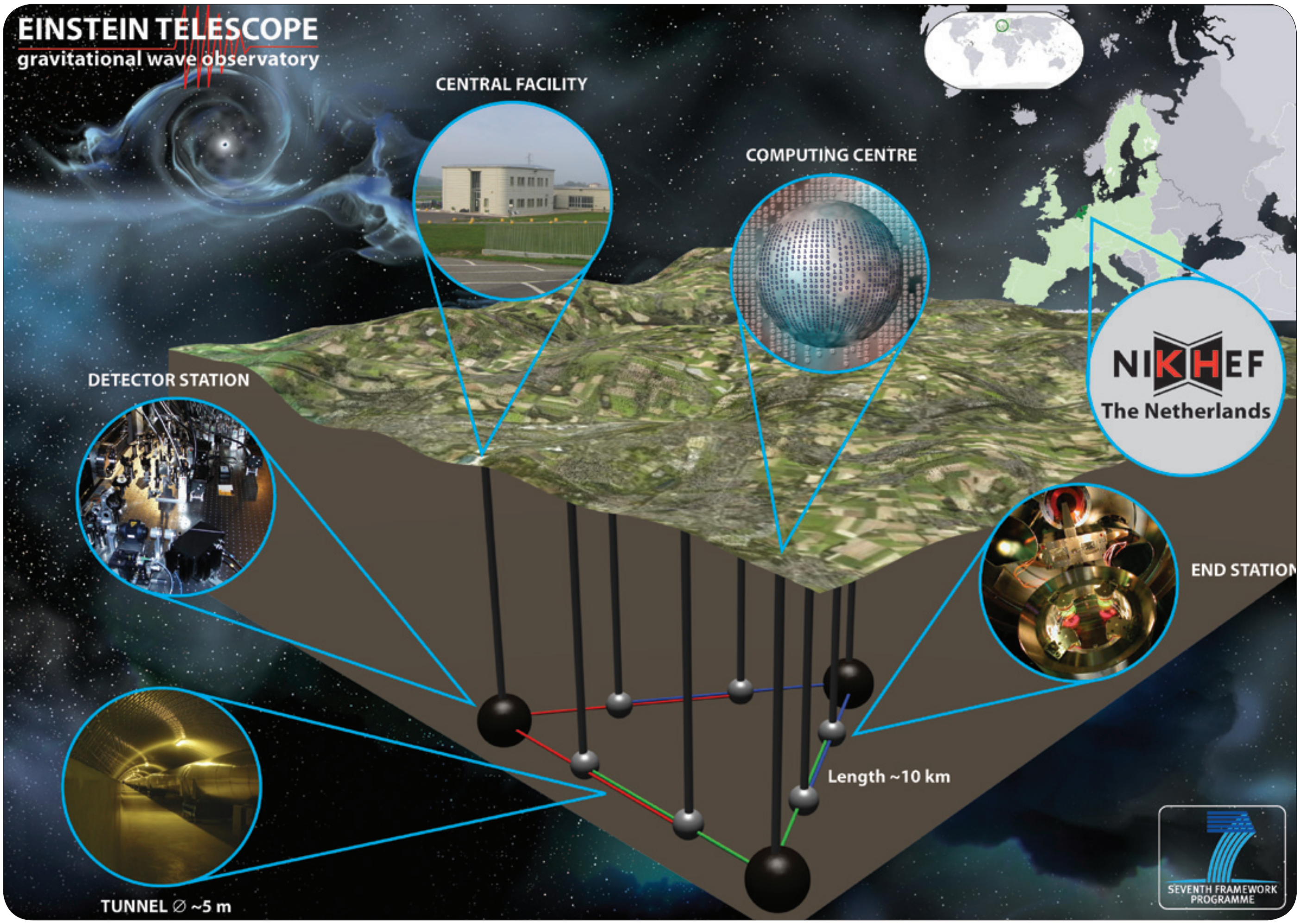

Figure 6. Conceptual diagram for the Einstein Telescope facility, a third-generation gravitational-wave observatory. Three interferometers with 10 km arms are placed underground to suppress micro-seismic noise. Optical components are placed in an ultra-high vacuum and cryogenic environment. Nikhef is the leading institute in coordinating the work package on site selection and infrastructure. (Source: Nikhef / K.Huyser)

the current one. While the enhanced detectors have a reasonable chance for discovering gravitational waves, the advanced detectors should see events within weeks.

Einstein Telescope is at present in the design phase (see Fig. 6). After the completion of the design study, a subsequent technical preparation phase is foreseen. The effective construction of Einstein Telescope is targeted at 2016–2017, after the second-generation observatories have collected first data. The technology required for third generation detectors is being studied in several countries besides Europe, including the USA and Japan.

LISA Pathfinder is to demonstrate the key technologies to be used in the future LISA mission. Pathfinder is approved and launch is scheduled for 2010. It is expected that final decisions about LISA will be made by ESA and NASA after evaluation of the LISA-Pathfinder mission, around 2012. LISA is an L-class mission concept of ESA's Cosmic Vision 2015–2025 plan with the earliest possible launch window in 2018.

International perspective

The search for gravitational waves belongs to the field of *Astroparticle Physics*, a rapidly growing research field at the interface of astronomy, cosmology and physics. Within Europe, the astroparticle physics community is coordinated by Astroparticle Physics European Coordination (ApPEC) (see http://appec.in2p3.fr). ApPEC announced a roadmap (which can be found at http://www.aspera-eu.org) on September 29, 2008, in which the scientific exploitation of Virgo figures prominently. Moreover, the roadmap identified Einstein Telescope as a third generation detector whose design should be pursued.

All future third-generation detectors will need to perform joint observations, as is the case for current gravitational-wave experiments. Einstein Telescope is a multi-national project of eight European research institutes and is listed in the ASPERA Roadmap as one of the '*Magnificent Seven*'. A conceptual design study for Einstein Telescope was submitted to the FP7 framework call in May 2, 2007. It received the maximum score for scientific content and has been subsequently approved. The design study formally started on May 5, 2008.

LISA is currently a candidate for the first large mission in ESA's Cosmic Vision 2015–2025 program and was part of NASA's Beyond Einstein program. The latter was recently reviewed by the BEPAC committee that strongly recommended LISA as *"the flagship mission of a long-term program addressing Beyond Einstein goals"*. A large LISA community has formed over the years, organized in the LISA International Science Community (LISC). Bi-yearly symposia are attended by over 200 scientists and the number of LISA related papers exceeds 1000 (more than 500 refereed papers).

The Netherlands has a strong starting position in the growing field of gravitational-wave physics, due to its involvement in Virgo and LIGO, Einstein Telescope and LISA. In order to benefit and further exploit this position in Europe, programmatic funding of astroparticle physics in the Netherlands is essential.

National perspective

The emerging Dutch astroparticle physics community has recognized that a country like the Netherlands can only have a significant impact in the field if the research effort is focused on a limited number of projects. For that reason the *"Strategic Plan for Astroparticle Physics in the Netherlands"* was written in 2005 (this report can be downloaded from http://www.astroparticlephysics.nl). From the beginning, gravitational-wave physics was foreseen as one of the three pillars of the national program, together with (radio) detection of cosmic rays and deep-sea neutrino detection. Note that these latter activities are funded through the FOM-program *"The origin of cosmic rays"*. The involvement in these areas allows for a multi-messenger approach to astroparticle physics and should result in a strong and internationally visible research program at this new frontier in science in the Netherlands.

