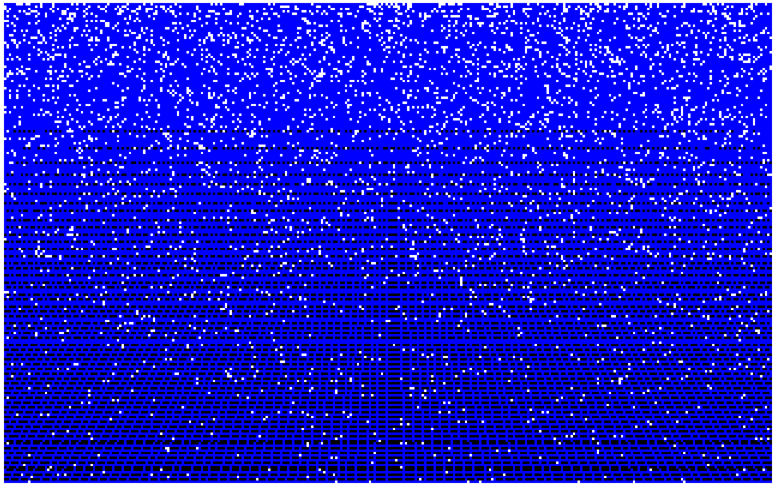
Gravitatie en kosmologie

FEW cursus



Jo van den Brand & Mathieu Blom

Gravitatiegolven: 14 november 2011

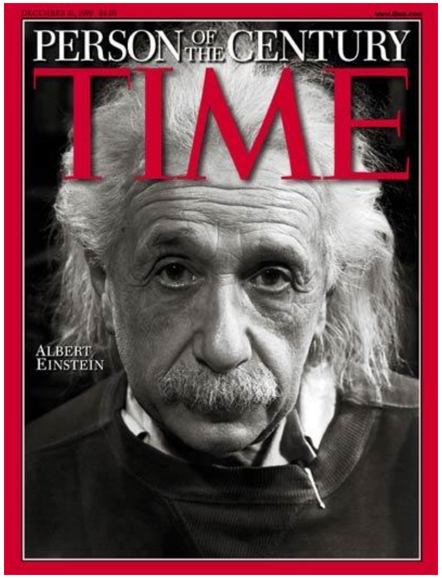
Motivatie

Einsteins gravitatie:

$$G_{\alpha\beta} = 8\pi T_{\alpha\beta}$$

Gravitatie is geometrie

Ruimte en tijd zijn fysische objecten

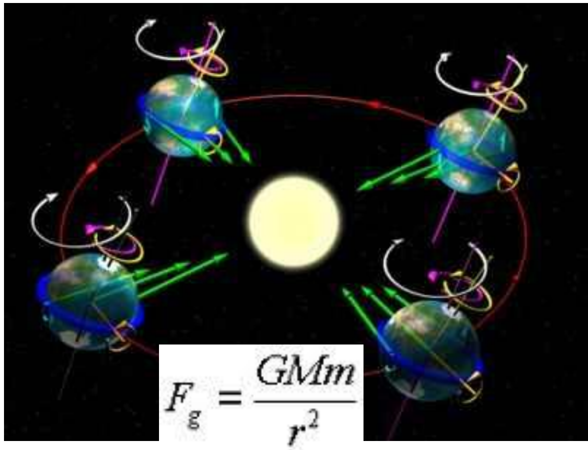


- Gravitatie
  - Minst begrepen interactie
  - Wereldwijde intellectuele activiteit
    - Theoretisch: ART + QM, kosmologie
    - Experimenteel: interferometers op Aarde en in de ruimte
- Gravitatiegolven
  - Dynamisch deel van gravitatie, ruimte is gevuld met GW
  - Ideale informatiedrager, bijna geen verzwakking
  - Het hele Universum was transparant voor GWs, helemaal tot aan de Oerknal

Gravitatie

- Newtons zwaartekrachtstheorie (1687)

  Gravitatie is een kracht die massa's op elkaar uitoefenen
  Deze kracht is *instantaan*



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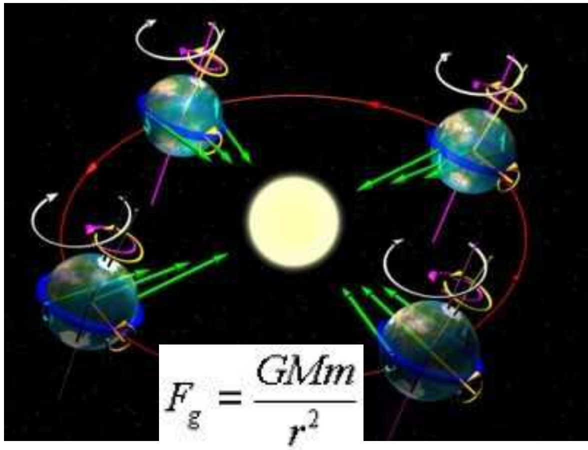

- Einsteins speciale relativiteitstheorie (1905)

  Natuurwetten zien er hetzelfde uit voor alle inertiële waarnemers
  Licht beweegt met dezelfde snelheid volgens alle waarnemers

  → Nauwe relatie tussen ruimte en tijd ("ruimtetijd")
  → Informatie kan hoogstens met lichtsnelheid worden overgedragen

  Hoe past zwaartekracht hierin?

Gravitatie

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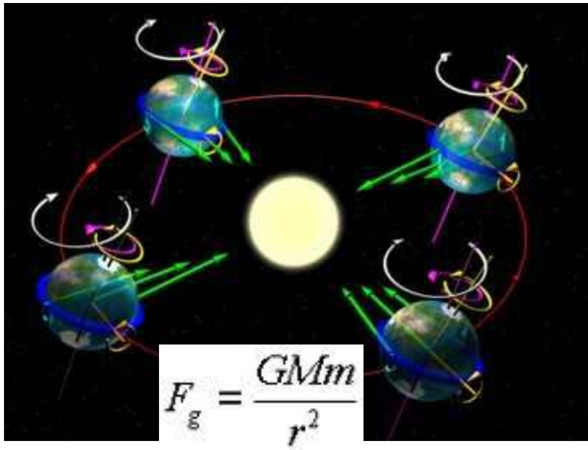

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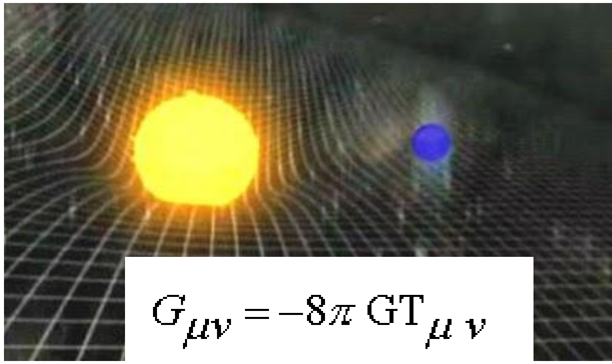
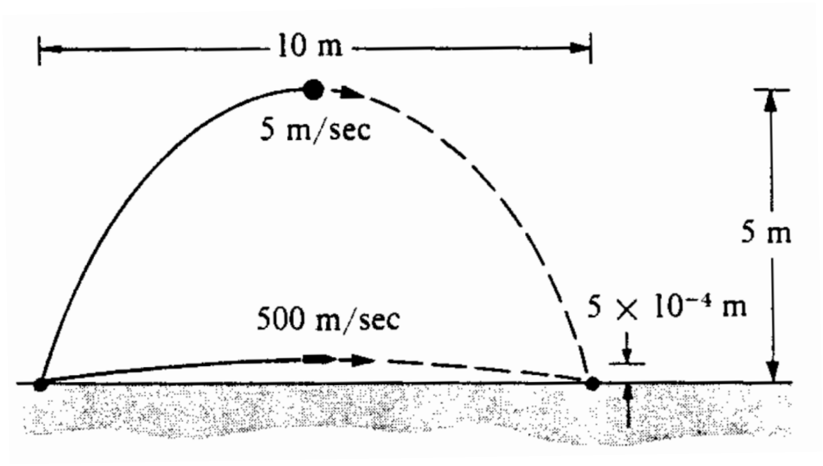


- Einsteins algemene relativiteitstheorie (1915)

  Inertiële waarnemers in *gekromde ruimtetijd*
  Materie veroorzaakt de kromming
  Zwaartekracht is neveneffect van die kromming

Kromming van ruimtetijd

Baan van een bal en een kogel

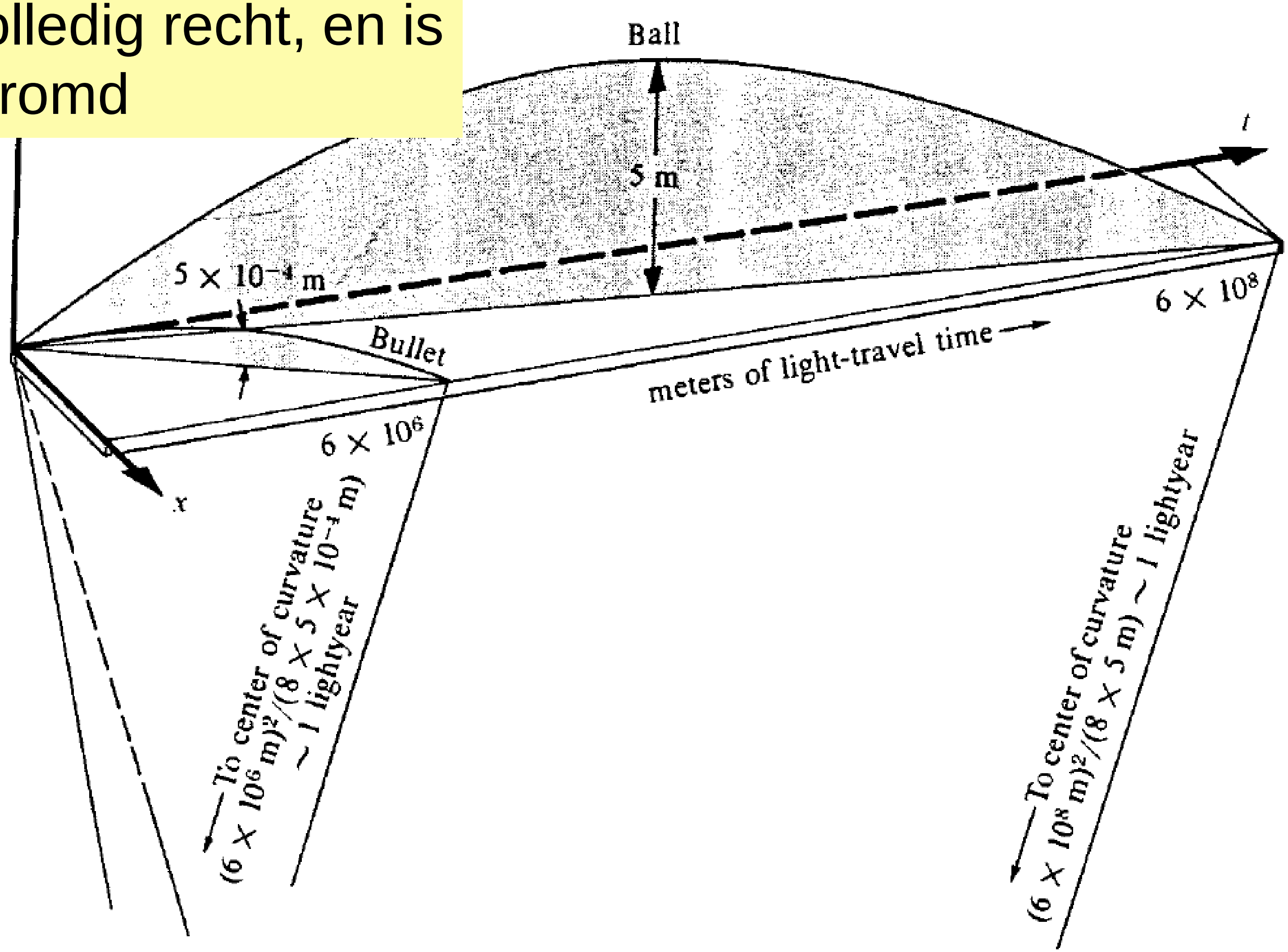


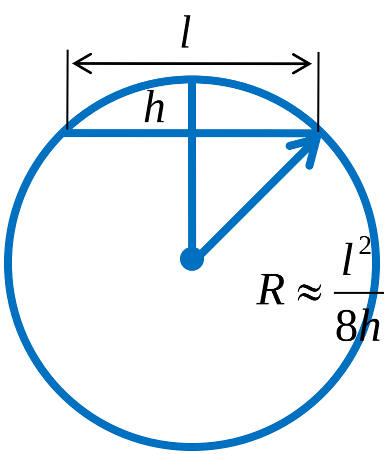
EP: alle massa's voelen dezelfde versnelling

Ruimtelijke kromming is zeer verschillend

Kromming van ruimtetijd

In werkelijkheid zijn alle banen (geodeten) volledig recht, en is ruimtetijd gekromd



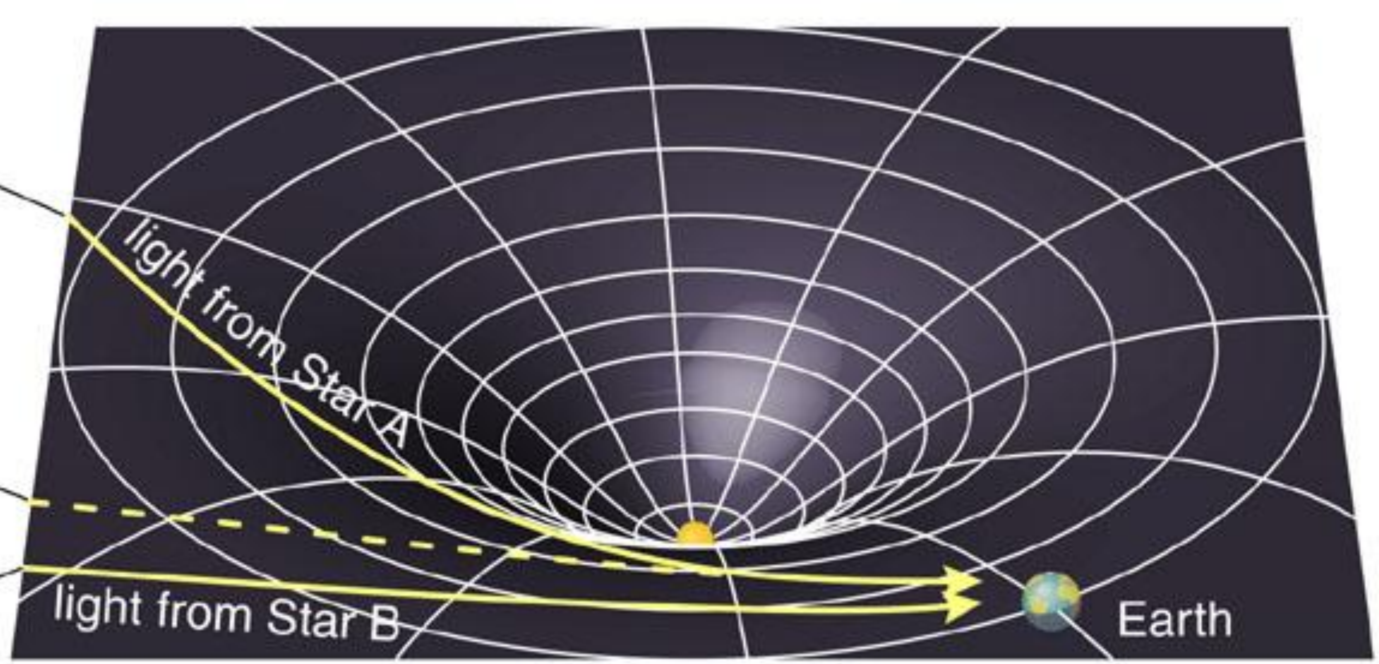


Banen in een gekromde ruimte: licht

Werkelijke positie
van ster A

Schijnbare positie
van ster A

Werkelijke en
schijnbare positie
van ster B



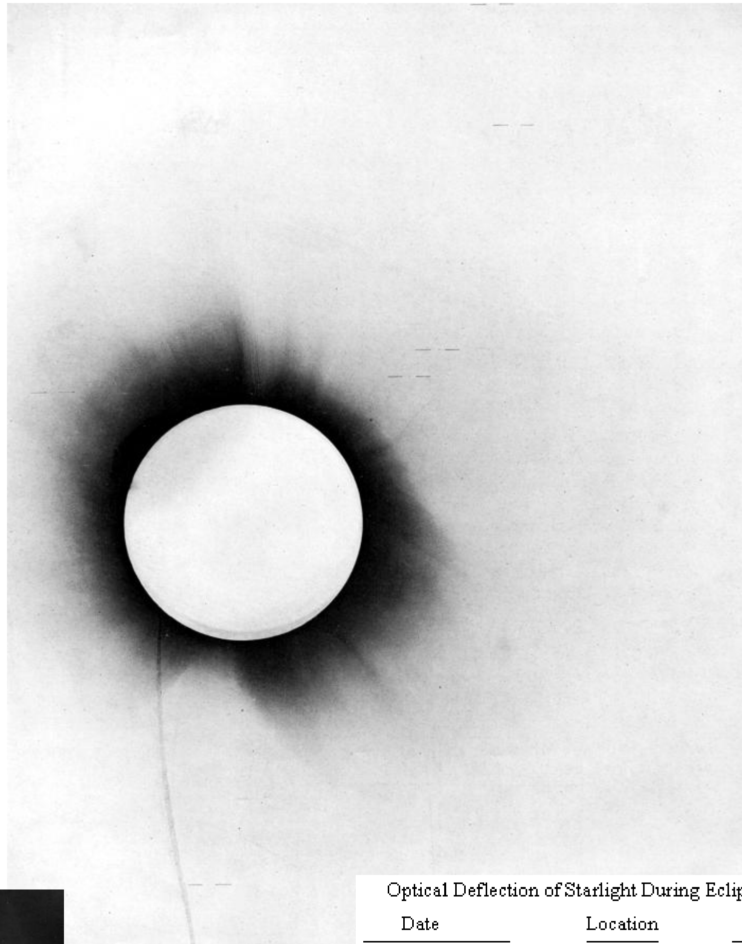
Zon

Aarde

Relativiteitstheorie:

$$\alpha = \frac{2GM}{c^2 r}$$

Afbuigen van licht



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

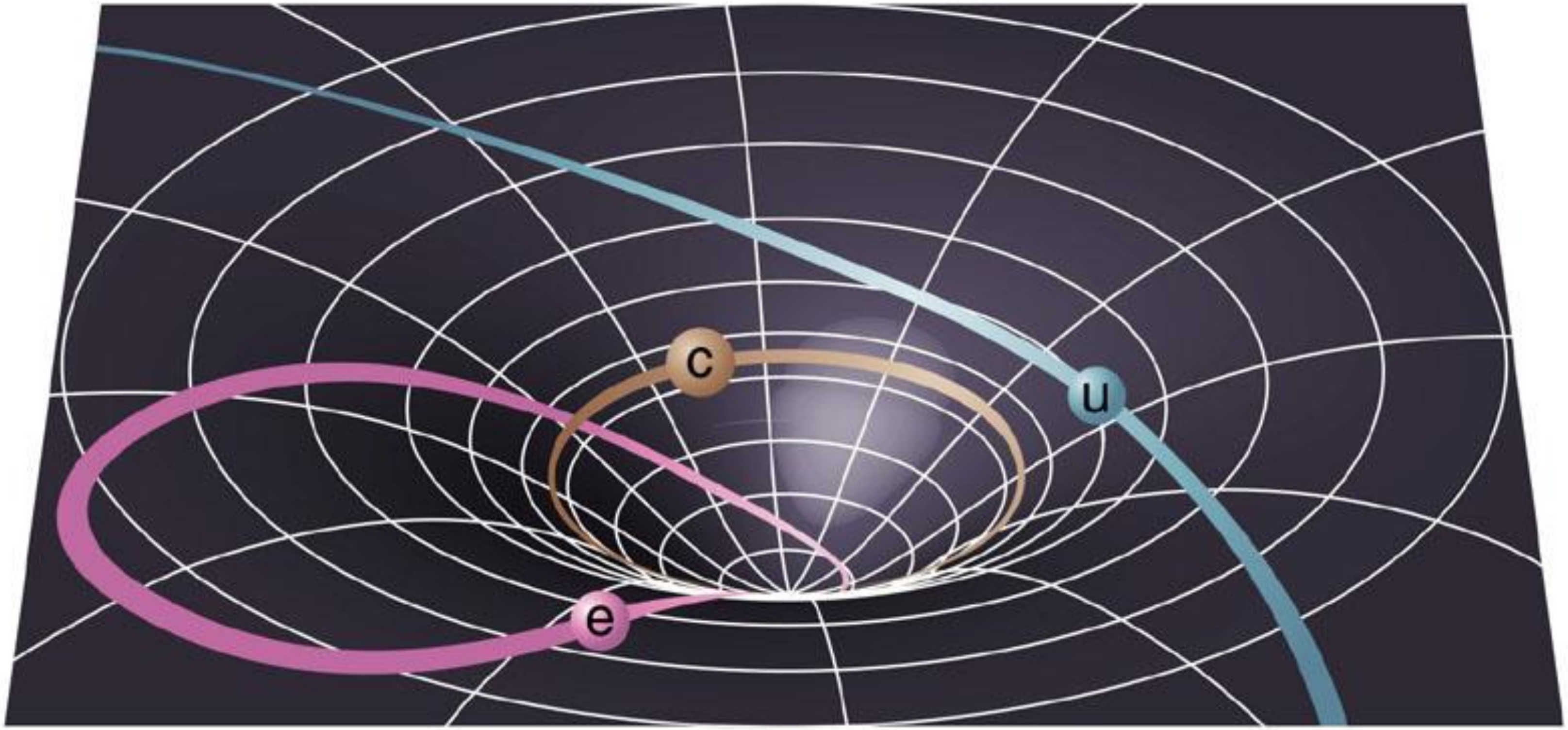
Optical Deflection of Starlight During Eclipses

Date	Location	arc secs
29 May 1919	Sobral	1.98 ± 0.16
	Principe	1.16 ± 0.40
21 Sep 1922	Australia	1.77 ± 0.40
		1.42 to 2.16
		1.72 ± 0.15
		1.82 ± 0.20
9 May 1929	Sumatra	2.24 ± 0.10
19 June 1936	USSR	2.73 ± 0.31
	Japan	1.28 to 2.13
20 May 1947	Brazil	2.01 ± 0.27
25 Feb 1952	Sudan	1.70 ± 0.10
30 Jun 1973	Mauritania	1.66 ± 0.19

New York Times, November 10, 1919

Banen in een gekromde ruimte: planeten

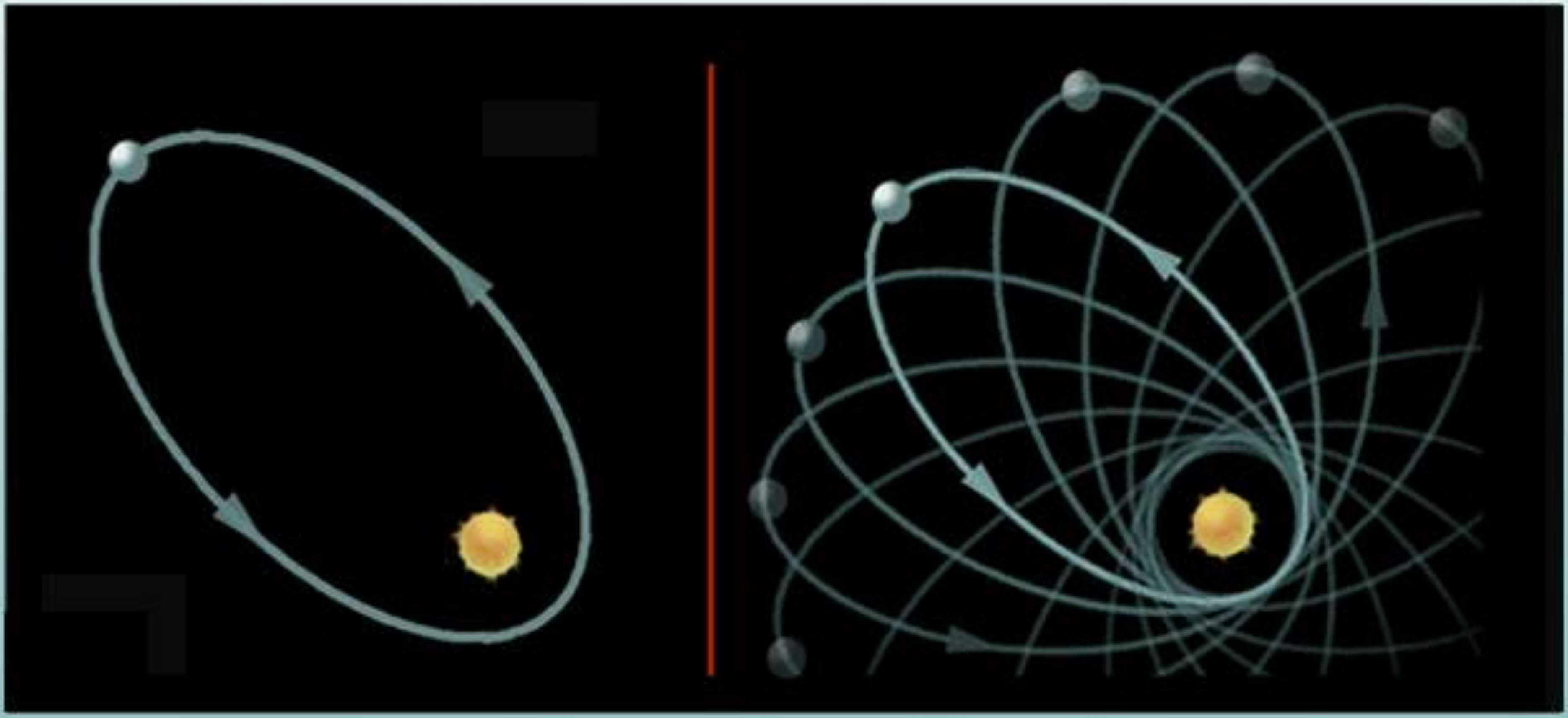
c Cirkelbaan
e Elliptische baan
u Ongebonden baan (parabool)



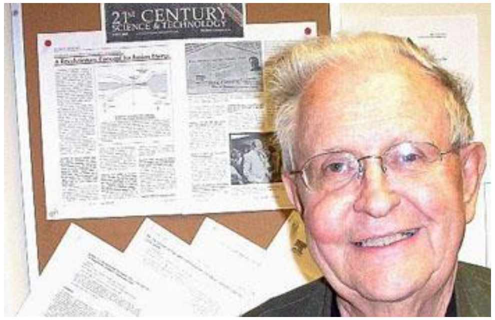
Experimenteel bewijs: precessie van de Mercuriusbaan

$$\delta\phi_{peri} = \frac{6\pi GM}{c^2 r}$$

4,8 x 10^{-7} rad = 0,1 boogseconde (415 omlopen per eeuw)

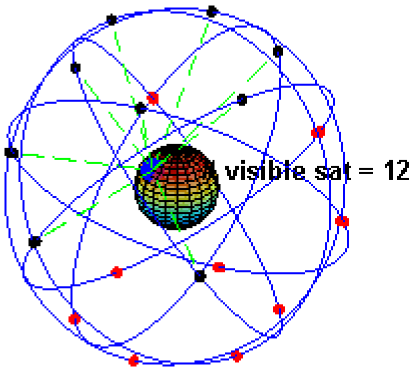


GPS (Global Positioning System)



Friedwardt Winterberg (1955): gebruik atoomklokken in orbit om ART te testen

Sputnik (1957): Doppler effect geeft lokatie (20 en 40 MHz radiosignalen)



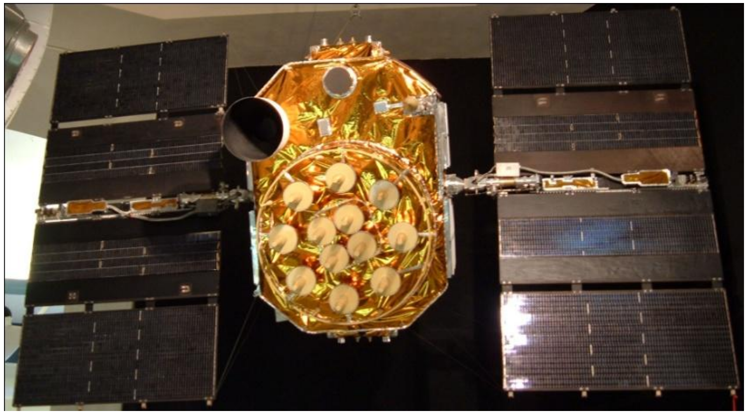
GPS (1973 bedacht, 1978 eerste satelliet, 1993 operationeel)

Precisie:

atoomklokken 1 ns/dag)
(licht legt 30 cm per ns af)
ART 45.900 ns/dag sneller dan op Aarde
SRT 7,200 ns/dag langzamer

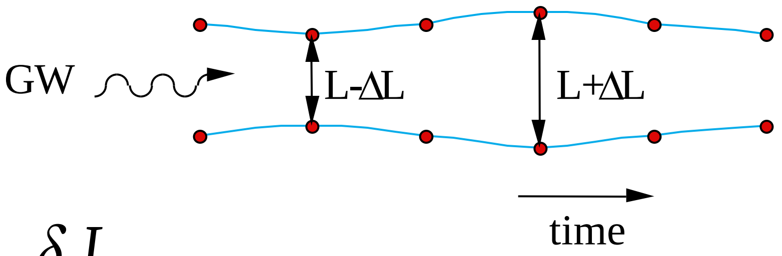
Alle GR testen betreffen statische effecten in zwakke gravitievelden

Hoe zit het met dynamica?



Dynamica: gravitatiegolven

- Volgen uit de relativiteitstheorie
- GW = ruimtetijd metrische golf
  - Afstandsvariatie
  - Amplitude *h*:



$$h = 2\frac{\delta L}{L}$$

- GW geproduceerd door versnelling
  - *d* = afstand tot bron
  - *Q* = quadrupoolmoment

$$h \approx \frac{2G}{c^4}\frac{d^2Q}{dt^2}\frac{1}{d}$$

$$10^{-44}\, s^2 kg^{-1} m^{-1}$$

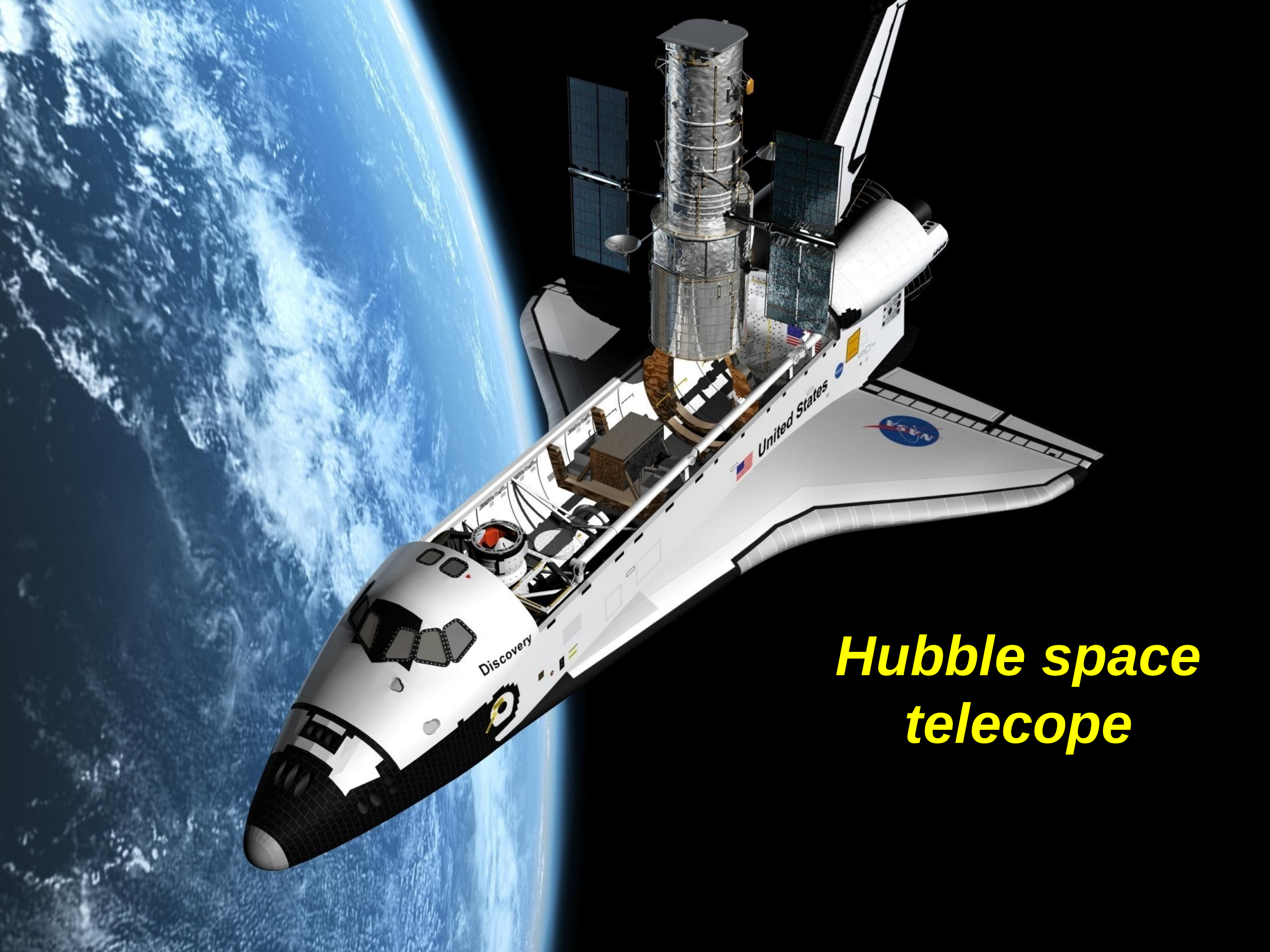
- Zwakke koppeling → astrofysische bronnen

L=20 m, d = 2 m, 27 rad/s

$L_G = 10^{-30}\, J/s$ $\quad \Sigma \approx 10^{-25} m^2 Hz \Rightarrow E_{absorbed} = 10^{-54}\, J$

