Future generation earth-based interferometric gravitational-wave detectors

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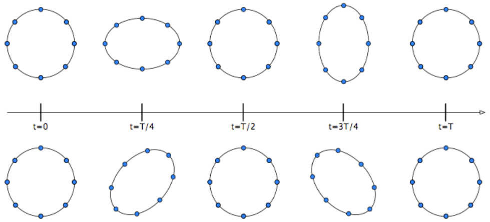
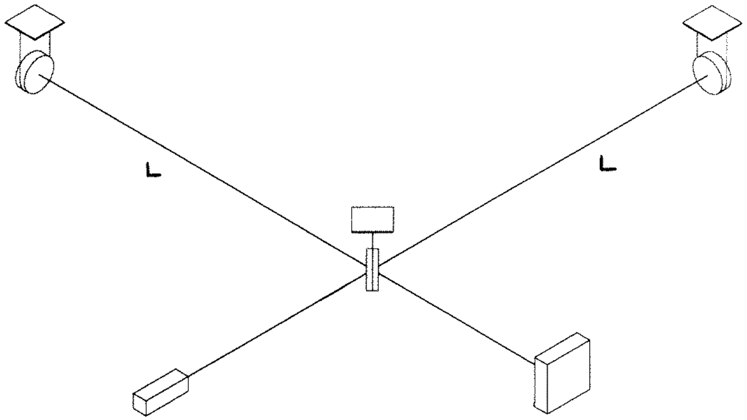
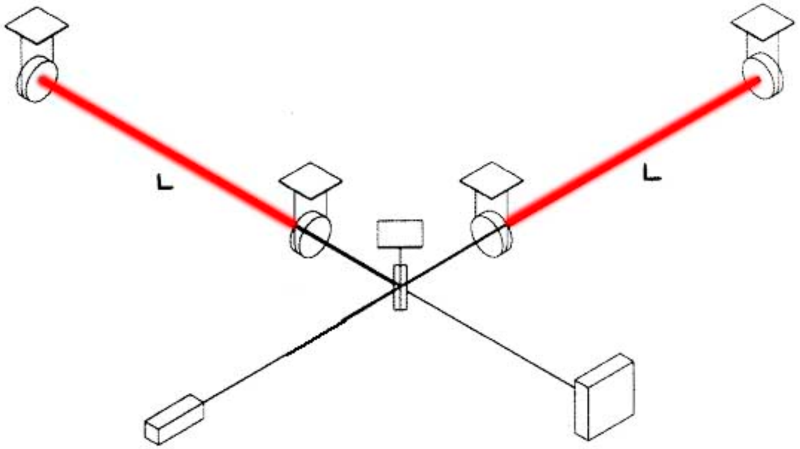
Outline

1. Introduction
2. From *first* to *third* generation detectors
3. The experimental challenges
4. The plans for future detectors

Interferometric detectors



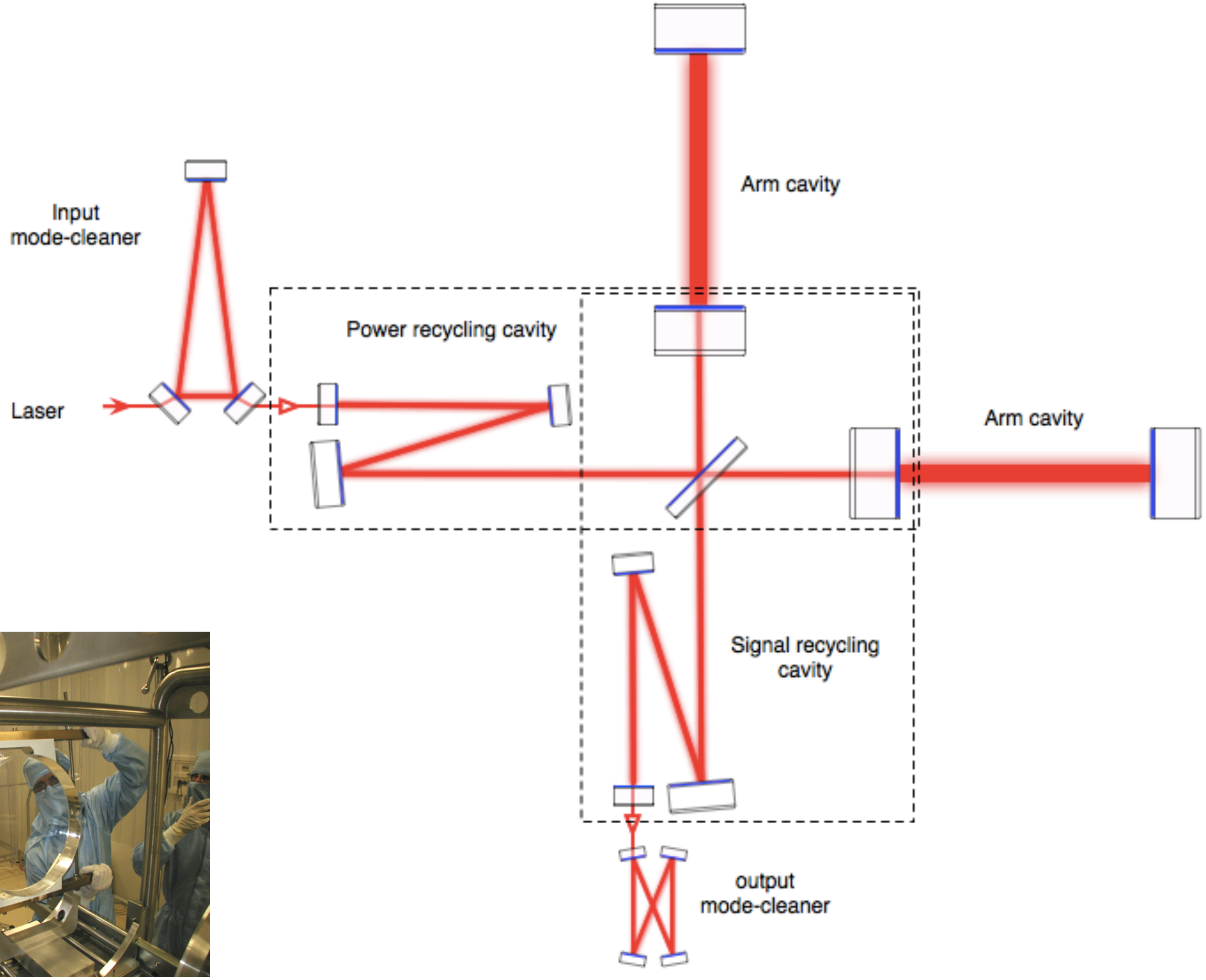


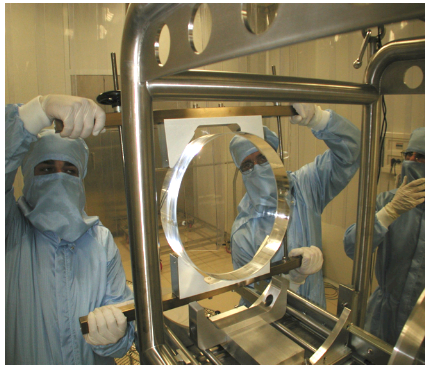


If target $h \sim 10^{-21}$ and $L \sim 10^{3}$ m

$\Delta L \sim 10^{-18}$ m

Interferometric detectors





Bigger instruments

Better instruments

Better places

More wavelenghts

Source: wikipedia

Bigger instruments

Better instruments

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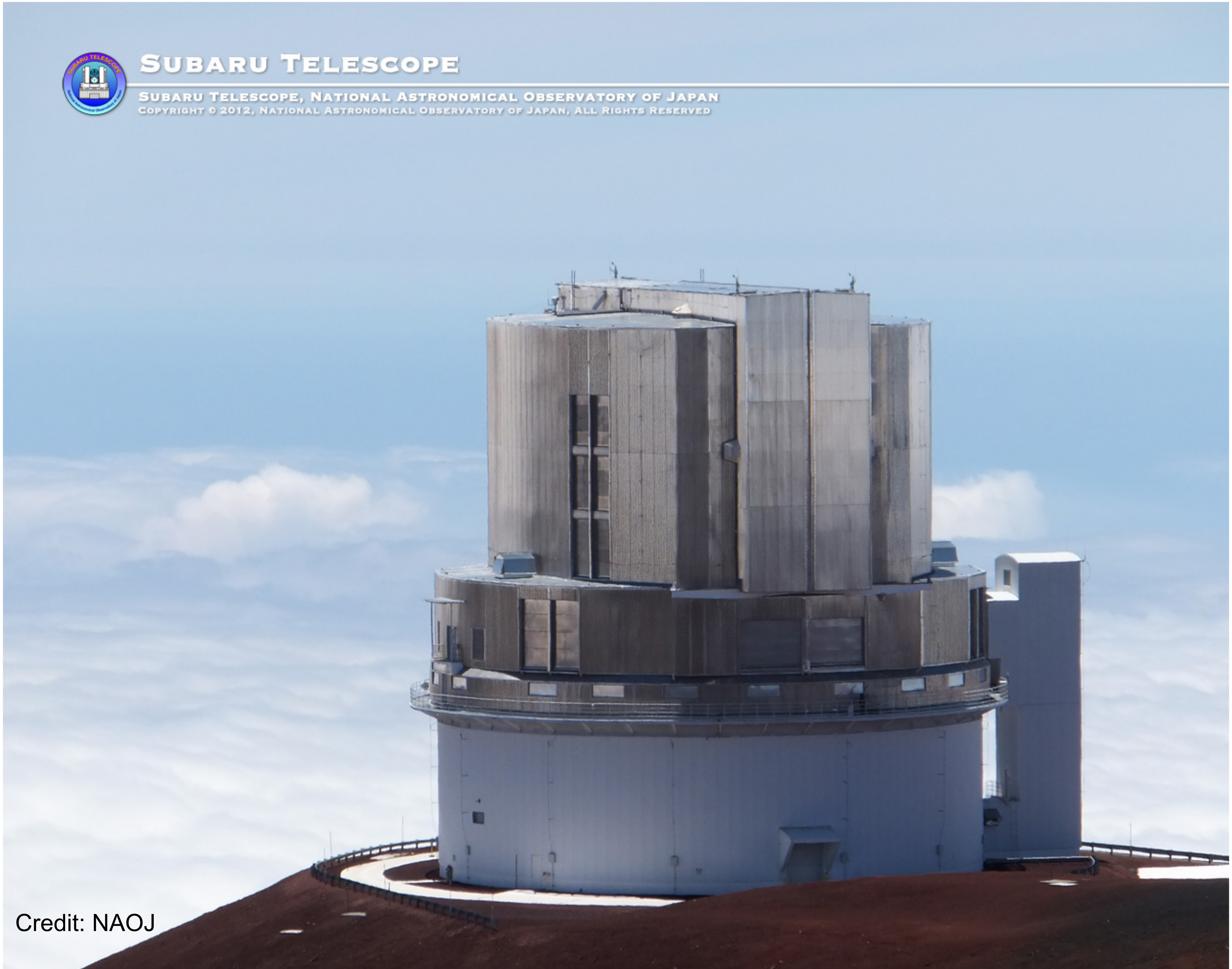
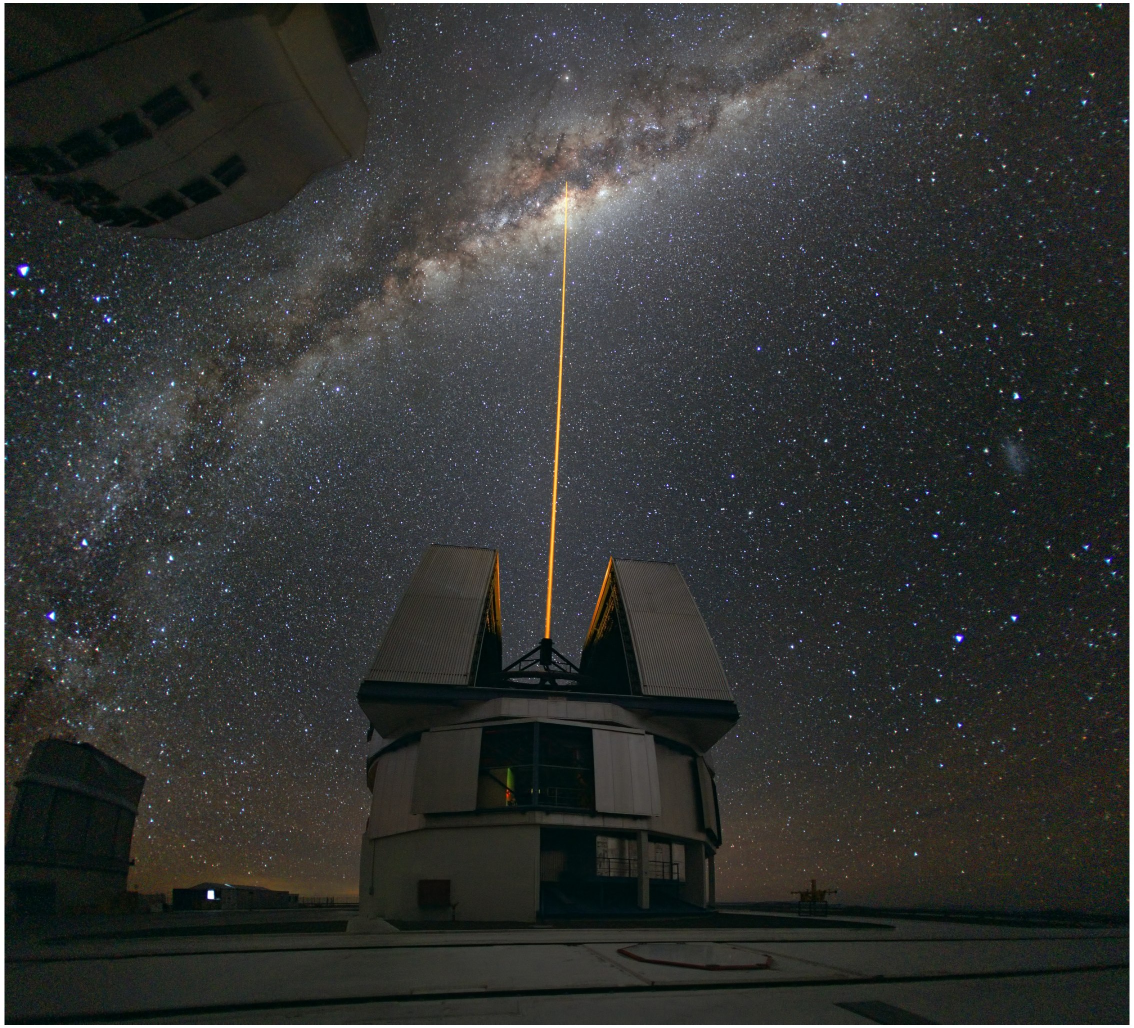
More wavelenghts



SUBARU TELESCOPE

SUBARU TELESCOPE, NATIONAL ASTRONOMICAL OBSERVATORY OF JAPAN

Credit: NAOJ



Source: wikipedia

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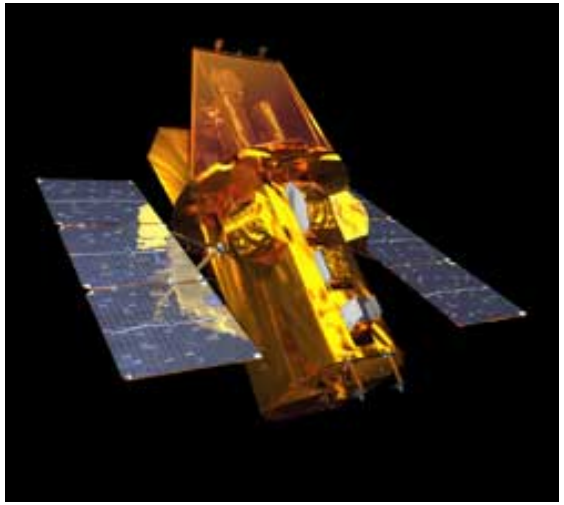
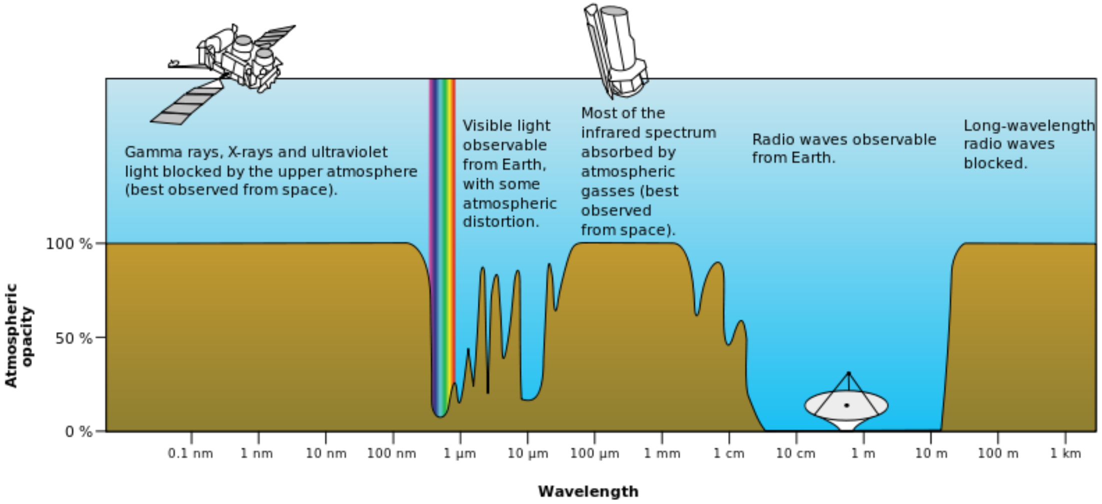


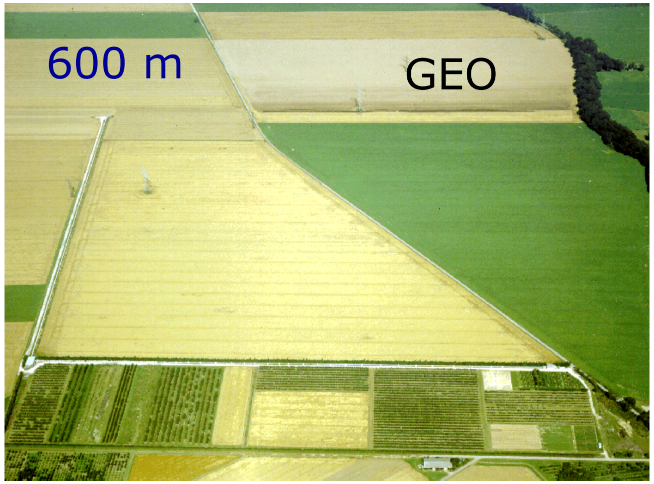


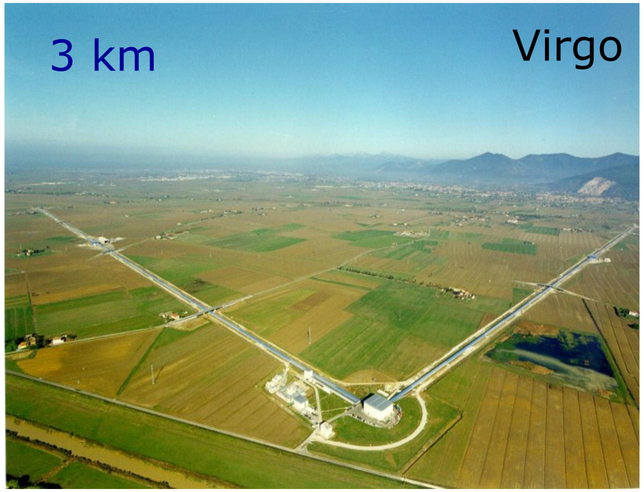
Source: wikipedia

First part

From first to third generation detectors

First generation detectors (~ 2005-2010)

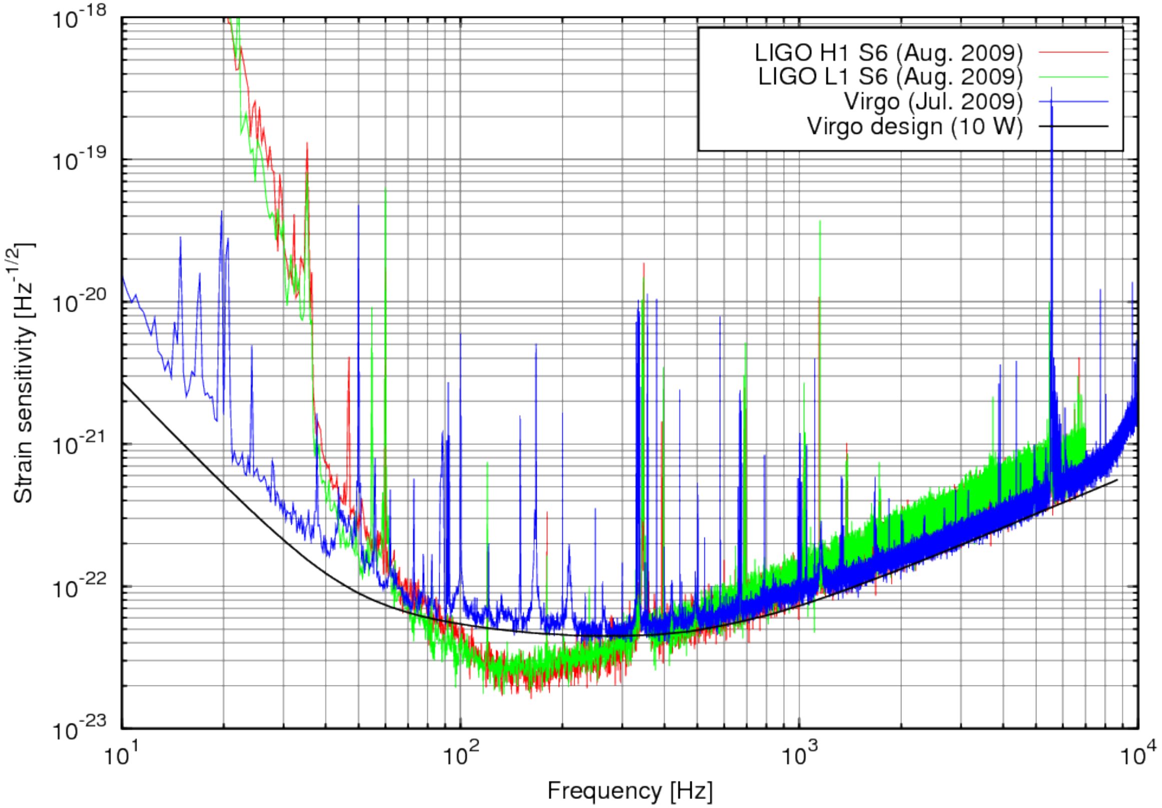




First generation detectors

1. Demonstration of the technology
2. Demonstration of the data analysis techniques
3. Upper limits on astrophysical sources
4. First multi-messenger observations

First generation detectors: sensitivities

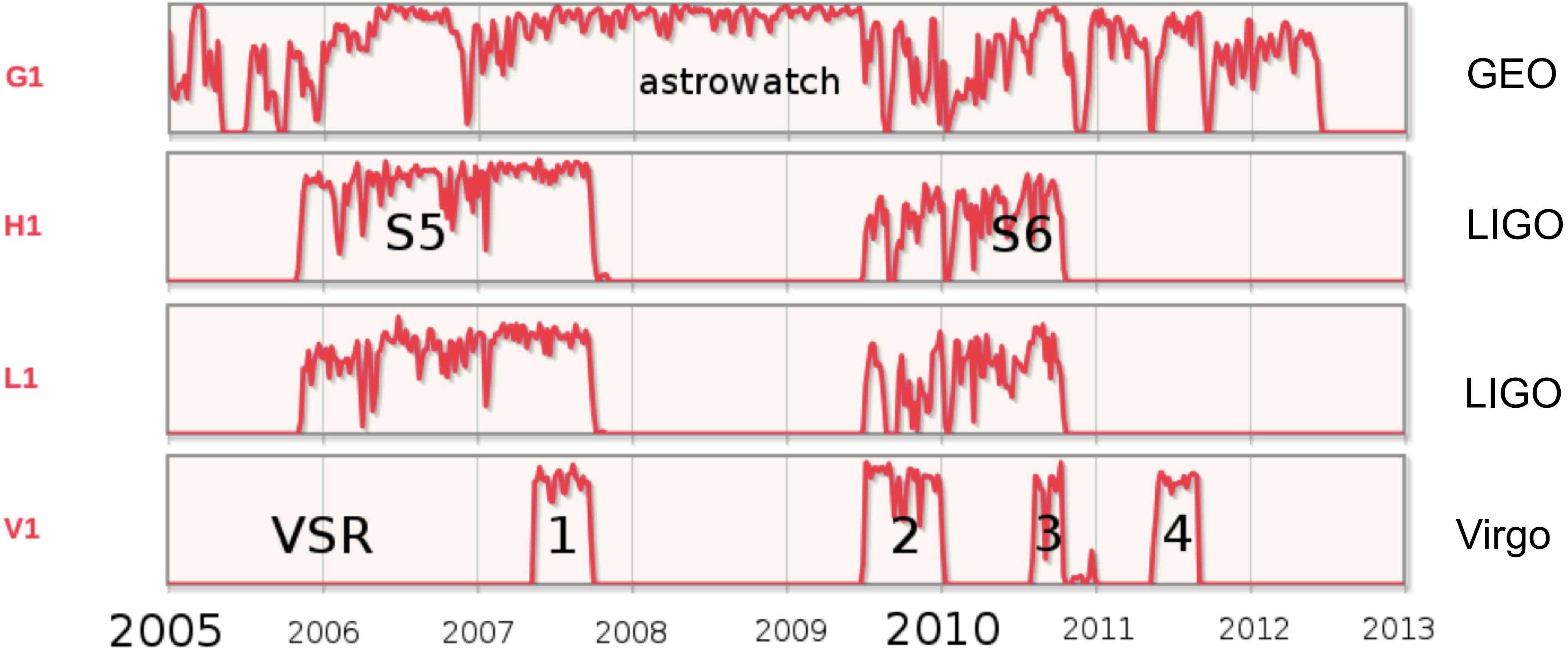


Best NS-NS horizon

LIGO ~ 20 Mpc
Virgo ~ 10 Mpc

- Sensitivities at design level
- Excellent duty cycles (up to ~80%)
- km scale GW interferometer technology demonstrated

Data takings



Data analysis challenges in gravitational-wave astronomy, E.Chassande-Mottin for the LIGO and Virgo Collaborations, arXiv 1210.7173v1 (2012)

Example of upper limits : pulsars

Upper limits on GW energy release by the pulsar, and on the pulsar ellipticity

116 known millisecond and young pulsars

- Best h limit 2.3 x 10 $^{-26}$ (J1603-7202)

- Best ε limit 7 x 10^{-8} (J2124-3358)