Gravitational-wave physics is an interdisciplinary activity between astronomy, particle physics and cosmology. Next, we list several of the research projects that are ongoing in the Netherlands. Note that these projects are funded through NWO, ASTRON or other funding agencies. No funding is requested for these activities in the present proposal.

- Within SRON, the Netherlands institute for space research, control and readout electronics for inertial sensors are being developed for the Inertial Sensor Test Module (ISTM) project of the LISA Pathfinder mission. SRON is also contributing to detailed software models of the Inertial Sensor, which are included in the industrial End-to-End Simulator being developed at EADS Astrium (Germany).
- Many of the questions addressed by the theoretical astroparticle physics community in the Netherlands are closely linked to the proposed science program. The investigations encompass physics beyond the Standard Model focusing on several mechanisms that may affect leptogenesis and baryogenesis, investigations in cosmic accelerators, string theory, cosmology and gravitation, as well as astroparticle physics research, such as the topology of cosmic defects, presence of extra dimensions and the understanding of inflation.
- The telescopes of Westerbork are part of the European Pulsar Timing Array, a collaboration that has recently been formed between the five major radio observatories in Europe: Jodrell Bank, Effelsberg, Westerbork, Nancay and Sardinia. The goal is detecting gravitational waves in the nano-Hertz regime, using high precision timing of an array of millisecond radio pulsars distributed across the sky. This allows studies of wide supermassive black hole binaries and stochastic signals of cosmic strings.
- Within the Netherlands Research School for Astronomy (NOVA) several gravitational-wave related topics are studied, in particular in relation to the Pulsar Timing Array (Y. Levin, Leiden) and the gravitational-wave emission of known accreting neutron stars (A. Watts, UvA). In addition, astrophysical sources of gravitational waves (compact binary systems involving neutron stars, white dwarfs and/or stellar mass black holes, as well as supermassive black holes in galactic nuclei) are studied in Amsterdam, Leiden, Nijmegen and Utrecht using radio, near-IR, optical, UV, X-ray and gamma-ray instruments.
- The resonant gravitational-wave detector MiniGRAIL is operated at the University of Leiden and was developed in collaboration with Twente University. MiniGRAIL is a 68 cm diameter spherical antenna with a resonant frequency of about 3 kHz cooled to ultra-low temperatures. The first of its kind, its primary target is the observation of gravitational waves from non-axisymmetric instabilities in rotating single and binary neutron stars, and the radiation from mergers of small black holes or neutron stars.

In conclusion, there is a significant gravitational-wave activity among Dutch astronomers and physicists. Also there are several relevant activities within the Dutch theory community. These joint gravitational-wave activities guarantee an excellent starting point for an interdisciplinary gravitational physics program between particle physics, cosmology and astronomy. The present proposal focuses on gravitational-wave research for fundamental physics. Within the context of this proposal, Nikhef intends to organize annual meetings for the gravitational-wave community. Such meetings will have a broad impact and will foster the coherence of a Dutch community for gravitational-wave research.

5 Distribution of scientific tasks

We have defined three related themes: *Direct observation of gravitational waves*, *Gravitational-wave signals*, and *Gravitational-wave observatories*. At present, Nikhef's role in LIGO/Virgo data analysis is concerned with the search for signals from periodic sources. This represents a huge computational challenge. Frasca *et al.* have shown that for one year of data taking, if a sufficient fine grid for all parameters is used, a computing power of about 10^{19} TFlops would be needed. This is clearly not feasible and smarter algorithms need to be developed. Nikhef (Bulten, van der Putten) is developing a hierarchical method for analyzing periodic signals from binary systems. The method alternates between coherent and incoherent steps and runs on the TIER-1 facility in Amsterdam. This Grid environment was primarily designed for processing particle-physics data produced by the LHC experiments at CERN, but now other applications are being considered as well.

Nikhef will use the requested funding to broaden the analysis (Van Den Broeck) towards coalescing binaries (black holes or neutron stars). One PhD student and a postdoc (3 years) will be allocated to this project. Studies include setting-up a data analysis pipe line to search for coalescing binary black holes with inspiral-merger-ringdown templates and the realization of Bayesian model selection and follow-ups of gravitational-wave detection candidates. The Radboud University group will add to these efforts by investigating the influence of using complementary electromagnetic signals in the data analysis. An inventory of possible electromagnetic counterparts will be made (*e.g.* the coupling of gravitational waves of mergers to magnetized plasmas, as studied by Kuijpers and Moortgat that may produce waves in the low-frequency radio (LOFAR) domain, as well as the optical, X-ray and gamma-ray signals from short gamma-ray bursts). The resulting improvement of parameter estimation using these data will be determined (1 postdoc).

Nikhef will also lead the study of primordial gravitational-wave signals from inflation and cosmic defects. Local expertise (van Holten, Postma) is available on the topics of inflation, cosmic strings, supergravity and classical solutions of general relativity. Postma holds a VIDI position to study *"The Universe as a Laboratory for fundamental physics"*. This expertise will be the starting point for initiating studies of sources of gravitational waves in the early Universe, taking account of the results of the WMAP and PLANCK missions. Such studies will be carried out in a joint effort with the relevant university groups. A postdoc (3 years) will be allocated to this project. Nikhef will also derive precision wave forms for EMRI systems using fully relativistic perturbation theory (1 PhD). This work is a natural extention of ongoing EMRI studies (van Holten, Koekoek). Besides theoretical studies, this manpower will be engaged in analysis tasks of Virgo and LIGO data, while contributing to performance studies for Einstein Telescope and LISA.

Both Nikhef and Nijmegen will contribute to the development of gravitational-wave observatories. Furthermore, Nikhef will be involved in the running of Virgo and take responsibility (Bauer, van den Brand, van der Graaf, Ketel) for part of the Advanced Virgo upgrade program (the PhD students and postdoc will contribute to these activities). Nikhef also focuses on the science case for Einstein Telescope (1 PhD) and will study compact binary coalescence. The Radboud University will address the preparation for LISA, and investigate possible LISA–ET synergies.

The preparation for LISA will focus on the verification sources, via detailed analysis of their signals and the improvements needed to optimally use them, including applying the joint electromagnetic-gravitational wave data-analysis techniques that will be developed at the Radboud University and Nikhef for the ground-based instruments. The close connection with the observational astrophysics group at the RU will ensure direct access to newly discovered sources and candidates. At the same time, the use of the gravitational-wave measurements to unravel the astrophysical questions of the formation of these binaries will be investigated (1 PhD).

Analysis of the expected source populations for both LISA and ET (1 PhD) will be embedded in the current compact binary population synthesis efforts at the RU (funded through NWO–EW) and will focus on the overlap between the observatories and the additional (astro)physics that can be studied for stellar-mass and intermediate-mass black holes. For instance, when intermediate-mass black holes will be discovered by LISA and can then be studied later by ET, or when the population characteristics of Galactic black-hole binaries found by LISA can be compared to the mergers seen in external galaxies.

A detailed overview of the various projects can be found in Appendix A.