Aarde - Zon: 313 W

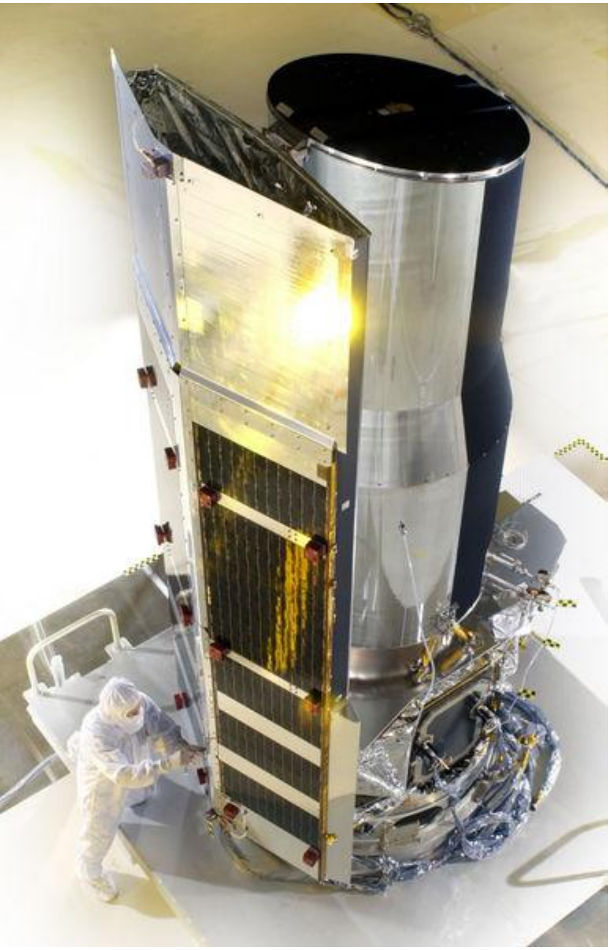

Op zoek naar
astrofysische objecten

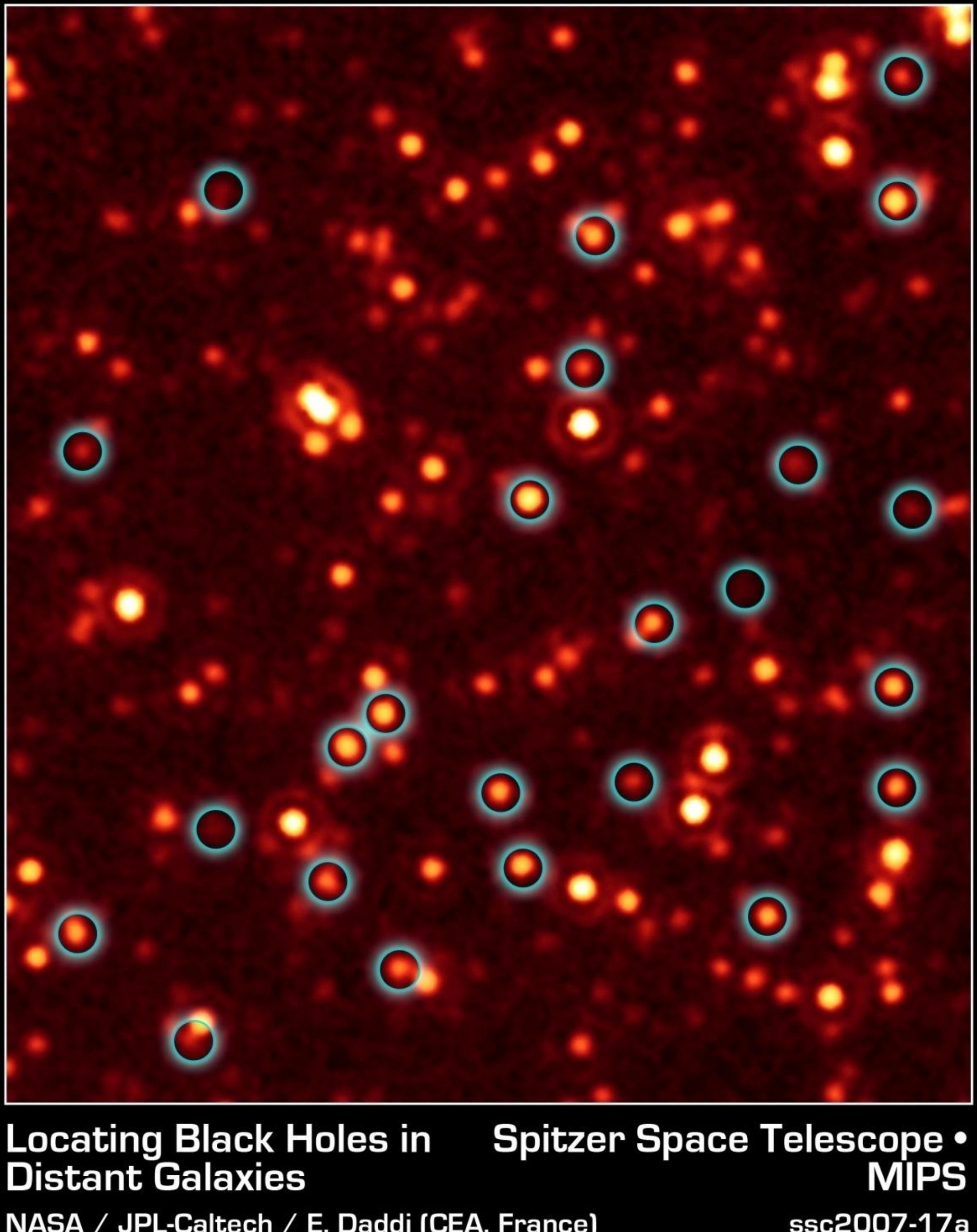


Hubble space telecope

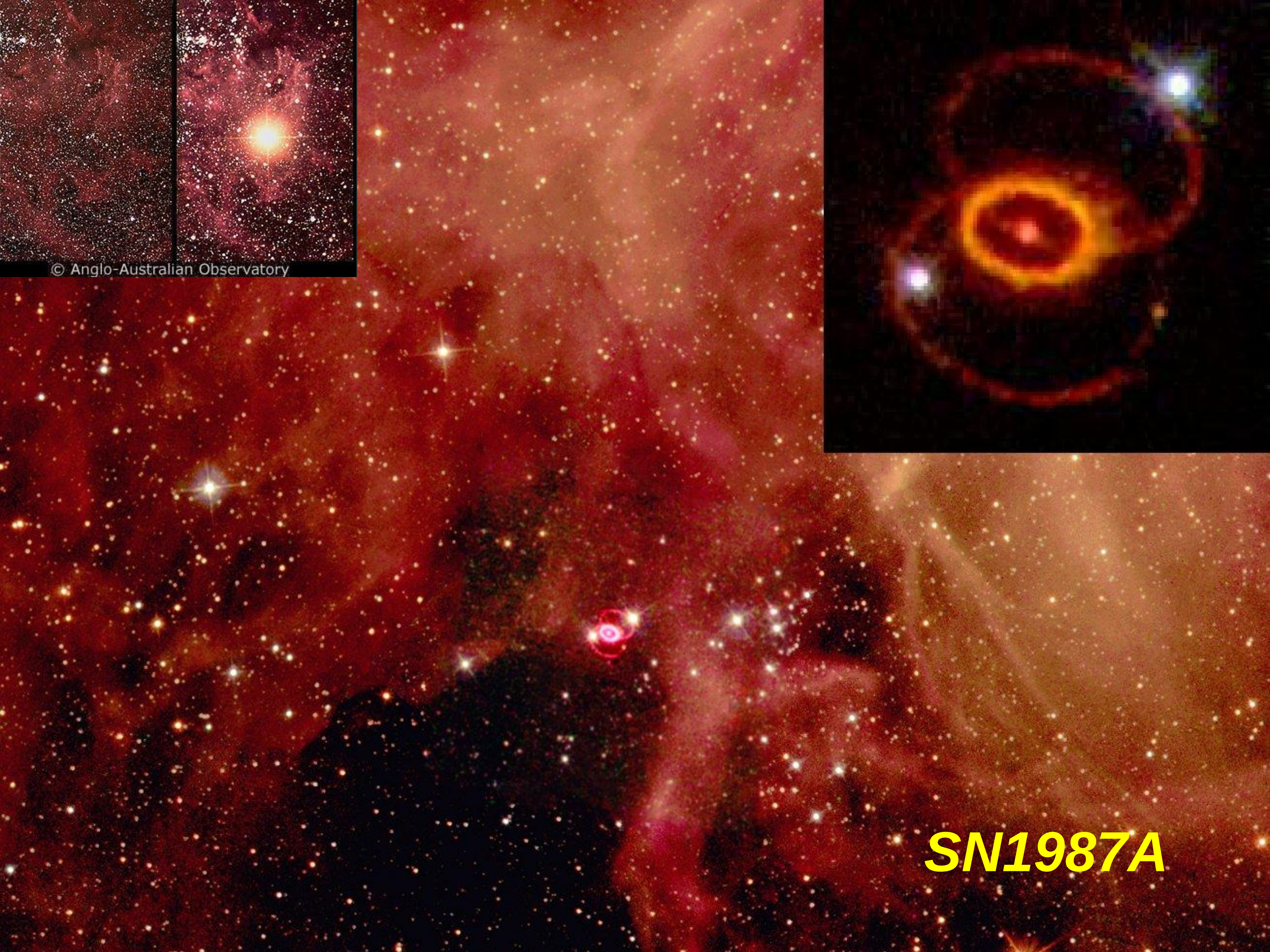
Hubble Ultra Deep Field

Spitzer space telecoop





NS en BH zijn de compacte objecten


© Anglo-Australian Observatory
SN1987A

Gravitatiestraling bestaat: PSR B1913+16

Russell A. Hulse
Joseph H. Taylor, Jr.
In 1974 werd de eerste pulsar in een binair systeem ontdekt

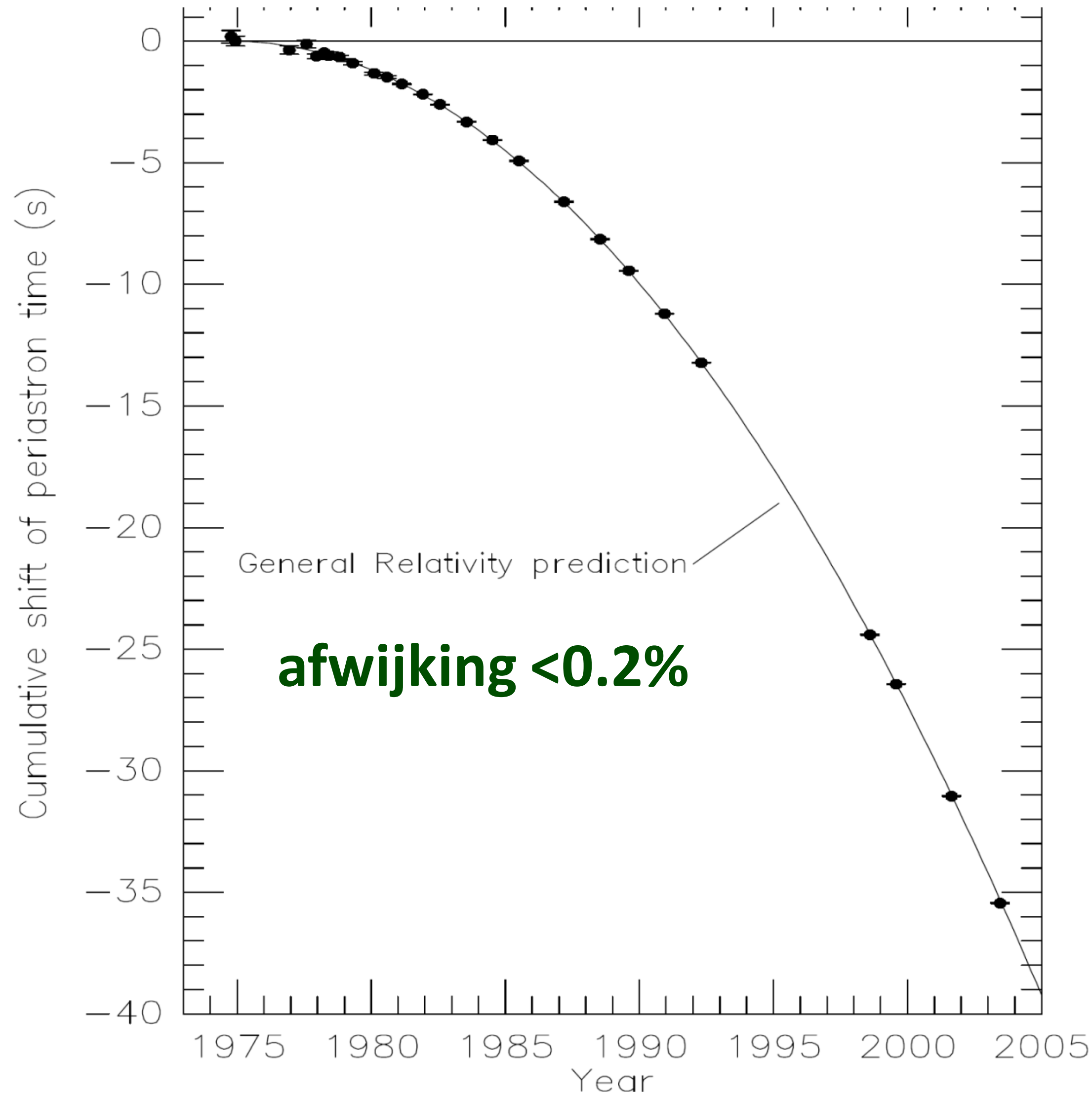
Periode ~ 8h

GW emissie verkort de periode

Indirecte detectie van GWs

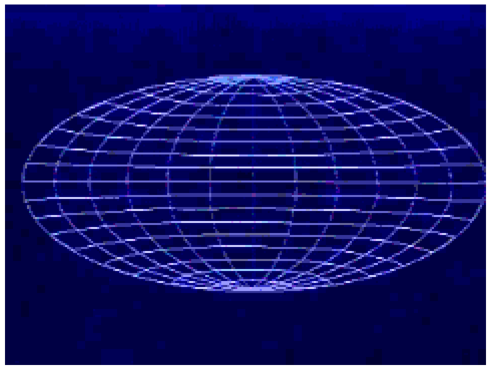
Nobelprijs 1993

Δt_P [s] **Periastron advance**

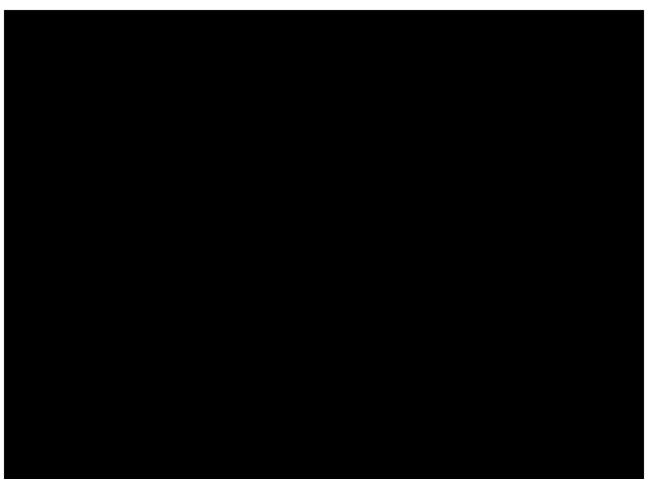


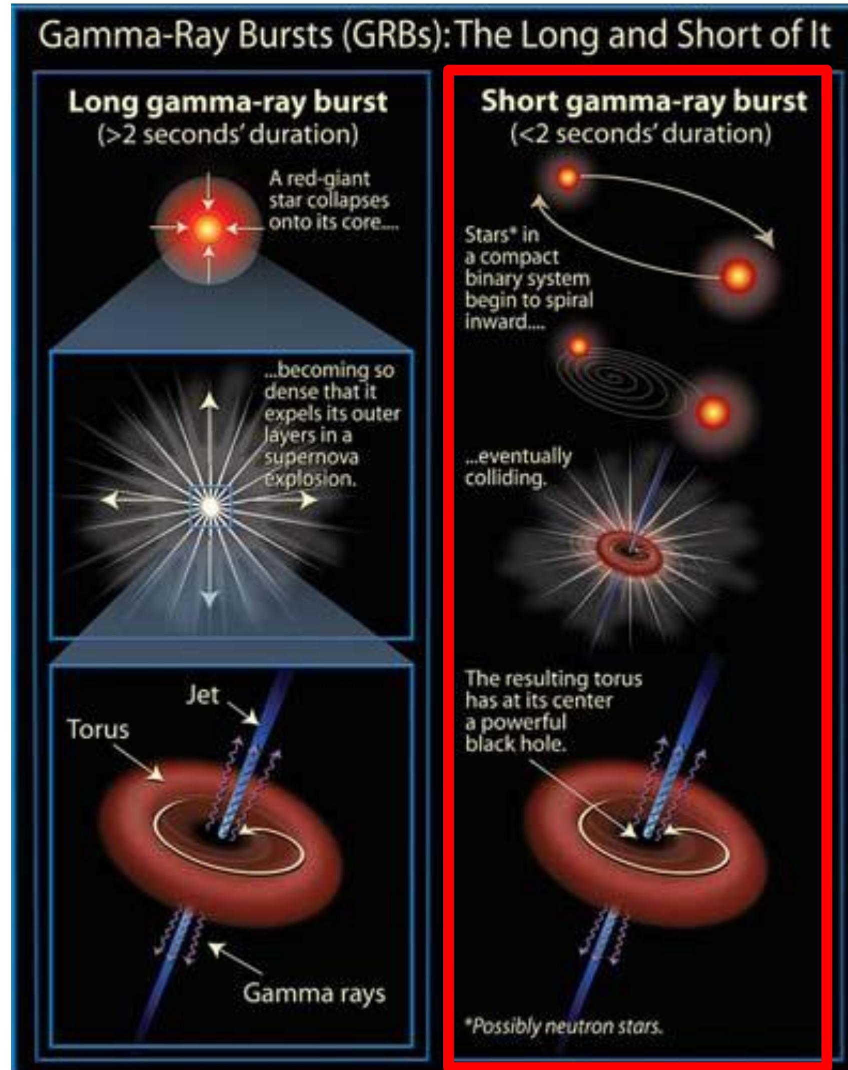
Burst bronnen: gamma-ray bursts

- Recente satelliet missies tonen reeks explosieve gebeurtenissen in Universum die enorme hoeveelheden energie genereren



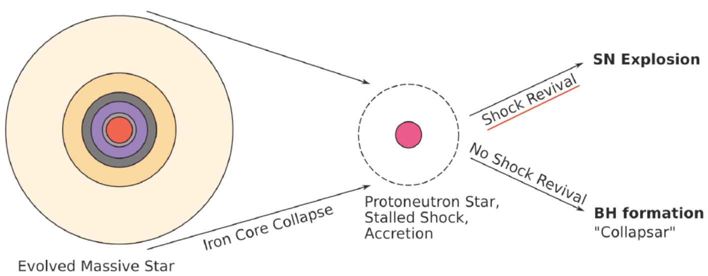
- De oorsprong van GRB is nog steeds onbekend, maar er zijn modellen

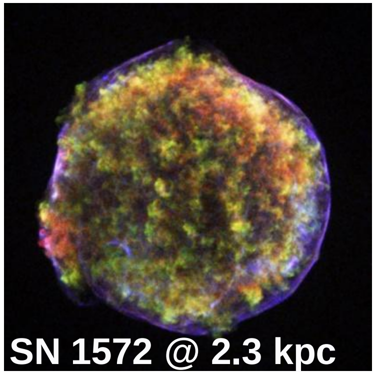


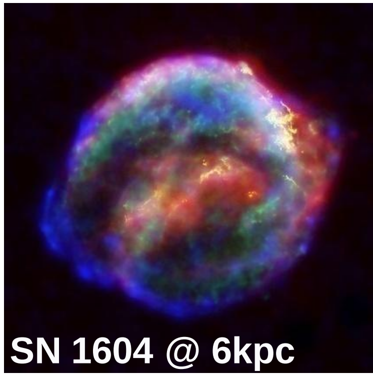


SUPERNOVAE

- Mechanisme van core-collapse SNe nog steeds niet duidelijk
  - Shock Revival mechanismw(s) na de core bounce TBC

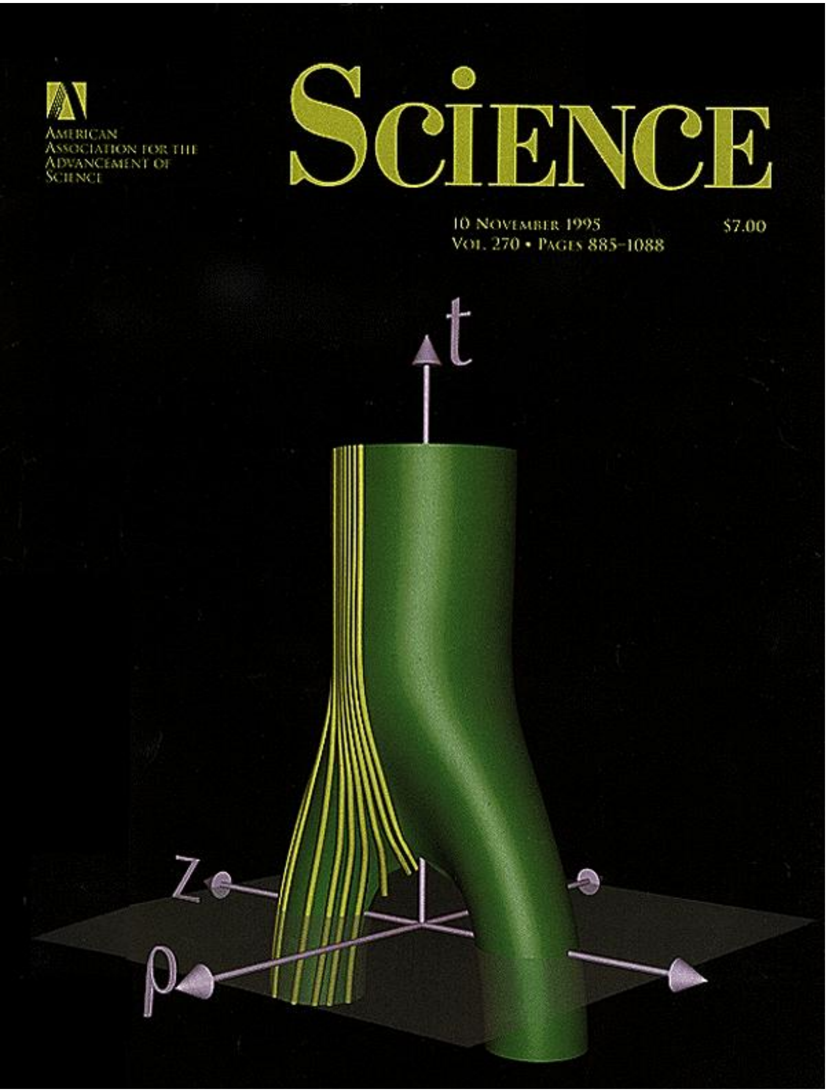




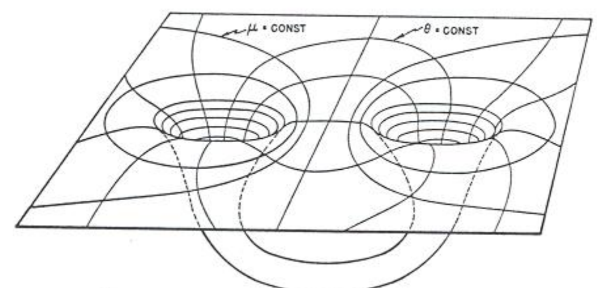


- GWs gegenereert door een SNe brengen informatie van het inwendige massieve deel van het proces en kan misschien iets zeggen over het mechanisme

Botsingen van twee zwarte gaten



- Twee-deeltjes probleem in algemene relativiteitstheorie
- Numerieke oplossing van de Einstein vergelijkingen
- Probleem studies begonnen 45 jaar geleden (1963 Hahn & Lindquist, IBM 7090)

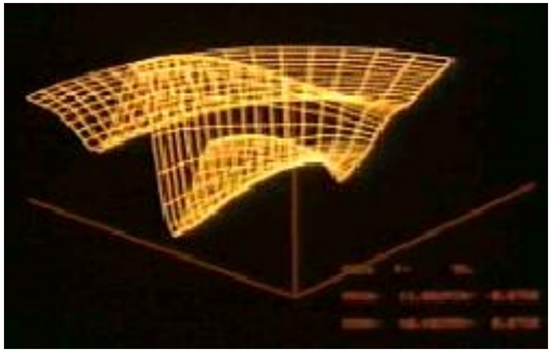


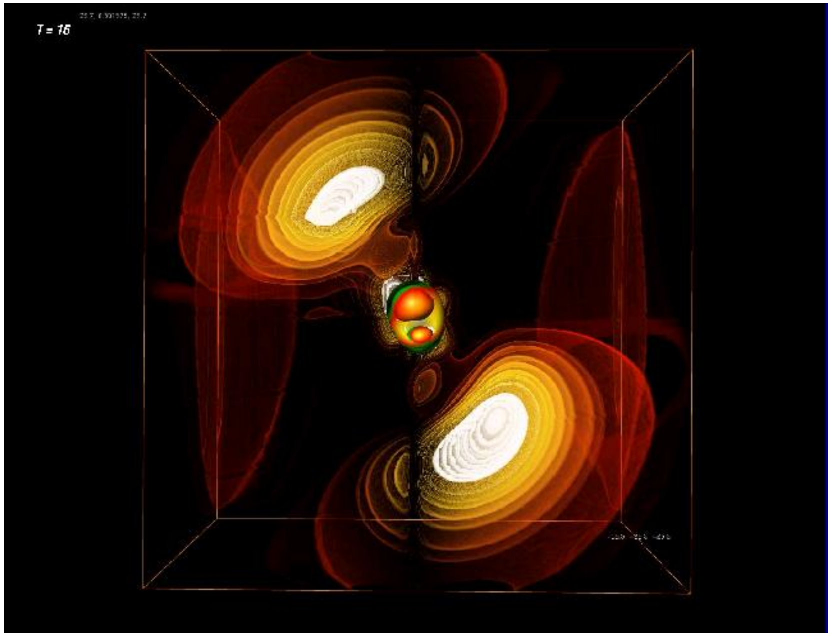
- Golfvorming zijn cruciaal voor gravitatiegolf detectoren
- Een PetaFLOPS-class grand challenge

Oct. 10, 1995

Matzner, Seidel, Shapiro, Smarr, Suen, Teukolsky, Winicuor

NUMERIEKE RELATIVITEITSTHEORIE





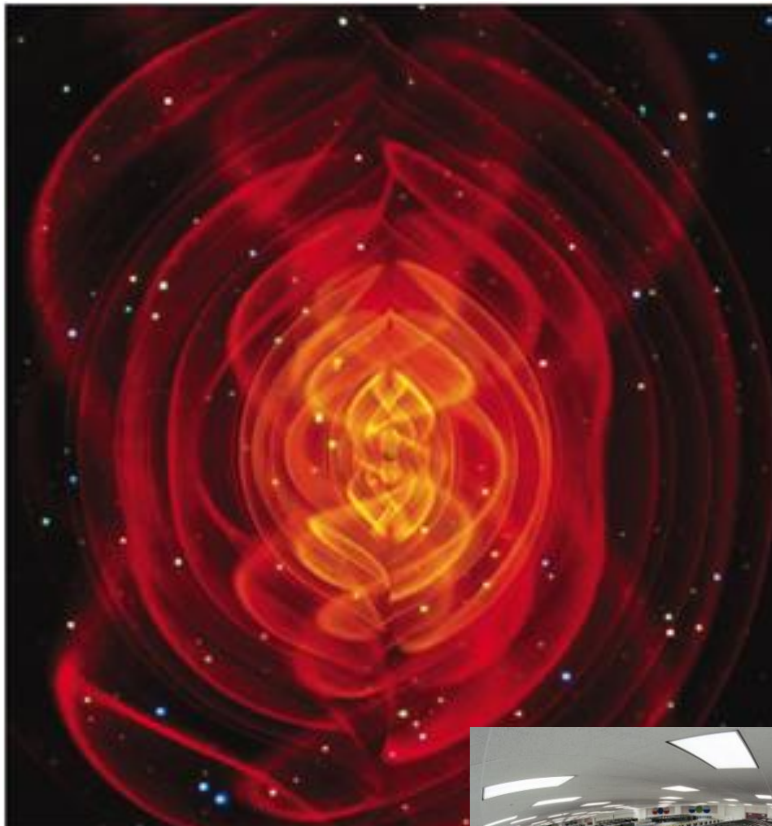
1977
Eppley & Smarr
CDC 7600
Een processor
Met 35 Mflops
5 uur

1999
Seidel & Suen, et al.
SGI Origin
256 processoren
Elk 500 Mflops
40 uur

300X

30.000X

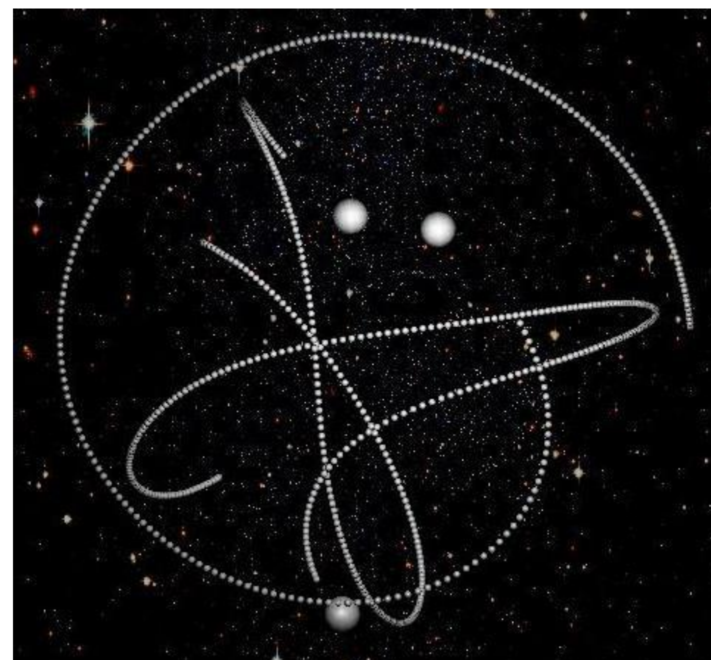
Numerieke relativiteitstheorie

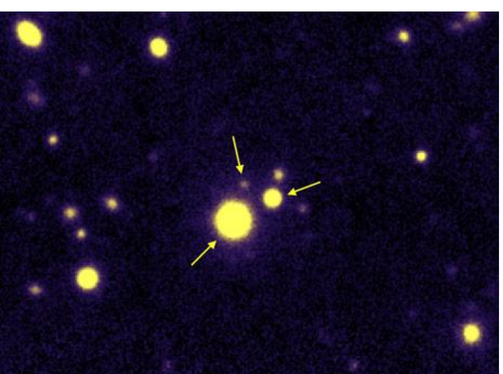


Eerste samensmelting van drie zwarte gaten gesimuleerd op een supercomputer

ScienceDaily (Apr. 12, 2008)

Manuela Campanelli, Carlos Lousto and Yosef Zlochower—Rochester Institute of Technology Center for Computational Relativity and Gravitation





Triple quasar (10.8 Gly)
S. G. Djorgovski et al.,
Caltech, EPFL (Jan. 2007)

Numerieke relativiteitstheorie

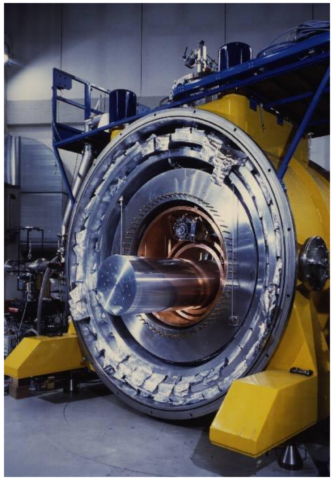
Vorming van zwarte gat

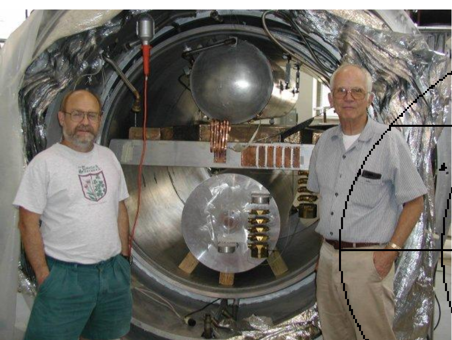
Coalescense van twee zwarte gaten

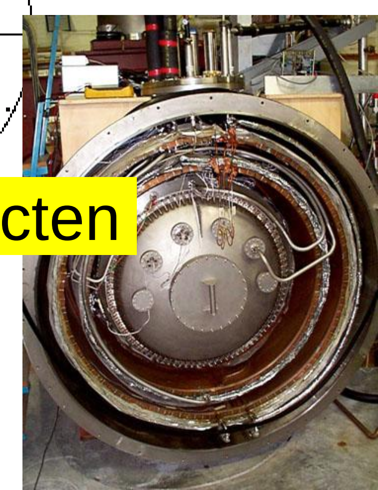
$$\Delta L = 1\mu m \rightarrow L = (10^{-6}\, m)/(10^{-22}) = 10^{16}\, m = 1\ ly$$

$$\Delta L = 10^{-18}\, m \rightarrow L = (10^{-18}\, m)/(10^{-22}) = 10^{4}\, m = 10\ km$$

Staaf detectoren: IGEC collaboration





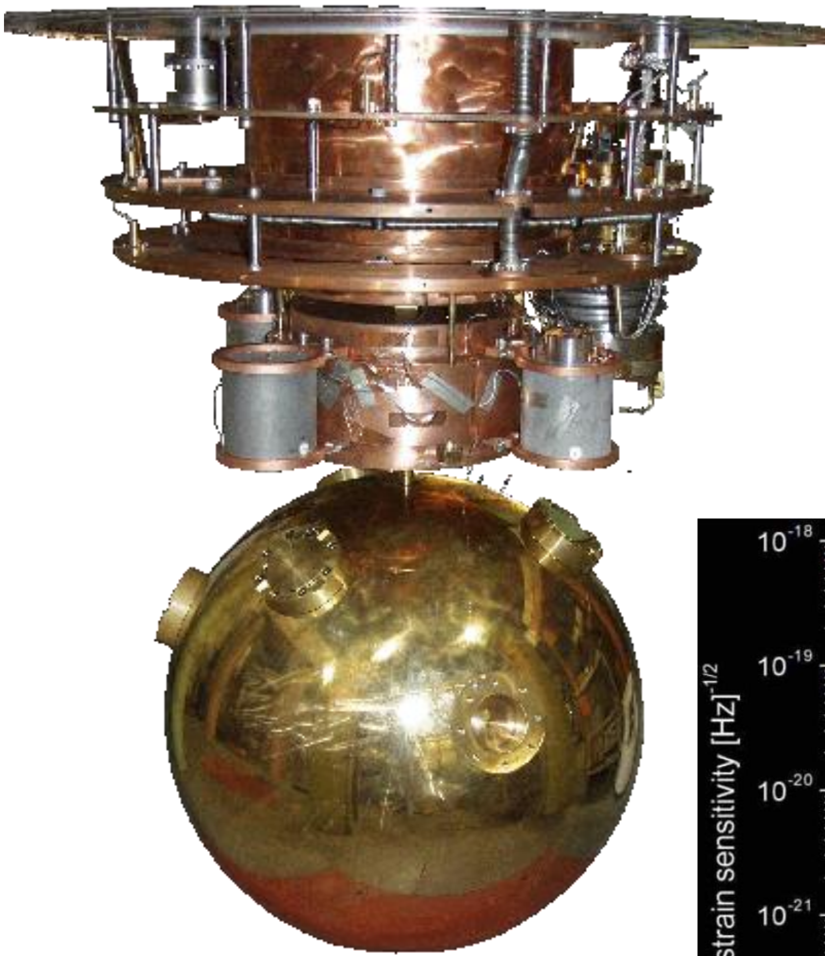


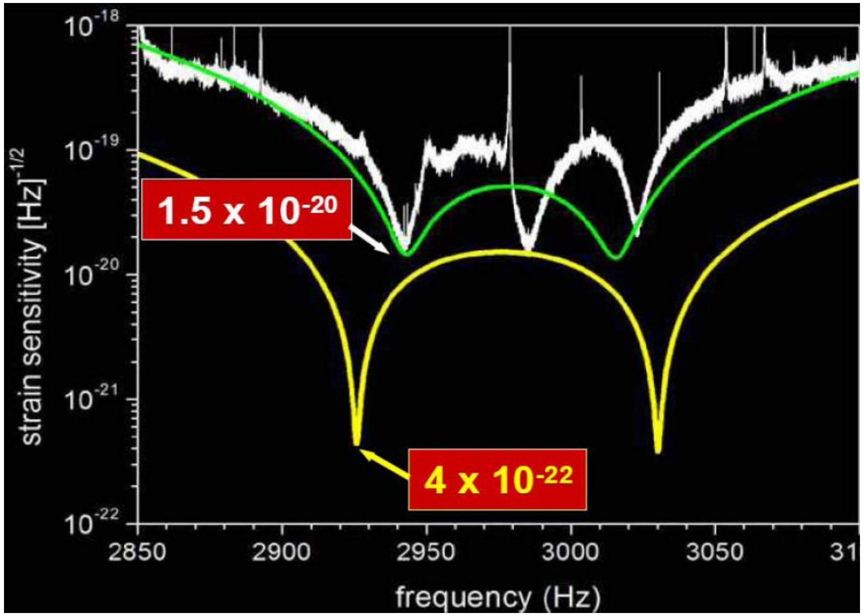
Meten van gravitatiegolven van compacte objecten

