Gravitational Wave Research
–Status and Perspectives-

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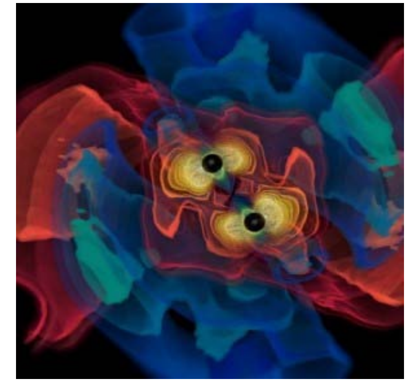
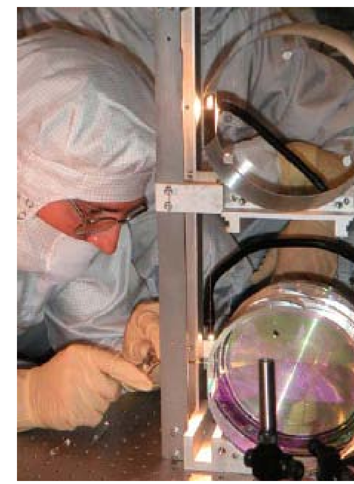
(Albert-Einstein-Institut)

Gravitational Wave Research

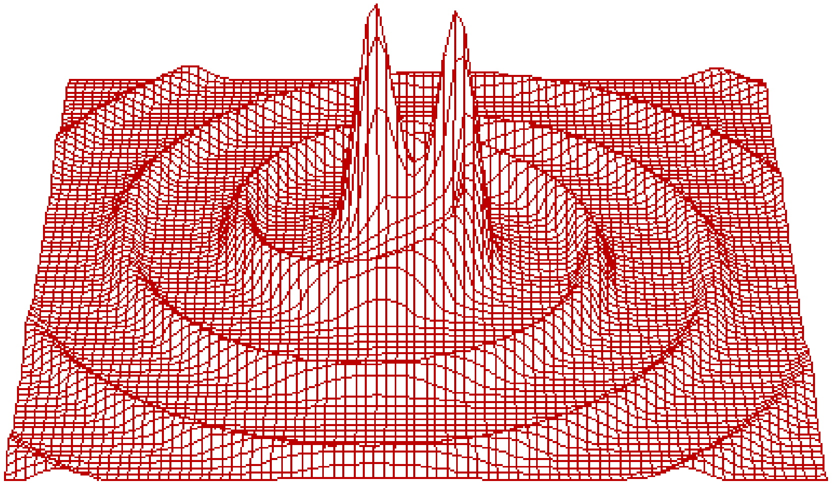
- astrophysical sources and their physics
- detection
  - laser technology and stabilization
  - thermal noise in mechanical systems
  - quantum optics – squeezing
  - interferometry
  - seismic isolation and gravity gradient
  - optical elements and scattering control
  - cryogenic low noise environment
  - drag free satellites, interferometry in space
- data analysis
  - data analysis algorithm
  - computer science

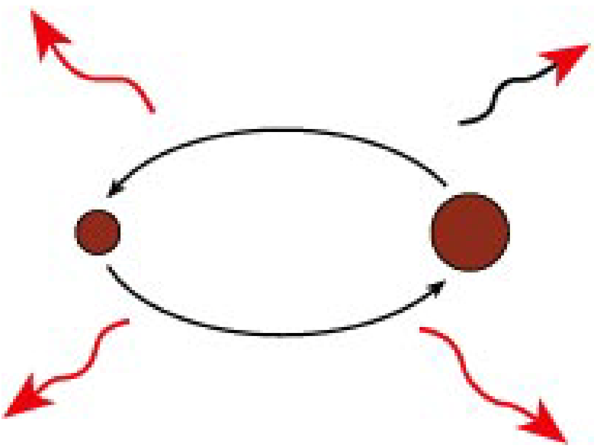


Credit: AEI, CCT, LSU



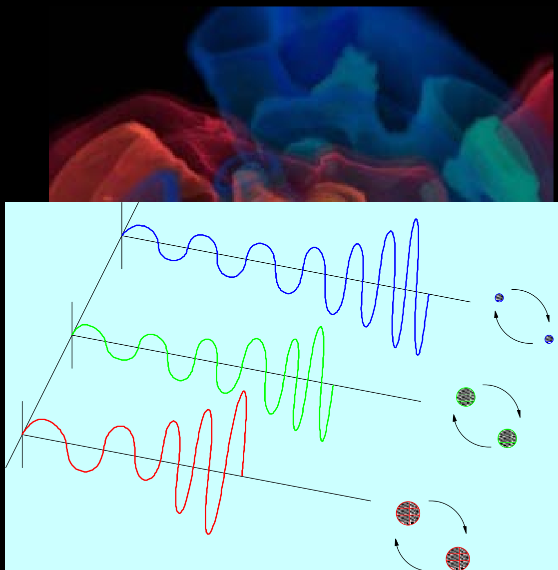
What are Gravitational Waves ?





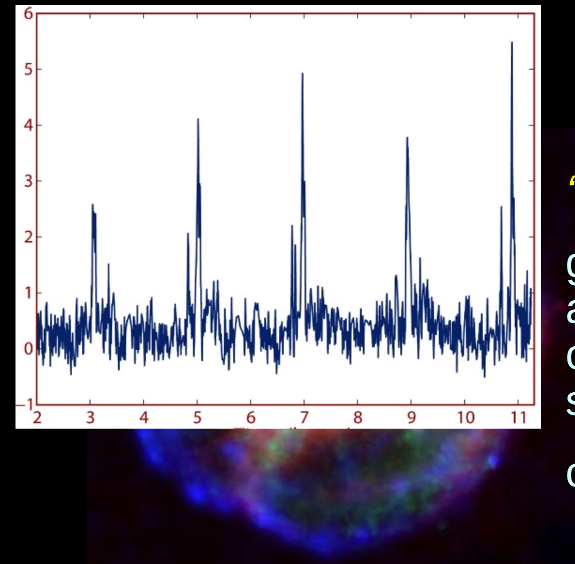
- Einsteins equation in vacuum allows for
  - transverse quadrupole waves
  - that travel at the speed of light
  - collinear with a photon
  - without dispersion
- sources are accelerated mass distributions

Potential Sources of Gravitational Waves



Coalescing Binary Systems

Neutron stars, low mass black holes, NS/BS systems



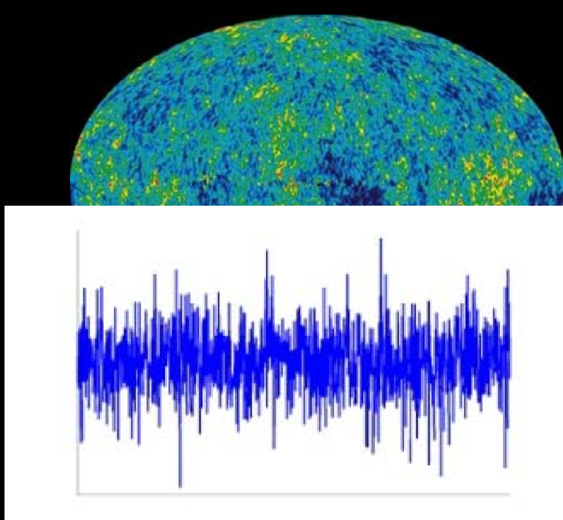
Credit: Chandra X-ray Observatory

'Bursts'

galactic asymmetric core collapse supernovae,

cosmic strings

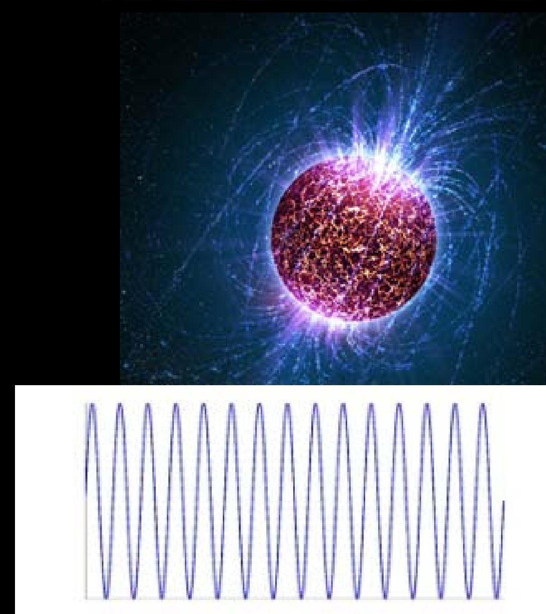
???



Cosmic GW background

stochastic, incoherent background

unlikely to detect, but can bound in the 10-10000 Hz range



Continuous Sources

Spinning neutron stars, normal modes of NS

probe crustal deformations, 'quarki-ness'

scientific questions

Fundamental physics and ge

- What are the propert
- Is general relativity t
- Is general relativity s
- Are Nature's bla
- How does matte

Is general relativity the correct theory of gravity?

Are Nature's black holes the black holes of general relativity?

Cosmology

- What is the h
- Were there p

Were there phase transitions in the early Universe?

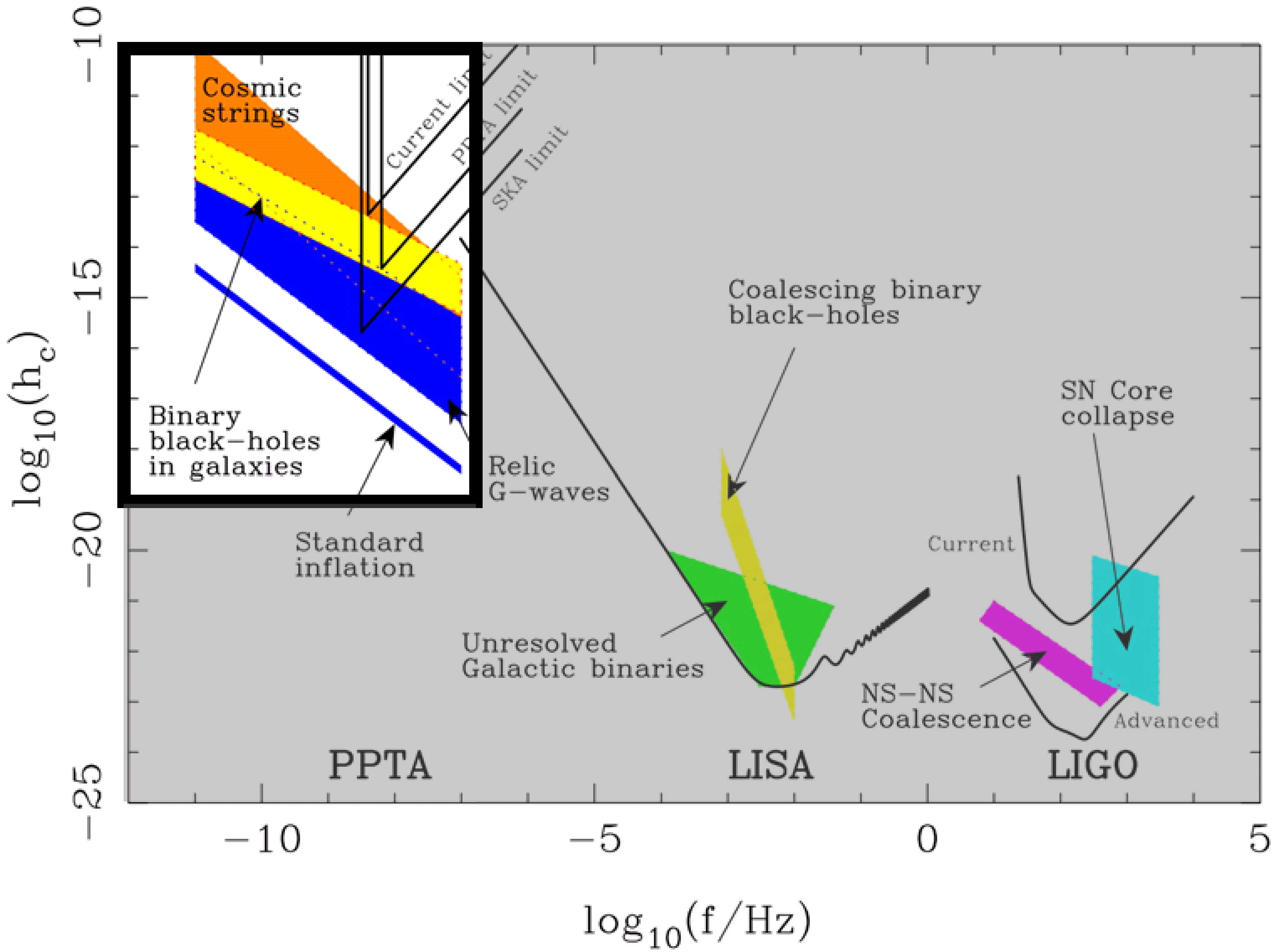
Astronomy and astrop

- How abundant
- What is the ce
- Do intermedia
- Where and wh are they conne
- What happens
- Do spinning ne
- What is the dist
- How massive ca
- What makes a pulsar glitch?
- What causes intense flashes of X- and gamma-ray radiation in magnetars?
- What is the history of star formation rate in the Universe?

Do intermediate mass black holes exist?

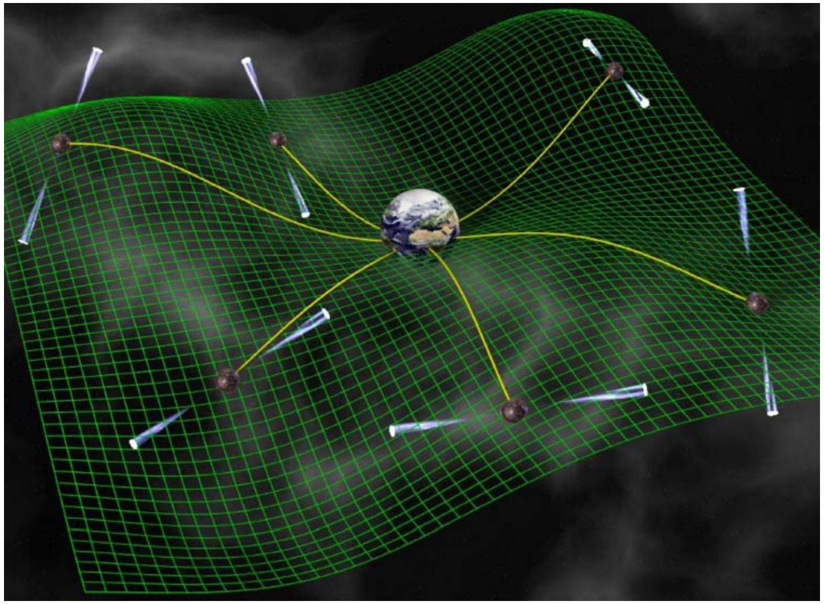
What happens if a massive star collapses?

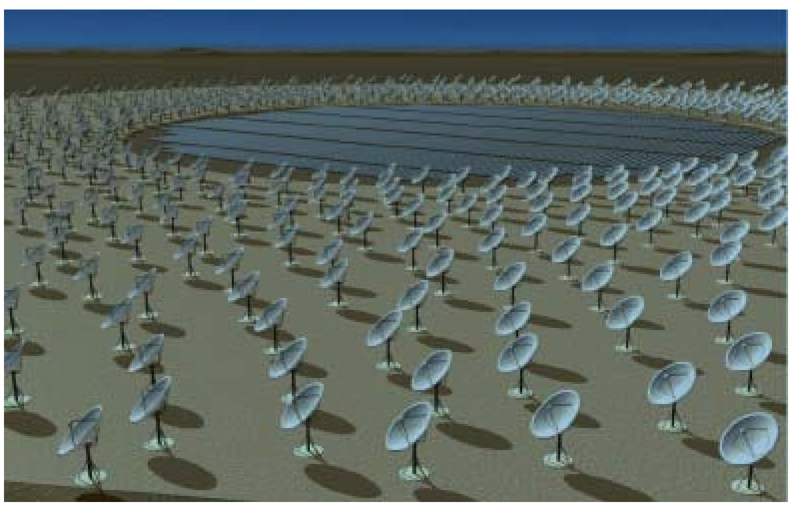
The Gravitational Wave Spectrum



Hobbs et al., 2009

pulsar timing





- time of arrival (TOA) of pulses is very regular
- TOA residuals depend on GW at source and detector
- correlation in TOA residual from different pulsars
  $\rightarrow$ Gravitational Wave
- required timing accuracy: several 100 ns over years

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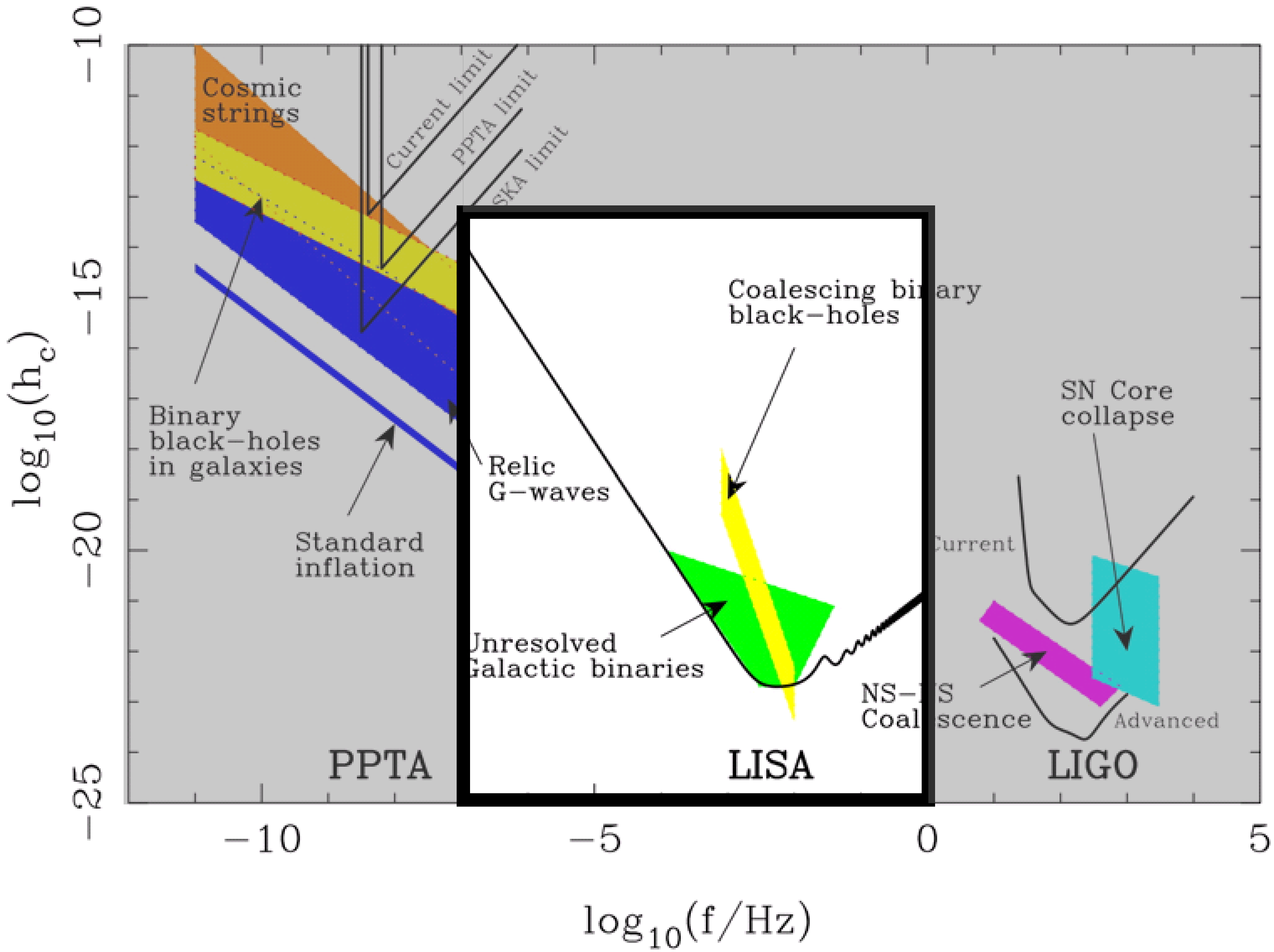
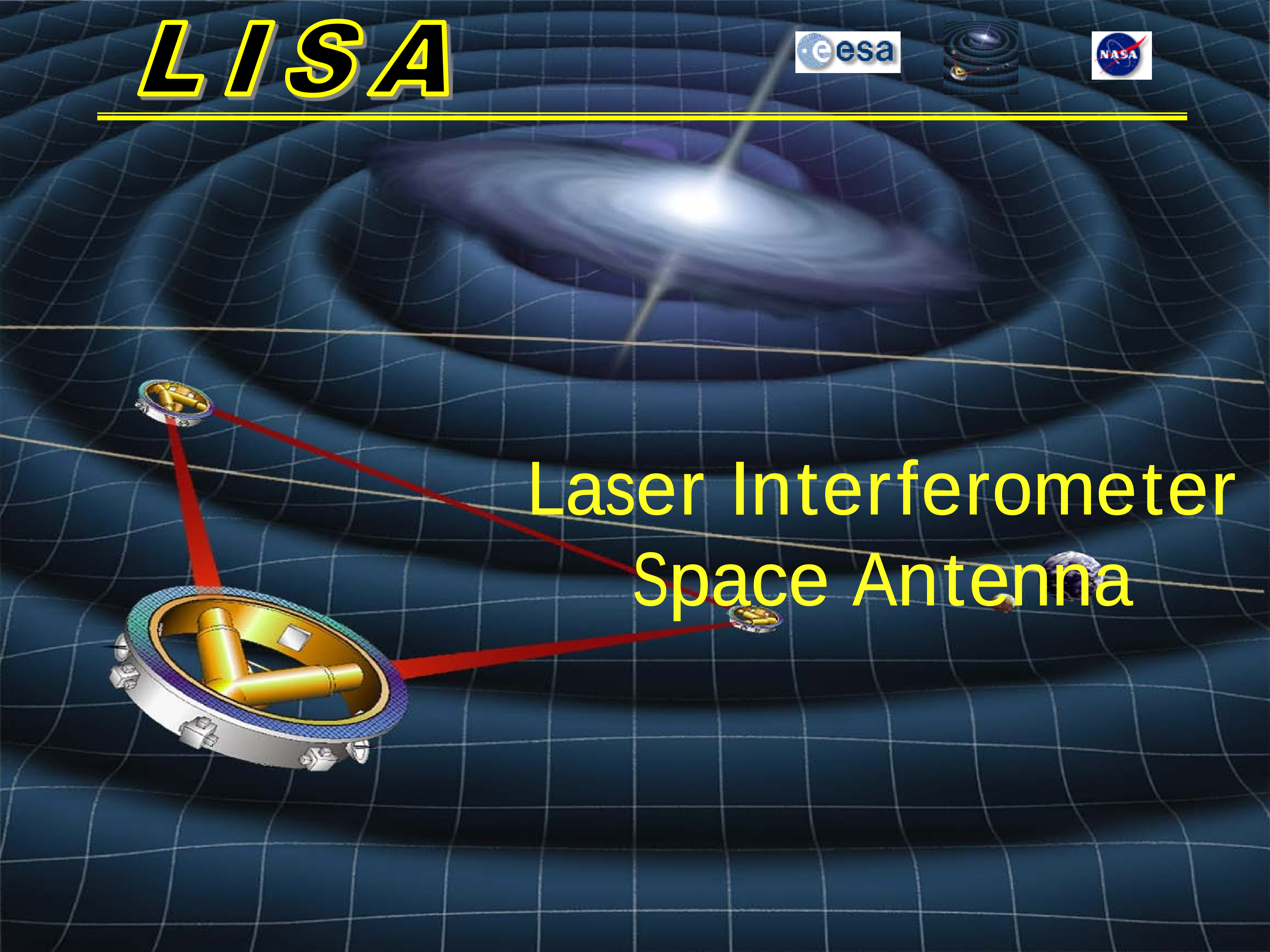
pictures from www.nanograv.org

