Search for gravitational waves

Jo van den Brand

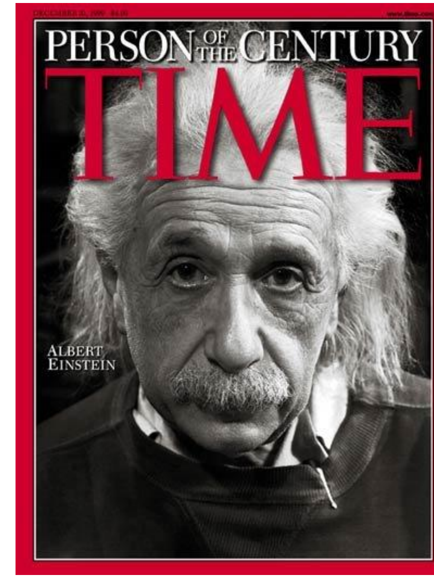
Introduction

Einstein gravity :

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

Gravity as a geometry

Space and time are physical objects



Gravitational waves

- Dynamical part of gravitation, all space is filled
- Very large energy, almost no interaction
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

Gravitational waves `squeeze' space: small effects

Proper distance between x^μ and $x^\mu + dx^\mu$

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \approx (\underline{\eta_{\mu\nu}} + h_{\mu\nu}) dx^\mu dx^\nu$$

Define $$\bar{h}_{\mu\nu} = h_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu} h^\alpha_\alpha$$

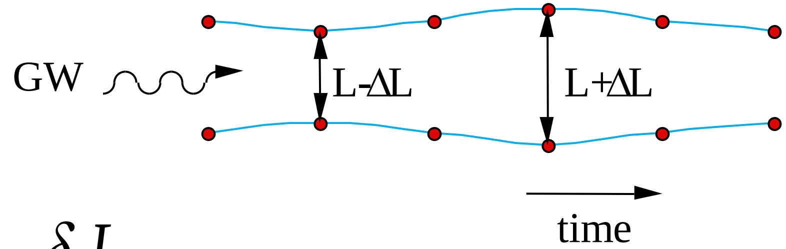
Wave equation $$\left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2}\right) \bar{h}_{\mu\nu} = 16\pi\, G_N T_{\mu\nu}$$

Plane GW propagating in *z*-direction

$$h_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Gravitational waves

- Predicted by general relativity
- GW = space-time metric wave
  - Distance variation
  - Strain amplitude *h*:



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

- GW produced by mass acceleration
  - *d* = source distance
  - *Q* = quadrupole moment

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

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

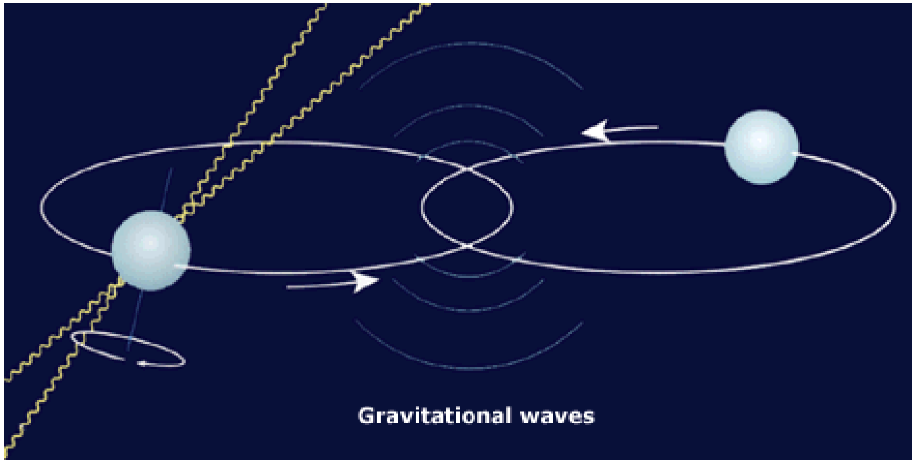
- Small coupling factor → astrophysical sources

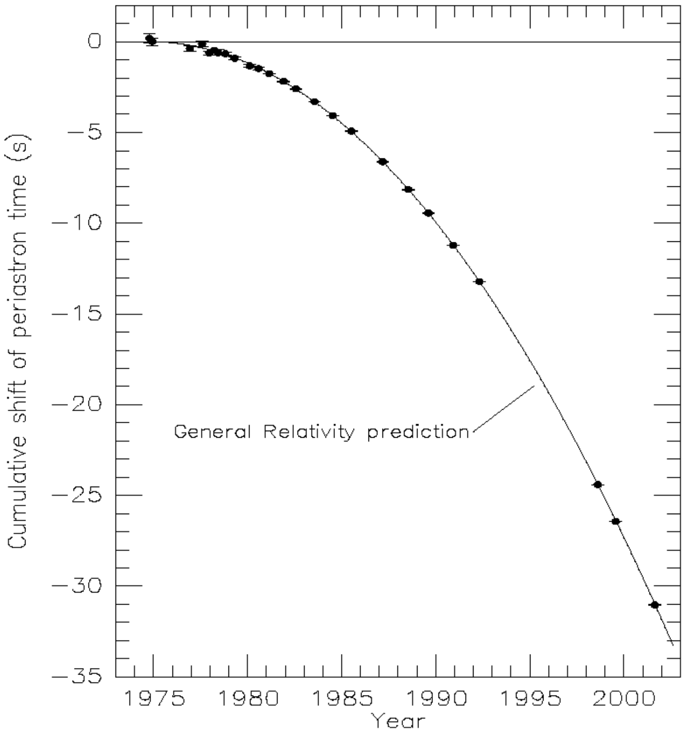
L=20 m, d = 2 m, 27 rad/s

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

Earth-sun: 313 W

Evidence for gravitational waves

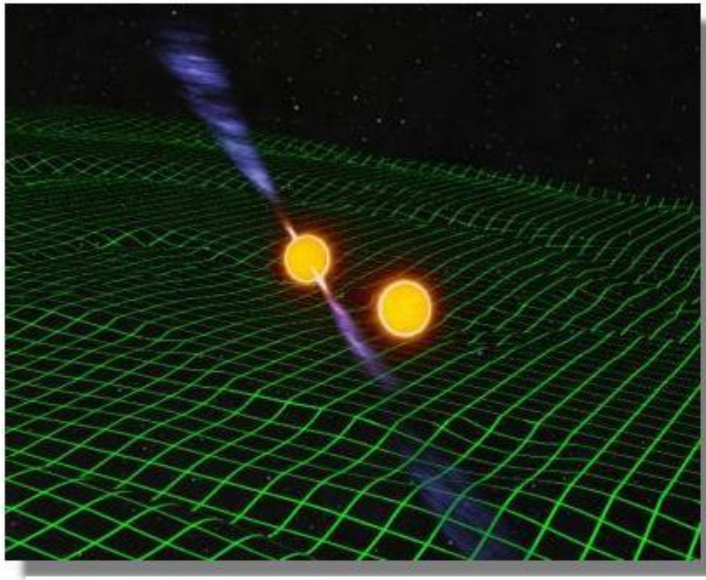


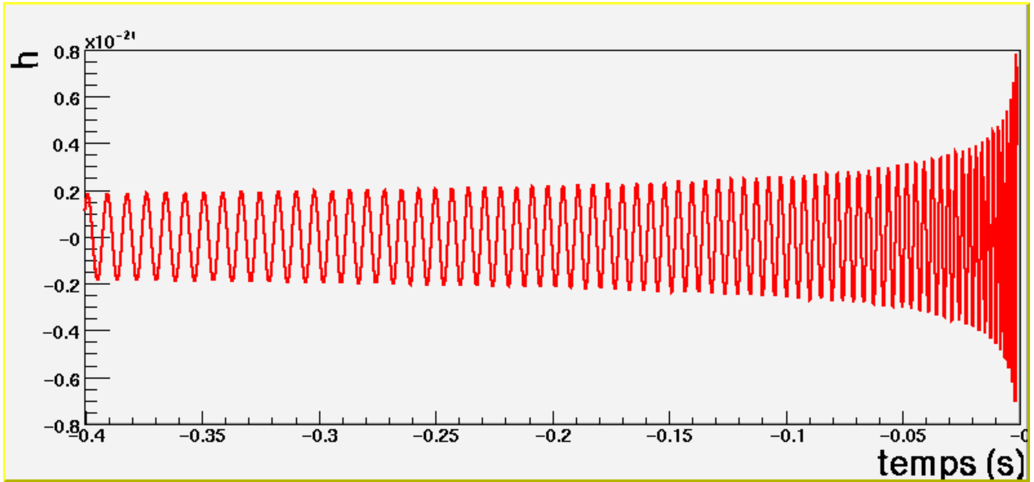


- PSR 1913+16
  - R. Hulse, J. Taylor (1974)
  - Binary pulsar (T = *7.75* hr)
  - 1 pulsar (17 rev/s) → get the orbital parameters
  - Orbital period decreases
    - Energy loss due to GW emission (~10^{25} W)
    - Good agreement with GR
    - Inspiral lifetime about 300 Myears (3.5 m/yr)
    - Expected strain, h~10^{-26} m

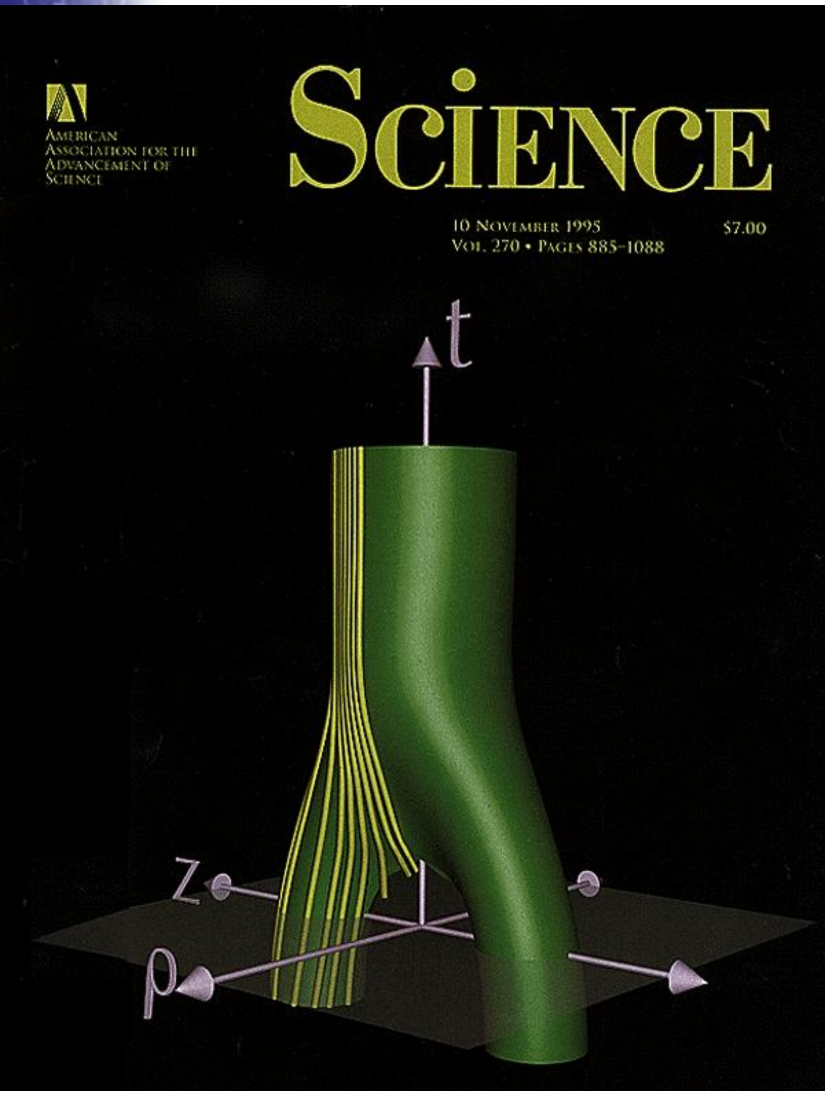
GW source: coalescing binary

- End of the life of compact binary systems
  - Neutron stars, systems have been observed
- Rare events
  - ~ 0.1 event/year (@20Mpc) ±1 order of magnitude
- Typical amplitude (NS-NS): $h \sim 10^{-22}$ @ 20 Mpc
- “Known” waveform
  - Search with matched filtering
  - General relativity tests
  - Standard candles: get the distance from the waveform
    - Coincidence with short gamma ray burst?
    - GRB070201, M31, No NSNS or BHBH.

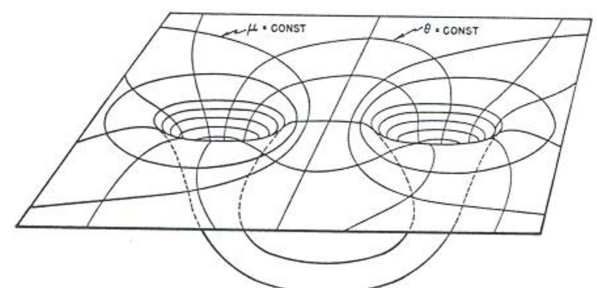




Collision of two black holes



- Two-body problem in general relativity
- Numerical solution of Einstein equations required
- Problem solution started 40 years ago (1963 Hahn & Lindquist, IBM 7090)

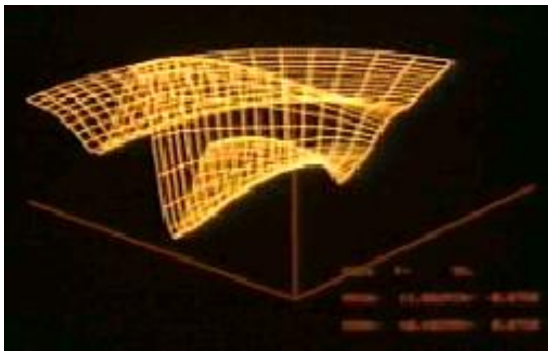


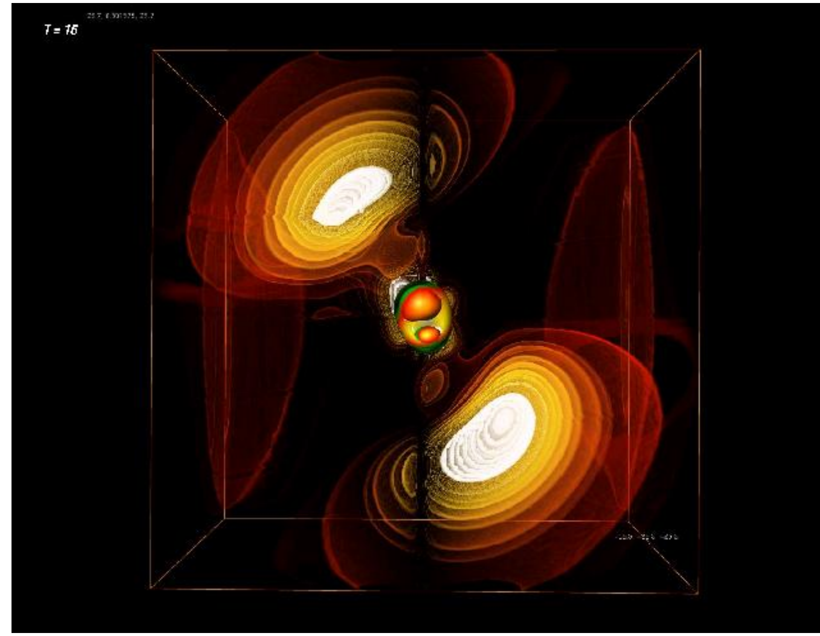
- Wave forms critical for gravitational wave detectors
- A PetaFLOPS-class grand challenge

Oct. 10, 1995

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

Numerical relativity





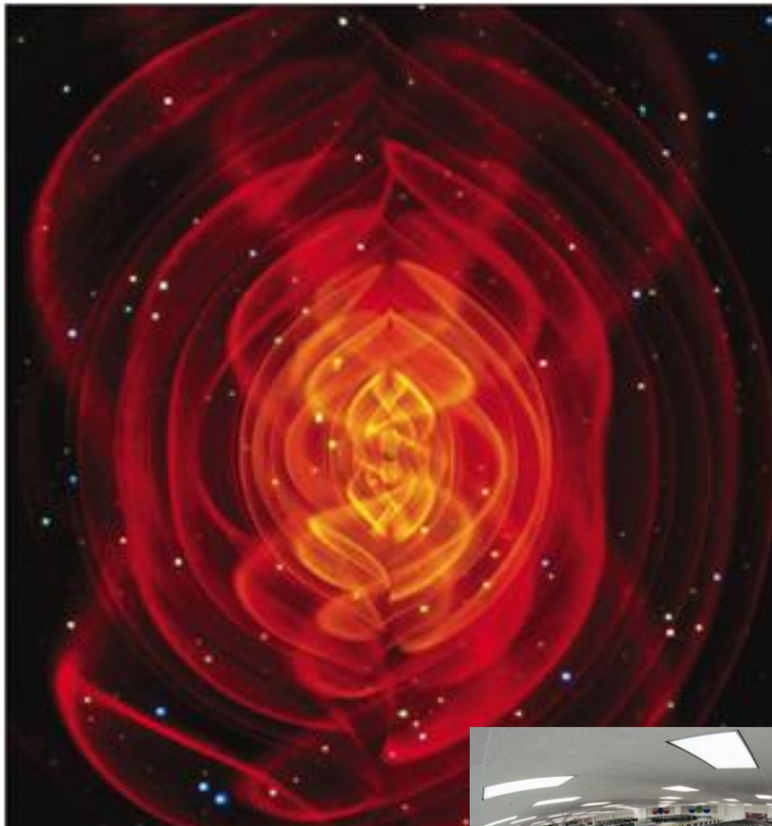
1977
Eppley & Smarr
CDC 7600
One processor
Each 35 Mflops
5 hours

1999
Seidel & Suen, et al.
SGI Origin
256 processors
Each 500 Mflops
40 hours

300X

30,000X

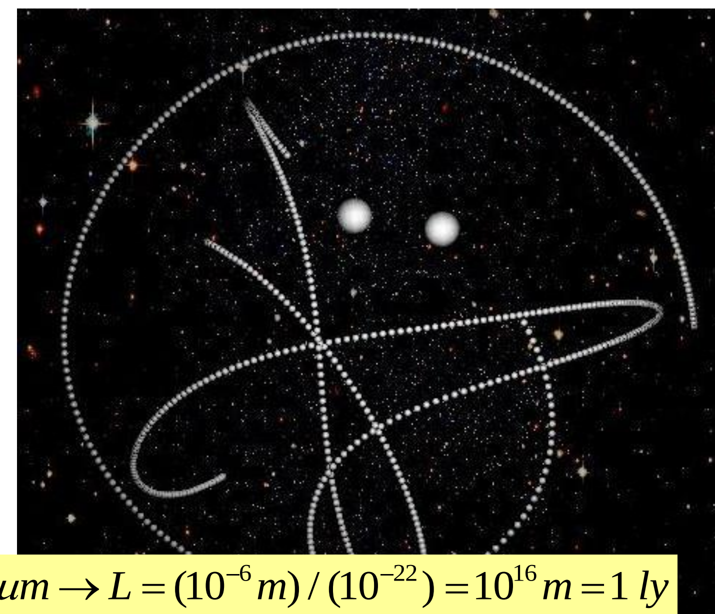
Numerical relativity

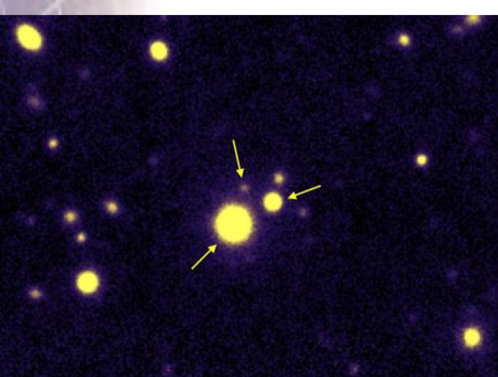


First merger of three black holes simulated on a supercomputer

ScienceDaily (Apr. 12, 2008)