Crab (~ 60 Hz) LIGO data

- GW energy < 2% spin-down limit
- $\varepsilon < 1.3 \times 10^{-4}$

Vela @ (~ 22 Hz) Virgo data

- GW energy < 2% spin-down limit
- $\varepsilon < 1.1 \times 10^{-3}$

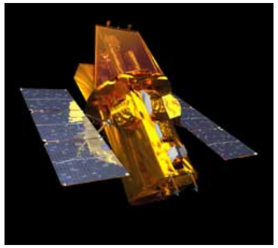
LIGO Scientific Collaboration, "*Beating the spin-down limit on gravitational wave emission from the Crab pulsar*", Astrophys. J. Lett. 683 (2008) 45

LIGO Scientific and Virgo Collaborations, "*First search for gravitational waves from the youngest known neutron star*", Astrophys. J. 722 (2010) 1504

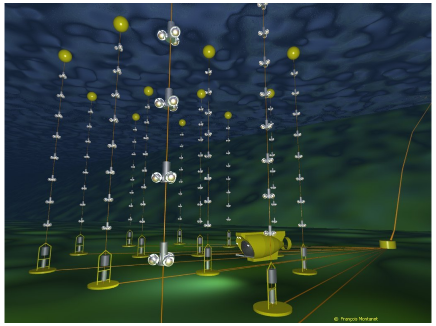
LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Vela pulsar,*" Astrophys. J. 737 (2011) 93

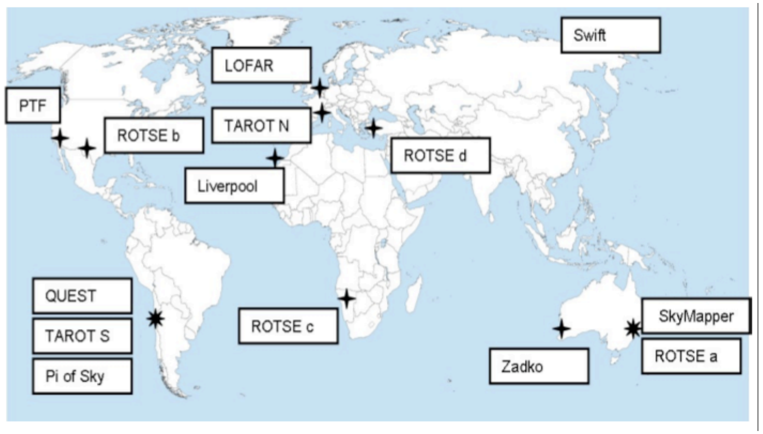
LIGO Scientific and Virgo Collaborations, "*Searches For Gravitational Waves From Known Pulsars With Science Run 5 LIGO Data*", Astrophys. J. 713 (2010) 671

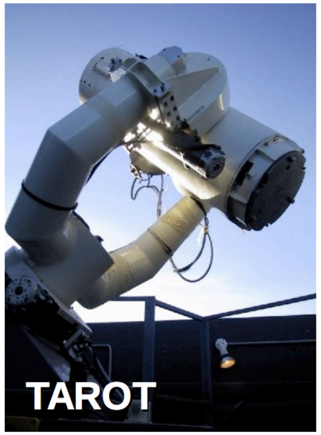
Multi-messenger projects



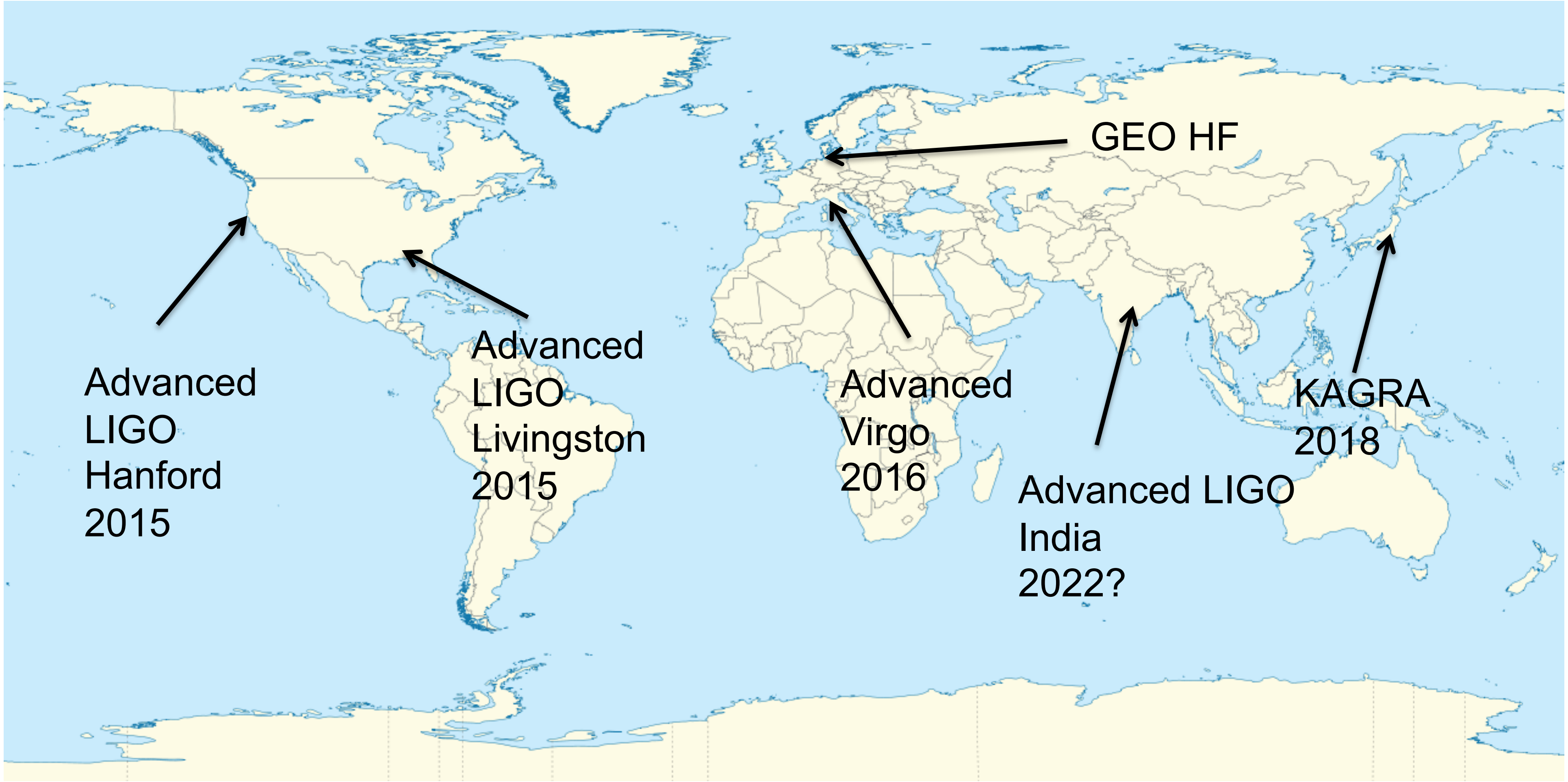
- Electromagnetic follow-up
  - SWIFT (X/UV/optical), Fermi (gamma), LOFAR (radio)
  - Wide field optical telescope (~ a few square degrees)
    - ROTSE, TAROT, SkyMapper, Pi of the Sky, PTF
  - Narrow-field telescopes (~ tens of arcmin)
    - Liverpool telescope, Zadko
- High-energy neutrinos
  - Exchange of triggers with Antares and IceCube







Second generation detectors



GEO HF

Advanced LIGO Hanford 2015

Advanced LIGO Livingston 2015

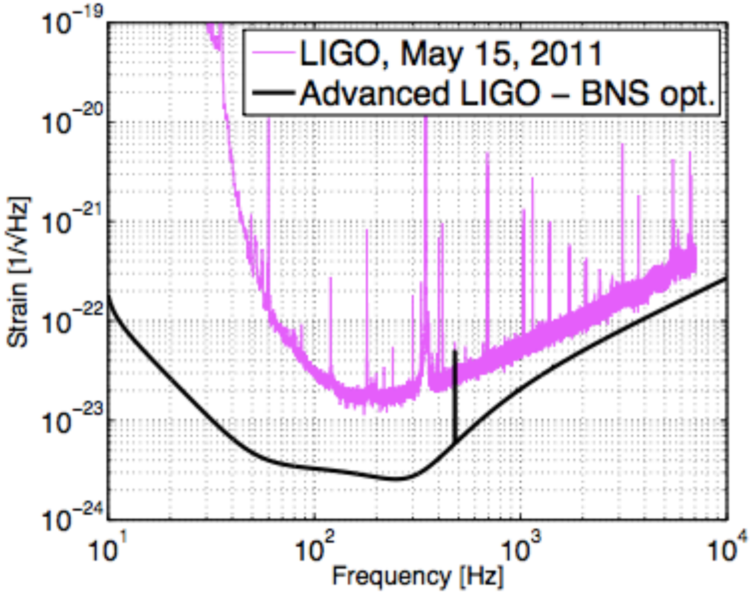
Advanced Virgo 2016

Advanced LIGO India 2022?

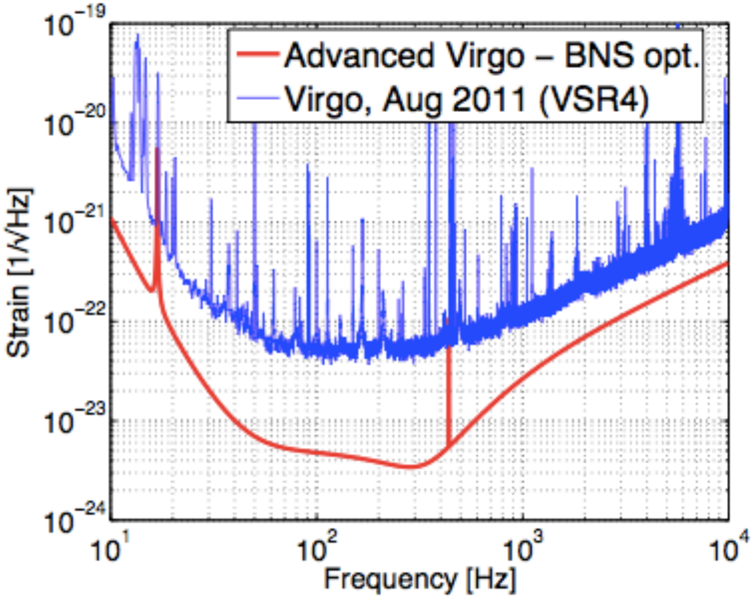
KAGRA 2018

Second generation detectors

Advanced LIGO



Advanced Virgo



X 10 sensitivity increase → x1000 rate increase

1 day of AdVirgo/aLIGO = 3 years of Virgo/LIGO

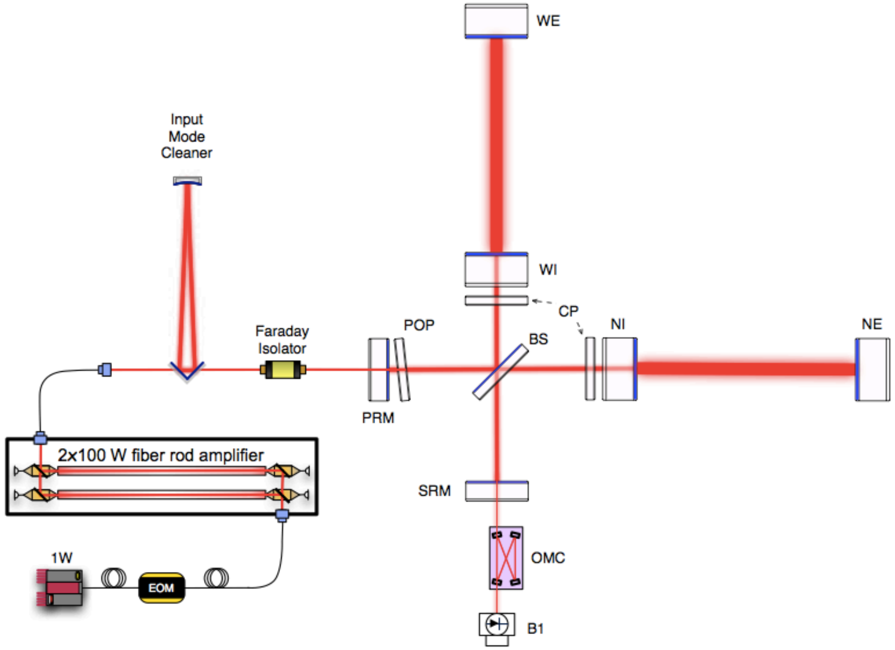
Advanced Virgo main improvements

Quantum noise

- Higher laser power (20→200 W)
- Signal recycling
- Higher Fabry-Perot cavities finesse (150→450)
- Heavier mirrors 20→ 40 kg
- Better mirrors optical quality
- Better thermal compensation system
- « DC » detection

Thermal noise

- Bigger beam size (2→ 5 cm)
- Monolithic suspensions (already tested in Virgo)
- Better mirrors material (mechanical losses)



Second generation detectors: science case

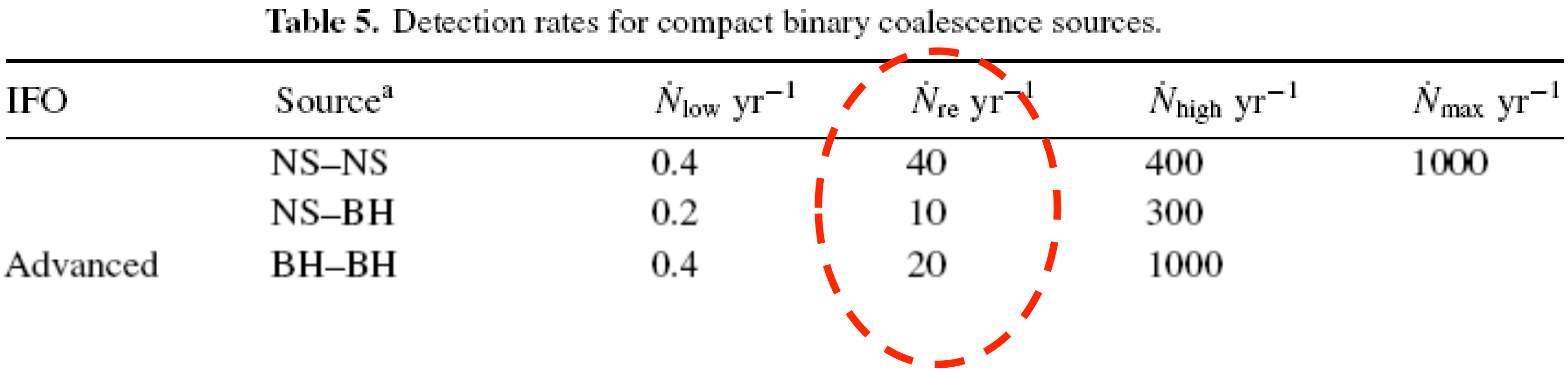


Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	

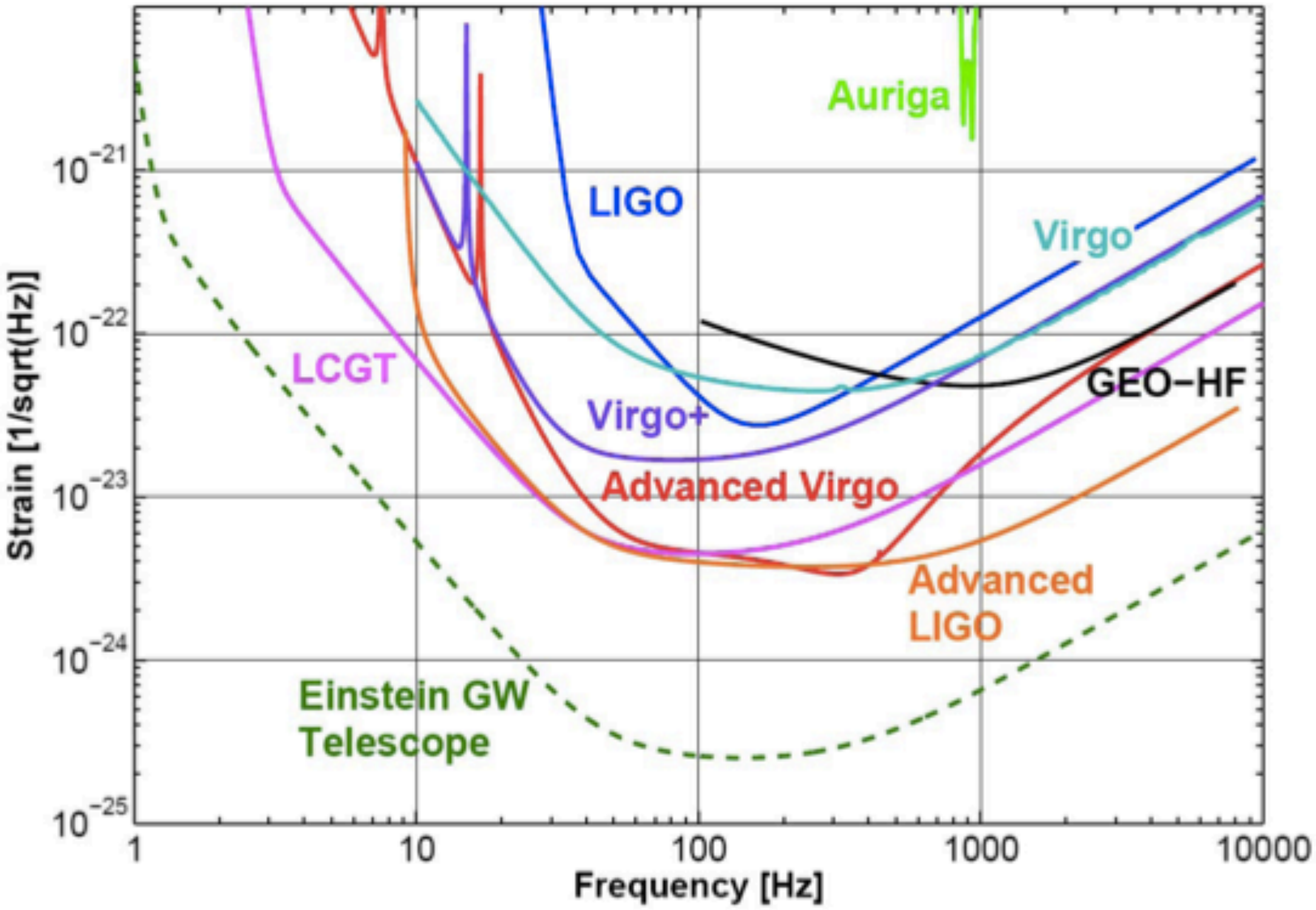
☐ NS-NS ~ 200 Mpc

☐ BH-BH ~ 1 Gpc

Likely detection by second generation interferometers

J.Abadie et al, “Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors", Class Quantum Grav. 27 173001(2010)

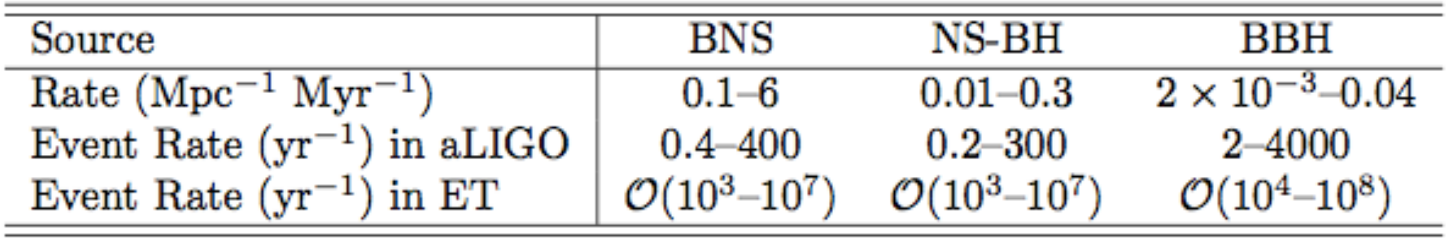
Sensitivities of present and future detectors



The science of a 3rd generation detector

- ☐ Huge number of sources
- ☐ Cosmological distances
- ☐ “Precision” gravitational-wave astronomy
- ☐ Complementary with eLISA

Example: compact coalescences with ET



Source	BNS	NS-BH	BBH
Rate ($\mathrm{Mpc}^{-1}\ \mathrm{Myr}^{-1}$)	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	$\mathcal{O}(10^3$–$10^7)$	$\mathcal{O}(10^3$–$10^7)$	$\mathcal{O}(10^4$–$10^8)$

- ❑ Detection of 500 NS-NS coalescences at low redshift → Hubble constant with an error of 0.5%
- ❑ Compact object coalescences can be used as distance standard: *standard sirens* (Shultz, Nature, 1986)

From: Einstein Telescope
conceptual design study,
www.et-gw.eu

Example: Understading SMBH with ET

- Which is the origin of supermassive black-holes at the center of galaxies?
- Do the intermediate black-holes exist?
- Observation of BH binaries in the range 10-10^3 will allow to discriminate between *seed scenarios* formation.
- Complementary information with respect to LISA

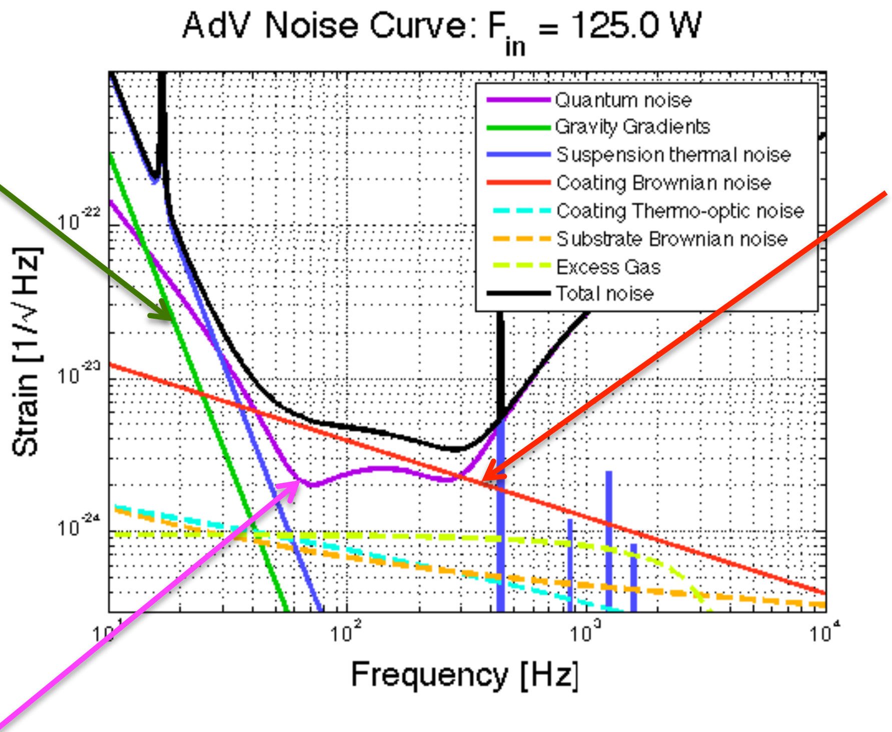
Einstein Telescope conceptual design study, www.et-gw.eu

Second part

(some of) The experimental challenges

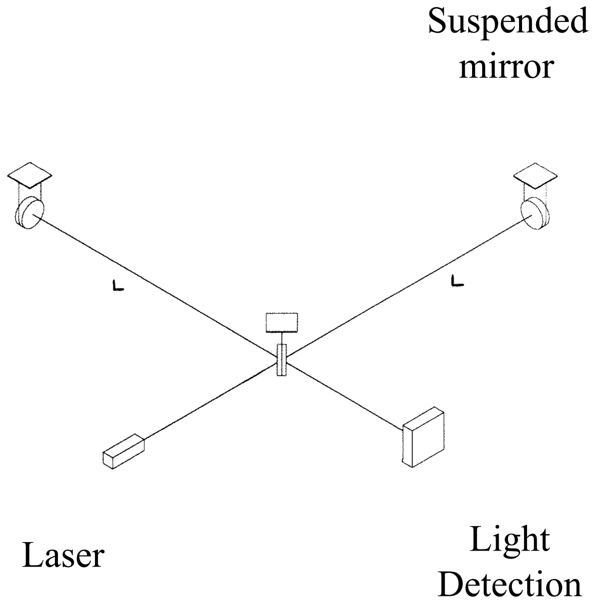
Noises limiting a 2nd generation detector

Seismic and gravity gradient noise
Geophysics



Thermal noise
Thermodynamics

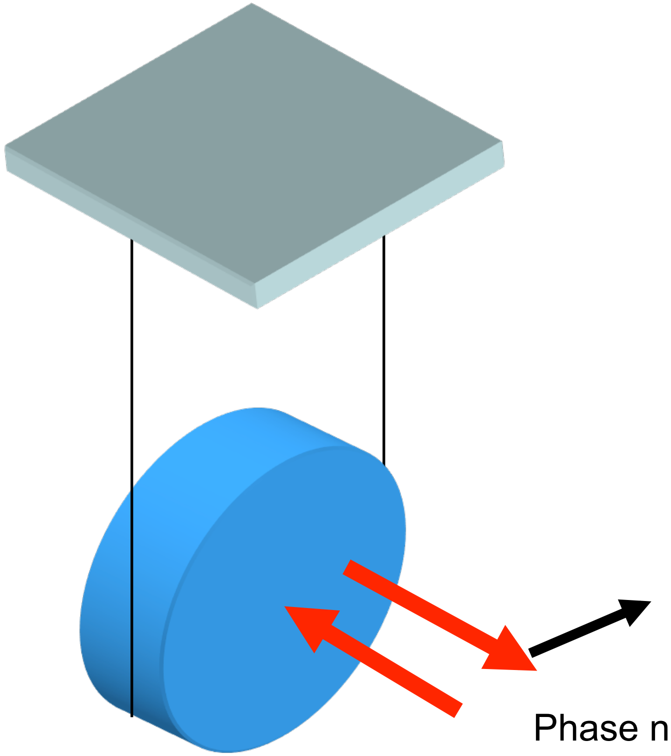
Quantum noise
Quantum mechanics



The thermal noise

For a review on the thermal noise:
Optical Coatings and Thermal Noise in Precision Measurement, Cambridge University Press, 2012

Thermal noise: introduction



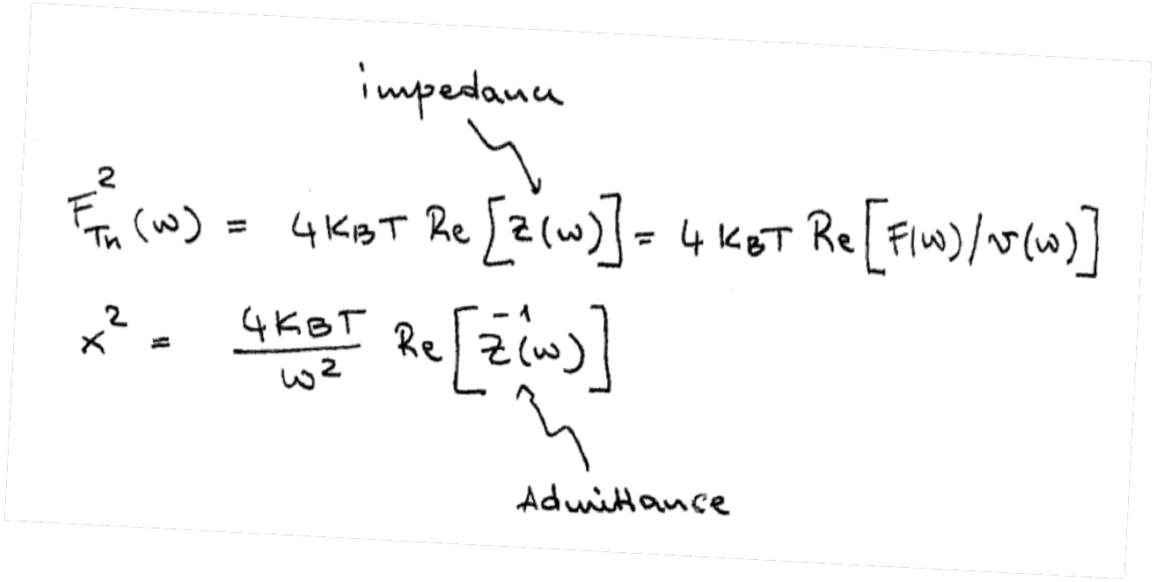
- E= ½ KT (per d.o.f.) → the RMS value of the displacement is constant

- What is the distribution of thermal energy versus the frequency? How this energy is converted in displacement?

