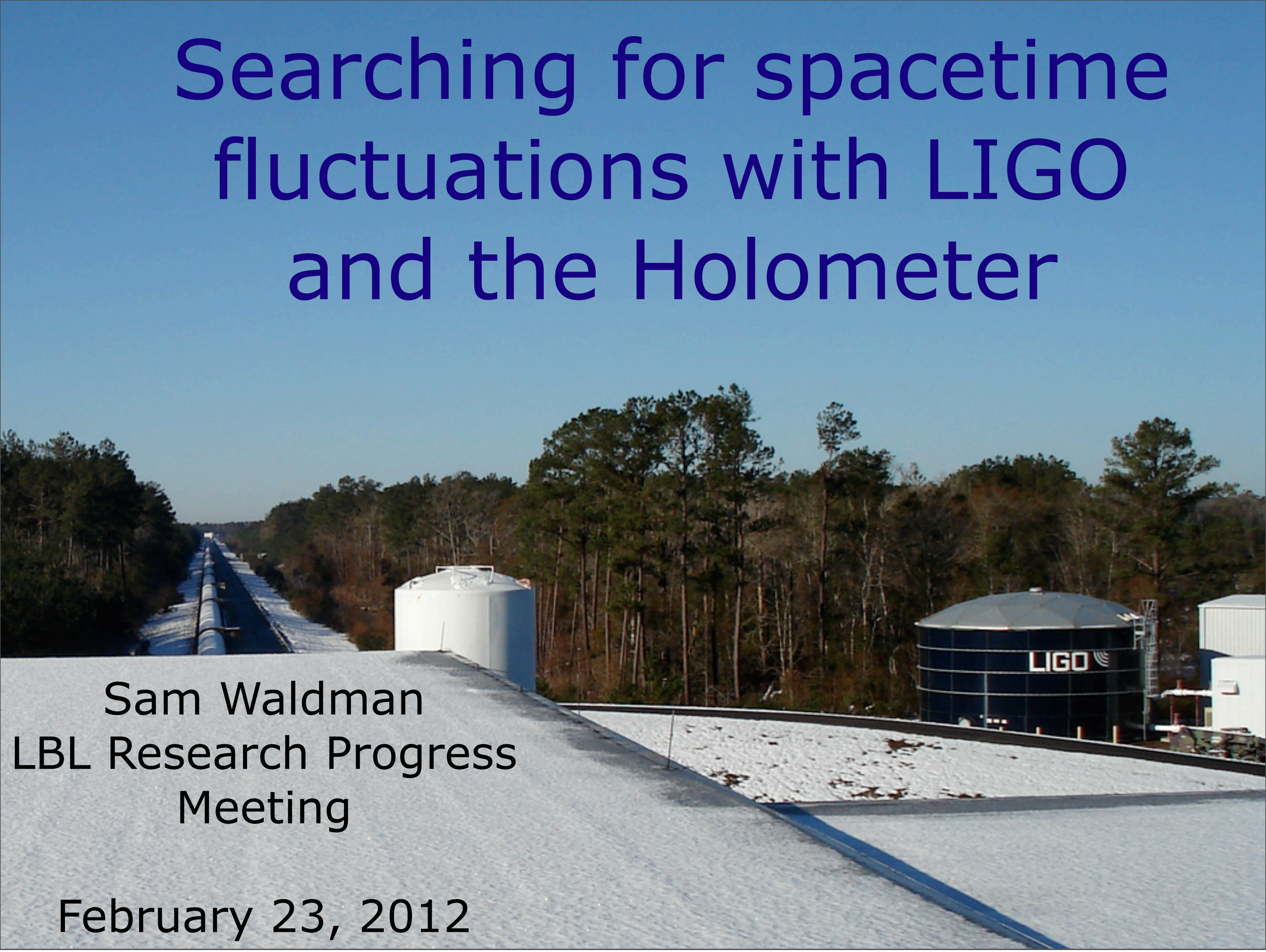
Searching for spacetime fluctuations with LIGO and the Holometer



Sam Waldman
LBL Research Progress Meeting

February 23, 2012

Initial LIGO

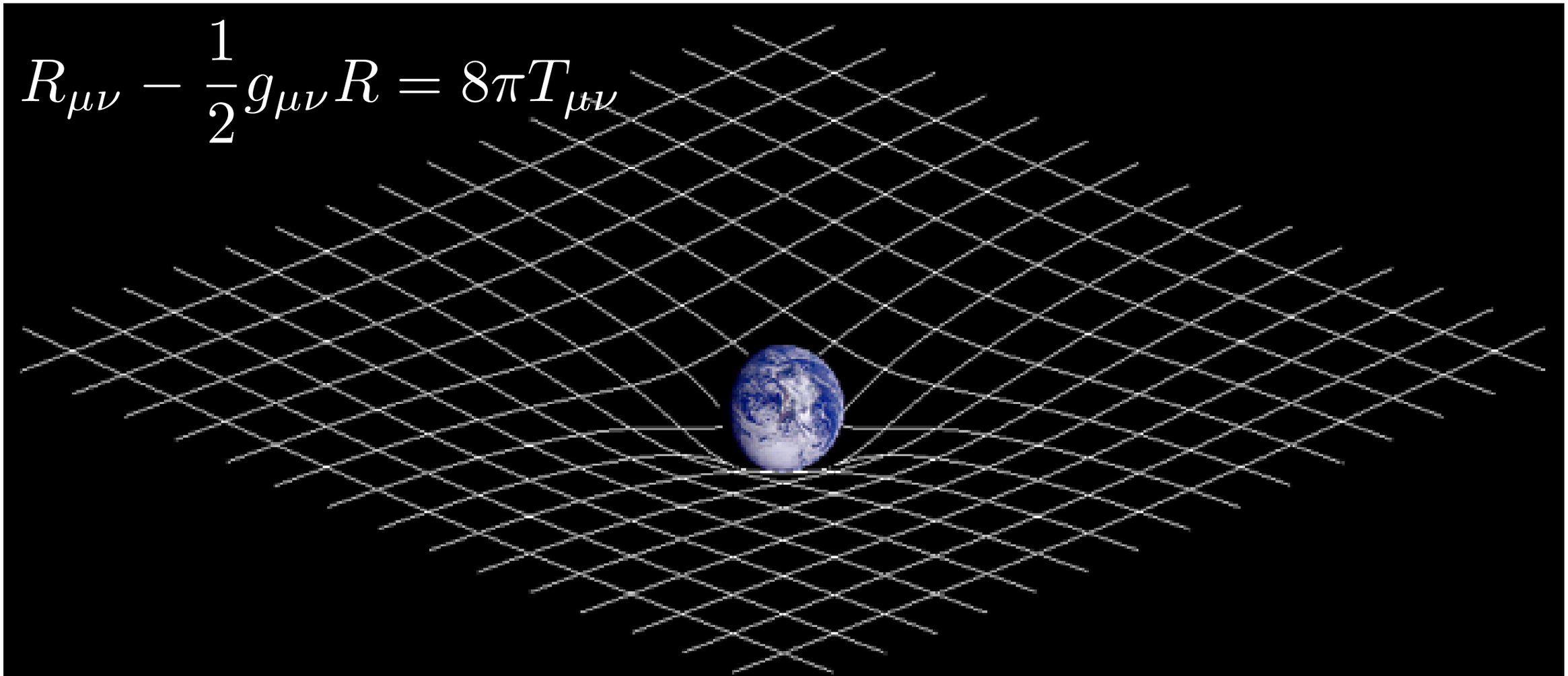
Advanced LIGO

Applied LIGO

General Relativity

"Mass tells space-time how to curve, and space-time tells mass how to move."
J.A. Wheeler

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$



GR Predictions
from 1916-1918

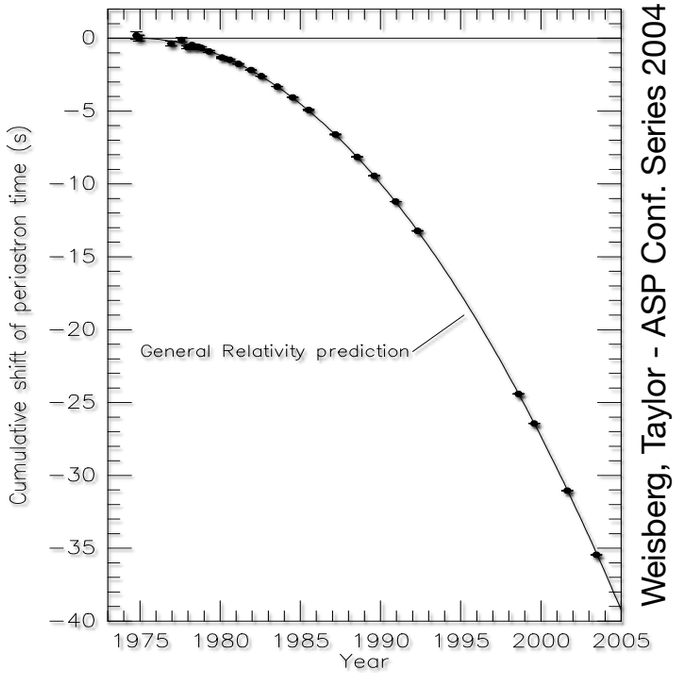
SpaceTelescope.org/opo9020a

1. Mercury's perihelion advance
   43" / century, first noted by Urbain Le Verrier in 1859

2. Gravitational deflection of light
   Observed by Eddington during the 1919 eclipse, repeated in 1922 by Lick Observatory

3. Gravitational redshift
   Definitively measured by the Pound-Rebka experiment in 1959 using Mössbauer spectroscopy.

4. **Gravitational waves**
   Predicted in 1918, indirectly observed via the orbital dynamics of the Hulse-Taylor binary pulsar, 1974



Weisberg, Taylor - ASP Conf. Series 2004

Modern Gravity

Black holes
- Active Galactic Nuclei
- Xray Binaries
- Sagittarius A*

Neutron Stars:
- Millisecond pulsars
- Soft Gamma Repeaters

Gamma Ray Bursts
- Long GRBs, core collapse supernova?
- Short GRBs, compact binary inspirals?

Cosmology
- *Inflation era GWs*
- *Dark Energy / Matter*
- *Large scale structure formation*

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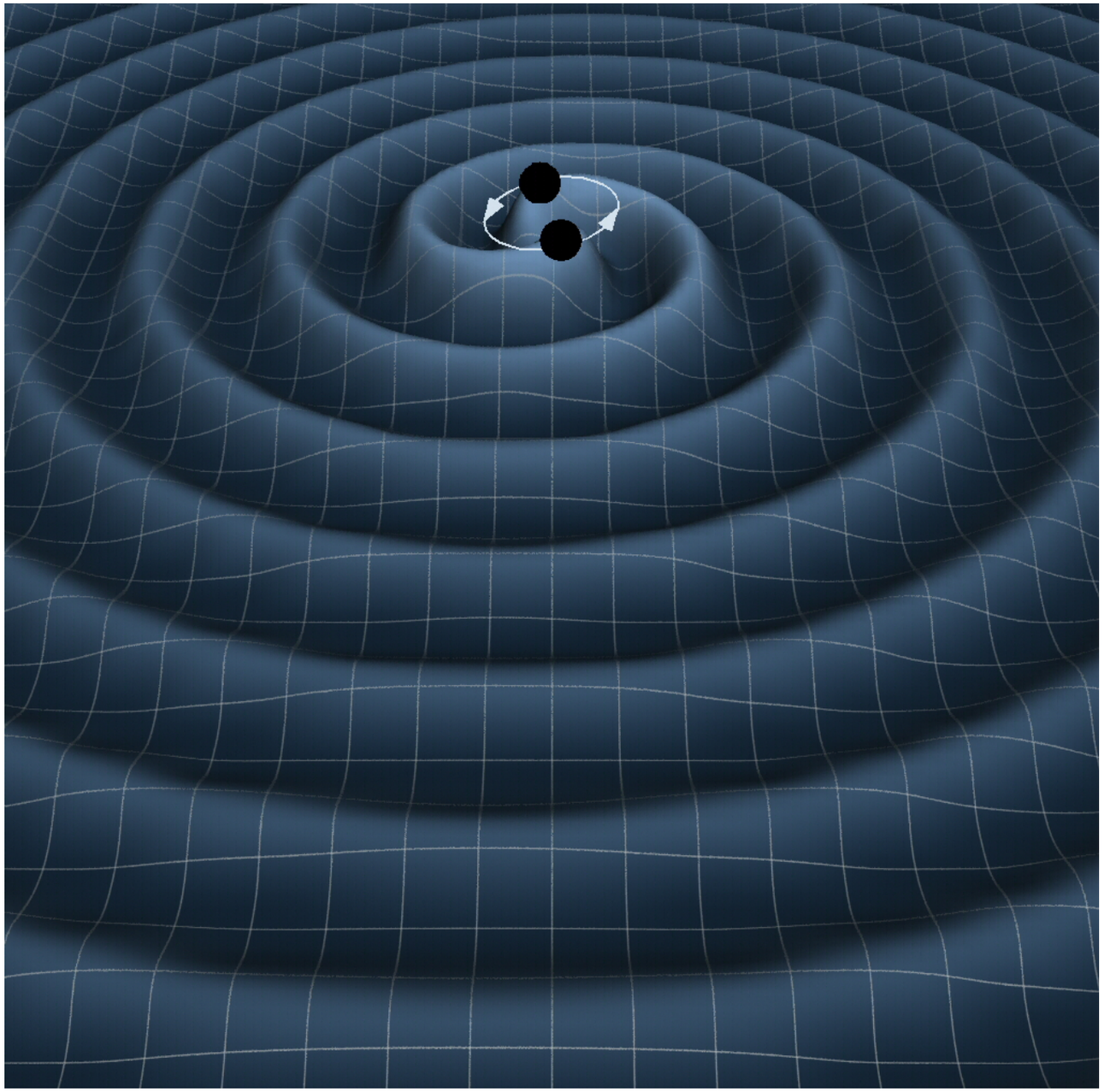
Directly observable with gravitational waves

Accessible with GW astronomy

GW generation



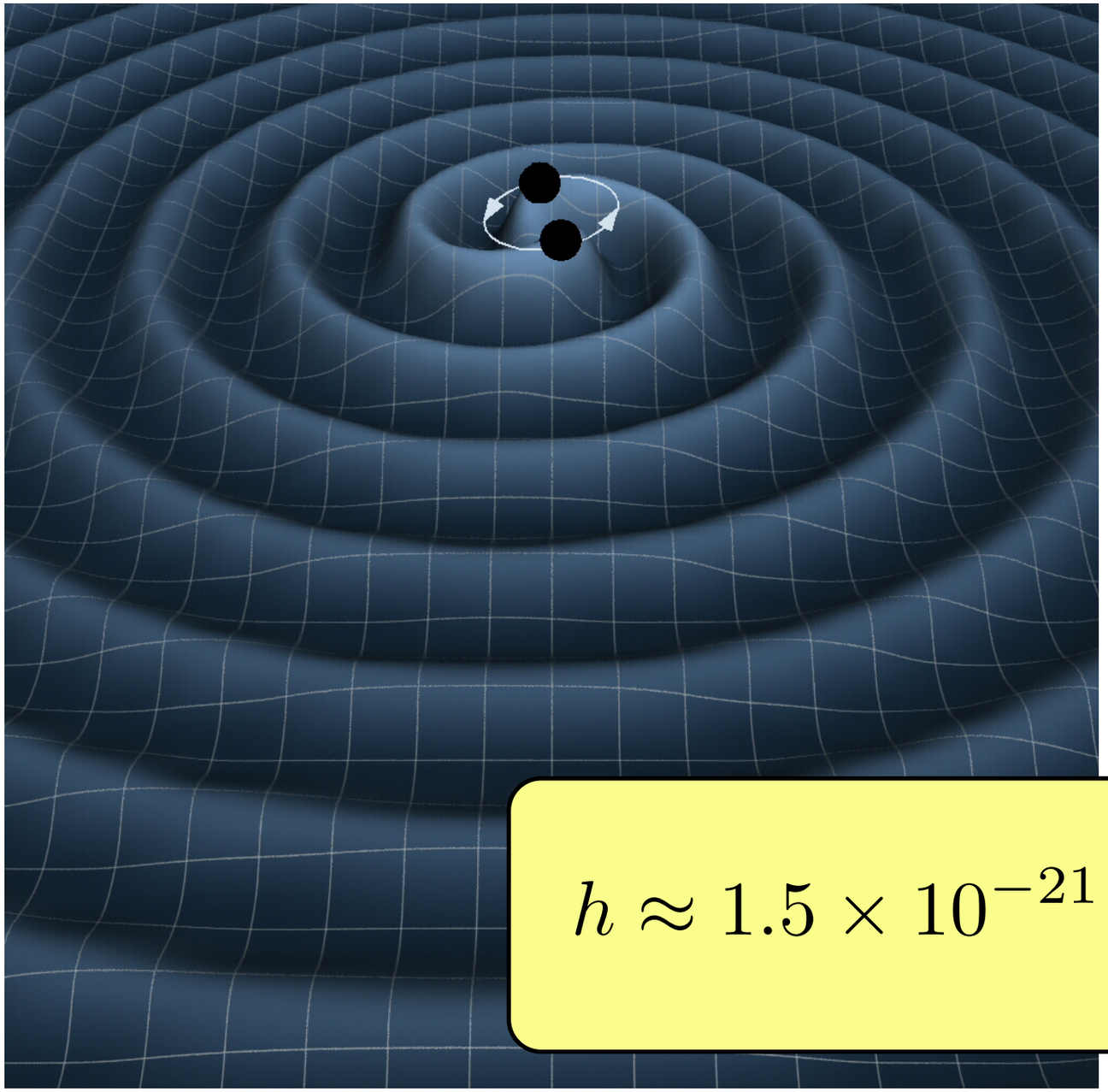
Observable as astrain:

$$h = \partial L / L$$

for a binary system:

$$h_{xx} = \frac{32\pi^2 G}{Rc^4} M r^2 f^2 \cos 4\pi f t$$

GW generation



Observable as astrain:

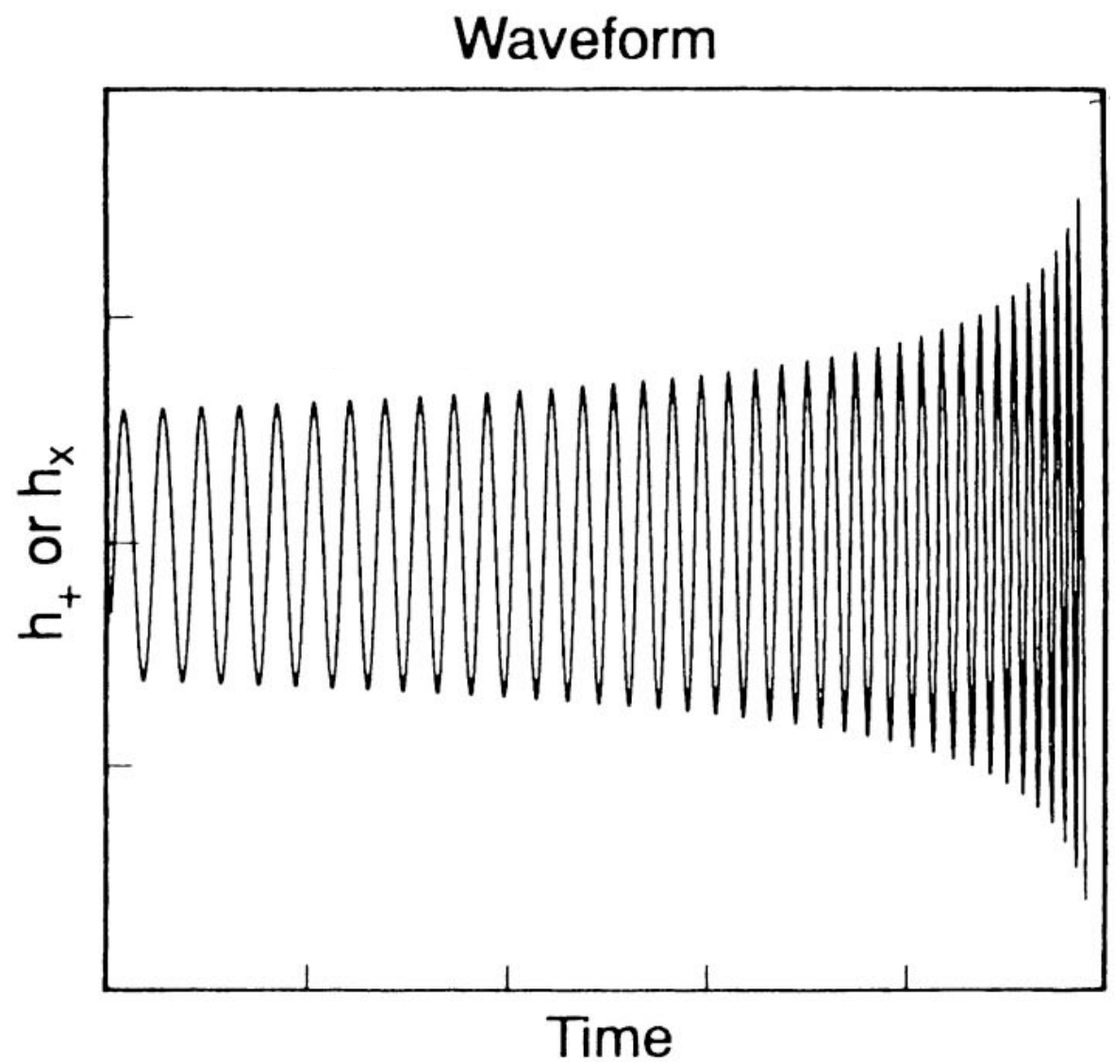
$$h = \partial L / L$$

for a binary system:

$$h_{xx} = \frac{32\pi^2 G}{Rc^4} M r^2 f^2 \cos 4\pi f t$$

$$h \approx 1.5 \times 10^{-21} \left[\frac{M}{1.4\ M_\odot}\right] \left[\frac{6\ r_S}{r}\right] \left[\frac{15\ Mpc}{R}\right]$$

GW generation

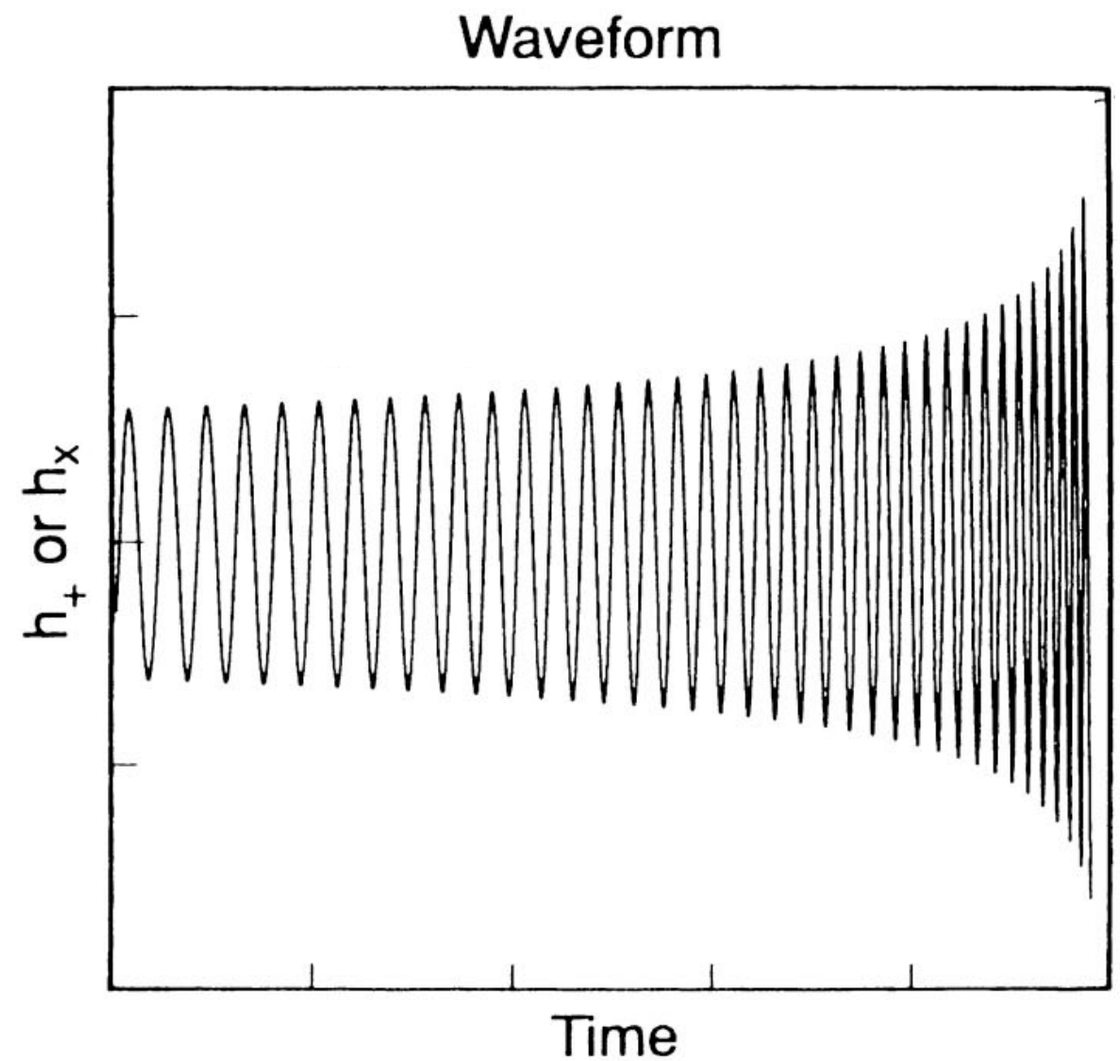


GW generation

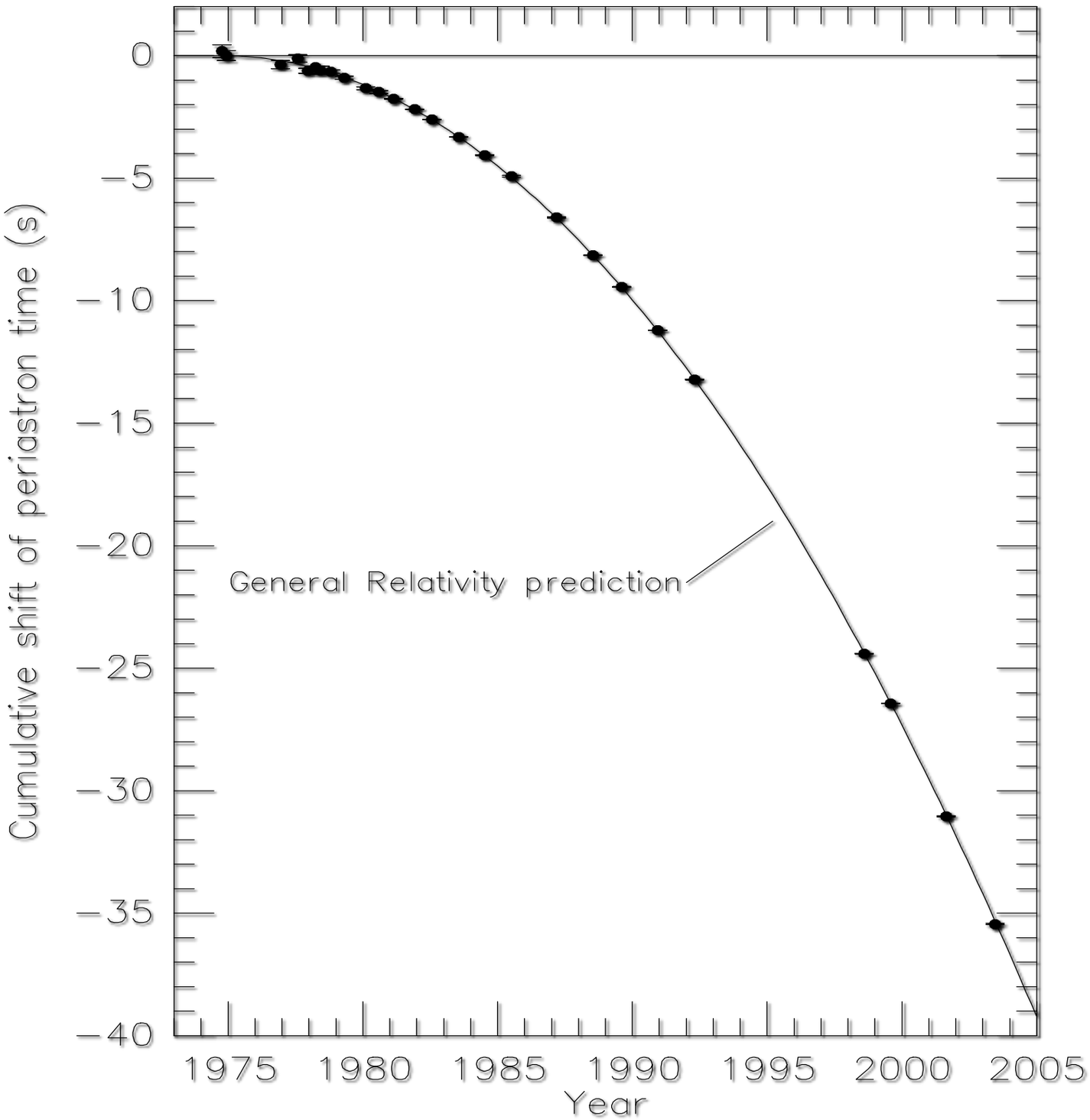
Quadrupole wave with two polarizations:

+ polarization

x polarization



PSR 1913+16



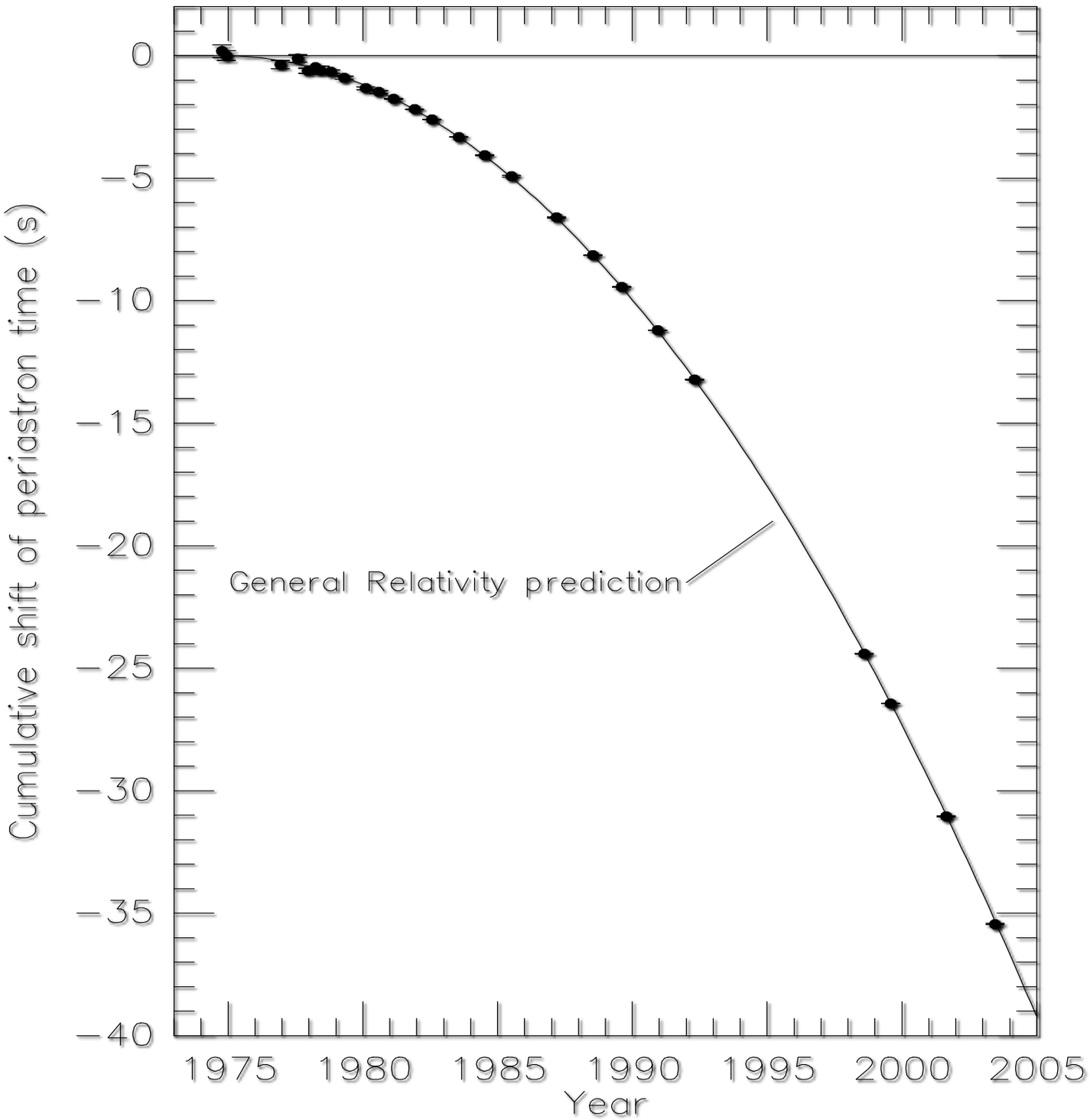
Weisberg, Taylor - ASP Conf. Series 2004