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



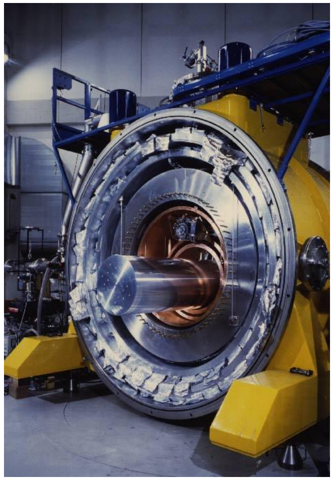


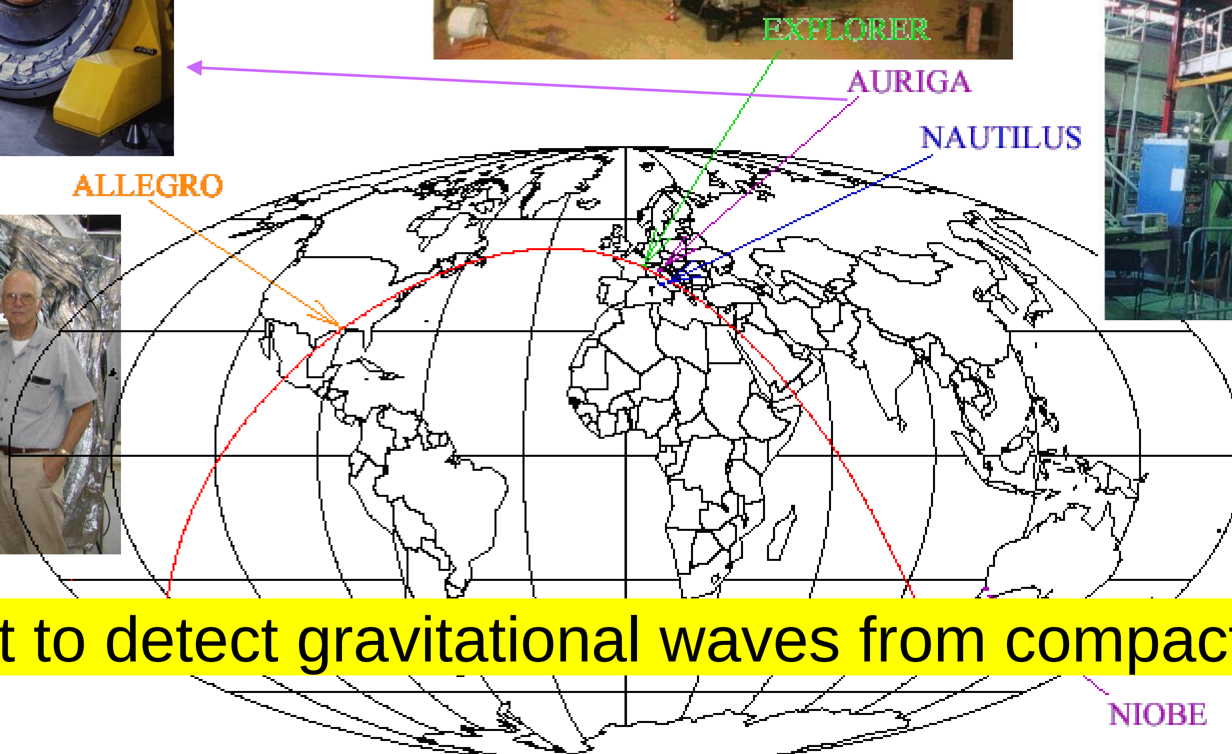
Triple quasar (10.8 Gly)
S. G. Djorgovski et al., Caltech, EPFL (Jan. 2007)

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

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

Bar detectors: IGEC collaboration



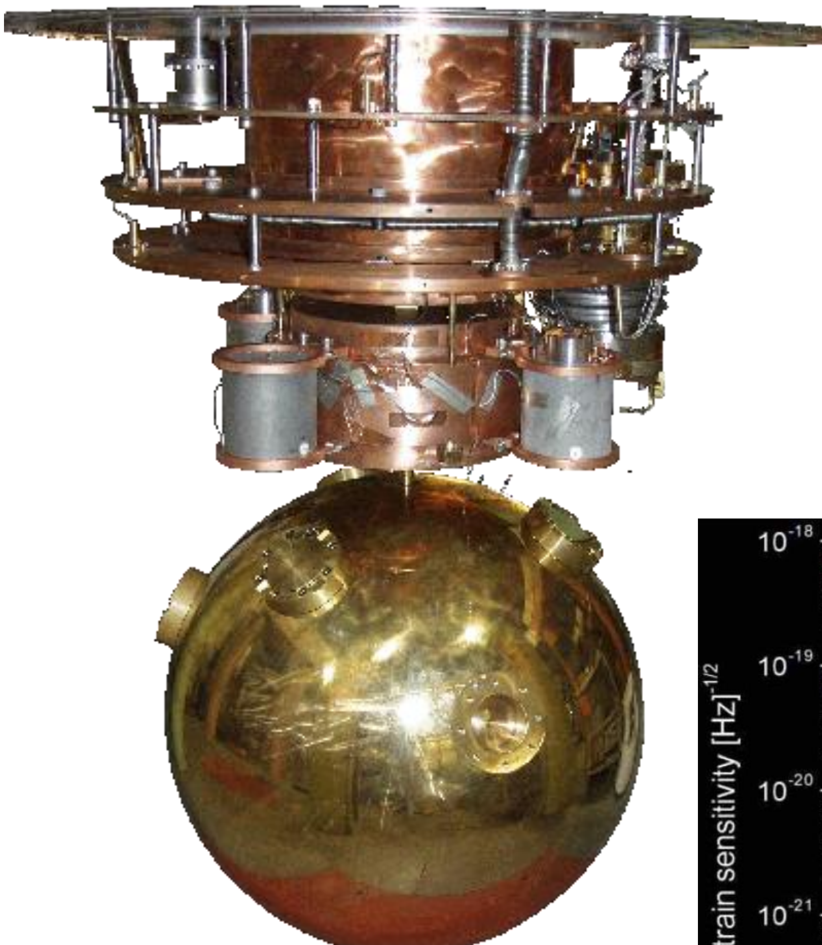


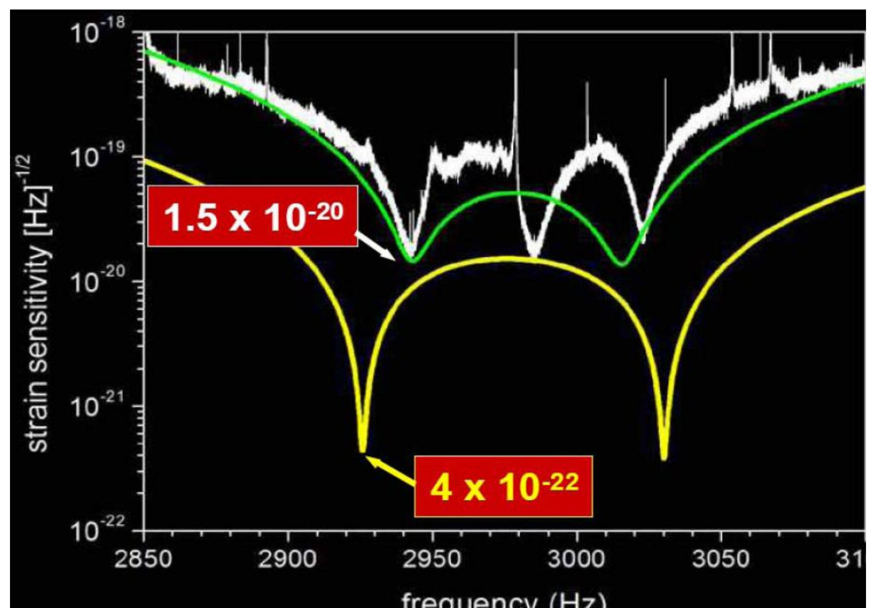
Built to detect gravitational waves from compact objects

IGEC

Ladbrokes.com

Mini-GRAIL: a spherical `bar' in Leiden





Interferometric detectors: an international dream

GEO600 (British-German)
Hanover, Germany

LIGO (USA)
Hanford, WA and Livingston, LA

TAMA300 (Japan)
Mitaka

AIGO (Australia),
Wallingup Plain, 85km north of Perth

VIRGO (French-Italian)
Cascina, Italy

Network of Interferometers

decompose the polarization of gravitational waves

Interferometer as GW detector

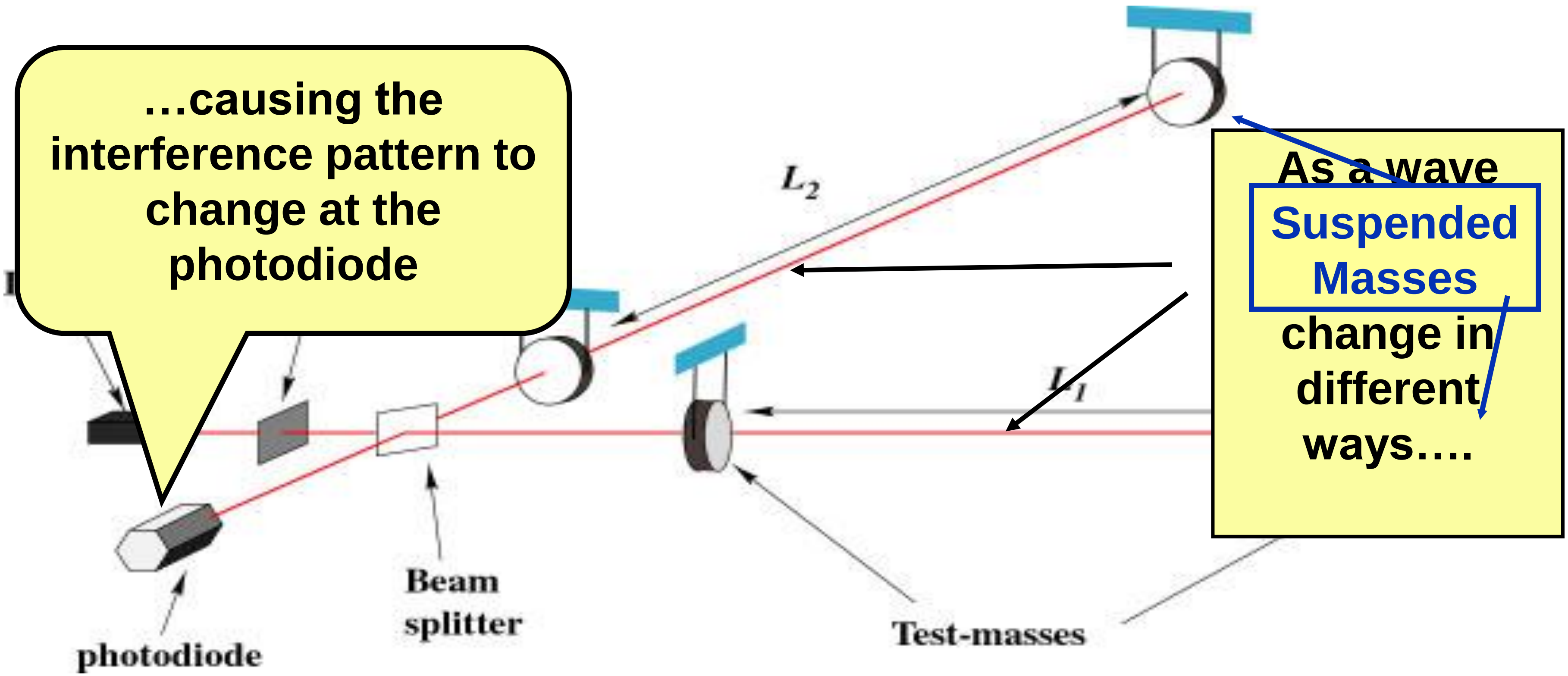
- Principle: Measure distances between free test masses
  - Michelson interferometer
  - Test masses = interferometer mirrors
  - Sensitivity: h = ΔL/L
    - We need large interferometer
    - For Virgo L = 3 km

Virgo: CNRS+INFN

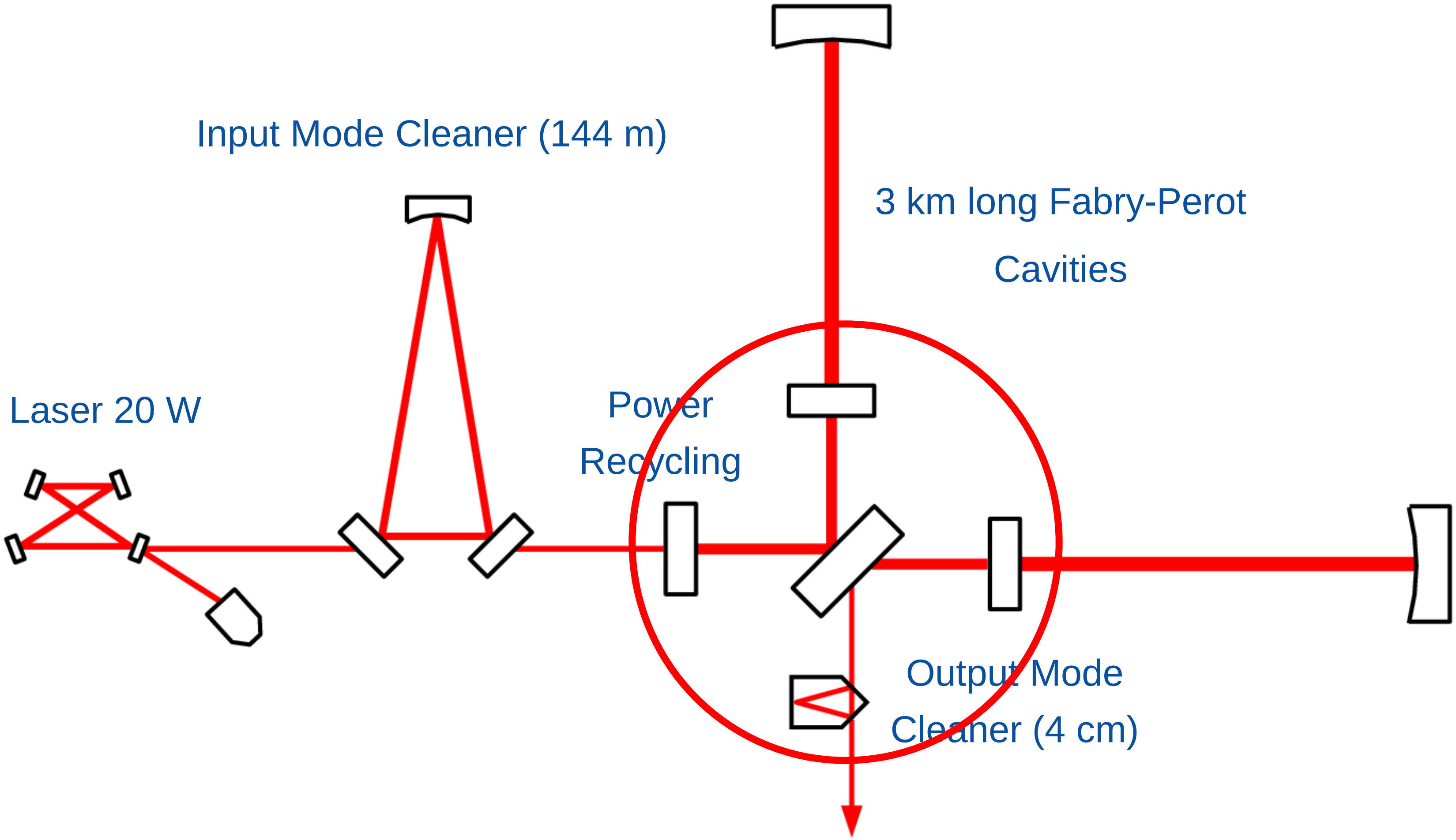
(ESPCI-Paris, INFN-Firenze/Urbino, INFN-Napoli, INFN-Perugia, INFN-Pisa, INFN-Roma,LAL-Orsay, LAPP-Annecy, LMA-Lyon, OCA-Nice)

+ NIKHEF joined 2007

Interferometer Concept

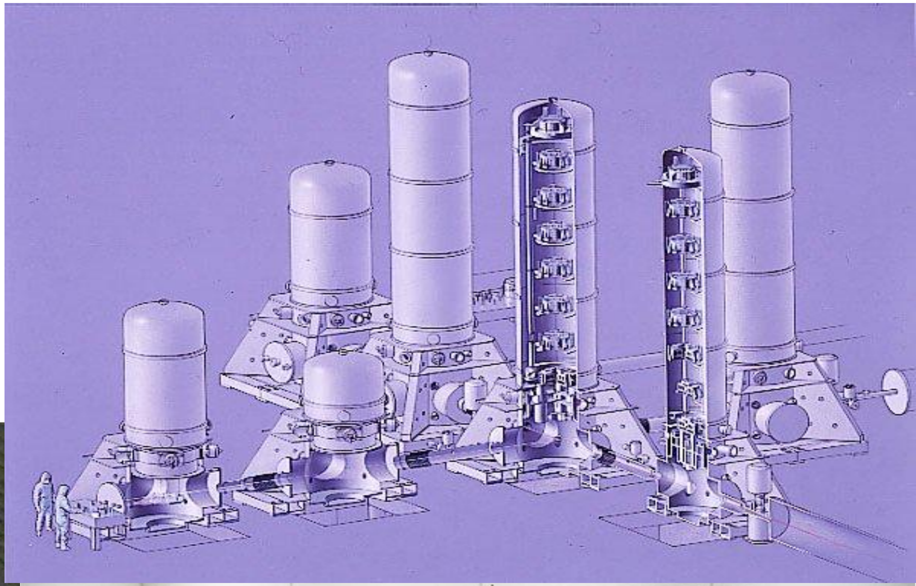


VIRGO Optical Scheme



Vacuum system

- UHV

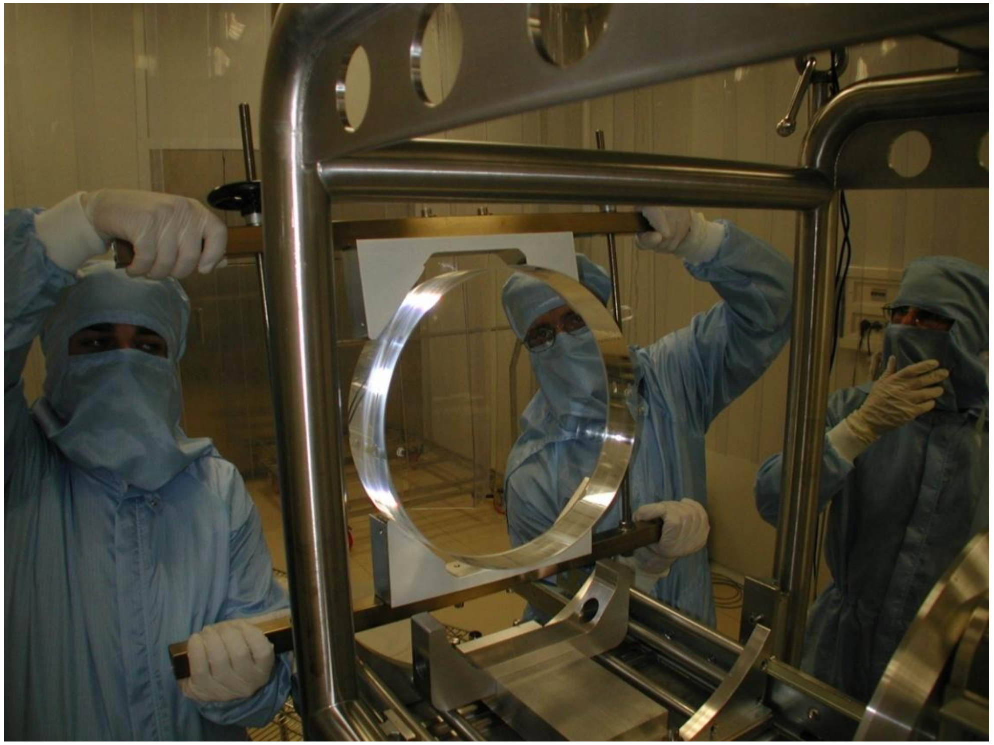


Mirrors

High quality fused silica mirrors

- 35 cm diameter, 10 cm thickness, 21 kg mass
- Substrate losses ~1 ppm
- Coating losses <5 ppm
- Surface deformation ~l/100

