Probing dynamical spacetimes

Direct detection of gravitational waves

Jo van den Brand

Outline

- Motivation
- First generation GW detectors
  - Some results
- Second generation GW detectors
  - Advanced Virgo and LIGO, and GEO-HF
  - Kagra
- Third generation GW detectors
  - Einstein Telescope
  - *e*LISA

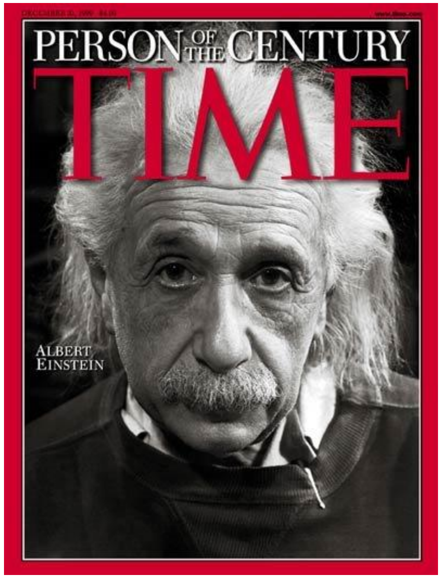
Motivation

Einstein gravity:

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

Gravity as a geometry

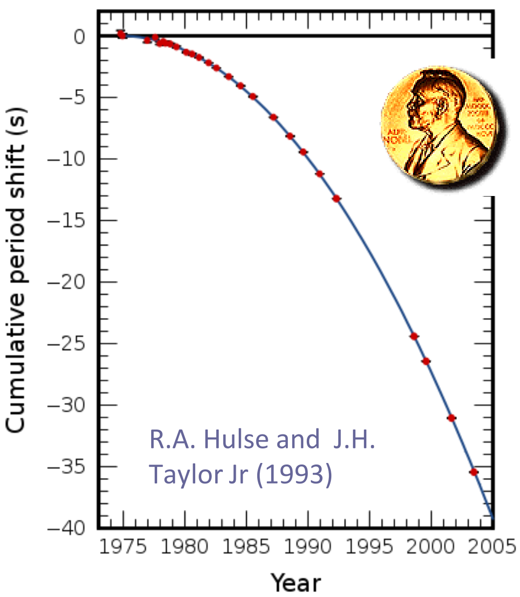
Space and time are physical objects

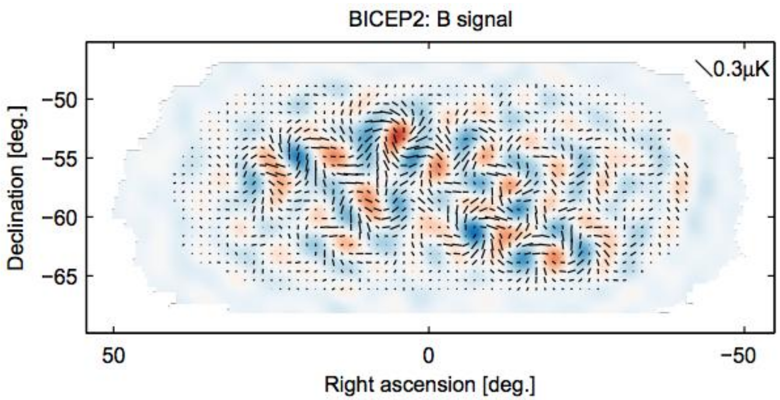


- Gravitation
  - Least understood interaction
  - Large world-wide intellectual activity
    - **Theoretical: GR + QFT, Cosmology**
    - **Experimental: Interferometers on Earth and in space**
- Gravitational waves
  - Dynamical part of gravitation, all space is filled with GW
  - Ideal information carrier, almost no scattering or attenuation
  - The entire Universe has been transparent for GWs, all the way back to the Big Bang

Indirect effects of gravitational waves

- Energy loss from BNS
  - Period shift in excellent agreement with GR
- BICEP2
  - B-modes in CMB
- Our goal: direct detection of GWs





What are gravitational waves?

- Newton's gravity comes from Poisson equation

$$\nabla^2 \Phi(t,\vec{x}) = 4\pi G \rho(t,\vec{x})$$

- In general relativity for weak gravitational fields

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}, \qquad |h_{\alpha\beta}| \ll 1$$

- Einstein's equations reduce to wave equations

$$\Box\, h_{\alpha\beta} = 8\pi G T_{\alpha\beta}$$

- Non-axisymmetric motion of mass-energy generates GW
- GWs are ripples in the curvature of spacetime

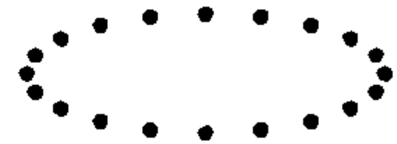
Motivation

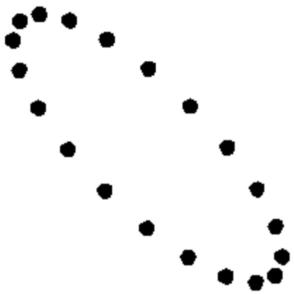
Einstein gravity:

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

Gravity as a geometry

Space and time are physical objects





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

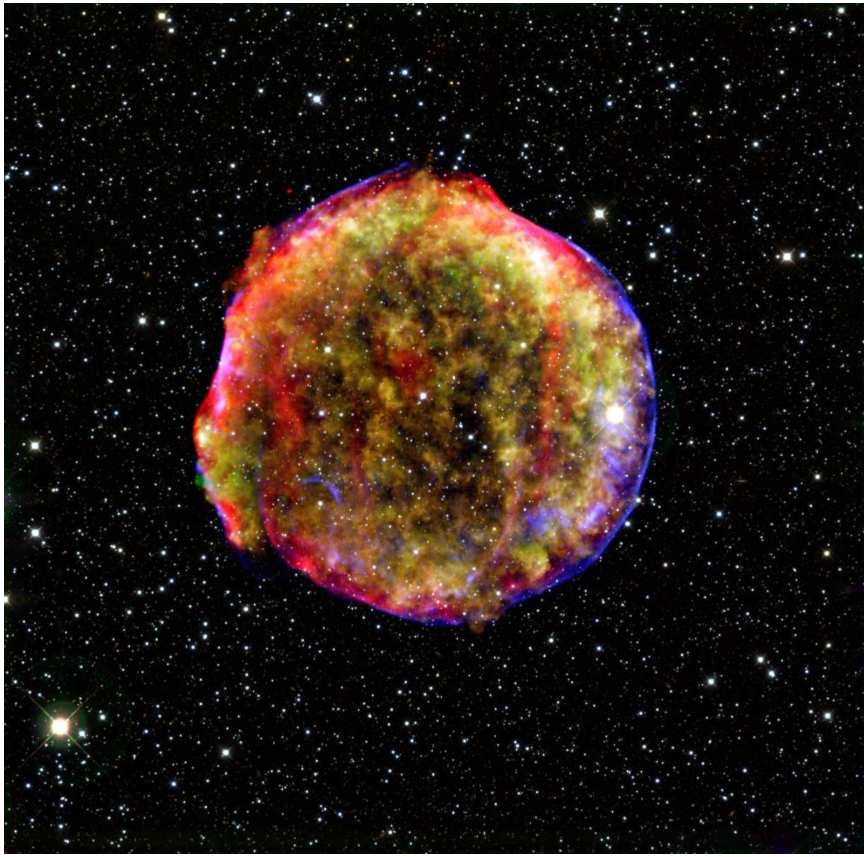
$$h \approx \frac{2\Delta L}{L} = \frac{2G}{c^4}\frac{d^2Q}{dt^2}\frac{1}{d}$$

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

$$L_G = 10^{-30} J/s$$

Burst Sources

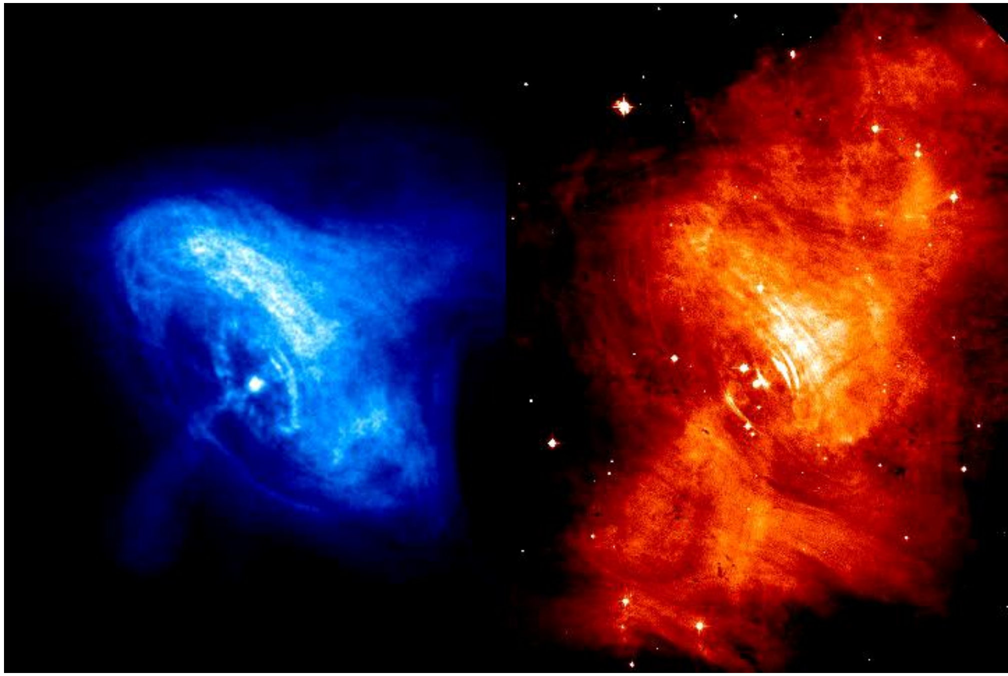
- Gravitational wave bursts
  - Black hole collisions
  - Supernovea
  - Gamma-ray bursts (GRBs)
- Short-hard GRBs
  - Could be the results of merger of a neutron star with another NS or a BH
- Long GRBs
  - Could be triggered by supernovae
- Formation of NS or BH
  - From type II supernova
  - About 1/100 yr in MWEG



SN1572 (Tycho) composite image (X + IR)

Continuous Wave Sources

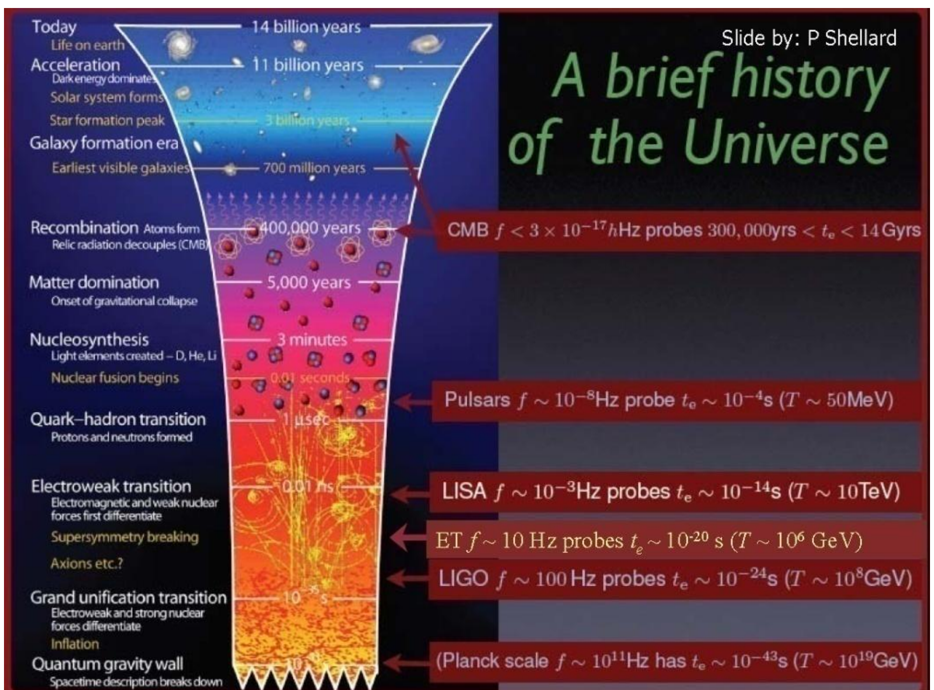
- Rapidly spinning NS
  - Mountains on neutron stars
- Low mass X-ray binaries
  - Accretion induced asymmetry
- Magnetars and other compact objects
  - Magnetic field induced asymmetries
- Relativistic instabilities
  - r-modes, *etc*.



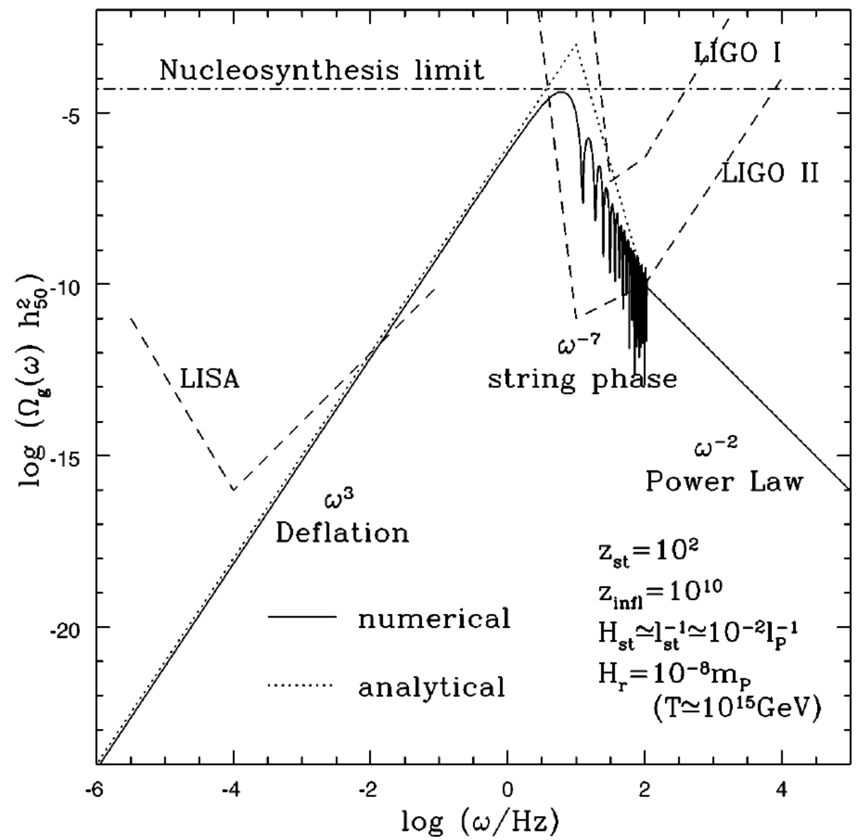
SN1052 (Crab) composite movie (X + visible)
X-Ray Image Credit: NASA/CXC/ASU/J.Hester *et al*.
Optical Image Credit: NASA/HST/ASU/J.Hester *et al*.

Stochastic background GW

- Theoretical (astro)particle physics community
  - GWs from inflation, string theory, cosmic defects, …
- Make templates, spectra, *etc*.
  - Search for signals in Virgo – LIGO data

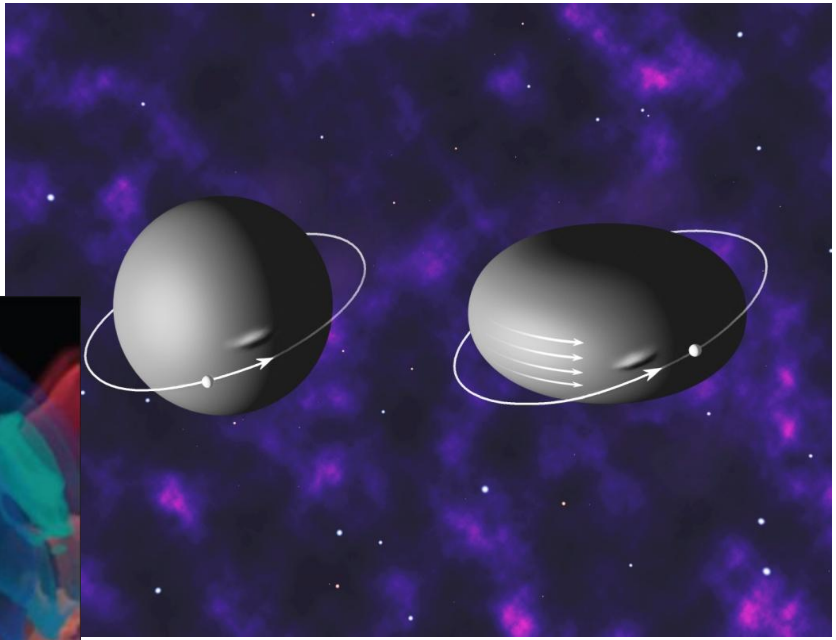


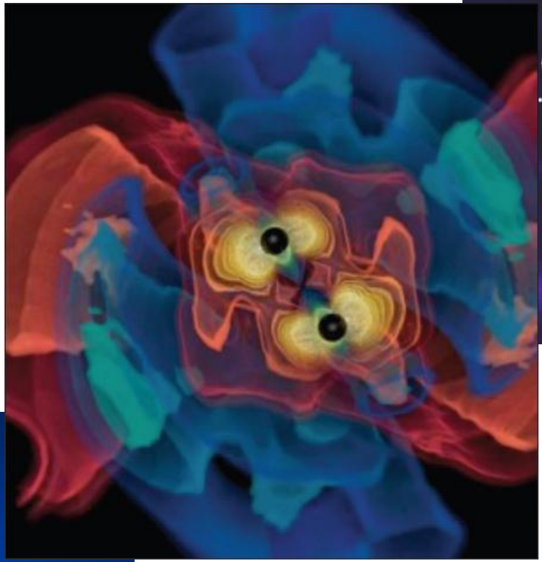
Galluccio *et al*; Phys. Rev. Lett. 79 (970)

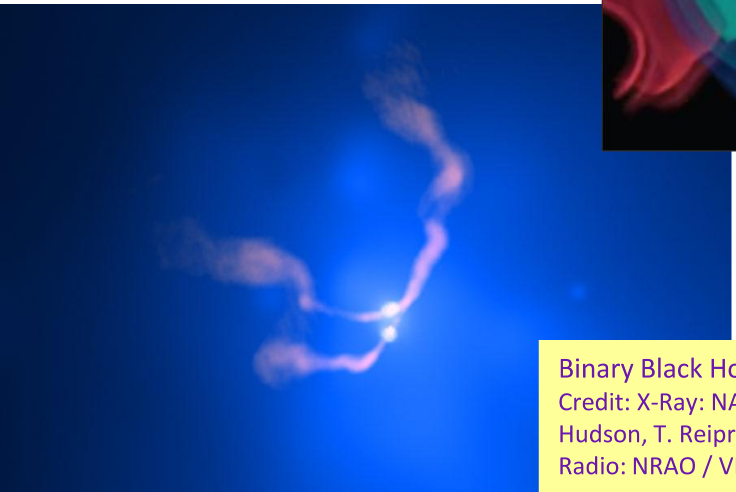


Compact Binary Mergers

- Binary neutrons stars
- Binary black holes
- Neutron star – black hole binaries







Binary Black Hole in 3C 75
Credit: X-Ray: NASA / CXC / D. Hudson, T. Reiprich et al. (AIfA); Radio: NRAO / VLA/ NRL

Loss of energy leads to steady inspiral whose waveform (phase) has been calculated to order v^7 in post-Newtonian theory

- Knowledge of the waveforms allows matched filtering

Gravitational radiation exists: PSR B1913+16

Russell A. Hulse
Joseph H. Taylor, Jr.
In 1974 discovery of the first pulsar in a binary system

Period ~ 8h

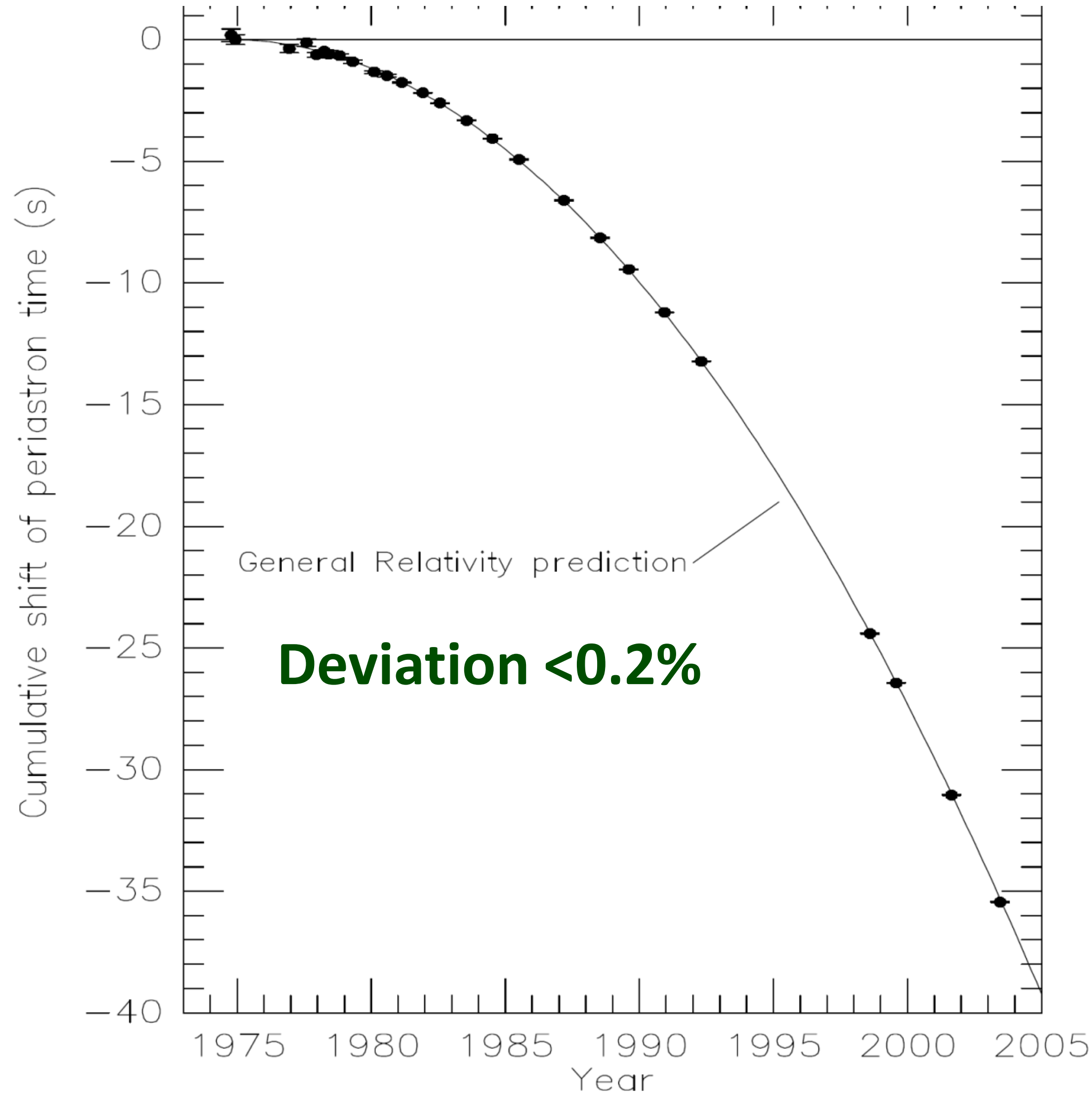
GW emission shortens the period

Indirect detection of GWs

Nobel price 1993

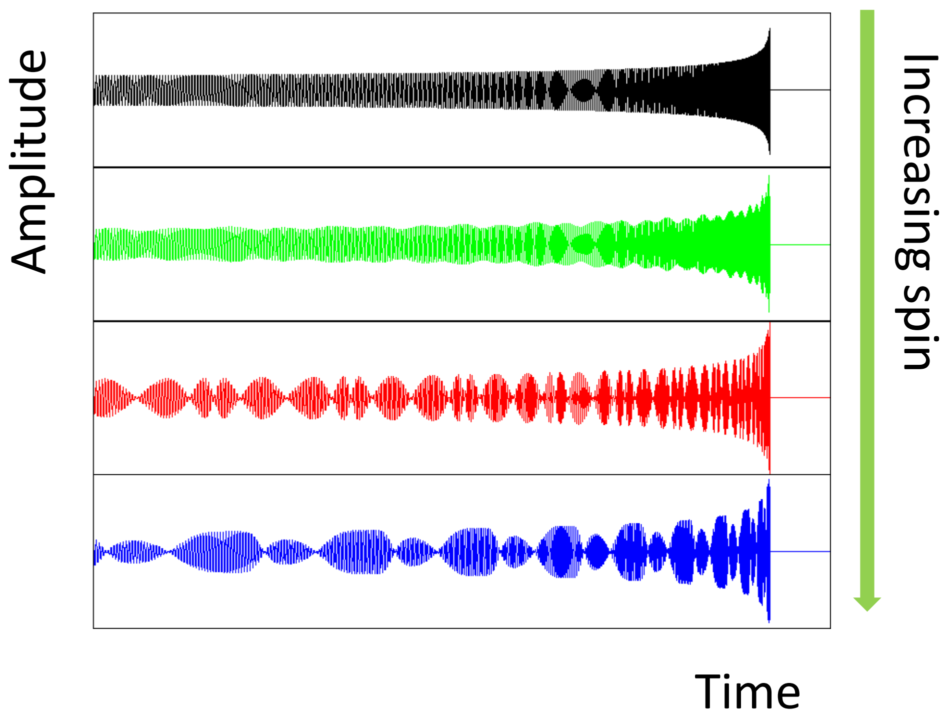
Not a strong-field test!
J0737-3039
Two pulsars: 16.8 deg/yr, 7 mm/d

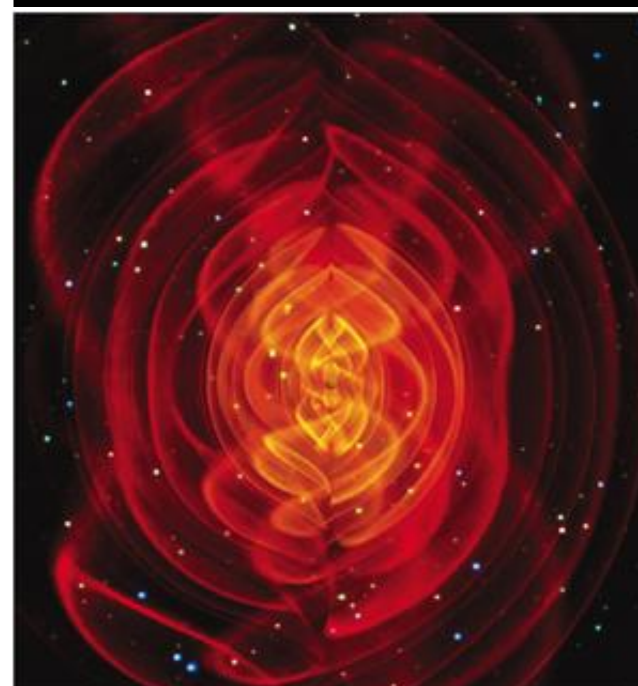
Δt_P [s] Periastron advance



Simulation – merging of BBH

- Pretorius 2005 (arXiv:gr-qc/0507014)
  - BBH orbit, merger and ringdown
  - Energy loss by GW
- Rezzolla
  - Templates with sufficient precision for Advanced LIGO and Virgo

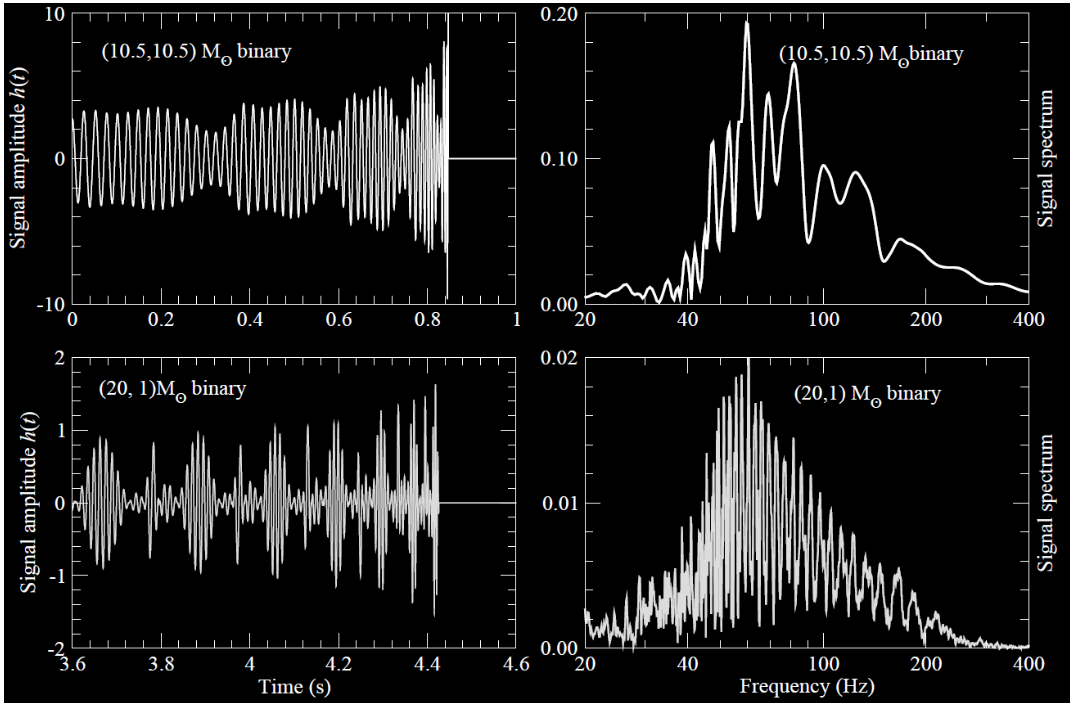




Waveforms BBH and NS-BH binary

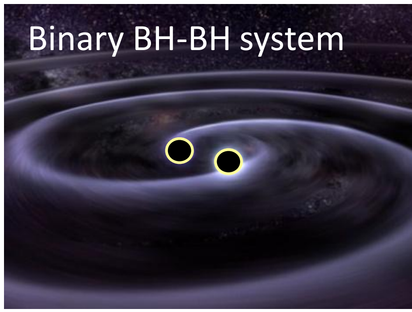
- Signal modulation
  - Amplitude and frequency
  - Due to spin-orbit precession of the orbital plane
- Gravitational waves
  - Merger phase dominates
  - Direct insight into dynamics of spacetime at extreme curvatures
  - Unambiguous evidence for existence of black holes