Binary NS system

- $m_1 \sim m_2 \sim 1.4\ M_\odot$
- $r = 1.6 \times 10^9$ m
- $T_{orbit} = 8$ hr
- 7.5 kpc from Earth

GR predicts periastron shift of -3mm/orbit

PSR 1913+16



Weisberg, Taylor - ASP Conf. Series 2004

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- $r = 1.6 \times 10^9$ m
- $T_{orbit} = 8$ hr
- 7.5 kpc from Earth

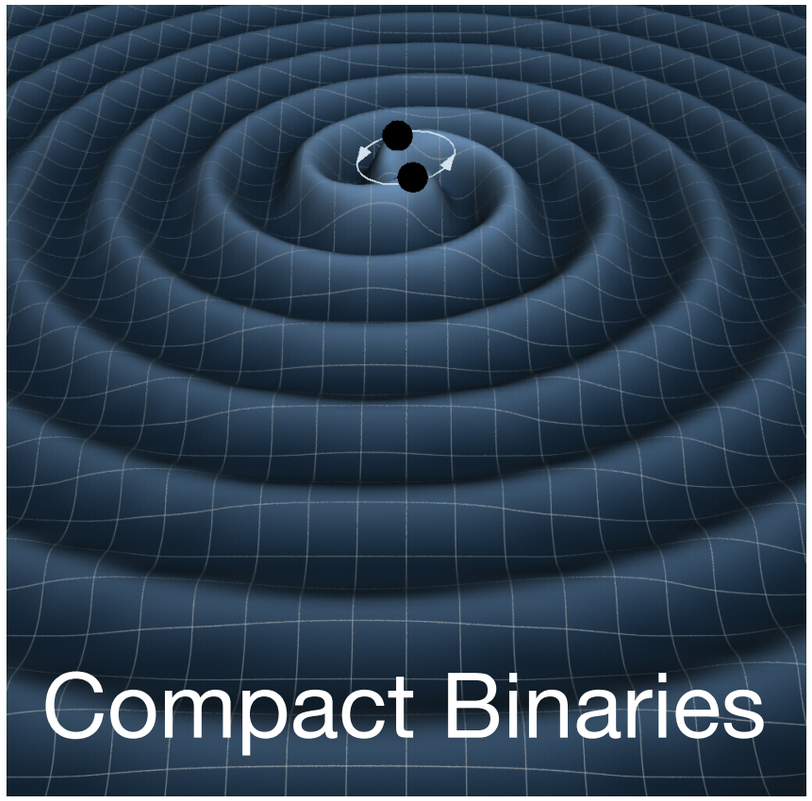
GR predicts periastron shift of -3mm/orbit

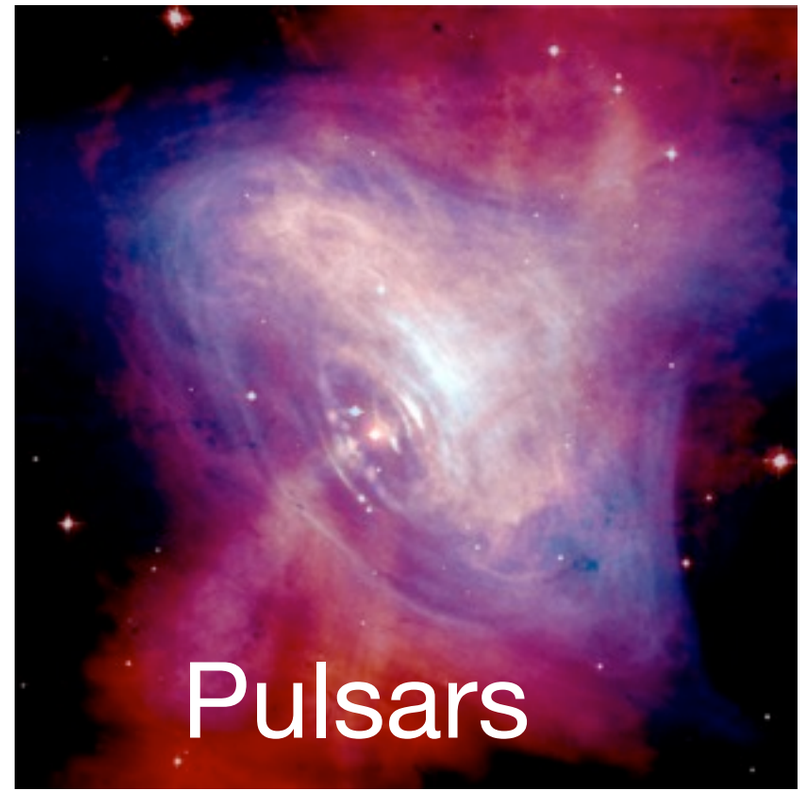
$$h_{now} = 5 \times 10^{-23}$$

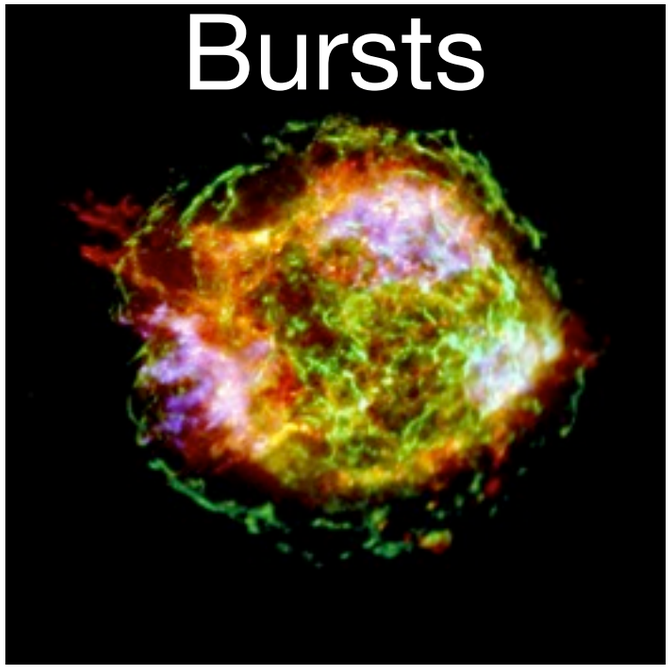
$$h_{isco} = 5 \times 10^{-18}$$

GW sources

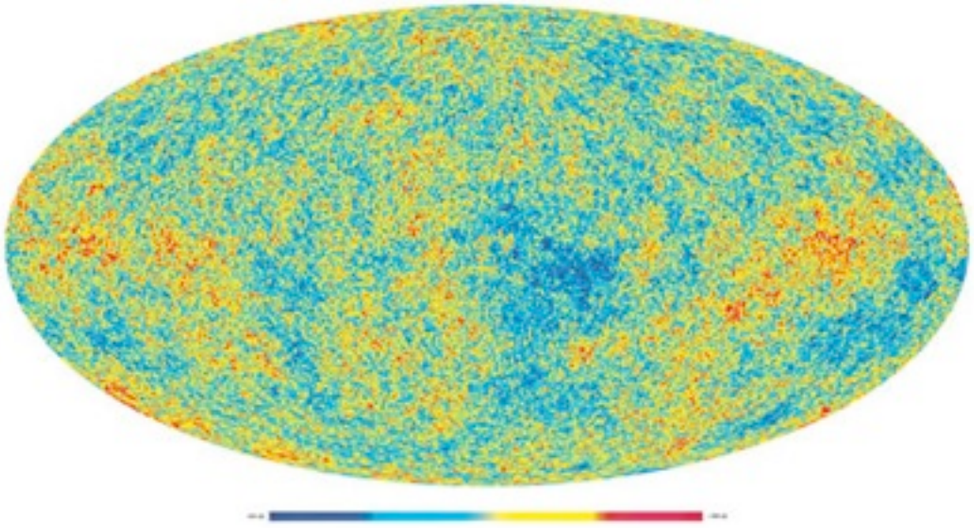
Coherence







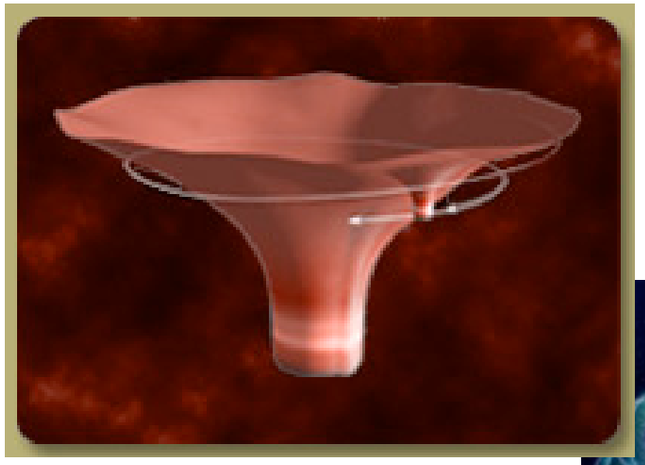
Stochastic

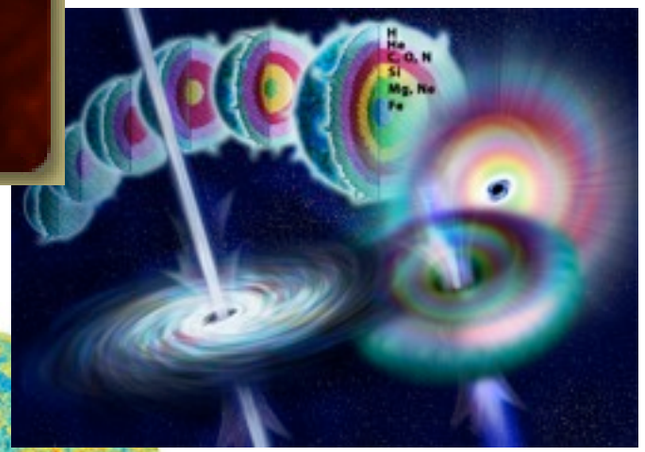


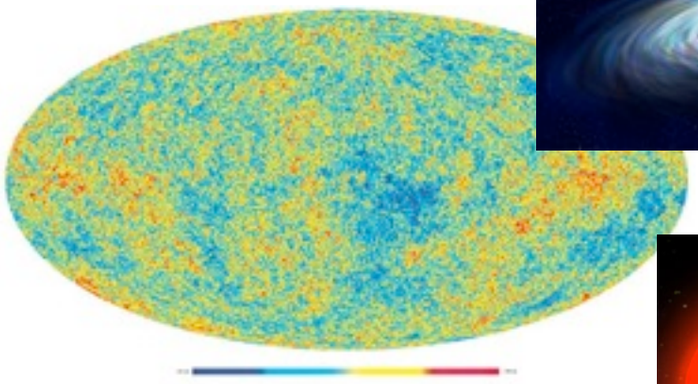
Duration

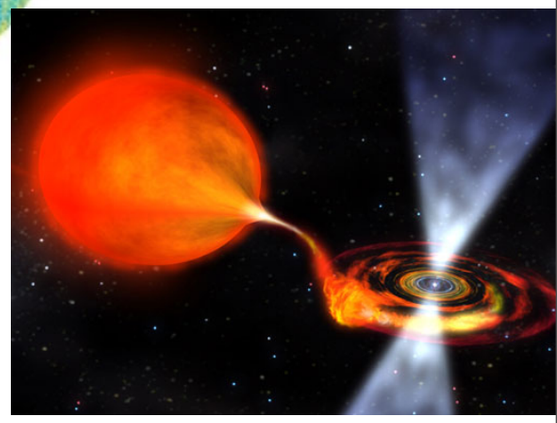
Einstein's messengers

- Strong-field GR
- Core collapse supernova
- z~1 standard candle
- Inflation era stochastic background
- Neutron star Equation of State
- No-hair theorem
- ...