6 Organizational structure

The proposed research program is led by a single *program leader*, Jo van den Brand (Vrije Universiteit – Nikhef), who carries the full executive responsibility. The program leader receives administrative support from the coordinating institution, the FOM *institute for subatomic physics Nikhef*, in Amsterdam. The program leader has formed —in consultation with all applicants— a management team in which all research groups are represented. Apart from the program leader, it has the following members: Gijs Nelemans (RU) and Jan Willem van Holten (Nikhef – Leiden). The membership of the management team will be reviewed every two years. The management team advises the program leader regarding all executive decisions, including the hiring of PhD students, appointing their supervisors, the organization of scientific meetings, and the allocation of resources. As a starting point for all management decisions the following set of rules has been agreed upon:

- The available resources will be allocated among the various groups as described in *section 8* of this proposal, but subject to a re-evaluation on an annual basis.
- The responsibility for the recruitment and supervision of PhD students hired by one of the participating groups in the framework of the present program rests with that same group.
- Each PhD student will be associated with one of the research schools 'OSAF' (for students based at Nikhef and VU) or 'NOVA' (RU). The mentioned research schools provide graduate courses and will monitor the progress of each student.
- Scientific progress will be exchanged on a quarterly basis in public meetings of all participants.
- Scientific publications resulting from research work financed through the present program are subject to the internal review system of either Virgo and LIGO, Einstein Telescope and LISA collaborations, whenever use has been made of one of these observatories.
- Each participating group informs the program leader whenever scientific output has been produced or expenses have been made associated with the present research program.

The scientific objectives of the present research program are well defined (see *section 4*). Based on these objectives a list of specified research topics was made and corresponding manpower (PhDs and postdocs) were allocated (see Appendix A). For each of these topics the observatory involved (Virgo and LIGO, Einstein Telescope or LISA) and the project supervisor is identified. Hence, no additional competitive mechanism is needed to allocate the PhD positions within the proposed research program. Moreover, as there are many national and European fellowship programs available for hiring postdocs, it has been decided to focus the present program on PhD students. In practice, each PhD student will spend part of his/her time on the various operational tasks that are needed for the scientific exploitation of an instrument of the size of the Virgo interferometer (see *section 4*), and part of his/her time on a scientific analysis of data collected.

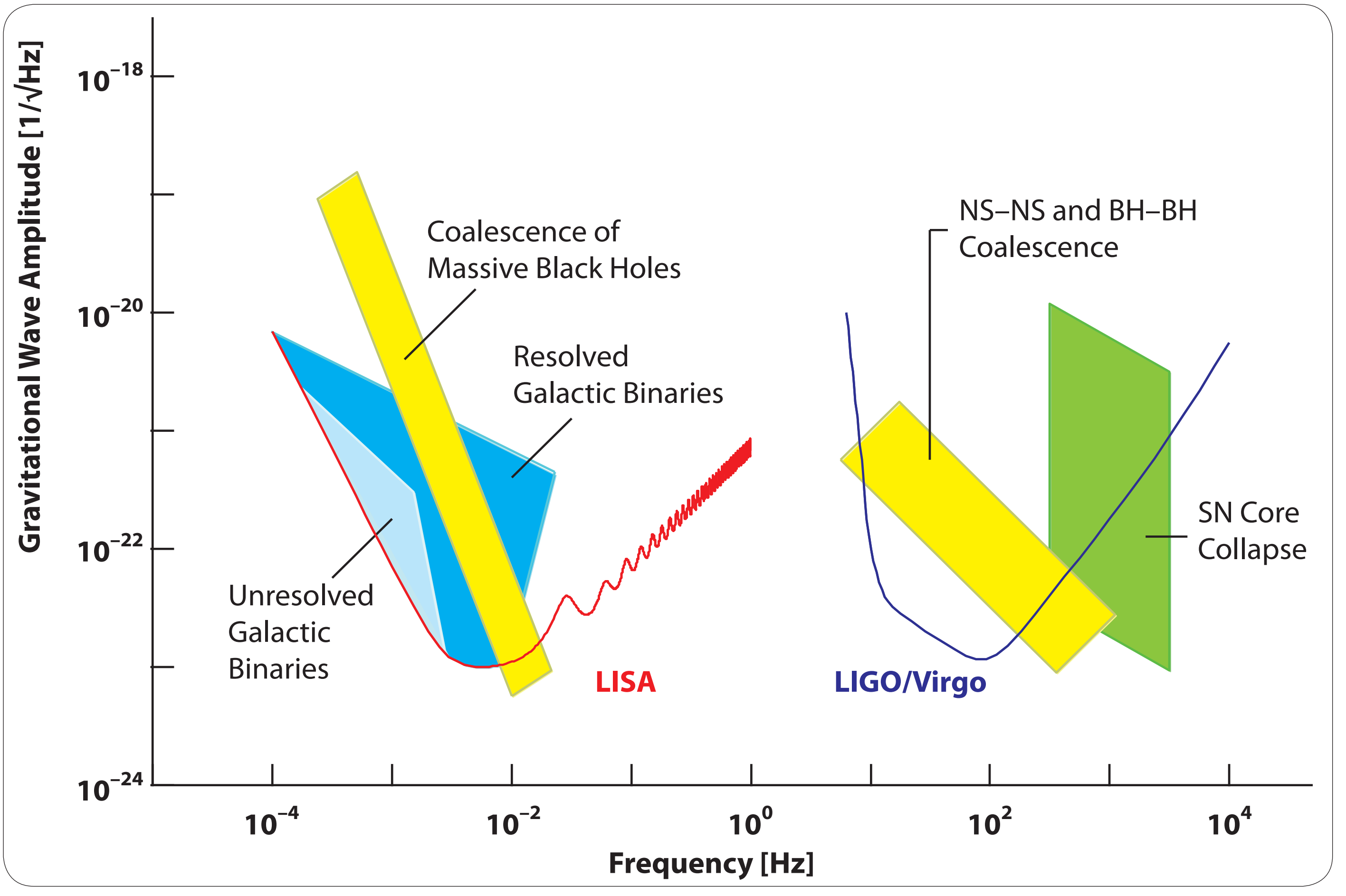

Figure 7. The spectrum shows the sensitivity LIGO, Virgo and LISA will obtain in their operating bands, as well as spectral regions where various sources are predicted to be. For LISA, the sensitivity below 3 mHz is dominated by spurious accelerations of the reference proof masses. The sensitivity from 3 mHz to 1 Hz reflects the shot noise limited performance of LISA. The sensitivity above 10 mHz has a complex behavior caused by the interferometer arm length being greater than the wave length of the gravitational waves. In the region marked 'Unresolved Galactic Binaries', gravity-wave sources are so numerous that they will appear to LISA as an unresolved background. For LIGO and Virgo, the sensitivity at low frequencies is limited by seismic noise and at high frequencies by shot noise. Thermal noise limits the sensitivity at intermediate frequencies. Einstein Telescope will be sensitive between 1 Hz and 10 kHz and attempts to reach sensitivities as low as $10^{-24}/\sqrt{Hz}$.