The Gravitational Wave Spectrum

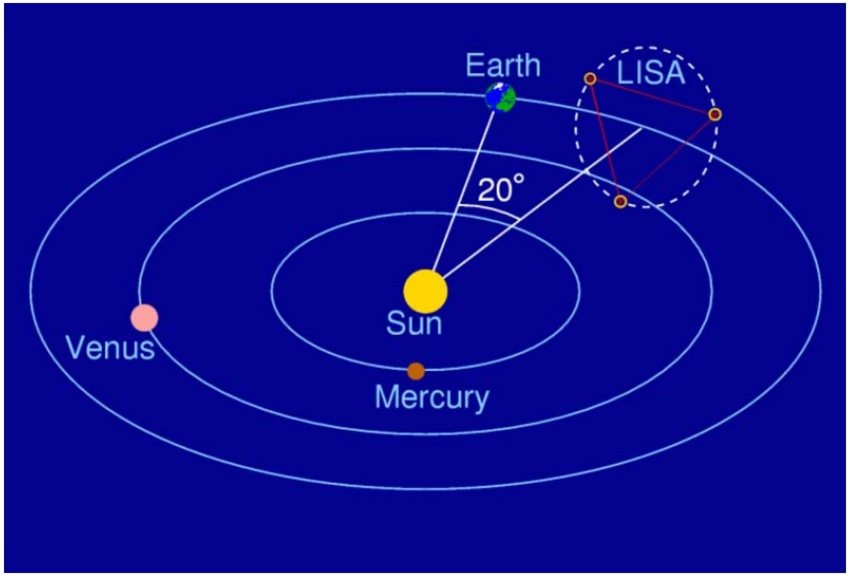


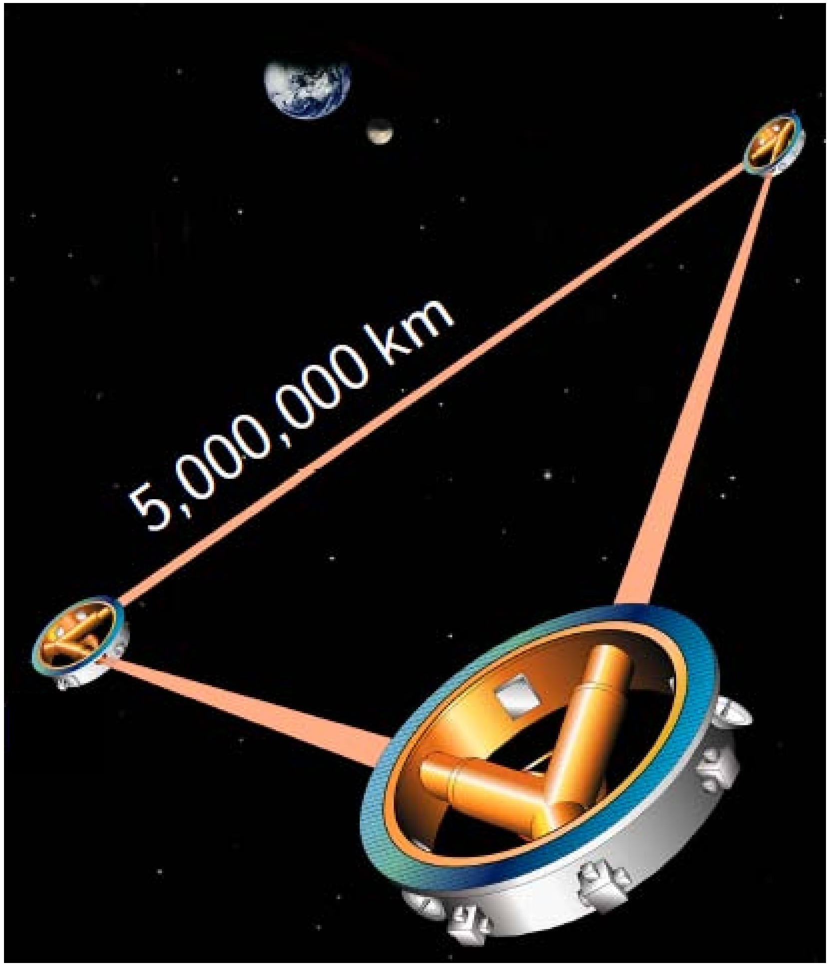
Hobbs et al., 2009


LISA
Laser Interferometer Space Antenna

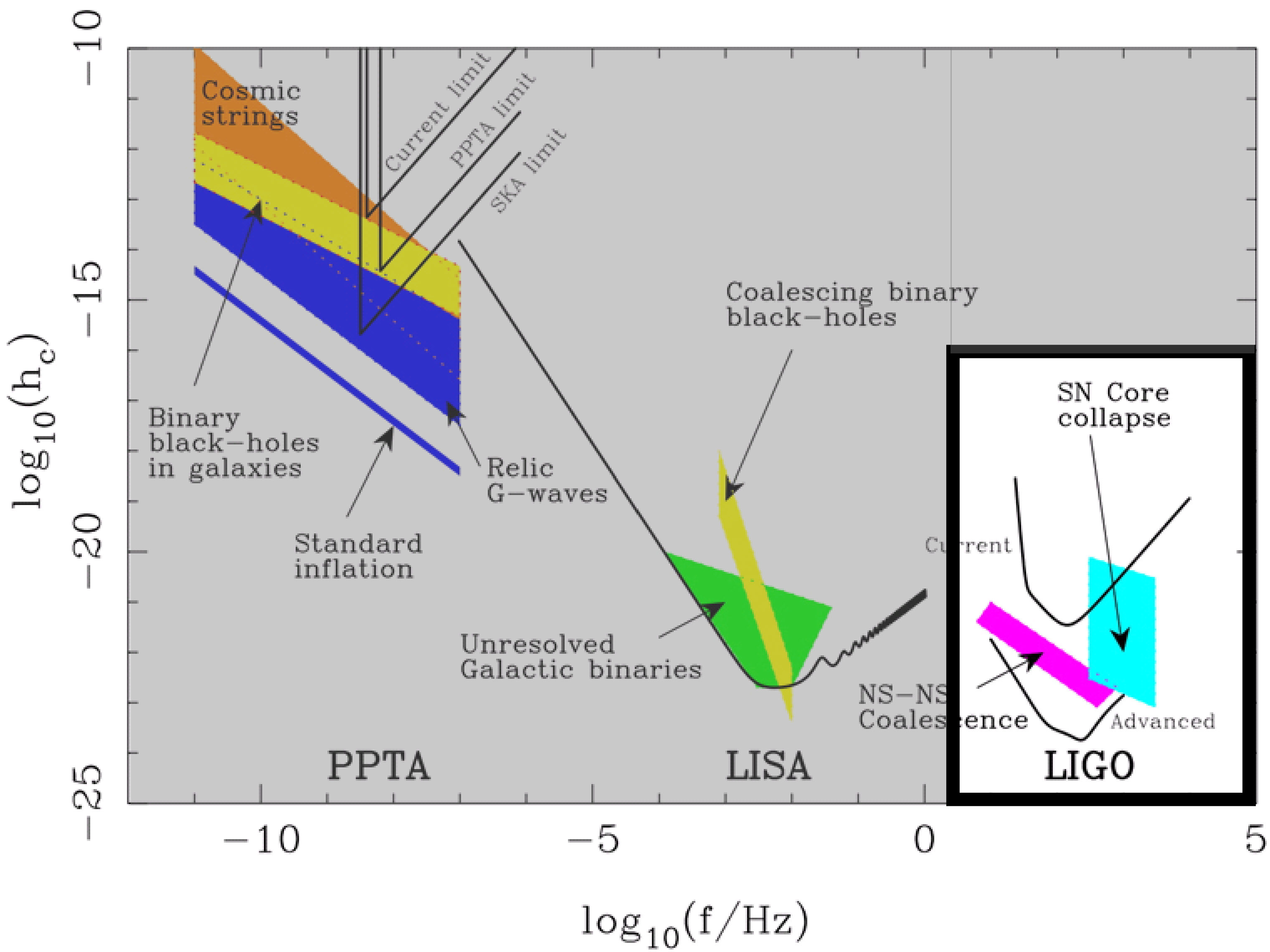
LISA Lay-Out

- cluster of 3 satellites in heliocentric orbit
- 20 ° (50 Mio km) behind earth
- Triangle with 5 Mio km arms
- Inclined 60 ° against ecliptic





The Gravitational Wave Spectrum

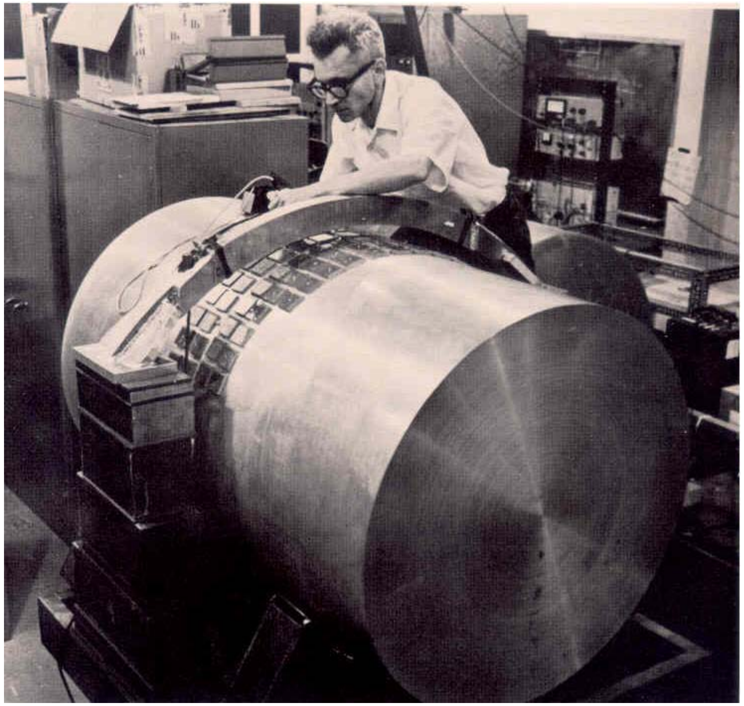


Hobbs et al., 2009

“Weber bars”

Joseph Weber (1919 – 2000)

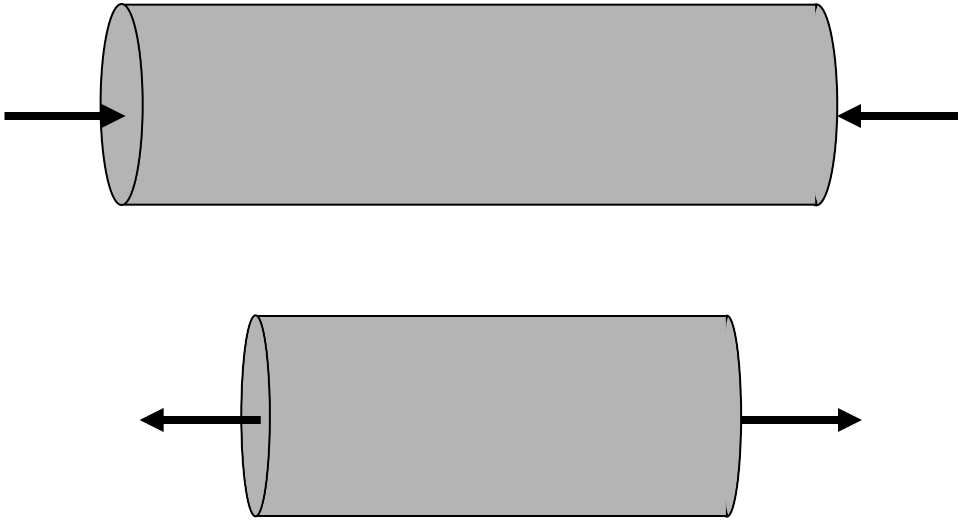
Pioneer of gravitational-wave detection:

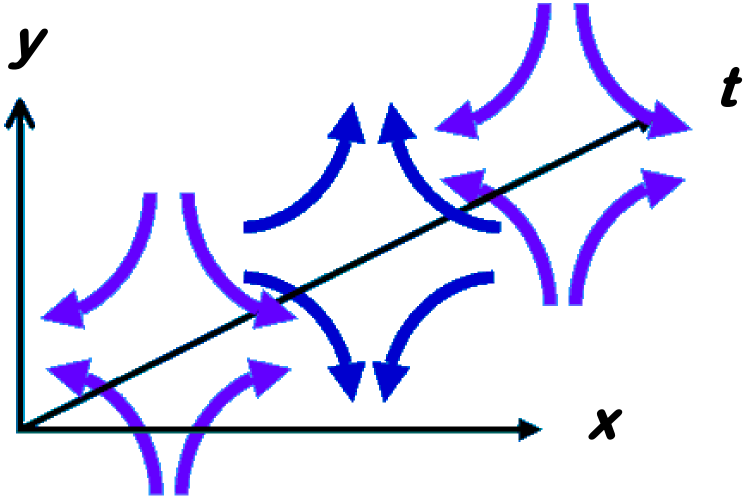


Resonant mass antenna („Weber bar“)

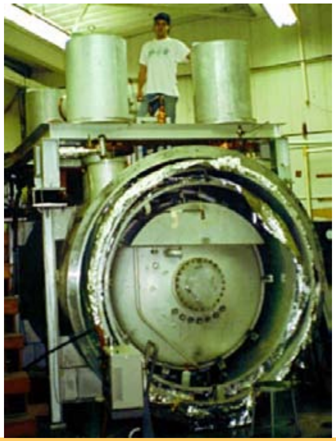
Effect of a GW on an elastic solid body

The gravitational wave acts like a tidal force across an extended object (i.e. they strech and compress it).





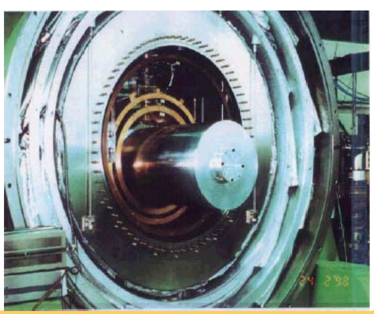
Resonant Bar Detectors



ALLEGRO
Baton Rouge, LSU (USA)

AURIGA
Legnaro, INFN (Italy)

EXPLORER
Geneva, CERN, INFN (Switzerland)

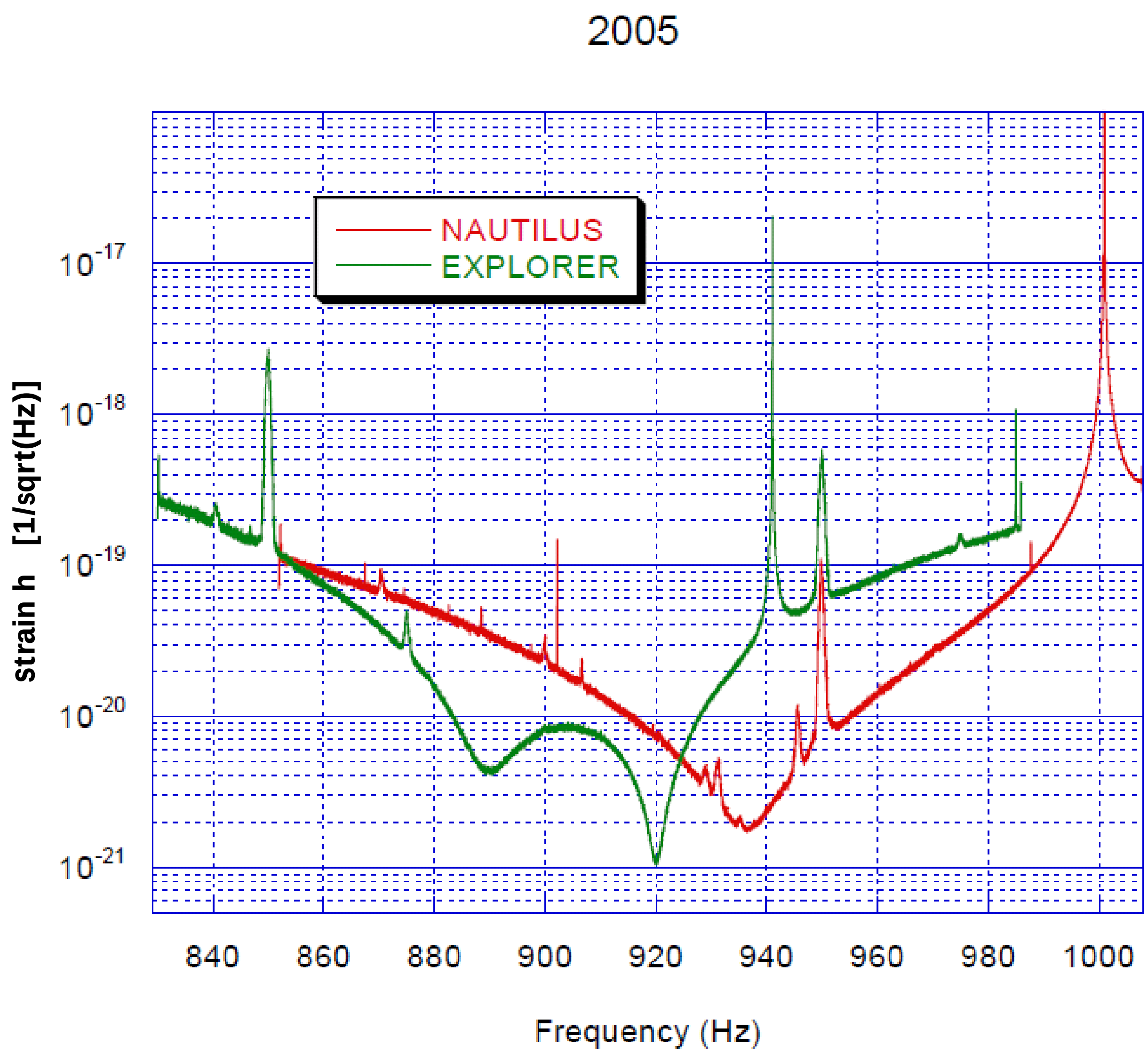


NAUTILUS
Frascati, INFN (Italy)

M **~ a few tons**
L **~ 3 m**
f **~ 900 Hz**

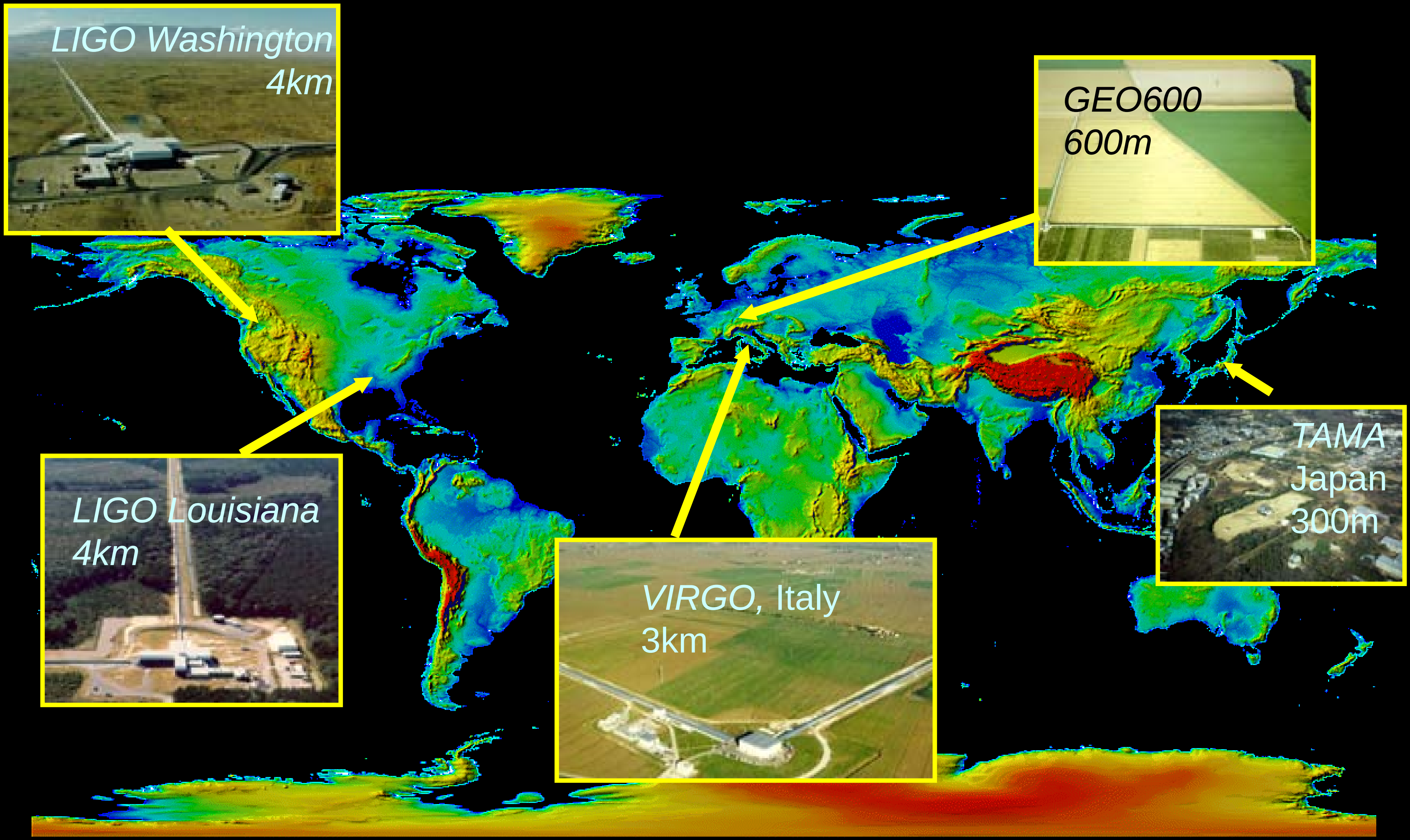
NIOBE
Perth, UWA (Australia)

Sensitivity Resonant Bar GWDs



source: E. *Coccia, Amaldi 6, Okinawa (2005)*

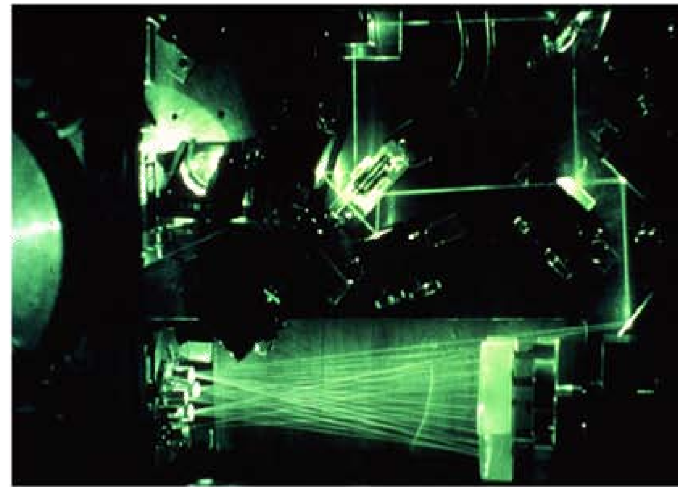
Today: The Global Network of Gravitational Wave Interferometers

