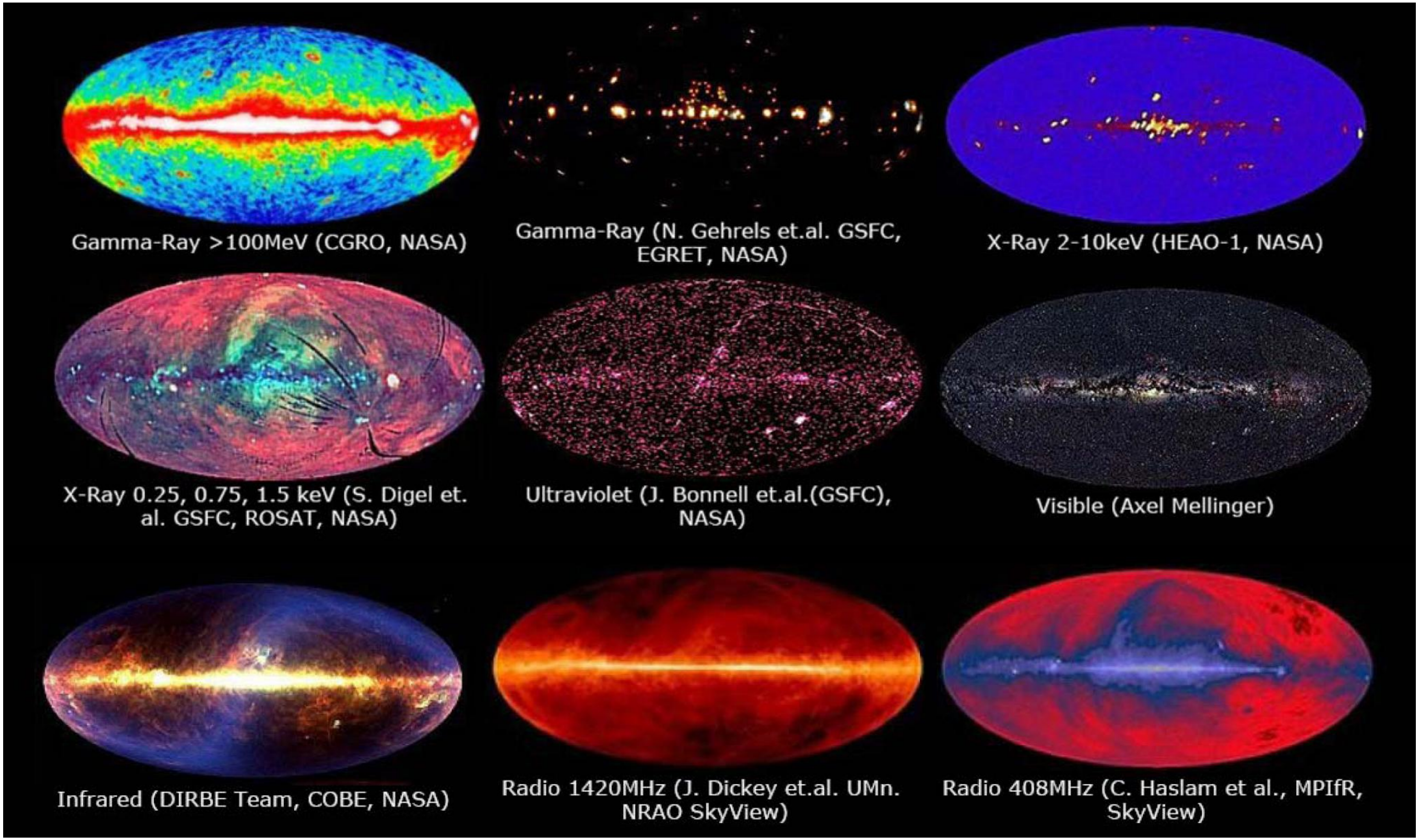
Gravitatie

Plannen voor Virgo en ET

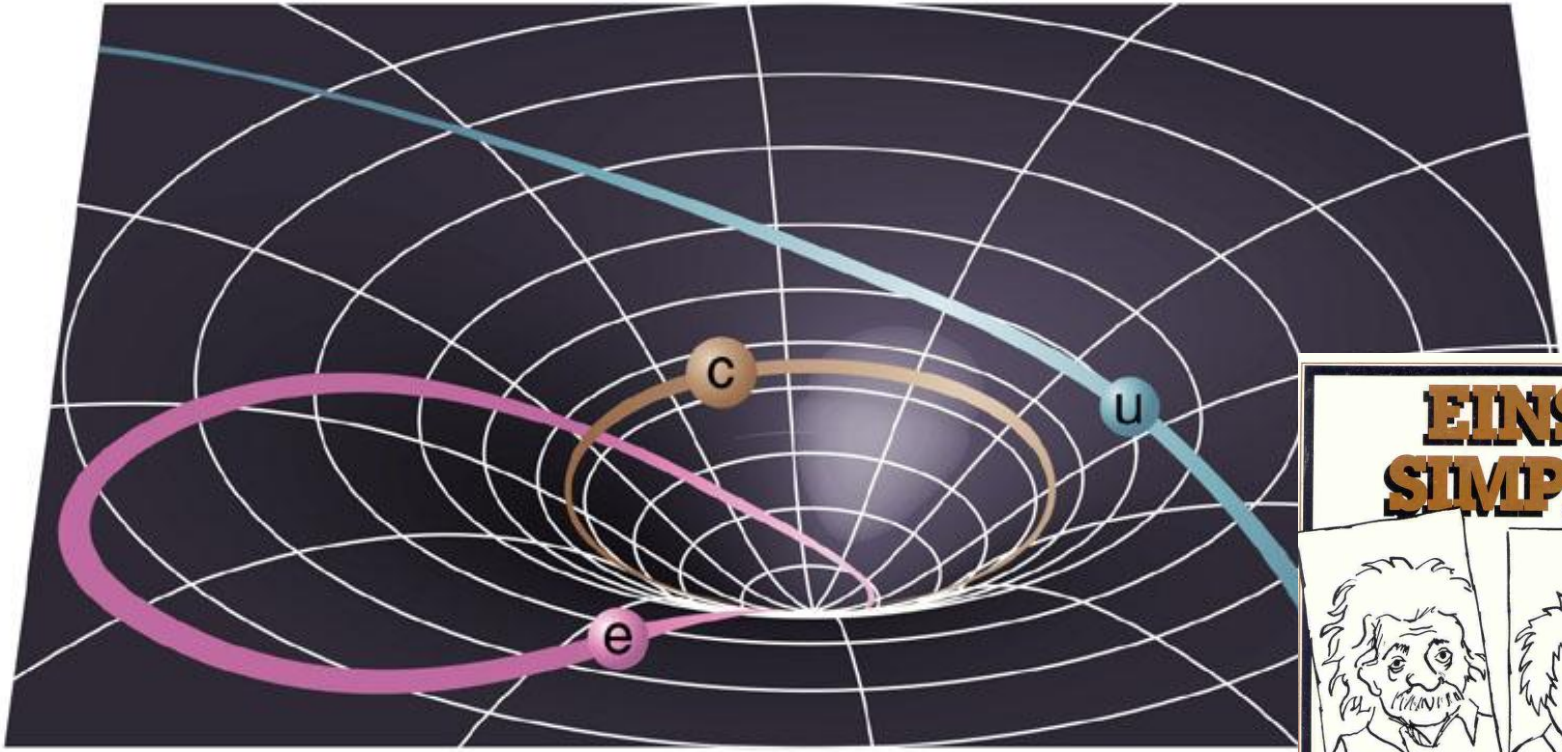
Jo van den Brand

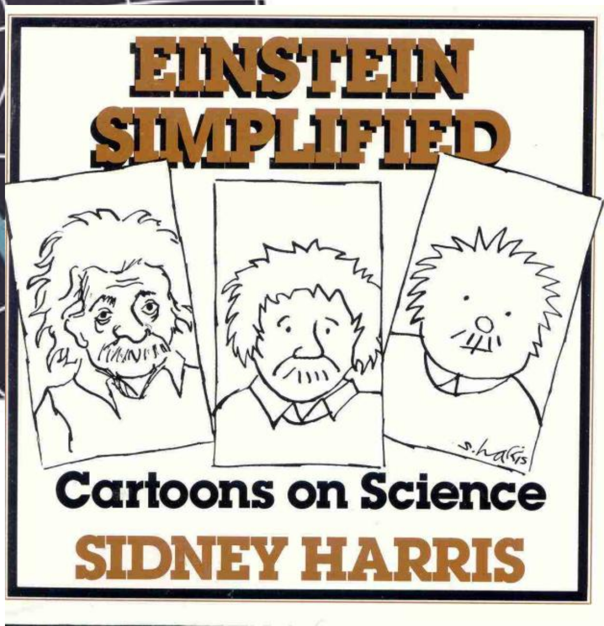
Studies van het Universum



Gravitatie is geometrie

- c Cirkelbaan
- e Elliptische baan
- u Ongebonden baan (parabool)





Breng ruimtetijd in trilling: gravitatiegolf

Gravitatiestraling bestaat: PSR B1913+16

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

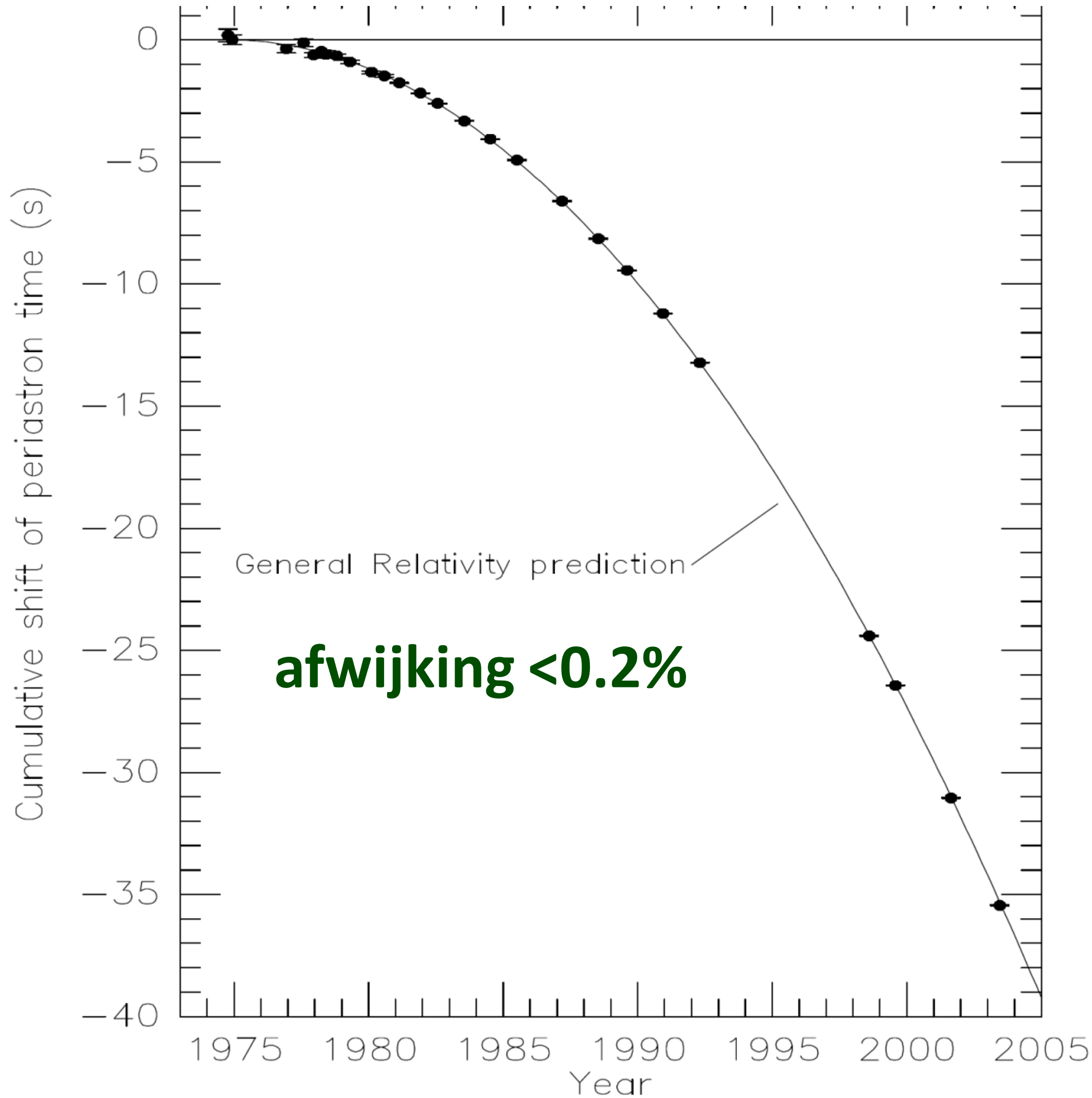
Periode ~ 8h

GW emissie verkort de periode

Indirecte detectie van GWs

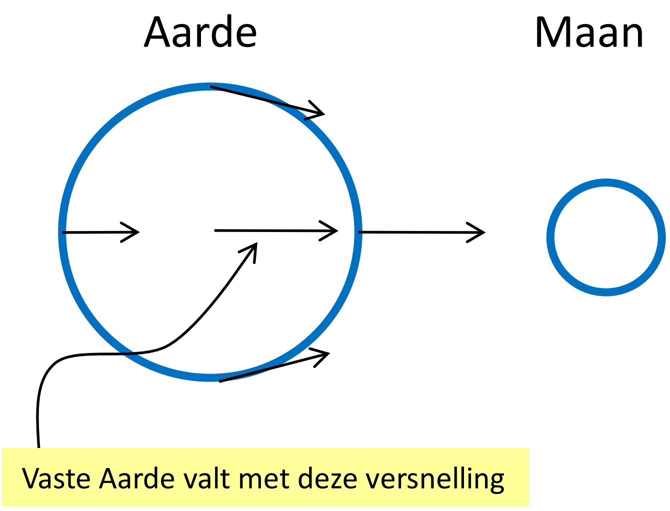
Nobelprijs 1993

Δt_P [s] **Periastron advance**

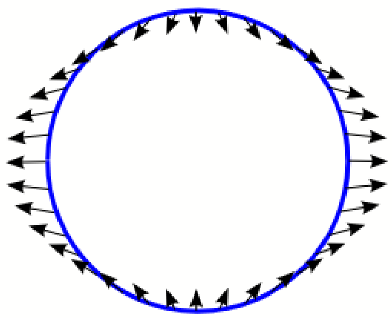


Effect van een gravitatiegolf

- Getijdenkrachten
  - Gravitationele effecten van een verre bron kunnen enkel gevoeld worden door *getijdenkrachten*
  - Getijden versnellingen Aarde-Maan systeem
  - GW kunnen beschouwd worden als lopende, tijdsafhankelijke getijdenkrachten
  - Getijdenkrachten schalen met grootte, en produceren typisch elliptische vervorming

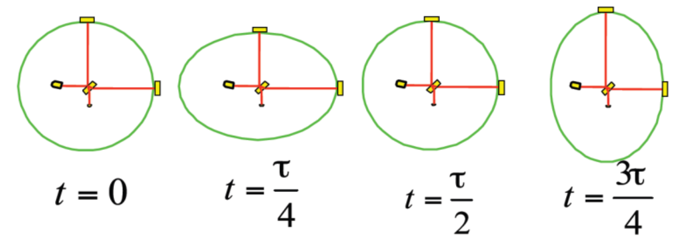


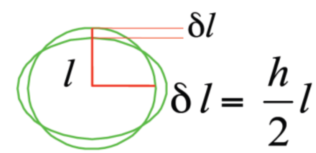
Na subtractie van centrale versnelling



Interferometer approach

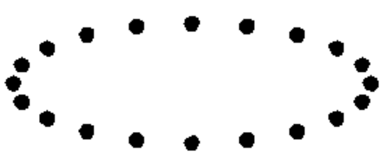
- Test masses
  - System of free-falling test masses is displaced by GW
  - Equip test masses with mirrors and measure relative displacement *(strain)*
  - Plus- and cross polarization states
  - Antenna pattern funtions

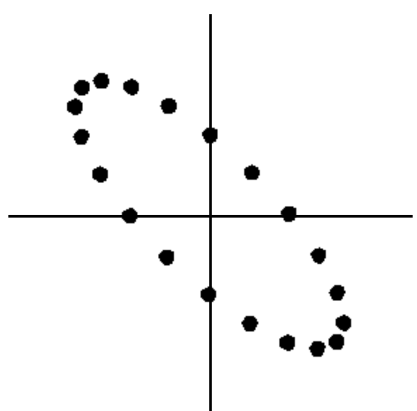


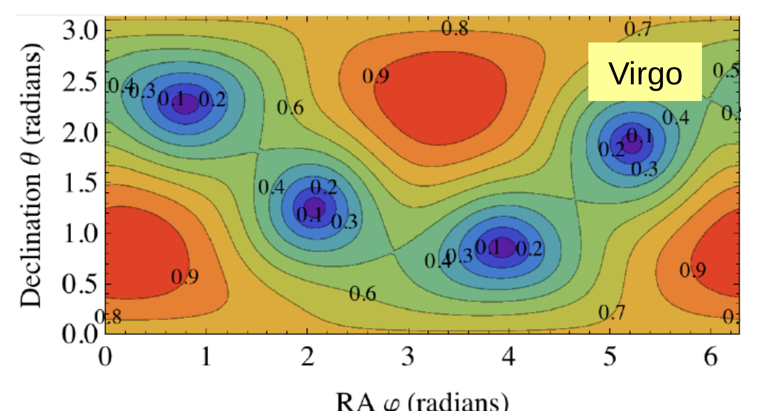


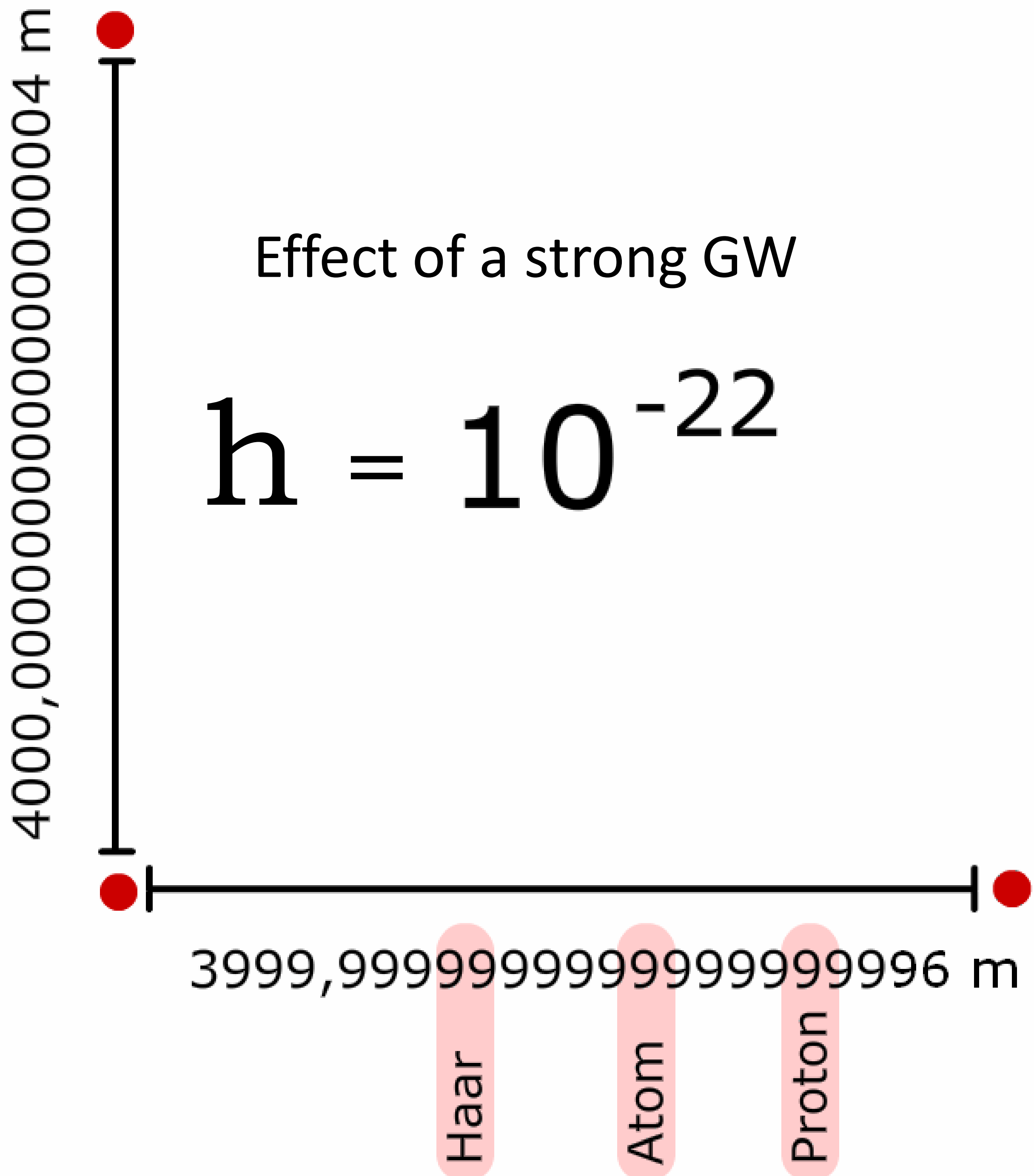
$$h(t) = F_+(\theta,\, \varphi,\, \psi)h_+(t) + F_\times(\theta,\, \varphi,\, \psi)h_\times(t)$$