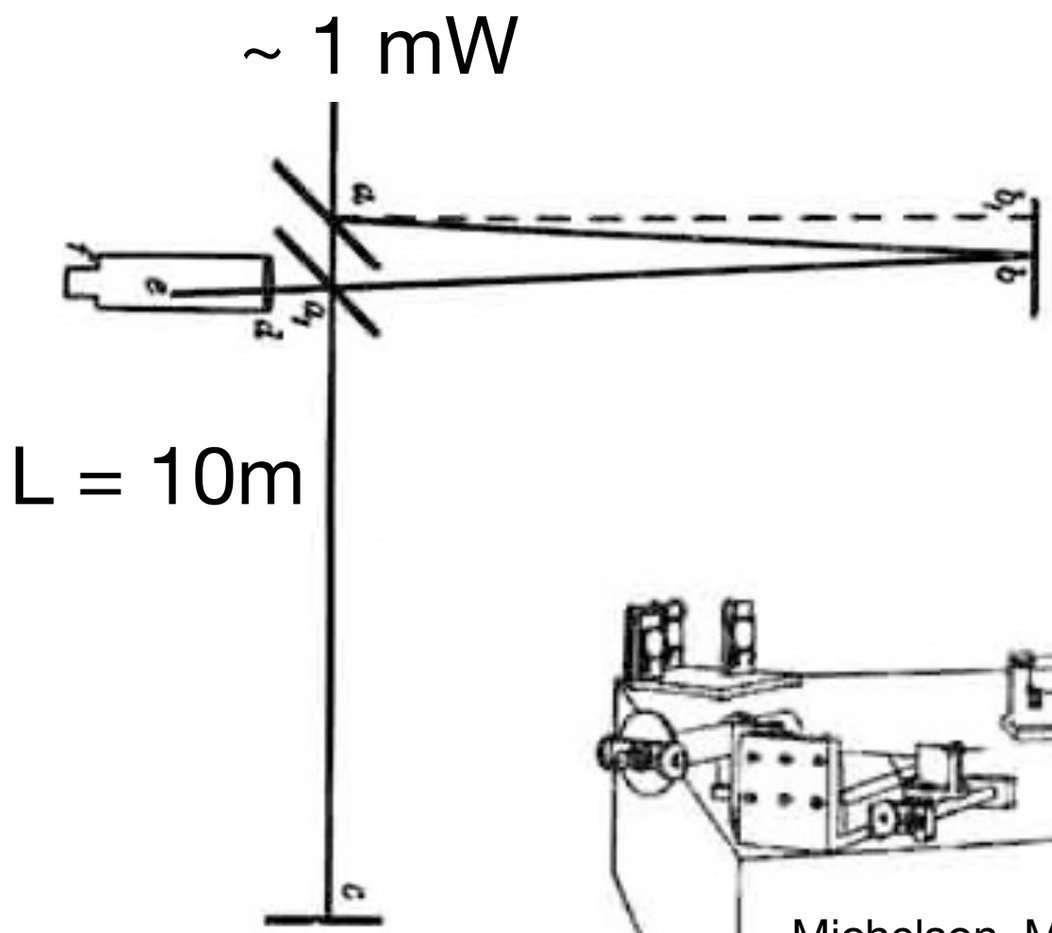


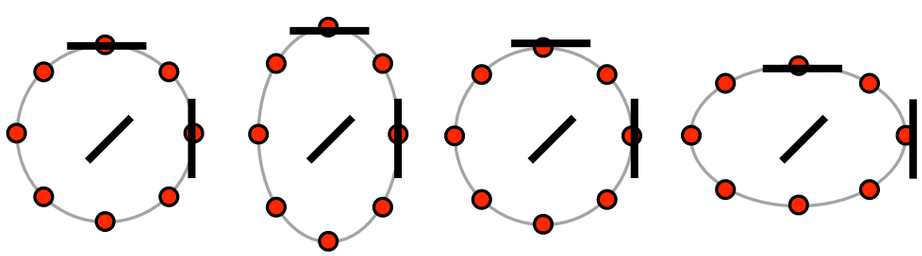


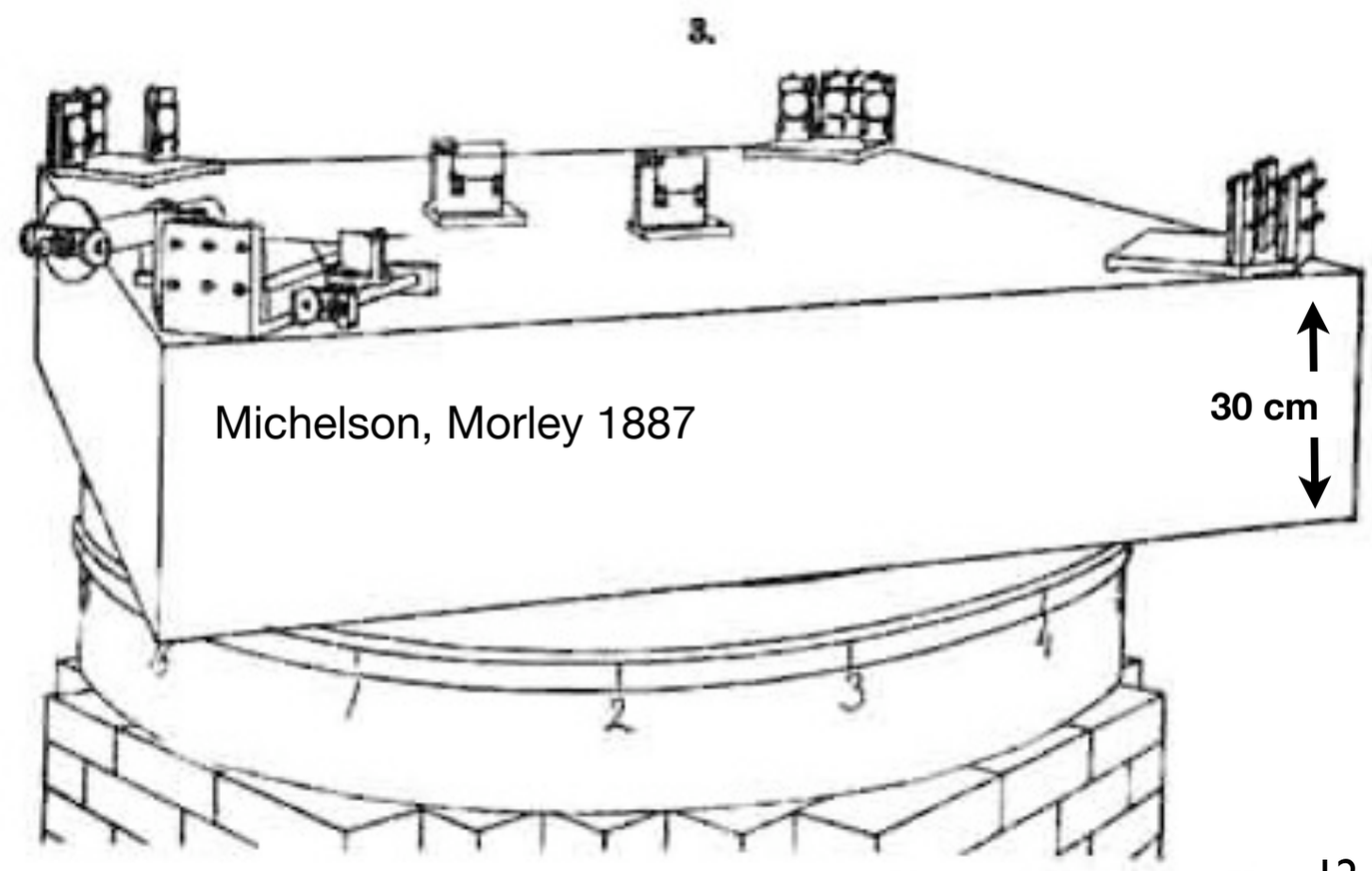




LIGO 0.01





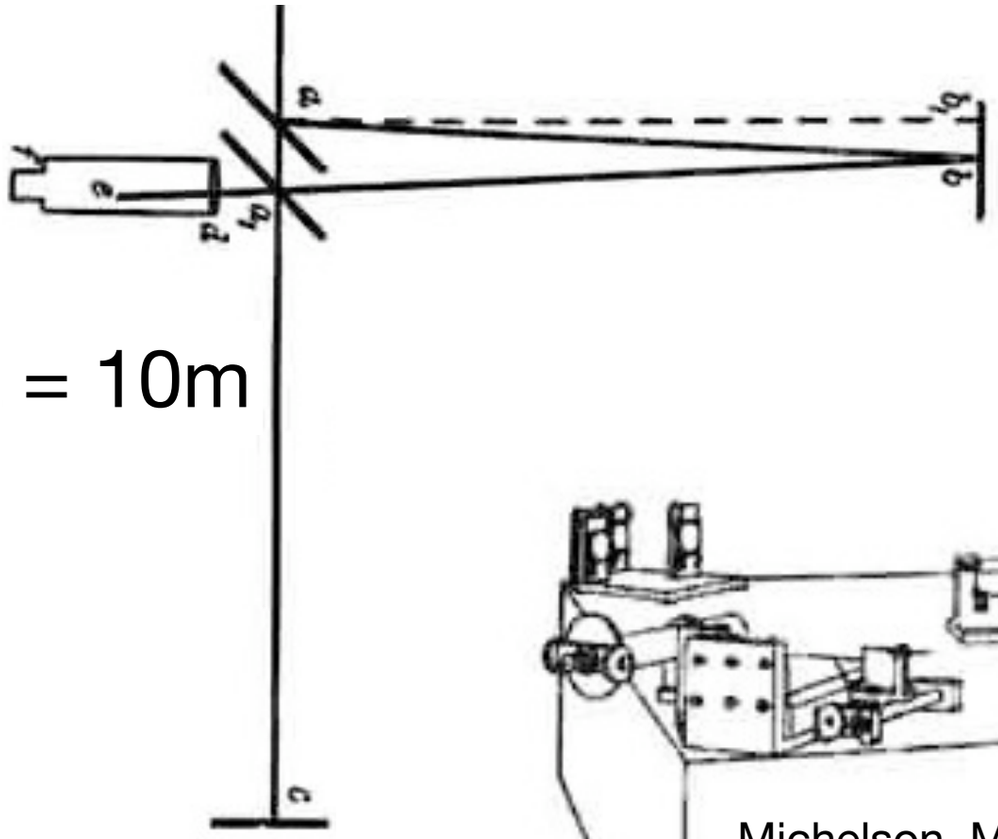


LIGO 0.01

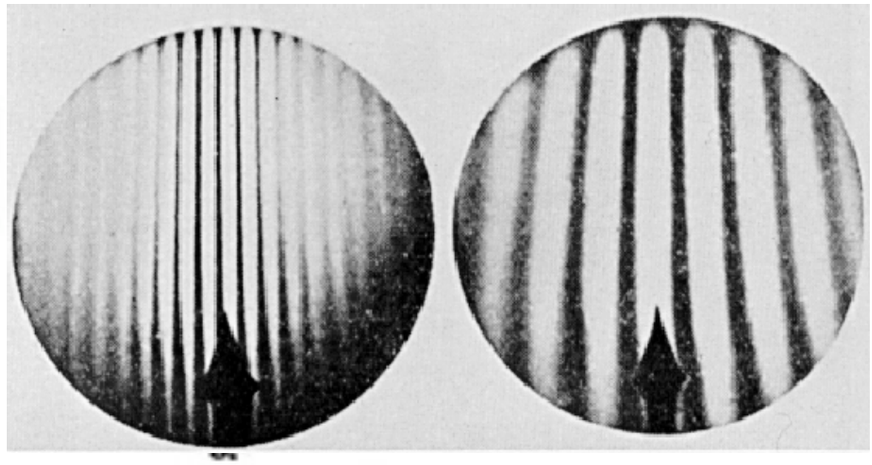
First GW detector
$dx/x \sim 5 \times 10^{-10}$

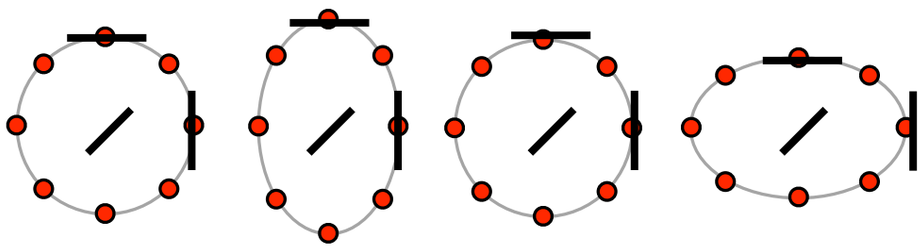
"0.01 λ = 5 nm"