What is the *power spectrum* of thermal noise?

Th. noise: Fluctuation-dissipation theorem

- *there is a relation between the response of a driven dissipative system and the spontaneous fluctuations of a generalized variable (i.e. the position) of the system in equilibrium:* the fluctuation dissipation-stheorem (Callen 1951).
- Brownian motion and Johnson-Nyquist noise are special cases $V^2 = 4K_BTR$



$$F^2_{Th}(\omega) = 4K_BT\,\mathrm{Re}\Big[\overset{\text{impedance}}{Z(\omega)}\Big] = 4K_BT\,\mathrm{Re}\big[F(\omega)/v(\omega)\big]$$

$$x^2 = \frac{4K_BT}{\omega^2}\,\mathrm{Re}\Big[\underset{\text{Admittance}}{Z^{-1}(\omega)}\Big]$$

Thermal noise: harmonic oscillator

P.R.Saulson, “Thermal noise in mechanical experiments”, Phys Rev D 42 8 (1990)

- ☐ Harmonic oscillator with viscous damping

$m\ddot{x} + \beta\dot{x} + Kx = F$ $\quad -\beta\dot{x}$ viscous damping

$Z(\omega) = \beta + i\omega m + \frac{K}{i\omega}$ $\quad \mathrm{Re}[Z(\omega)] = \beta$

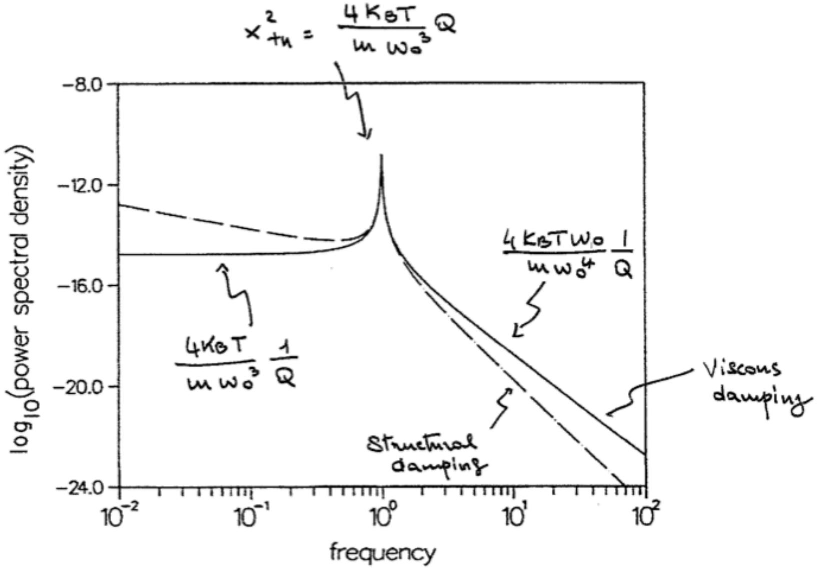
$$x^2_{th} = \frac{4k_BT\beta}{(K-m\omega^2)^2+\omega^2\beta^2}$$ Thermal noise

- ☐ Harmonic oscillator with structural damping

$m\ddot{x} + K(1+i\phi)x = F$ $\quad$ structural damping

$$x^2 = \frac{4k_BT\phi}{(K-m\omega^2)^2+K^2\phi^2}\cdot\frac{1}{\omega}$$

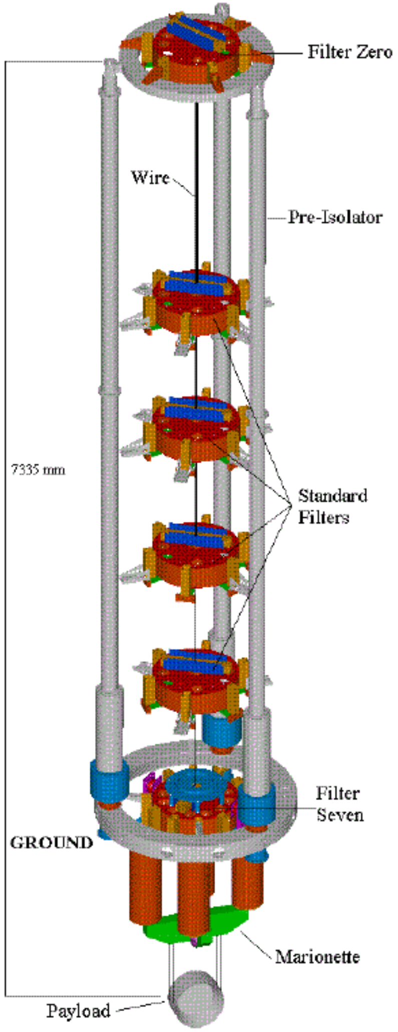
$$Q = \frac{1}{\phi(\omega_0)}$$



Q = sharpness of the resonance $= \frac{\omega_0}{\Delta\omega}$

$Q = \frac{m\omega_0}{\beta}$

Thermal noise in GW detectors

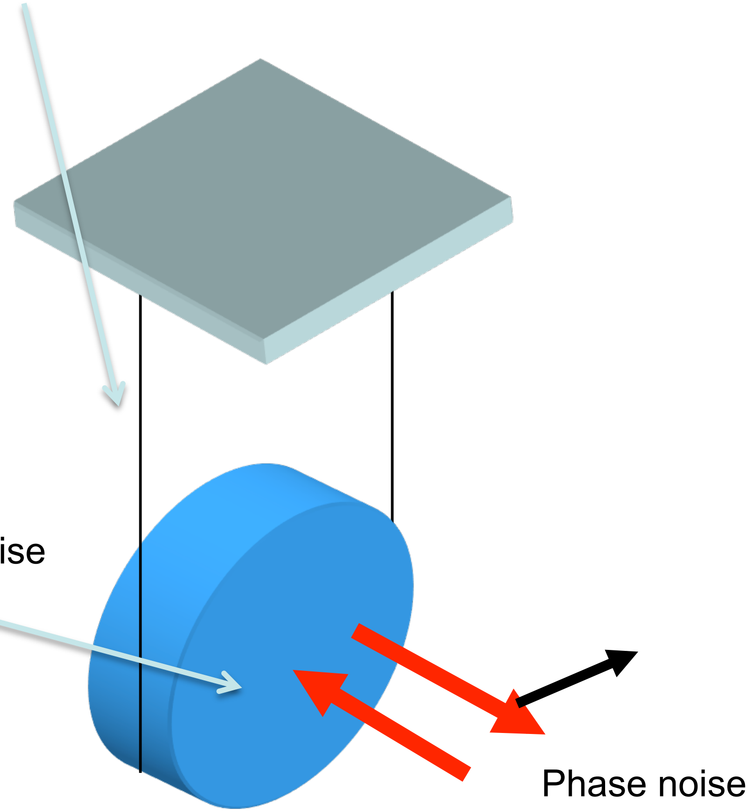


« Pendulum » thermal noise

f ~ 1 Hz → thermal noise above resonance

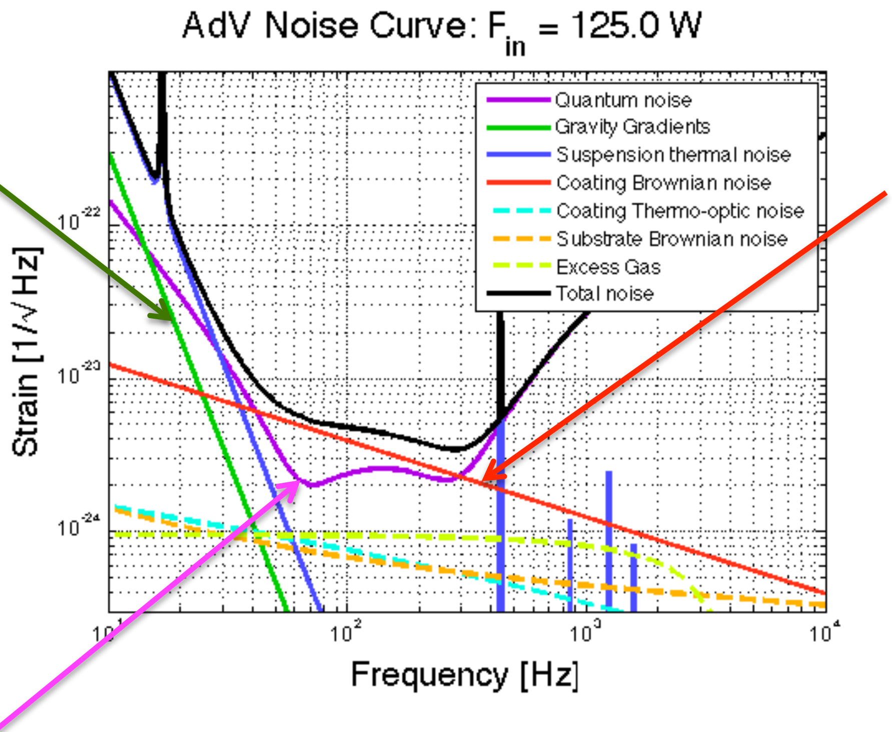
« Mirror » thermal noise

f ~ a few kHz → Thermal noise below resonance



Noises limiting a 2nd generation detector

Seismic and gravity gradient noise
Geophysics



Thermal noise
Thermodynamics

Quantum noise
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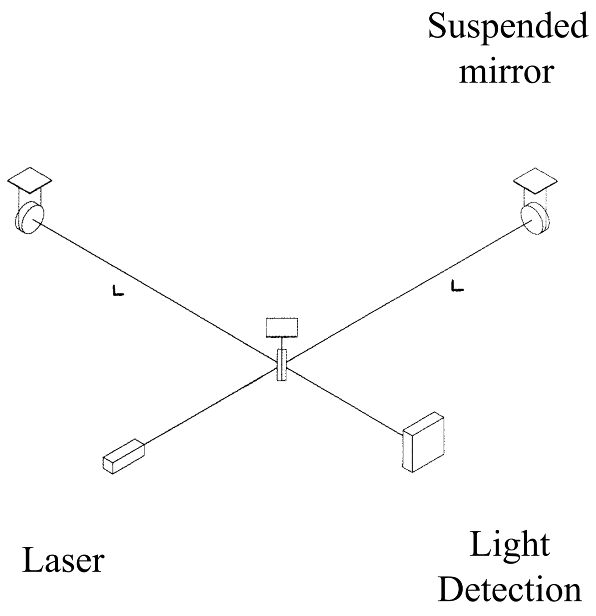
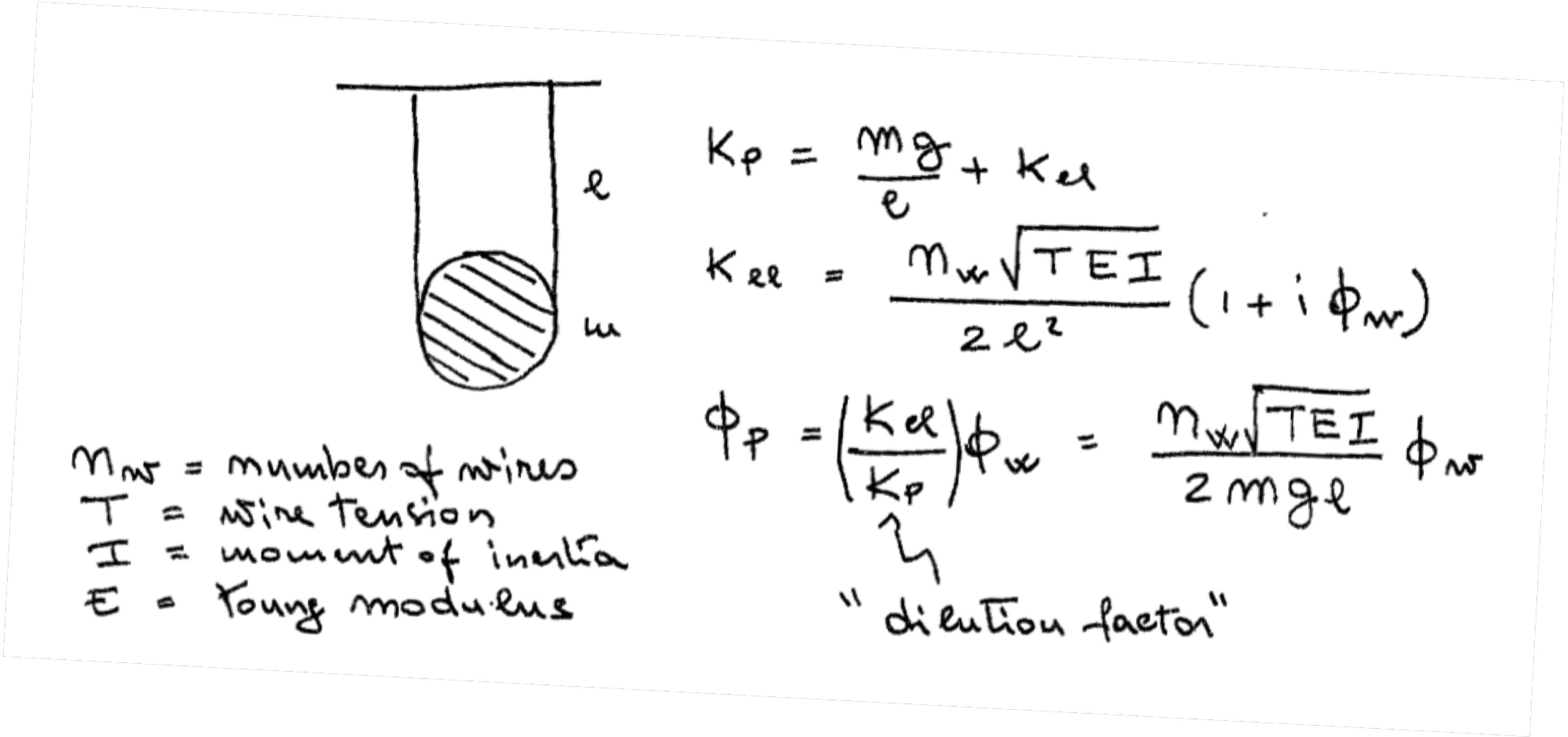


Pendulum thermal noise



$$K_p = \frac{mg}{\ell} + K_{e\ell}$$

$$K_{e\ell} = \frac{n_w \sqrt{TEI}}{2\ell^2}(1 + i\phi_w)$$

$$\phi_p = \underbrace{\left(\frac{K_{e\ell}}{K_p}\right)}_{\text{"dilution factor"}} \phi_w = \frac{n_w \sqrt{TEI}}{2mg\ell}\phi_w$$

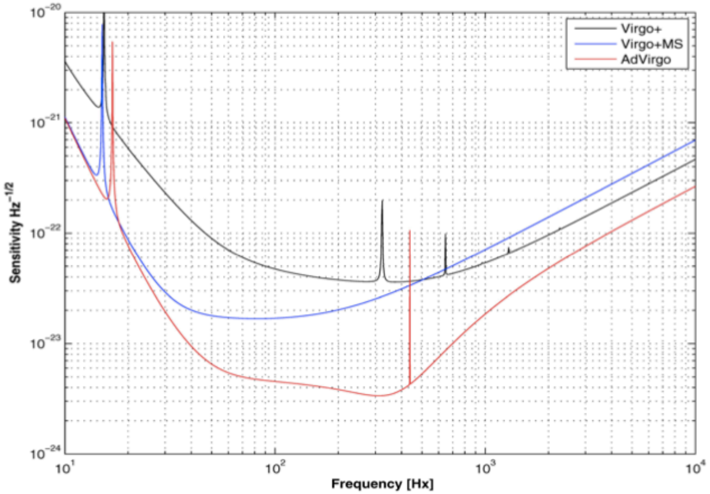
n_w = number of wires
T = wire tension
I = moment of inertia
E = Young modulus

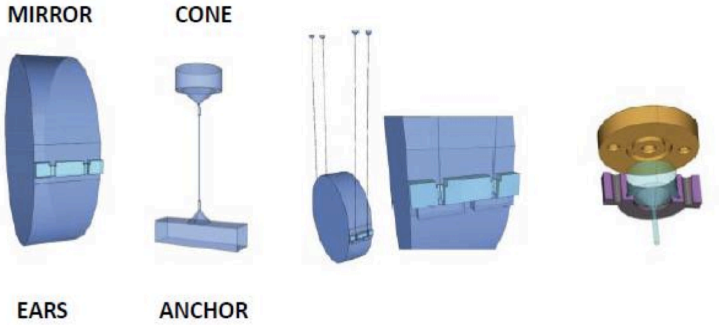
Pendulum thermal noise in Virgo

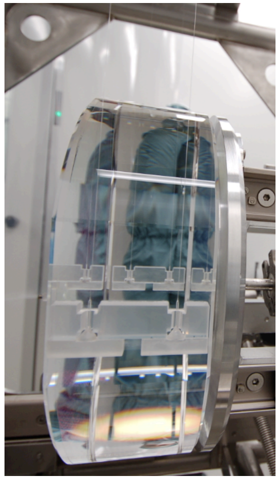
Dilution factor $\frac{k_{el}}{k_p} \sim 10^{-3} \div 10^{-2}$

$\phi_w \sim 10^{-4} \div 10^{-3} \Rightarrow \phi_p \sim 10^{-6}$ $Q \sim 10^{6}$
Steel wires

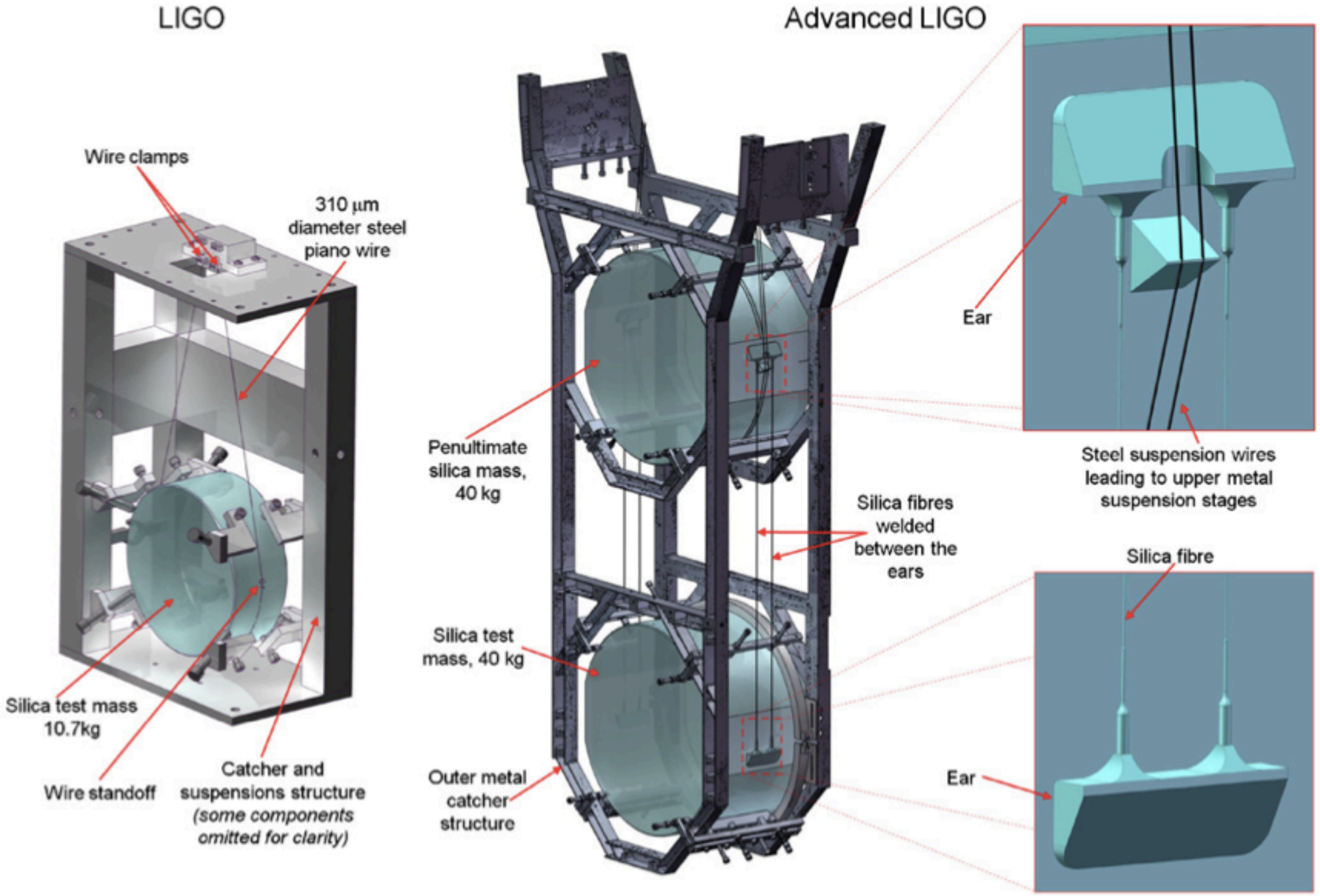
$\phi_w \sim 10^{-7} \Rightarrow \phi_p \sim 10^{-9}$ $Q \sim 10^{9}$
Silica wires







aLIGO suspensions



A.V.Cumming et al., “Design and development of the Advanced LIGO monolithic fused silica suspension”, Class Quantum Grav. 29 (2012) 035003

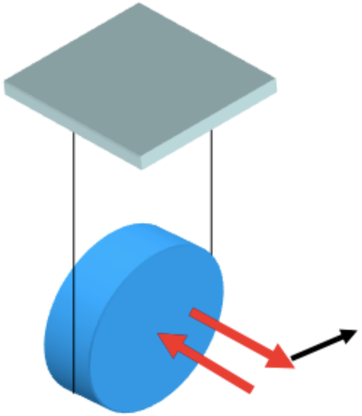
How to reduce the pendulum th. noise

How to reduce the pendulum thermal noise

- ☐ Decrease dissipation (steel wires→fused silica fibers): $x \sim \text{loss}^{1/2}$
- ☐ Increase length (Advanced Virgo ~ 0.7 m): $x \sim \text{length}^{-1/2}$
- ☐ Increase mass (Advanced Virgo 40 kg): $x \sim m^{-1/4}$
- ☐ Decrease temperature → Cryogenics: $x \sim T^{1/2}$

Mirror thermal noise

- ❑ Mirror = continuum system
- ❑ 2 ways to apply the Fluctuation/dissipation theorem to a mirror:
  - ❑ Decomposition in normal modes → application of the FDT at each mode and sum of the modes
  - ❑ Direct application of the thermal noise to the interferometer's observable (the equivalent displacement induced by the phase shift)



$$x(f) = \alpha \sqrt{\frac{4k_b T\phi}{f} \frac{1}{w}}$$

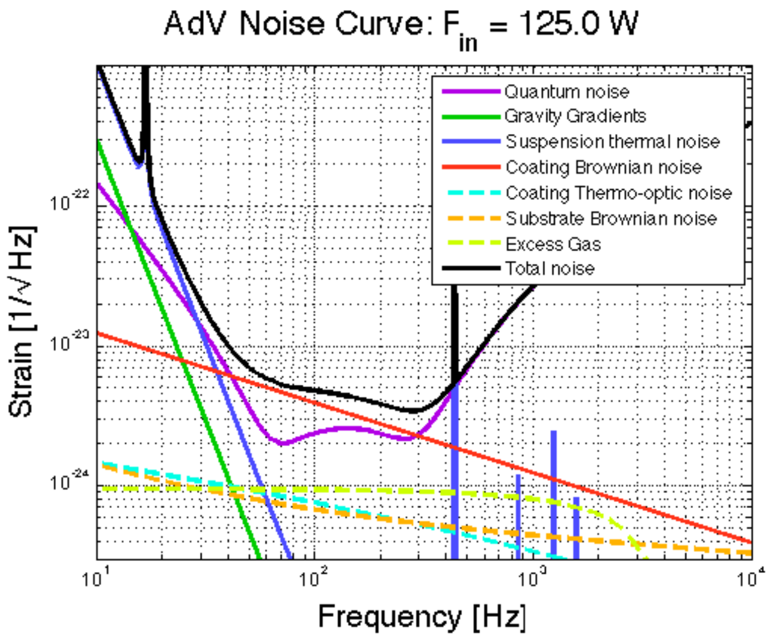
A. Gillespie and F. Raab, *Thermally excited vibrations of the mirrors of laser interferometric gravitational-wave detectors,* Phys. Rev. D **52,** 577-585 (1995).