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

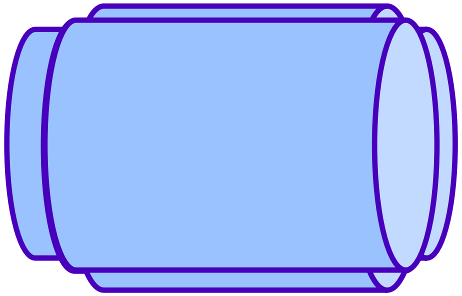


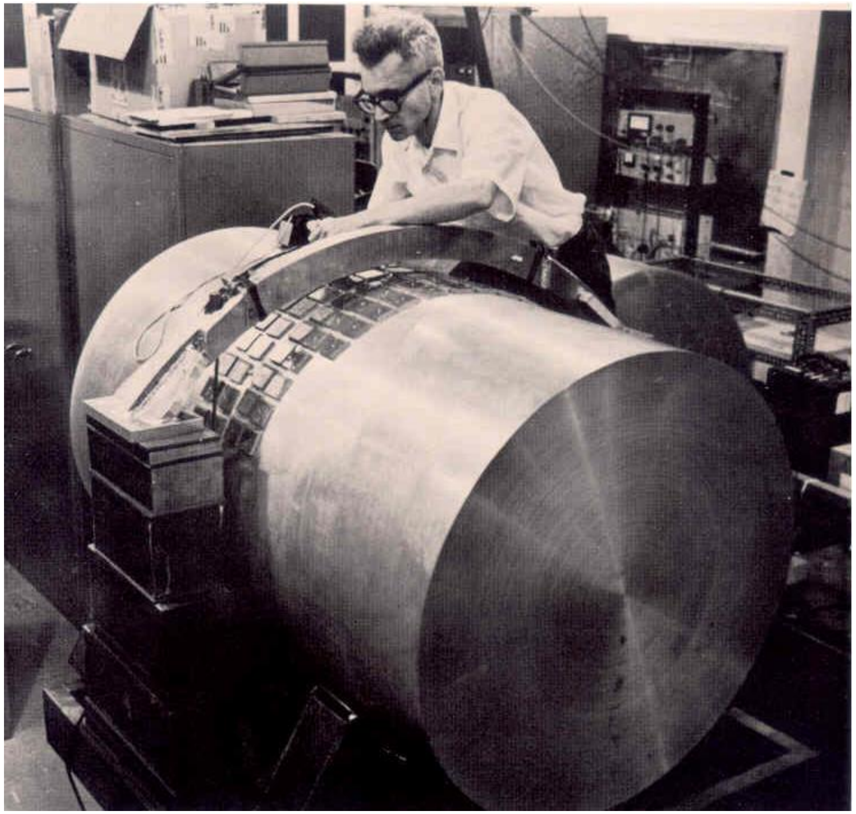





Effect of a strong GW
h = 10-22
4000,0000000000000000004 m
3999,9999999999999999996 m
Haar
Atom
Proton

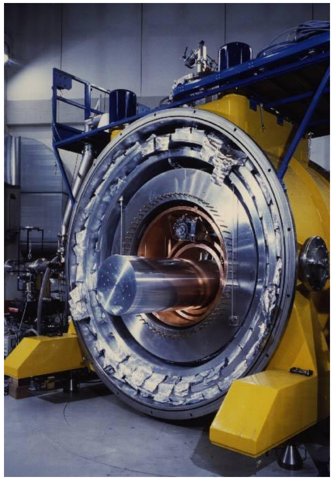
Resonant mass antennas

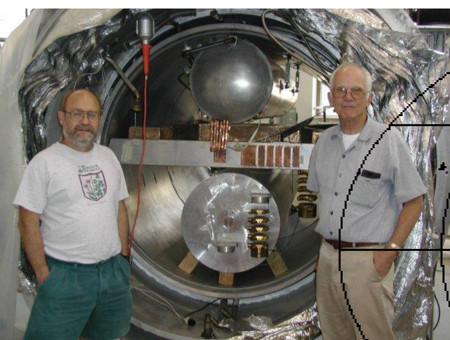


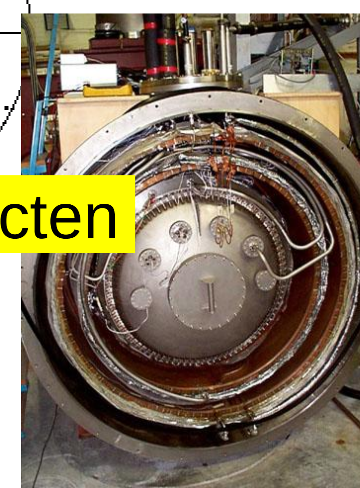


Joe Weber (after 1960)

Staaf detectoren: IGEC collaboration

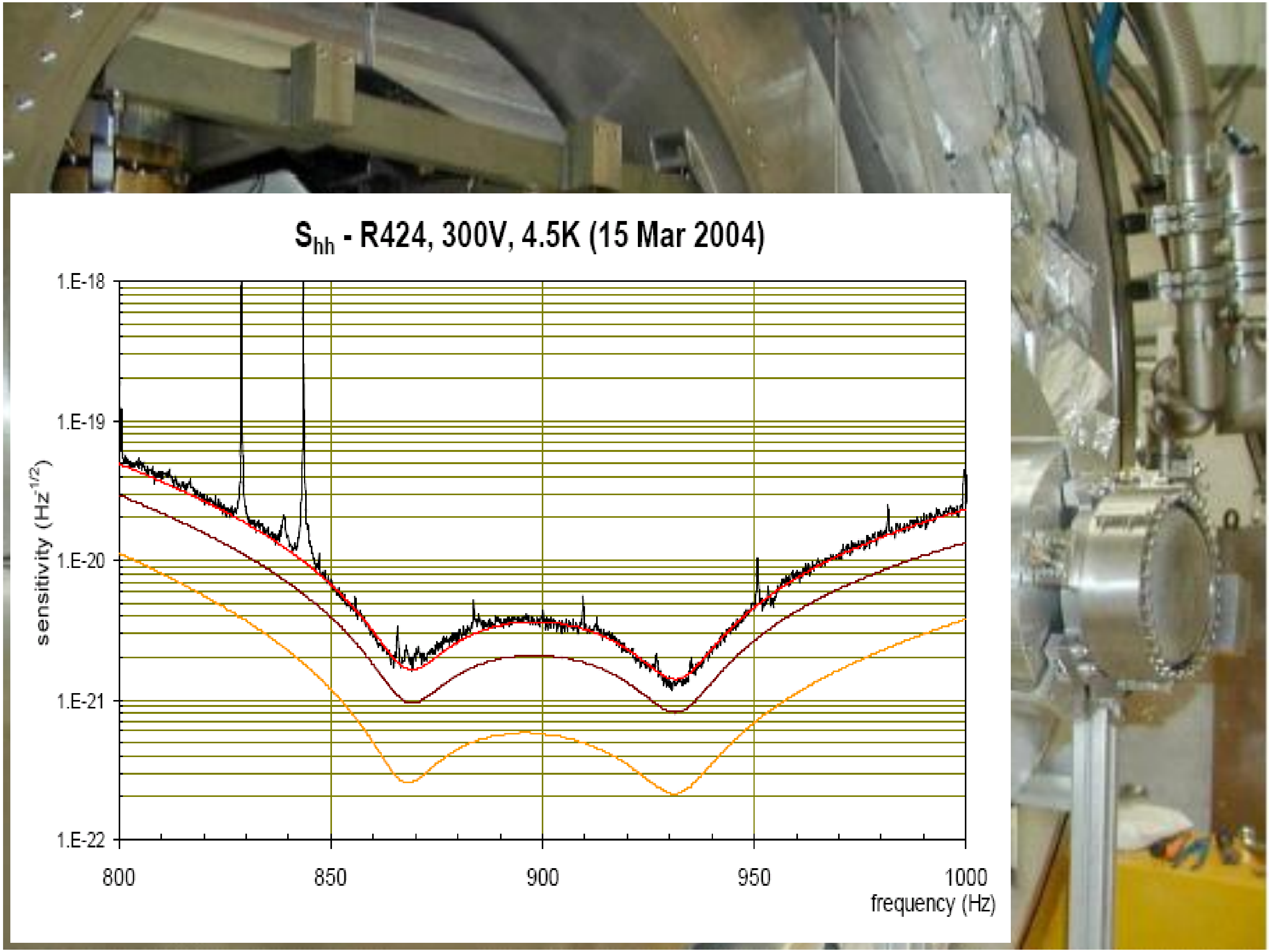






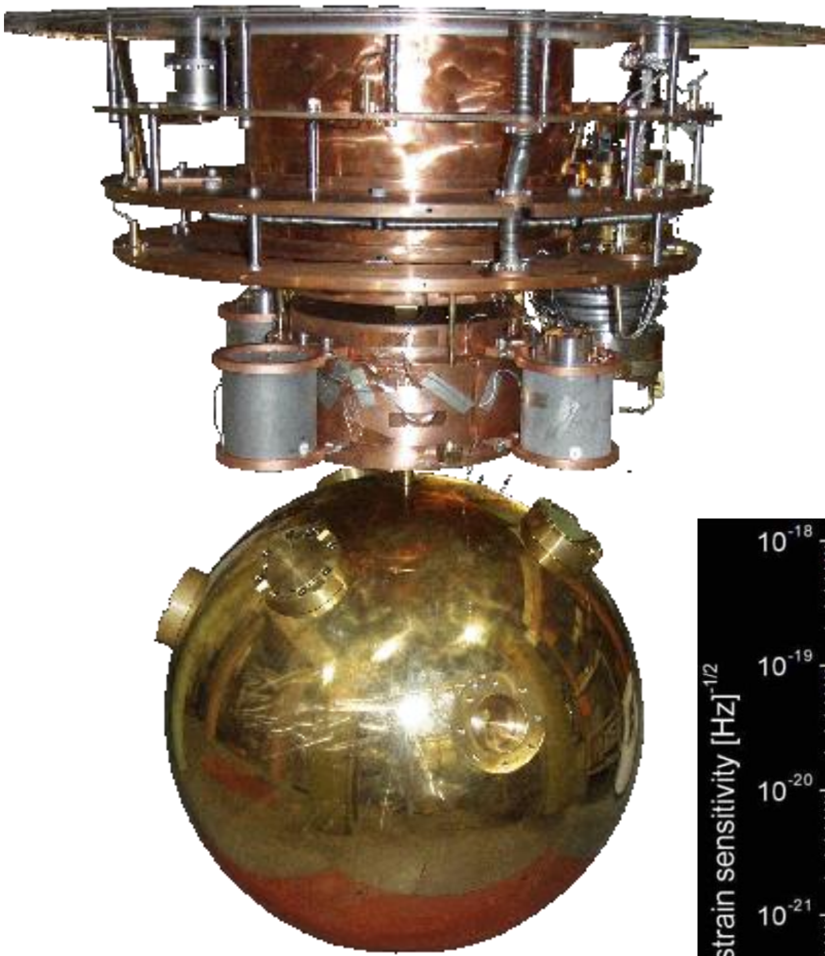
Meten van gravitatiegolven van compacte objecten

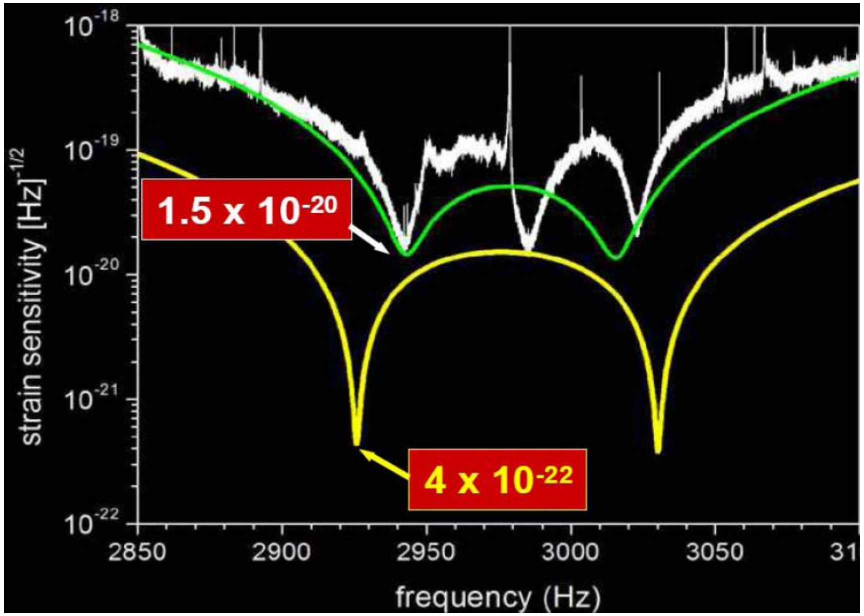
Auriga



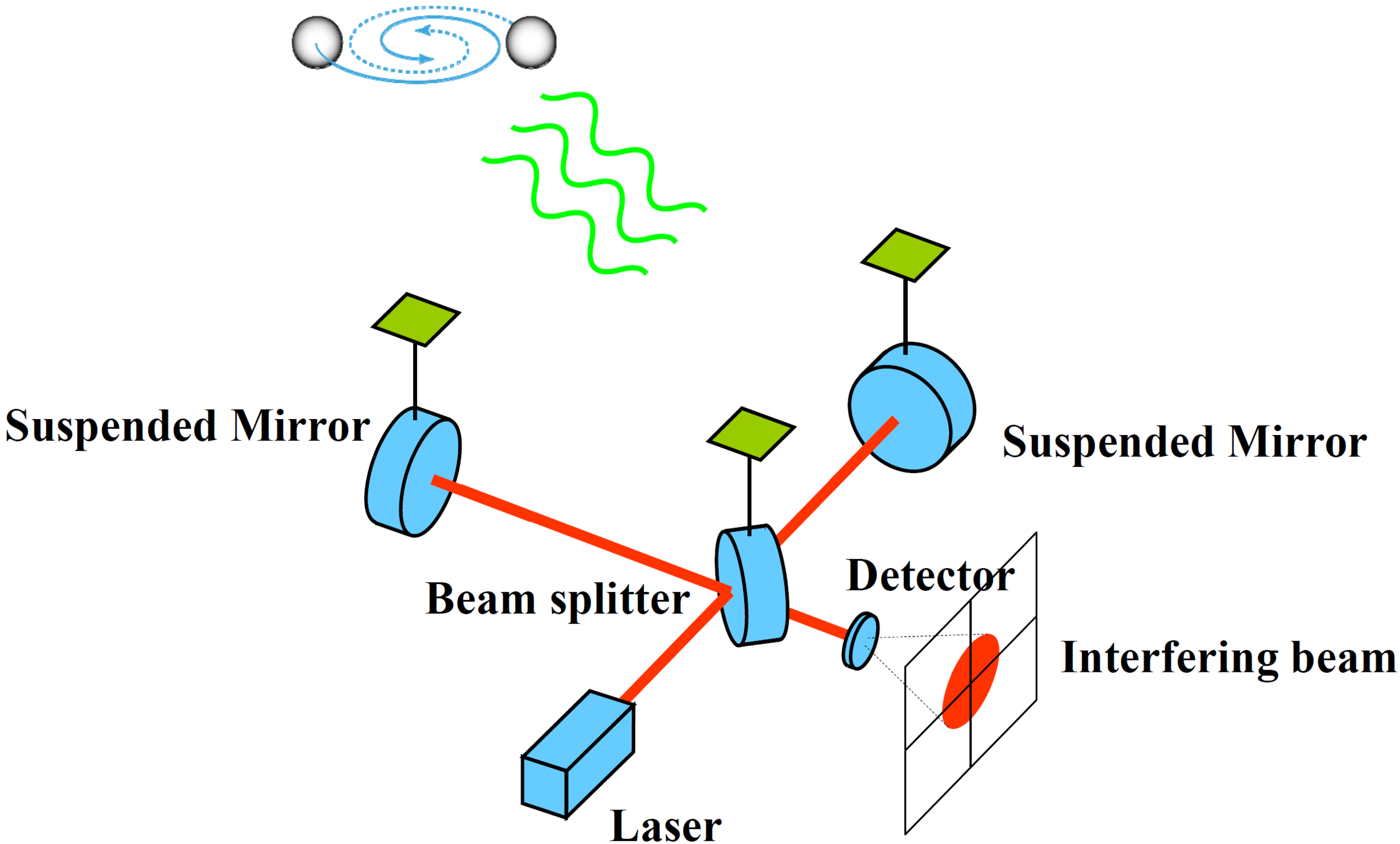
S_{hh} - R424, 300V, 4.5K (15 Mar 2004)
1.E-18
1.E-19
1.E-20
1.E-21
1.E-22
sensitivity (Hz$^{-1/2}$)
800
850
900
950
1000
frequency (Hz)

