Future generation earth-based gravitational-wave detectors

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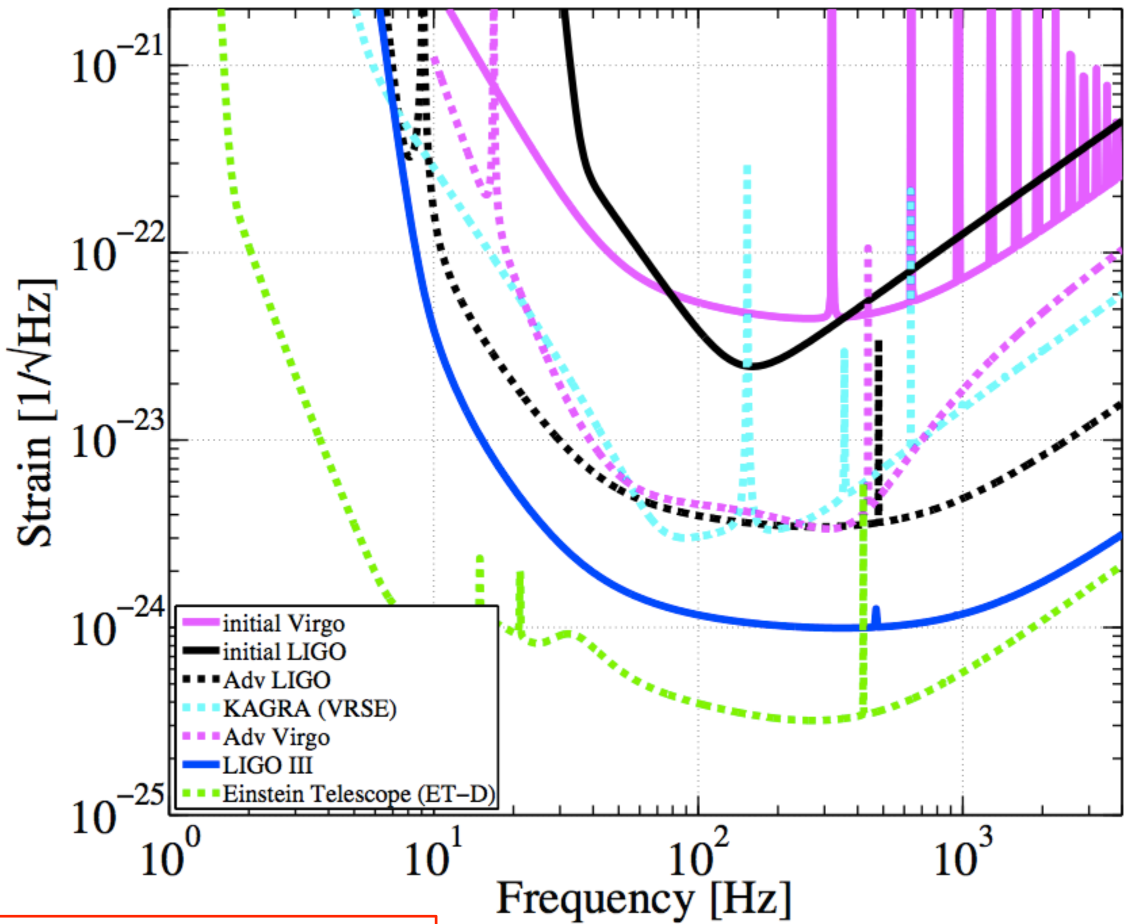
Outline

1. (some of) The science with future earth-based GW detectors
2. (some of) The experimental challenges
3. (some of) The plans for future detectors

First part

(some of the) Science with a *third* generation earth based detector

Sensitivities of present and future detectors



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

Compact objects coalescences with ET

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

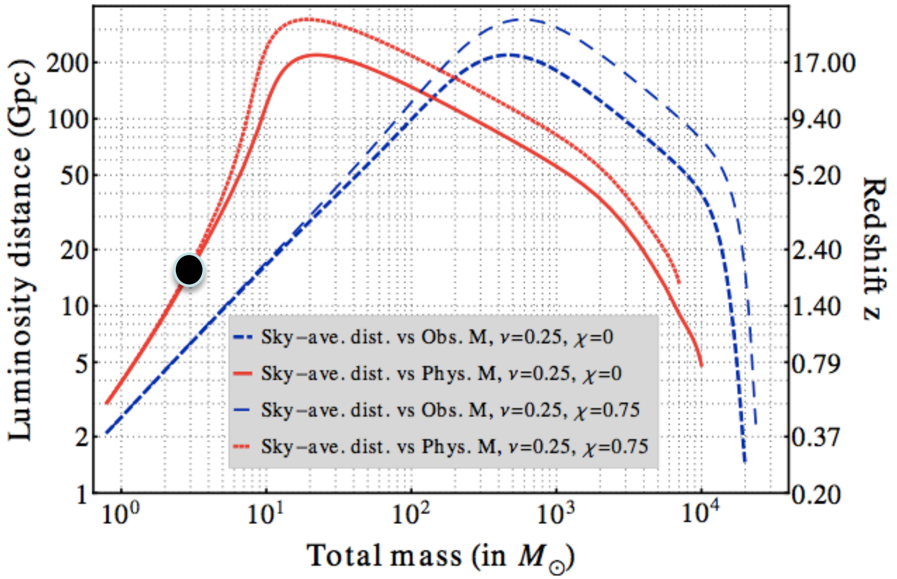


Figure 18: ET's distance reach for signals from coalescing compact binaries as a function of the *intrinsic* (red curves) and *observed* (blue curves) total mass, averaged over sky position and binary's orientation relative to the line-of-sight. We assume that a source is visible if it produces an SNR of at least 8 in ET. Solid red and short-dashed blue curves correspond to binaries composed of non-spinning objects. Dotted red and long-dashed blue curves correspond to binaries composed of objects whose spins are aligned with the orbital angular momentum of the binary, with spin parameter $\chi = 0.75$.

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

Cosmology with ET

- Compact object coalescences can be used as distance standard: *standard sirens* (Shultz, Nature, 1986)
- Need redshift, detection of host galaxy
- Detection of 500 NS-NS coalescences at low redshift → Hubble constant with an error of 0.5% (Planck precision ~ 1.8%)

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

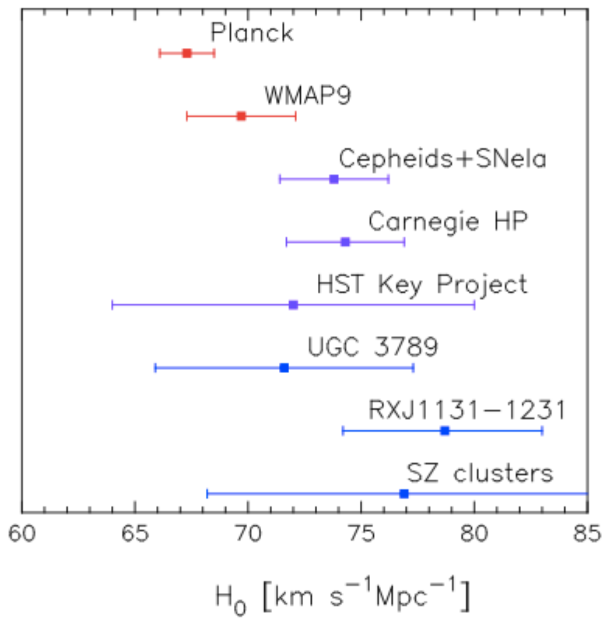


Fig. 16. Comparison of H_0 measurements, with estimates of $\pm 1\,\sigma$ errors, from a number of techniques (see text for details). These are compared with the spatially-flat ΛCDM model constraints from *Planck* and *WMAP*-9.

Planck 2013 results.XVI. Cosmological parameters, arXiv:1303.5076

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 $10\text{-}10^3$ will allow to discriminate between *seed scenarios* formation.
- Complementary information with respect to LISA

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

Spinning neutron stars with Virgo and LIGO

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
- $\varepsilon < 1.1 \times 10^{-3}$

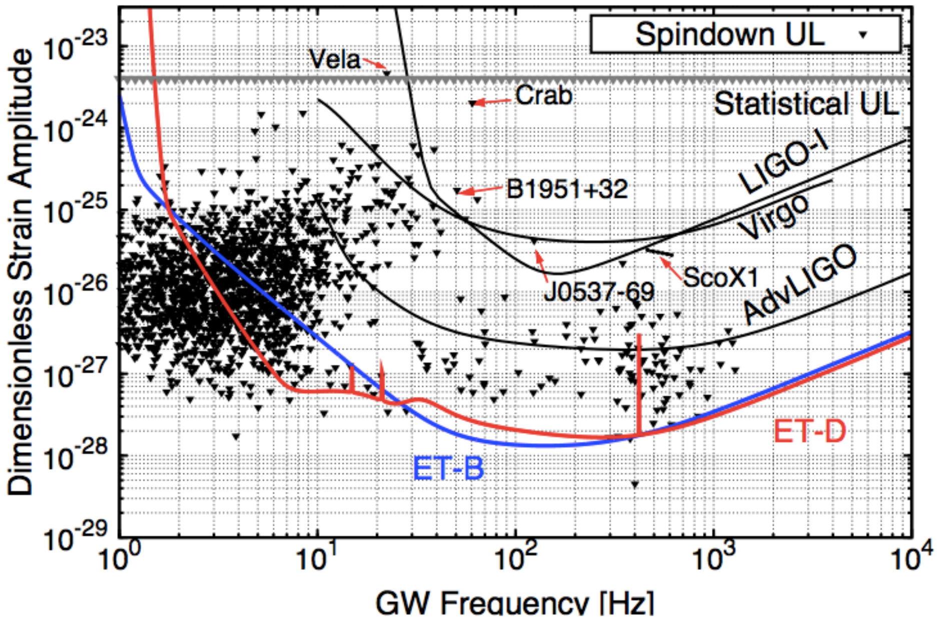
LIGO Scientific Collaboration, "*Beating the spin-down limit on gravitational wave emission from the Crab pulsar*", Astrophys. J. Lett. 683 (2008) 45

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

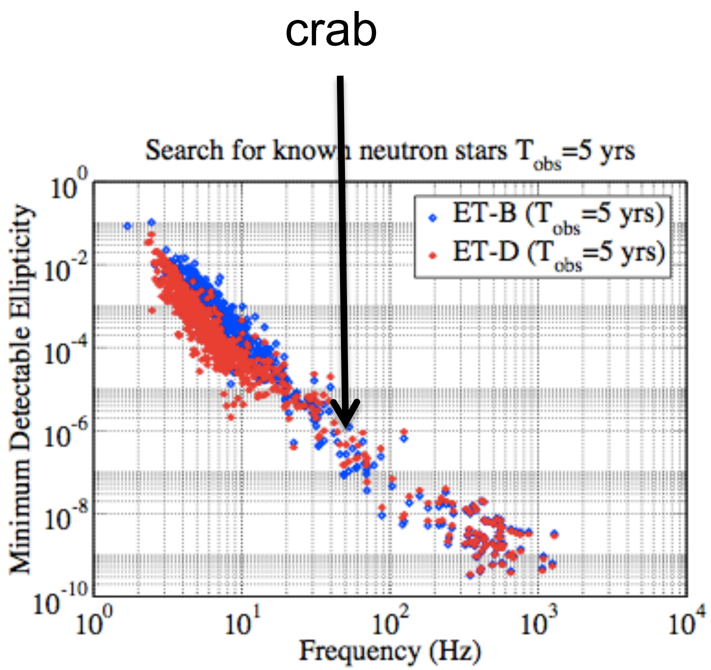
LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Vela pulsar,*" Astrophys. J. 737 (2011) 93

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

Spinning neutron stars with ET



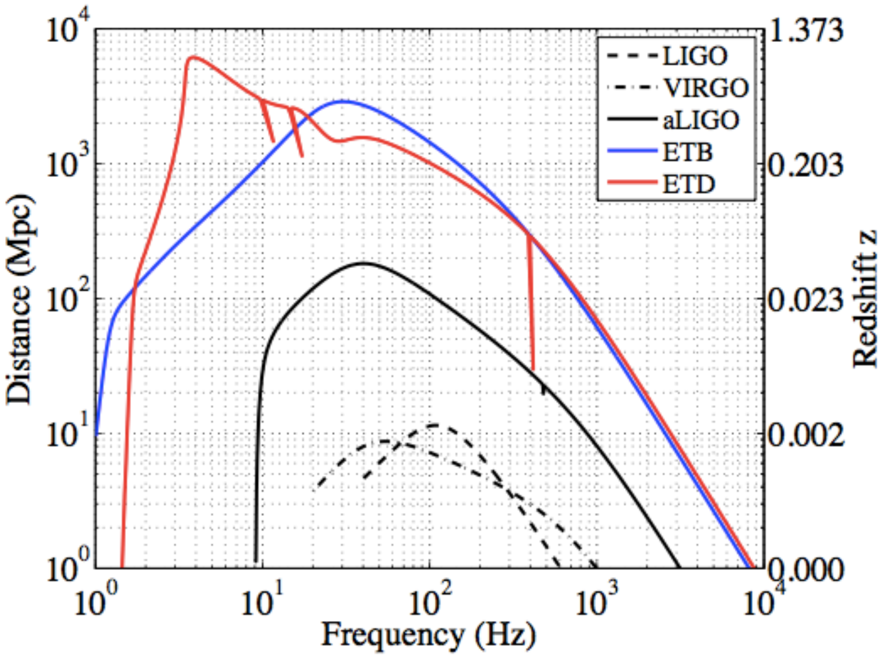
From: Einstein Telescope conceptual design study, www.et-gw.eu



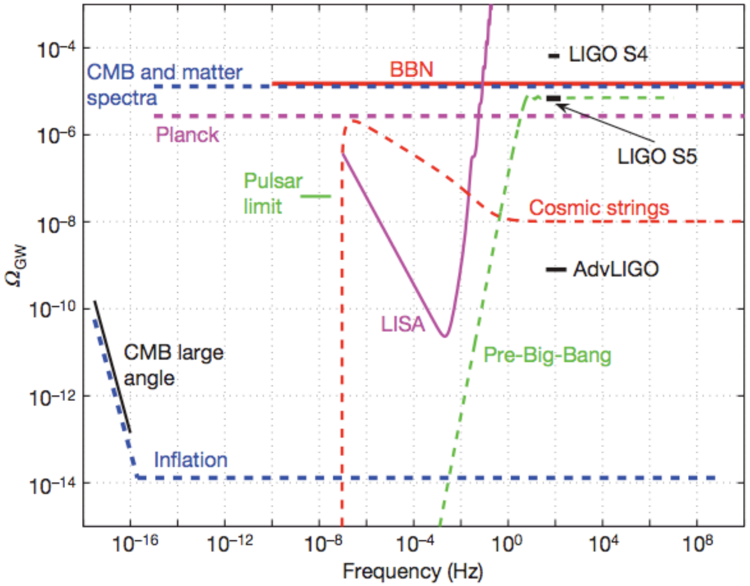
Burst sources with ET

- Supernovae collapse → Understand the physics of a core collapse supernovae
- Gamma-ray bursts → Understand the progenitor of GRB
- Others: Pulsar glitches, magnetar flares, relativistic instabilities of compact stars

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

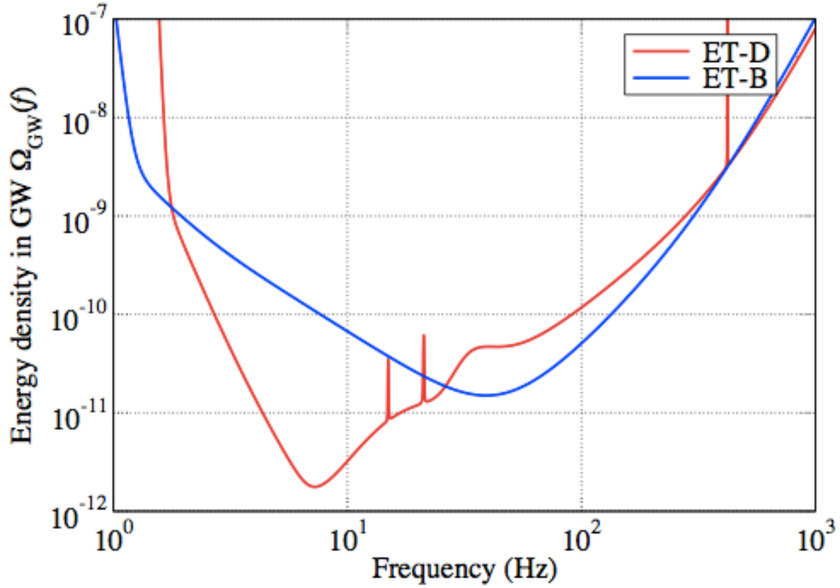


Stochastic background with ET



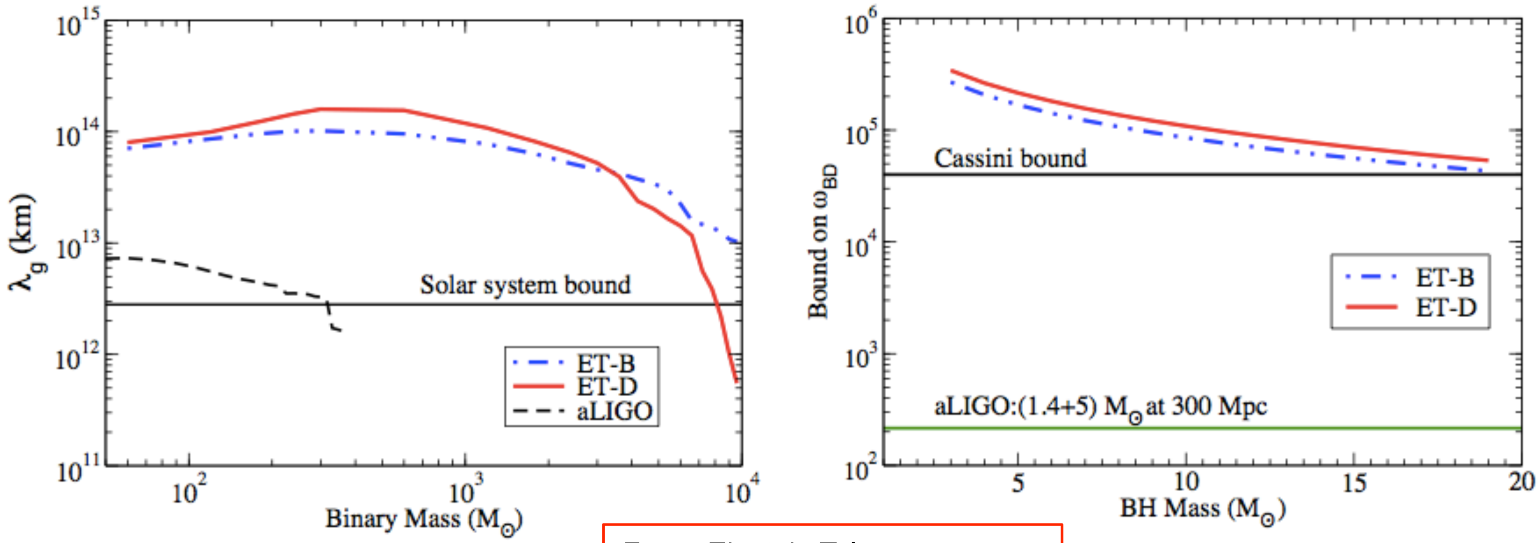
LIGO Scientific and Virgo Collaborations, "*An upper limit on the stochastic gravitational-wave background of cosmological origin*", Nature 460:990 (2009)

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



Testing GR in strong field regime with ET

- Bounding number of polarization (2 for GR, more for alternative theories)
- Bounding graviton mass (through dispersion relation or time of flight)
- Testing gravity in the strong field regime



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

The science: summary

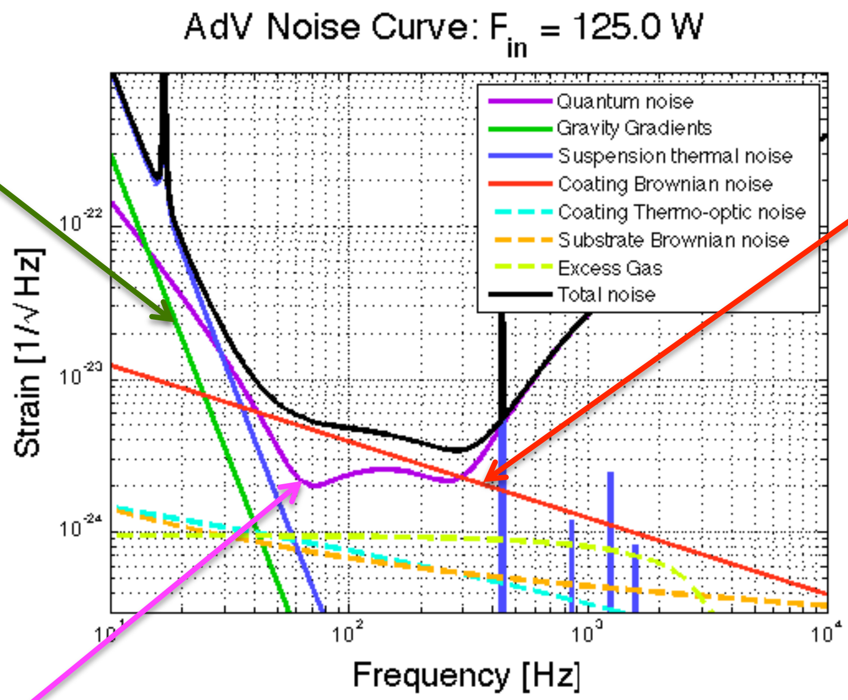
- Huge number of sources
- Cosmological distances
- Enormous scientific potential in astrophysics, fundamental physics, cosmology
- “Precision” gravitational-wave astronomy
- Complementary with eLISA

Second part

(some of) The experimental challenges

Noises limiting AdVirgo

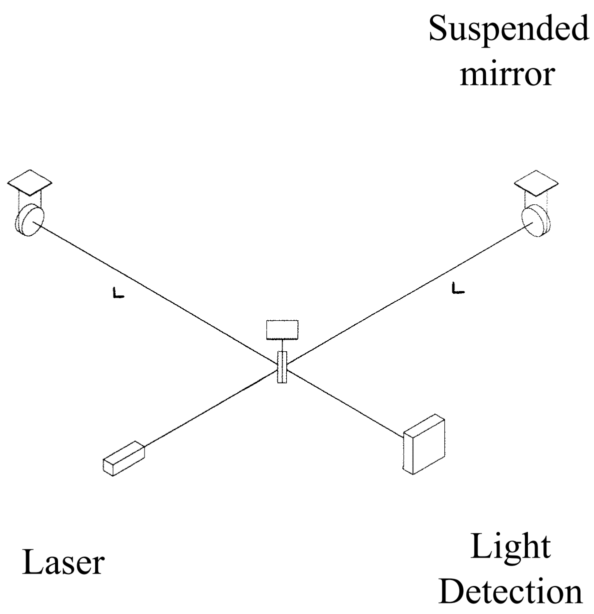
Seismic and gravity gradient noise
Geophysics



Thermal noise
Thermodynamics

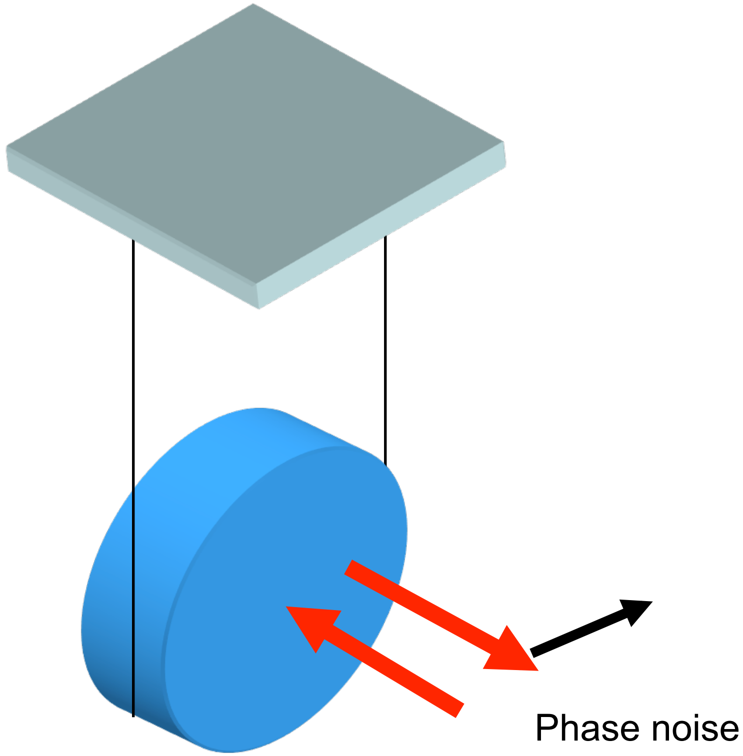
Quantum noise
Quantum mechanics

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



The thermal noise

Thermal noise: introduction



• E= ½ KT (per d.o.f.) → the RMS value of the displacement is constant ($K_B T/k$)

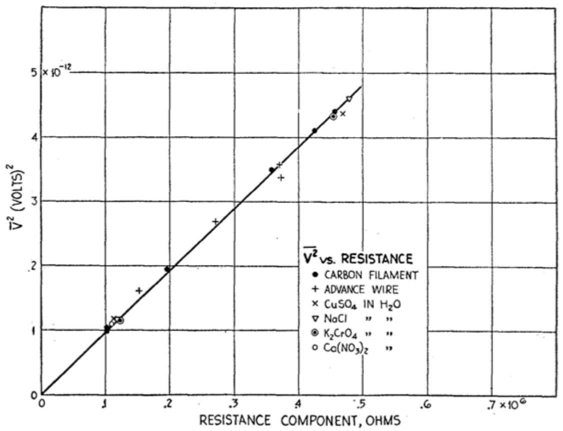
• What is the distribution of thermal energy versus the frequency? How this energy is converted in displacement?

• What is the *power spectrum* of thermal noise?