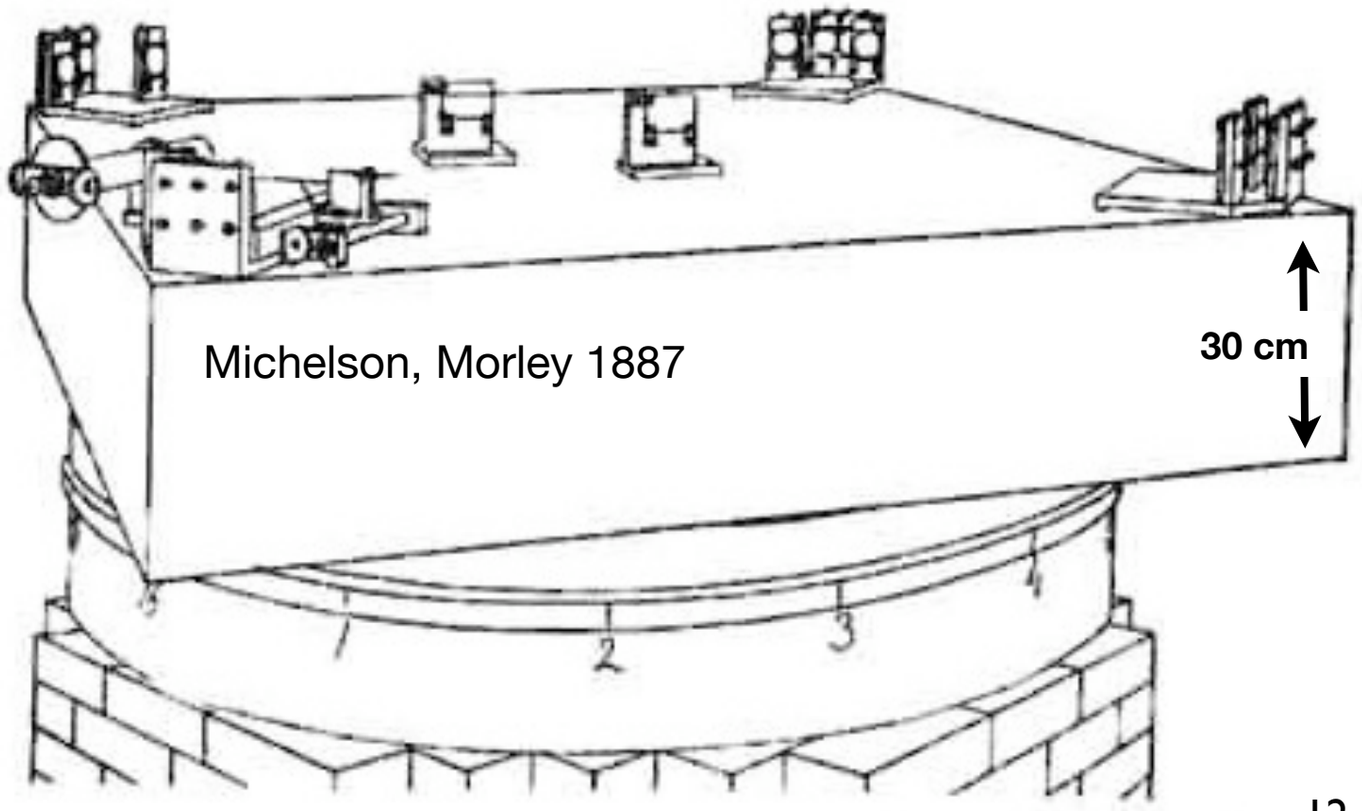
~ 1 mW



L = 10m



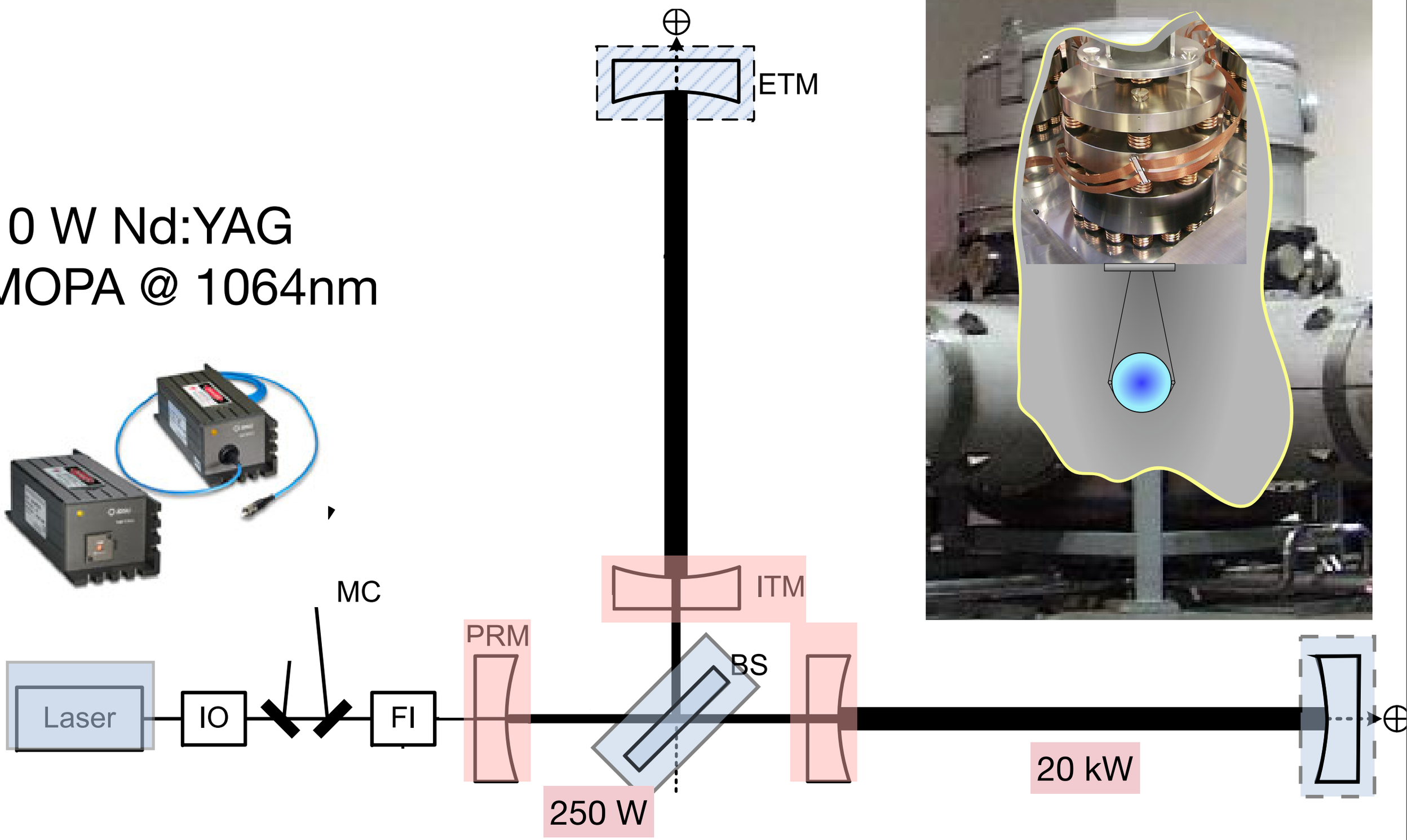




LIGO detectors

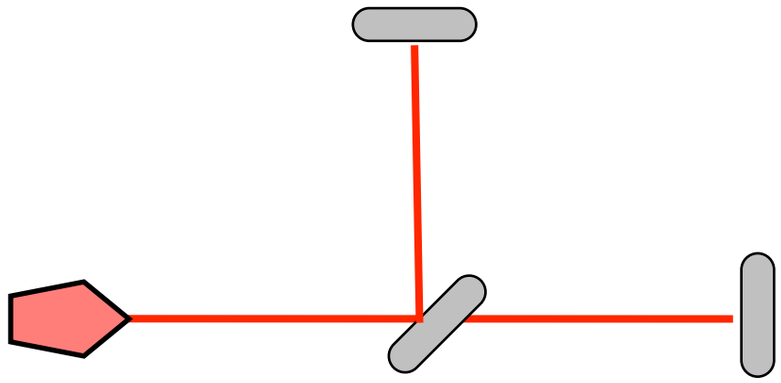
Initial LIGO

10 W Nd:YAG
MOPA @ 1064nm



21st century Interferometers

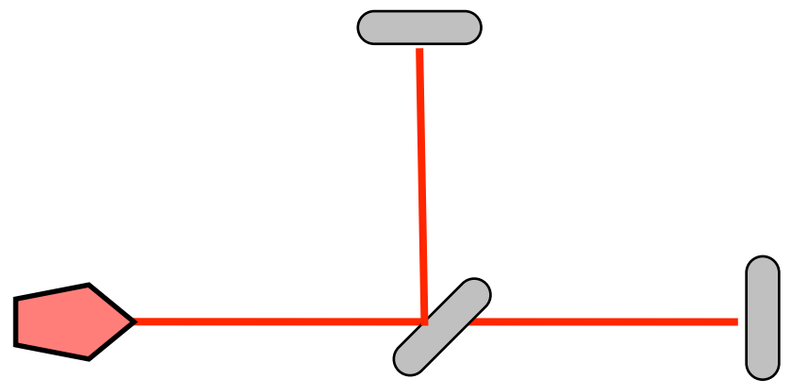
Shot noise limited Michelson



$$dx = \sqrt{\frac{\hbar\, c\, \lambda}{16\pi P\, \tau}}$$

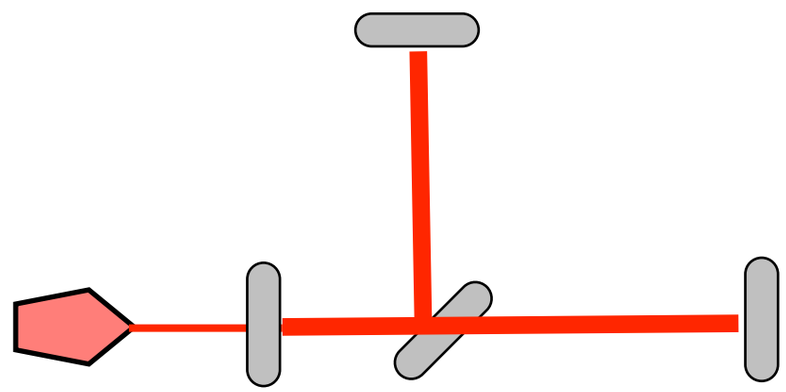
21st century Interferometers

Shot noise limited Michelson



$$dx = \sqrt{\frac{\hbar\, c\, \lambda}{16\pi P\, \tau}}$$

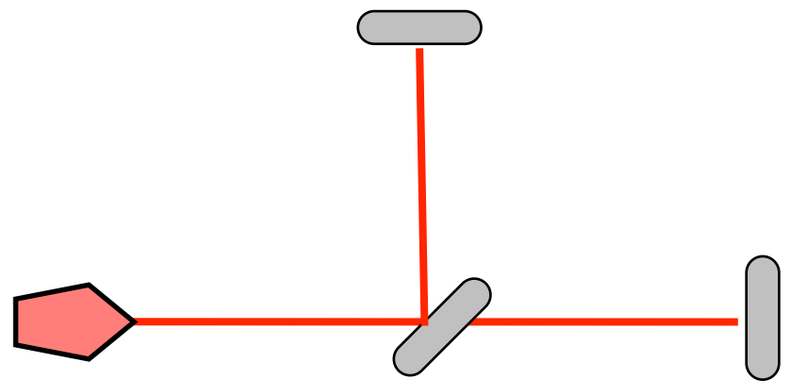
Power recycled Michelson



$$dx = \sqrt{\frac{\hbar\, c\, \lambda}{16\pi P\, \tau}\frac{1}{g_r}}$$

21st century Interferometers

Shot noise limited Michelson



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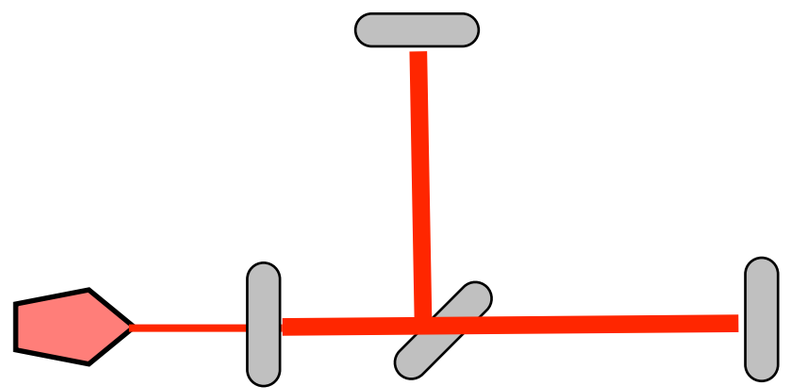
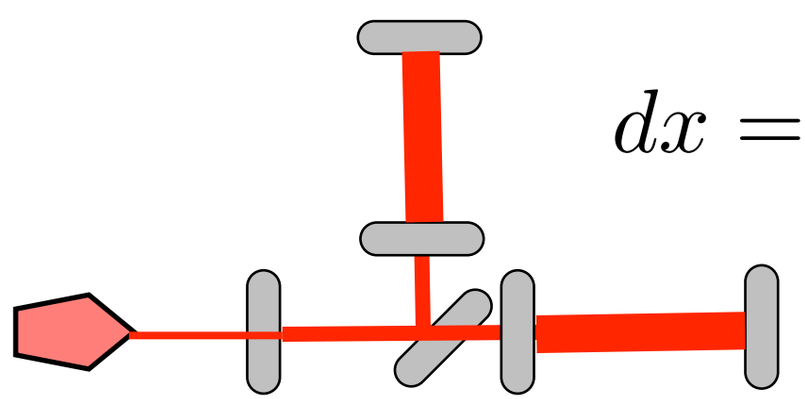
Power recycled Michelson



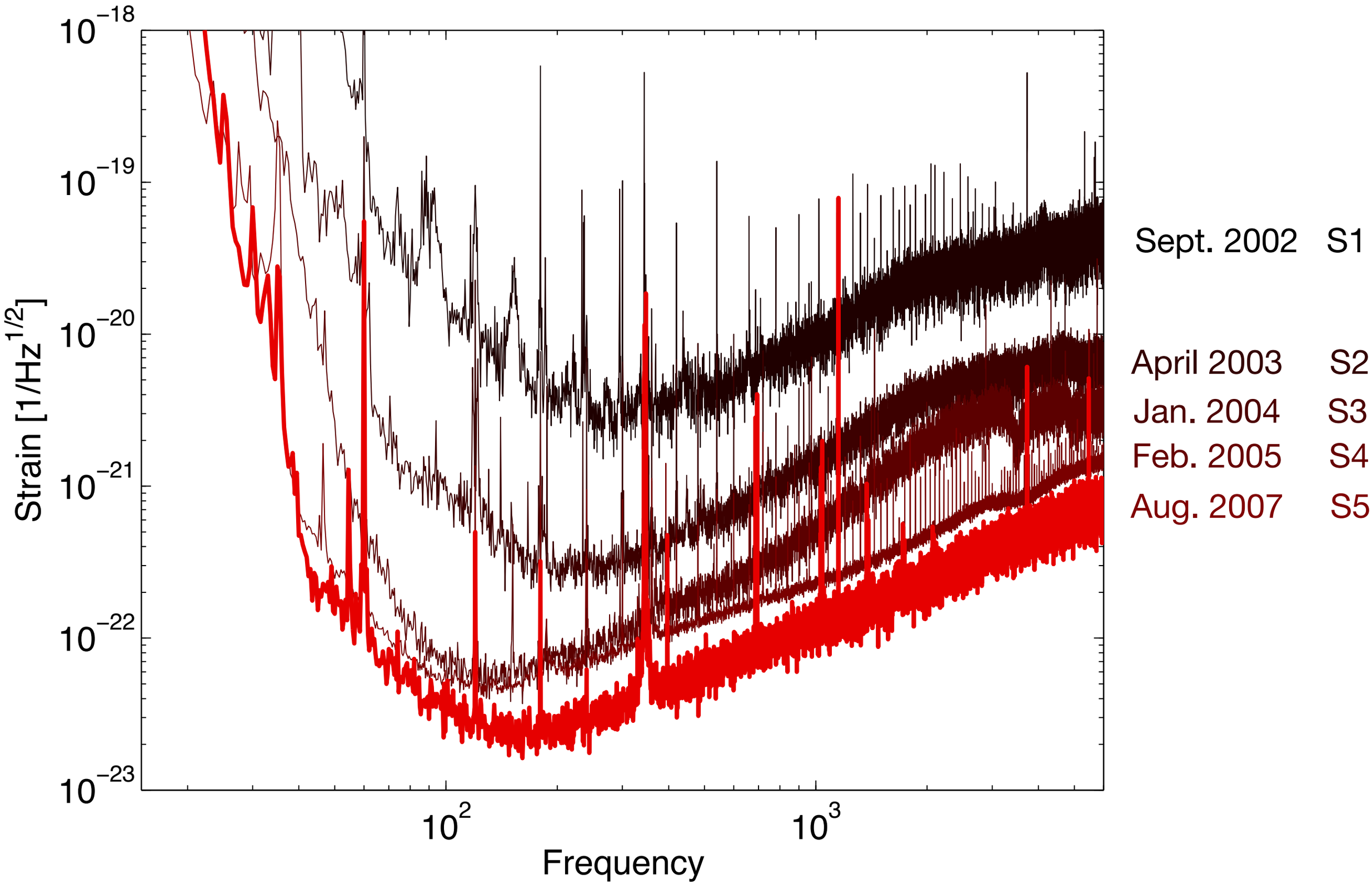
$$dx = \sqrt{\frac{\hbar\, c\, \lambda}{16\pi P\, \tau}\frac{1}{g_r}}$$