IGEC

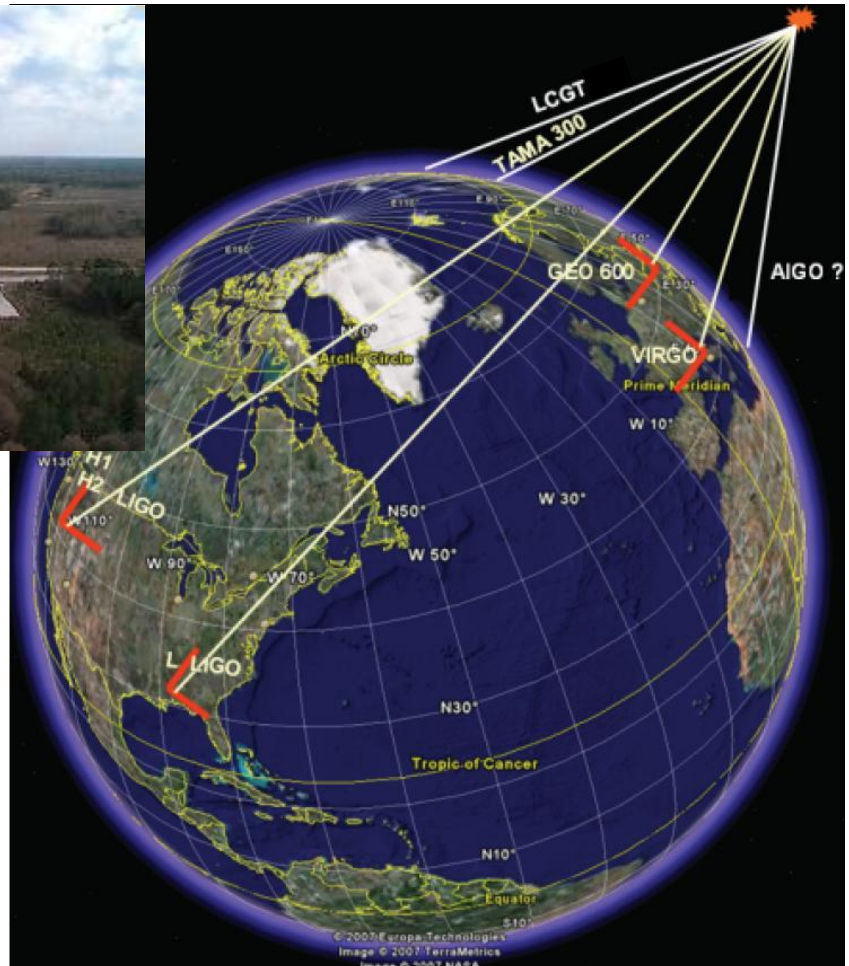
Ladbrokes.com

Mini-GRAIL: een bolvormige `staaf' in Leiden

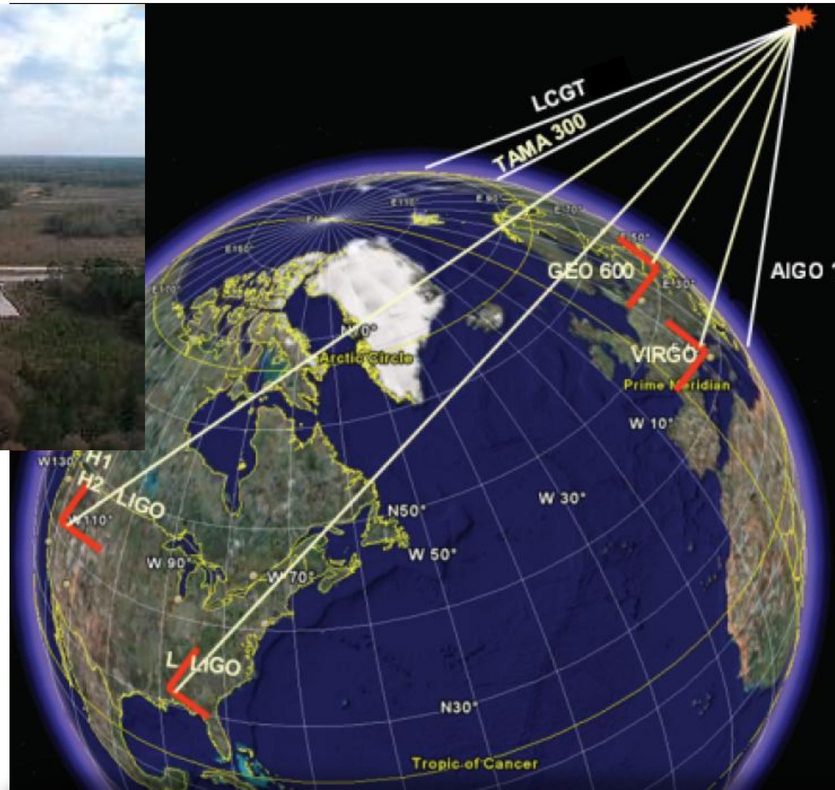


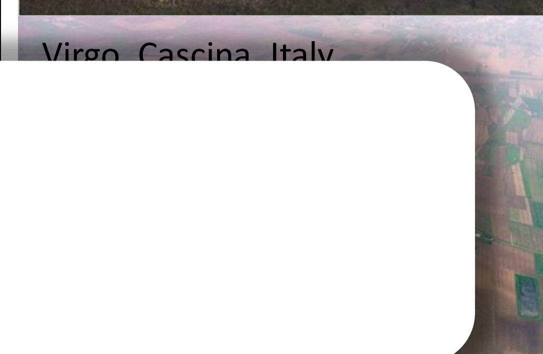


International context



International context



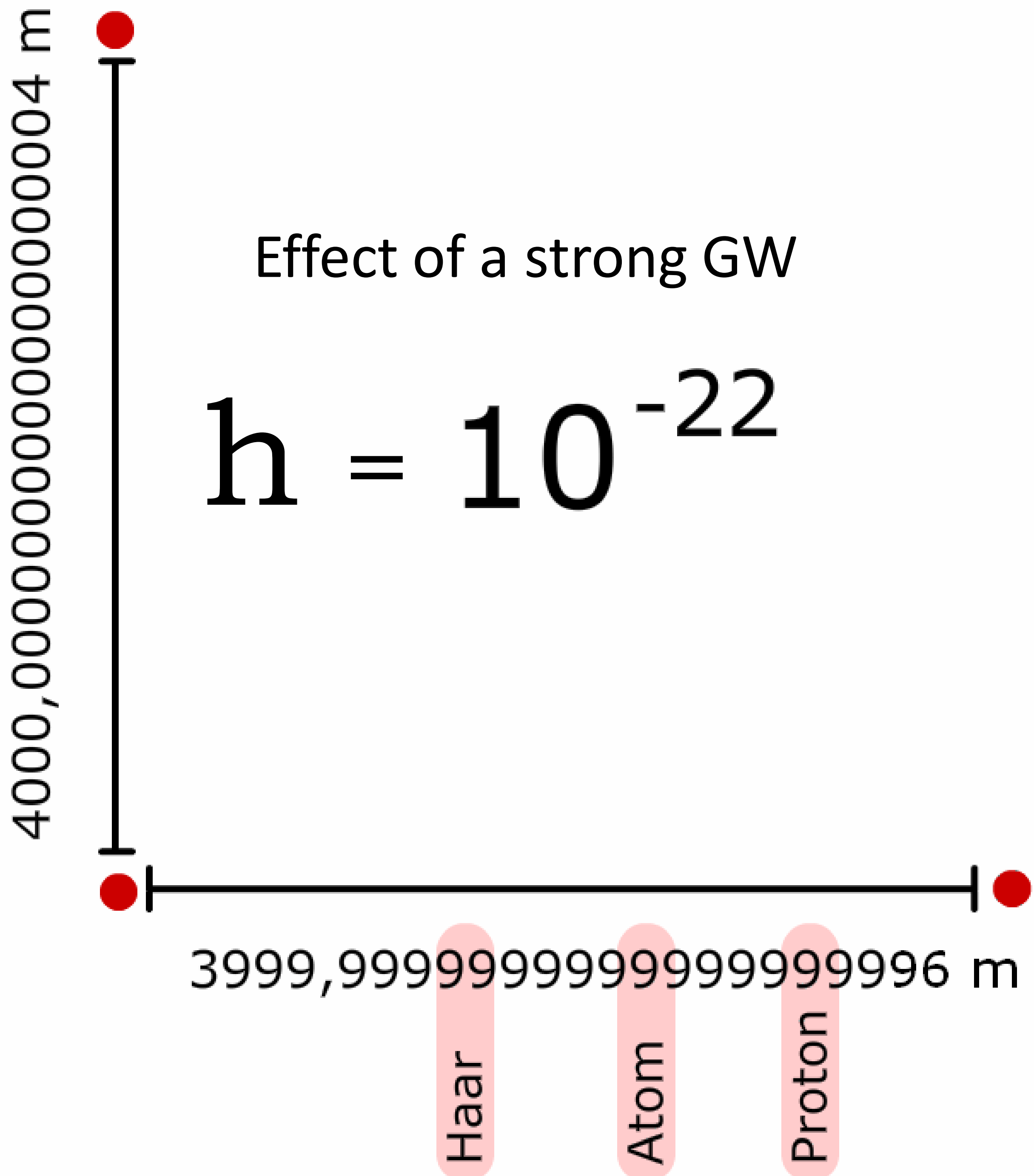


- USA, Italy, Germany and Japan
  - Sites for LIGO, Virgo, GEO and LCGT
    - Large investments (~ 1G€)
    - Caltech and MIT driven in USA

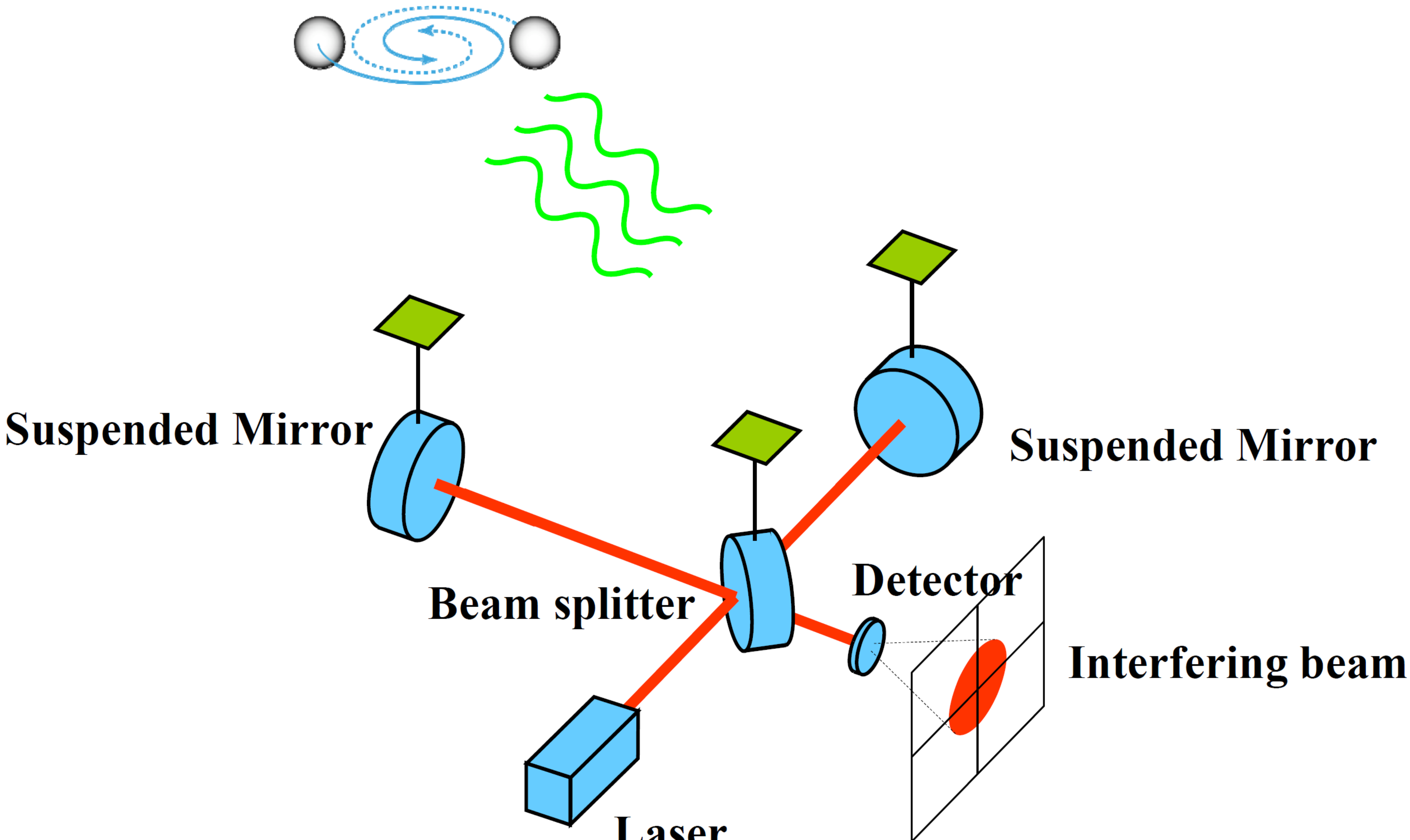
Interferometer als GW detector

- Principe: meet de afstanden tussen vrije test massa's
  - Michelson interferometer
  - Test massa = interferometer spiegels
  - Gevoeligheid: h = $\Delta L/L$
    - We willen en lange interferometer
    - Voor Virgo L = 3 km

Virgo: CNRS+INFN
(ESPCI-Paris, INFN-Firenze/Urbino, INFN-Napoli, INFN-Perugia, INFN-Pisa, INFN-Roma,LAL-Orsay, LAPP-Annecy, LMA-Lyon, OCA-Nice)
+ Nikhef werd lid in 2007

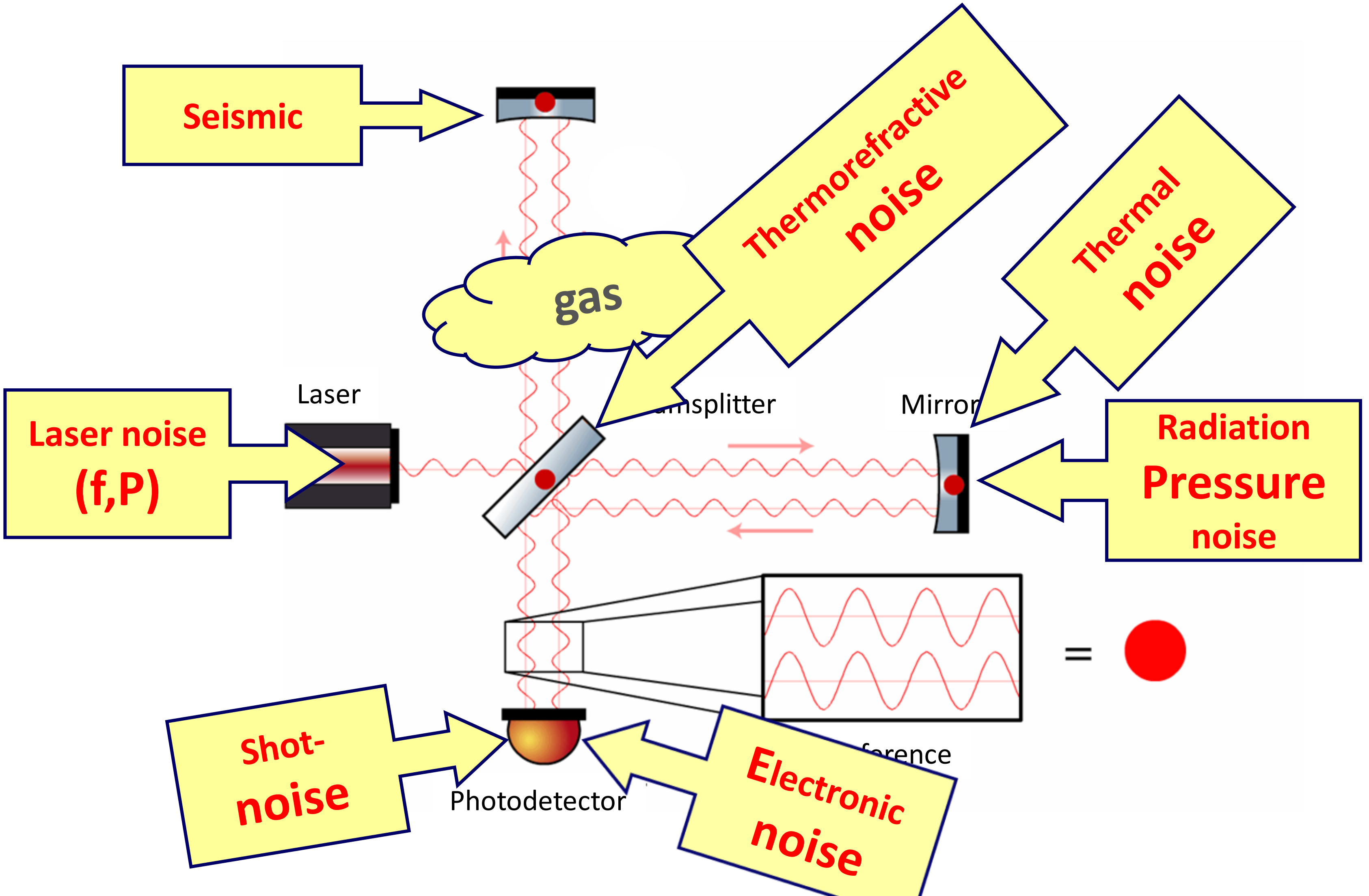

Effect of a strong GW
h = 10-22
4000,00000000000000004 m
3999,99999999999999996 m
Haar
Atom
Proton

GW DETECTIE MET INTERFEROMETER

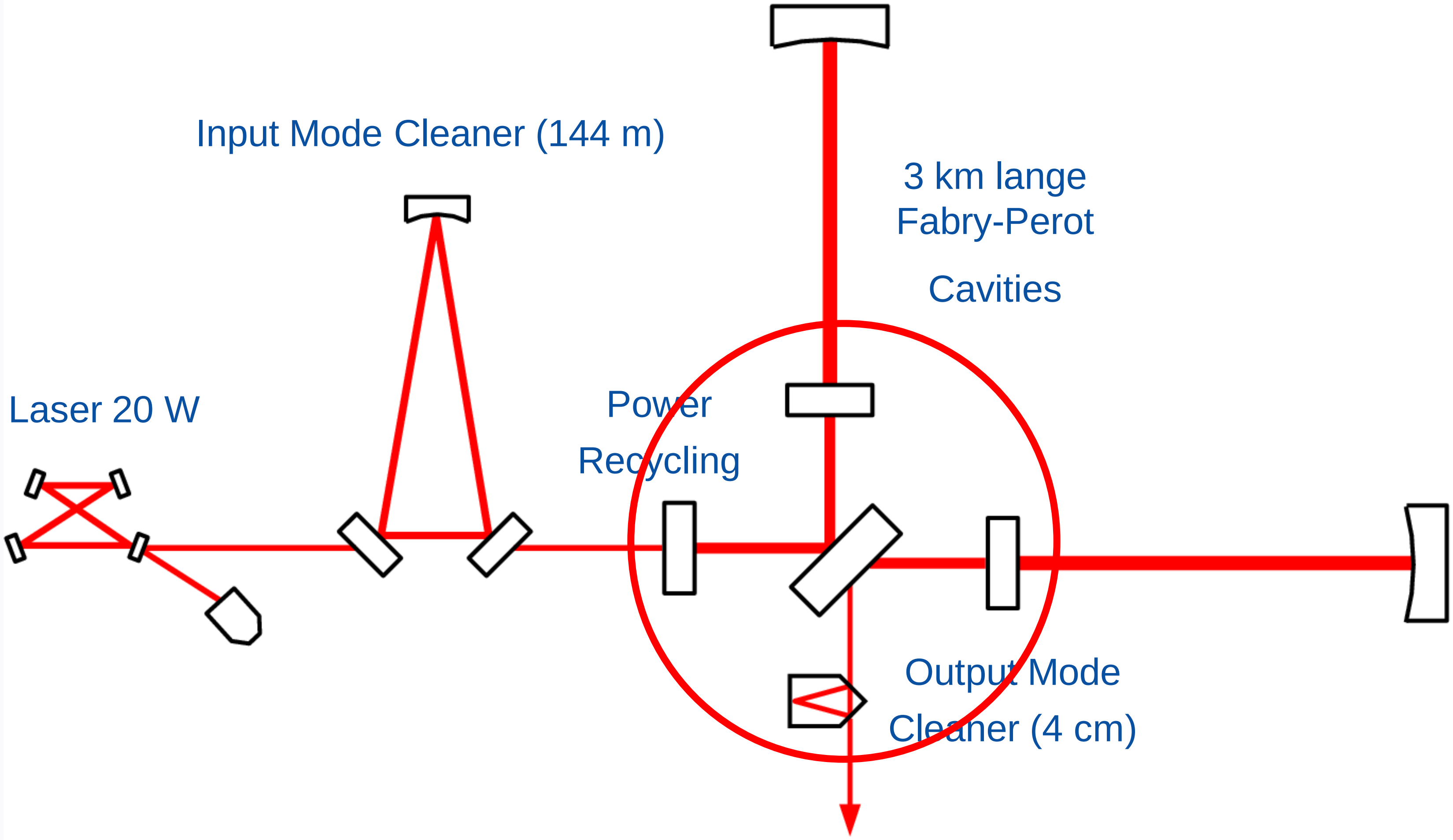


Kawamura

Interferometer: principe

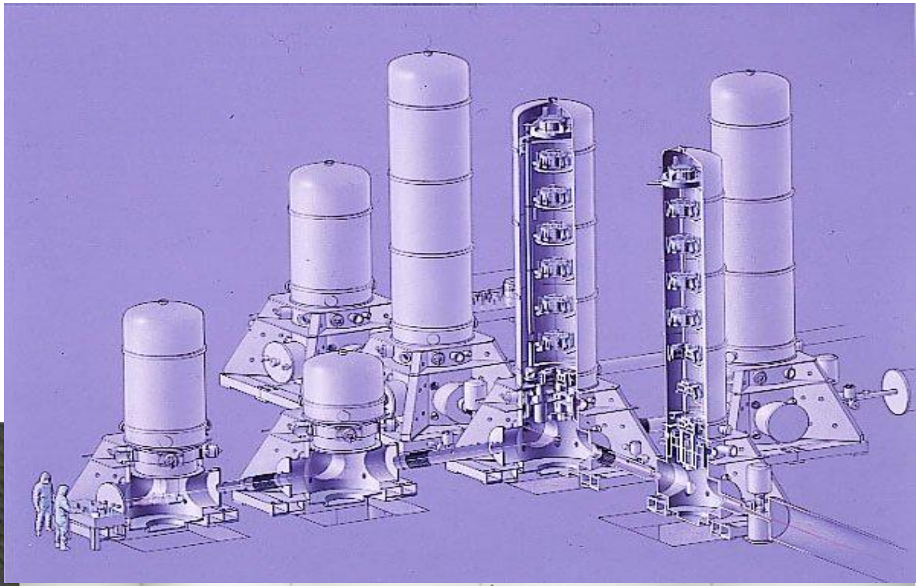


VIRGO Optica layout



Vacuum systeem

- Ultra-hoog vacuum
  - Grootste vacuum systeem in Europa

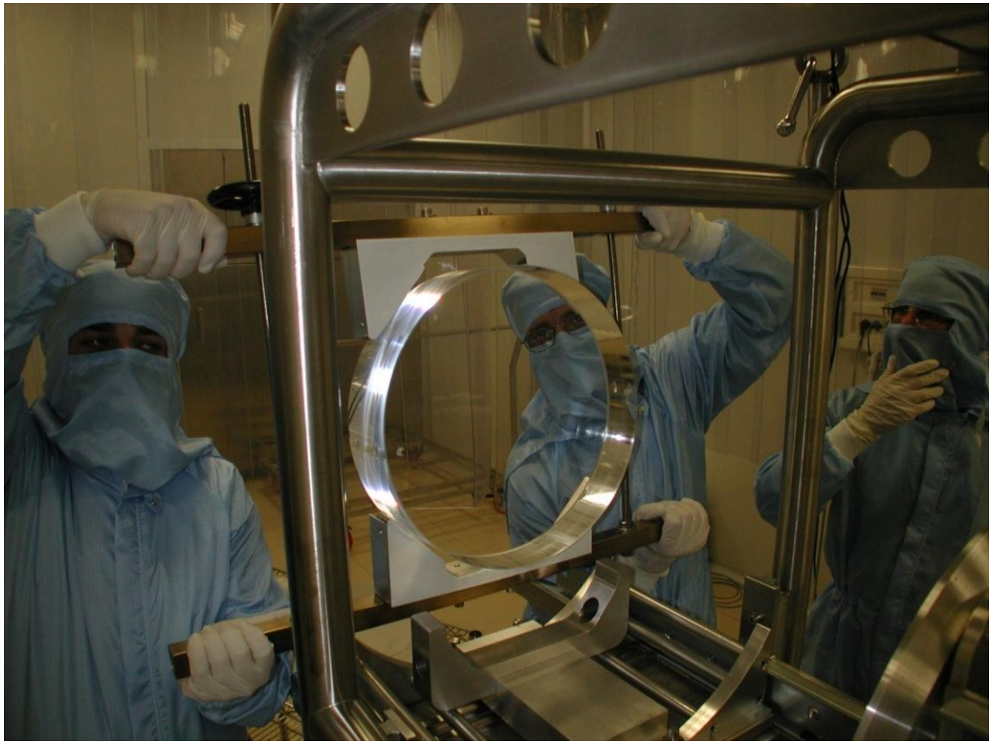


Spiegels

Hoge kwaliteit quarts spiegels

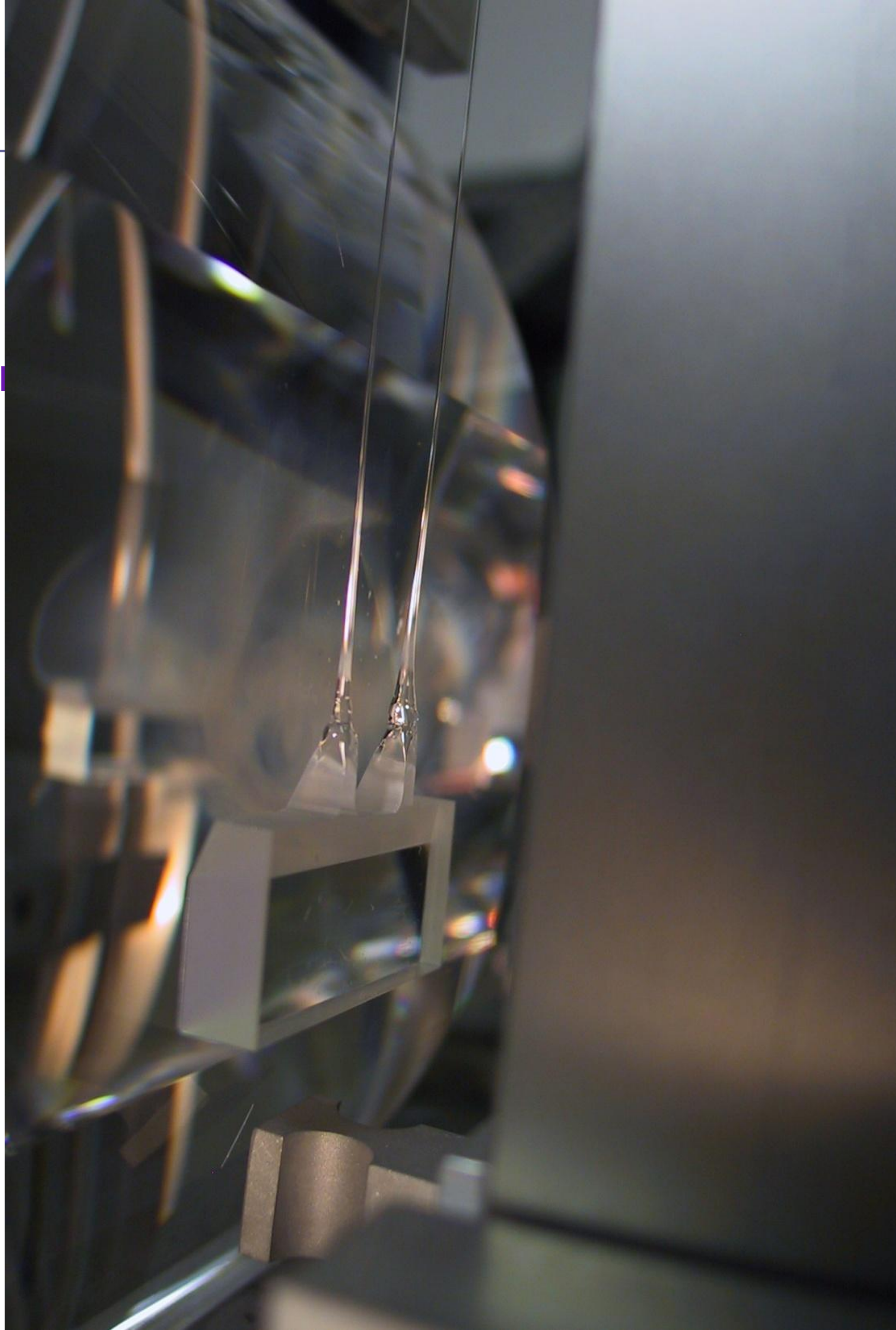
- 35 cm diameter, 10 cm dikte, 21 kg massa
- Lichtverlies in het glas ~1 ppm
- Verlies in de coatings <5 ppm
- Vlakheid ~l/100

Quantumeffecten belangrijk



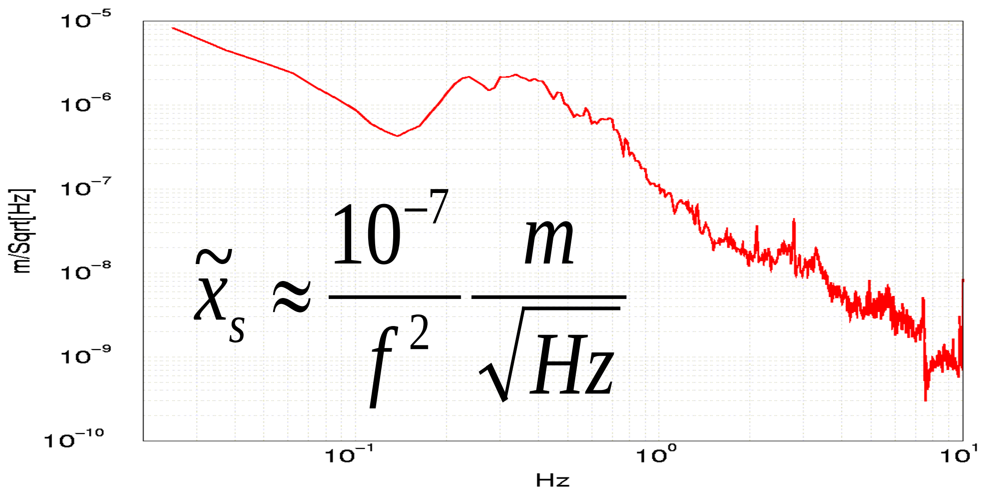
Thermische ruis

- Mechanische modes zijn in ther
  - Modes:
    - Pendulum mode
    - Draad vibratie
    - Spiegel interne modes
    - Coating oppervlak
  - Energie: $k_B T$
- Thermisch spectrum:
- Strategie:
  - Gebruik speciale materialen:
    → concentreer de beweging op de



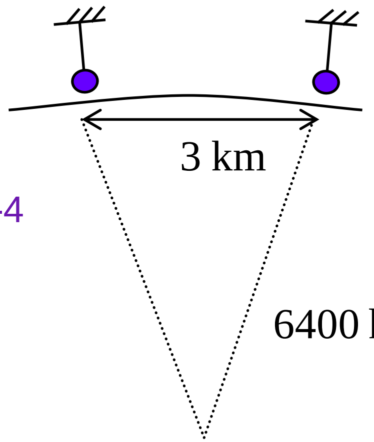
De uitdaging van seismische ruis

- Ruis spectrum:



$$\tilde{x}_s \approx \frac{10^{-7}}{f^2} \frac{m}{\sqrt{Hz}}$$

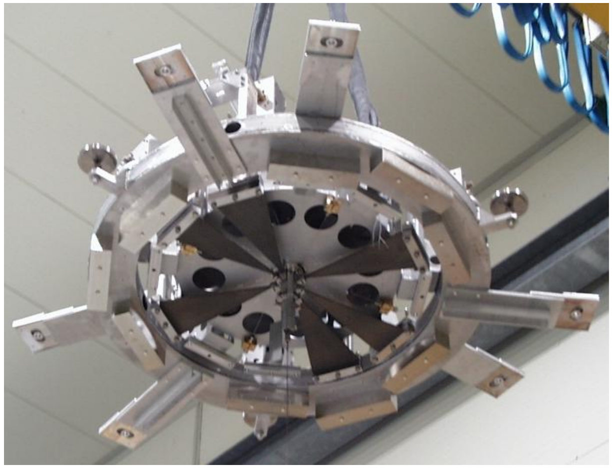
- Doel:
  - Meer dan 10 ordes van verzwakking boven 4Hz



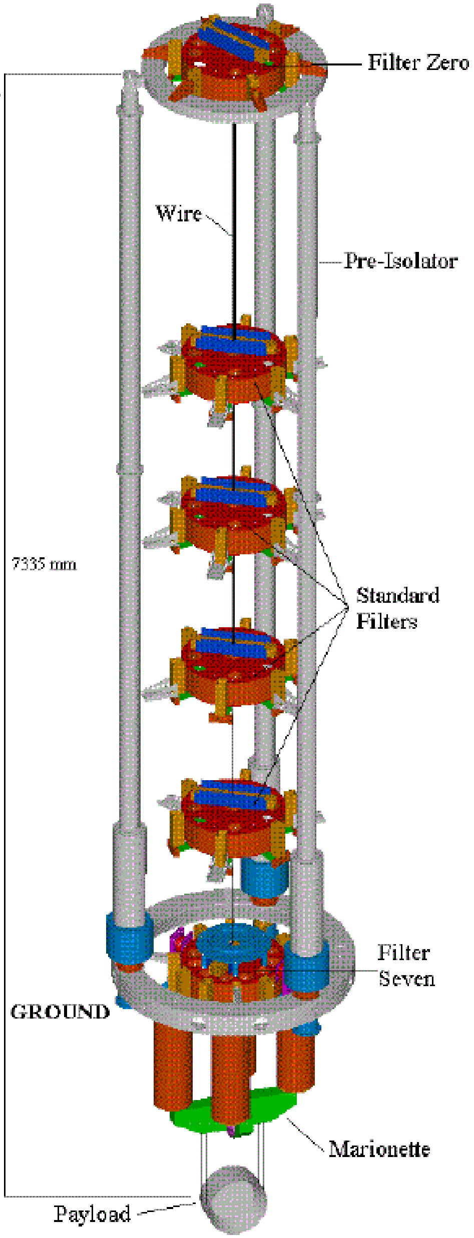
- Verticale naar horizontale koppeling > 2 $\times 10^{-4}$
  - We moeten ook verticale bewegingen filteren!