Thermal noise: Nyquist theorem

- 1928 Johnson observes the "Johnson-Nyquist" noise

amplifier a mean-square potential $\overline{V}^2$. By this method of comparison was determined the fact that the phenomenon is independent of the material and shape of the resistance unit and of the mechanism of the conduction,[6] but does depend on the electrical resistance. A few of the results are reproduced



J.B.Johnson, Thermal agitation of electricity in conductors, Phys Rev 32, 1928

- Explanation by Nyquist in terms of thermodynamics and statistical mechanics: thermal agitation of charges

$$V^2 = 4K_B TR$$

$$V(nV/\sqrt{Hz}) = 0.13\sqrt{R}$$

H.Nyquist, Thermal agitation of electric charge in conductors, Phys Rev D 42 8 (1990)

Th. noise: Fluctuation-dissipation theorem

- Brownian motion and Johnson-Nyquist noise are special cases of a general law: the fluctuation dissipation theorem (Callen 1951).
- Fundamental relation between the dissipation in a system and the fluctuation
- More precisely: *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*

impedance

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

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

Admittance

- For the Johnson-Nyquist noise: V=F, R = Resistance = Re(Z)

Th. noise: harmonic oscillator

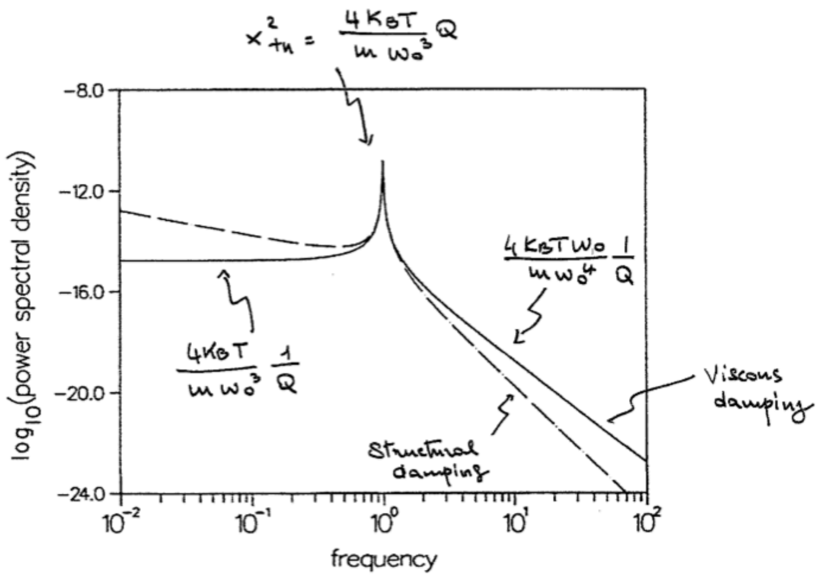
- Harmonic oscillator with viscous damping

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

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

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

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



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

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

- Harmonic oscillator with structural damping

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

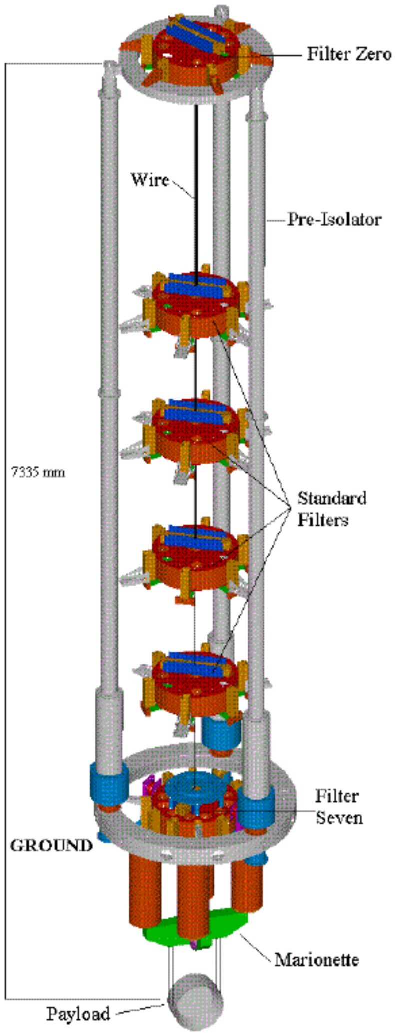
$$x^2 = \frac{4 k_B T \phi}{(K - m\omega^2)^2 + K^2\phi^2} \cdot \frac{1}{\omega}$$

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

Note

$$\int_0^\infty x^2\, df = \frac{k_B T}{K} \qquad \text{since } E = \frac{1}{2} k_B T \text{ from the equipartition theorem}$$

Thermal noise in GW detectors

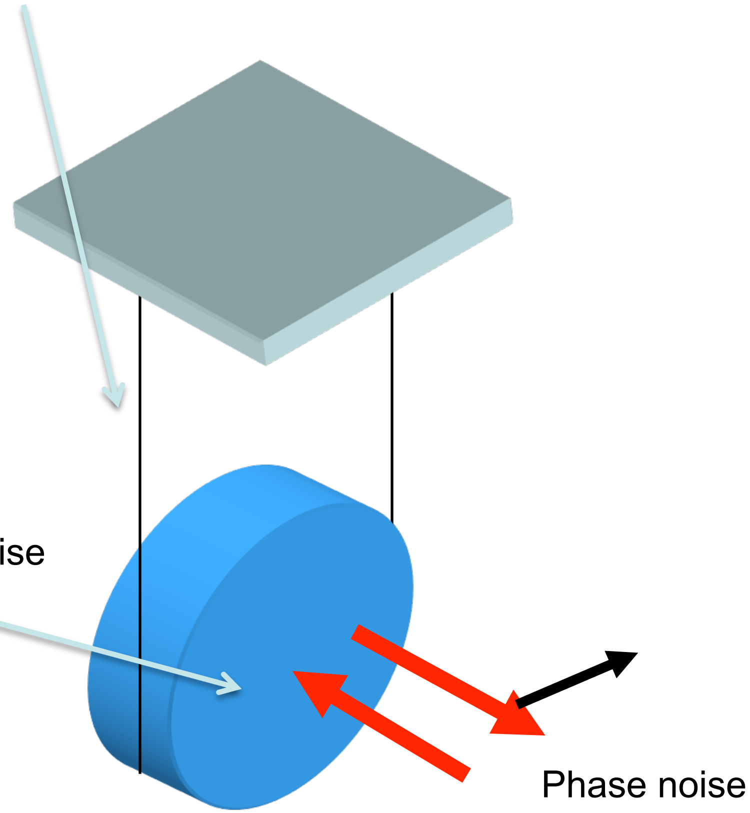


« Pendulum » thermal noise

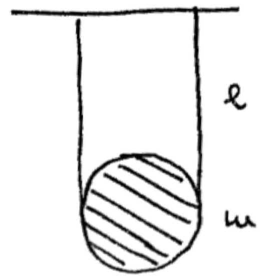
f ~ 1 Hz → thermal noise above resonance

« Mirror » thermal noise

f ~ a few kHz → Thermal noise below resonance



Pendulum thermal noise



$$K_p = \frac{mg}{l} + K_{el}$$

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

$$\phi_p = \left(\frac{K_{el}}{K_p}\right)\phi_w = \frac{n_w\sqrt{TEI}}{2mgl}\phi_w$$

"dilution factor"

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

$$x^2 = \frac{4K_B T \omega_0^2}{m}\phi_p \cdot \frac{1}{\omega^5}$$

$$x^2 \sim \omega_0^2 \sim \frac{1}{l}$$

Thermal noise decreases when pendulum length increases

$$\phi_p = \phi_w \frac{n_w\sqrt{TEI}}{2mgl} \sim \sqrt{m}$$

$T \sim m$
$I \sim m^2$

$$\Rightarrow x^2 \sim \frac{1}{\sqrt{m}}$$

Thermal noise decreases when mass increases

Pendulum thermal noise in Virgo

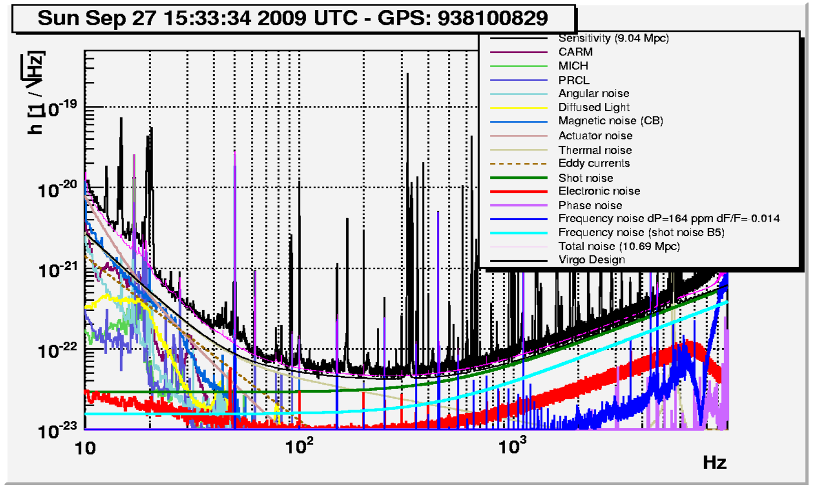
Dilution factor $\frac{k_{el}}{k_p} \sim 10^{-3} \div 10^{-2}$

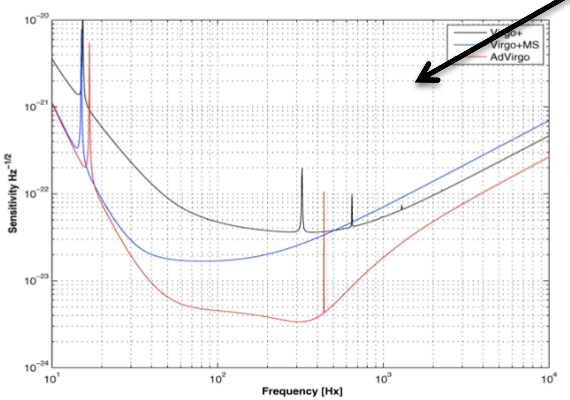
$\phi_w \sim 10^{-4} \div 10^{-3} \Rightarrow \phi_p \sim 10^{-6}$ $Q \sim 10^6$

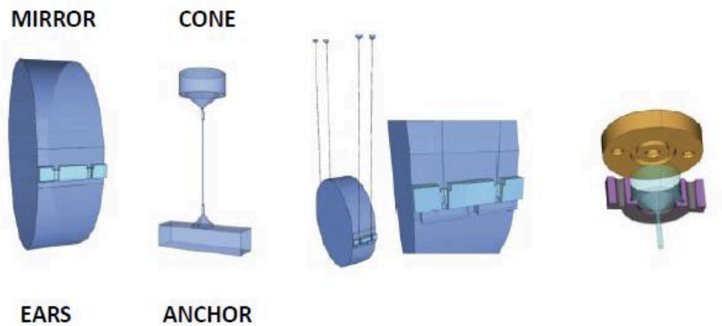
Steel wires

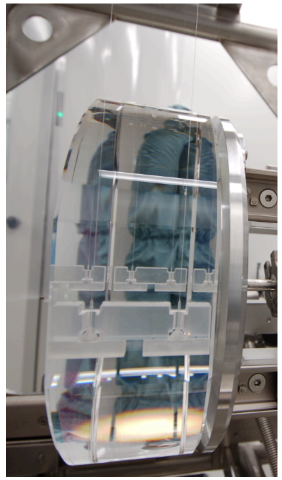
$\phi_w \sim 10^{-7} \Rightarrow \phi_p \sim 10^{-9}$ $Q \sim 10^3$

Silica wires

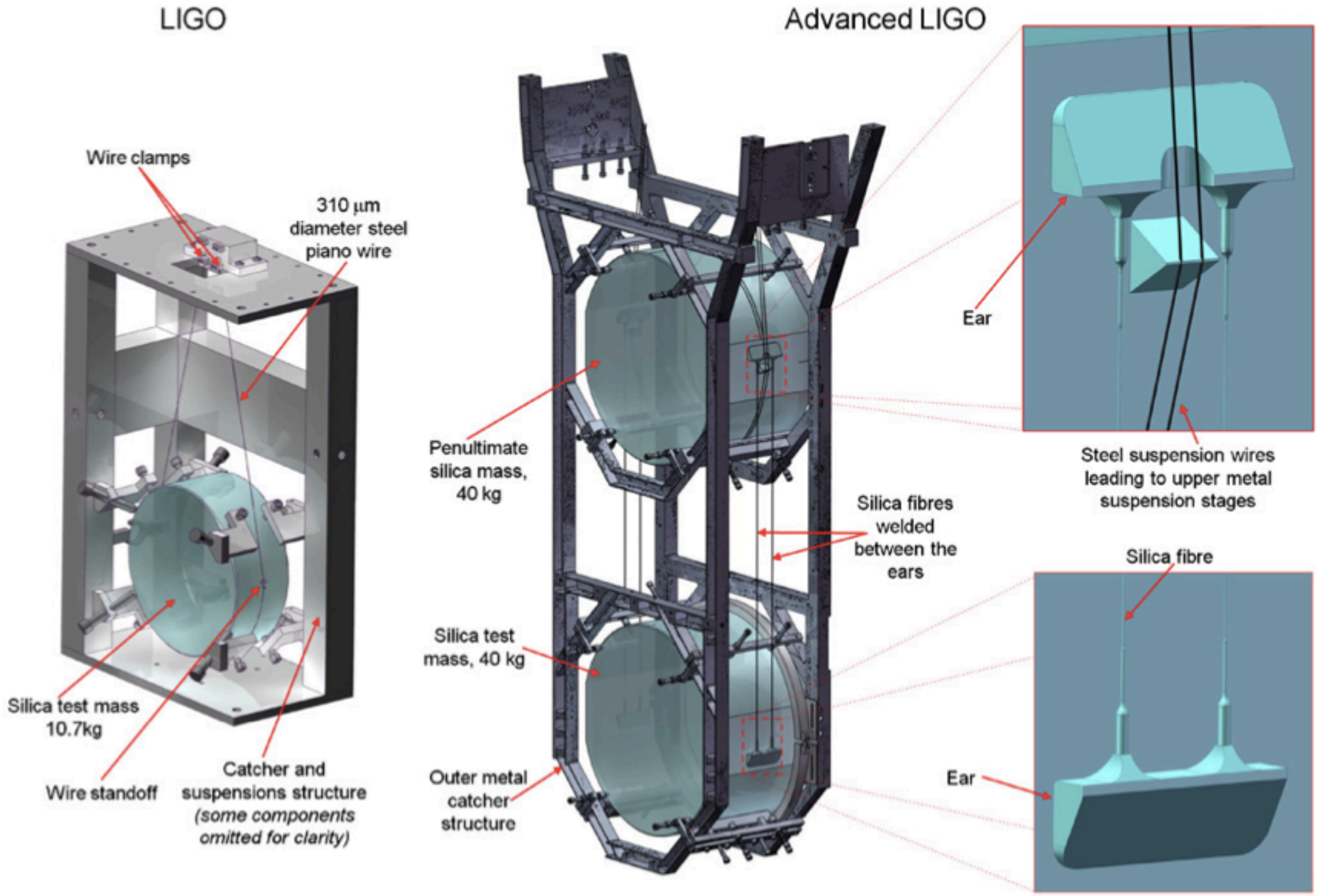






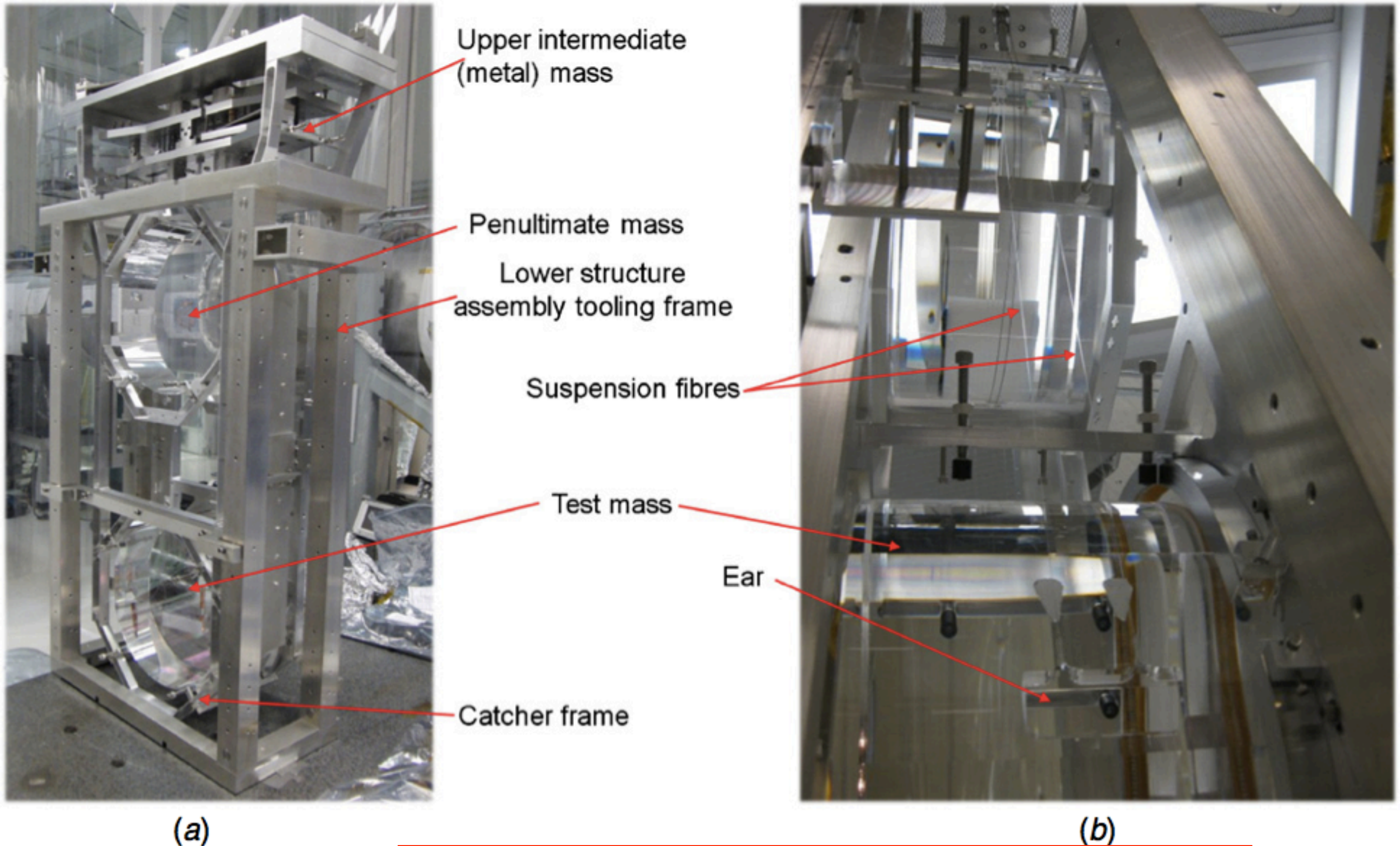


aLIGO suspensions



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

Advanced LIGO 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

$$x^2 = \frac{4 k_B T' \omega_0^2}{m} \phi_P \cdot \frac{1}{\omega^5}$$

$$x^2 \sim \omega_0^2 \sim \frac{1}{\ell}$$

Thermal noise decreases when pendulum length increases

$$\phi_P = \phi_W \frac{n_w \sqrt{T' E I}}{2 m g \ell} \sim \sqrt{m}$$

$T' \sim m$

$I \sim m^2$

$$\Rightarrow \quad x^2 \sim \frac{1}{\sqrt{m}}$$

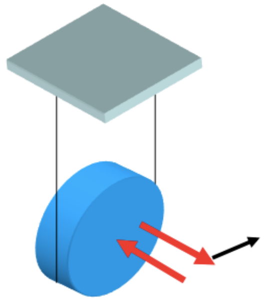
Thermal noise decreases when mass increases

How to reduce the pendulum thermal noise

- ❑ Decrease dissipation (steel wires→fused silica fibers) $x \sim loss^{1/2}$
- ❑ Increase length (Advanced Virgo ~ 0.7 m): $x \sim length^{-1/2}$
- ❑ 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)



$$x(t) = \int I(\vec{r})\, u(\vec{r},t)\, dS$$

$x(t)$: observable

For a gaussian beam $I(\vec{r}) = \alpha\, e^{-2r^2/w^2}$

$$x^2(\omega) = \frac{4k_BT}{\omega^2} Re[Y(\omega)] = \frac{8k_BT}{\omega^2} \frac{W_{diss}}{|F(\omega)|^2}$$

Fluctuation-dissipation theorem

$F(\omega)$: Force with a gaussian profile

$$W_{diss}(\omega) = \omega\, \phi(\omega)\, U_{max}(\omega)$$

$$U_{max} = \frac{1-\sigma^2}{2\sqrt{\pi} E_0 w} |F(\omega)|^2$$

Energy stored in the mirror when it is subject to a constant "gaussian" force

$$\Rightarrow x^2(\omega) = \frac{4k_BT}{\omega} \frac{1-\sigma^2}{\sqrt{\pi} E_0 w} \phi(\omega)$$

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).

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Thermo-elastic noise

V. B. Braginsky, M. L. Gorodetsky, S. P. Vyatchanin, *Thermodynamical fluctuations and photo- thermal shot noise in gravitational wave antennae,* Phys. Lett. A **264,** 1-10 (1999).

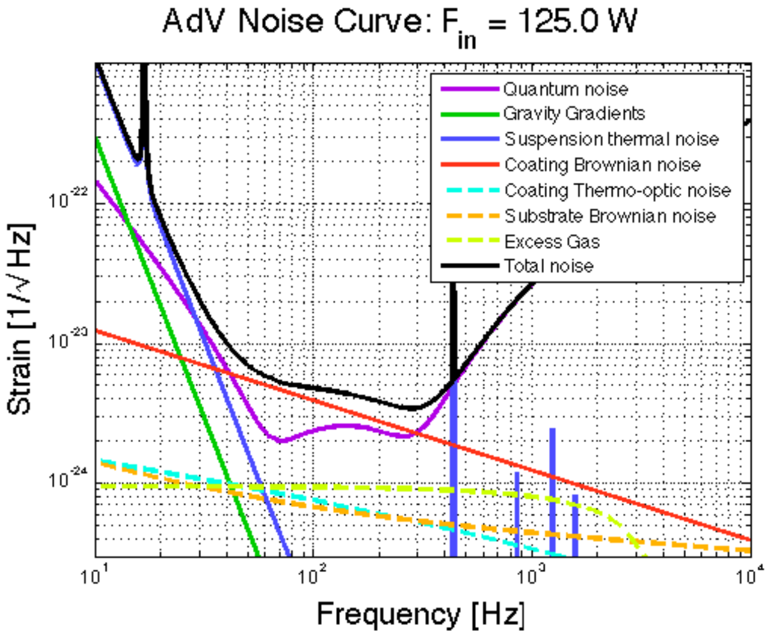
$$\langle \delta T^2 \rangle = \frac{\kappa T^2}{\rho C V},$$

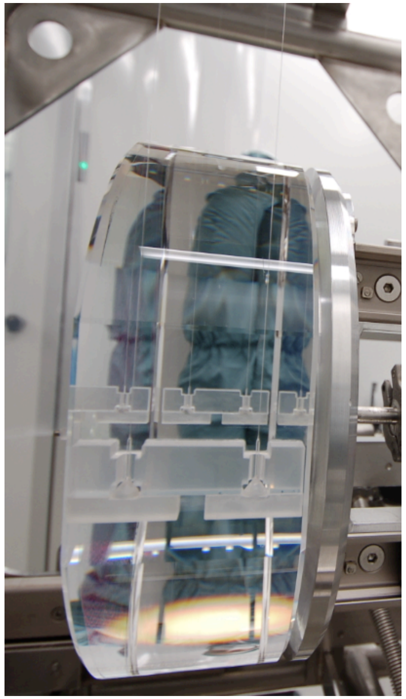
Temperature fluctuations → hot and cold spots inside the test mass
Thermal expansion → position « seen » by laser beam fluctuates

$$S_{\mathrm{TD}}(\omega) \simeq \frac{8}{\sqrt{2\pi}} \alpha^2 (1+\sigma)^2 \frac{\kappa T^2}{\rho C} \frac{a^2}{r_0^3} \frac{1}{\omega^2}$$

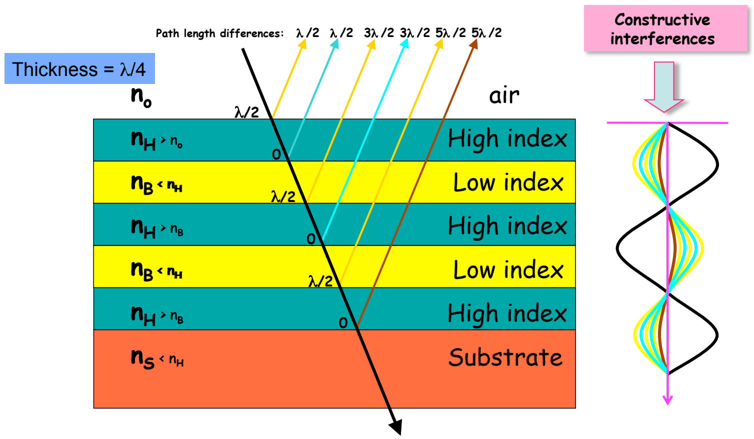
Substrate for aLIGO and AdVirgo

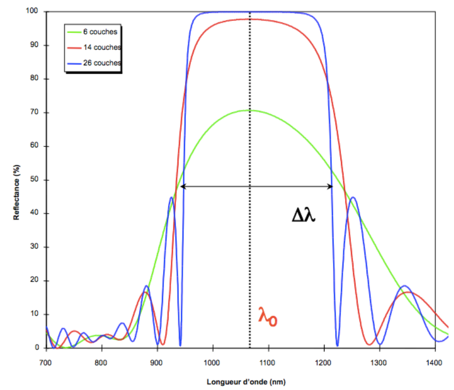
- Fused silica is used in Virgo/Advanced Virgo – LIGO/ Advanced LIGO
  - Low optical absorption (<1 ppm)
  - Low birefringence
  - High homogeneity
  - Low mechanical losses ($\phi \sim 10^{-9}$)

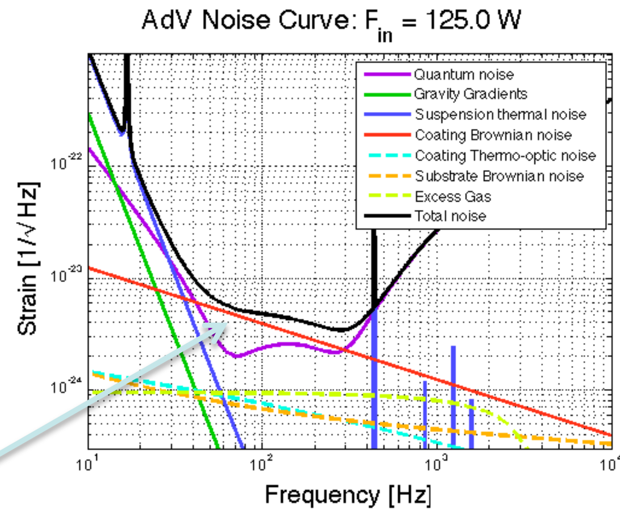




Mirror = substrate + coating





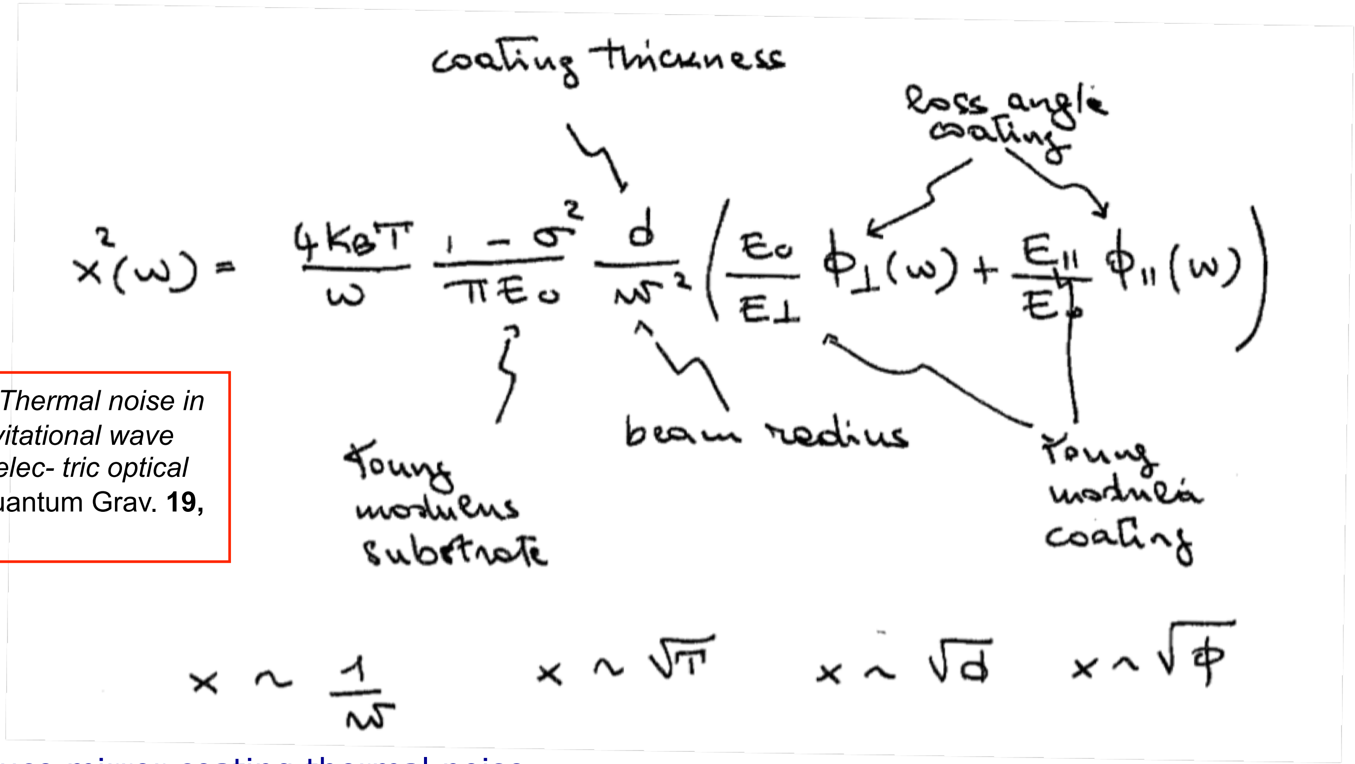


Credit: LMA, www.lma.in2p3.fr

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).