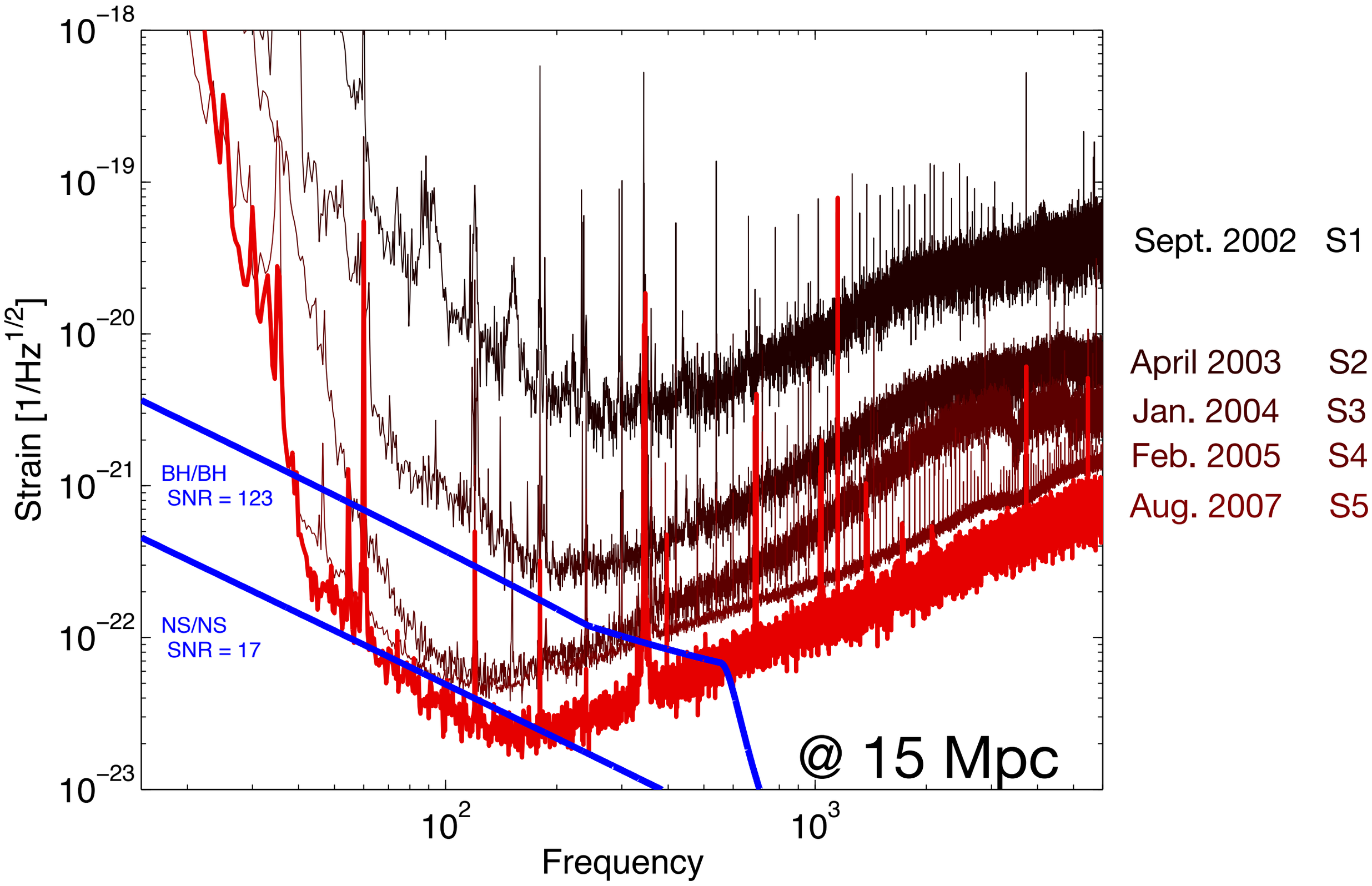
Power recycled Fabry-Perot Michelson



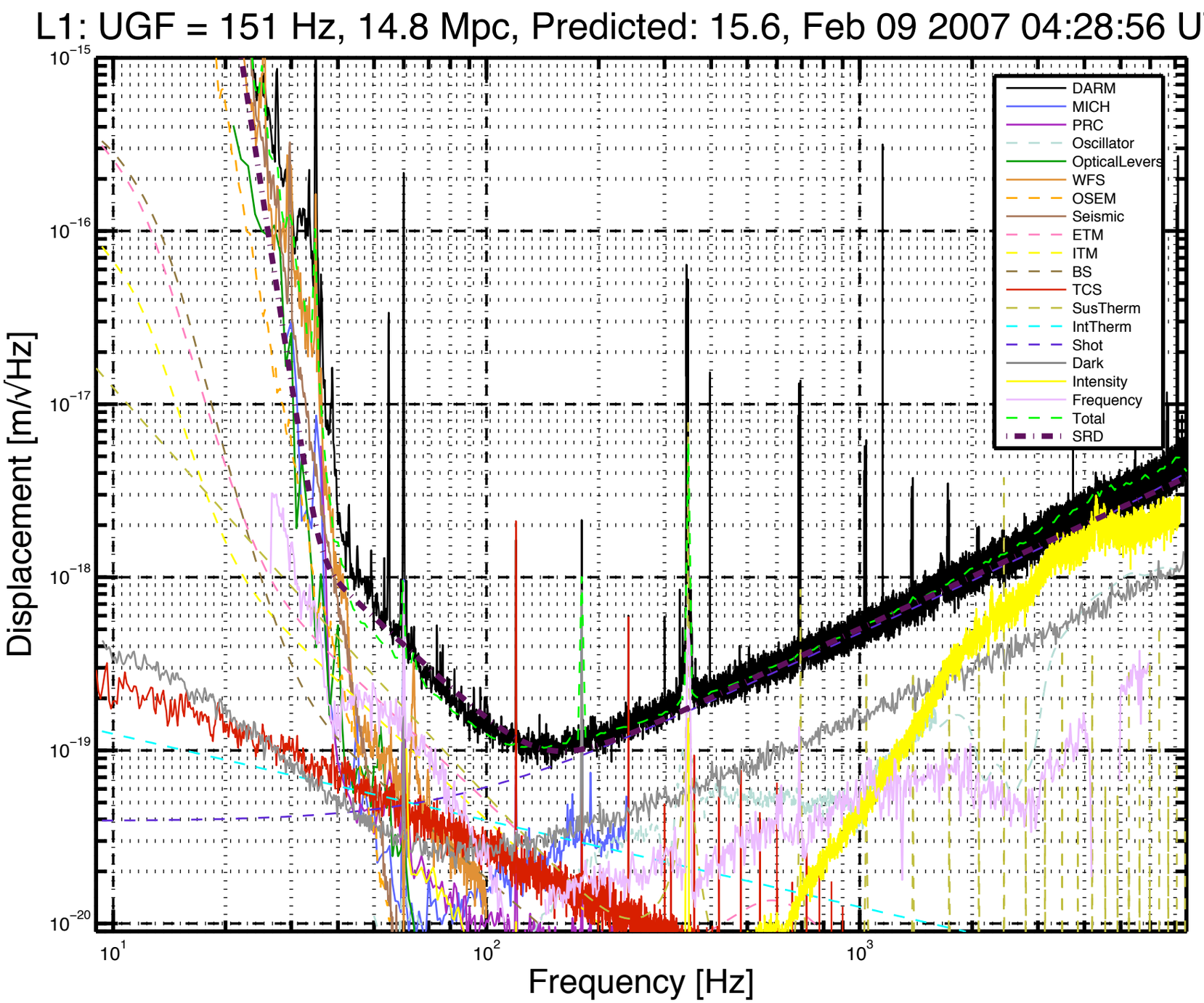
$$dx = \sqrt{\frac{\hbar\, c\, \lambda}{16\pi P\, \tau}\frac{|1 + i f / f_{cav}|^2}{g_{cav} g_r}}$$

Initial LIGO




Strain [1/Hz^1/2]
10^−18
10^−19
10^−20
10^−21
10^−22
10^−23
10^2
10^3
Frequency
BH/BH
SNR = 123
NS/NS
SNR = 17
@ 15 Mpc
Sept. 2002 S1
April 2003 S2
Jan. 2004 S3
Feb. 2005 S4
Aug. 2007 S5

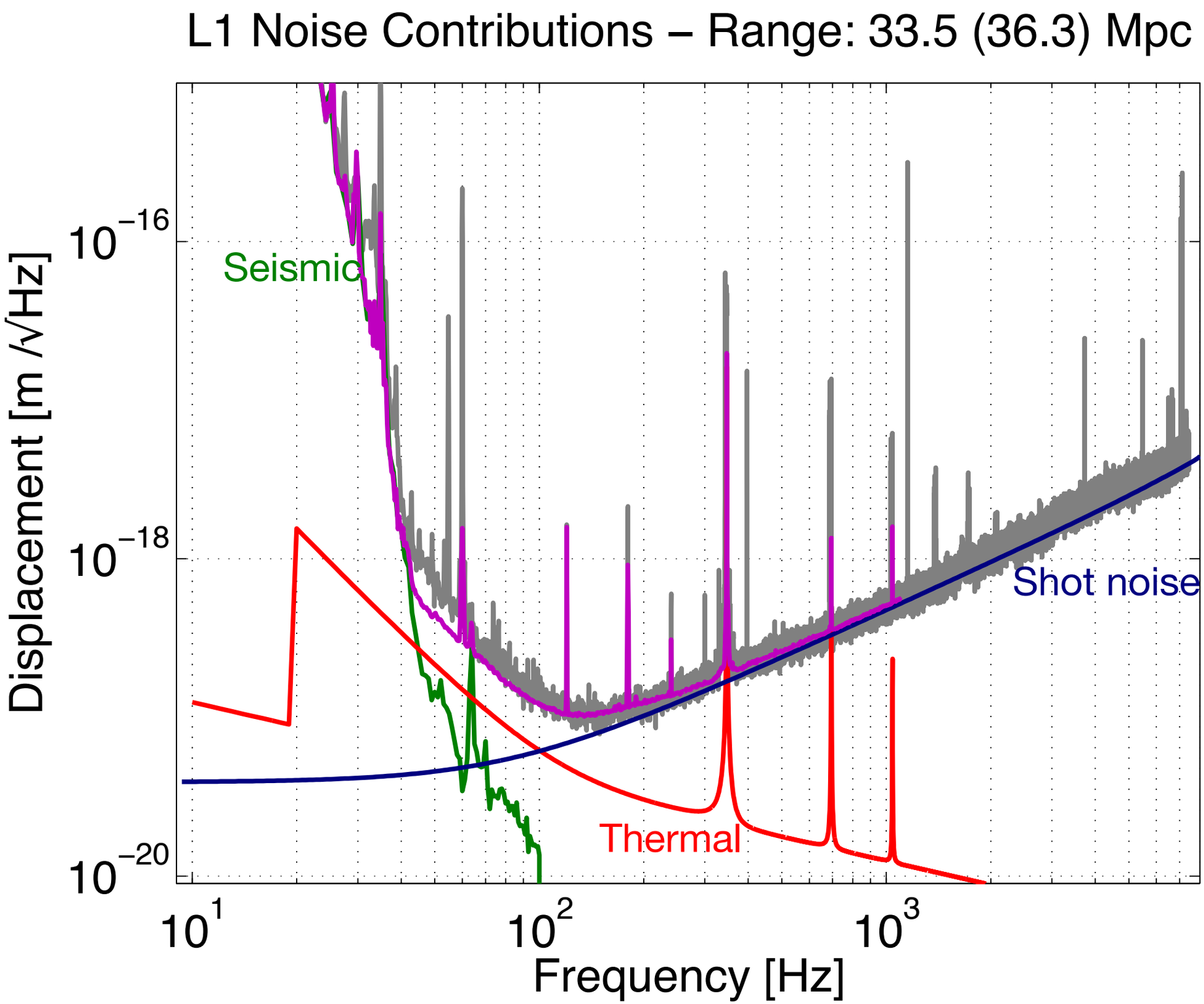
Noise Budget



injection/response measurements of 17 noise couplings to test mass displacement

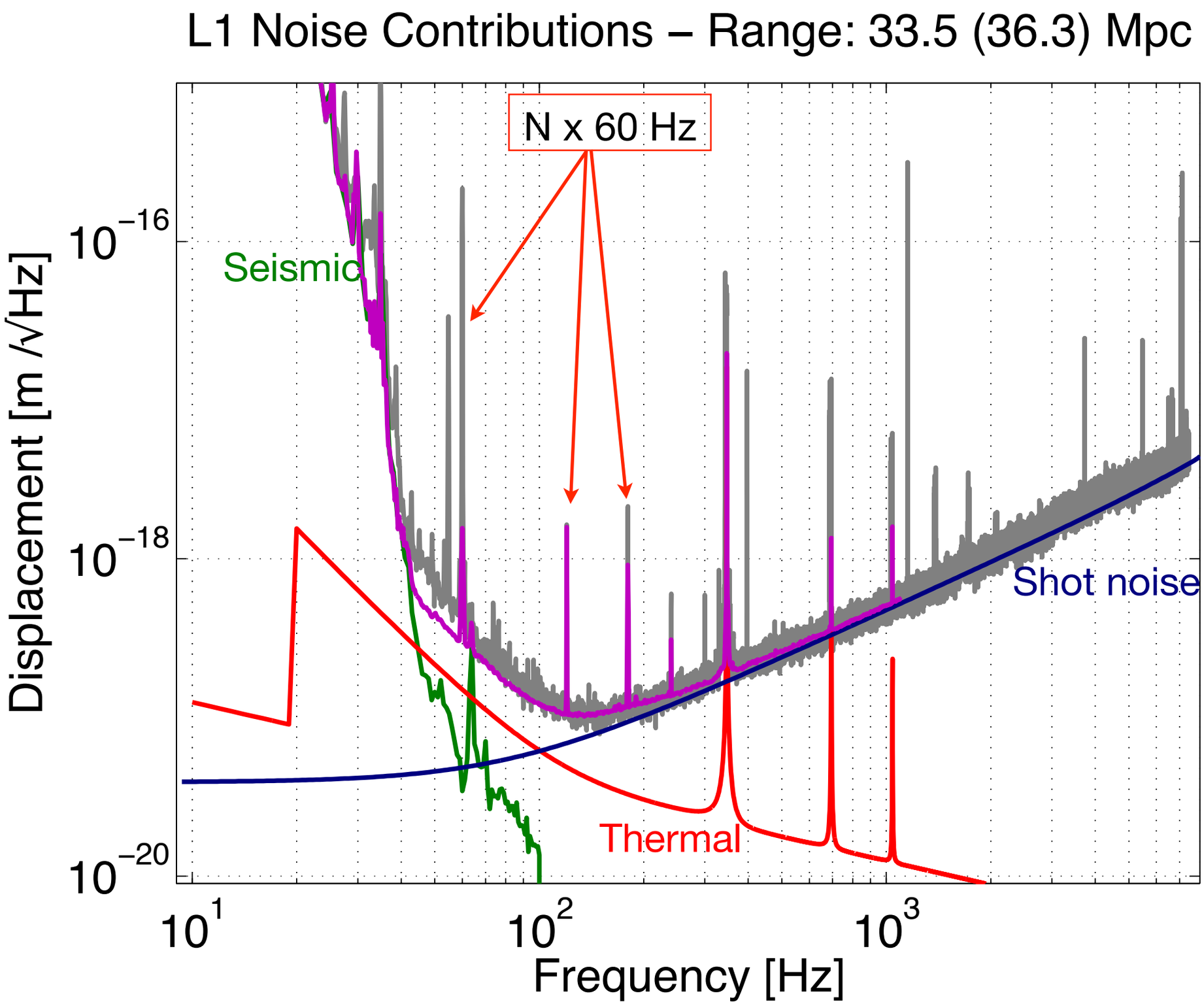
SJW, R Adhikari, V. Mandic, K Kawabe, V. Frolov, J. Smith et al.