Time domain Frequency domain

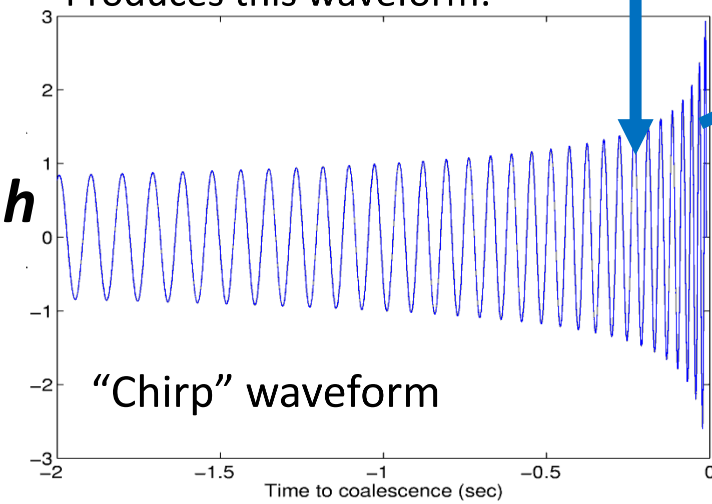


Searches for binary mergers

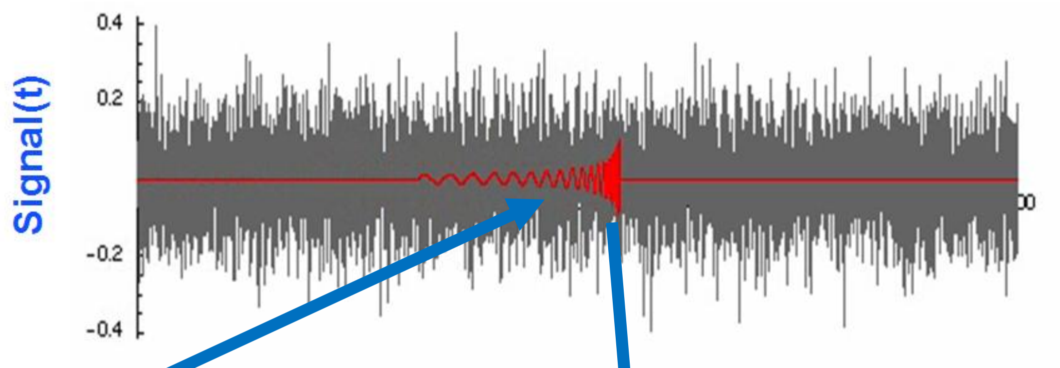
This source:



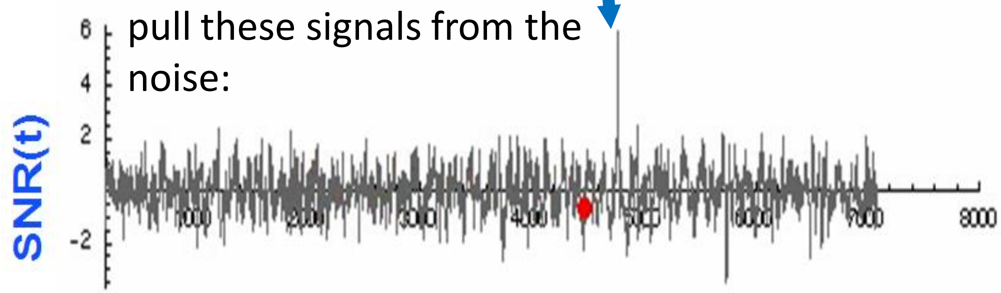
Produces this waveform:



Buried in this noise stream:



We use different methods (in this case optimal Wiener filtering using matched templates) to pull these signals from the noise:

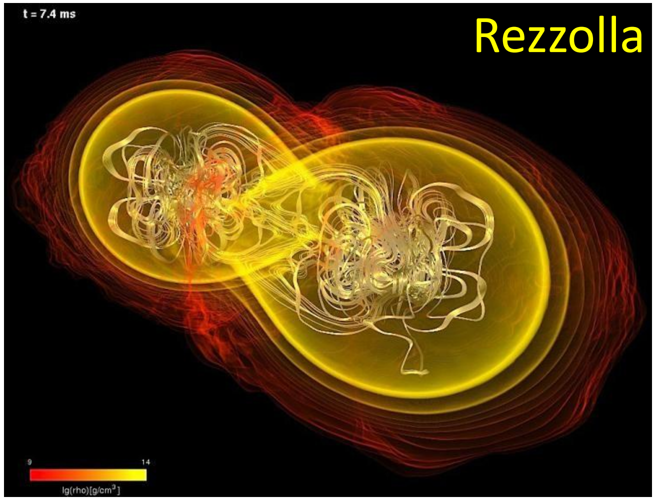


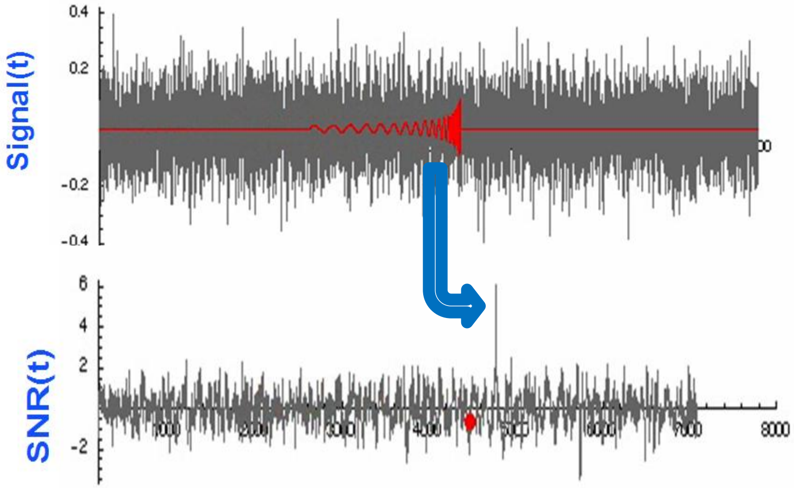
The problem is that non-astrophysical sources also produces signals (false positives)

Scientific focus

To Detect and Observe Gravitational Waves

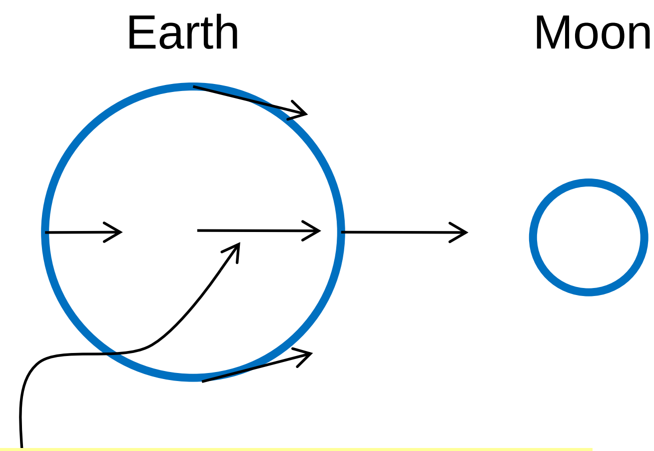
- Scientific promise
  - Direct discovery of gravitational waves
  - Fundamental tests
    - GR, BH uniqueness theorem, …
  - Cosmography
  - Signals from the early Universe
- Sources exist
  - Binary systems of black holes and neutron stars
  - Signal shape known in GR $\rightarrow$ templates
  - Strong analysis groups in place
- Bundle existing strengths
  - Instrumentation, analysis and theory
  - Astrophysics, astronomy and cosmology





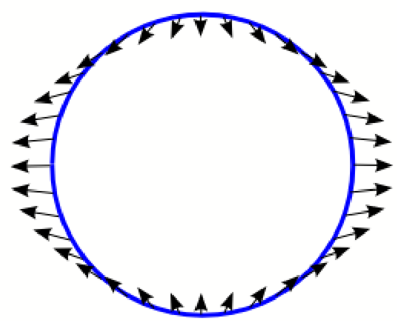
TIDAL GRAVITATIONAL FORCES IN GR

- Tidal forces
  - Gravitational effect of distant source can only be felt through its *tidal forces*
  - Tidal accelerations Earth-Moon system
  - GW can be considered as traveling, time dependent tidal forces
  - Tidal forces scale with size, typically produce elliptical deformations



Solid Earth will fall with this acceleration

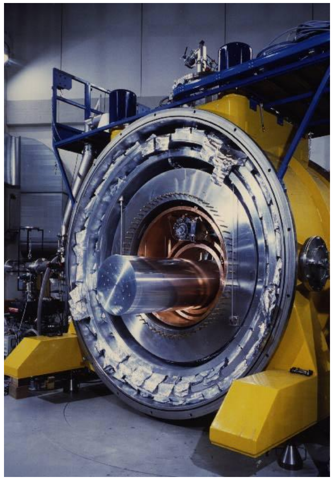
After subtraction of central acceleration

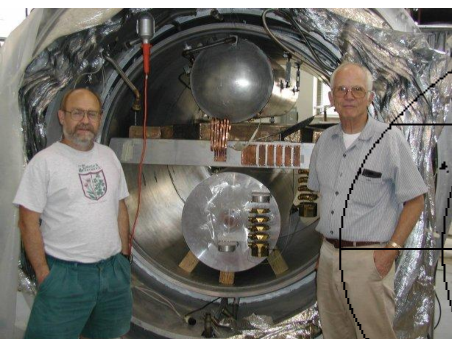


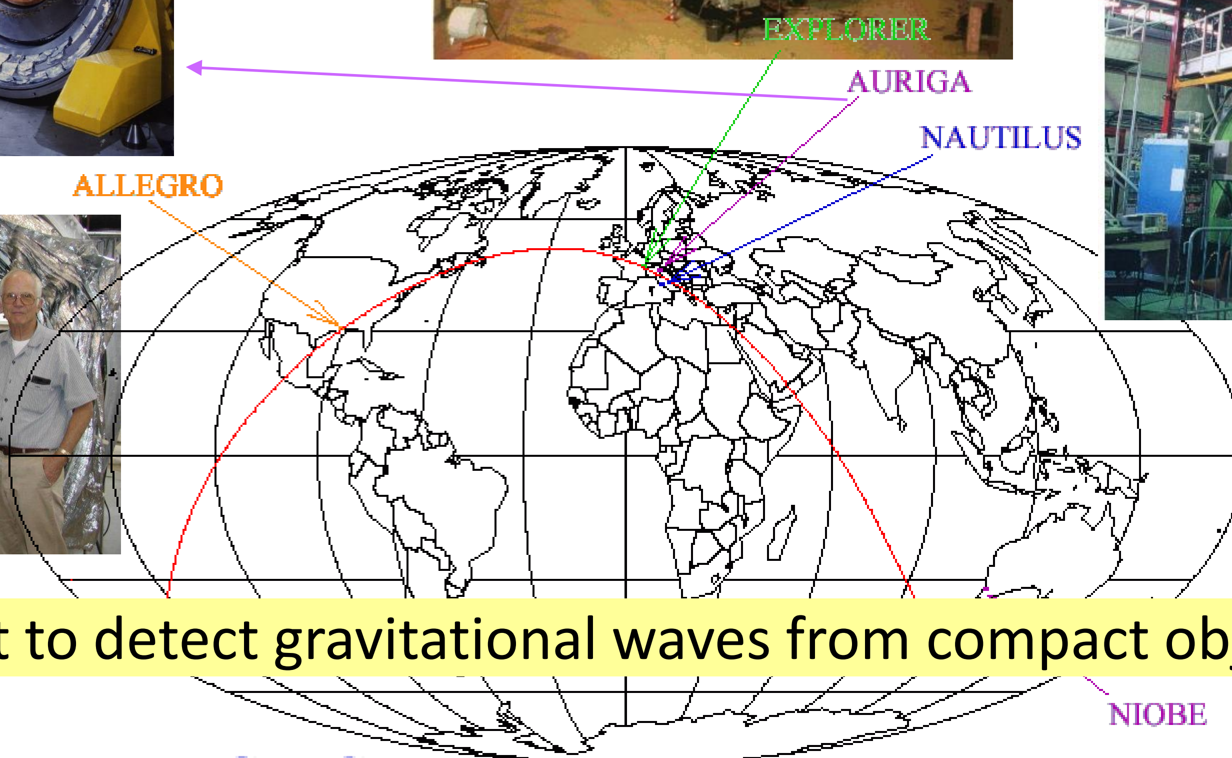
$$\Delta L = 1\mu m \rightarrow L = (10^{-6} m)/(10^{-22}) = 10^{16} m = 1\ ly$$

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

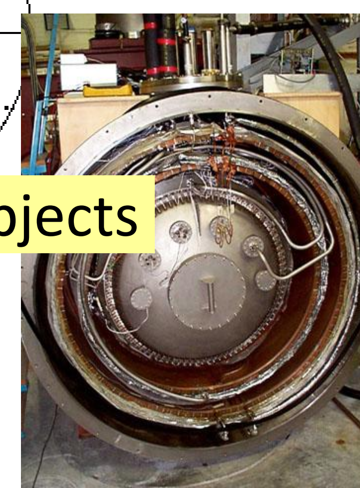
Past attempts: bar detectors





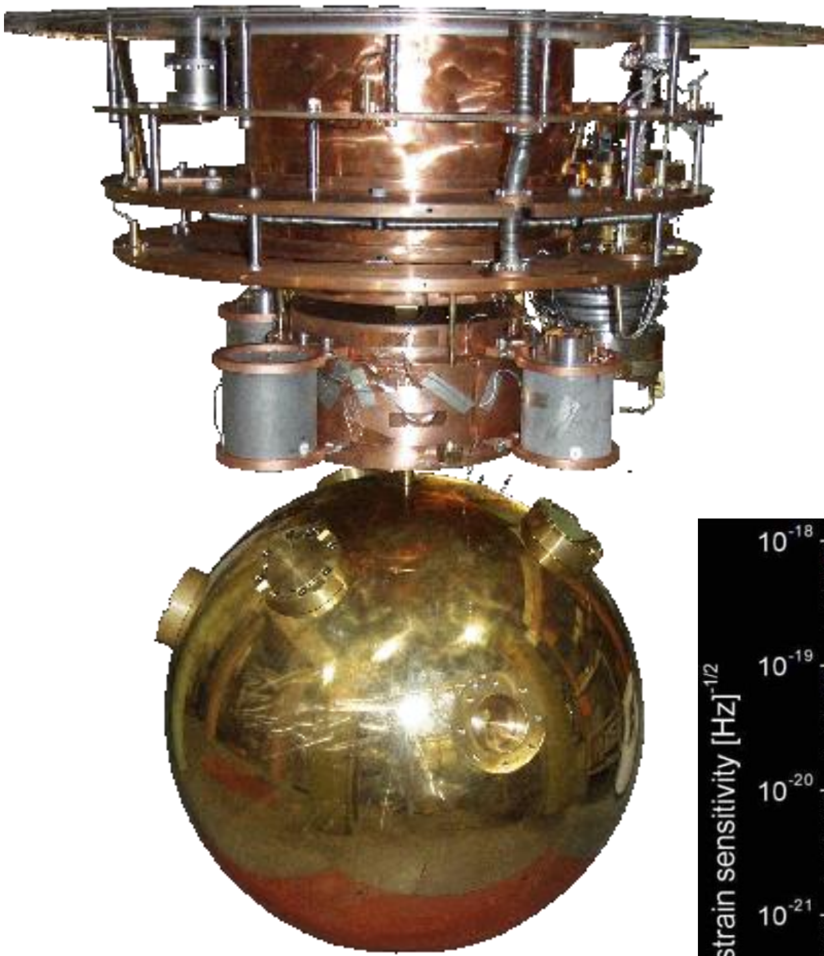


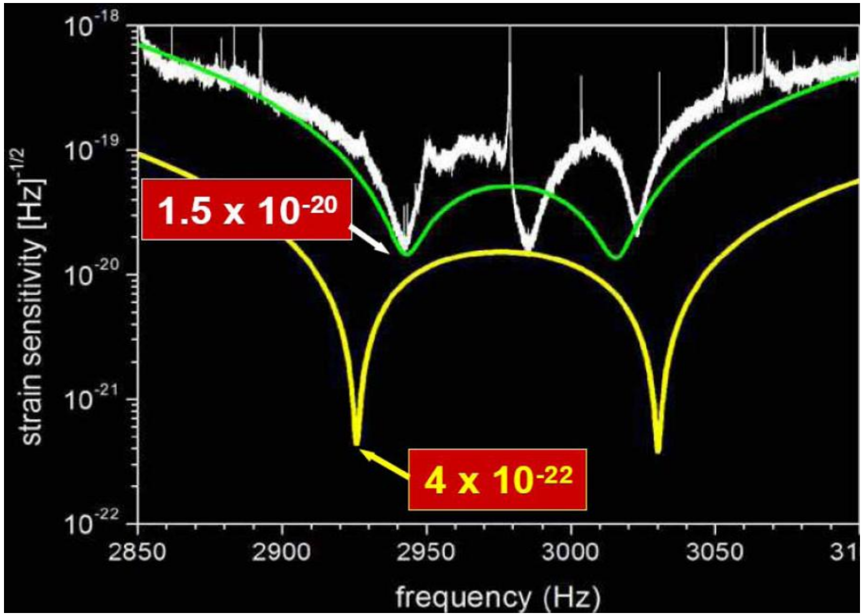
Built to detect gravitational waves from compact objects



Mini-GRAIL: a spherical `bar'

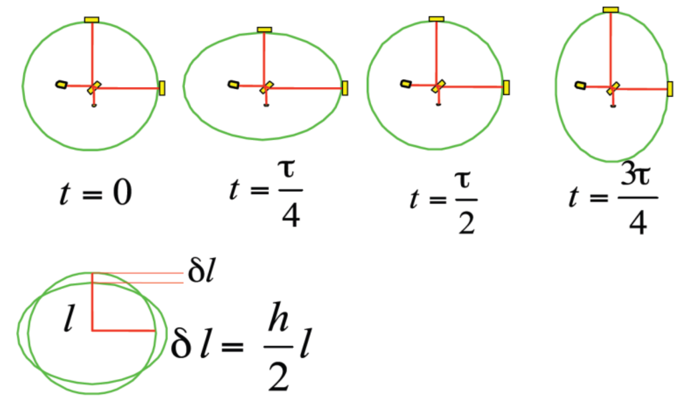
Frossati *et al.*, Leiden





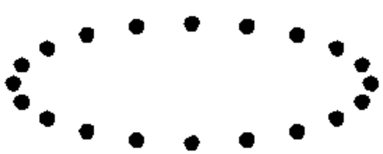
Interferometer approach

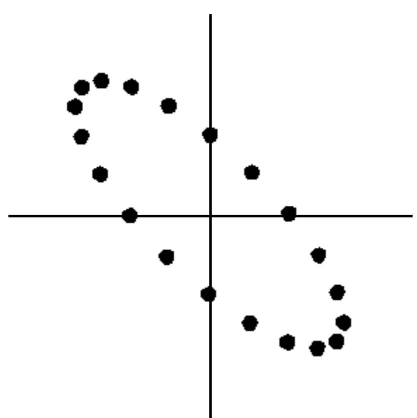
- Test masses
  - System of free-falling test masses is displaced by GW
  - Equip test masses with mirrors and measure relative displacement *(strain)*
  - Plus- and cross polarization states
  - Antenna pattern funtions

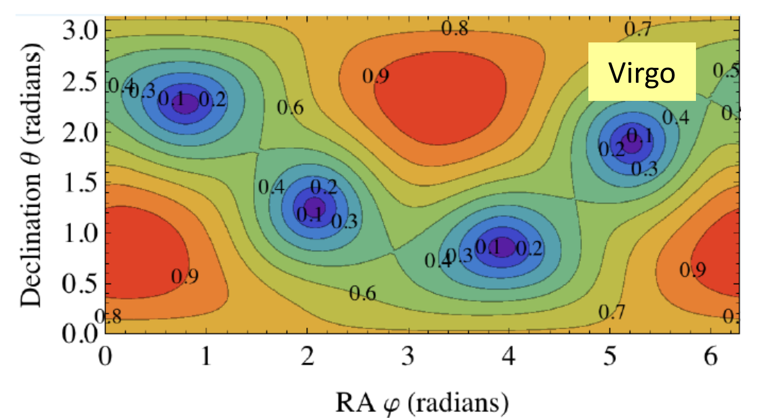


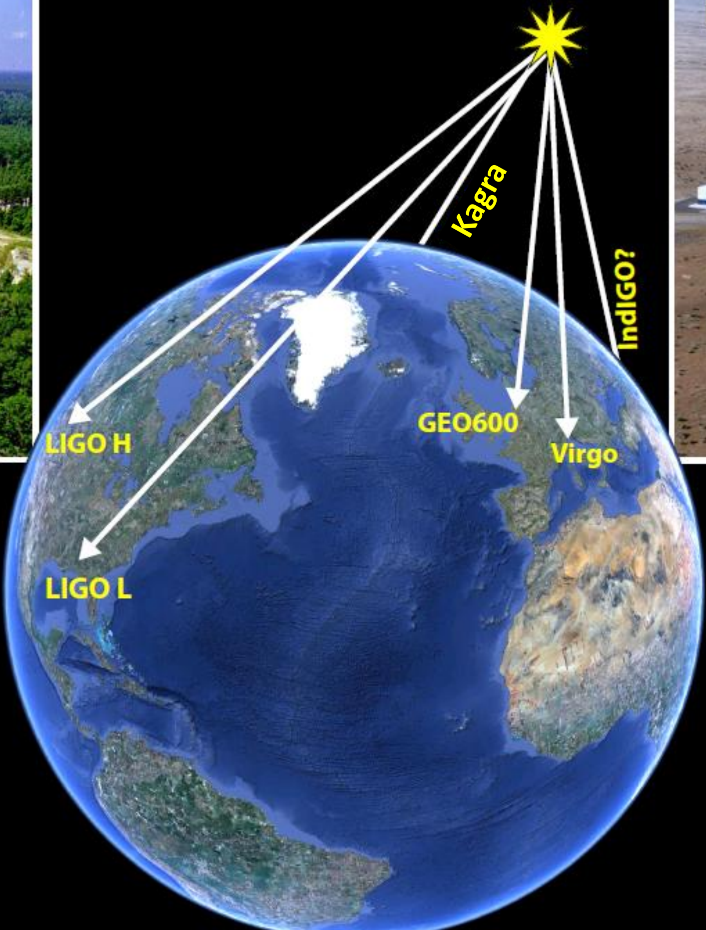
$$h(t) = F_+(\theta,\, \varphi,\, \psi) h_+(t) + F_\times(\theta,\, \varphi,\, \psi) h_\times(t)$$

$$h(t) = F(t)\,(\cos\xi\, h_+ + \sin\xi\, h_\times)\,, \quad F = \sqrt{F_+^2 + F_\times^2}, \quad \tan\xi = F_\times / F_+$$







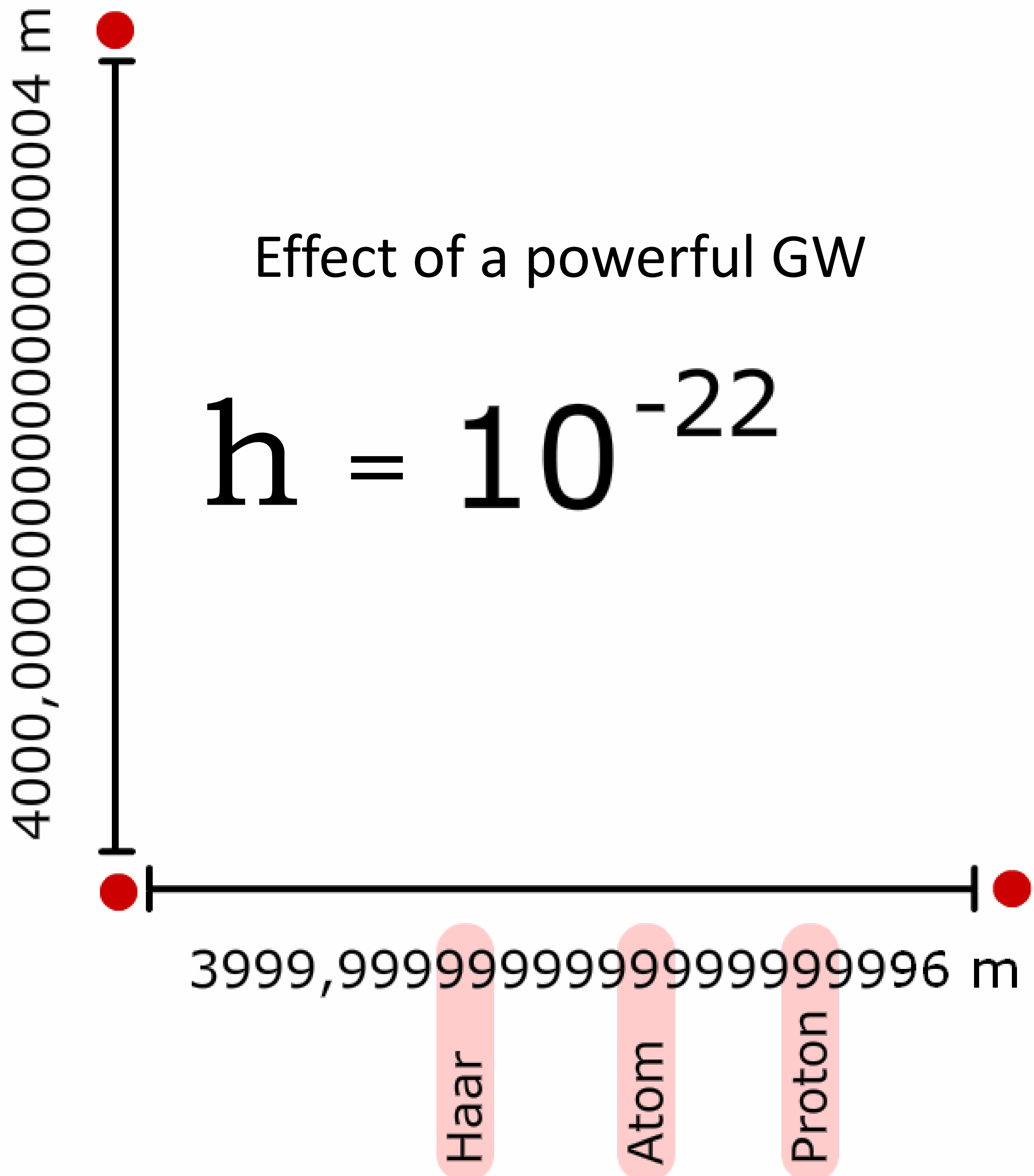


Advanced LIGO and Virgo
First common run in 2016

Kagra joins 2020
LIGO India?