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

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

How to reduce mirror coating thermal noise

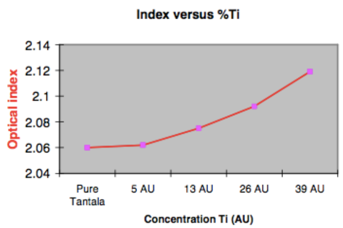
- Improve materials:
  - Decrease loss angle
  - Decrease coating thickness
- Reduce the coupling with the laser beam (increase beam size, change the shape of the beam
- Other (remove the coating, Khalili cavities,…)

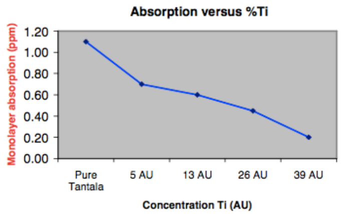
Coatings for second generation detectors

- $\lambda/4$ 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	$3 \cdot 10^{-4}$
Ta_2O_5 : Co	2.11	5000	$11 \cdot 10^{-4}$
Ta_2O_5 : W	2.07	2.45	$7.5 \cdot 10^{-4}$
Ta_2O_5 : W+Ti	2.06	1.65	$3.3 \cdot 10^{-4}$
Ta_2O_5 : Ti	2.07	0.5	$2.4 \cdot 10^{-4}$

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)





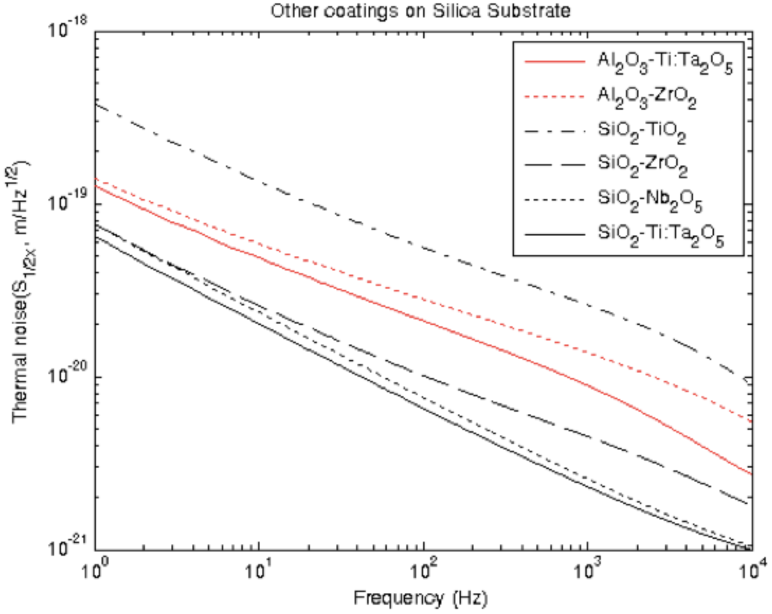
Best loss angle value for tantala doped with Titanium: 1.5×10^{-4}

Other amorphous materials

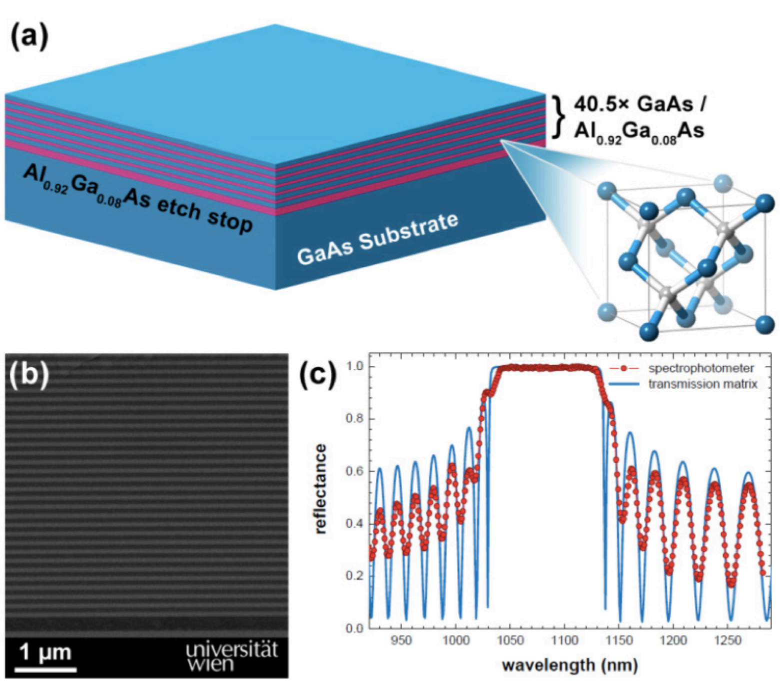
- The high index material (tantala) dominates the losses → try to replace it with other high index materials

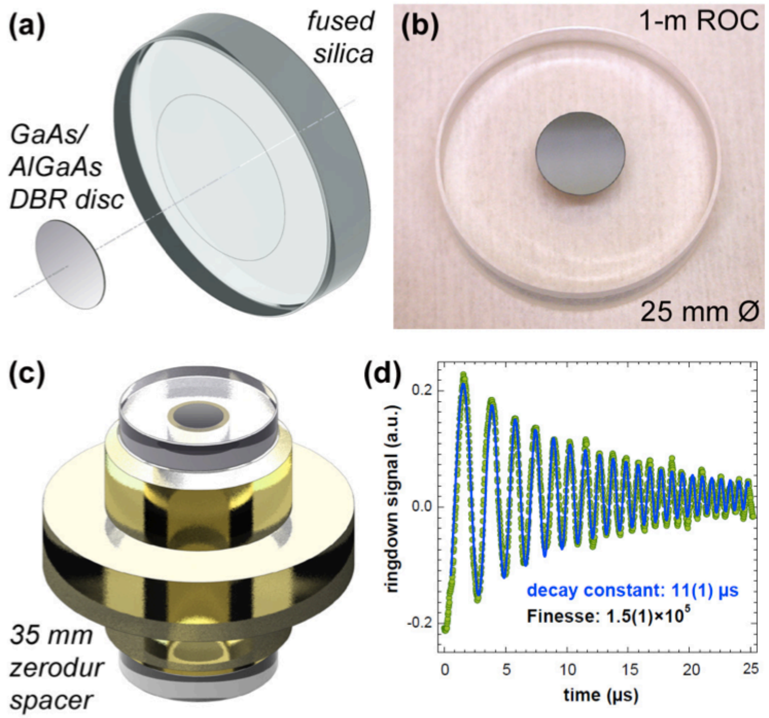
Coating	Refraction index	Absorption (ppm)	Mechanical losses	Stress (MPa)
ZrO_2	2.10	11	$2.3 \cdot 10^{-4}$	-1780
ZrO_2 : Ti	2.15	37	$6.8 \cdot 10^{-4}$	-180
ZrO_2 : W	2.12	10	$2.8 \cdot 10^{-4}$	-600

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)



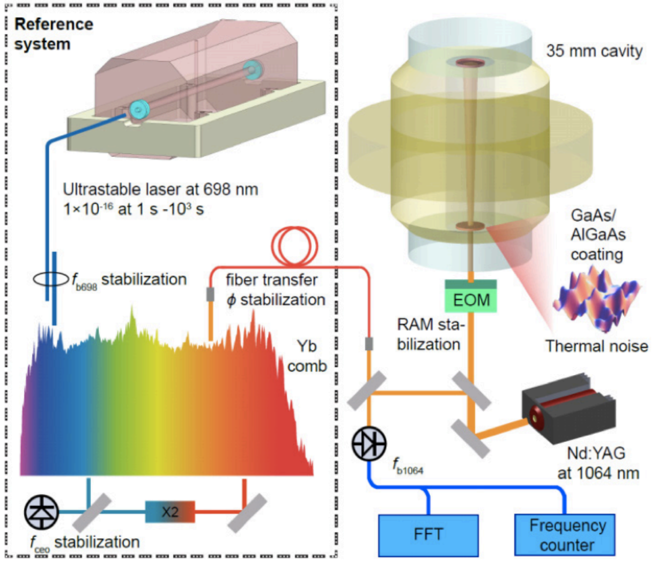
Crystalline coatings: recent results

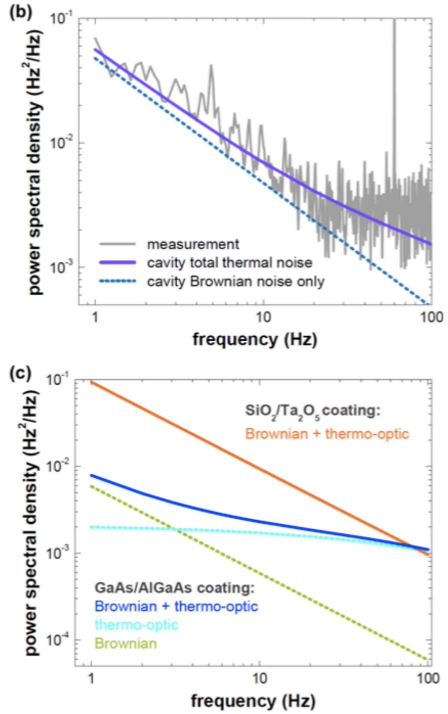




G.D. Cole et al, Tenfold reduction of Brownian noise in optical interferometry, Cole et al, arXiv:1302.6489, 2013

Crystalline coatings/2: TN measurement





- Extrapolation 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, Cole et al, arXiv:1302.6489, 2013

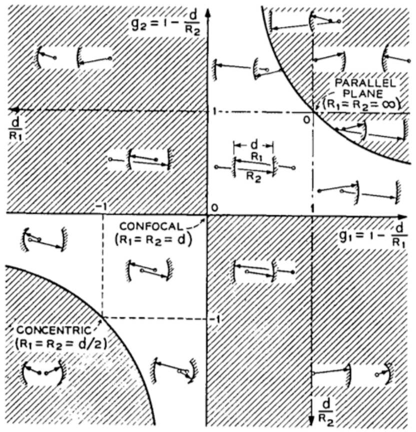
Improving CTN using optical methods

Bigger beams

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

Credit: LMA, www.lma.in2p3.fr

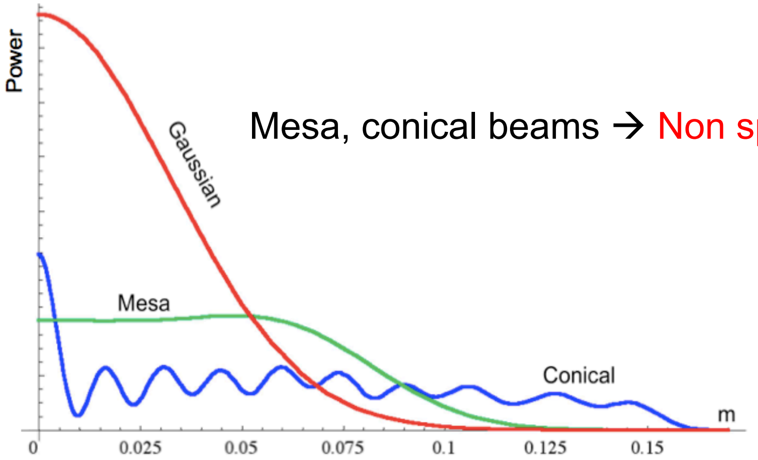
- Limitations:
  - Mirror technology (Advanced Virgo 35 cm diameter mirrors with sub nm flatness)
  - For a factor 10 improvement, beam radius = 50 cm, beam diameter = 50 x5 = 2.5 m !
  - For a given length → max beam allowed to avoid instabilities
    - For a 3 km cavity, 5 cm radius already very near the instability
    - For ET (10 km), 9 cm beam radius: improvement ~ 1.3



Kogelnik and Li, Applied Optics, Vol. 5, N.10, 1966

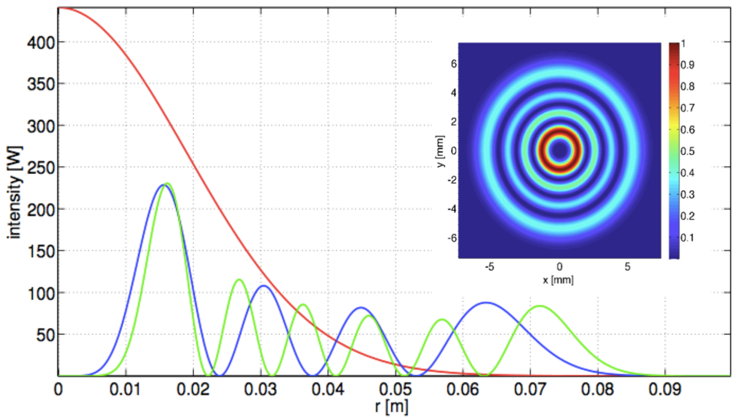
Ways to improve the CTN: beam shape/1

M.Tarallo et al., Generation of a flat-top laser beam for gravitational wave detectors by means of a nonspherical Fabry-Perot resonator, Applied Optics, Vol. 46, Issue 26, pp. 6648-6654 (2007)



Mesa, conical beams → Non spherical mirrors

Laguerre-Gauss modes



$$u_p^\ell(r,\phi,z) = \sqrt{\frac{2P}{\pi}}\sqrt{\frac{p!}{(p+|\ell|)!}}\,\frac{1}{w(z)}\,\exp\left[\frac{-r^2}{w^2(z)}\right]$$

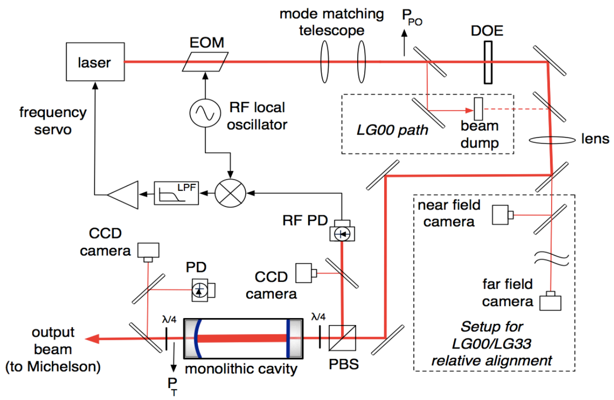
$$\times\left(\frac{2r^2}{w^2(z)}\right)^{|\ell|/2} L_p^{|\ell|}\left(\frac{2r^2}{w^2(z)}\right)\,\exp\left[-i\ell\phi\right]$$

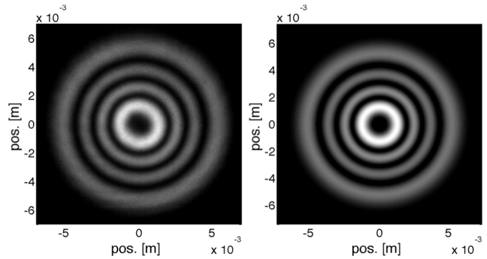
$$\times\,\exp\left[-i\left(k\left(z+\frac{r^2}{2R(z)}\right)-(2p+|\ell|+1)\Phi_G\right)\right]$$

Mours et al., Thermal noise reduction in interferometric gravitational wave antennas: using high order TEM mode, CQG 23 (2006) 5777)5784

Ways to improve the CTN: beam shape/2

Promising results in table top experiments

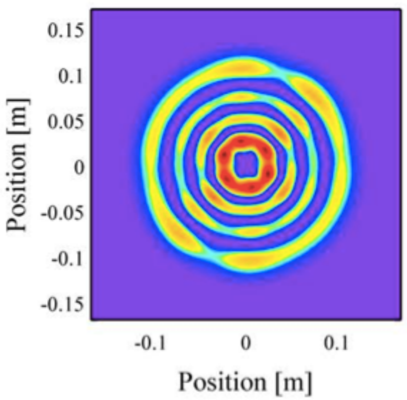


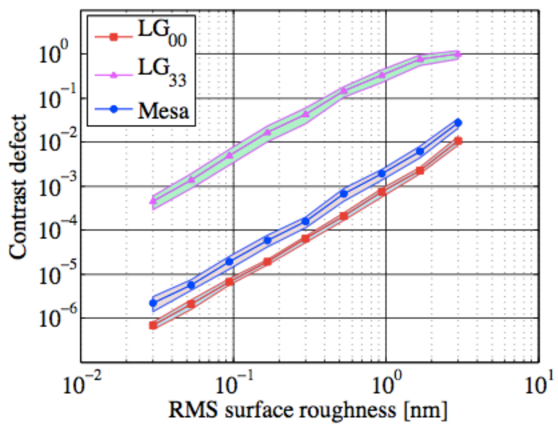


M.Granata et al., Higher-Order Laguerre-Gauss Mode Generation and Interferometry for Gravitational Wave Detectors, Phys. Rev. Lett. 105, 231102 (2010)

L.Carbone et al., Generation of high-purity higher-order Laguerre-Gauss beams at high laser power, arXiv:1303.3627, 2013

Problem of the degeneracy

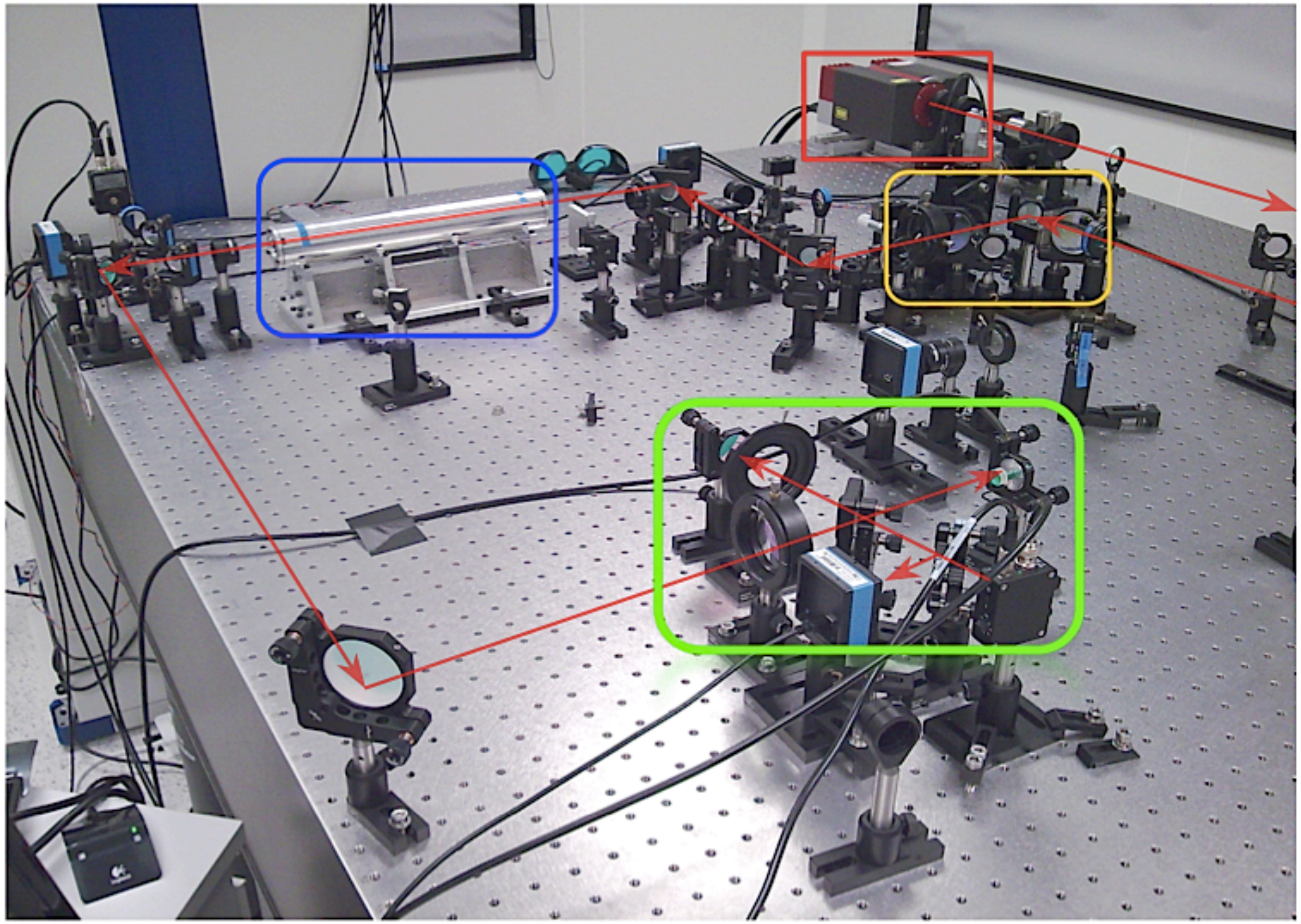




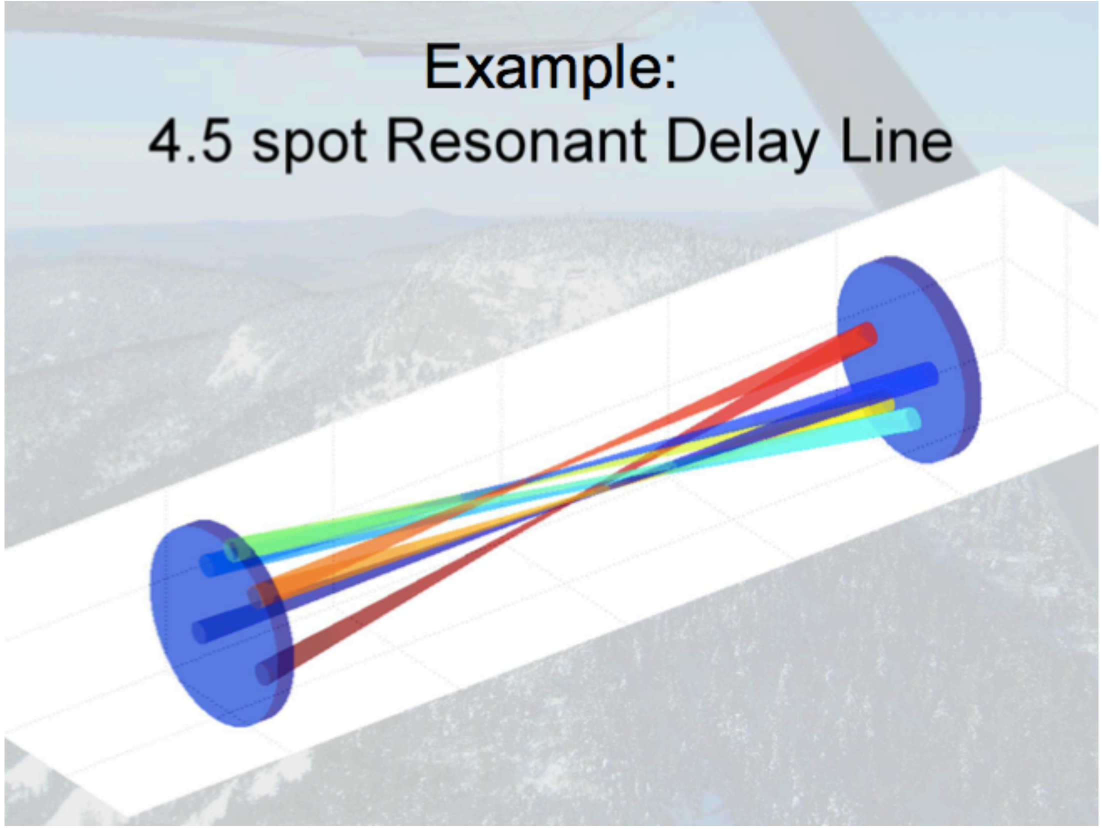
T.Hong et al., Effects of Mirror Aberrations on Laguerre-Gaussian Beams in Interferometric Gravitational-Wave Detectors, Phys. Rev. D 84, 102001 (2011)

R.Day et al., Reduction of higher order mode generation in large scale gravitational wave interferometers by central heating residual aberration correction, PRD Volume 87 Issue 8, 2013

APC experiment



Ways to improve the CTN: multiple beams



S.Ballmer, presentation at the GWADW 2013, Elba, Italy

Cryogenics

impedance

$$F^2_{Th}(\omega) = 4 k_B T \, \mathrm{Re}\left[Z(\omega)\right] = 4 k_B T \, \mathrm{Re}\left[F(\omega)/v(\omega)\right]$$

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

Admittance

Cryogenics

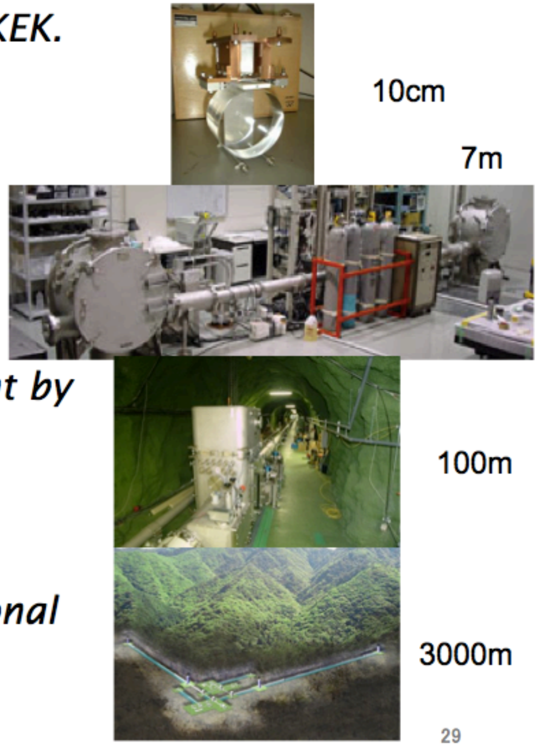
KAGRA History of cryogenic mirrors in Japan

1997 Stating of feasibility study at KEK. Sapphire mirror & fiber suspension.

2001 CLIK: Control of cryogenic Fabry-Perot cavity at Kashiwa.

2002~ CLIO: Sensitivity Improvement by Thermal noise reduction by cooling.