Mini-GRAIL: een bolvormige `staaf' in Leiden



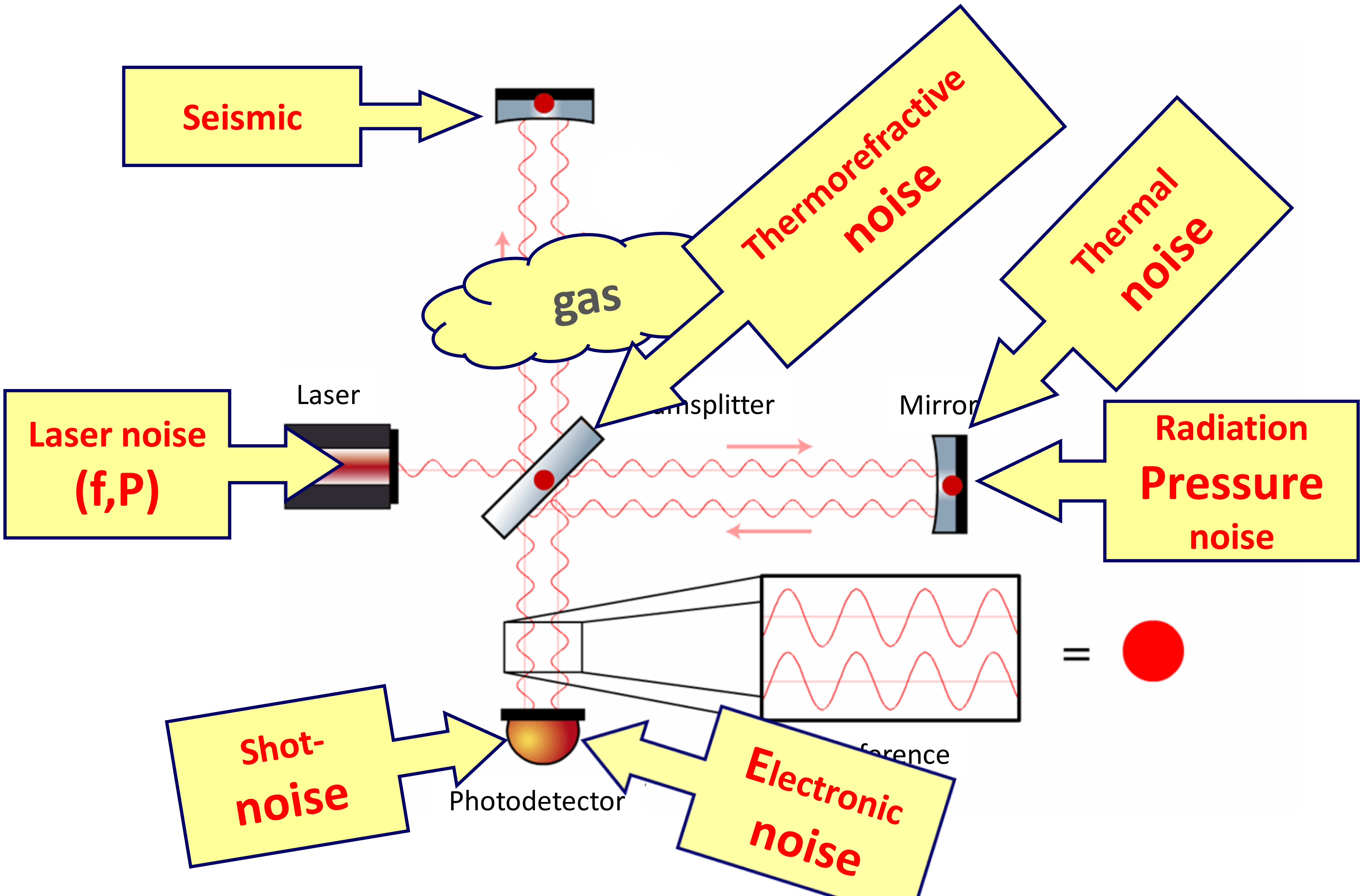


GW DETECTIE MET INTERFEROMETER

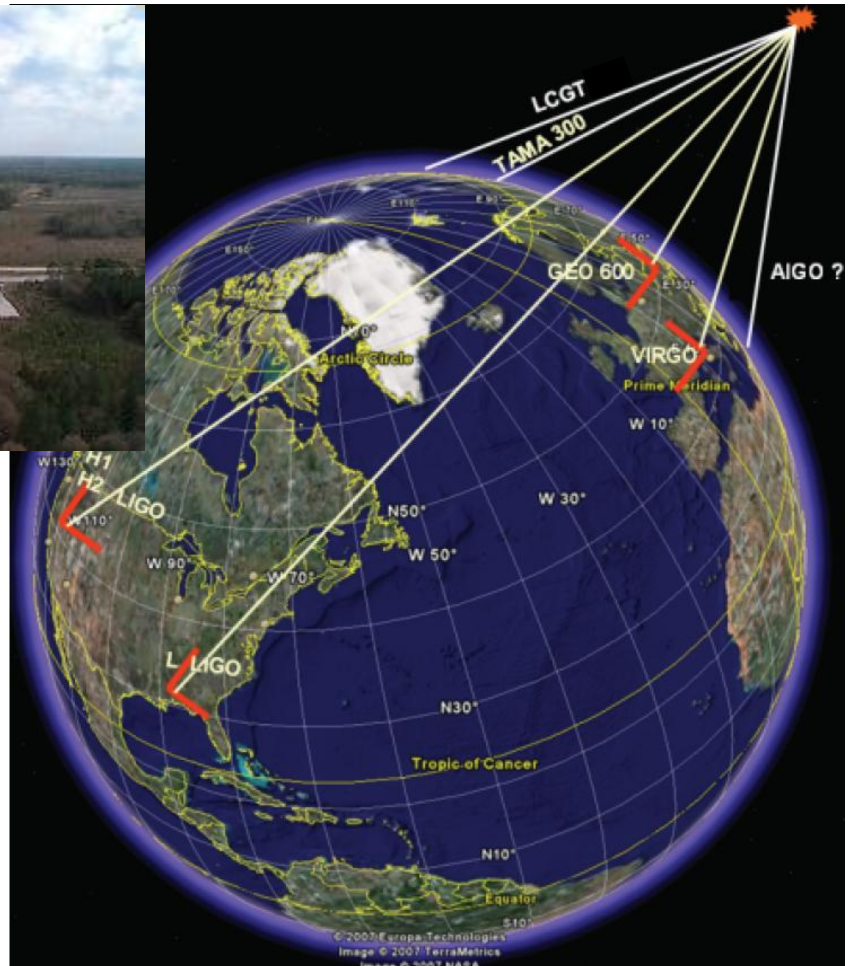


Kawamura

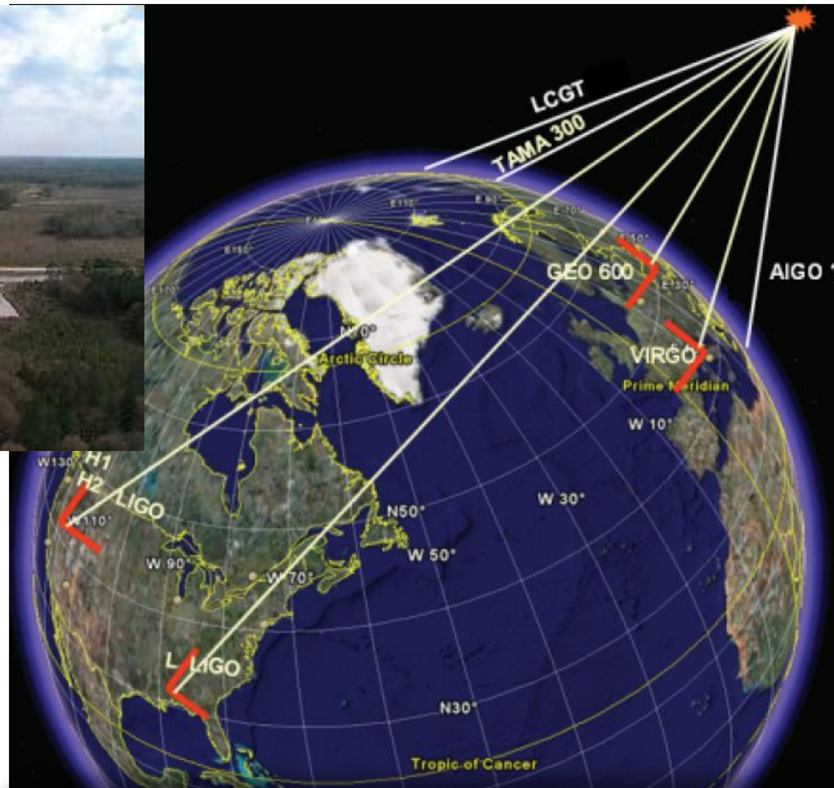
Interferometer: principe

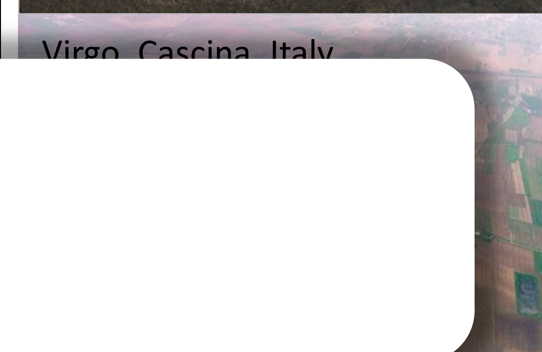


International context



International context





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

Interferometer as GW detector

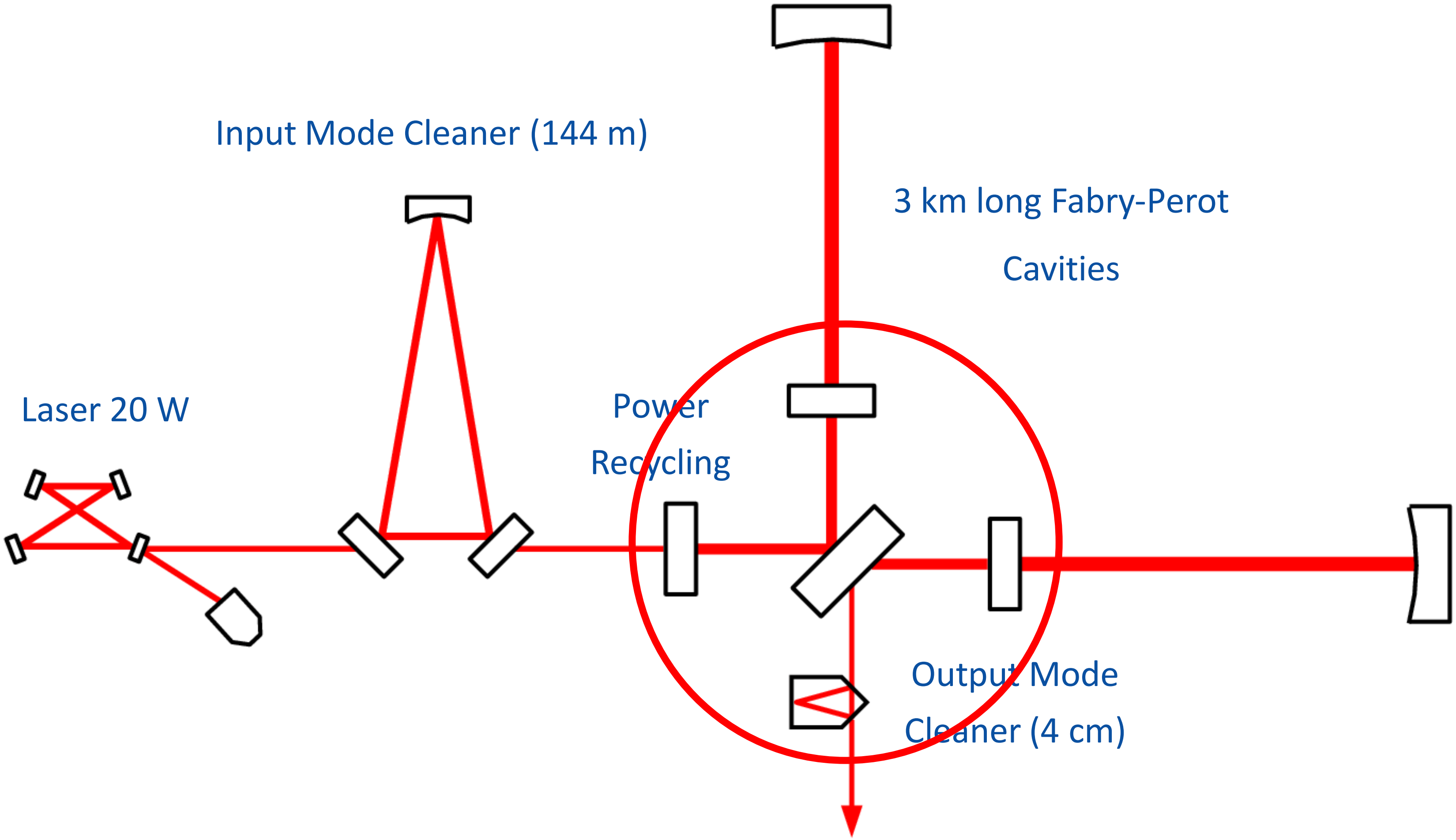
- Principle: measure distances between free test masses
  - Michelson interferometer
  - Test masses = interferometer mirrors
  - Sensitivity: h = DL/L
    - We need large interferometer
    - For Virgo L = 3 km

Virgo: CNRS+INFN

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

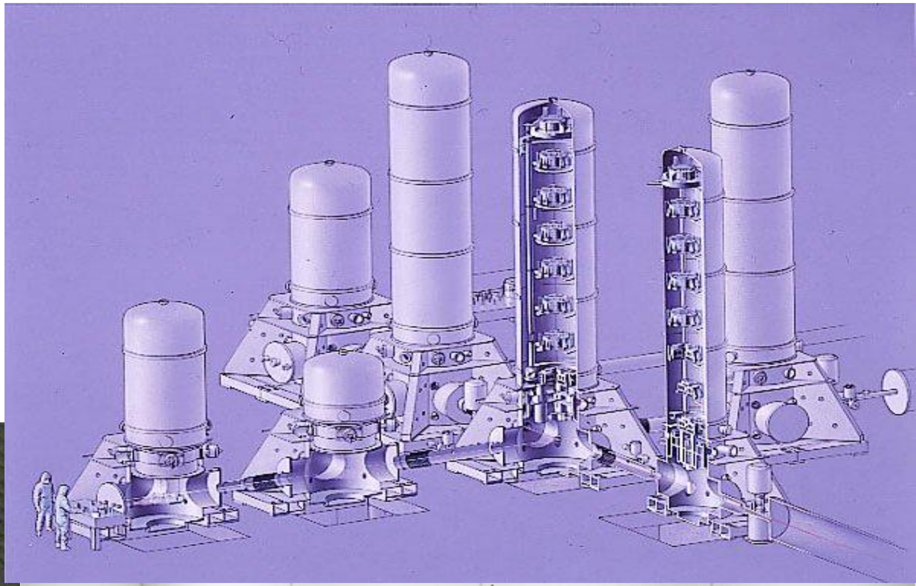
+ Nikhef joined 2007

VIRGO optical scheme



Vacuum system

- UHV
  - Largest ultra-high vacuum system in Europe

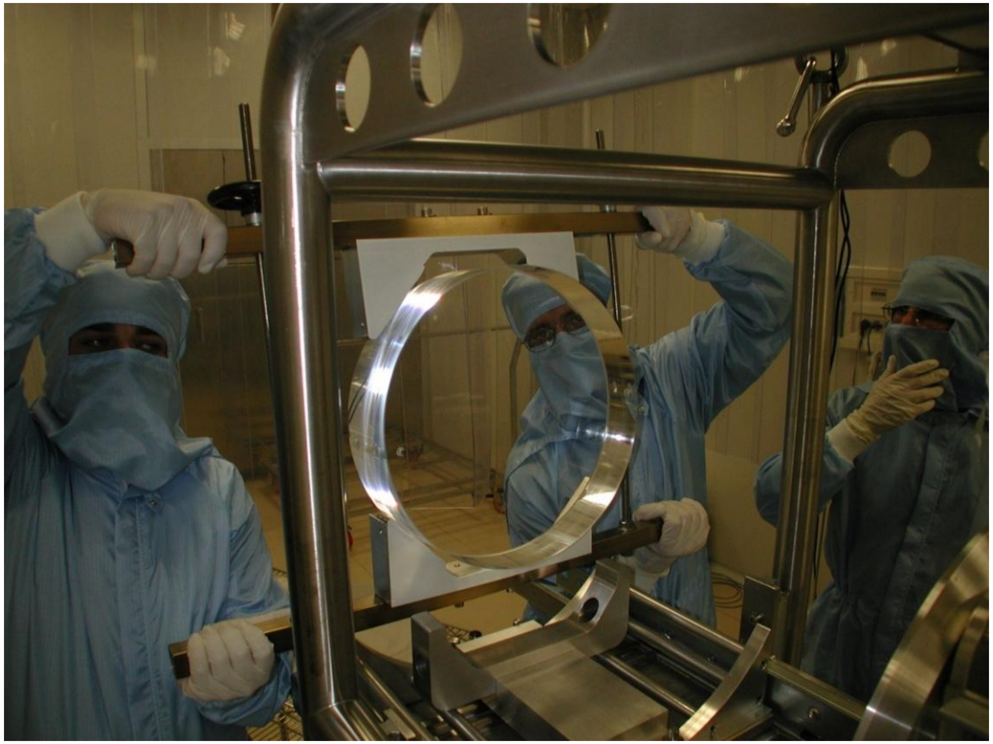


Mirrors

High quality fused silica mirrors

- 35 cm diameter, 10 cm thickness, 21 kg mass (40 kg for AdV)
- Substrate losses ~1 ppm
- Coating losses <5 ppm
- Surface deformation ~l/100

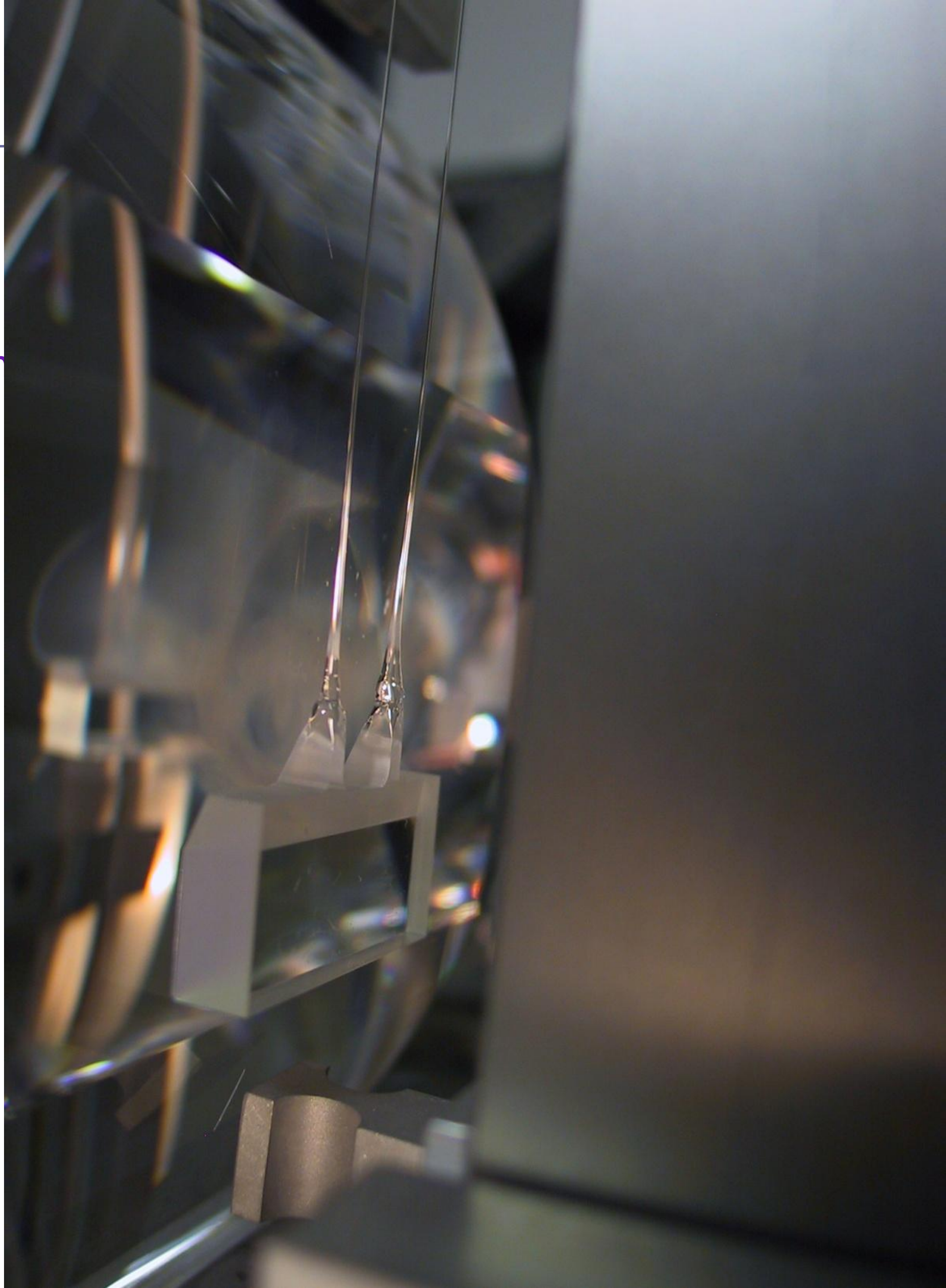
Quantum non-demolition measurements



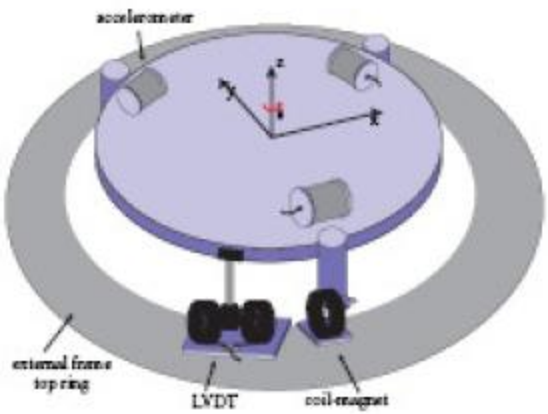
Thermal noise

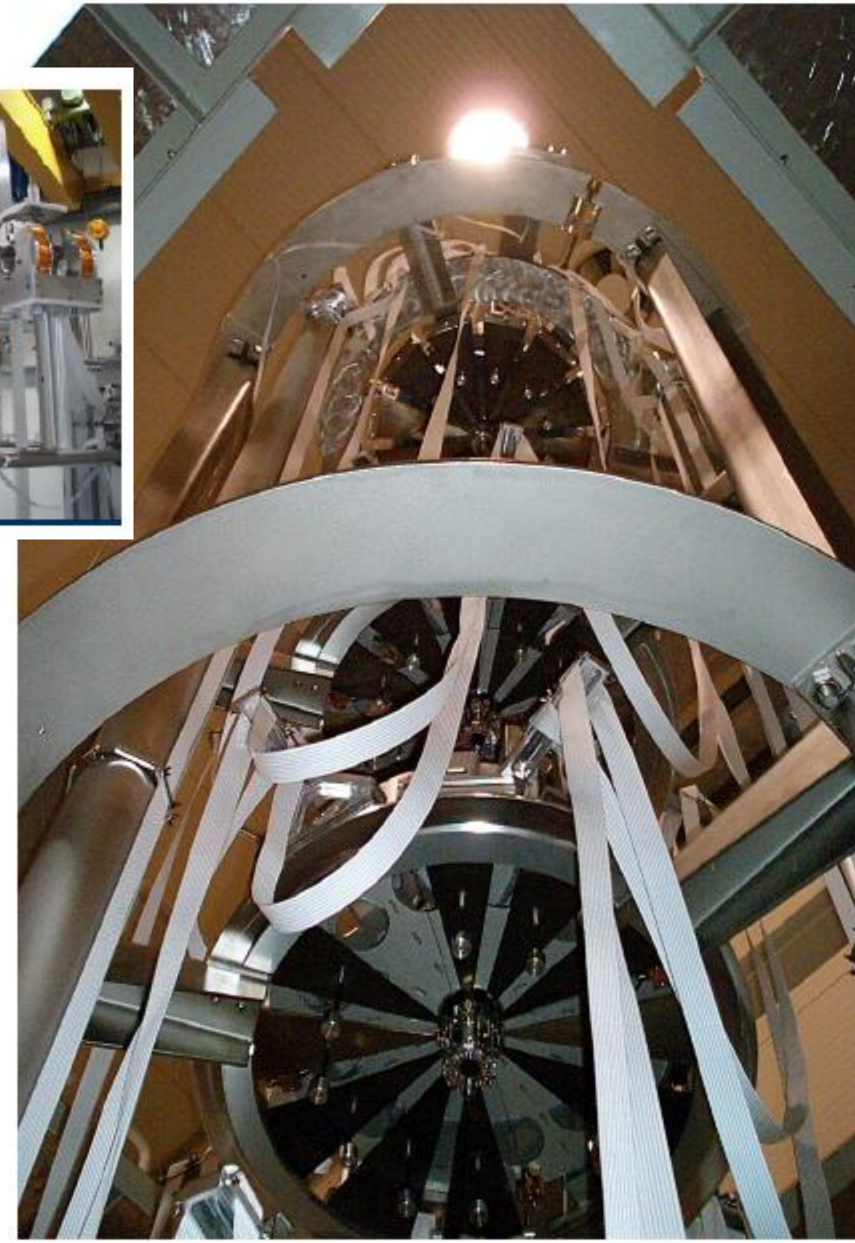
- Mechanical modes are in therr
  - Modes:
    - Pendulum mode
    - Wire vibration
    - Mirror internal modes
    - Coating surface
  - Energy associate: $k_B T$
- Thermal motion spectrum:
- Strategy:
  - use low dissipative materials:

  → concentrate the motion at the



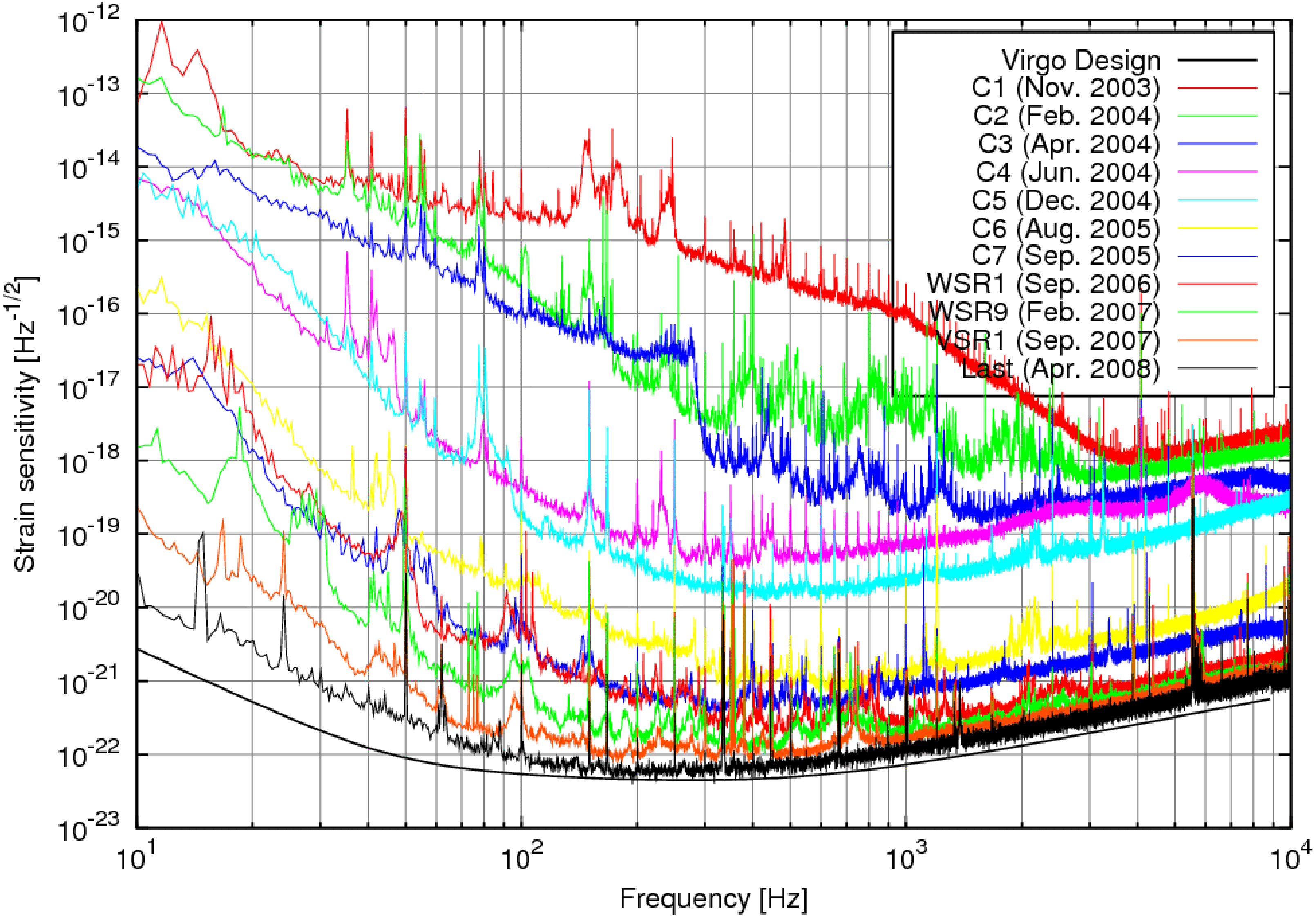
Superattenuators



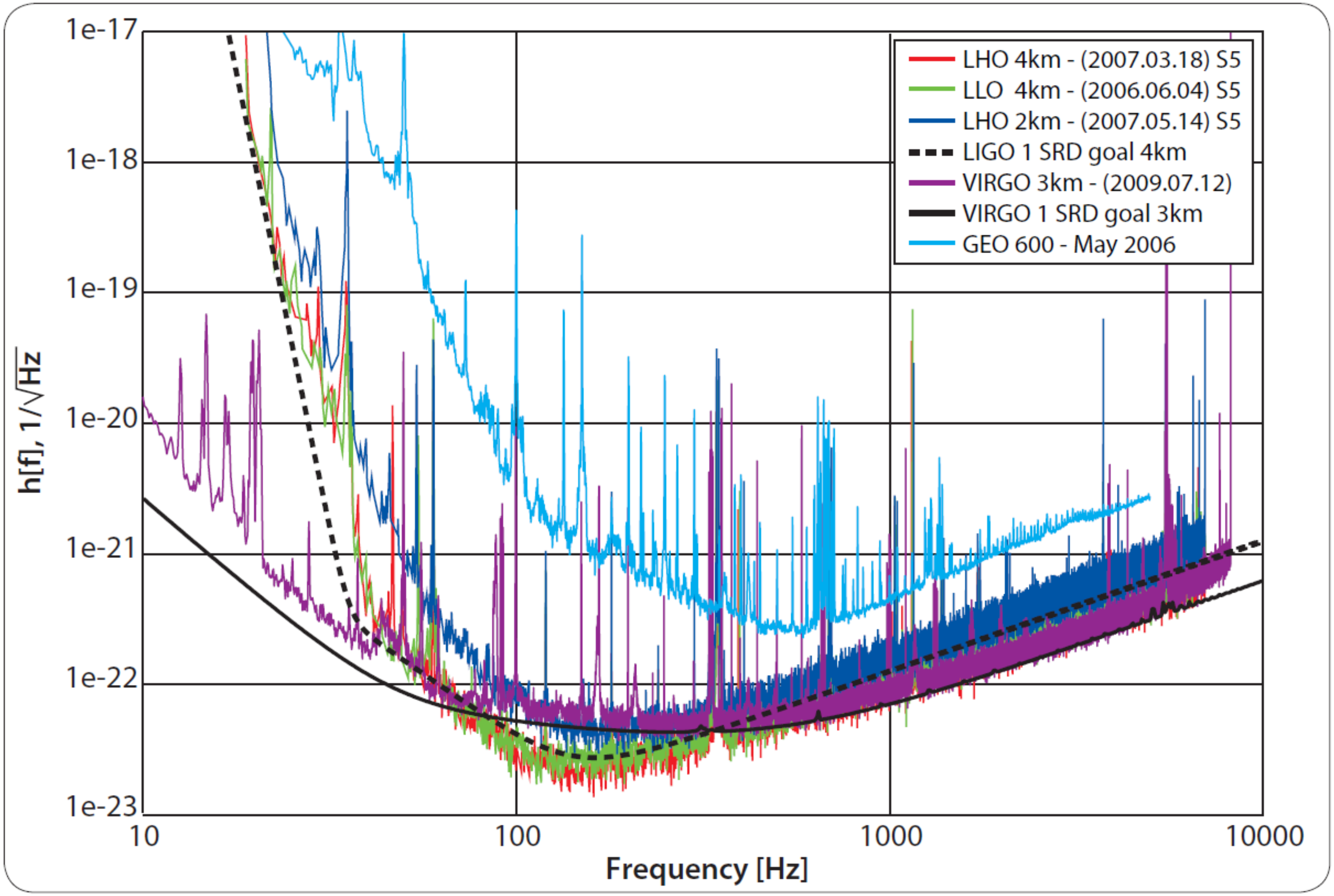


Virgo Status
& Commissioning

Evolution of sensitivity



Interferometers – sensitivity

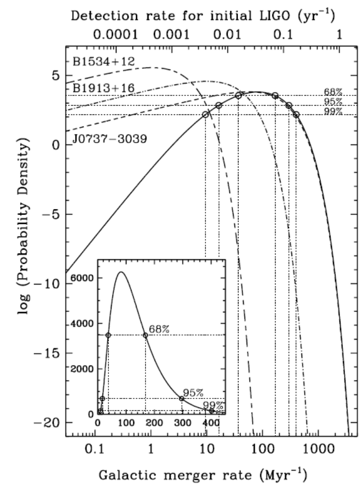


The horizon (best orientation) for a binary system of two neutron stars is 22 Mpc and of two 10 solar mass black holes is 110 Mpc

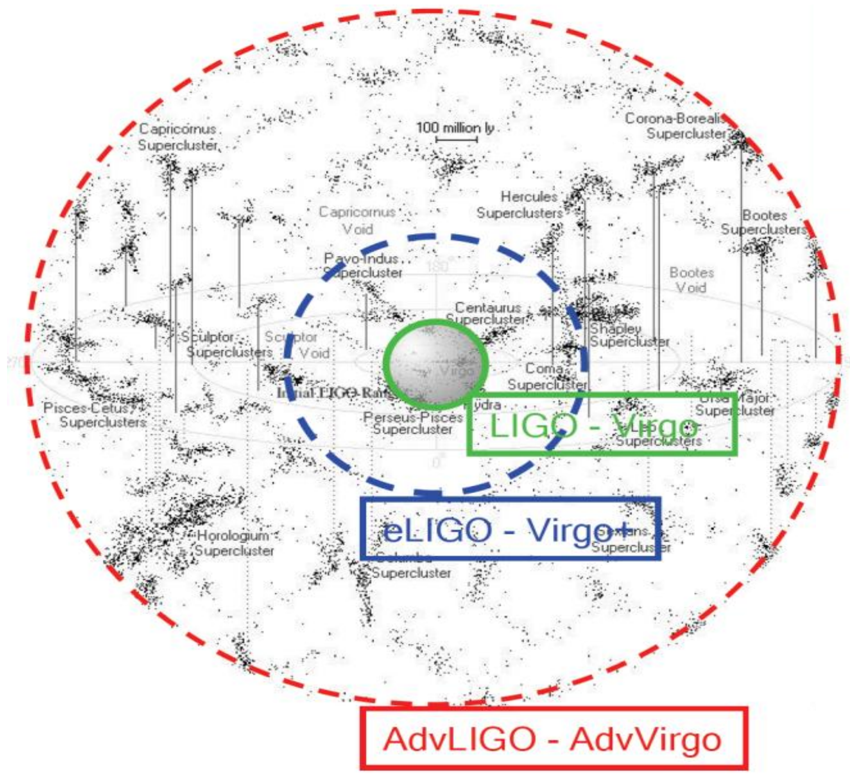
Direct discovery of GW

- 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



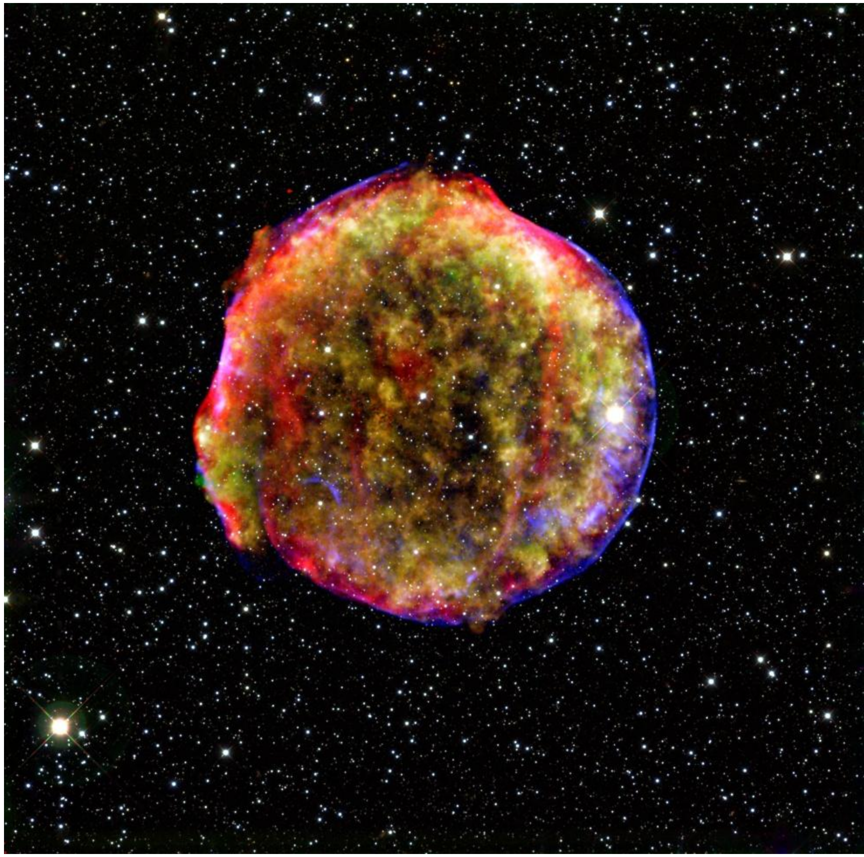
Astronomy: we know GW sources exist!



Burst Sources

- Gravitational wave bursts
  - Black hole collisions
  - Supernovae
  - Gamma-ray bursts (GRBs)

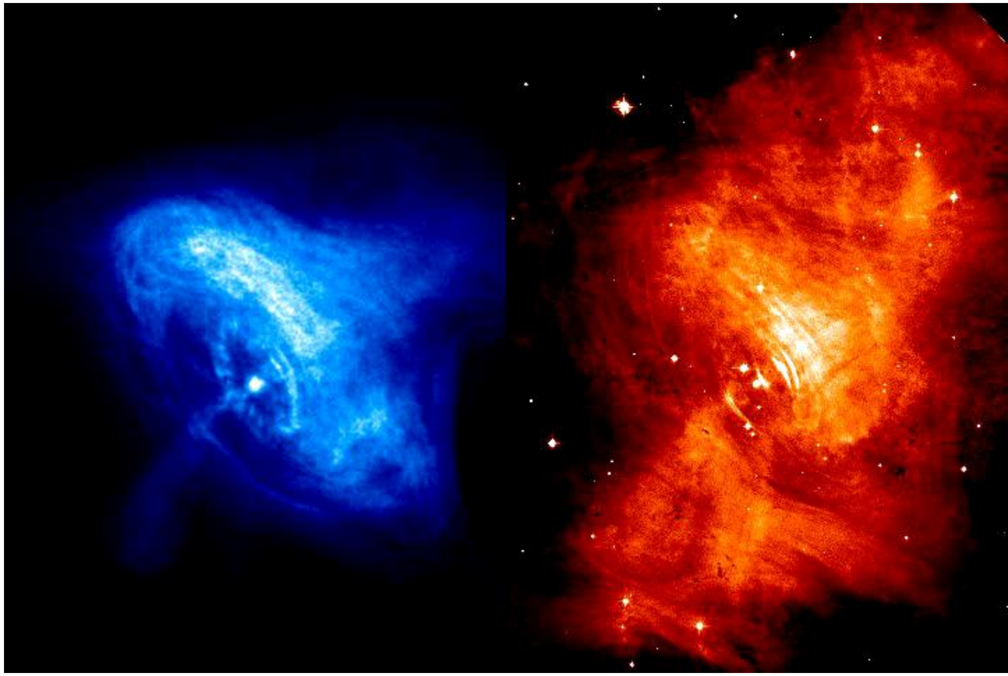
- Short-hard GRBs
  - Could be the results of merger of a neutron star with another NS or a BH
- Long GRBs
  - Could be triggered by supernovae



SN1572 (Tycho) composite image (X + IR)

Continuous Wave Sources

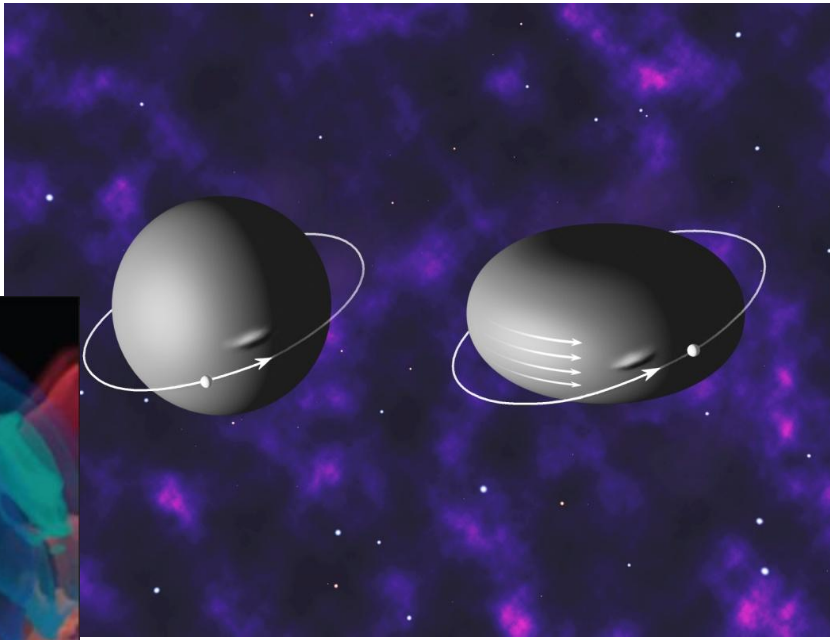
- Rapidly spinning NS
  - Mountains on neutron stars
- Low mass X-ray binaries
  - Accretion induced asymmetry
- Magnetars and other compact objects
  - Magnetic field induced asymmetries
- Relativistic instabilities
  - r-modes, etc.

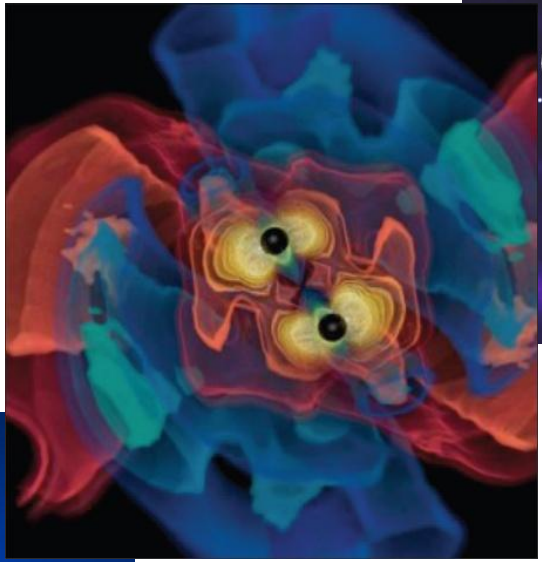


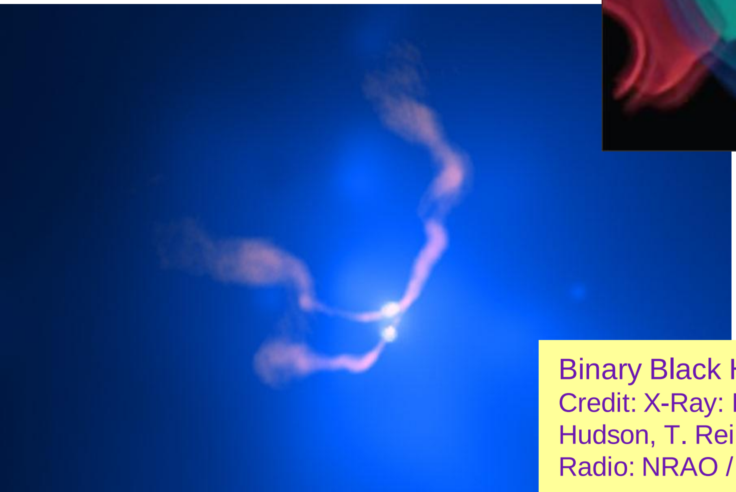
SN1052 (Crab) composite movie (X + visible)
X-Ray Image Credit: NASA/CXC/ASU/J.Hester et al.
Optical Image Credit: NASA/HST/ASU/J.Hester et al.

Compact Binary Mergers

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







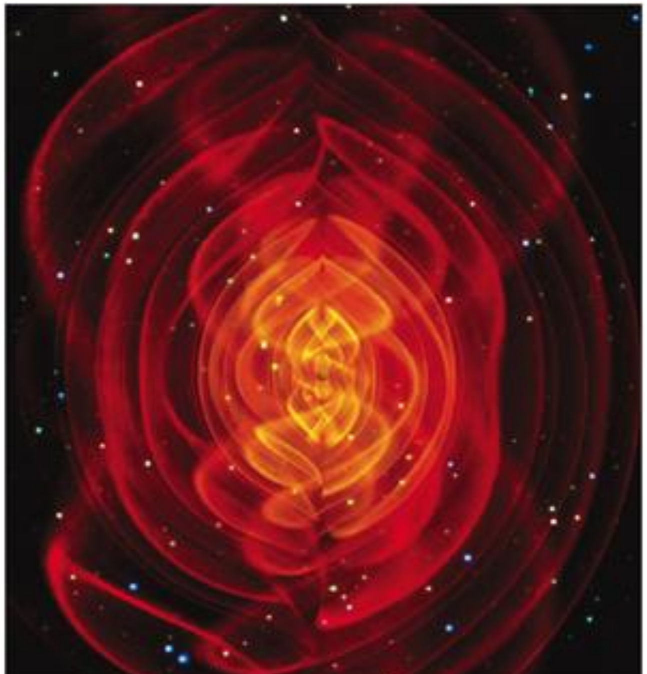
Binary Black Hole in 3C 75
Credit: X-Ray: NASA / CXC / D. Hudson, T. Reiprich et al. (AIfA); Radio: NRAO / VLA/ NRL

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

Simulation – merging of BBH

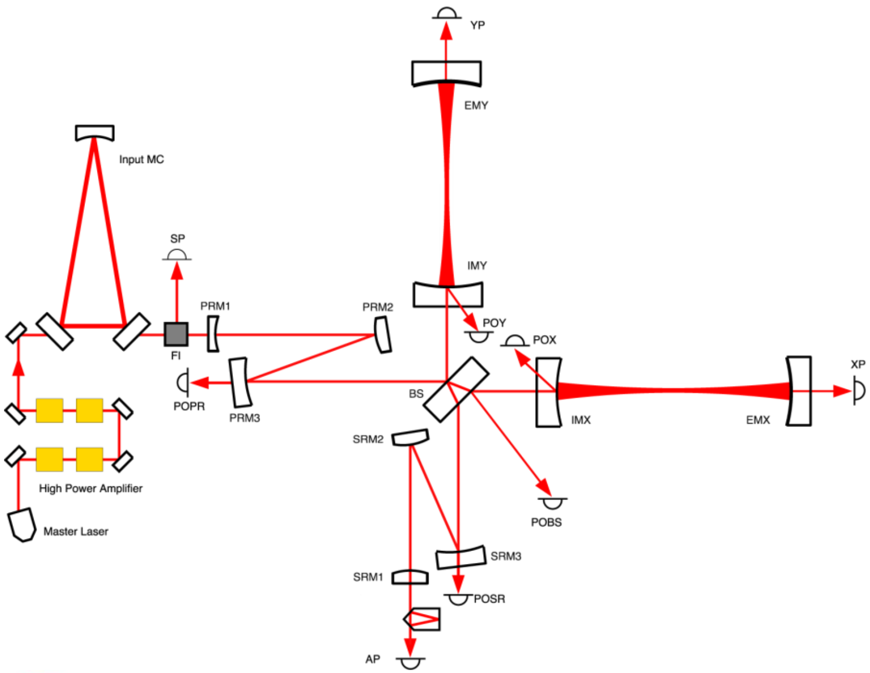
- Pretorius 2005 (arXiv:gr-qc/0507014)
  – BBH orbit, merger and ringdown
  – Energy loss by GW
- Rezzolla
  – Templates with sufficient precision for Advanced LIGO and Virgo