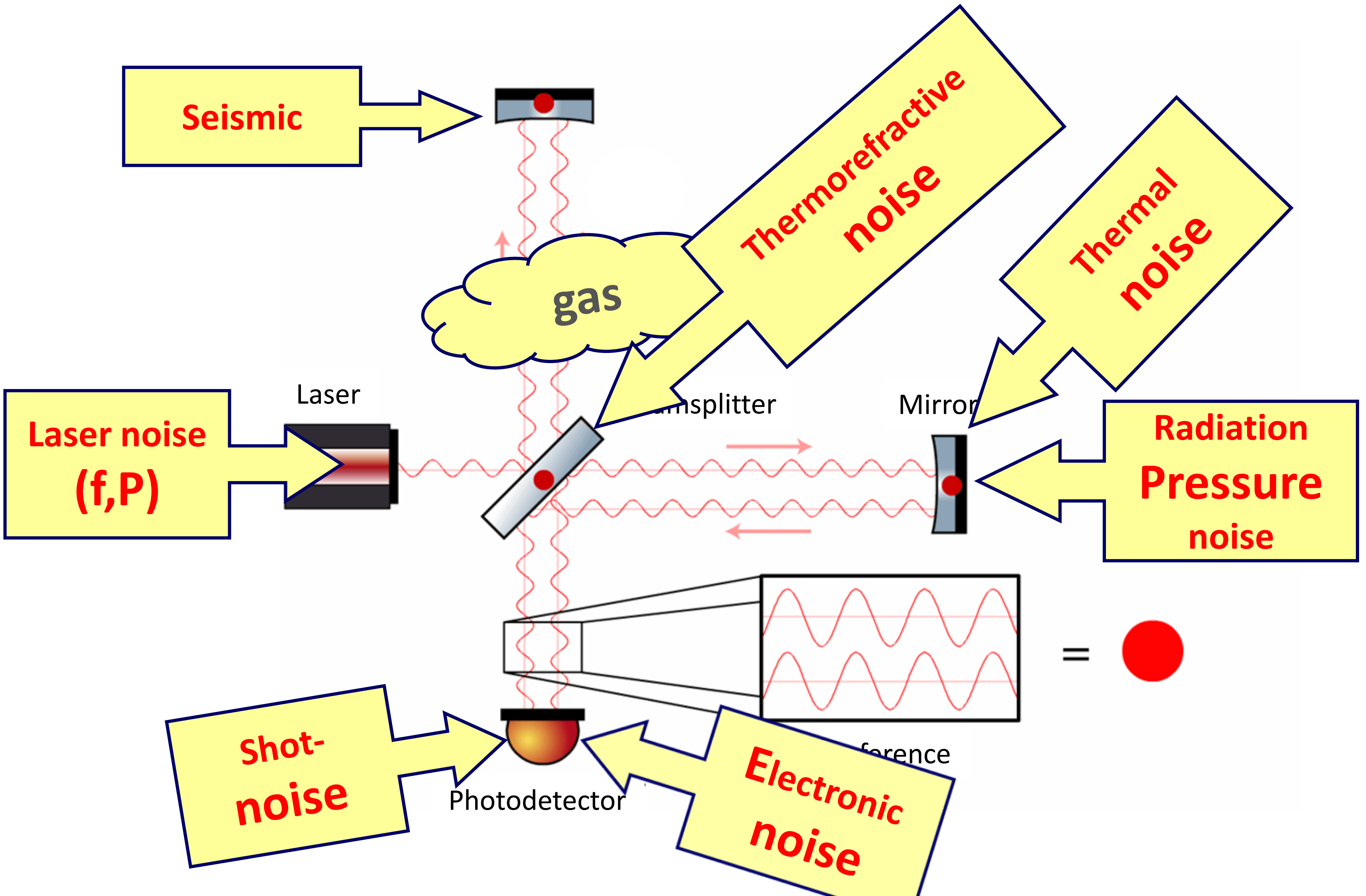
Virgo interferometer

- Virgo project
  - Interferometer with 3 km arms
  - France, Italy, Netherlands, Poland and Hungary

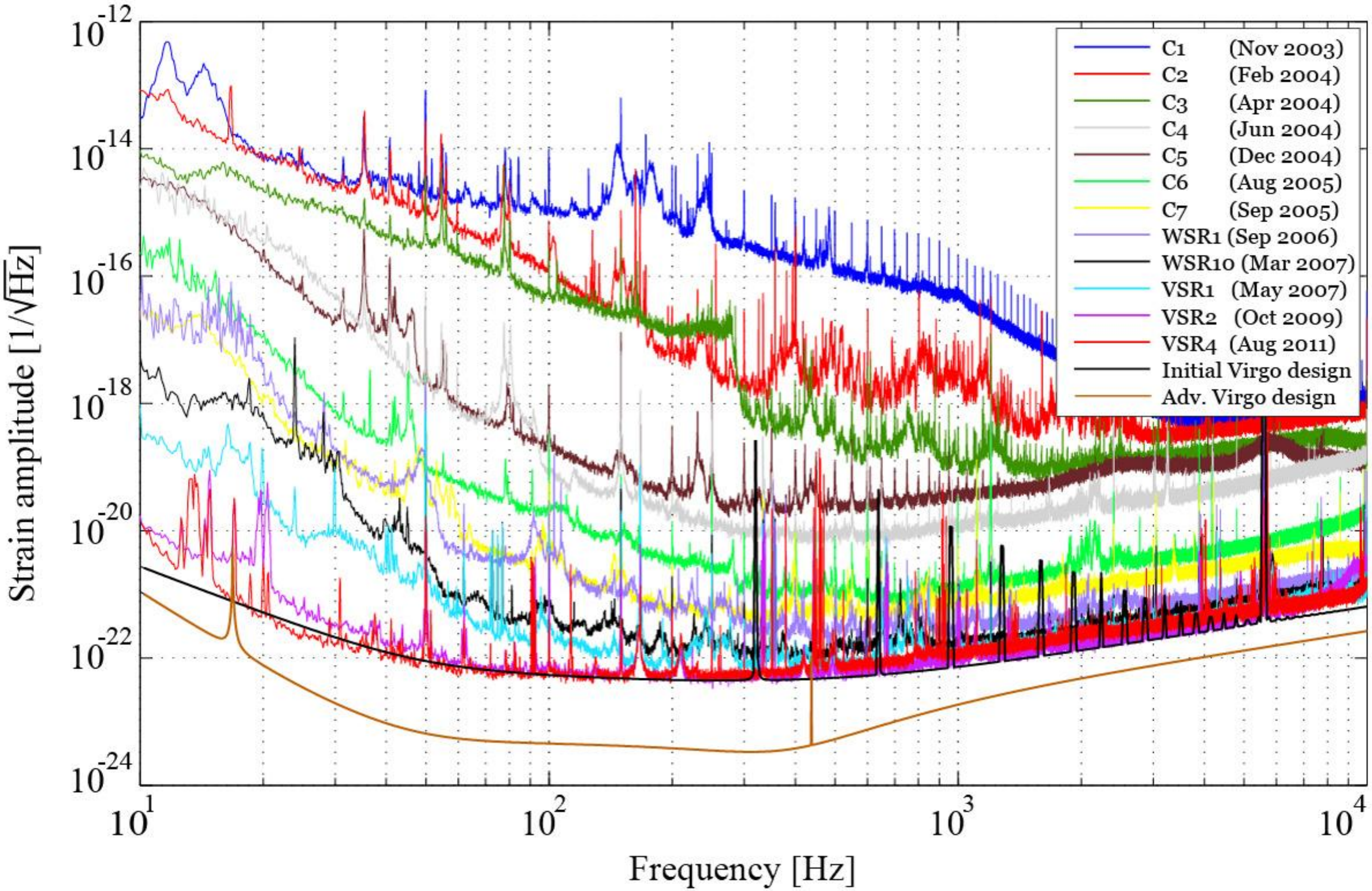


Effect of a powerful GW
h = 10^-22
4000,000000000000000004 m
3999,999999999999999996 m
Haar
Atom
Proton

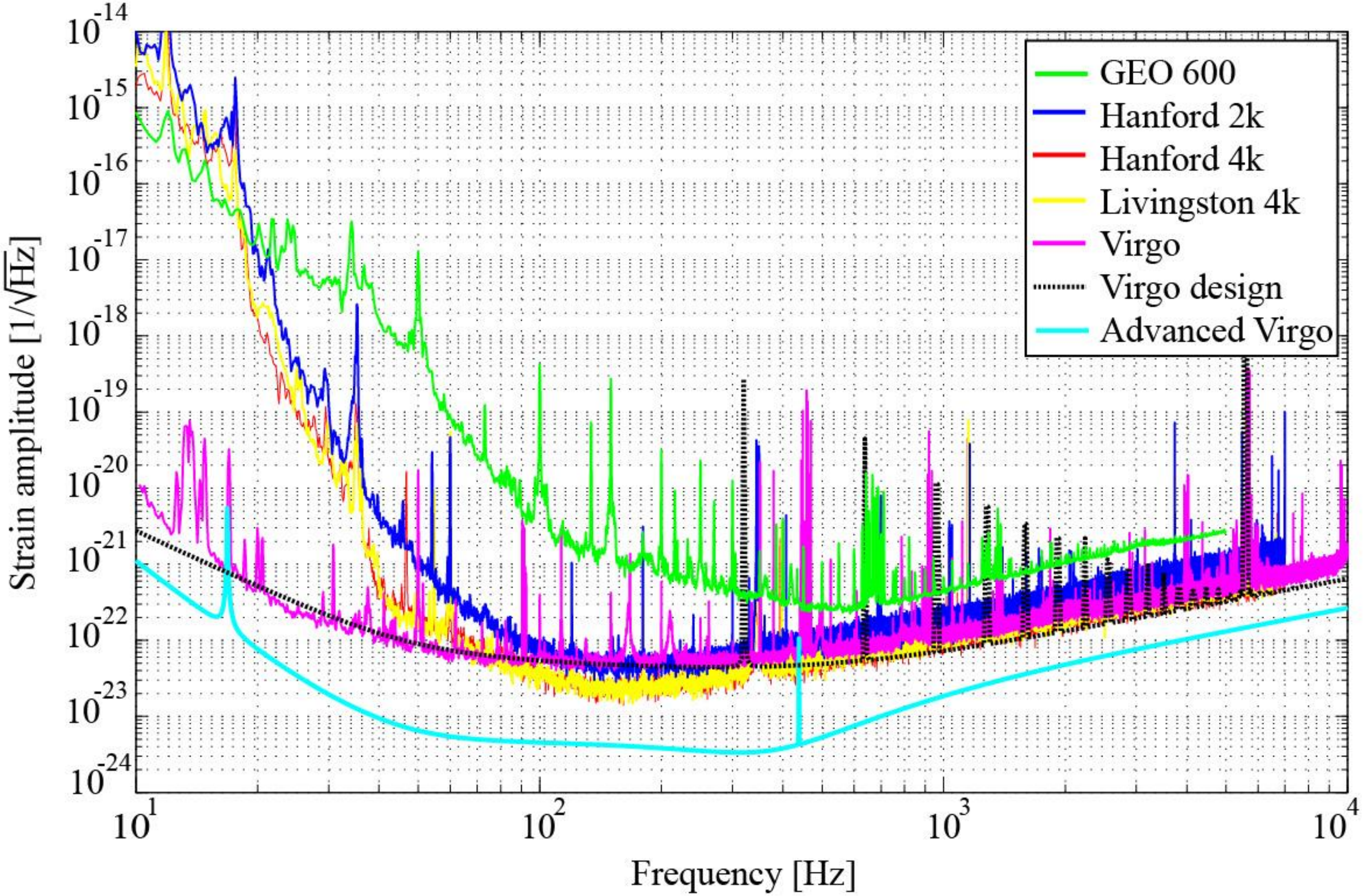
Interferometer



Evolution of sensitivity

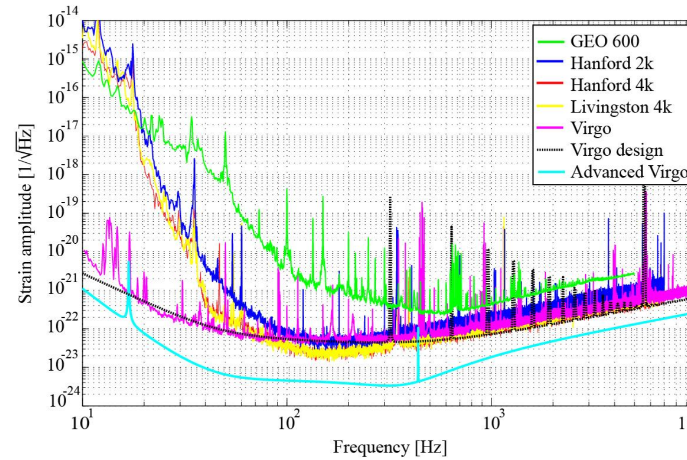


Initial interferometers



1st Generation interferometers

- Nominal sensitivity achieved
  - Virgo: low frequency performance
  - 1.2 years of scientific data taking
  - No detection



THE ASTROPHYSICAL JOURNAL, 715:1438–1452, 2010 June 1

doi:10.1088/0004-637X/715/2/1438

SEARCH FOR GRAVITATIONAL-WAVE BURSTS ASSOCIATED WITH GAMMA-RAY BURSTS USING DATA FROM LIGO SCIENCE RUN 5 AND VIRGO SCIENCE RUN 1

O(100) PAPERS ON ASTROPHYSICS/COSMOLOGY/ ASTROPARTICLE PHYSICS

PHYSICAL REVIEW D **82,** 102001 (2010)

Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1

PHYSICAL REVIEW D **87,** 022002 (2013)

Search for gravitational waves from binary black hole inspiral, merger, and ringdown in LIGO-Virgo data from 2009–2010

PHYSICAL REVIEW D **81,** 102001 (2010)

All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run

THE ASTROPHYSICAL JOURNAL, 715:1453–1461, 2010 June 1

doi:10.1088/0004-637X/715/2/1453

SEARCH FOR GRAVITATIONAL-WAVE INSPIRAL SIGNALS ASSOCIATED WITH SHORT GAMMA-RAY BURSTS DURING LIGO'S FIFTH AND VIRGO'S FIRST SCIENCE RUN

A first search for coincident gravitational waves and hi neutrinos using LIGO, Vir ANTARES data from 200

The ANTARES collaboration, the LIGO scie the Virgo collaboration

nature Vol 460 | 20 August 2009 | doi:10.1038/nature08278

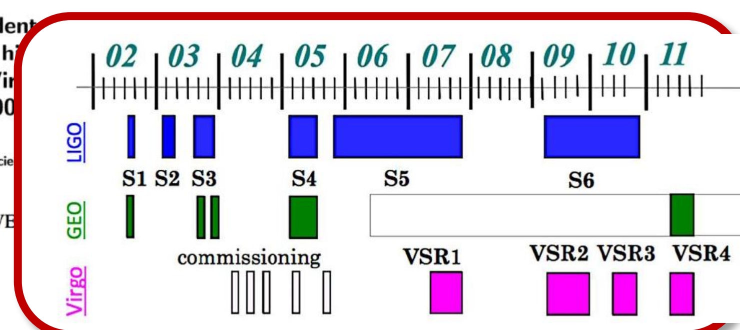
LETTERS

THE ASTROPHYSICAL JOURNAL, 737:93 (16pp), 2011 August 20

BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE VE

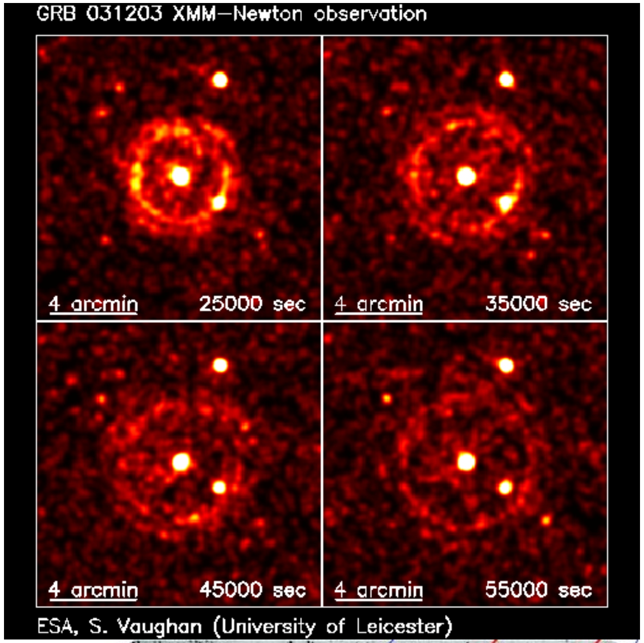
An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*



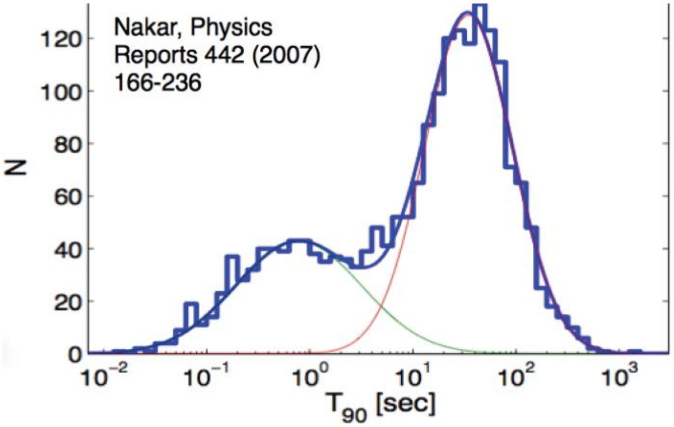
LSC-Virgo on GRBs

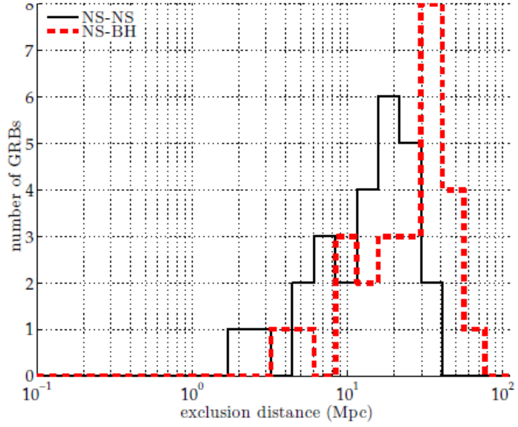
- GRB 070201
  - LSC searched for binary inspirals and did not find any events (ApJ 681 1419 2008)
  - Excludes binary progenitor in M31
  - Soft Gamma-ray Repeater (SGR) models predict energy release
  - SGR not excluded by GW limits
- LSC – Virgo search
  - 2009 – 2010: 154 GRBs
  - Null results

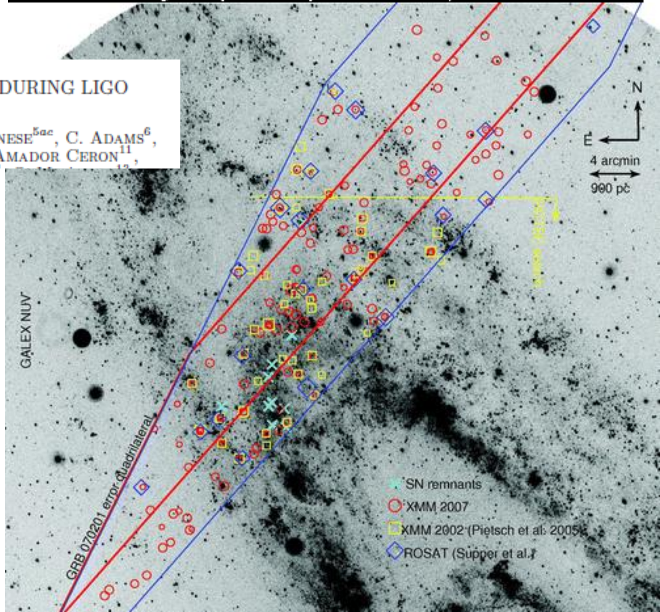


SEARCH FOR GRAVITATIONAL WAVES ASSOCIATED WITH GAMMA-RAY BURSTS DURING LIGO SCIENCE RUN 6 AND VIRGO SCIENCE RUNS 2 AND 3

J. Abadie[1], B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. Abernathy[3], T. Accadia[4], F. Acernese[5ac], C. Adams[6], R. X. Adhikari[1], C. Affeldt[7,8], M. Agathos[9a], K. Agatsuma[10], P. Ajith[1], B. Allen[7,11,8], E. Amador Ceron[11],







Detection limits for known pulsars

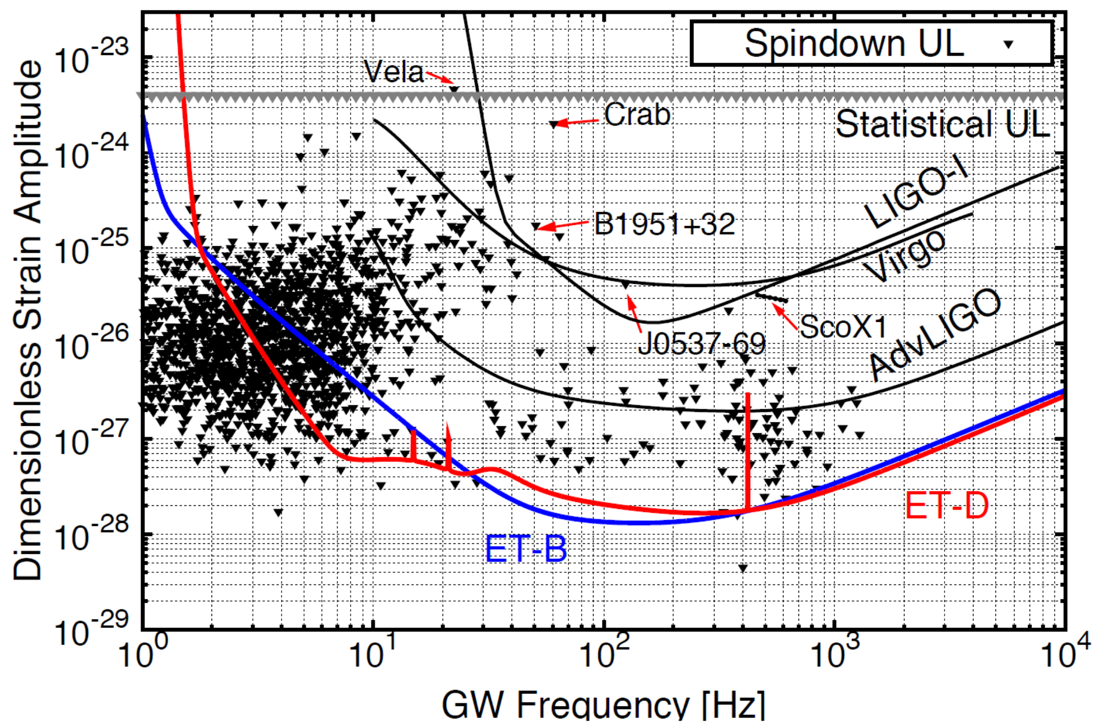
- Upper limits and spin-down limits
  - Averaged over sky positions and pulsar orientations
  - False alarm rate 1%
  - False dismissal rate 10%
  - Spin-down limits assume
    - 1 – 3 x 10^{38} kg m^2 MOI
    - ±10% distance uncertainty
  - Integration time
    - Initial LIGO and Virgo: 2 years, the rest 5 years

$$h_+(t) = A_+ \cos\Phi(t), \qquad h_\times(t) = A_\times \sin\Phi(t),$$

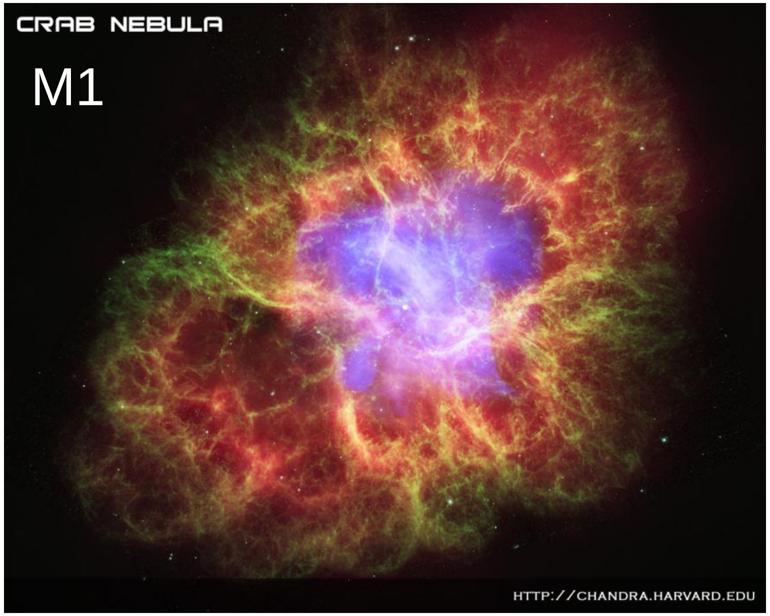
$$\Phi(\tau) = \phi_0 + 2\pi \sum_{n=0}^{s} \frac{f_{(n)}}{(n+1)!}\tau^{n+1}$$

$$A_+ = \frac{1}{2}h_0(1+\cos^2\iota), \qquad A_\times = h_0\cos\iota$$

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz}\epsilon f^2}{d} \qquad \epsilon = \frac{I_{xx}-I_{yy}}{I_{zz}}$$



Spin-down limit on Crab pulsar

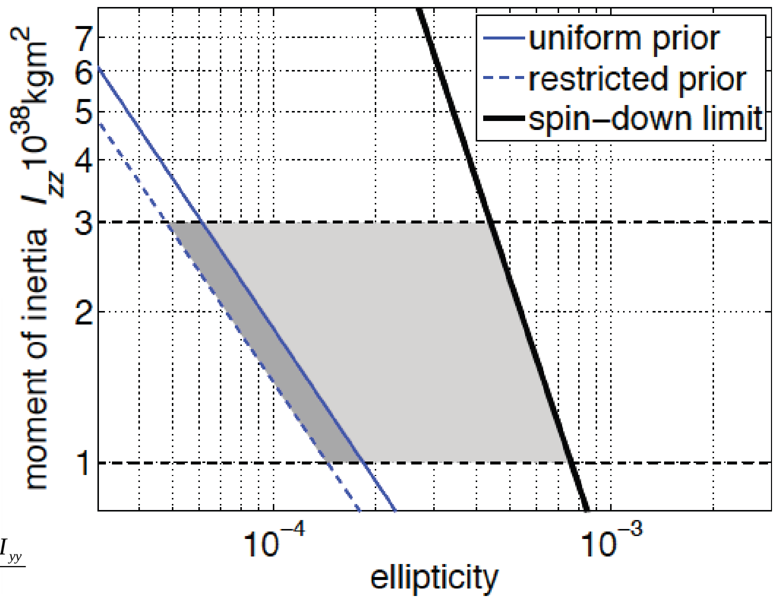


- Crab pulsar
  - 2 kpc away, formed in 1054 AD
  - Losing energy in the form of particles and radiation, leading to its spin-down
    - Spin frequency ν = 29.78 Hz
    - Spin-down rate -3.7×10^{-10} Hz s^{-1}

$$P = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times10^{31}\ \mathrm{W}$$

$$h_0^{sd} = 8.06\times10^{-19} I_{38} r_{\mathrm{kpc}}^{-1}\varepsilon\left(|\dot{\nu}|/\nu\right)^{1/2}$$

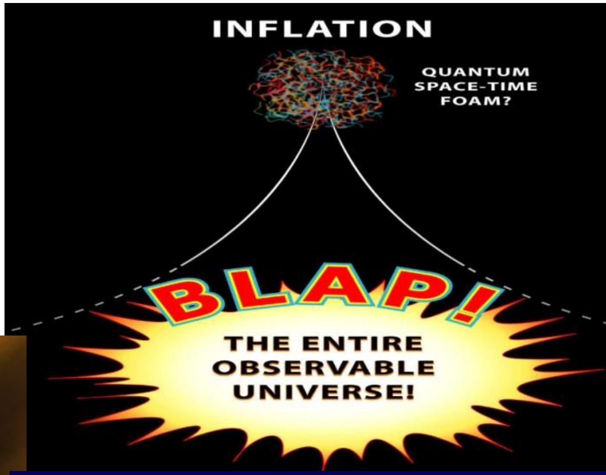
- LSC – Virgo search
  - Search for GW in data in S5 and VSR1
  - Limit on ellipticity about 4x better than spin-down limit
  - Less than 2% of energy in GW
- LSC – Virgo search for VELA
- All-sky search for CWs

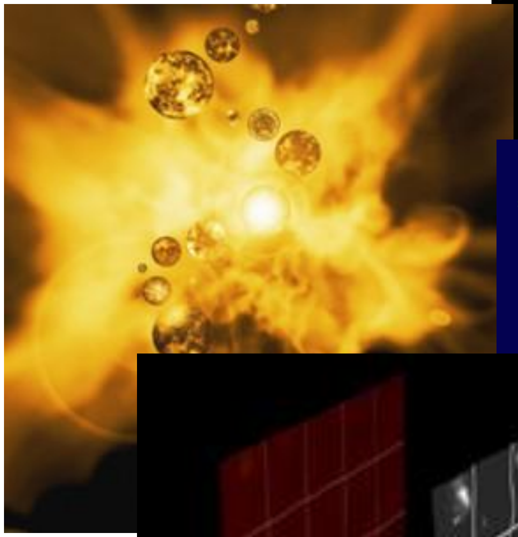


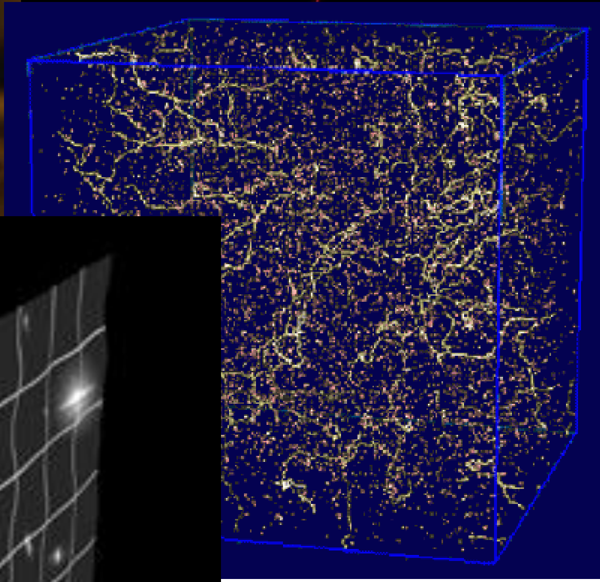
$$h_0^{95\%} = 3.4\times10^{-25} \quad \varepsilon = 1.8\times10^{-4} \quad h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz}\varepsilon\nu^2}{d} \quad \varepsilon = \frac{I_{xx}-I_{yy}}{I_{zz}}$$

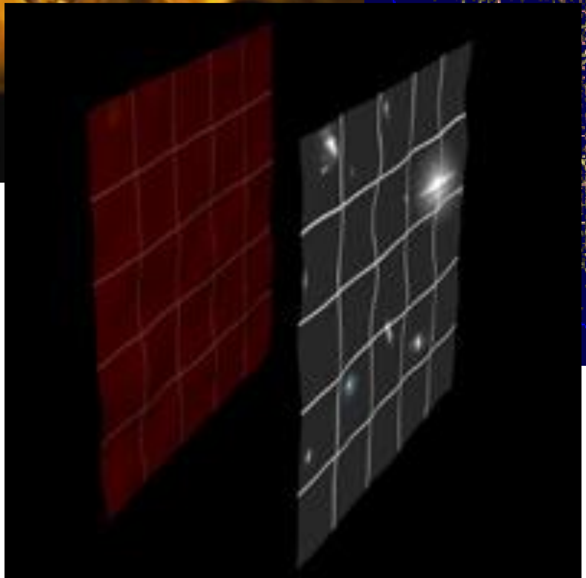
Primeordial gravitational waves

- Primeordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field
- Stochastic background
  - Inflation
    - Period of exponential growth of the Universe
  - Phase transitions
    - Forces of Nature splitting off
  - Cosmic strings
    - Topological defects or fundamental (super)strings
  - Predictions quantum gravity theories
    - Pre-Big-Bang cosmology
    - Brane world scenarios
    - “Bounce” cosmologies
    - …