7 Application perspective

Direct industrial application of the scientific results obtained from the measurements at the various interferometers is not to be expected. Nevertheless, the proposed research program will have valorization aspects: high precision interferometry has many applications. The former developments at Virgo and LIGO have already impact on other scientific and industrial activities. Sophisticated seismic isolation systems and ultra sensitive accelerometers find many applications in other fields of science and industry. The state-of-the-art technologies for Einstein Telescope will be developed in close collaboration with industry. Einstein Telescope will house the largest ultra-high vacuum chamber in Europe with vessels tens of kilometers long. The construction requires the development of special metallurgical production processes and the realization of large welded tube assemblies with high accuracy. For Virgo a special optical coating facility was realized in Lyon, France, which also attracts industrial clients. The extremely low absorption and high homogeneity required for Virgo optics has triggered considerable improvement of the production process of fused silica. Extremely low-absorption optical coatings on large substrates will be employed for the mirrors and/or gratings of Einstein Telescope.

Data analysis at instruments draws heavily on both signal enhancing techniques and large scale computing (the excellent Dutch Grid infrastructure is a valuable asset). These techniques play an important role in digital image processing (the field of Computer Vision). Applications extend from remote sensing (analysis of street patterns in photographs taken from space), over medical industry (automatic counting of specific blood cells), automatic lane detection for cars, to translation of hand-drawn (architectural) designs into construction drawings.

The cutting edge scientific and technological enterprise at LIGO, Virgo, Einstein Telescope and LISA is extremely suited to be positioned in outreach projects.

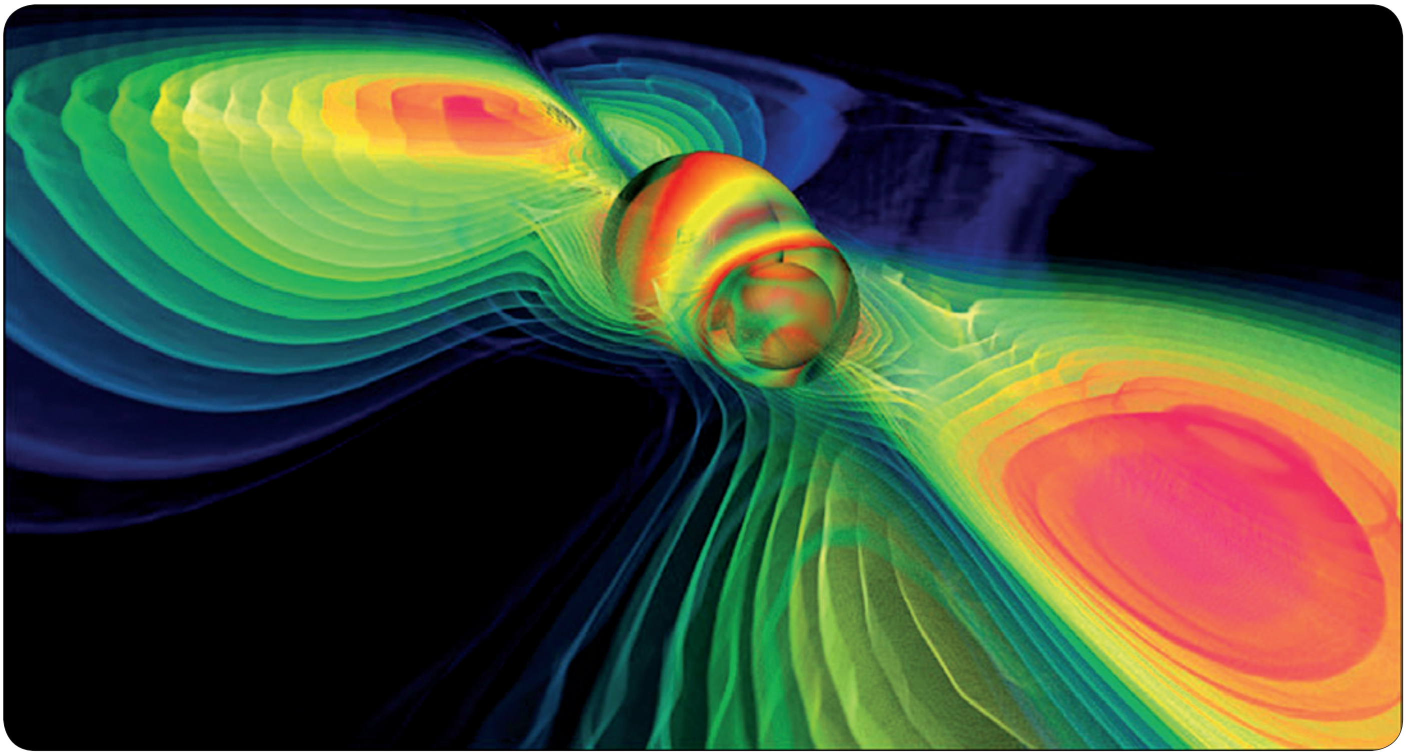

Figure 8. Modeling the complexity of the merging of two black holes (Source: MPI for Gravitational Physics / W.Benger–ZIB).

Total budget request	**2010**	**2011**	**2012**	**2013**	**2014**	**≥ 2015**	**Total**
participating group							
Nikhef (incl. VU)	298	298	398	398	223	223	1 838
RU (IMAPP)	83	133	183	183	183	70	835
To be allocated later	0	0	50	50	50	50	200
general costs							
steering budget	10	10	10	10	10	10	60
Total program budget (k€)	**391**	**441**	**641**	**641**	**466**	**353**	**2 933**

Table 1. Summary.

Research group Nikhef (incl. VU)	**2010**	**2011**	**2012**	**2013**	**2014**	**≥ 2015**	**Total**
personnel positions (fte)							
PhD students	1	1	3	3	2	2	12
postdocs	1	1	1	1	1	1	6
technicians, guests							
other personnel							
personnel budget	113	113	213	213	163	163	978
running budget	60	60	60	60	60	60	360
investment budget	125	125	125	125	0	0	500
Total group budget (k€)	**298**	**298**	**398**	**398**	**223**	**223**	**1 838**

Table 2. Requested budget for personnel positions, running and investment budgets at Nikhef, including Vrije Universiteit.

Research group RU (IMAPP)	**2010**	**2011**	**2012**	**2013**	**2014**	**≥ 2015**	**Total**
personnel positions (fte)							
PhD students	0	1	2	2	2	1	8
postdocs	1	1	1	1	1	0	5
technicians, guests							
other personnel							
personnel budget	63	113	163	163	163	50	715
running budget	20	20	20	20	20	20	120
investment budget	0	0	0	0	0	0	0
Total group budget (k€)	**83**	**133**	**183**	**183**	**183**	**70**	**835**

Table 3. Requested budget for personnel positions and running budget at Radboud Universiteit Nijmegen.

8 Duration and requested budget

The research program will start in 2010 and will cover a period of 6 years, *i.e.* the time needed to collect the most important scientific results from the Virgo and LIGO interferometers and the technical data from the LISA-Pathfinder mission and overlap with the start-up of Einstein Telescope and LISA. A total budget of 2 933 k€ is requested to carry out the proposed physics program, corresponding to an average annual budget of 489 k€. The budget is primarily intended for hiring junior scientists (PhD students and postdocs), for annual operational contributions to the EGO observatory, travel costs, investment in the Advanced Virgo upgrade, and for some small material expenses.