VIRGO SUPERDEMPERS

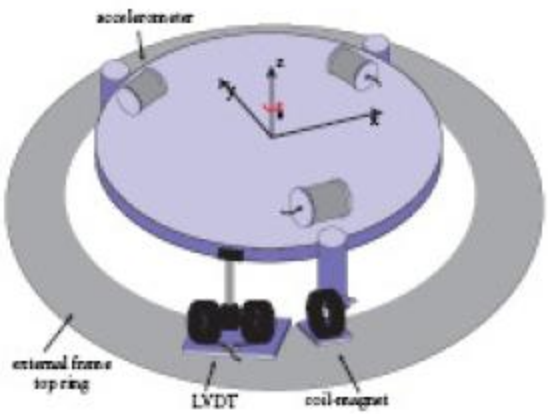
- Oplossing:
  - Keten van filters
- Passief apparaat
  - Combineer:
    - bladen (verticaal)
    - Draden (pendulum)

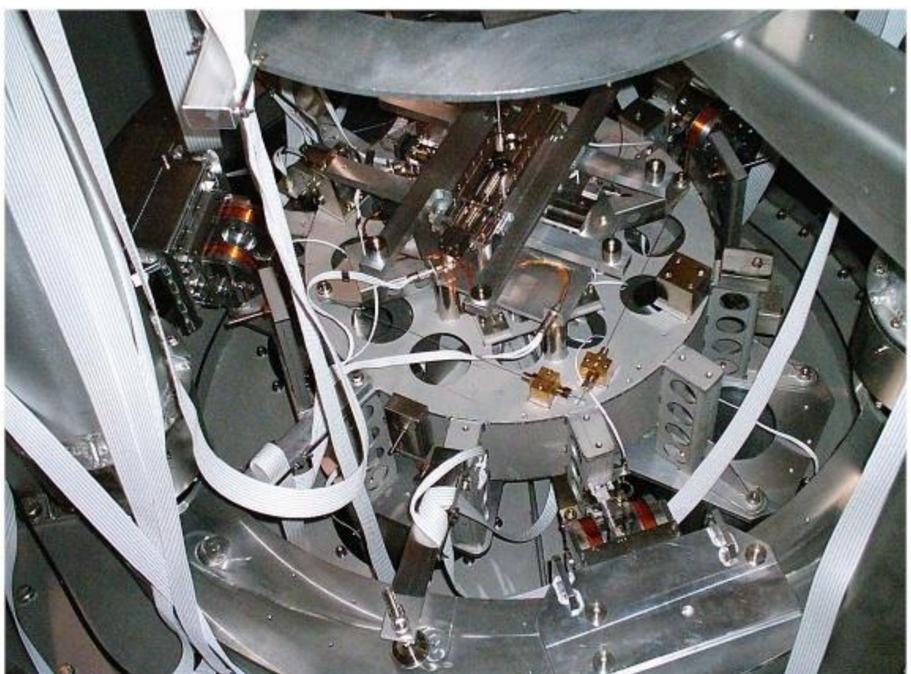


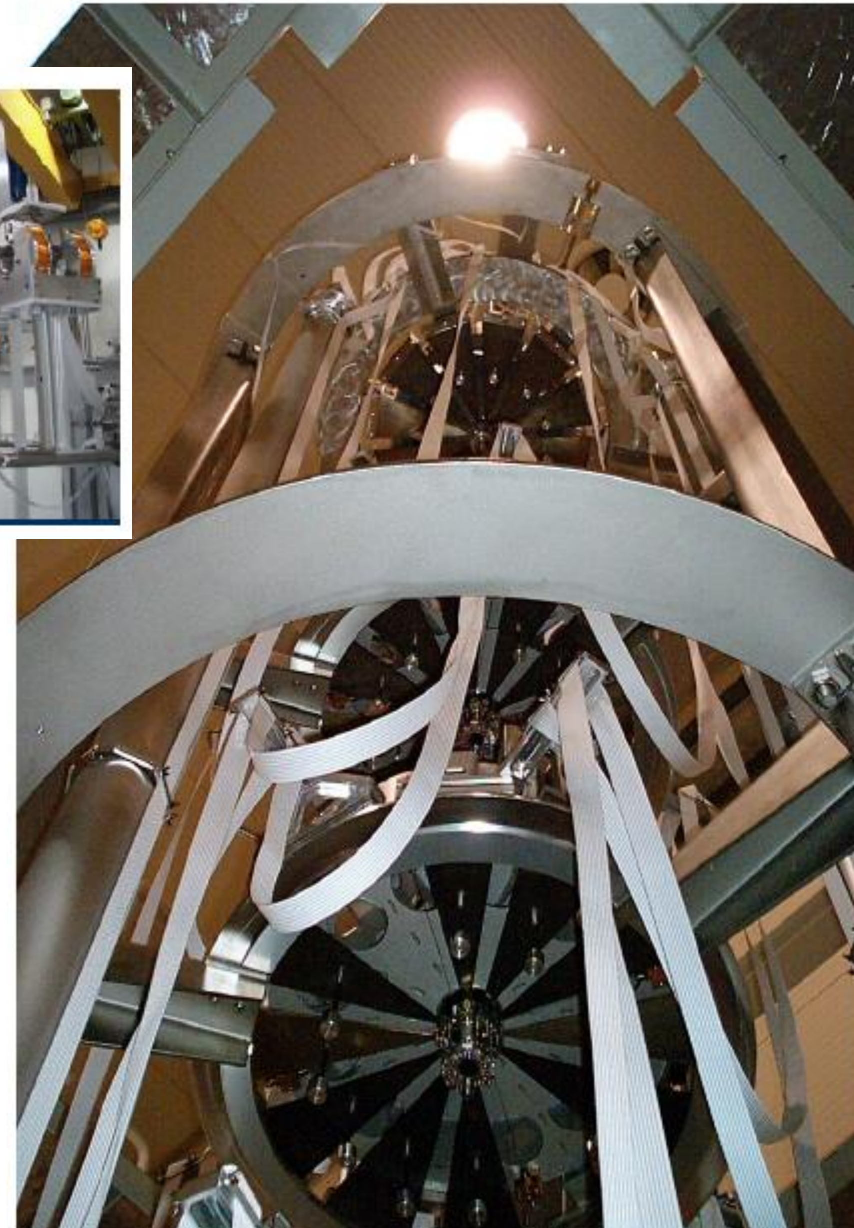
- 6 seismische filters (in alle vrijheidsgraden)
- Inverted pendulum voor regeling bij lage freq.
- 2 regel oplossingen:
  - Marionette (longitudinaal-hoek)
  - Referentie massa (longitudinaal)
- Verwachte verzwakking: 10^{14} @ 10 Hz
- Diverse regelstrategieën



Superdempers

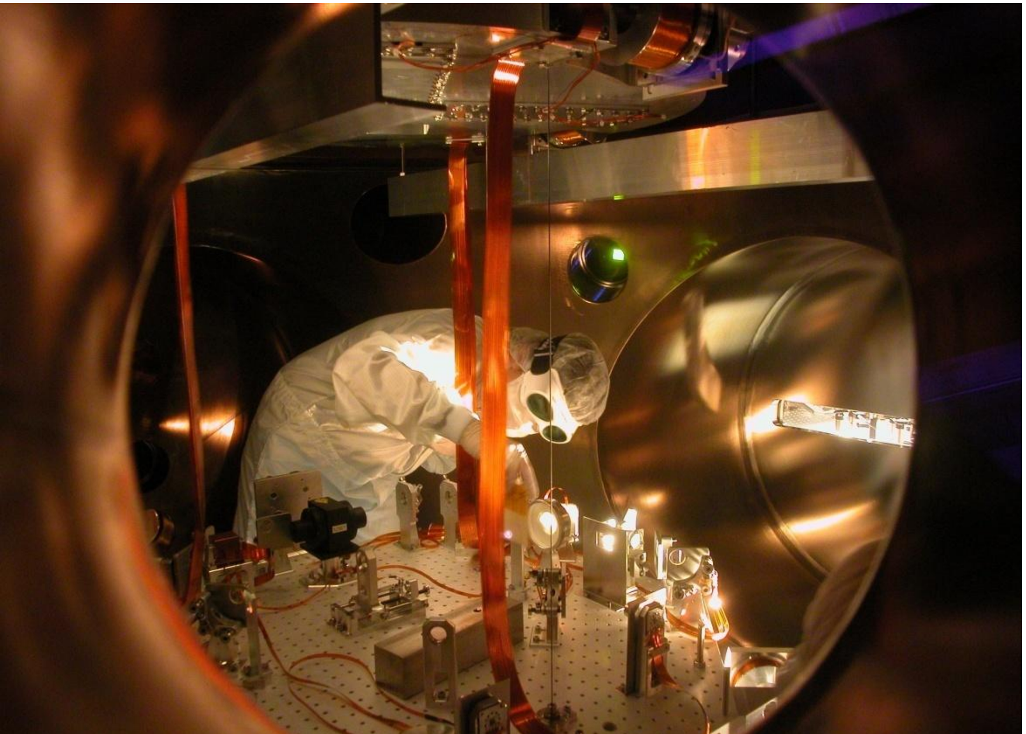


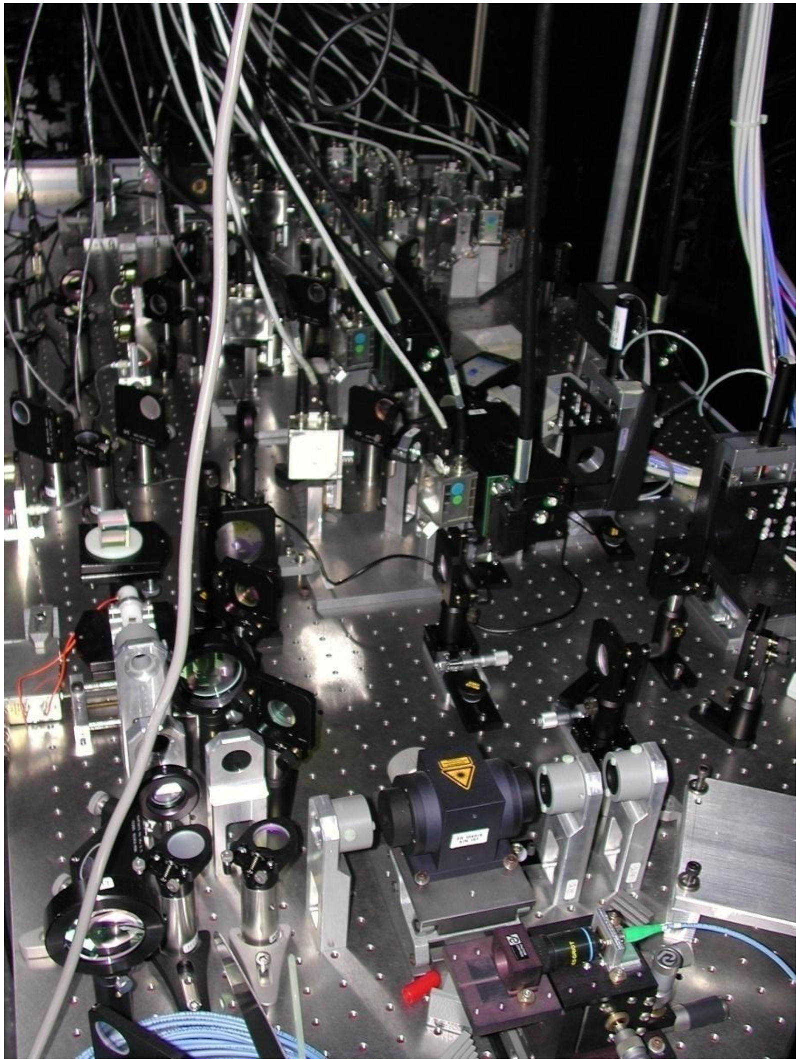




Detectiesysteem

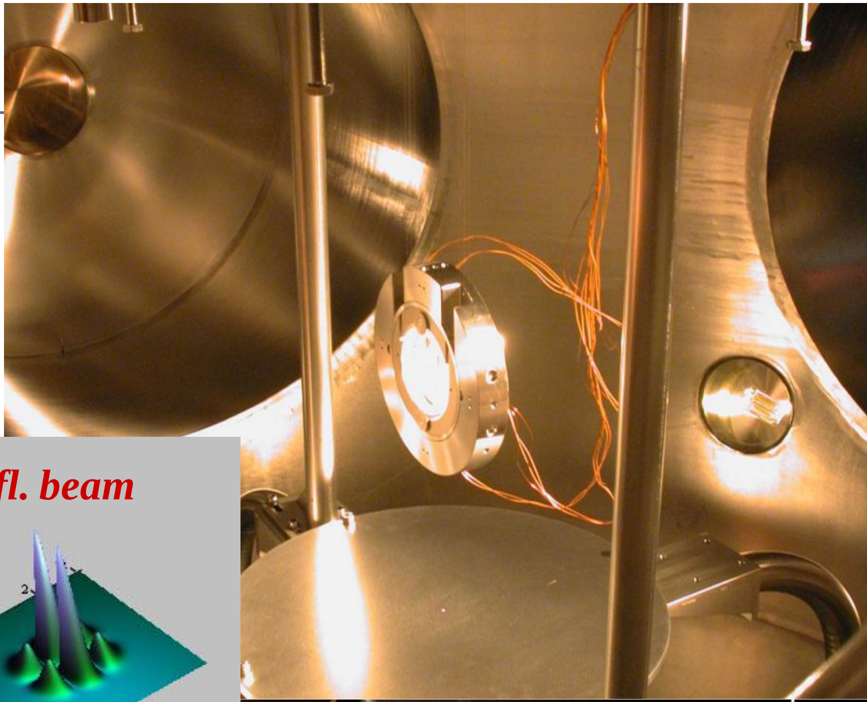
- In theorie:
  - Een fotodiode
- Realiteit
  - Veel bundels, veel fotodiodes, mod/demodulatie elektronica, camera's, DAQ,…
  - > 1400 « ADC channels »
  - 18 Mbytes/s of ruwe data

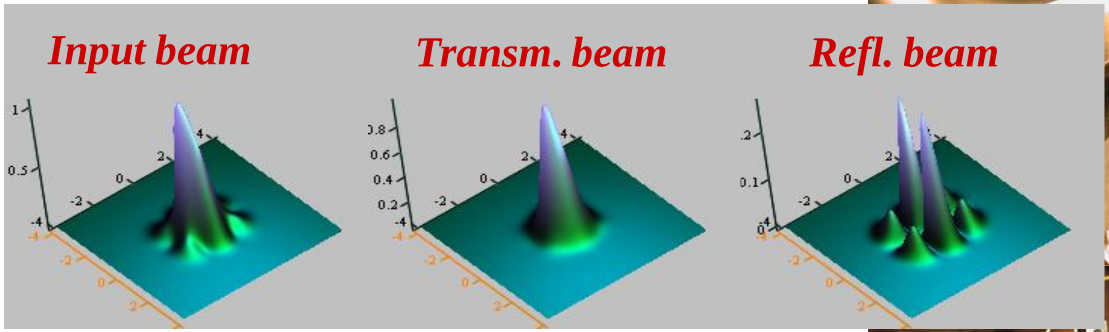


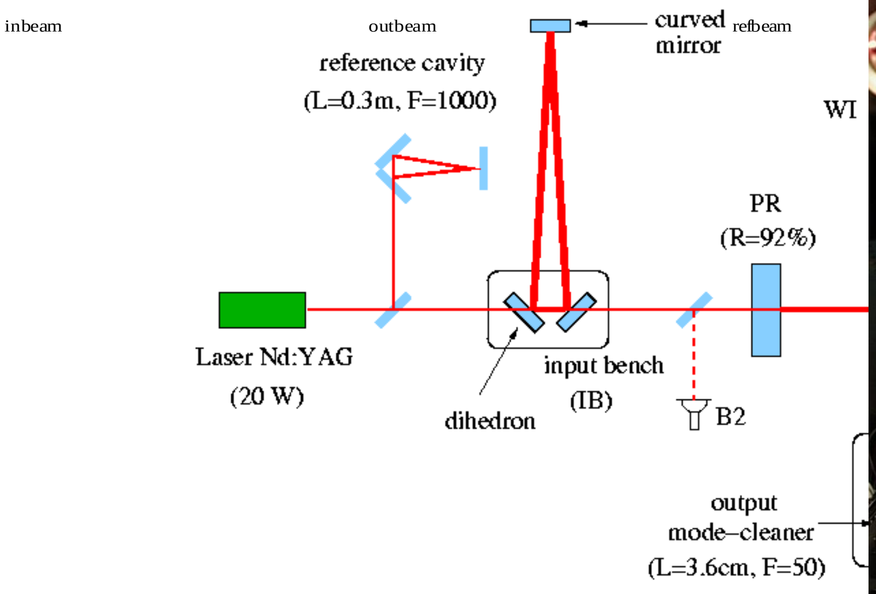


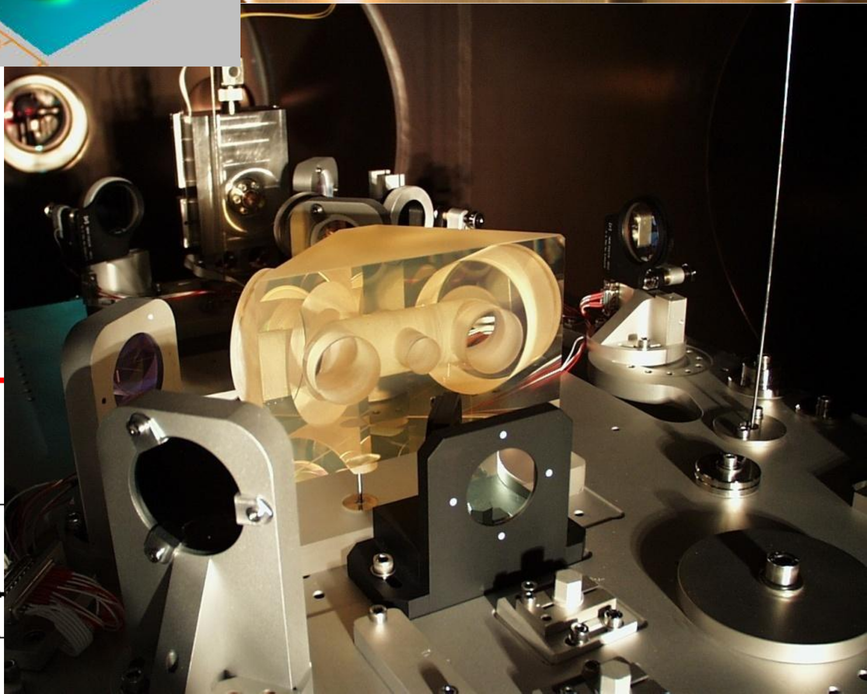
Input mode cleaner

- Mode cleaner cavity: filter laser ruis, selecteer TEM00 mode

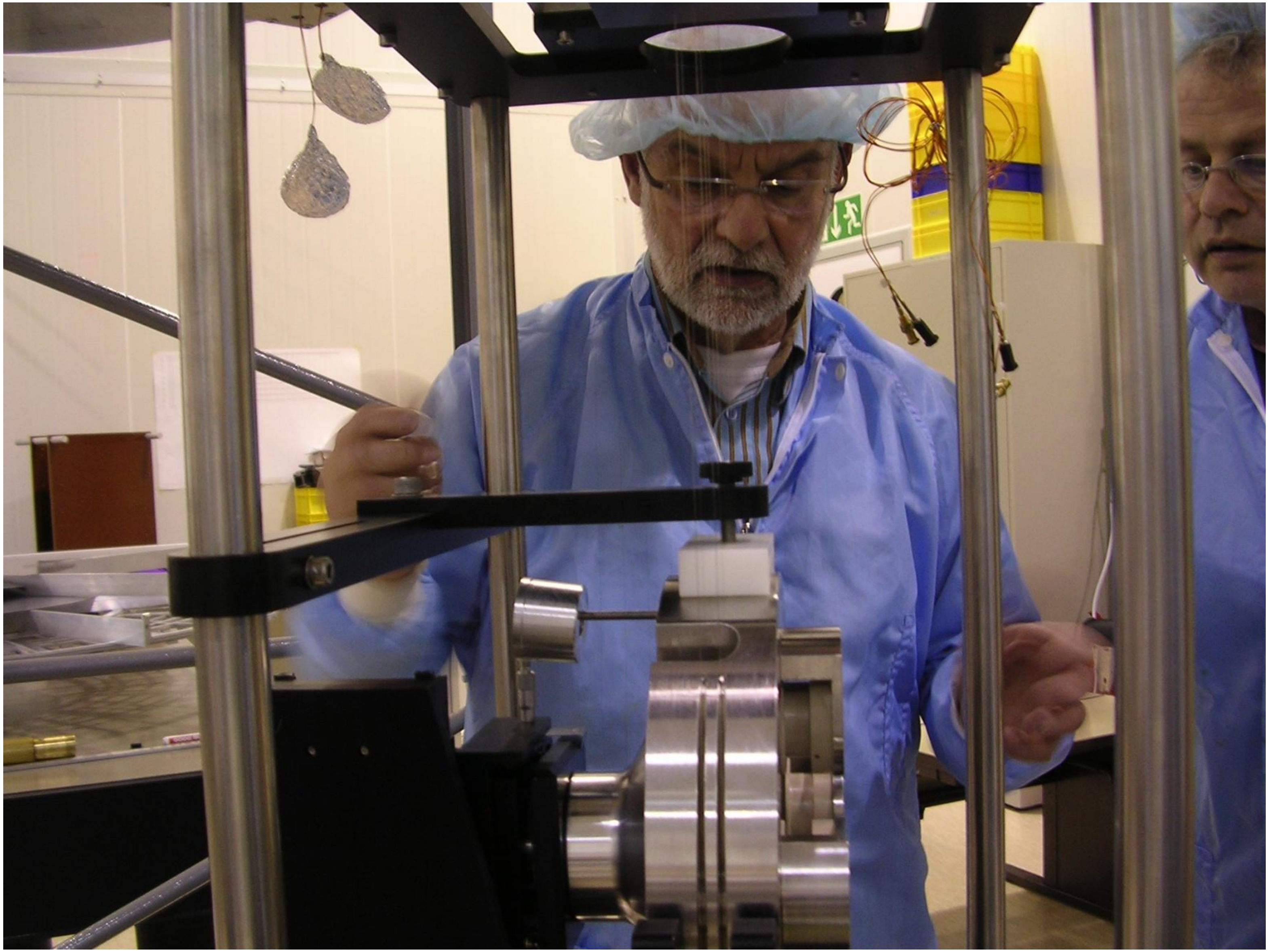




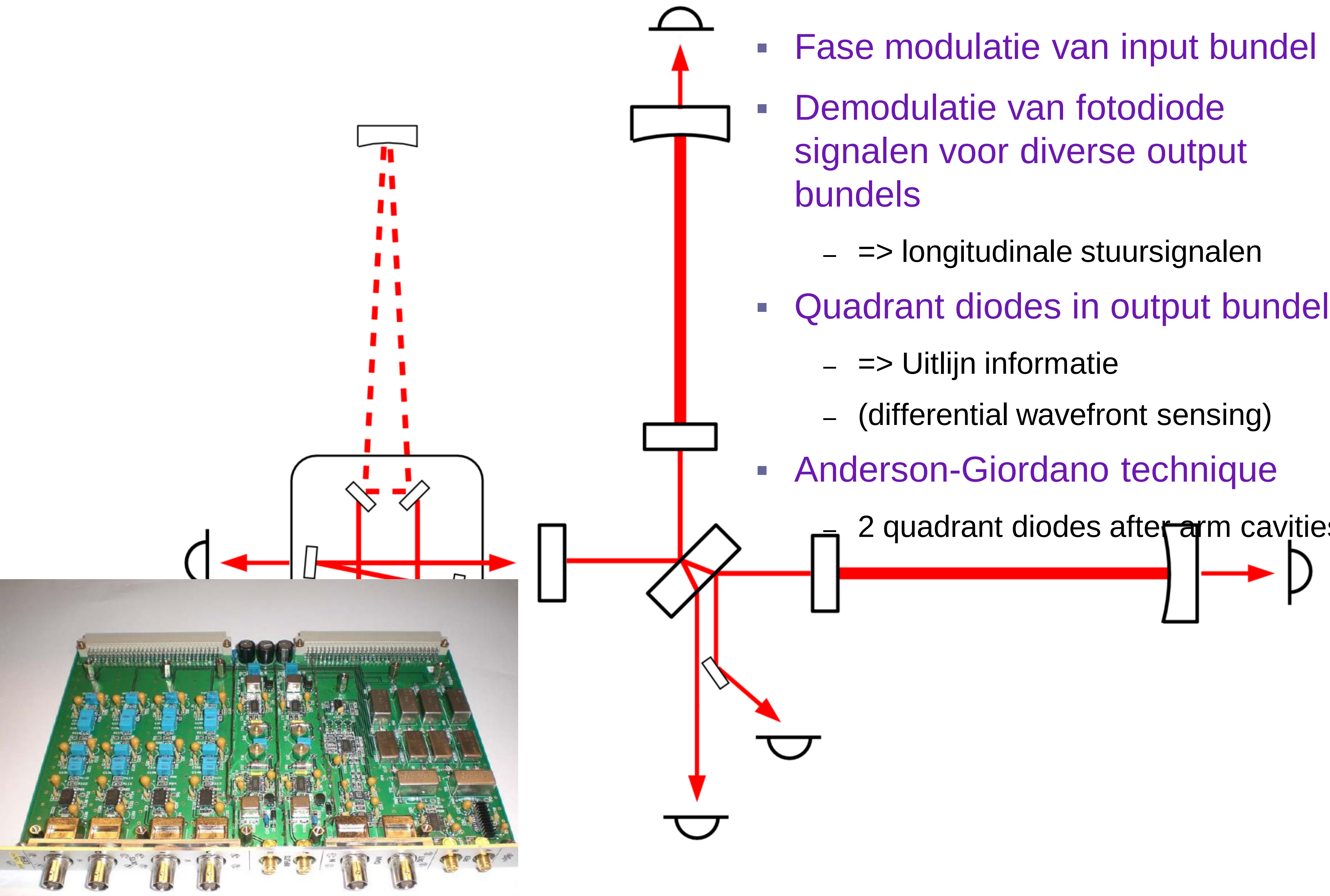




IMC eindspiegel gemaakt op Nikhef

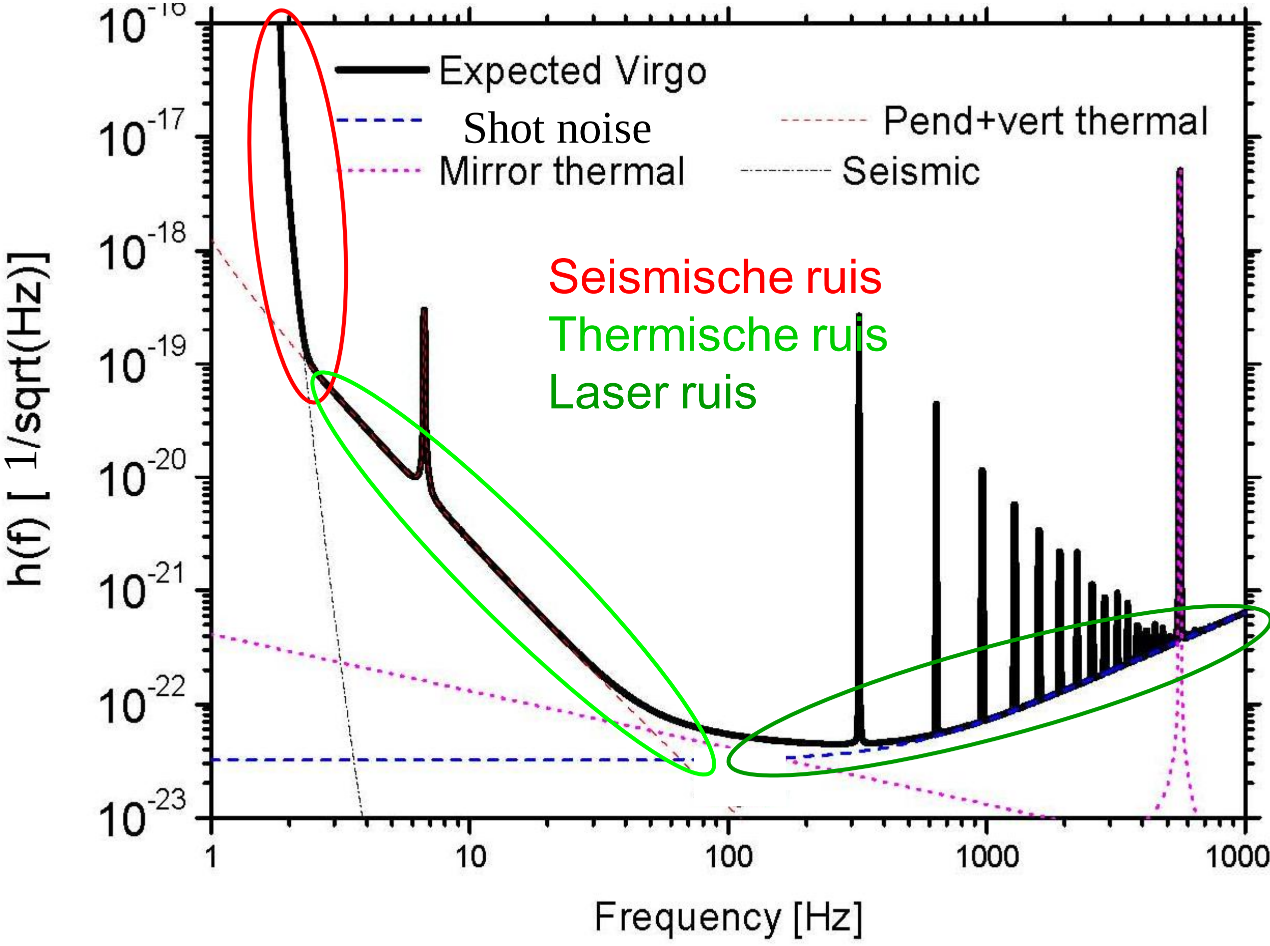


Nikhef: Hoek uitlijning van Virgo



- Fase modulatie van input bundel
- Demodulatie van fotodiode signalen voor diverse output bundels
  - => longitudinale stuursignalen
- Quadrant diodes in output bundels
  - => Uitlijn informatie
  - (differential wavefront sensing)
- Anderson-Giordano technique
  - 2 quadrant diodes after arm cavities

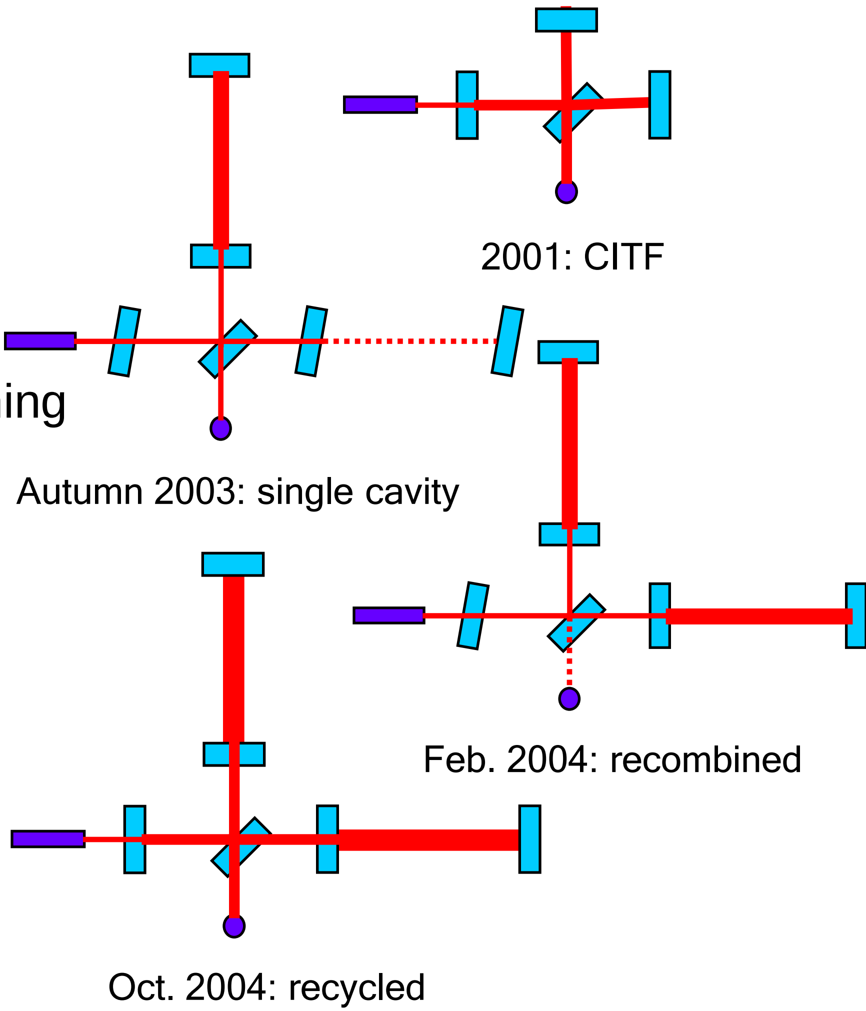
VIRGO ONTWERP GEVOELIGHEID



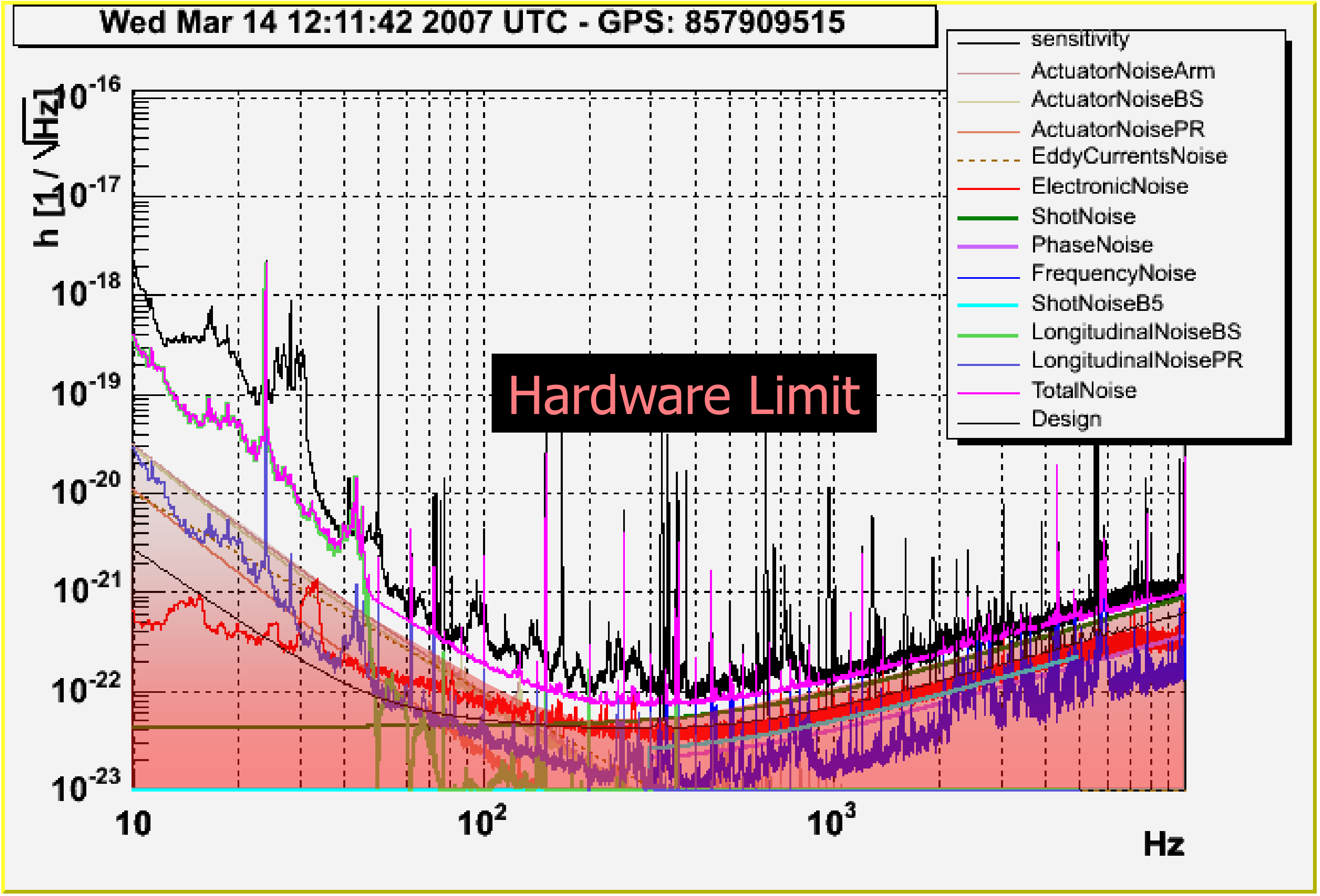
Virgo Status & Commissioning

A SHORT SUMMARY

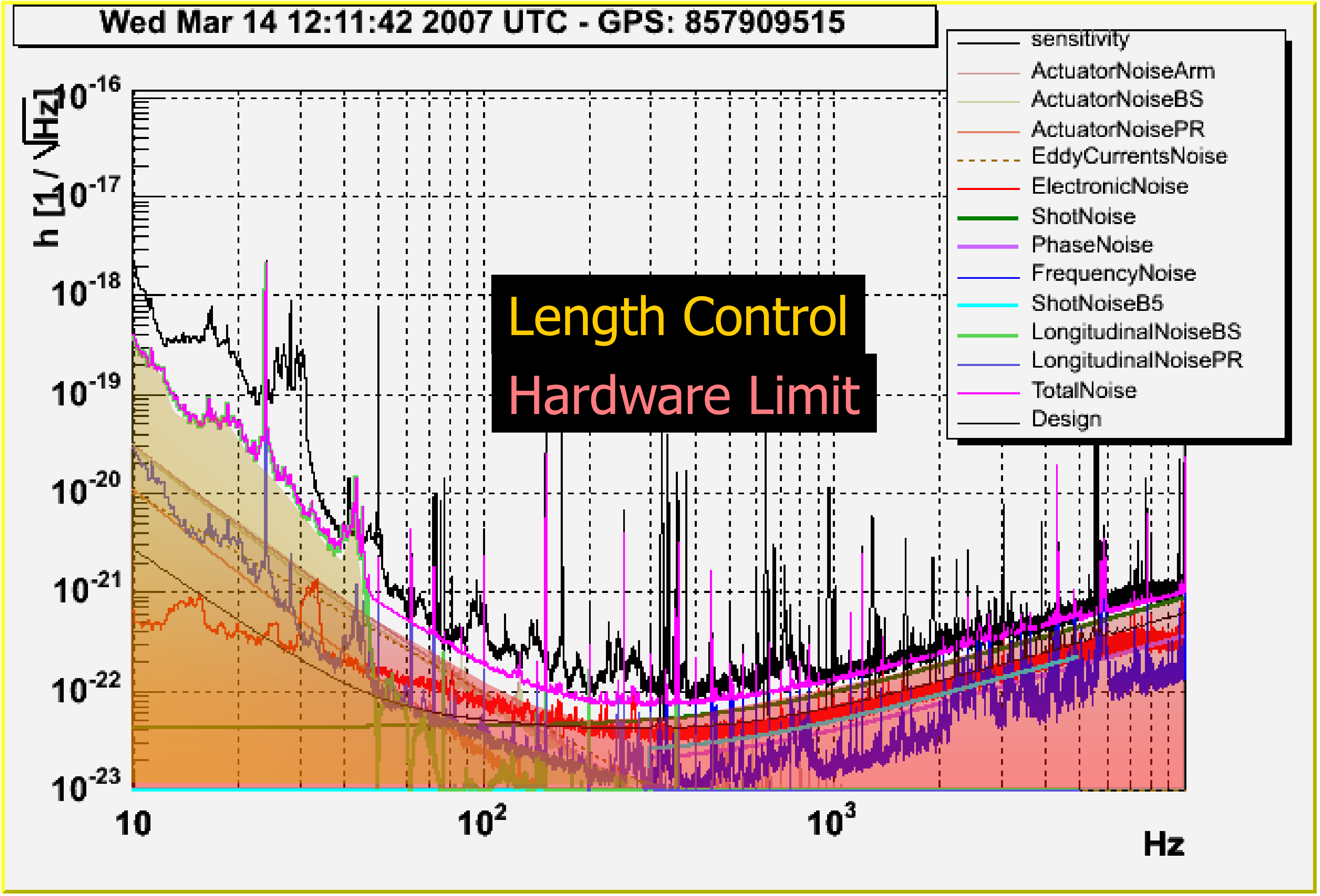
- 1993
  - Virgo approved by CNRS & INFN
- 1996
  - Start construction at the Site
- 2001-02
  - Central Interferometer commissioning
- July 2003:
  - Inauguration;
  - Start the full Virgo commissioning
- February 2004:
  - First Lock in recombined mode
- October 2004:
  - First lock in recycled mode
- September 2006
  - First lock at high power