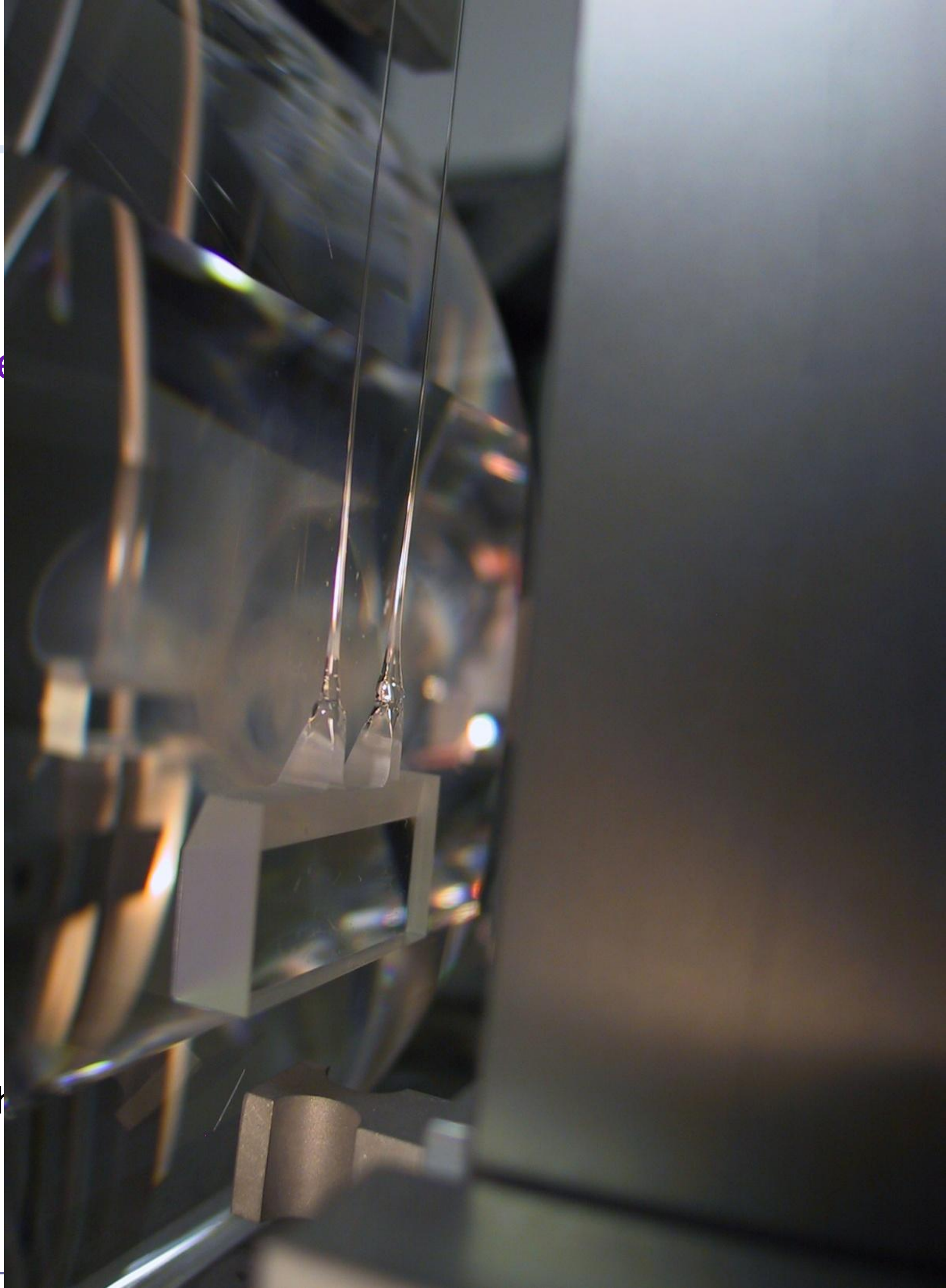
Quantum Non-demolition Measurements



Thermal noise

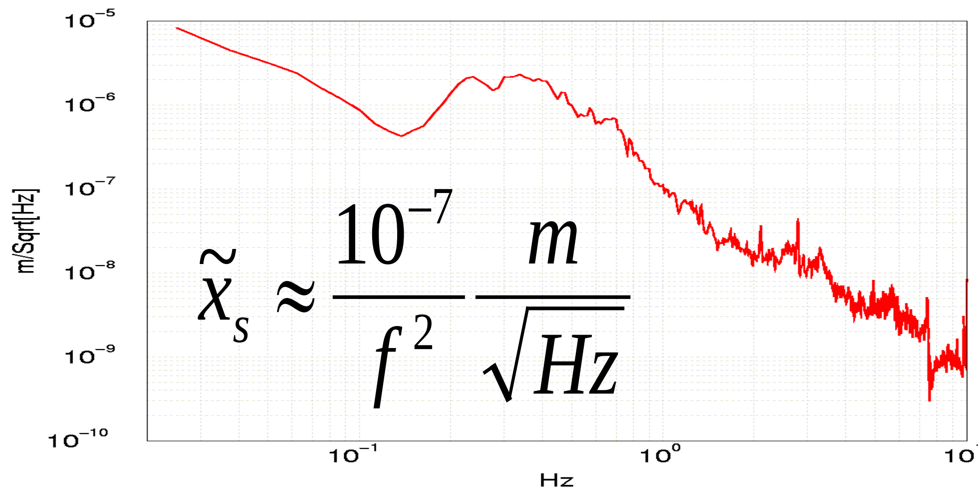
- Mechanical modes are in the
  - Modes:
    - Pendulum mode
    - Wire vibration
    - Mirror internal modes
    - Coating surface
  - Energy associate: $k_B T$
- Thermal motion spectrum:
- Strategy:
  - use low dissipative materials:

    → concentrate the motion at th



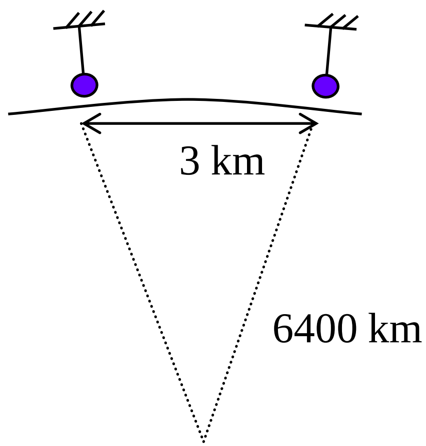
The seismic noise challenge

- Noise spectrum:



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

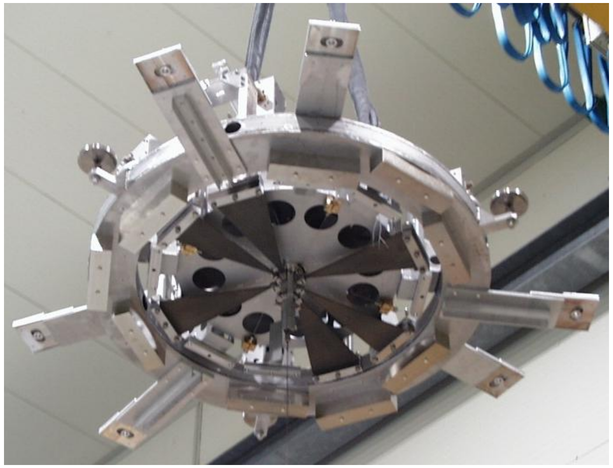
- Goal:
  - More than 10 orders of magnitude above 4Hz

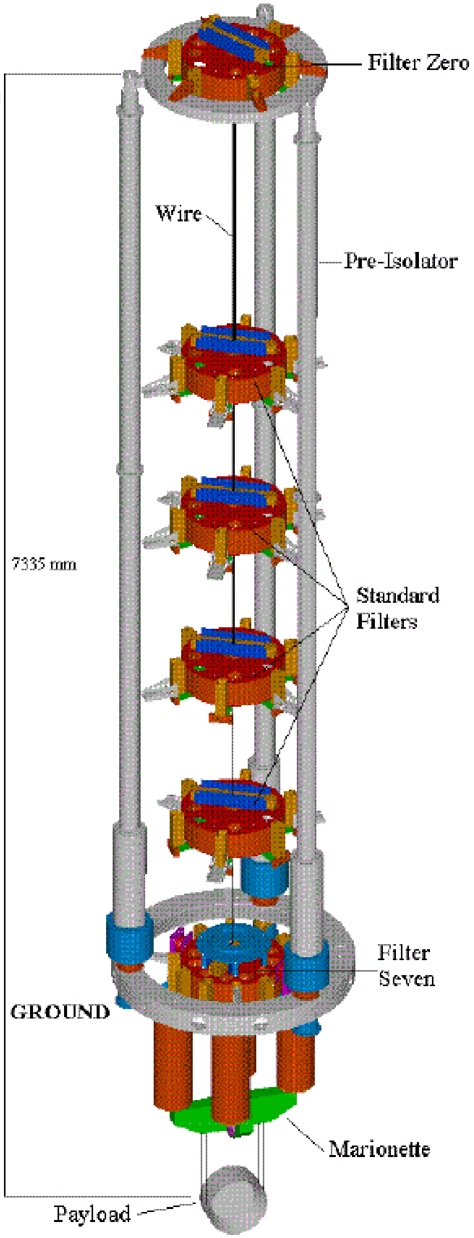


- Vertical to horizontal coupling > 2 $\times 10^{-4}$
  - Need to filter vertical motions!

VIRGO super attenuator

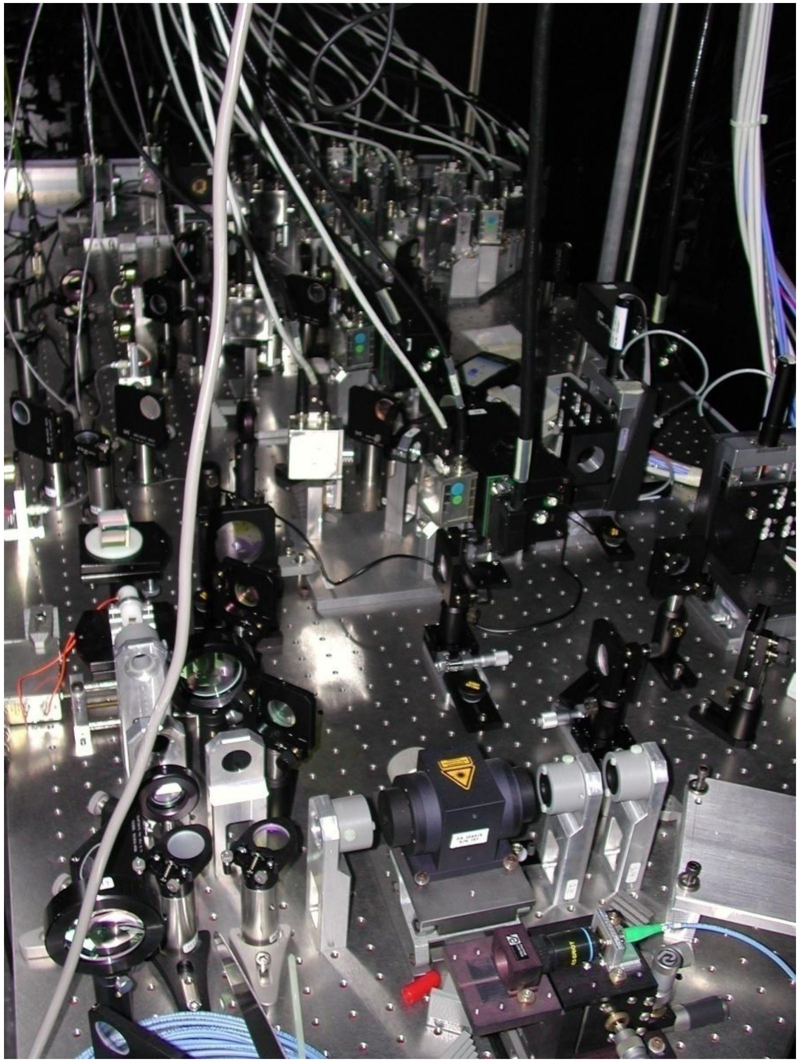
- Solution:
  - Chain of filters
- Passive device
  - Combine:
    - blades (vertical)
    - wires (pendulum)
- 6 seismic filter (in all DOFs)
- Inverted pendulum for low freq. control
- 2 Control stages:
  - Marionetta (longitudinal-angular)
  - reference mass (longitudinal)
- Expected attenuation: 10^{14} @ 10 Hz
- Various control strategies

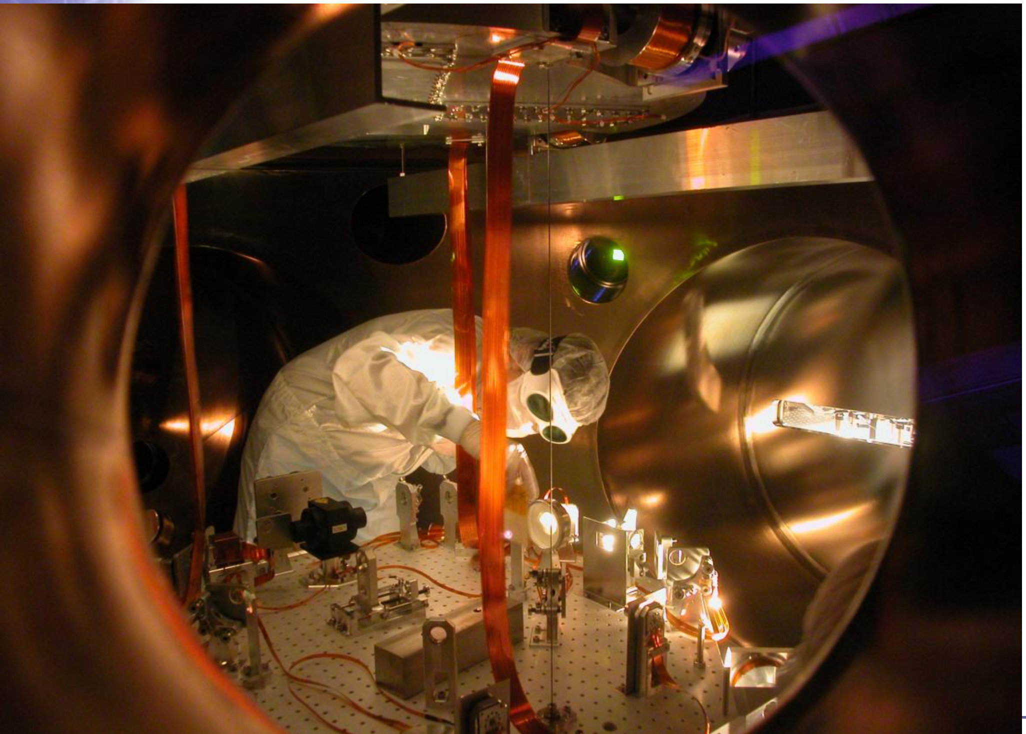




Detection system

- Theory:
  - One photodiode
- Reality
  - Multiple beams, multiple photodiodes, mod/demodulation electronics, camera, DAQ,…
  - > 1400 « ADC channels »
  - 18 Mbytes/s of raw data