201? KAGRA: Detection of Gravitational wave.



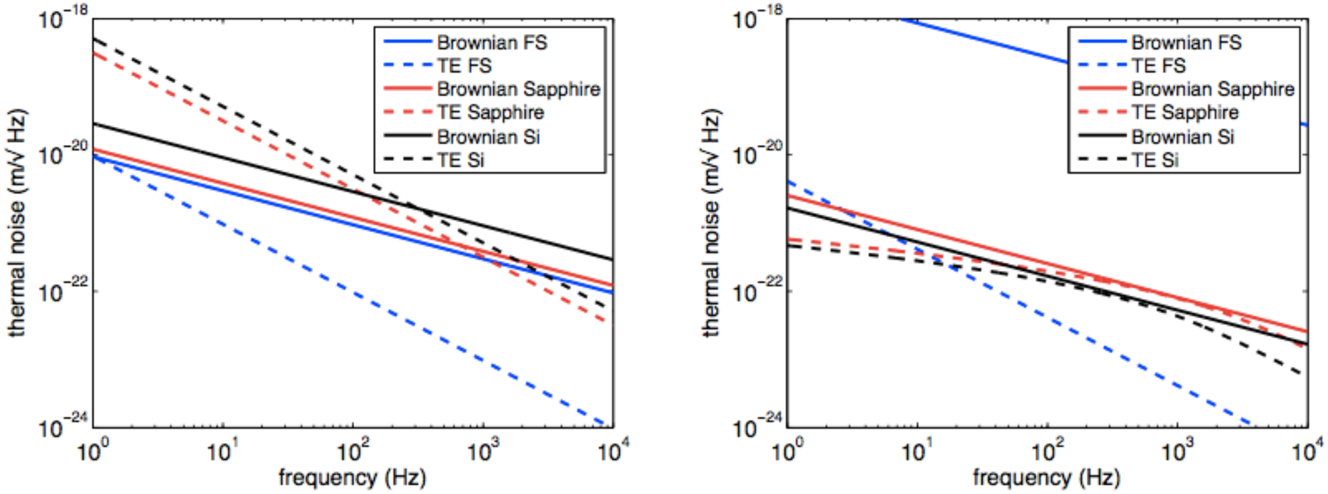
JGW-G130166 29

O.Myakawa, GWADW Elba 2013

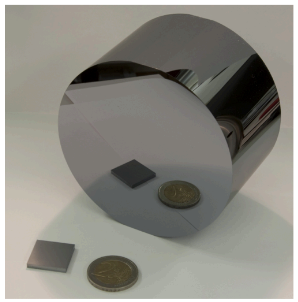
Cryogenics

$$x^2(\omega) = \frac{4 k_B T}{\omega^2} \frac{1-\sigma^2}{\sqrt{\pi} E_0 w} \phi(\omega)$$

300 K   18 K

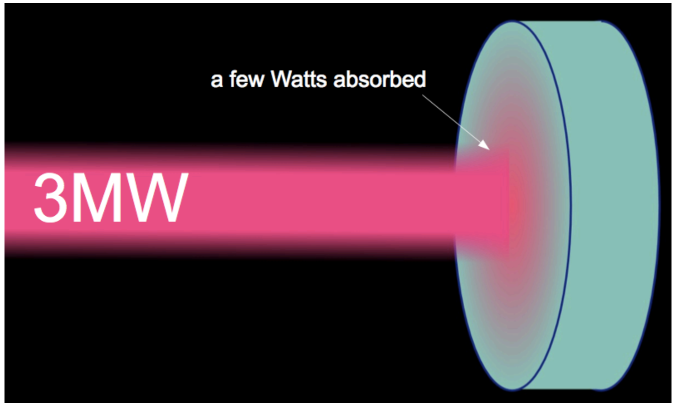


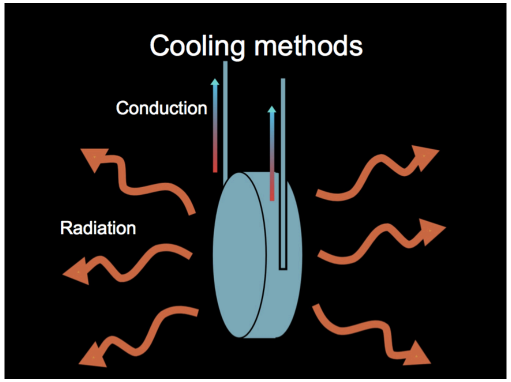
(a)   (b)

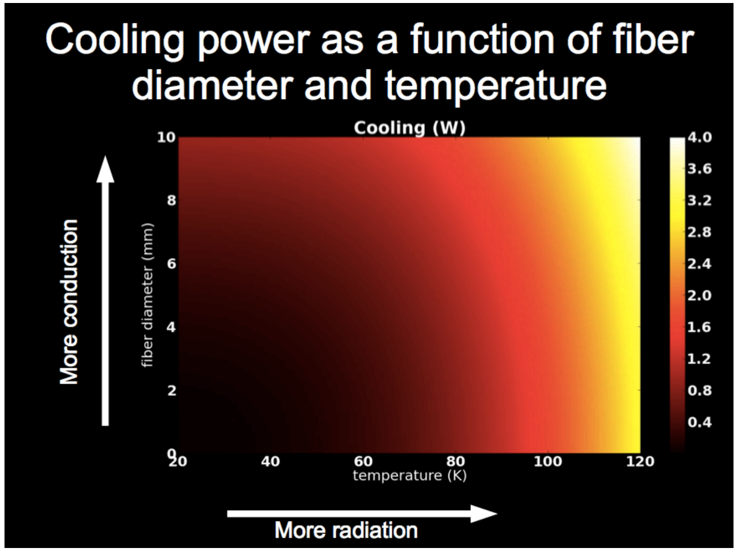


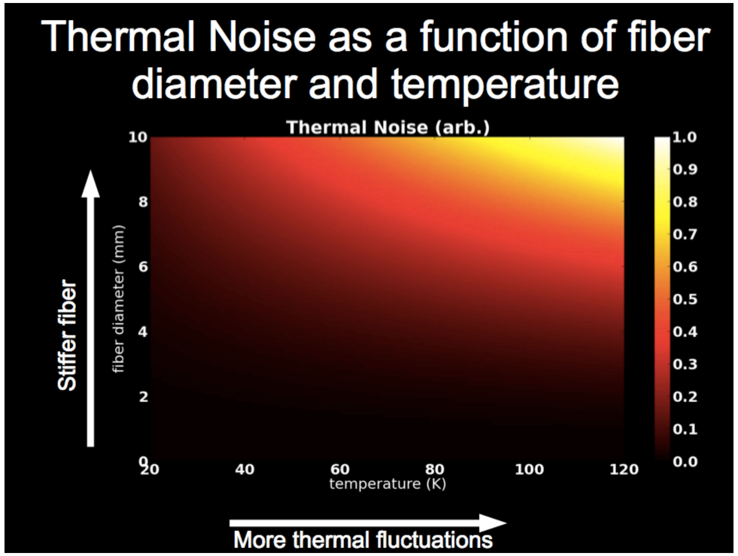
Einstein Telescope conceptual design study, www.et-gw.eu

Cryogenics









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

Different approaches for cryogenics

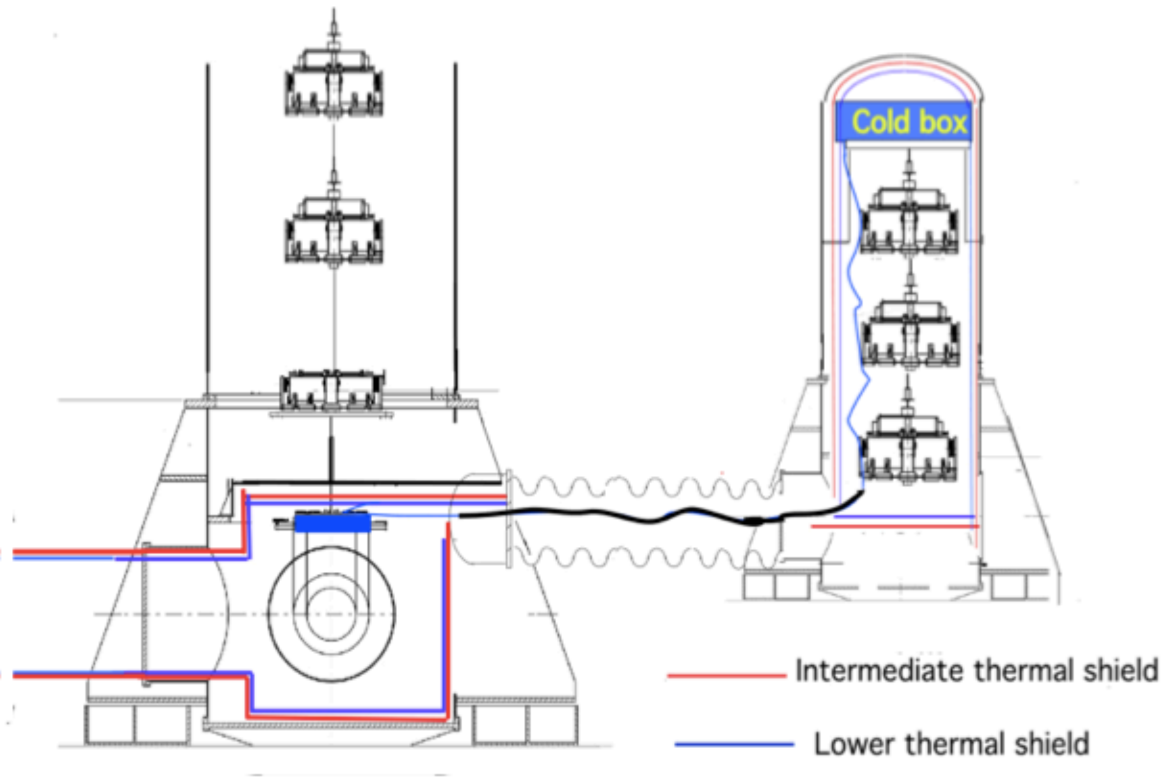
Temperature and cooling trade-off

- Differing approaches
- KAGRA - Sapphire 20K Thick fibers (higher thermal noise than thin)
- ET - Silicon 20K Low power (requires two independent interferometers)
- LIGO3 Blue - Silicon 120K radiative cooling (not as cold)

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

Isolated cryostat for Einstein Telescope

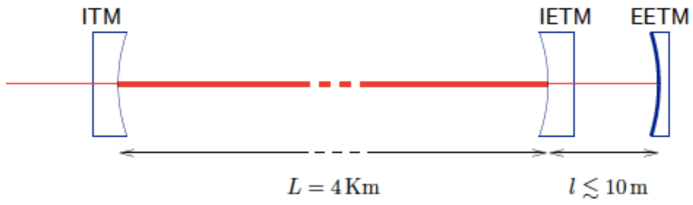
Einstein Telescope design, 18 K



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

Other methods to reduce thermal noise

F.Khalili, Reducing the mirrors coating noise in laser gravitational-wave antennae by means of double mirrors, Phys.Lett A334 (2005)



- Khalili cavities
- Waveguide grating mirrors
- …
- …

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

Thermal noise summary

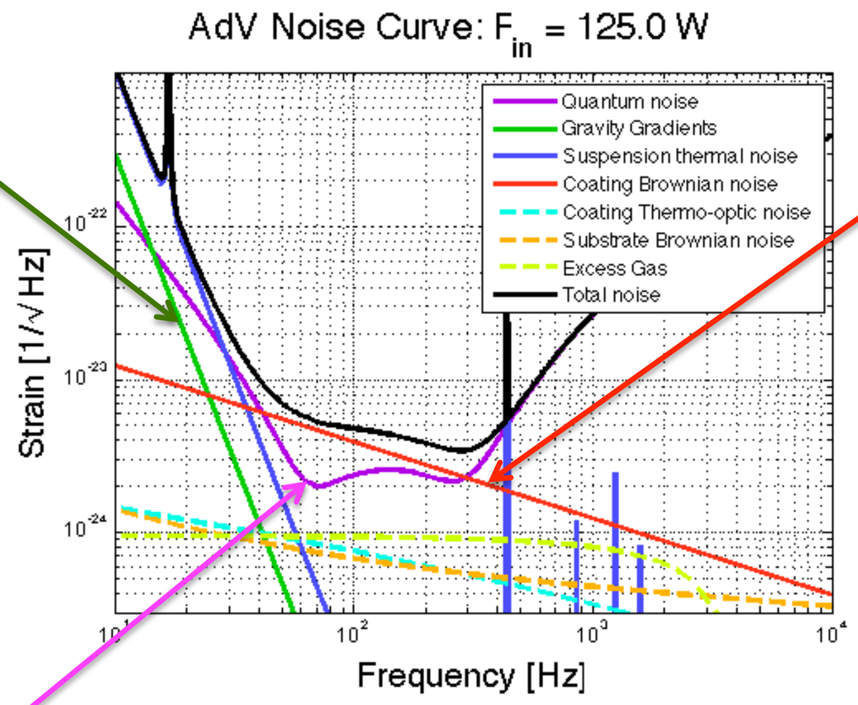
- Huge progress, since ‘90 in the understanding of thermal noise in GW experiments (and other metrology experiment)
- Coating (a few micron of material on a 40 kg mirror) is the main limitagion for future detectors

- Materials
  - Crystalline coatings are a promising direction with
- Optical methods
  - Small improvements (~1.3-1.5) in increasing beam size (unless big increase in the length of the interferometer)
  - Non-gaussian beams: degeneracy problem to be addressed (Laguerre-Gauss) or non-spherical mirrors technology (flat beams)
  - Others…multiple beams.
- Cryogenics
  - need to change material: silicon or sapphire (silicon requires 1.5 micron lasers), evacuate heat, care in the cryostat isolation
  - different approaches (Kagra, LIGO-III, ET)

The quantum noise

Noises limiting AdVirgo

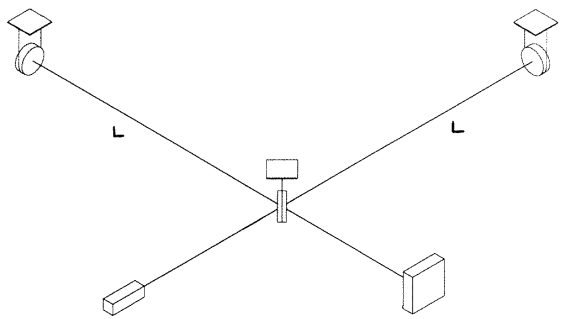
Seismic and gravity gradient noise
Geophysics



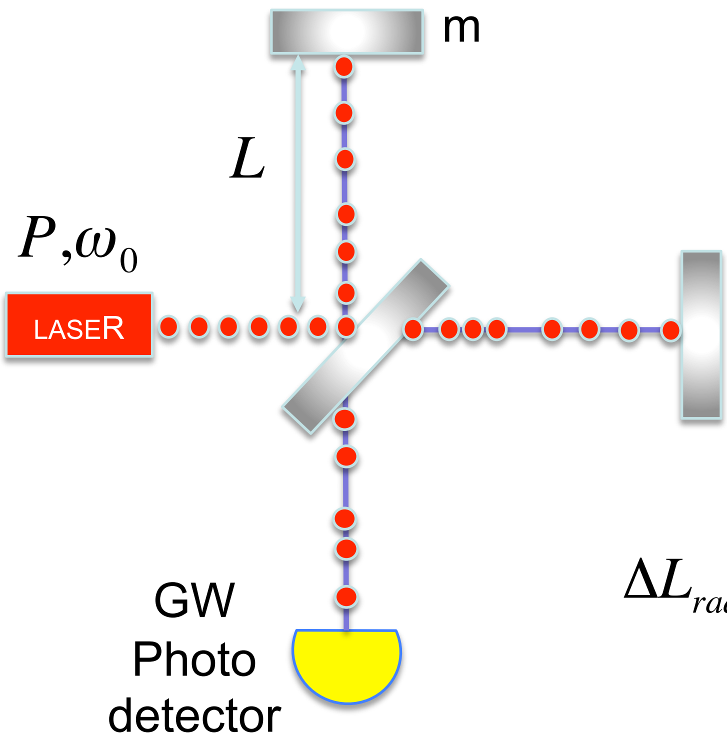
Thermal noise
Thermodynamics

Quantum noise
Quantum mechanics

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



Quantum noise



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

Fourier frequency

Laser carrier frequency

$$\Delta L_{rad} = \frac{1}{cm\Omega^2}\sqrt{8\hbar P\omega_0} \qquad \Delta L_{shot} = c\sqrt{\frac{\hbar}{2P\omega_0}}$$

$$\Delta L_{Quantum} = \sqrt{\Delta L^2_{rad} + \Delta L^2_{shot}}$$

Credit: Lisa Barsotti, APS, Denver 2013

Standard quantum limit (SQL)

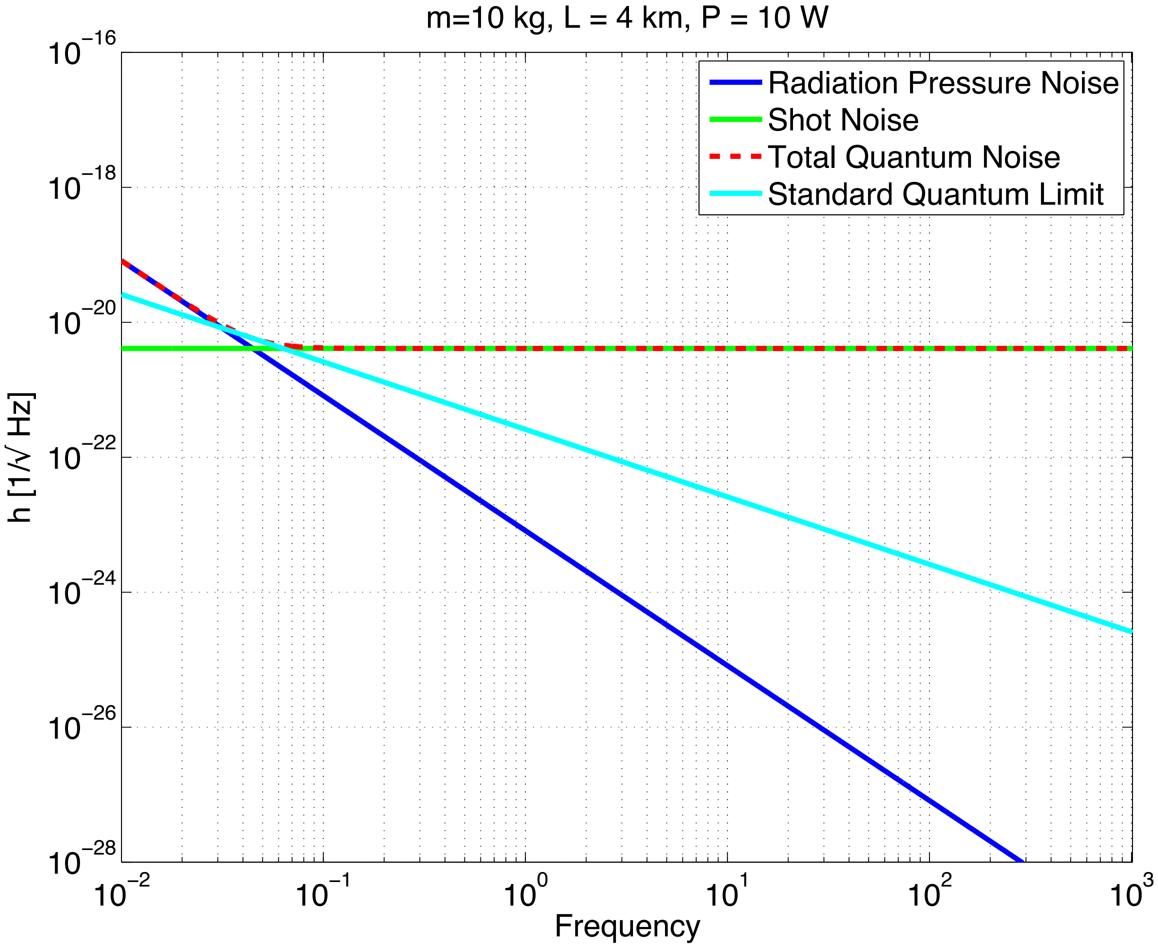
$$\Delta L_{Quantum} = \sqrt{\frac{4\hbar}{m\Omega^2}}\sqrt{\frac{1}{2}\left(\mathrm{K} + \frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

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

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

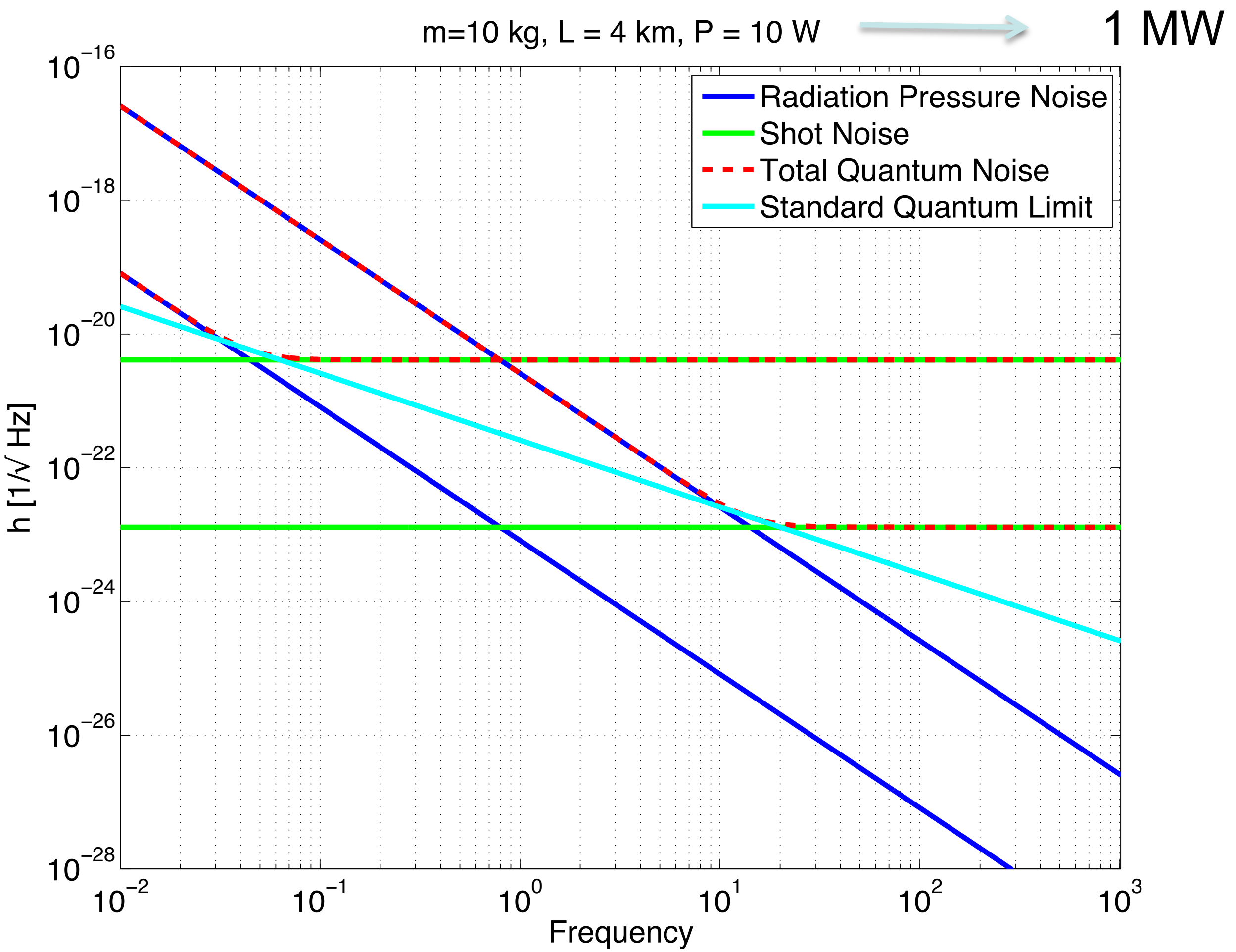
SQL for a simple Michelson interferometer

Credit: Lisa Barsotti, APS, Denver 2013



SQL for a simple Michelson interferometer

Credit: Lisa Barsotti, APS, Denver 2013



Easy ways to reduce quantum noise

- Make your interferometer longer ($h = \delta L/L$)
  - Advanced Virgo 3km, ET 10 km
  - To do more…problems: 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
  - To do more…problems: Thermal effects, radiation pressure driven instabilities

Vacuum fluctuations

PHYSICAL REVIEW LETTERS

VOLUME 45 — 14 JULY 1980 — NUMBER 2

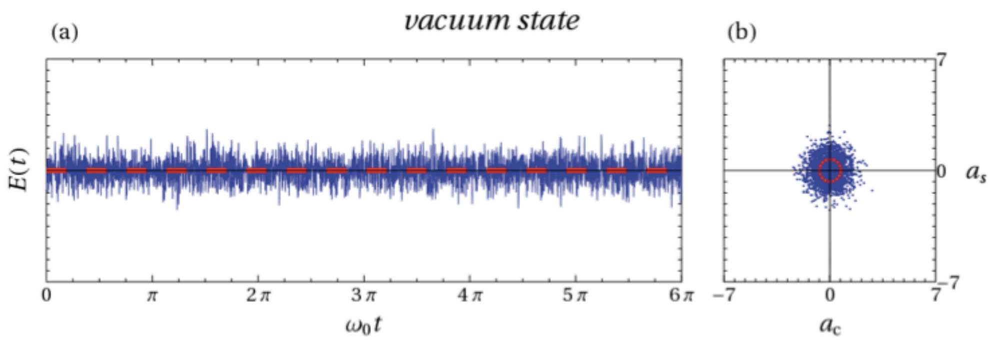
Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

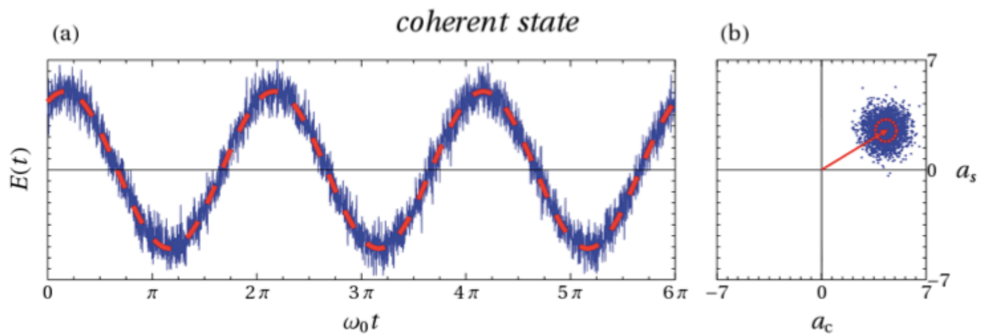
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

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
  - Uncertainty principle applied to the two (amplitude and phase) field quadratures
  - Zero-point energy
- Zero-point Fluctuations entering in the interferometer from the anti-symmetric port generates shot noise and radiation pressure noise.