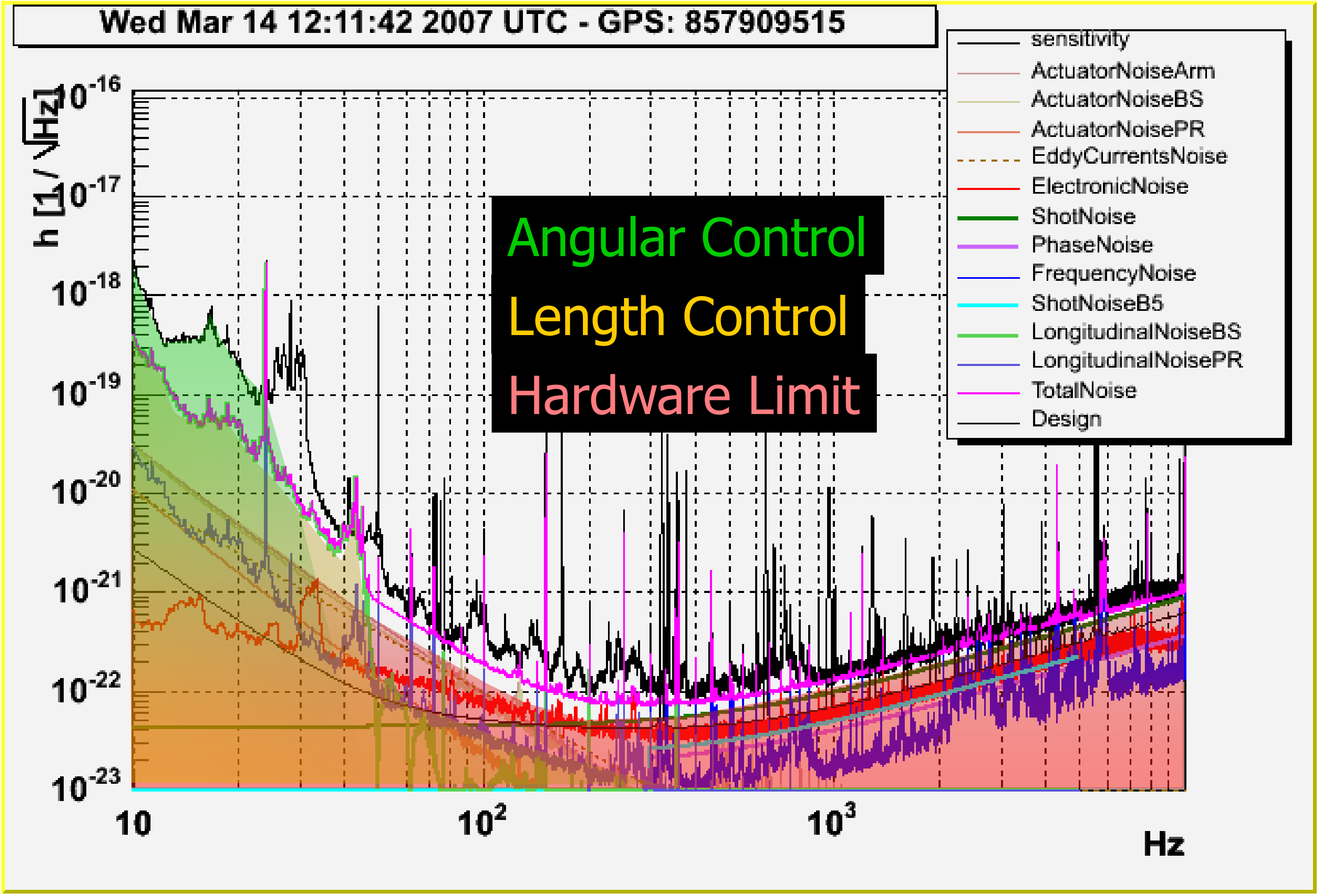
Sensitivity today



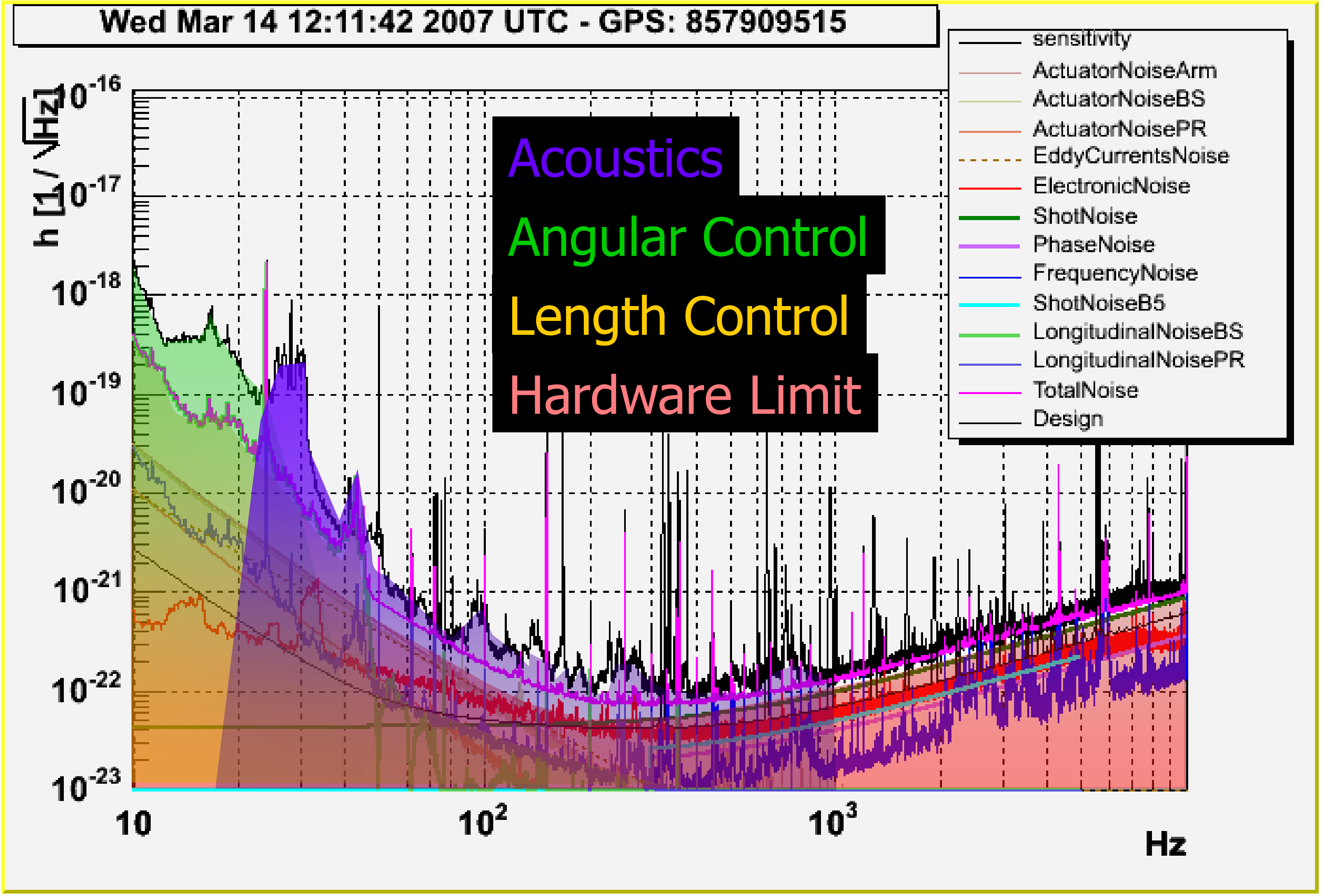
Sensitivity today



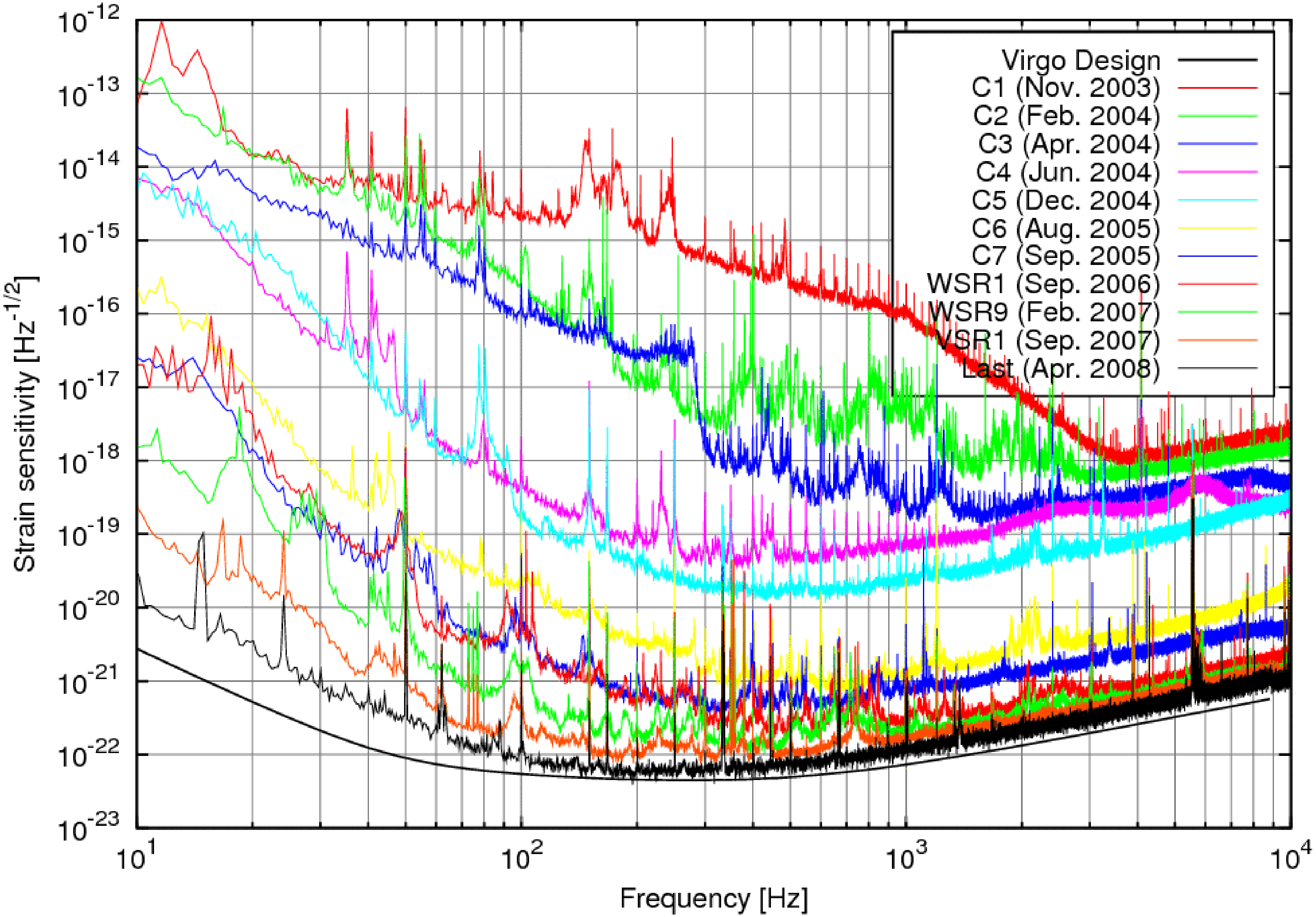
Sensitivity today



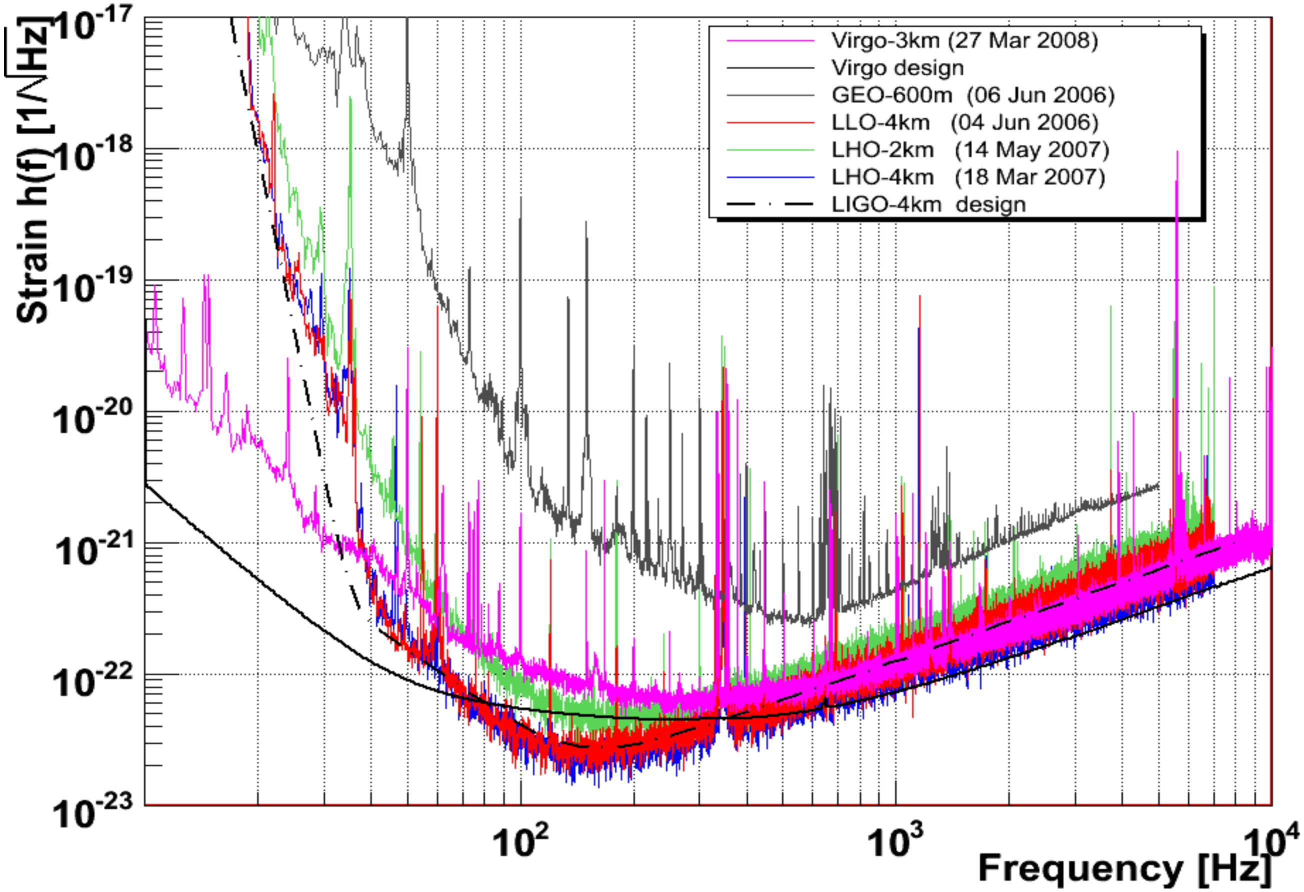
Sensitivity today



Evolutie van gevoeligheid

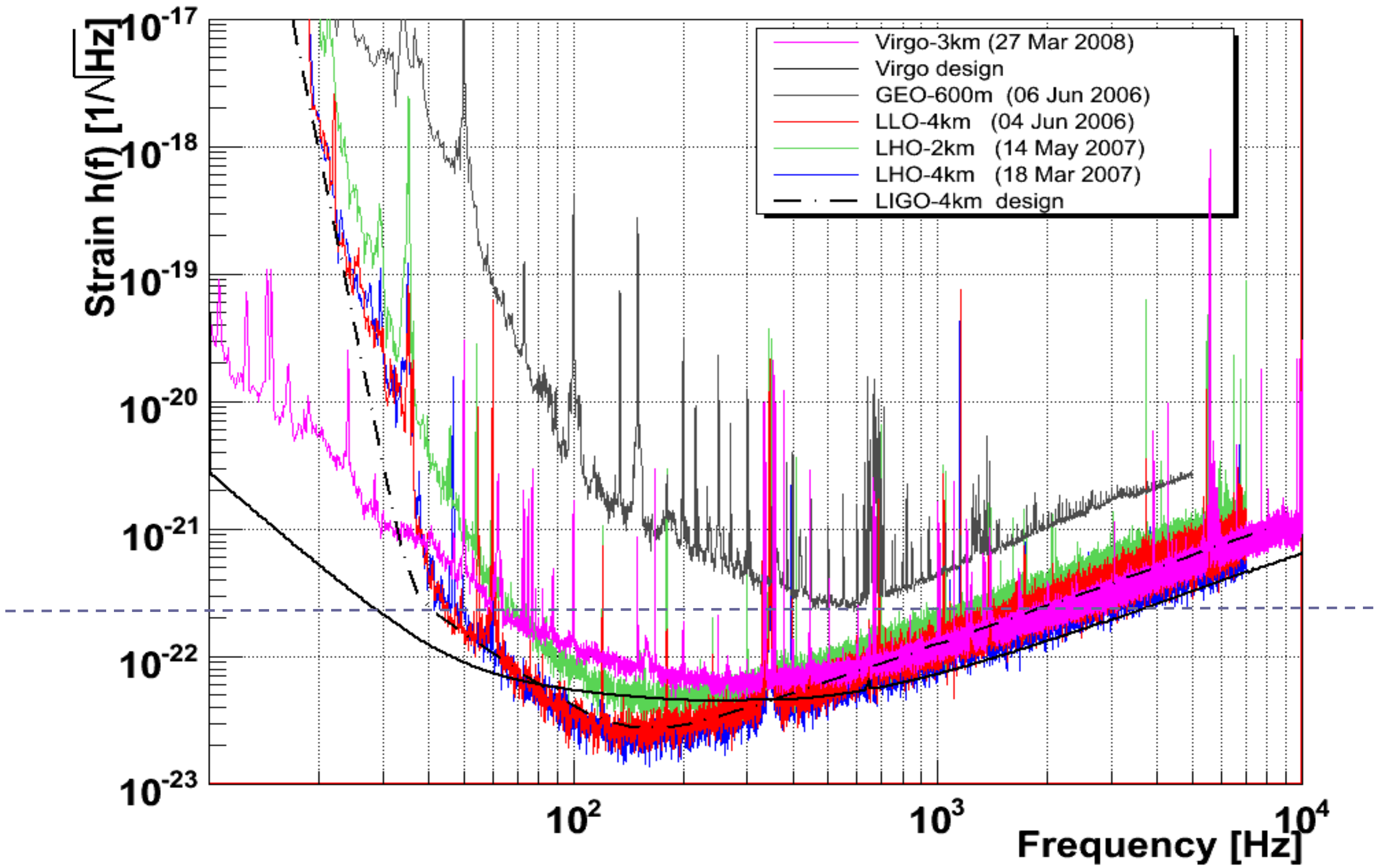


Interferometers – gevoeligheid



De horizon (optimale orientatie) voor een binair systeem van twee 10 zonnemassa's zwarte gaten is 63 Mpc

Interferometers – gevoeligheid



De horizon (optimale orientatie) voor een binair systeem van twee 10 zonnemassa's zwarte gaten is 63 Mpc

Vergelijk met wortel uit Planck tijd: $t_P \equiv l_P c \equiv \sqrt{\hbar G_N / c^5} = 5 \times 10^{-44}\,\mathrm{Hz}^{-1}$

Voor $h \le \sqrt{t_P} = 2.3 \times 10^{-22} \sqrt{\mathrm{Hz}}$ mogelijk om details op Planck schaal te zien

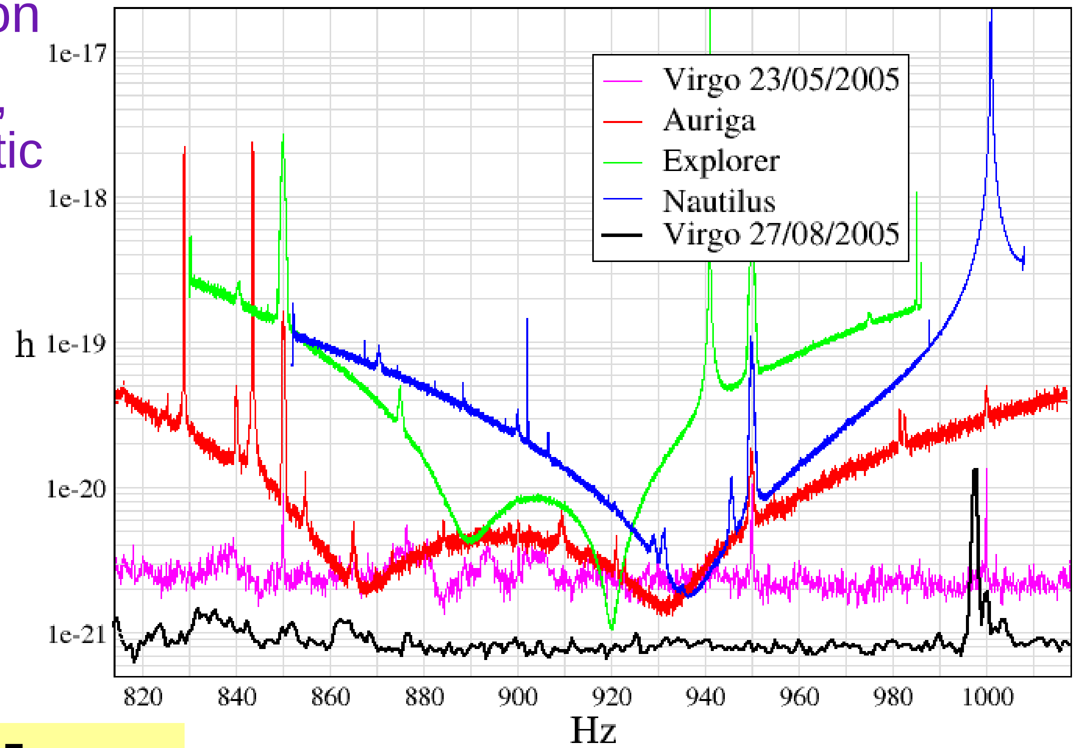
Virgo joint analyses

Virgo – Bars joint analysis

- Burst events and stochastic signals
- Bars, GEO600 and 2km Hanford in Astrowatch

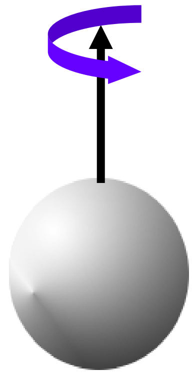
Virgo – LIGO collaboration

- Working group for burst, inspiral events, stochastic and periodic sources
- Formal MoU
- Publish together

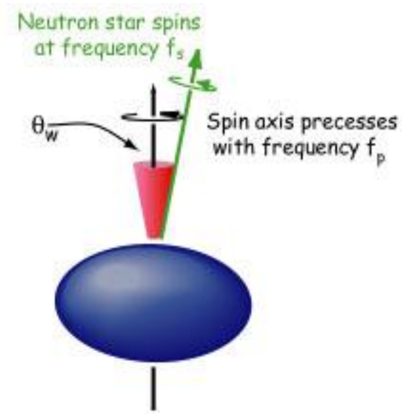


Virgo now at <1e-22 / rtHz

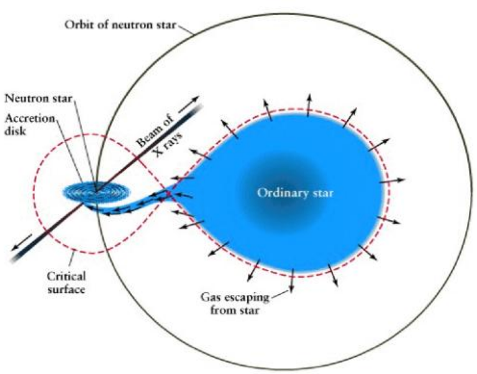
Straling van roterende neutronensterren



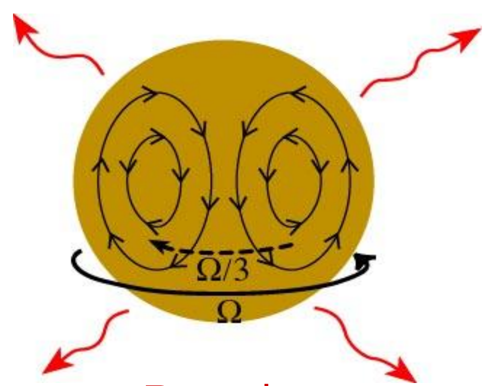
“Berg” op neutronenster



Tollende neutronenster

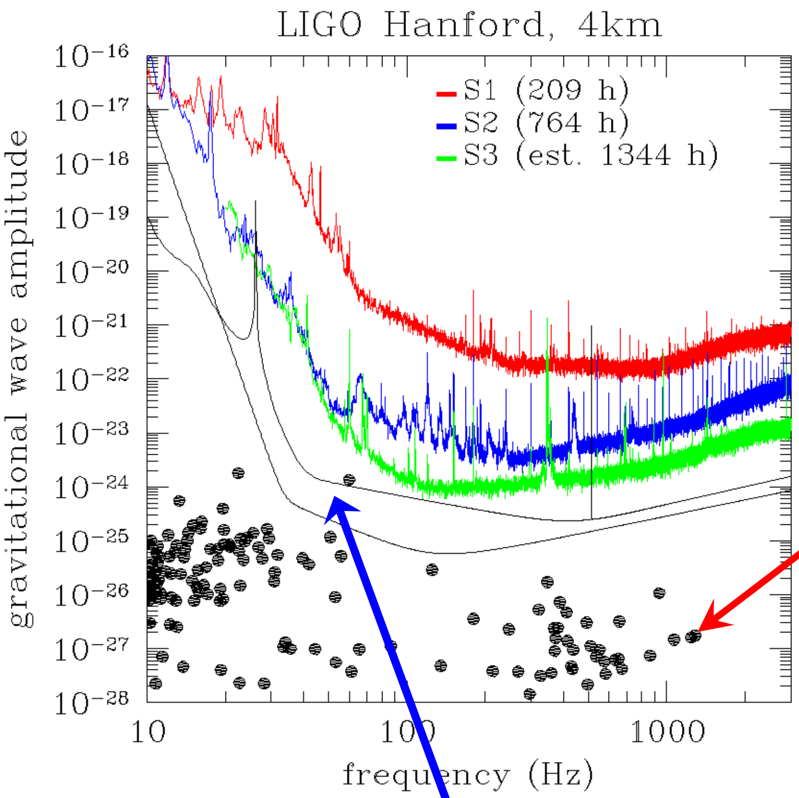


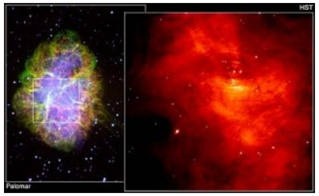
Accretie door neutronenster



R-modes

Pointing at known neutron stars



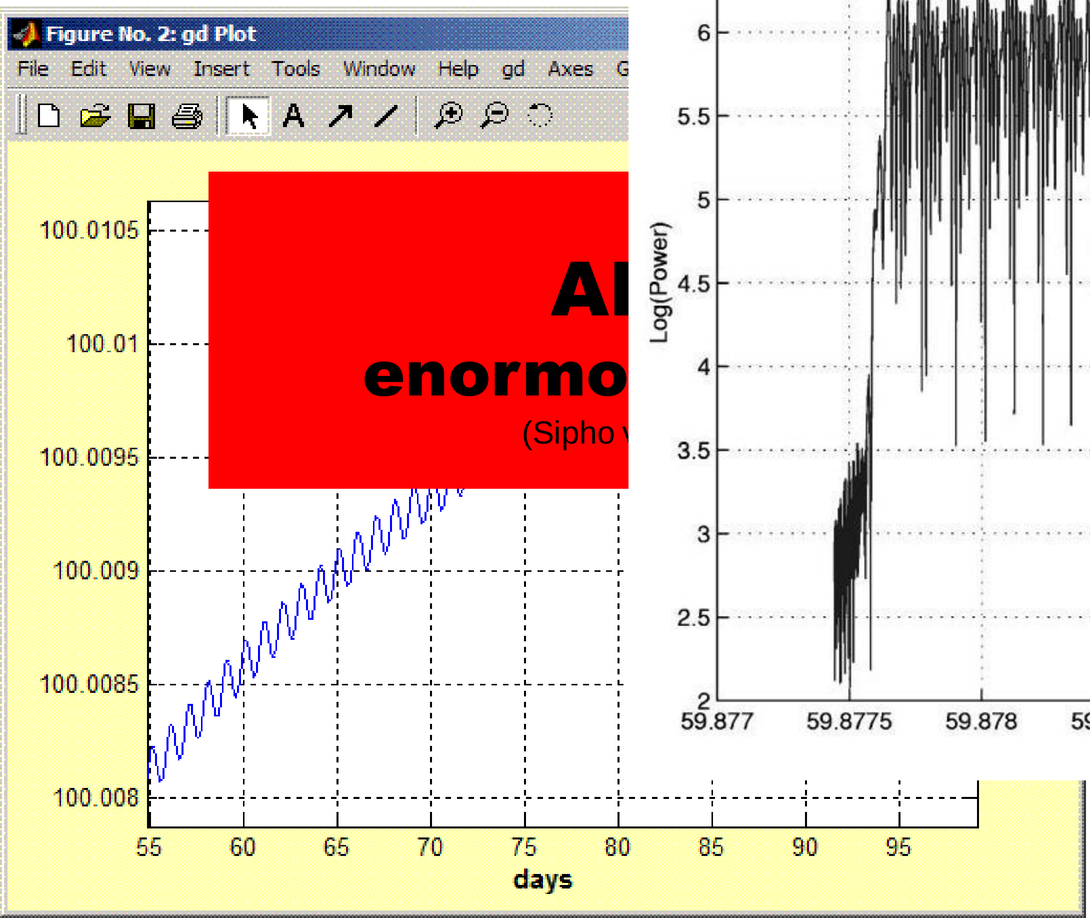


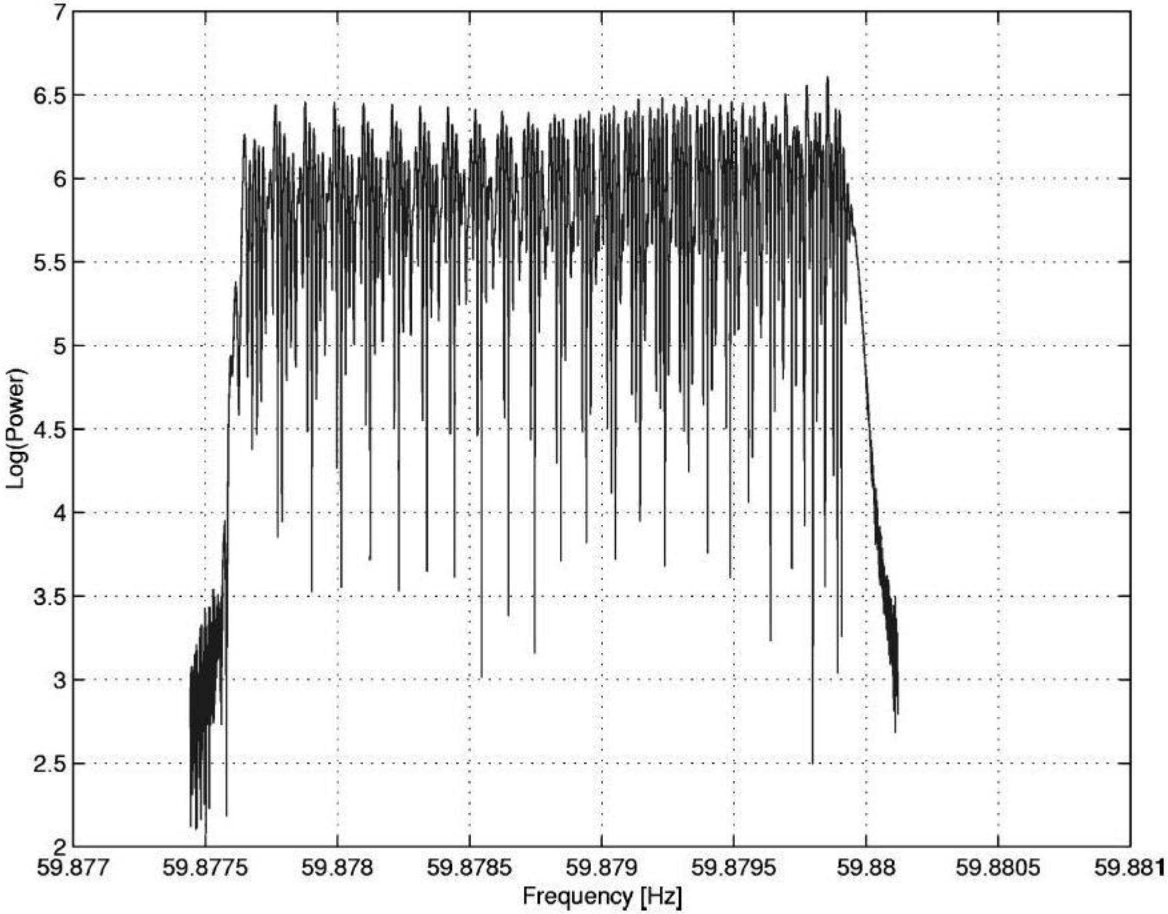
- Targeted search of GWs from known isolated radio pulsars
- S1analysis: upper-limit (95% confidence) on PSR J1939+2134:

  $h_0 < 1.4 \times 10^{-22}$ ($e < 2.9 \times 10^{-4}$) Phys Rev D 69, 082004 (2004)
- S2 analysis: 28 pulsars (all the ones above 50 Hz for which search parameters are "exactly" known)