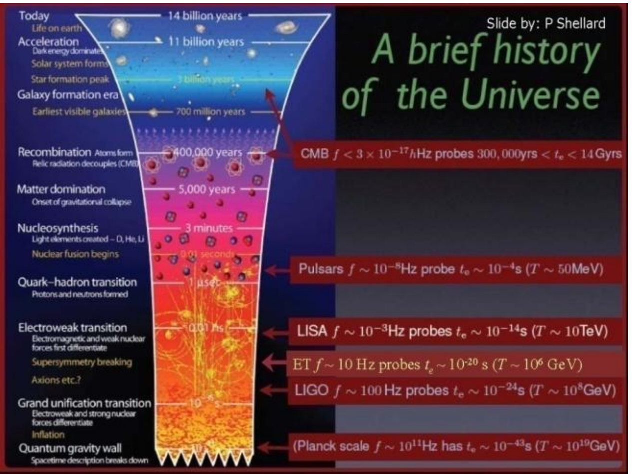


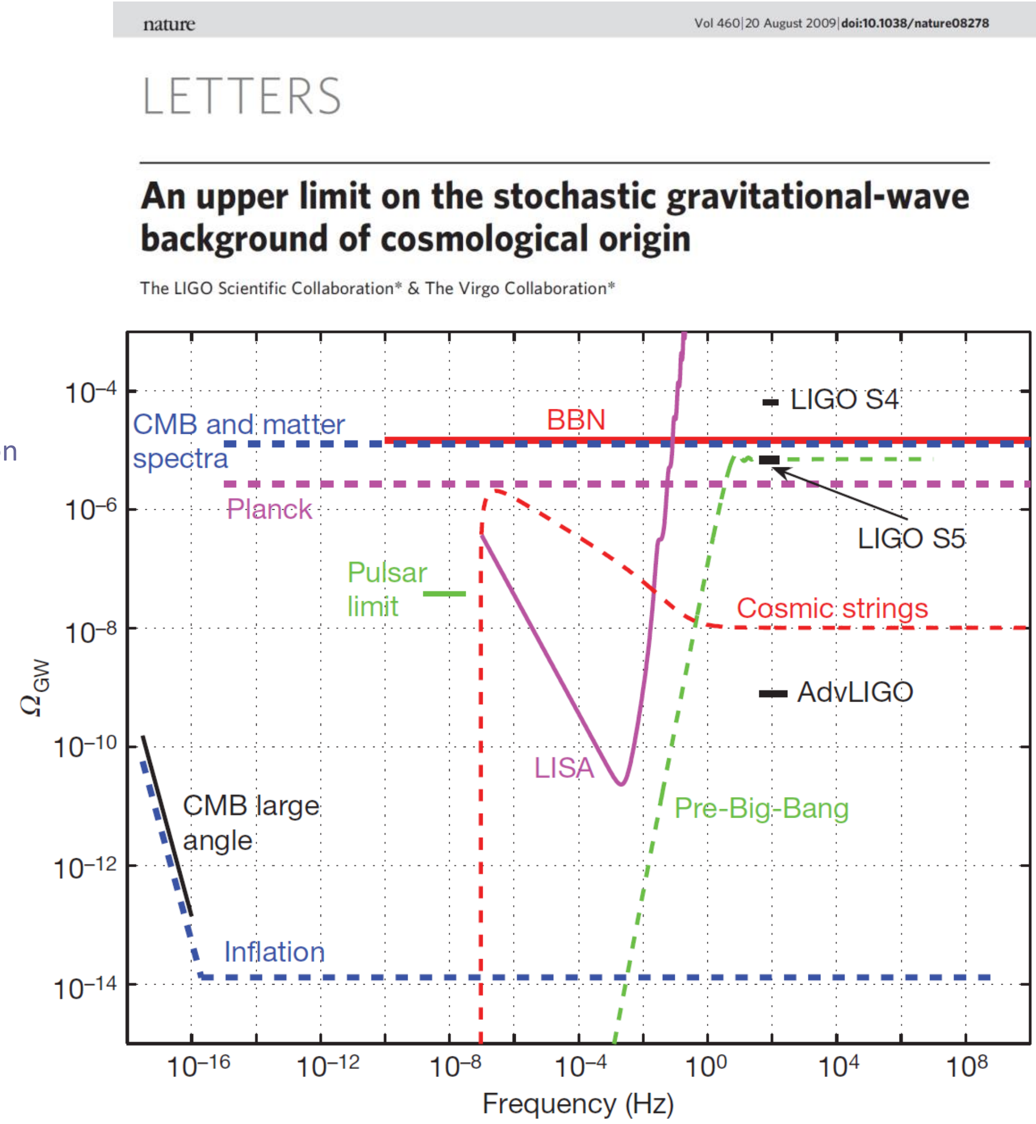




Stochastic background search

- S5 data improve this to better than the nucleosynthesis limit
  - LIGO and Virgo now provide best limit on Ω_{GW}
- Other limits
  - Models involving cosmic strings
    - Network with string tension μ
    - CMB limit $G\mu < 10^{-6}$
    - Reconnection probability p
    - Loop size determined by gravitational back reaction and parametrized by ε
  - Pre-Big-Bang models
    - Above turn-over frequency $\Omega_{GW}(f) \sim f^{3-2\mu}$




nature   Vol 460|20 August 2009|doi:10.1038/nature08278

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

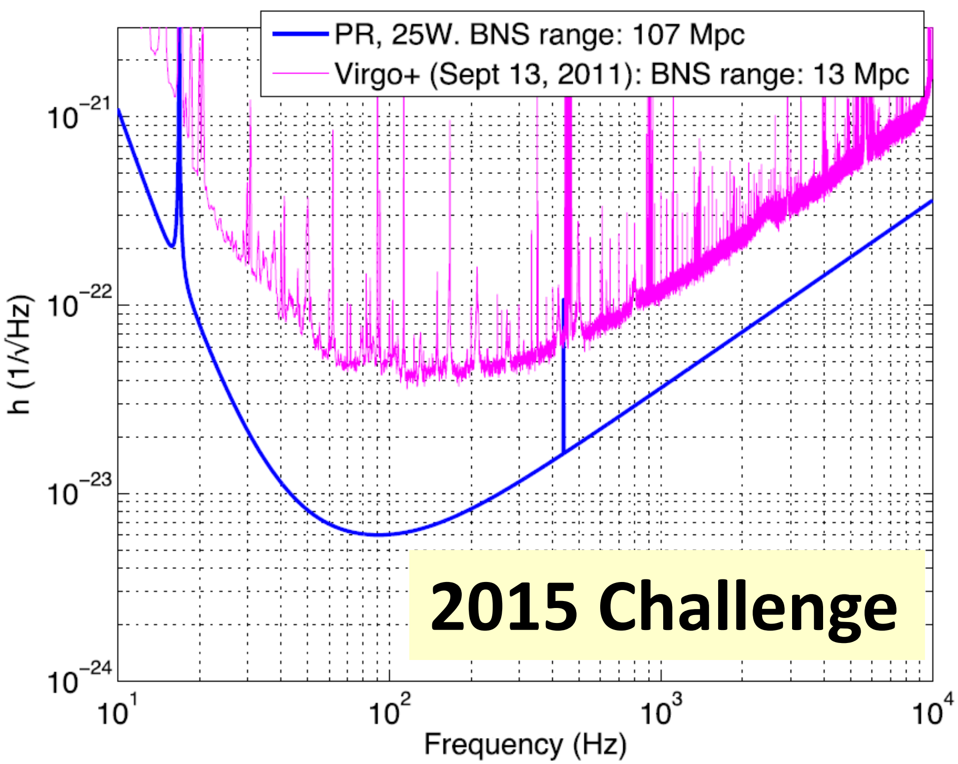
Instrumentation

Advanced Virgo

PROJECT GOALS

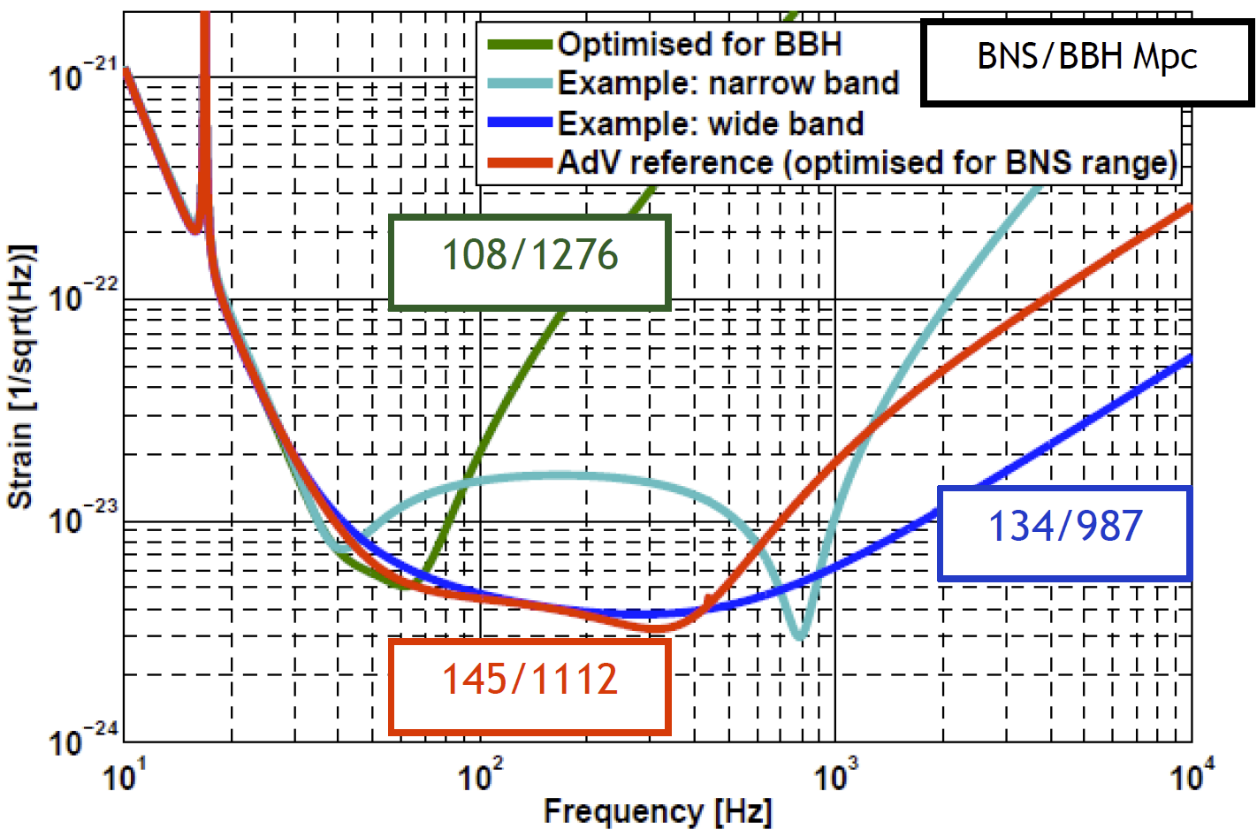
- Upgrade Virgo to a 2nd generation detector. Sensitivity: 10x better than Virgo
- Be part of the 2nd generation GW detectors network.
  Timeline: data taking with Advanced LIGO

- Improvements
  - High quality optics
    - Heavier mirrors
    - Low absorption
    - Coating thermal noise
    - 0.2 nm rms surfaces
    - Thermal compensation
    - Monolithic suspensions
  - Sensing devices under vacuum
  - Larger beams
    - Modification of UHV system
  - Signal recycling
  - ...



AdV sensitivity is tunable

- Signal recycling: sensitivity can be adjusted
  - Within limits
- Can be tuned to detect/study various sources
  - Requires signal recycling
  - Not scheduled for first AdV science run

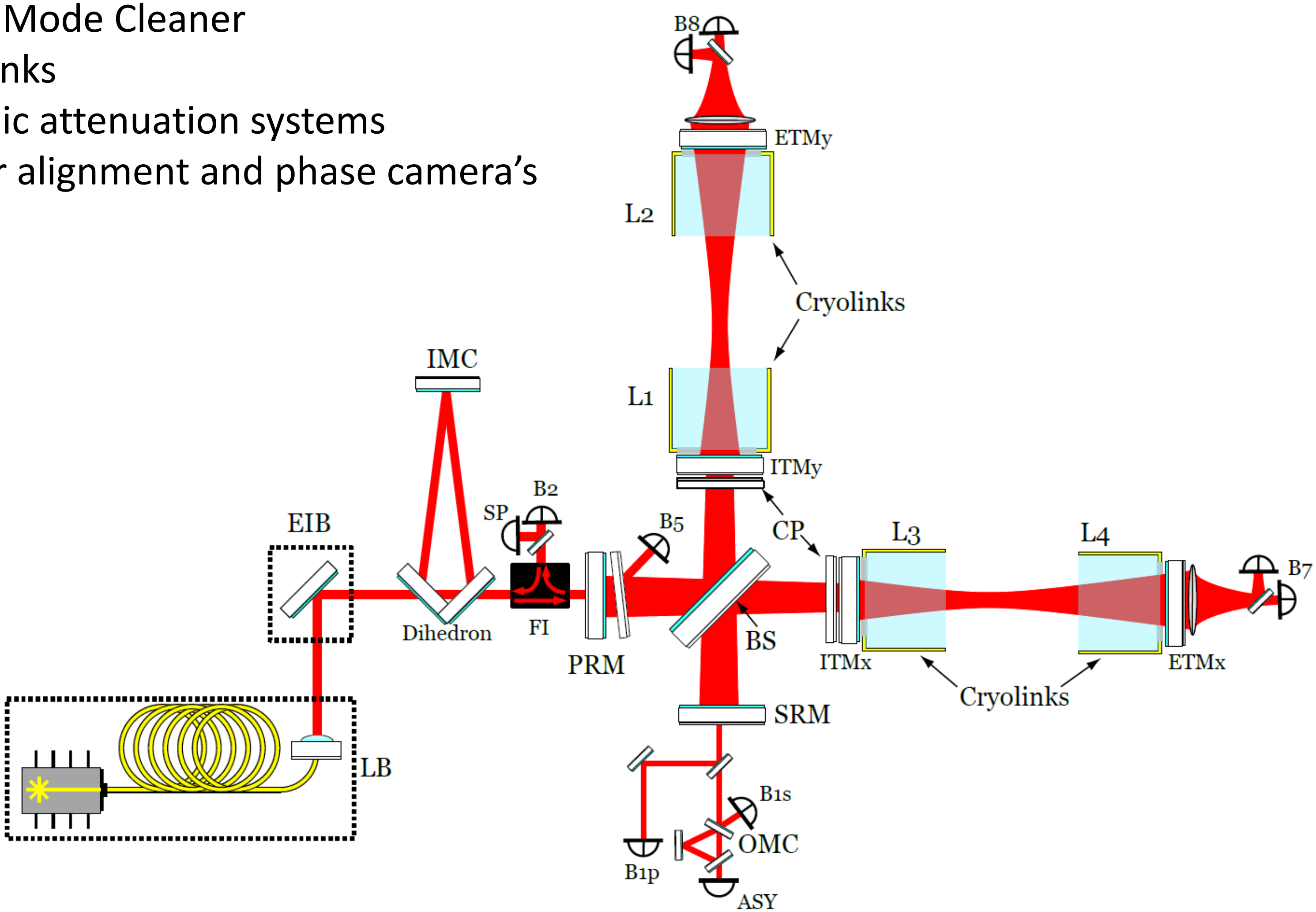


Advanced Virgo

With focus on NL contributions

Nikhef

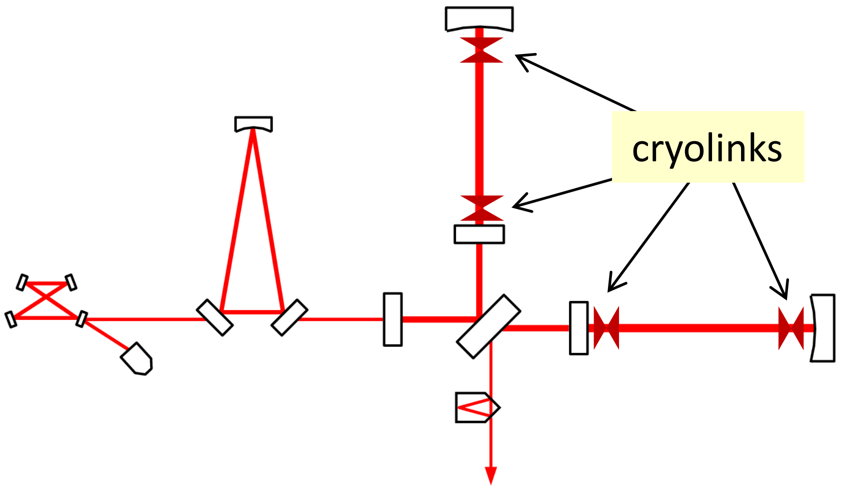
Input Mode Cleaner
Cryolinks
Seismic attenuation systems
Linear alignment and phase camera's

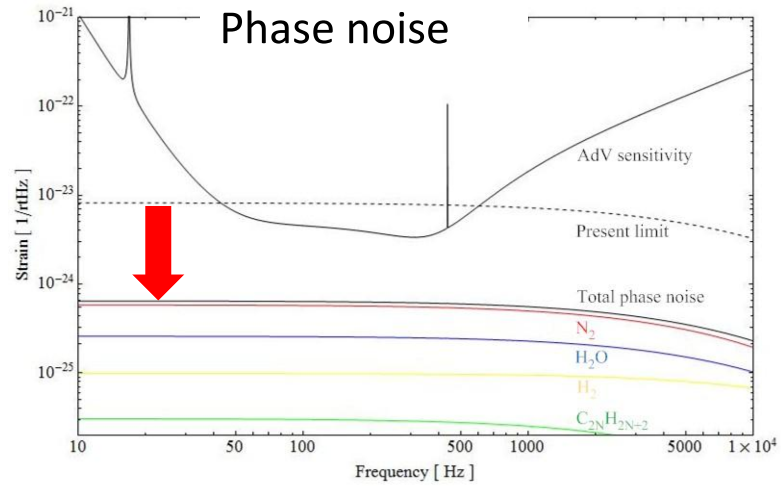


Vacuum system

- Ultra-high vacuum
  - Largest vacuum system in Europe
  - Performance limited by residual gas, mostly water vapour

Cryolinks

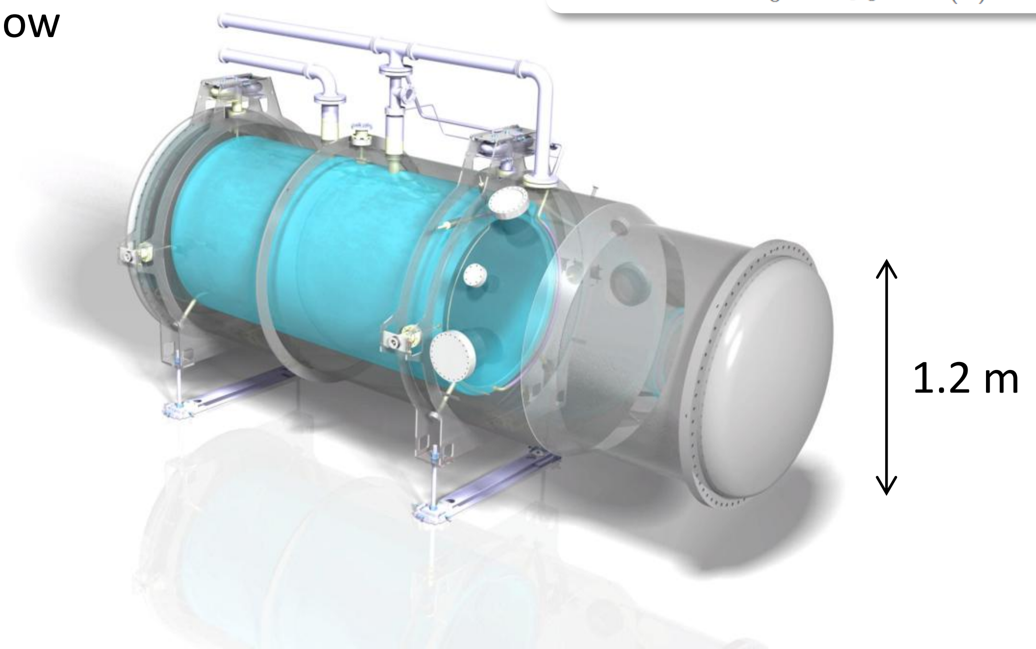


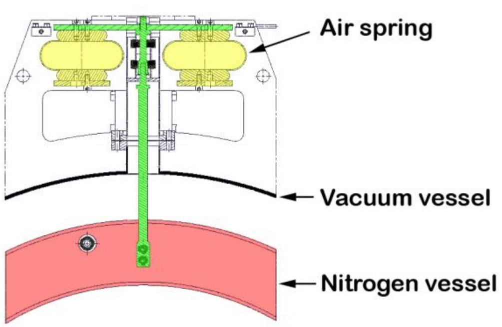


$$S_L(f) = \frac{4\rho\,(2\pi\alpha)^2}{v_0}\int_0^{L_0}\frac{1}{w(z)}e^{-2\pi f w(z)/v_0}dz$$

