Beyond Advanced LIGO: 3G Gravitational-Wave Detectors

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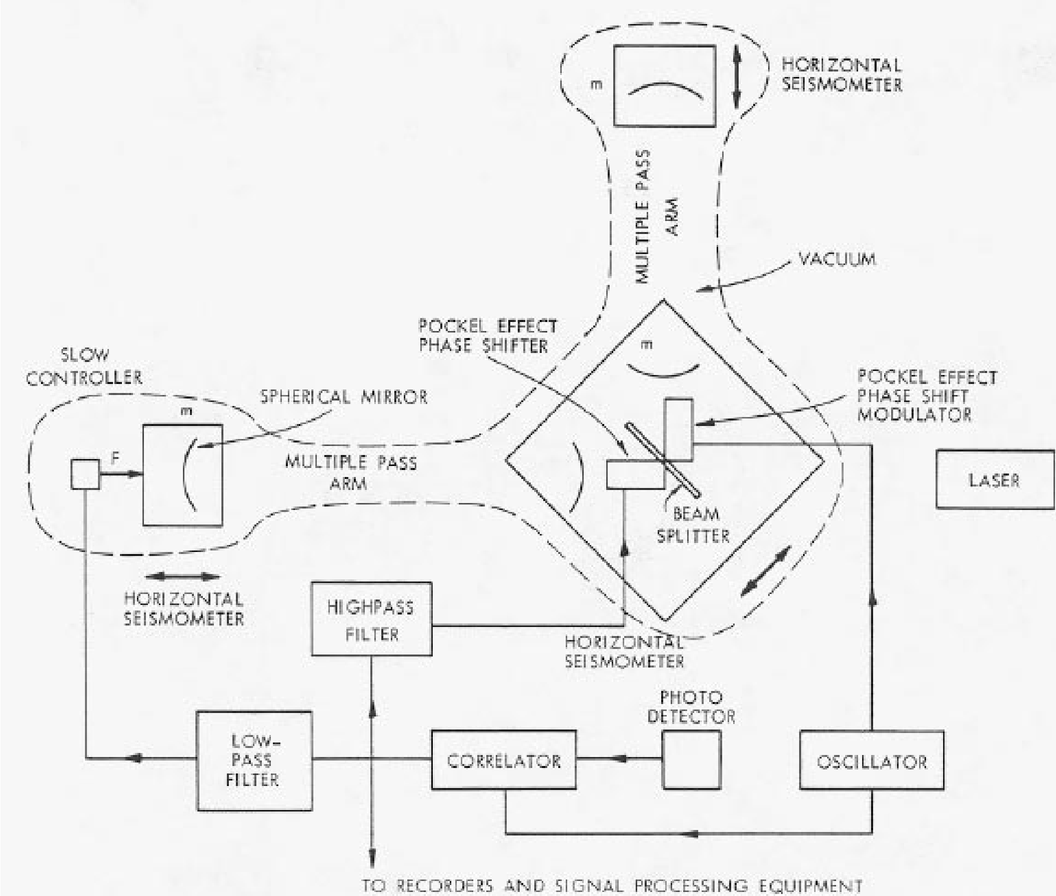
July 30, 2012

Outline

- Introduction: The brief history of LIGO
- What can we achieve in the next 2 decades?
  - Science case: GW astrophysics
  - Technological challenges & required R&D
  - Steps on the way: possible upgrades

A short history of LIGO

- Electromagnetically coupled broad-band gravitational wave antenna, R.Weiss, MIT RLE QPR 1972
- NSF funding and construction in the 1990's
- Design sensitivity and observation in 2005