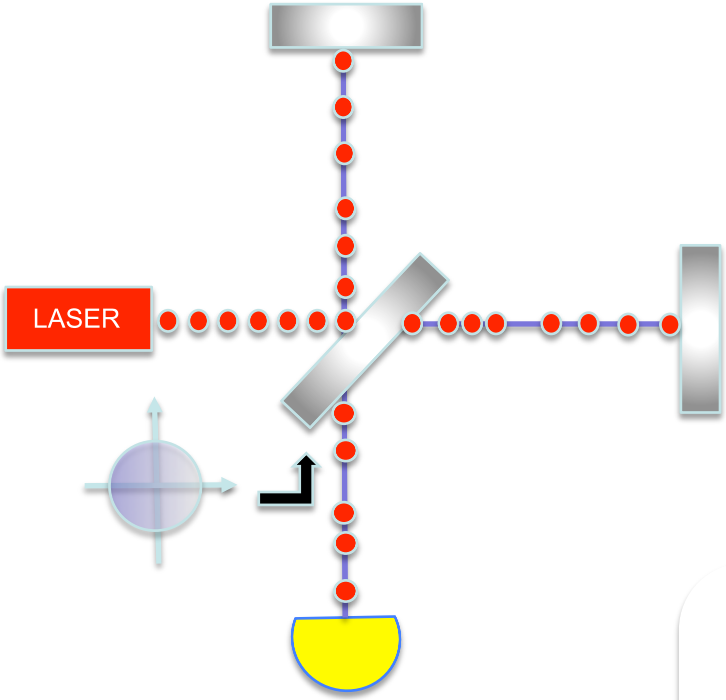
Vacuum and coherent states

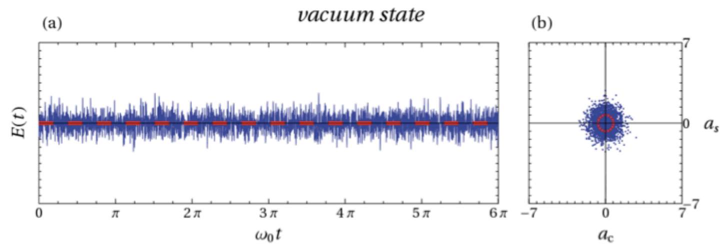


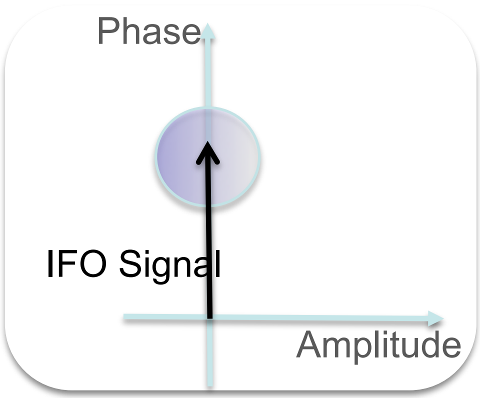


S.L. Danilishin and F.Y. Khalili Quantum Measurement Theory in Gravitational-Wave Detectors, Living Rev. Relativity, 15, (2012)

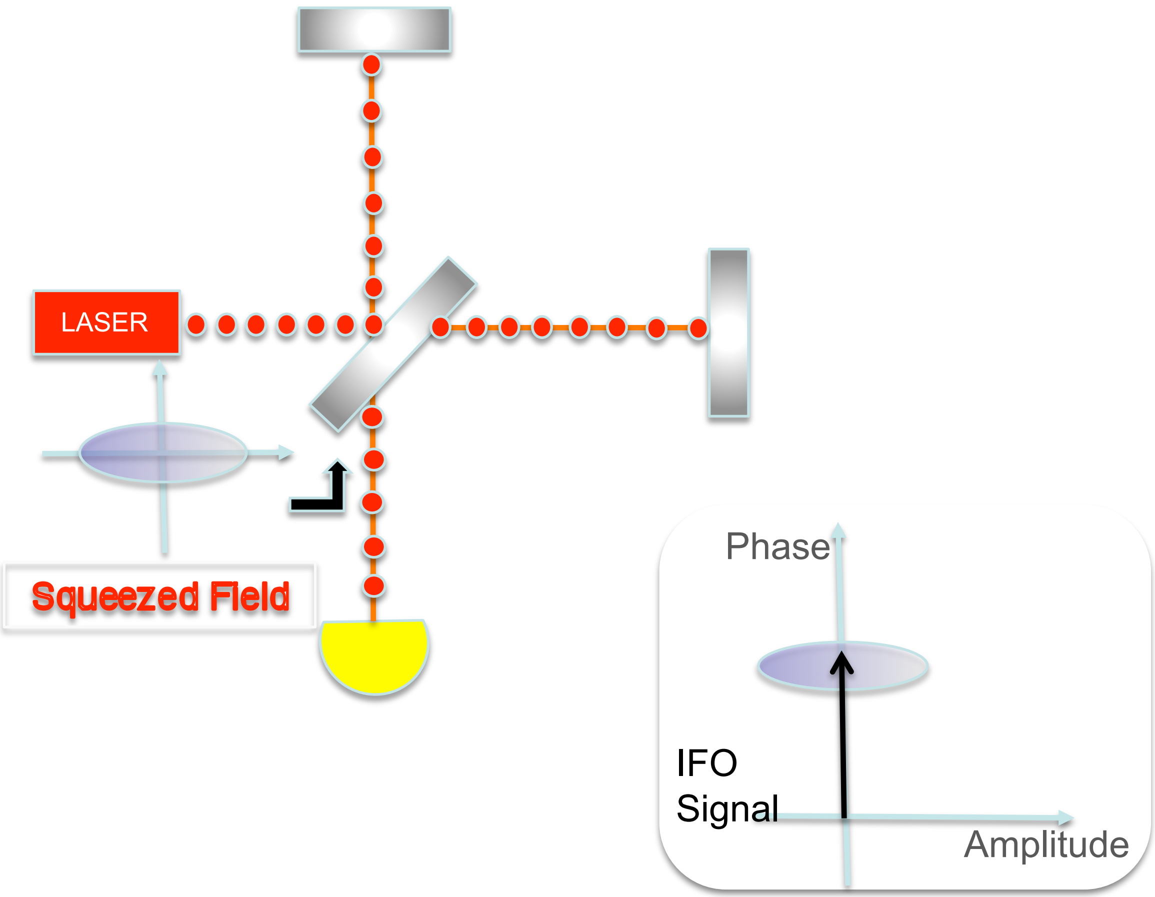
Qu. noise given by zero-point fluctuations



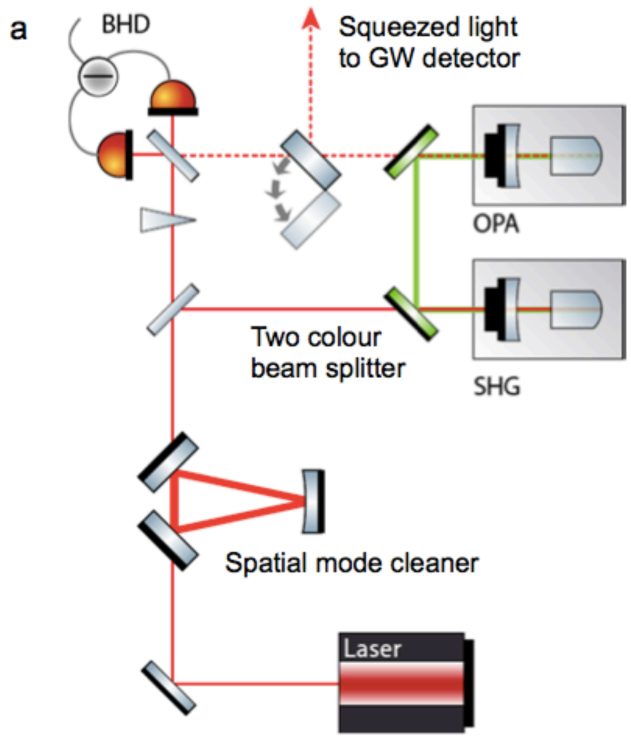


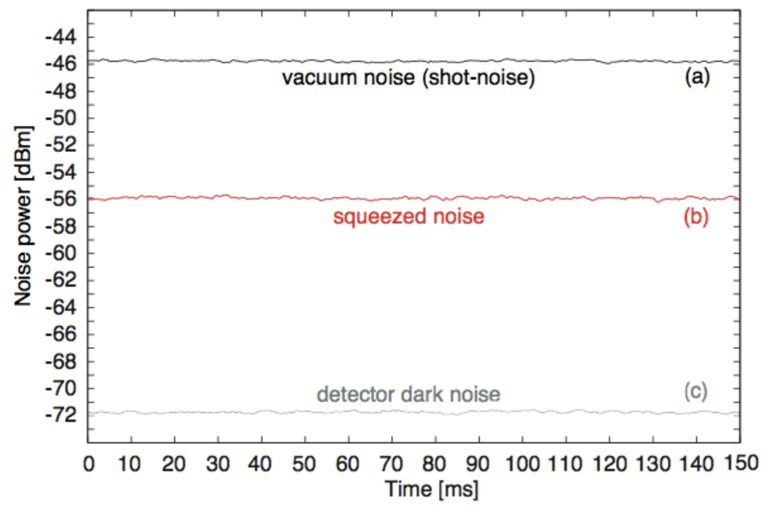


Injecting squeezing in an interferometer



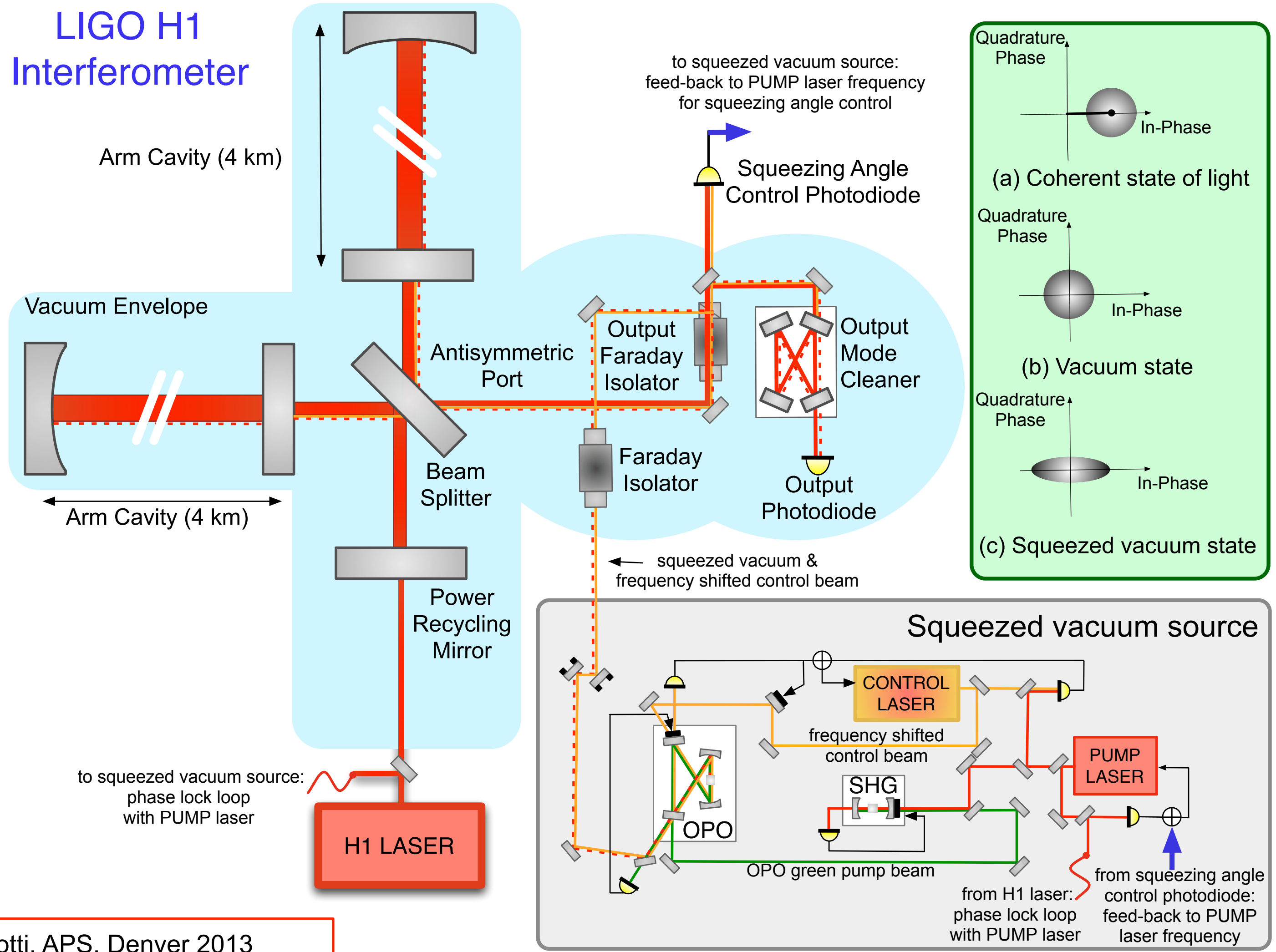
How to produce squeezing





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

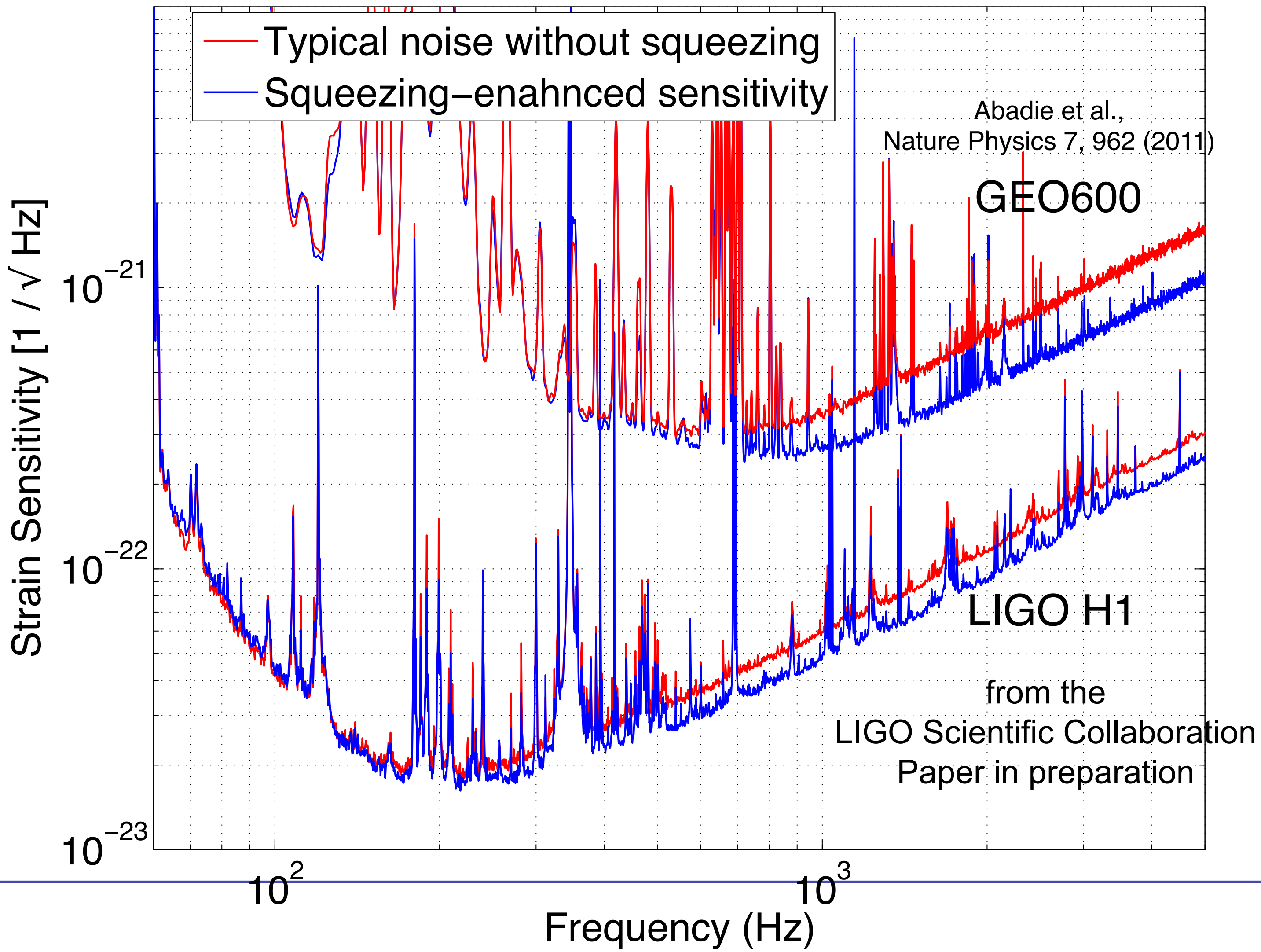
Squeezing in LIGO Hanford



Credit: Lisa Barsotti, APS, Denver 2013

Squeezing in GEO and LIGO

Credit: Lisa Barsotti, APS, Denver 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]

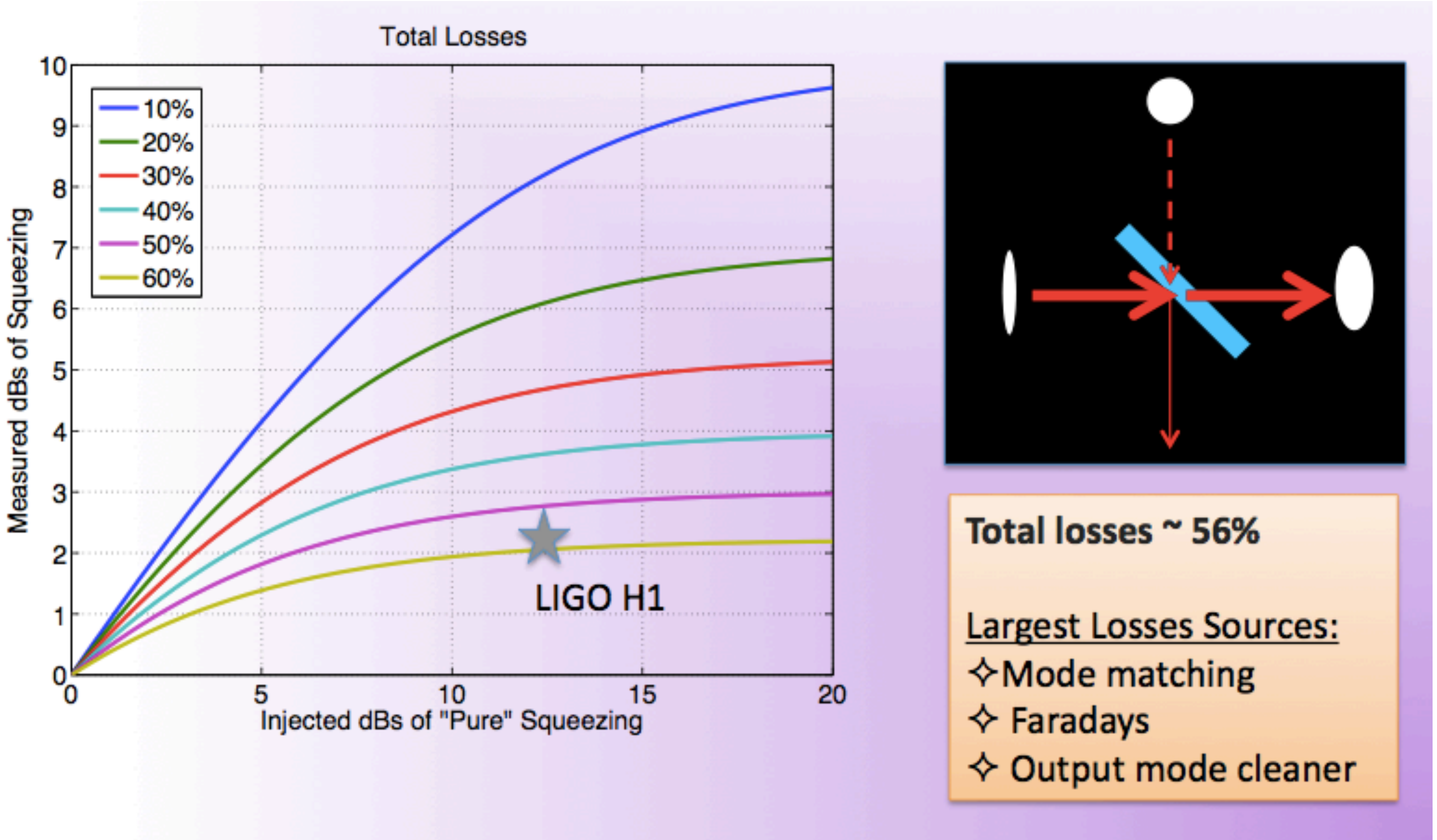
[1] *Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institut) und Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany*

(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.