Vibrationless two-phase flow

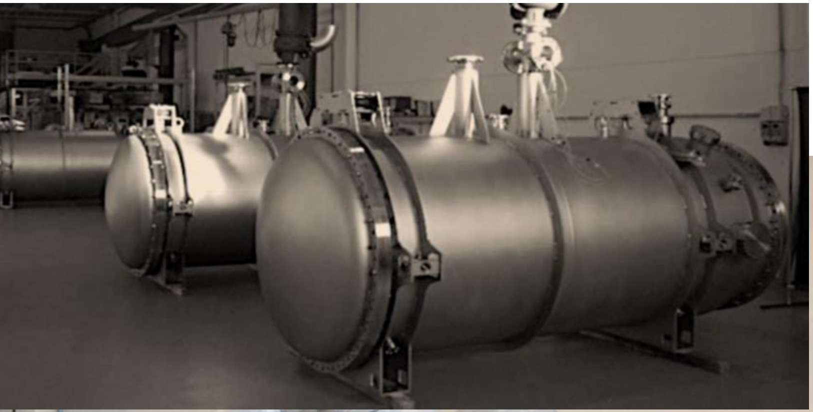
Prototype under test



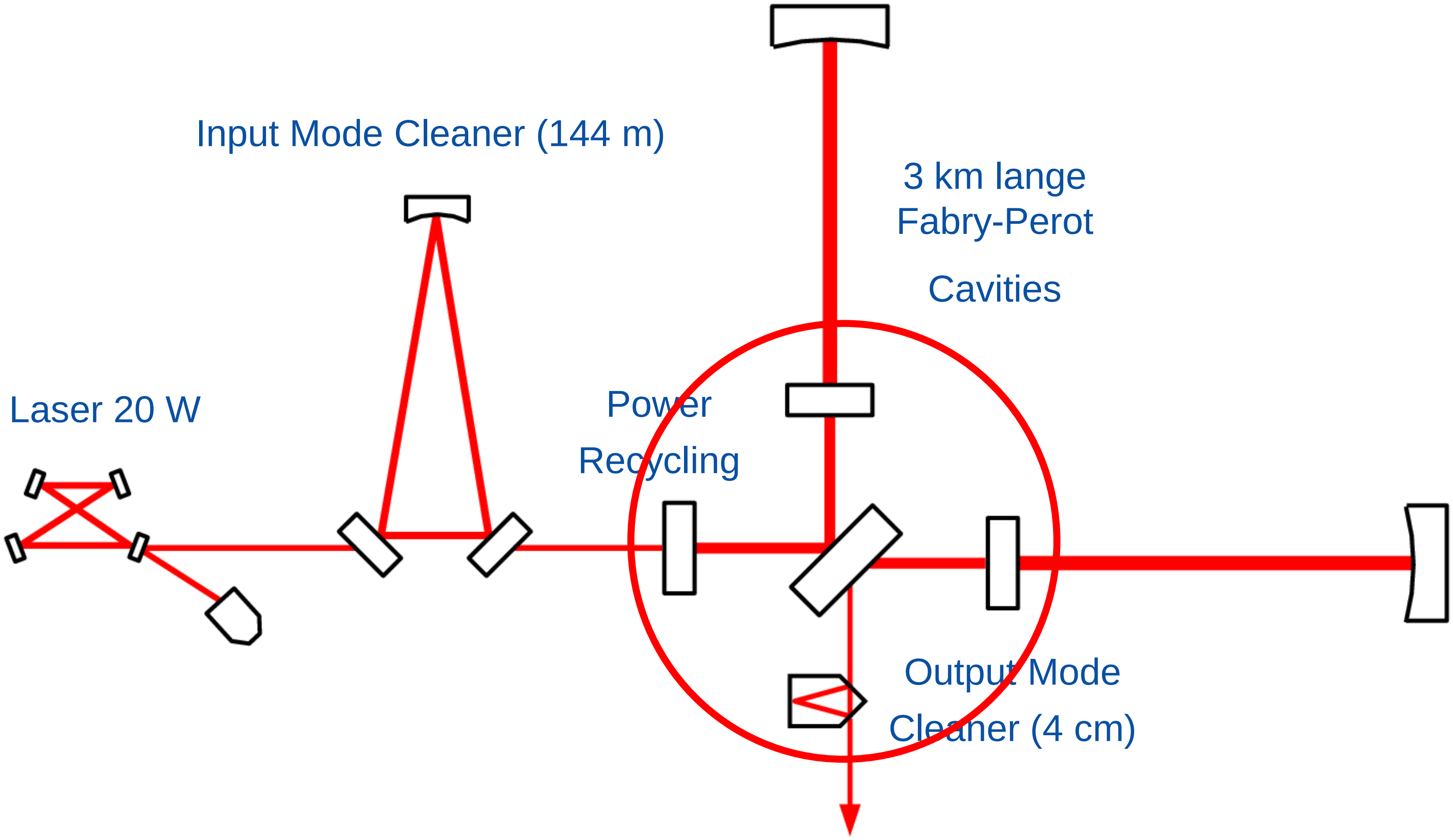


First installations for AdV

April 2014

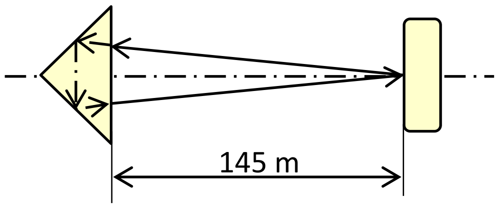


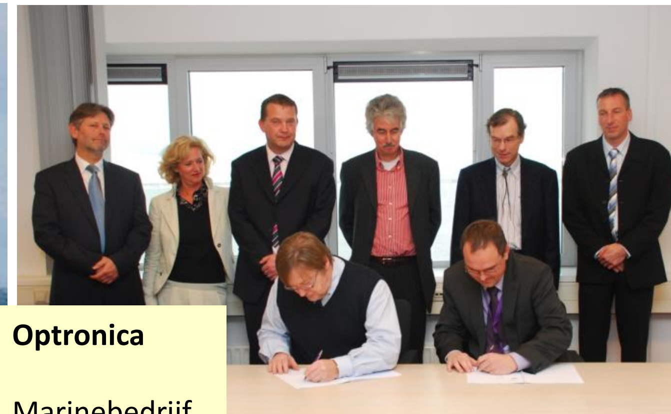
VIRGO optics layout



Input mode cleaner

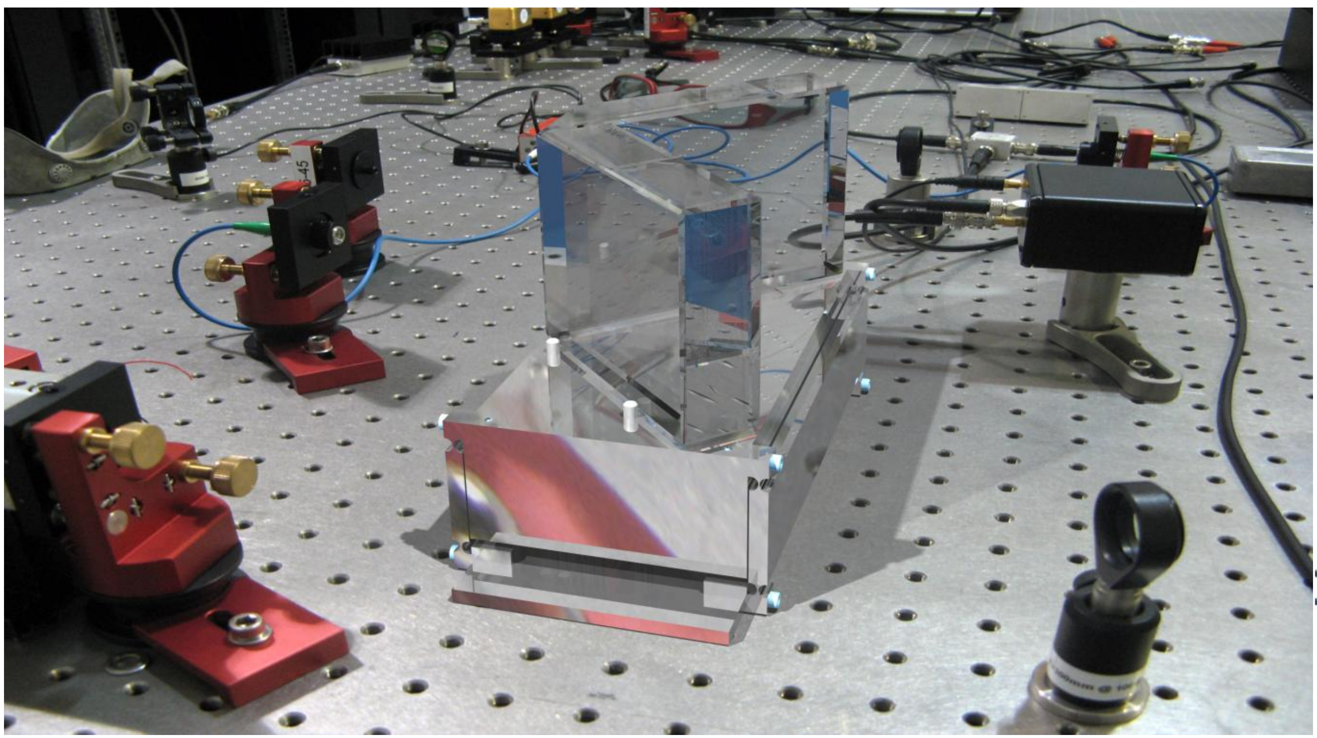
- Industry
  - Optics
    - Optronica

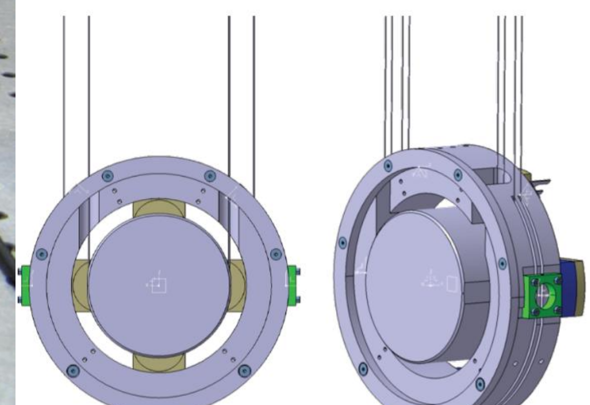




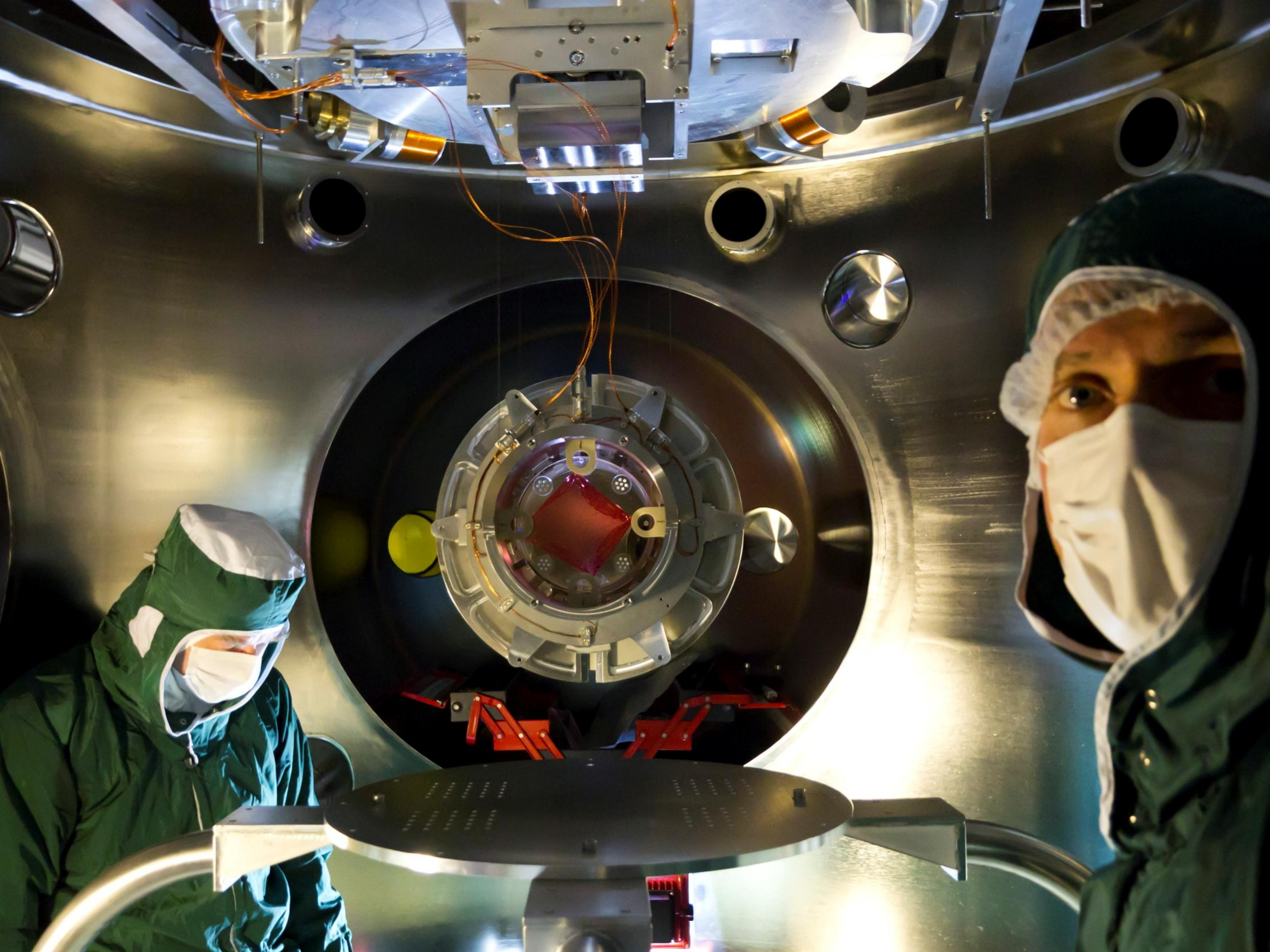
Optronica

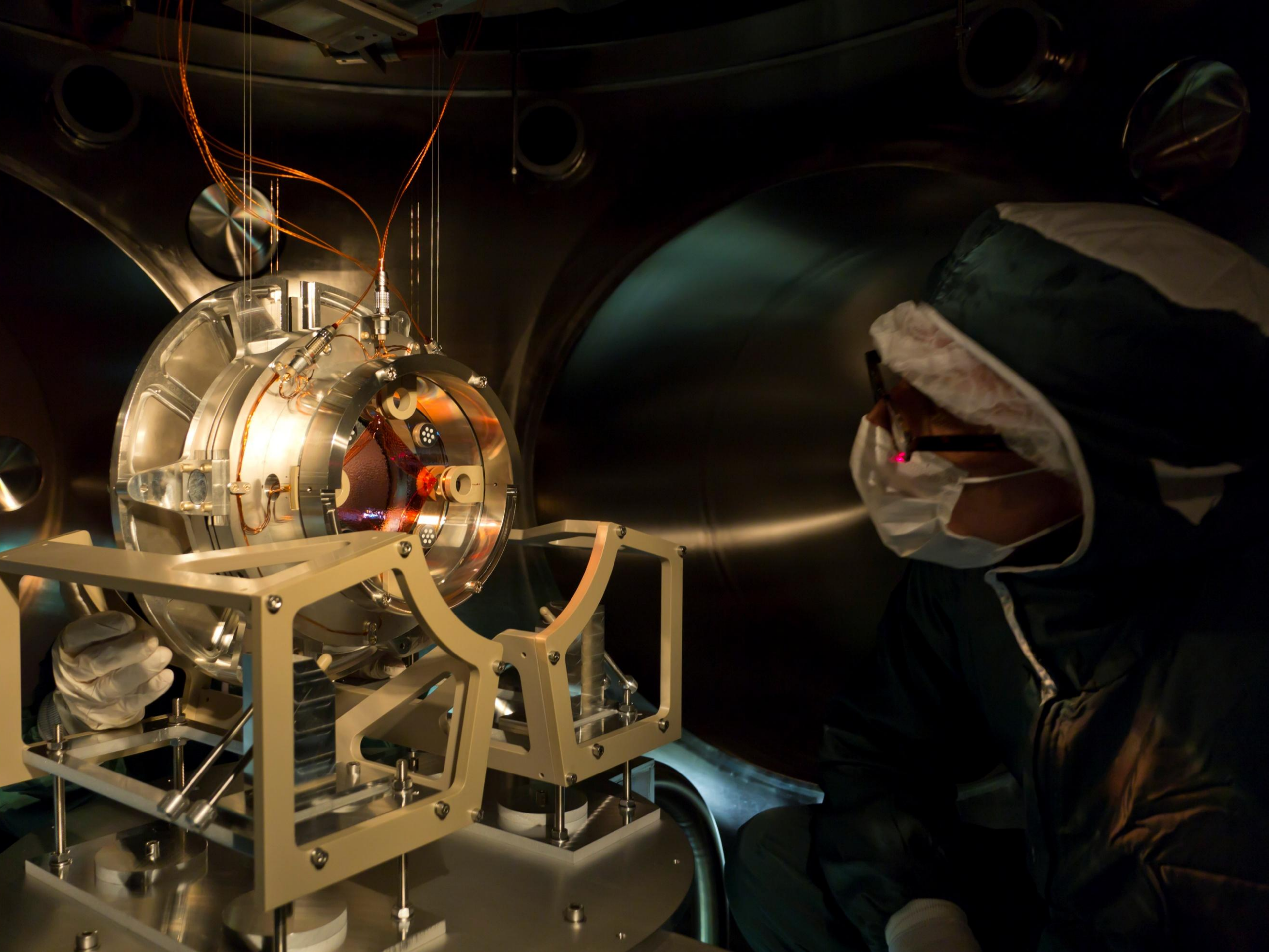
Marinebedrijf
Den Helder






Input mode cleaner
Advanced Virgo end mirror



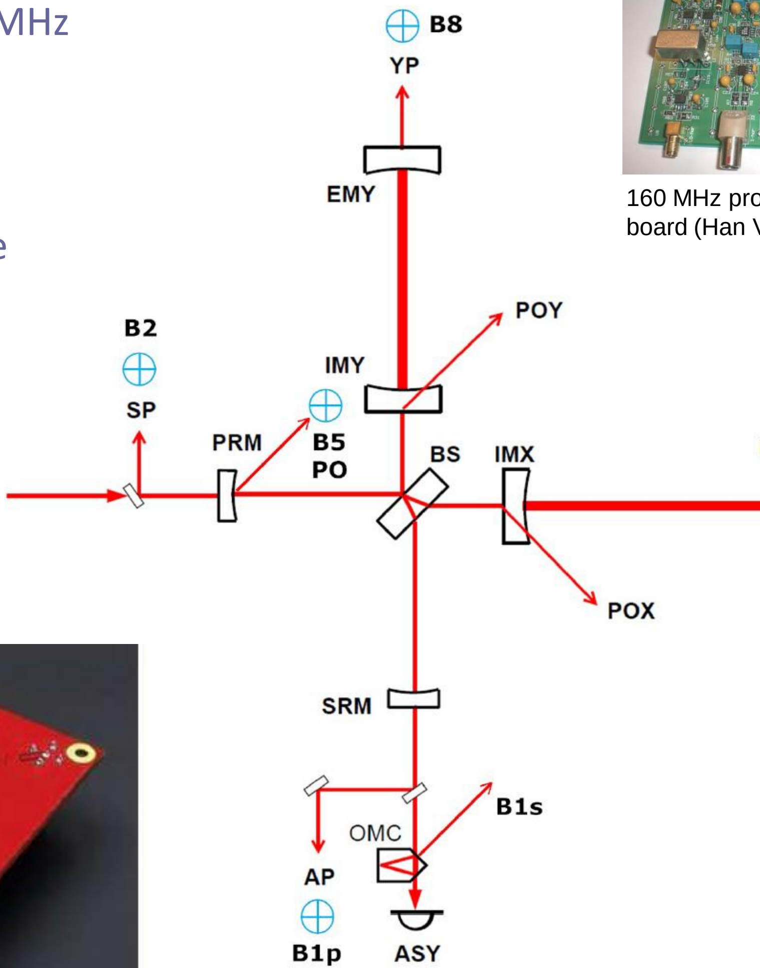


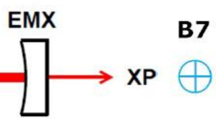
Angular cavity alignment systems

Niels van Bakel

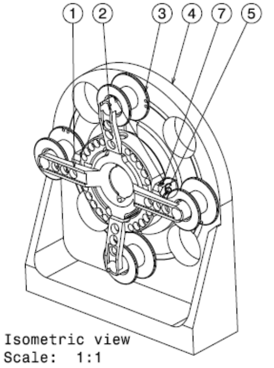
- Angular control of optical elements
  - Modulate carrier
    - DC and 6.26, 8.35, 56 and 131 MHz
  - QPD front-end systems
    - Transimpedance amplifiers
    - Shot noise limited performance
    - Operate in vacuum

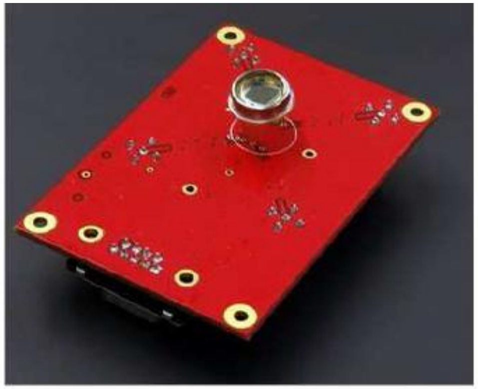
160 MHz prototype demodulation board (Han Voet, VU Amsterdam)





galvano

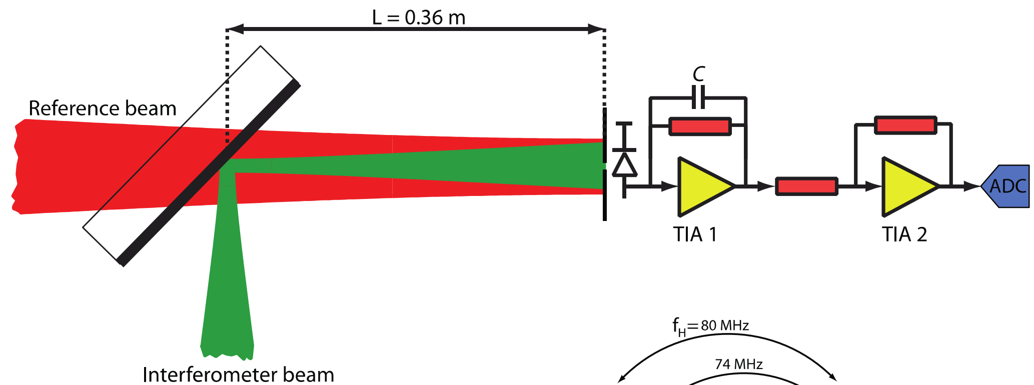


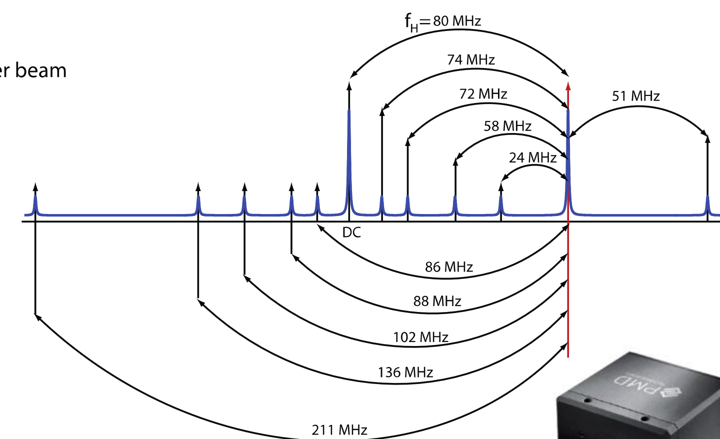


Phase camera's: 3D imaging

Martin van Beuzekom

- Imaging of cavity fields
  - Both carrier and sidebands
    - f1 = 6.270 777 MHz
    - f2 = 56.436 993 MHz
    - f3 = 8.361 036 MHz
    - f4 = 131.686 317 MHz
    - f5 = 22.38 MHz
    - fH= 80.00 MHz
  - Amplitude and phase
    - High speed imaging of HOM
    - Avoid moving parts (CCD based)
  - AdV optical design: MSRC
  - Main diagnostics for Advanced Virgo
  - Input for Thermal Compensation Systems





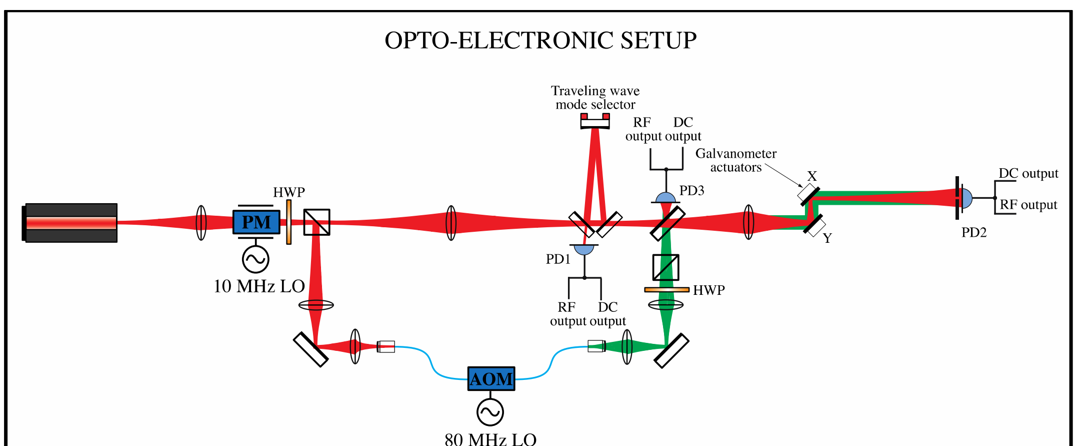
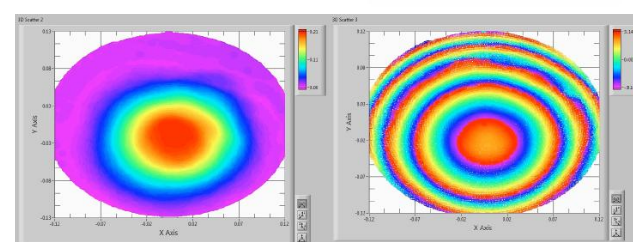
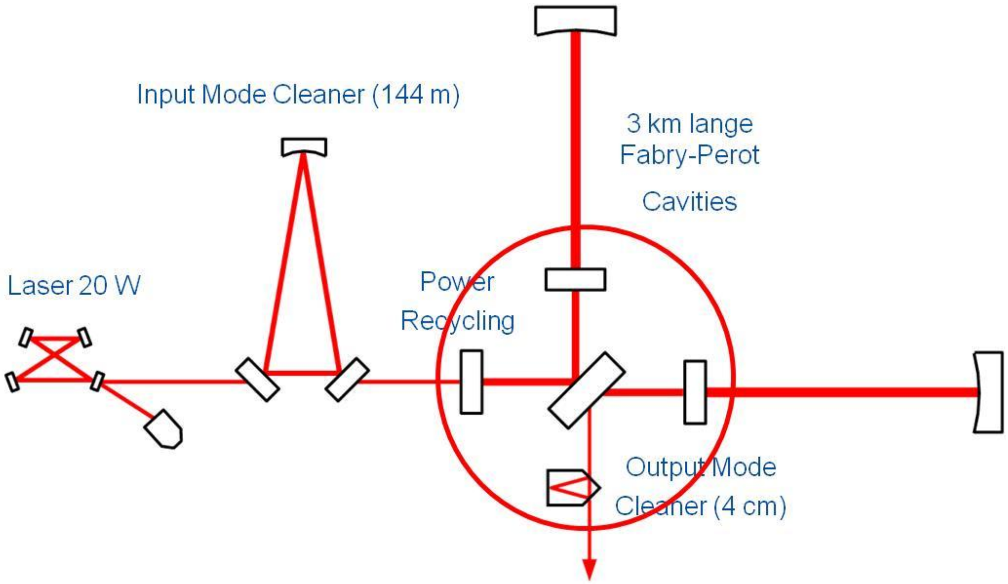
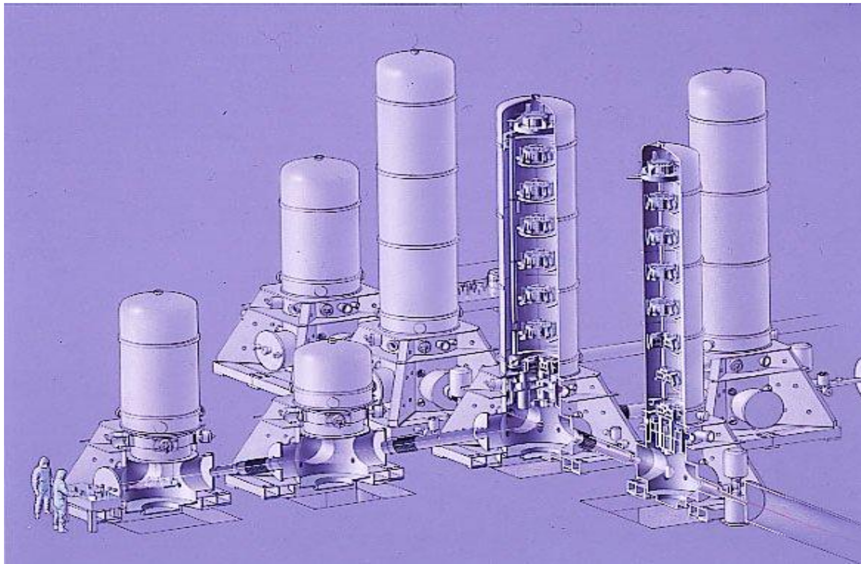


Figure 1: Current opto-electronic set up of the phase camera at Nikhef. The system uses modulation/demodulation techniques to allow for frequency selective wave-front sensing.



Central interferometer





Commissioning order

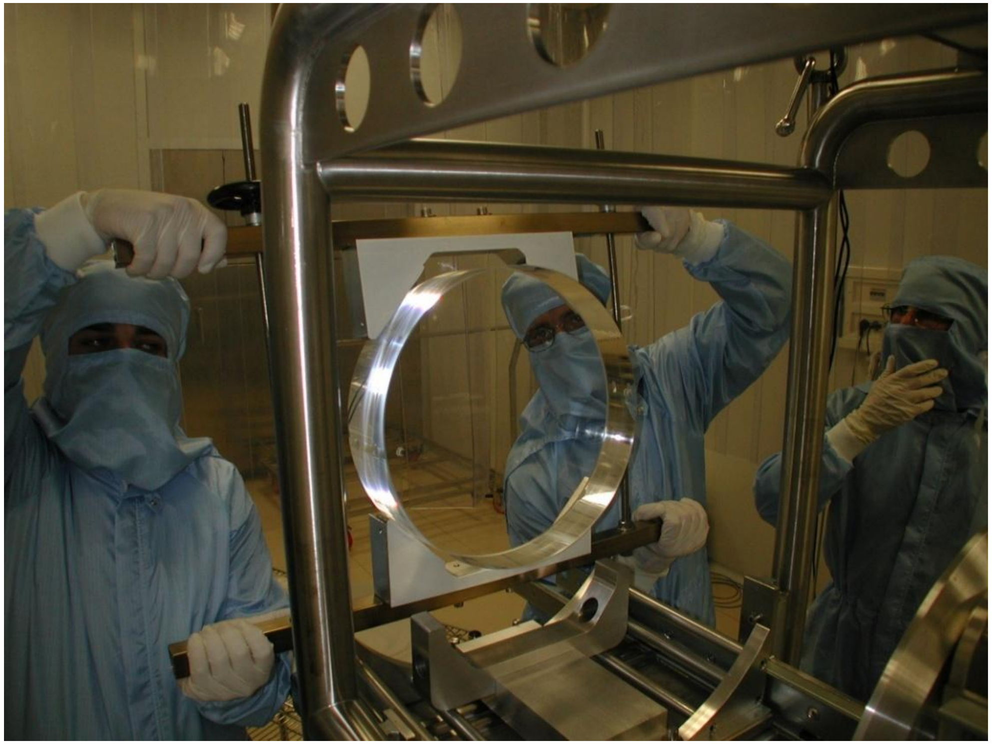
1. Injection system
2. IMC
3. CITF
4. ITF arms

Mirrors as test masses

High quality quartz

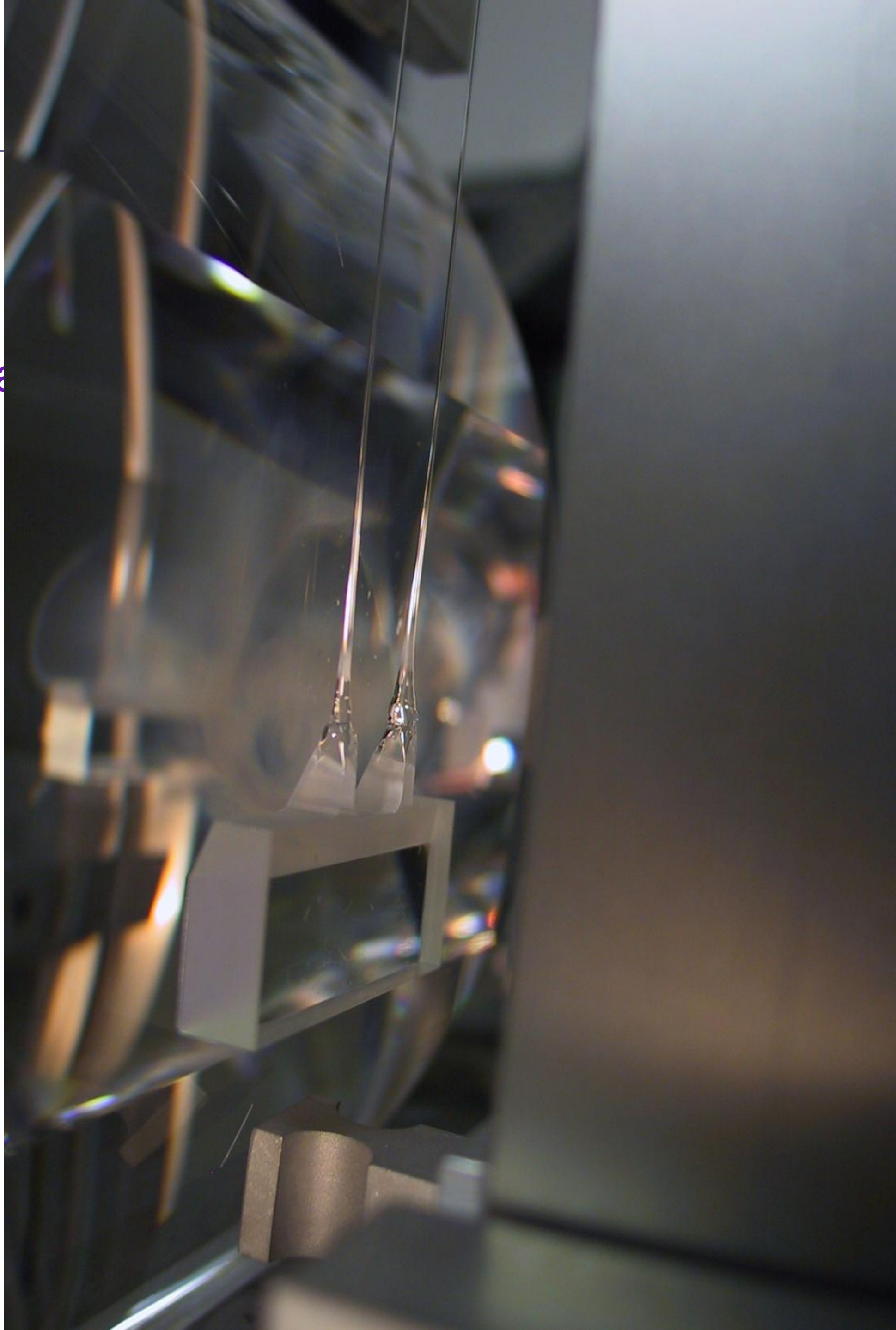
- 35 cm diameter, 20 cm thick, 40 kg mass
- Losses in ppm range
- Flatness smaller than 1 nm

Quantum effects are important

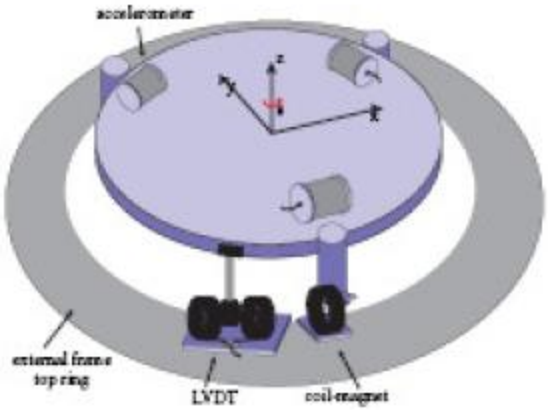


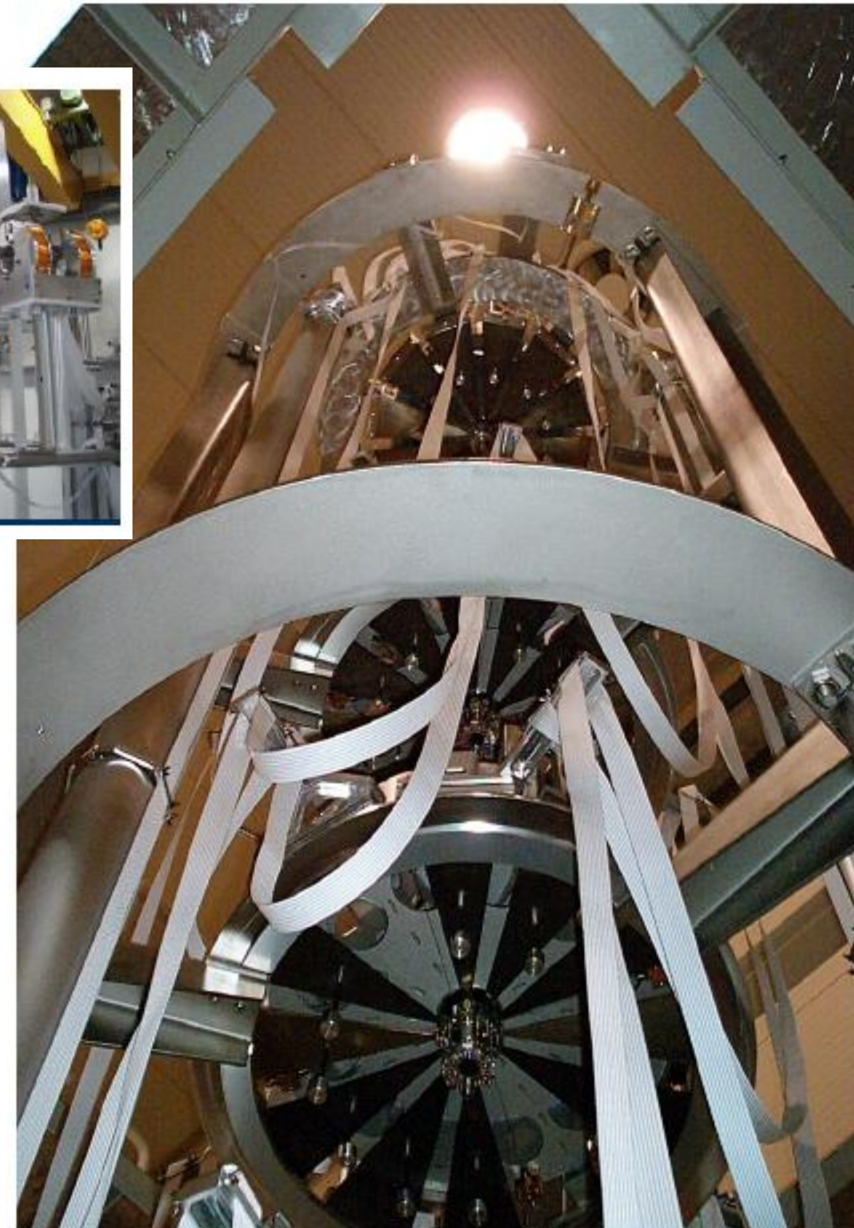
Thermal noise

- Mechanical modes are in therma
  - Modes:
    - Pendulum mode
    - Wire vibrations
    - Mirror internal modes
    - Coating surface
  - Energy: $k_B T$
- Thermal spectrum:
- Strategy:
  - Use special materials:
    → concentrate motion near resona