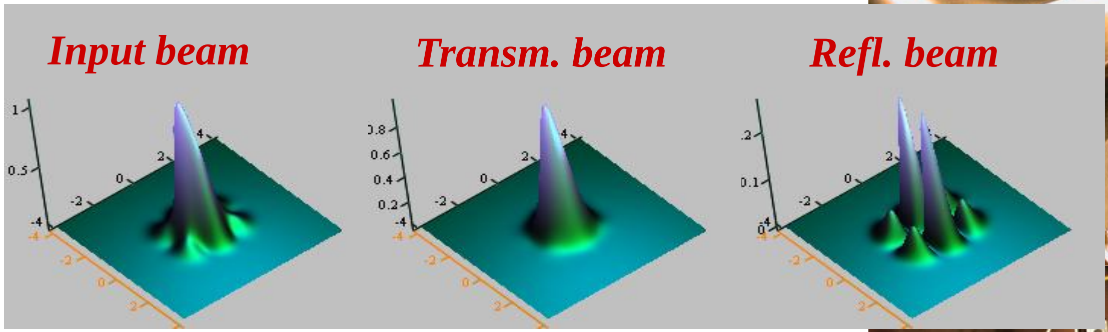


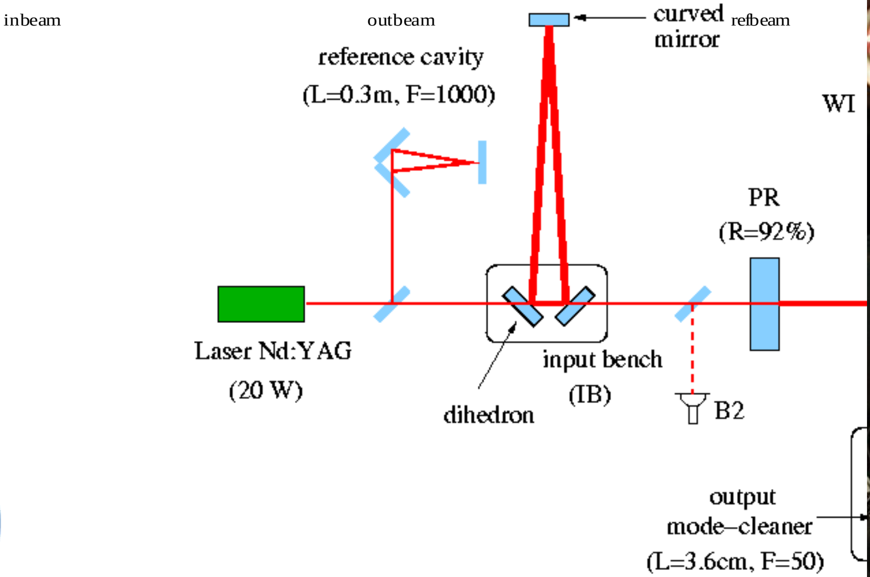


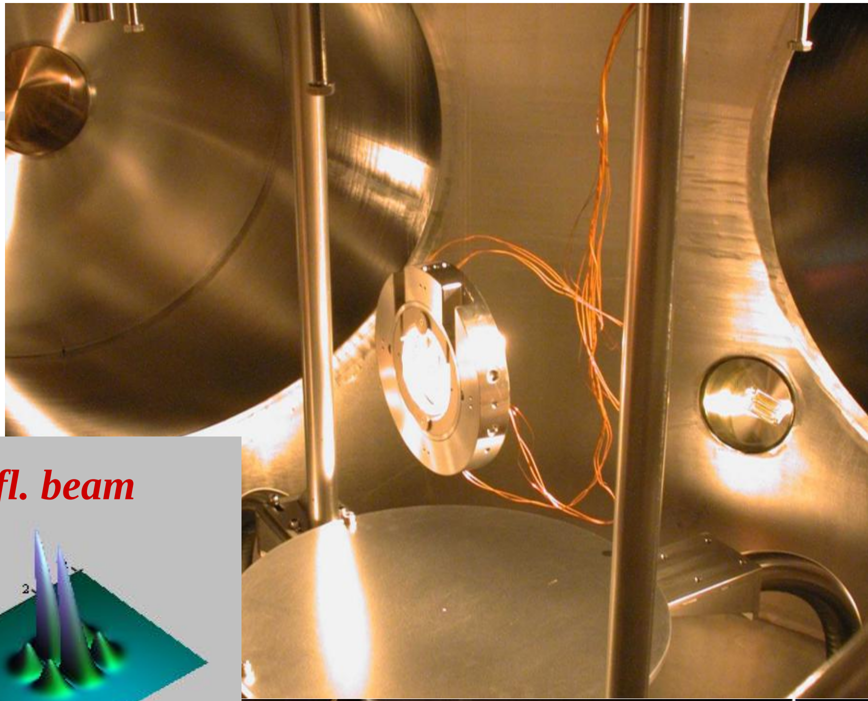
NIKHEF activities

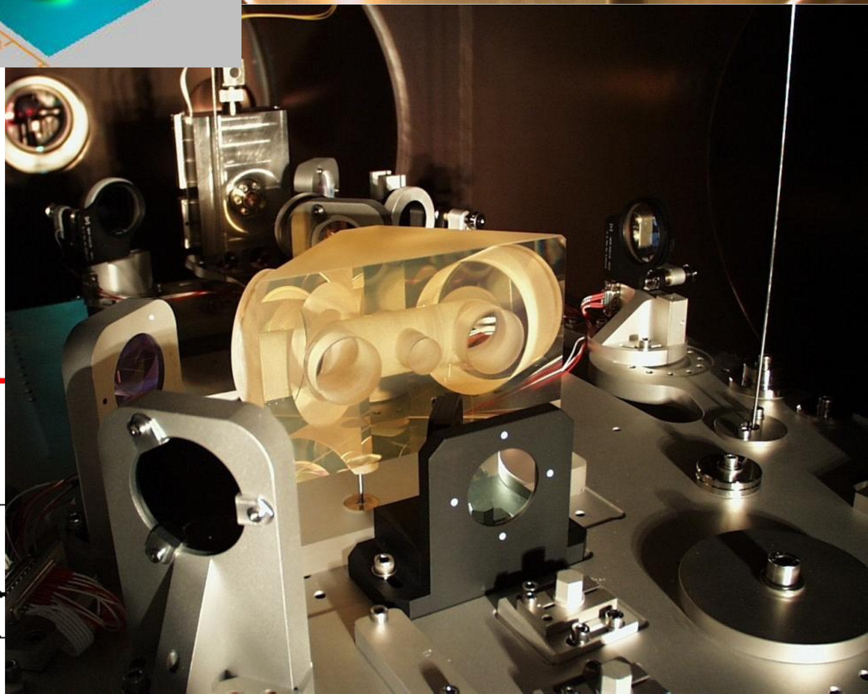
Input mode cleaner

- Mode cleaner cavity: filters laser noise, select TEM00 mode

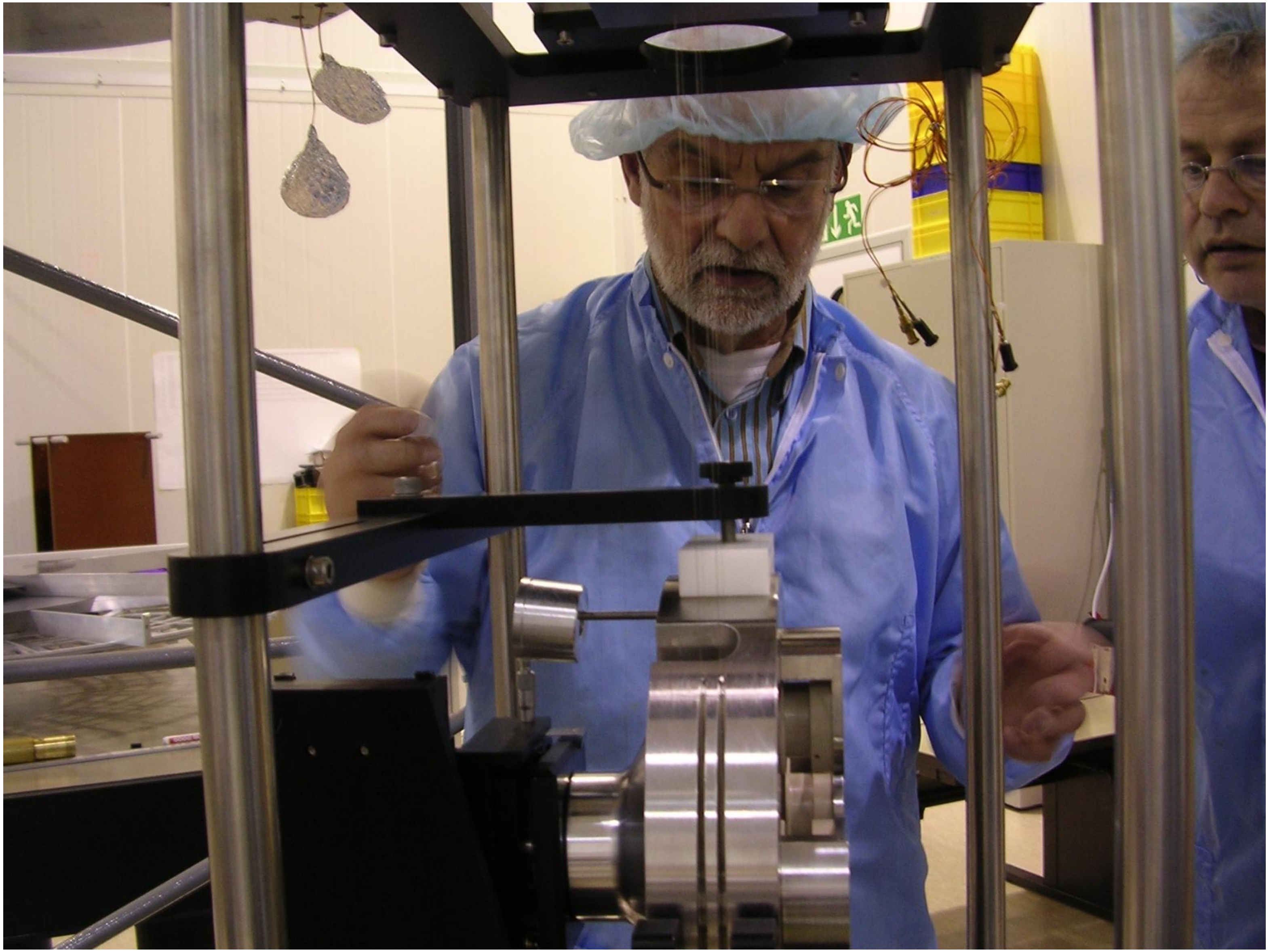




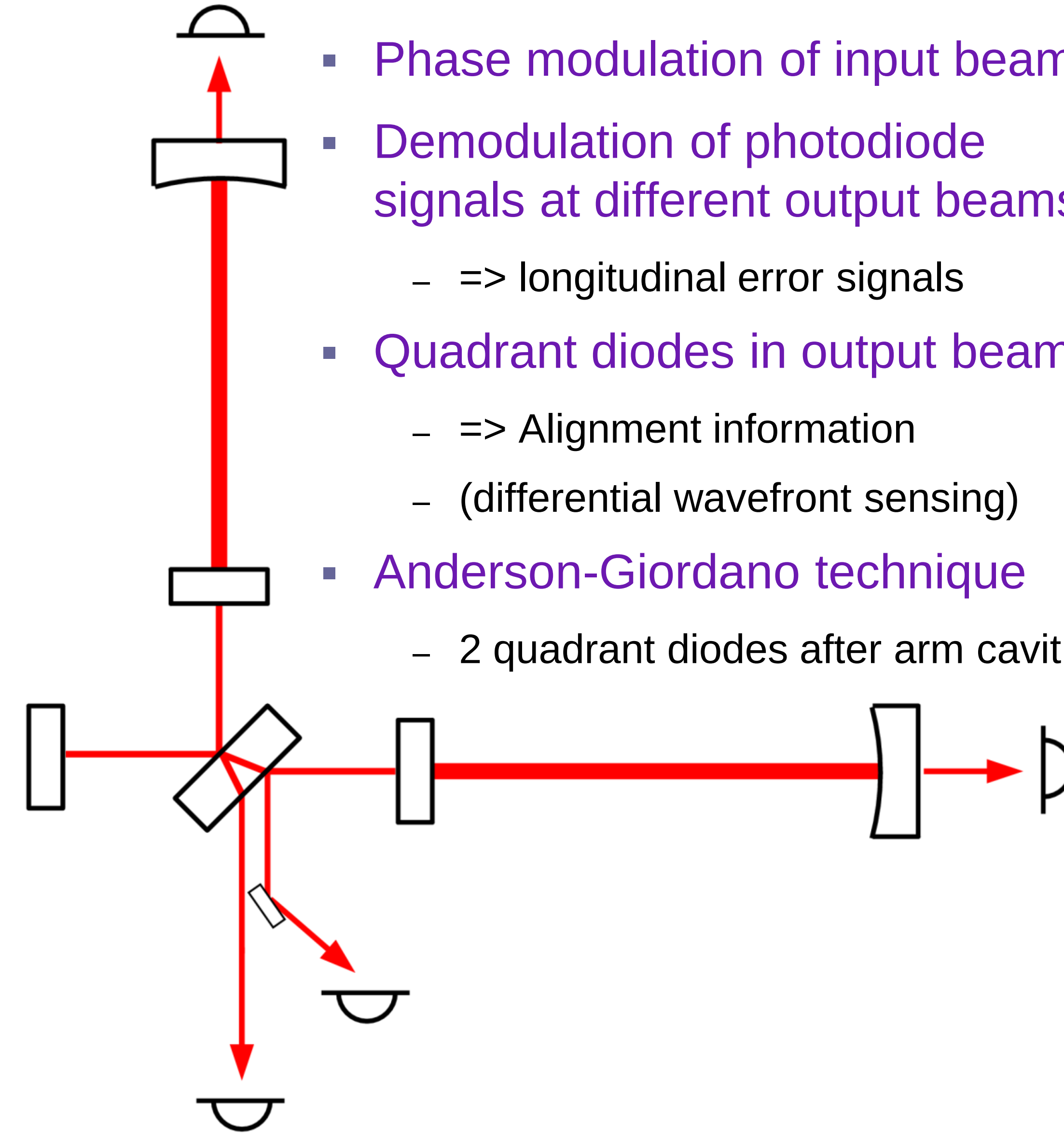


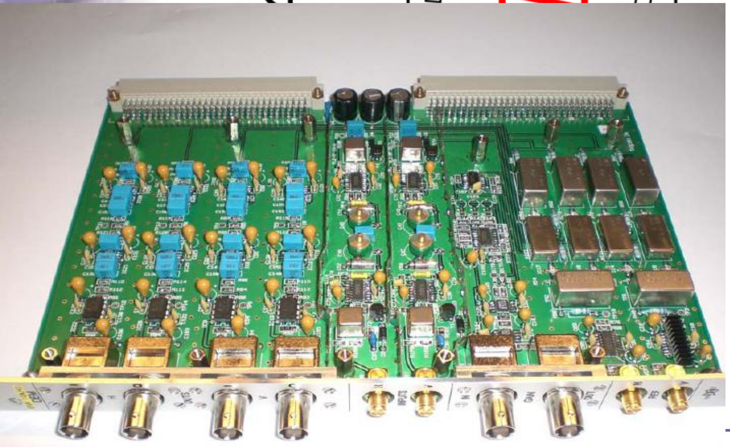


Input mode cleaner end-mirror



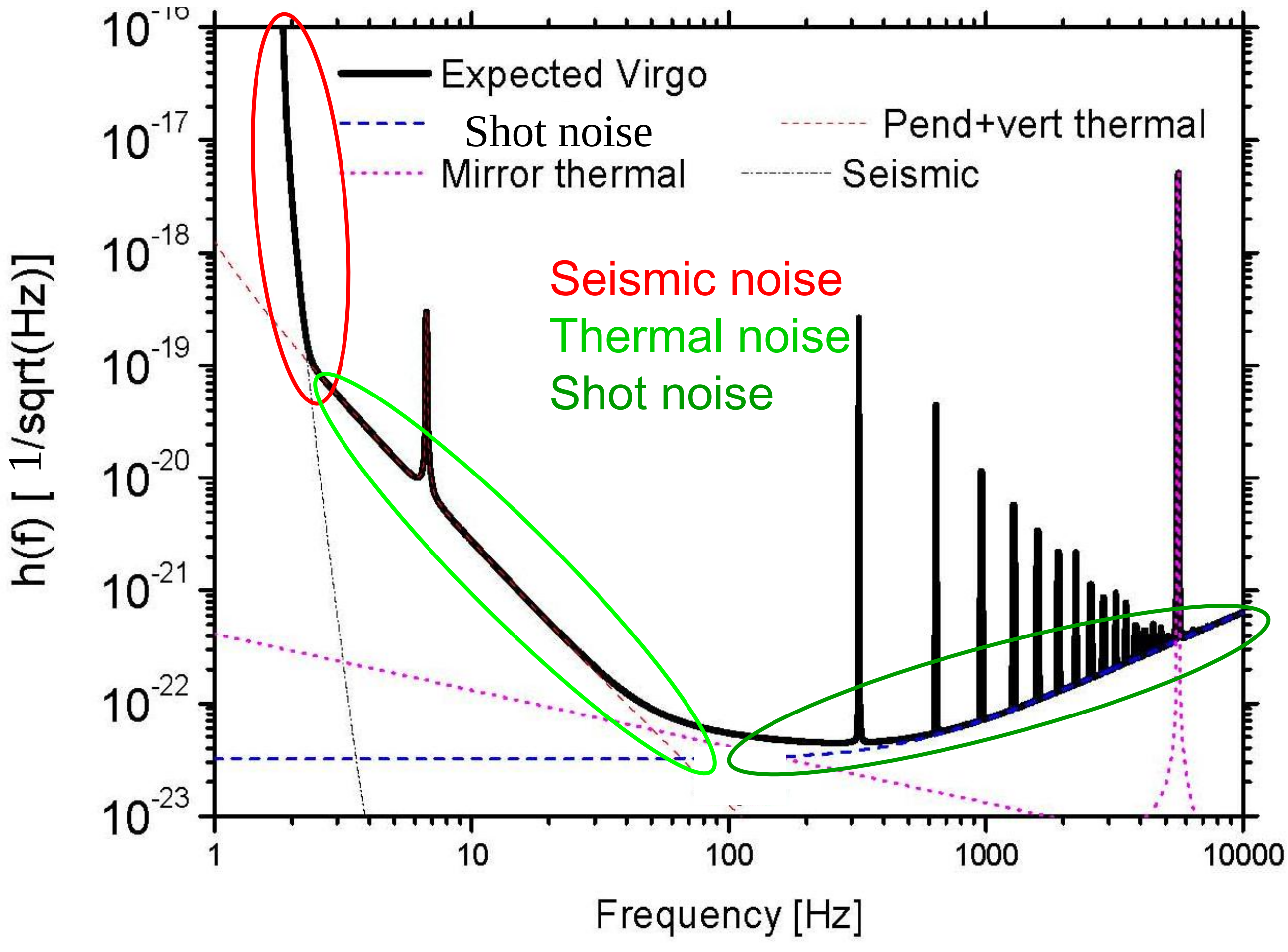
NIKHEF: Linear alignment of VIRGO





- Phase modulation of input beam
- Demodulation of photodiode signals at different output beams
  - => longitudinal error signals
- Quadrant diodes in output beams
  - => Alignment information
  - (differential wavefront sensing)
- Anderson-Giordano technique
  - 2 quadrant diodes after arm cavities

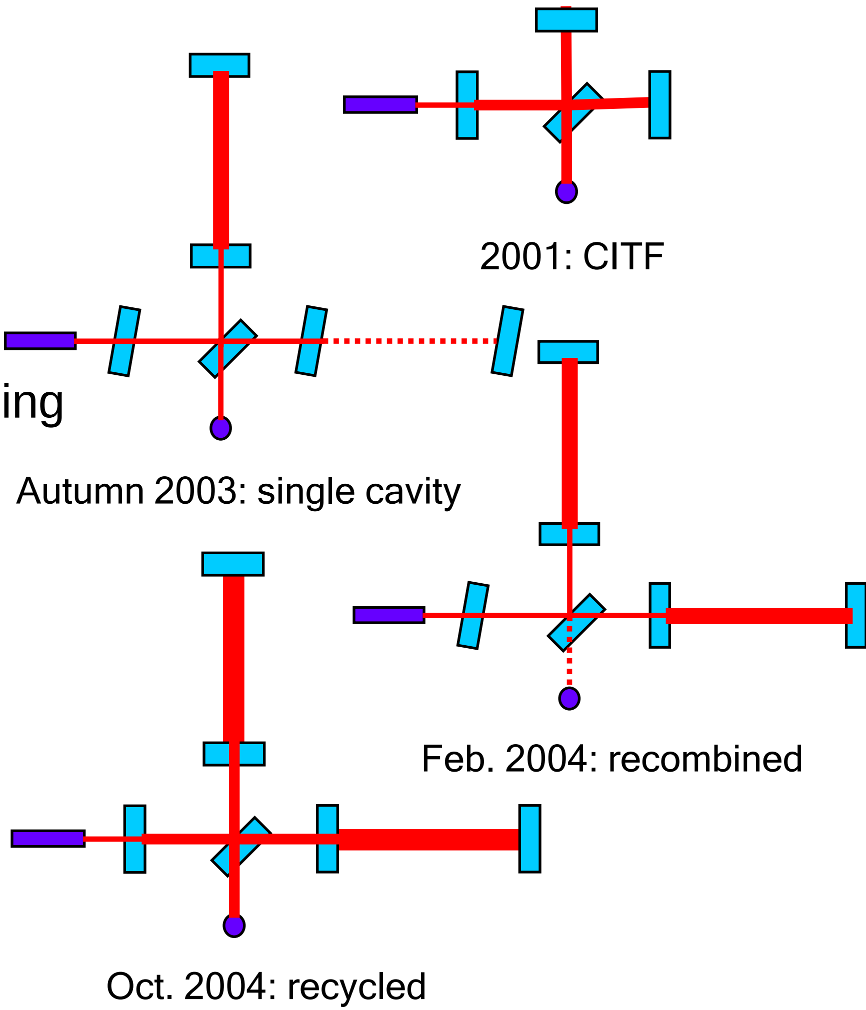
VIRGO design sensitivity



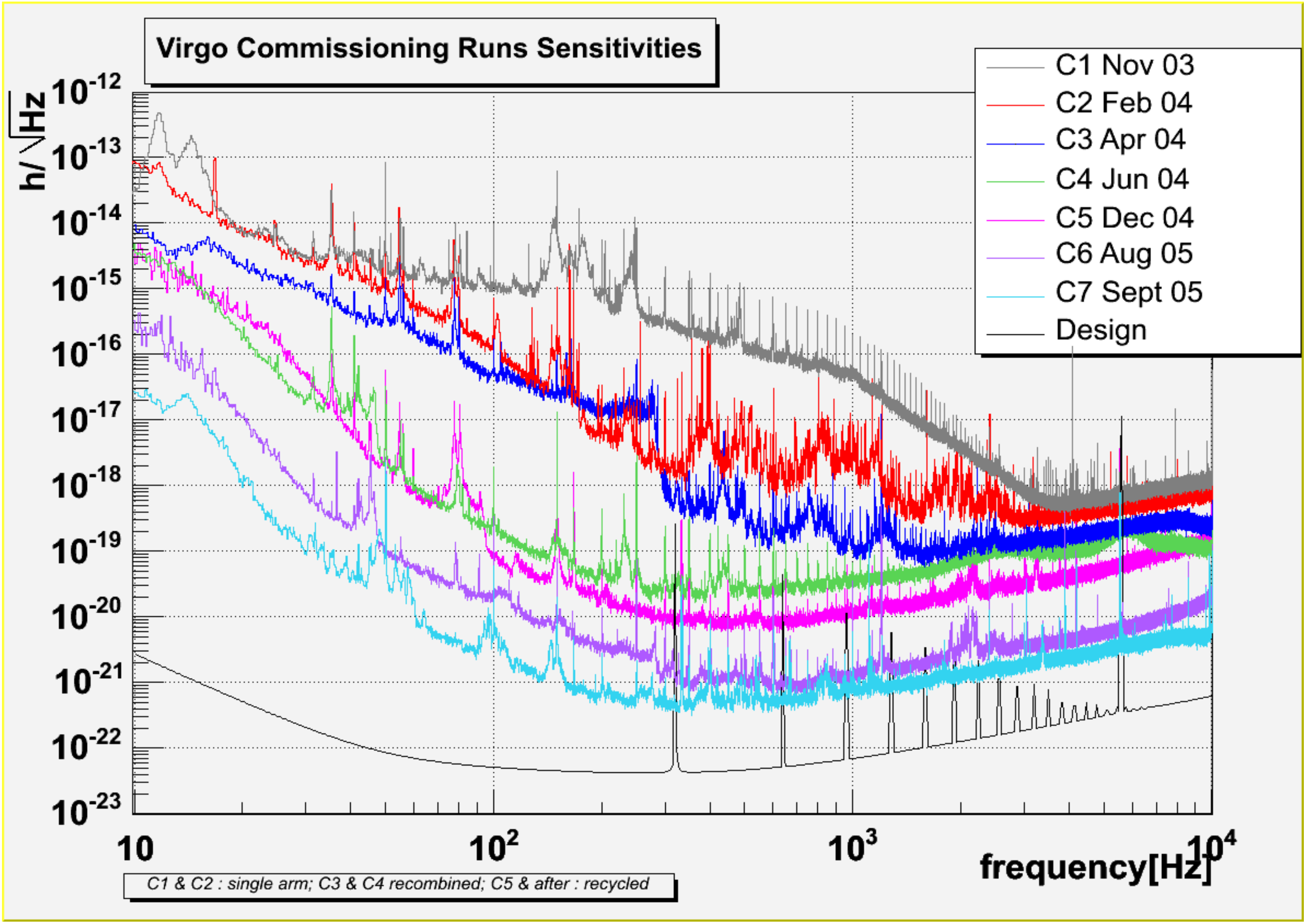
Virgo Status
& Commissioning

A short summary

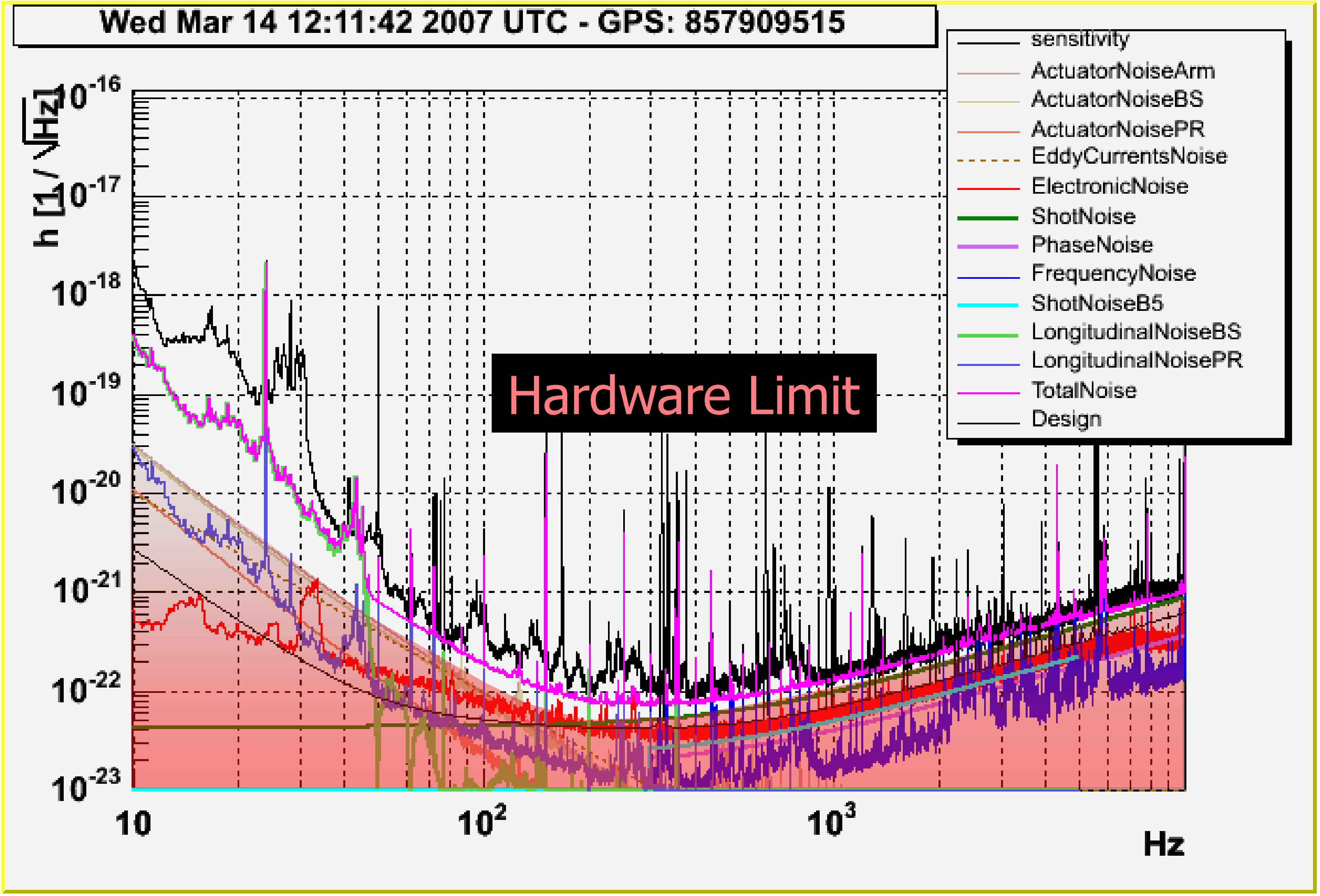
- 1993
  - Virgo approved by CNRS & INFN
- 1996
  - Start construction at the Site
- 2001-02
  - Central Interferometer commissioning
- July 2003:
  - Inauguration;
  - Start the full Virgo commissioning
- February 2004:
  - First Lock in recombined mode
- October 2004:
  - First lock in recycled mode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