Noise Budget

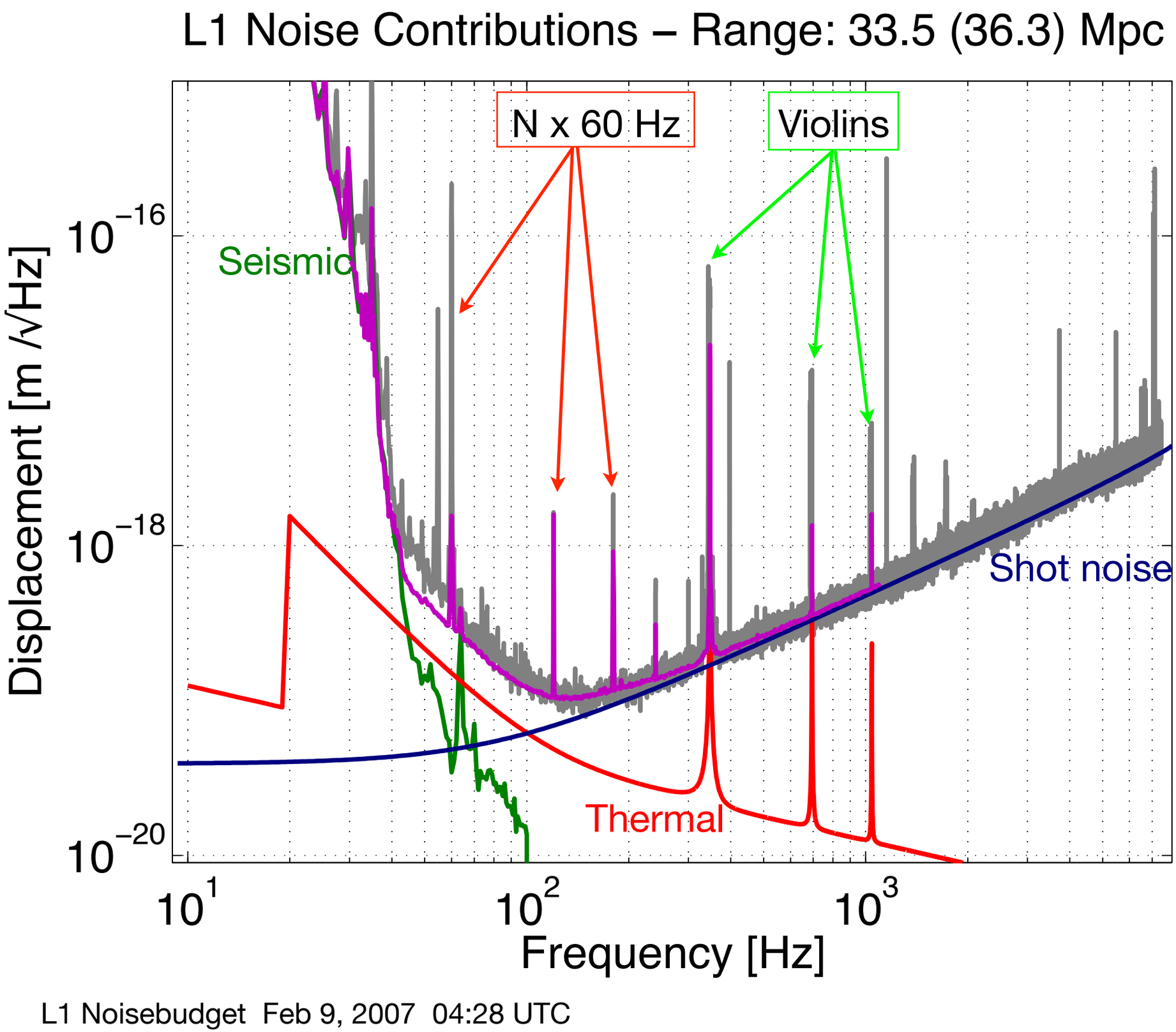


L1 Noisebudget Feb 9, 2007 04:28 UTC

Noise Budget

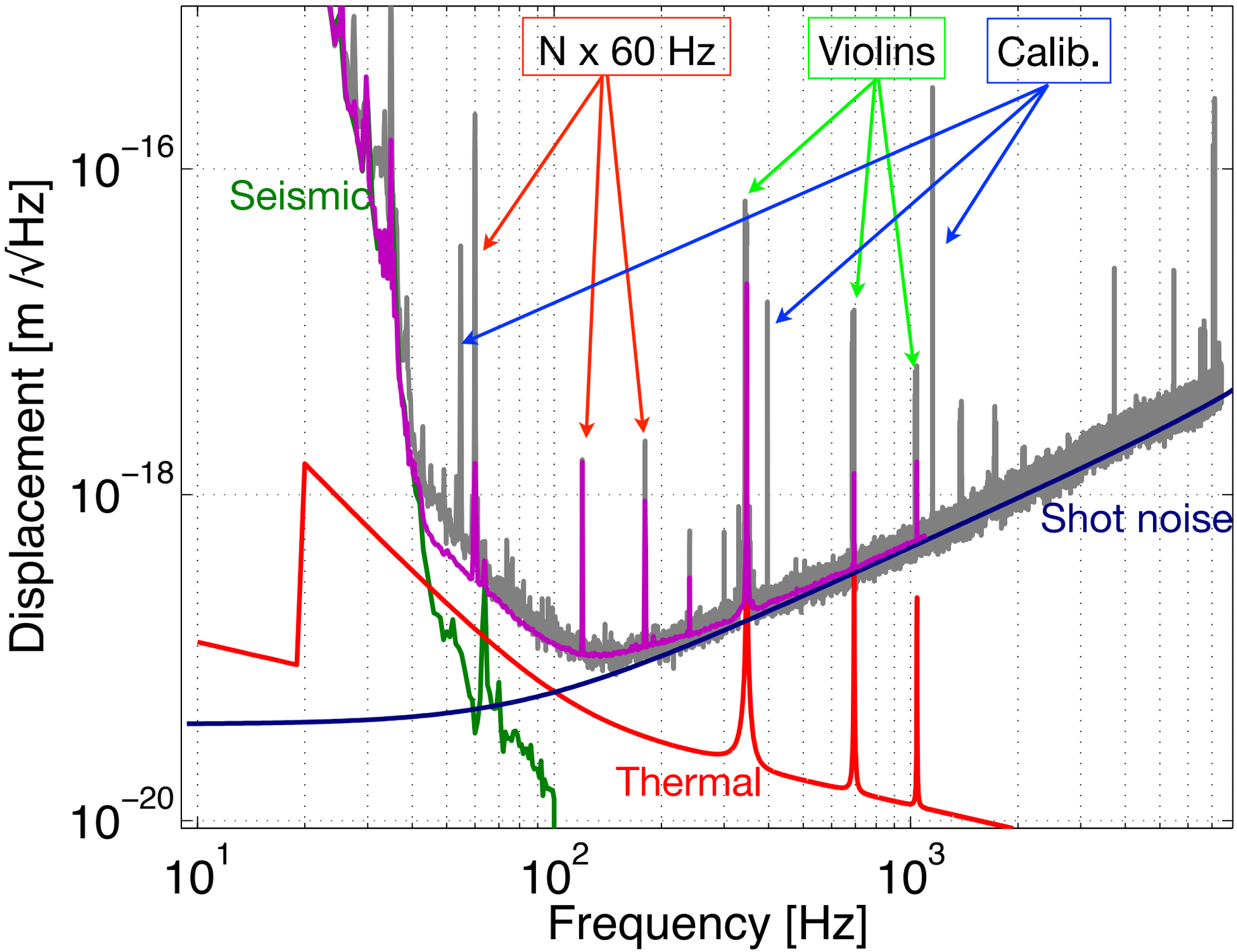


Noise Budget



Noise Budget

L1 Noise Contributions – Range: 33.5 (36.3) Mpc



L1 Noisebudget Feb 9, 2007 04:28 UTC

Noise Budget

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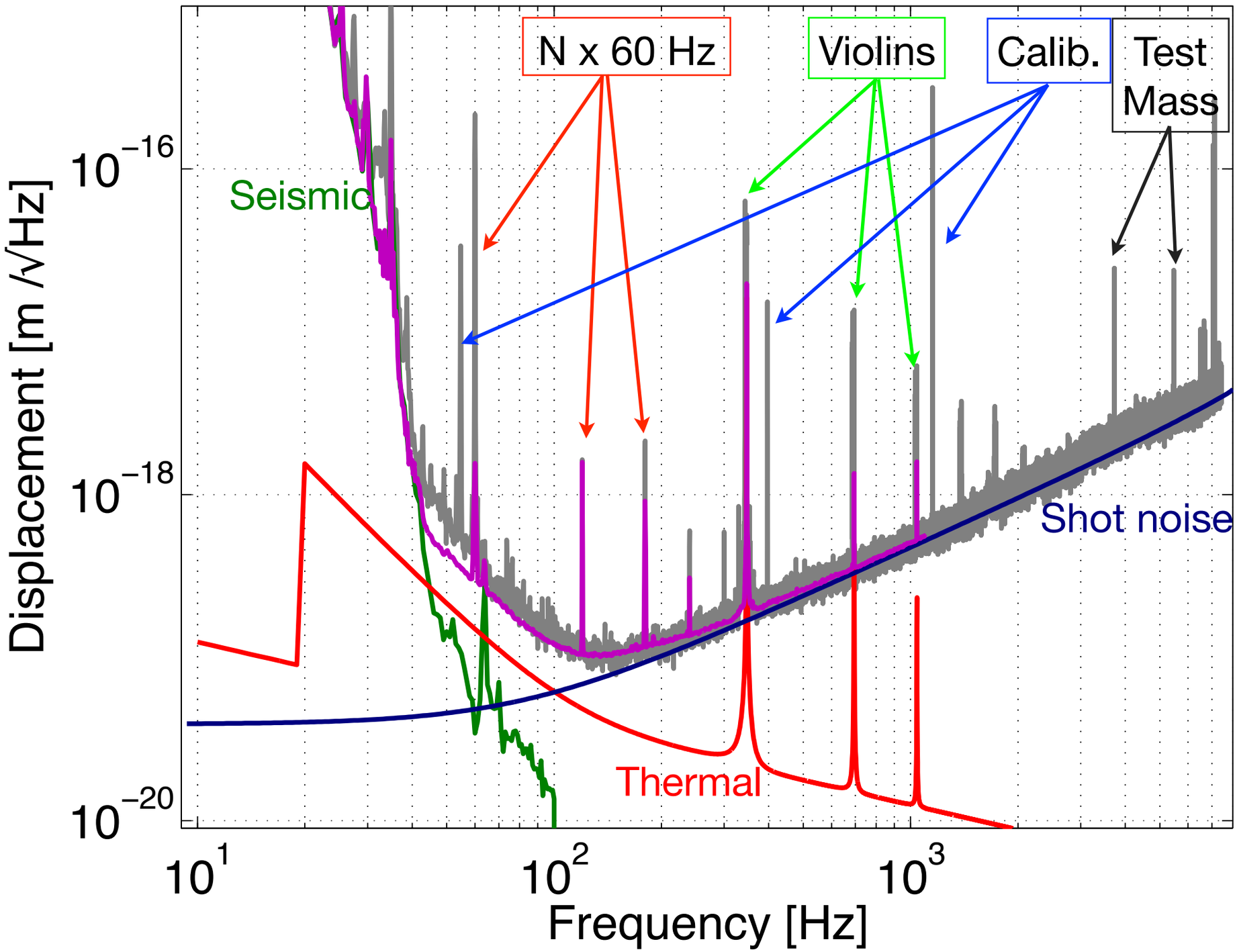
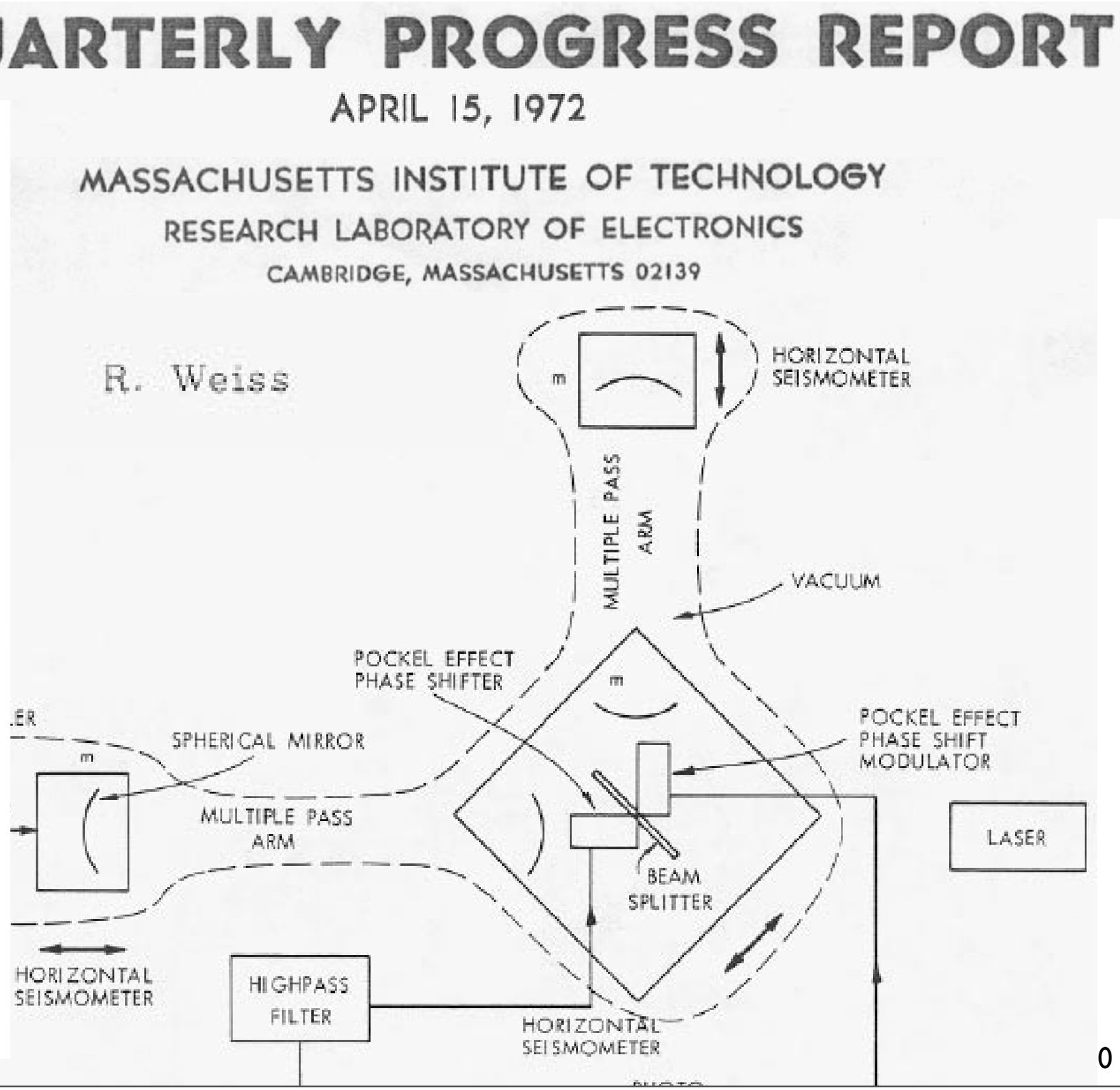


L1 Noisebudget Feb 9, 2007 04:28 UTC

Historical Aside

Noise sources

a. Laser amplitude
b. Laser phase
c. Mechanical thermal
d. Radiation pressure
e. Seismic
f. Thermal gradient
g. Cosmic ray
h. Gravitational gradient
i. Electric/Magnetic field



Rates

Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors
Classical and Quantum Gravity 27 (2010) 173001

	NS-NS	NS-BH	BH-BH
Rate ($\mathrm{MWEG}^{-1}\ \mathrm{yr}^{-1}$)	$100\,^{1000}_{1}$	$3\,^{100}_{0.05}$	$0.4\,^{30}_{0.01}$

Rates

Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors
Classical and Quantum Gravity 27 (2010) 173001

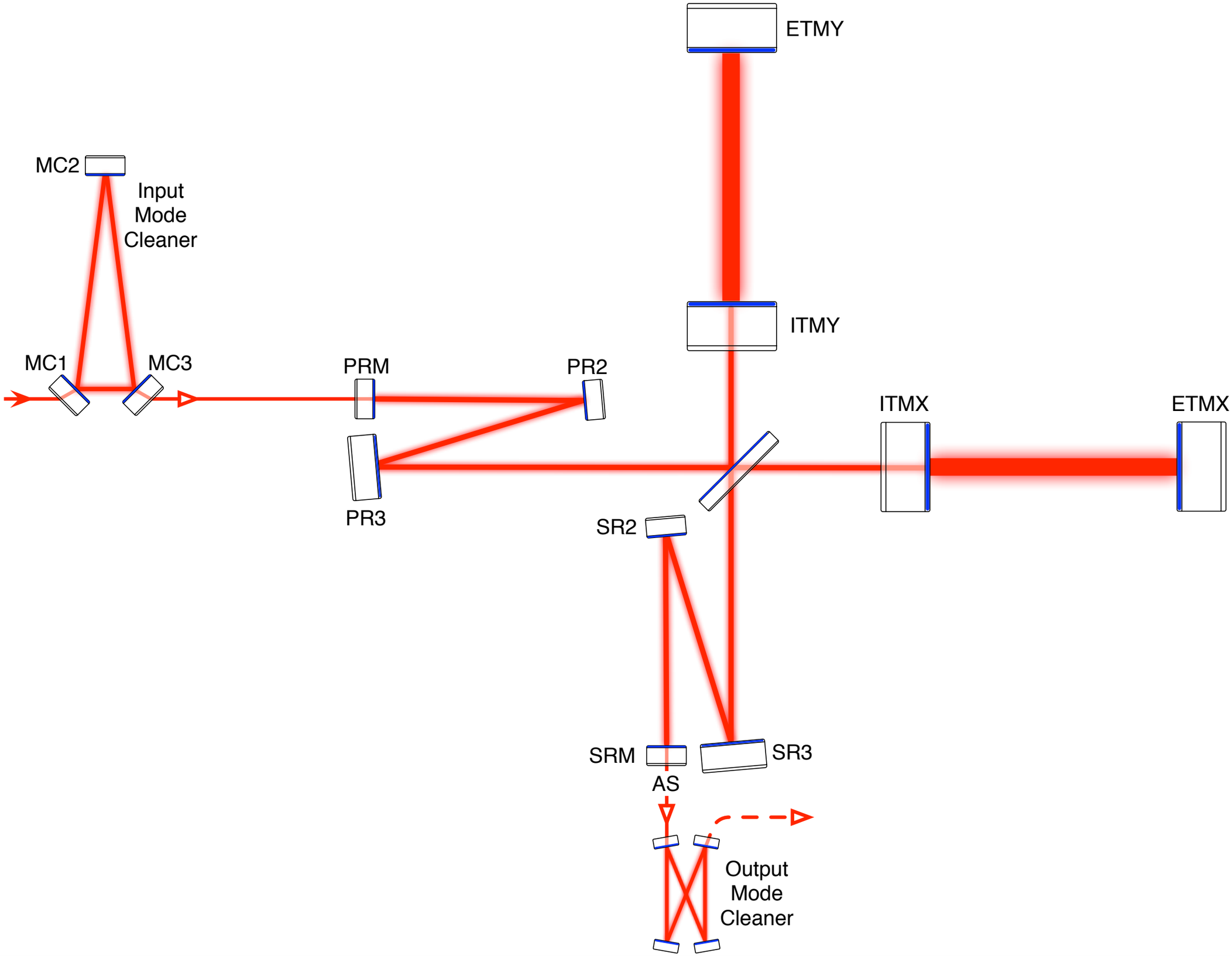
	NS-NS	NS-BH	BH-BH
Rate ($\mathrm{MWEG^{-1}\ yr^{-1}}$)	$100\,^{1000}_{1}$	$3\,^{100}_{0.05}$	$0.4\,^{30}_{0.01}$
iLIGO ($\mathrm{yr^{-1}}$)	$0.02\,^{0.2}_{2\times10^{-4}}$	$0.004\,^{0.1}_{7\times10^{-5}}$	$0.007\,^{0.5}_{2\times10^{-4}}$