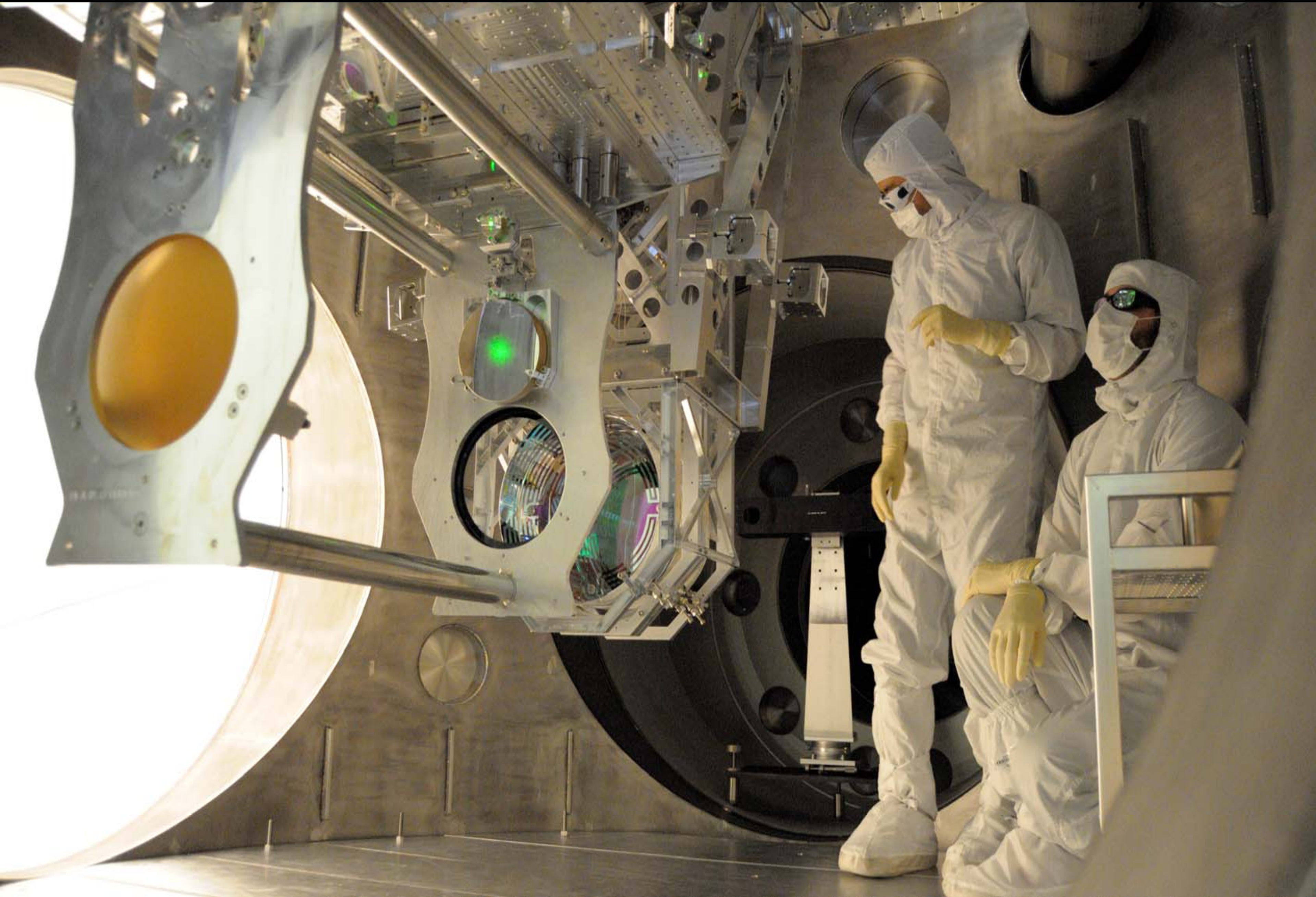
Built and commissioned Initial LIGO…

LIGO Livingston Observatory

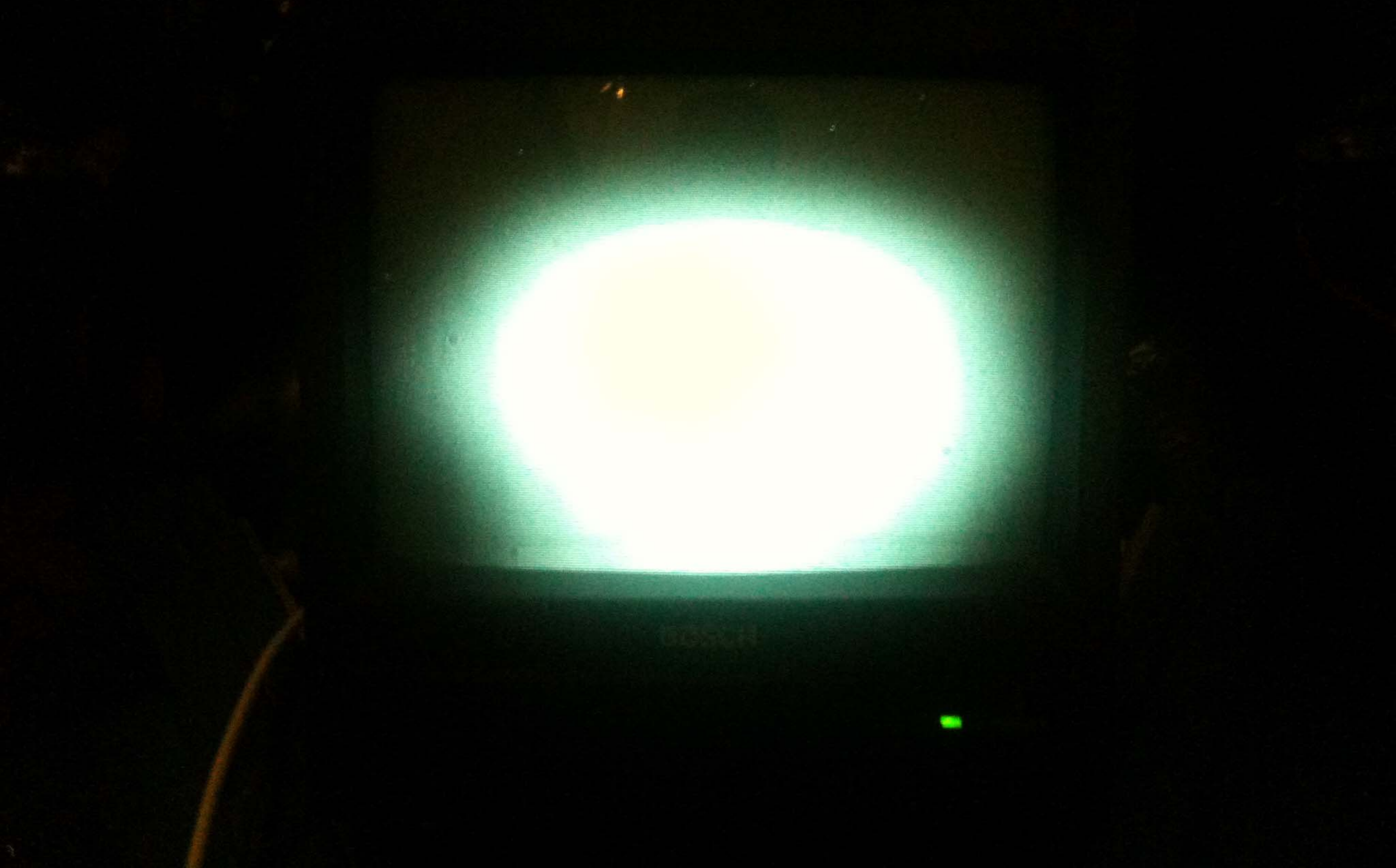
LIGO Hanford Observatory

… taken apart…

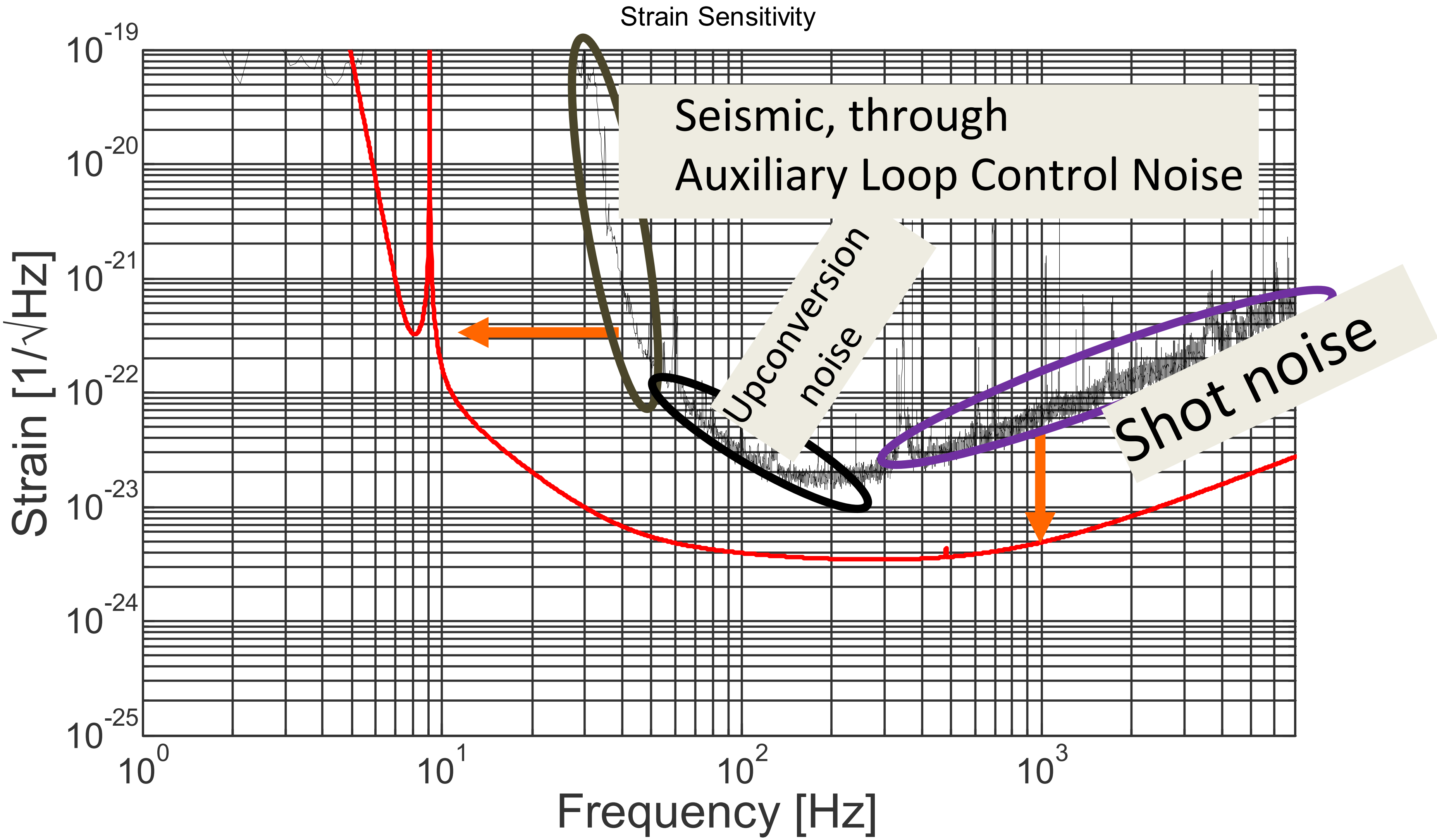
…and rebuilt: Advanced LIGO…



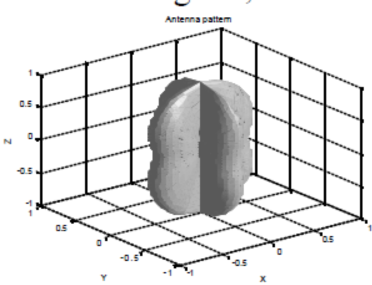
… slowly starts working
(Livingston mode cleaner first lock, 7/28/2012)



From initial LIGO to Advanced LIGO

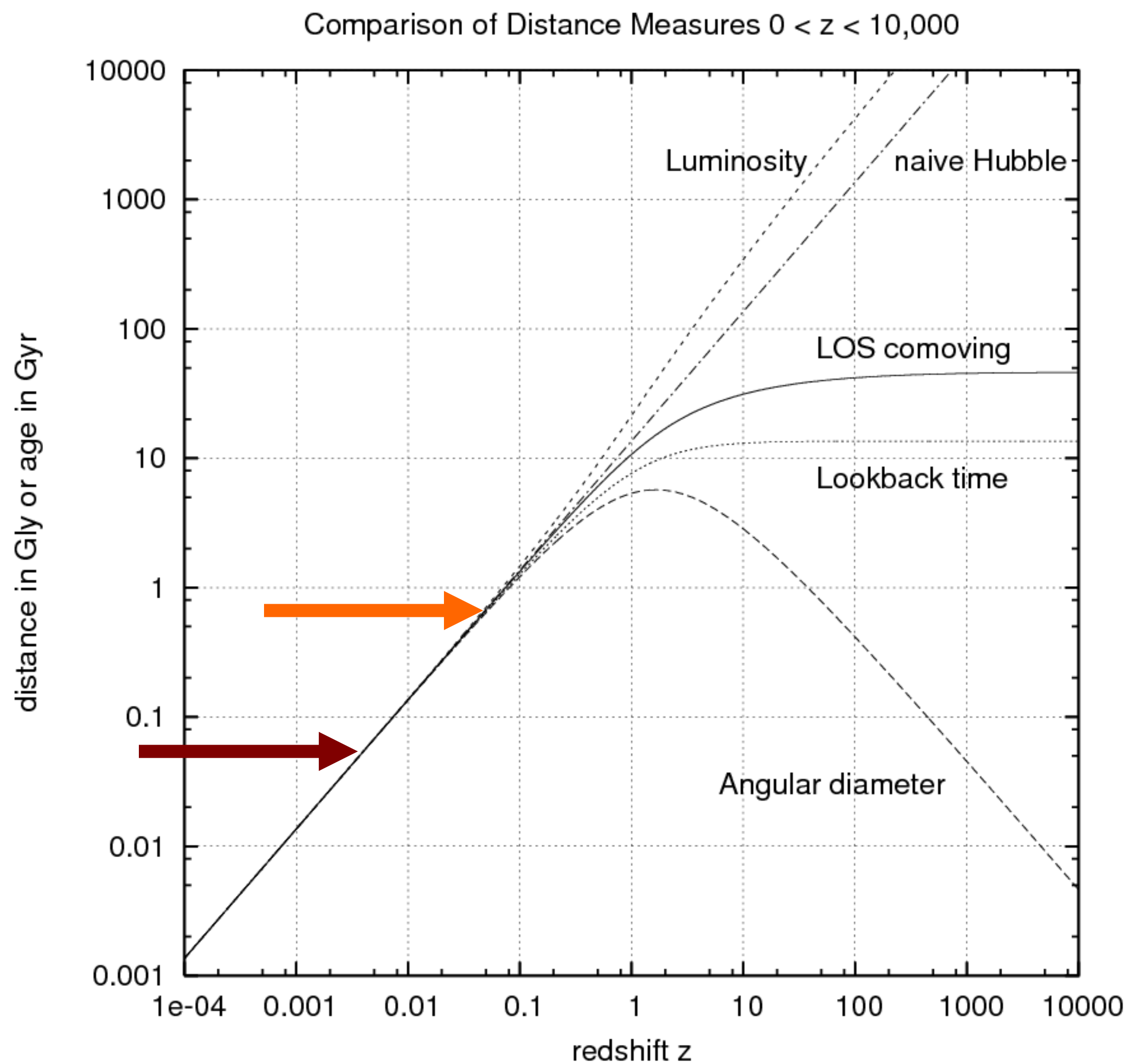


NS-NS standard candle (sky-averaged distances)



- Initial LIGO (1st gen.) 20 Mpc

- Adv LIGO (2nd gen) ~200Mpc



The next two decades

GW Astronomy Science Goals
Highlights only

- Fundamental Physics
  - Do black holes really have "no hair" ?
  - What is the neutron star equation of state?
- Astrophysics
  - What is the black hole mass distribution?
  - What are the progenitors of GRBs?
- Cosmology
  - What is the equation of state of dark energy?
  - Can we directly see past the CMB?

What is needed to achieve this?

- Advanced LIGO will observe NS/NS mergers, but it is a detection machine
  - SNR = 10 → signal fidelity ~10%
  - Many interesting science goals out of reach

- We want to see NS/NS mergers to cosmological distances (z>1)
  - i.e. another factor of 10x & down to 1Hz

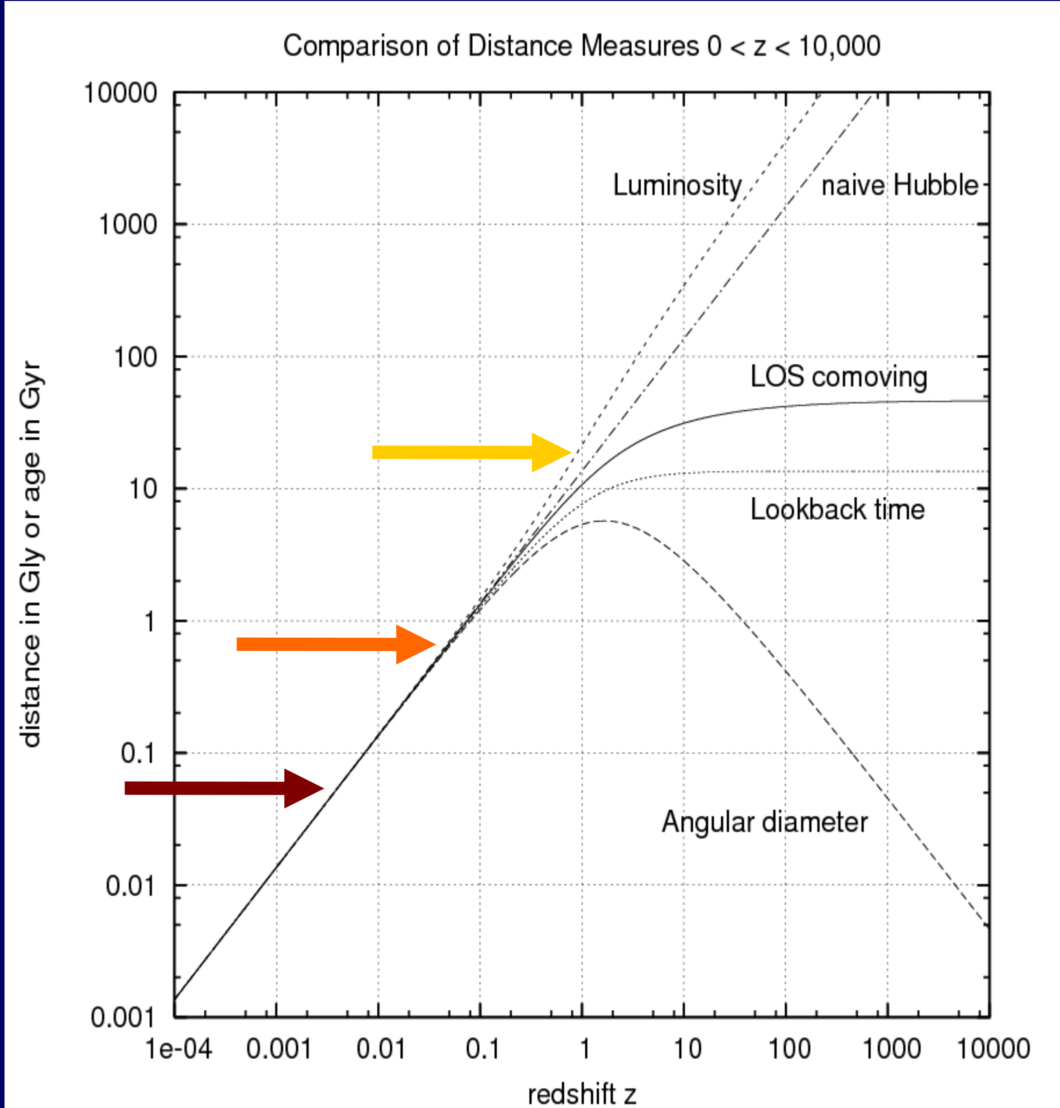
- So far every new telescope has raised more questions than it answered.
- So we need…