Superattenuators

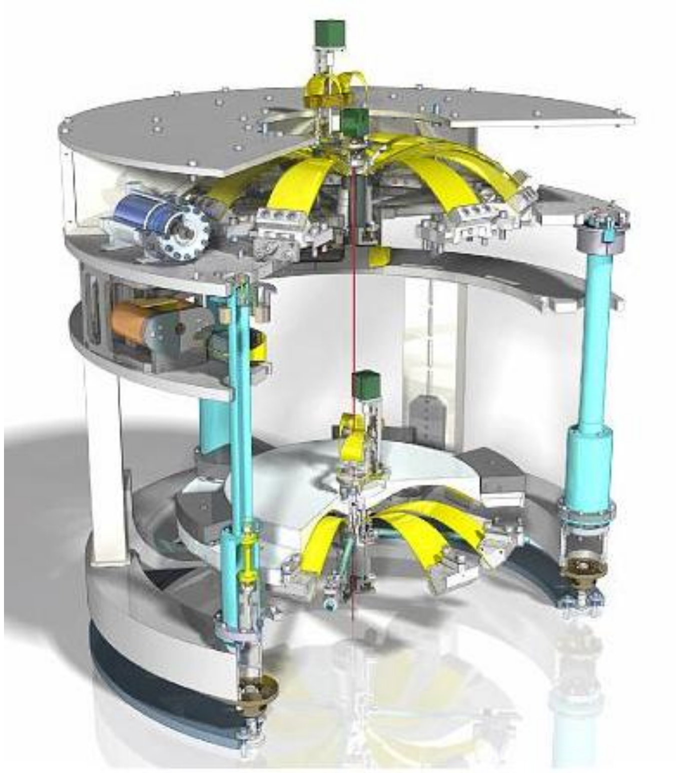




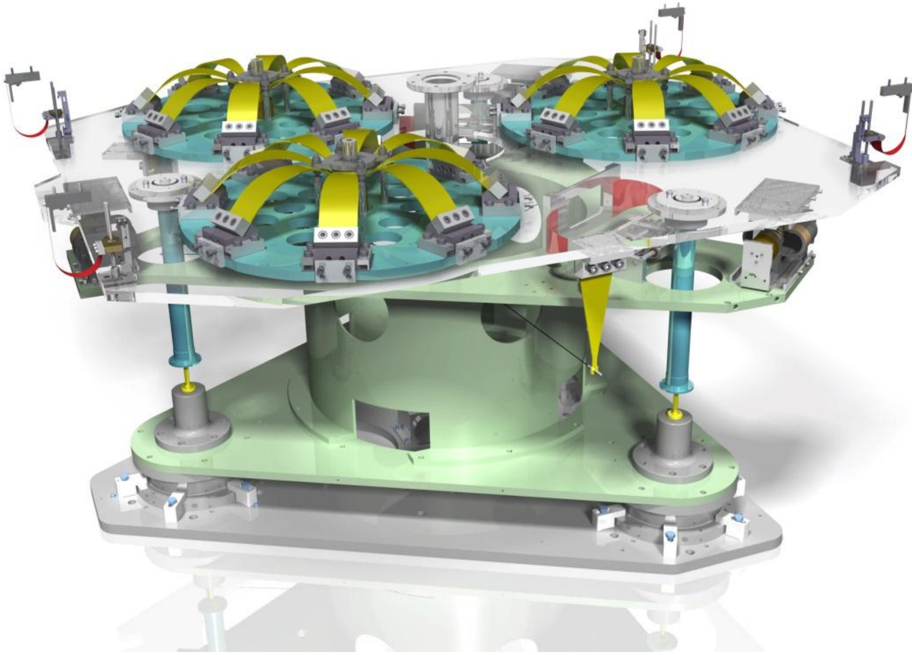
Vibration isolation – SBE

Nikhef responsibility

MultiSAS



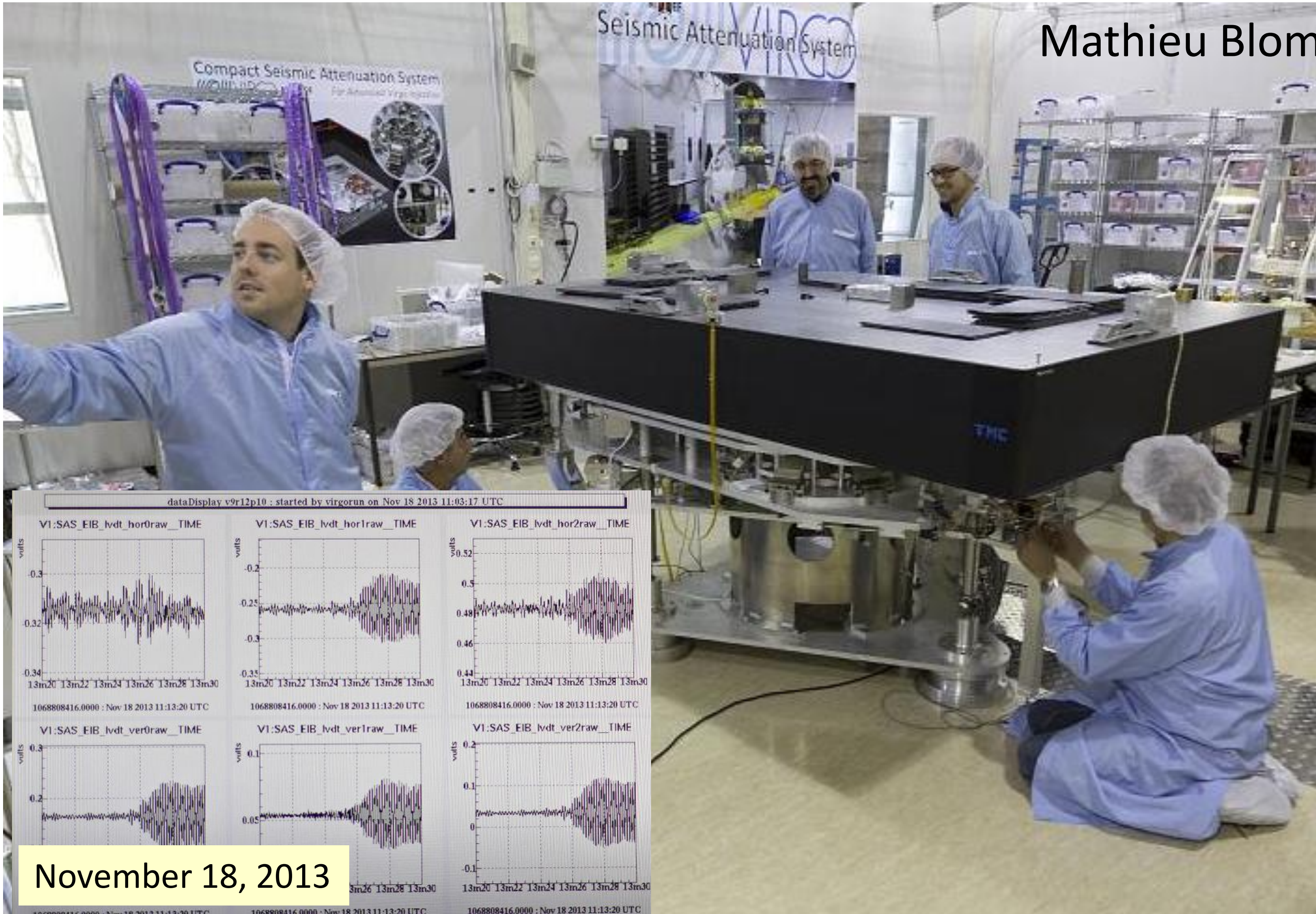
EIBSAS



External injection bench

- SAS features
  - Single-stage attenuation system
  - Six degrees of freedom
  - Sensors: 6 accelerometers, 6 LVDTs
  - Consistent with 10^{-12} m/rtHz
  - Compact design
  - Installed and tested in Virgo

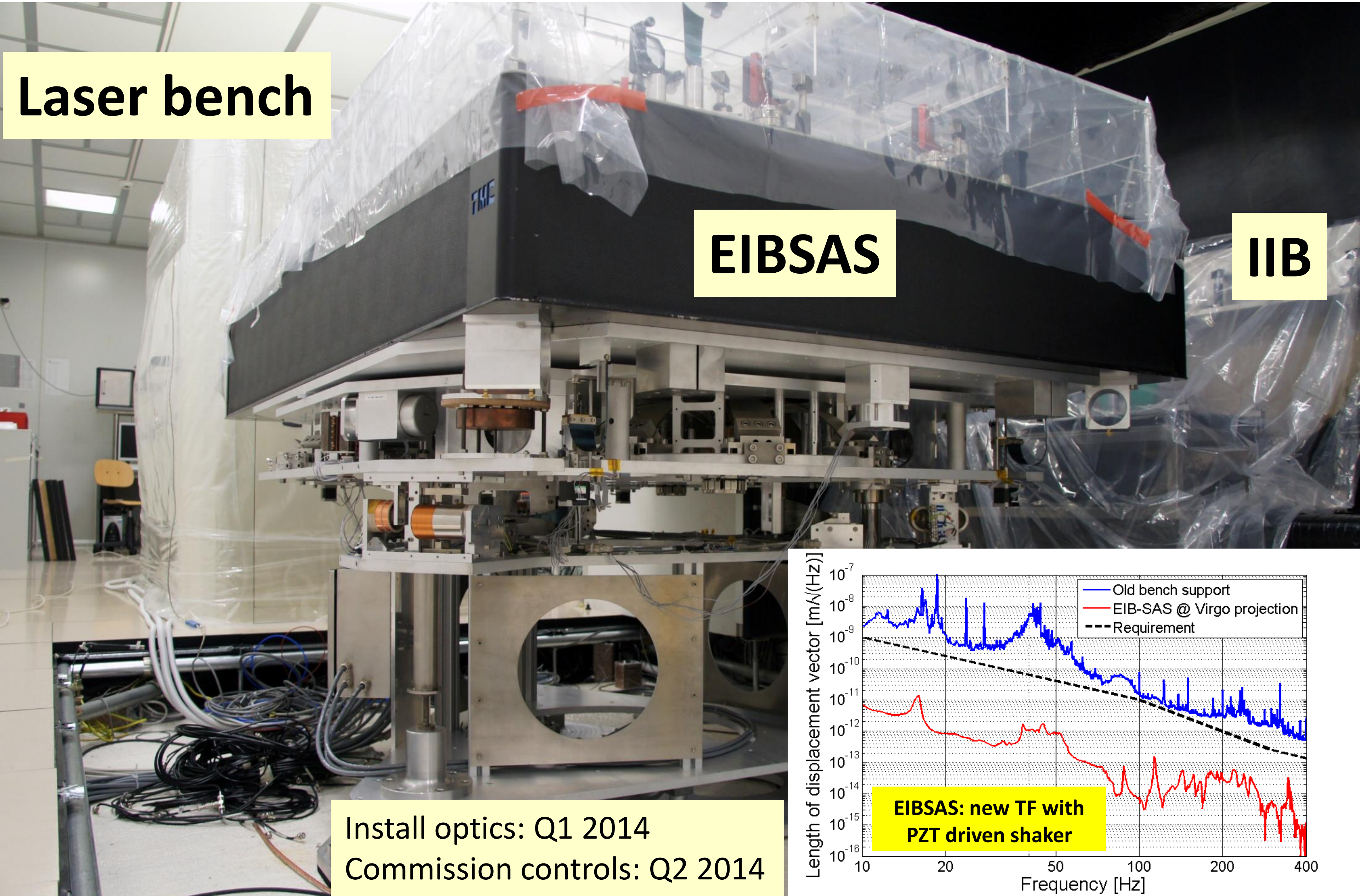
EIBSAS: finishing touch(es)



Mathieu Blom

November 18, 2013

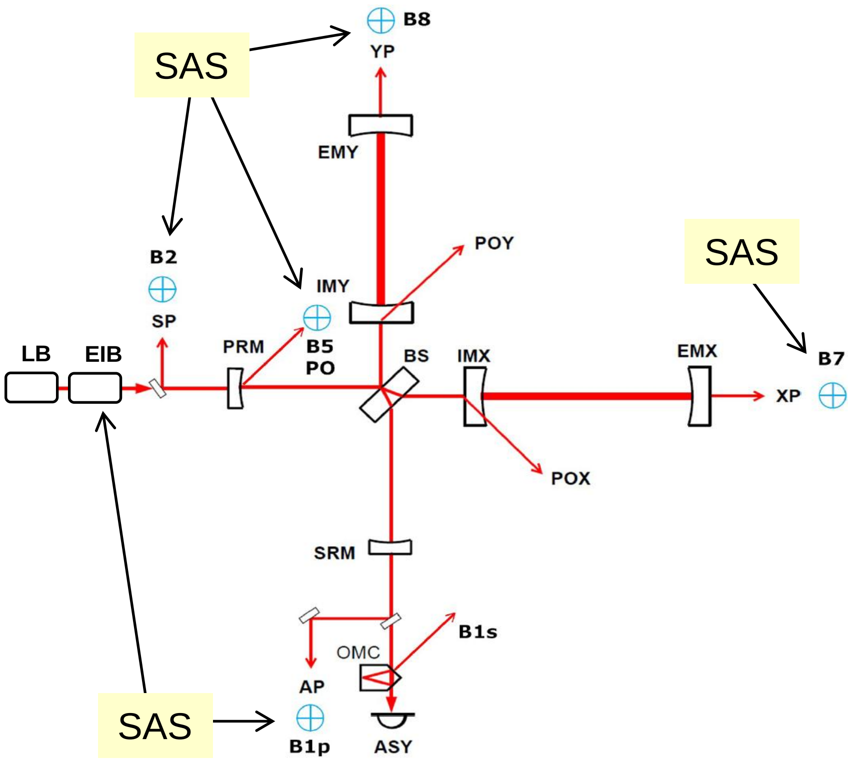
EIBSAS in Advanced Virgo

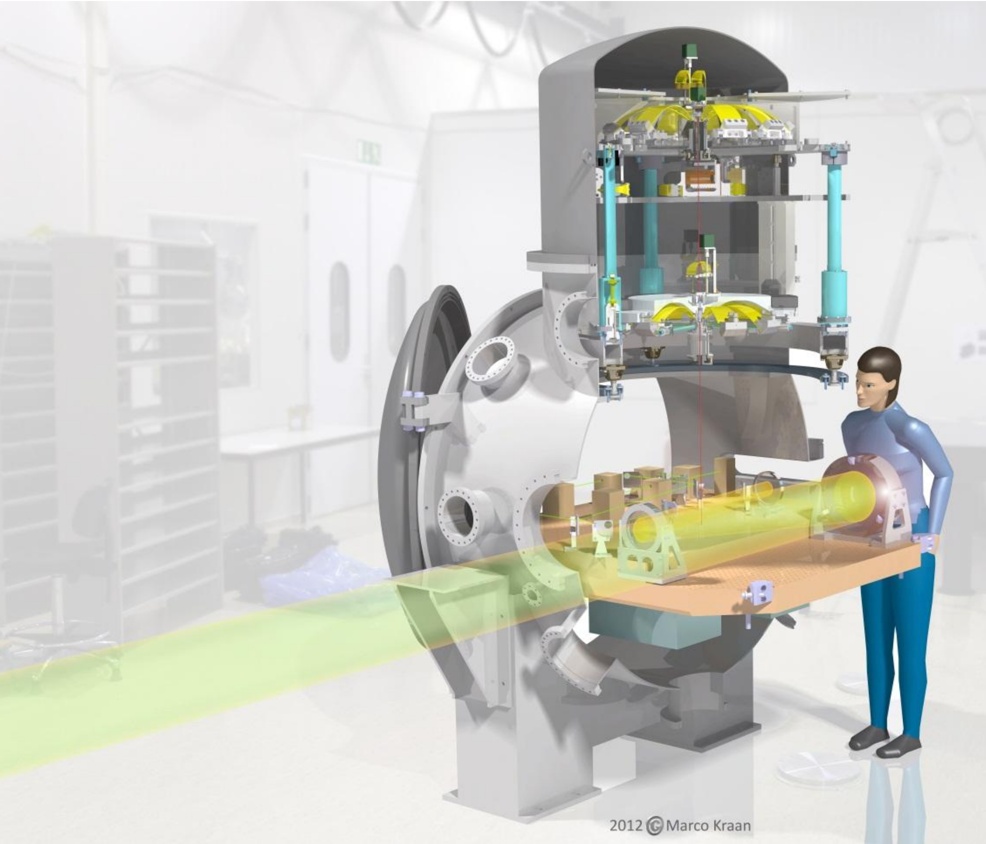


MultiSAS: 6 systems

- Isolate optical components for AdV
  - Femtometer/rtHz level
    - Above 10 Hz, 6 DOFS
    - Active damping of resonances below 1 Hz

Alessandro Bertolini
Martin Doets
Eric Hennes
Mark Beker
Henk Jan Bulten
Willem Kuilman
Michiel Jaspers
Arnold Rietmeijer
Guido Visser
.....

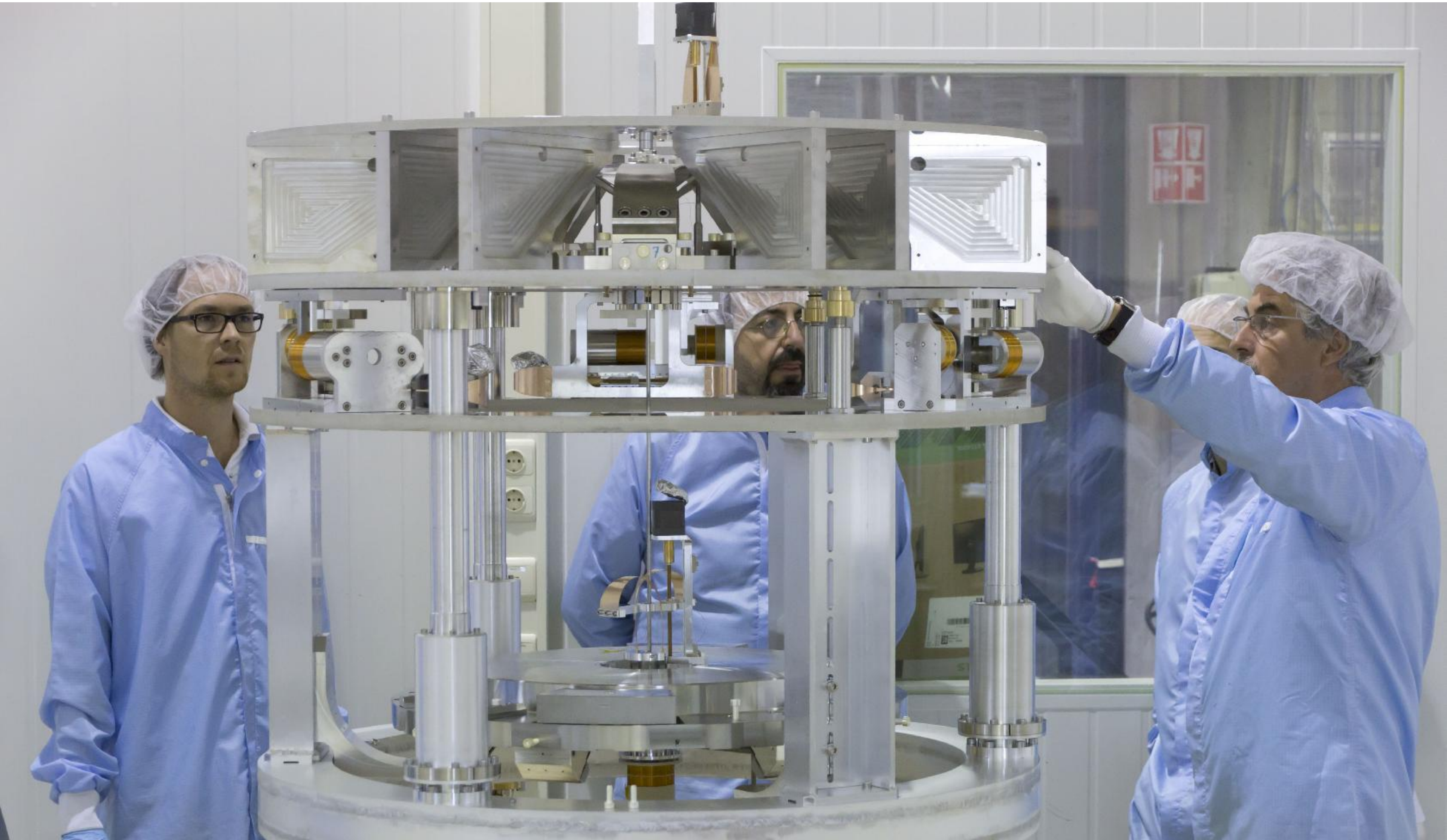




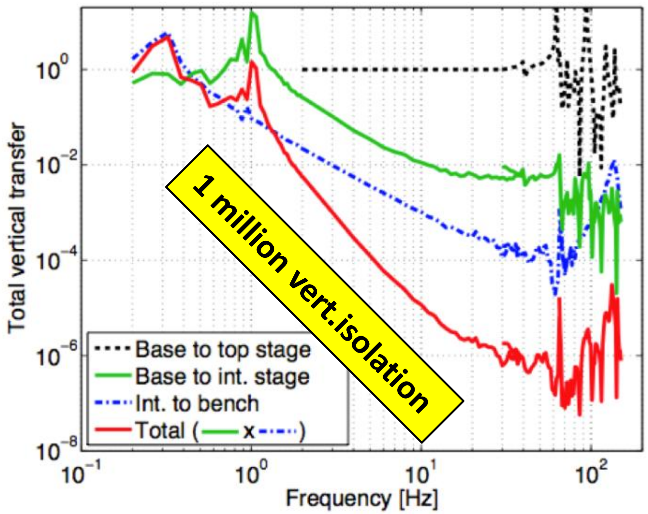
Seismic attenuation systems

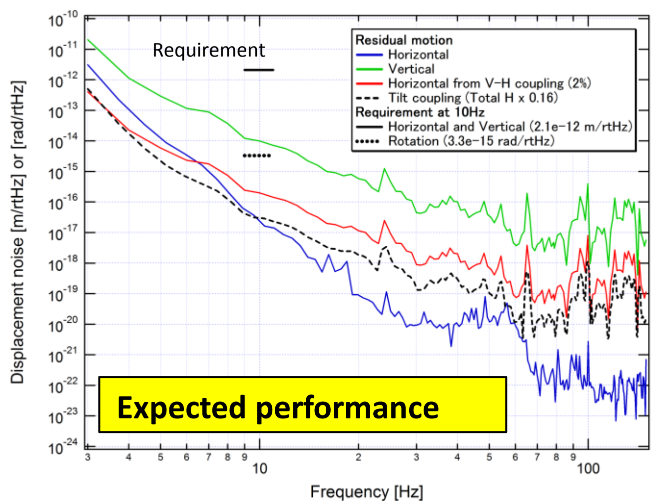
- Prototype development

Alessandro Bertolini
Kazuhiro Agatsuma
Joris van Heijningen



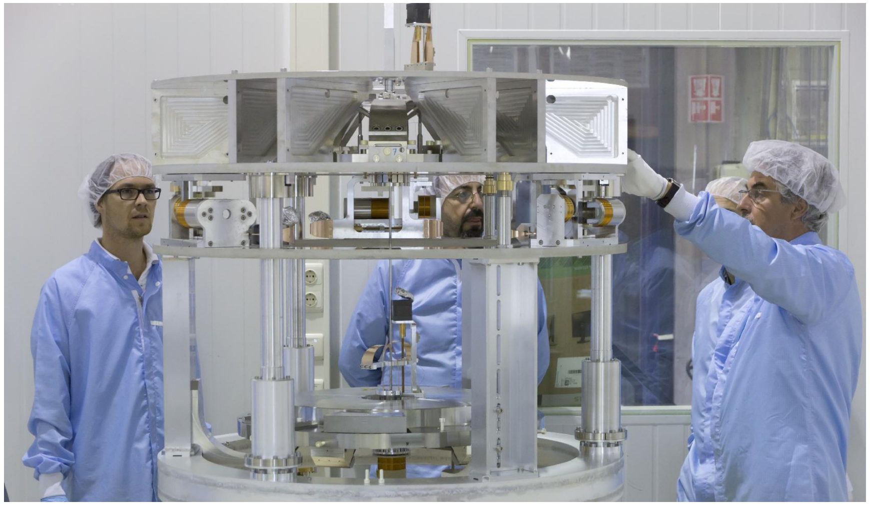
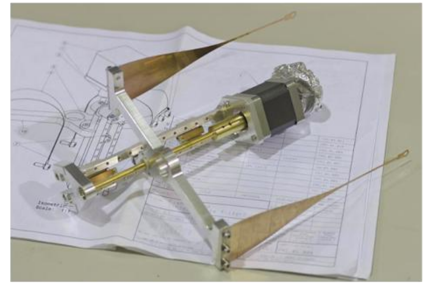
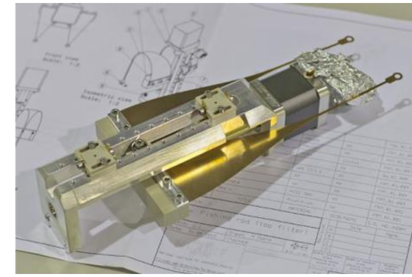
Vibration isolation





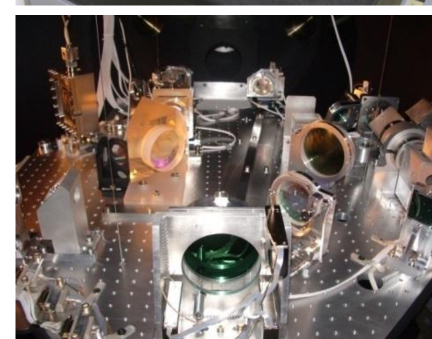
Used by industry

NL contributions to AdV



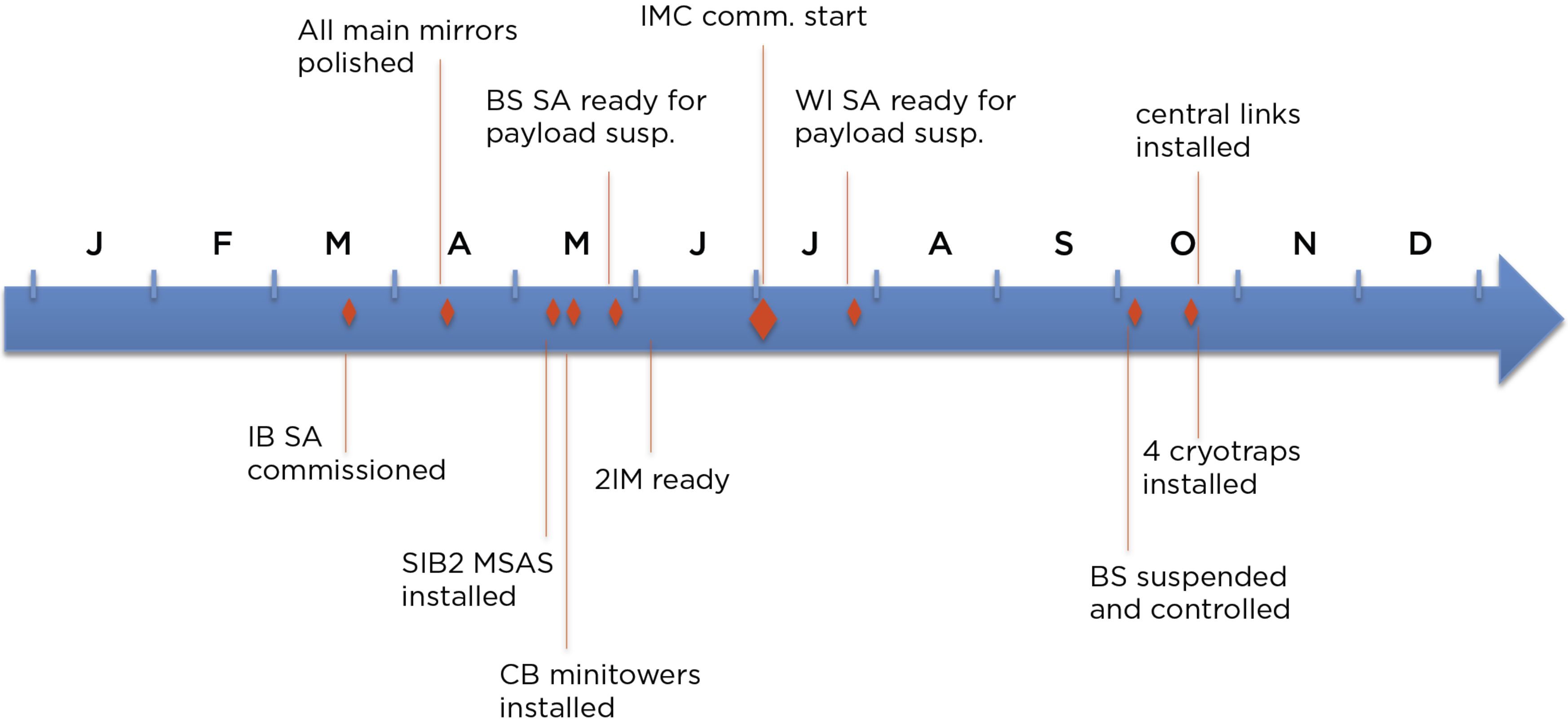


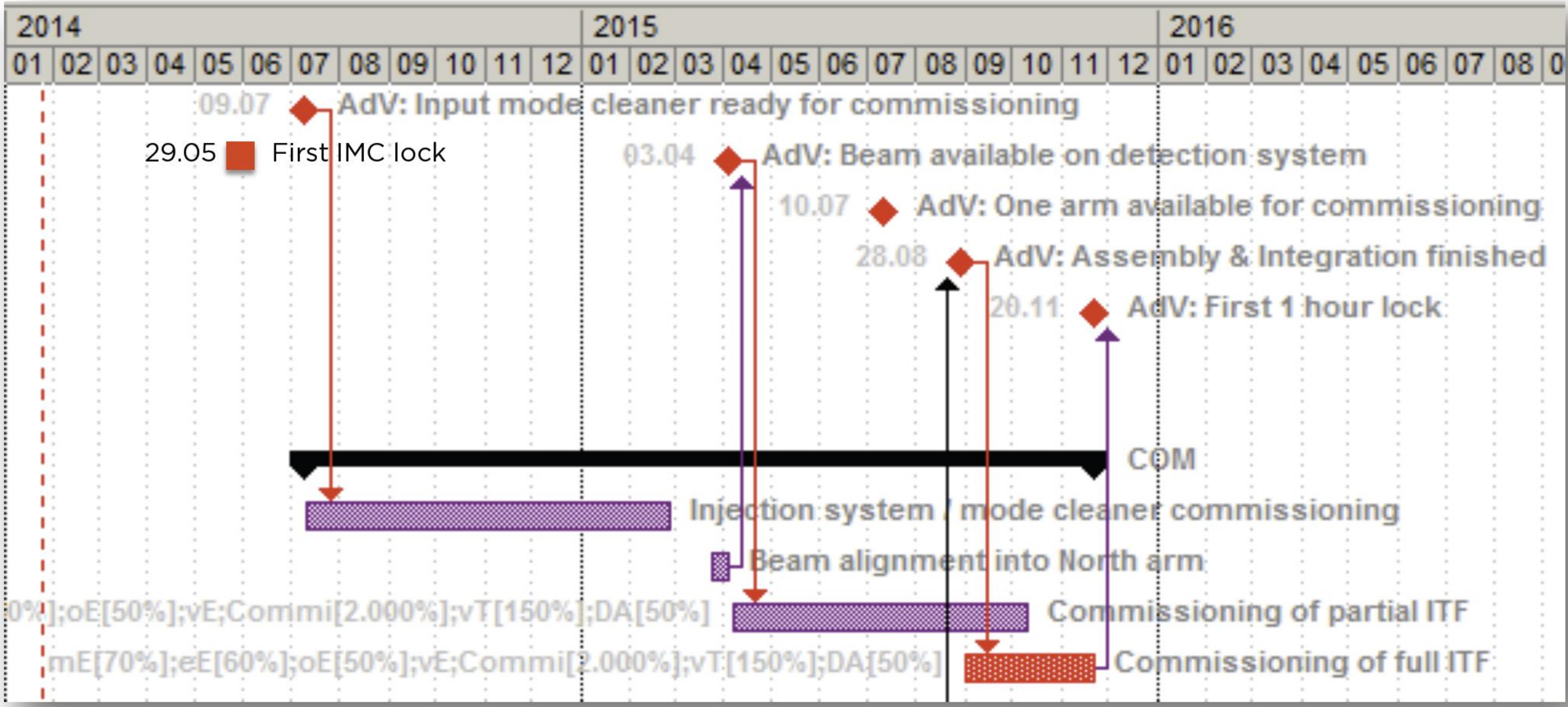

16t

Milestones 2014

According to latest planning …



Planning



Name	Ref. Plan	Diff.	Prev.Plan	Diff.	New Plan
AdV: Input mode cleaner ready for commissioning	08.09.14	-9	04.07.14	1	09.07.14
AdV: Beam available on detection system	03.03.15	-3	13.02.15	7	03.04.15
AdV: One arm available for commissioning	12.06.15	-5	11.05.15	9	10.07.15
AdV: Assembly & Integration finished	11.09.15	-8	17.07.15	6	28.08.15
AdV: First 1 hour lock	04.12.15	-5	30.10.15	3	20.11.15

Other projects

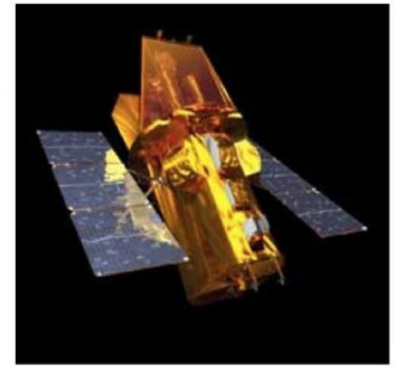
Multi-messenger astronomy

radio

infrared

visible

X-rays



gamma-rays (keV)

gamma-rays (MeV)

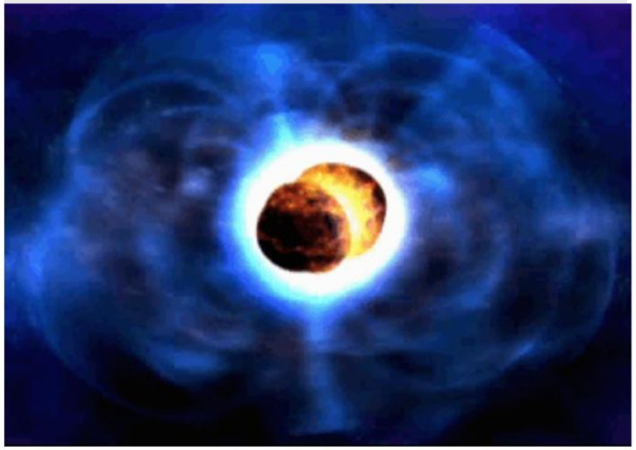
OBSERVE THE SAME EVENT WITH DIFFERENT INSTRUMENTS: DEEPER AND RICHER UNDERSTANDING OF ITS PHYSICAL NATURE

IDENTIFICATION AND FOLLOW UP OF ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVE CANDIDATE EVENTS

The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration currently plan to start taking data in 2015, and we expect the sensitivity of the network to improve over time. Gravitational-wave transient candidates will be identified promptly upon acquisition of the data; we aim for distributing information with an initial latency of a few tens of minutes initially, possibly improving later. The LSC and the Virgo Collaboration (LVC) wish to enable multi-messenger observations of astrophysical events by GW detectors along with a wide range of telescopes and instruments of mainstream astronomy.