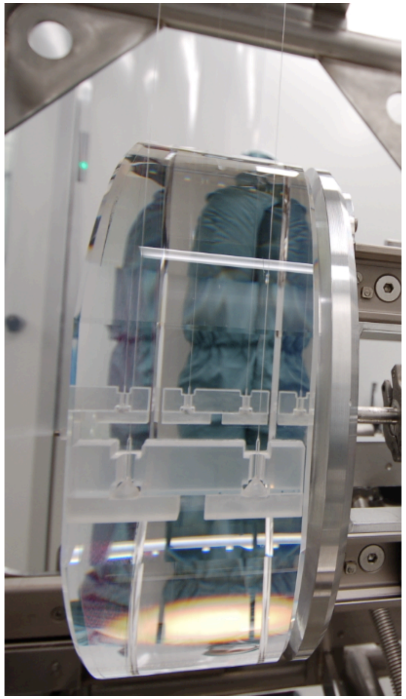
F. Bondu and J.-Y. Vinet, *Mirror thermal noise in interferometric gravitational-wave detectors,* Phys. Lett. A **198,** 74-78 (1995)

Y. Levin, *Internal thermal noise in the LIGO test masses: A direct approach,* Phys. Rev. D **57,** 659-663 (1998).

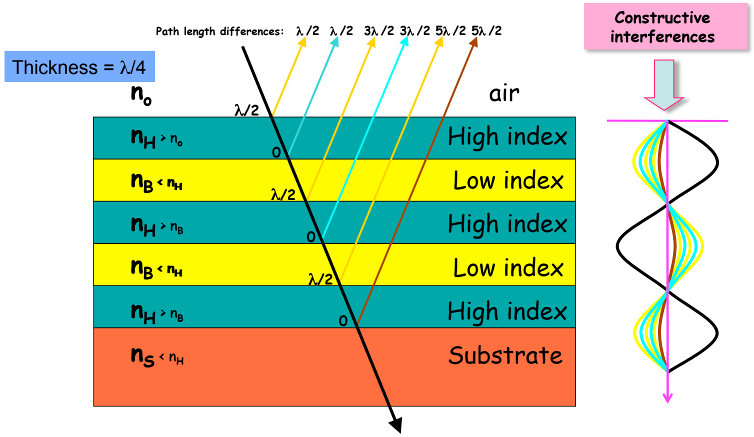
Substrate for aLIGO and AdVirgo

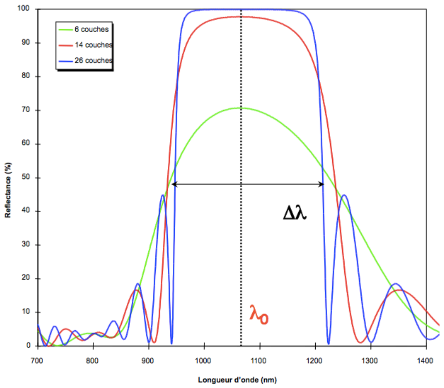
- Fused silica is used in Virgo/Advanced Virgo – LIGO/ Advanced LIGO
  - Low optical absorption (<1 ppm)
  - Low birefringence
  - High homogeneity
  - Low mechanical losses ($\phi \sim 10^{-9}$)


AdV Noise Curve: F_{in} = 125.0 W

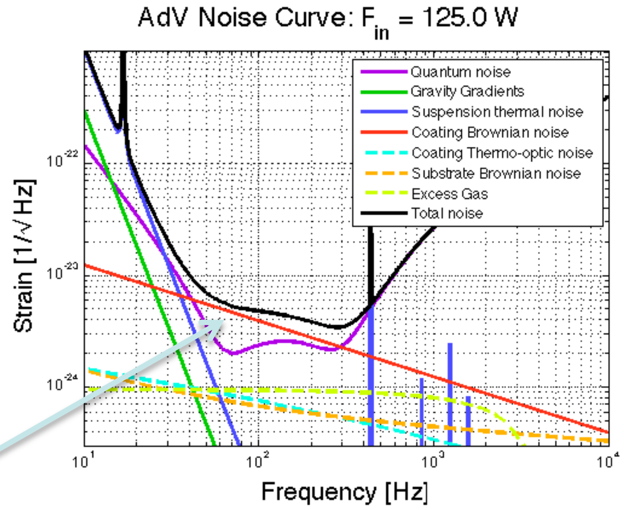


Mirror = substrate + coating





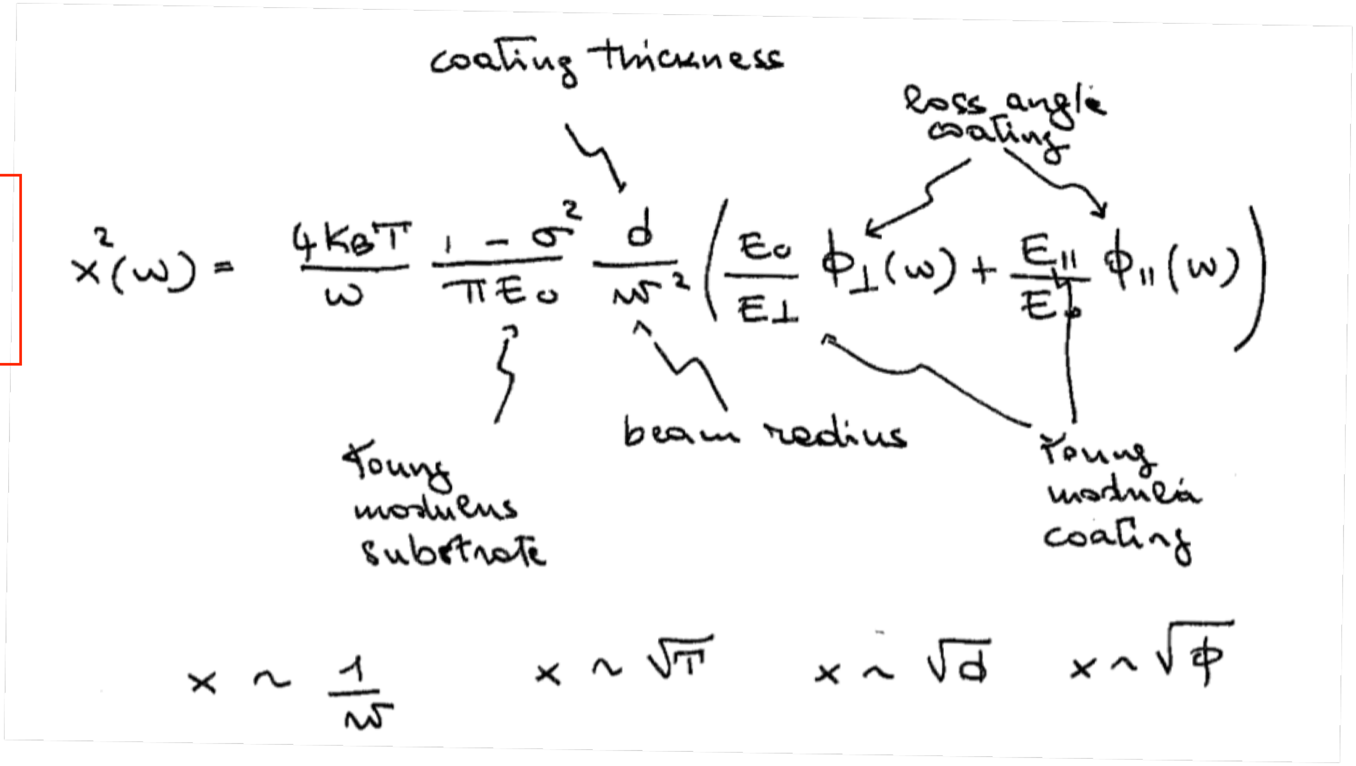
Credit: LMA, www.lma.in2p3.fr



The performances of a km scale interferometer are limited by ~ 5 micron surface coating !

Coating thermal noise

G. M. Harry, *et al.*, *Thermal noise in interferometric gravitational wave detectors due to dielec- tric optical coatings,* Class. Quantum Grav. **19,** 897-917 (2002).



$$x^2(\omega) = \frac{4 k_B T}{\omega}\,\frac{1-\sigma^2}{\pi E_0}\,\frac{d}{w^2}\left(\frac{E_0}{E_\perp}\phi_\perp(\omega) + \frac{E_\parallel}{E_0}\phi_\parallel(\omega)\right)$$

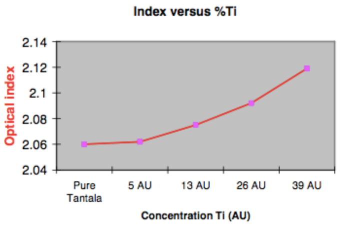
$x \sim \frac{1}{w}$ $\quad x \sim \sqrt{T}$ $\quad x \sim \sqrt{d}$ $\quad x \sim \sqrt{\phi}$

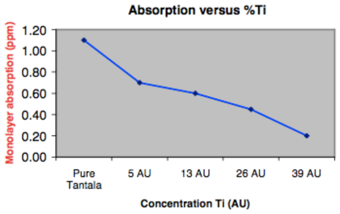
Coatings for second generation detectors

- $\lambda/4$ Layers of silica (low index) + $\lambda/4$ Layers of Ta_2O_5 - tantalum pentoxide, or tantala (high index)
- Loss angle dominated by high index material (by one order of magnitude)
- Important parameters: mechanical losses, absorption, stress
- Different materials tried, different concentrations

	Refraction index	Absorption (ppm)	Mechanical losses
Ta_2O_5	2.035	1.22	$3\cdot10^{-4}$
Ta_2O_5 : Co	2.11	5000	$11\cdot10^{-4}$
Ta_2O_5 : W	2.07	2.45	$7.5\cdot10^{-4}$
Ta_2O_5 : W+Ti	2.06	1.65	$3.3\cdot10^{-4}$
Ta_2O_5 : Ti	2.07	0.5	$2.4\cdot10^{-4}$

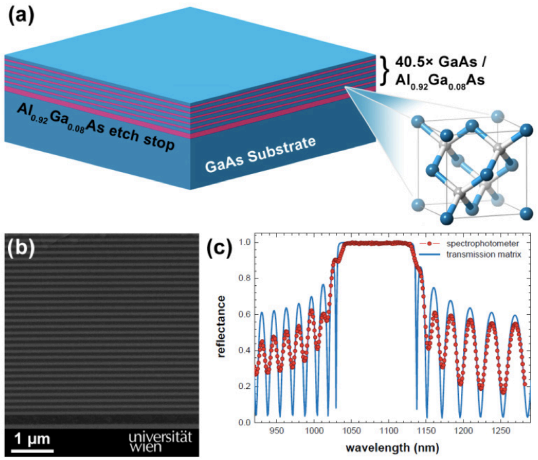
Study of coating mechanical and optical losses in view of reducing mirror thermal noise in gravitational wave detectors, Flaminio et al., CQG 27, 8 (2010)

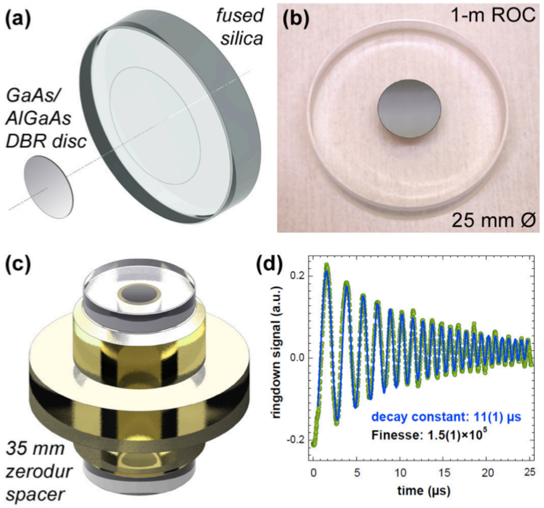




Best loss angle value for tantala doped with Titanium: $1.5\text{x}10^{-4}$

Crystalline coatings





- Extraplolation of coating thermal noise → Loss angle = 2.5x10^{-5} (~ 10 improvement)
- Potential improvements in the thermal noise ~ x 3
- Check absorption, scattering, possibility to realize large mirrors

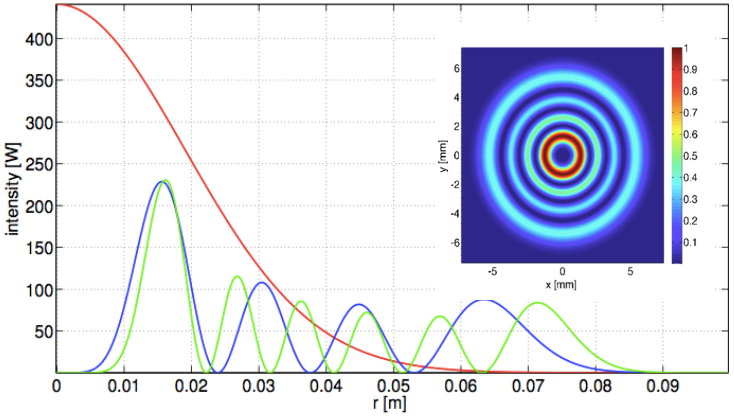
G.D. Cole et al, Tenfold reduction of Brownian noise in optical interferometry,, 2013

Improving CTN using optical methods

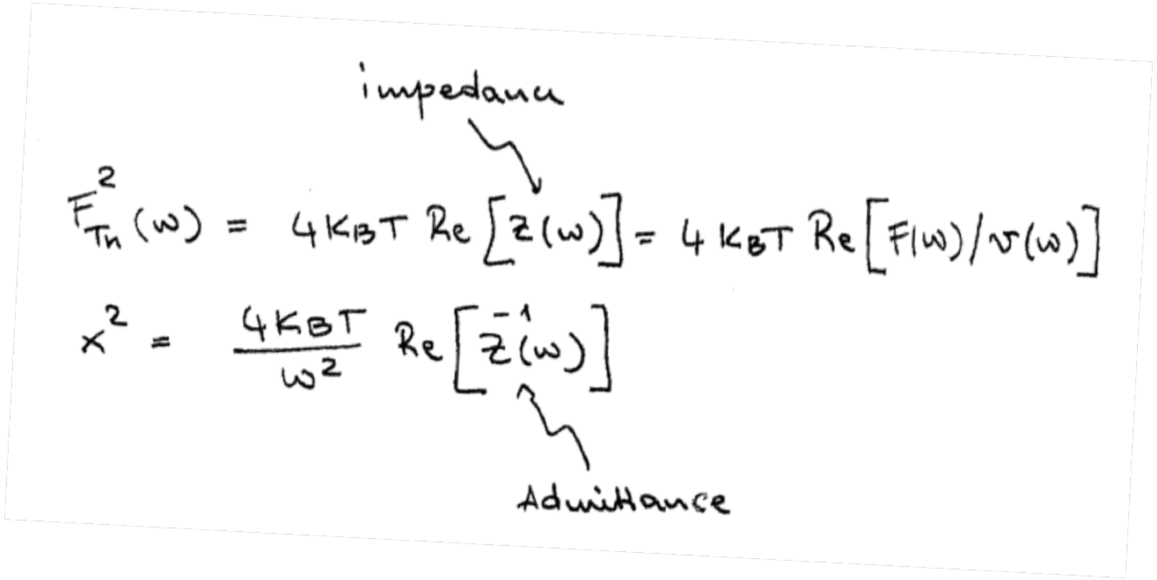
Bigger beams

$x \sim \frac{1}{w}$ $x \sim \sqrt{T}$ $x \sim \sqrt{d}$ $x \sim \sqrt{\phi}$

Credit: LMA, www.lma.in2p3.fr



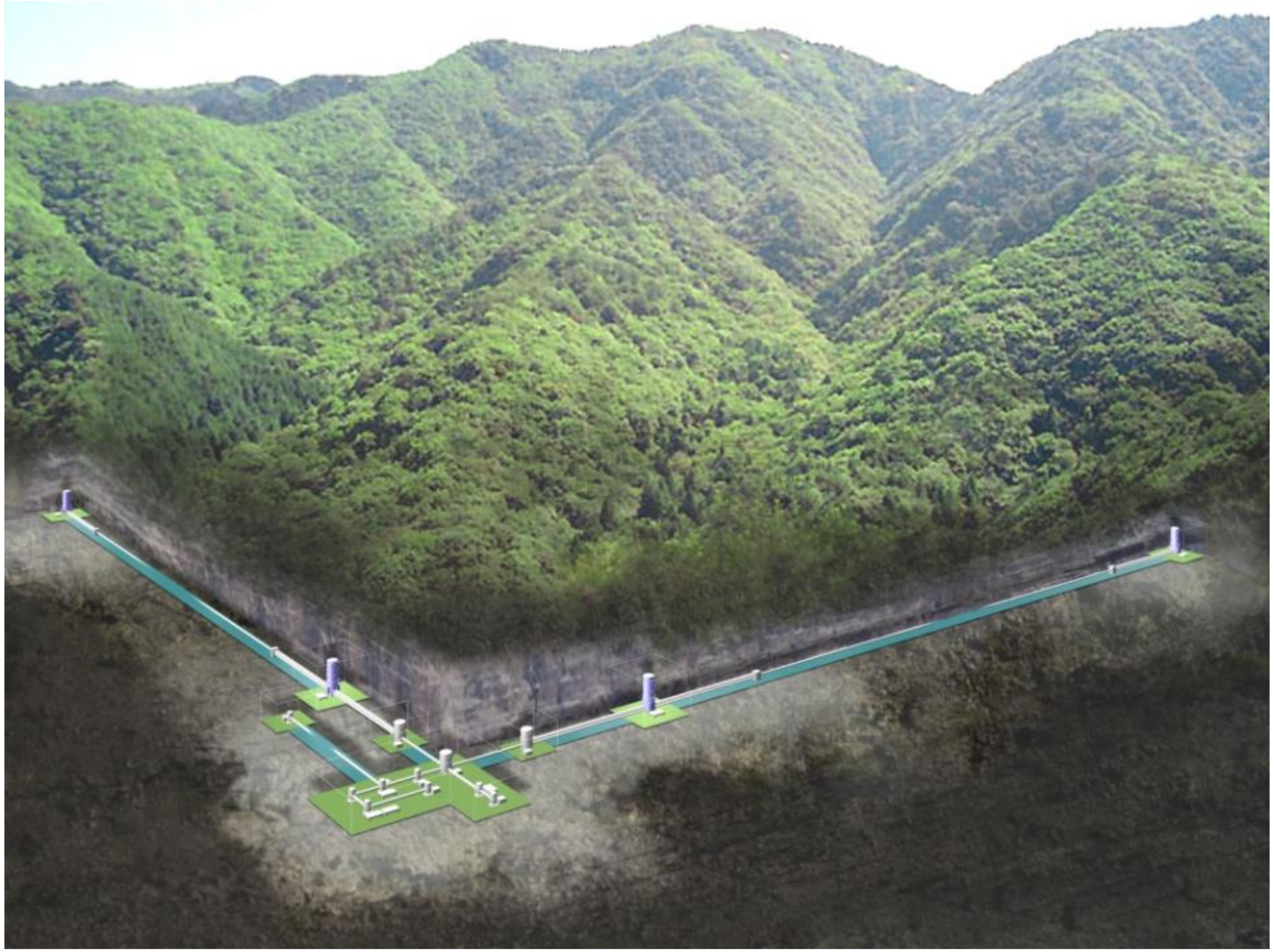
Cryogenics



$$F_{Th}^2(\omega) = 4 K_B T \,\mathrm{Re}\left[\overset{\text{impedance}}{Z(\omega)}\right] = 4 K_B T \,\mathrm{Re}\left[F(\omega)/v(\omega)\right]$$

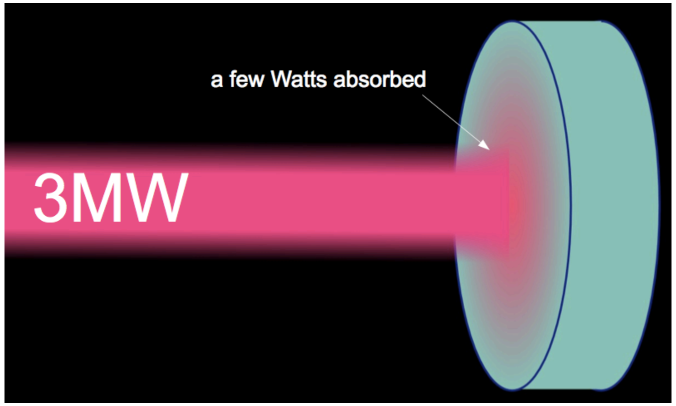
$$x^2 = \frac{4 K_B T}{\omega^2}\,\mathrm{Re}\left[\underset{\text{Admittance}}{Z^{-1}(\omega)}\right]$$

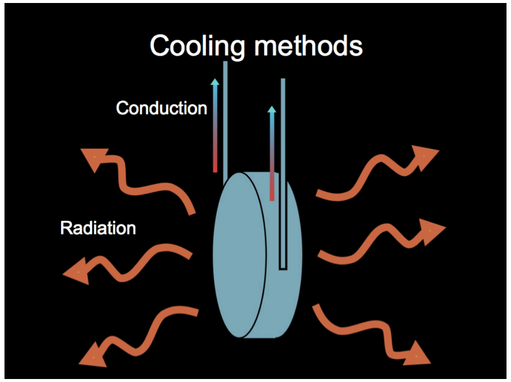
Cryogenics: Kagra

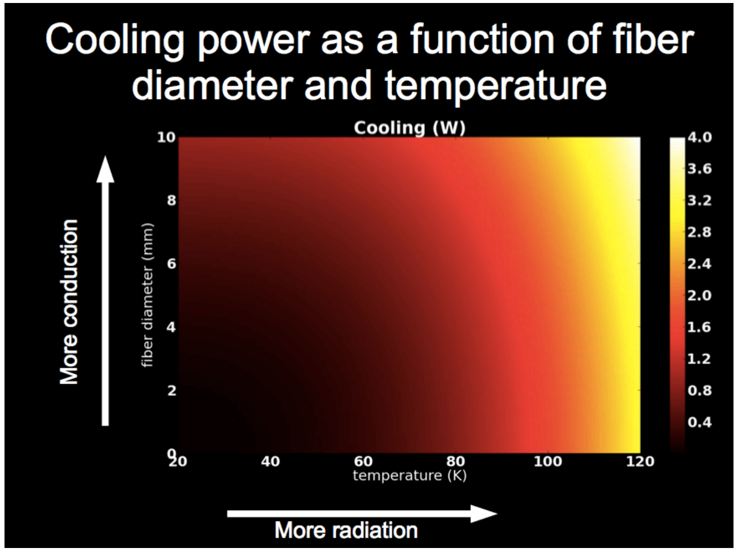


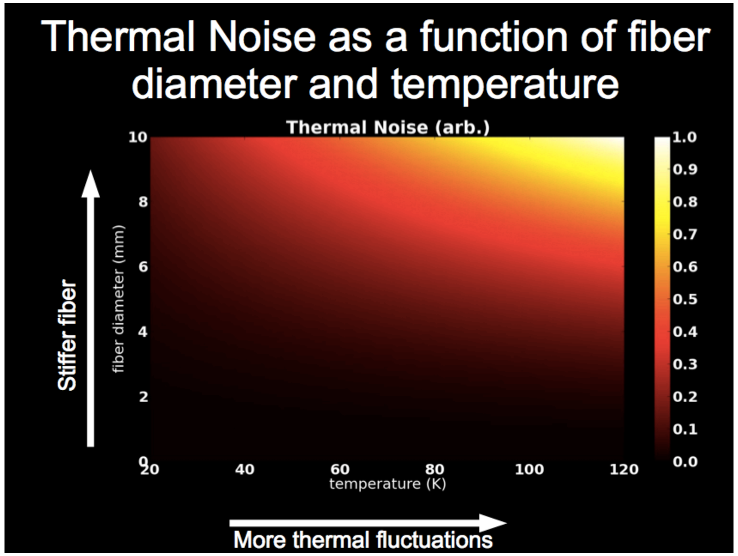
Credit: Kagra

Cryogenics





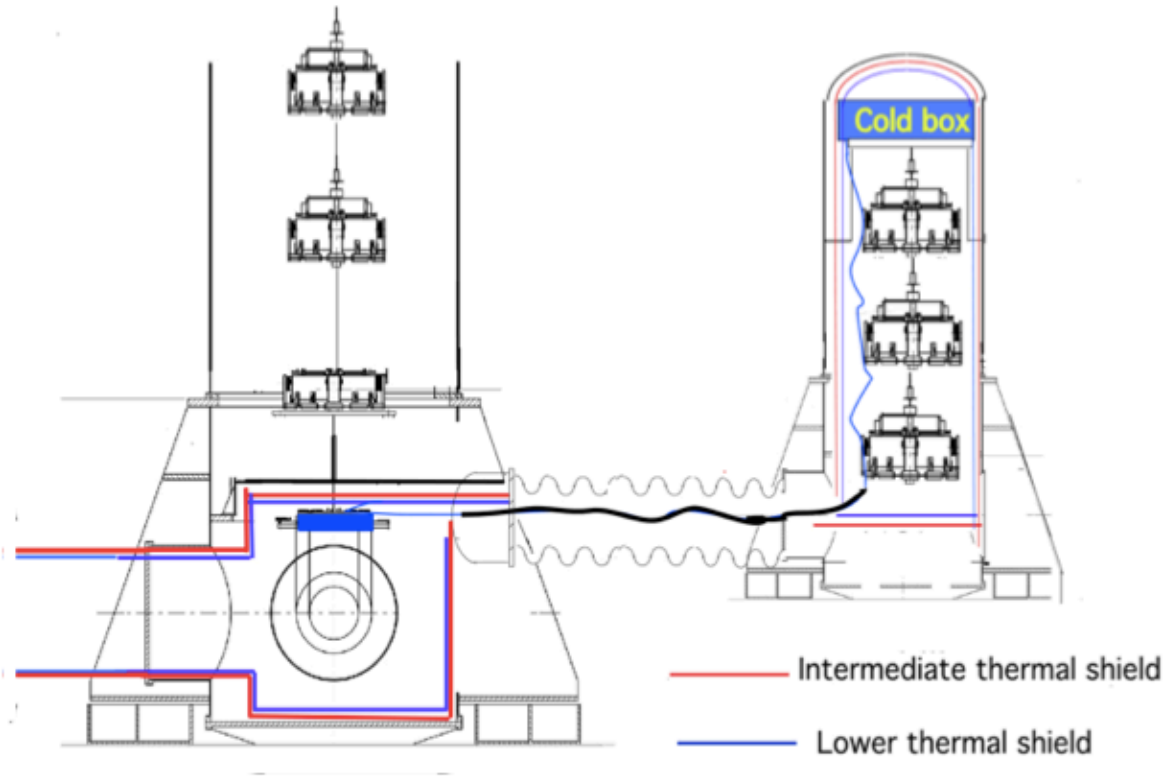




N.Smith-Lefebvre, presentation at GWADW 2013, Elba, Italy

Isolated cryostat for Einstein Telescope

Einstein Telescope design, 18 K



Einstein Telescope conceptual design study, www.et-gw.eu

Thermal noise: summary

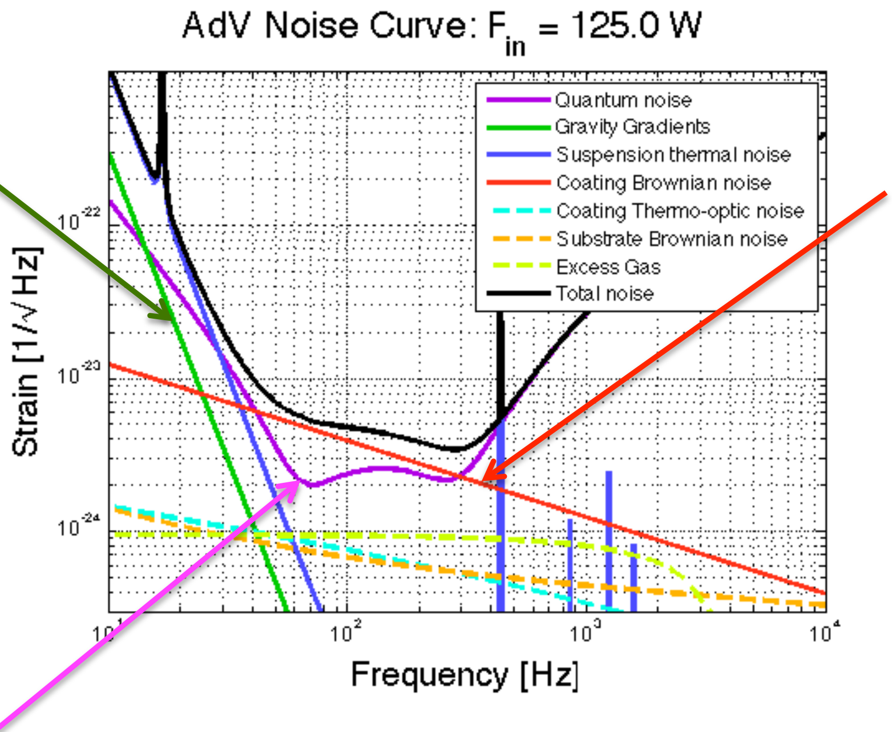
- Huge progress, since ‘90 in the understanding of thermal noise in GW experiments (and other metrology experiment)
- Coating (a few micron of material on a 40 kg mirror) is the main limitation for future detectors in the central region of the spectrum