G. Galilei

… bigger observatories!

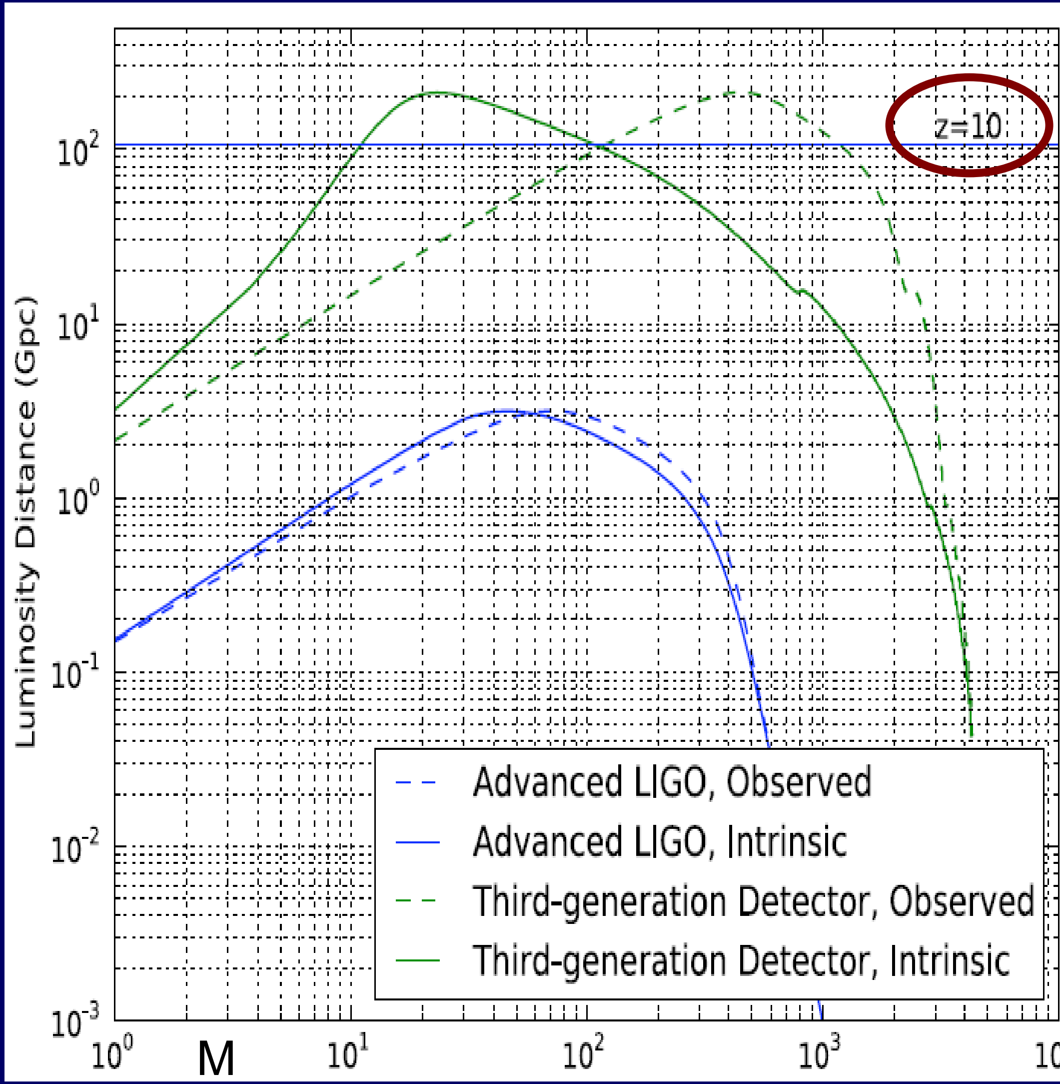
The science case for the next generation GW detector

- **NS-NS merger:**
- **aLIGO**
- **Next generation**
  - **Observe NS-NS mergers up to redshift 1**
  - **Expect O(10)/day**
  - **SNR sufficient to explore Nuclear equation of state**



The science case for the next generation GW detector

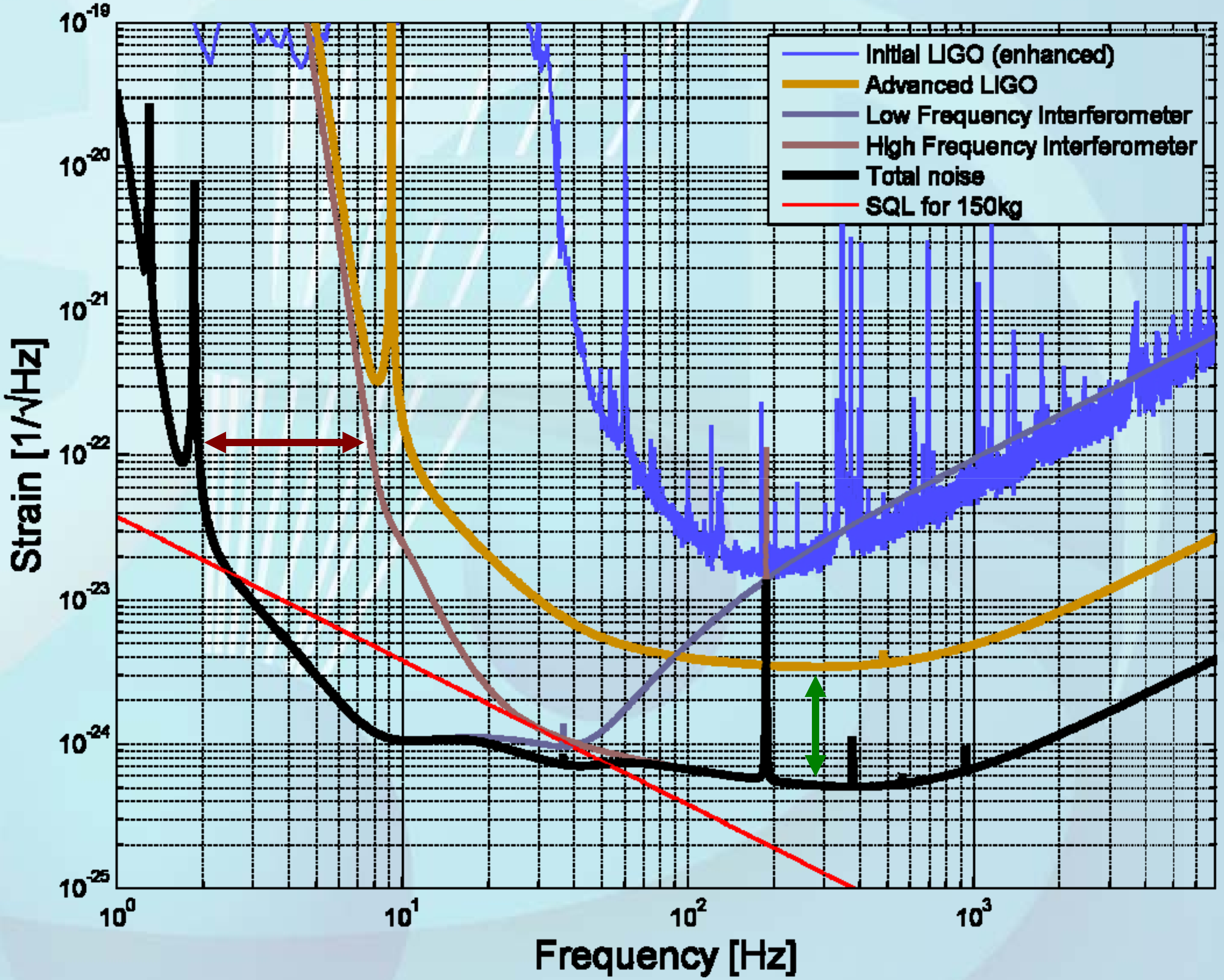
- **Exploring the Early Relativistic Universe with Intermediate Mass Black Holes.**
  - The existence of intermediate-mass black holes (IMBHs) is an open question in astrophysics.



Example strain sensitivity

- Required sensitivity

- Can we achieve that?