The budget is presented in a summary table and two separate tables specifying the requested budget of Nikhef and IMAPP (see opposite page). The Nikhef budget includes the expenses requested by the group at the Vrije Universiteit (VU) as the corresponding group is a full Nikhef partner. The numbers provided with the tables are based on the standard annual costs for graduate students (50 k€) and postdocs (63 k€), and estimated contributions to the operation of the observatory. The budget request is dominated by costs associated with the funding of junior scientists. One PhD position will be allocated later to reinforce promising developments. We intend to hire additional postdocs partly through national ("NWO *vernieuwingsimpuls*") and European ("*Marie Curie*") fellowship programs. The contributions to the operational costs of the observatory is listed in the tables as *running budget*. The total expenses of Nikhef and IMAPP are collected in the summary table, which therefore represents the total budget request to FOM in the framework of the presently proposed research program. The summary table also includes a modest annual steering budget of 10 k€. This budget is at the discretion of the program leader and will be used in the project management, *e.g.* workshops, guests.

The budget includes 500 k€ investment in the Advanced Virgo upgrade. This complements the contribution that has already been secured from other sources. For the development and construction of Advanced Virgo a contribution from Nikhef of 1.5 M€ will be allocated from its mission budget for the period 2010–2013. The requested resources will be used for the design and construction of cryogenic links in the interferometer arms to reduce optical path-length fluctuations, for the developments of linear-alignment electronics, and for the realization of optical payloads and seismic-attenuation systems. For Einstein Telescope a FP7 proposal was approved in 2008. Initial start-up funds for Nikhef's participation in Virgo were financed from Nikhef's mission budget and VU funding. A time line for the various projects is presented in Fig. 9. A break-down of the investment funding is given in Appendix B.

The senior staff and local infrastructure of the participating institutes and universities are not included in the requested budget. At the FOM institute Nikhef about 4 fte senior staff are supported annually, while about 3 fte senior staff are supported by the other participating groups (mostly universities) every year. Hence, a total of 7 fte senior staff members will be working on this program in the coming years —if it is approved. The numbers do not include engineering support or overhead.

In the multi-annual budget overviews no distinction is made between the resources required for Virgo and LISA. The requested resources for Nikhef will mostly benefit Virgo, while those at IMAPP will mostly be spent on LISA. In order to support additional PhD positions not covered by the present program, the applicants will actively pursue additional project funding available at FOM, the universities and the European Union.

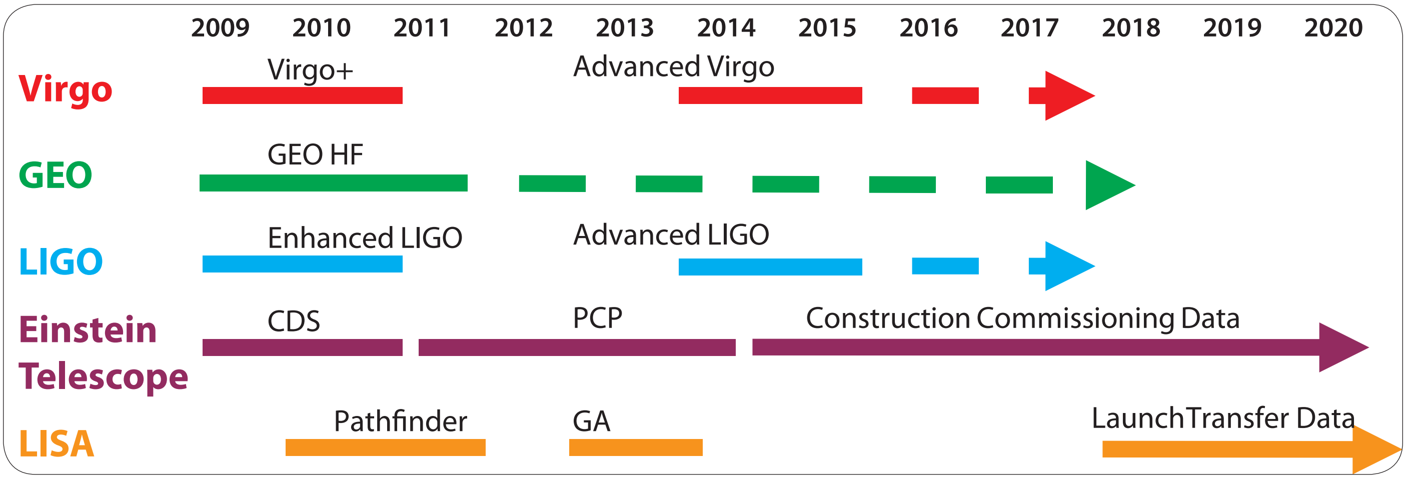

Figure 9. Timeline of current detector operation and planned detector upgrades. The solid lines for the existing detectors indicate data taking times. In the regions of the dashed lines the mode of operation is not yet defined. In the scenario shown, a go-ahead decision for LISA will be taken in 2012 after analysis of the LISA Pathfinder mission; LISA will be launched in 2018 and start data taking in 2020 for a duration of at least 5 years. Limited by the supply of consumables this period may be extended up to 10 years. Einstein Telescope plans start with a 3 year design study approved in 2008, followed by a 4 year preparatory construction phase. Construction and commissioning will last for 6 years and allow data taking from 2021 onwards.

9 Subfield classification

The present astroparticle-physics project is multi-disciplinary by nature with strong ties to subatomic physics, theoretical physics, astrophysics and cosmology. According to the present FOM subfield classification system the proposed research program mainly (estimated at 70%) belongs to the subfield *Subatomic Physics*. The remainder (estimated at 30%) belongs to the subfield *Other Physics* and is concerned with astrophysics.

Appendix A Projects

The scientific objectives of the proposal have been defined and manpower has been allocated to the different projects. The projects that constitute this proposal are relevant for its central focus, and are based on the specific expertise of the principal scientist. To stimulate broadening of expertise we have also indicated where appropriate other senior scientists, often from a different institution, who will be sufficiently involved with the project to be co-authors on scientific papers. Our chosen projects address not only a main challenge, but also relate to other challenges, strengthening the coherence of our approach (see Fig. 10).

The projects in activity 1 are chosen such that our present Virgo/LIGO analysis effort on continuous waves (CW) from periodic sources, is broadened to include coalescing binaries. The latter are prime candidates for first direct gravitational-wave detection. Also compact binary coalescence and the science case for Einstein Telescope is addressed. The projects in activity 2 are concerned with specific modeling of both the stochastic gravitational-wave background from brane-world scenarios and EMRI systems. Numerical simulations will be performed and results will be incorporated in data analysis schemes for existing and/or future detectors. Projects in activity 3 focus on multi-messenger analyses combining gravitational wave and electromagnetic data. Closely related is the study of LISA verification binaries. Finally, the synergy between LISA and ET is studied. Through activity 3 we contribute to present (*e.g.* EGO) and future observatories (LISA and ET). In addition to the projects discussed here, important improvements (see Appendix B) will be made to the instrumentation of Virgo in the context of Advanced Virgo. These improvements will enhance the sensitivity and lead to regular detection of gravitational-wave events.