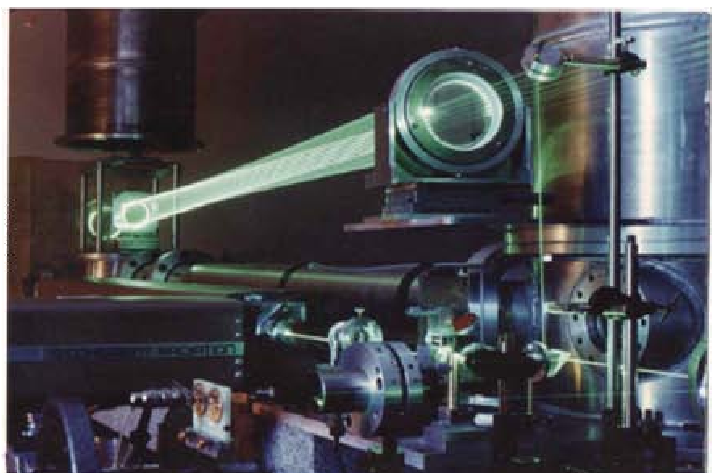


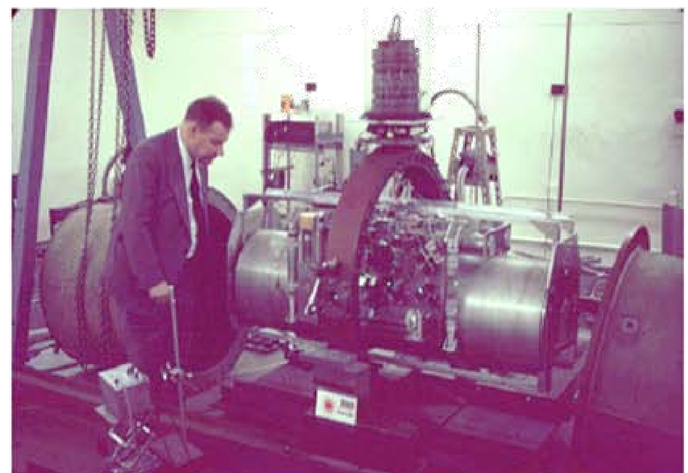
European Interferometer Prototypes

Garching MPA/MPQ

Glasgow





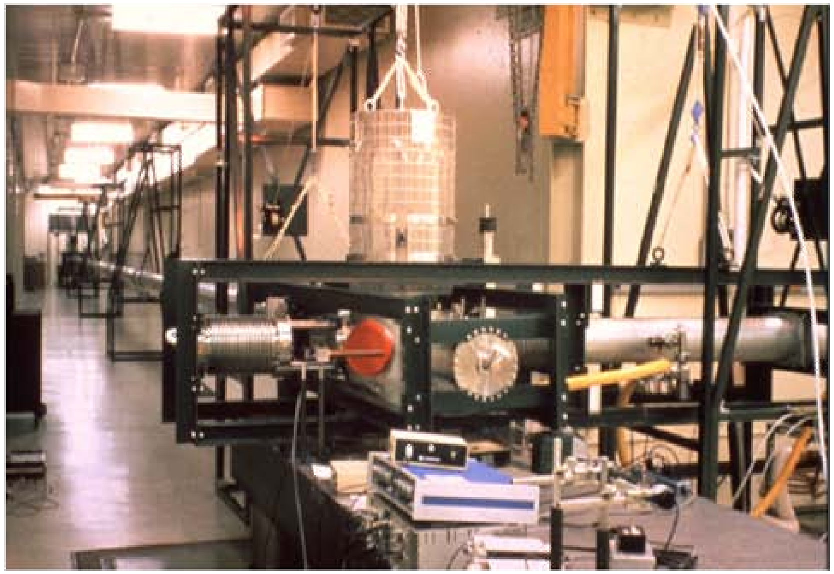


Garching 3m, Glasgow 1m – late 70s early 80s

Bigger Prototypes in 1980s

Garching 30m

Glasgow 10m



Caltech 40m

The GEO600 Project

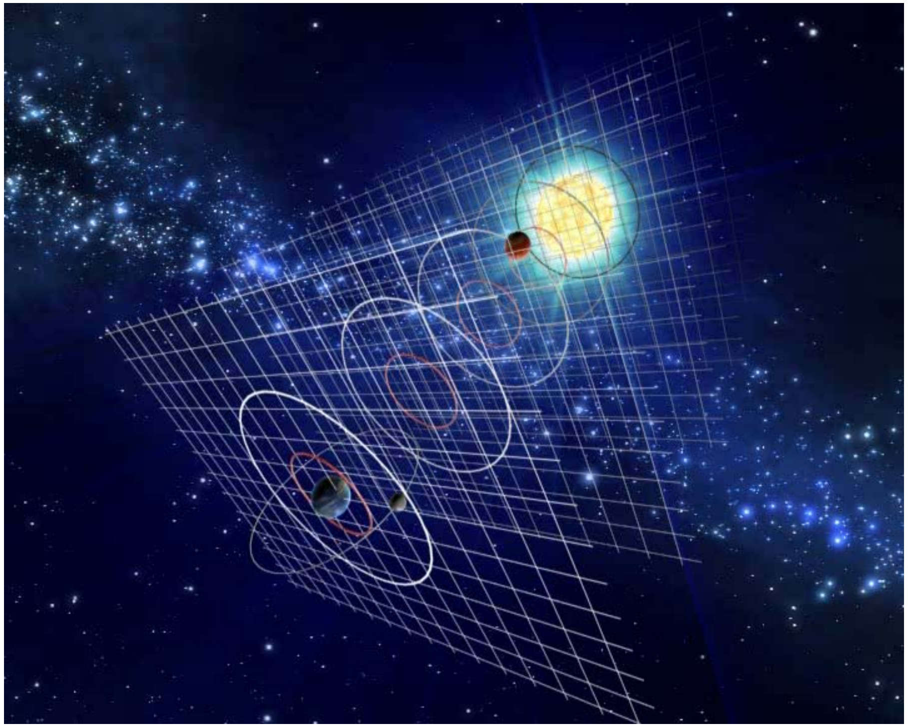
- German-British collaboration, location Hannover / Germany
- Michelson Interferometer with power- and signal-recycling (folded 600m long arms, no armcavities)

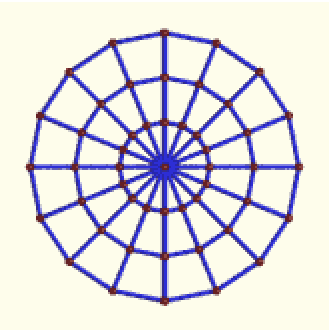
U Birmingham
U Mallorca

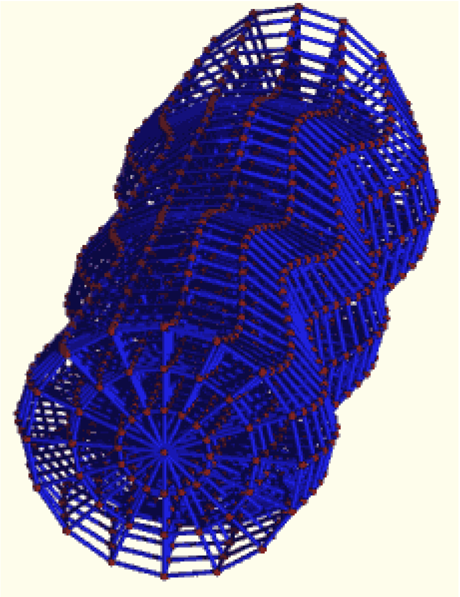
Glasgow

Action of a Gravitational Wave

GWs change the geometry of spacetime and thus the proper distances between objects therein.







GWs cause force on free test mass B in local inertial frame of test mass A.

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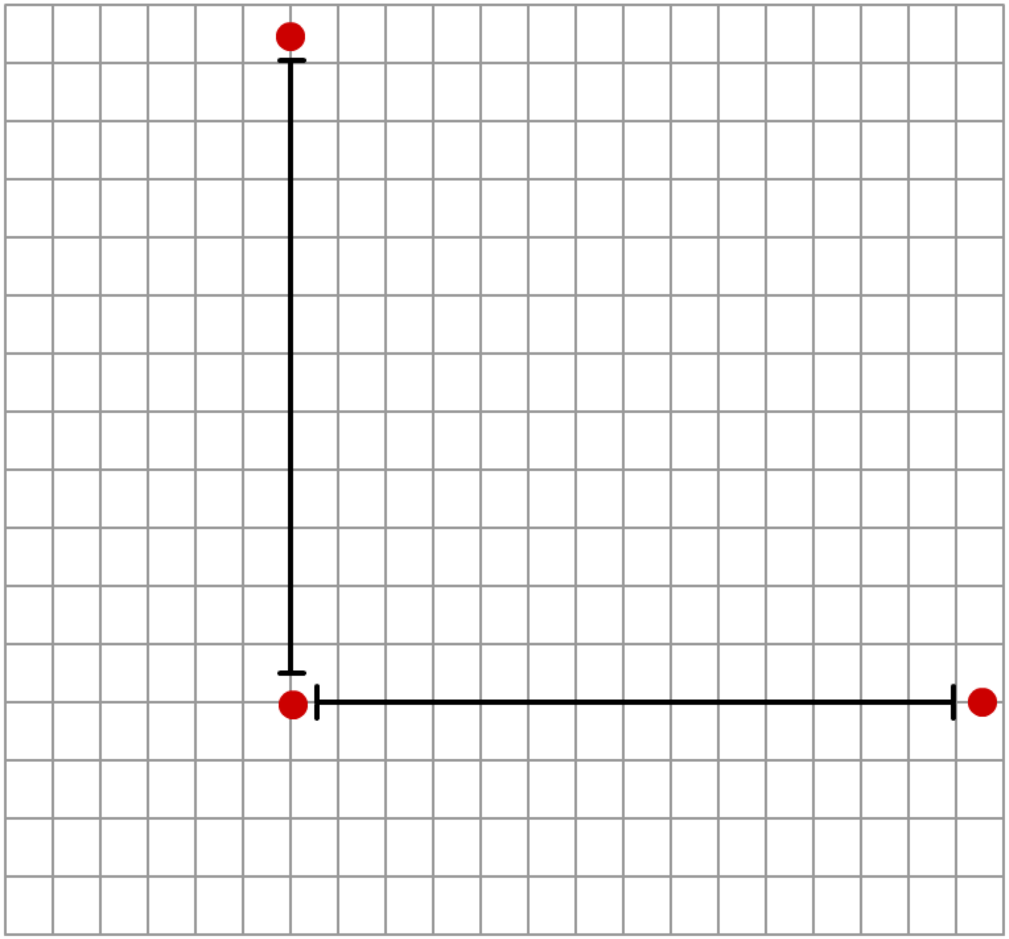
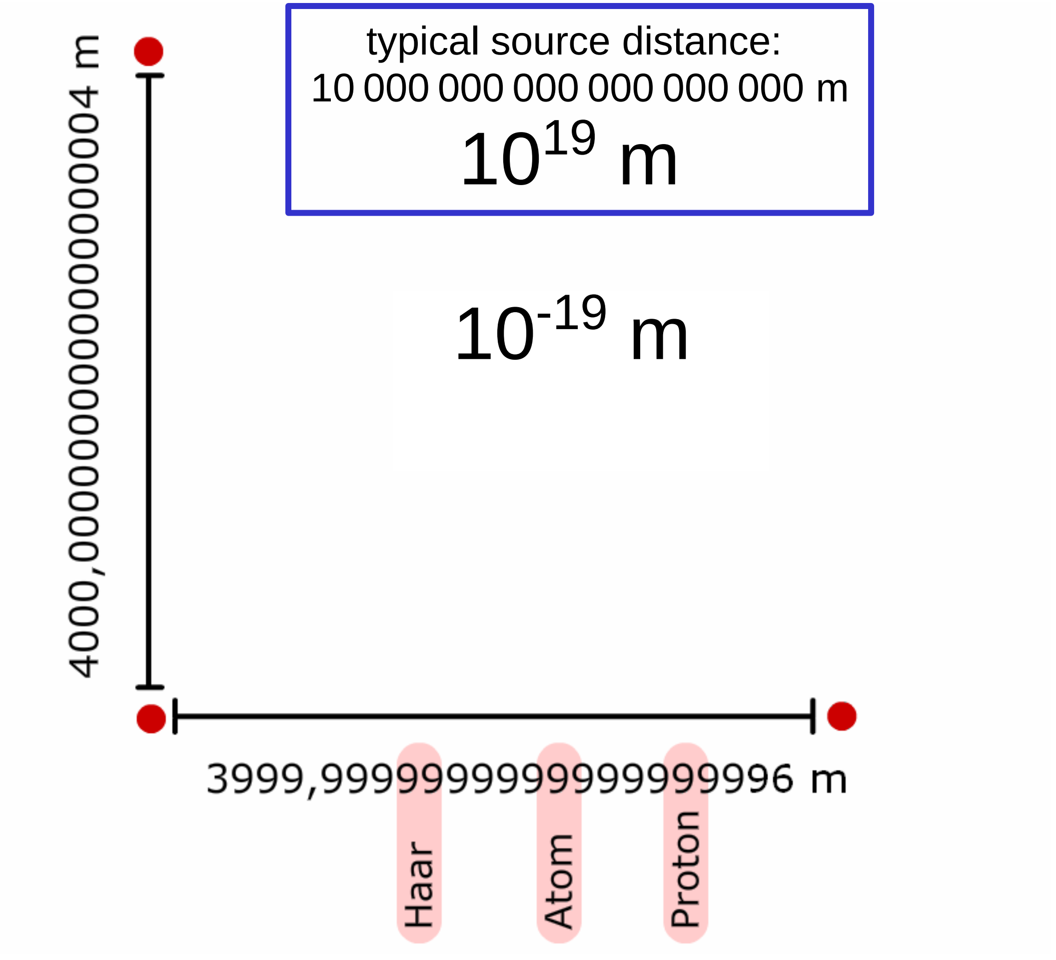
Interferometer response to GW



credit: Patrick Kwee, AEI

Interferometer response to GW

typical source distance:
10 000 000 000 000 000 000 m
10^{19} m

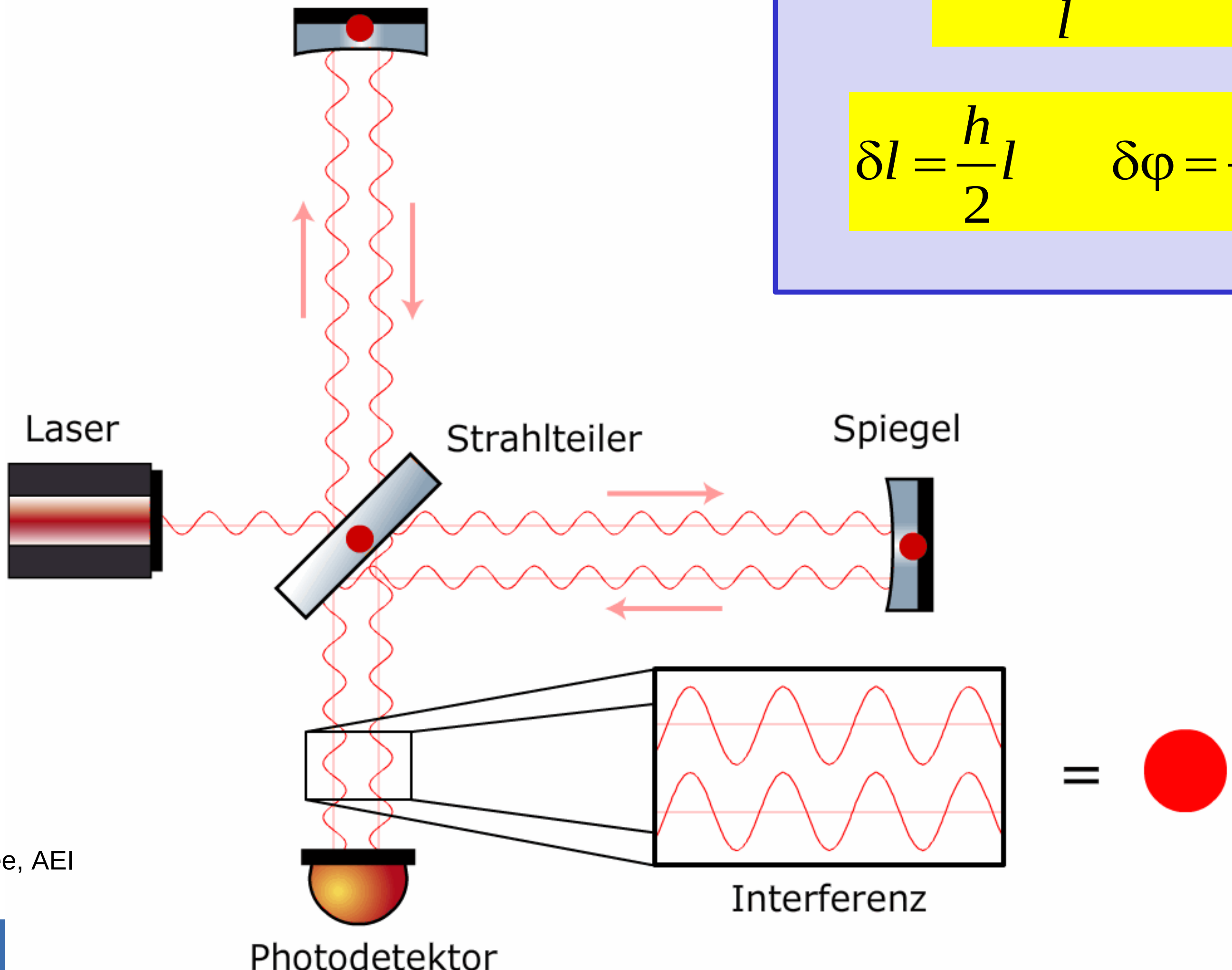


credit: Patrick Kwee, AEI

Interferometer response to GW

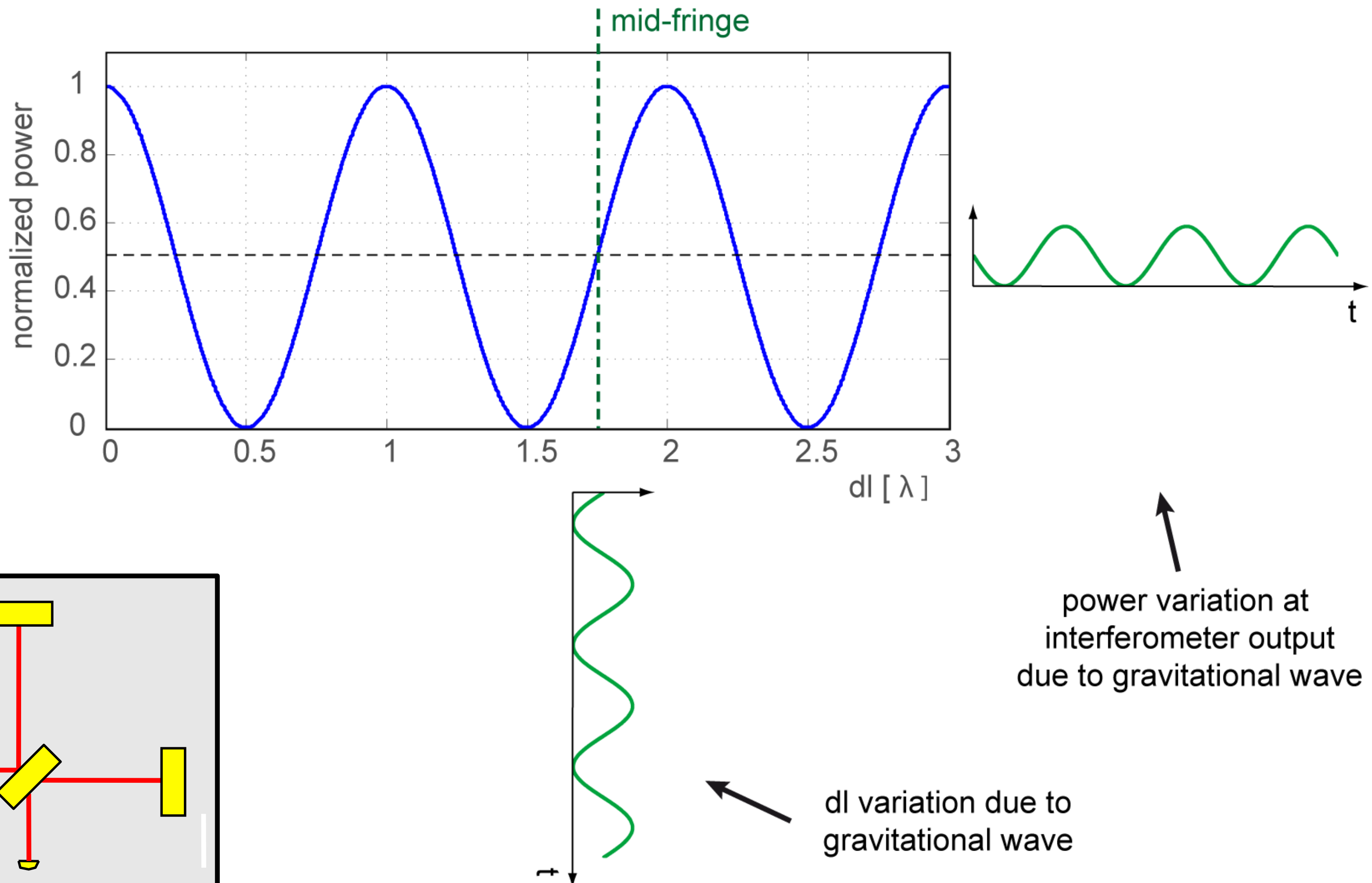
$$h = \frac{2\delta l}{l} \leq 10^{-22}$$

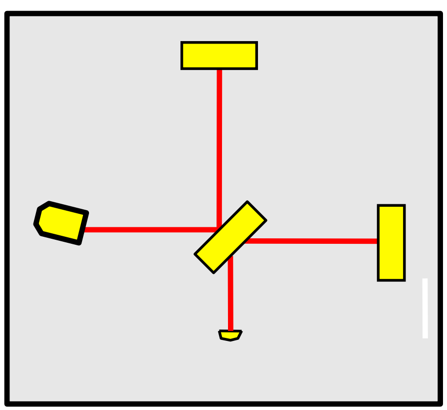
$$\delta l = \frac{h}{2} l \qquad \delta\varphi = \frac{2\pi h}{\lambda} l$$



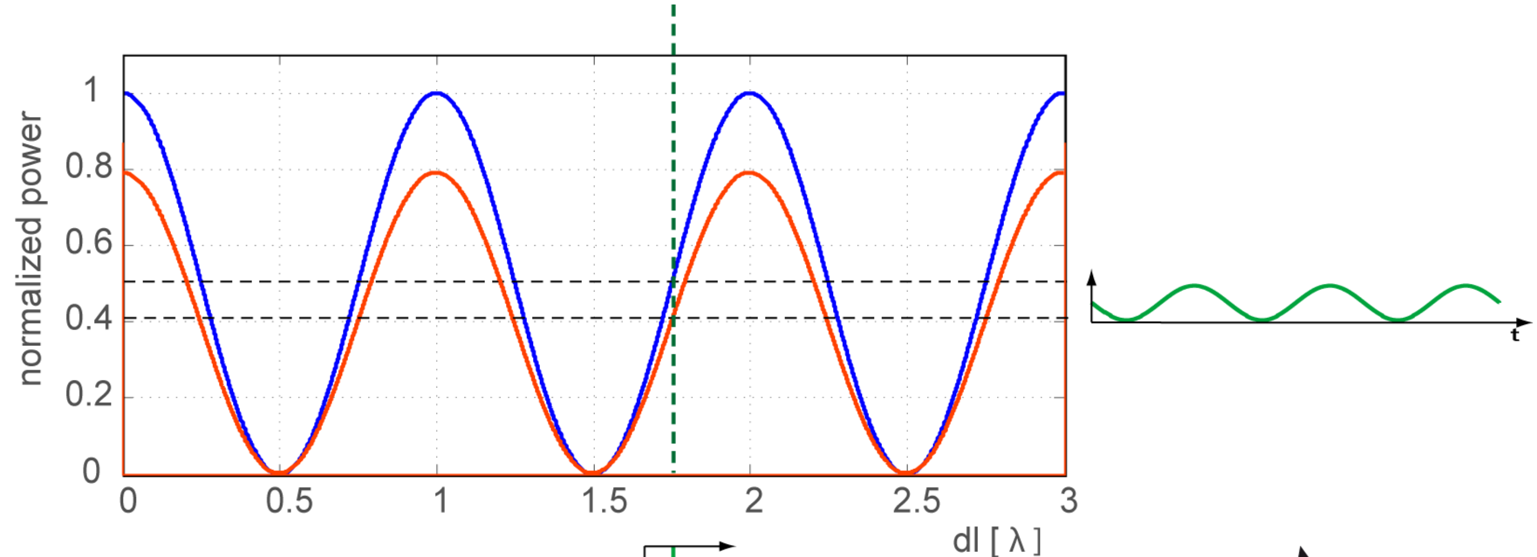
credit: Patrick Kwee, AEI

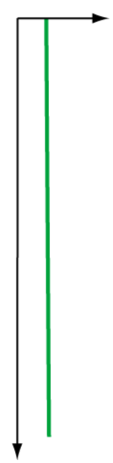
Michelson IFO at mid-fringe





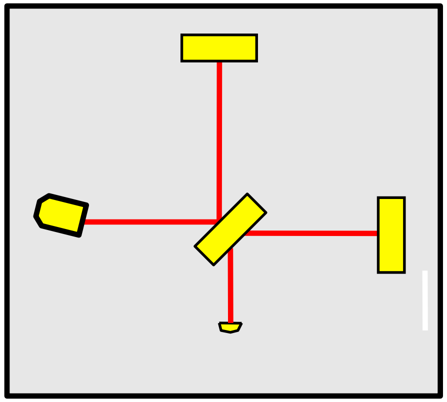
Michelson IFO with varying intensity



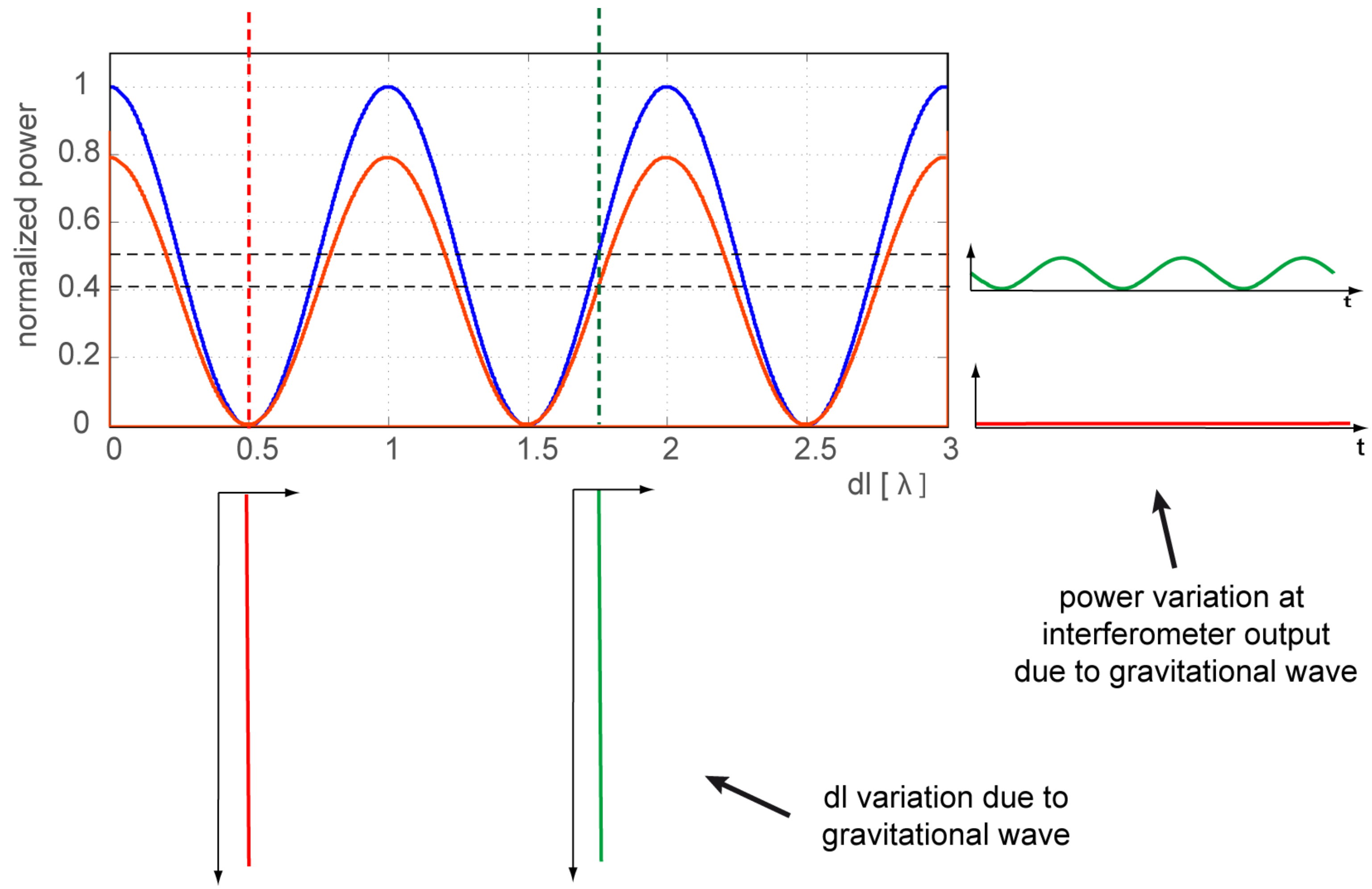


power variation at
interferometer output
due to power fluctuations
in the interferometer