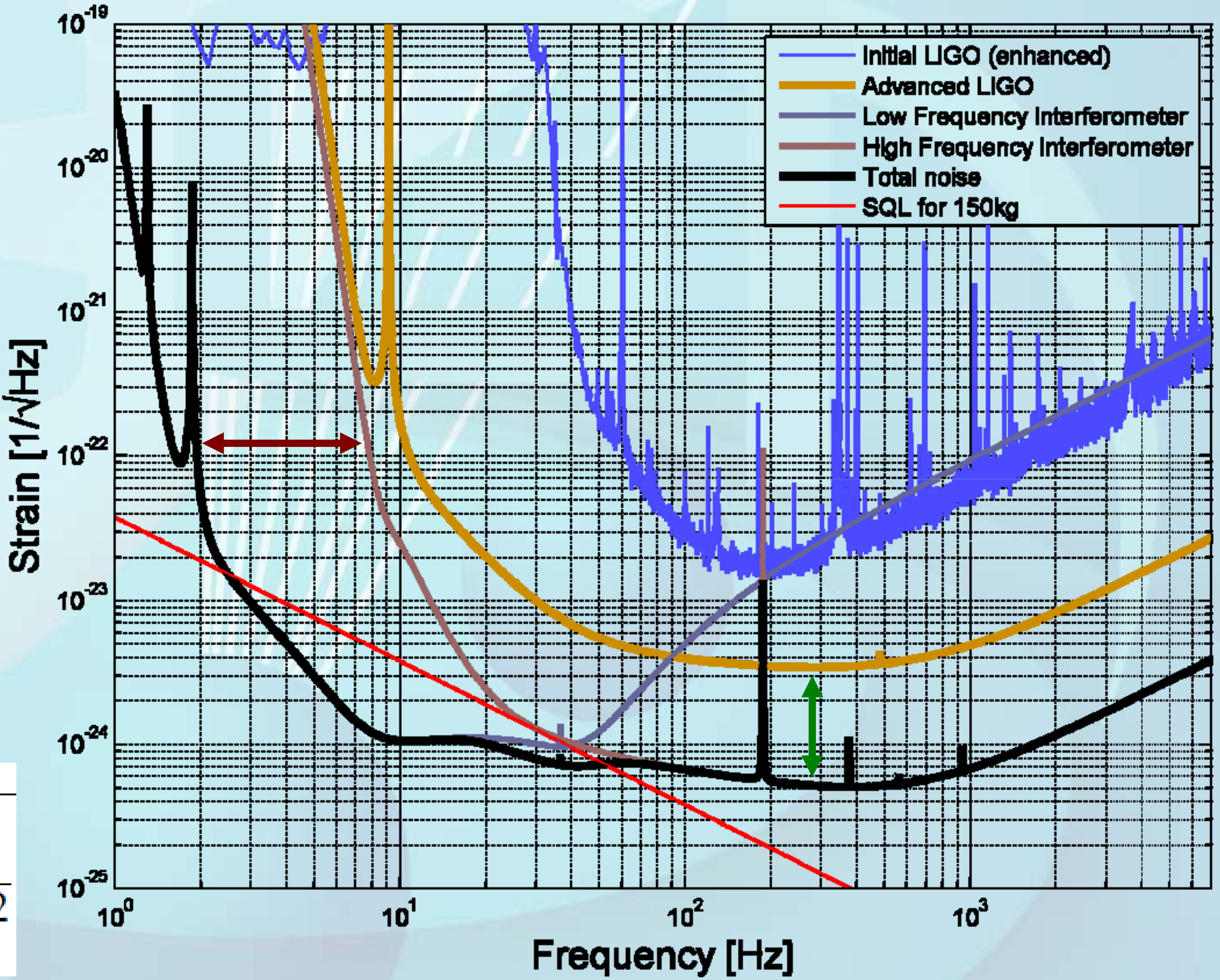


Example strain sensitivity

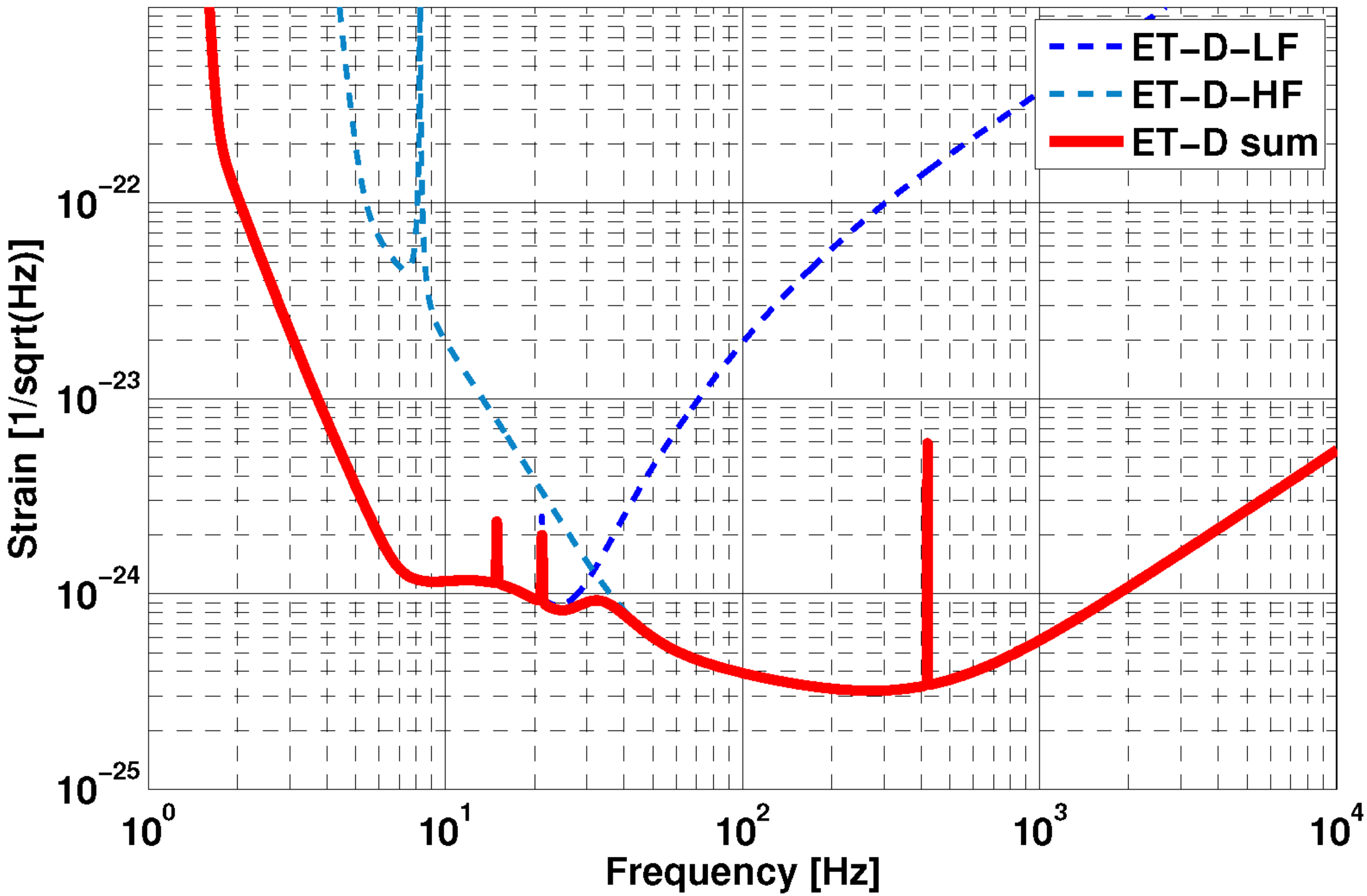
- Xylophone
  LF + HF detector

- Sub-SQL sensitivity

$$x_{\mathrm{SQL}} = \sqrt{\frac{2\hbar}{m\pi^2 f^2}}$$

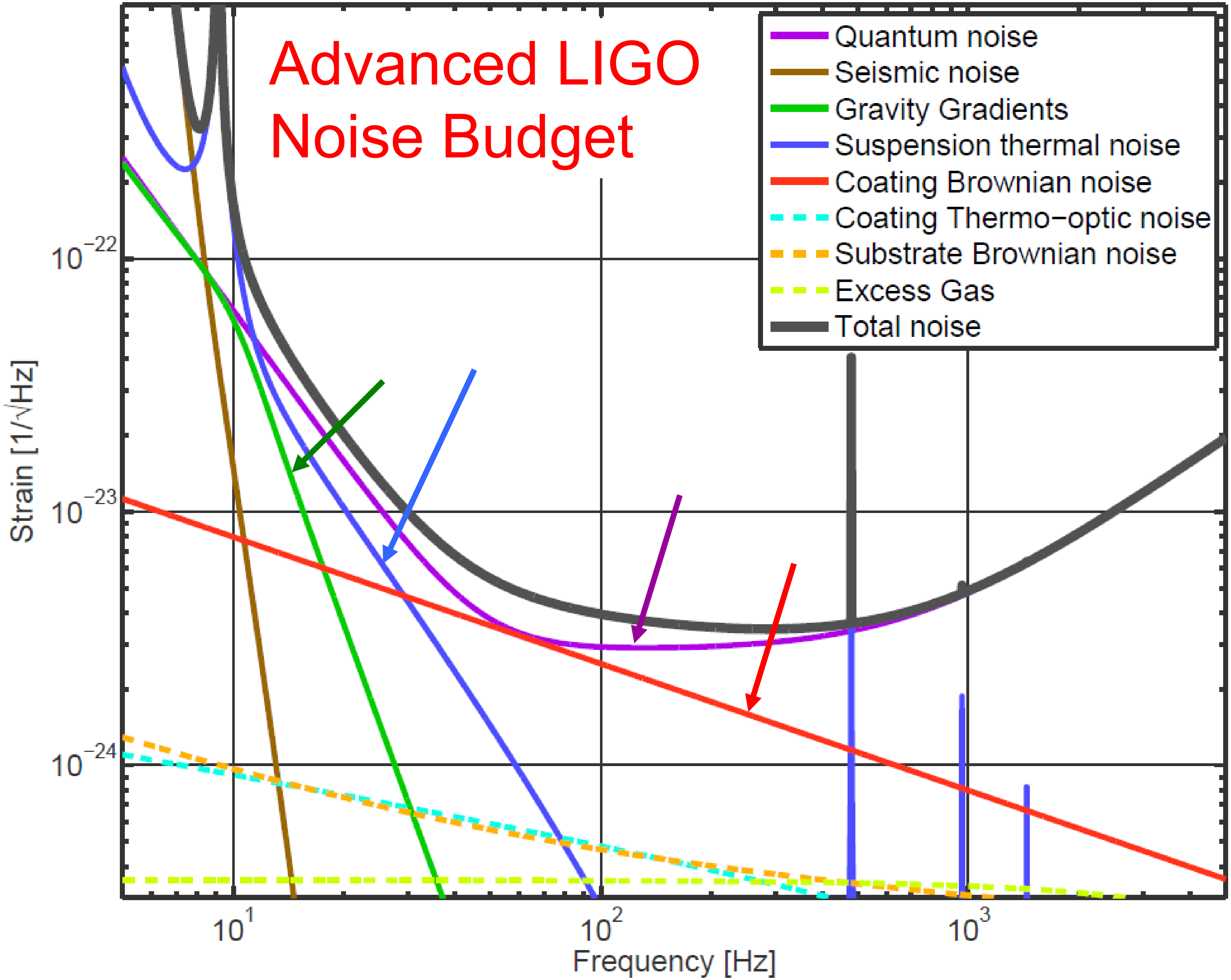


Design study



Key technological hurdles

- Thermal noise (coating)
  - Thermal motion of the mirror surface
- Quantum noise (radiation pressure/shot)
  - Quantum mechanical measurement limitations
- Newtonian (Gravity Gradient) noise
  - Newtonian gravity short-circuits suspensions



Advanced LIGO
Noise Budget
Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Excess Gas
Total noise
Strain [1/√Hz]
10^−22
10^−23
10^−24
10^1
10^2
10^3
Frequency [Hz]

Thermal Noise - basics

- Fluctuation-dissipation theorem: It's the loss!