Periodic sources – all sky search – Roma / Nikhef

- Doppler shifts
  - Frequency modulation: due to Earth's motion
  - Amplitude m

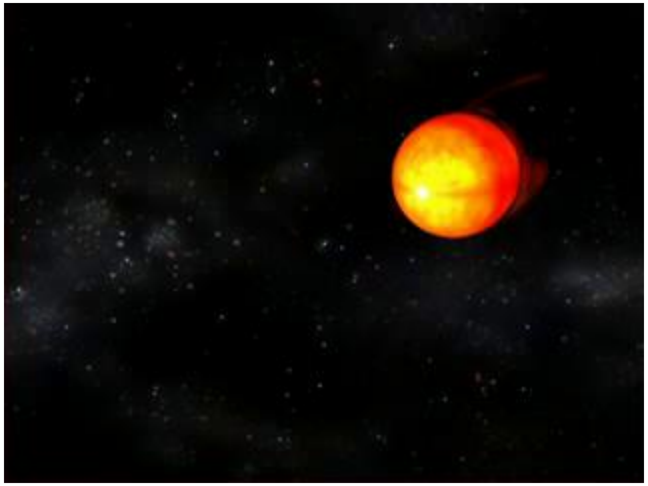


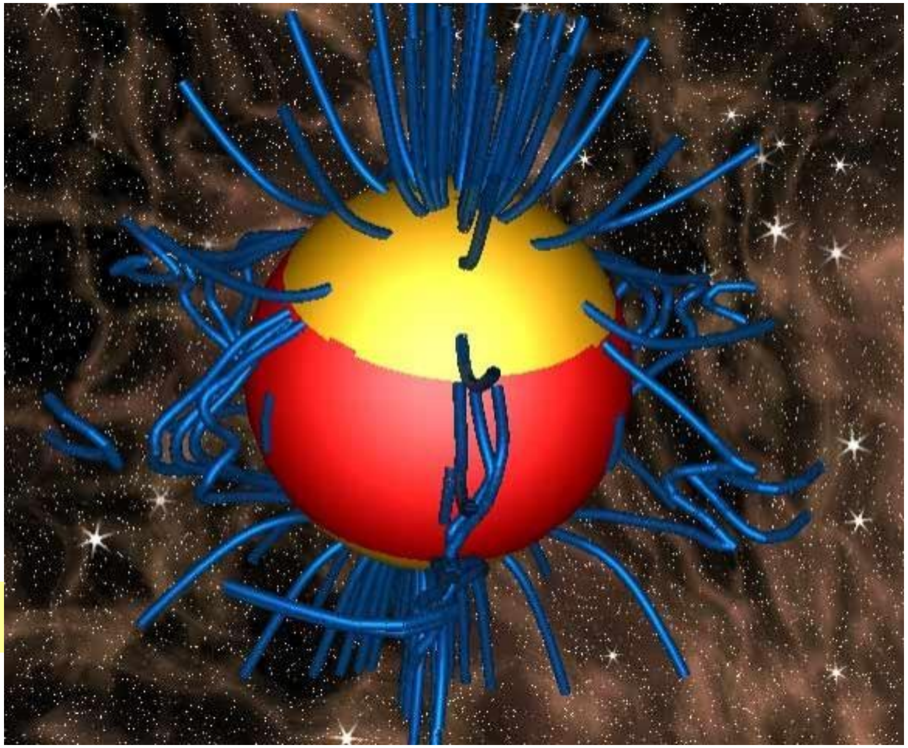


- Hough maps
- Include binary systems

Binaire pulsars

$$h = 3 \cdot 10^{-27} \left(\frac{10\,kpc}{r} \right) \left(\frac{I_{zz}}{10^{45} g\, cm^2} \right) \left(\frac{f}{200 Hz} \right)^2 \left(\frac{\varepsilon}{10^{-6}} \right)$$

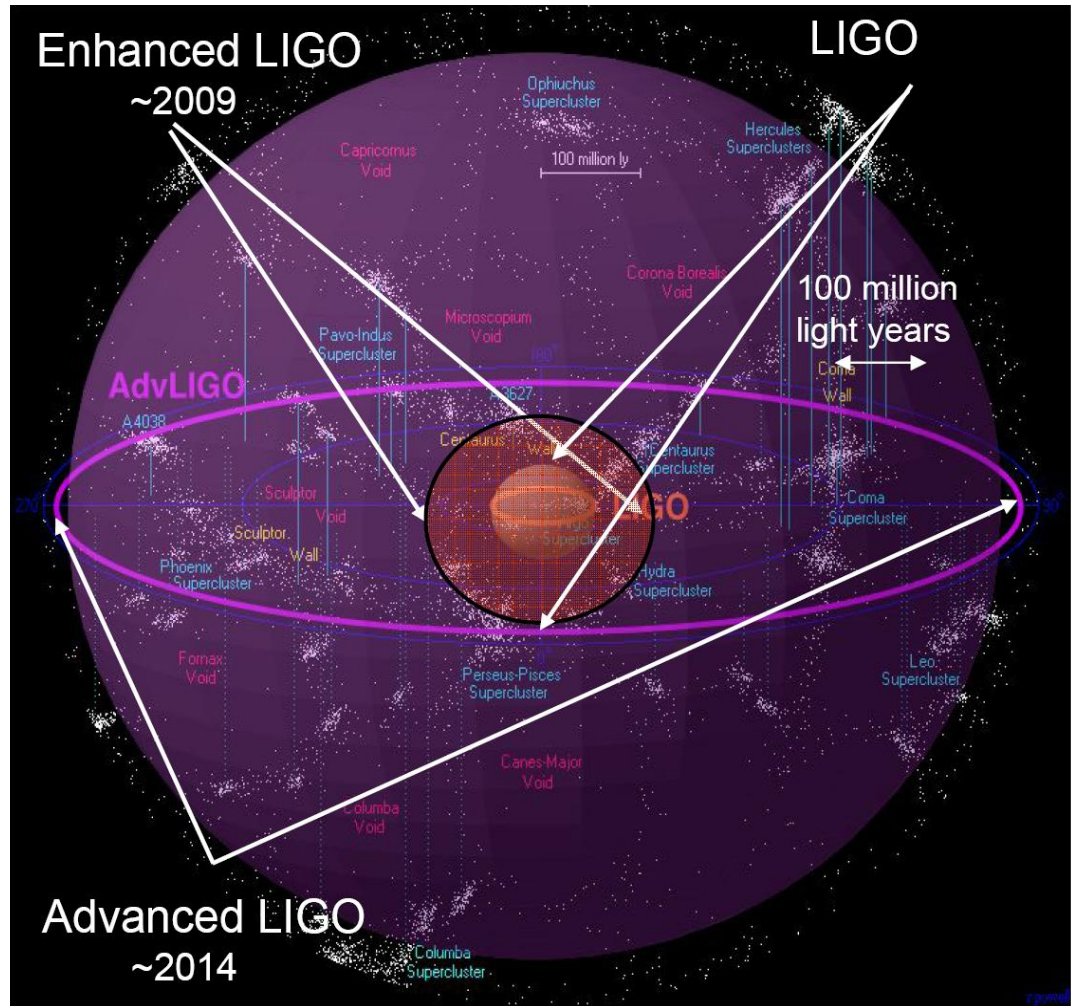




Include binary system in analysis

LIGO en VIRGO: evolutie

- Op dit moment honderden sterrenstelsels binnen bereik
- Virgo+ programma
  - In 2009 ongeveer 10 keer meer stelsels binnen bereik
- Advanced detectoren
  - Ongeveer 1000 keer meer sterrenstelsels binnen bereik
  - In 2014 verwachten we 1 signaal per dag of week
  - Begin van gravitatie astrofysica



Evolution of ground-based GW detectors

Unlikely detection

- 1^{st} generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Science data taking
Set up network observation

We are here

Plausible detection

  - Enhanced LIGO, Virgo+

Lay ground for multi-messenger astronomy

- 2^{nd} generation detectors

Likely detection

  - Advanced LIGO, Advanced Virgo, GEO-HF

Routine observation
Towards GW astronomy

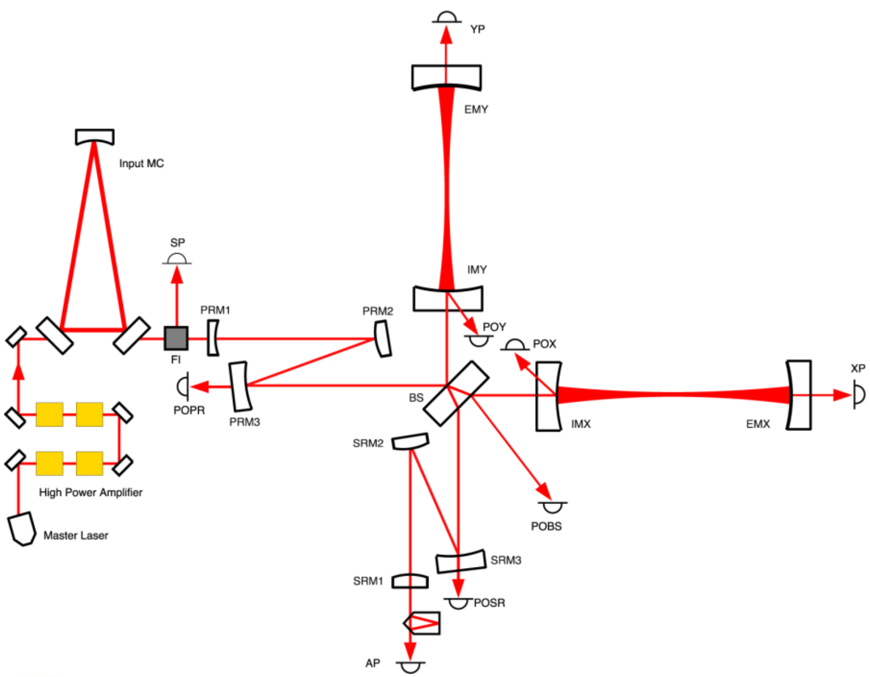
Thorough observation
of Universe with GW

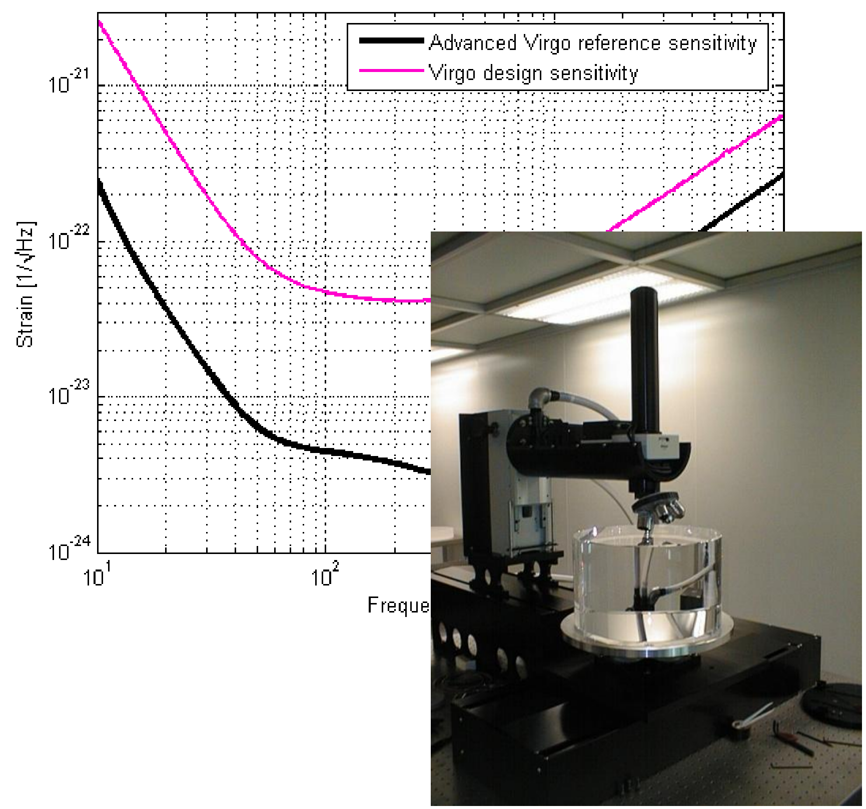
- 3^{rd} generation detectors
  - Einstein Telescope, US counterpart to ET

Advanced Virgo (AdV)

PROJECT doelen

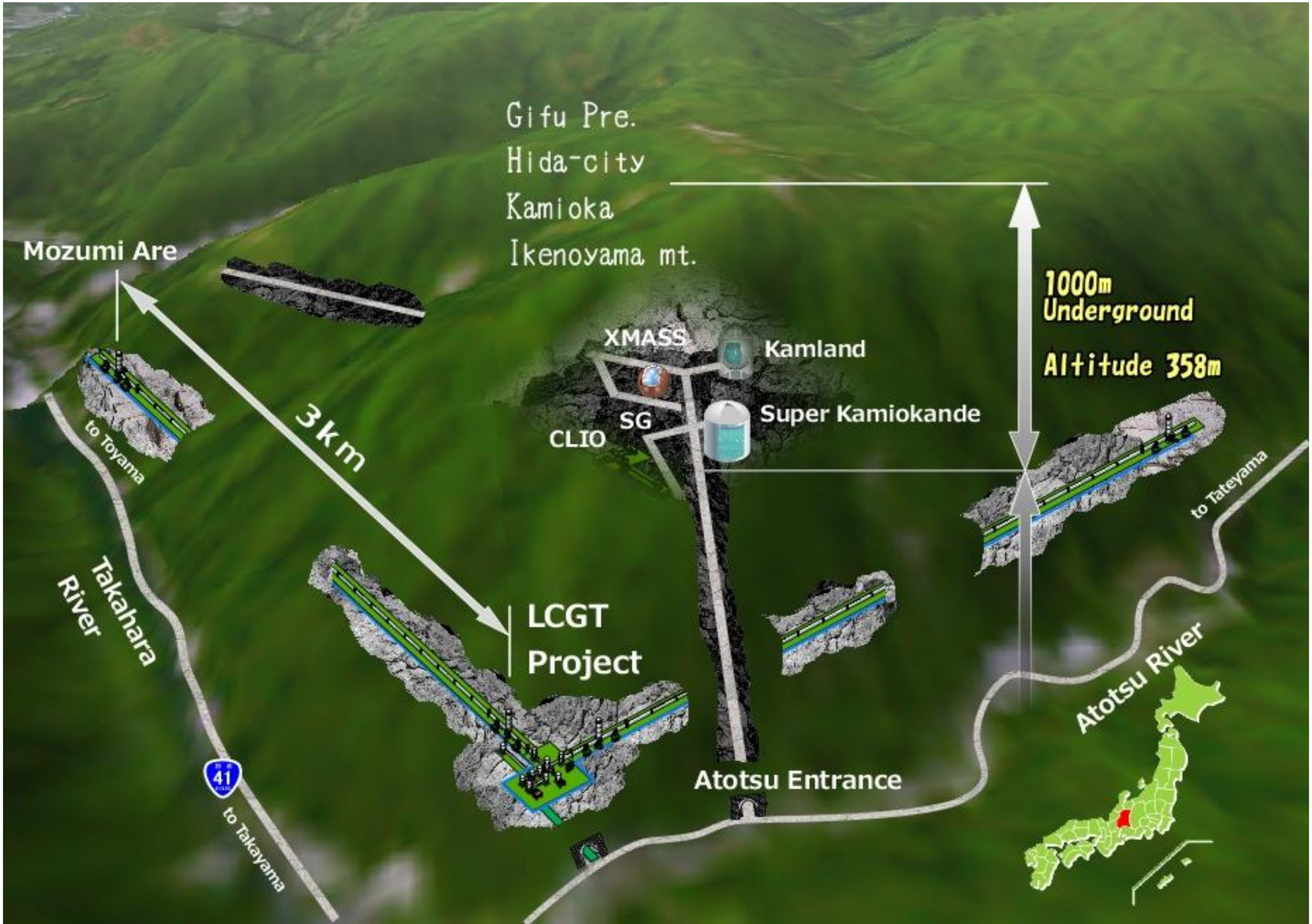
- Verbeter Virgo tot een 2nd generatie detector. Gevoeligheid: 10x beter danVirgo
- Maak deel uit van 2nd generatie GW detectoren netwerk. Tijdlijn: verzamel data samen met Advanced LIGO





Andere GW projecten

Ondergrondse detector in Kamioka



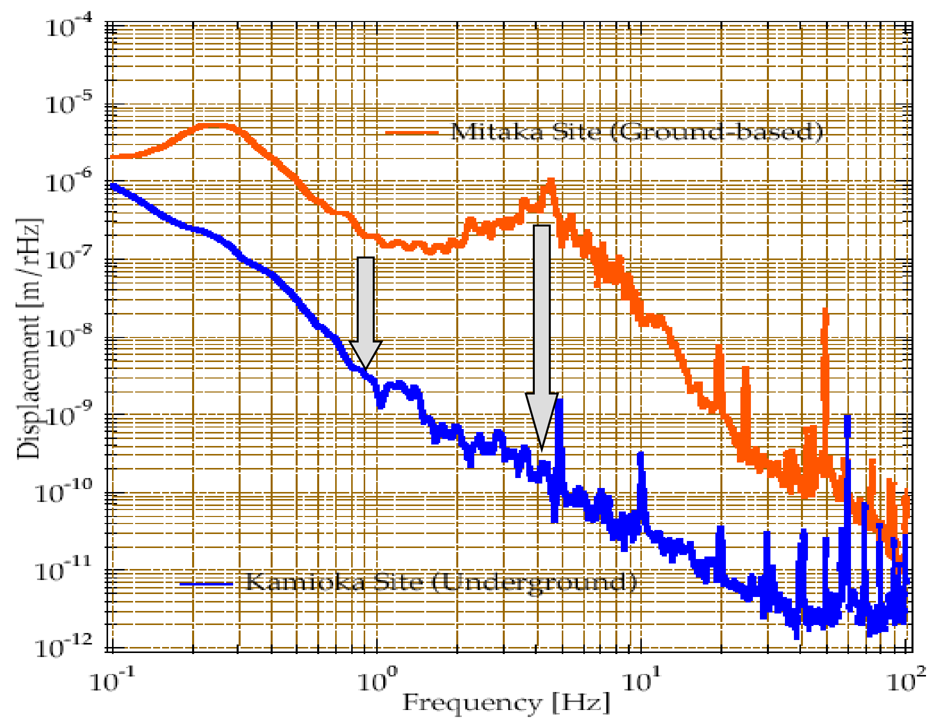
Ervaring: ondergrondse interferometers

- LISM: 20 m Fabry-Perot interferometer, R&D for LCGT, moved from Mitaka (ground based) to Kamioka (underground)
- Seismische ruis veel lager

10^2 verbetering
10^3 bij 4 Hz

- Bedrijf eenvoudiger

	TAMA300	LISM (Sato)
Maximum Continuous Locking	24 hours (summer 2001)	170 hours (Spring 2001)
Duty Cycle	86% (for the 2001 summer run)	99.8% (for the last week of 2001 summer run)



Design Study Proposal approved by EU within FP7

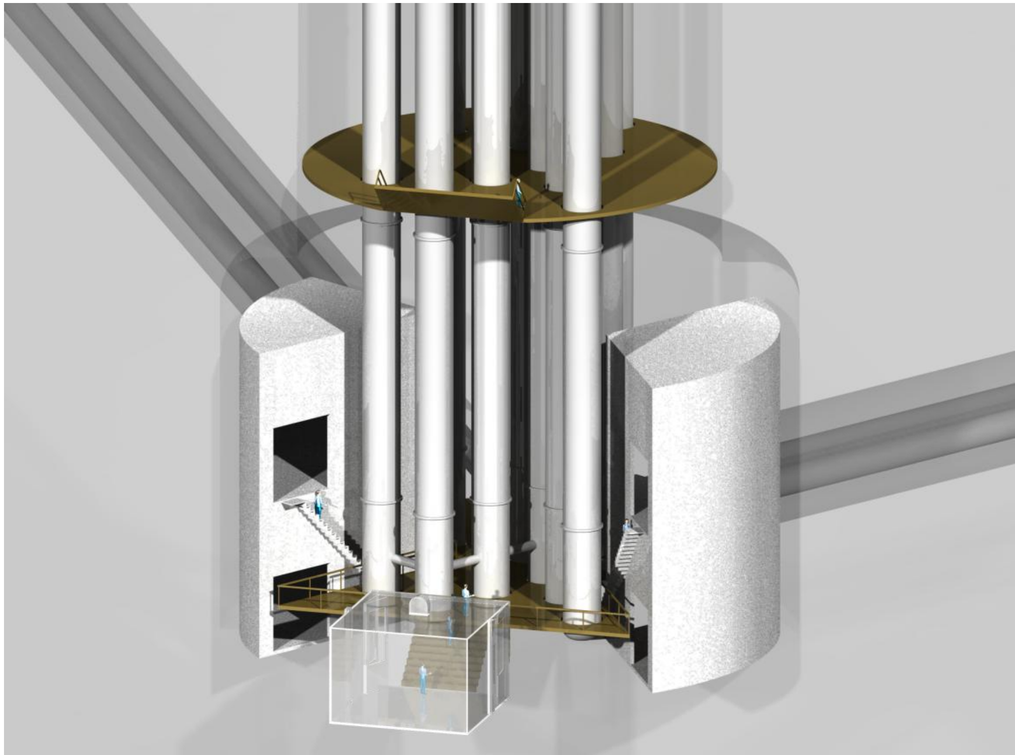
Large part of the European GW community involved

EGO, INFN, MPI, CNRS, Nikhef, Univ. Birmingham, Cardiff, Glasgow

Recommended in Aspera / Appec roadmap

ET WP1 – Infrastructure

- Infrastructure: big cost items
  - Tunnels, caverns, buildings
  - Vacuum, cryogenics, safety systems
  - Collaborate with industry
    - COB (Amsterdam, October 9, 2008)
    - Saes Getters Italy
    - Demaco Netherlands
- Input from WG2 & 3
  - Topology (Albrecht Ruediger)
  - Length of superattenuators
- Experience
  - Virgo, GEO, Gran Sasso, Kamioka, LIGO, etc.



Gravity gradient noise

- Gravity gradient noise
  - Time varying contributions to Newtonian background driven by seismic compression waves, ground-water variations, slow-gravity drifts, weather, cultural noise
  - Determines low-frequency cut-off
  - Cannot be shielded against
- Counter measures
  - Network of seismometers and development of data correction algorithms
    - Analytical studies: G. Cella
    - Numerical studies: E. Hennes

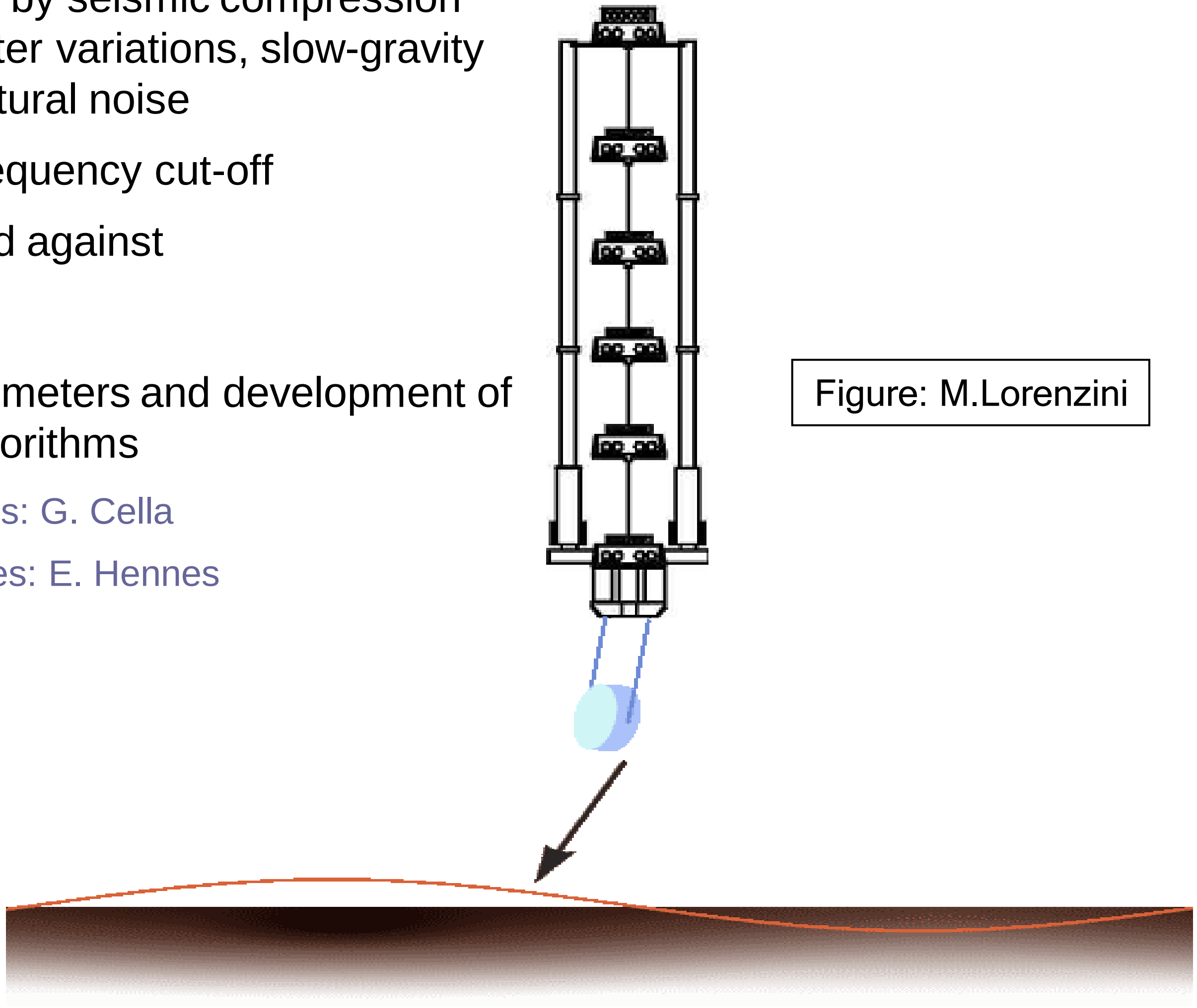
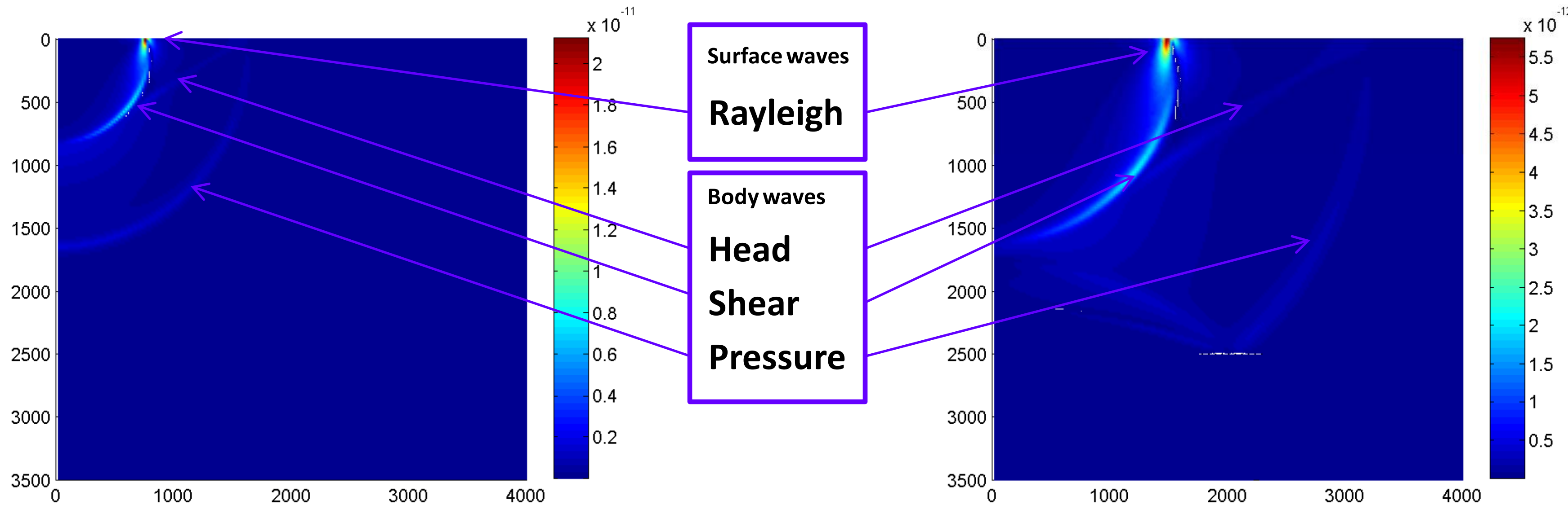
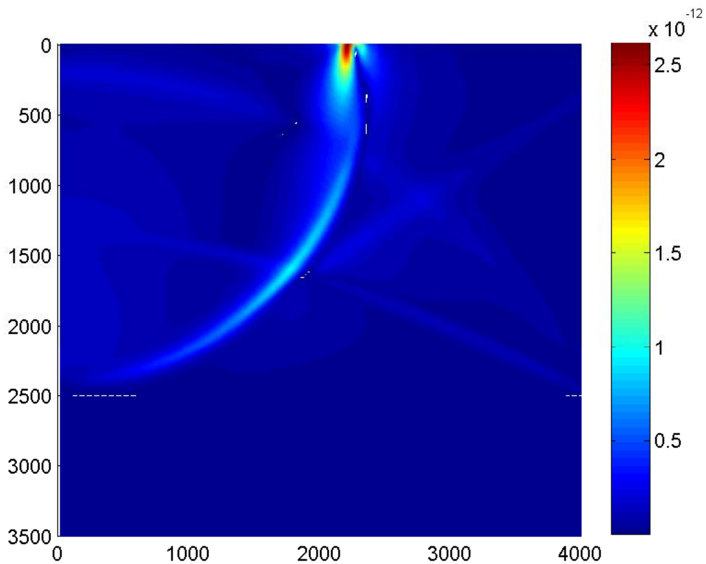


Figure: M.Lorenzini

Surface (Rayleigh) and body (P/S/Head) waves as a result of vertical point source load

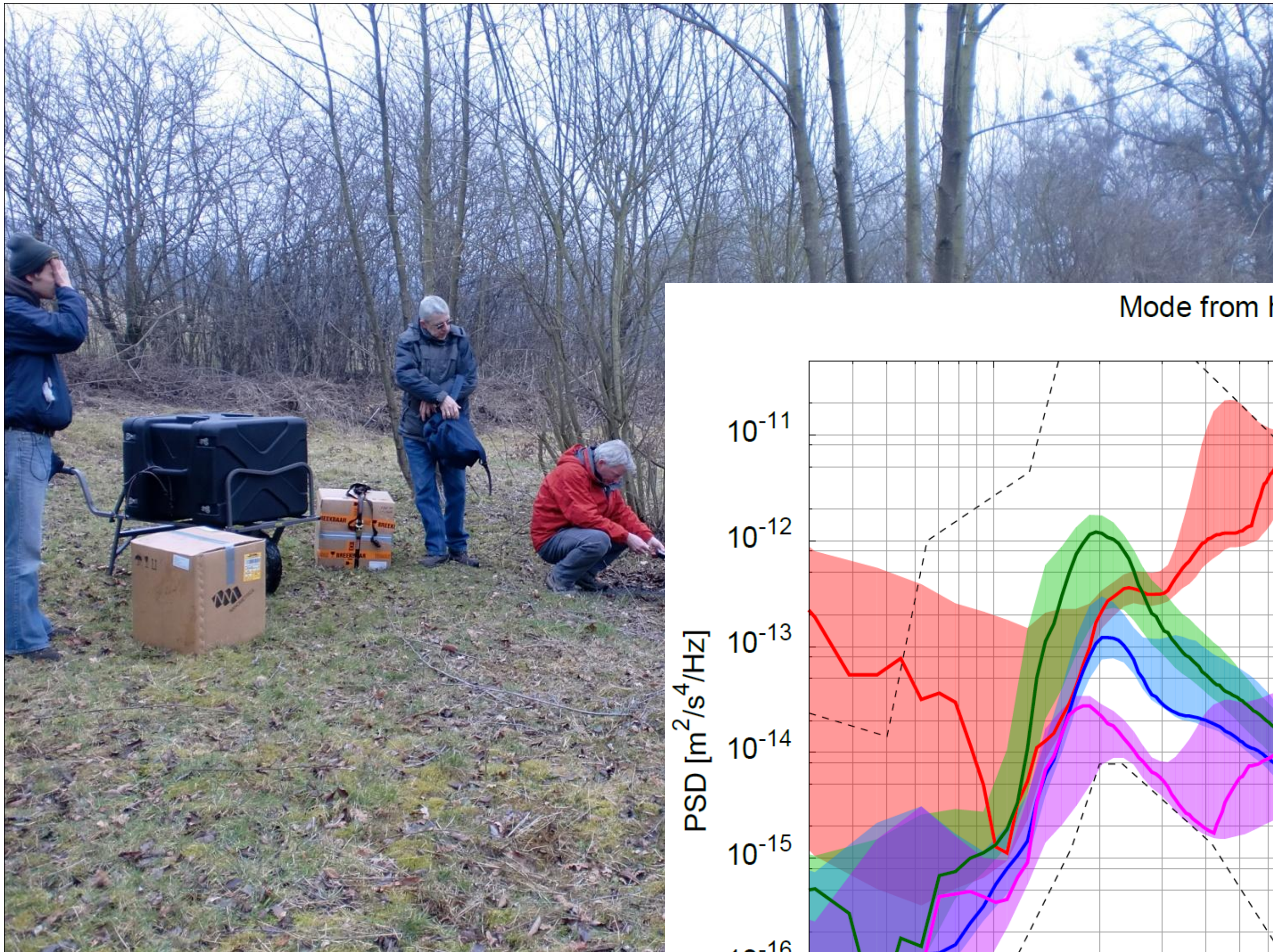


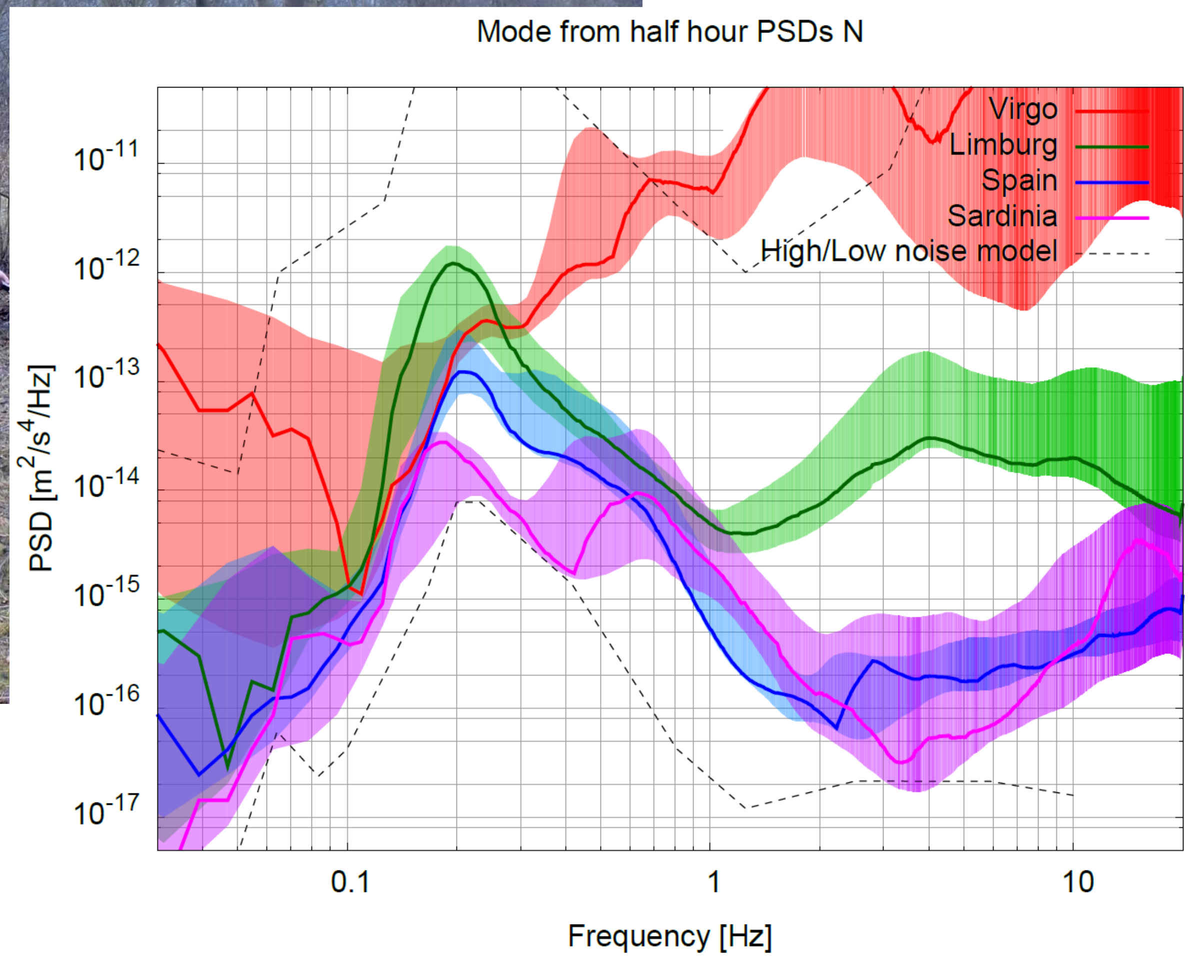


- Wave attenuation has two components
  - Geometrical (expansion of wave fronts) ~ r^n
    - Raleigh, n=-1/2
    - Body waves on surface, n=-2
    - Body waves at depth, n=-1
  - Material (damping)
  - Geometrical damping could be why S-wave has maximum at 45 degrees, still trying to find reference to confirm this.