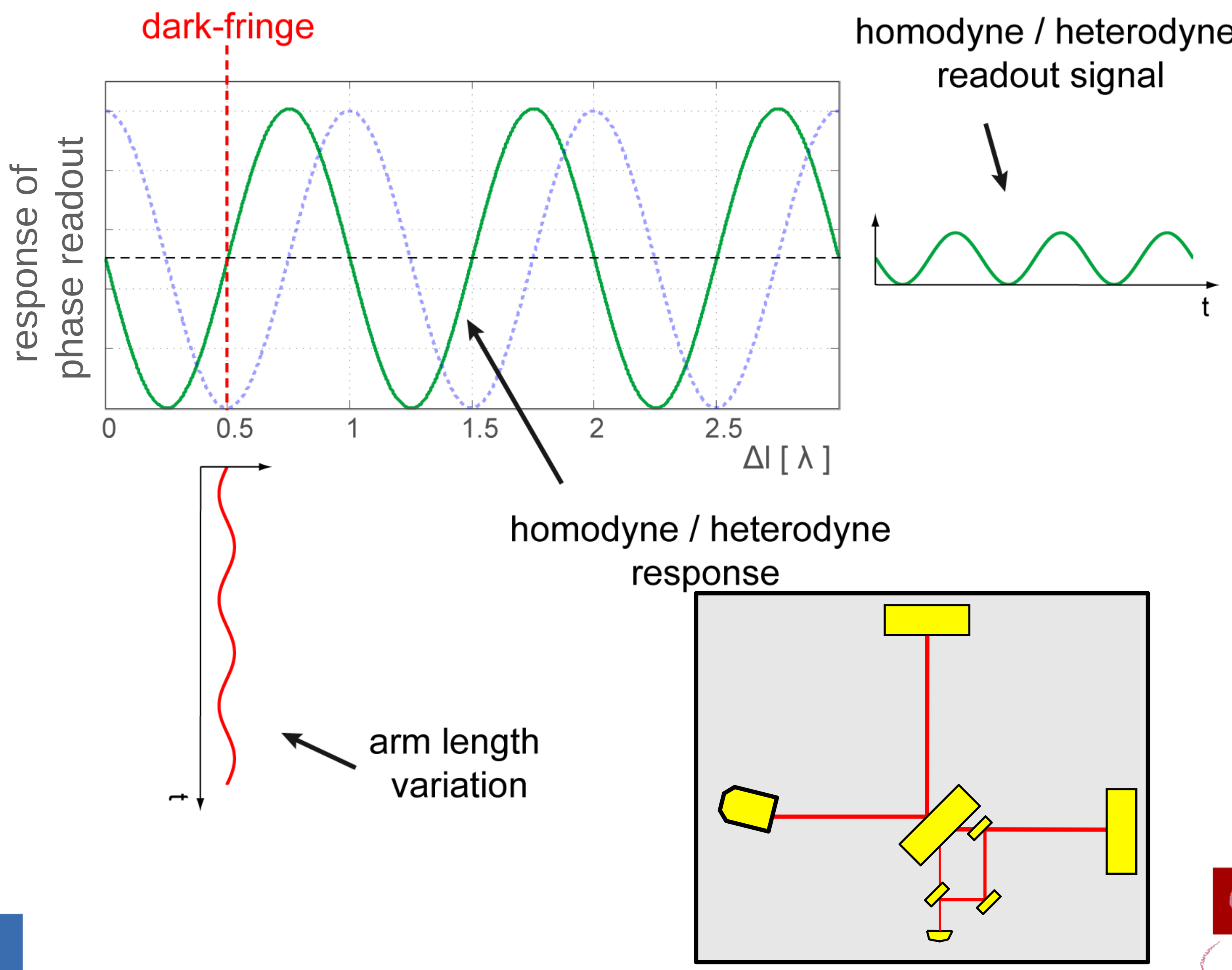
no dl variation !



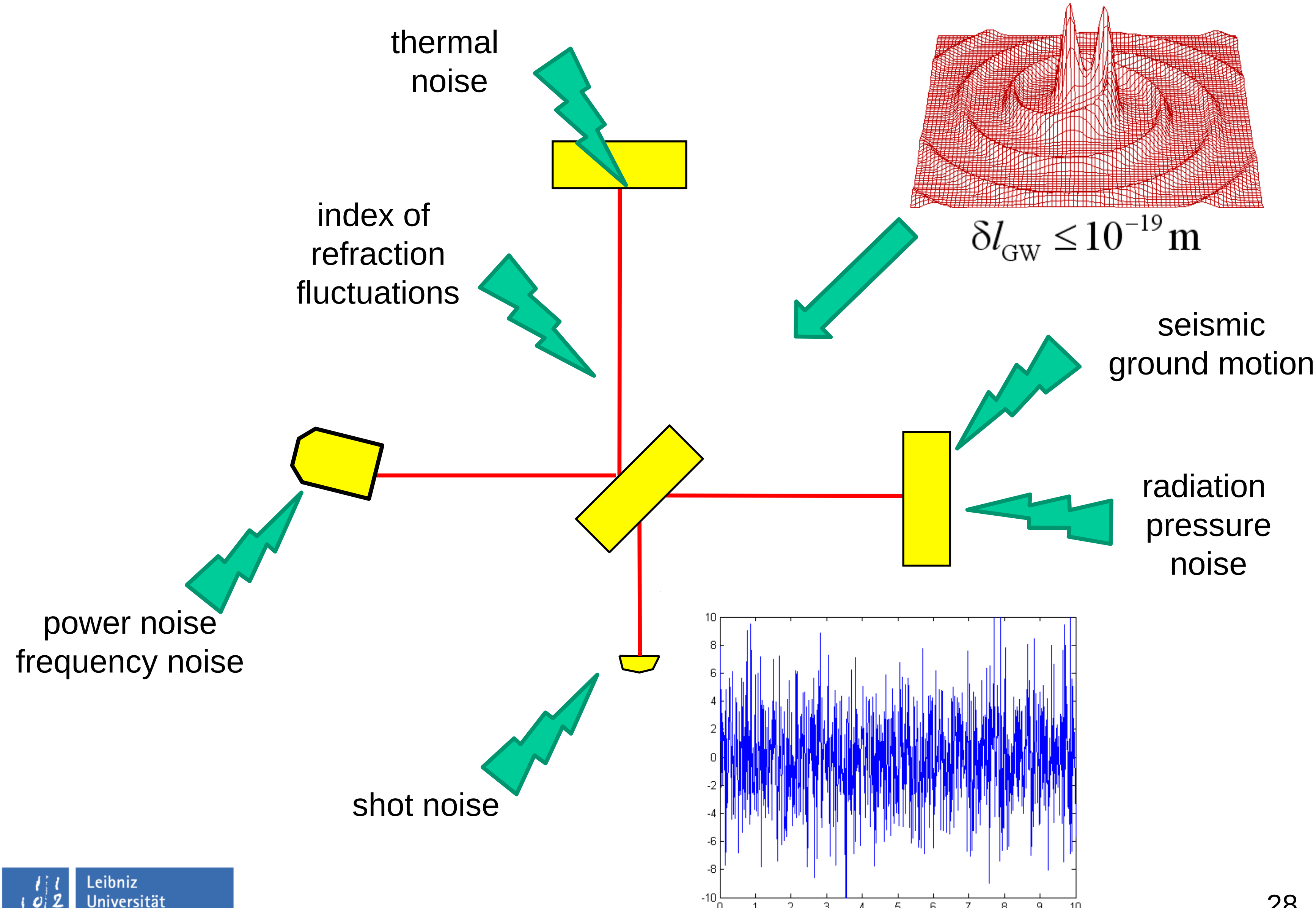
Michelson IFO with varying intensity



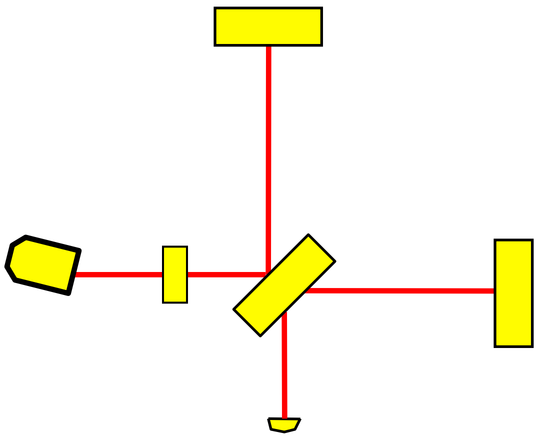
homodyne / heterodyne readout



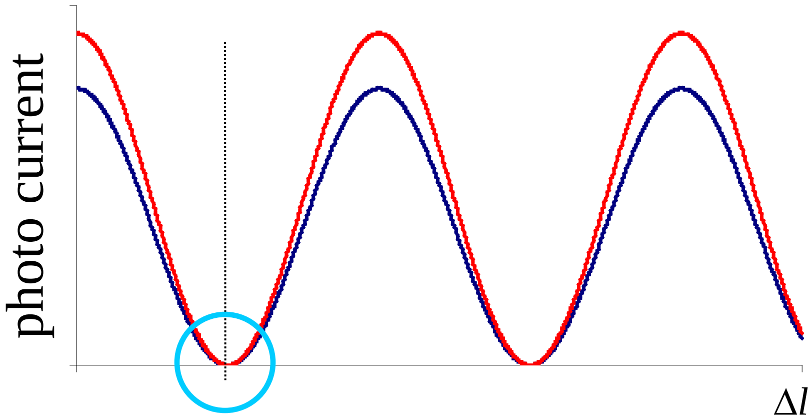
noise sources



Noise Sources – Shot Noise



$$\left.\begin{aligned}\delta I_S &\propto I_0 \delta l_{GW} \\ \delta I_{SN} &\propto \sqrt{I_0}\end{aligned}\right\} \Rightarrow \frac{\delta I_S}{\delta I_{SN}} \propto \sqrt{I_0}\,\delta l_{GW}$$

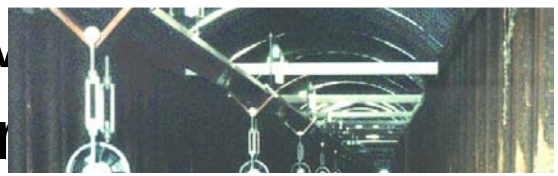


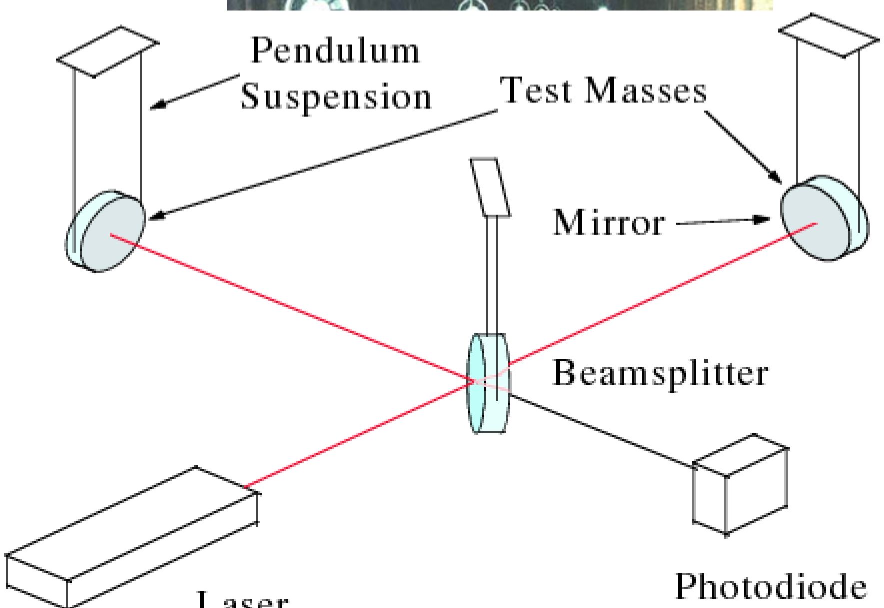
shot noise

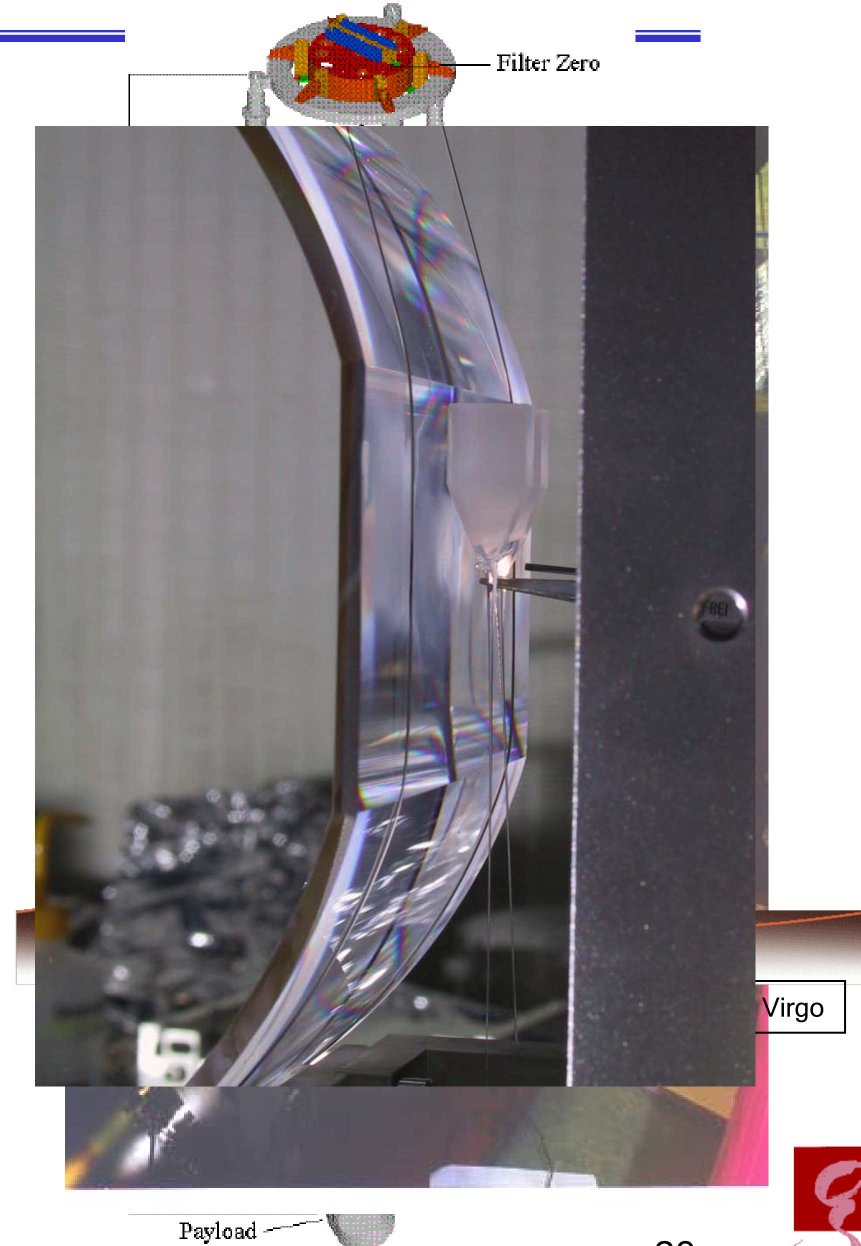
- readout noise
- radiation pressure fluctuation on mirrors
- optimum: Standard Quantum Limit

Displacement noise

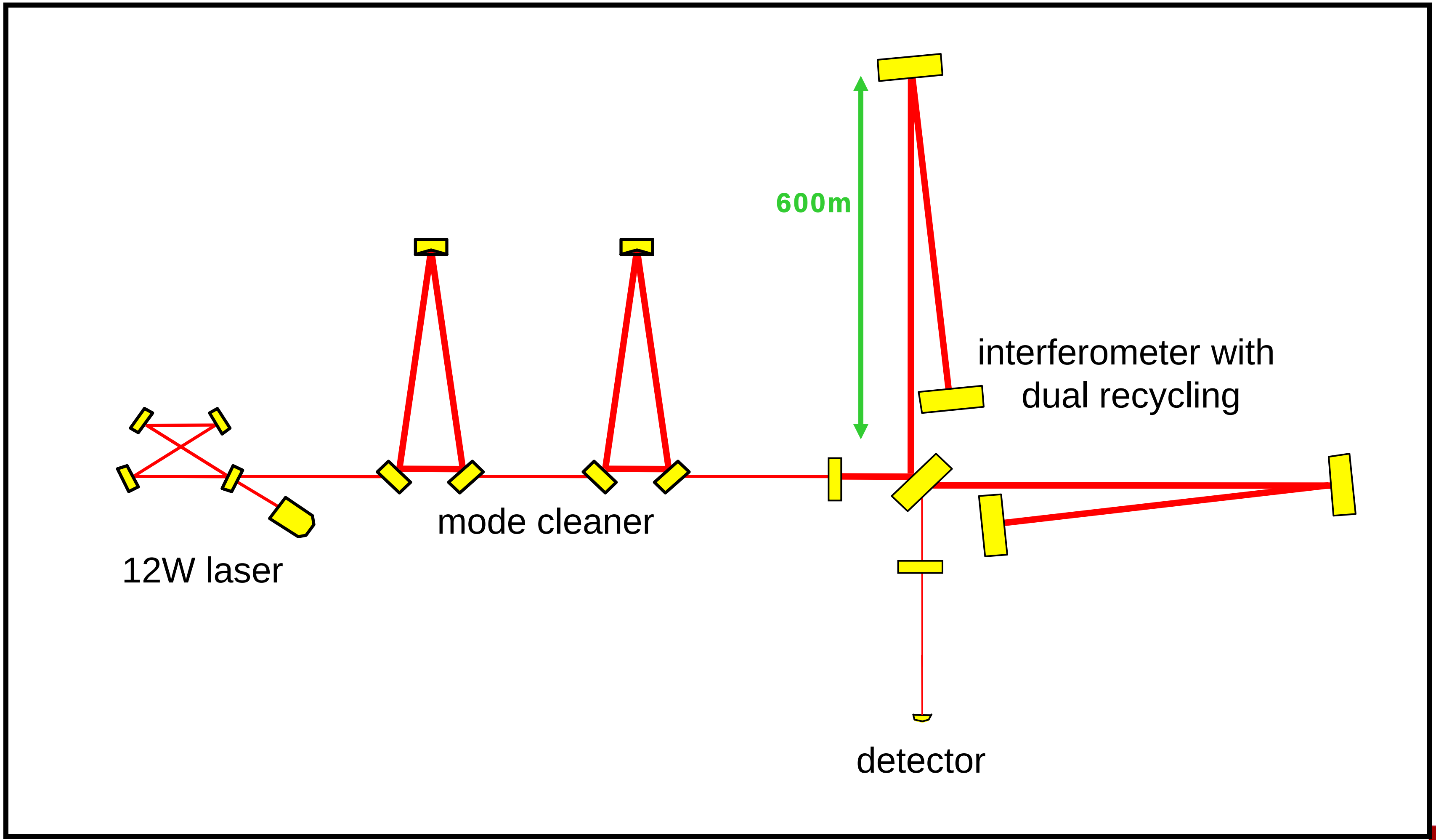
- index of refraction fluctuations
- seisminc motion
- grav
- ther