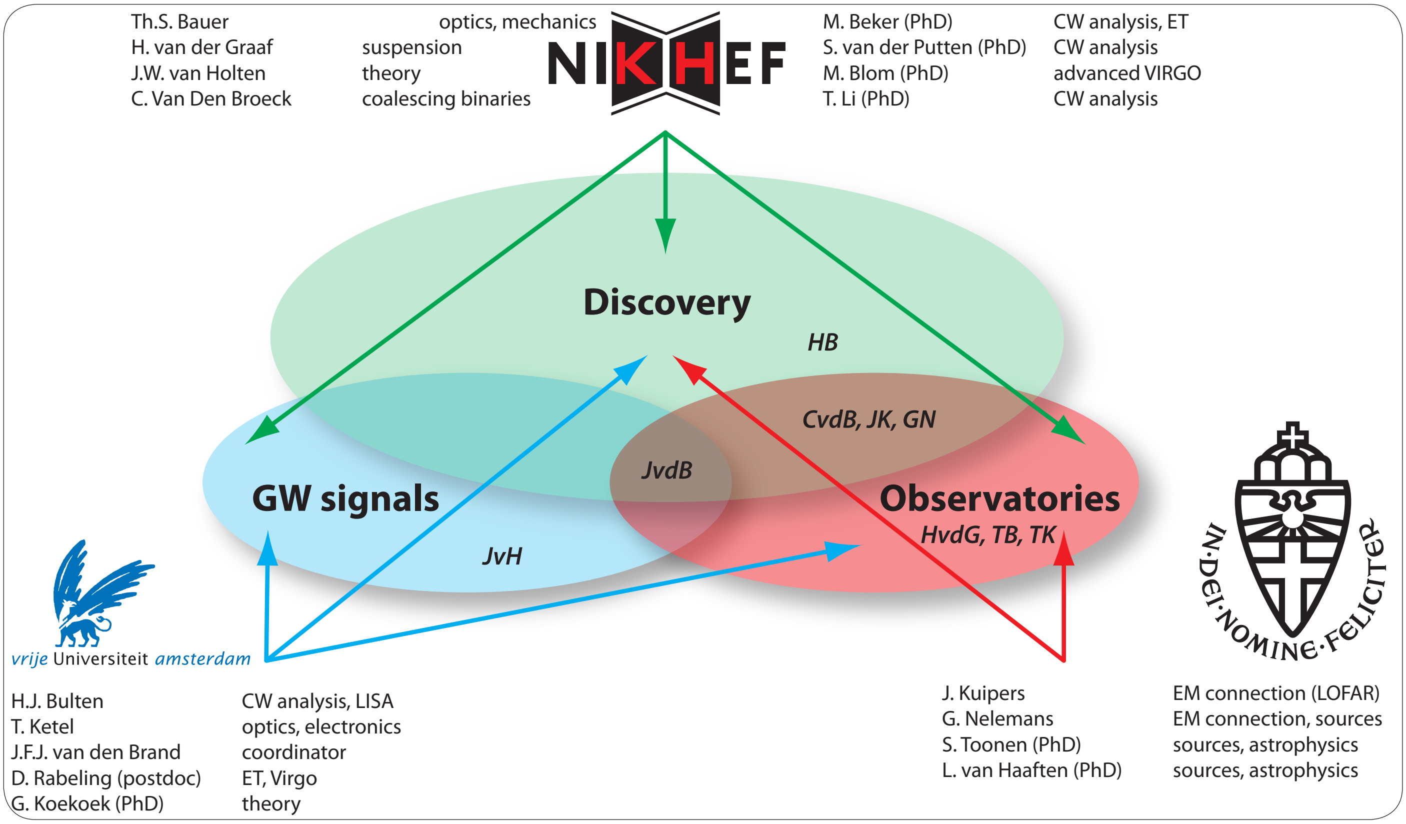

Figure 10. Schematic representation of how principal scientists, indicated by their initials, are related to the three research activities. Also indicated are junior scientists presently working on gravitation-wave related physics. The emphasis of the present proposal is on discovery and improvement of Virgo's sensitivity.

I A data analysis pipeline to search for coalescing binary black holes with inspiral-merger-ringdown templates

Principal scientist: C. Van Den Broeck (Nikhef)
Additional scientist: J.F.J. van den Brand (Nikhef)
Position: PD (3 yrs)
Location: Nikhef, Amsterdam

The coalescence of binary black holes happens in three stages: a gradual 'inspiral' as orbital energy is lost in gravitational waves, a violent merger, and 'ringdown' of the resulting black hole as it settles into a quiescent state. In the past, the template waveforms used in searches for compact binary coalescences in the existing LIGO and Virgo data have only taken into account either the inspiral or the ringdown process. Following recent advances, both in perturbation theory and numerical relativity, reliable waveform approximants are being developed which cover all three regimes in one go. One approach is to construct phenomenological waveforms through analytical fits with numerical ones[1], another to suitably 'stitch' the so-called effective one-body (EOB) inspiral waveforms[2] onto ringdown waveforms. Our ability to find signals from coalescences with the Virgo and LIGO detectors could increase significantly if such waveforms were to be used as templates for matched filtering. When incorporated into a data analysis pipeline, inspiral-merger-ringdown (IMR) templates are likely to become standard ingredients in the analysis of data from second and even third generation detectors.

This project has two aspects. One is to improve the 'stitched' EOB-ringdown waveforms by incorporating black hole spins as well as higher signal harmonics in the inspiral waveform; both are well-known to dramatically improve parameter estimation. The second, which can be done largely in parallel, is to develop the tools needed to use IMR waveforms as templates in searches. A suitable detection statistic will need to be found, as well as a way of placing templates in parameter space. To reduce the number of spurious coincident events in different detectors, parameter-based vetoing techniques need to be worked out, and waveform-based tests have to be implemented to decide which of the surviving events in the data best resemble a genuine signal.

Local expertise
- Waveform approximants
- Template placement algorithms
- Structure of analysis pipelines

References

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2. T. Damour and A. Nagar, *The effective one body description of the two body problem*, arXiv:0906.1769

II Bayesian model selection and follow-ups of gravitational-wave detection candidates

Principal scientist: C. Van Den Broeck (Nikhef)
Additional scientist: J.F.J. van den Brand (Nikhef)
Position: PhD
Location: Nikhef, Amsterdam

Once a gravitational-wave signal has been detected, one will want to extract as much information as possible about the properties of the source. For signals resulting from compact binary coalescence, this includes the masses and spins of the component objects, but also the position of the source in the sky and its distance, with a view on identifying a possible electromagnetic counterpart in cases where at least one of the coalescing objects is a neutron star. This involves the selection of a 'most likely' signal waveform from a family of realistic waveform approximants. Bayesian model selection techniques, which incorporate a quantitative version of 'Occam's razor' (the idea that the simplest model should be preferred), have proved well-suited to this problem[1]. However, the quality of parameter estimation will be contingent upon how close the waveforms approximants are to real signals, and in particular how much of the signal they take into account. Here too, the emphasis in the past has been almost entirely on the inspiral part of the coalescence process. For coalescences involving high mass black holes (*i.e.*- binaries with a combined mass >$20M_{\odot}$), parameter estimation is known to improve drastically with the inclusion of merger and ringdown[2].