arXiv: 1302.2188, 20123

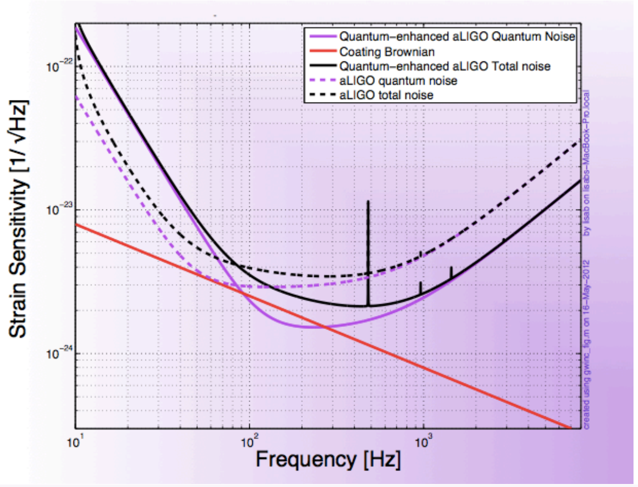
Squeezing and losses

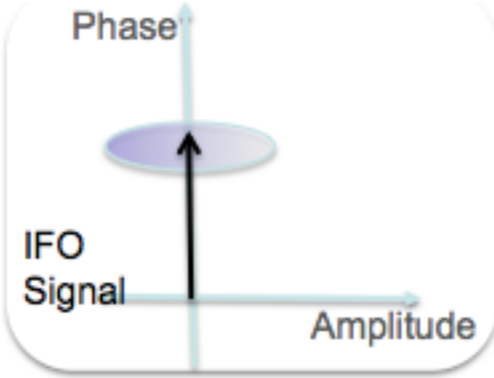


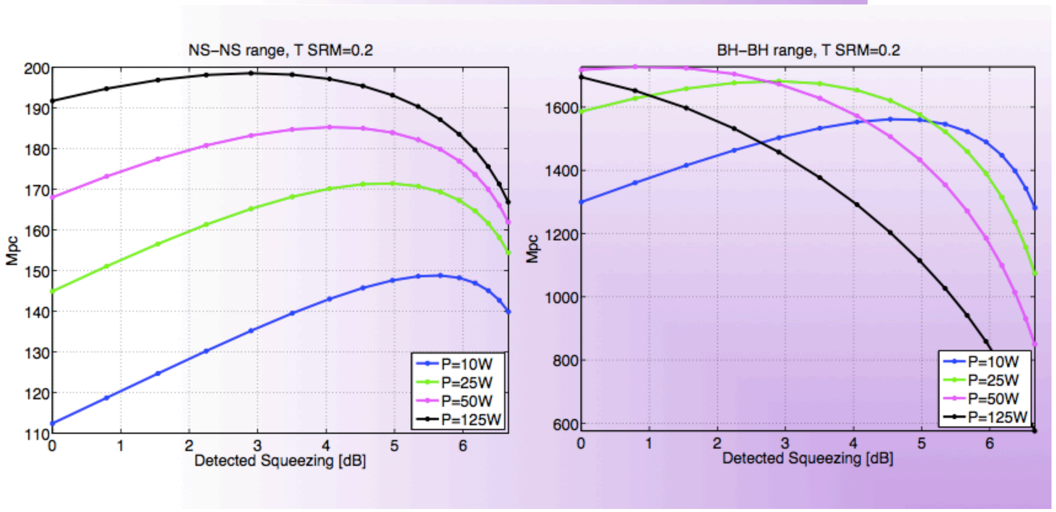
Credit: Lisa Barsotti, APS, Denver 2013

Freq. Independent squeezing in aLIGO

Credit: Lisa Barsotti, APS, Denver 2013

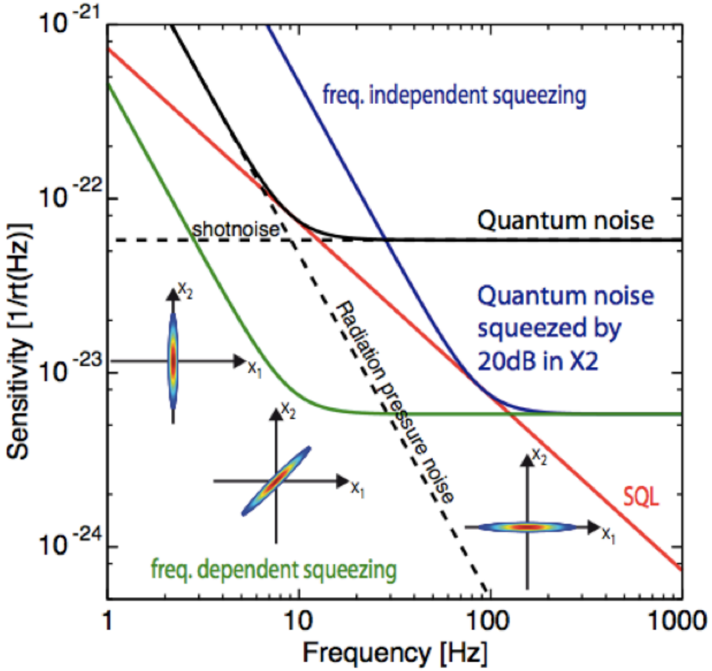


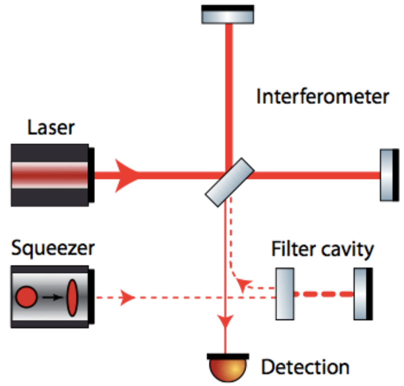


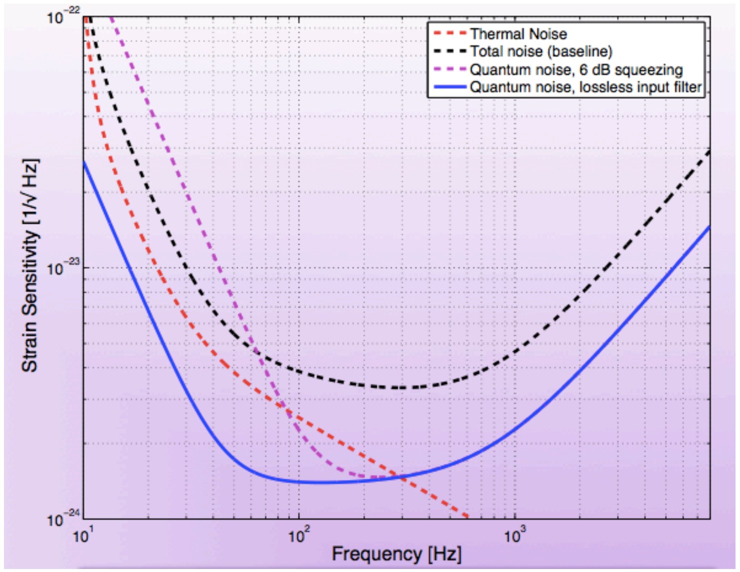


Freq. dependent squeezing: Filter cavities

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







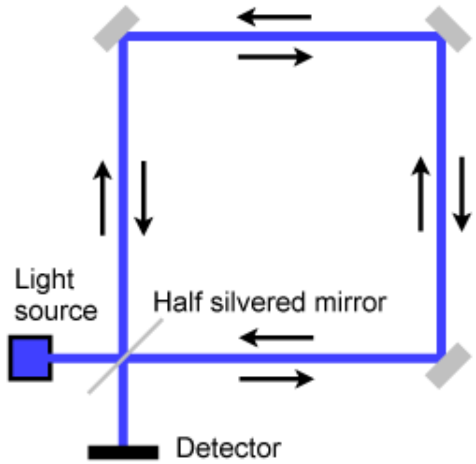
Credit: Lisa Barsotti, APS, Denver 2013

Other possible QND schemes

- Variational read-out
- Sense momentum instead position: speedmeter (i.e. Sagnac interferometer)

For a review of different techniques:

Thomas Corbitt and Nergis Mavalvala, Quantum noise in gravitational-wave interferometers, J. Opt. B: Quantum Semiclass. Opt. 6 (2004) S675–S683



Credit: wikipedia

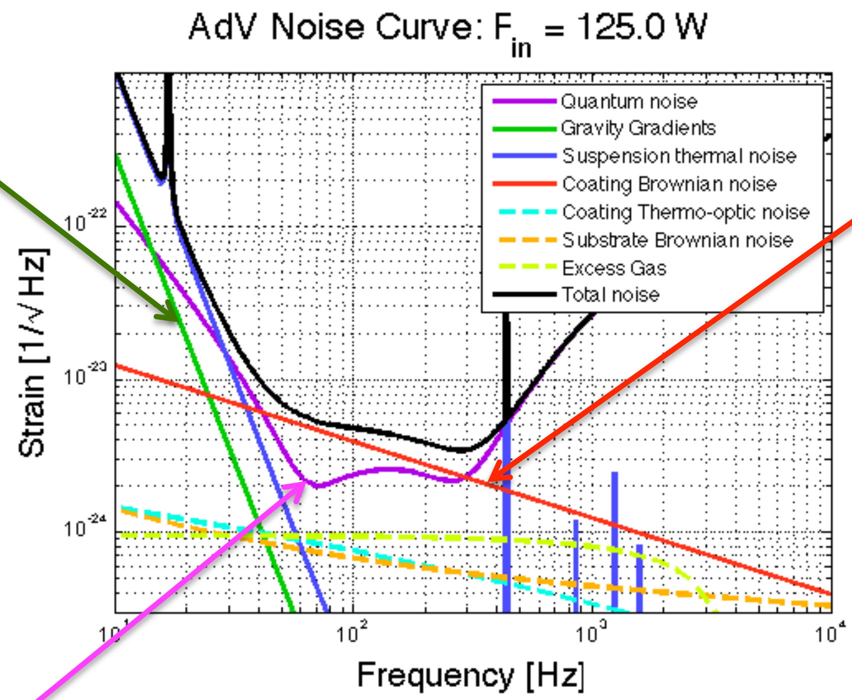
Quantum noise: summary

- 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
- R&D
  - Improve squeezing sources
  - Decrease losses
  - Test filter cavities

Newtonian or gravity gradient noise

Noises limiting AdVirgo

Seismic and gravity gradient noise
Geophysics

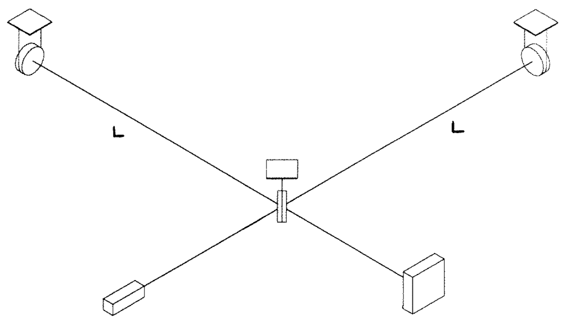


Thermal noise
Thermodynamics

Quantum noise
Quantum mechanics

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

Suspended mirror



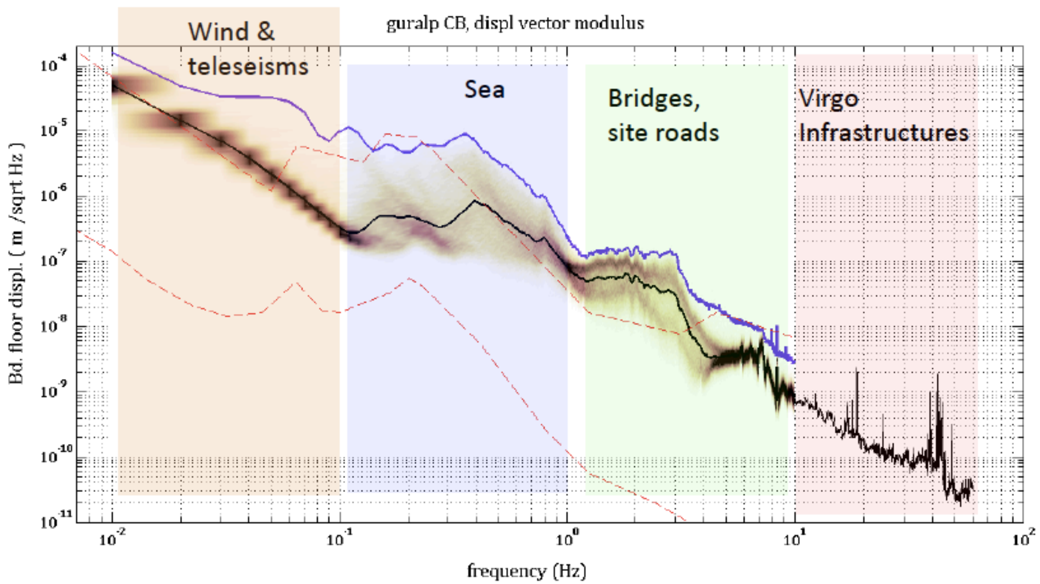
Laser

Light Detection

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

37

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

Newtonian noise estimation

gravitational constant $6{,}67 \cdot 10^{-11} \frac{m^3}{kg\, s^2}$

$$h_{NN}(f) = \frac{1}{\sqrt{3}} \cdot \frac{1}{L} \cdot \rho \cdot G \cdot x_{ground}(f) \frac{1}{f^2}$$

- $h_{NN}(f)$: Linear spectral density of Newtonian noise
- L: arm length
- ρ: density of the ground, $2300 - 2700 \frac{kg}{m^3}$
- $x_{ground}(f)$: Linear spectral density of seismic noise
- f: Fourier frequency

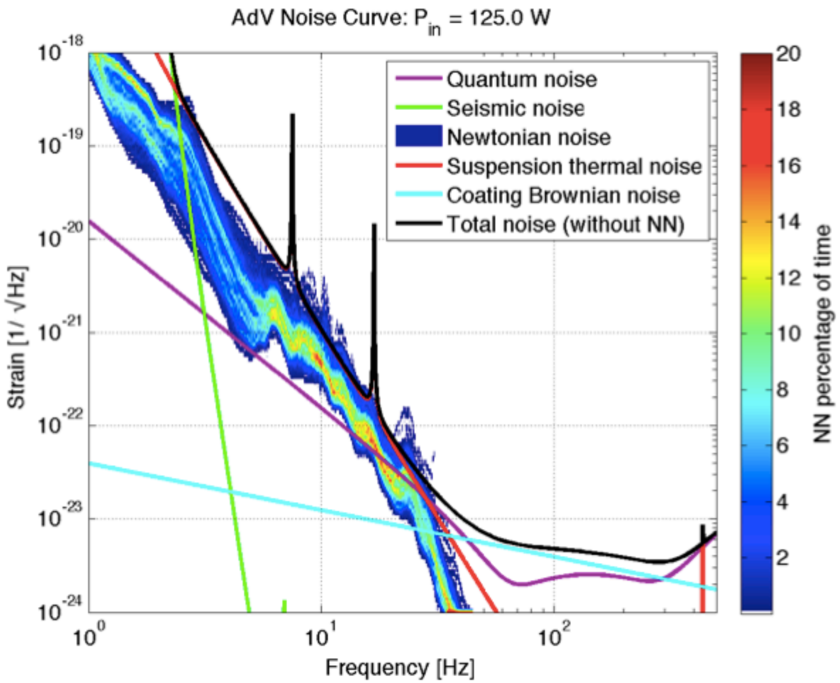
For $x_{ground} \simeq \frac{10^{-7}}{f^2}$ m/Hz at 10 Hz $= 10^{-9}$ m/$\sqrt{Hz}$

$$h_{NN} \cong 2 \cdot 10^{-22}\ 1/\sqrt{Hz}$$

Saulson, Phys. Rev. D 30, 4, 1984

- More sophisticated estimations, including correlations between seismic waves, atmospherical perturbations and antrophogenics noise, underground effects

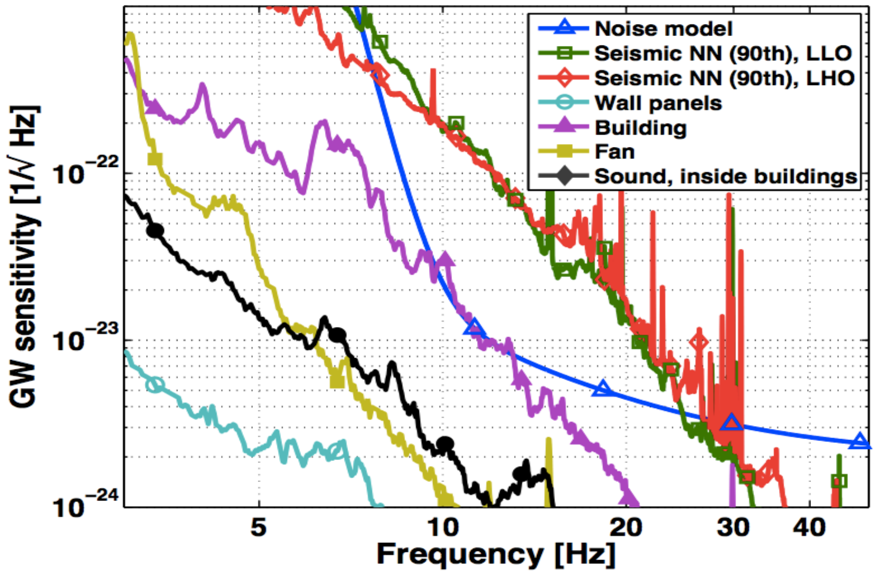
The newtonian noise limit



Beker, presentation at GWADW 2012

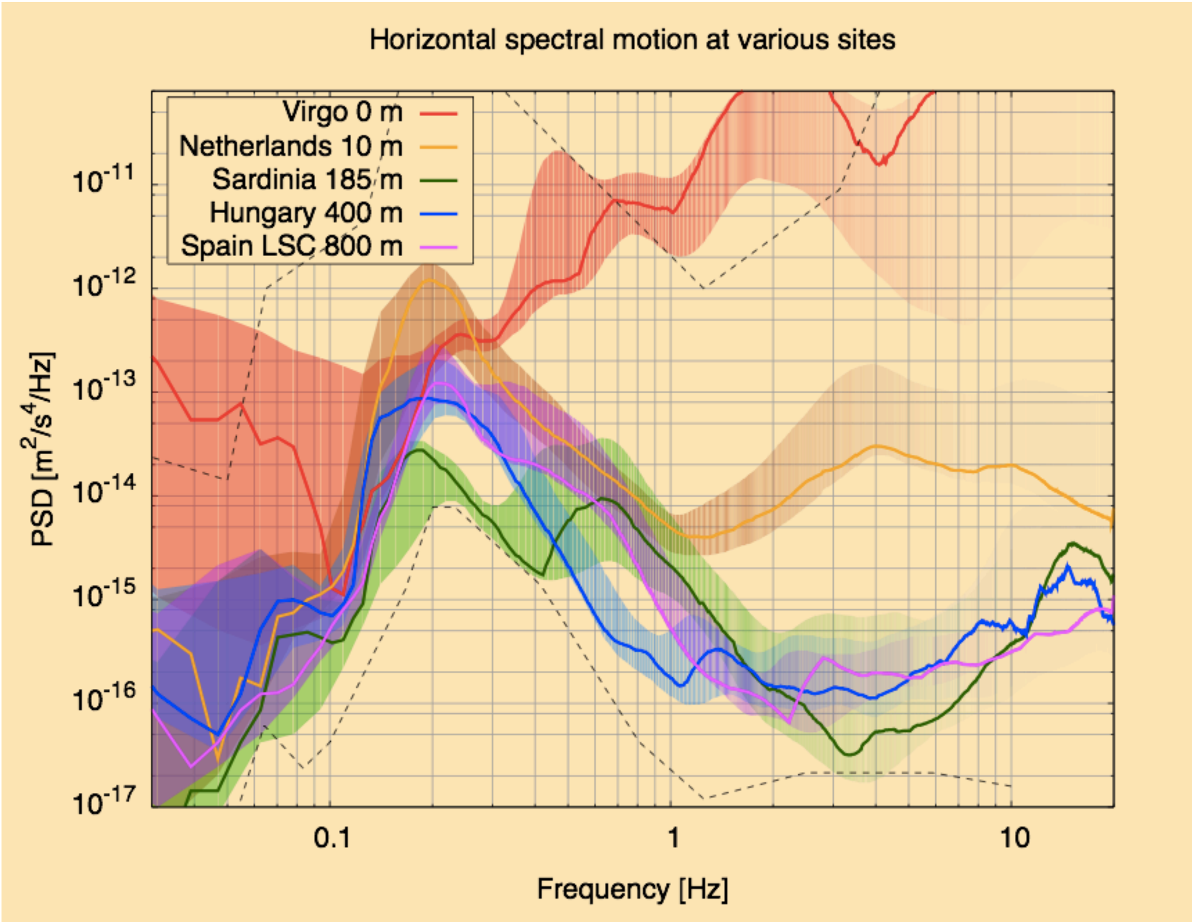
Newtonian noise estimation for Advanced Virgo (bad weather)

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



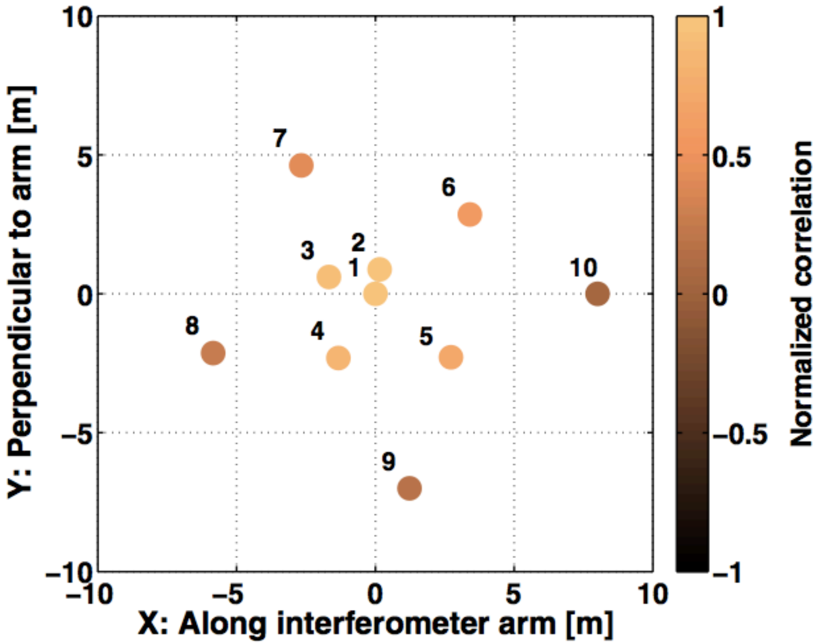
Newtonian noise estimation for Advanced LIGO

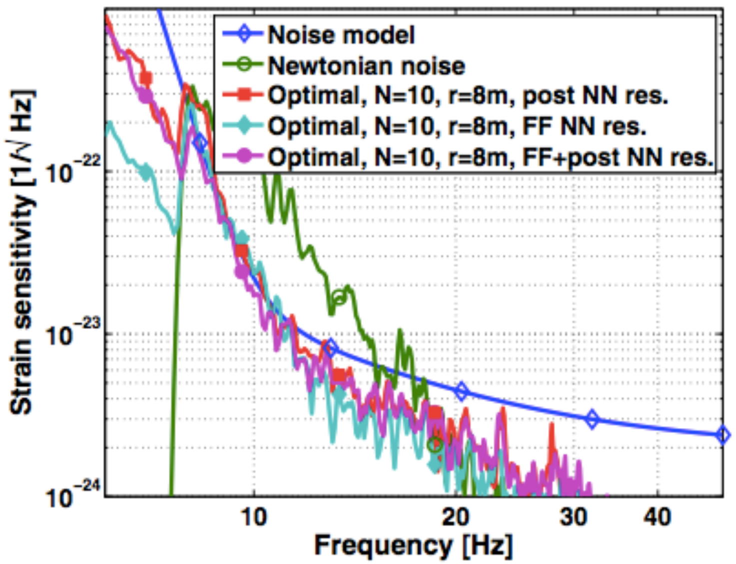
Reducing newtonian noise/1: underground



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

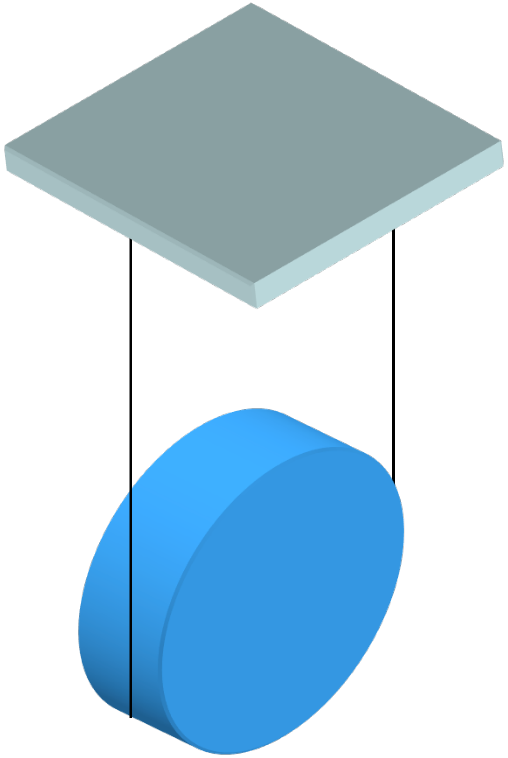
Reducing newtonian noise/2: subtraction





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

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

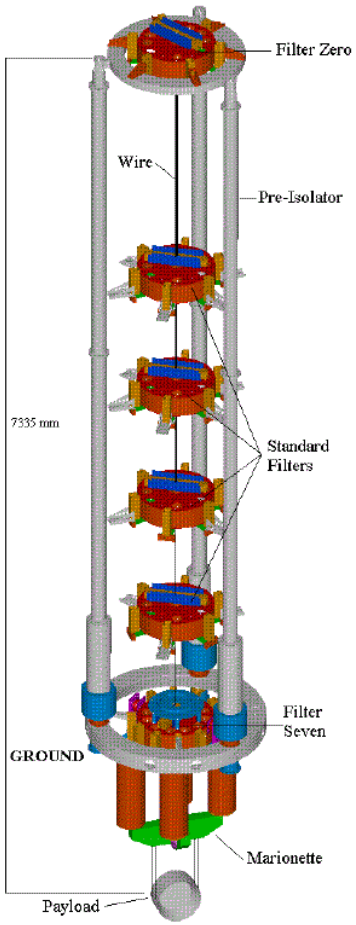
For $\omega \gg \omega_0 \Rightarrow \frac{X(\omega)}{X_0(\omega)} \simeq -\frac{\omega_0^2}{\omega^2}$

$$\left|\frac{X(\omega)}{X_0(\omega)}\right| \sim \frac{1}{\ell}$$

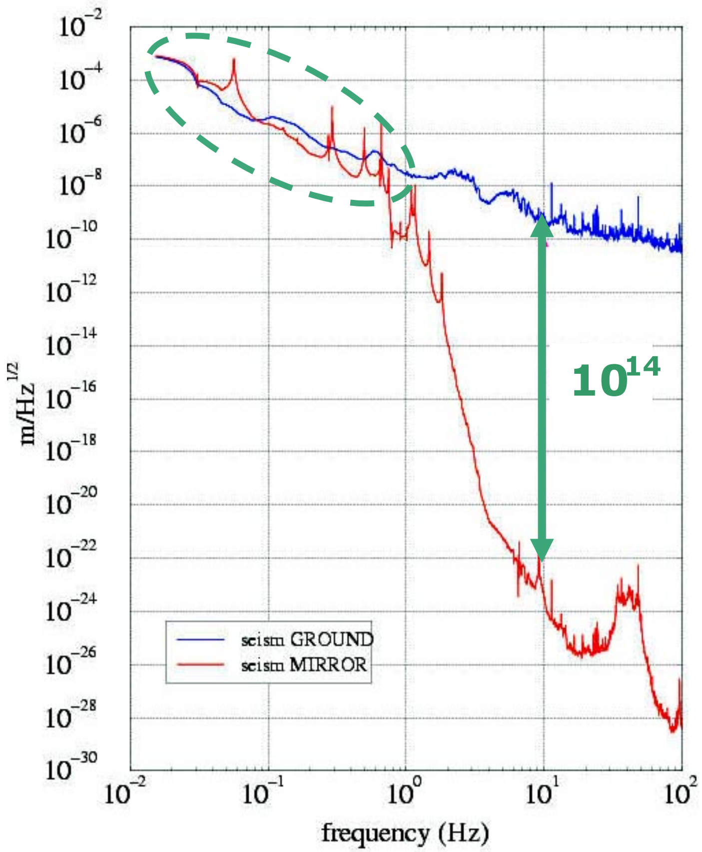
For N pendula $\frac{X(\omega)}{X_0(\omega)} = \prod_{i=1}^{N} \frac{\omega_i^2}{\omega_i^2 - \omega^2}$