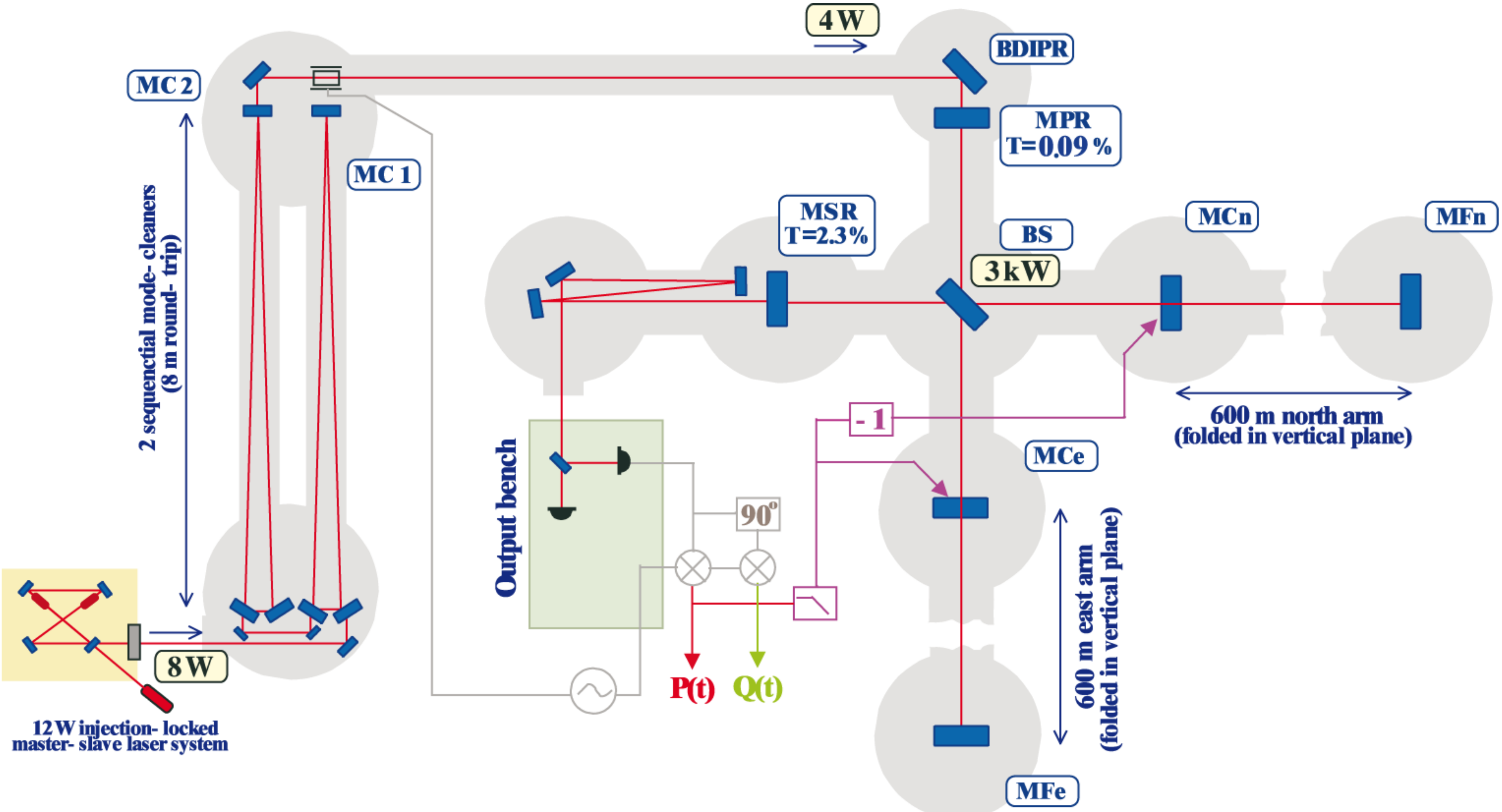




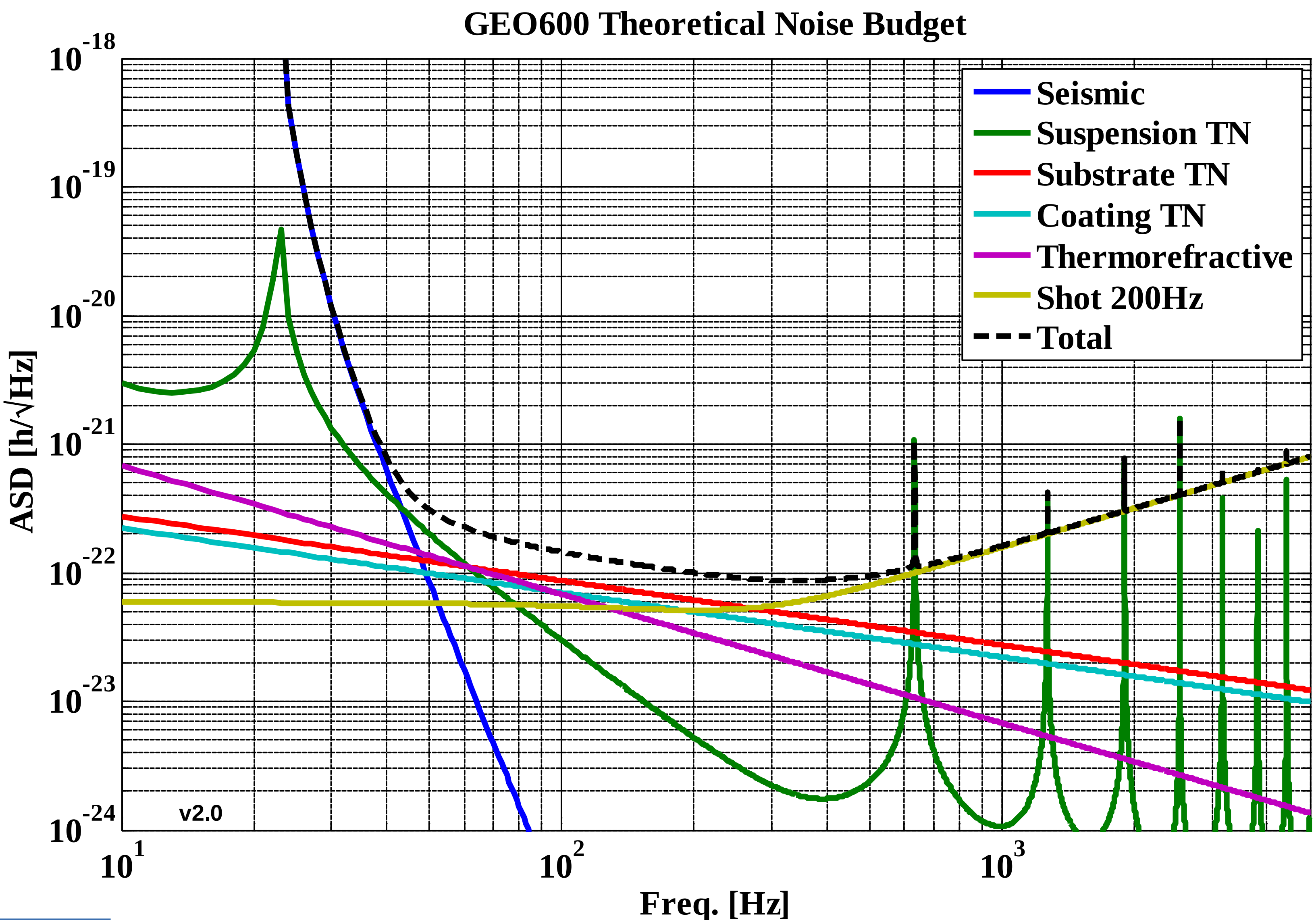
GEO600 optical layout



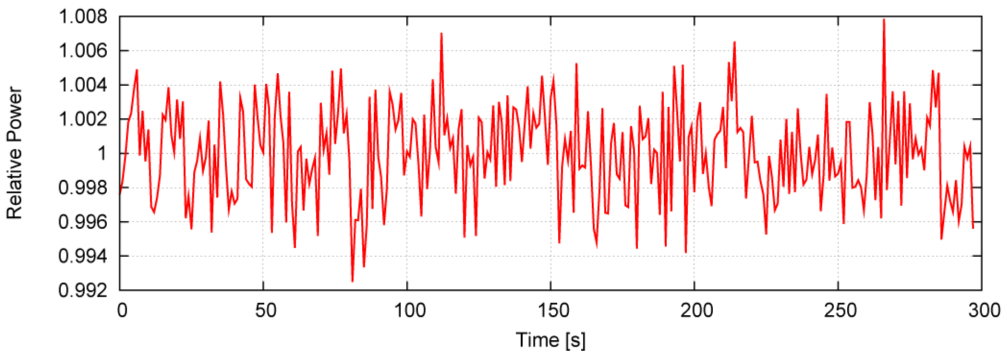
Optical Layout of GEO600

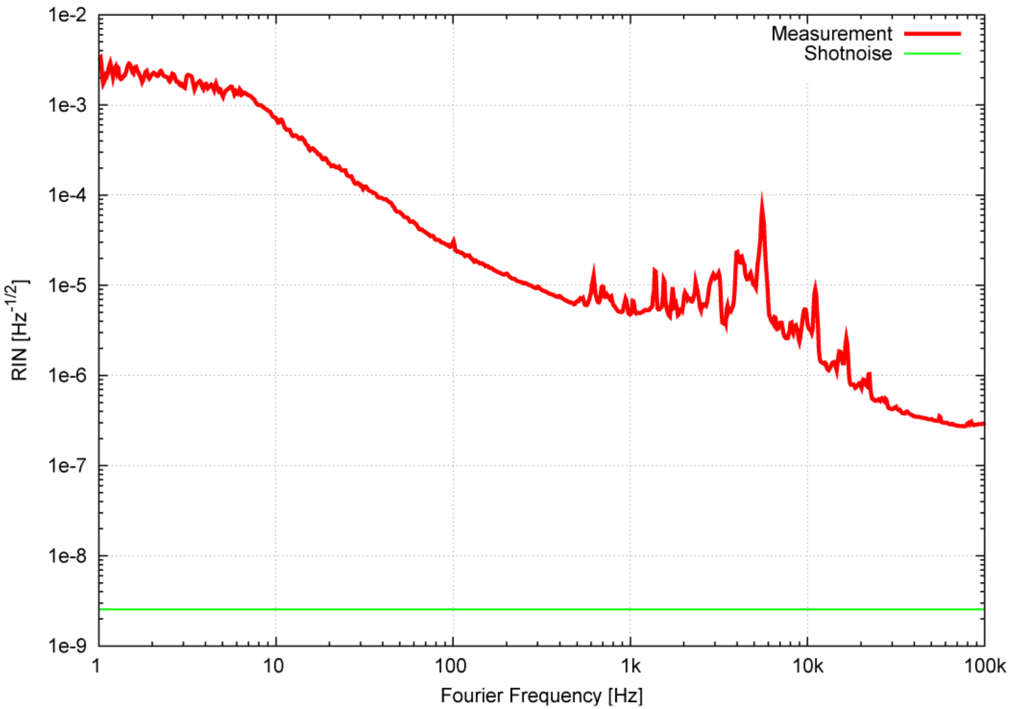


GEO - expected noise contributions



How to describe fluctuations?





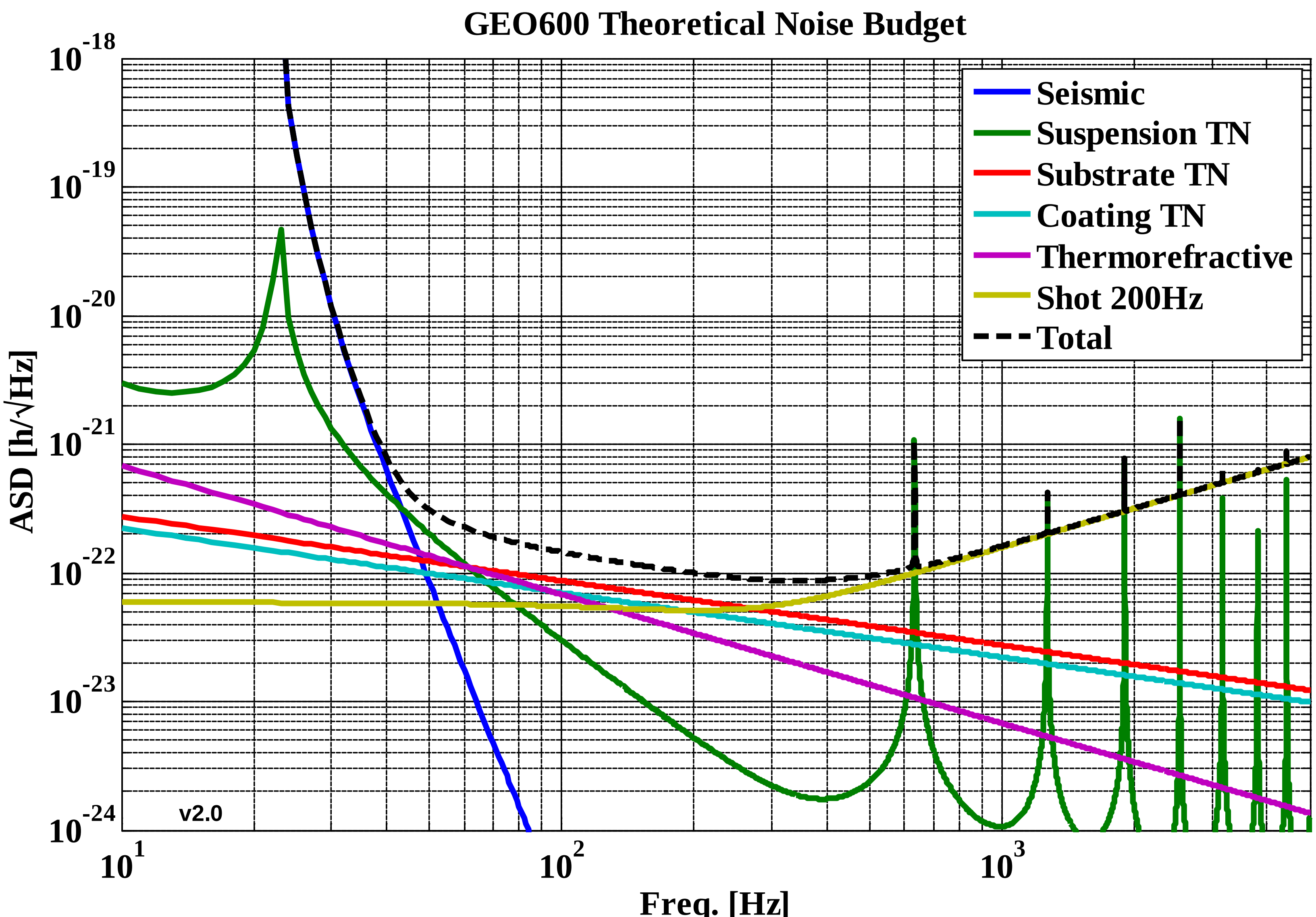
time-domain

- peak-peak value
- root-mean-square value
- both dependent on measurement time and detector bandwidth
- time-domain analysis is important to design sensor and actuator range

frequency-domain

- noise spectral density
- inherently includes detector bandwidth and measurement time
- meaningful only for stationary noise behavior
- enables easy identifications of deterministic and stationary noise processes like line noise or harmonics

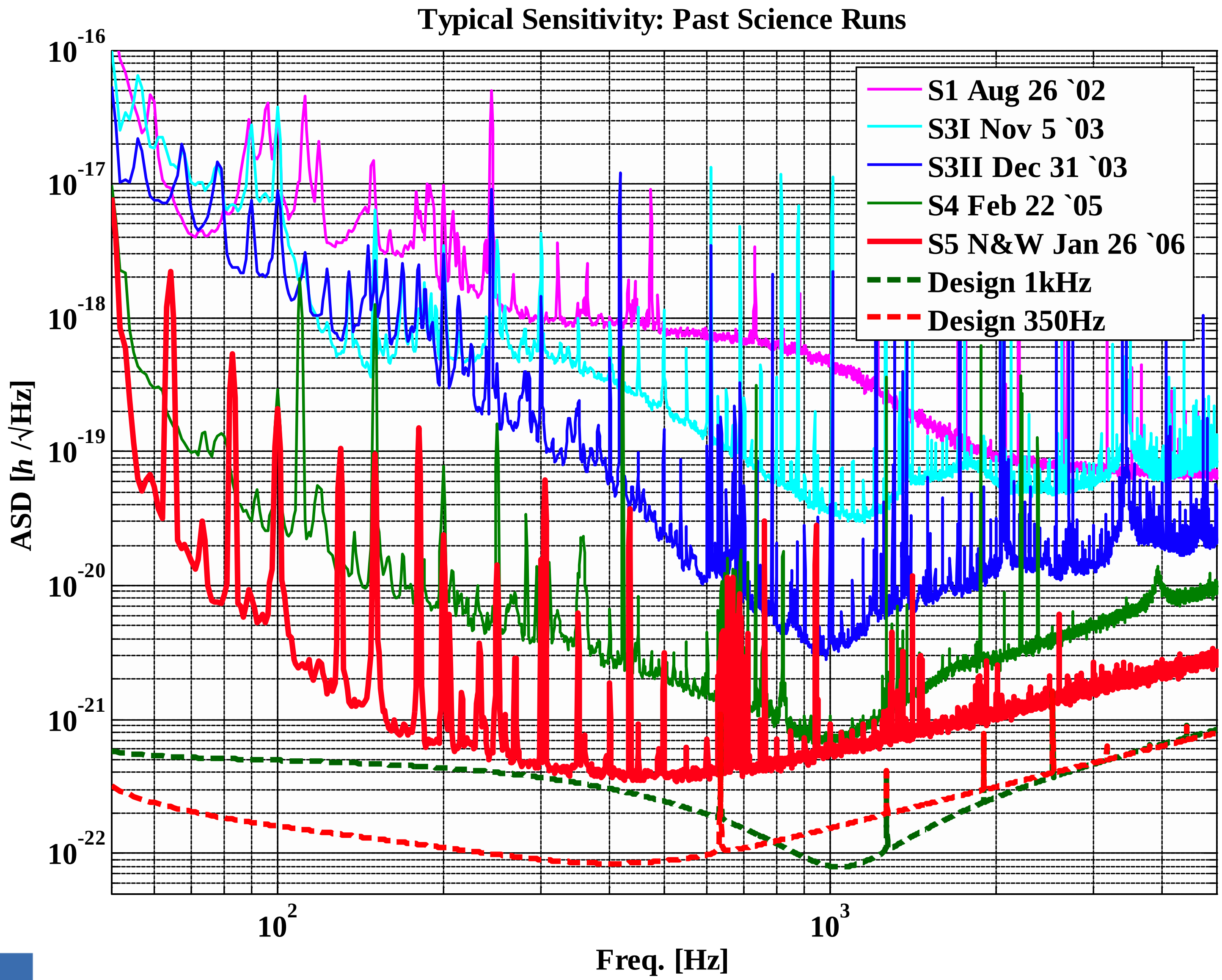
GEO - expected noise contributions



real life is much more complicated ...

- all suspended components need local damping
- all optical cavities and the interferometer need length and alignment control
  - low noise (rf-) electronic
  - complicated lock-acquisition procedure
- scattering control via apertures and baffles
- stabilization of laser fluctuations
- detailed detector and environmental monitoring
- avoid and control thermal loading
- accurate and reliable calibration

Sensitivity Improvements



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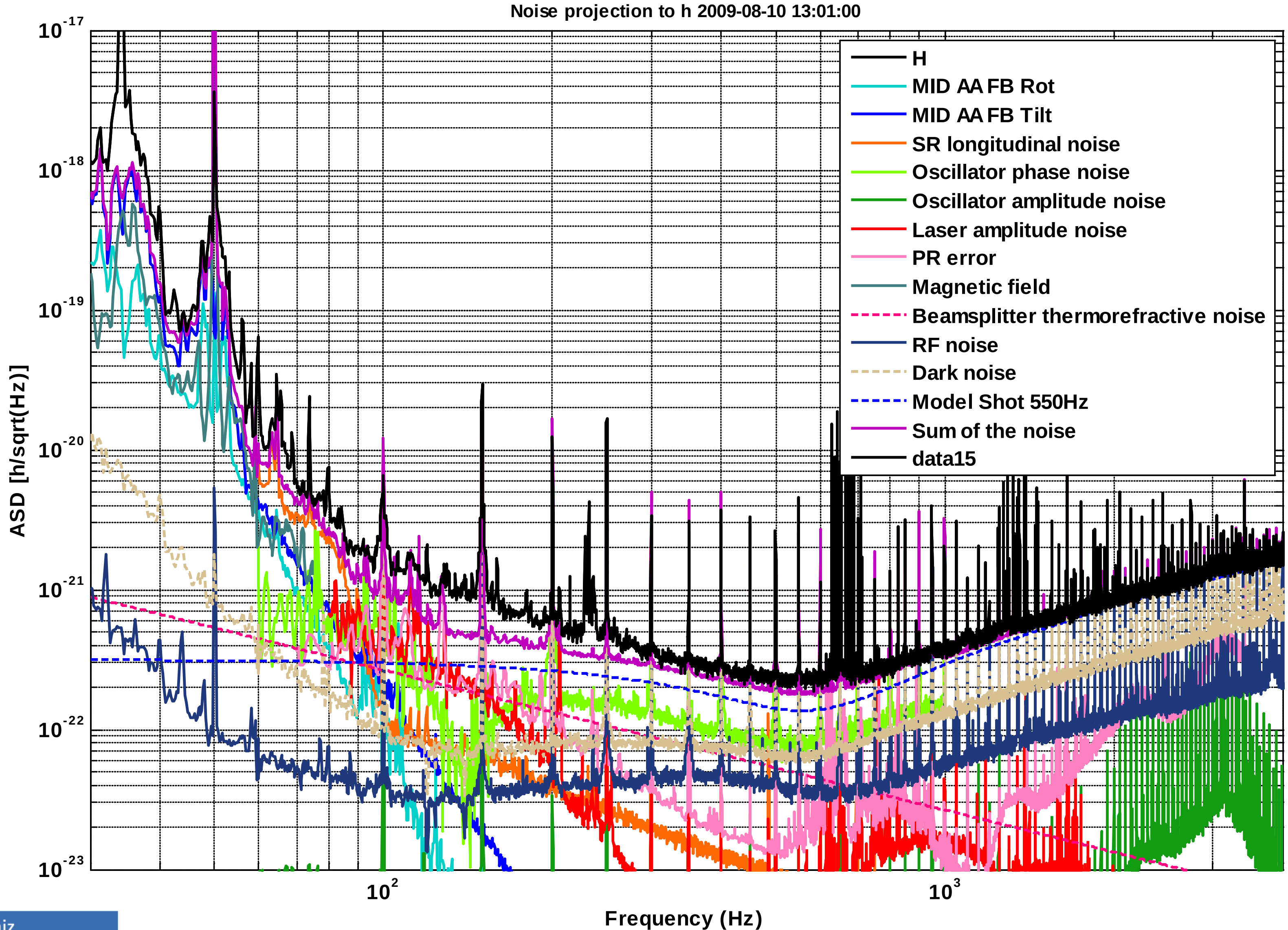
noise projections



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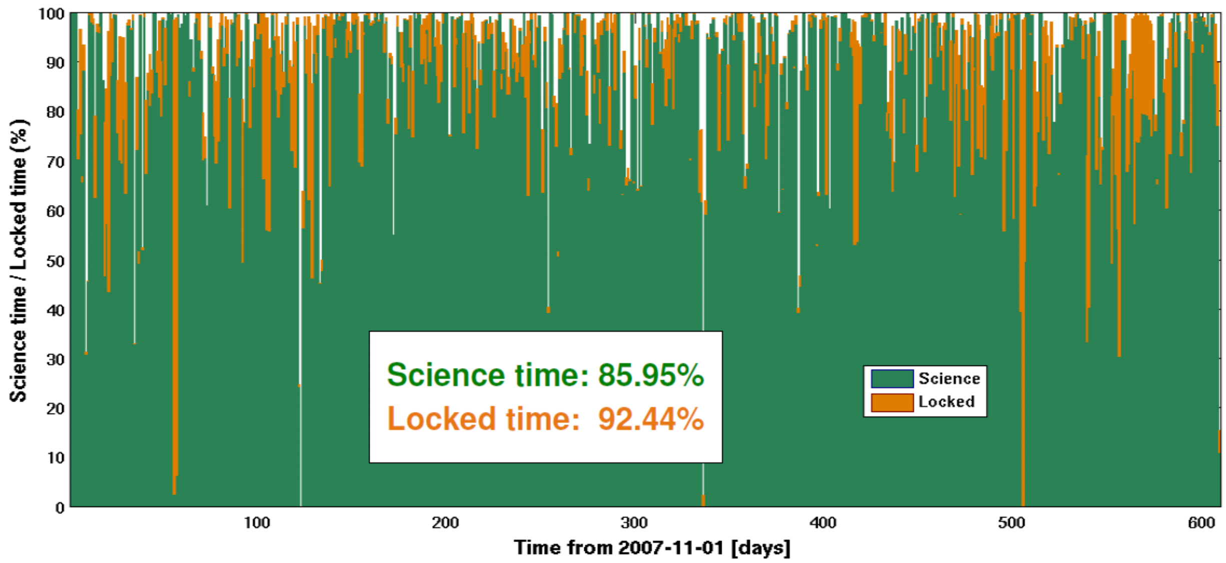
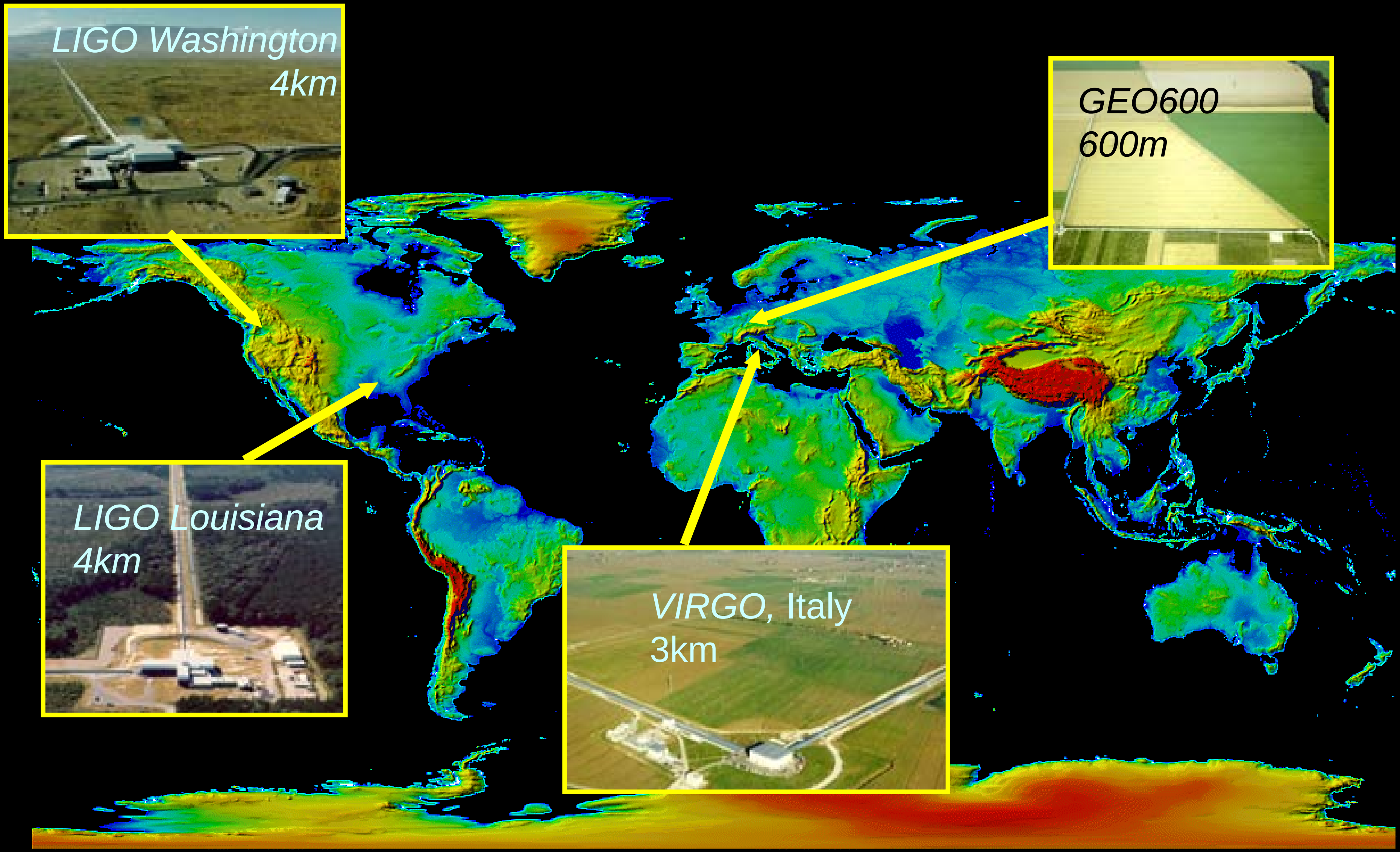
S5 - first long data-taking periode