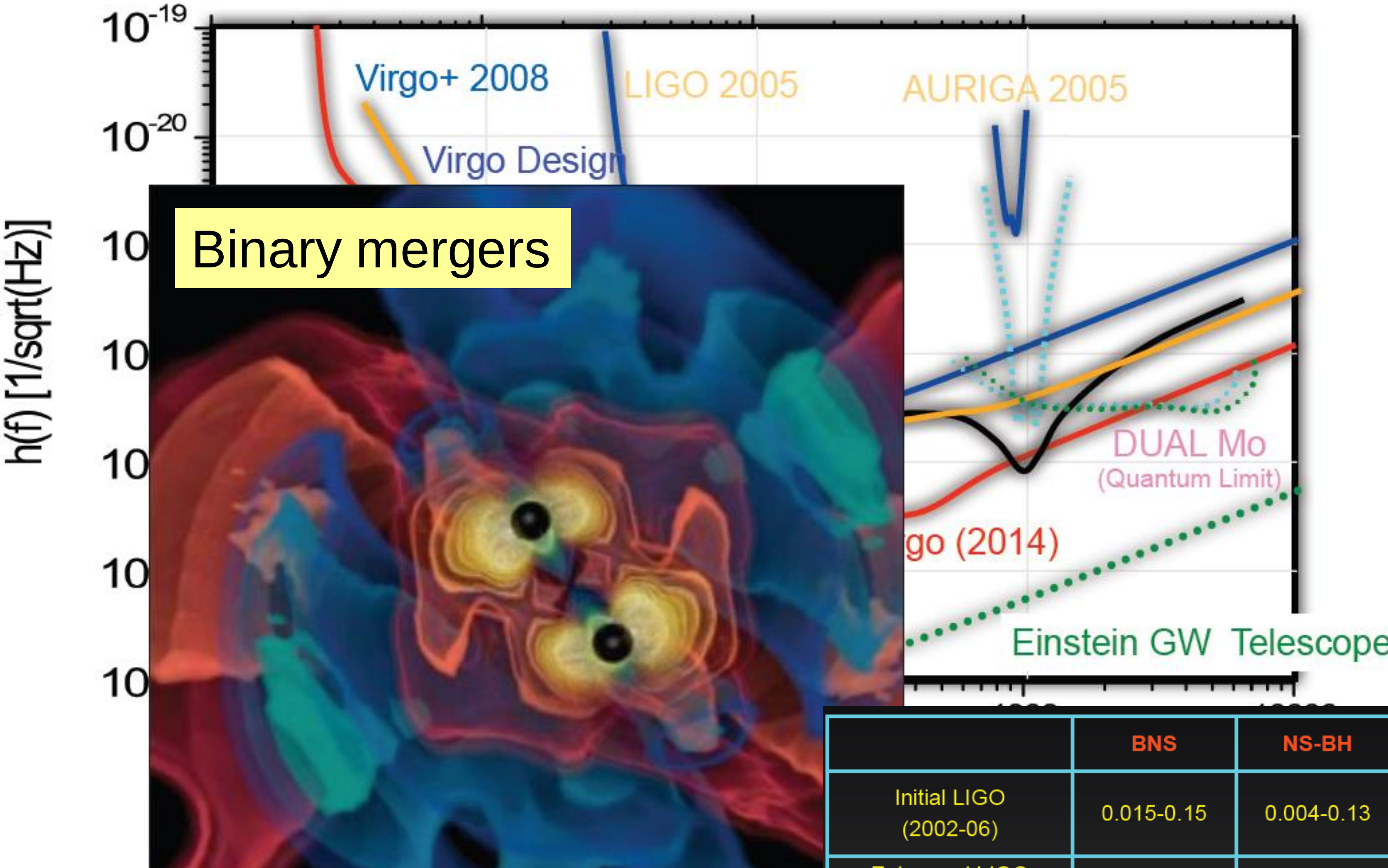
Seismisch onderzoek

Seismisch onderzoek (met KNMI)





Expected sensitivities – rates

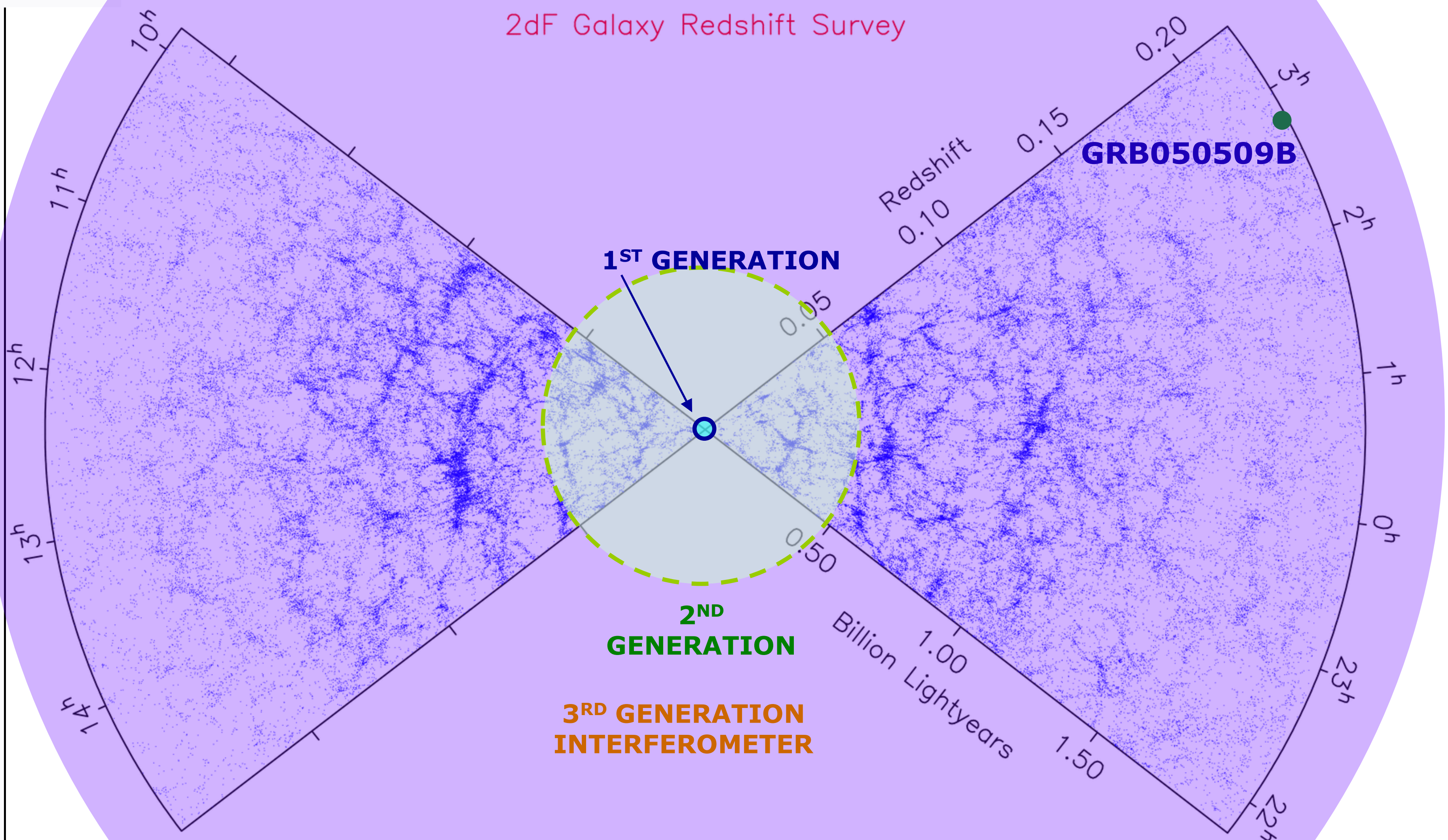


Binary mergers

	BNS	NS-BH	BBH
Initial LIGO (2002-06)	0.015-0.15	0.004-0.13	0.01-1.7
Enhanced LIGO x2 sensitivity (2009-10)	0.15-1.5	0.04-1.4	0.11-18
Advanced LIGO 2 sensitivity (2014+)	20-200	5.7-190	16-2700

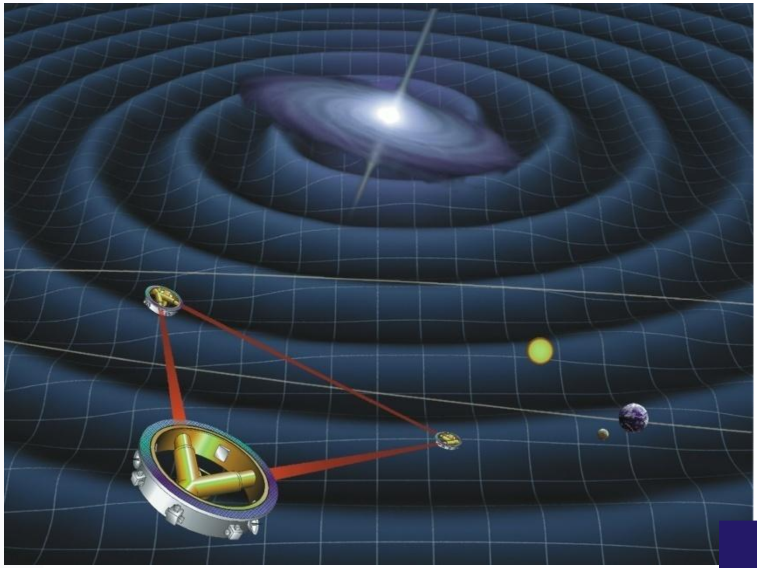
Einstein Telescope: ~1000 per day
GW observatory

NS - NS INSPIRAL RANGE

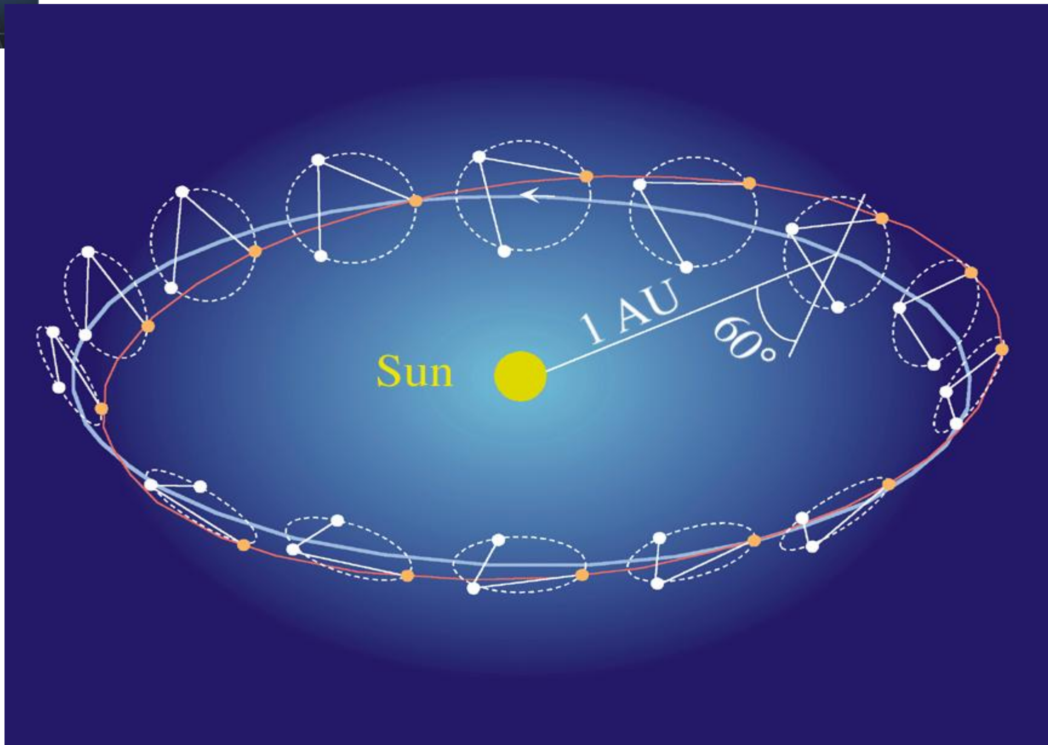


Credit G.Cagnoli

Gravitational wave antenna in space - LISA

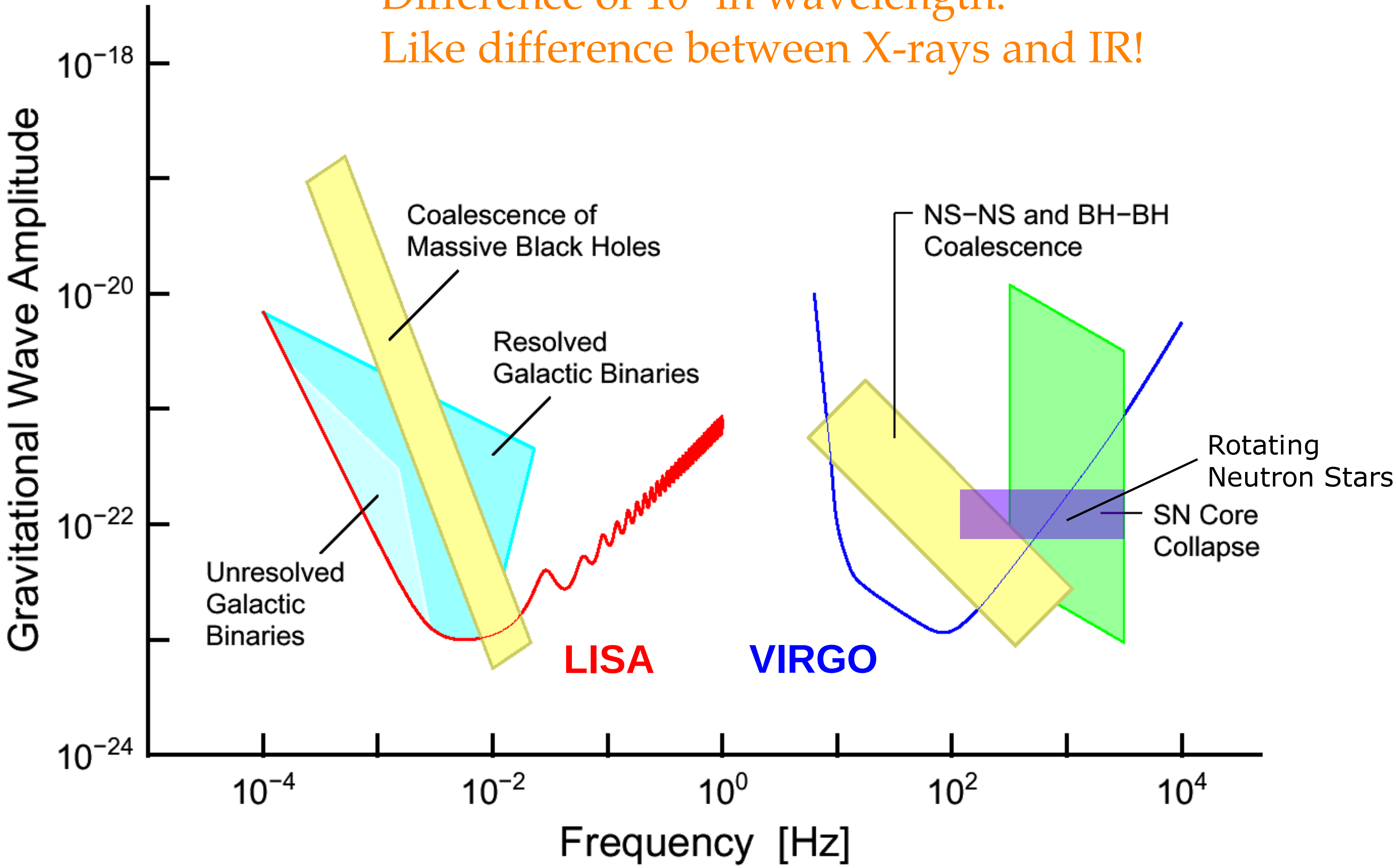


- 3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.
- Measure changes in distance between fiducial masses in each spacecraft
- Partnership between ~~NASA~~ and ESA
- Launch date > 2020

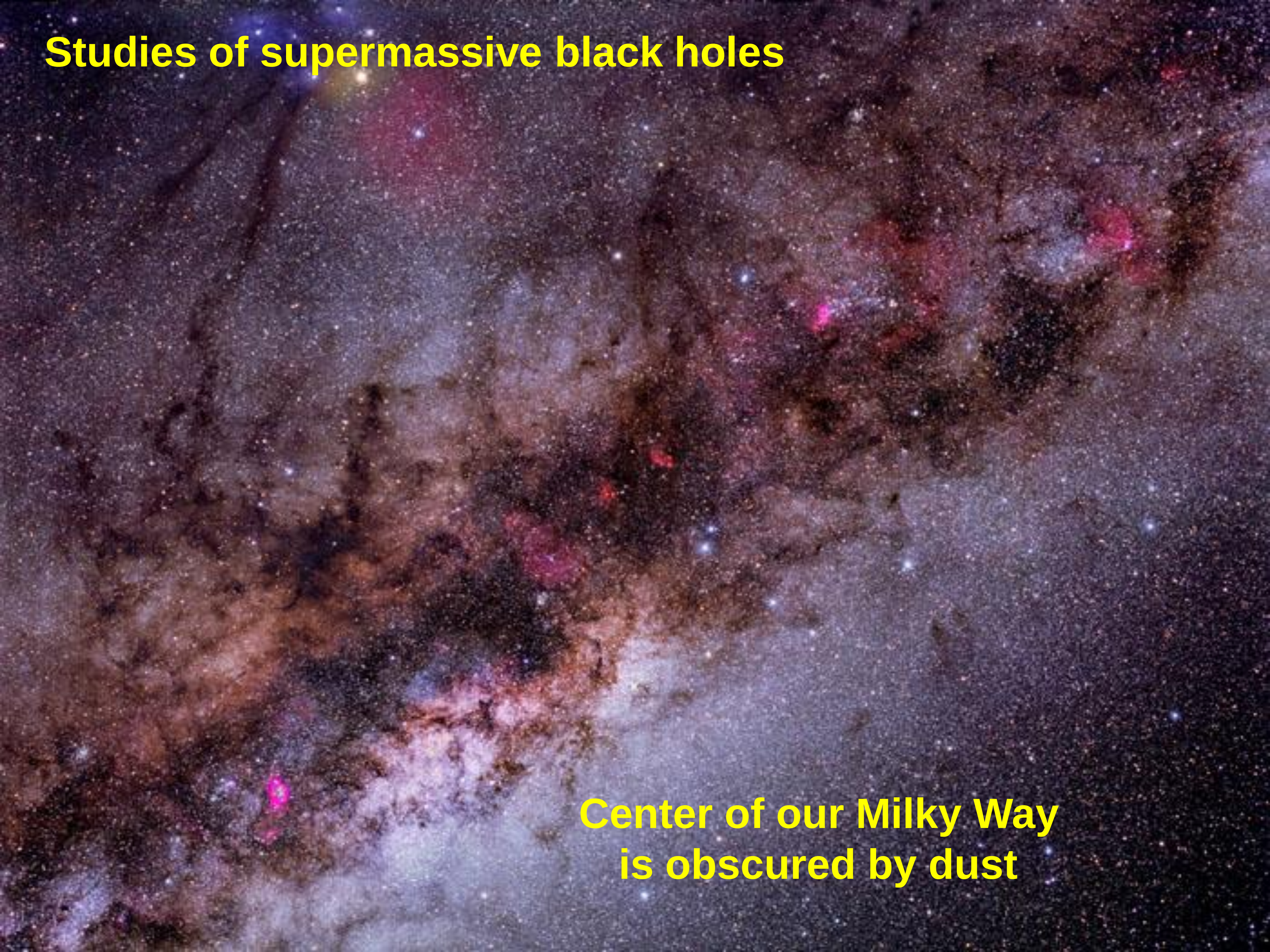


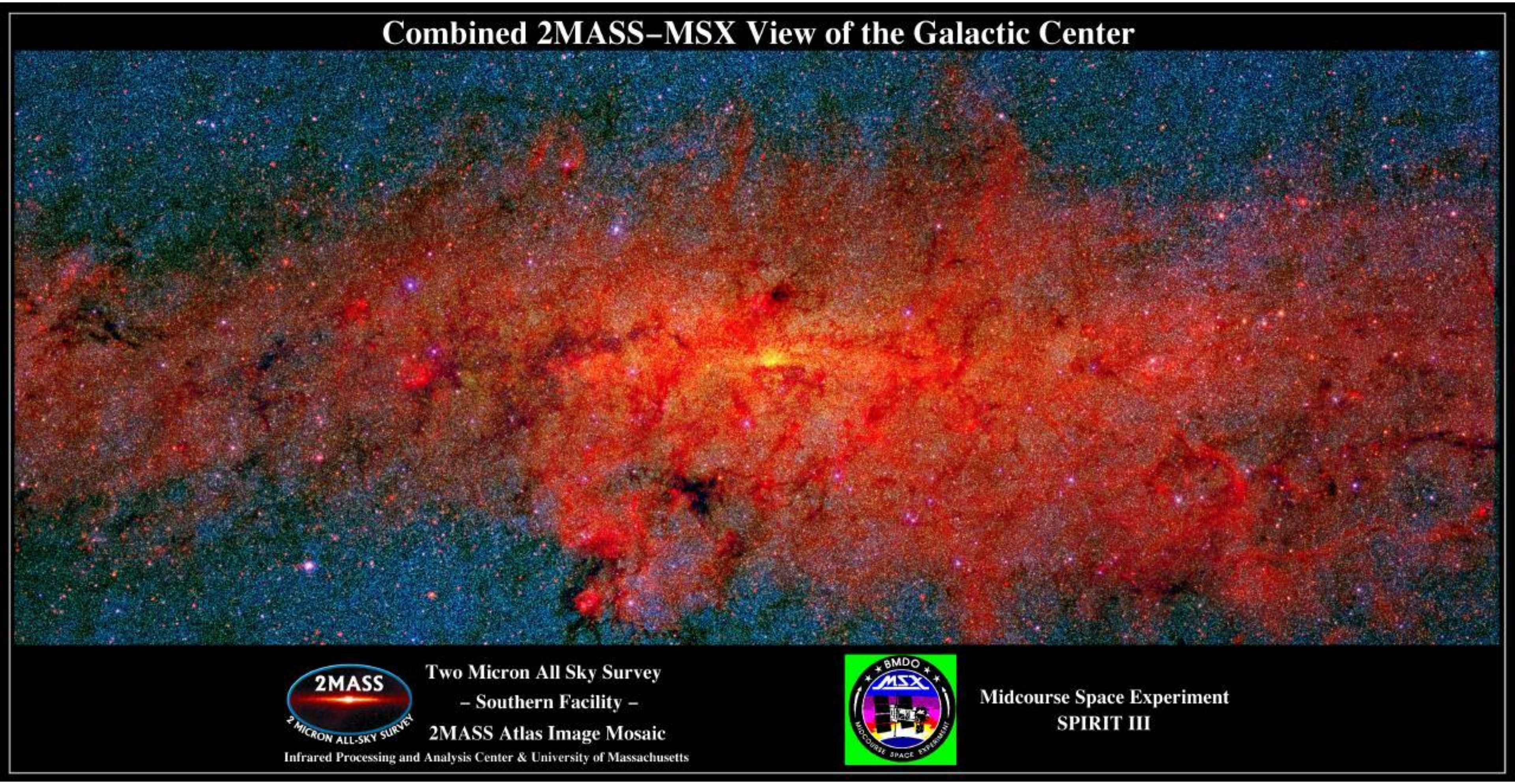
Complementarity of Space- & Ground-Based Detectors

Difference of 10^4 in wavelength:
Like difference between X-rays and IR!

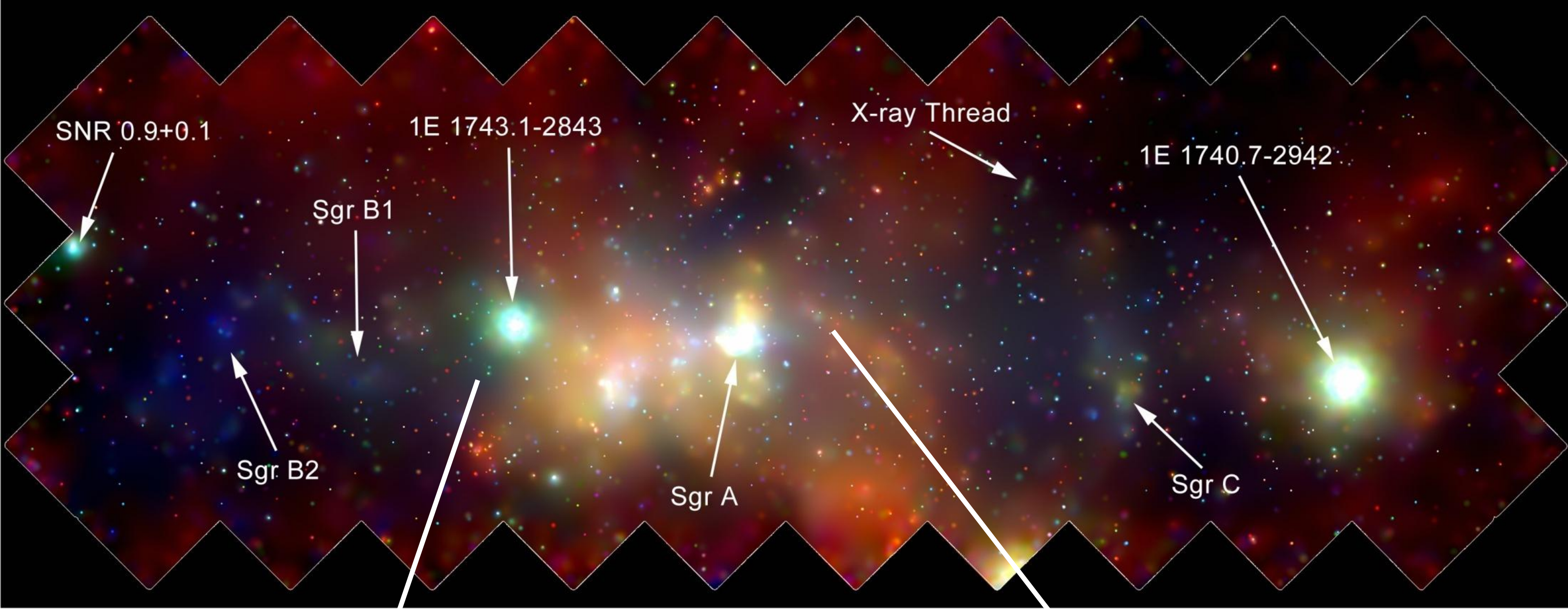


LISA will see all the compact white-dwarf and neutron-star binaries in the Galaxy (Schutz)

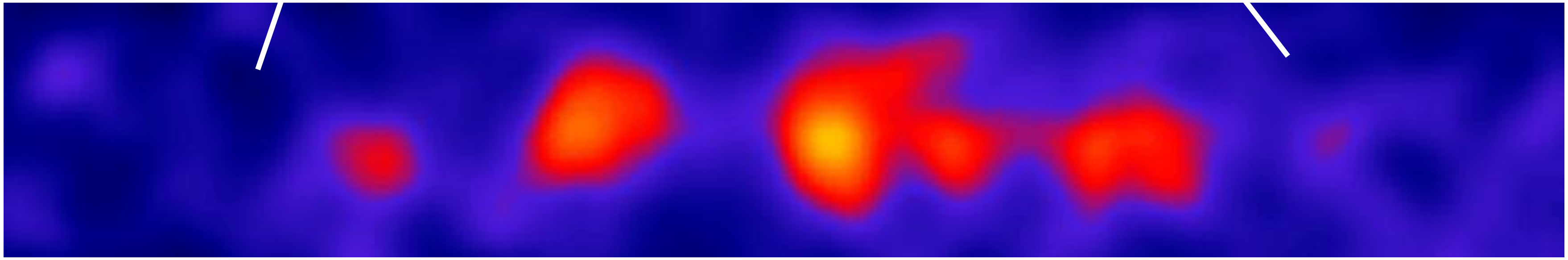

Studies of supermassive black holes
Center of our Milky Way
is obscured by dust



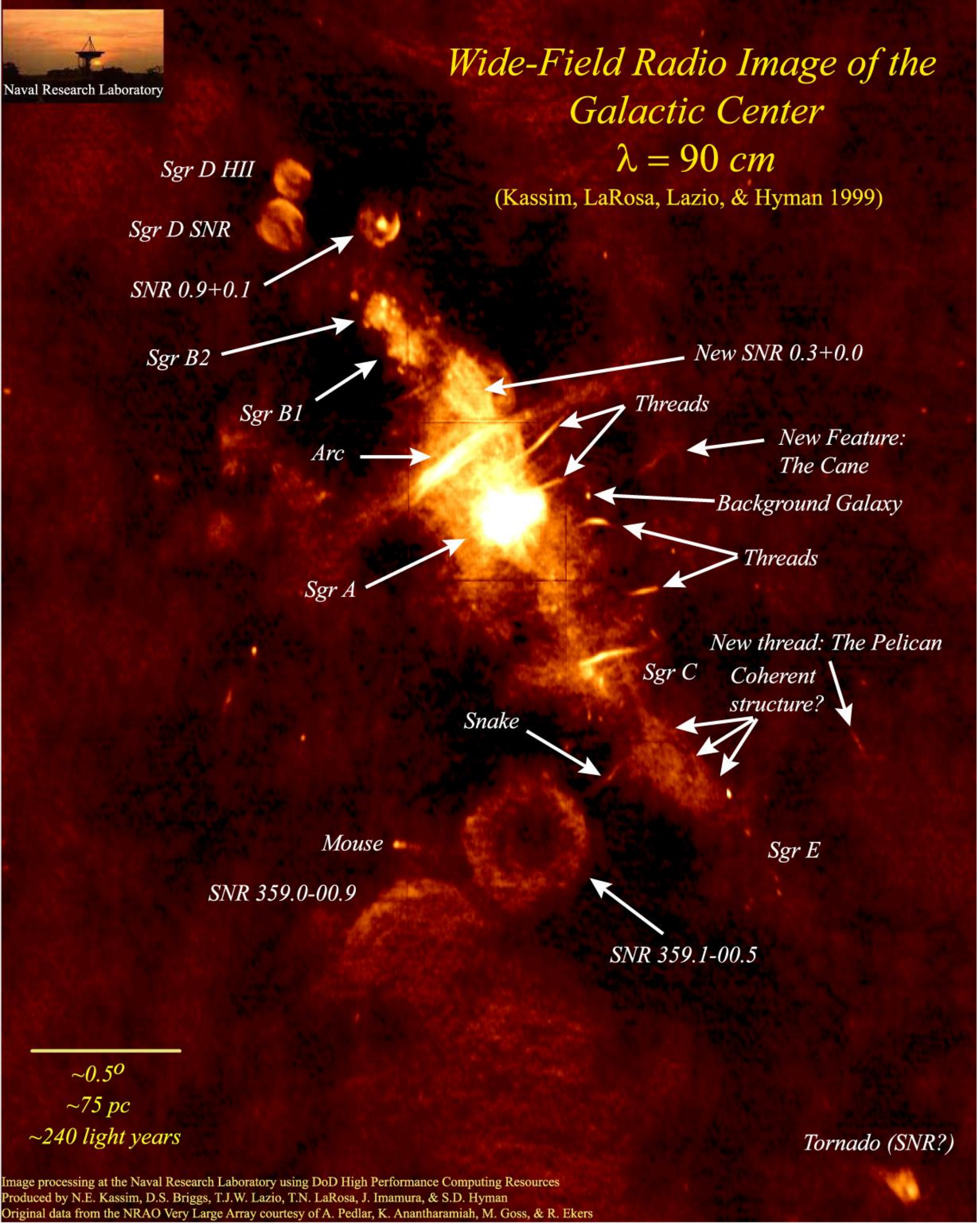
Infrared telescopes peer through the dust



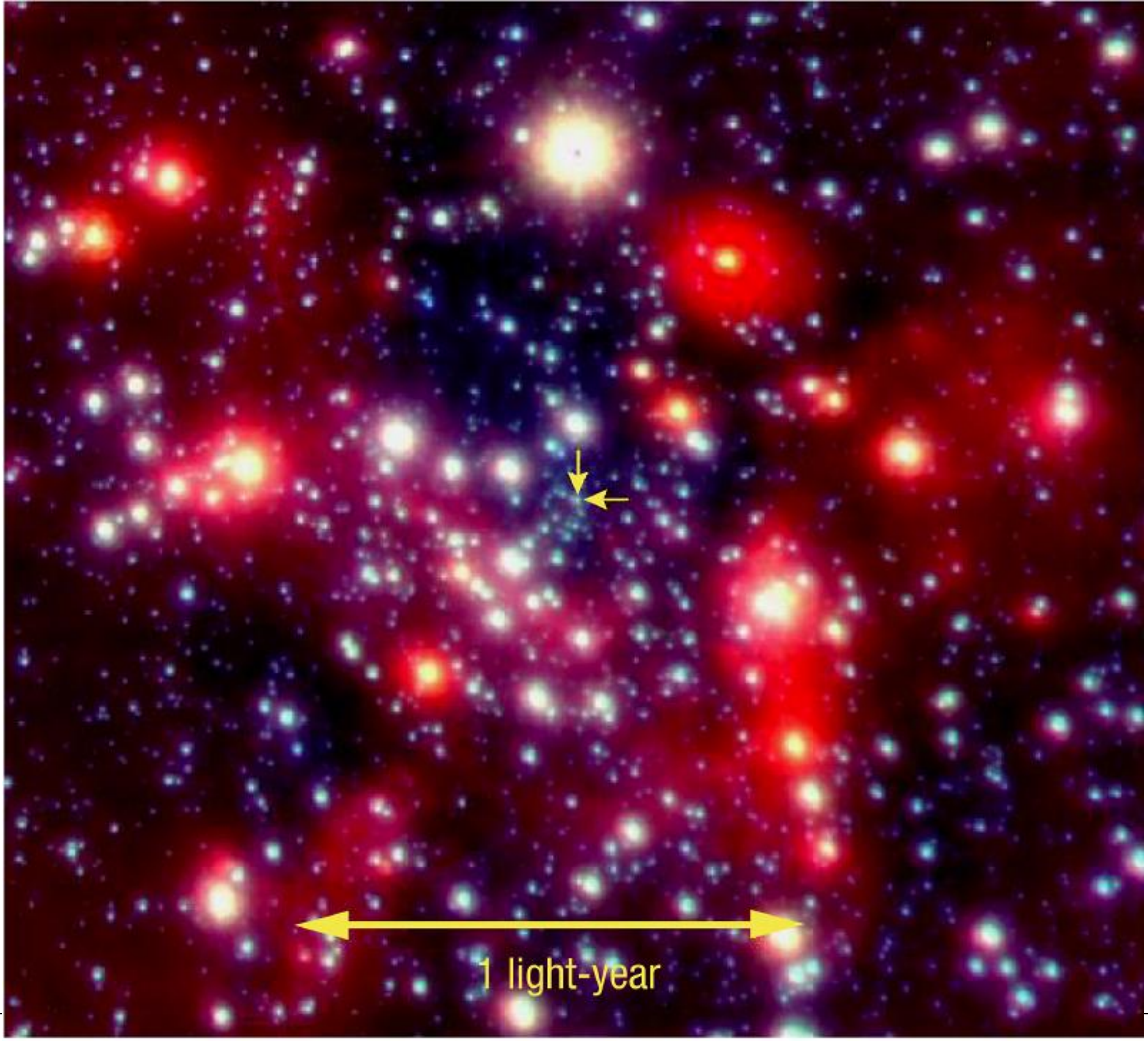
Röntgen radiation



Gamma radiation

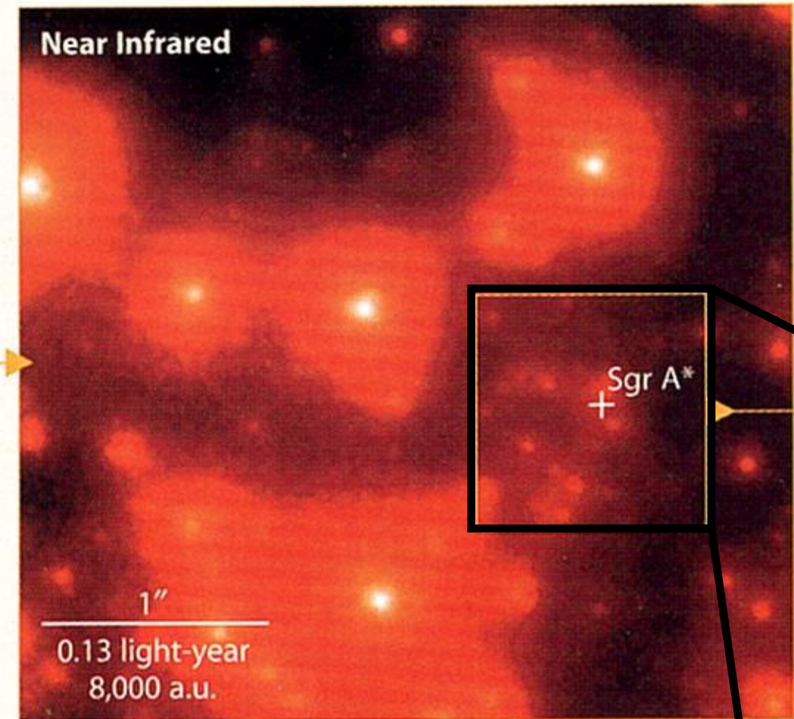

Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
Arc
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