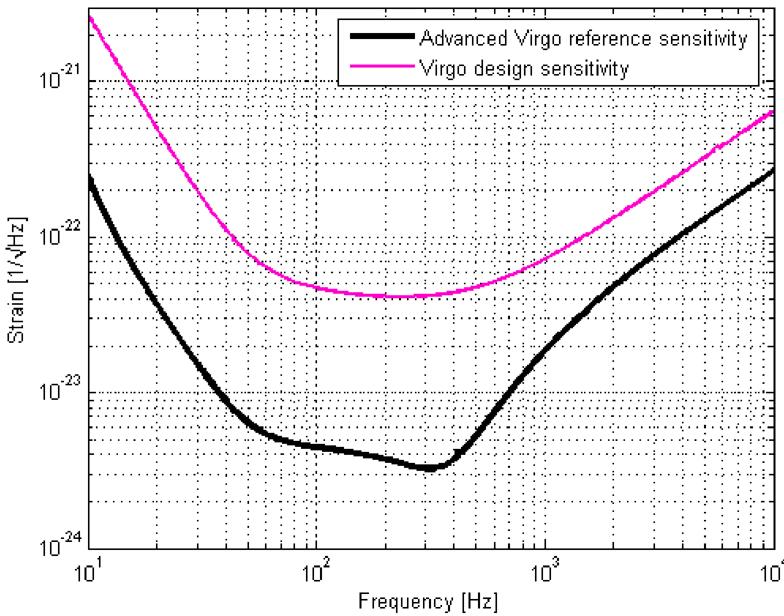


Advanced Virgo

PROJECT GOALS

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

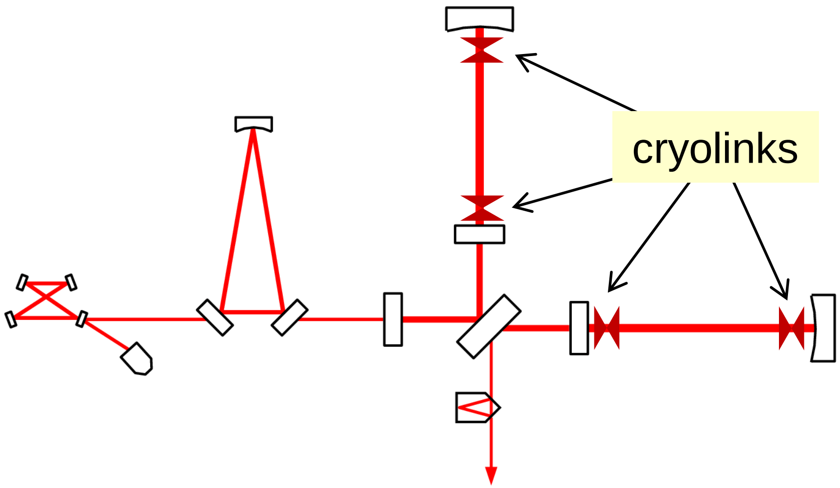


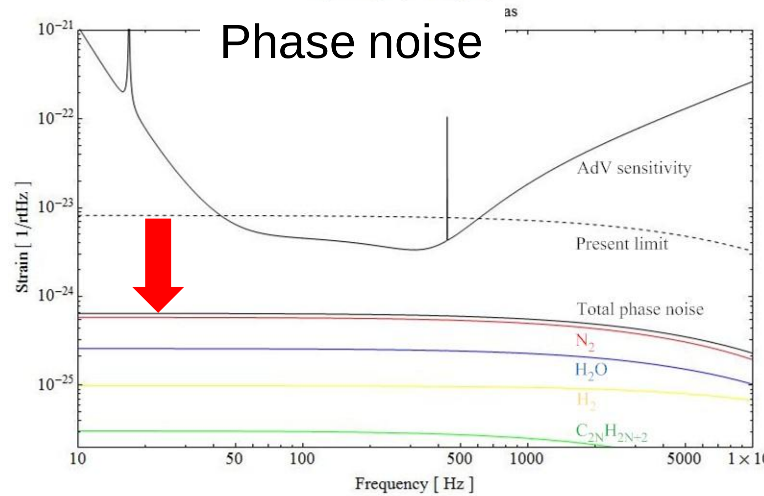


Nikhef

- Cryolinks
- Seismic attenuation systems
- Linear alignment and phase camera's

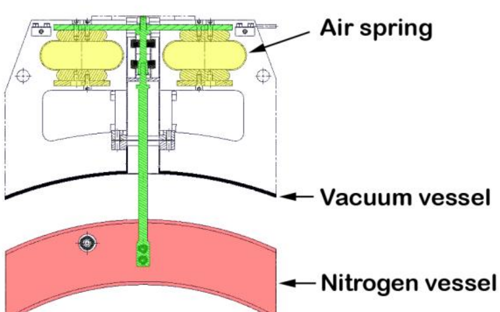
Cryolinks

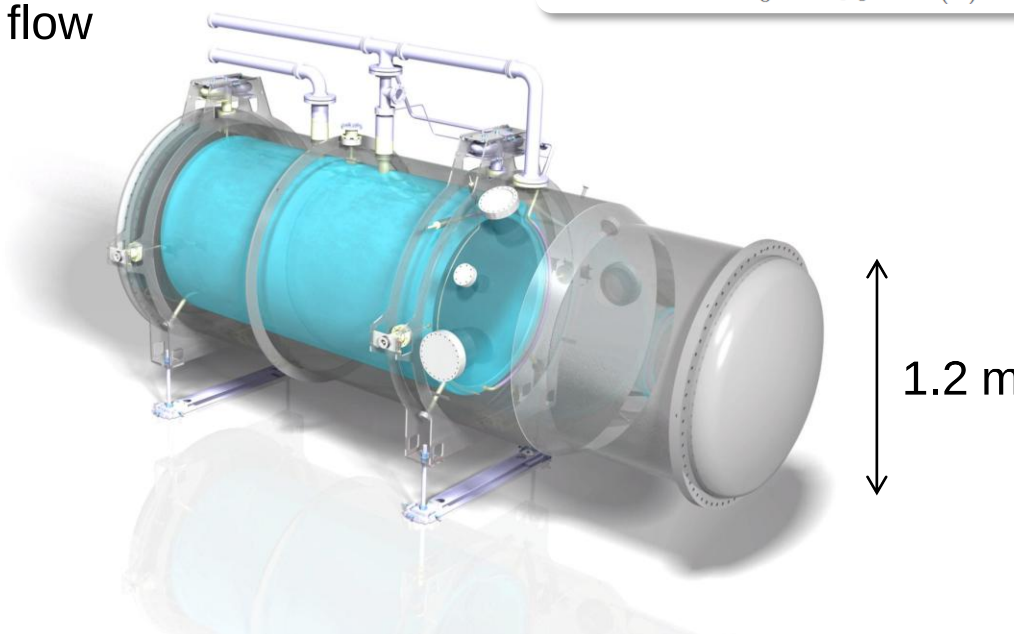




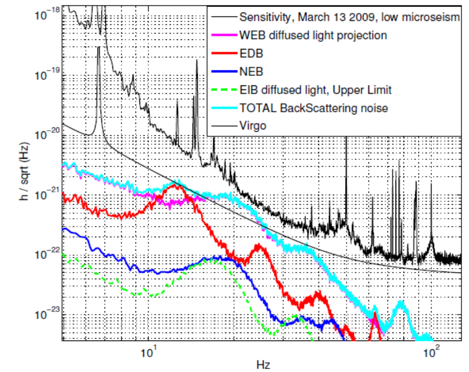
$$S_L(f) = \frac{4\rho\,(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{1}{w(z)} e^{-2\pi f w(z)/v_0} dz$$

Vibrationless two-phase flow

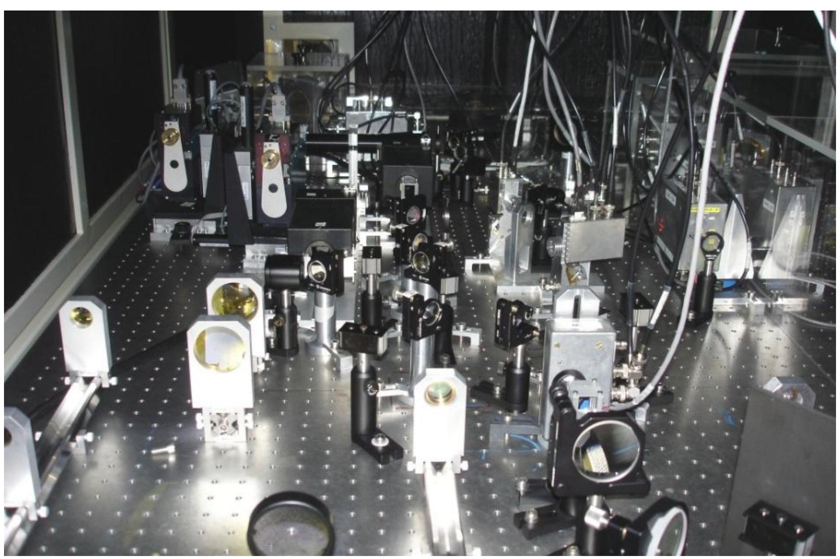


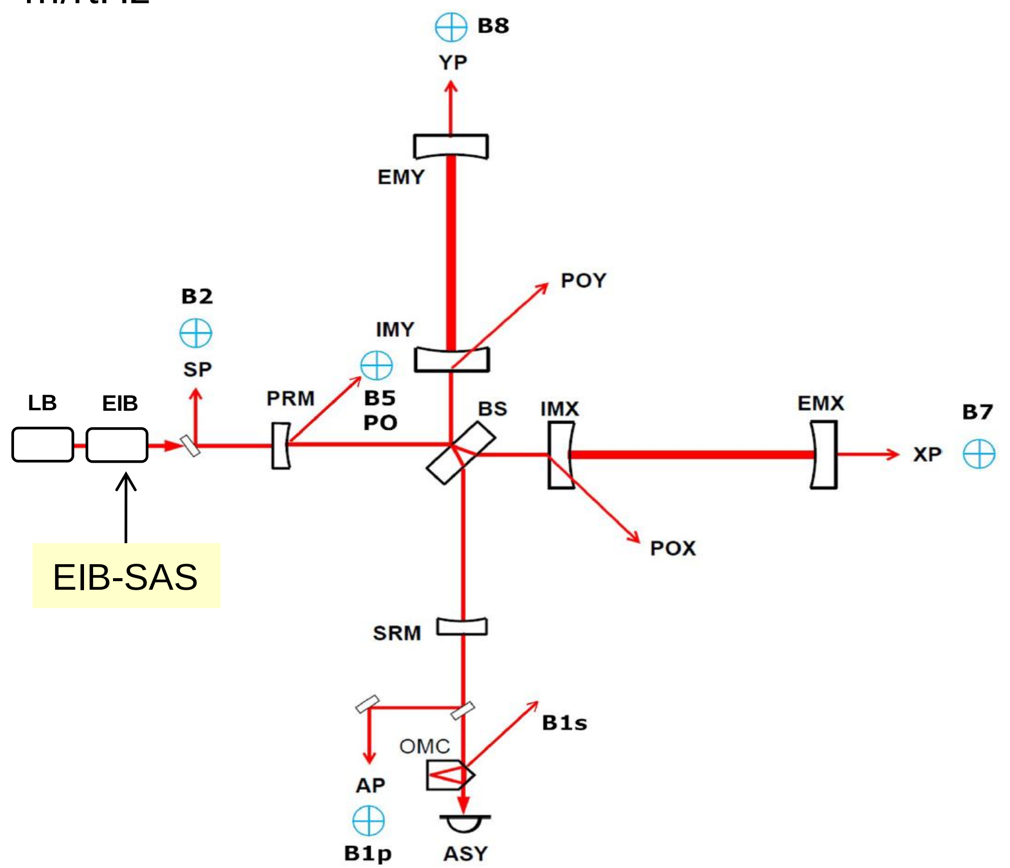


Seismic attenuation systems



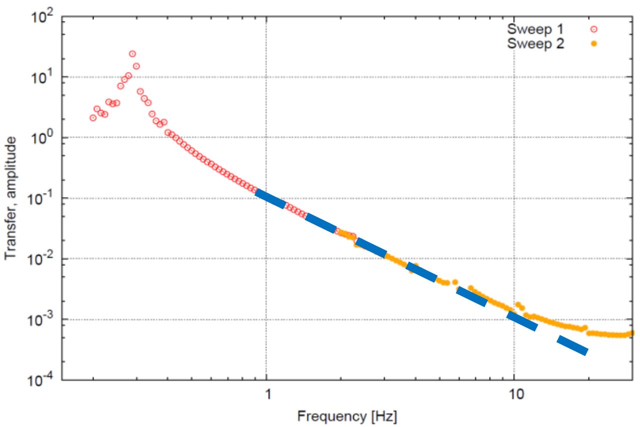
- EIB-SAS features
  - External Injection Bench
  - Realize seismic attenuation system
    - Factor 1000 in 6 degrees of freedom
  - Displacement noise less than 10^{-12} m/rtHz





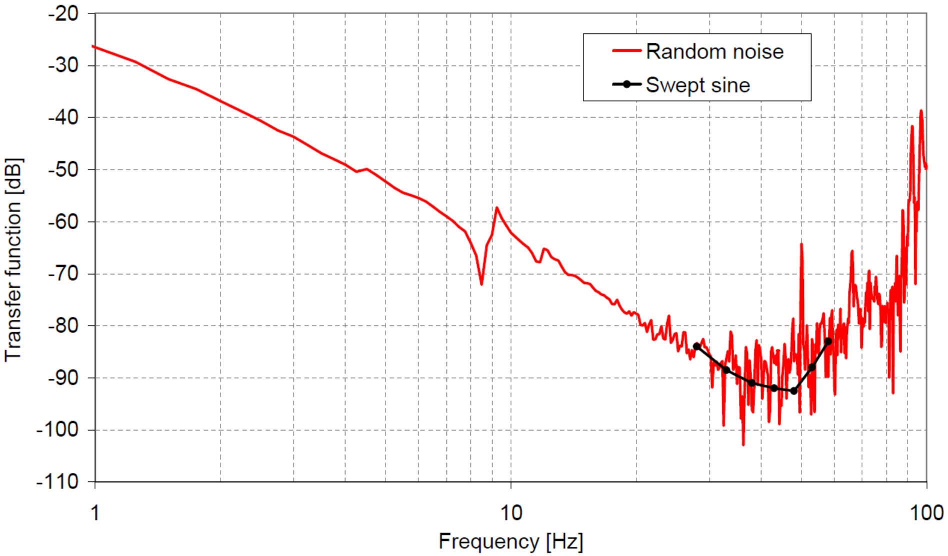
Antispring technology

- Attenuation
  - Horizontal: inverted pendula
  - Vertical: GAS filters
- Transfer function
  - 60 dB above 10 Hz
  - Achieved > 65 dB at 20 Hz
  - Single stage
- No commercial solutions
  - Interest from industry



GAS AT AEI

- 10 m prototype ITF
  - GAS design
    - 12 GAS filters total
    - In vacuum operation
  - Features
    - 8 GAS blades per filter
    - SiC magic wands
  - Results
    - > 90 dB at 40 Hz



Alessandro Bertolini
Alexander Wanner
AEI, Hannover

External injection bench

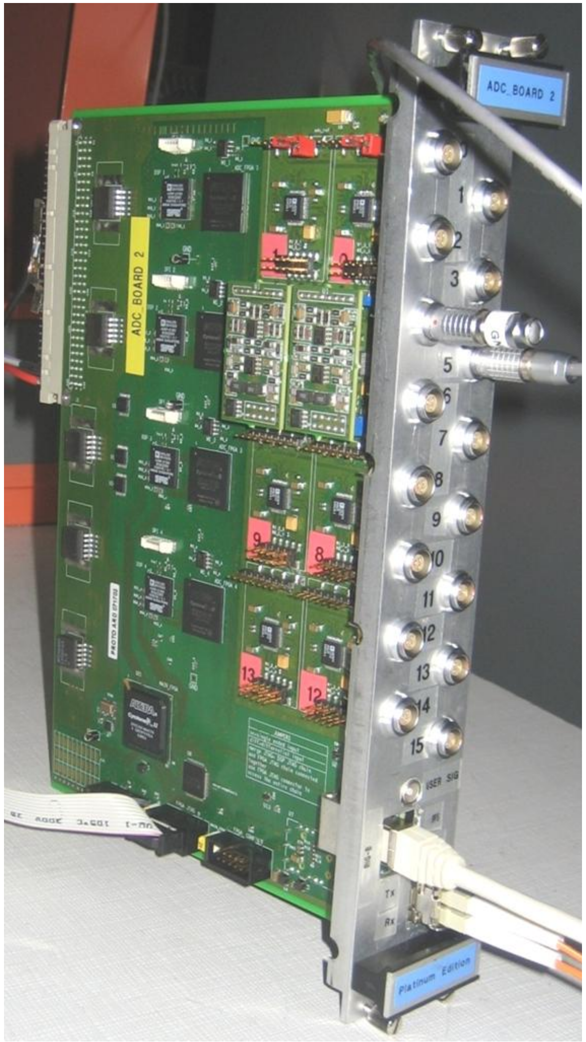
- SAS features
  - Single-stage attenuation system
  - Six degrees of freedom
  - Sensors: 6 accelerometers, 6 LVDTs
  - Consistent with10^{-12} m/rtHz
  - Compact design
  - Installation Q4 2011

Control system: ADC7674

A.Masserot, B.Mours, E.Pacaud, LAPP
Henk Jan Bulten, Nikhef

ADC7674

- Analog part:
  - VME size board (only for power supplies)
  - ADC : AD7674 18-bit @ 800kHz
  - 16 ADC channels
  - Mezzanine : anti-alias and compression filter
  - Differential or single-ended input
- Digital Part
  - DSP computing for 8th order filters (DSP Sharc ADSP21262)
  - Decimation to reduce the output data rate
  - TOLM interface
- Nikhef setup
  - 16 analog flat mezzanines
  - One optical transceiver connected to the *RTPC* TOLM_PCI
  - One RJ45 cable connected to the TDB to receive the IRIGB signal
- Configuration file: /virgoData/Adc7674/ADC0.cfg

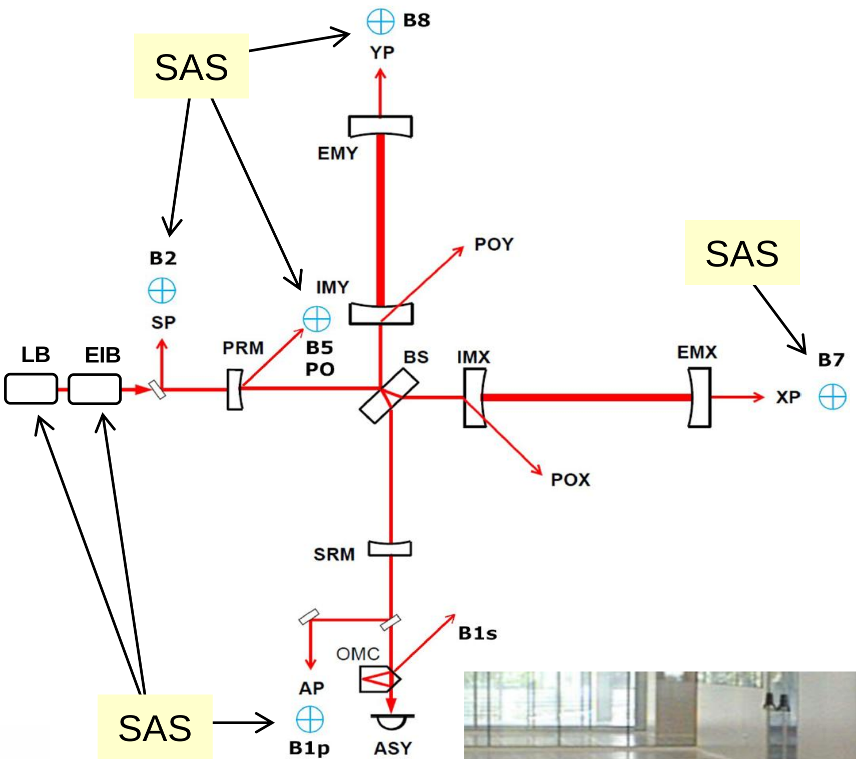


PCI DAC board

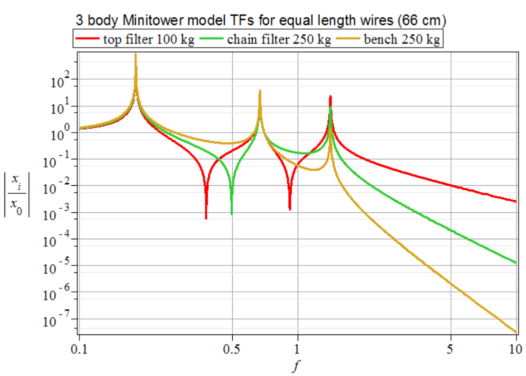
- 8 DAC channels, 16 bits DAC chip
- No external trigger, no anti-image analog filter

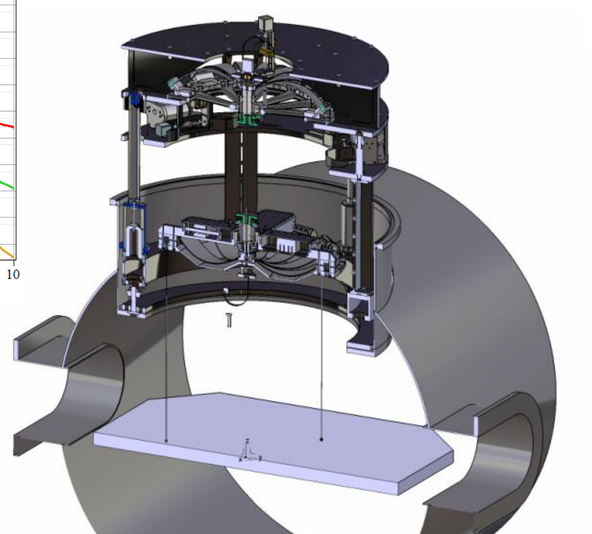
Seismic attenuation systems

- SAS features
  - 2 external, 5 internal SAS
  - Consistent with10^{-15} m (rad)/rtHz (6 dof)
  - Compact design
  - Vacuum compatible



Sensor	Power	Limit	Current	Spot size	Ddelta	QPD shift	Bench shift	Bench tilt
	mW		pA	um	1/rtHz	m/rtHz	m/rtHz	rad/rtHz
QP45	25	shot noise	34	330	9,30E-09	2,40E-12	6,00E-12	8,38E-15
	25	shot noise	34	1650	9,30E-09	1,20E-11	3,00E-11	4,19E-14

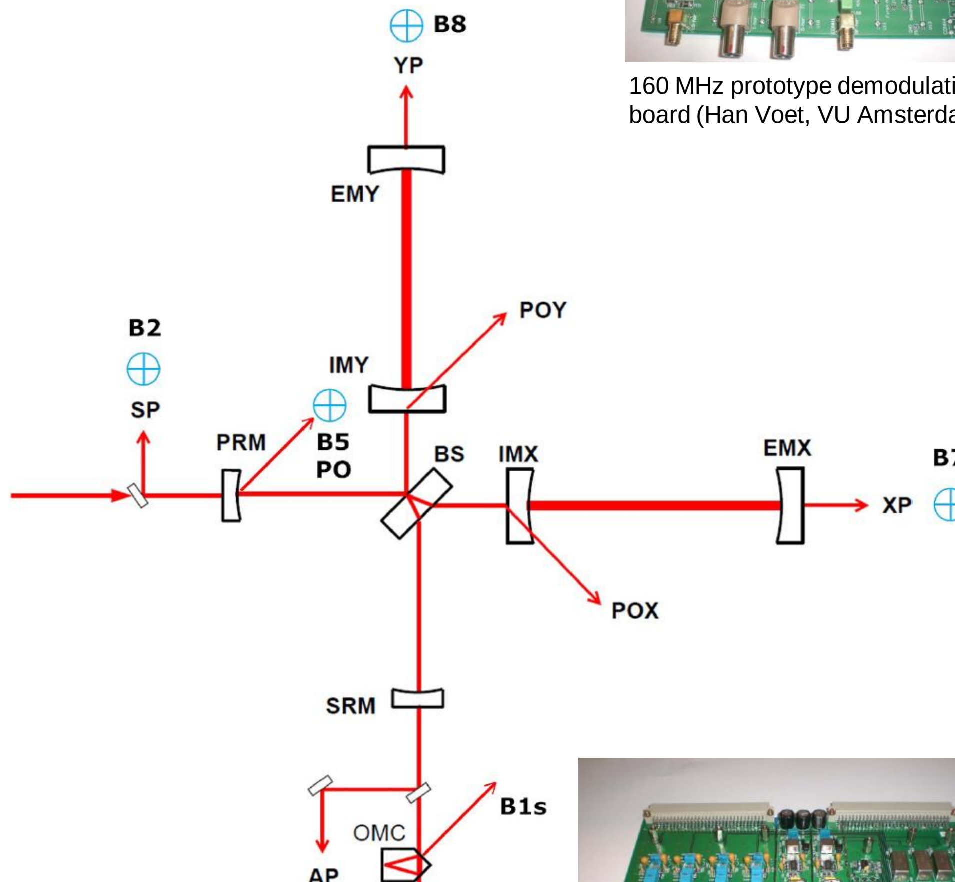




Linear alignment systems

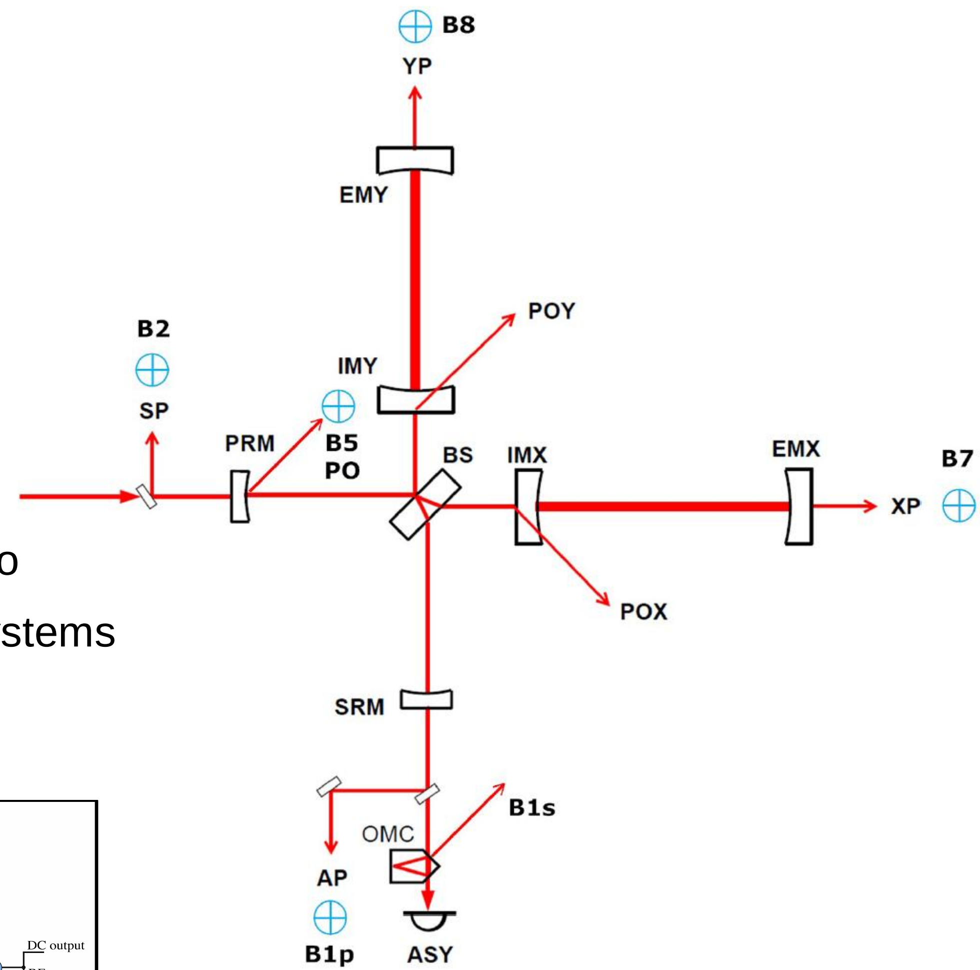
- Angular control of optical elements
  - Modulate carrier
    - 6.26, 8.35, 56 and 131 MHz
  - QPD front-end systems
    - Transimpedance amplifiers
    - Shot noise limited performance
  - Demodulation electronics
  - Seismic attenuation systems