Nov 2007 – July 2009: 522 days of science data collected
Jan 2006 – July 2009: 943 days (s5 + astrowatch)

Today: The Global Network of Gravitational Wave Interferometers



LIGO

- two 4km detectors in the USA
- was upgraded to "*enhanced LIGO*"
- since Jul 2009 in Science Run S6 (until fall 2010)

Abbott, et al., "The laser interferometer gravitational-wave observatory"
Rep. Prog. Phys. **72** 076901 (2009)

Virgo

- one 3km detectors in Italy
- was upgraded to "*Virgo+*"
- Jul 2009 – Dec 2010 in Science Run VSR2
- currently upgraded with monolithic suspensions

F Acernes, et al., "Virgo Status", *Class.Quantum Grav.* **25** 184001 *(*2008)

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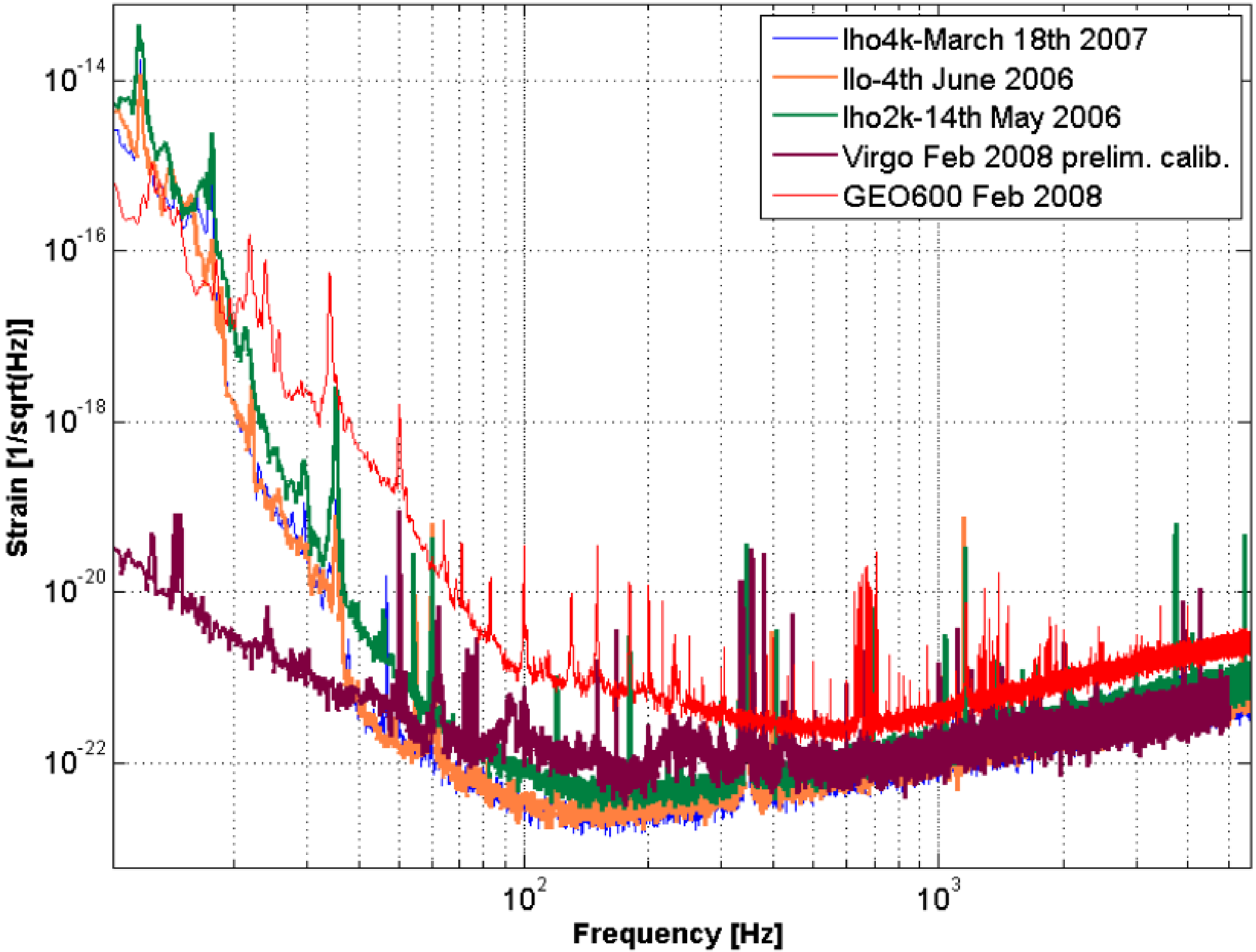
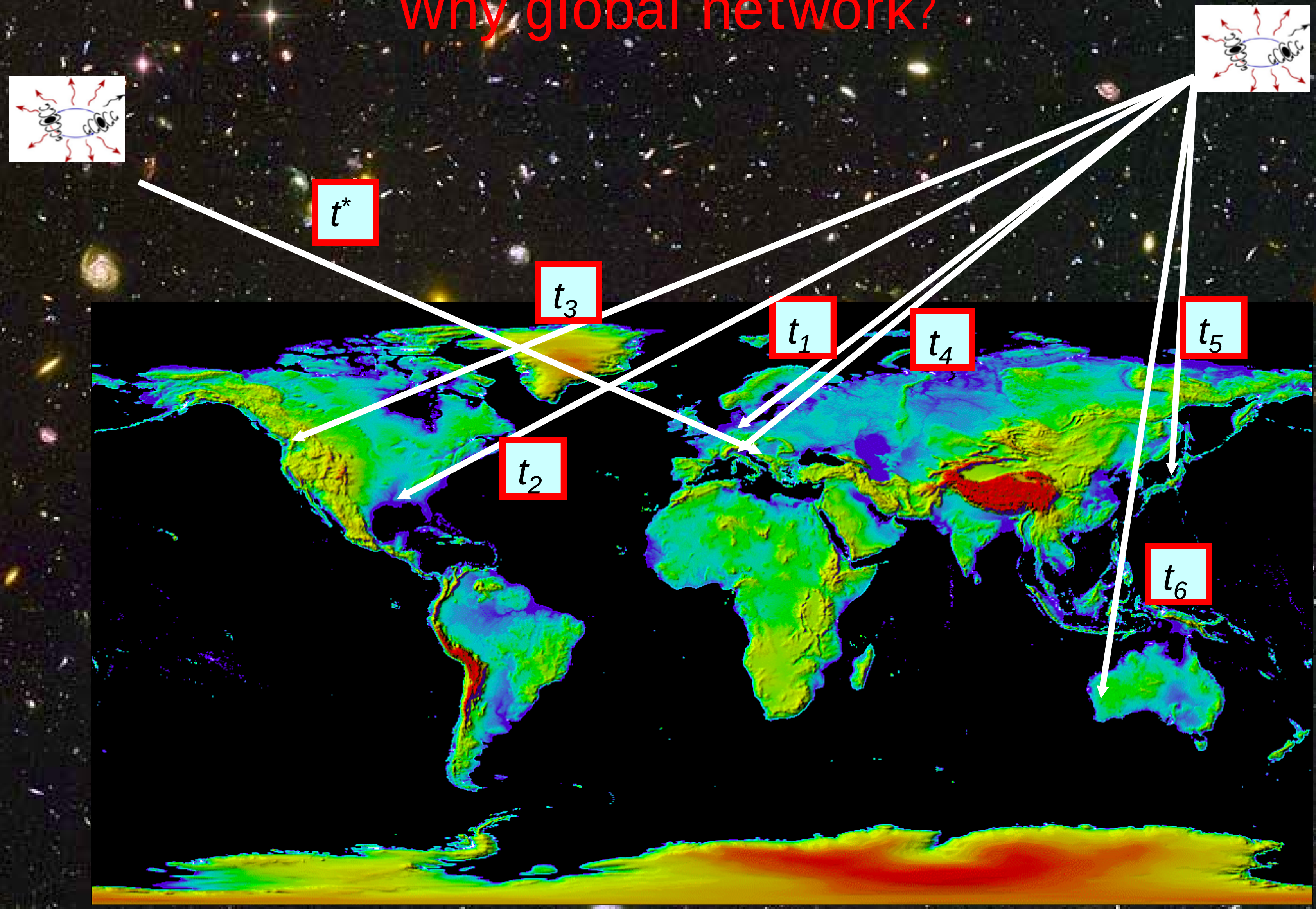
sensitivity of the worldwide network

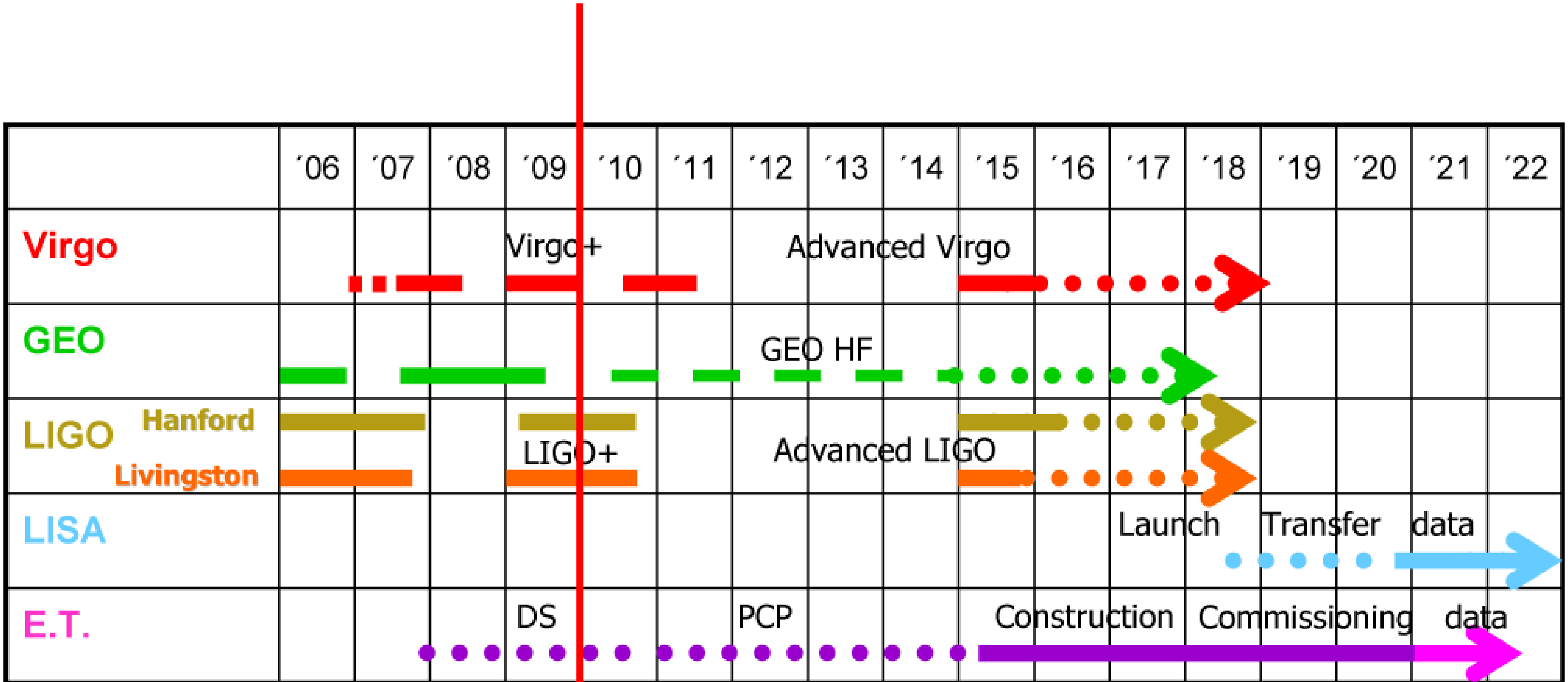


Why global network?



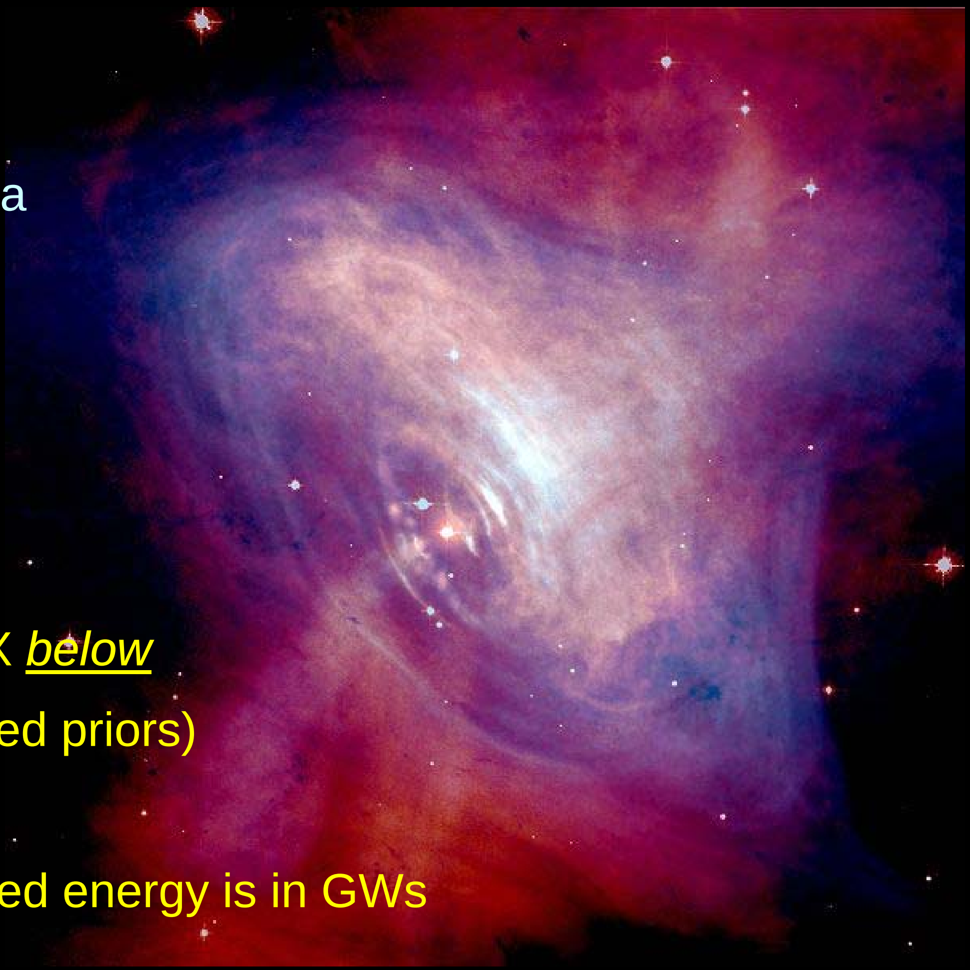
Source: A. Lazzarini, modified

past and future of the GW network



ET and LISA from ET DS proposal, V/L/G as of Jan 2010

The Crab Pulsar: *Beating the Spin Down Limit!*



- Remnant from supernova in year 1054
- Spin frequency ν_{EM} = 29.8 Hz
  → $\nu_{gw} = 2\ \nu_{EM}$ = 59.6 Hz
- observed luminosity of the Crab nebula accounts for < 1/2 spin down power
- spin down due to:

  electromagnetic braking

  particle acceleration

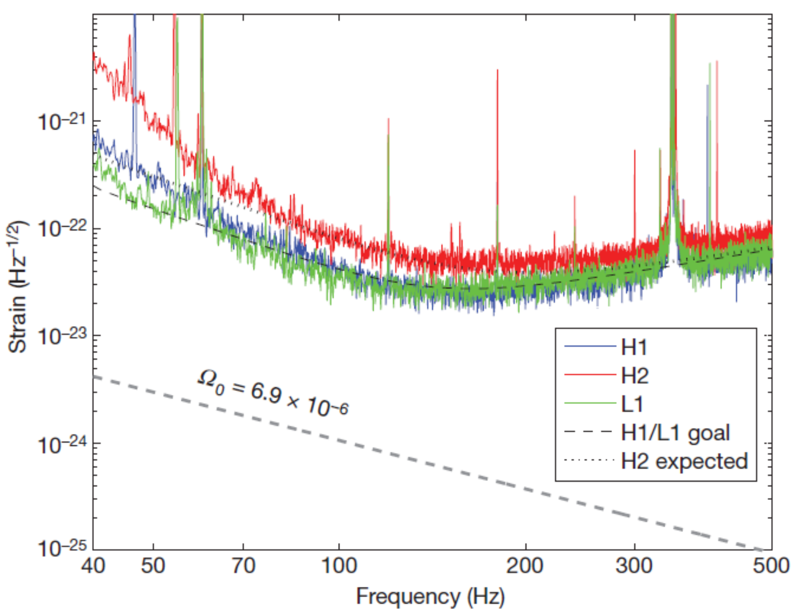
  GW emission?
- early S5 result: $h < 3.9 \times 10^{-25}$ → ~ 4X <u>*below*</u> the spin down limit (assuming restricted priors)
- ellipticity upper limit: $\varepsilon < 2.1 \times 10^{-4}$
- GW energy upper limit < 6% of radiated energy is in GWs

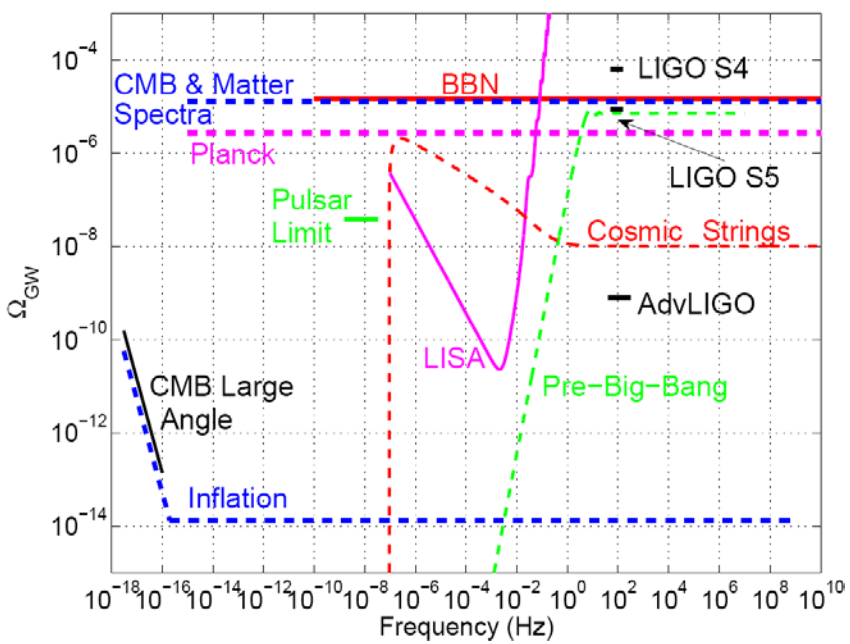
Abbott, et al., *"Beating the spin-down limit on gravitational wave emission from the Crab pulsar,"* Ap. J. Lett. 683, L45-L49, (2008).

Stochastic Gravitational Wave Background

- cross-correlation analysis allows to set upper limit on energy in stochastic gravitational wave background (SGRB)
- S5/VSR1 upper limit: $\Omega_{0,\,\mathrm{LIGO}} < 6.9 \times 10^{-6}$ (95% confidence)
- this is better than Big-Bang nucleosynthesis limit
- result starts to rule out some "early Universe evolution models"

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}f}$$





LSC and Virgo collaboration, "An upper limit on the stochastic gravitational-wave background of cosmological origin," Nature **460**, 990-994, (2009).