$$\frac{1}{2}m\langle\dot{x}^2\rangle = \frac{k_B T}{2}$$ vs. $$Z\dot{x} = m\ddot{x} + kx + \gamma\,\dot{x} = F_{\text{noise}}$$

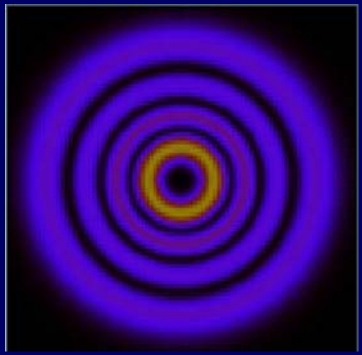
- 2 types of losses:

$$dF(T,\vec{\varepsilon}) = -SdT + \vec{\sigma}d\vec{\varepsilon}$$

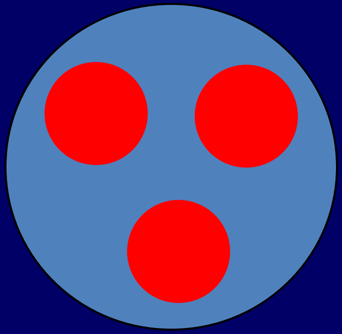
  - Mechanical loss → Brownian noise
  - Thermal loss → Thermo-optic noise (thermo-elastic & thermo-refractive)

Improving Thermal Noise

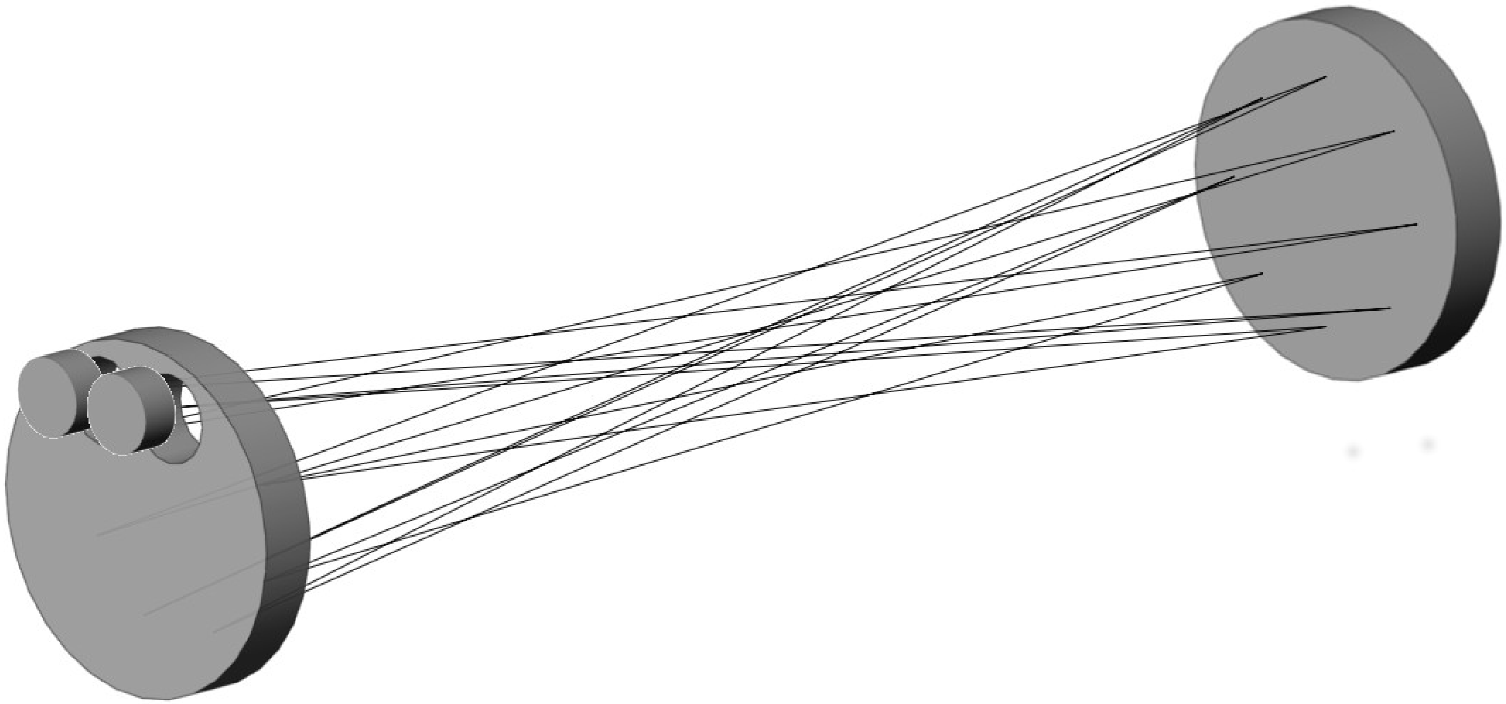
- Beam size, arm length (pricy)
- Laguerre-Gaussian modes
  - Effective beam area larger (Noise averages)
  - But mode degenerate



- Three beams, 3x in Area!
  - Polish 3 spherical dents on one large optic
  - Angular control can be easy.



Example mirror layout (8 bounces)



Cryogenic operation

- Thermal Noise? Cool!
  - Young's modulus, Thermal conductivity and capacity need to be well-behaved at low T.
  - Requires change of substrate material e.g. crystalline Si

- Implications:
  - Need to change laser wavelength to 1.6u (band edge)
  - Affects coating choice
  - Technical integration nightmare
    - Vibrations, cooling beam pipes, etc.

Measuring pulse tube cooler vibrations, at Cryomech, Syracuse

Crystal coatings - AlGaAs

- aLIGO coating are performance-limiting.
  - High-index material: Ta_2O_5 …high mechanical loss (loss angle ~2.3e-4)
- Aluminum gallium arsenide $Al_xGa_{1-x}As$
  - Lower mechanical loss ~10^{-5} → better Brownian noise
  - Needs to be grown on matched crystal
  - Worse thermo-optic parameters
    - Possible to design coating to reduce TO noise
  - Benefits and challenges likely to carry over to other crystals

G.Cole, VCQ,
M.Martin, C. Benko, J. Ye JILA

Quantum Noise

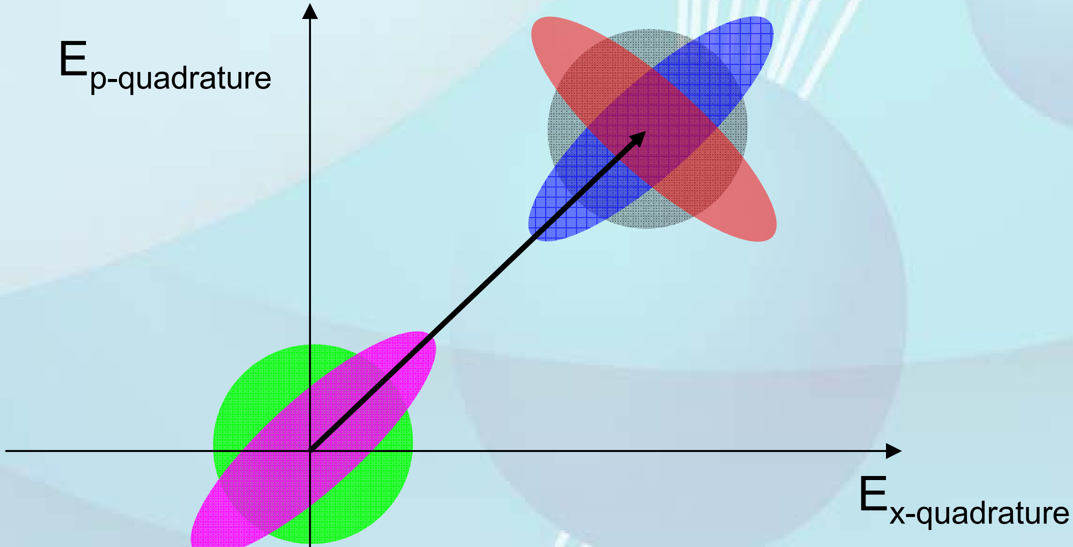
- Go heavy…

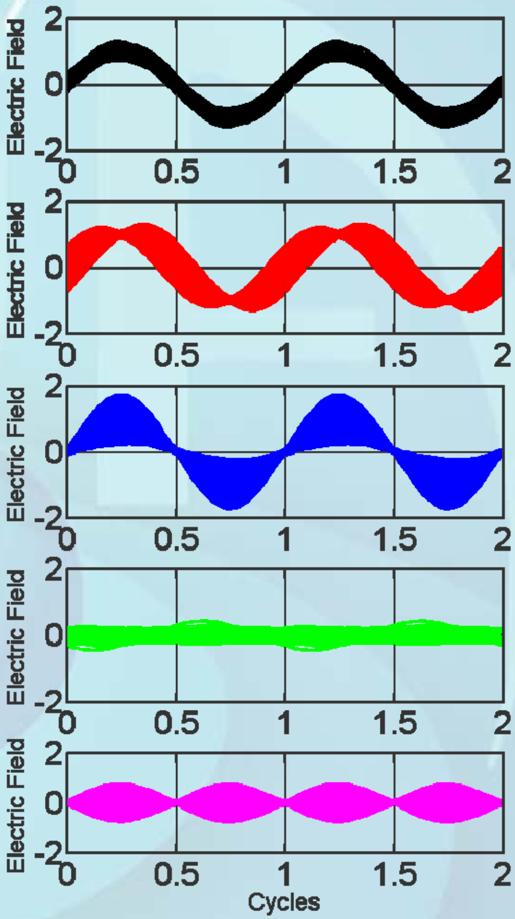
$$x_{\mathrm{SQL}} = \sqrt{\frac{2\hbar}{m\pi^2 f^2}}$$

- Squeezing
  - External squeezed light injection
  - Filter cavities (pre-filter cavities)
  - Variational readout (post-filter cavities)
- Speedmeters