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



Phase camera's

- Imaging of cavity fields
  - Both carrier and sidebands
    - 6.26, 8.35, 56 and 131 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
  - Nikhef optics laboratory



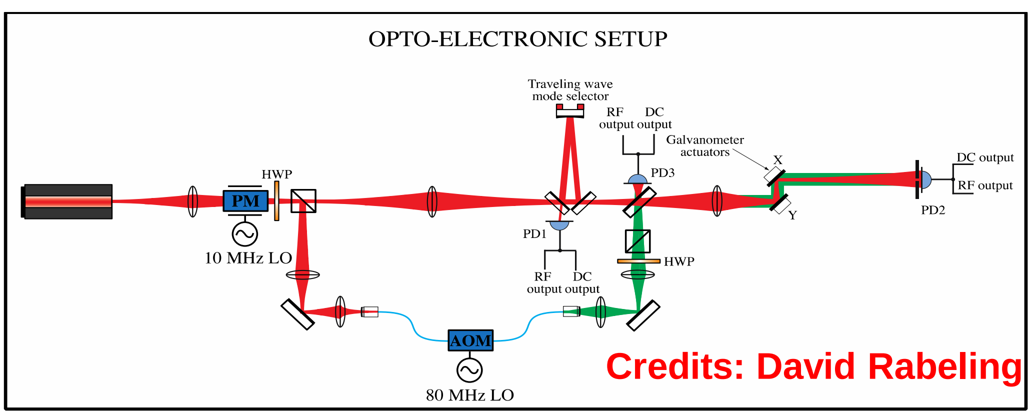
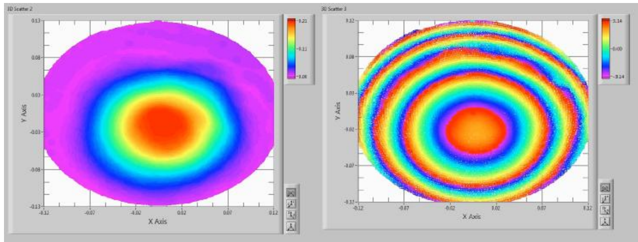
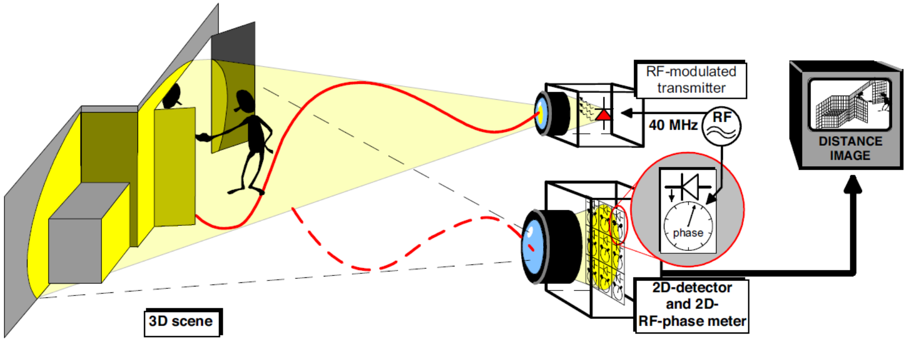


Figure 1: Current opto-electronic set up of the phase camera at Nikhef. The system uses modulation/demodulation techniques to allow for frequency selective wave-front sensing.

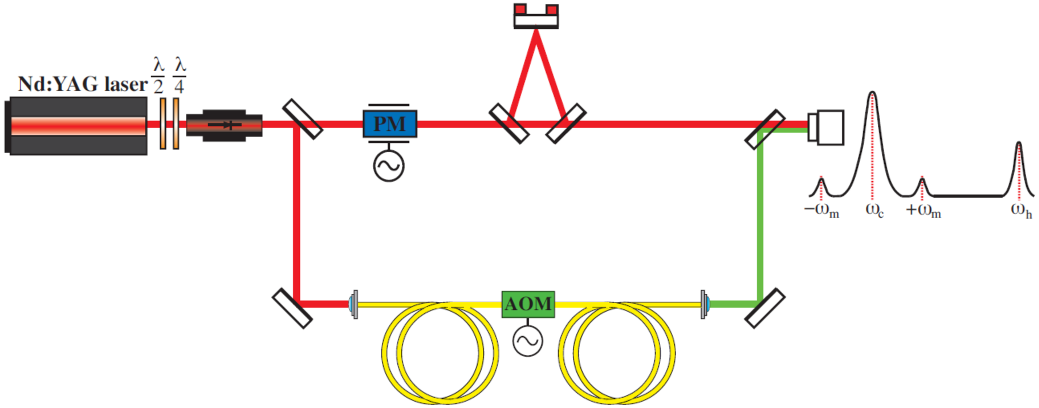


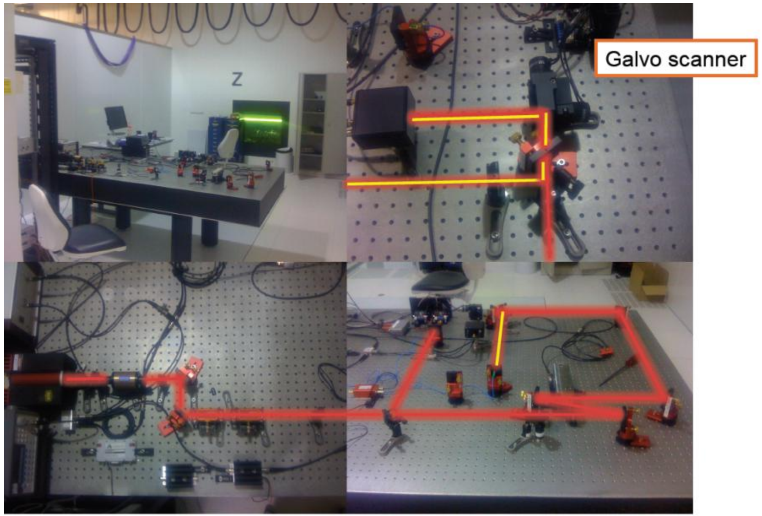
Phase camera's

- Time of flight camera's
  - 3D imaging
    - PMD, Mesa (SLIM)
    - CCD, IR LEDs
    - Operate at 30 MHz
  - Software framework
    - Waveform decomposition
      - Hermite-Gauss polynomials



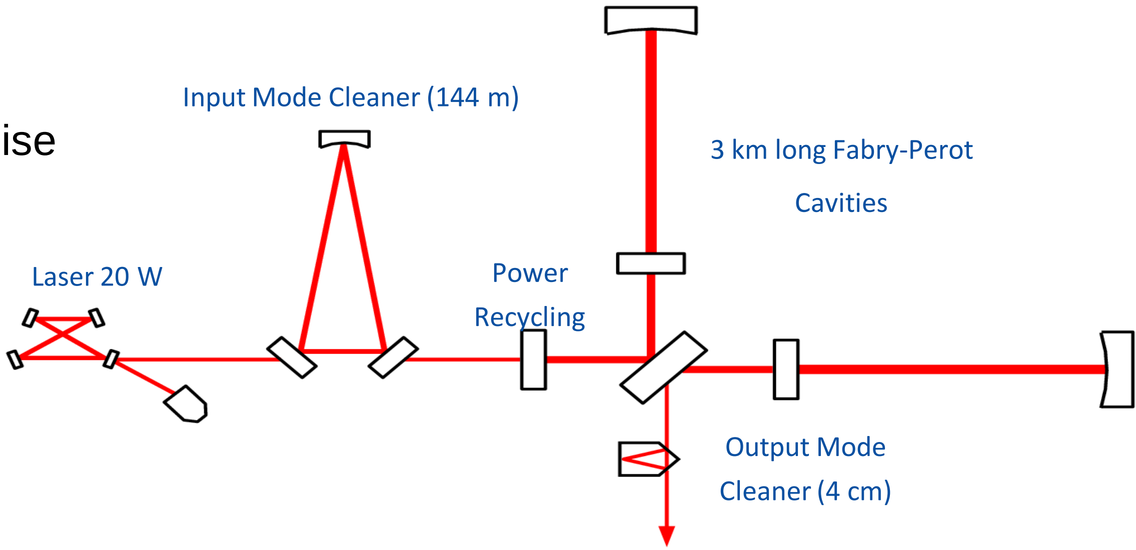
MESA IMAGING

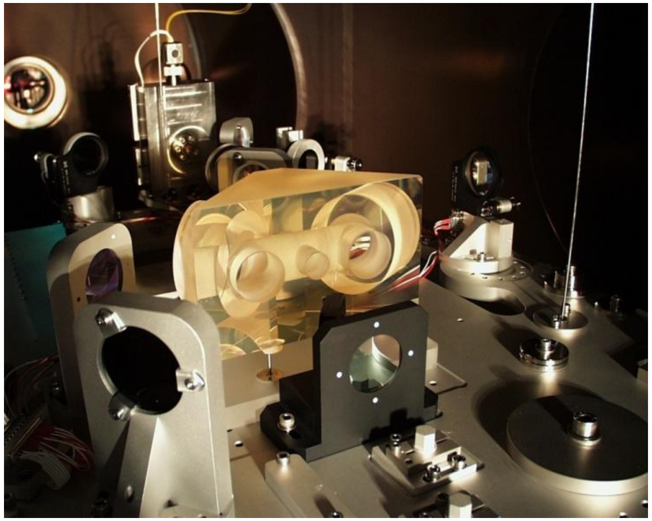




Optical components – dihedron

- Input mode cleaner
  - IMC cavity: filters laser noise
  - Select TEM00 mode
  - New dihedron
    - Precision optics
    - Under testing now



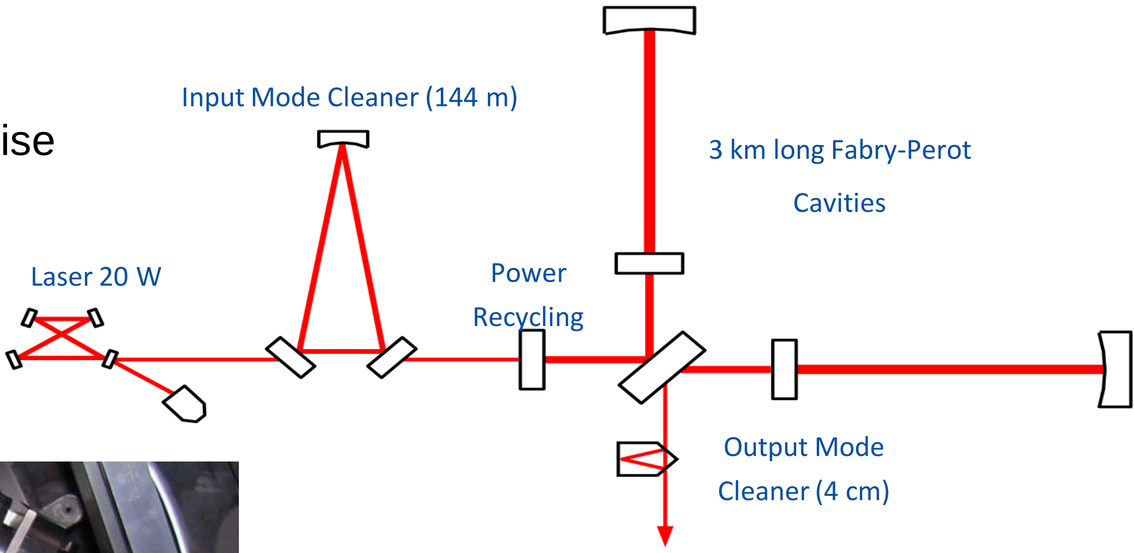


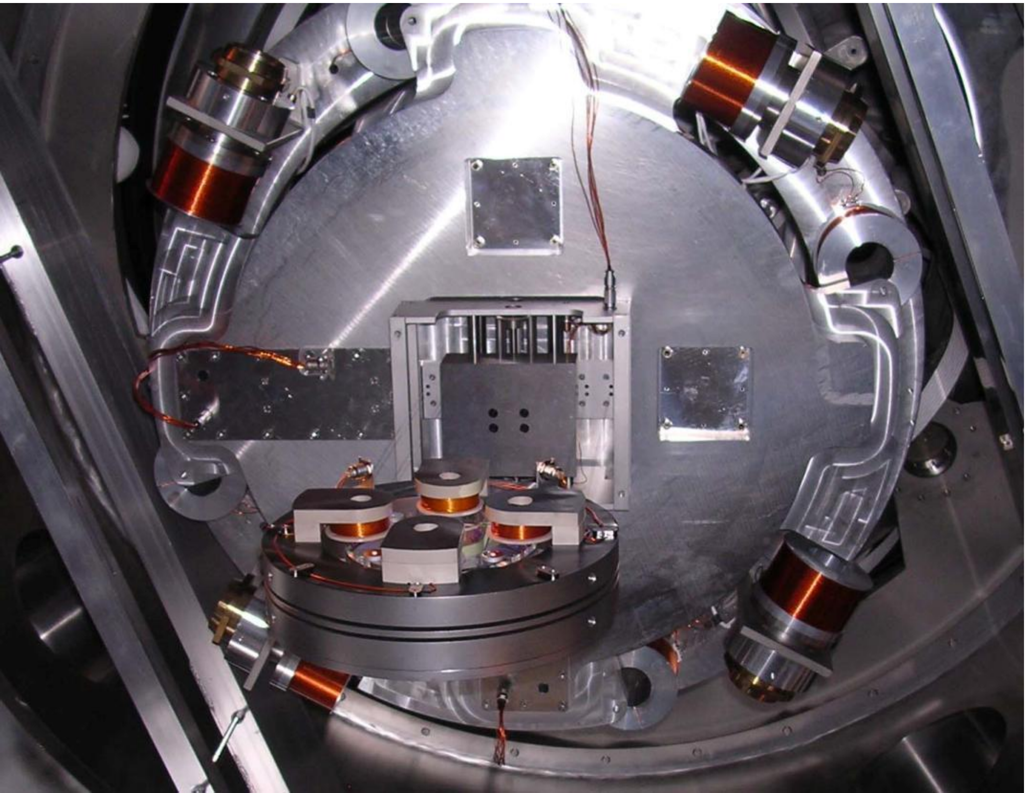
Optronica

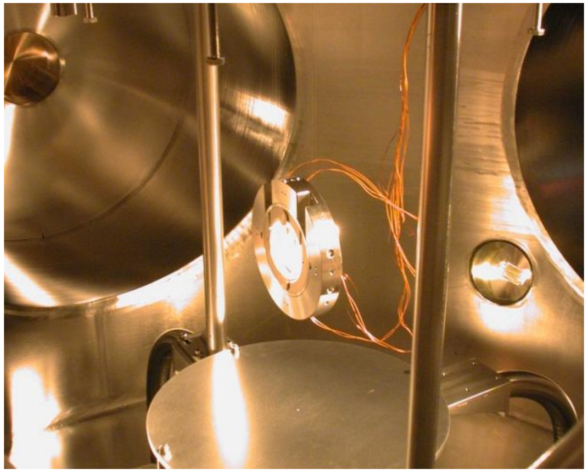
Marinebedrijf
Den Helder

Optical components – end mirror

- Input mode cleaner
  - IMC cavity: filters laser noise
  - Select TEM00 mode
  - New end mirror
    - Radiation pressure
    - Heavier mirror



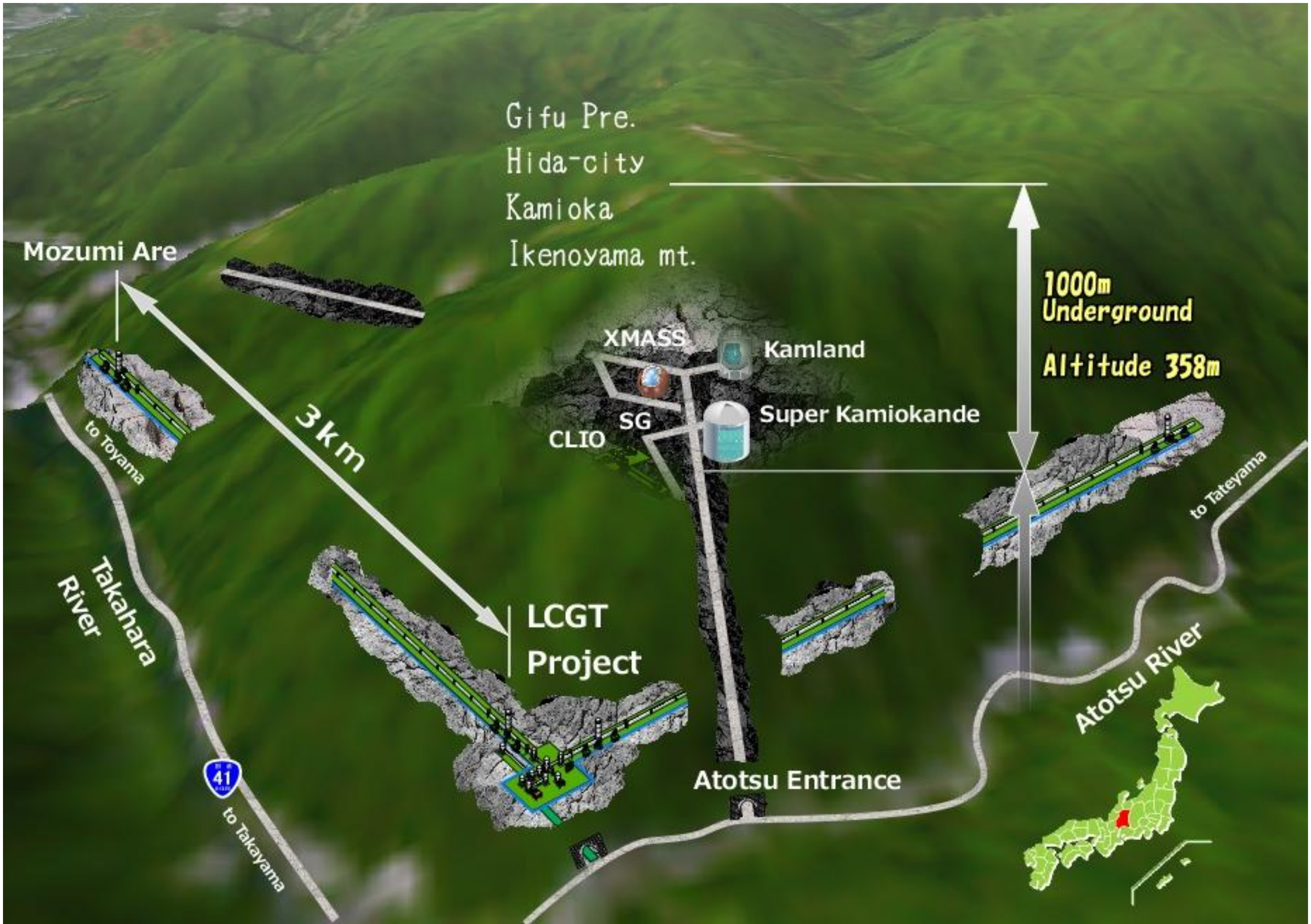




End mirror system for IMC

Other GW projects

Underground detector in Kamioka



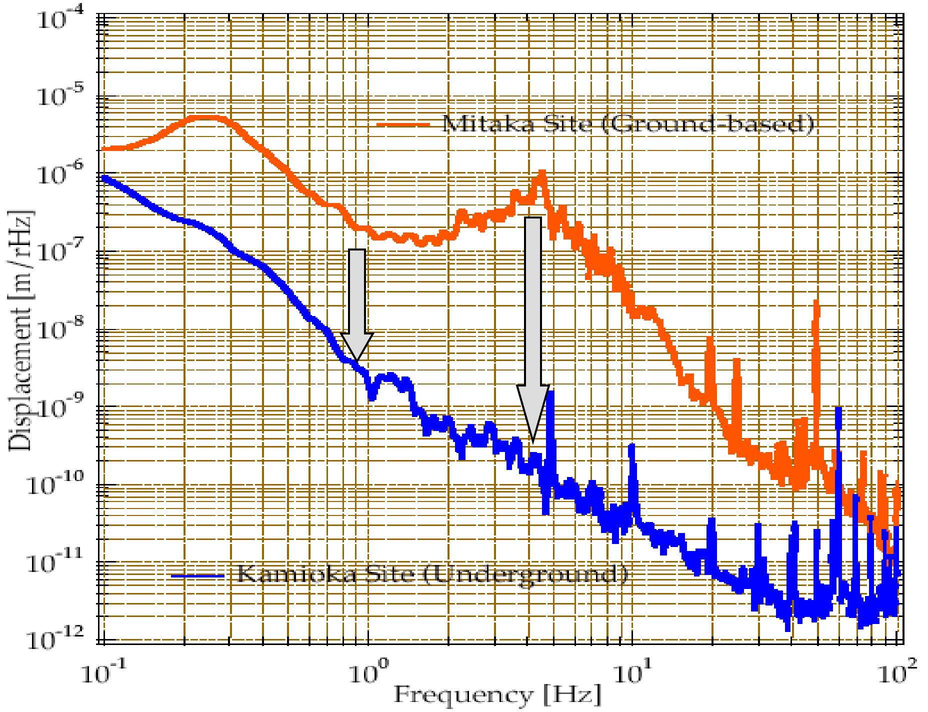
Experience: Japan

- 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)