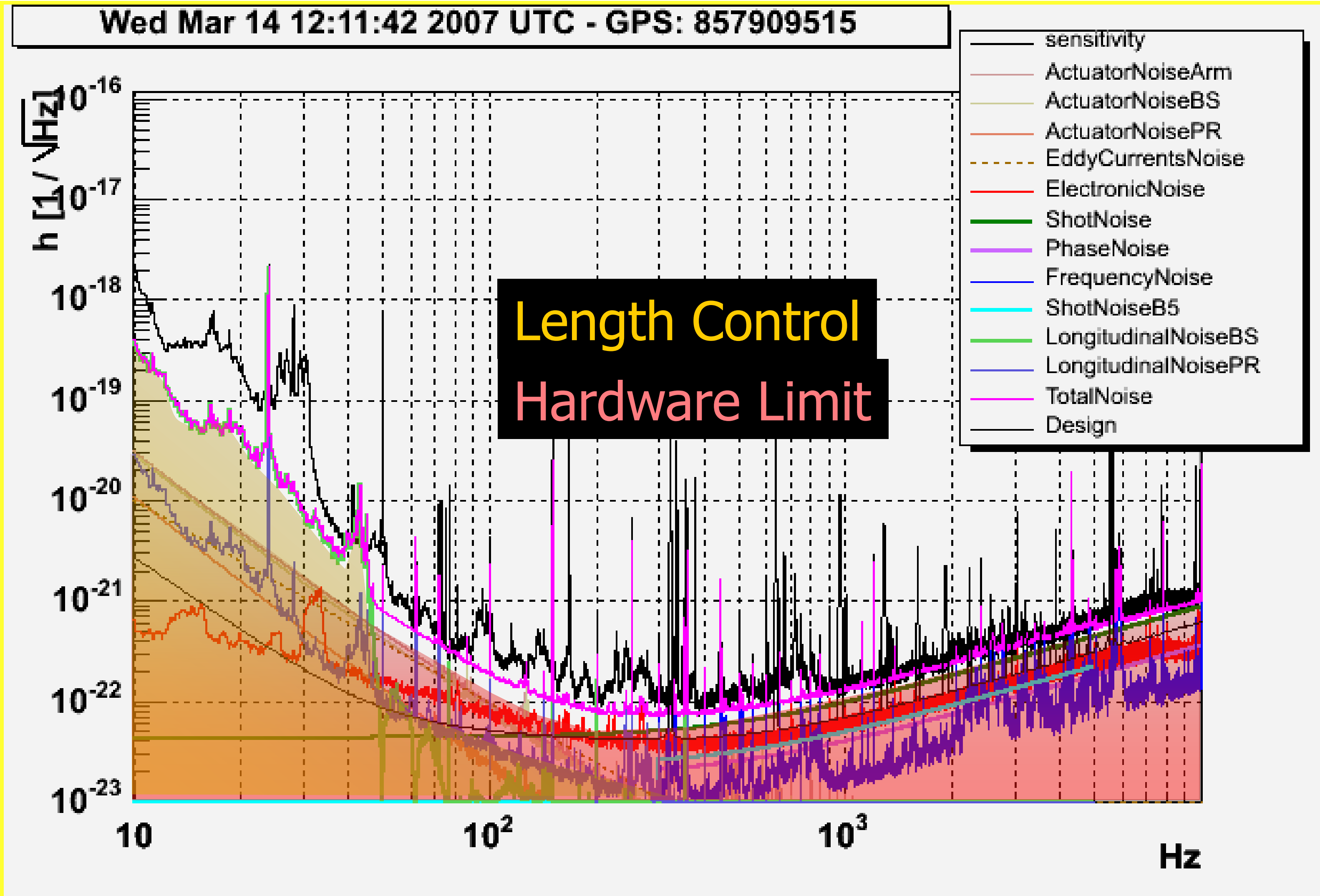
Sensitivity evolution



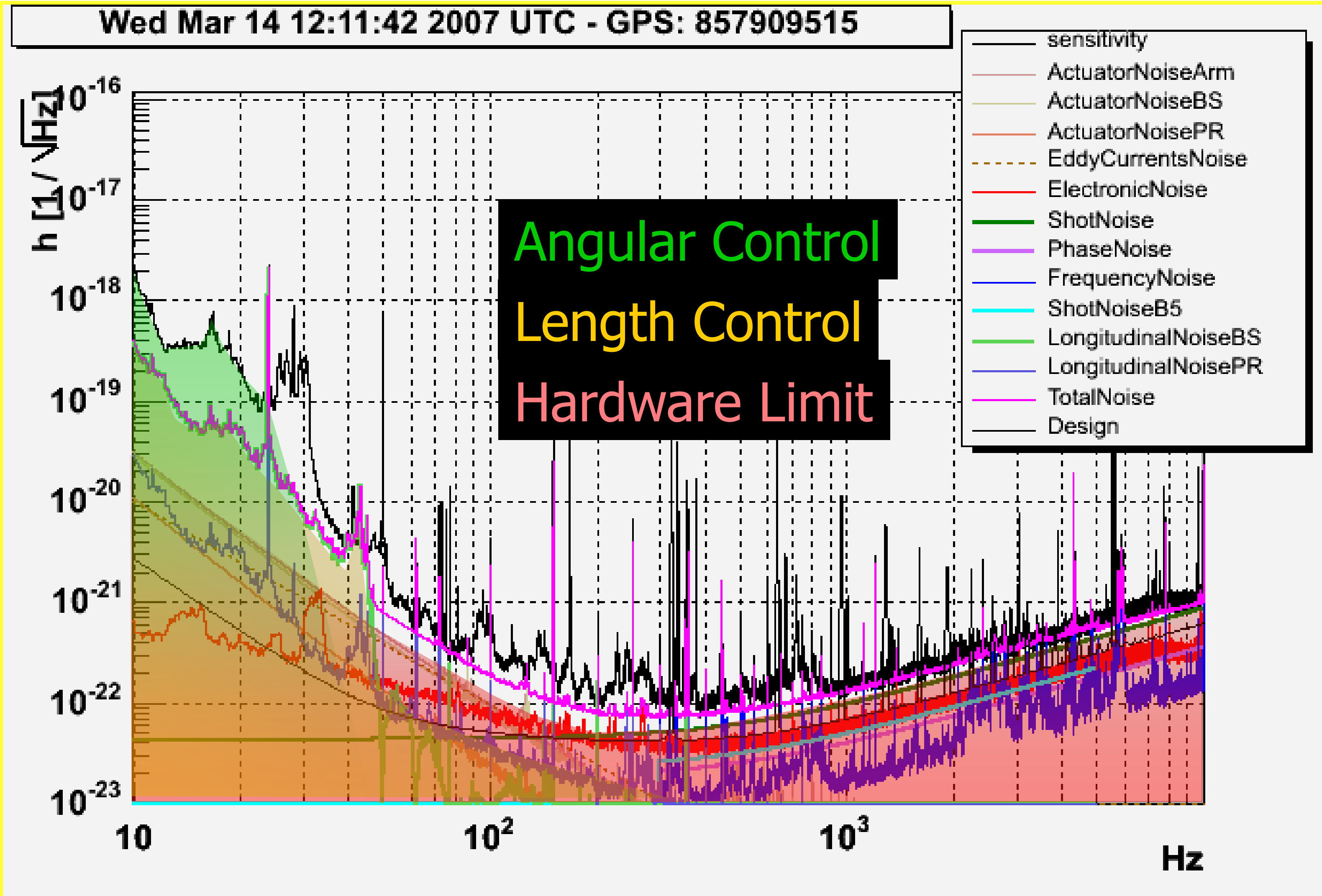
Sensitivity today



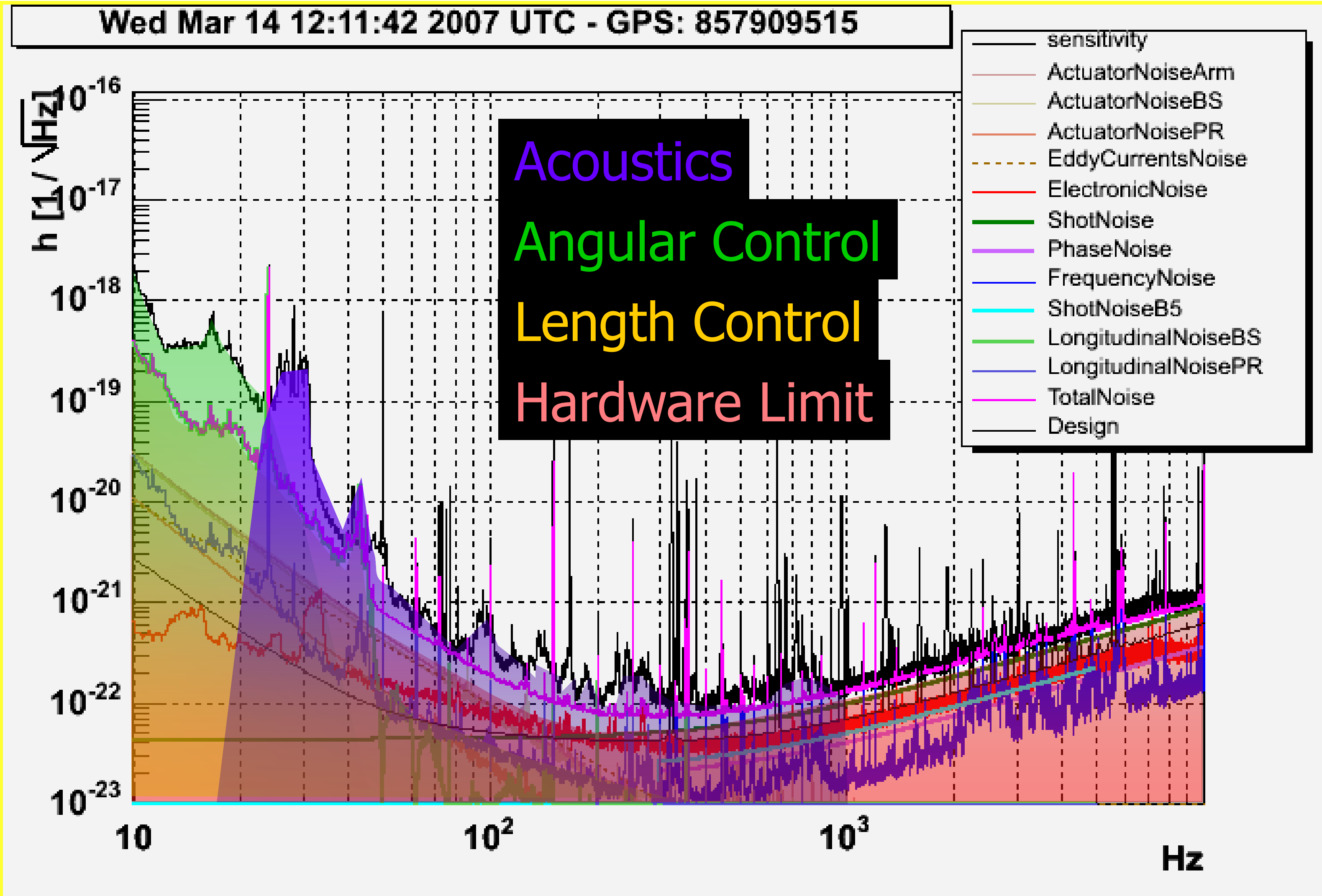
Sensitivity today



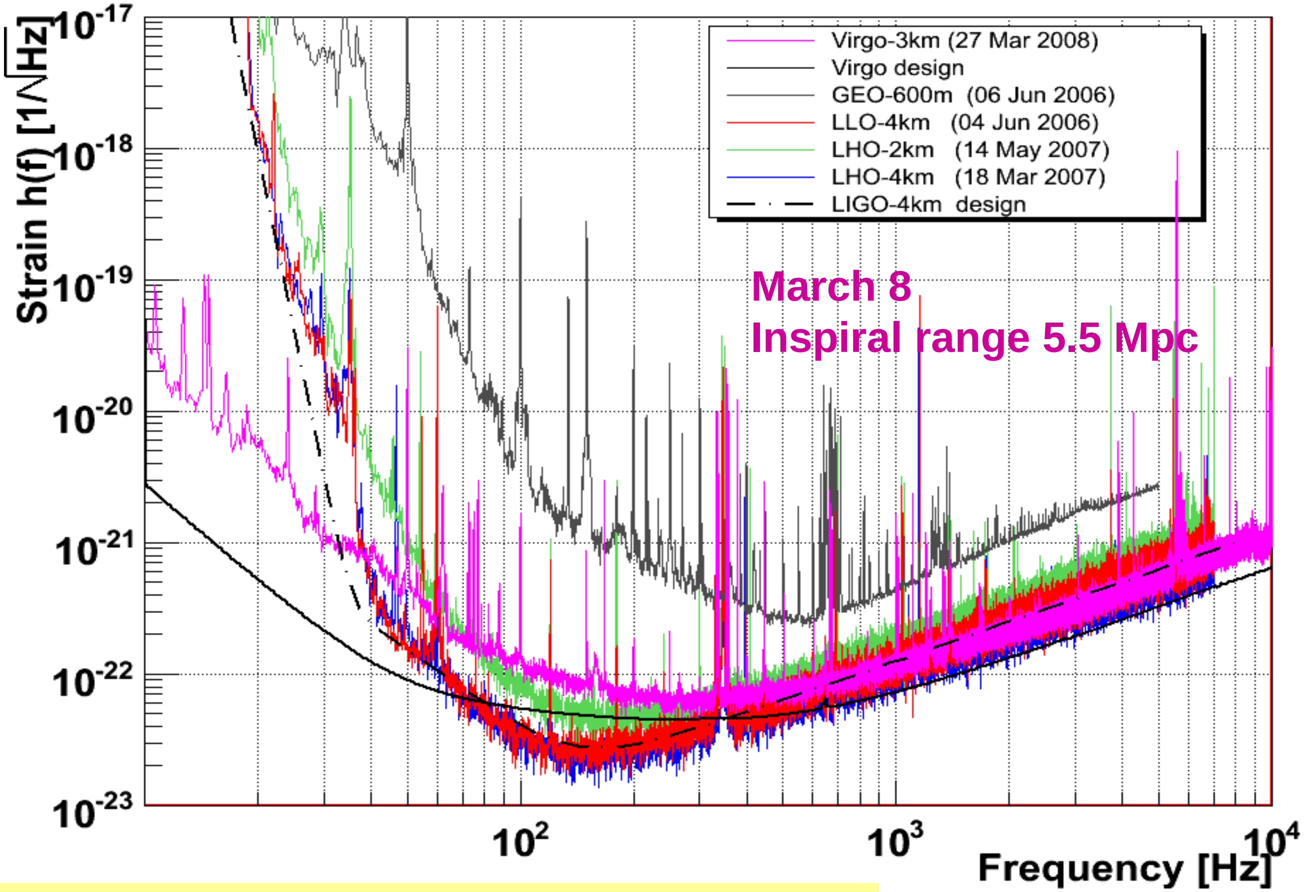
Sensitivity today



Sensitivity today



Virgo sensitivity compared to LIGO and GEO600



The horizon (best orientation) for a binary system of two 10 solar mass black holes is 63 Mpc

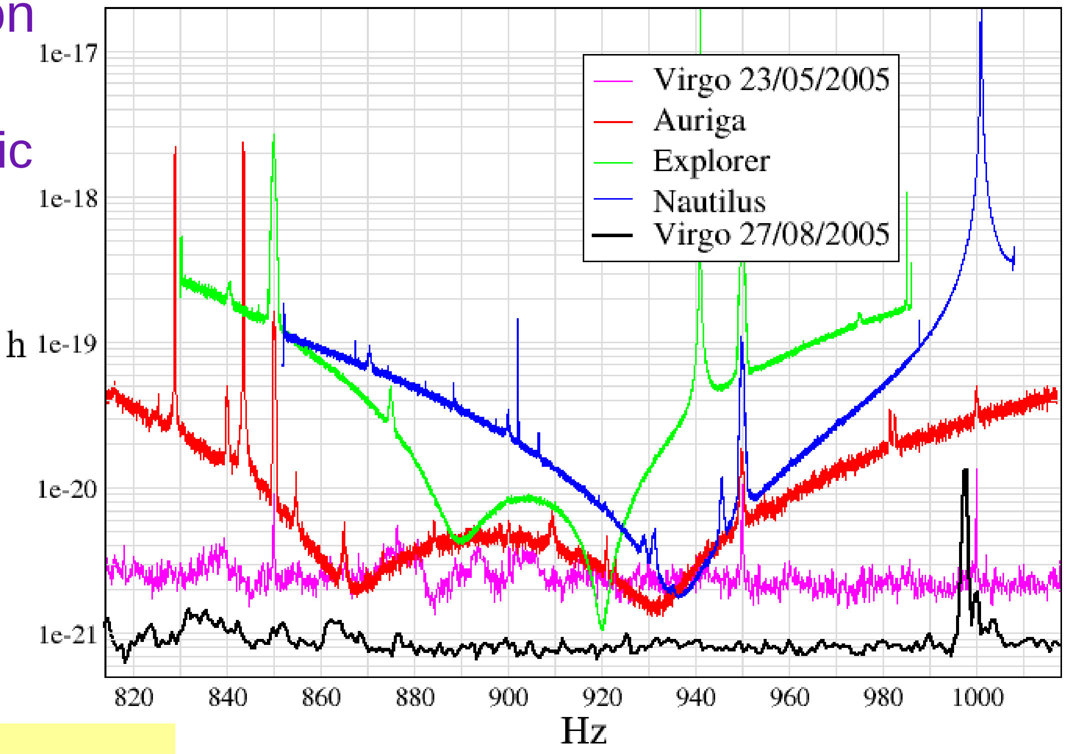
Virgo joint analyses

Virgo – Bars joint analysis

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

Virgo – LIGO collaboration

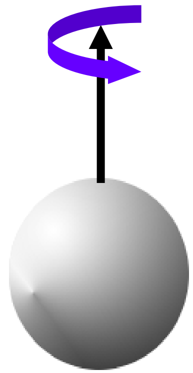
- Working group for burst, inspiral events, stochastic and periodic sources
- Formal MoU
- Publish together