- Materials
  - Crystalline coatings are a promising direction
- Optical methods
  - Increase beam size
- Cryogenics
  - need to change material: silicon or sapphire (silicon requires 1.5 micron lasers), evacuate heat, care in the cryostat isolation
  - different approaches (Kagra, aLIGO+, ET)

The quantum noise

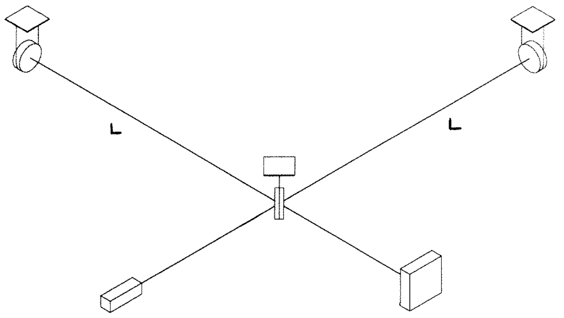
Noises limiting a 2nd generation detector

Seismic and gravity gradient noise
Geophysics

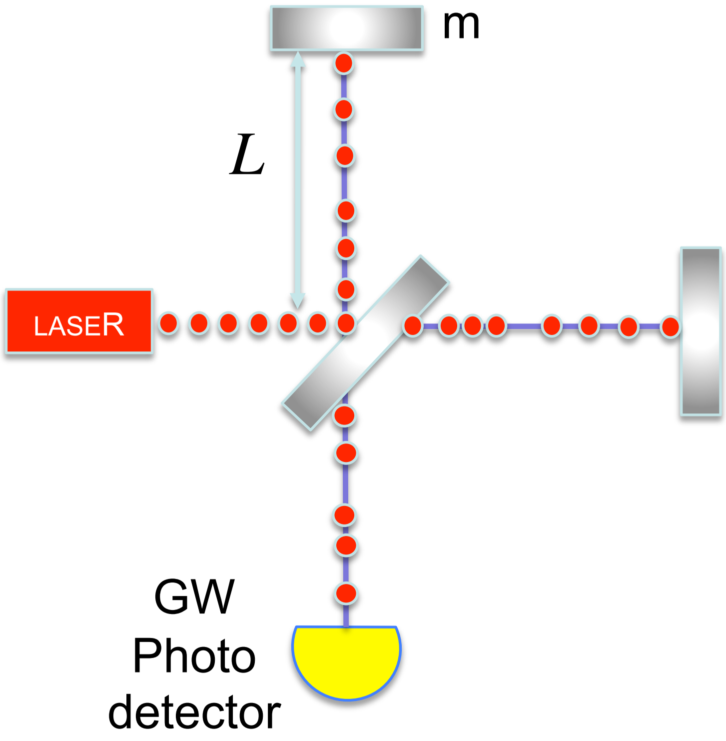


Thermal noise
Thermodynamics

Quantum noise
Quantum mechanics



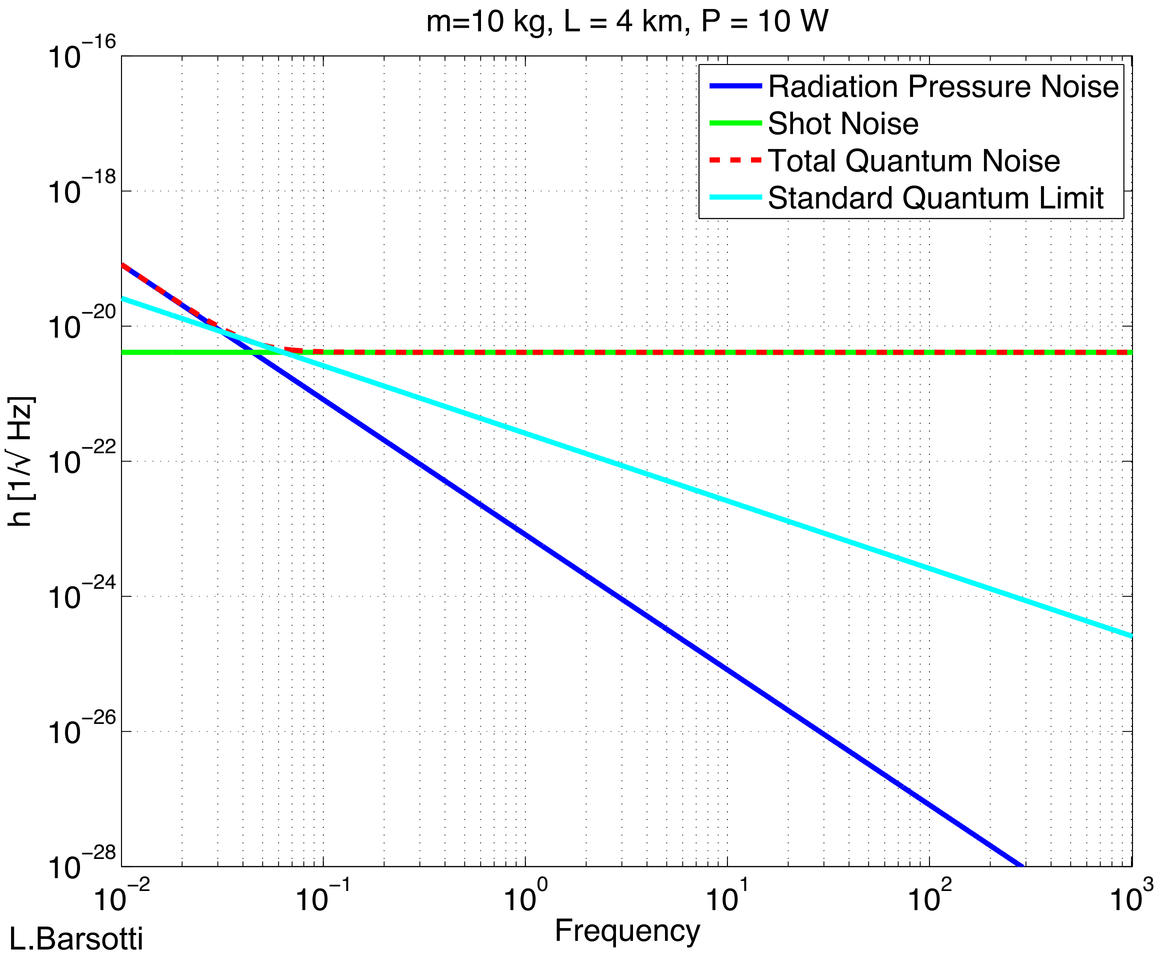
Quantum noise



Credit L.Barsotti

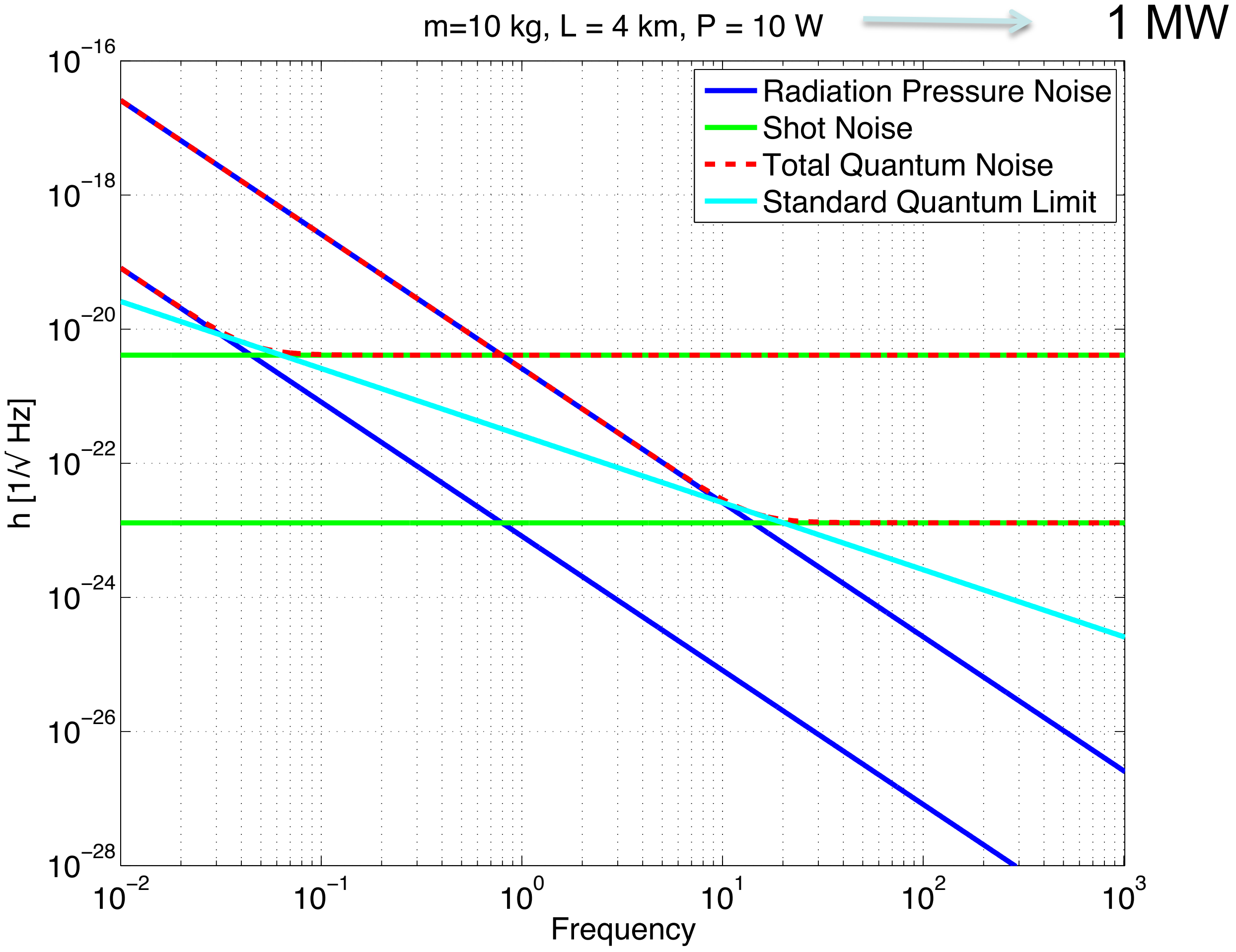
- ❑ Photon counting noise (or shot noise)
  - ❑ Limitation on the precision you can make arm displacement
- ❑ Radiation pressure (back-action)
  - ❑ Additional displacement noise

SQL for a simple Michelson interferometer



Credit L.Barsotti

SQL for a simple Michelson interferometer



Standard quantum limit (SQL)

$$\Delta L_{Quantum} = \sqrt{\frac{4\hbar}{m\Omega^2}}\sqrt{\frac{1}{2}\left(\mathrm{K}+\frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

$$h_{Quantum} = \frac{\Delta L_{Quantum}}{L} = \boxed{\sqrt{\frac{4\hbar}{m\Omega^2 L^2}}}\sqrt{\frac{1}{2}\left(\mathrm{K}+\frac{1}{\mathrm{K}}\right)}$$

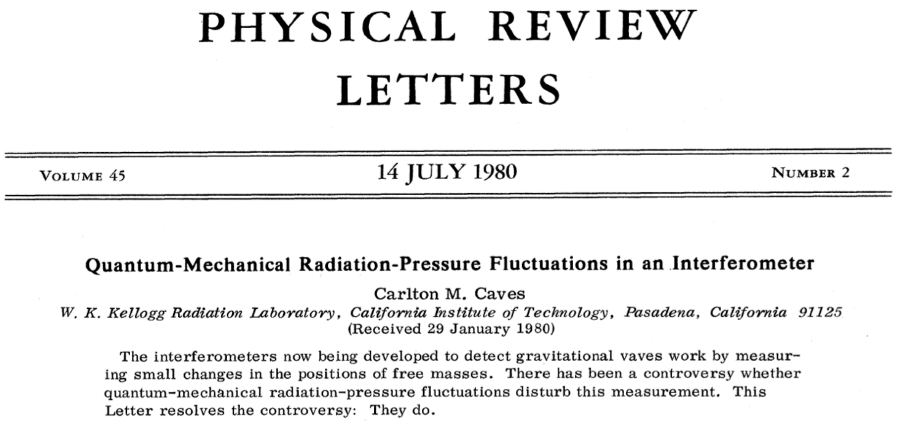
This can be derived also as a consequence of the Heisemberg principle

Easy ways to reduce equiv. quantum noise

- Increase the length of the interferometer ($h= \delta L/L$)
  - Advanced Virgo 3km, ET 10 km
  - problems related to further increase: Cost, tube, find a place, long cavities → large mirrors

- More power (to reduce shot noise) and heavier masses (to compensate for radiation pressure noise)
  - Virgo m=20 kg → Advanced Virgo m=40 kg, ET~ 160 kg
  - To do more…problems: technology, cost
  - Advanced Virgo ~ 700 kW in the arms, ET ~ 3 MW
  - problem related to further increase: Thermal effects, radiation pressure driven instabilities

Vacuum fluctuations



PHYSICAL REVIEW
LETTERS

VOLUME 45 14 JULY 1980 NUMBER 2

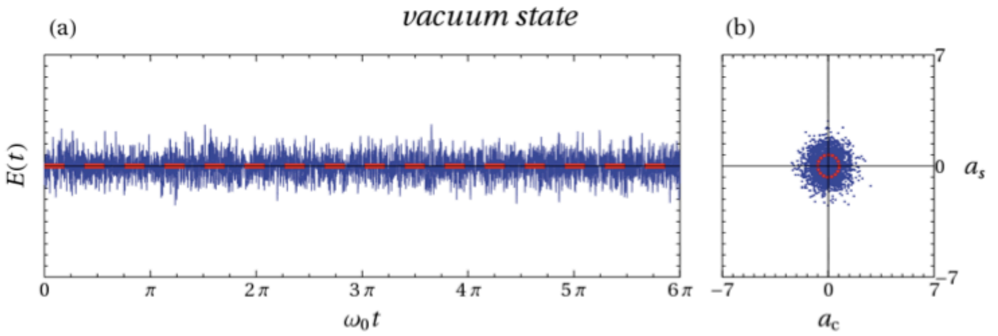
Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

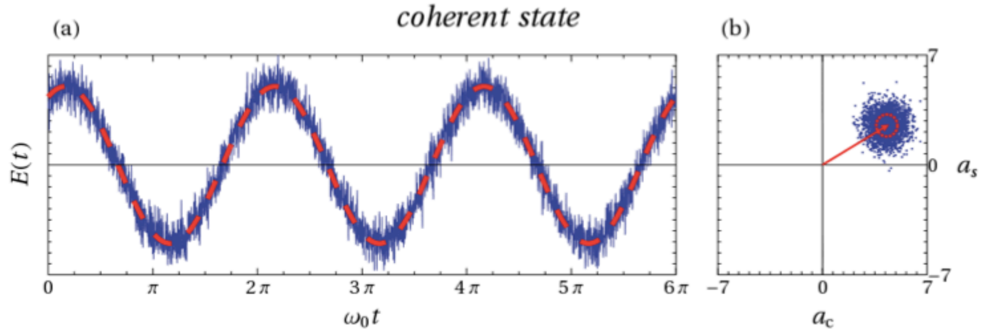
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

- Quantization of the e.m. field
- Zero-point Fluctuations entering in the interferometer from the anti-symmetric port generates shot noise and radiation pressure noise.

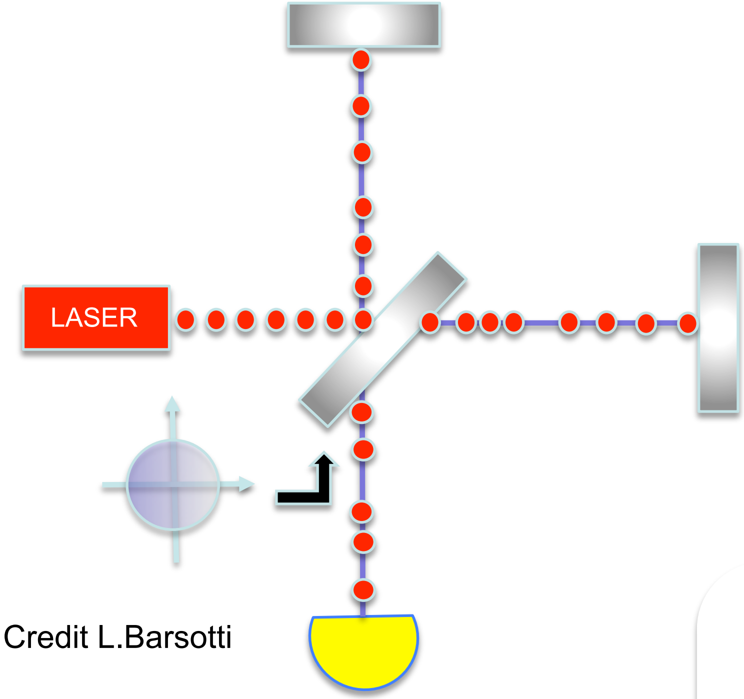
Vacuum and coherent states



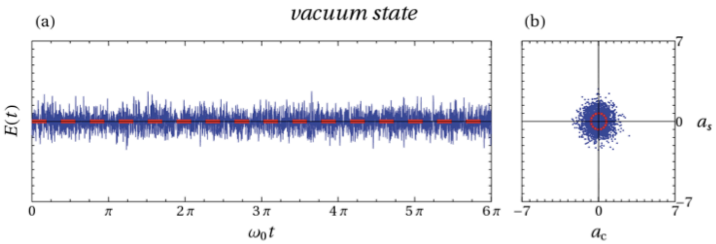


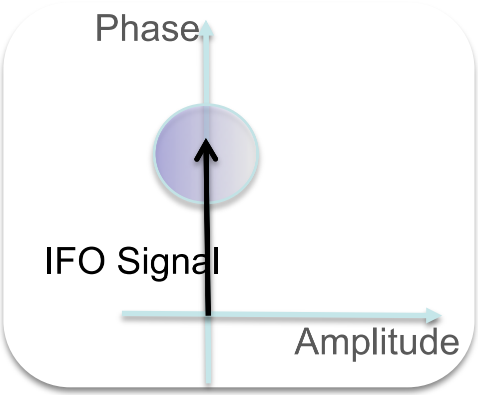
S.L. Danilishin and F.Y. Khalili Quantum Measurement Theory in Gravitational-Wave Detectors, Living Rev. Relativity, 15, (2012)

Qu. noise given by zero-point fluctuations

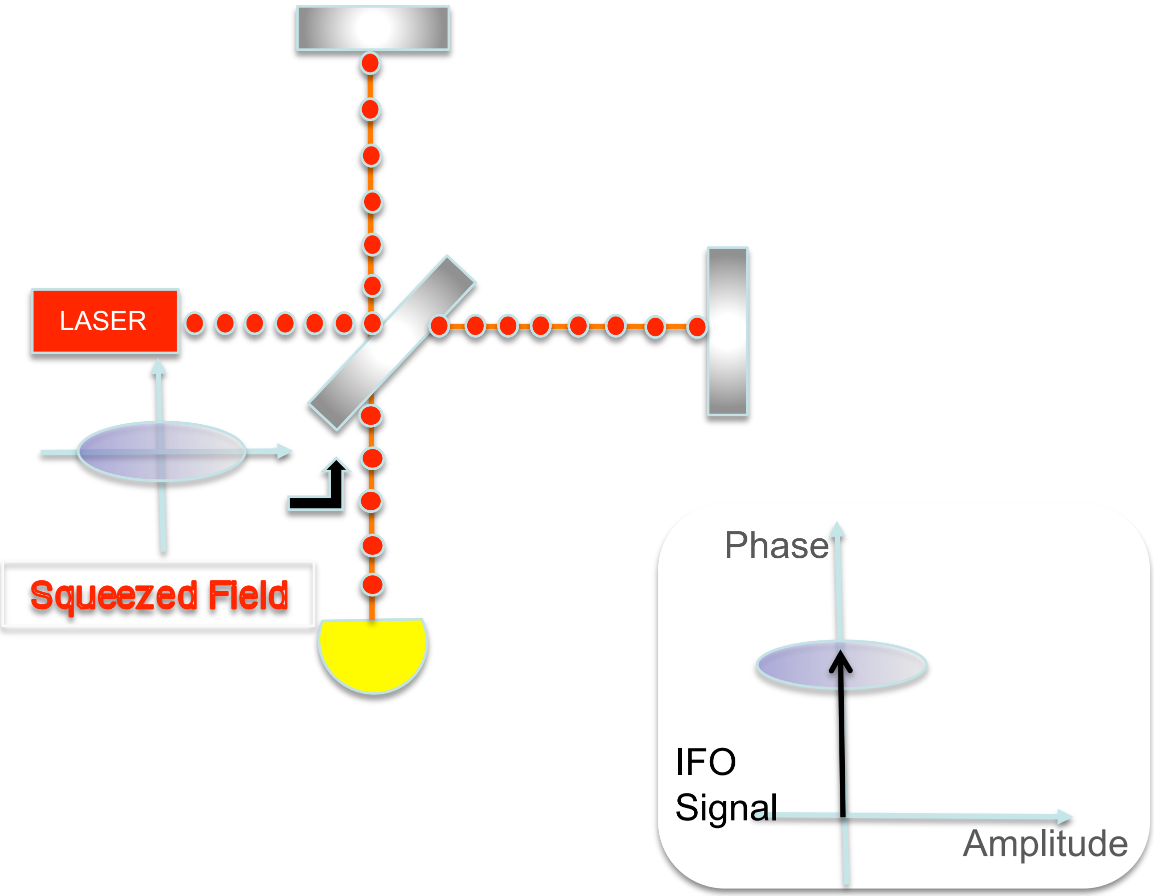


Credit L.Barsotti

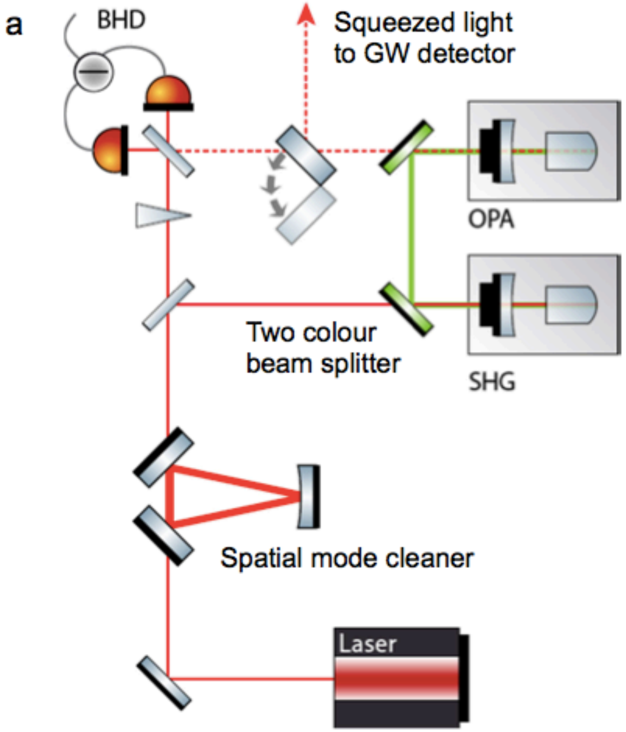


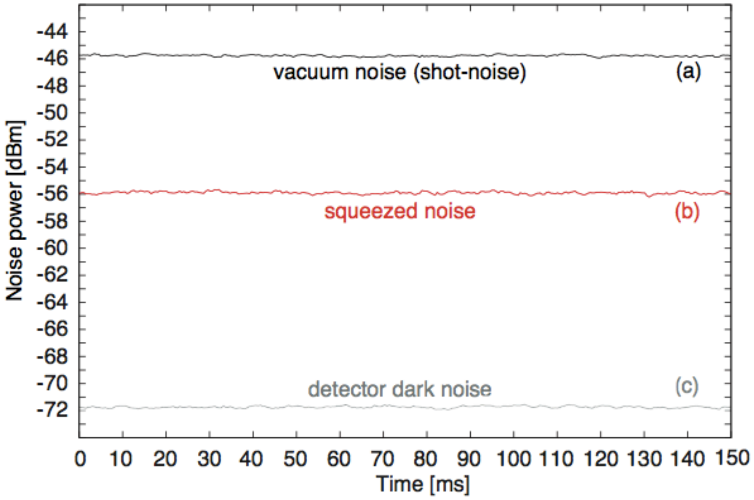


Injecting squeezing in an interferometer



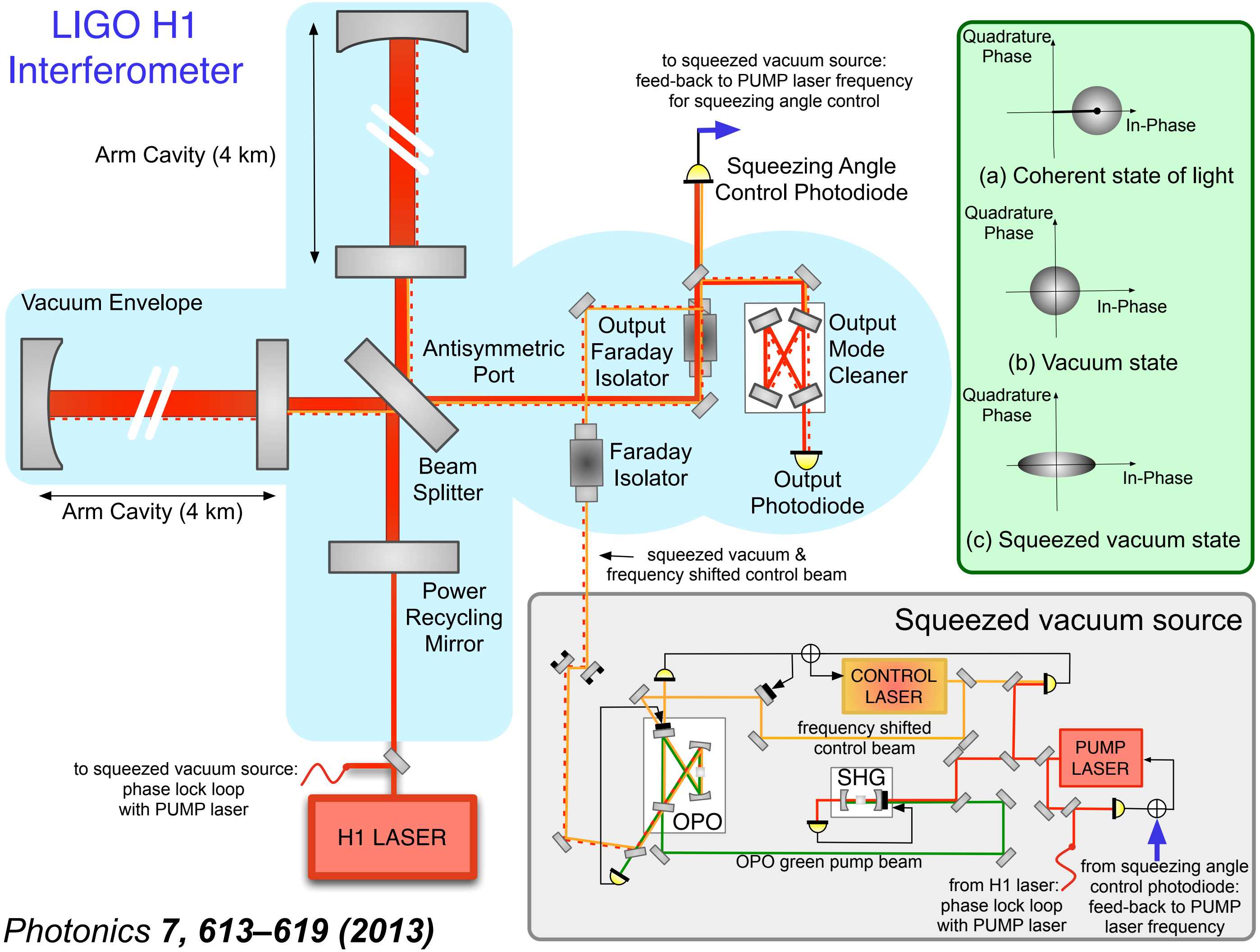
How to produce squeezing





H.Vahlbruch et al., bservation of Squeezed Light with 10-dB Quantum-Noise Reduction, Phys. Rev. Lett. 100, 033602 (2008)