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



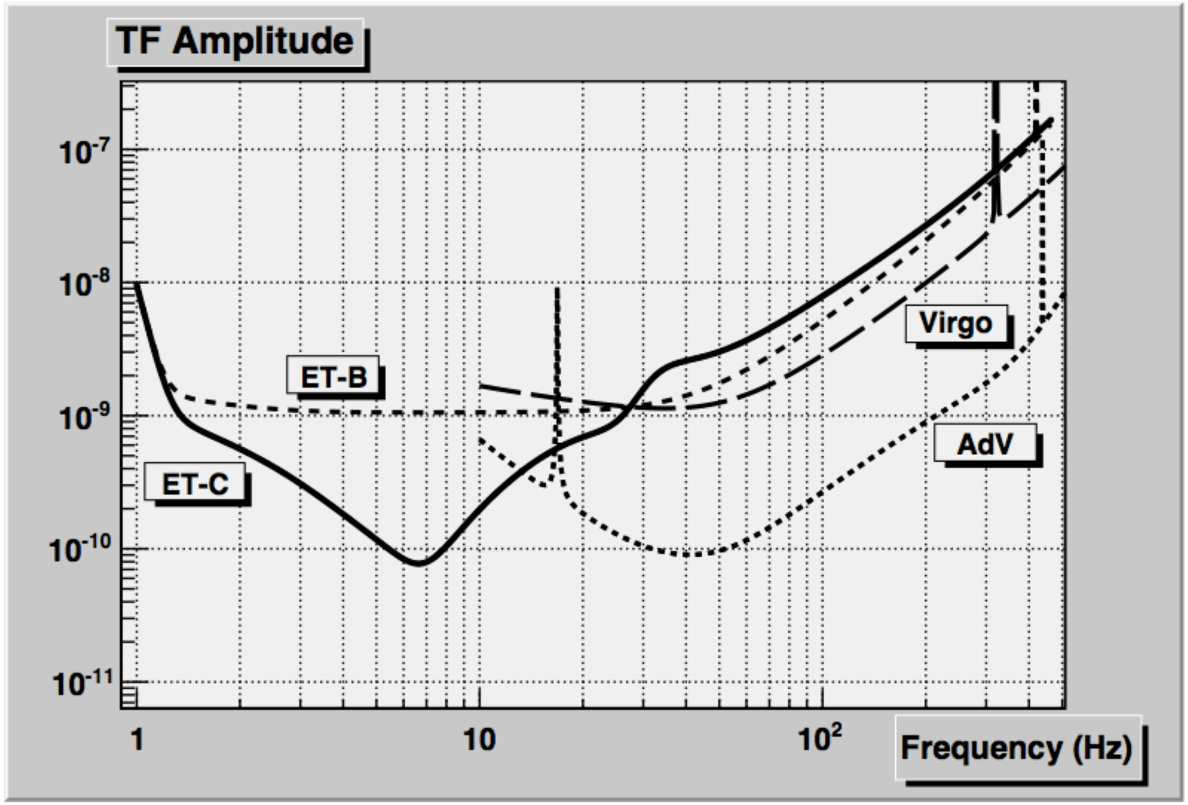
Virgo superattenuator transfer function

Improving the suspensions

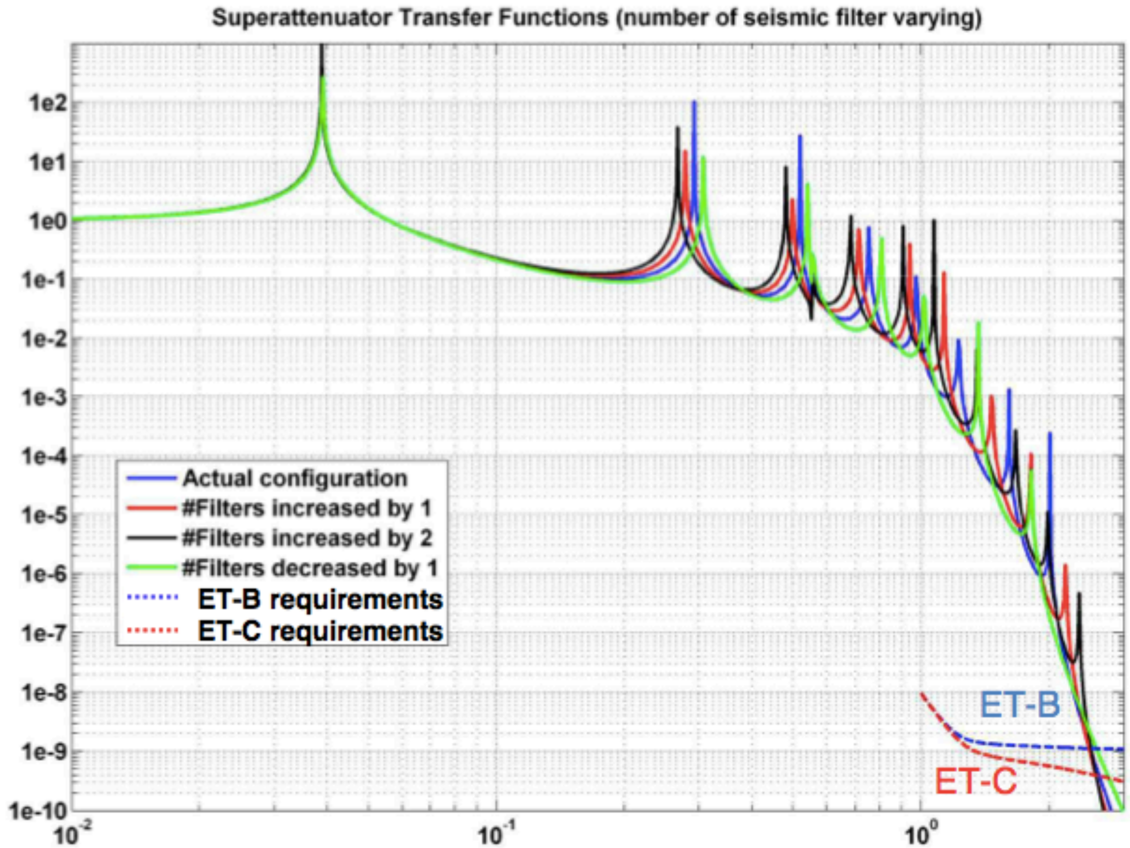
$$x \approx \frac{10^{-7}}{f^2} m/\sqrt{Hz} \rightarrow x \approx \frac{10^{-9}}{f^2} m/\sqrt{Hz}$$

Going undergrond

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



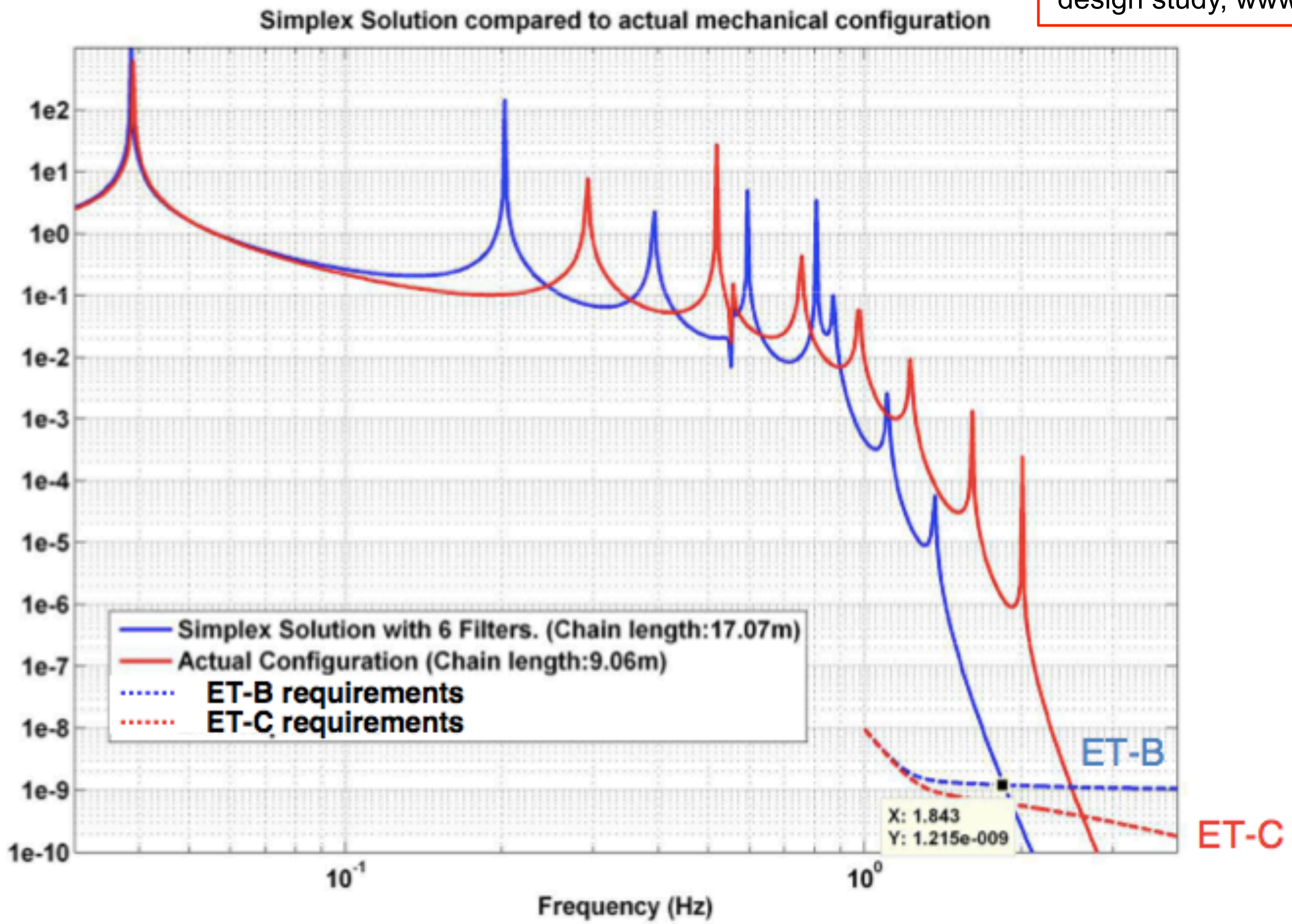
Improving the suspensions/2



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

Improving the suspensions/3

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



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

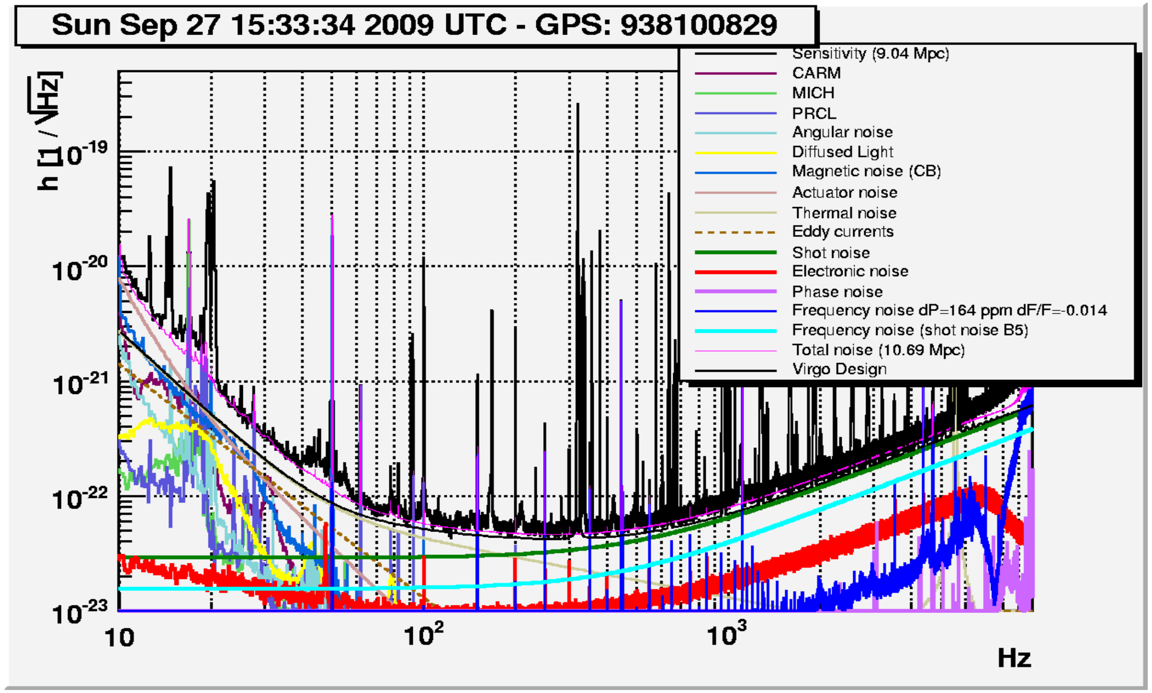
Gravity gradients and seismic: summary

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

Other noises: Virgo noise budget

- 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

Plans for upgrades in Advanced LIGO

3 working groups (red, blue, green)

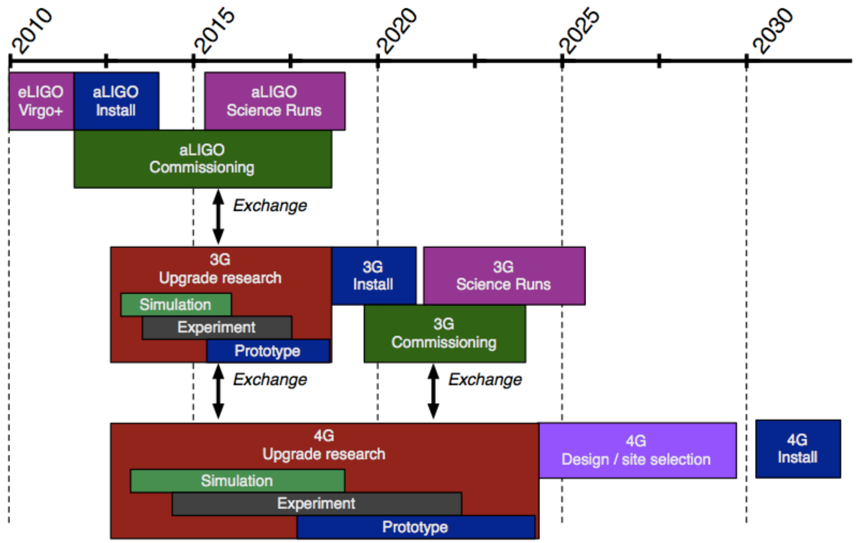
LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
================================
LIGO SCIENTIFIC COLLABORATION

Technical Note	LIGO-T1200199–v2	2012/06/21

Instrument Science White Paper

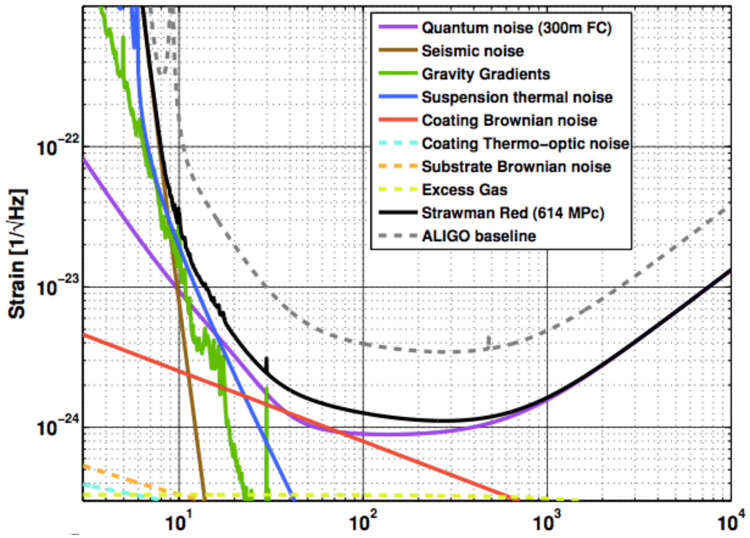
LIGO Scientific Collaboration

Distribution of this document:
LIGO Scientific Collaboration



LIGO upgrades – « red » design

- Quantum noise: reduced by ~3 by frequency dependent squeezing injection (initial squeezing 20 dB and 300 m class cavity)
- Mirror thermal noise: reduced by ~3 increase beam size (factor 1.6), improvement of coatings or non-gaussian beams, or khalili cavities (factor 2)
- Newtonian noise: reduced by ~ 5 by substraction
- Suspension thermal noise reduced by ~3-4: longer suspension (0.6→1.2), larger mass (40 kg→160 kg).



LSC, Instrument Science White paper, 2012

LIGO upgrade – « blue » design

- Change the material and use cryogenics with 150 kg silicon mirrors and silicon suspension at 120 K
- Use of silicon make possible increase in power
- Quantum noise reduced by ~3 with frequency dependent squeezing
- Newtonian noise reduce by 30 with seismometer arrays
- Crystalline coating (reduction 3-10) of mirror thermal noise

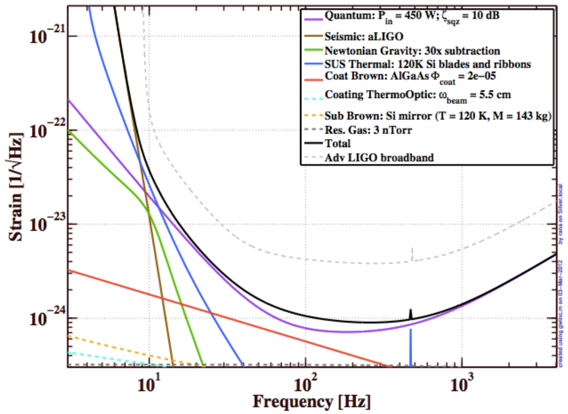


Figure 5: Noise budget for the LIGO-3 Strawman Blue design.

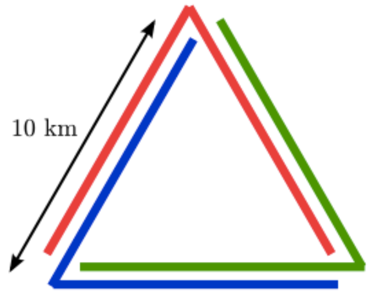
LSC, Instrument Science White paper, 2012

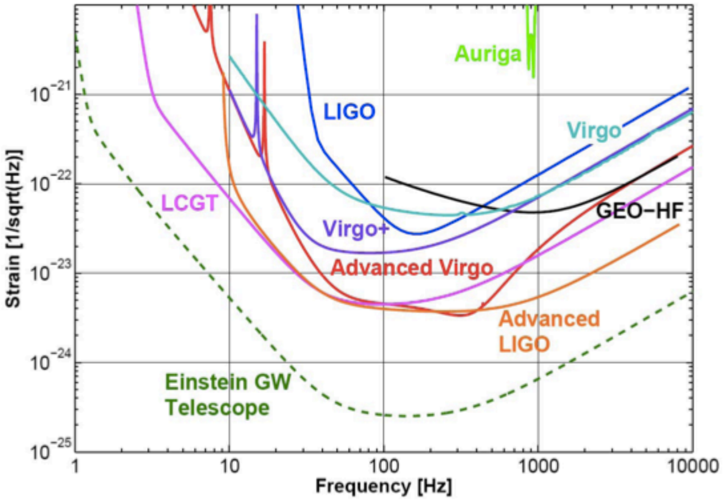
Einstein Telescope – introduction

- Study for an European detector funded by FP7 in the period 2008-2011
- Conceptual design study released in 2011
- X10 sensitivity with respect to AdVirgo

(best strain ~ a few 10^{-25} 1/sqrt(Hz))

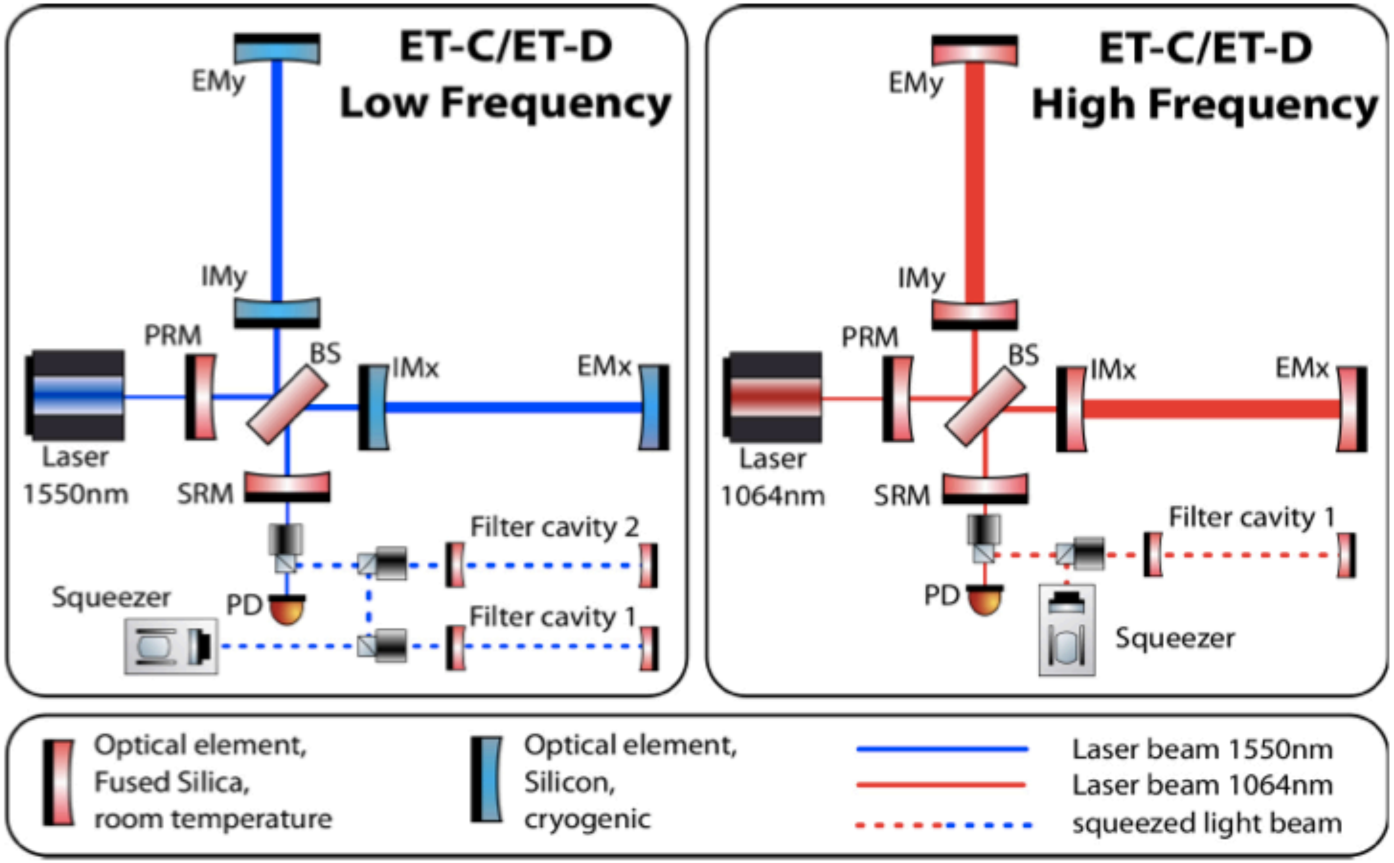
- Goal: routine precision gravitational astronomy
- Underground (100, 200 meters)
- Triangle arms 10 km
- Dual recycling Fabry-Perot Michelson
- Xylophone





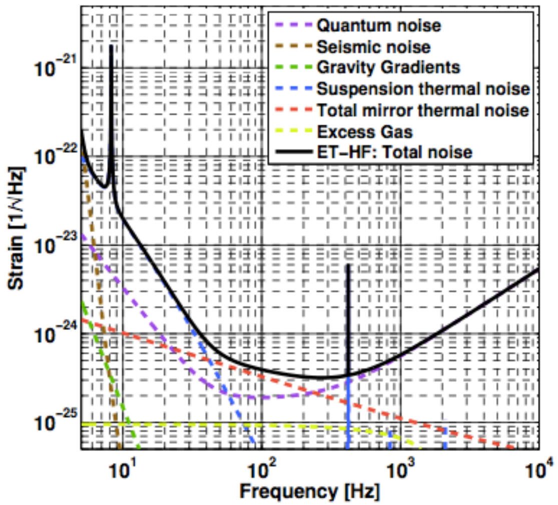
www.et-gw.eu
https://tds.ego-gw.it/itf/tds/index.php?callContent=2&callCode=8709