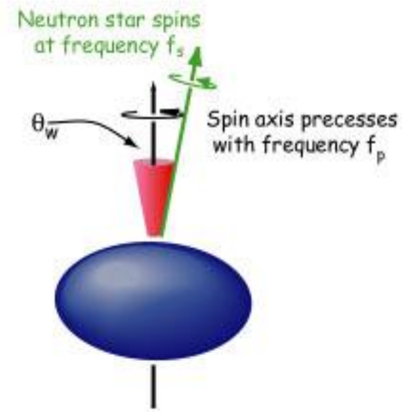
Virgo now at 1e-22 / rtHz

Virgo analysis at NIKHEF

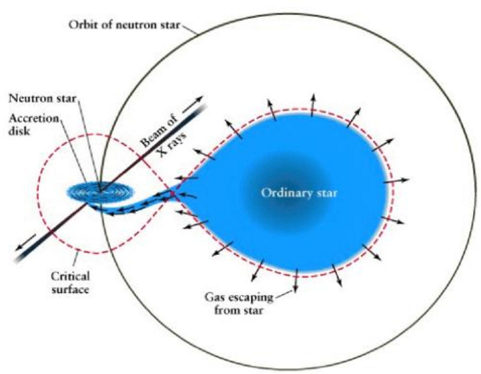
Radiation from rotating neutron stars



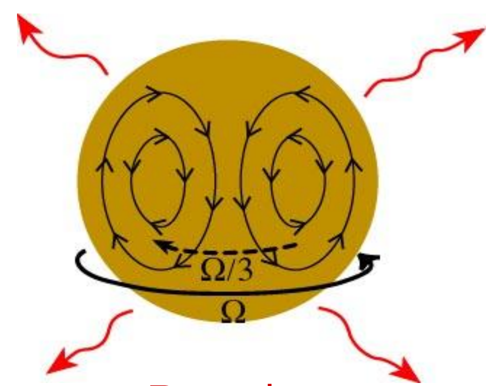
“Mountain” on neutron star



Wobbling neutron star

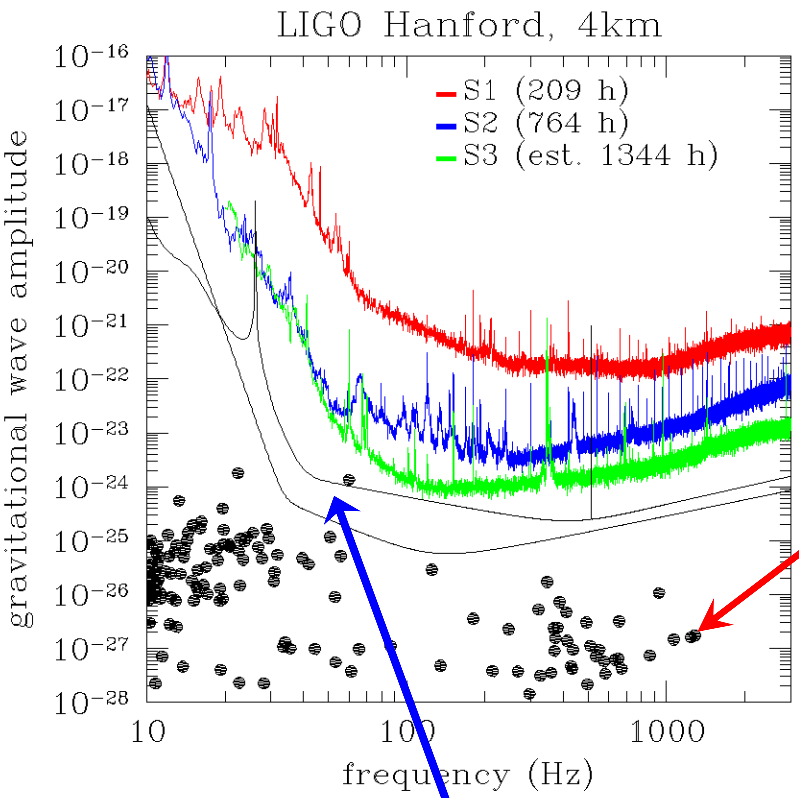


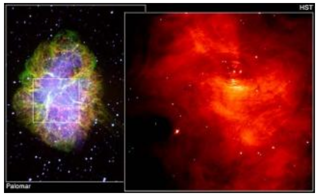
Accreting neutron star



R-modes

Pointing at known neutron stars



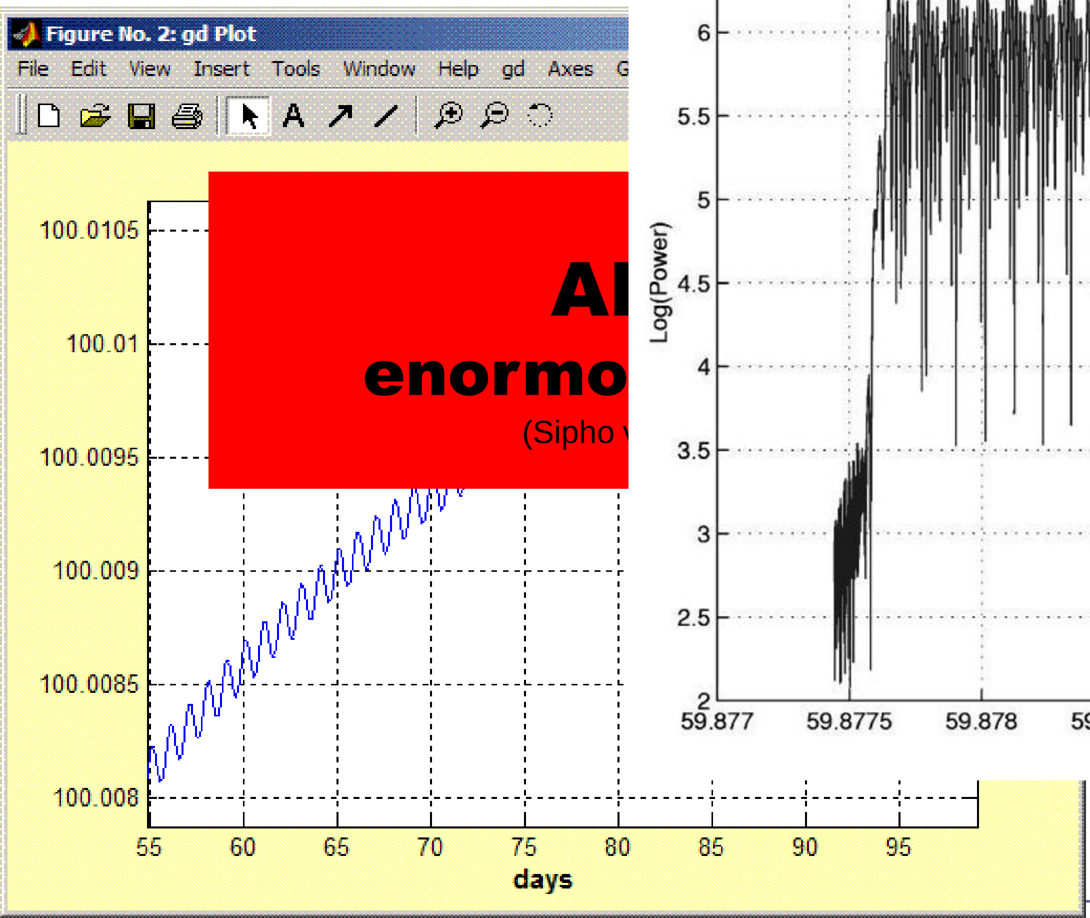


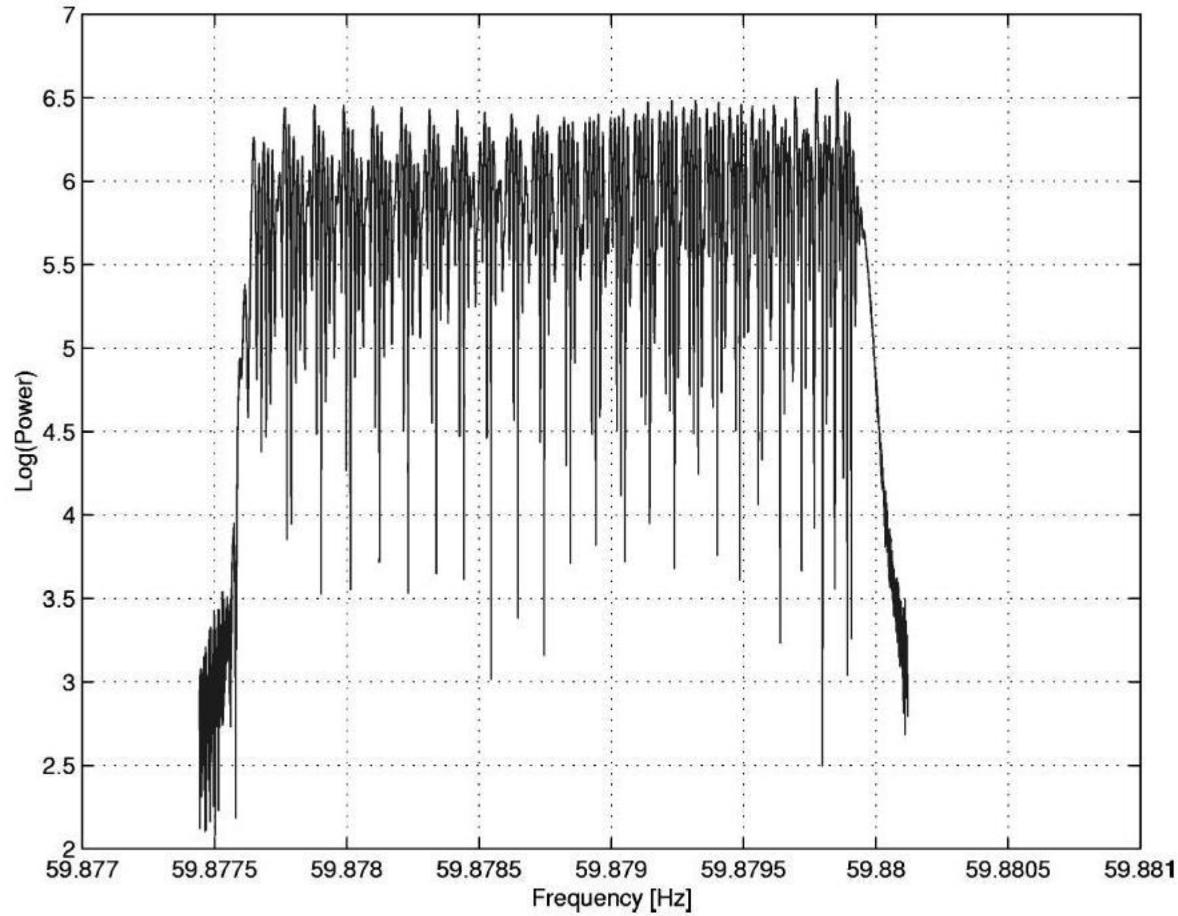
- Targeted search of GWs from known isolated radio pulsars
- S1analysis: upper-limit (95% confidence) on PSR J1939+2134:

  $h_0 < 1.4 \times 10^{-22}$ ($e < 2.9 \times 10^{-4}$) 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

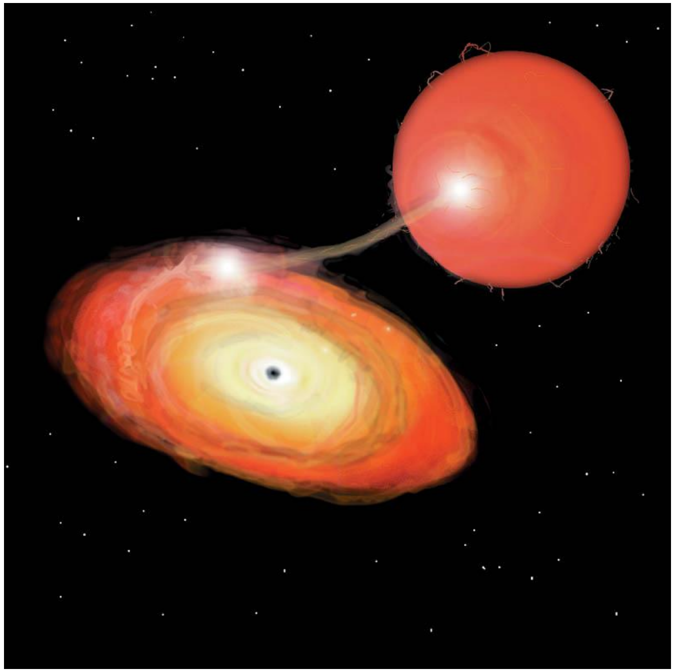


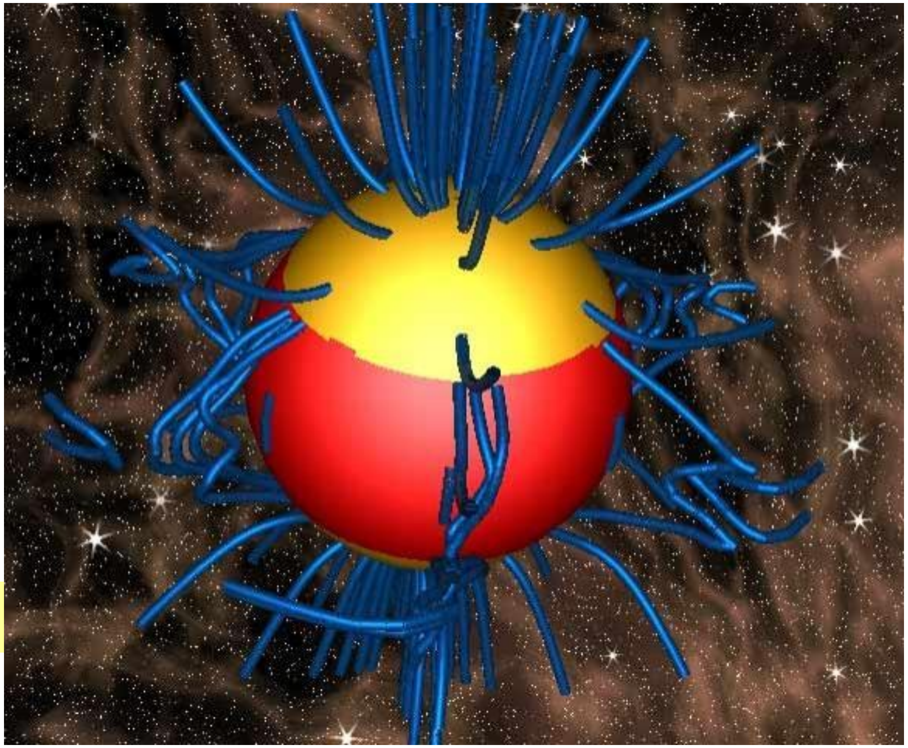


- Hough maps
- Include binary systems

Binary 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

The future?

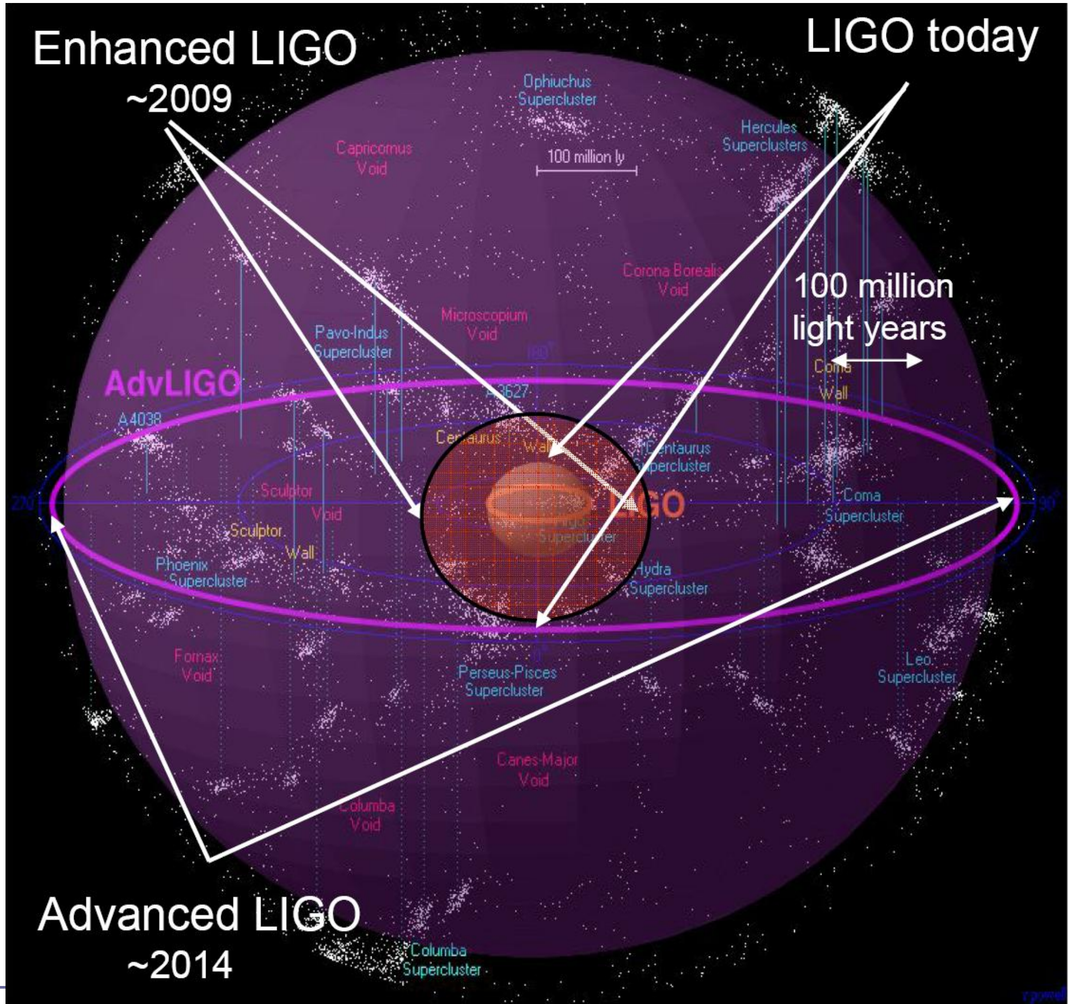
Supernovae – with present detector only sensitive to Milky Way

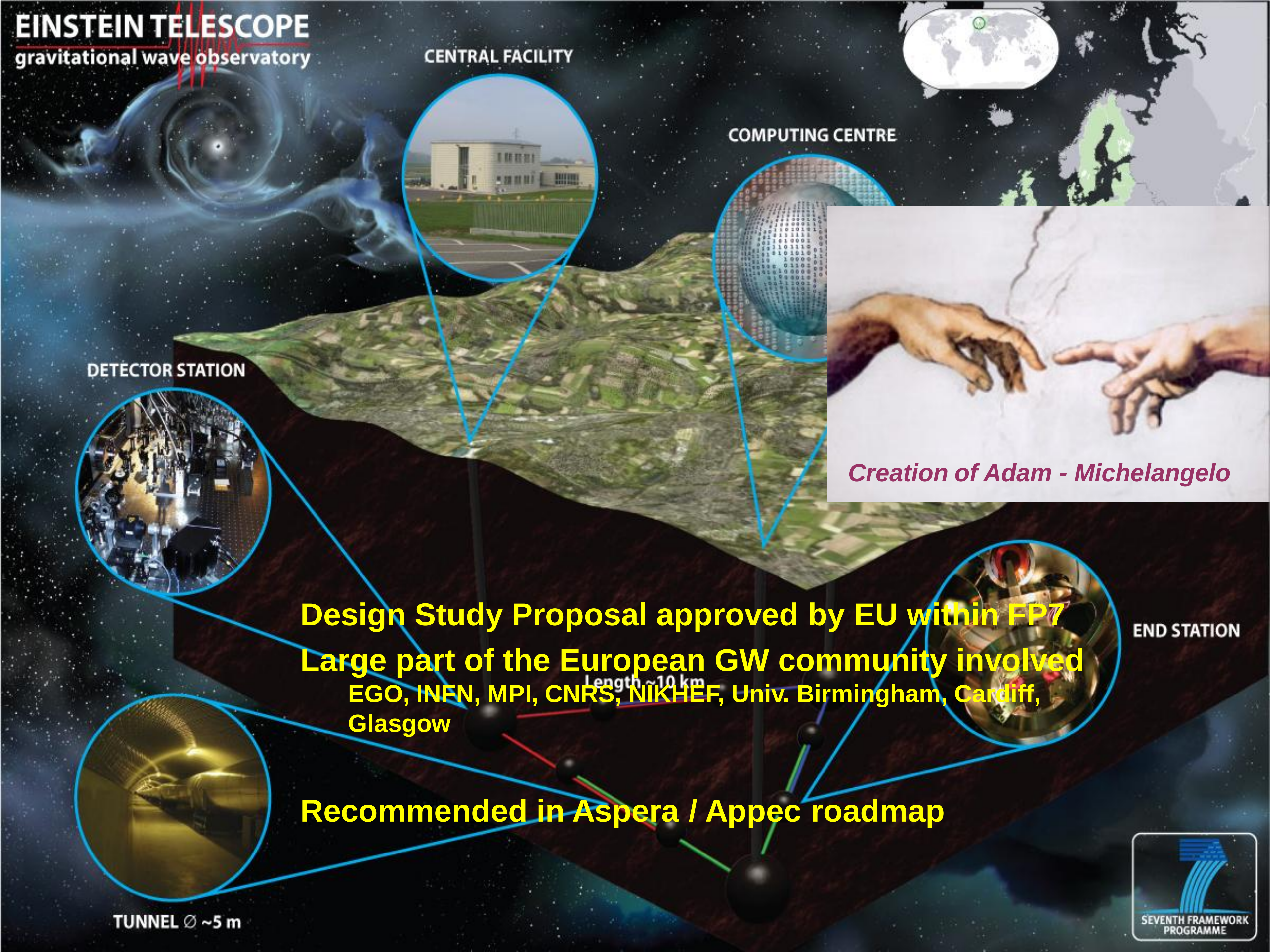
Coalescent binaries – with present detector

	Horizon	Rates (min - max)
NS-NS	30 Mpc	0.0003/yr – 0.3/yr
NS-BH	40 Mpc	0.0004/yr – 0.5/yr
BH-BH	145 Mpc	0.001/yr – 3/yr

LIGO and VIRGO: scientific evolution

- At present hundreds of galaxies in range for 1.4 M_o NS-NS binaries
- Enhanced program
  - In 2009 about 10 times more galaxies in range
- Advanced detectors
  - About 1000 times more galaxies in range
  - In 2014 expect 1 signal per day or week
  - Start of gravitational astrophysics
  - Numerical relativity will provide templates for interpreting signals





Creation of Adam - Michelangelo

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

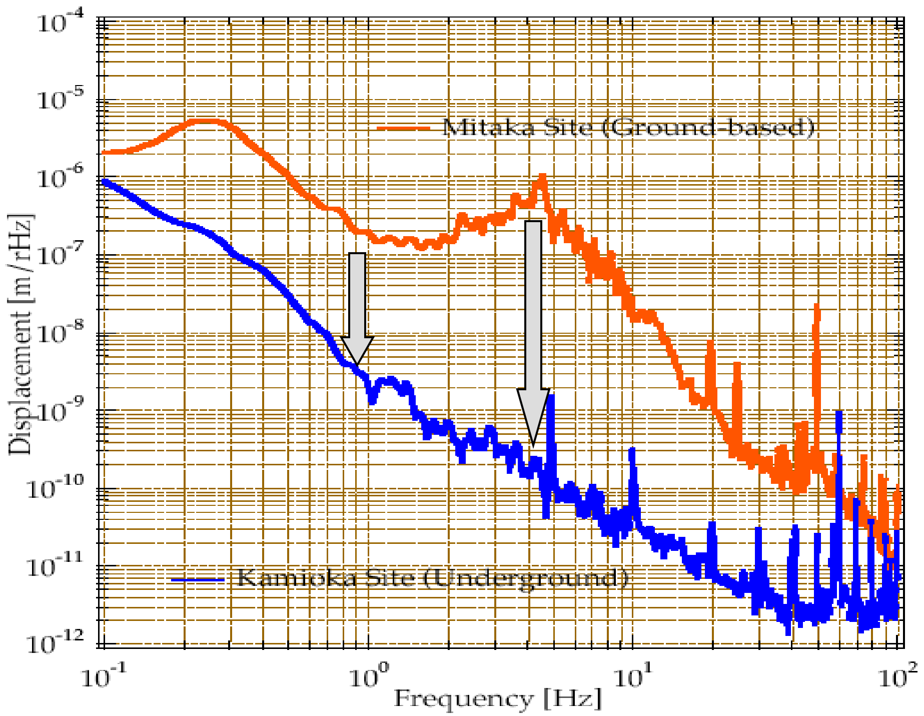
Experience: underground interferometers

- LISM: 20 m Fabry-Perot interferometer, R&D for LCGT, moved from Mitaka (ground based) to Kamioka (underground)
- Seismic noise much lower:

10^2 overall gain
10^3 at 4 Hz

- Operation becomes easier

	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)



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

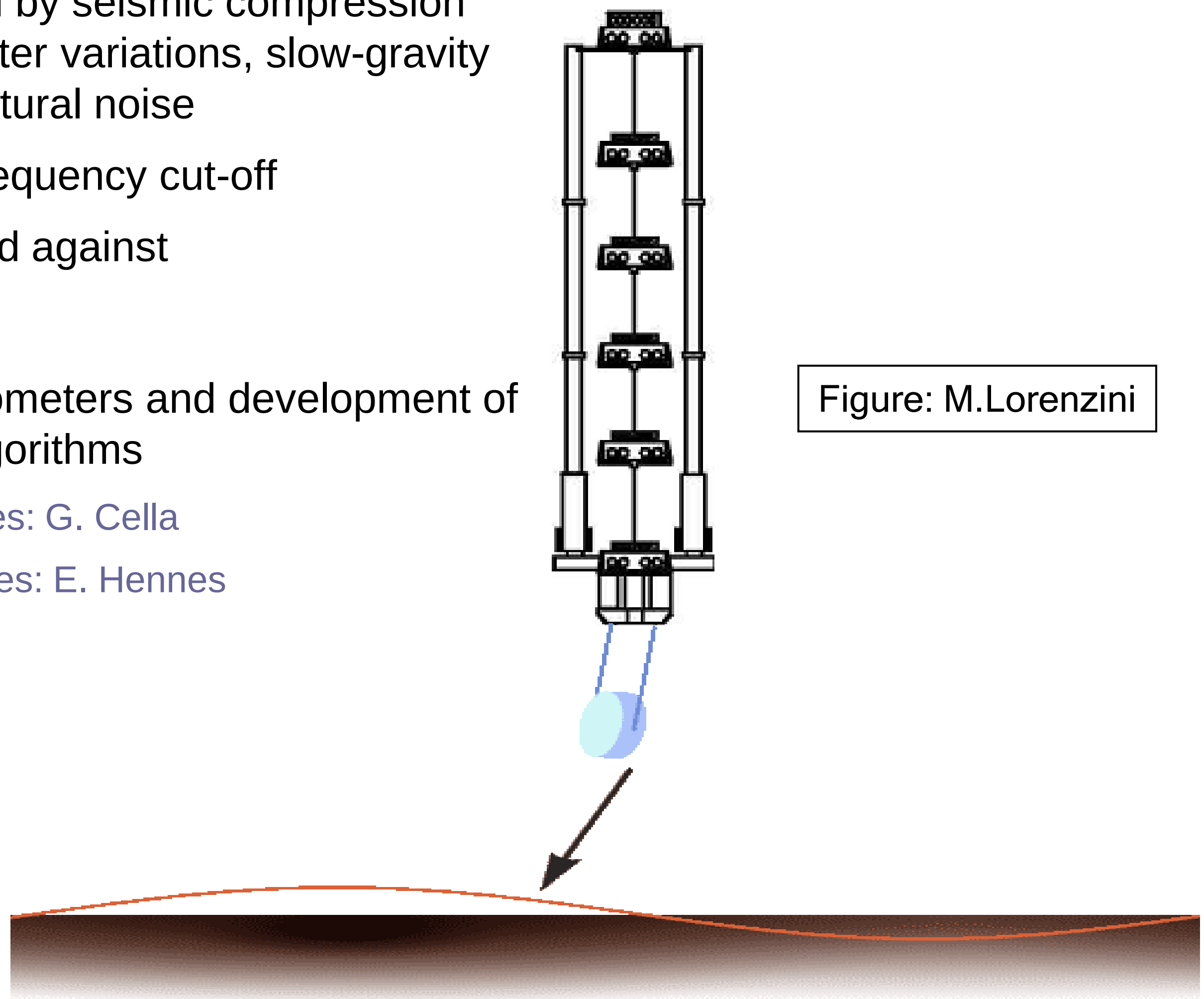
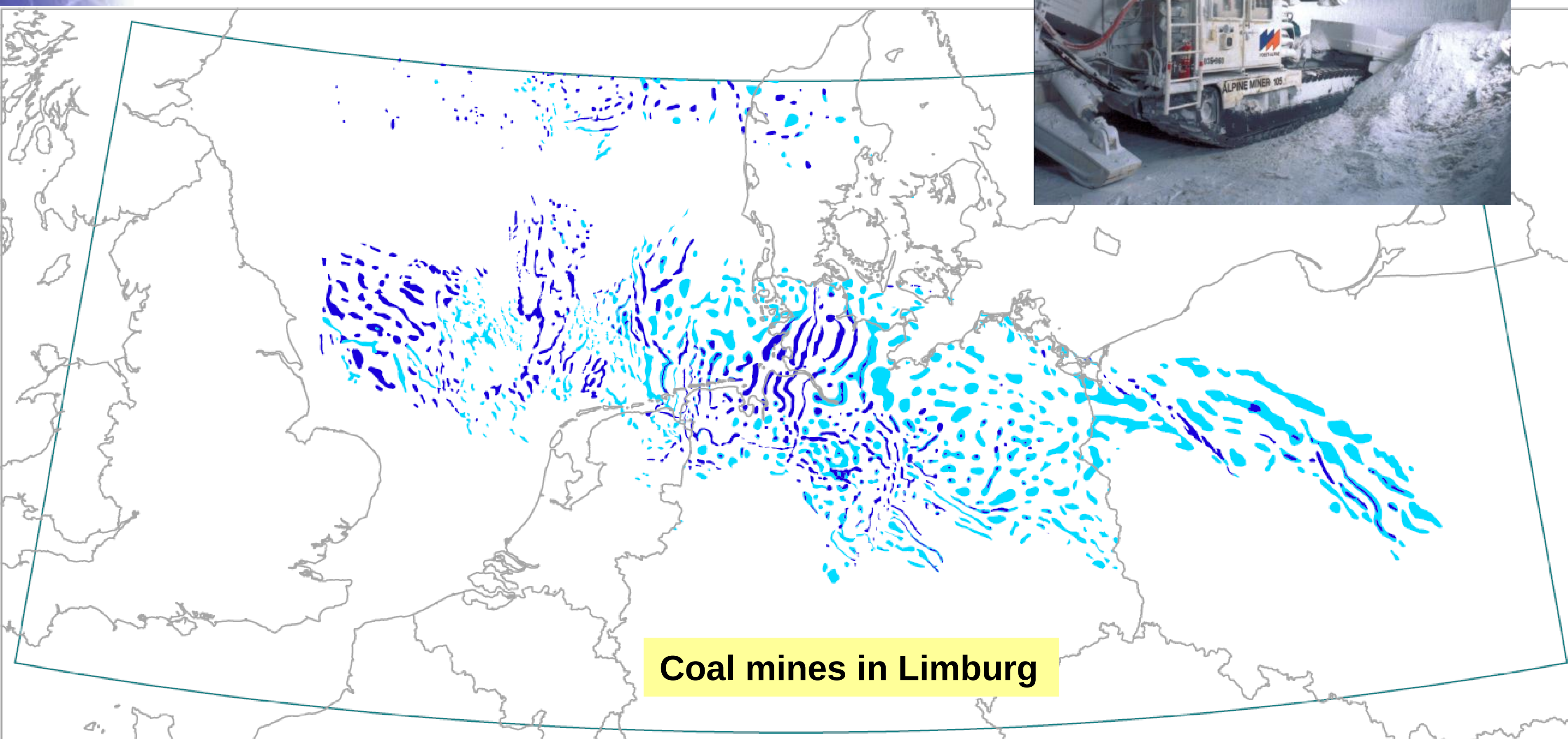


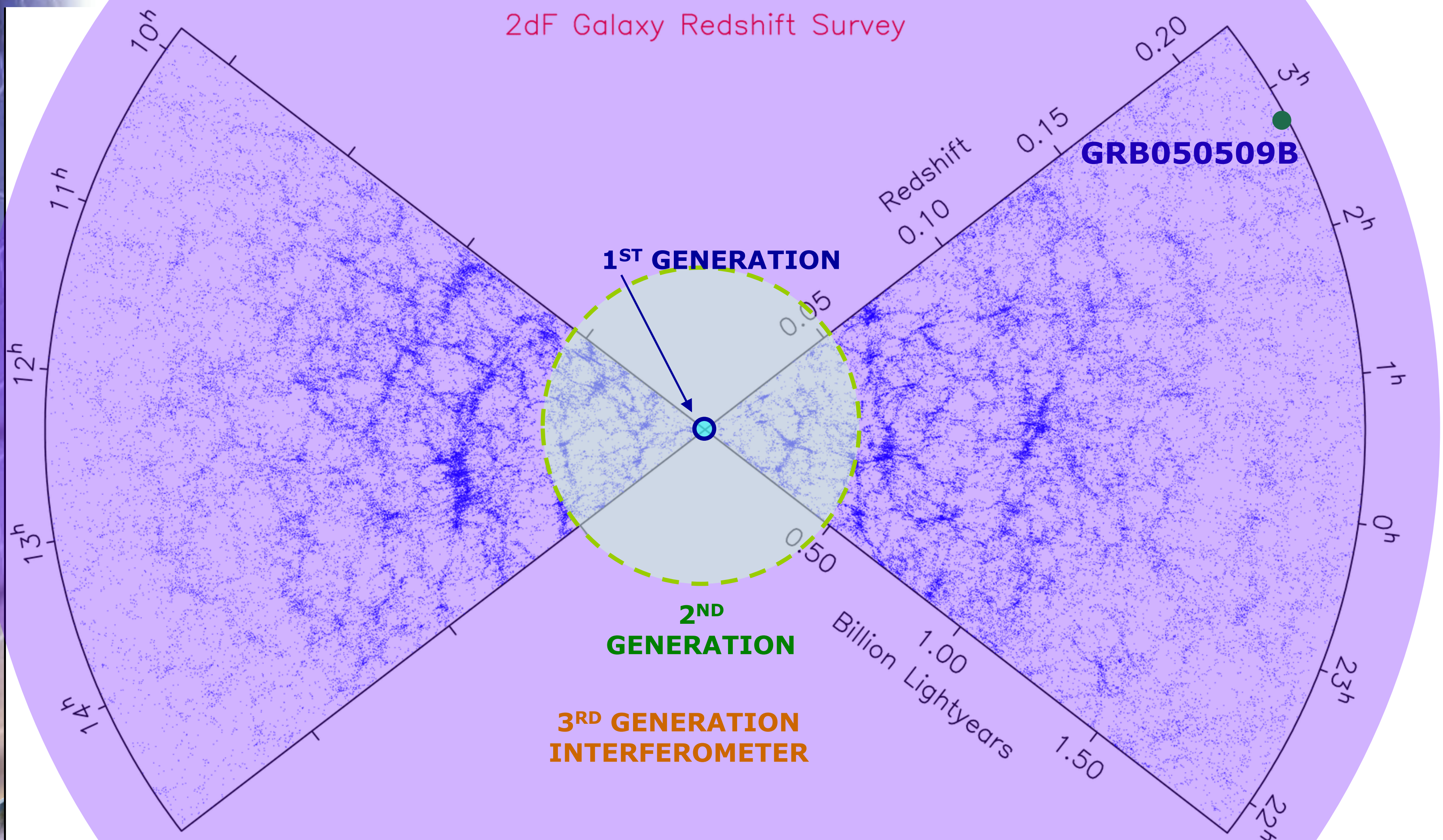
Figure: M.Lorenzini

Site selection: Einstein Telescope and the Netherlands

- Discussion with Earth scientists
  - VU, Delft, TNO
  - KNMI: microseismic activity

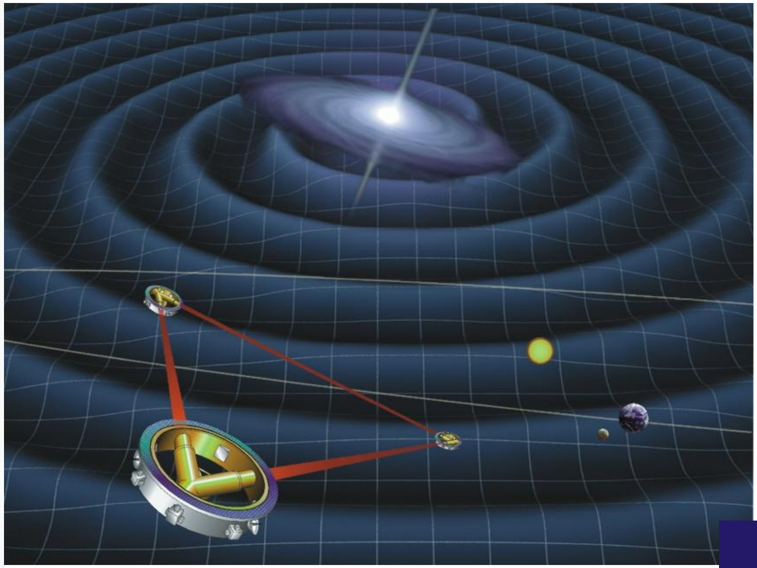


NS - NS INSPIRAL RANGE

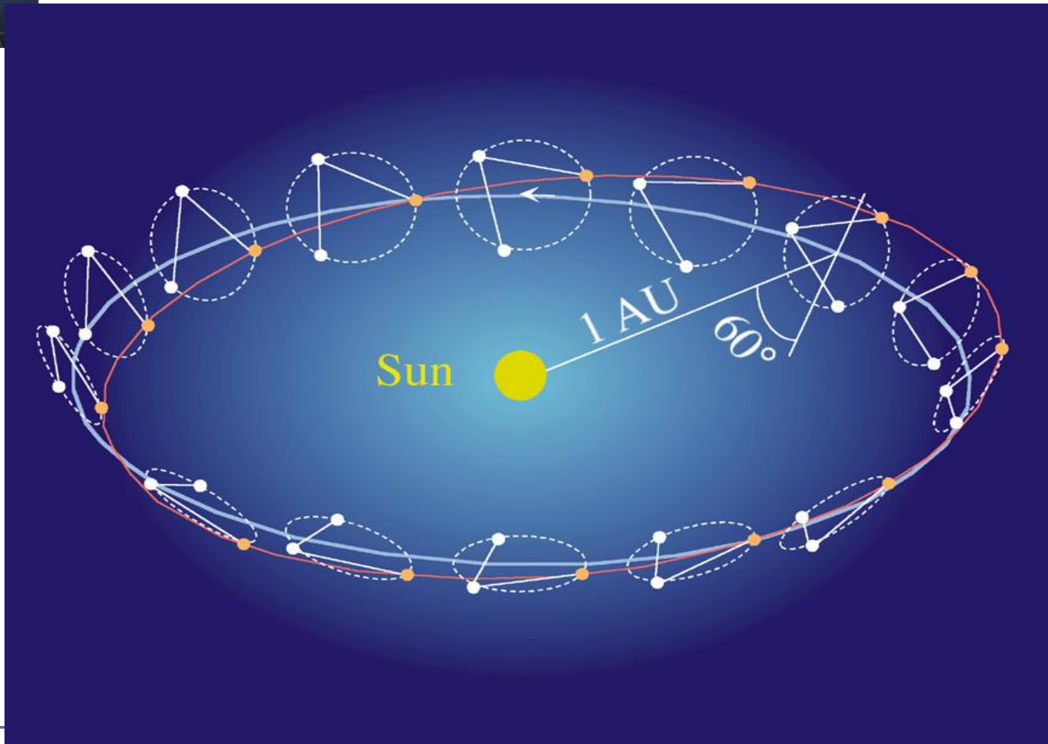


Credit G.Cagnoli

Gravitational wave antenna in space - LISA

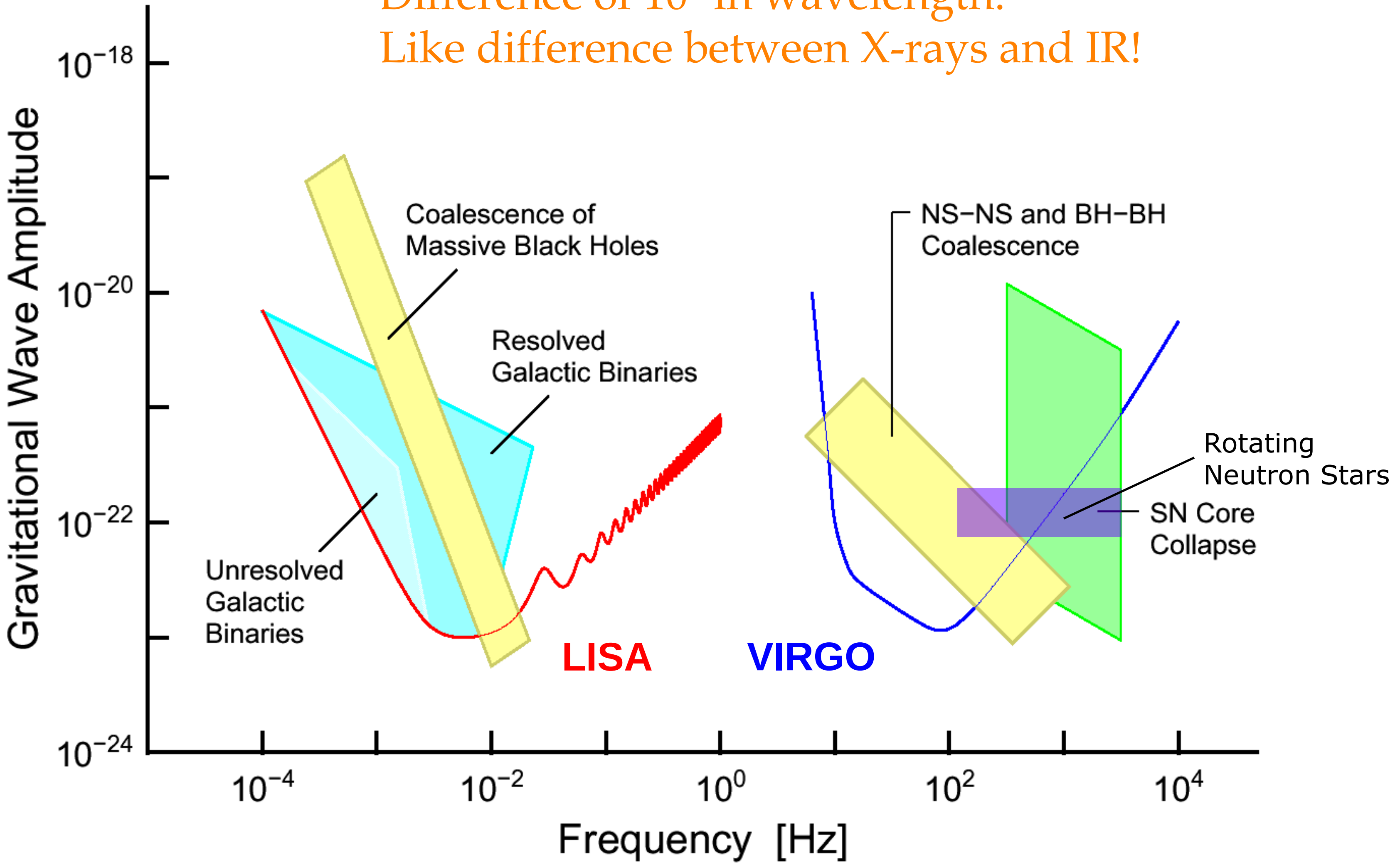


- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *Partnership between NASA and ESA*
- *Launch date ~2016+*



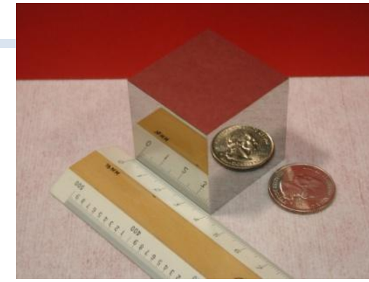
Complementarity of Space- & Ground-Based Detectors