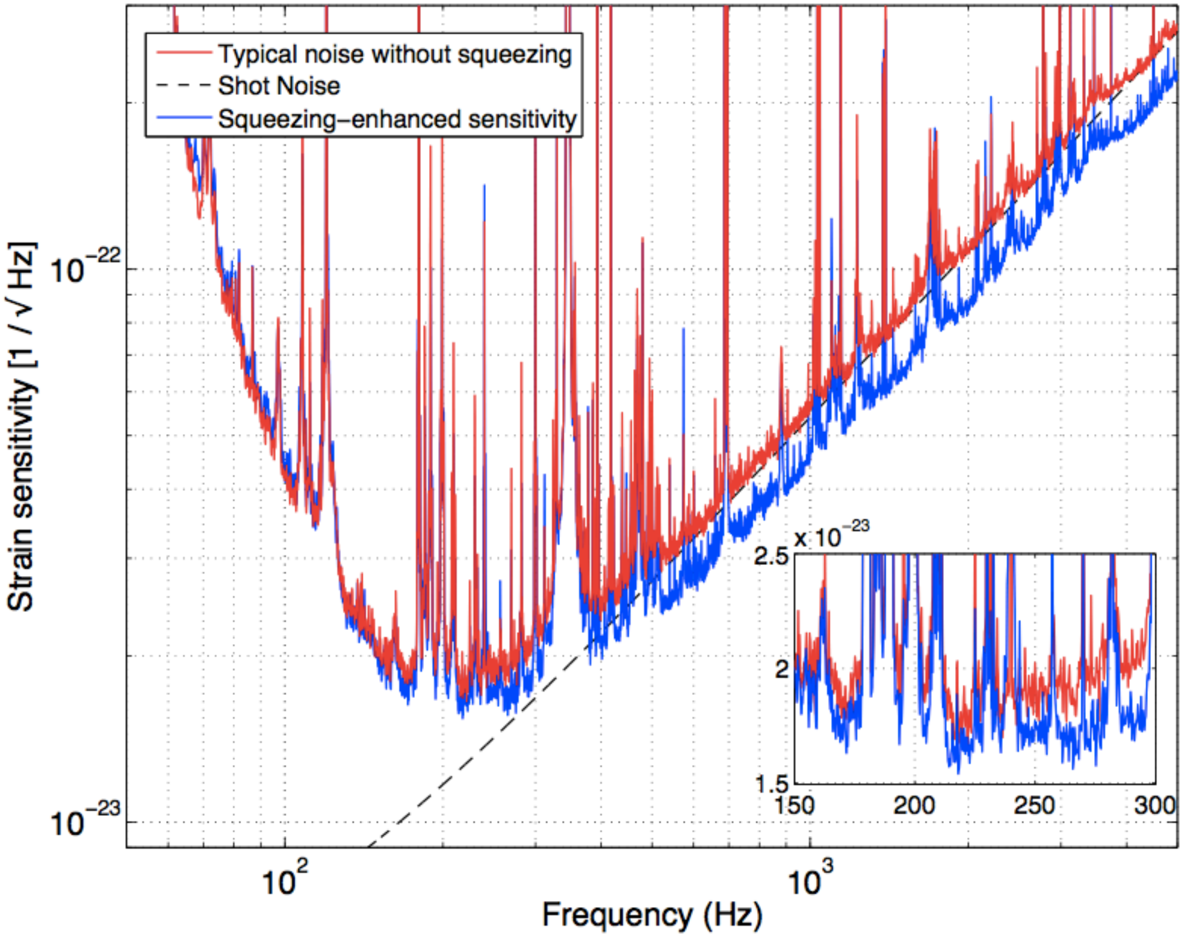
Squeezing in LIGO Hanford



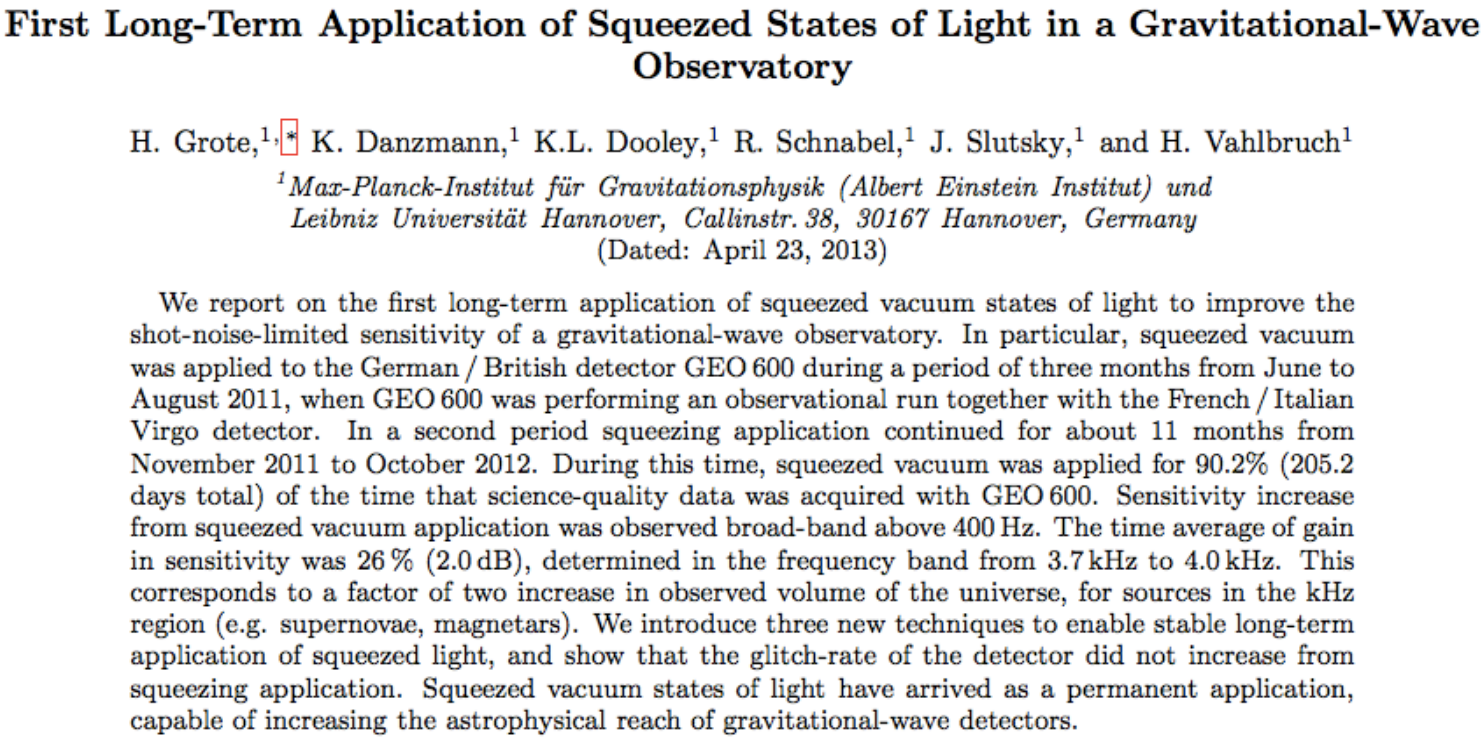
Nature Photonics ***7*****, 613–619 (2013)**

Squeezing in LIGO

Nature Photonics ***7, 613–619 (2013)***



Long term application of squeezing



First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory

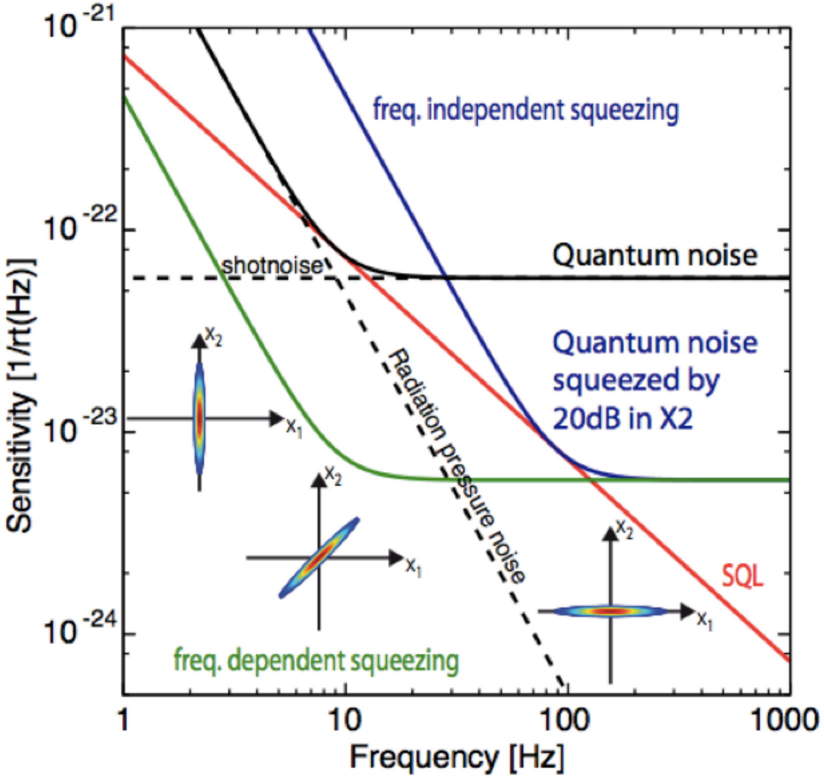
H. Grote,[1,*] K. Danzmann,[1] K.L. Dooley,[1] R. Schnabel,[1] J. Slutsky,[1] and H. Vahlbruch[1]
[1] *Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institut) und Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany*
(Dated: April 23, 2013)

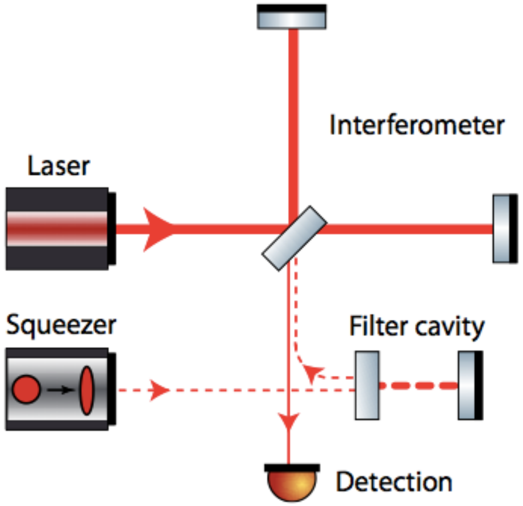
We report on the first long-term application of squeezed vacuum states of light to improve the shot-noise-limited sensitivity of a gravitational-wave observatory. In particular, squeezed vacuum was applied to the German / British detector GEO 600 during a period of three months from June to August 2011, when GEO 600 was performing an observational run together with the French / Italian Virgo detector. In a second period squeezing application continued for about 11 months from November 2011 to October 2012. During this time, squeezed vacuum was applied for 90.2% (205.2 days total) of the time that science-quality data was acquired with GEO 600. Sensitivity increase from squeezed vacuum application was observed broad-band above 400 Hz. The time average of gain in sensitivity was 26 % (2.0 dB), determined in the frequency band from 3.7 kHz to 4.0 kHz. This corresponds to a factor of two increase in observed volume of the universe, for sources in the kHz region (e.g. supernovae, magnetars). We introduce three new techniques to enable stable long-term application of squeezed light, and show that the glitch-rate of the detector did not increase from squeezing application. Squeezed vacuum states of light have arrived as a permanent application, capable of increasing the astrophysical reach of gravitational-wave detectors.

Phys. Rev. Lett. **110, 181101**

Freq. dependent squeezing: Filter cavities

Einstein Telescope conceptual design study, www.et-gw.eu





M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao, Phys. Rev. D **88, 022002**

Quantum noise: summary

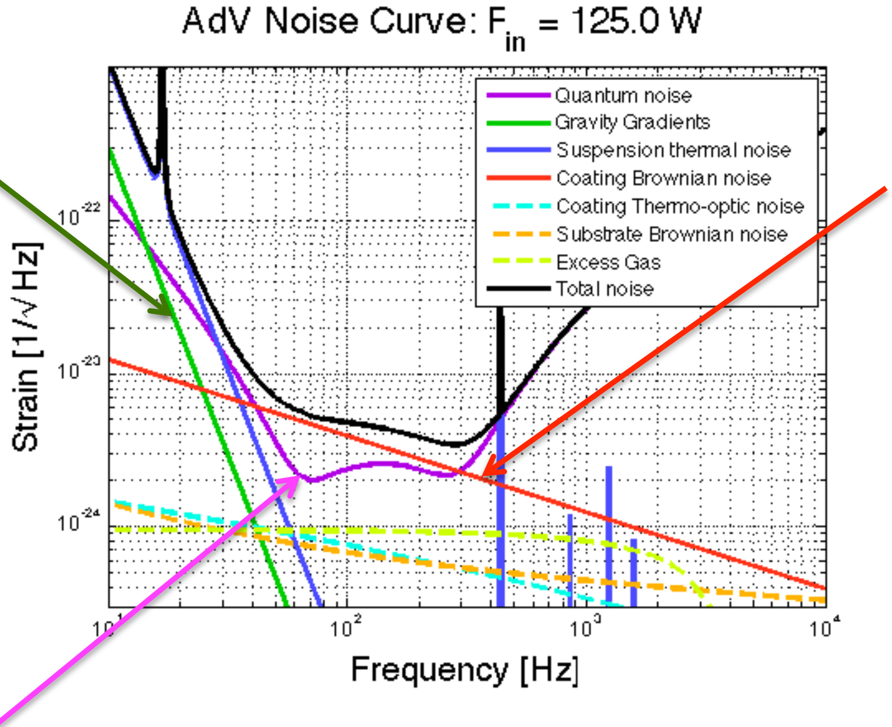
- Frequency independent squeezing routinely injected in GEO – also injected in LIGO
- In the future: filter cavities to decrease at the same time shot noise and radiation pressure noise
- First test of filter cavities in the audio-band successful
- Plan to inject squeezing in LIGO in 2017
- R&D
    - Improve squeezing sources
    - Decrease losses
    - Test ~ 10-100 m filter cavities

Newtonian or gravity gradient noise

Noises limiting AdVirgo

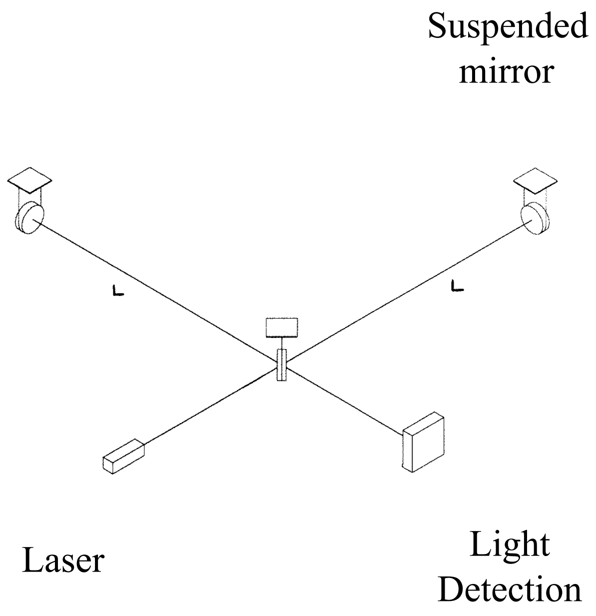
Seismic and gravity gradient noise
Geophysics

Thermal noise
Thermodynamics

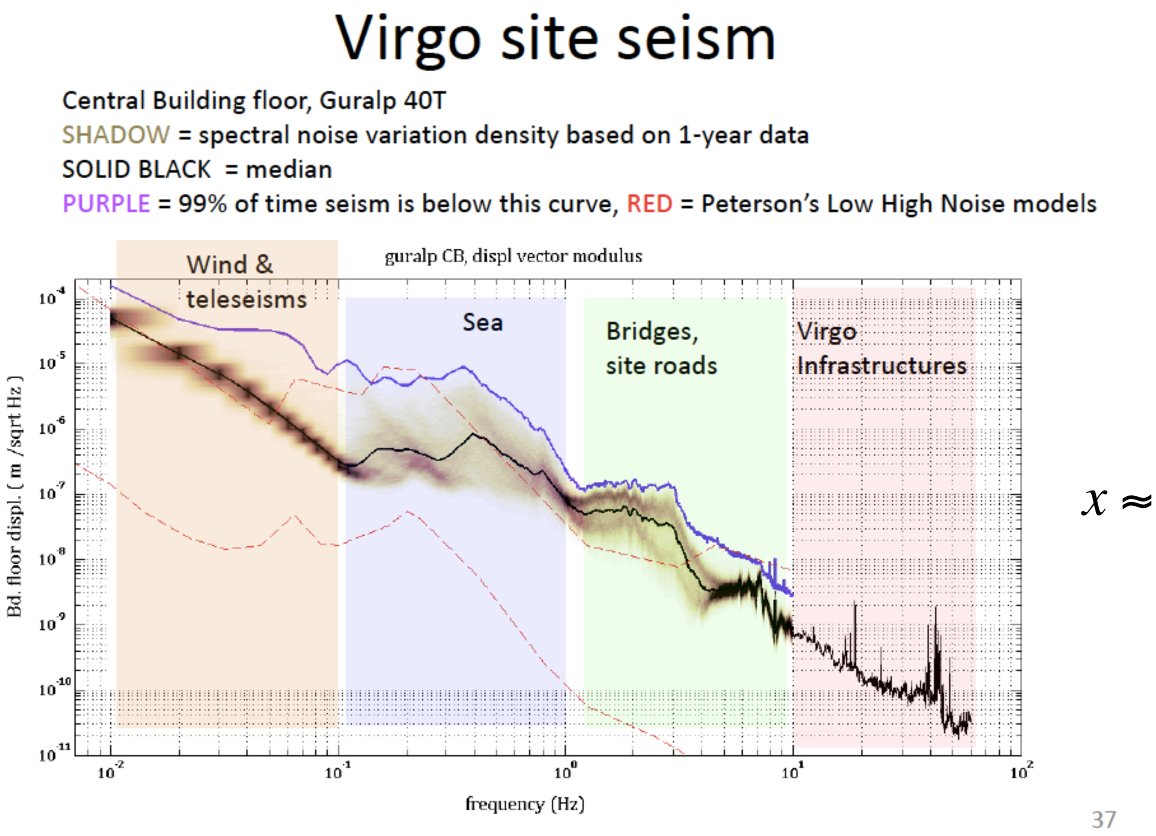


Quantum noise
Quantum mechanics

Virgo Collaboration, Advanced Virgo technical design report,Virgo internal document VIR-0128A-12,2012



Seismic noise effects



Virgo site seism

Central Building floor, Guralp 40T

SHADOW = spectral noise variation density based on 1-year data

SOLID BLACK = median

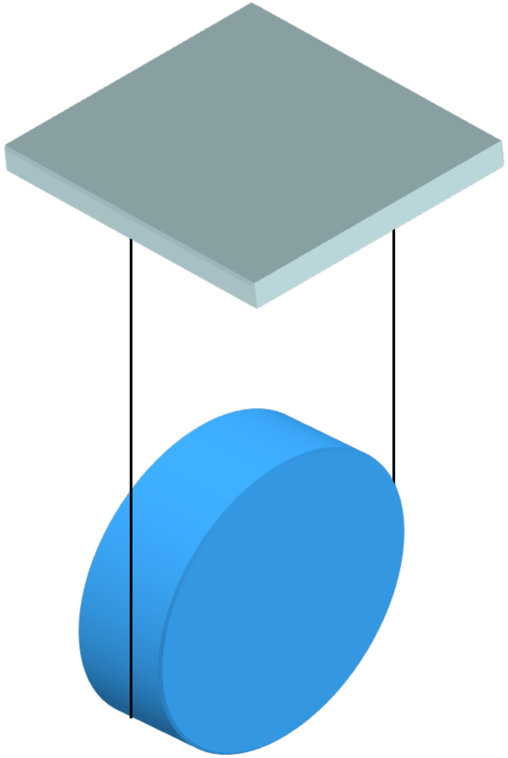
PURPLE = 99% of time seism is below this curve, RED = Peterson's Low High Noise models

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

Credit I.Fiori, VIrgo

Two effect:
1) shaking of the mirror through the suspension system
2) Direct coupling: gravity gradient noise

The pendulum



$$\frac{x(\omega)}{x_0(\omega)} = \frac{\omega_0^2}{\omega_0^2 - \omega^2} \qquad \omega_0^2 = \frac{g}{\ell}$$

For $\ell = 1$ m $\Rightarrow f = \frac{1}{2\pi}\sqrt{\frac{g}{\ell}} \simeq 0.5$ Hz

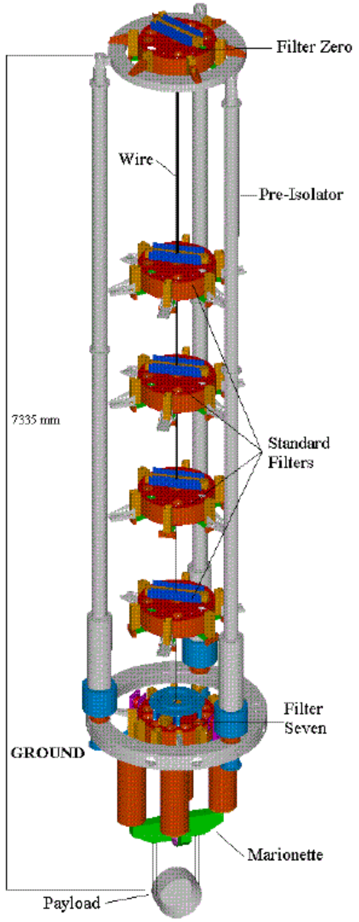
For $\omega \gg \omega_0 \Rightarrow \frac{x(\omega)}{x_0(\omega)} \simeq -\frac{\omega_0^2}{\omega^2}$

$$\left|\frac{x(\omega)}{x_0(\omega)}\right| \sim \frac{1}{\ell}$$

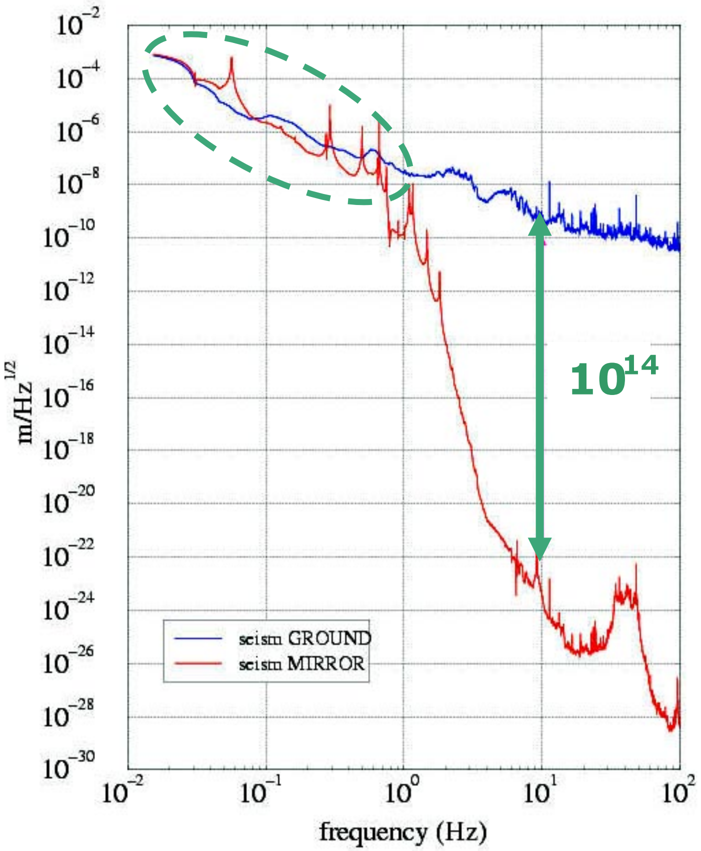
For N pendula $\frac{x(\omega)}{x_0(\omega)} = \prod_{i=1}^{N} \frac{\omega_i^2}{\omega_i^2 - \omega^2}$

For $\omega \gg \omega_i \ \forall i \Rightarrow \frac{x(\omega)}{x_0(\omega)} \simeq \frac{\prod_i \omega_i^2}{\omega^{2N}}$