In 2012, the LVC approved a statement (LSC, Virgo) that broadly outlines LVC policy on releasing GW triggers (partially-validated event candidates). Initially, triggers will be shared promptly only with astronomy partners who have signed an Memorandum of Understanding (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting. After four GW events have been published, further event candidates with high confidence will be shared immediately with the entire astronomy community (and the public), while lower-significance candidates will continue to be shared promptly only with partners who have signed a MoU.

Through June to October 2013, we organized rounds of consultations with groups of astronomers that have expressed interest in the GW-EM follow-up program. Thanks to these consultations, we could define the framework and guiding rules for this program that are collected into a standard MoU template.



Devour thy Neighbor: An artist's illustration of two neutron stars close to merger look misshaped, becoming more oblong the closer they get to one another. A black hole is then formed and gamma rays shoot out as a GRB. (Credit: NASA/Swift)

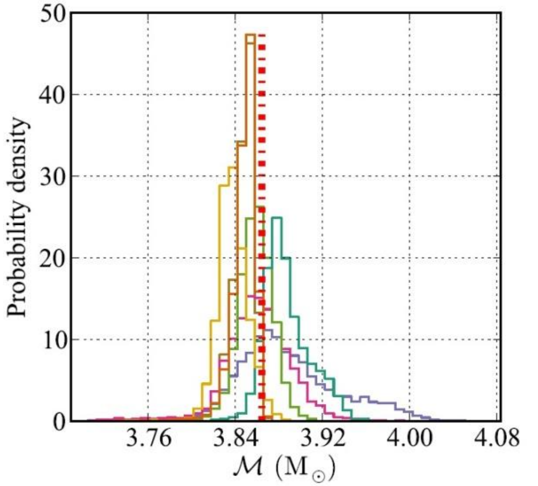
OPEN CALL FOR PARTICIPATION TO GW-EM FOLLOW-UP PROGRAM, DUE FEB 16 2014.

On Dec 16 2013, we issued a call for proposals to sign standard MoU with the LVC. This call is open to all professional astronomers with demonstrated experience, and require that a partner bring some useful observing resource(s), not just astronomy expertise, to participate. GW triggers will be sent to groups that are in position to make observations in the course of next science runs circa 2015-2017 (arXiv:1304.0670, LIGO-P1200087, VIR-0288A-12). Our intent is to accept and sign MoUs with all qualified applicants. We expect to issue this call yearly in spring.

If you are interested in signing this agreement with LSC and Virgo, please read this document that provides important details of the GW-EM follow-up program, fill the application form in LIGO-F1300021, and email it to emf@ligo.org. **Also**, please fill the information fields below (including the filename of the file you emailed to us) and submit it before Feb 16, 2014.

Electromagnetic follow-up

- Astrophysics at RU
  - Joined Virgo in May 2012
  - First Astrophysics group in Virgo
- BlackGEM Proposal
  - Approved by NOVA Phase-4 Instrum. Prop.
    - **Design phase approved, with PHASE-I reservation**
    - **Black-hole merger GW-EM radiation array**
    - https://www.astro.ru.nl/wiki/research/blackgemarray
- Parameter estimation
  - For example: chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
  - Determines leading-order GW amplitude (in GR)

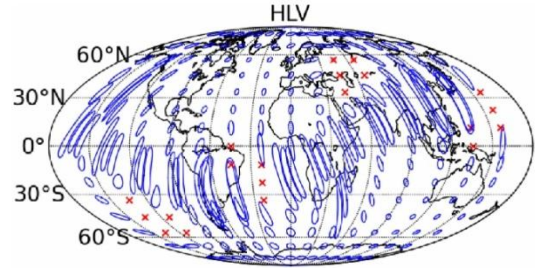


BlackGEM-Phase1: Optical Array for Gravitational Wave Astrophysics

1. Applicants

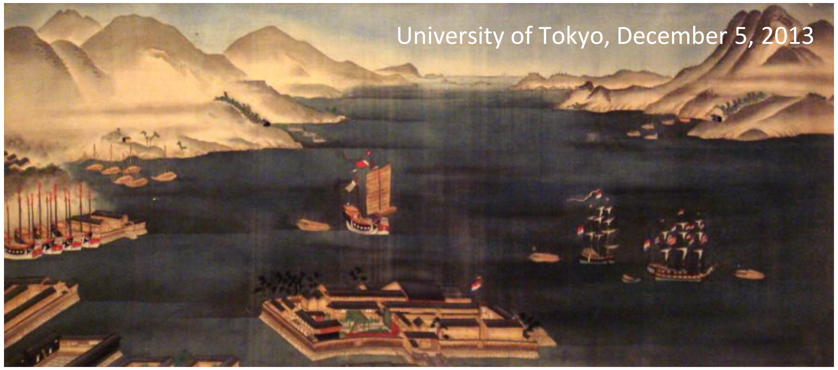
Principal Investigator:	Paul Groot (RU Nijmegen)
Project Scientist:	Gijs Nelemans (RU Nijmegen)
Project Manager:	Marc Klein-Wolt (RU Nijmegen)
Team members:	Anna Watts (UvA), Elena Rossi (UL), Frank Verbunt (RU), Simon Portegies Zwart (UL), Michiel van der Klis (UvA), Alex de Koter (UvA), Onno Pols (RU), Huib Henrichs (UvA), Rudolf le Poole (UL), Marco Spaans (RUG), Peter Jonker (SRON/RU), Ralph Wijers (UvA), Elmar Körding (RU), Tom Heskes (RU Computer Science), Jo van den Brand (VU/Nikhef), Ben Stappers (Manchester), Patrick Woudt (UCT), Stephan Rosswog (Stockholm), Andrea Viceré (Urbino)

Figure X: Proposed site of BlackGEM at ESO La Silla, on the parking lot of the defunct 1m Marly telescope



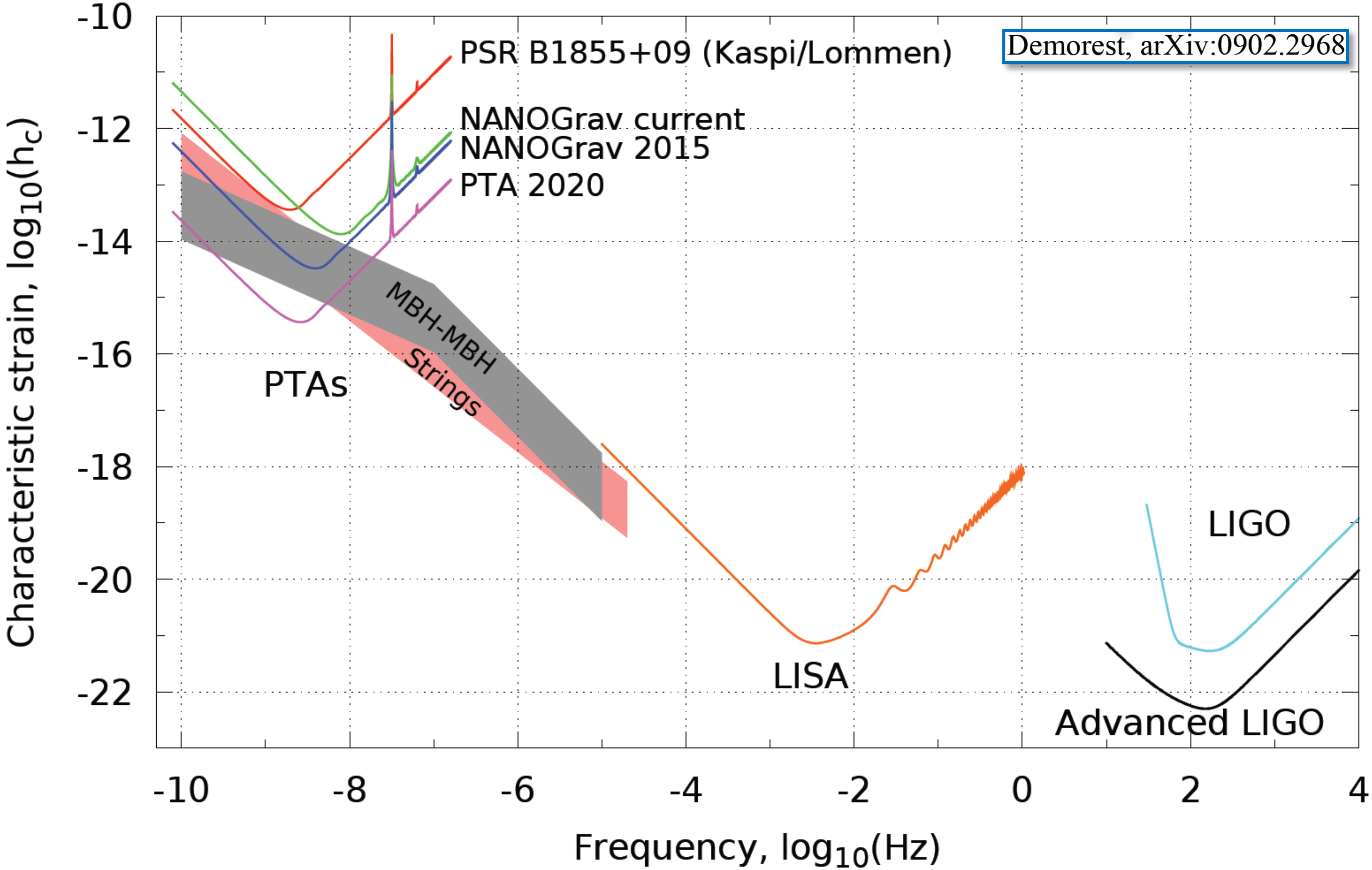
Kagra

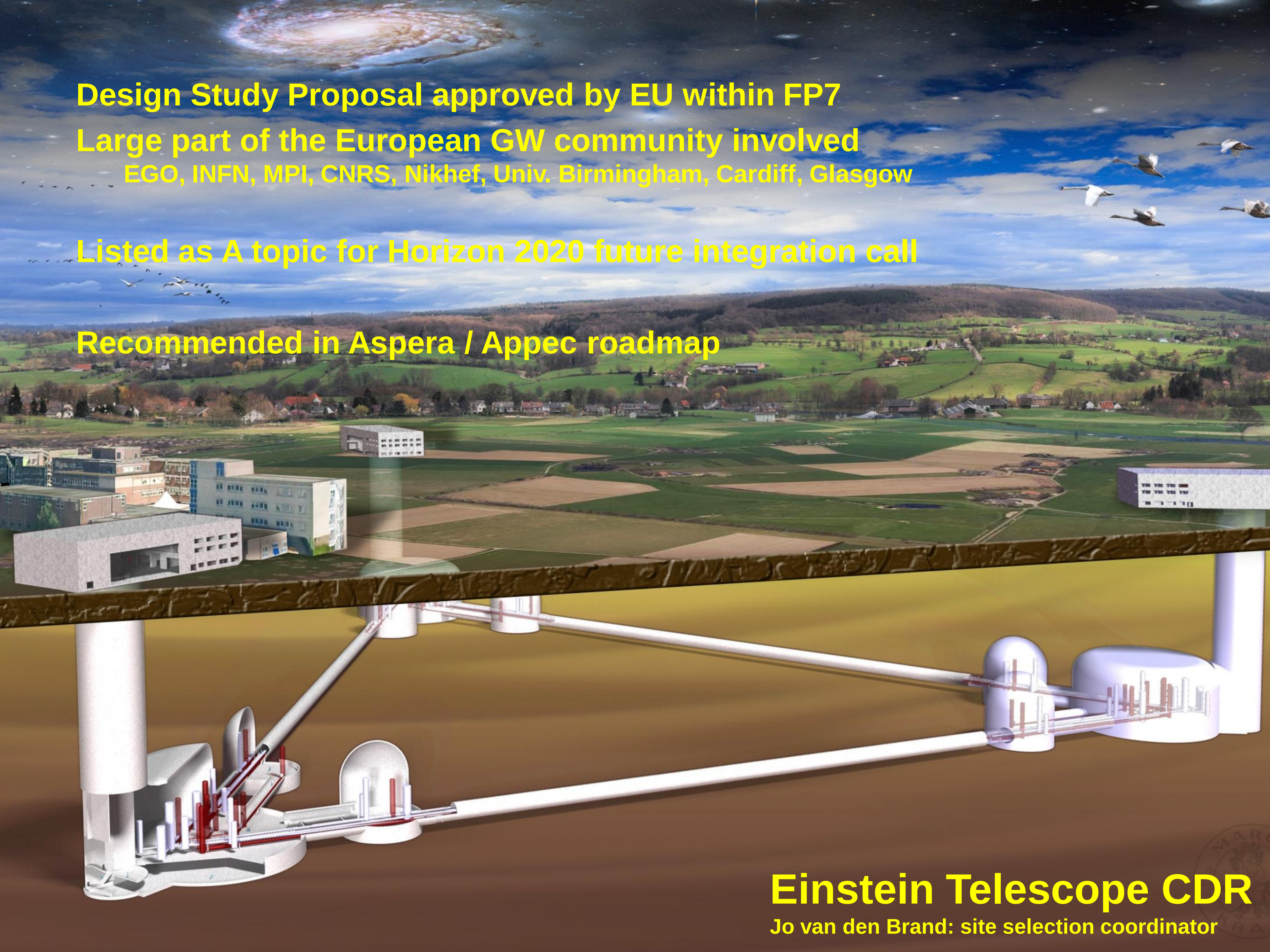
- Kamioka gravitational-wave antenna
  - Towards 3rd generation GW detectors
    - See http://www.et-gw.eu
  - EU funding via approved ELiTES proposal
    - ELiTES Japanese-European collaborative FP7 project, between ET and Kagra
  - Technology transfer from Nikhef to Kagra
  - Europe House in Tokyo



University of Tokyo, December 5, 2013

Pulsar timing arrays





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

Listed as A topic for Horizon 2020 future integration call

Recommended in Aspera / Appec roadmap

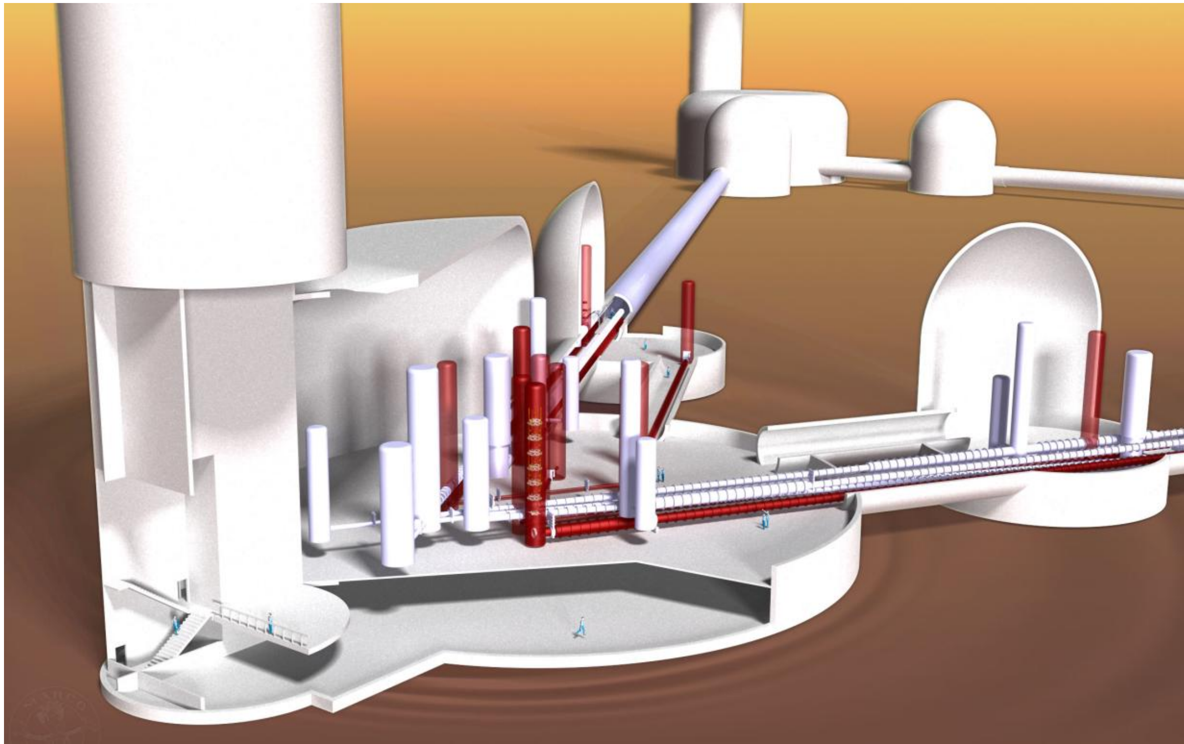
Einstein Telescope CDR

Jo van den Brand: site selection coordinator

ET infrastructure

- Infrastructure: largest cost driver
  - Tunnels, caverns, buildings
  - Vacuum, cryogenics, safety systems
  - Collaborate with industry
    - Underground construction
    - Vacuum systems
    - Vibrationless cooling

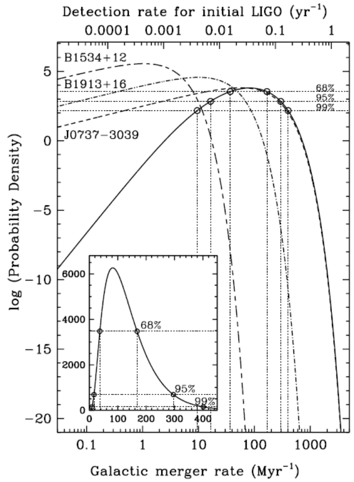
- Experience
  - LIGO, Virgo, GEO
  - Underground labs
    - Gran Sasso, Canfranc,
    - Kamioka, Dusel, etc.
  - Mines
  - Particle physics
    - ILC, Cern, Desy, FLNL
  - Seismology
    - KNMI, Orfeus
  - Geology



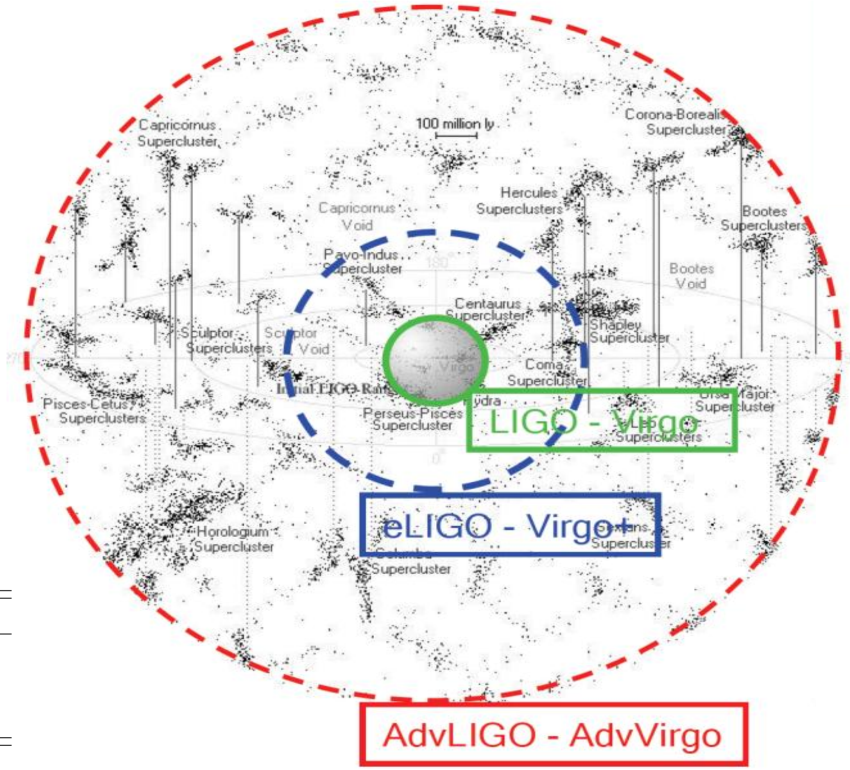
Event rate estimates

- Advanced Virgo
  - Improve sensitivity by factor 10
- Probable sources
  - Binary neutron star coalescence
  - Binary black holes mergers, supernovae, pulsars
- BNS Rates: (most likely and 95% interval)
  - Initial Virgo (30Mpc)
    - 1/100yr (1/500 - 1/25 yr)
  - Advanced detectors (350Mpc)
    - 40/yr (8 - 160/yr)

  Kalogera et al; astro-ph/0312101; Model 6
- BBH more difficult to predict

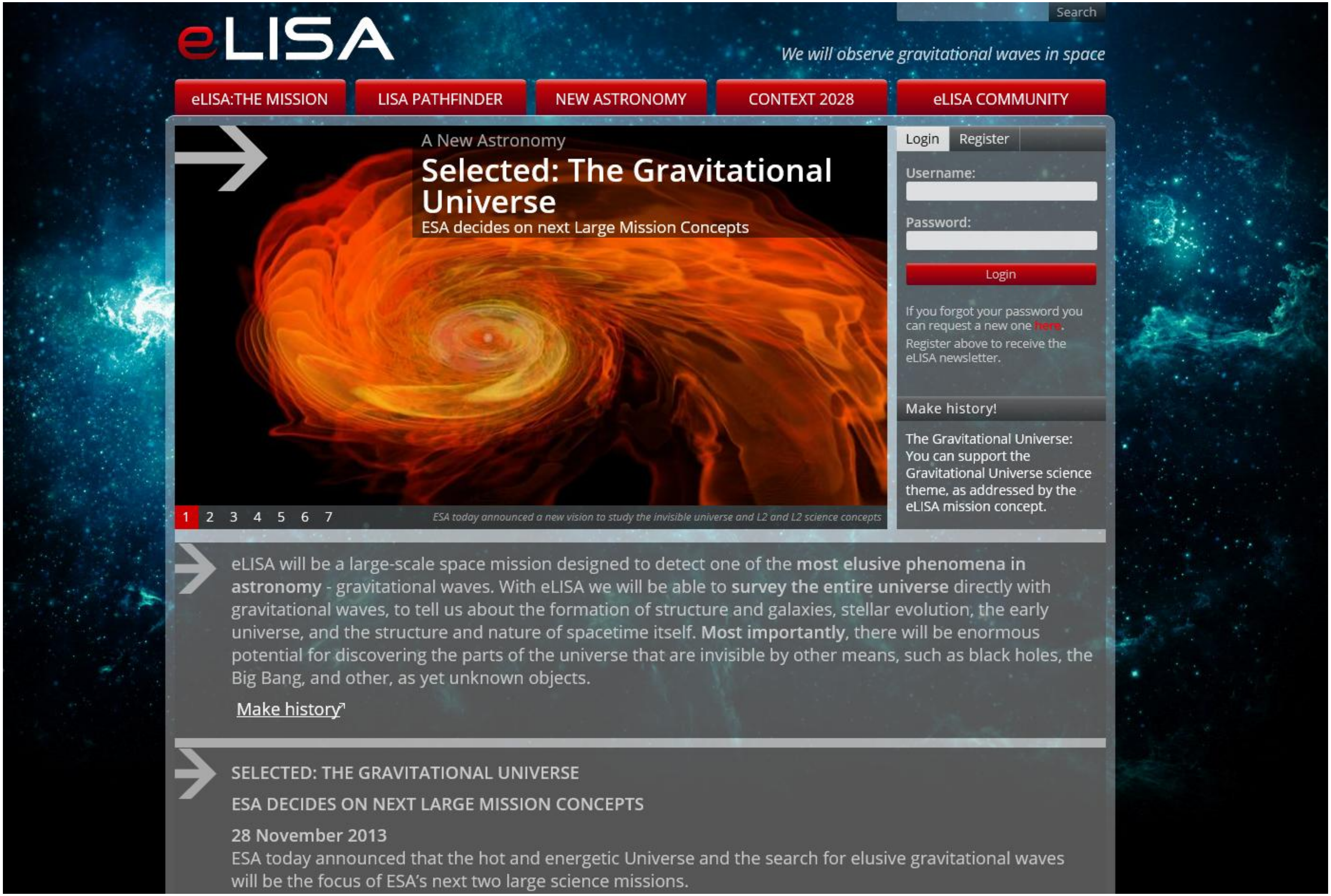


Astronomy: we know GW sources exist!

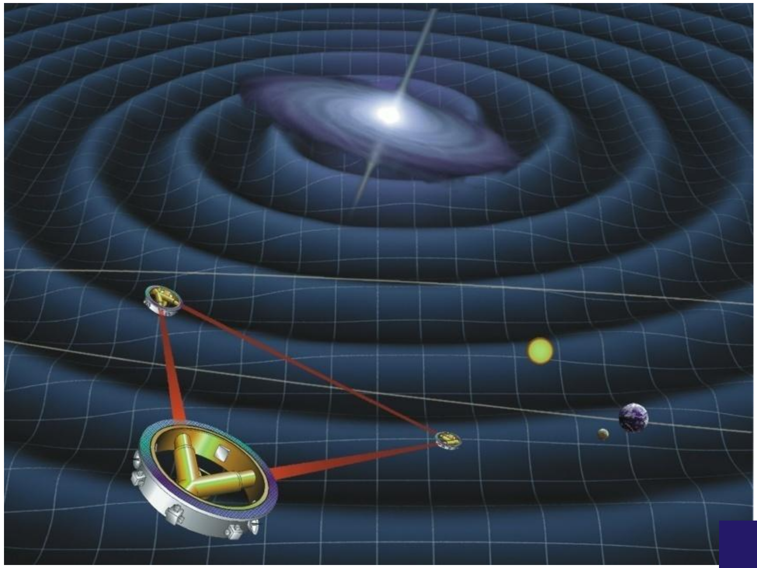


Source	BNS	NS-BH	BBH
Rate (Mpc^{-1} Myr^{-1})	0.1–6	0.01–0.3	2×10^{-3}–0.04
Event Rate (yr^{-1}) in aLIGO	0.4–400	0.2–300	2–4000
Event Rate (yr^{-1}) in ET	$\mathcal{O}(10^3$–$10^7)$	$\mathcal{O}(10^3$–$10^7)$	$\mathcal{O}(10^4$–$10^8)$

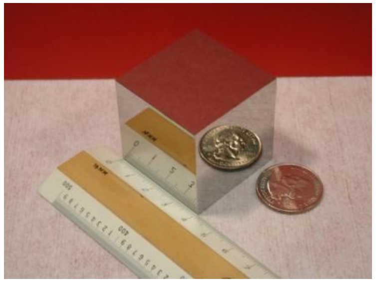
November 28, 2013: eLISA approved!