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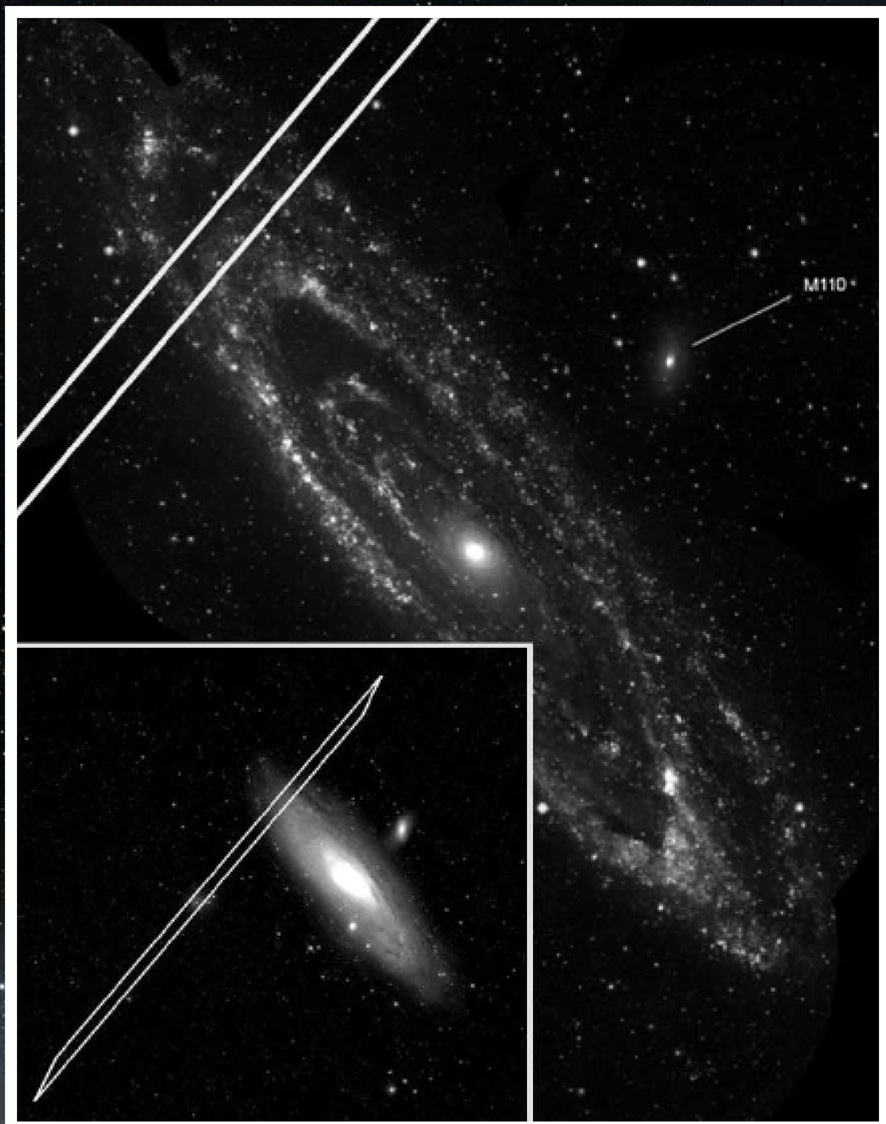
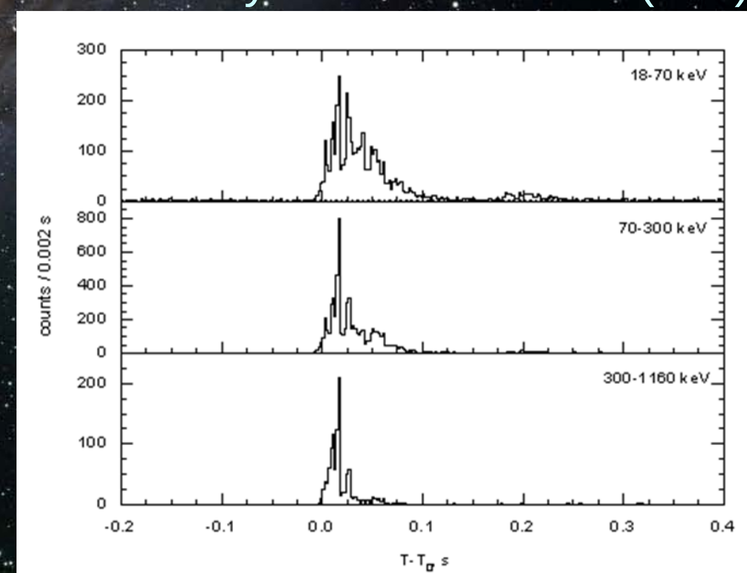
GRB 070201

Abbott et al. "Implications for the origin of GRB 070201 from LIGO observations" ApJ **681**,1419-1430 (2008)



X-ray emission curves (IPN)



Dave Reitze, MG12 talk

constantly updated list of publications

LSC Publications

Observational results   Conference proceedings

$Id: Papers.html,v 1.87 2010/01/05 17:36:53 rayfrey Exp $

Contact: lsc-pp @ ligo.caltech.edu

Observational results and LSC instrument papers

[Papers currently in LSC review]

	Run	Group	Authors	Journal	Preprint	Date	Title
1	S1	Detector	LSC	Nucl. Instrum. Meth. A **517** (2004) 154-179	gr-qc/0308043	200308	*Detector description and performance for the first coincidence observatior*
2	S1	Bursts	LSC	Phys. Rev. D **69** (2004) 102001	gr-qc/0312056	200312	*First upper limits from LIGO on gravitational-wave bursts.*
3	S1	Inspiral	LSC	Phys. Rev. D **69** (2004) 122001	gr-qc/0308069	200308	*Analysis of LIGO data for gravitational waves from binary neuton stars.*
4	S1	Pulsar	LSC	Phys. Rev. D **69** (2004) 082004	gr-qc/0308050	200308	*Setting upper limits on the strength of periodic gravitational waves from PS*
5	S1	Stochastic	LSC	Phys. Rev. D **69** (2004) 122004	gr-qc/0312088	200312	*Analysis of first LIGO science data for stochastic gravitational waves.*
6	S2	Bursts	LSC	Phys. Rev. D **72** (2005) 042002	gr-qc/0501068	200501	*A search for gravitational waves associated with the gamma ray burst GR*
7	S2	Bursts	LSC				
8	S2	Bursts	LSC, TAMA				
9	S2	Inspiral	LSC				
10	S2	Inspiral	LSC				
11	S2	Inspiral	LSC				
12	S2	Inspiral	LSC, TAMA				
13	S2	Pulsar	LSC				
14	S2	Pulsar	LSC, Kramer, Lyne				
15	S2	Pulsar	LSC				
16	S3	Bursts	LSC				
17	S3	Bursts	LSC, AURIGA				
18	S3	Inspiral	LSC				
19	S3	Stochastic	LSC				
20	S4	Bursts	LSC				
21	S4	Bursts	LSC				
22	S4/S3/S2	Bursts	LSC				
23	S4	Bursts	LSC				
24	S4/S3	Inspiral	LSC				
25	S4/S3	CW	LSC, Kramer, Lyne				
26	S4	CW	LSC				
27	S4	CW	LSC				

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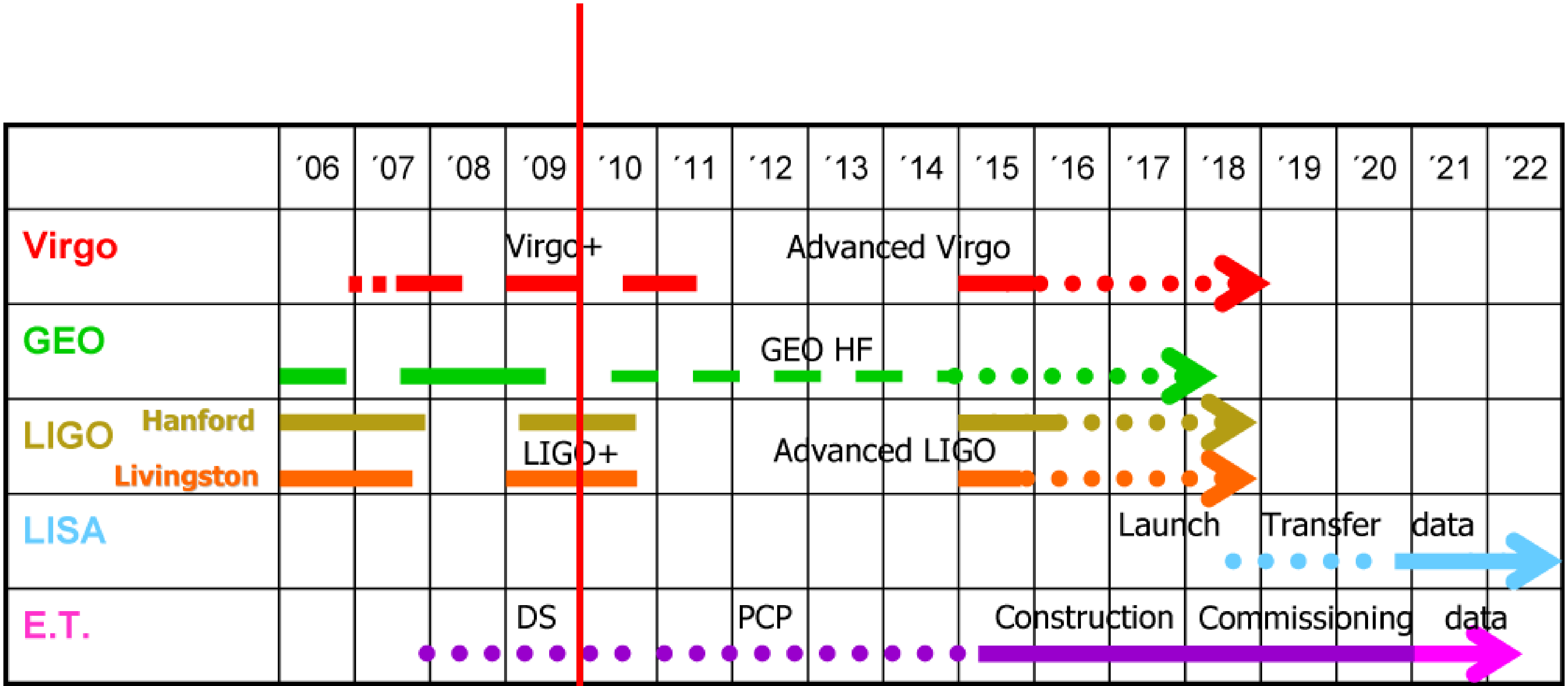
future projects / future technologies



ET and LISA from ET DS proposal, V/L/G as of Jan 2010

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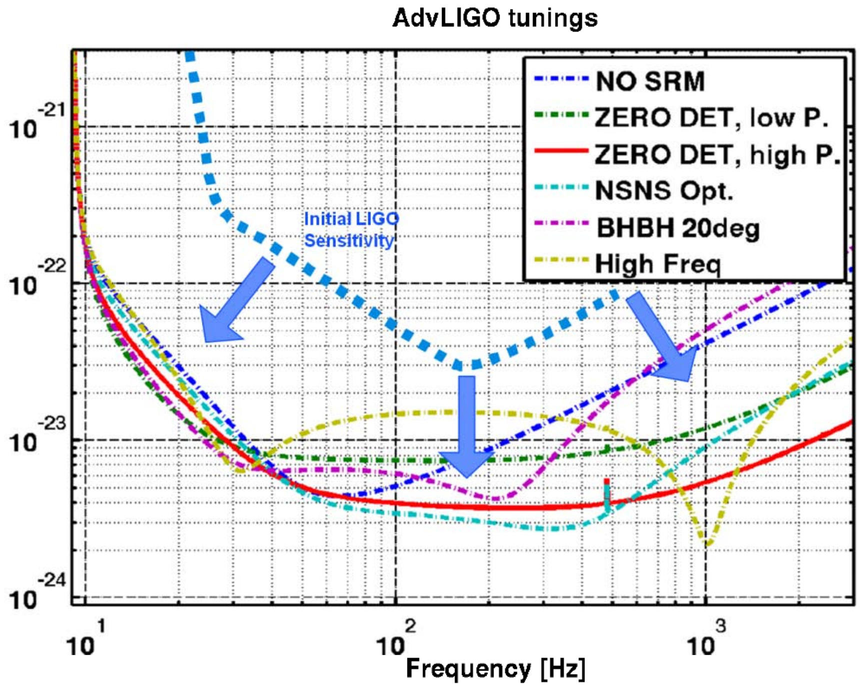
What Advanced Detectors Bring Us ?

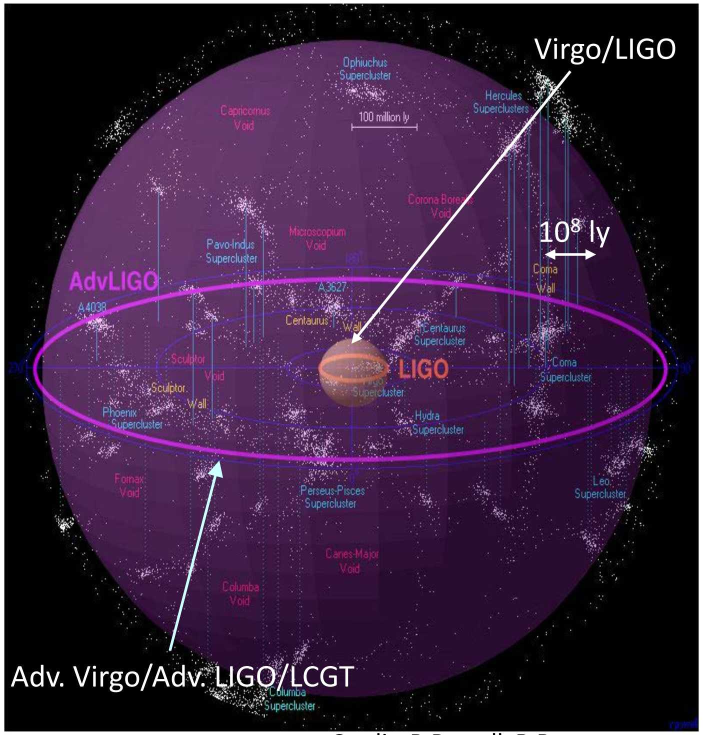
Neutron Star Binaries:

- Initial LIGO (S5): ~15 Mpc → rate ~1/50yr
- Adv LIGO: ~ 200 Mpc → rate ~ 40/year

Black Hole Binaries (Less Certain):

- Initial LIGO (S5): ~100 Mpc → rate ~1/100yr
- Adv LIGO: ~ 1 Gpc → rate ~ 20/year





Credit: R.Powell, B.Berger

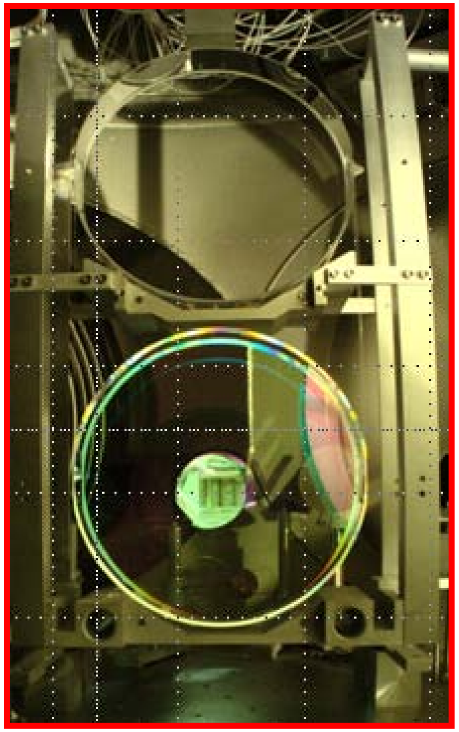
x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

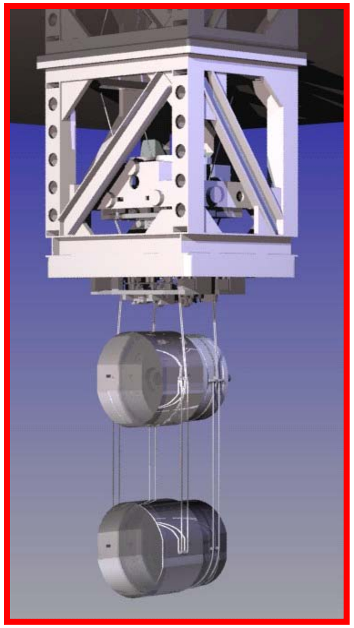
⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO

monolithic suspensions

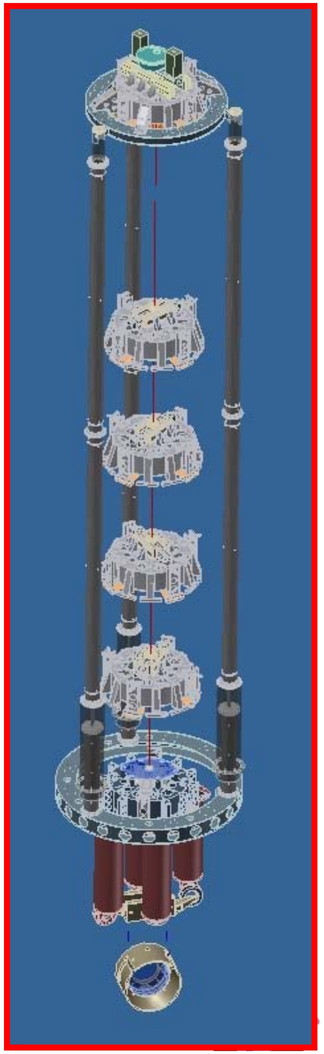
- goal: provide seismic isolation without spoiling the mechanical quality factor
- solution: all-fused silica suspensions




GEO 600



Adv. LIGO



Adv. Virgo

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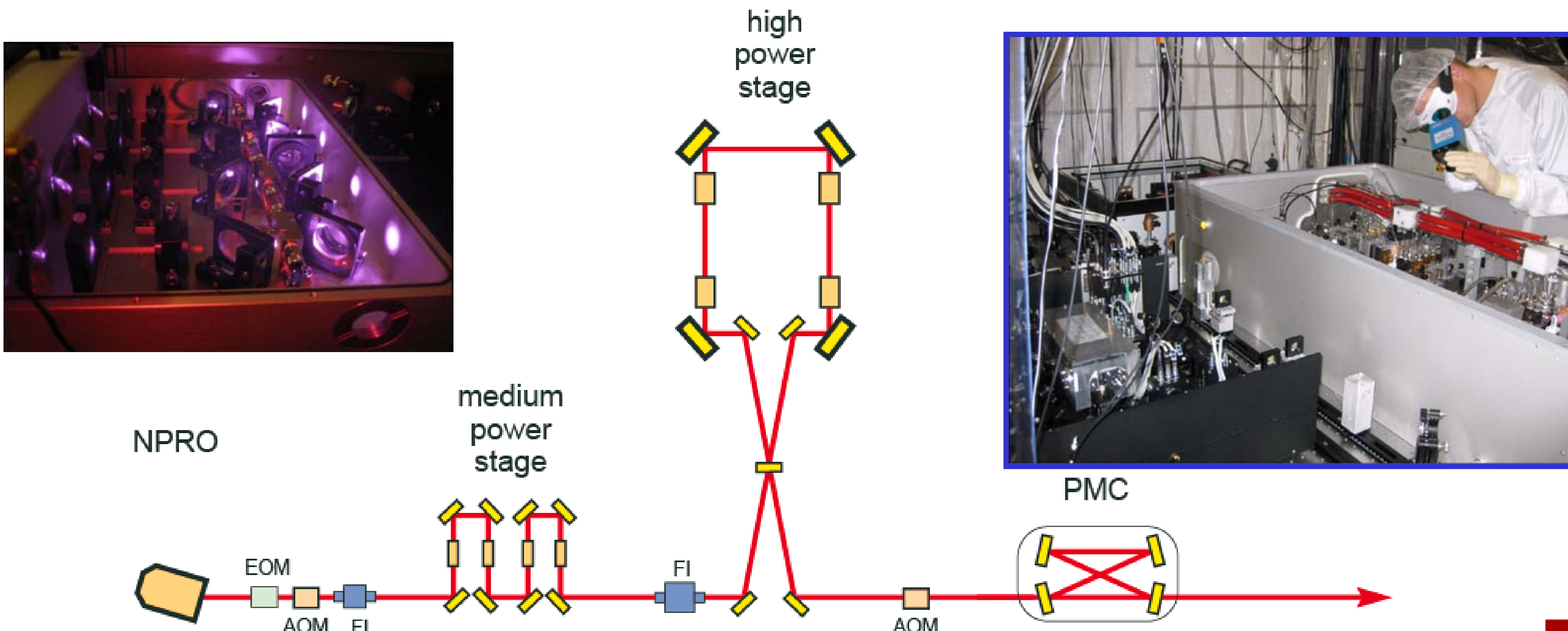
High Power Laser

- single-mode, single- frequency, linear- polarized laser
- Nd:YAG master laser (2 W)
- Nd:YVO amplifier (35 W)
- Nd:YAG injection locked oscillator (200 W)



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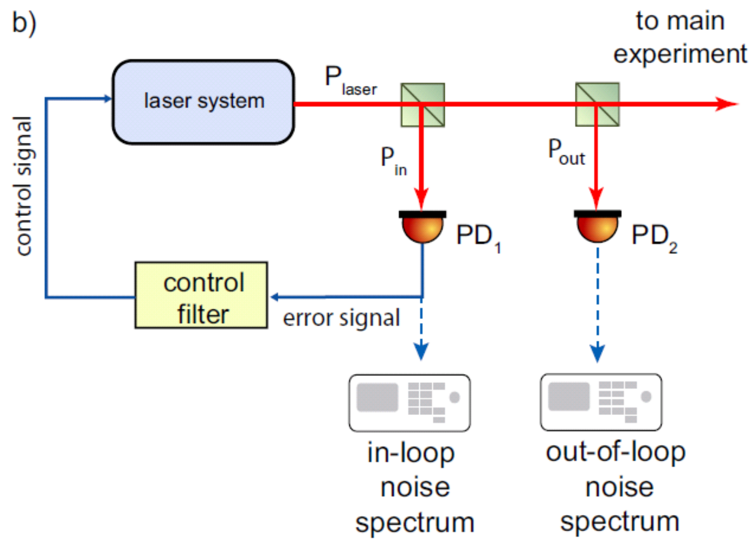
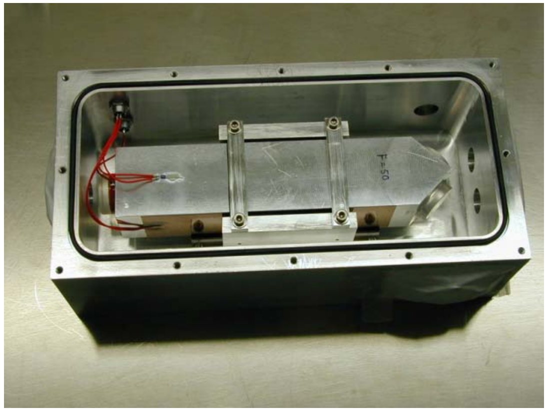
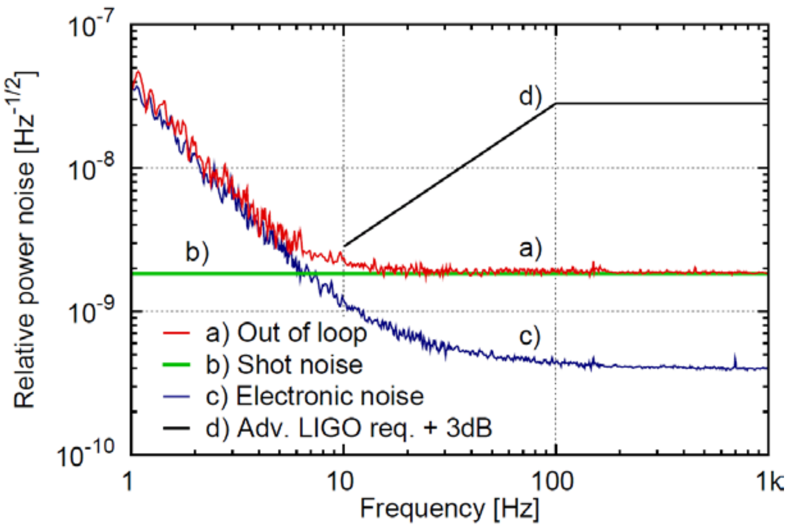
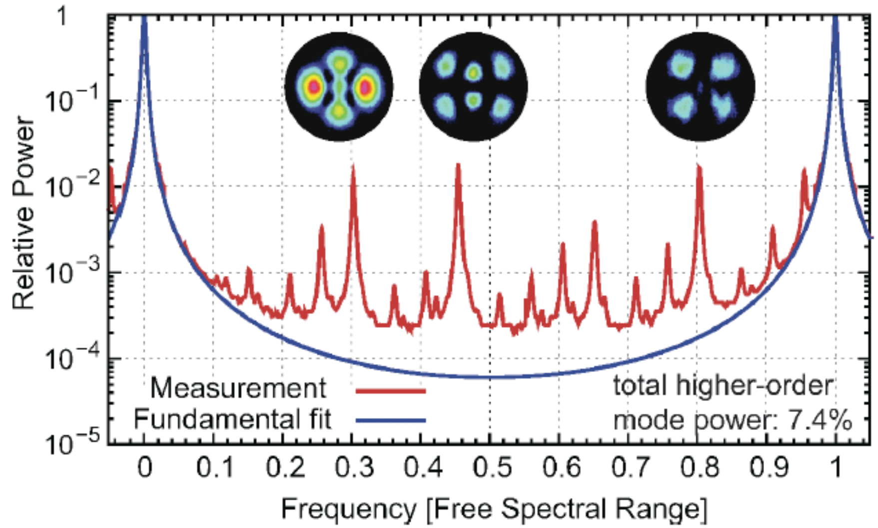
Willke “Stabilized lasers for advanced gravitational wave detectors”
Laser & Photon. Rev., DOI: 10.1002/lpor.200900036

Laser Stabilization



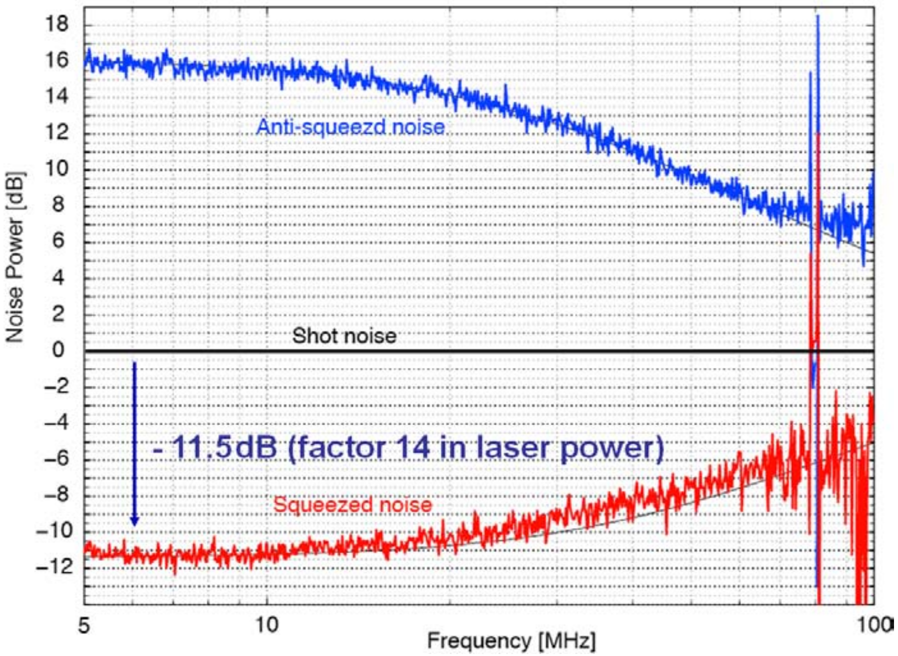


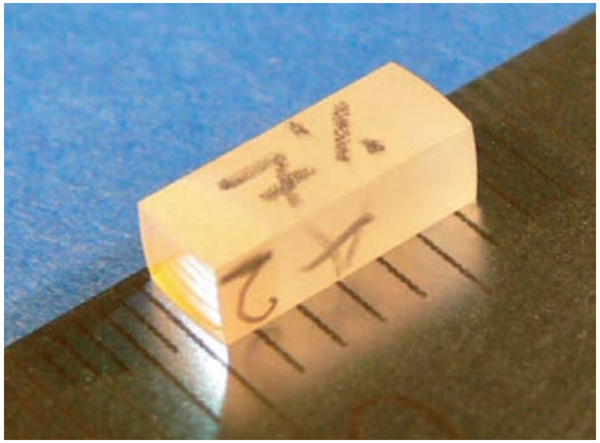




Kwee et al., “Shot-noise-limited laser power stabilization with a high-power photodiode array”, *Opt. Lett*. **34**, 2912 (2009)