Squeezed light source

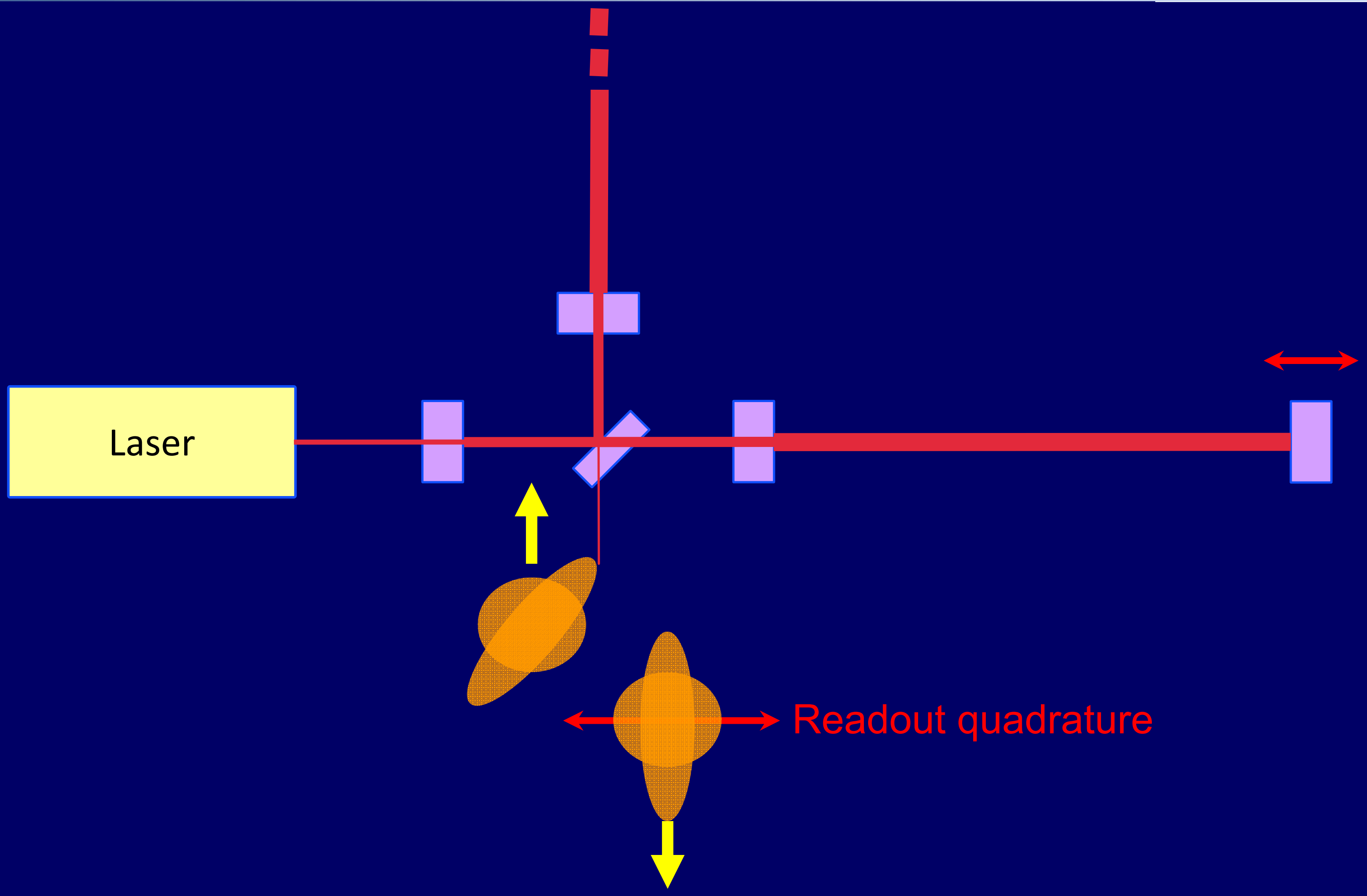
- Quantum trade-off between phase and amplitude noise
- Strain sensing is only sensitive to one of them
- Can be generated in Optical Parametric Oscillator



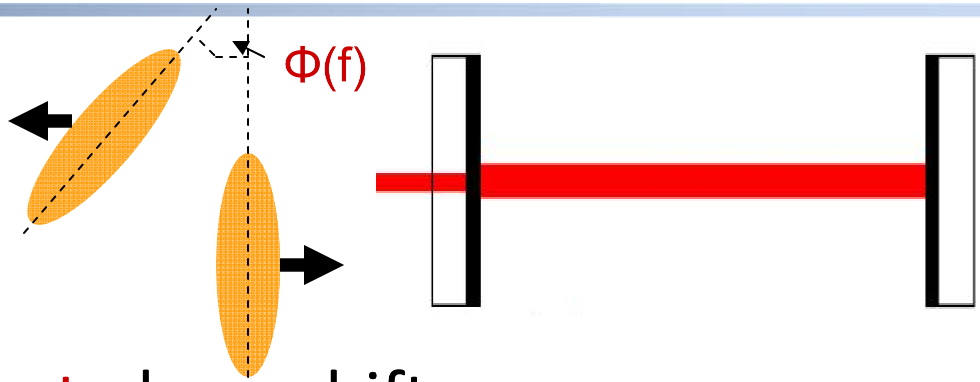


Schematic representation of Electric field, various states

Why does squeezing work?



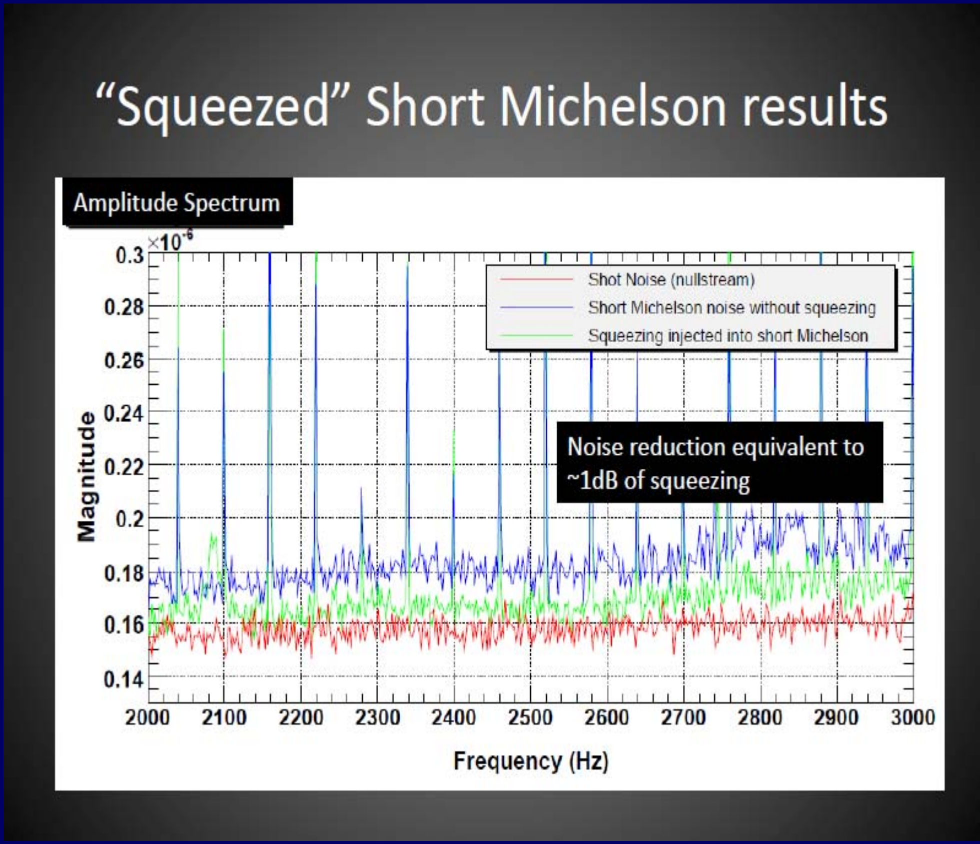
Filter cavities



- Concept:
  - A cavity operated in reflection:
    → frequency dependent phase shift
      - No delay above cavity pole
  - Used on squeezed light: frequency dependent rotation on squeezing ellipse
- Keep squeezing ellipse in correct orientation
- Draw-back: very sensitive to optical losses

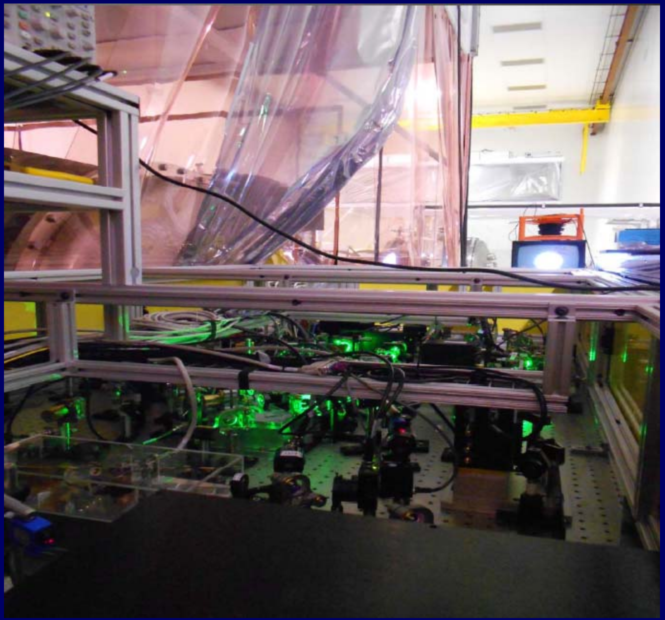
Squeezing in LIGO and GEO: current status

- Test on Hanford 4km



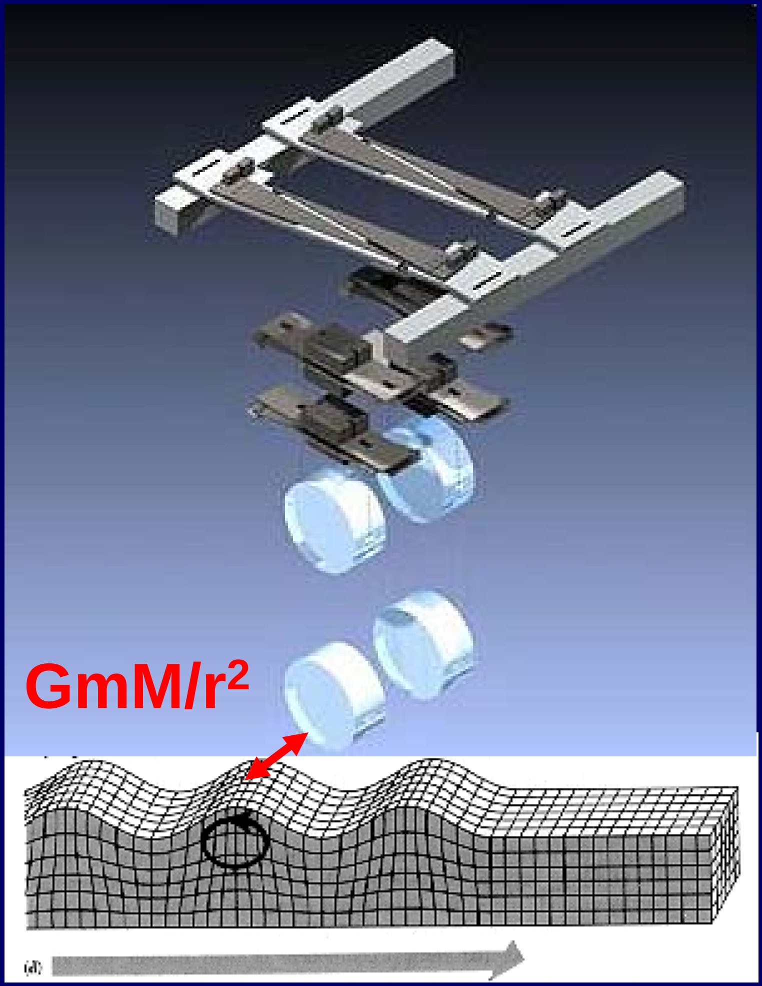
- ..and GEO600

Nature Physics 4, 440 - 441 (2008)