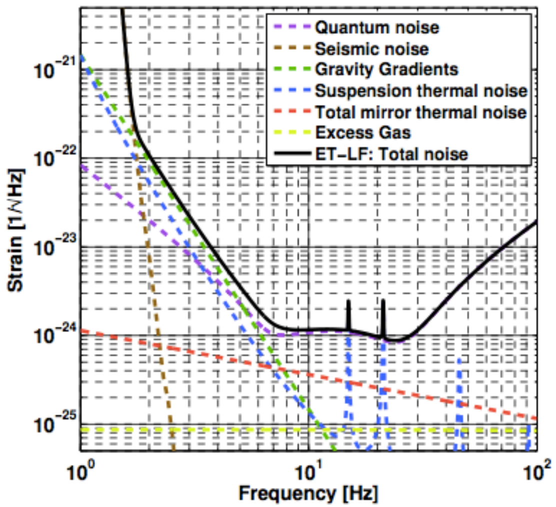
Einstein Telescope – optical scheme

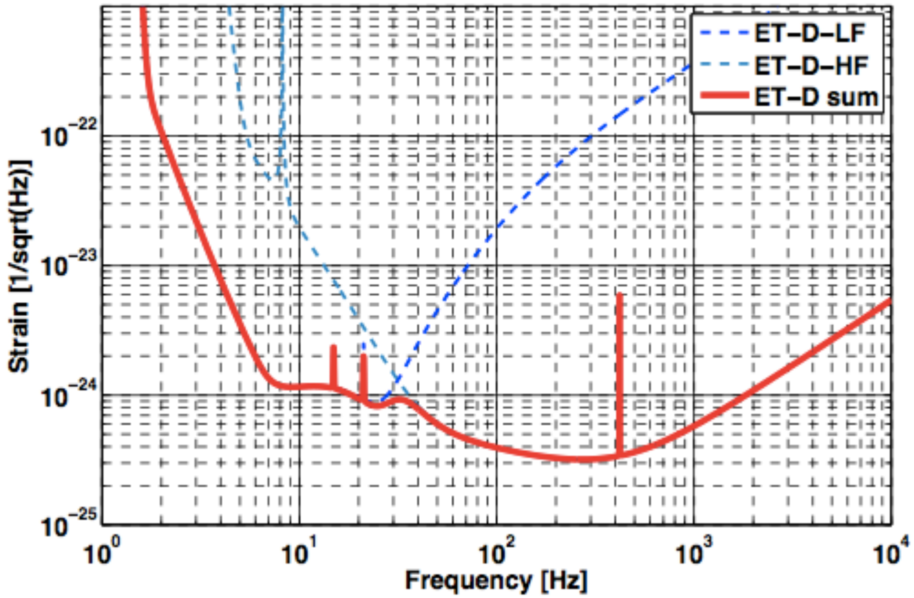


Einstein Telescope conceptual design study, www.et-gw.eu

Einstein Telescope – optical scheme

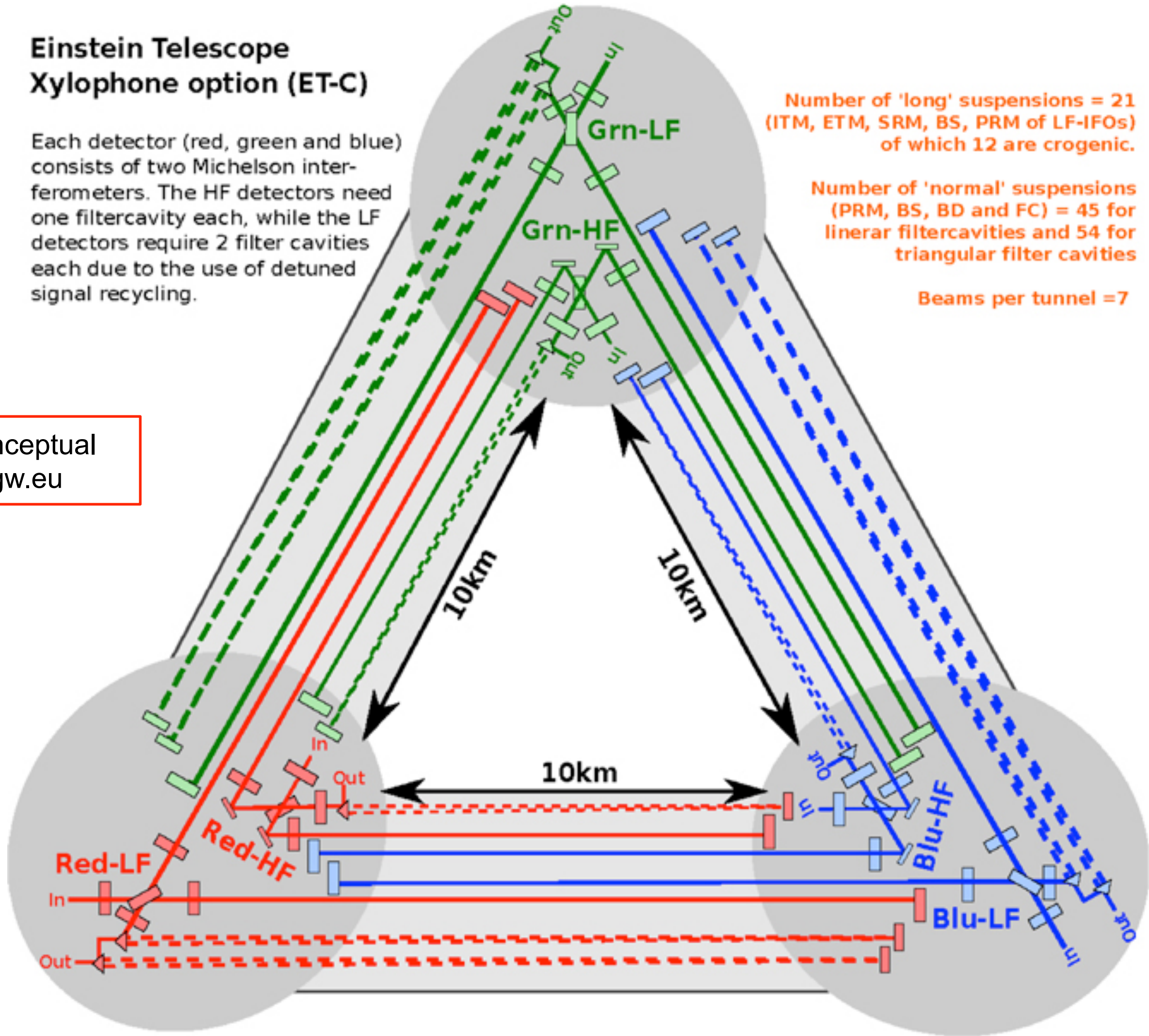






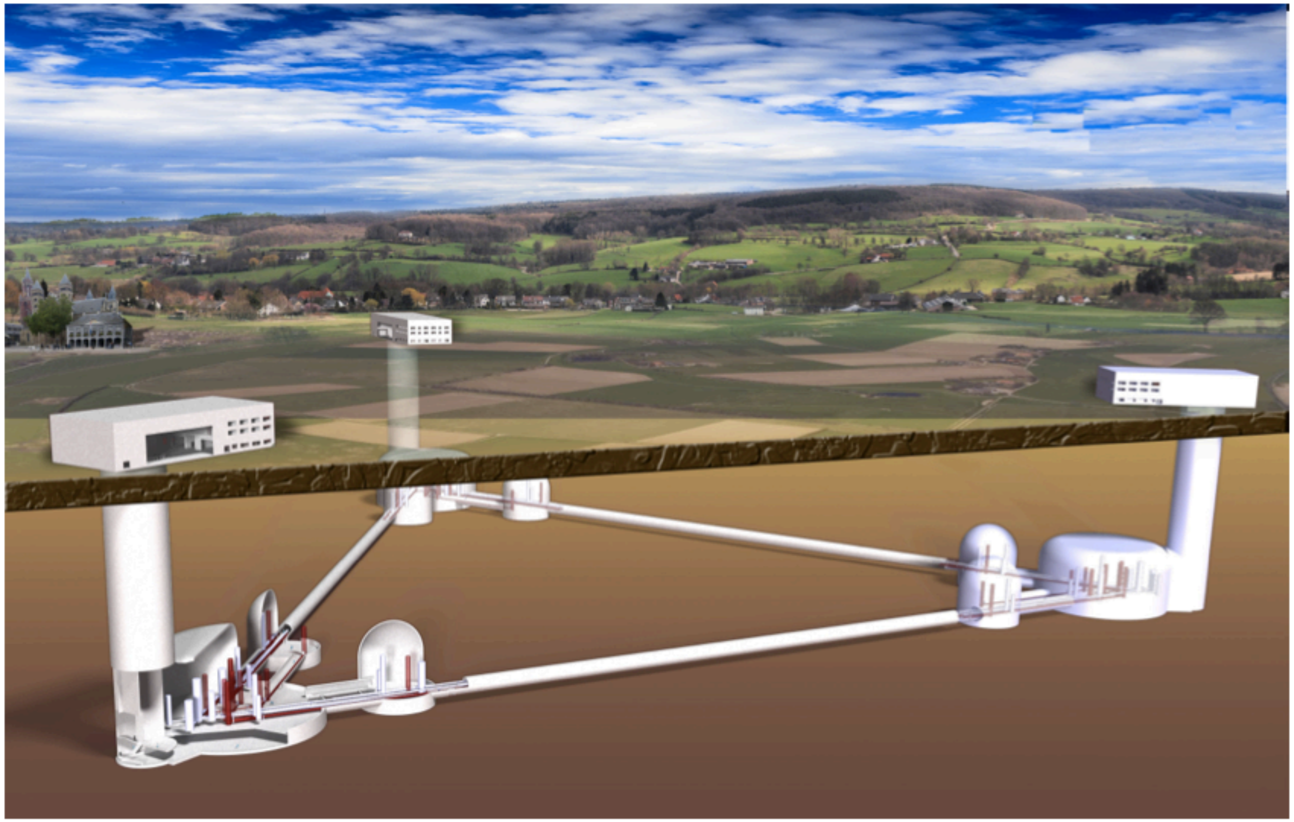
Einstein Telescope conceptual design study, www.et-gw.eu

Einstein Telescope – implementation



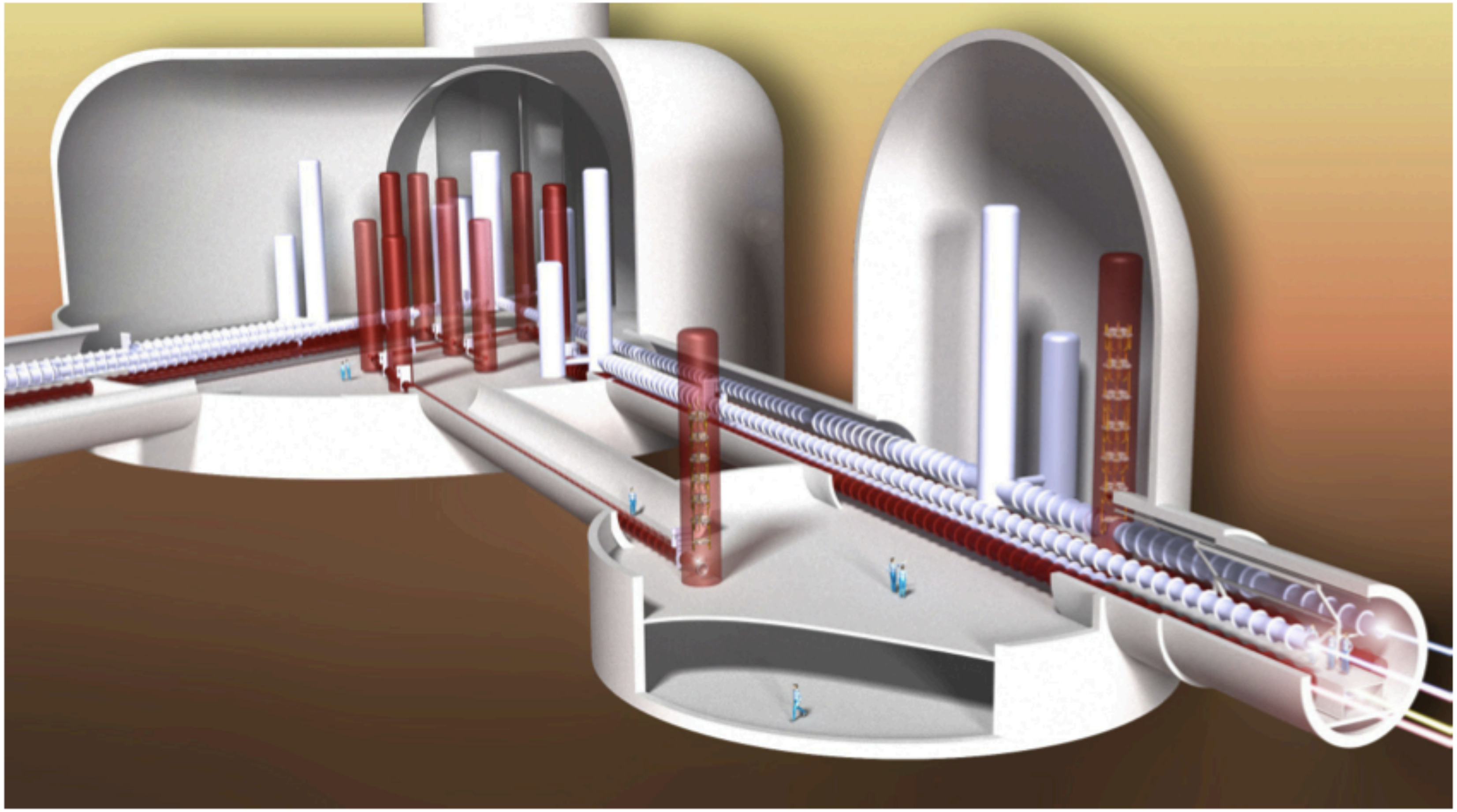
Einstein Telescope conceptual design study, www.et-gw.eu

Einstein Telescope – implementation

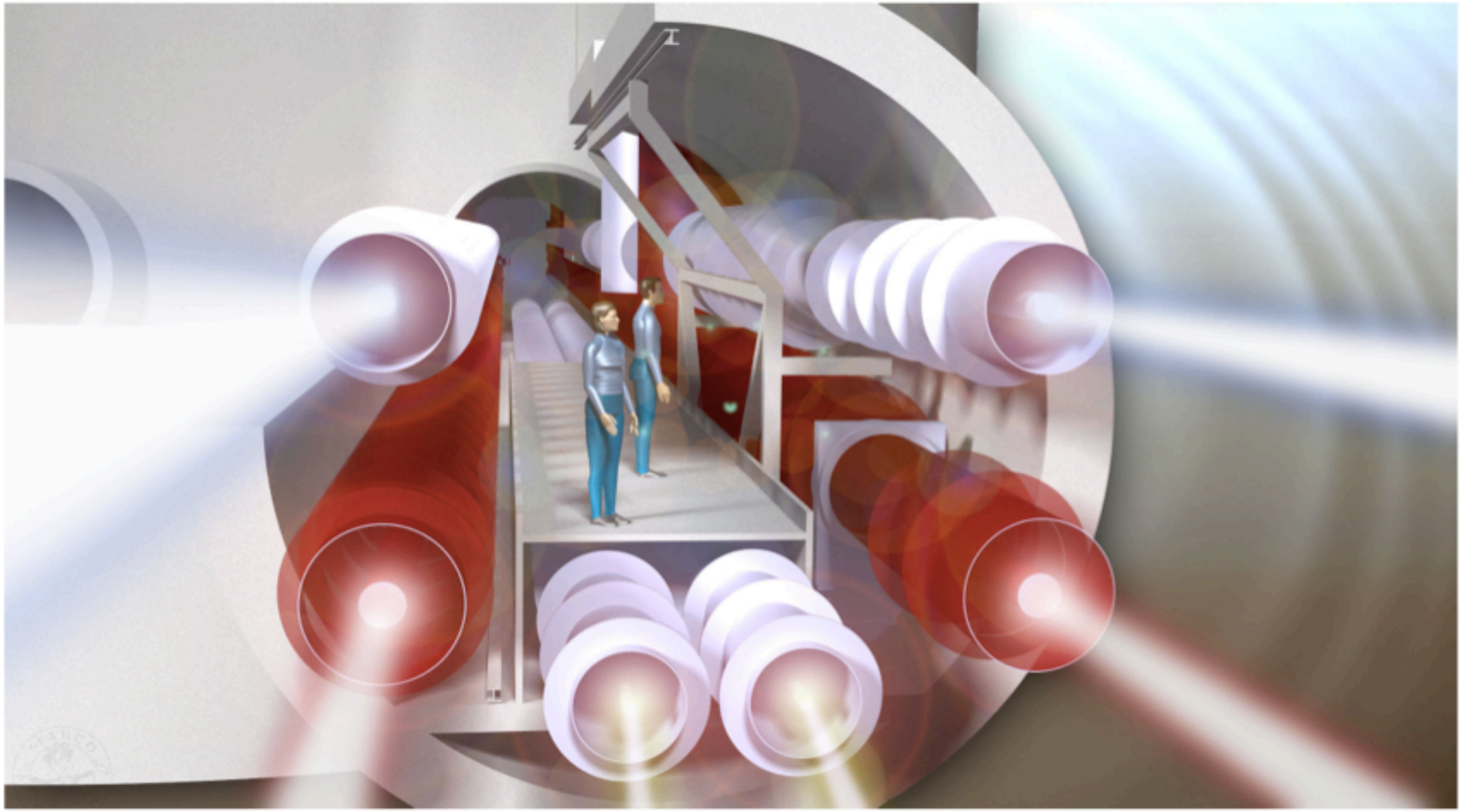


Einstein Telescope conceptual design study, www.et-gw.eu

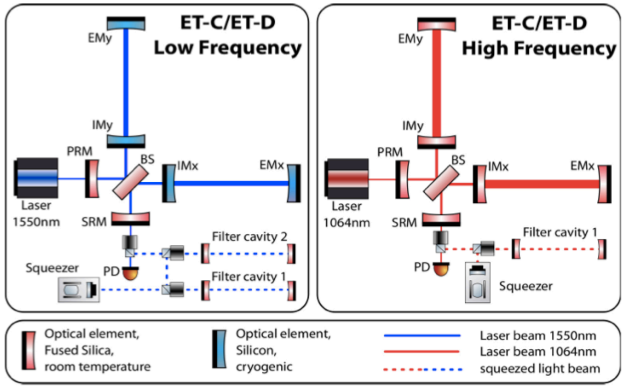
Einstein Telescope – implementation



Einstein Telescope – implementation



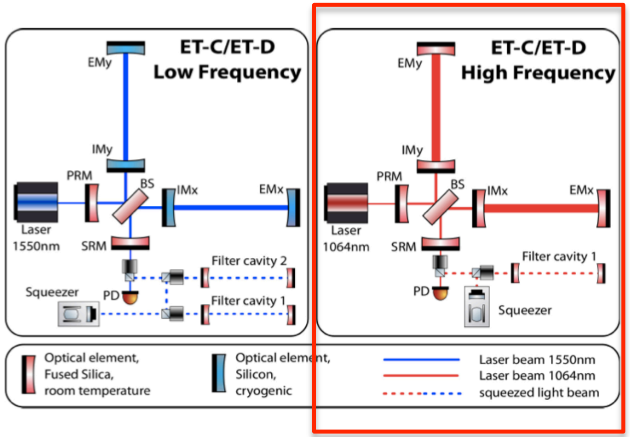
Einstein Telescope – Technical choices

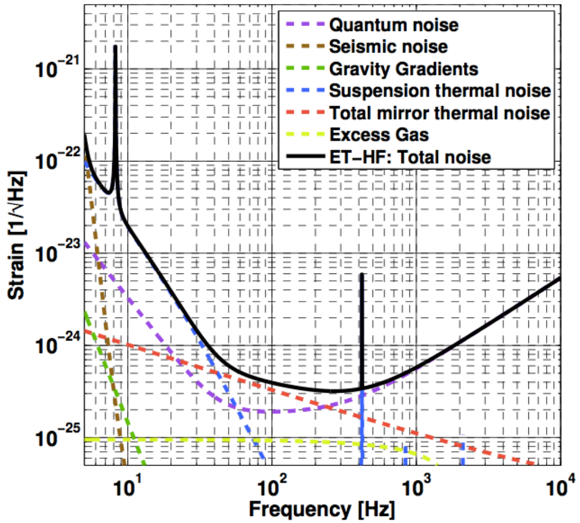


Einstein Telescope conceptual design study, www.et-gw.eu

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 – 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
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SR-phase	tuned (0.0)	detuned (0.6)
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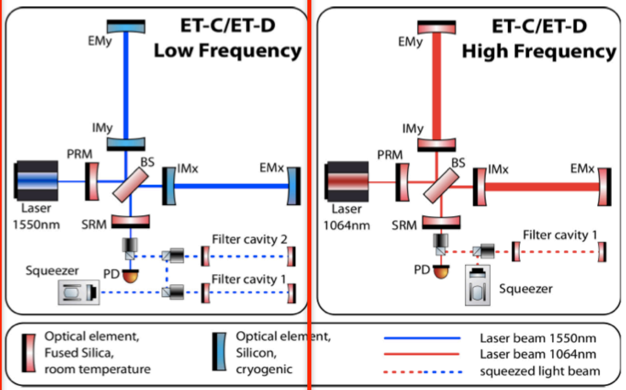
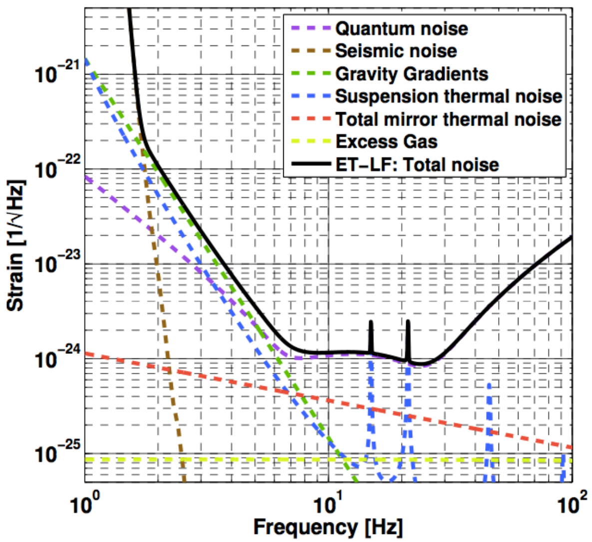
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×10 km	2×10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (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
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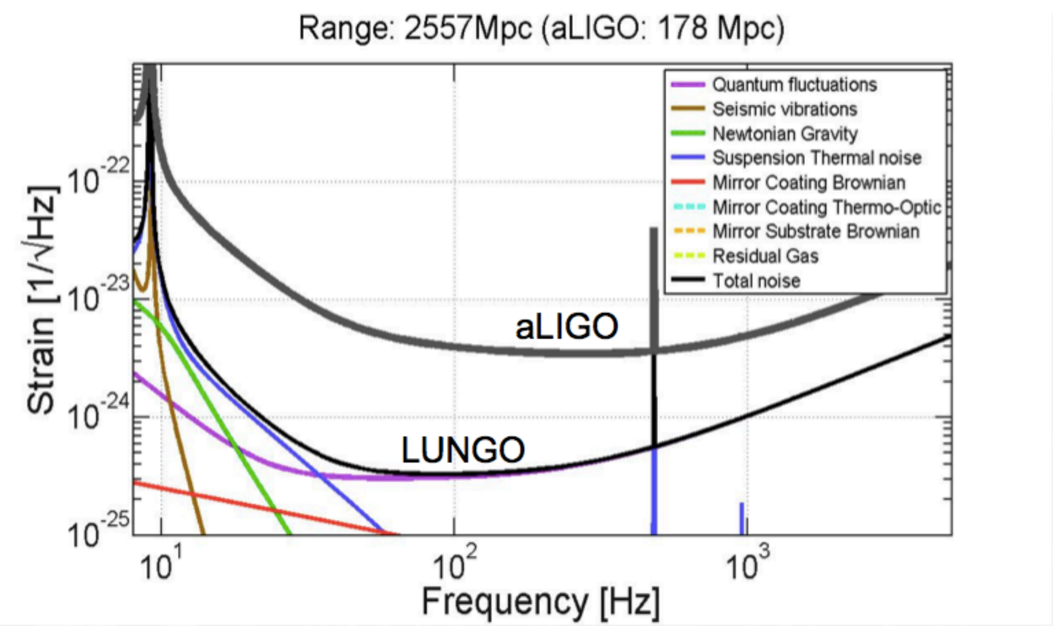
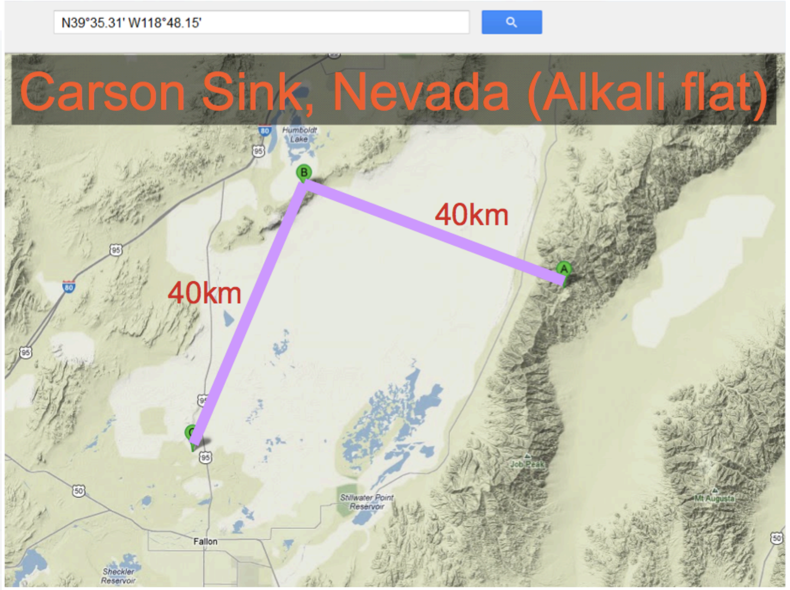
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1 × 10 km	2 × 10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	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

Too complex? Just make the detector longer

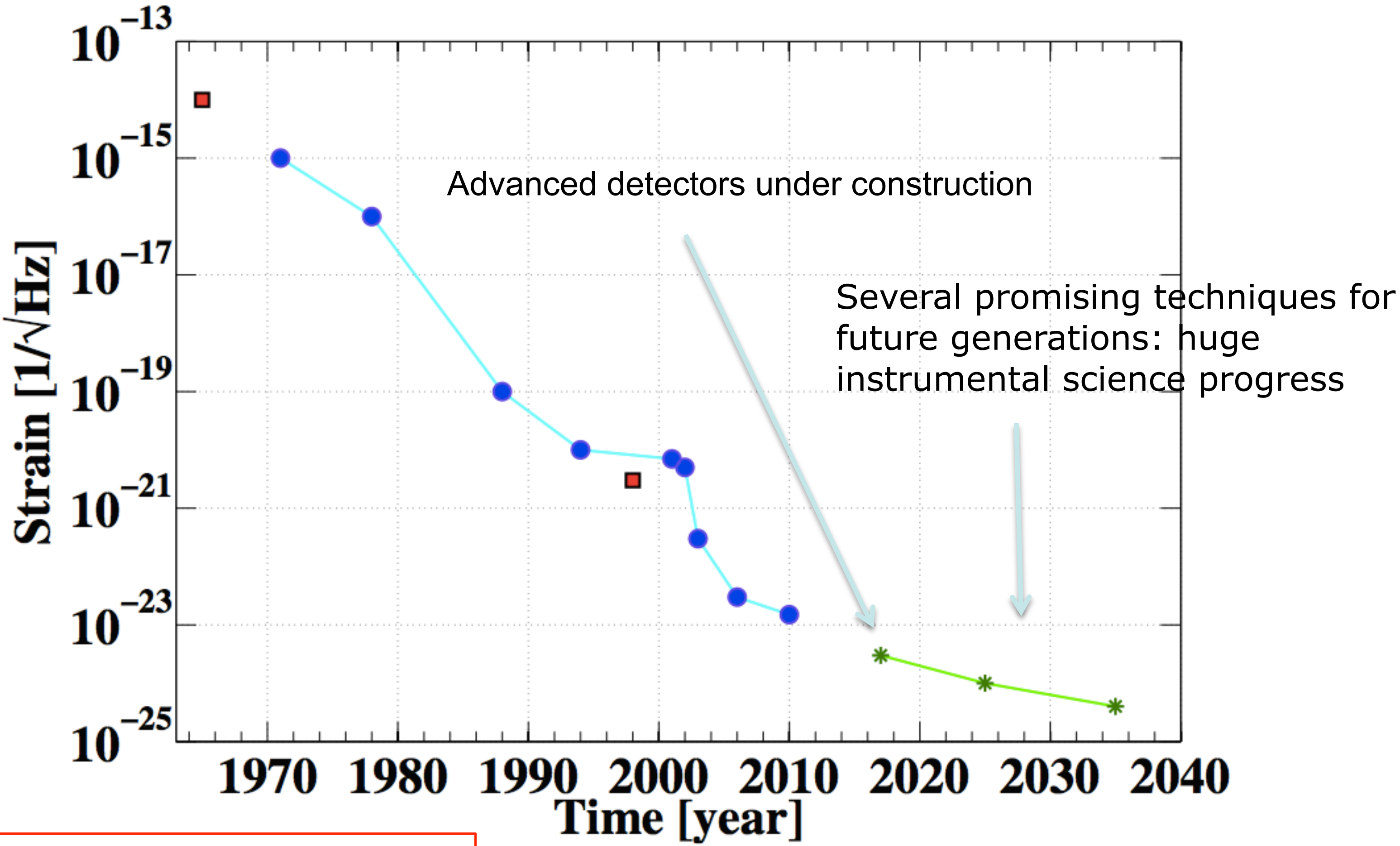
Why not a 40 km interferometer?





Ballmer et al., presentation at the GWADW 2013, Isola d'Elba

Conclusions: future earth-based detectors



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

Huge scientific potential