The pendulum/2



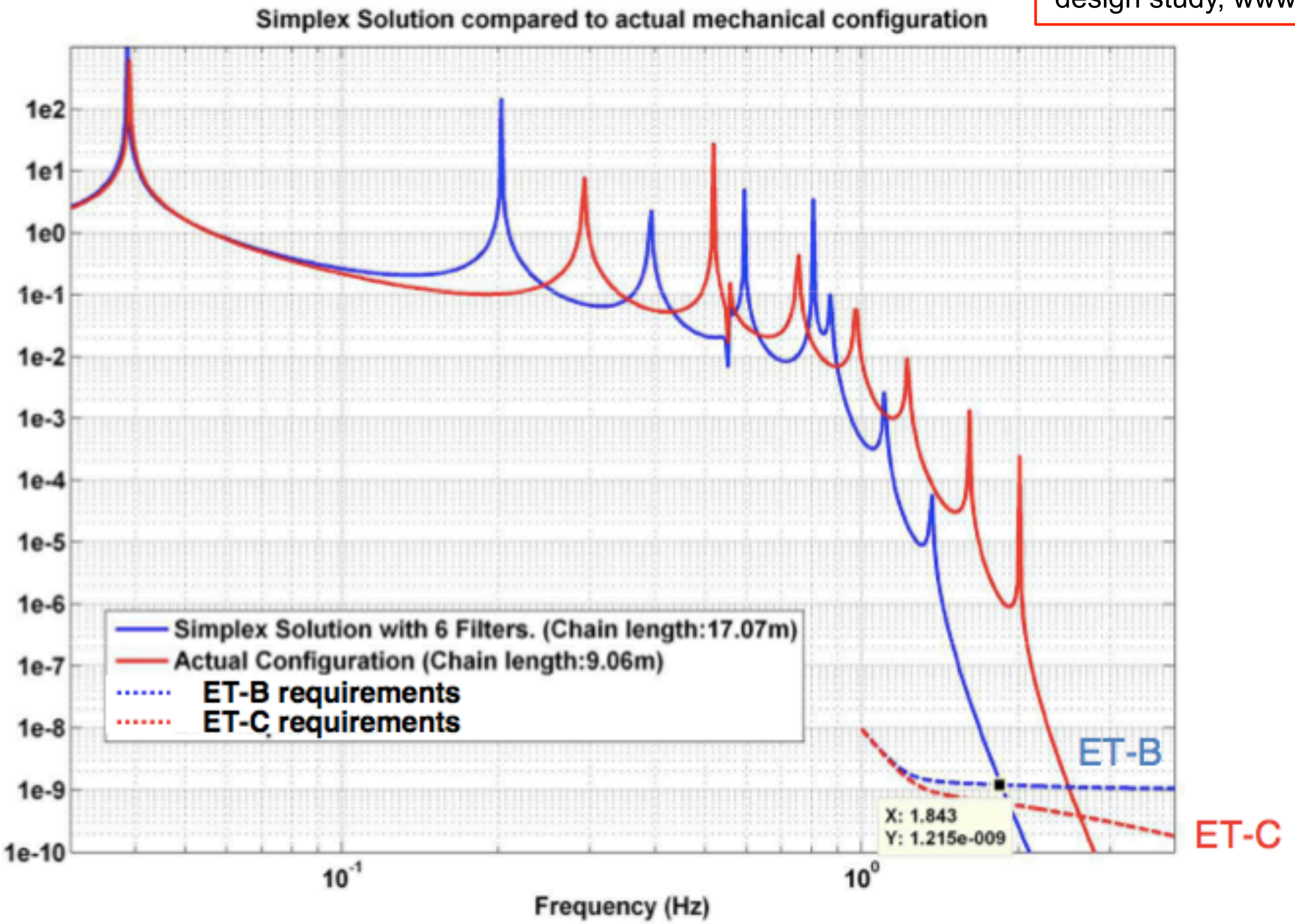
Virgo superattenuator



Virgo superattenuator
transfer function

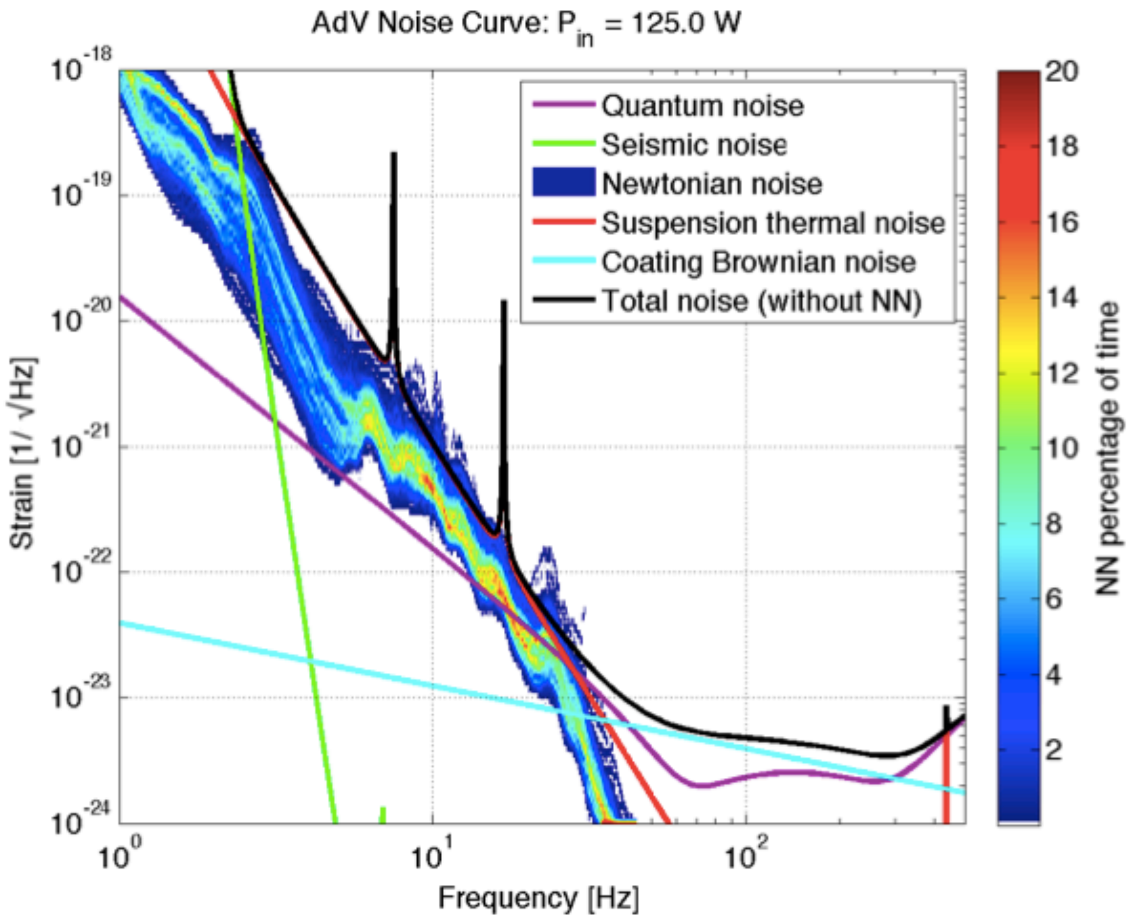
Improving the suspensions: increasing L

Einstein Telescope conceptual design study, www.et-gw.eu



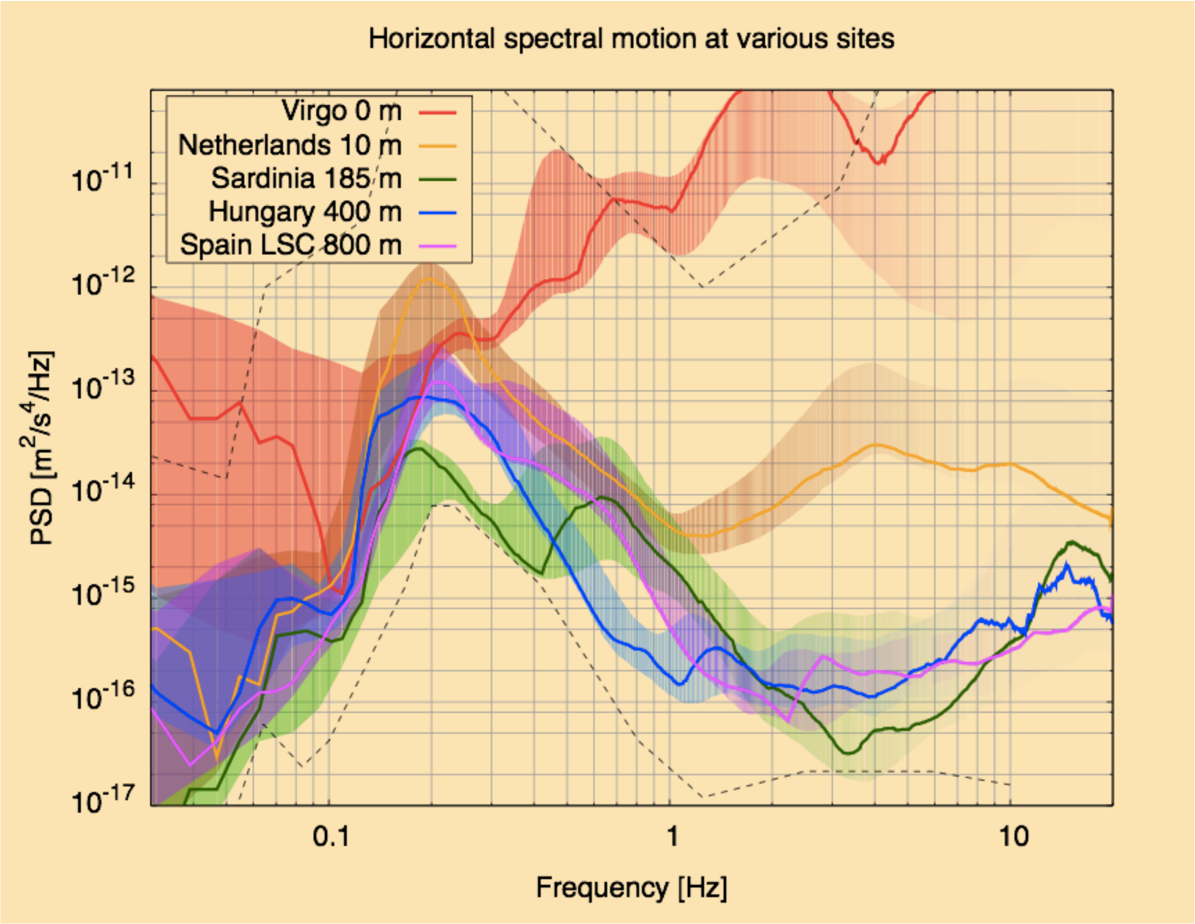
Increasing length from 9 m → 17 m ET matches the requirements at 1.8 Hz

The newtonian noise limit



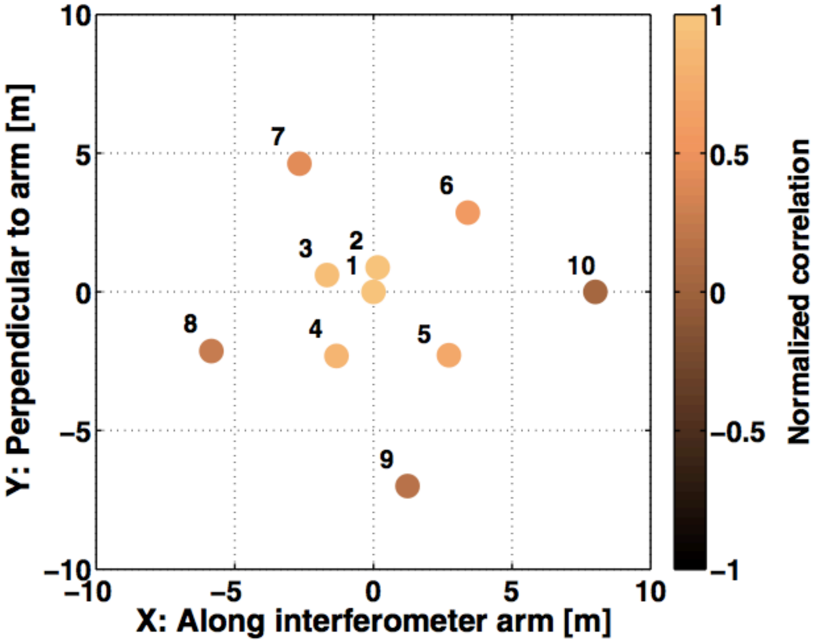
Credit: M.Beker

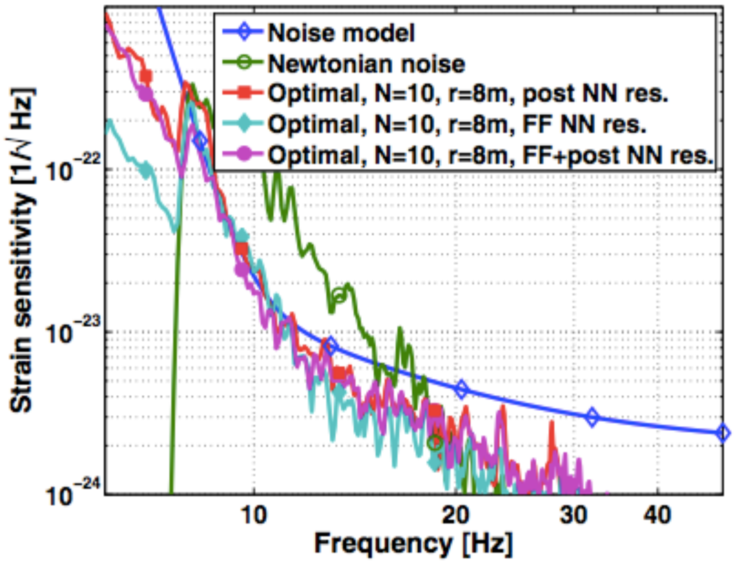
Reducing newtonian noise/1: underground



Einstein Telescope conceptual design study, www.et-gw.eu

Reducing newtonian noise/2: subtraction





SJ.Diggers et al., *Subtraction of Newtonian noise using optimized sensor arrays*, Phys. Rev. D 86, 102001 (2012)

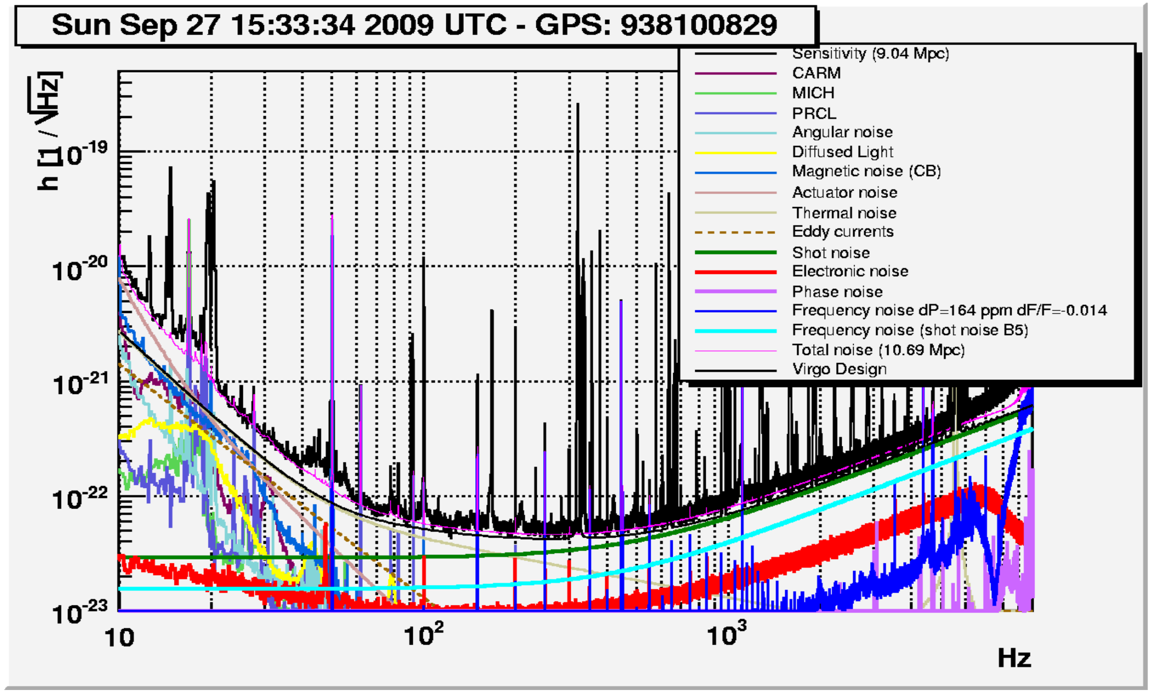
Gravity gradients and seismic: summary

- To decrease newtonian noise:
  - Noise substraction procedures
  - Go underground
- To decrease the seismic wall frequency: increase pendulum length

Technical noises

- Control noises
- Laser frequency noise
- Laser amplitude noise
- Electronic noise
- Phase oscillator noise
- Magnetic noise
- Diffused light noise

Virgo *noise budget*



Third part

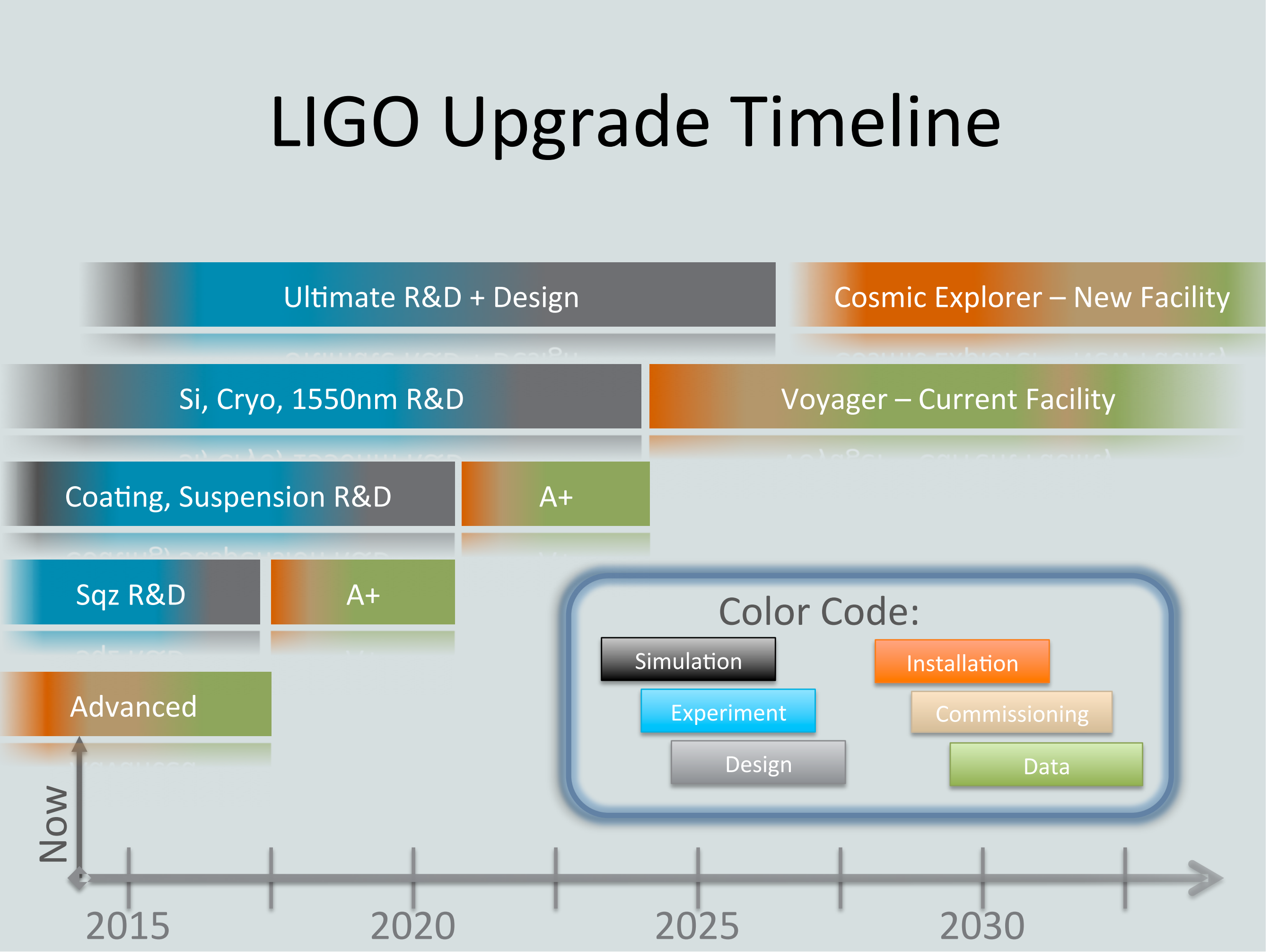
How these developments/ideas can become real detectors: (some of the) plans for future projects

Possible upgrades for advanced detectors

Possible incremental upgrades

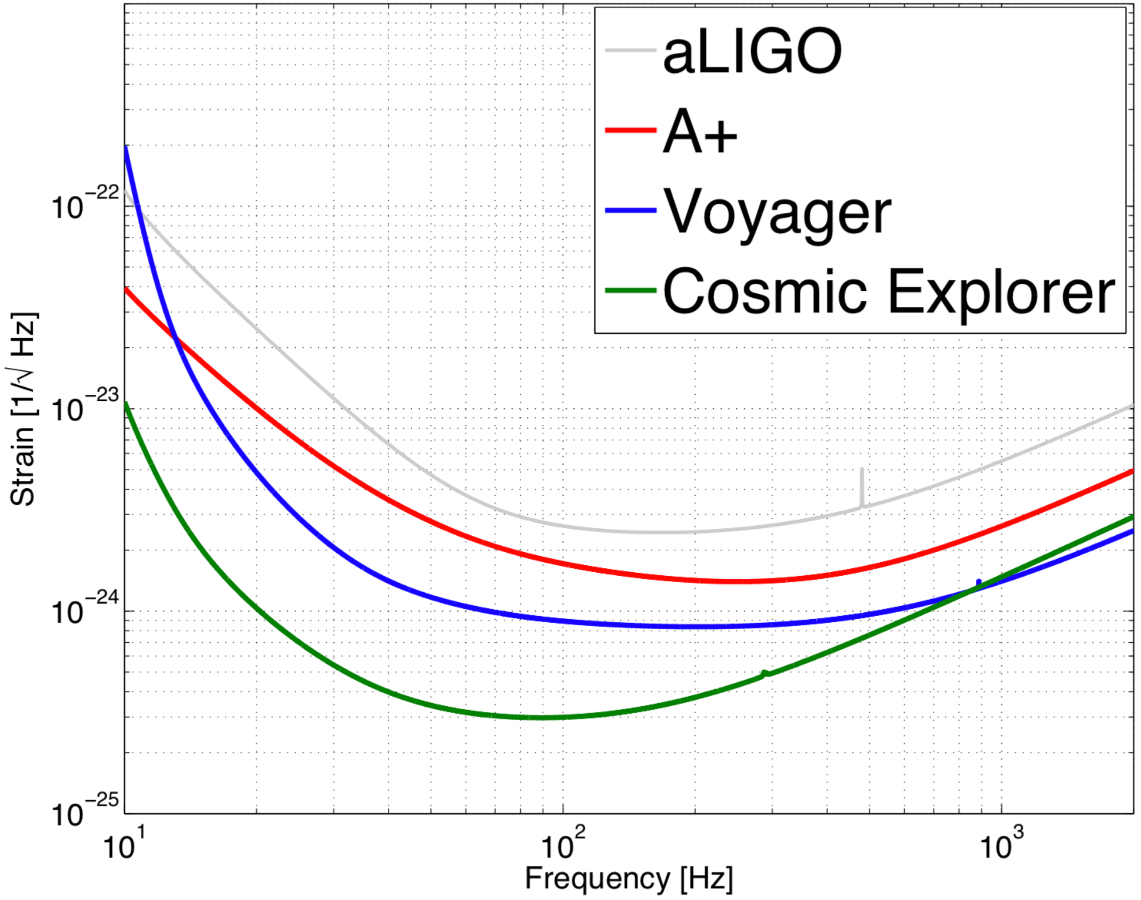
- ❑ Quantum noise: frequency independent and frequency dependent squeezing injection (filter cavity)
- ❑ Mirror thermal noise: improvement of coatings (Crystalline coatings?), non gaussian-beams, bigger beams
- ❑ Newtonian noise: substraction

LIGO upgrades



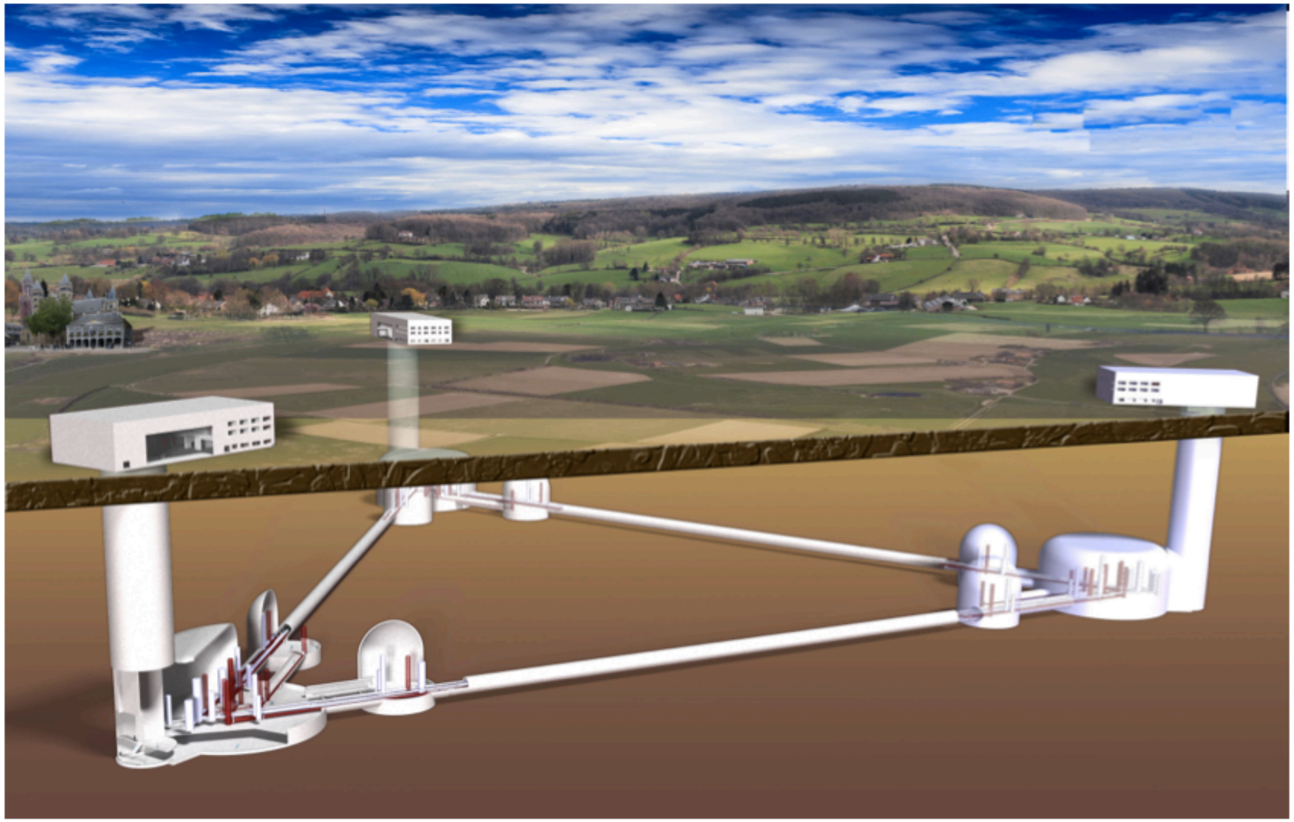
from *LIGO instrument science paper, dcc.ligo.org*