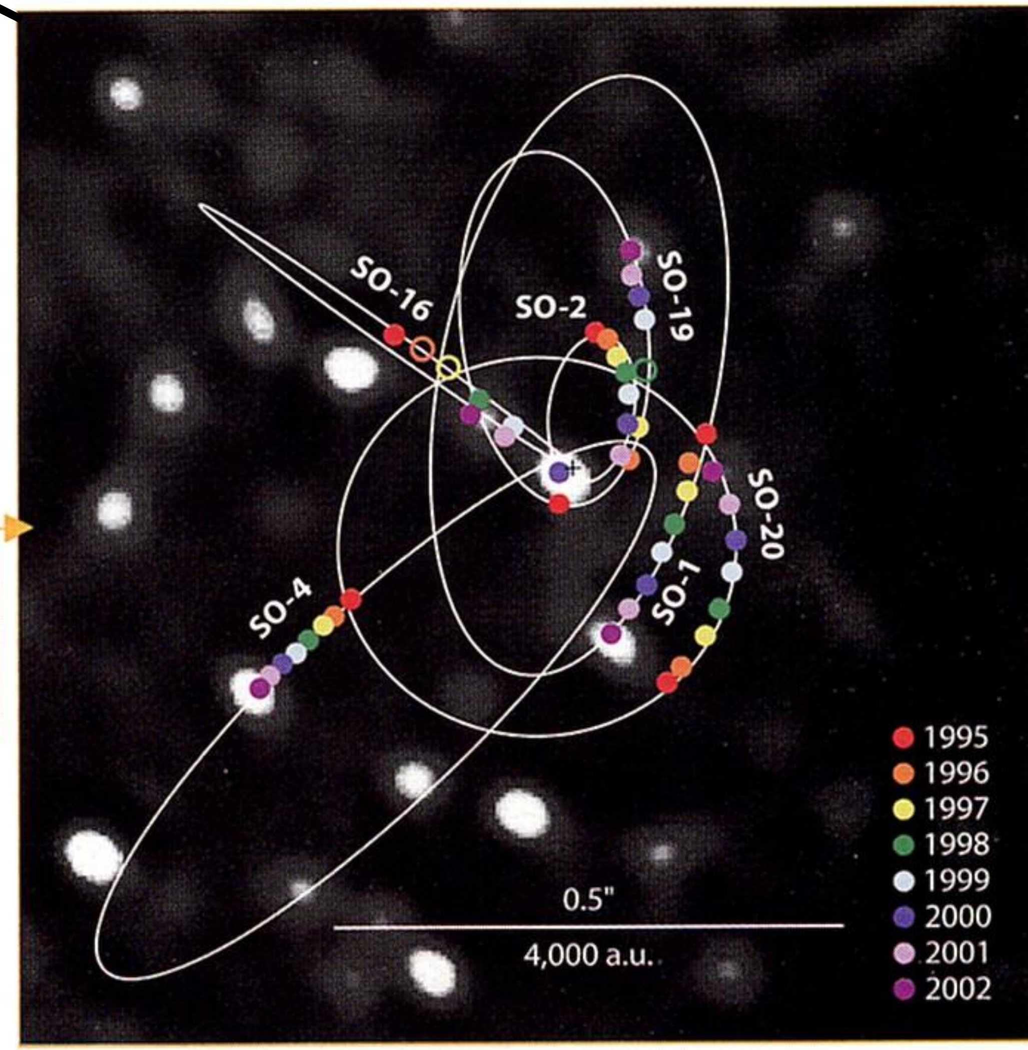
Radio image



The Centre of the Milky Way
(VLT YEPUN + NACO)

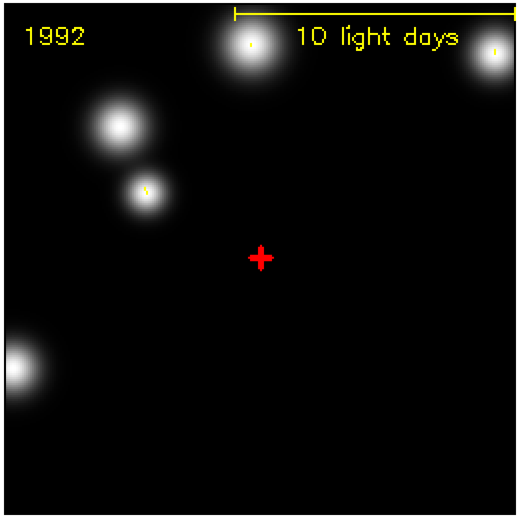
ESO PR Photo 23a/02 (9 October 2002)

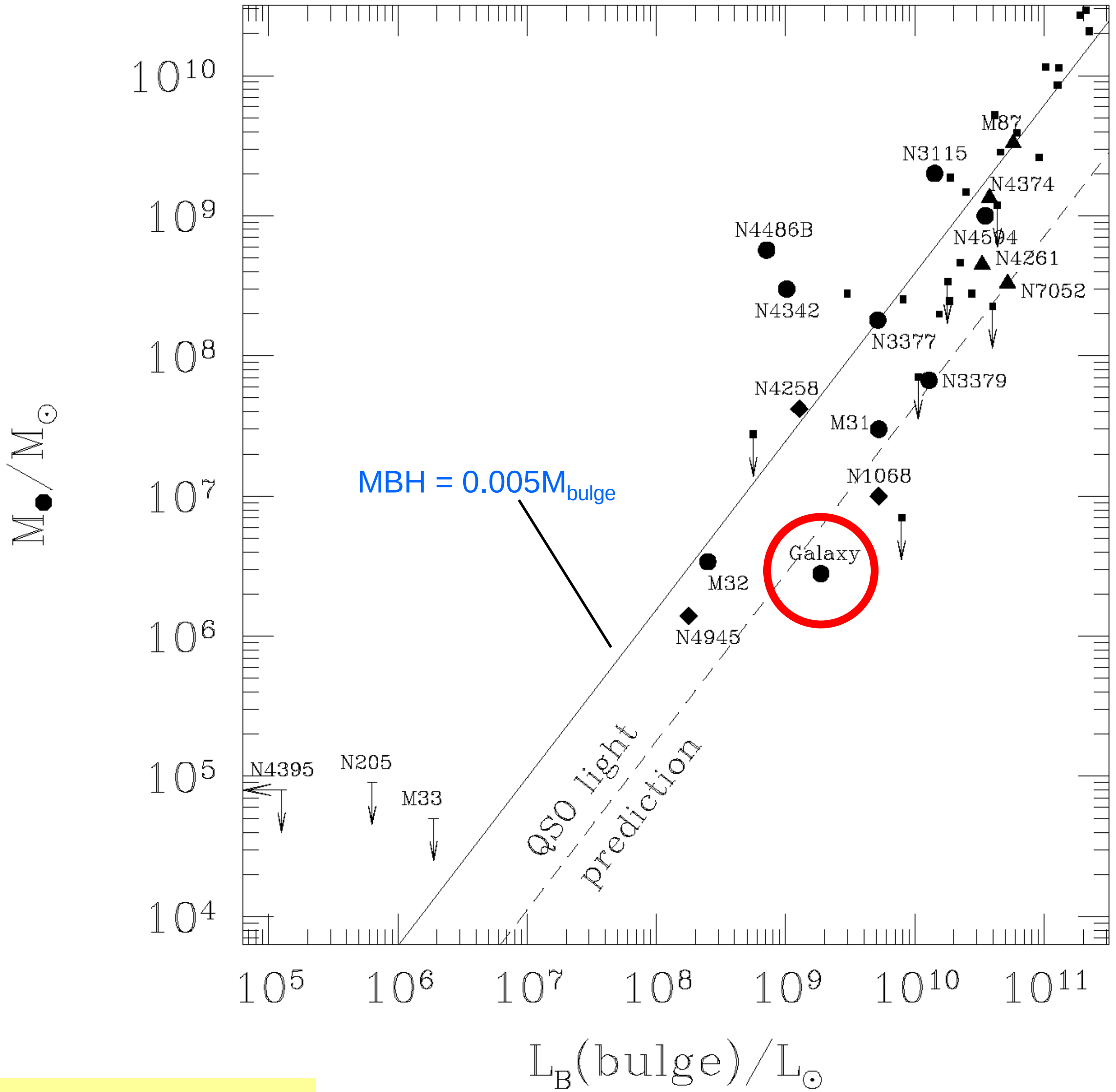




Banen van sterren in de directe omgeving van Sagittarius A^*

Massive black hole mergers



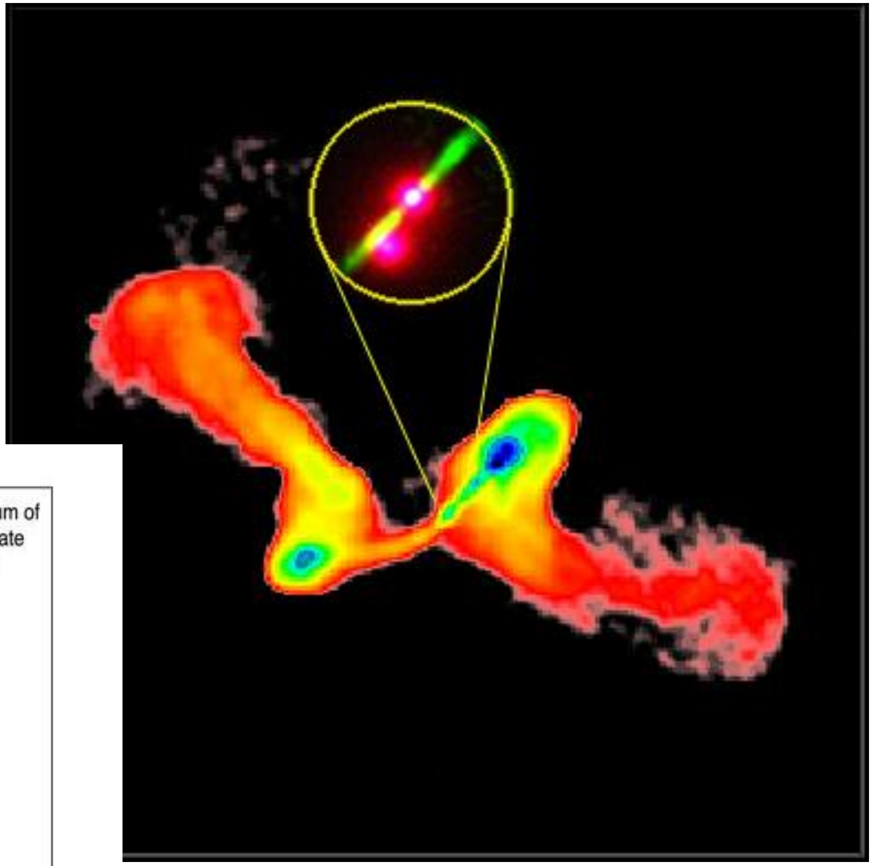


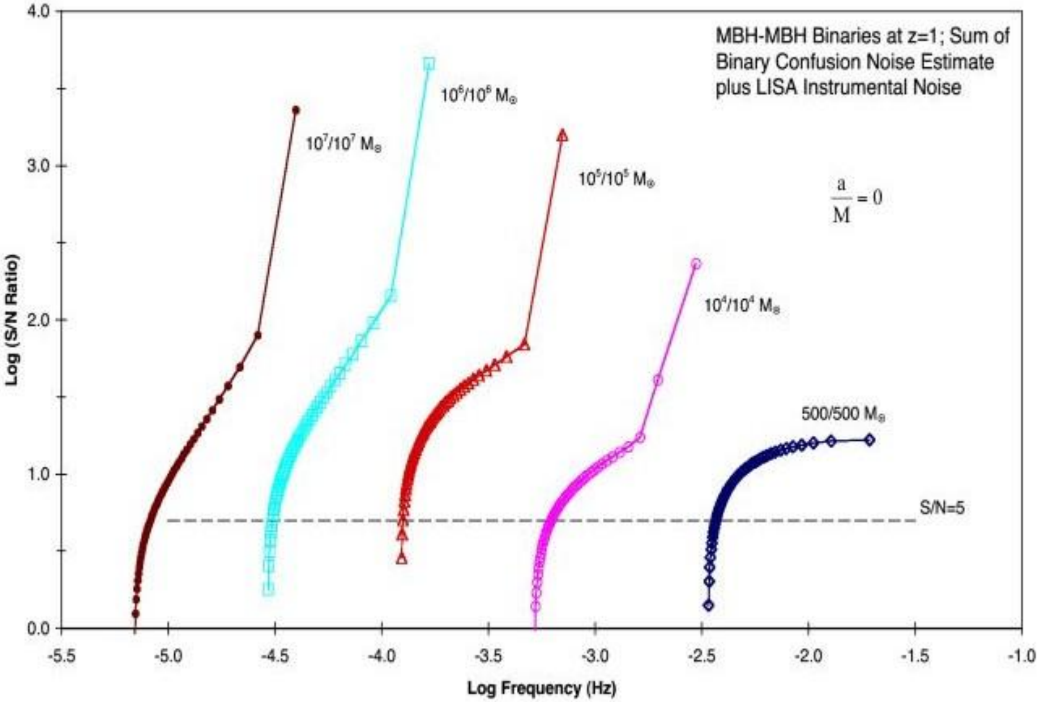
D. Richstone et al., Nature **395**, A14, 1998

Maar smelten ze samen?

Massive black hole mergers

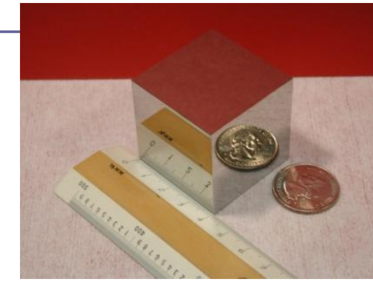
- Several observed phenomena may be attributed to MBH binaries or mergers
  - X-shaped radio galaxies (see figure)
  - Periodicities in blazar light curves (e.g. OJ 287)



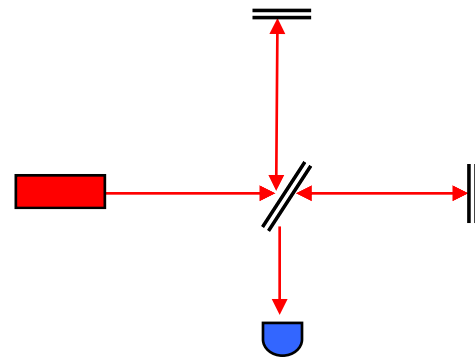


[Merritt and Ekers, 2002]

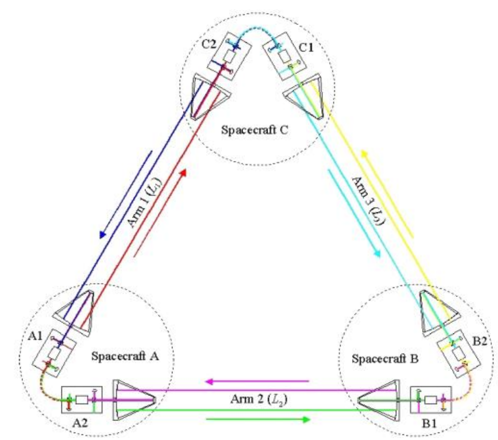
LISA INTERFEROMETRY



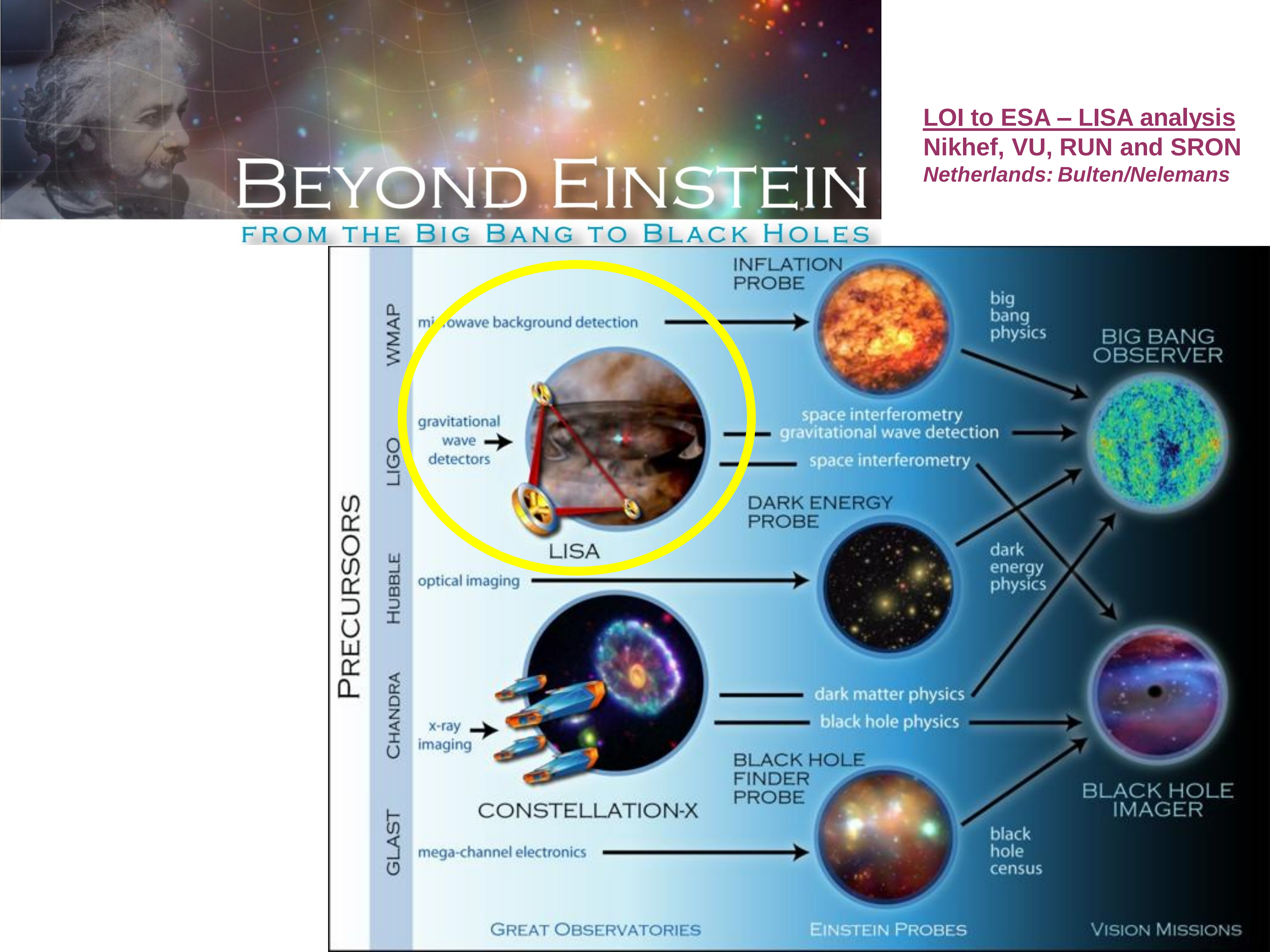
- "LISA is essentially a Michelson Interferometer in Space"



- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal
  - Arm lengths change continuously
  - Light travel time ~17 seconds
  - Constellation is rotating and translating in space



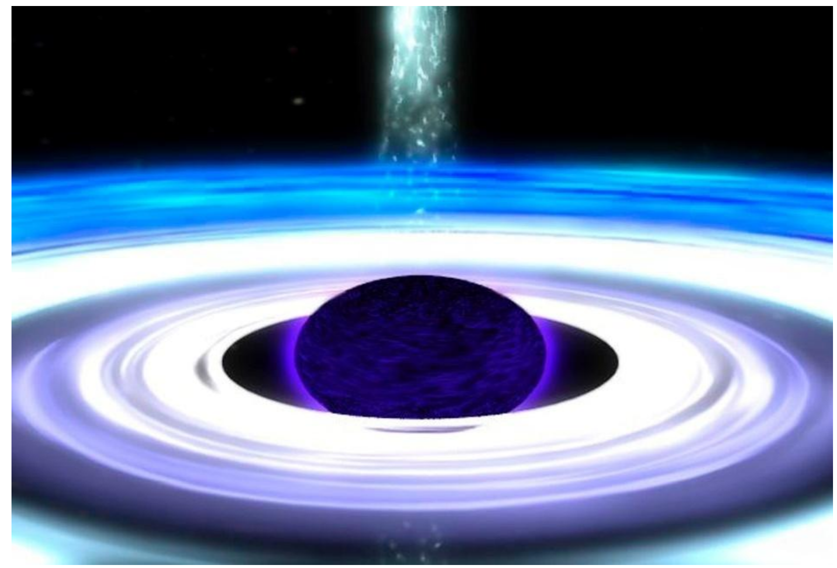
LOI to ESA – LISA analysis
Nikhef, VU, RUN and SRON
Netherlands: Bulten/Nelemans



Video

Wetenschappelijke doelstelling

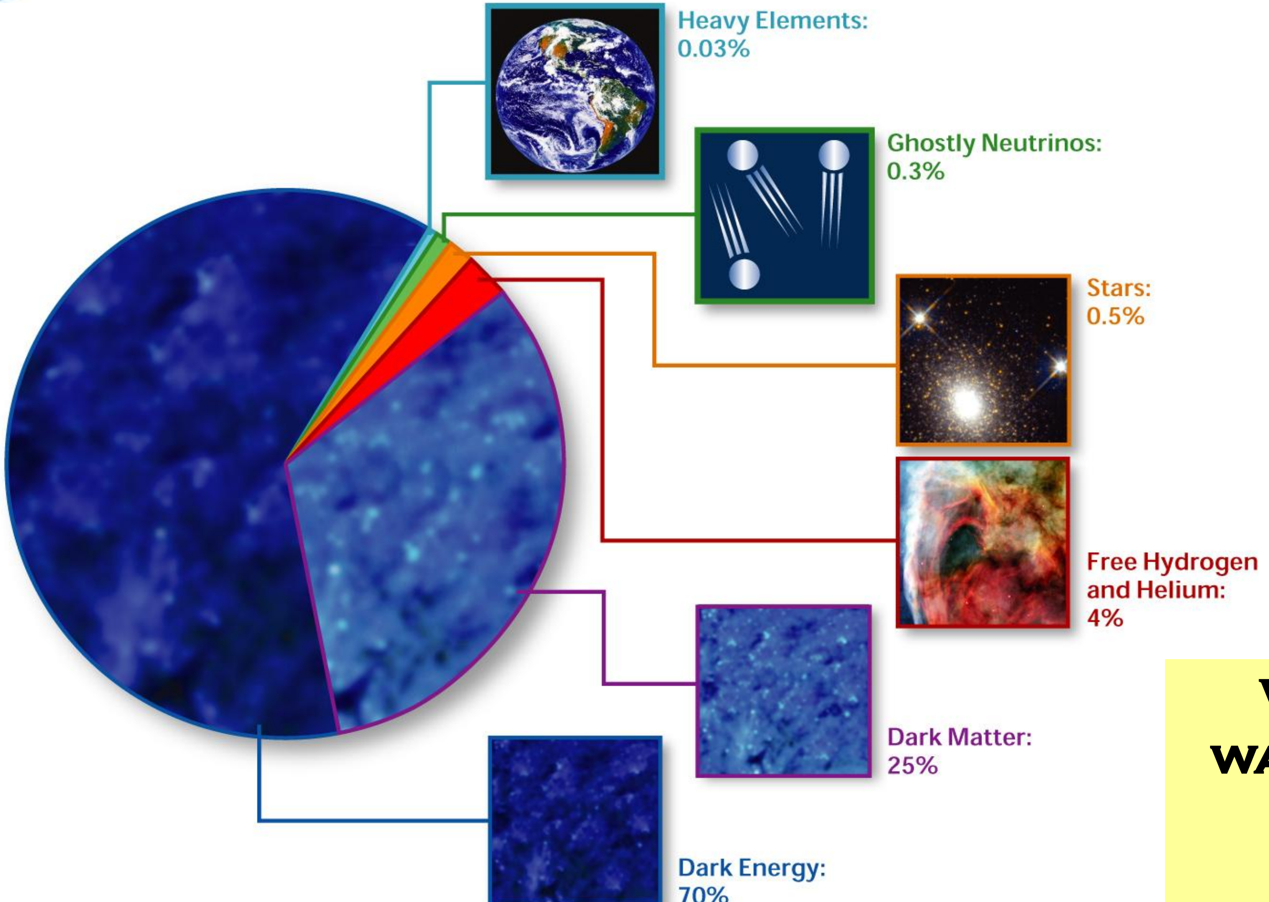
Wat gebeurt er aan de rand van een zwart gat?



Is Einsteins theorie nog steeds correct onder deze extreme condities? Of wacht ons nieuwe fysica?

Wetenschappelijke doelstelling

Wat is die mysterieuze donkere energie die het Heelal uiteen trekt?

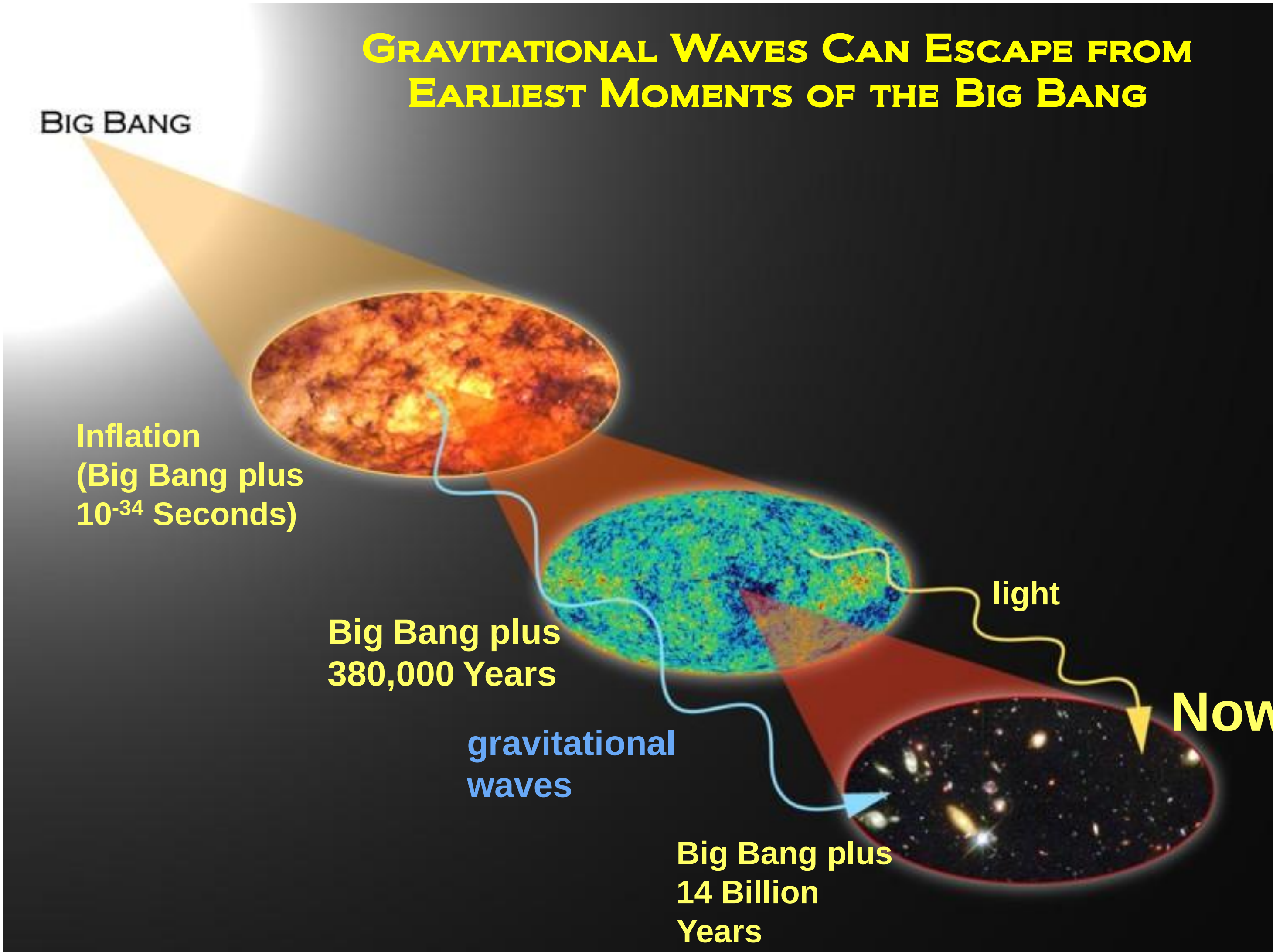


We weten niet waar 95% van het Universum uit bestaat!

Donkere energie en materie veroorzaken gravitie

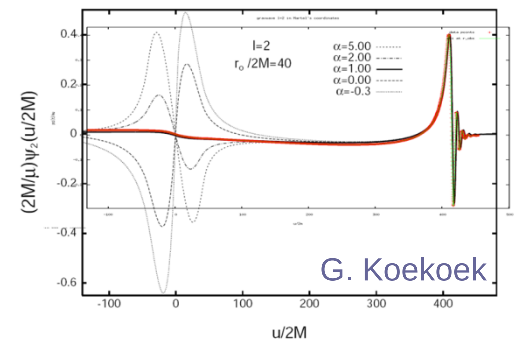
Wetenschappelijke doelstelling

Wat gebeurde er ten tijde van de Oerknal?

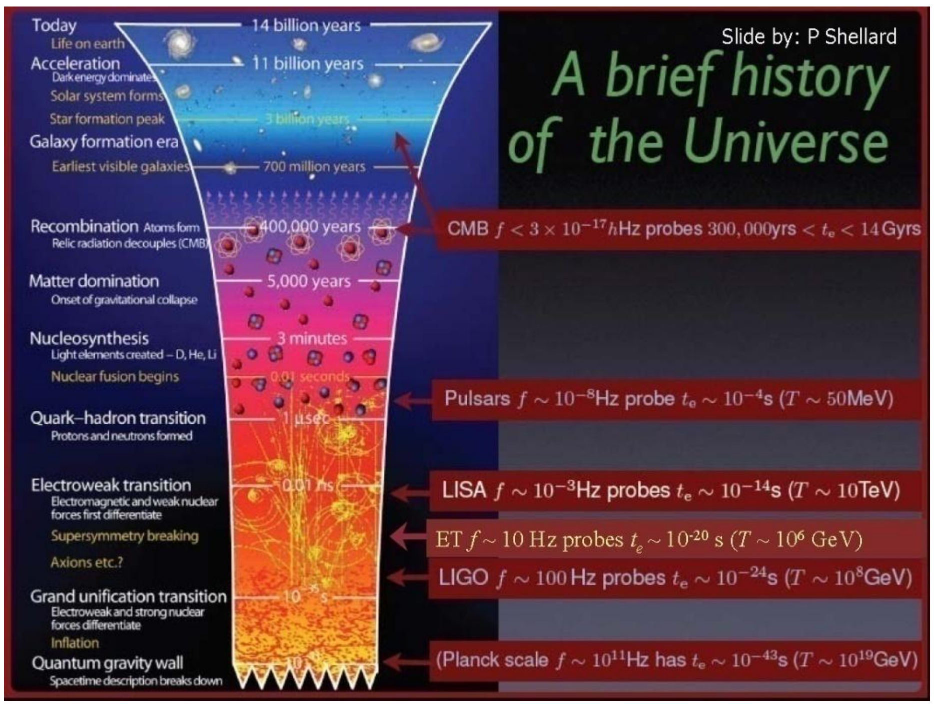


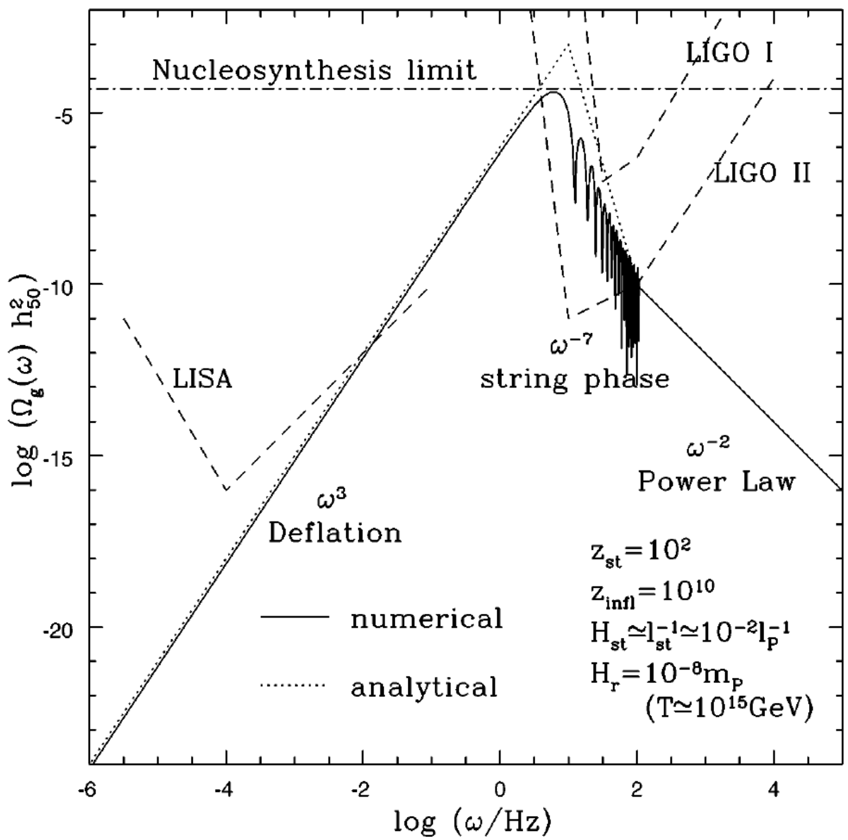
Signalen van inflatie en fase overgangen

- Theoretische (astro)deeltjes fysica gemeenschap
  - GW, inflatie, string theorie, kosmische defecten
- Maak templates, spectra, etc.
  - Zoek naar signalen in Virgo – LIGO data



Galluccio et al; Phys. Rev. Lett. 79 (970)





Samenvatting

- Gravitatiegolf fysica
  - Onderdeel van het Nederlands Astrodeeltjes fysica initiatief
  - Een nieuw fysica programma
    - Belangrijke vragen
    - Lange termijn perspectief
- VIRGO en LIGO
  - Gevoeligheid wordt snel beter
  - Eerste wetenschappelijke metingen afgesloten
  - Advanced Virgo project is net gestart