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

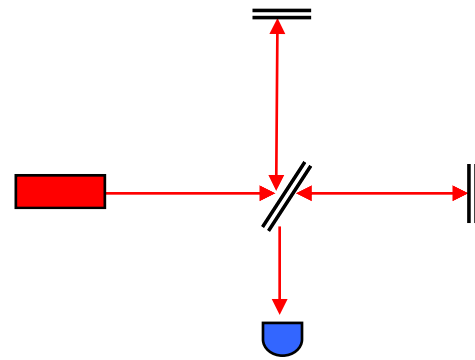


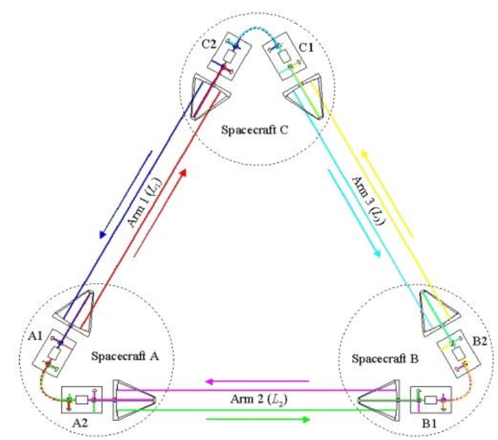
LISA will see all the compact white-dwarf and neutron-star binaries in the Galaxy (Schutz)

LISA interferometry

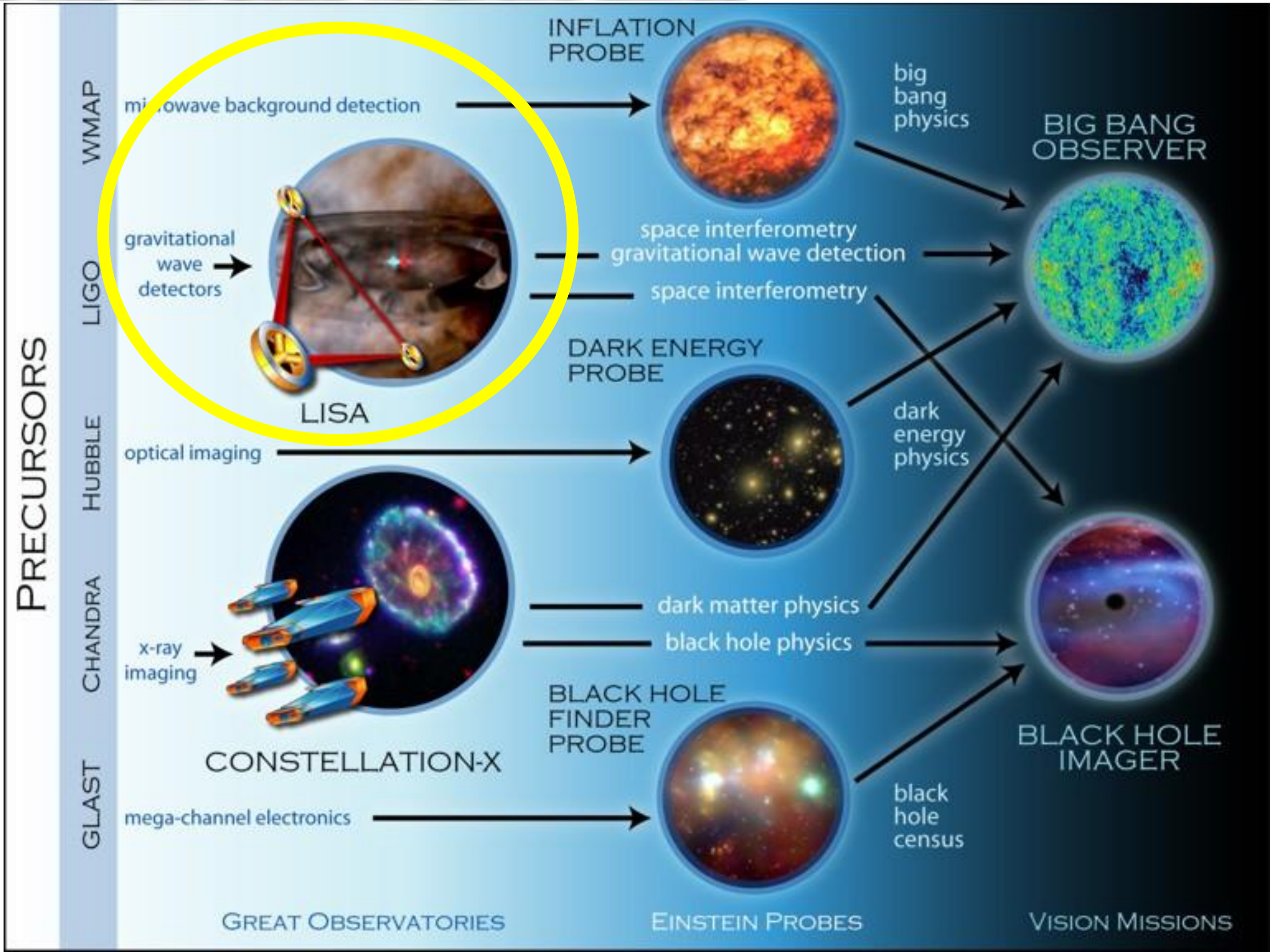


- “LISA is essentially a Michelson Interferometer in Space”
- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal
  - Arm lengths change continuously
  - Light travel time ~17 seconds
  - Constellation is rotating and translating in space



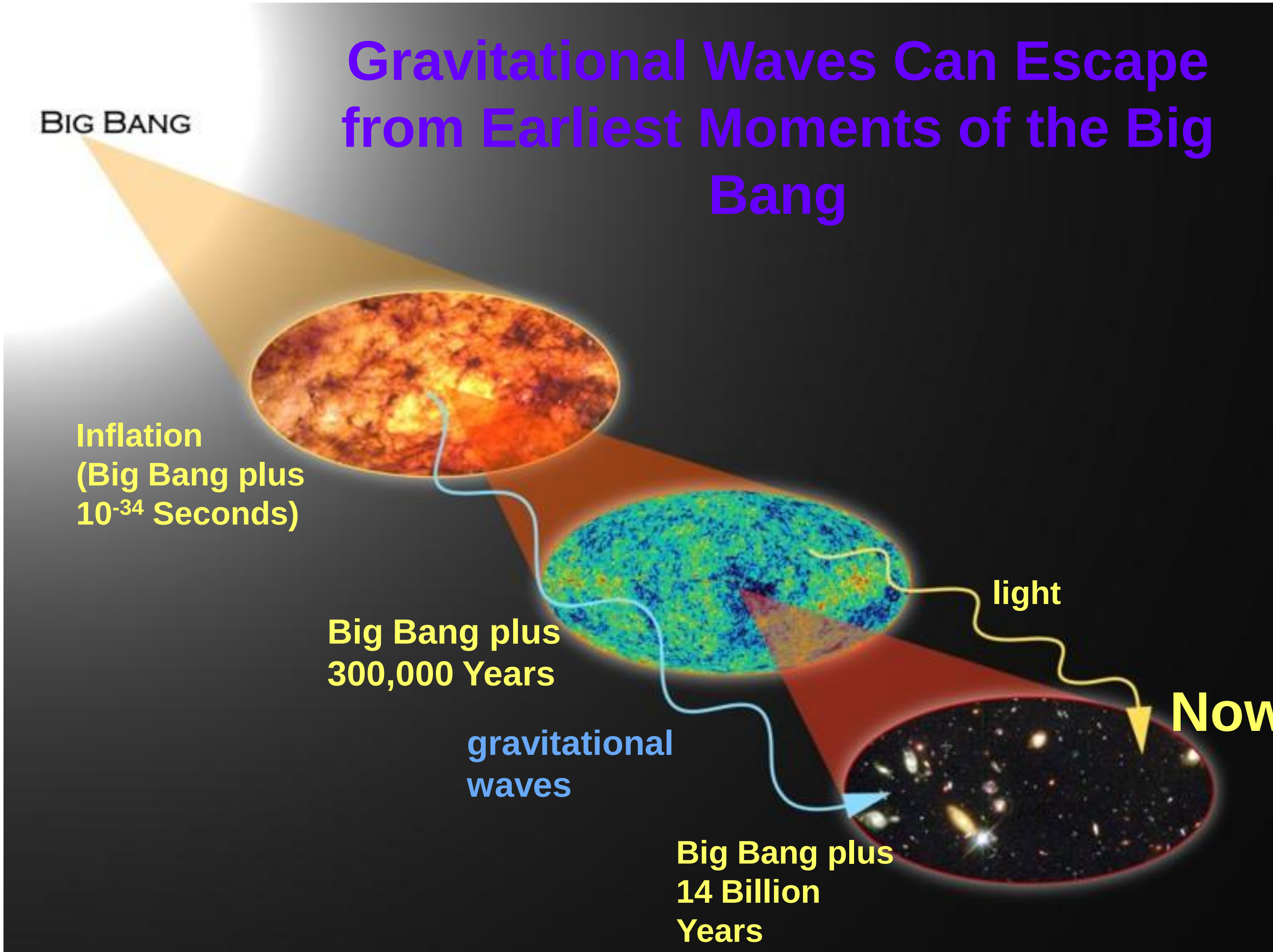


LOI to ESA – LISA analysis
Nikhef, VU, RUN and SRON
Netherlands: Bulten/Nelemans



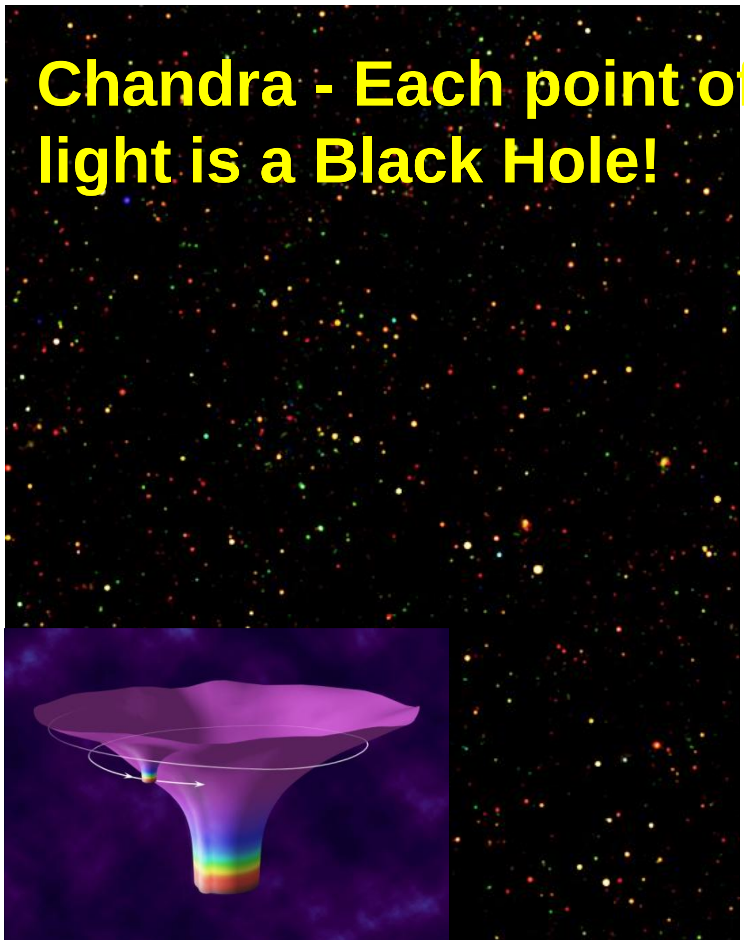
Beyond Einstein is the umbrella program for a series of NASA/ESA missions linked by powerful new technologies and common science goals to answer the questions:

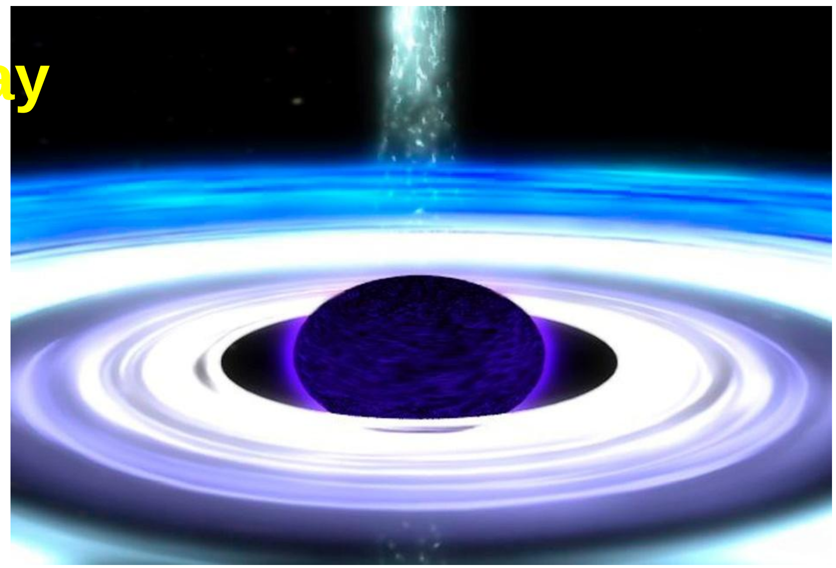
What powered the Big Bang?



Beyond Einstein is the umbrella program for a series of NASA/ESA missions linked by powerful new technologies and common science goals to answer the questions:

What happens at the edge of a Black Hole?

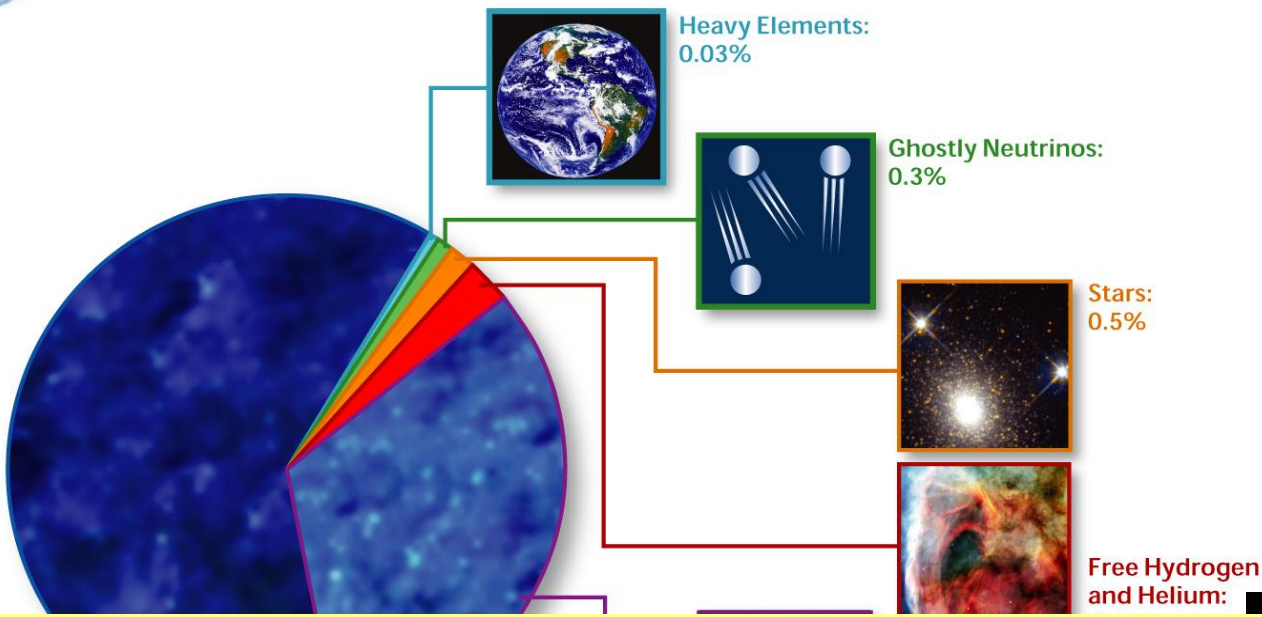




Is Einstein's theory still right in these conditions of extreme gravity? Or is new physics awaiting us?

Beyond Einstein is the umbrella program for a series of NASA/ESA missions linked by powerful new technologies and common science goals to answer the questions:

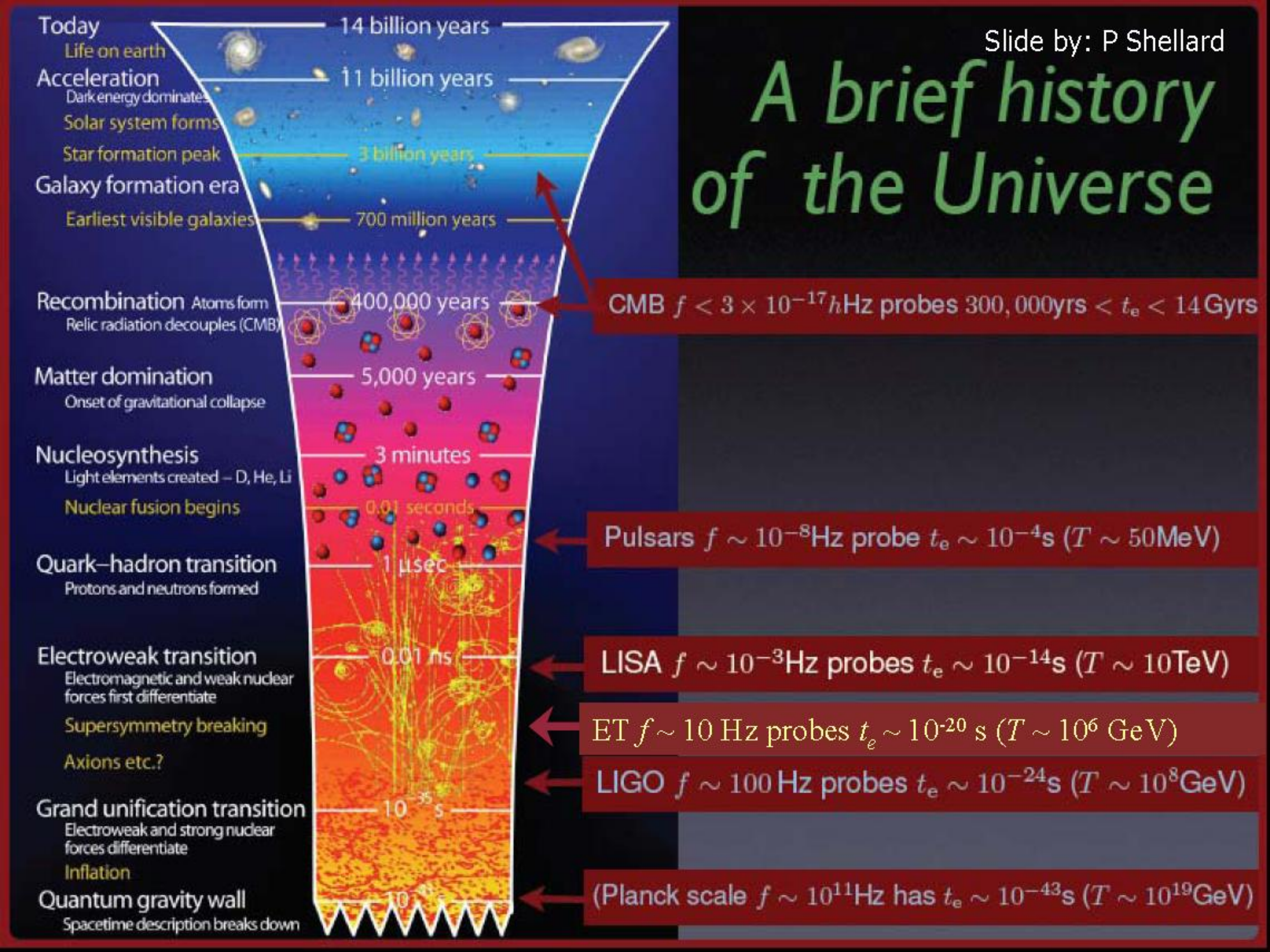
What is the mysterious Dark Energy pulling the Universe apart?



September 6, 2007: Committee on NASA's Einstein Program: An Architecture for Implementation, National Research Council

Finding 4. LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways. <u>LISA, in the committee's view, should be the flagship mission</u> of a long-term program addressing Beyond Einstein goals.

Dark energy and matter interact through gravity


Slide by: P Shellard
A brief history of the Universe
Today
Life on earth
Acceleration
Dark energy dominates
Solar system forms
Star formation peak
Galaxy formation era
Earliest visible galaxies
Recombination Atoms form
Relic radiation decouples (CMB)
Matter domination
Onset of gravitational collapse
Nucleosynthesis
Light elements created – D, He, Li
Nuclear fusion begins
Quark–hadron transition
Protons and neutrons formed
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
Spacetime description breaks down
14 billion years
11 billion years
3 billion years
700 million years
400,000 years
5,000 years
3 minutes
0.01 seconds
1 μsec
0.01 ns
10^{-35} s
CMB $f < 3 \times 10^{-17} h$ Hz probes $300,000$yrs $< t_e < 14$ Gyrs
Pulsars $f \sim 10^{-8}$Hz probe $t_e \sim 10^{-4}$s ($T \sim 50$MeV)
LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim 10$TeV)
ET $f \sim 10$ Hz probes $t_e \sim 10^{-20}$ s ($T \sim 10^6$ GeV)
LIGO $f \sim 100$ Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^8$GeV)
(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

Summary

- Gravitational wave physics
  - Dutch Astroparticle Physics initiative
  - Exciting new physics program
    - Important questions are addressed
    - Long-term scientific perspective
- VIRGO and LIGO
  - Sensitivity is improving fast
  - First science run underway
  - MOU between LIGO and Virgo
- NIKHEF commitment
  - Modest at this moment
  - Expand to FOM research program