LIGO upgrades/2



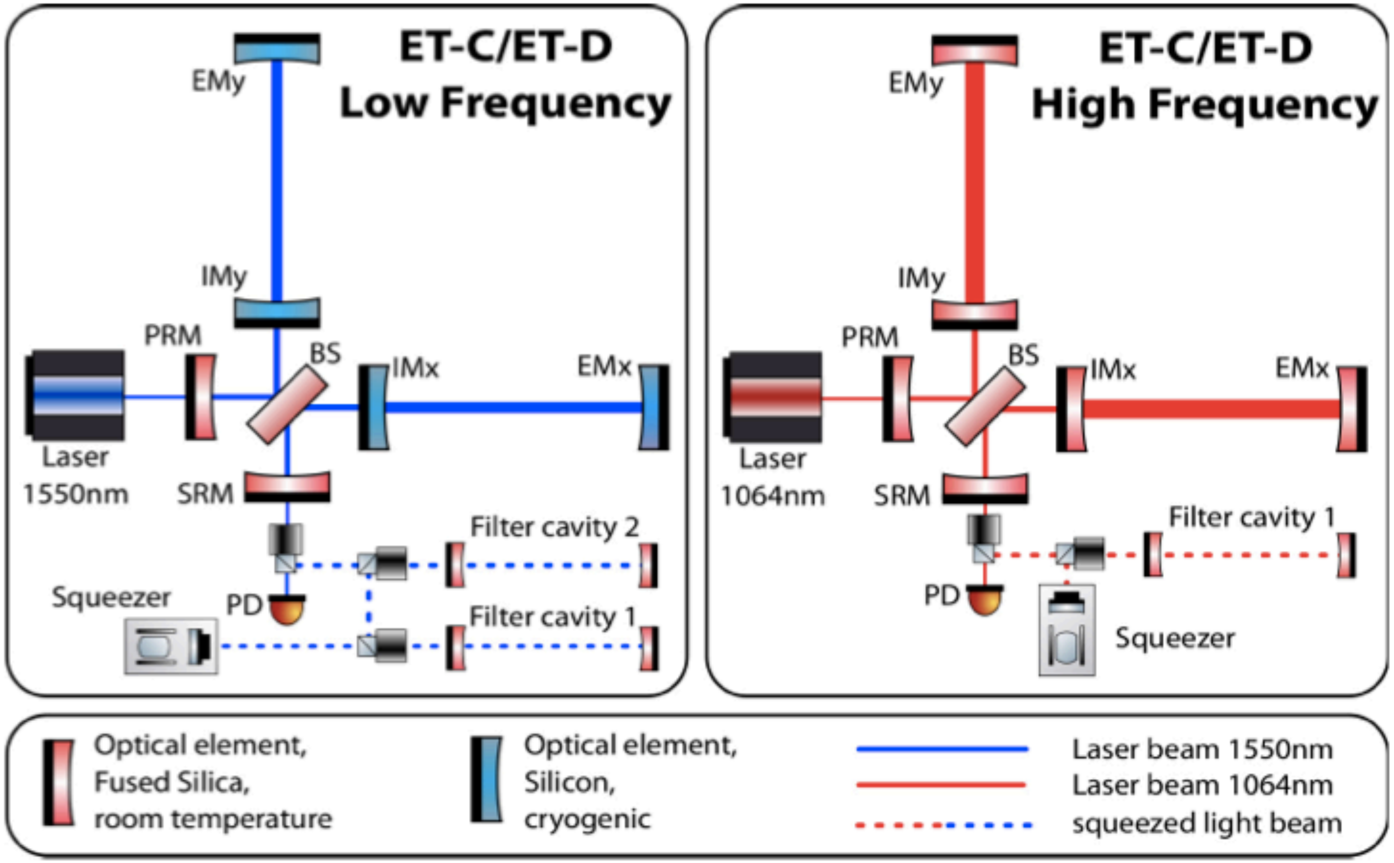
from *LIGO instrument science paper, dcc.ligo.org*

Einstein Telescope



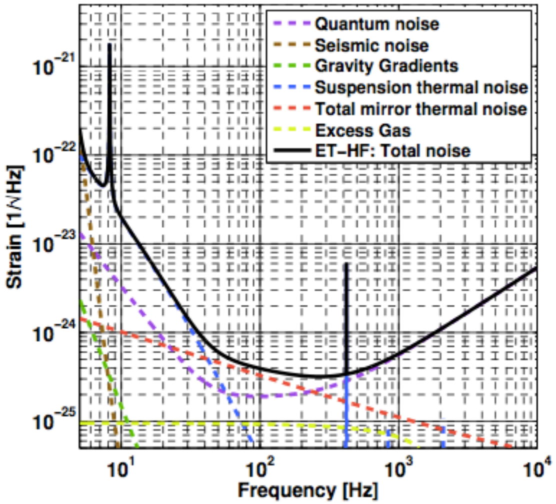
Einstein Telescope conceptual design study, www.et-gw.eu

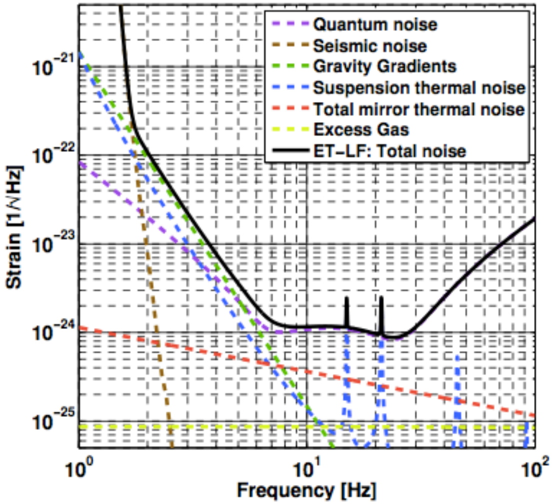
Einstein Telescope – optical scheme

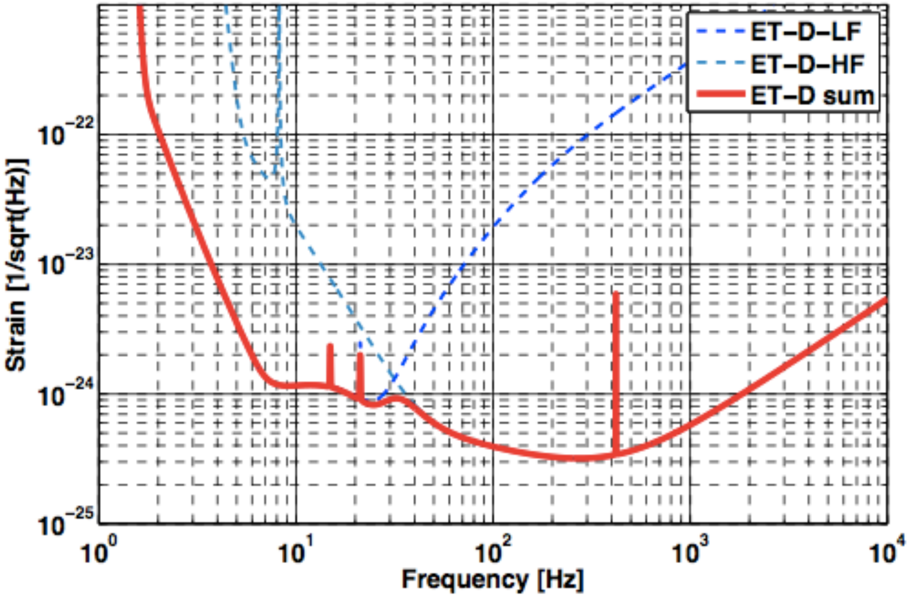


Einstein Telescope conceptual design study, www.et-gw.eu

Einstein Telescope – optical scheme

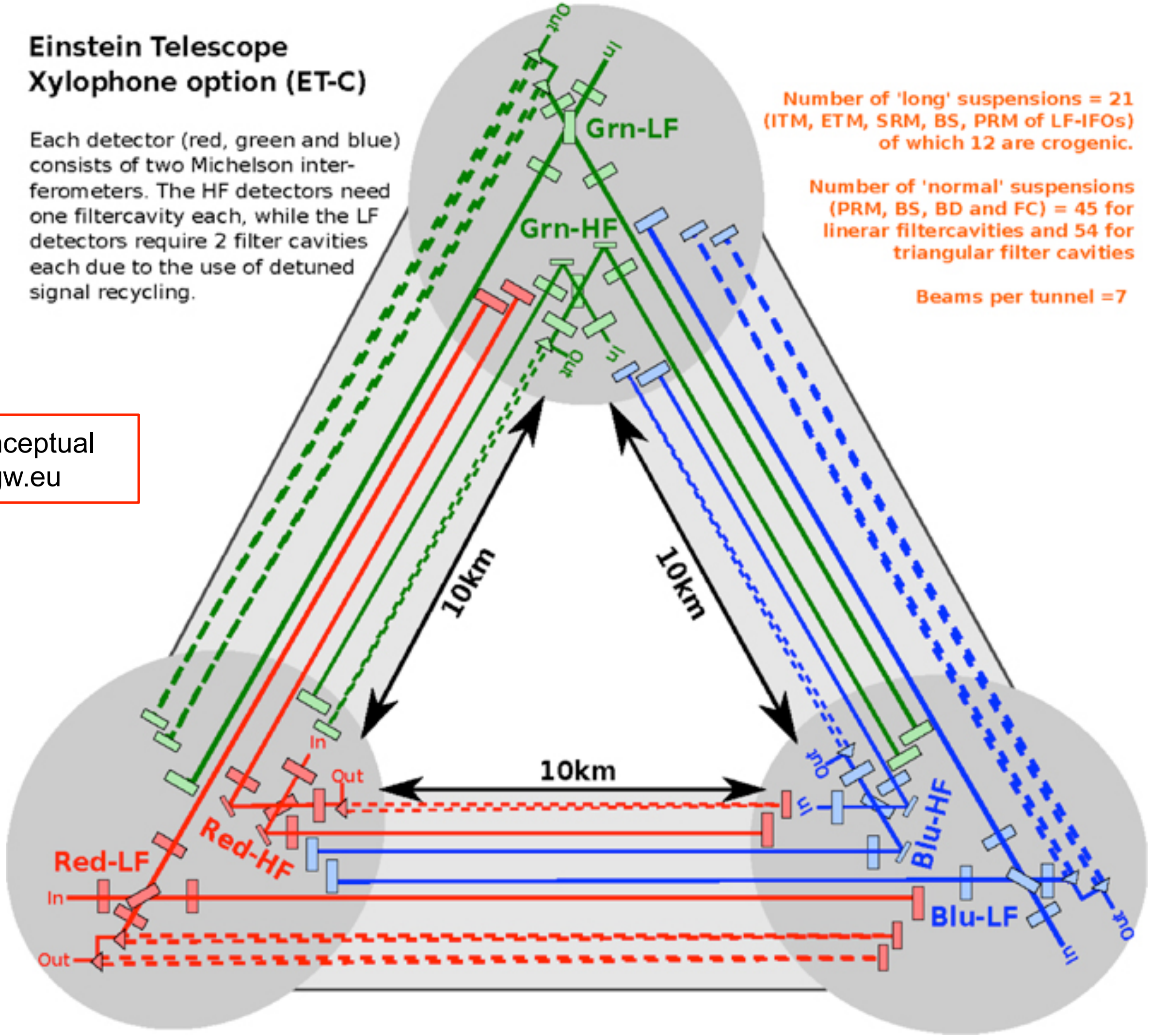






Einstein Telescope conceptual design study, www.et-gw.eu

Einstein Telescope – implementation



Einstein Telescope
Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

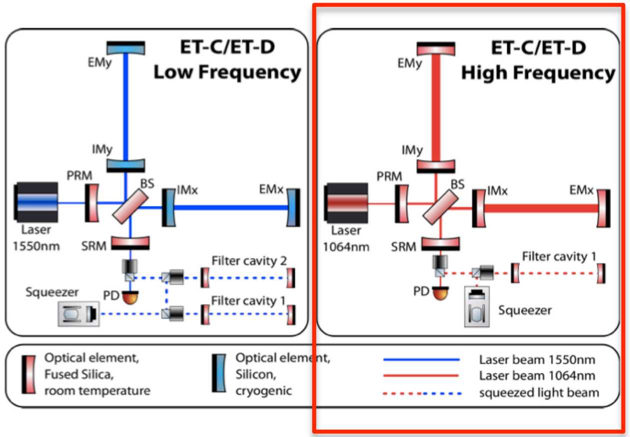
Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

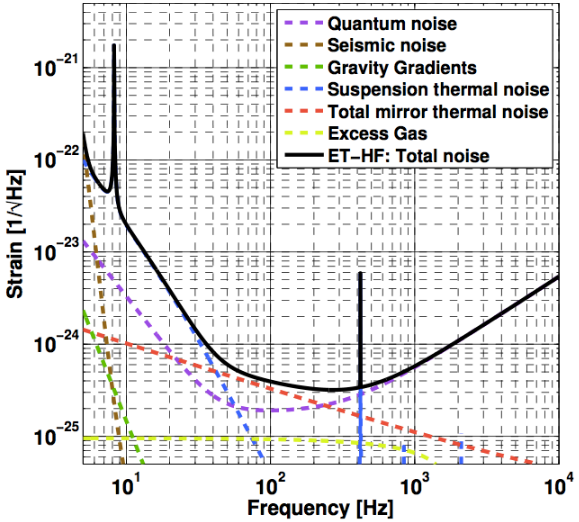
Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linerar filtercavities and 54 for triangular filter cavities

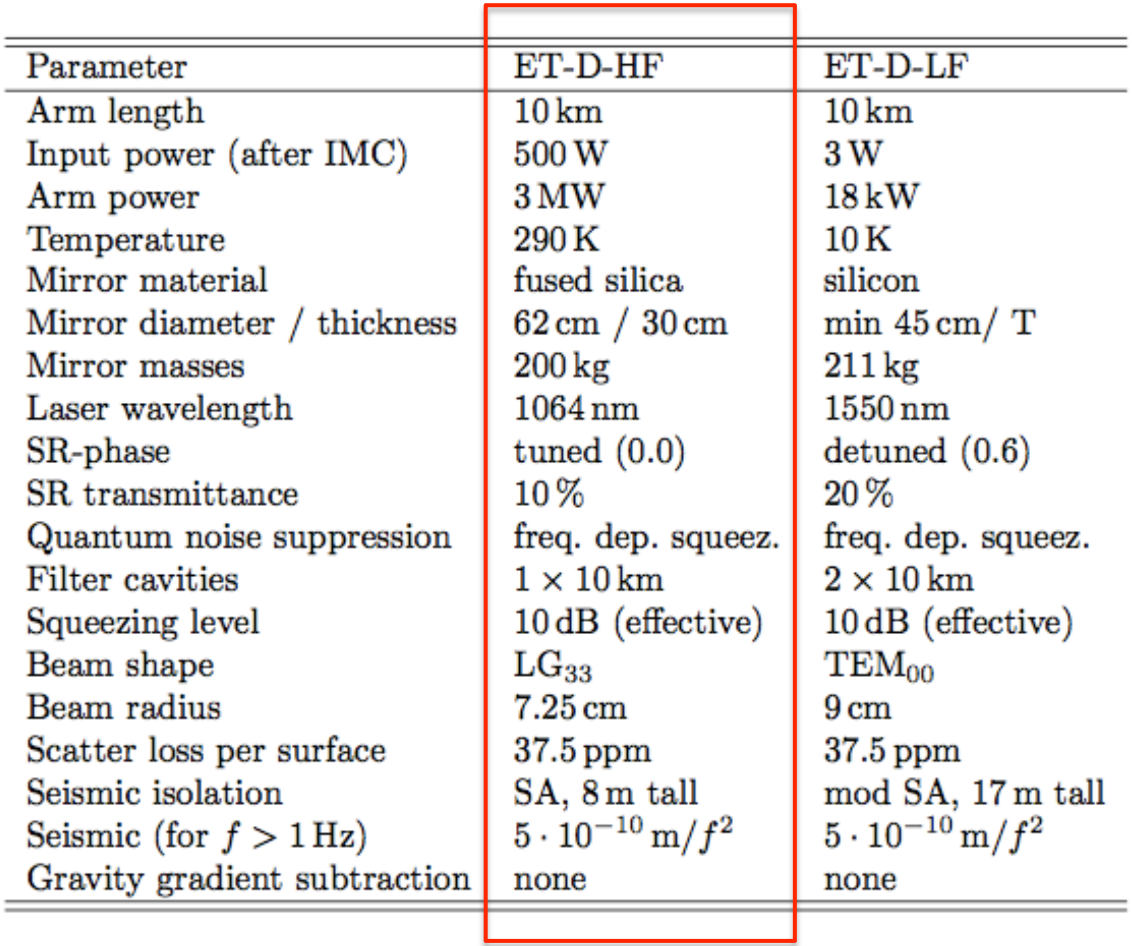
Beams per tunnel =7

Einstein Telescope conceptual design study, www.et-gw.eu

Einstein Telescope – High-frequency

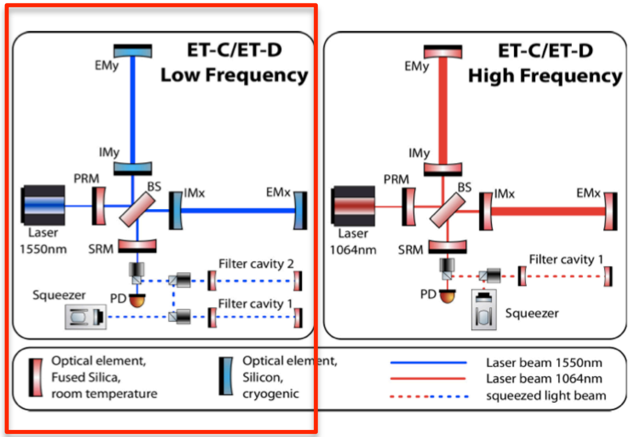


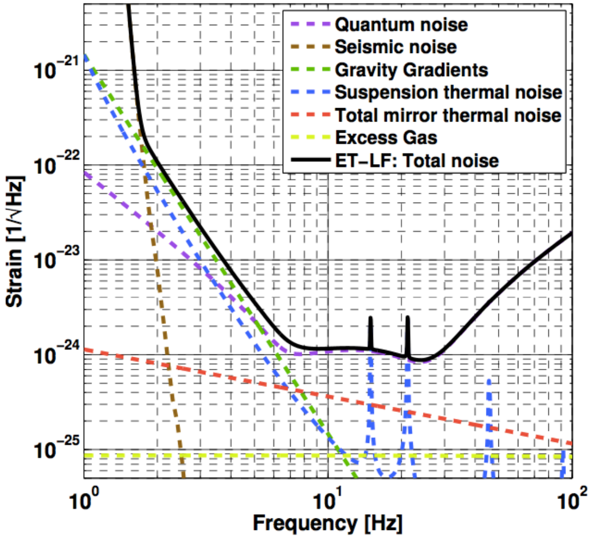




Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ T
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1 × 10 km	2 × 10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1\,$Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

Einstein Telescope – Low frequency





Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ T
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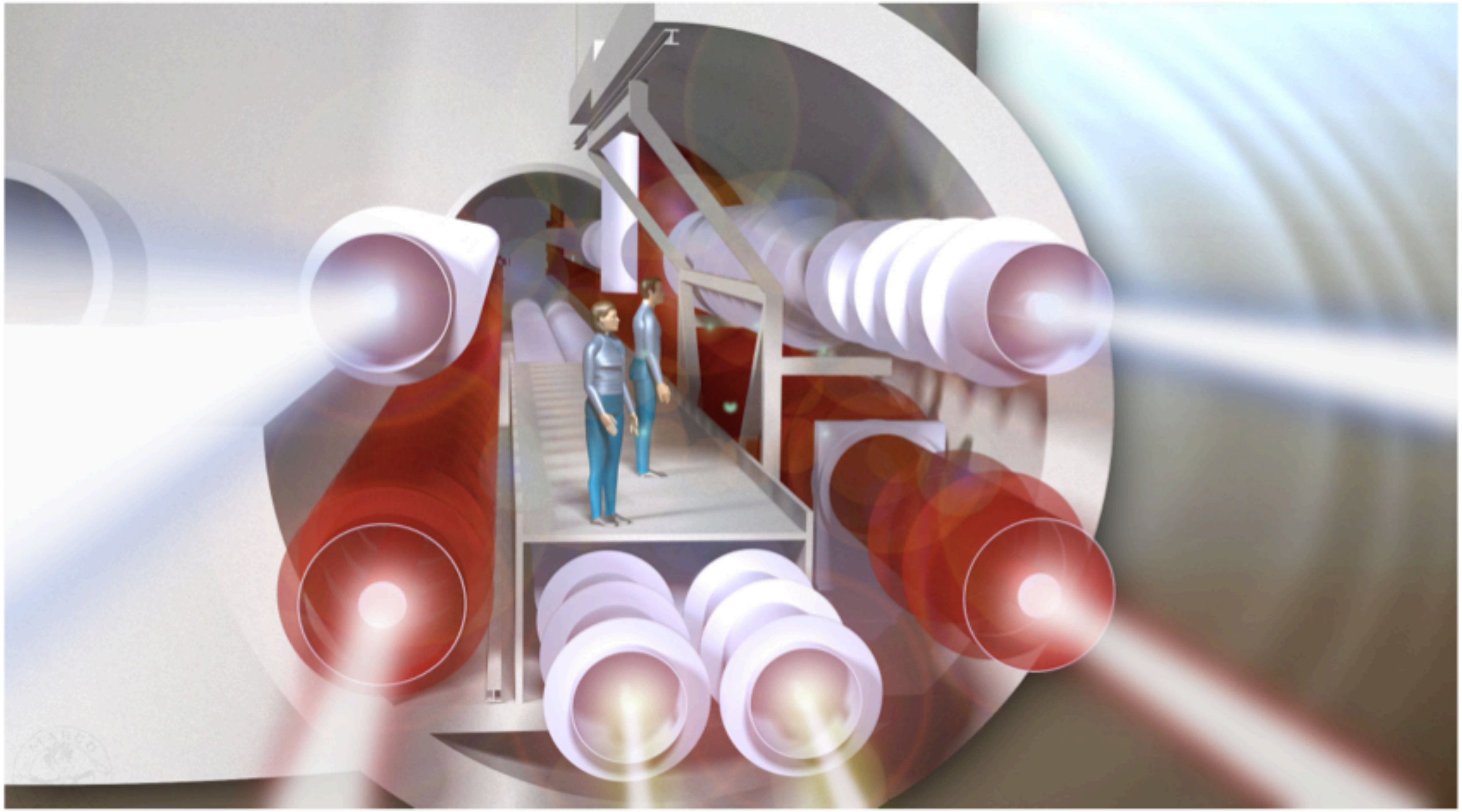
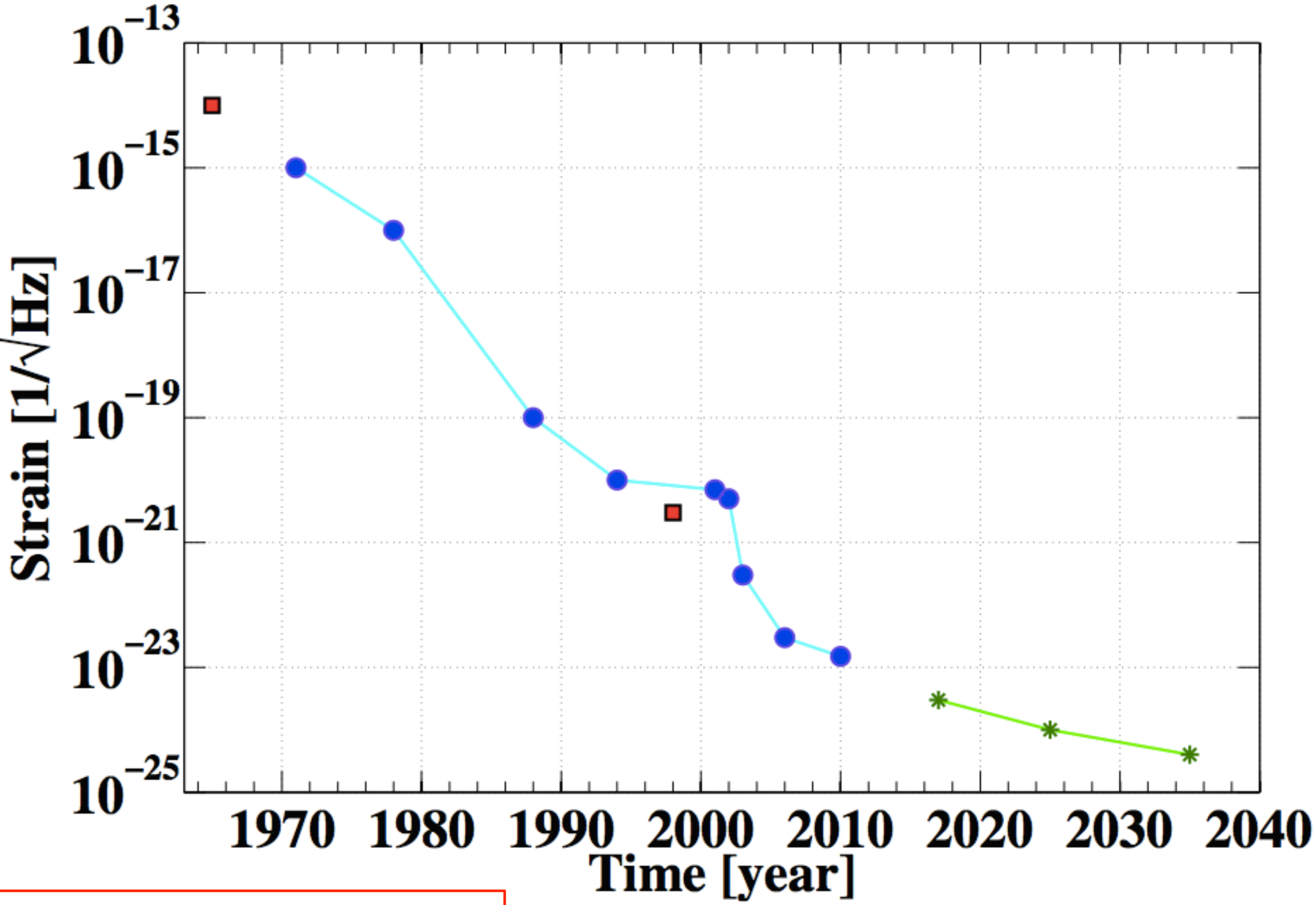
Filter cavities	1 × 10 km	2 × 10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

Einstein Telescope – implementation



Summary



R.Adhikari, Gravitational Radiation Detection with Laser Interferometry, arXiv:1305.5188, 2013