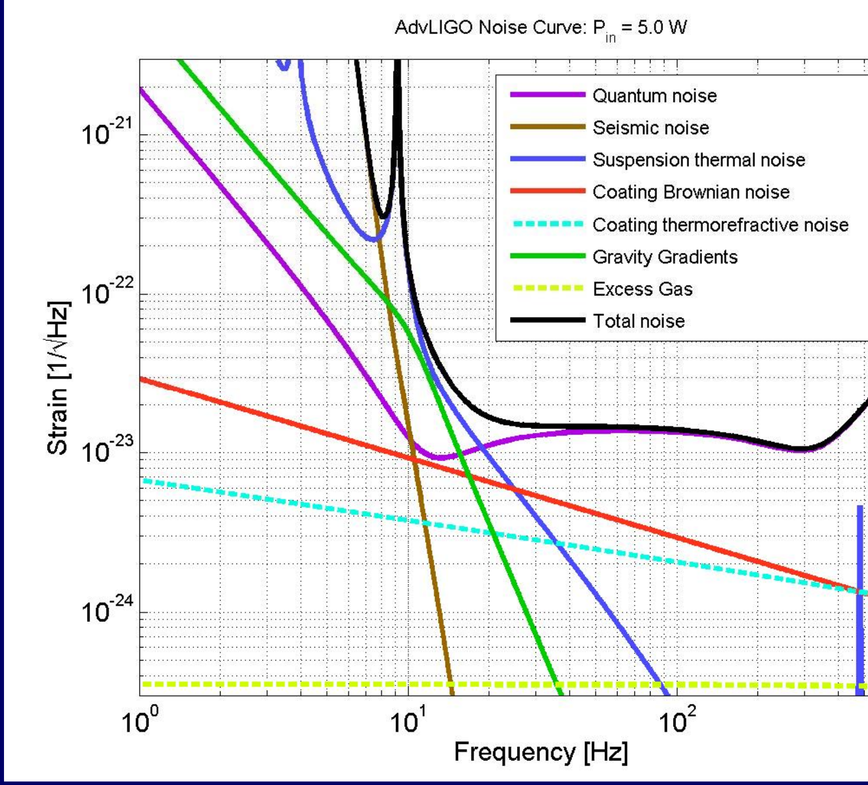
Newtonian Noise

- Direct gravitational force on mirror
- Bypasses any seismic isolation system



Newtonian Noise

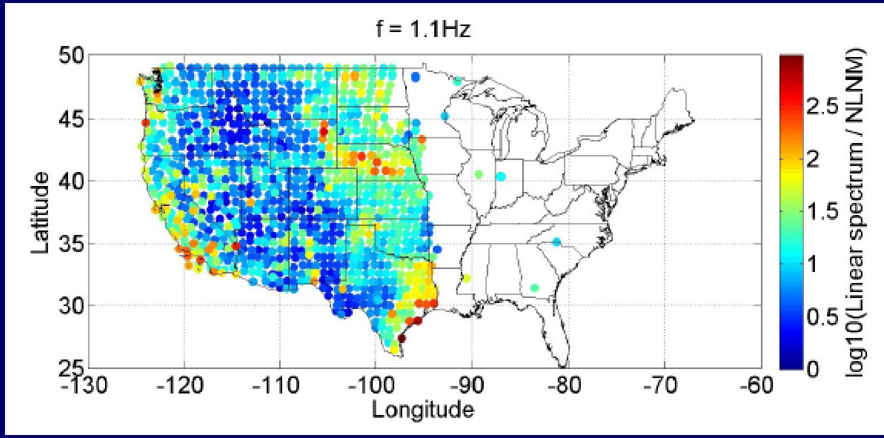
- At surface:
  - Newtonian (gravity-gradient) noise dominates below 10 Hz
- Newtonian noise sources:
  - Seismic waves (dominated by surface waves).
  - Atmospheric fluctuations.
  - Human factor (traffic etc).
- ~10^{-20} $Hz^{-1/2}$ at 1 Hz.
  - Need to suppress by 10^2–10^3x.



Mitigating Newtonian Noise

- Better location?
  - Survey of US locations
- Underground option:
  - Controllable environment, atmospheric and human-induced effects suppressed.
  - Surface seismic waves exponentially suppressed with depth (10x at 1 Hz).
- Active suppression…

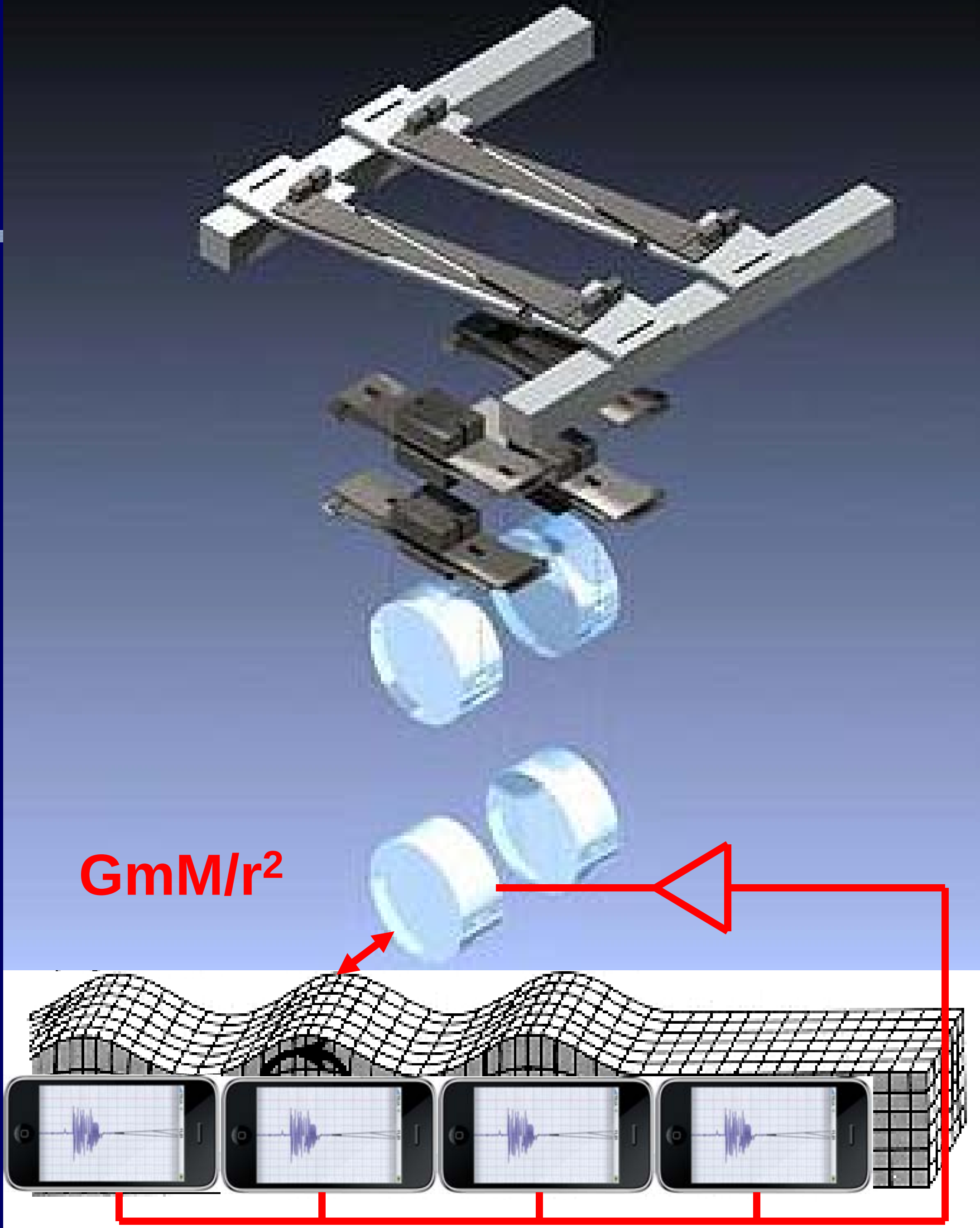
Average seismic levels at 1.1 Hz
USArray seismometer data



Jan Harms, et. al.

Active feedback

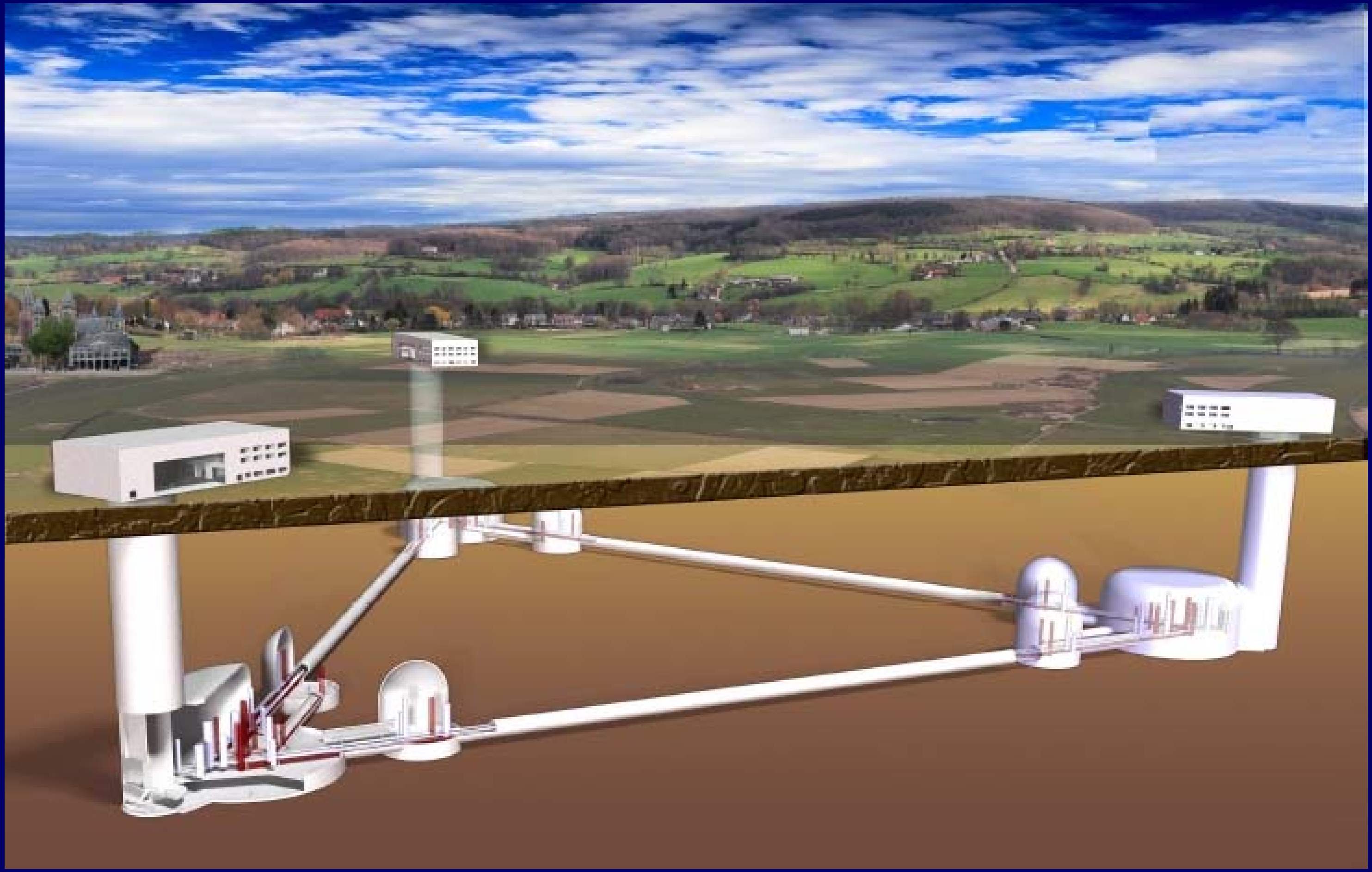
- Adaptive Newtonian noise cancellation
  - Seismometer array



EINSTEIN TELESCOPE

Underground

Artist's impression of Einstein Telescope



Triangular configuration,
10 km arms,
multiple detectors

Marco Kraan,
Nikhef,
ET science team

Facility limits

- Arm length (4km)
  - ALL (amplitude) displacement noises: ~ L^{-1}
  - Thermal noise: ~ $L^{-1.5}$ (beam spot grows with L)

LIGO Hanford Observatory

- Surface seismic motion
  - Newtonian noise limit

- But what can be done at existing sites?