The first task will be to construct more accurate inspiral-merger-ringdown approximants (IMR). This part of the work can be a collaborative effort with project I; other than that it is complementary. Once waveforms are available, computer code will be written to incorporate them in a model selection scheme. This can then be tested by artificially adding waveforms from numerical simulations to stretches of Virgo or LIGO data. As the code becomes mature, one could start using it on highest-ranked candidate events from the S6/VSR2 data taking runs. In upcoming and advanced detectors, parameter estimation with IMR approximants will be most useful for relatively massive systems, although in the case of third generation observatories such as Einstein Telescope, the merger signal may be in the sensitivity band even for binary neutron stars. In this way the project also ties in with project III.

Local expertise
- Waveform approximants
- Parameter estimation

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III Compact binary coalescence and the science case for Einstein Telescope

Principal scientist: C. Van Den Broeck (Nikhef)
Additional scientists: G. Nelemans (RU), J.F.J. van den Brand (Nikhef)
Position: PhD
Location: Nikhef, Amsterdam

Einstein Telescope (ET) is expected to see hundreds of thousands of stellar mass binary coalescence events per year, out to a redshift of z ~ 2 for binary neutron stars and z ~ 8 for binary black holes. Thus, ET will be in a position to address a number of issues that cannot be studied by electromagnetic means. A few examples are: ultra-high precision tests of the genuinely strong field dynamics of general relativity[1]; the use of coalescences as self-calibrating 'standard sirens' (similar to the 'standard candles' of conventional cosmology, but without reliance on a cosmic distance ladder)[2]; constraining the equation of state of neutron stars[3]; and studying star formation rates over cosmological timescales through the neutron stars and black holes that are formed. To advance the science case for ET, it will be important to find out with which precision such things can be done.

Data analysis and parameter estimation with ET will pose a new set of difficulties, different from those associated with other planned detectors. For instance, currently the main techniques in the search for signals from known waveform families have been based on matched filtering. Given that the ET data set may contain many partially overlapping signals, will this still be adequate, and if not, what should replace it? One way to shed light on such problems would be to create a mock data set containing realistic signals (*e.g.* from numerical relativity simulations) buried in simulated noise, and to study how good existing methods are in finding and reconstructing the signals, or develop new methods. This way one would arrive at a realistic assessment of how well ET will meet the science goals mentioned above. Such a project could be extended to a 'mock data challenge', similar to the very successful Mock LISA Data Challenge where groups around the world were given a simulated data set for the future space-based detector LISA and were asked to find hidden signals.

Local expertise
- Close involvement in previous and ongoing ET science case studies
- Data analysis techniques

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IV Gravitational waves and large extra dimensions

Principal scientist: J.W. van Holten (Nikhef)
Additional scientist: J.F.J. van den Brand (Nikhef)
Position: PD (3 yrs)
Location: Nikhef, Amsterdam

The existence of extra space dimensions would have profound consequences for cosmology. In traditional Kaluza-Klein scenarios these extra dimensions are supposed to be of microscopic size, becoming relevant only at the Planck scale of energies of the order of 10^{19} GeV. In recent times it has been realized that extra dimensions could be much larger; in such scenarios gravity might become stronger and the Planck scale in the higher-dimensional space-time could be as low as 10^4 GeV.

In a universe with large extra dimensions our four-dimensional world exists as a (3+1)-dimensional hypersurface, commonly refered to as the worldbrane. By hypothesis most of the matter and interactions we observe are tied to our worldbrane, but gravity as the dynamical geometry of the full space-time would act in all dimensions. Even if gravity in the bulk of space-time is strong, it could then effectively be weak in our worldbrane. Observable effects of the brane-world scenario are to be found in the spectrum of the cosmological gravitational-wave background[1,2,3]. Due to the strong gravity effects in the bulk, and the associated lower Planck scale, both the intensity and the frequency of these waves may be higher than in traditional four-dimensional space-time cosmology. We propose to study brane-world scenarios and analyze the consequences for the gravitational-wave spectrum, both generic and in the context of specific models. Numerical simulations of the gravitational dynamics will be undertaken, to provide input for present and future experiments. The project will be performed in close collaboration with Dr. M. Postma (Nikhef).

Local expertise
- Gravitational-wave theory
- Brane-world scenarios
- Inflationary cosmology

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V *Precision wave forms for EMRI systems*

Principal scientist: J.W. van Holten (Nikhef)
Additional scientists: J.F.J. van den Brand (Nikhef), C. Van Den Broeck (Nikhef), H.J. Bulten (Nikhef), G. Nelemans (RU)
Position: PhD
Location: Nikhef, Amsterdam

Giant black holes, with masses in the range 10^6–10^7 solar masses, are known to exist in almost all major galaxies. Evidence for intermediate mass black holes of 10^3–10^5 solar masses in dwarf galaxies and globular star clusters has been presented in the literature[1]. Compact objects such as white dwarfs and neutron stars, or stellar mass black holes, orbiting such extremely massive objects (so called Extreme Mass-Ratio Inspirals, EMRI) are an important and interesting source of gravitational waves in the domain of planned gravitational-wave observatories, as they can be used as probes to test the physics of black holes.

The starting point for the calculation of EMRI signals is the motion of test masses in the background of a Schwarzschild or Kerr black hole[2,3]. As an alternative to the post-Newtonian scheme[4], we have developed a fully relativistic perturbation theory for this purpose in the past[5]. However, for precision calculations the test-mass approximation using geodesics is not sufficient, especially for orbits near the ISCO or describing the inspiral phase[6]. In this regime radiation reaction effects are non-negligible, and corrections from finite size and spin of the test mass become relevant. In the present project we will develop analytical and numerical methods to calculate EMRI signals with high precision, including the effects of radiation reaction and spin. The existing formalism of MiSaTaQuWa[7,8] has to be adapted to our framework, translated into numerical algorithms and coded to allow numerical evaluation. The results can be used as input for the data analysis studies of Dr. C. Van Den Broeck.

Local expertise
• Experience with the calculations of orbits of test masses.
• Experience with the coding of numerical algorithms for motion in a Schwarzschild background.
• Expertise on the description of spin-orbit coupling in relativistic point-particle systems.

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VI *Improving gravitational-wave data analysis using electromagnetic data*

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Position: PD (5 years)
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The focus of all gravitational-wave data-analysis tools, both for ground-based instruments as well as LISA, has been on using gravitational-wave data alone. However, a crucial aspect of optimizing data analysis will be the use of complementary electromagnetic observations. Although this is widely acknowledged[1], very little actual work has been done in this area.

The postdoc will use the techniques developed for different gravitational-wave data-analysis problems (LIGO/Virgo double neutron-star inspirals, different LISA sources) to analyze the different simulated gravitational-wave data sets and will make an inventory of the possible electromagnetic data (radio, infrared, optical, UV and X-ray). Ideally, the candidate would have a background in gravitational-wave data analysis and have to familiarize himself/herself with the astronomical data. Alternatively, it could be an astronomer who first has to learn gravitational-wave data analysis.

The main part of the project will be to develop data-analysis techniques that use the electromagnetic data, either as priors, or for joint optimization of parameters. First application will be to high-frequency Virgo/LIGO data, investigating the use of possible electromagnetic data from neutron-star and black-hole mergers, such as gamma-ray bursts or low-frequency radio transients[2]. After that the techniques will be applied to Galactic ultra-compact binaries and super-massive black-hole mergers in the LISA data, building on the strong track record of both the gravitational-wave and electromagnetic expertise[3]. The aim is to investigate the improvements in parameter estimation that are possible with complementary electromagnetic observations and the (astro)physical questions that come within reach with these tools.