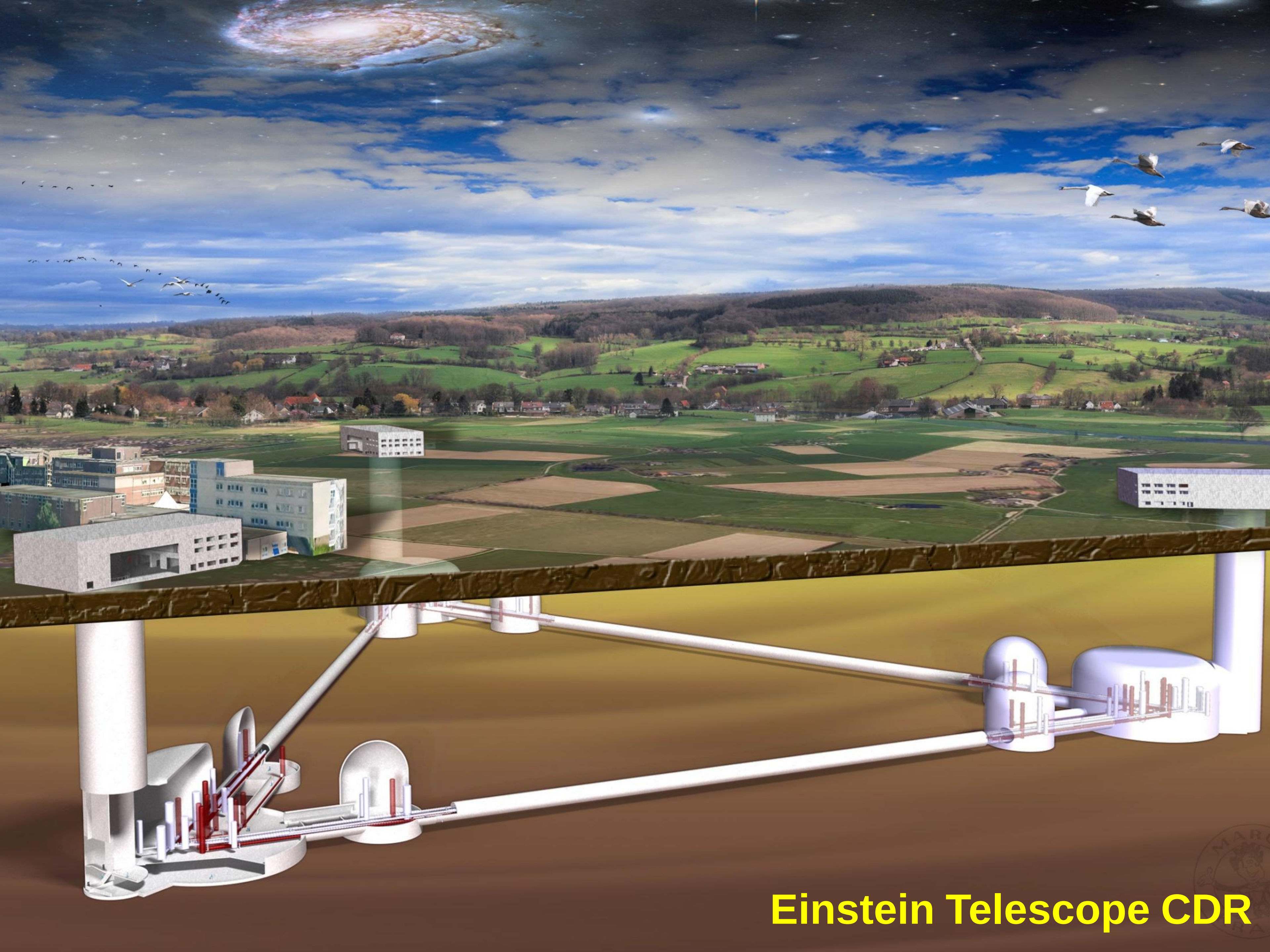


Design Study Proposal approved by EU within FP7

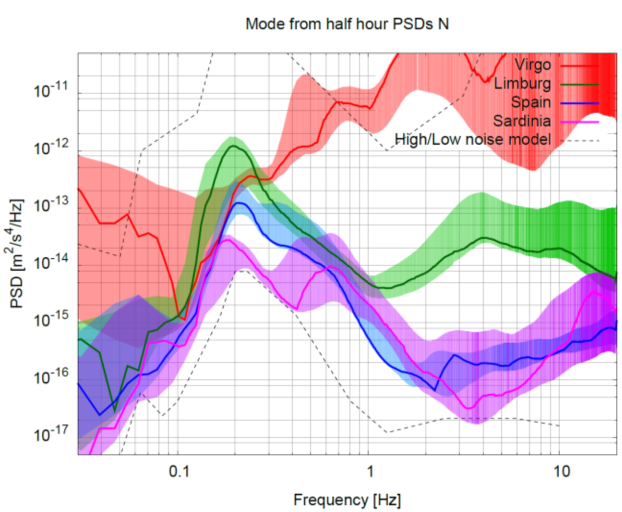
Large part of the European GW community involved

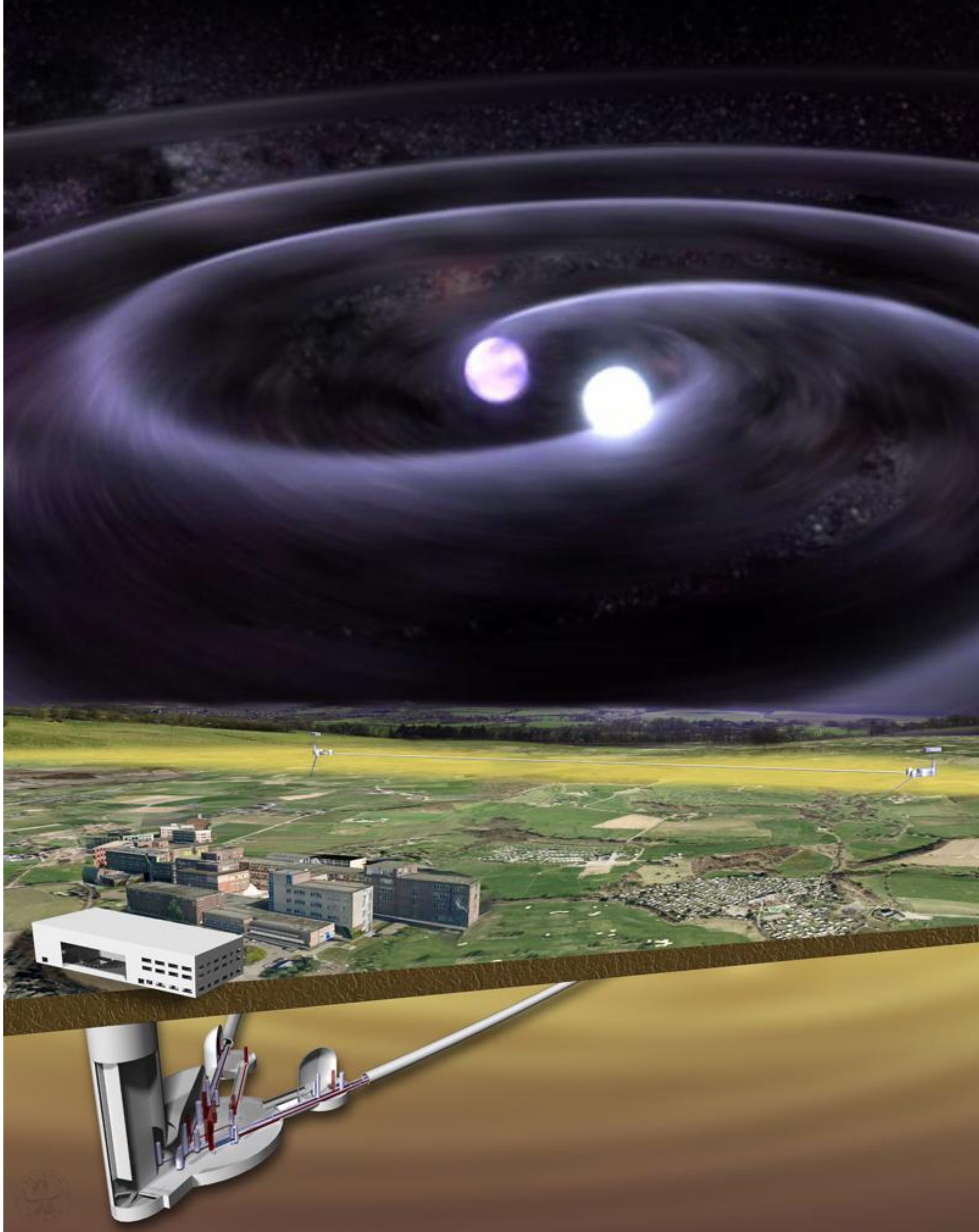
EGO, INFN, MPI, CNRS, Nikhef, Univ. Birmingham, Cardiff, Glasgow

Recommended in Aspera / Appec roadmap


Einstein Telescope CDR

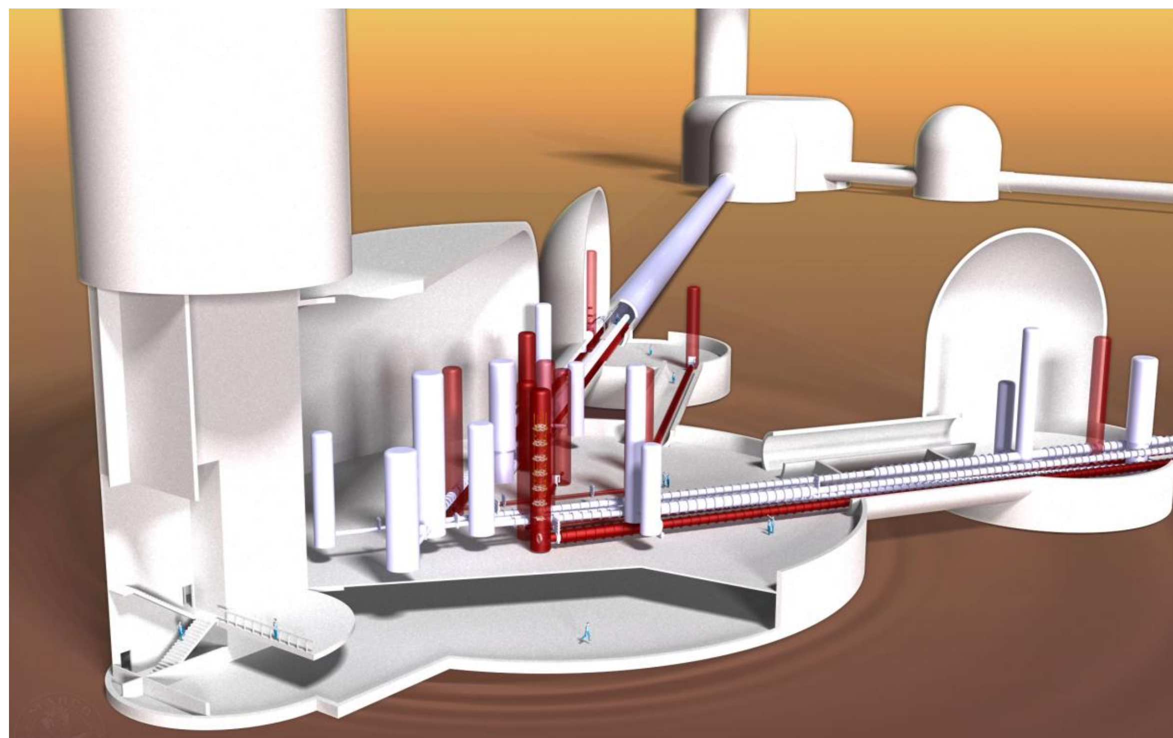
- Einstein Telescope
  - Triangular topology
  - Underground
    - Depth: 100 – 200 m
    - Gravity gradient noise
  - Cryogenic mirrors
  - 10 km arms
  - Xylophone detector
    - HF ITF
    - LF ITF
    - Up to 6 ITFs



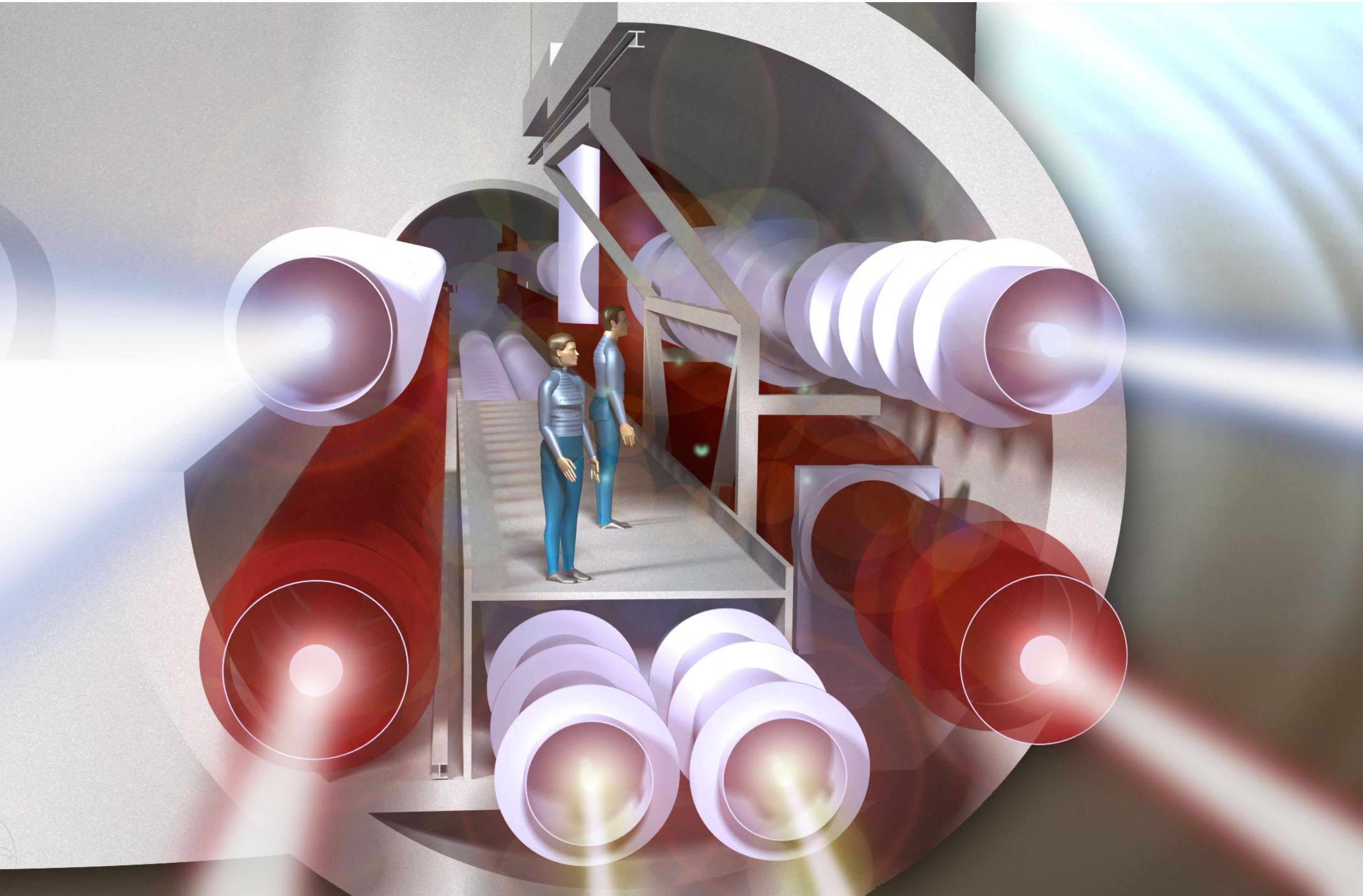


ET INFRASTRUCTURE

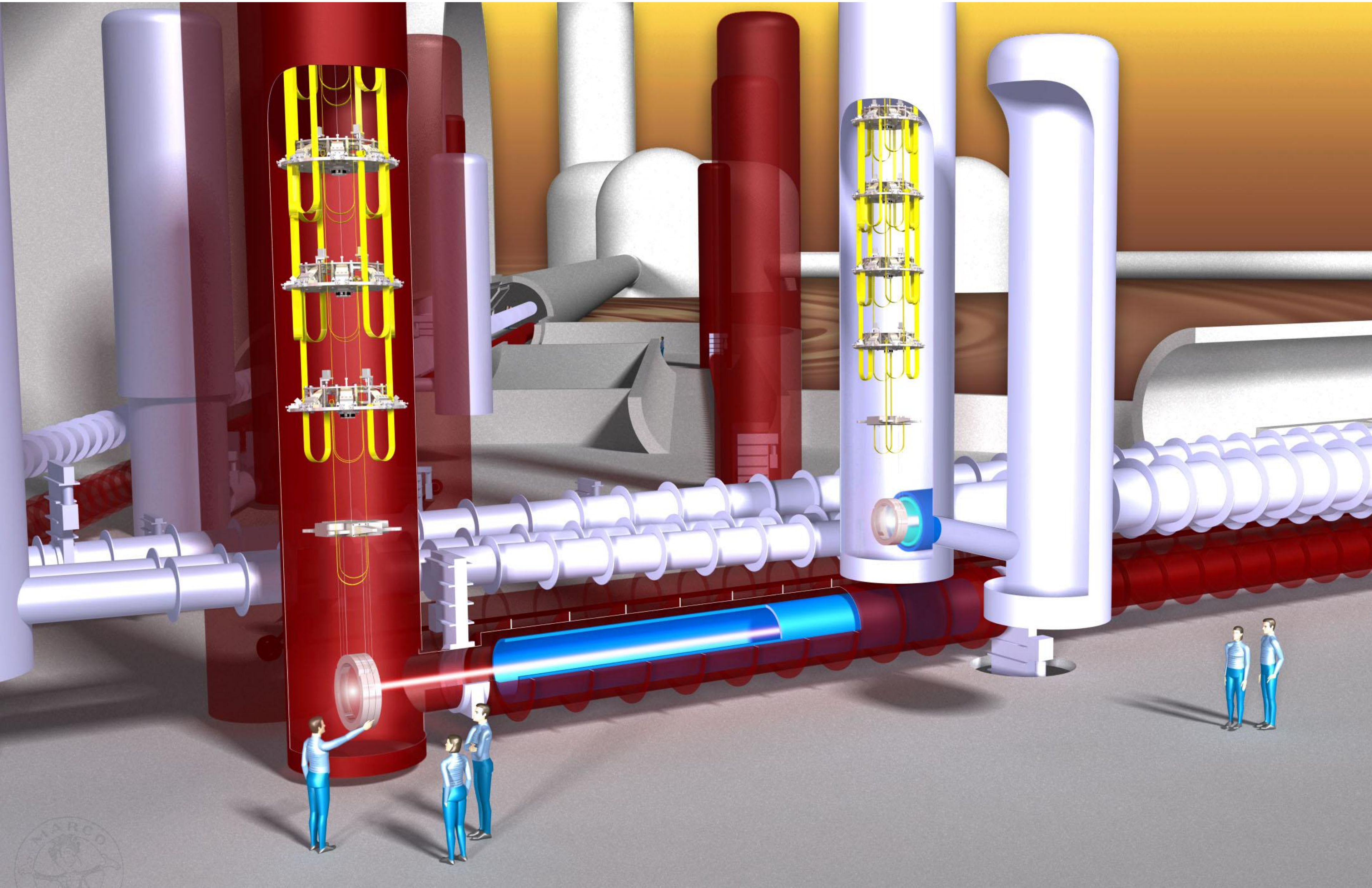
- Infrastructure: largest cost driver
  - Tunnels, caverns, buildings
  - Vacuum, cryogenics, safety systems
  - Collaborate with industry
    - COB (Amsterdam, October 9, 2008)
    - Saes Getters Italy
    - Demaco Netherlands
- Experience
  - LIGO, Virgo, GEO
  - Underground labs
    - Gran Sasso, Canfranc,
    - Kamioka, Dusel, etc.
  - Mines
  - Particle physics
    - ILC, Cern, Desy, FLNL
  - Seismology
    - KNMI, Orfeus
  - Geology