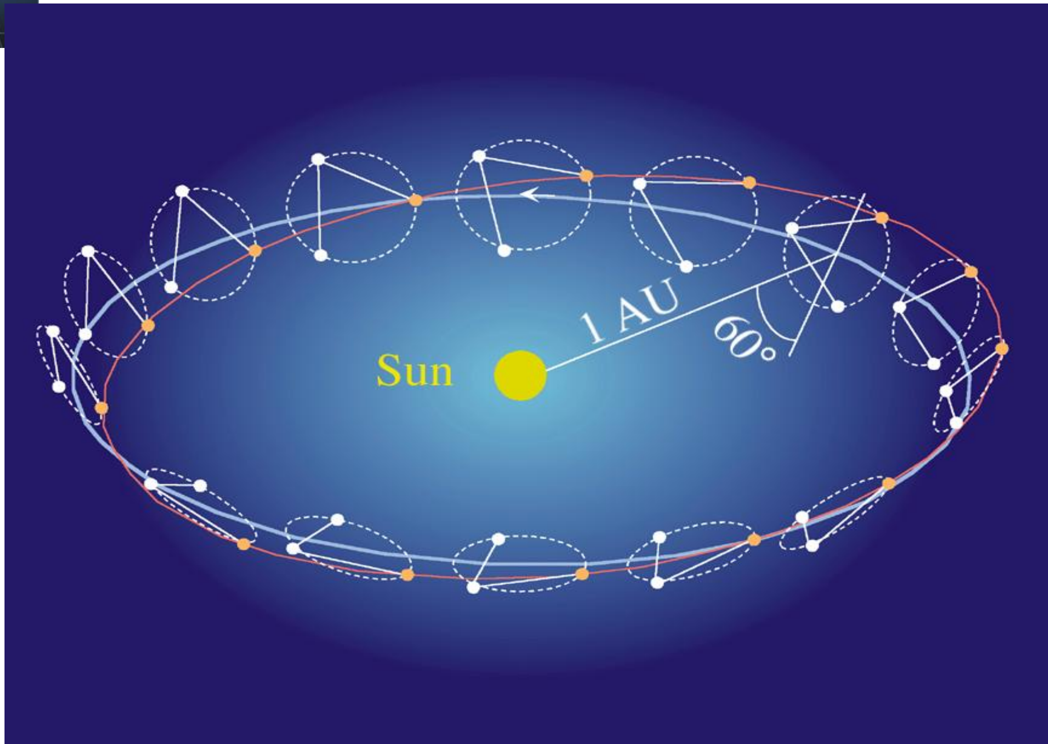


GW antenna in space - *e*LISA

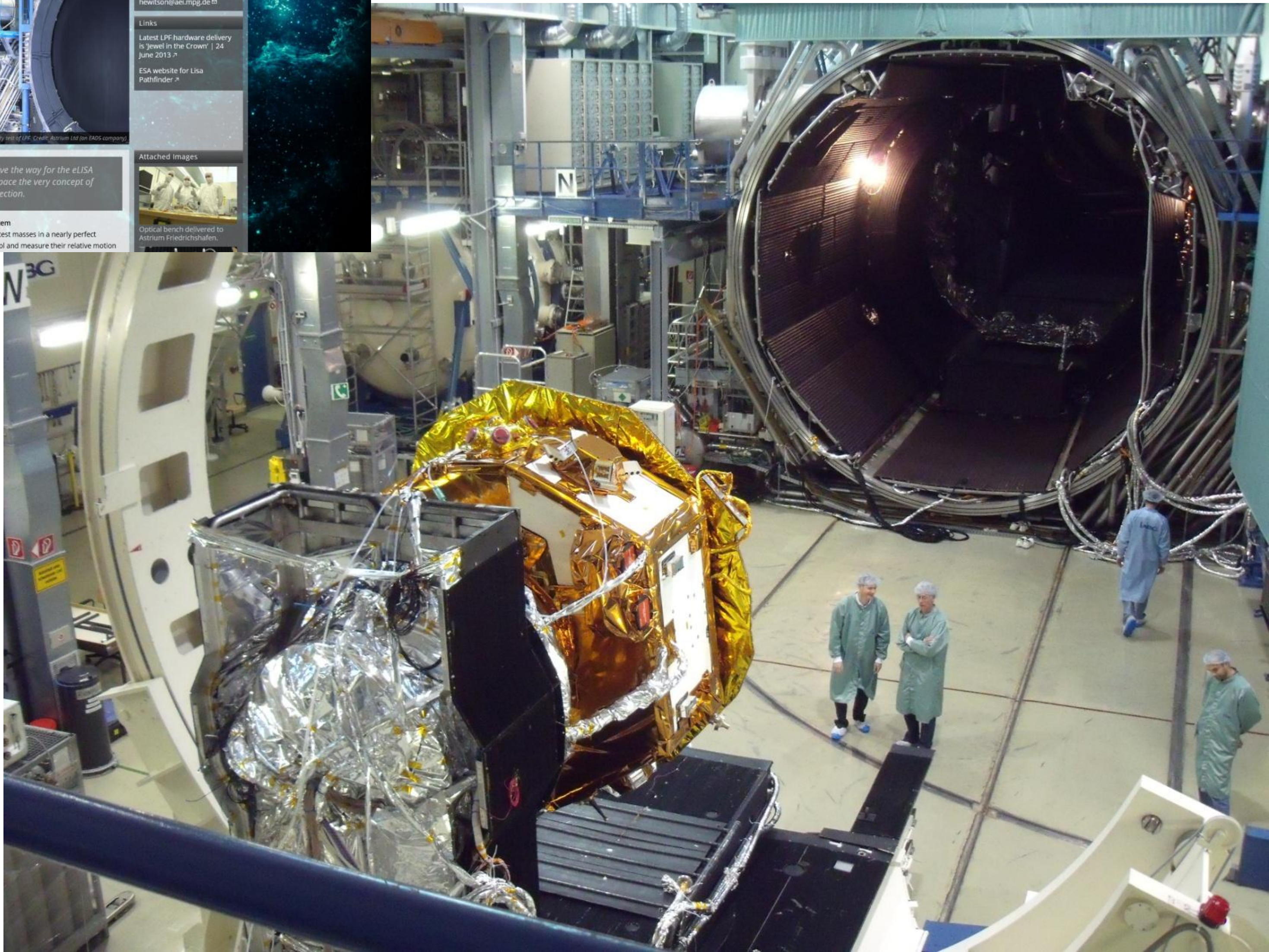


- *3 spacecraft in Earth-trailing solar orbit separated by 10^6 km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *ESA funded*
- *Launch date 2034*





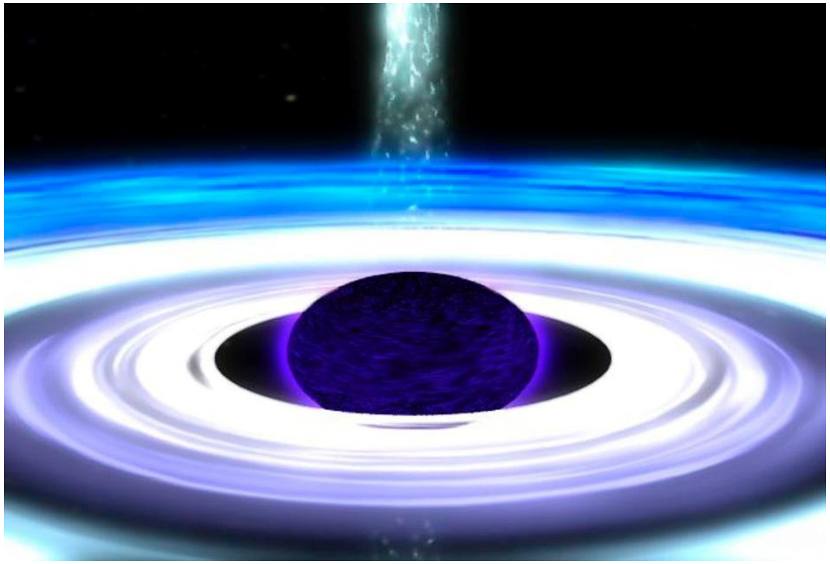
LISA pathfinder



Science goals

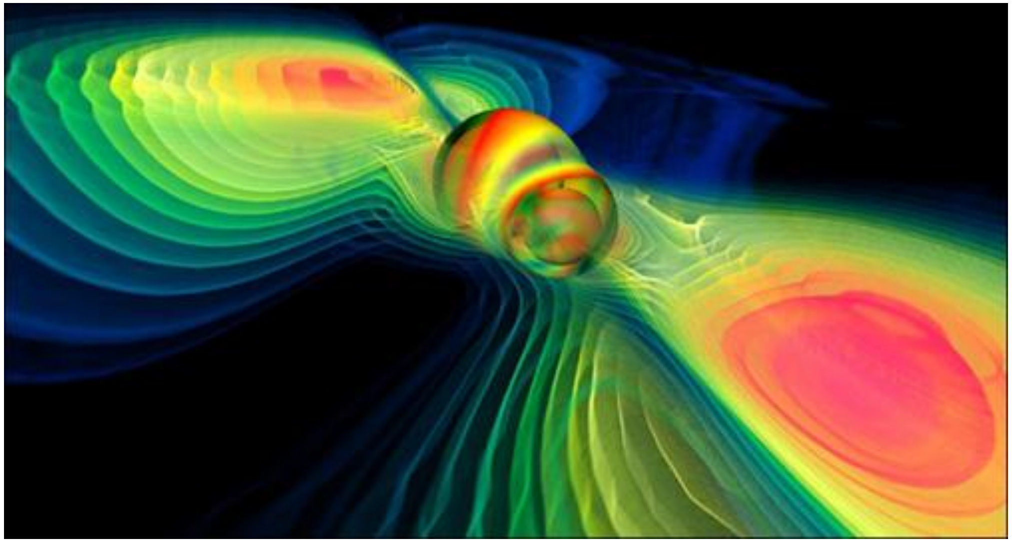
Science goals

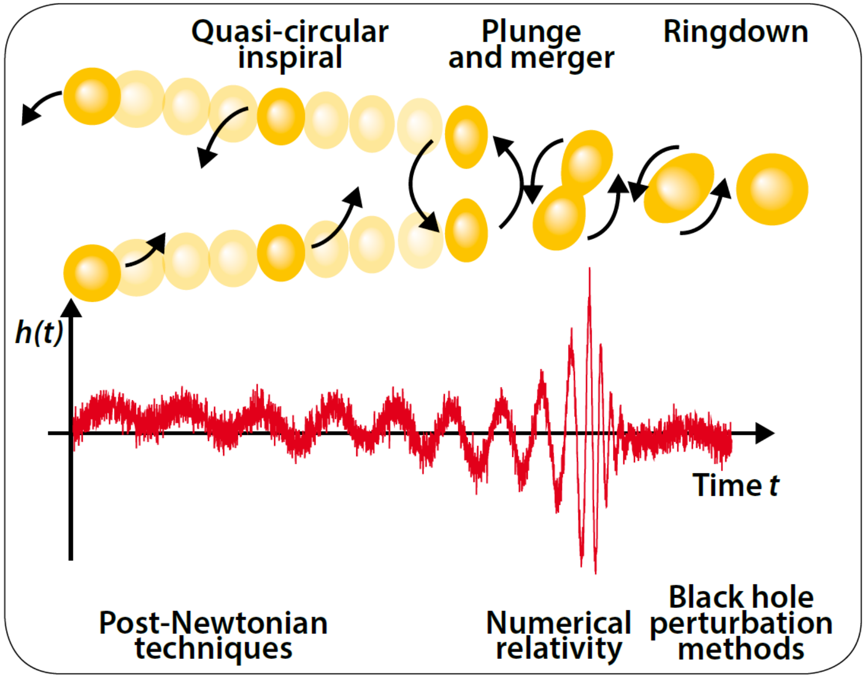
What happens at the edge of a Black Hole?



Is Einstein's theory still right in these conditions of extreme gravity? Or is new physics awaiting us?

Coalescence of compact binaries



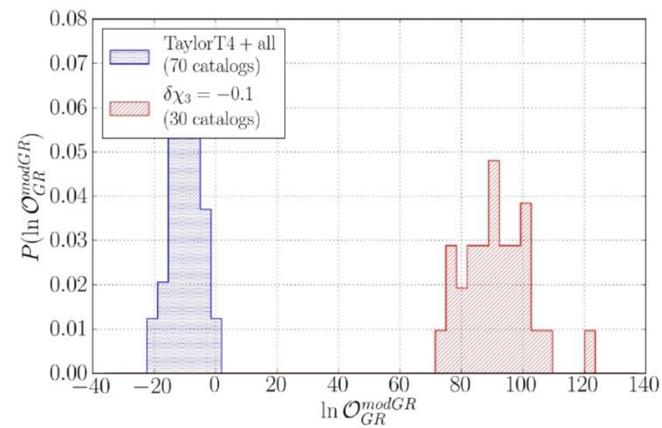


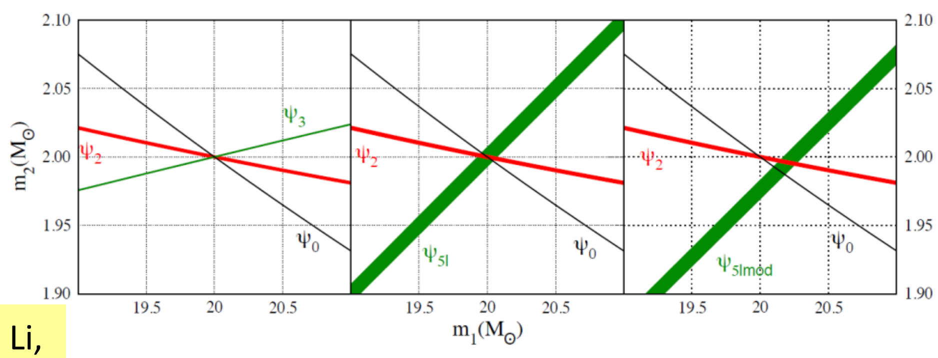
Tests of post-Newtonian theory

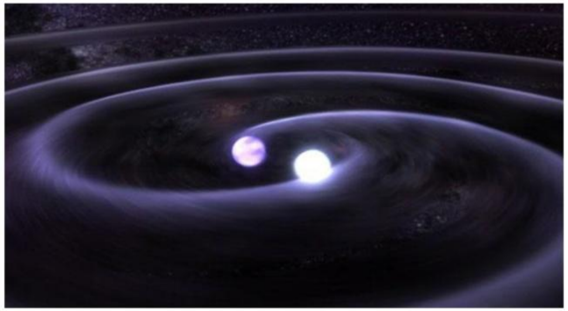
- Test of GR without assuming alternative model
  - Based on post-Newtonian phase expansion of BBH inspiral signal

$$\Psi(f) = \sum_{j=0}^{7} [\psi_j + \psi_{jl} \ln(f)] \; f^{(j-5)/3}$$

  - Single (2, 20) M_{sun} BBH merger (zero spin): PN coefficients *all* depend on only the component masses. Thus only two are independent
  - Fit to a model where three PN coefficients are treated as independent
  - Test non-linear predictions (*e.g.* tail terms, logarithmic terms)







Van Den Broeck, Li, Del Pozzo, Vitale

Science goals

What happens at the edge of a Black Hole?

Towards a generic test of the strong field dynamics of general relativity using compact binary coalescence: Further investigations

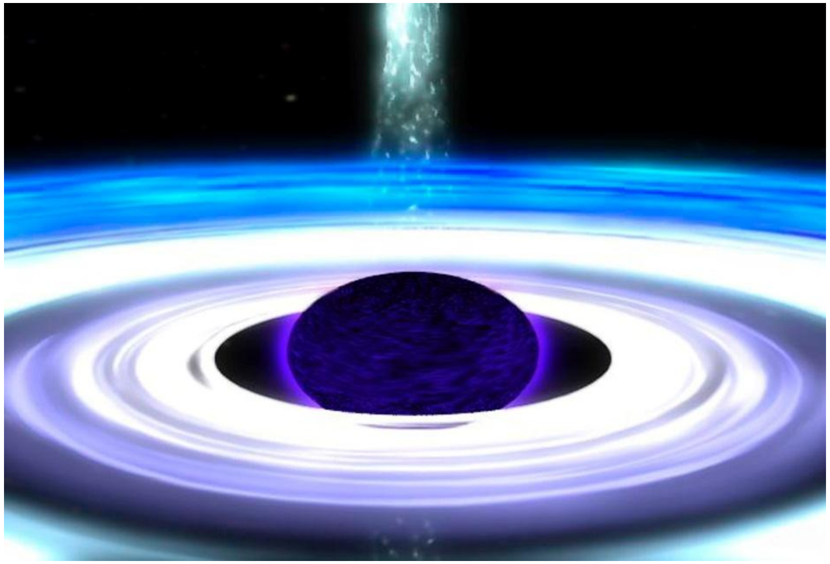
T.G.F. Li[1], W. Del Pozzo[1], S. Vitale[1], C. Van Den Broeck[1], M. Agathos[1], J. Veitch[1,2], K. Grover[3], T. Sidery[3], R. Sturani[4,5], A. Vecchio[3]

[1]Nikhef – National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, The Netherlands
[2]School of Physics and Astronomy, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, United Kingdom
[3]School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom
[4]Dipartmento di Scienze di Base e Fondamenti, Università di Urbino, I-61029 Urbino, Italy
[5]INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Italy

First model-independent precision test of strong field dynamics of spacetime using signals from coalescing compact binaries

- Robust against unknown instrumental features (e.g. calibration errors)
- Robust against currently unknown GR effects (e.g. neutron star tidal effects)
- Expand to BBH, pure spacetime process, rich dynamics

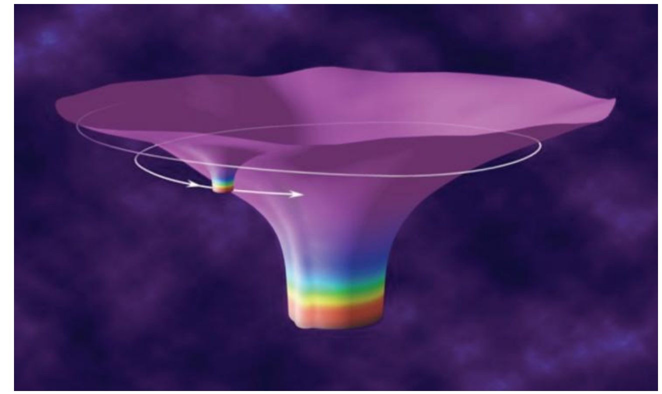
Prompted formation of new LSC-Virgo technical sub-group, led by Del Pozzo



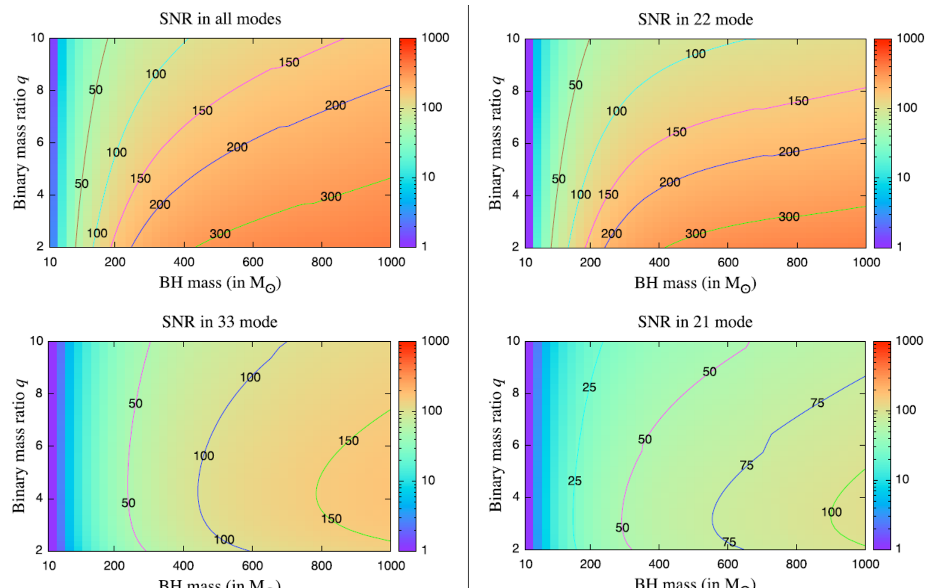
Is Einstein's theory still right in these conditions of extreme gravity? Or is new physics awaiting us?

Test of BH uniqueness theorem

- Kerr metric is the unique end state of gravitational collapse
  - Based on assumptions
    - Spacetime is vacuum, axisymmetric (stationary), asymptotically flat
    - There is a horizon in spacetime
- IMRI can map spacetime
  - ET can see IMRIs out to $z \approx 3$
  - See few % deviation quadrupole
- BH no-hair theorem
  - Perturbed GW has QNM given by M and S
  - Kerr relation for multipole moments

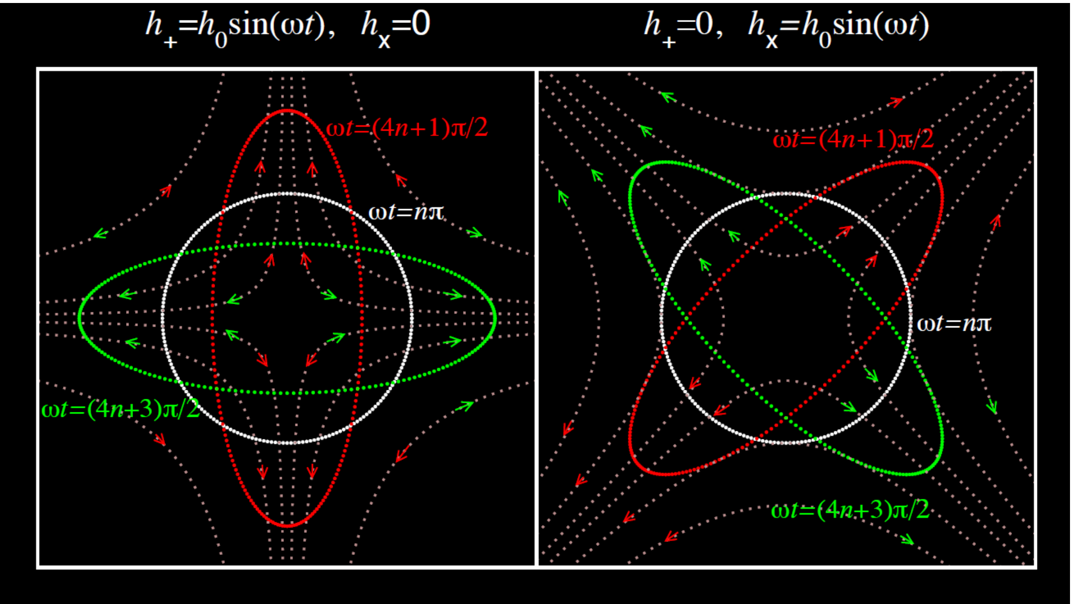


$$\omega_{\ell m} = \frac{F_{\ell m}(j)}{M}, \quad \tau_{\ell m} = M G_{\ell m}(j)$$

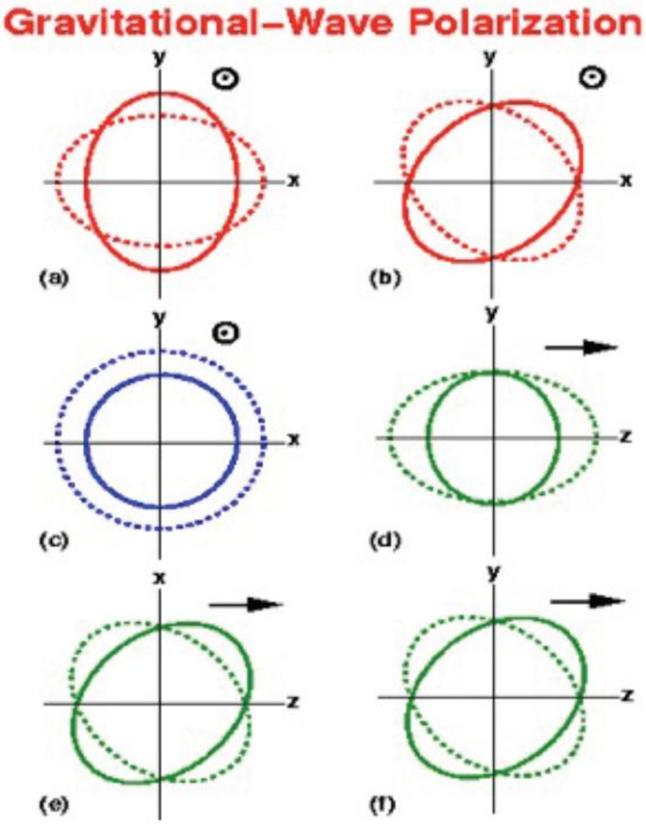


Counting polarization states

- Polarization tests are qualitative tests
- A single measurement is good enough to rule the theory out
- Only two states in GR
  - Plus and cross polarizations
- Polarization states in a scalar-tensor theory
  - Six different polarization modes

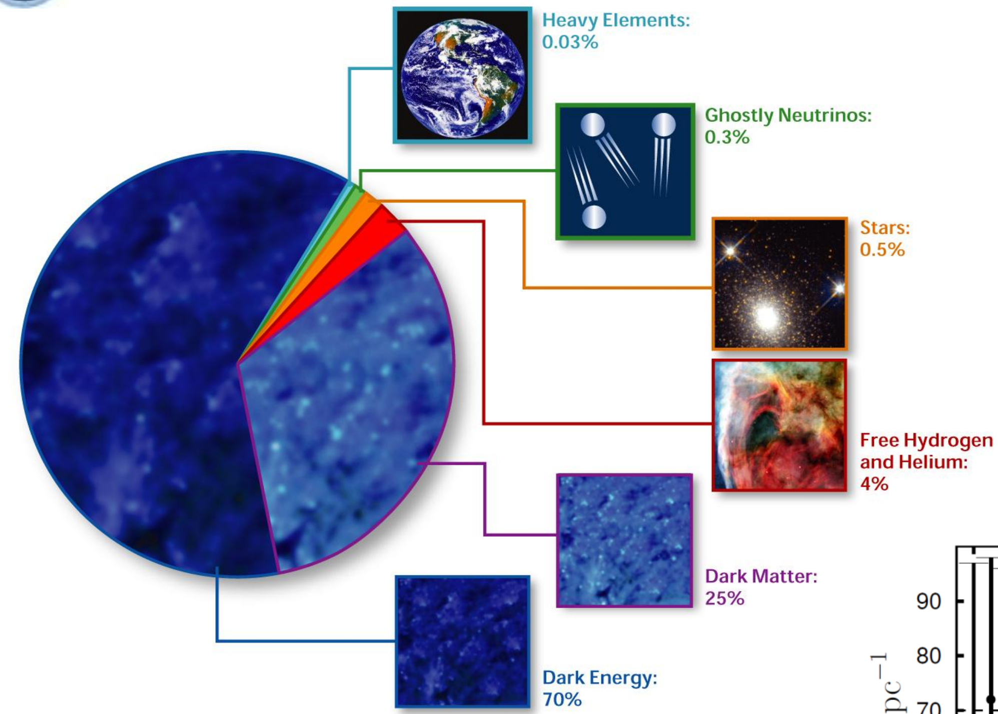


Cliff Will, Living Rev. in Relativity

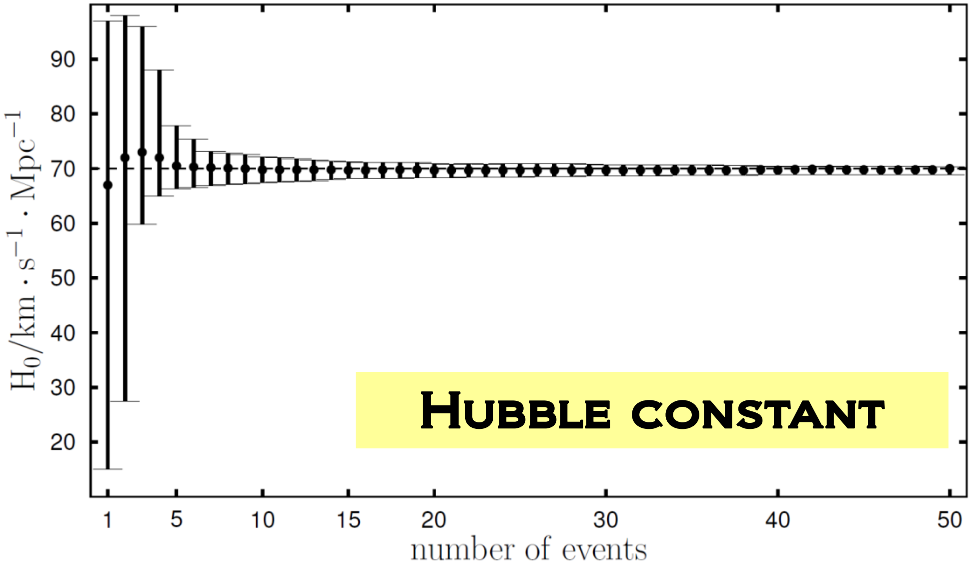


Science goals

What is the mysterious Dark Energy pulling the Universe apart?



CBC as standard candles (sirens)

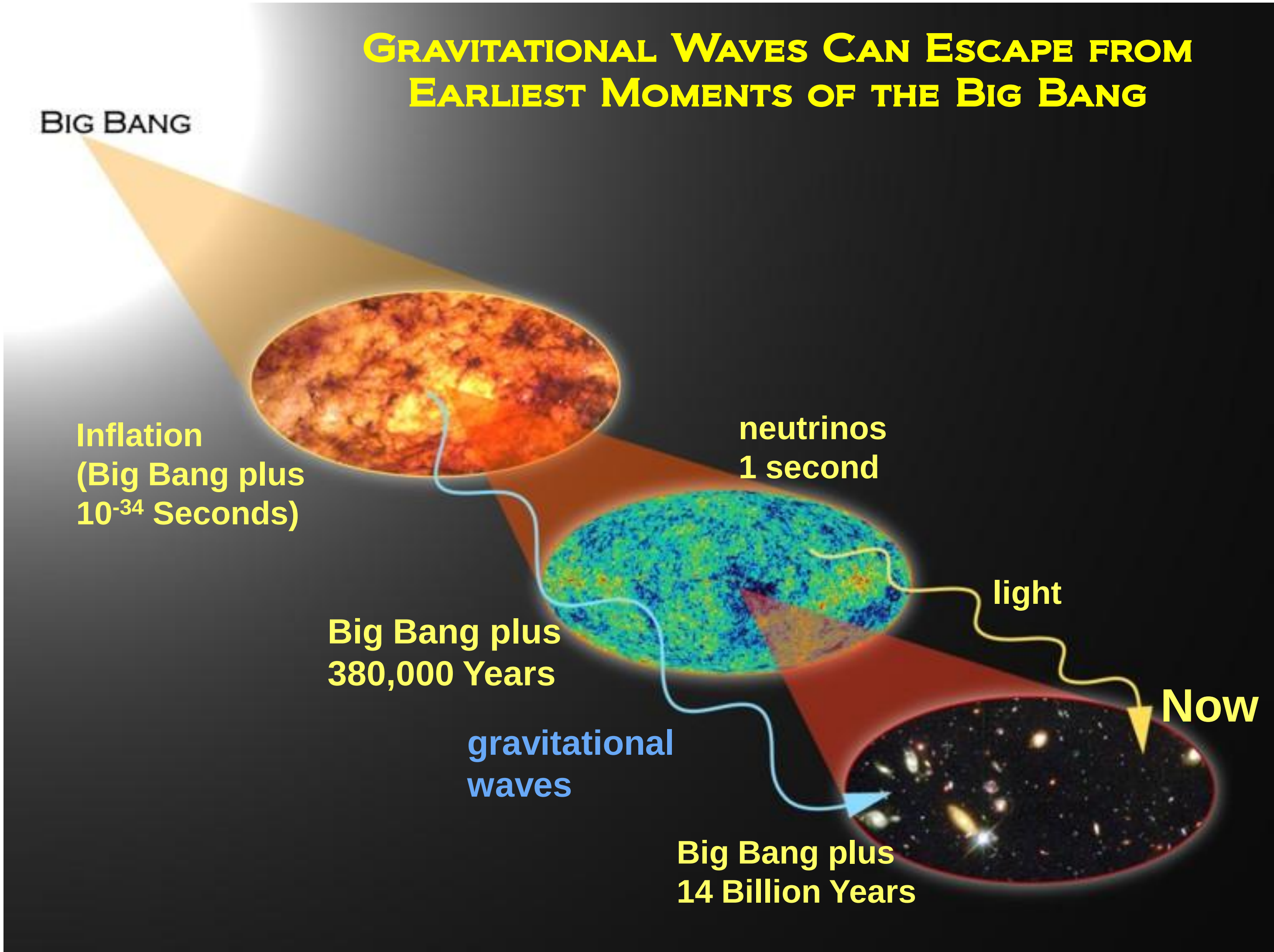


Hubble constant

Dark energy and matter interact through gravity

Science goals

What powered the Big Bang?



Nature 460, 990-994 (20 August 2009)

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration & The Virgo Collaboration

CONCLUDING REMARKS

- Interferometer technology demonstrated
- LIGO/Virgo upgrades to 2nd generation funded, construction in progress. More detectors to come.
- Preparing for multi-messenger observation
- First long run in 2016: stay tuned!

2016: CENTENNIAL OF GENERAL RELATIVITY
We look forward to celebrating it with a discovery