The group at the Radboud University has strong background in theoretical as well as observational study of double neutron-star mergers and Galactic compact binaries and their models have been used as the basis for the Mock LISA Data Challenge data sets. When combined with gravitational-wave data-analysis expertise, as proposed here, a unique group will be formed that can, for the first time, properly address the importance of complementary electromagnetic observations.

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VII The LISA verification sources

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Closely related to project VI, one PhD student will use the joint gravitational-wave and electromagnetic data analysis to study the Galactic compact binaries, in particular the LISA verification binaries.

The estimated population of ultra-compact binaries in the Galaxy is around 100 million, of which several thousand might be detectable with LISA[1]. At present, using electromagnetic tools, only several tens have been discovered, although the number is increasing rapidly. For a handful of the currently known systems the electromagnetic observations have provided enough information to derive reasonably accurate system parameters, which makes it possible to estimate their LISA signal[2]. These objects should be easily detectable and thus can be used as verification binaries for the mission. The first project of the PhD student will be to update these estimates, both for any new electromagnetic data, as well as using the joint GW-EM data analysis.

These techniques will then be applied to all ultra-compact binaries, working closely together with the (NWO-EW funded) current PhD students working on Galactic populations of binary stars. In particular it will be investigated to what extent the LISA measurements will allow us to constrain the different uncertainties in the formation of ultra-compact binaries, such as the exact outcome of mass transfer between stars. This will most likely depend strongly on the available complementary electromagnetic data. Therefore different scenarios will be developed, depending on the availability of several future (radio, infrared, optical, UV and X-ray) instruments.

This project will bridge the gap between the gravitational-wave data analysis efforts in Nijmegen and the observational astrophysics groups. The group of Paul Groot is one of the key players in the optical European Galactic Plane Surveys, and involved in the near-infrared survey of the same area. Gijs Nelemans is heavily involved in the optical and X-ray Galactic Bulge Survey (PI Peter Jonker of SRON). Finally, Heino Falcke's group is part of the LOFAR transients key science project.

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VIII Gravitational-wave sources, LISA - ET synergies

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For both high-frequency, as well as low-frequency gravitational-wave detectors, many sources are stellar mass compact objects, often in binary systems. Binary systems containing neutron stars and black holes can evolve from sources for low-frequency detectors into sources for high-frequency detectors. Relatively little attention has been paid to the synergy between the two types of detections.

For most expected sources (neutron stars or stellar mass black holes with masses around 10 solar mass) the shortest time between observation in the low-frequency band (*i.e.* below 0.1 Hz) and the high-frequency band (above 10 Hz) is several tens to hundreds of years. In addition, the estimated number of such sources in the Galaxy is small enough that most likely the shortest observed binary has a significantly lower frequency than 0.1 Hz. Therefore, the chance of seeing the *same source* in LISA as well as ET is not very large. However, statistically the ET merger rates and the LISA detection numbers should provide independent constraints on the formation of neutron star and black hole binaries, in particular they can test the predictions that many double neutron stars systems are formed at very short periods, and thus do not show up in the radio pulsar surveys[1].

More speculatively, but also much more interesting, is the possibility of forming close pairs of intermediate mass black holes (with masses between 100 and 1000 solar mass) or intermediate mass – stellar mass black hole pairs[2]. These have low enough masses to still be detectable with ET, but their evolution time from the low-frequency to the high-frequency band is only of the order of years. In addition, they are detectable for LISA to much larger distances, greatly increasing the probability of finding them. These intermediate mass black holes may form from the first population of stars formed in the Universe, or in the centers of dense star clusters, where frequent stellar collisions lead to very massive central objects. In particular the cluster environment is interesting, as further interactions between stars or stellar mass black holes and the intermediate mass black holes can lead to the formation of close pairs[3].

The aim of this project is to estimate potential rates and simulate the data analysis for joint detections between LISA and ET. For the stellar mass objects, the constraints obtained on the formation of neutron star binaries will be determined, using simulated populations for different astrophysical assumptions. For the intermediate mass systems, it will be derived what (extra) constraints/test of general relativity can be obtained when combining the relatively long LISA observations with the short ET observations.

This project uses the expertise on binary populations available at the Radboud University, as well as the gravitational-wave data analysis expertise (Bulten, Van Den Broeck) in the consortium. Jan Kuijpers as well as Jan Willem van Holten will provide the general relativity expertise.

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Appendix B Advanced Virgo activities and investment budget

Advanced Virgo will transform Virgo into a dual recycled interferometer. This upgrade will allow Virgo to scan a 1000 times larger volume of the Universe than initial Virgo. Numerous systems need to be improved. Nikhef has responsibility for

- **Vacuum-cryolinks:** The current Virgo vacuum level needs to be improved by a factor of about 100 in order to be compliant with the required sensitivity of $3 \times 10^{-24}/\sqrt{\text{Hz}}$ at 200–400 Hz. Such an improvement requires baking out the interferometer arms. To separate these arms from the towers and allow the bakeout, four cryotraps will be installed.
- **Suspended injection and detection benches:** With the use of non-degenerate power recycling cavities both the injection- and detection bench will host one of the recycling cavity mirrors. These mirrors will have to be suspended in vacuum, either from a structure attached on the suspended bench or from the marionette located above the bench. The required control elements will add complexity on the detection bench.
- **External benches:** The mechanical structure will have to be redesigned to avoid resonances at low frequency (now around 20 Hz). This will probably require the external benches to be suspended as well in order to avoid the current resonances of the system.
- **Linear alignment system:** The electronics of the quadrant photodiodes (transimpedance amplifier, and demodulation boards) will have to be redesigned in order to work with the new modulation frequencies and to provide all the needed demodulated signals. The present quadrant photodiodes may be used if their bandwidth can be increased.

Investment Budget	k€
Vacuum cryolinks	
R&D phase	12
Design & engineering	54
Prototype	149
Production	595
Valves	386
Phase separator	71
Evacuation station	89
	1356
Suspended optical benches	
Injection	107
Detection	107
IMC end-mirror	18
	262
External optical benches	
End benches	48
Injection bench	107
Detection bench	71
	226
Linear alignment system	
Front-end system	131
Demodulators	54
	184
Total	2028

The table shows the required investment funds for Nikhef's participation in Advanced Virgo. The cost estimate has been based for a large part on industrial quotations (vacuum cryolinks) or on previous experience in Virgo+ (linear alignment). The numbers include 19% VAT. No contingency or manpower costs are included. Note, that at this moment the budget estimate is still uncertain. For example, four 800 mm diameter ultra-high vacuum valves are included. At present optical diffused light calculations are performed to investigate whether 650 mm diameter valves can be used instead (this would result in a cost savings of about 227 k€).

The proposal requests a contribution of 500 k€ for investment in Advanced Virgo. An additional 1.5 M€ will be allocated by Nikhef from its mission budget for the period 2010–2013.

Detailed technical information on the design of Advanced Virgo can be obtained from:
https://workarea.ego-gw.it/ego2/virgo/advanced-virgo/erc/