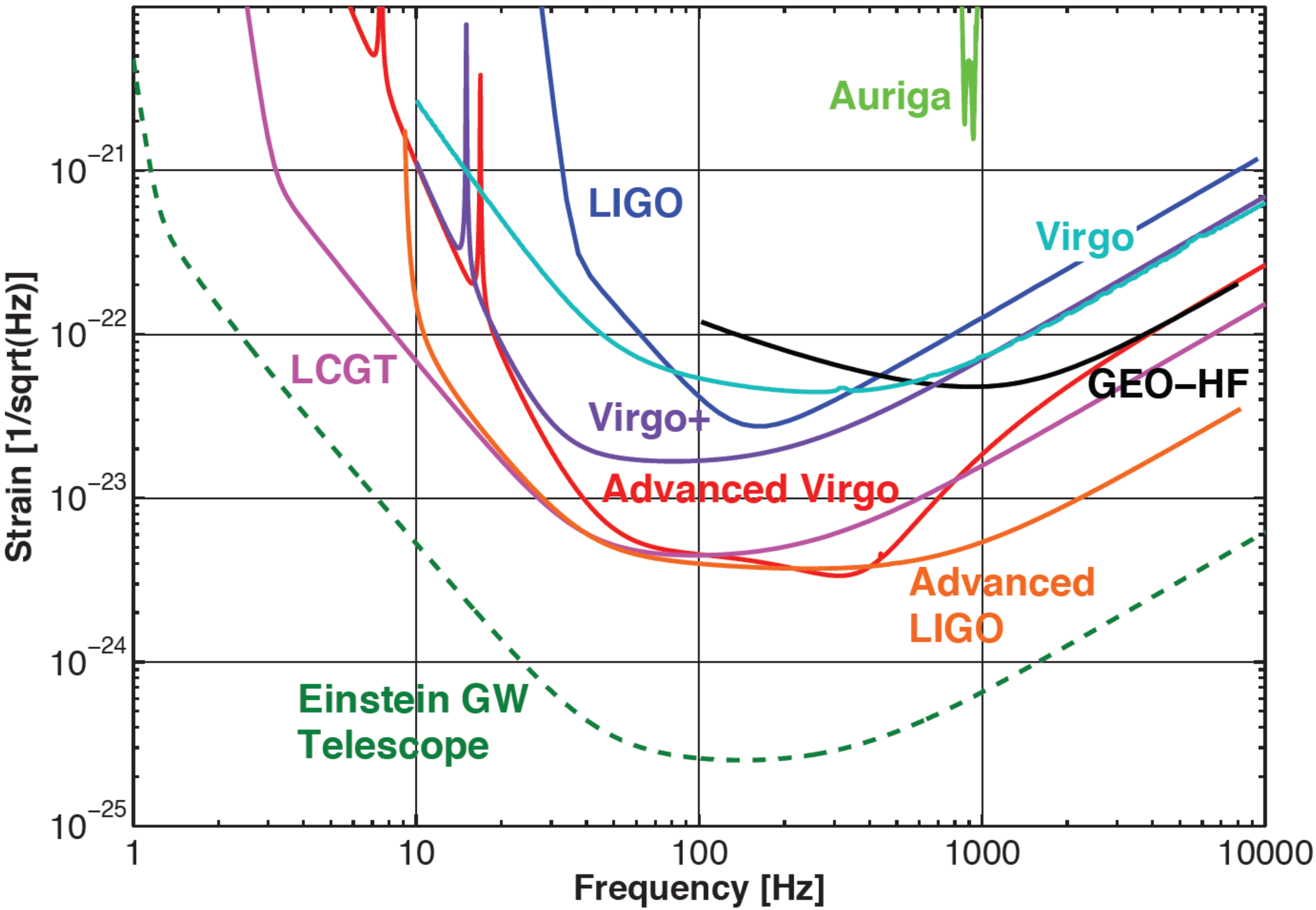
ET infrastructure



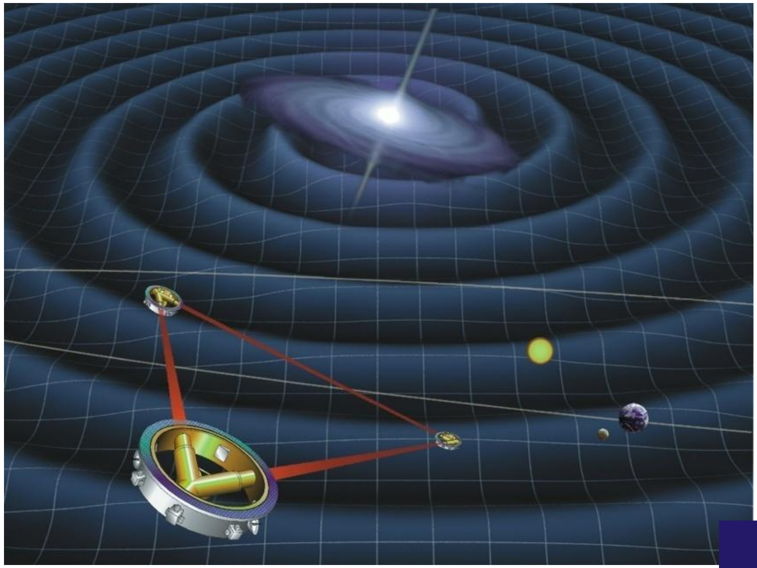
ET infrastructure



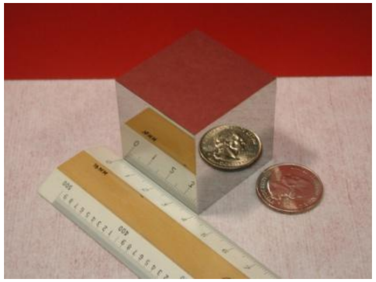
Expected future sensitivities

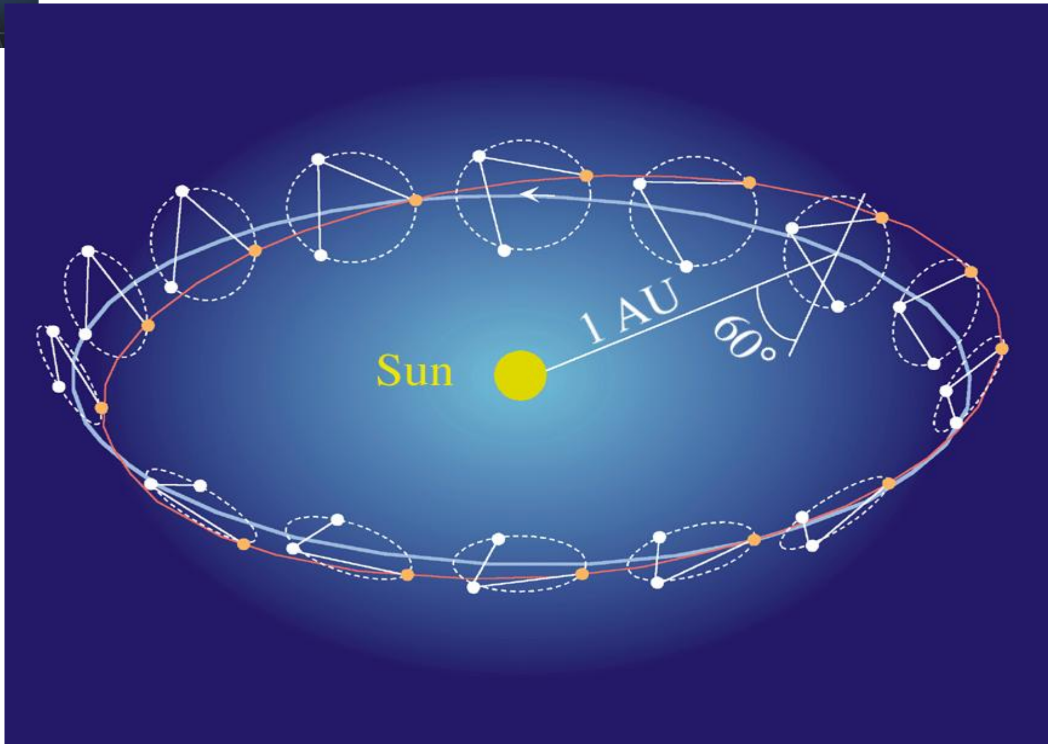


GW antenna in space - LISA



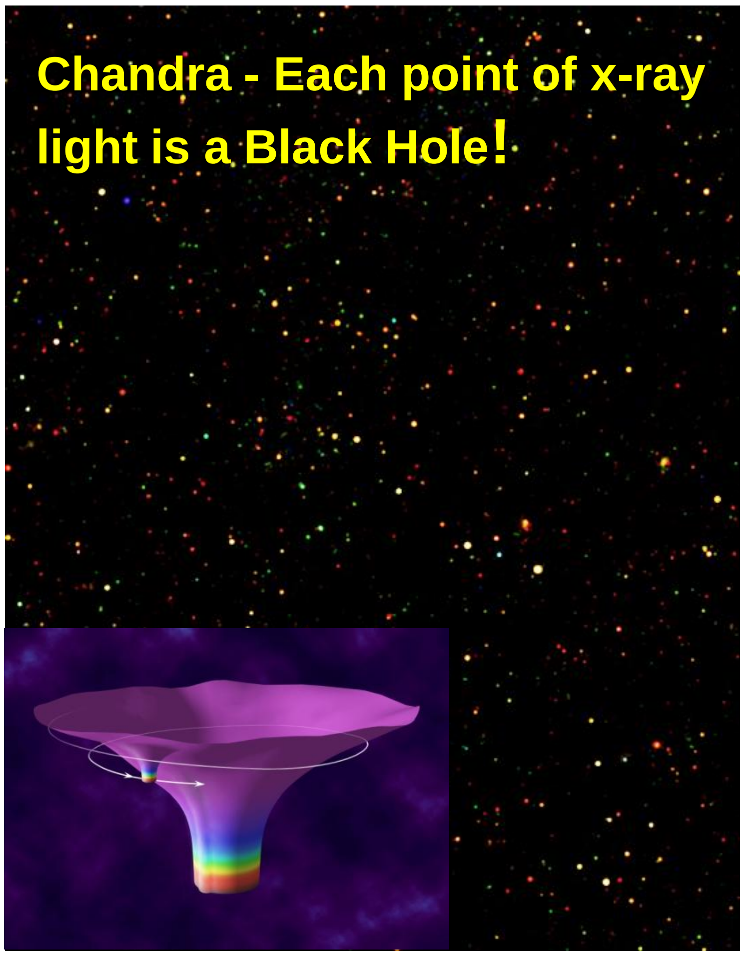
- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^{6} km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *Partnership between ~~NASA~~ and ESA*
- *Launch date >2020+*

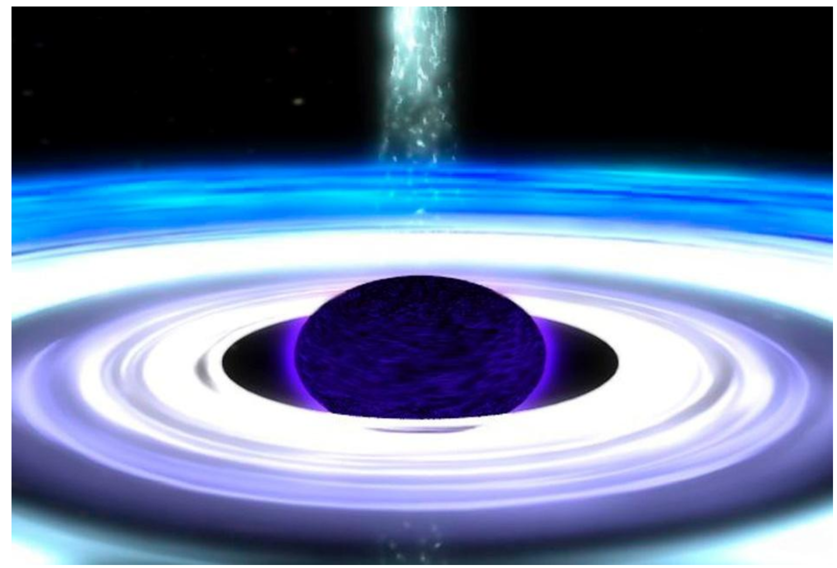




Science goals

What happens at the edge of a Black Hole?

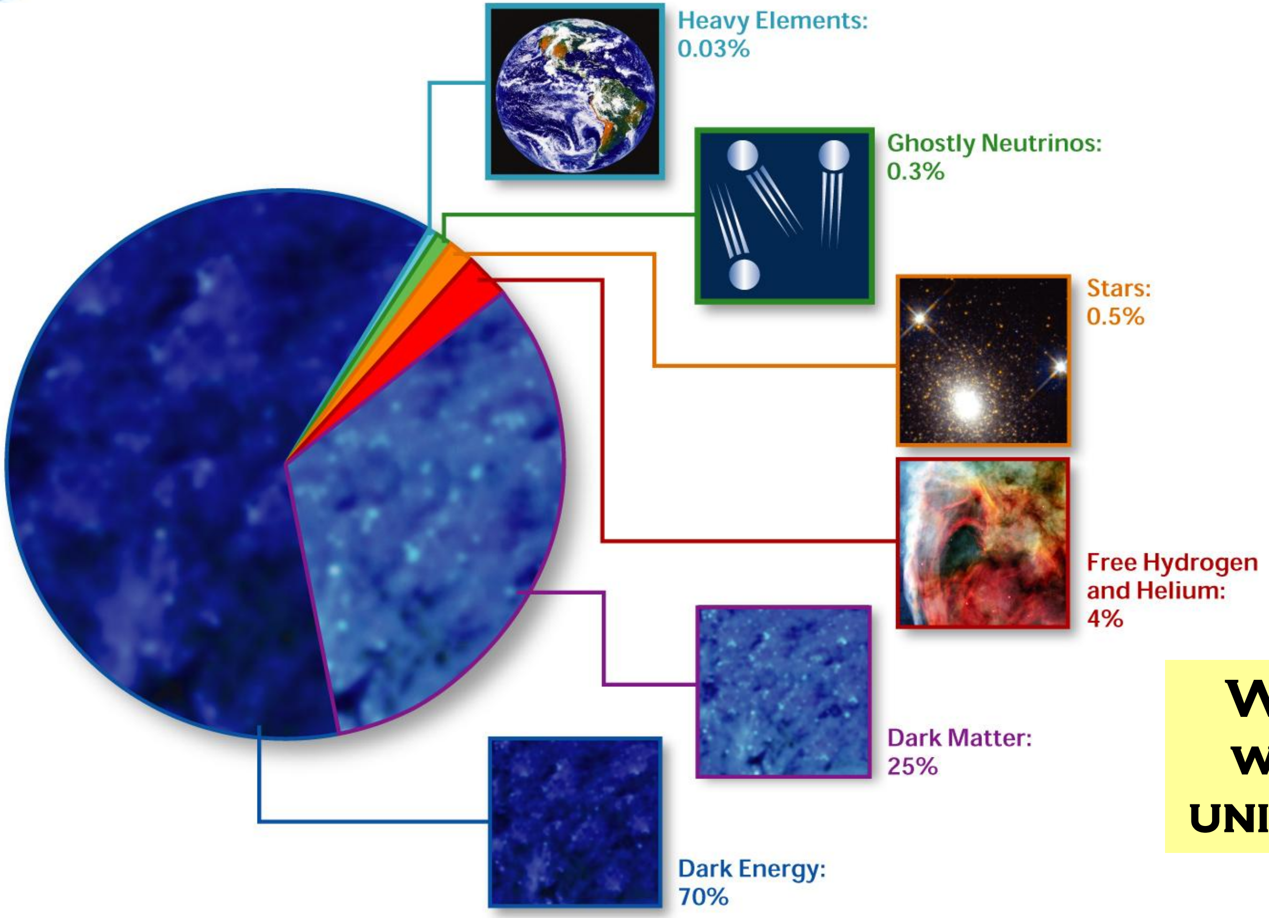




Is Einstein's theory still right in these conditions of extreme gravity? Or is new physics awaiting us?

Science goals

What is the mysterious Dark Energy pulling the Universe apart?

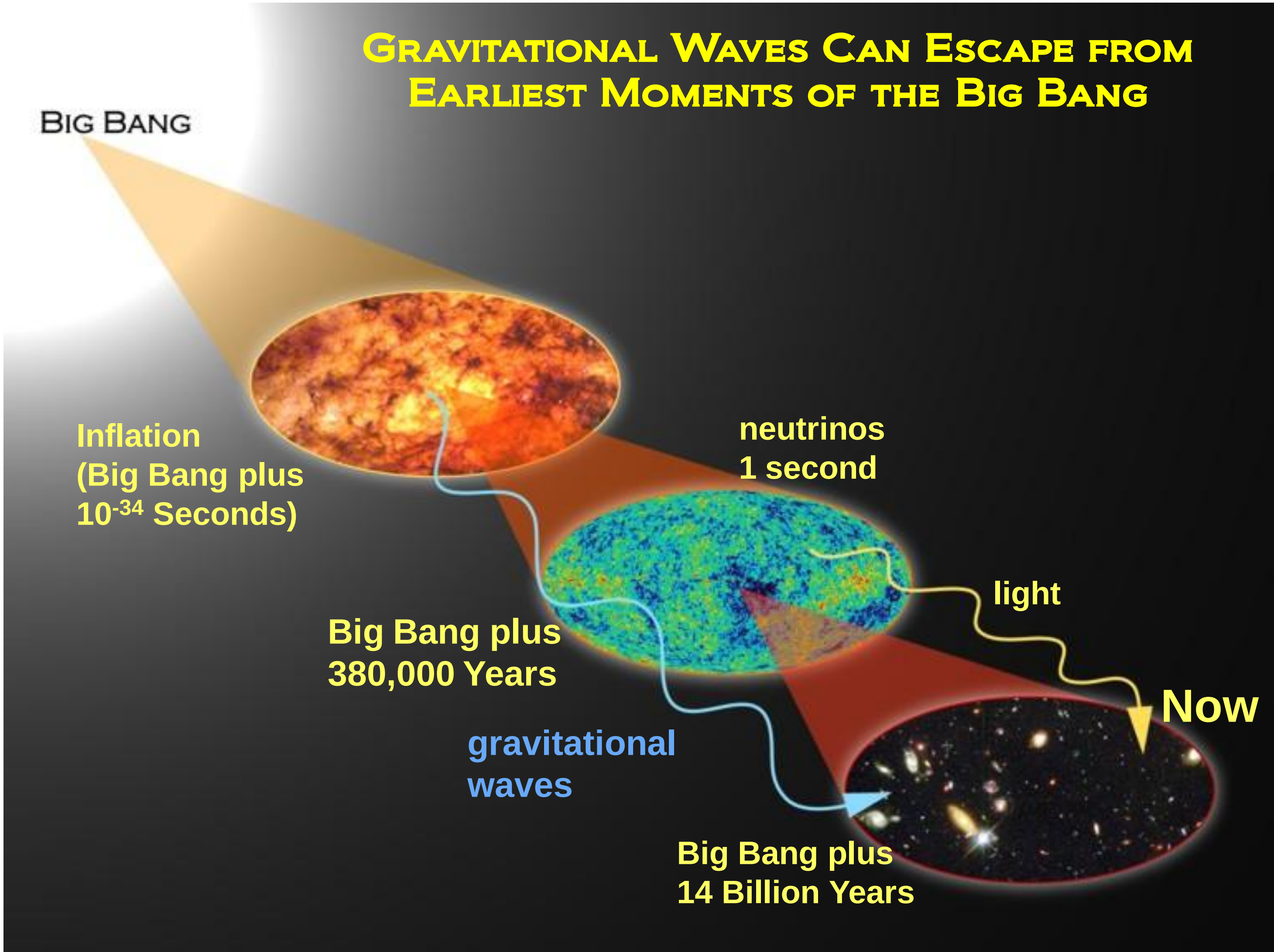


We do not know what 95% of the universe is made of!

Dark energy and matter interact through gravity

Science goals

What powered the Big Bang?



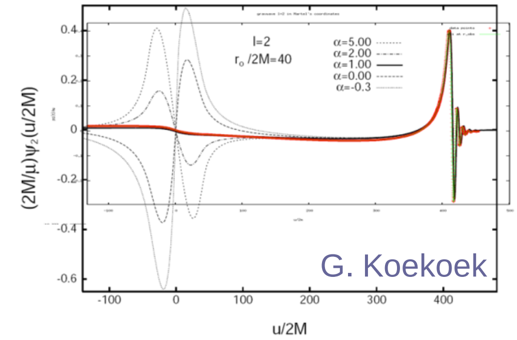
Nature 460, 990-994 (20 August 2009)

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

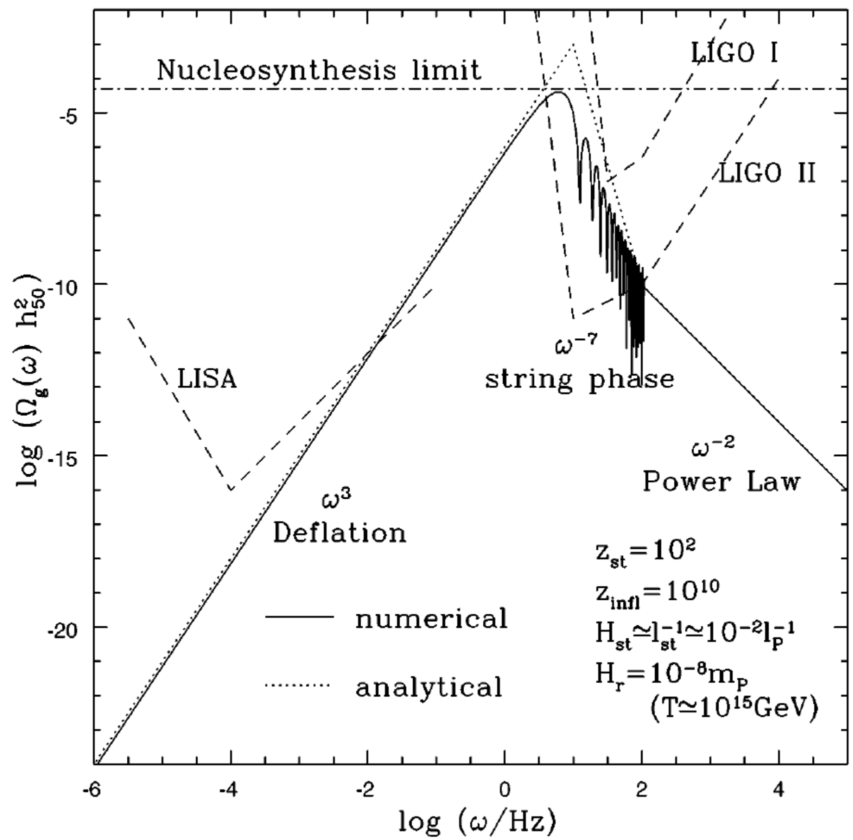
The LIGO Scientific Collaboration & The Virgo Collaboration

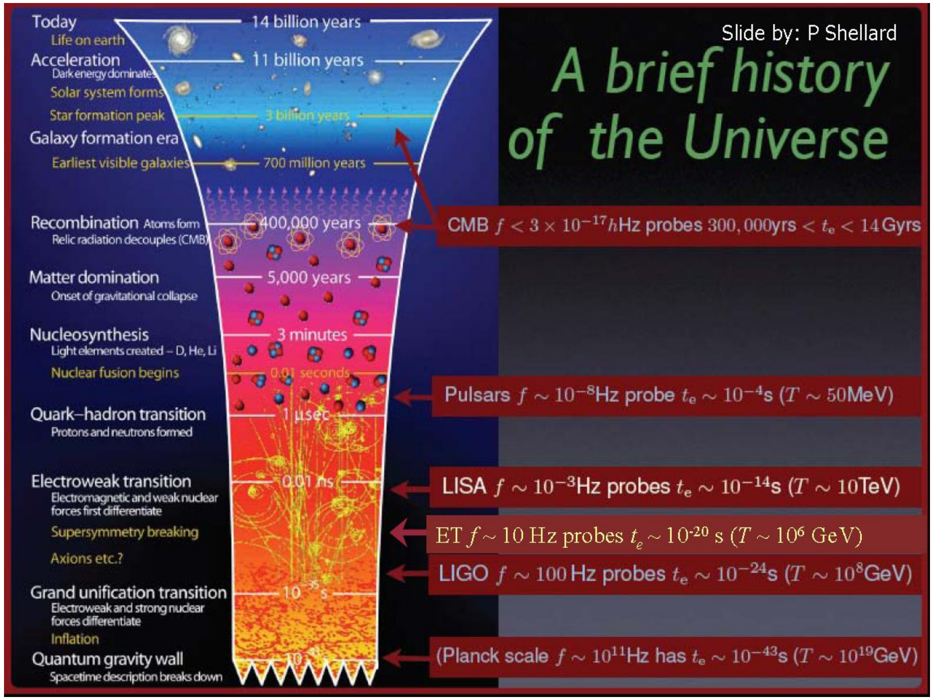
Inflation and phase transitions

- Theoretical (astro)particle physics community
  - GW, inflation, string theory, cosmic defects (M. Postma, Nikhef)
  - Jan Willem van Holten *et al.* (Nikhef, Leiden)
- Provide templates, spectra, *etc*.
  - Participate in Virgo – LIGO analysis



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





Summary

- Gravitational wave physics
  - Component of Dutch Astroparticle Physics initiative
  - Exciting new physics program
    - Important questions are addressed
    - Program with a long-term scientific perspective
- Virgo and LIGO
  - Sensitivity is improving fast
  - First science runs completed
  - Advanced detectors in preparation
- Future
  - Third-generation GW detector: Einstein Telescope
  - LISA: GW in space