An upgrade for Advanced LIGO

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

Technical Note	LIGO-T1200031–v3	2012/05/15

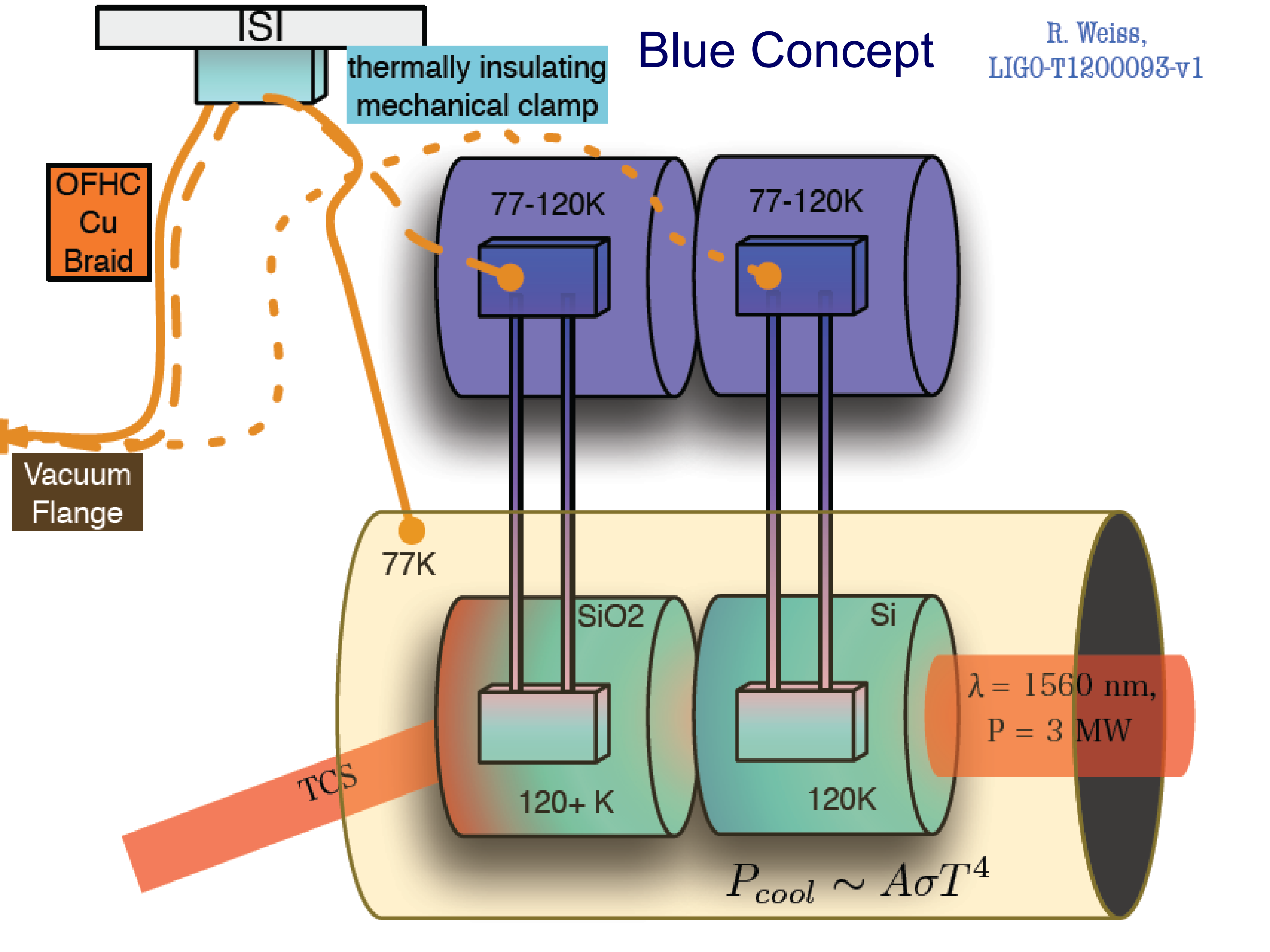
Report of the 3rd Generation LIGO Detector Strawman Workshop

R. Adhikari, K. Arai, S. Ballmer, E. Gustafson, S. Hild

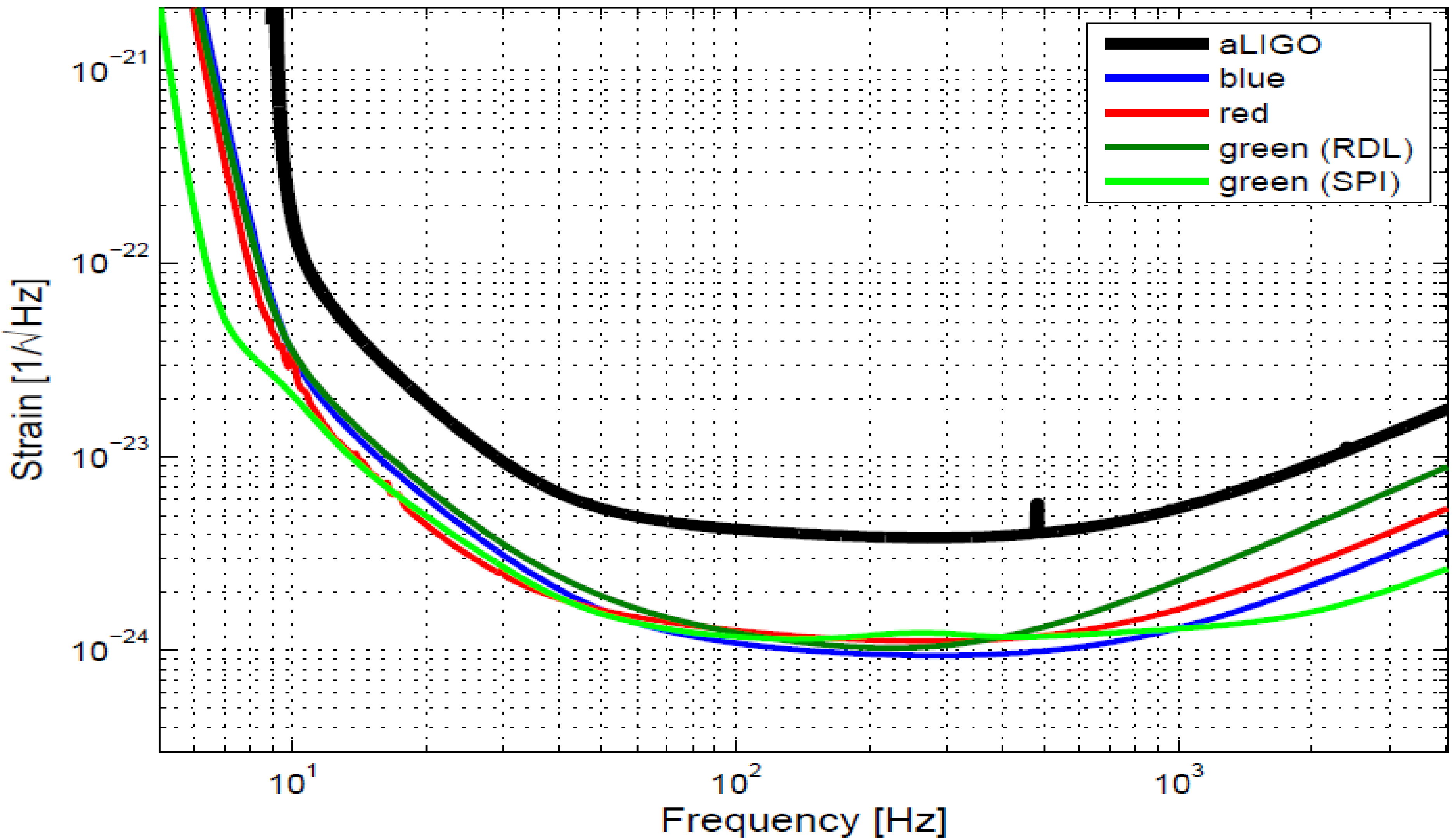
Ideas for upgrading Advanced LIGO

IFO Cases	Blue	Red	Green RDL	Green SPI (PUM/UM)	aLIGO
Mirror Mass [kg]	143	160	160	14/157	40
Mirror Material	Silicon	Silica	Silica	Silica	Silica
Mirror Temp [K]	120	295	295	295	295
Sus Temp [K]	120	295	295	120	295
Sus Fiber	0.6m Si	1.2m SiO2	TBD	0.6m Si	0.6m SiO2
Fiber Type	Ribbon	Fiber	TBD	Ribbon	Fiber
Input Power [W]	450	125	125	250/50	125
Arm Power [kW]	2800	800	210	1503/295	800
Wavelength [nm]	1560	1064	1064	1064	1064
NN Sub	30	5	10	30	1
Coating Type	AlAs:GaAs	SiO:TaO	SiO:TaO	SiO:TaO	SiO:TaO
Beam Size [cm]	5.3 / 6.2	8.5 / 10	8.3 / 9.3	(4/4) / (11/11)	5.3 / 6.2
SQZ Factor [dB]	10	20	20	20	0
F. C. Length [m]	100	300	100	100/100	N. A.

Table 1: Baseline parameters for aLIGO and the Strawman IFO configurations


ISI
thermally insulating mechanical clamp
Blue Concept
R. Weiss, LIGO-T1200093-v1
OFHC Cu Braid
77-120K
77-120K
Vacuum Flange
77K
SiO2
Si
λ = 1560 nm,
P = 3 MW
TCS
120+ K
120K
$P_{cool} \sim A\sigma T^4$

Ideas for upgrading Advanced LIGO



Conclusion

- Advanced LIGO will whet our appetite for more
- A factor of 10x of sensitivity improvement (z=1 for NS/NS) seems possible, but requires research
- A factor of 3x is possible at existing sites
- The scientific pay-off would be enormous
  - Hence this conference…


Thank you!