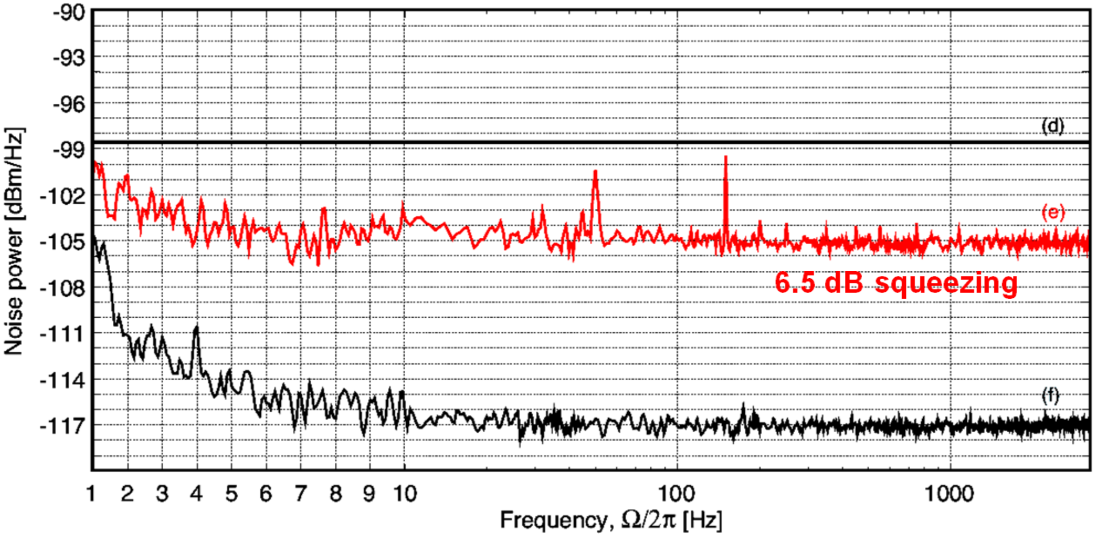
squeezing results at AEI Hannover





χ_2-nonlinear crystal:
$MgO:LiNbO_3$

Mehmet *et al.*,
arXiv:0909.5386v1 [quant-ph]



H. Vahlbruch *et al.*,
New J. Phys. **9**, 371 (2007)

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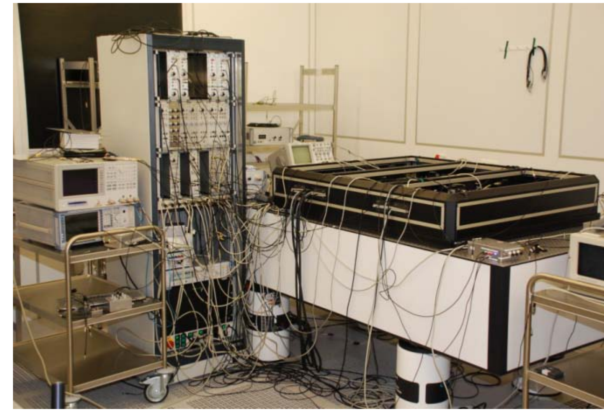
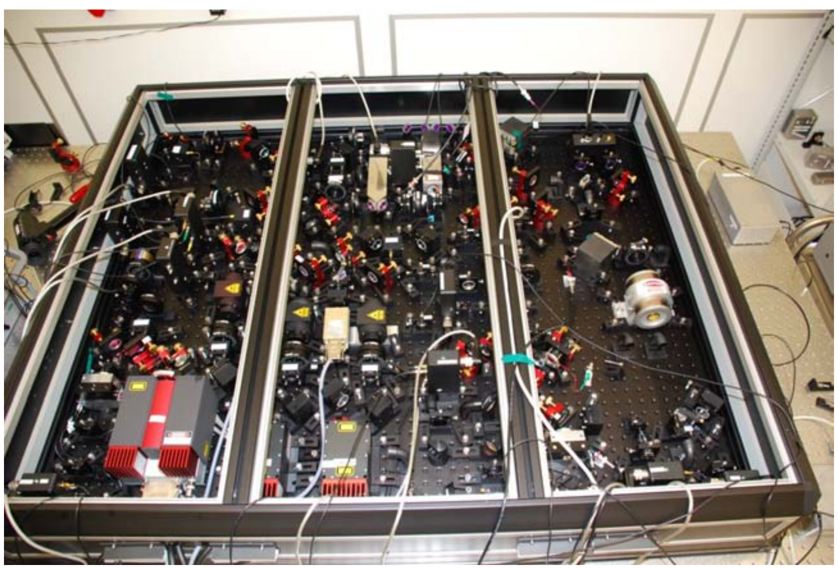
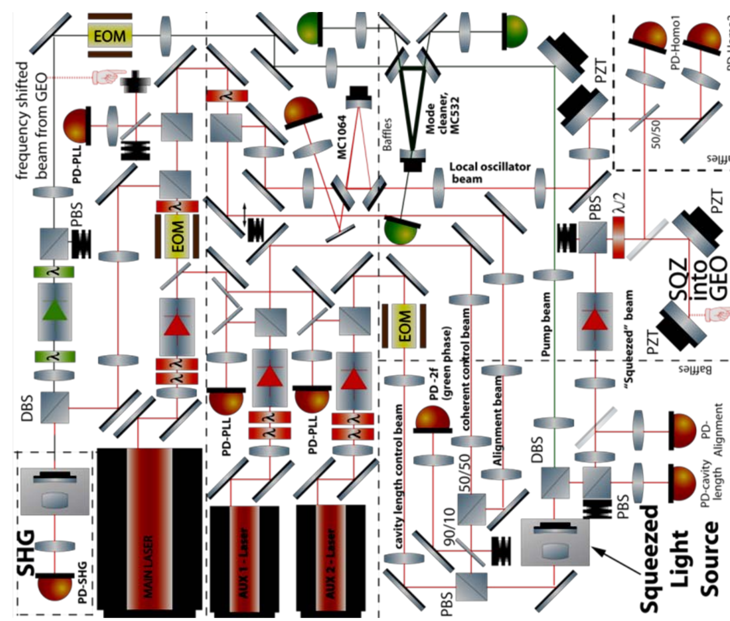
first use of squeezed light in GWDs

- injection of squeezed light into interferometer can reduce quantum noise
- first test at GEO600 in Feb. 2010
- possible implementation in Advance LIGO and Advanced Virgo later

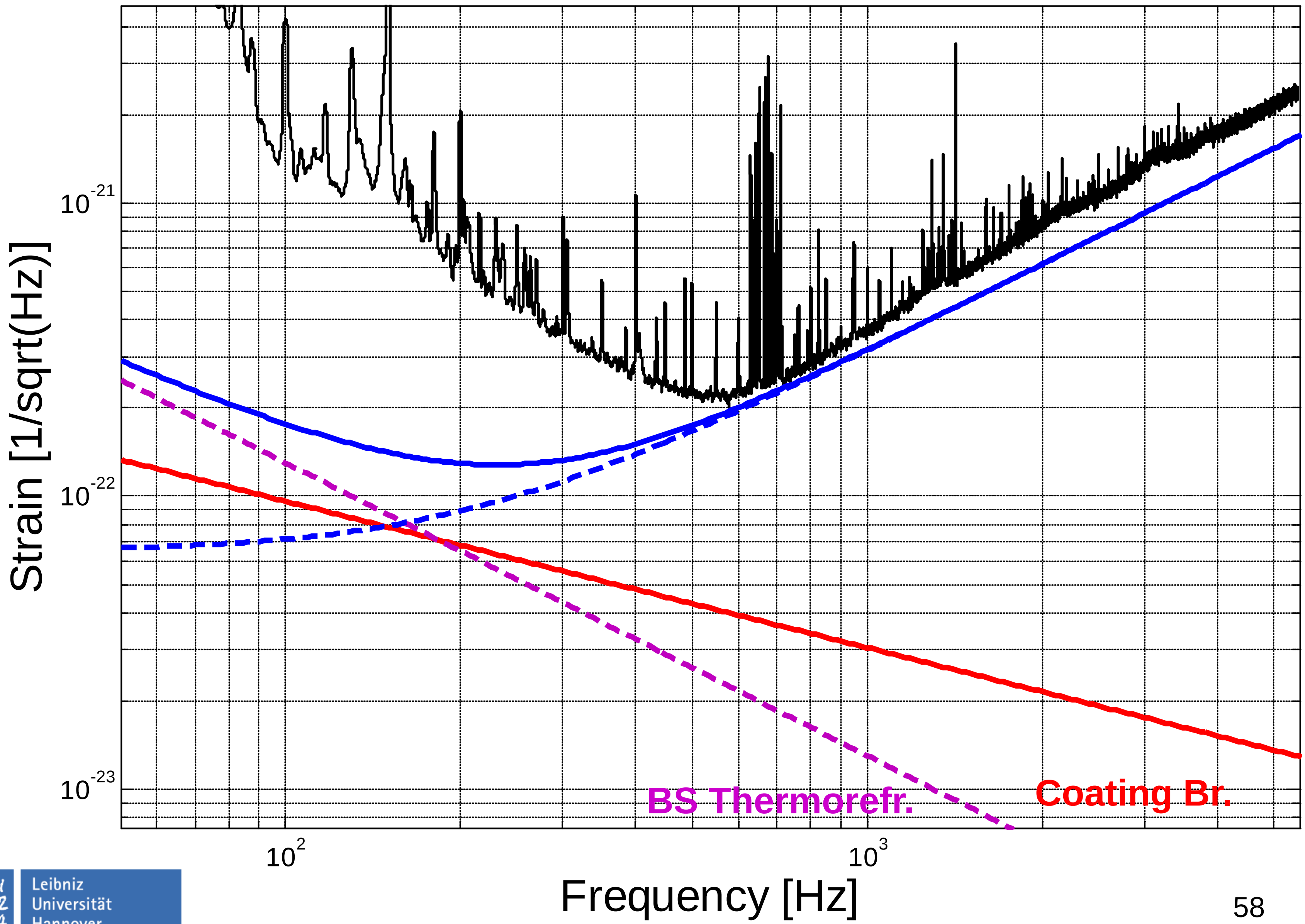






GEO-HF Sensitivities

DC readout, Tuned SR



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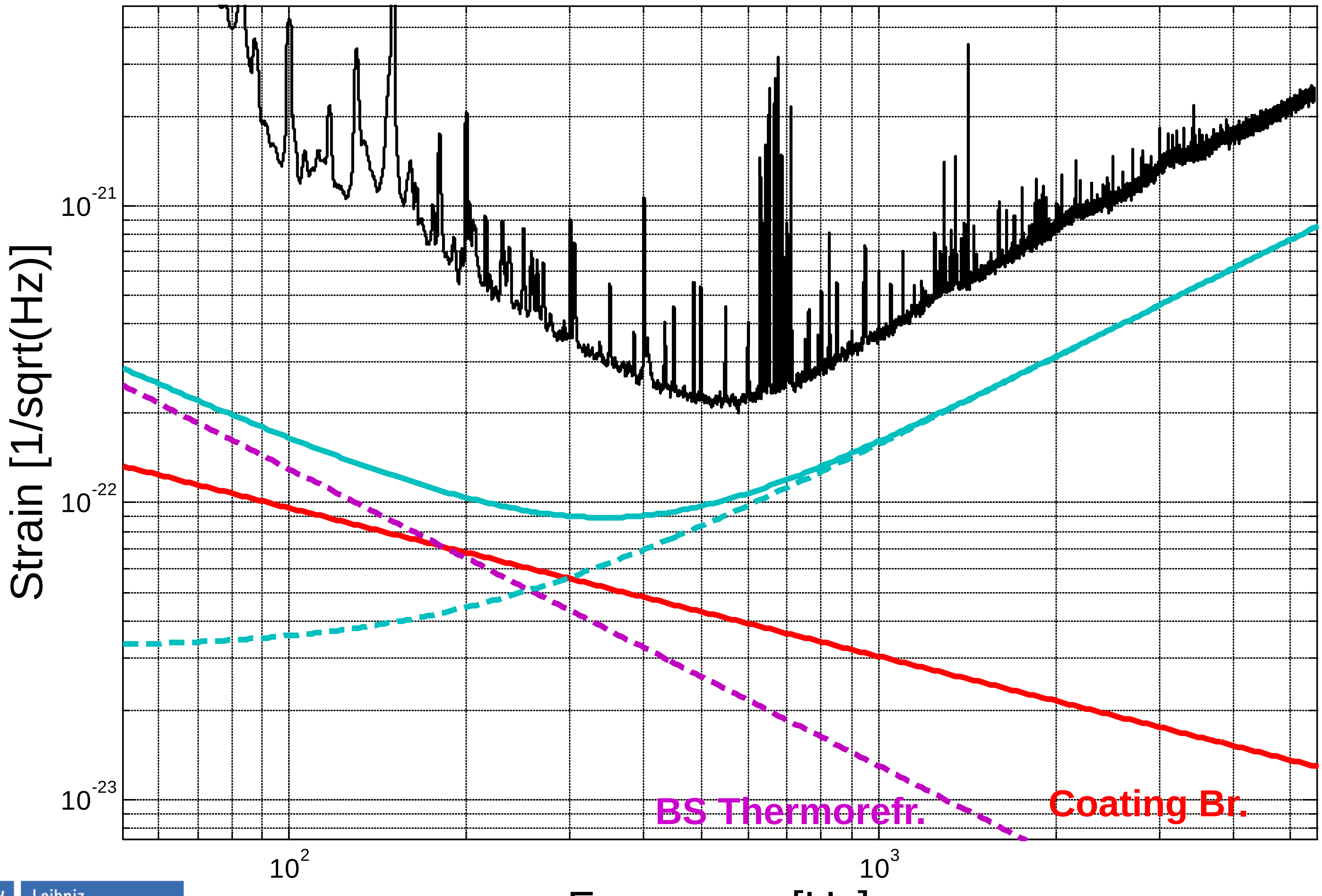
GEO-HF Sensitivities

DC readout, Tuned SR, 6dB Squeezing



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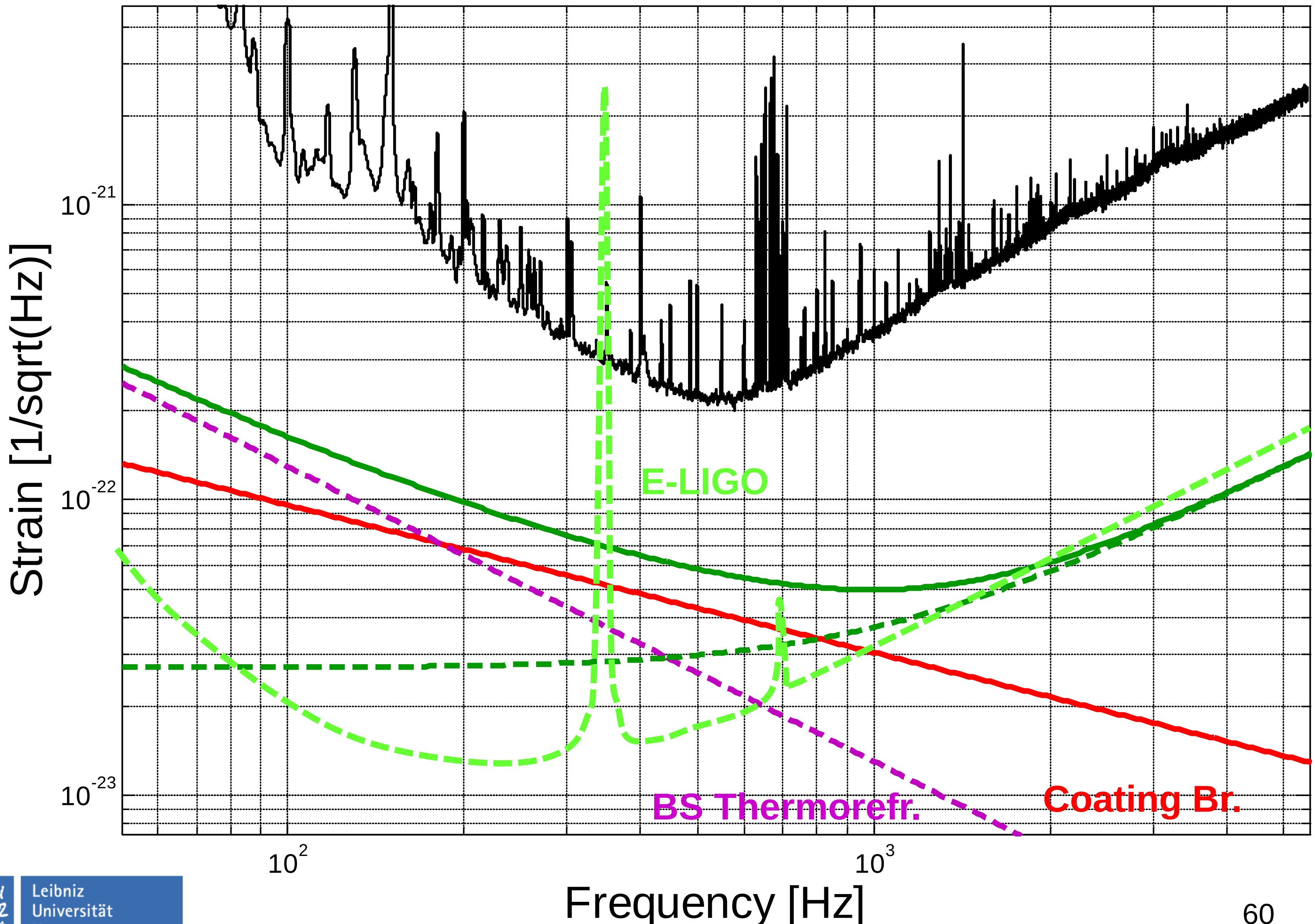
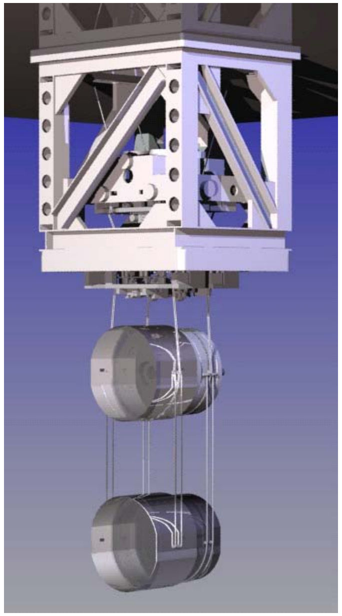
GEO-HF Sensitivities

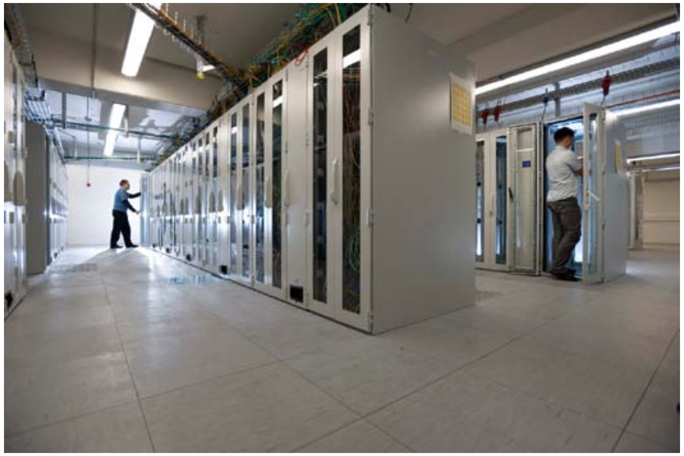
DC readout, Tuned SR, 6dB Squeezing, MSR 10%, 25W input



GEO's involvement in AdvLIGO

- monolithic technology, pendulum damping and control electronic (BOSEMS)
- pre-stabilized high power laser
- data analysis (ATLAS computer cluster)
- intellectual support





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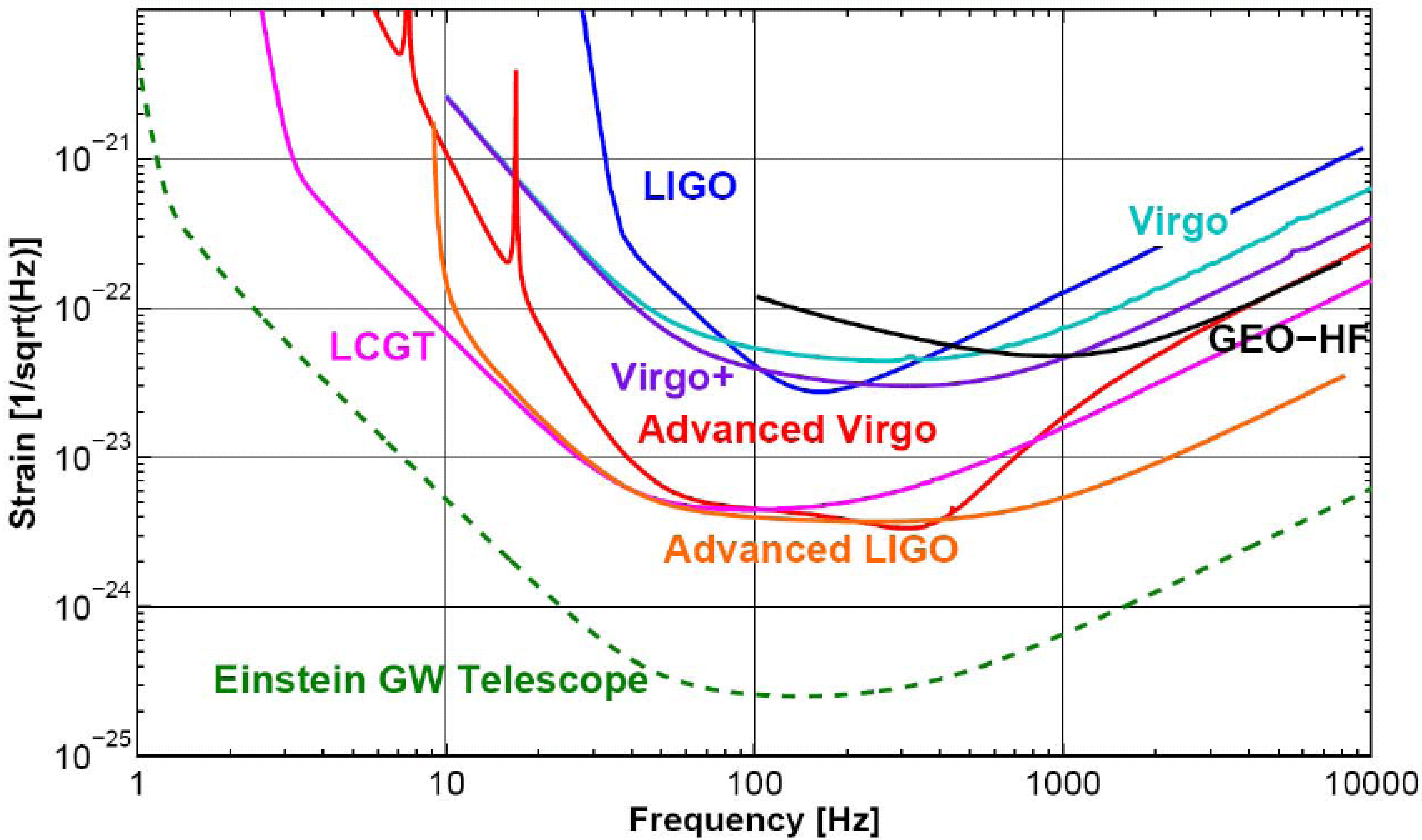
The future of Gravitational Wave Detectors



Our Goal: The Third Generation
The Einstein Gravitational Telescope
E.T.

SEVENTH FRAMEWORK PROGRAMME

- Overall beam tube length ~ 30km
- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic
- Squeezing
- QND Readout

The *Future* Global Network of Gravitational Wave Detectors