Initial LIGO

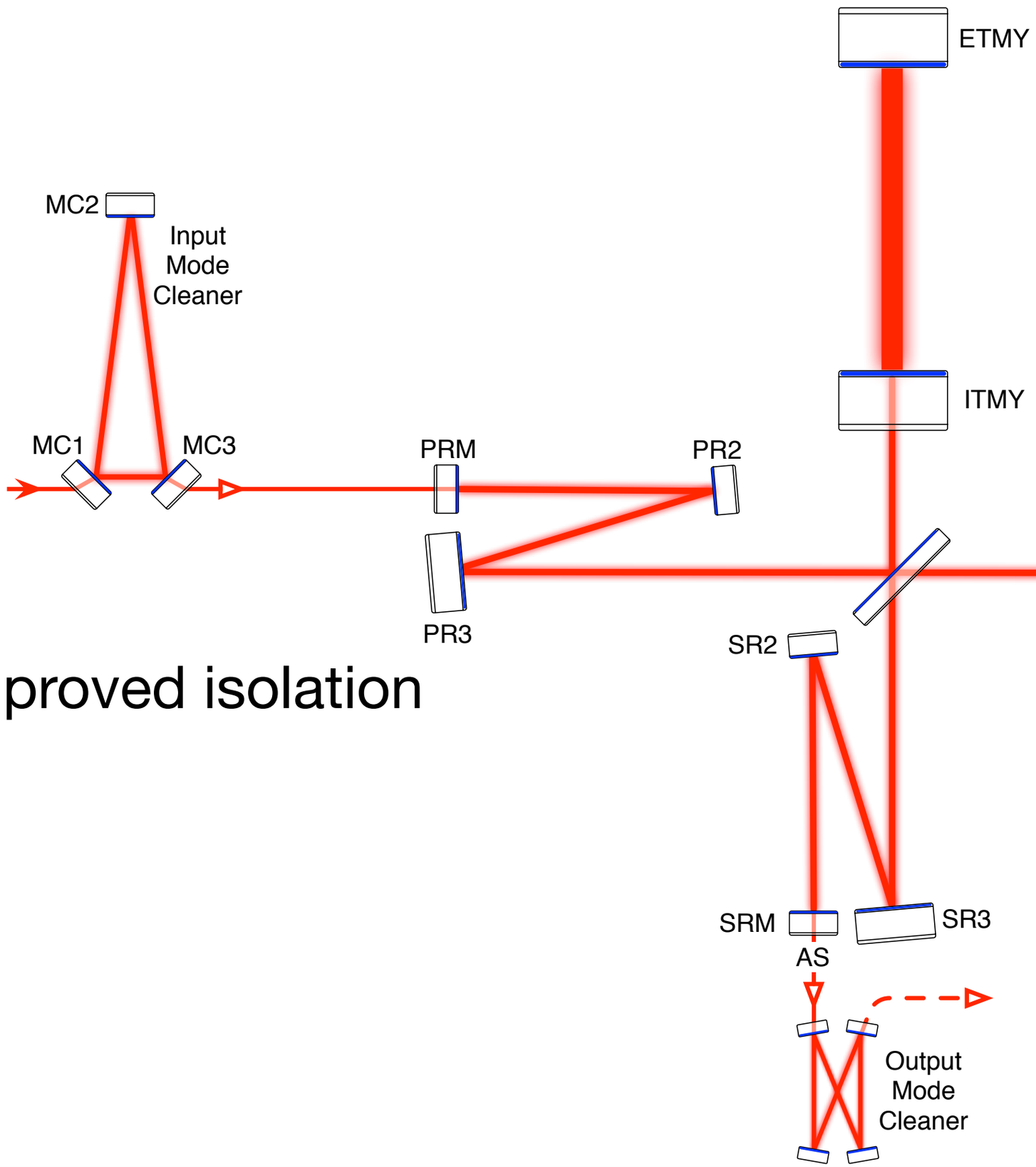
Advanced LIGO

Applied LIGO

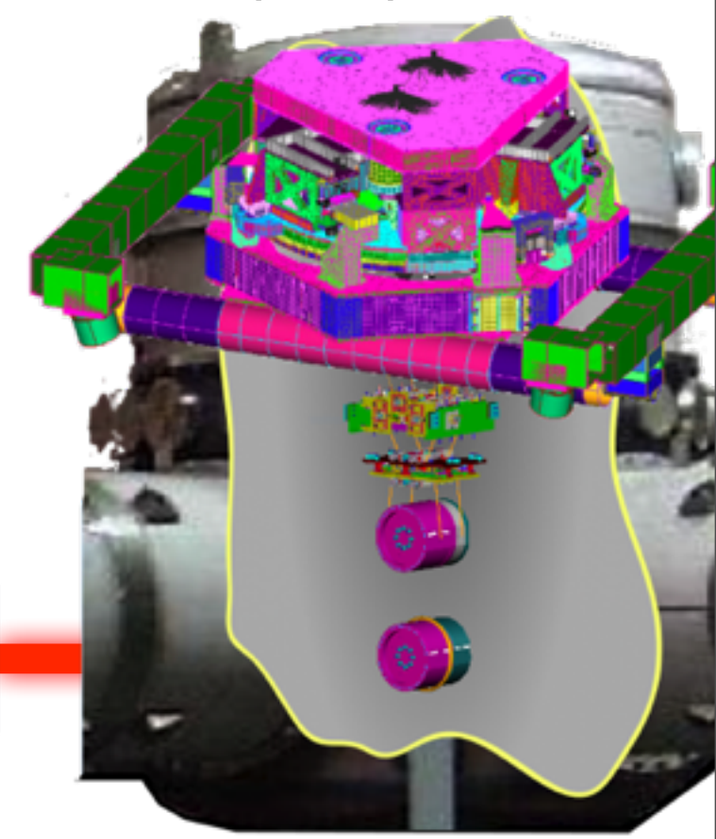
Advanced LIGO



Advanced LIGO

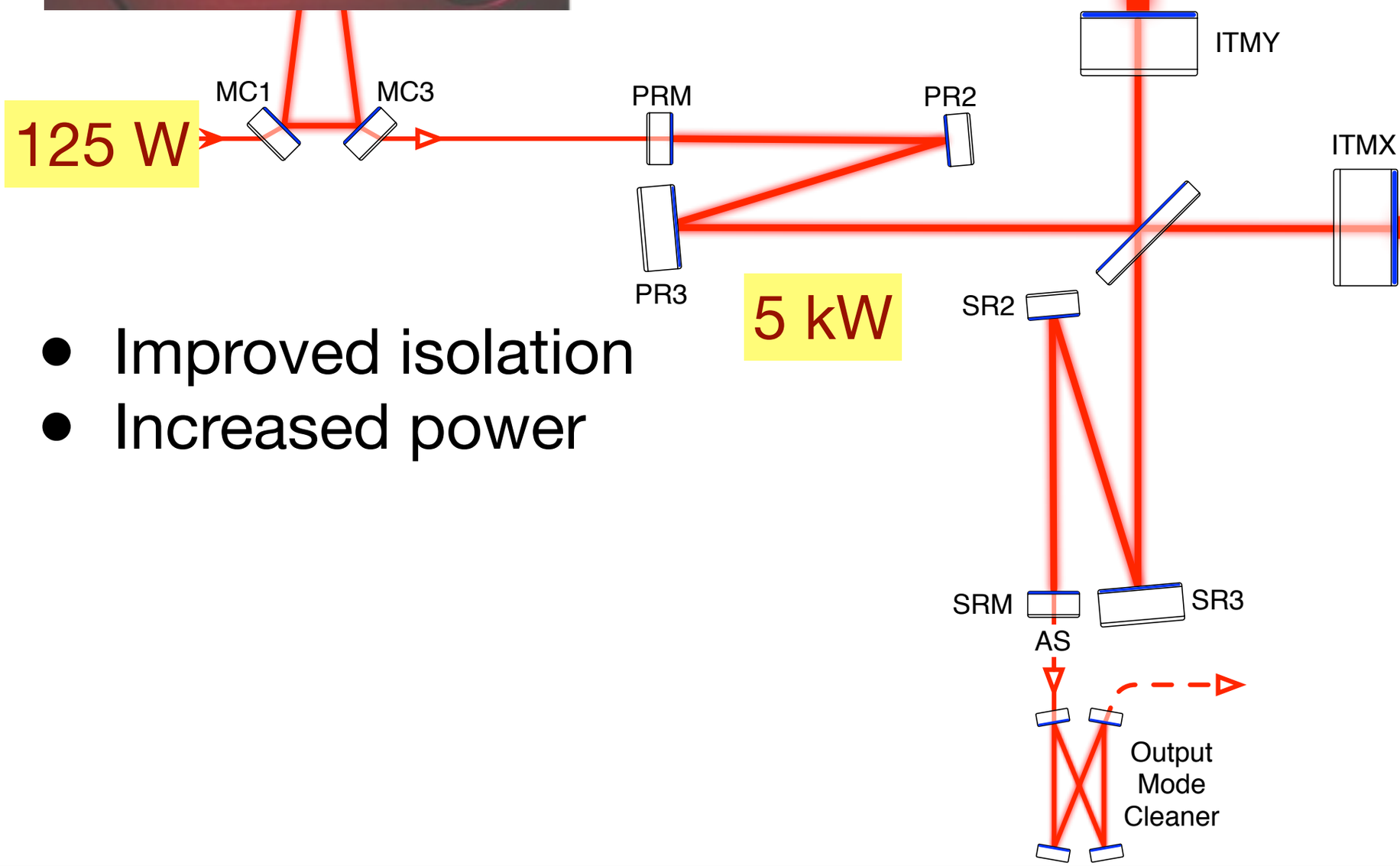


Active isolation & quad pendulum

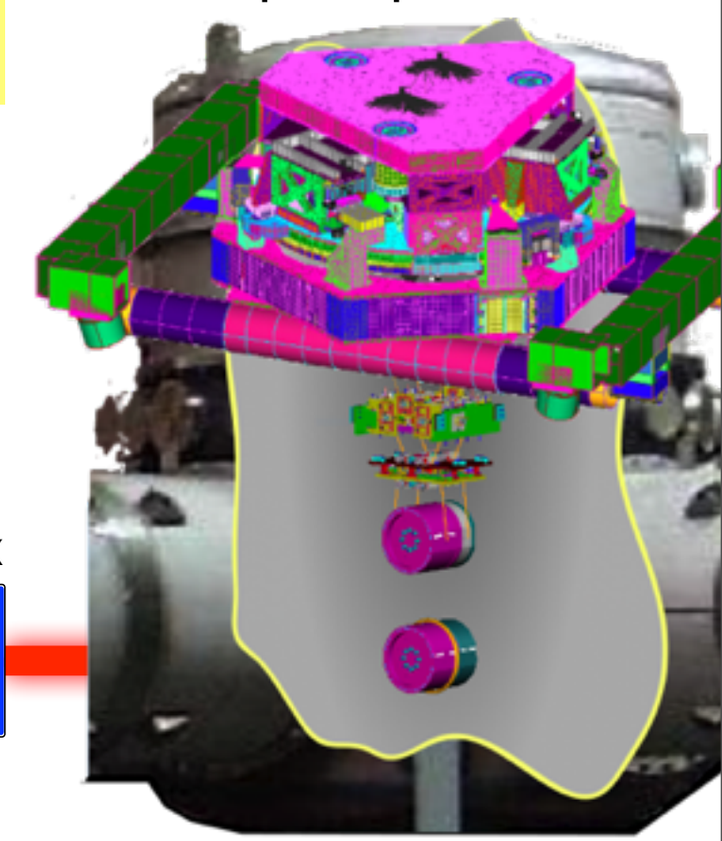


- Improved isolation

Advanced LIGO

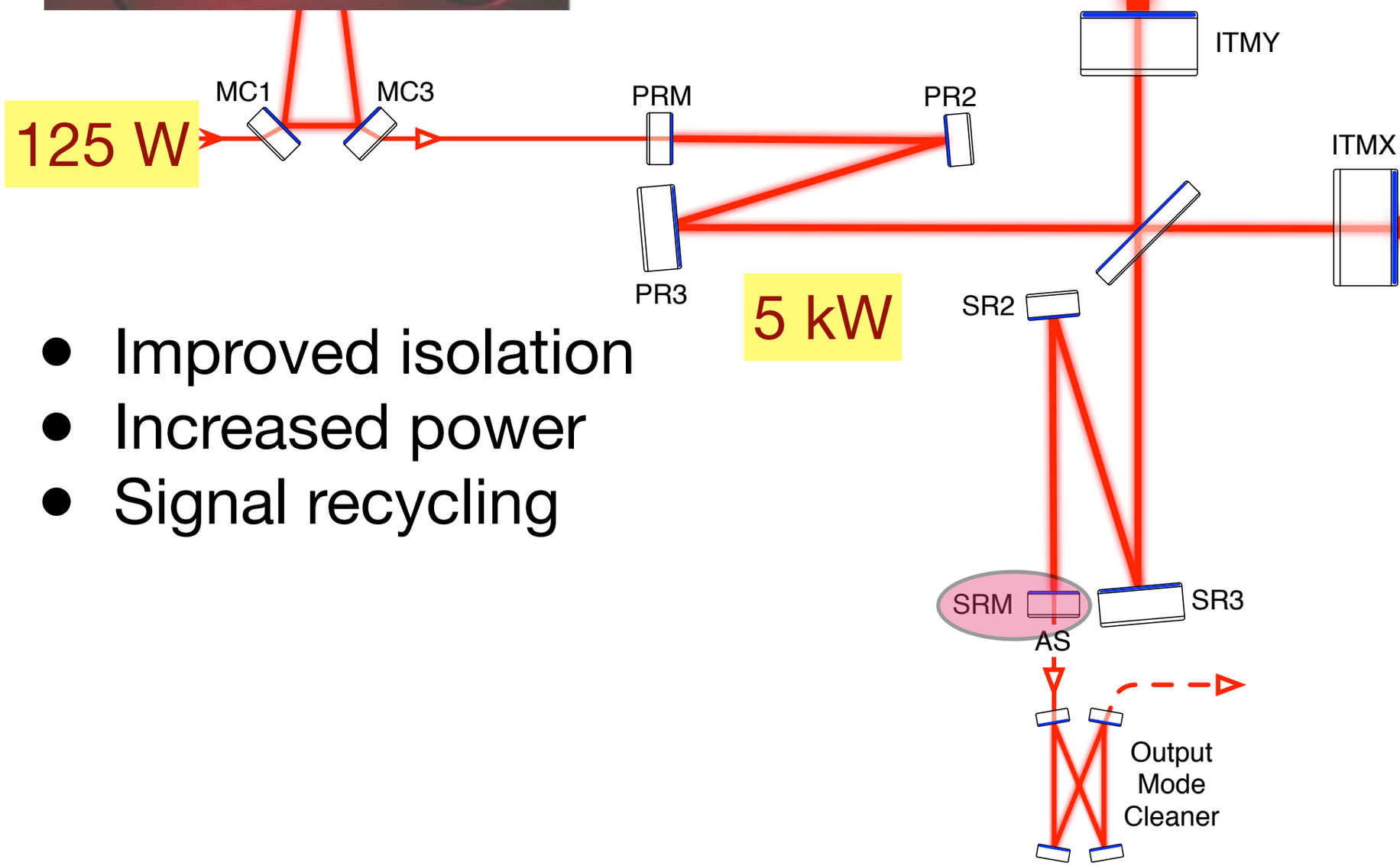


Active isolation &
quad pendulum

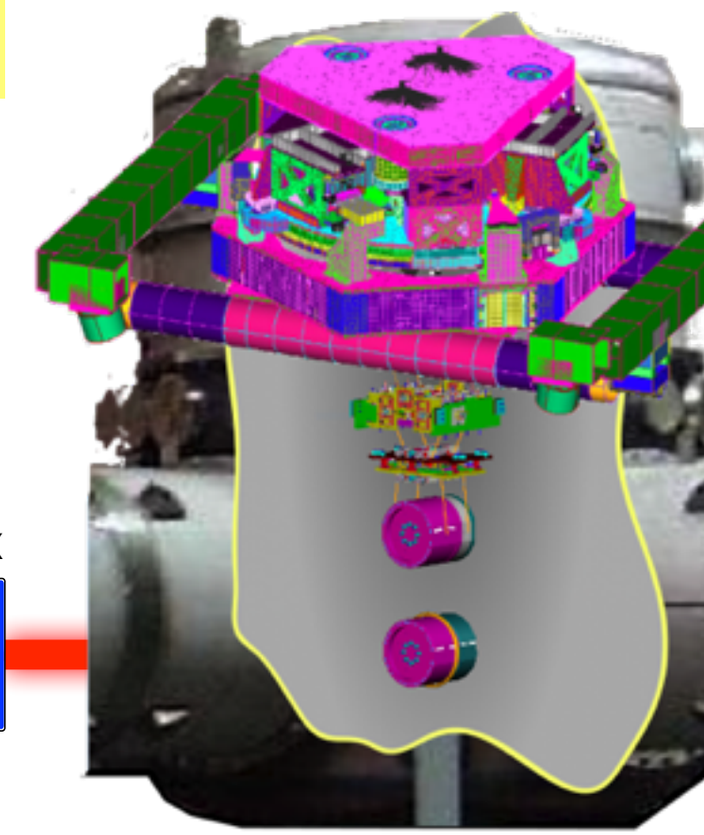


- Improved isolation
- Increased power

Advanced LIGO

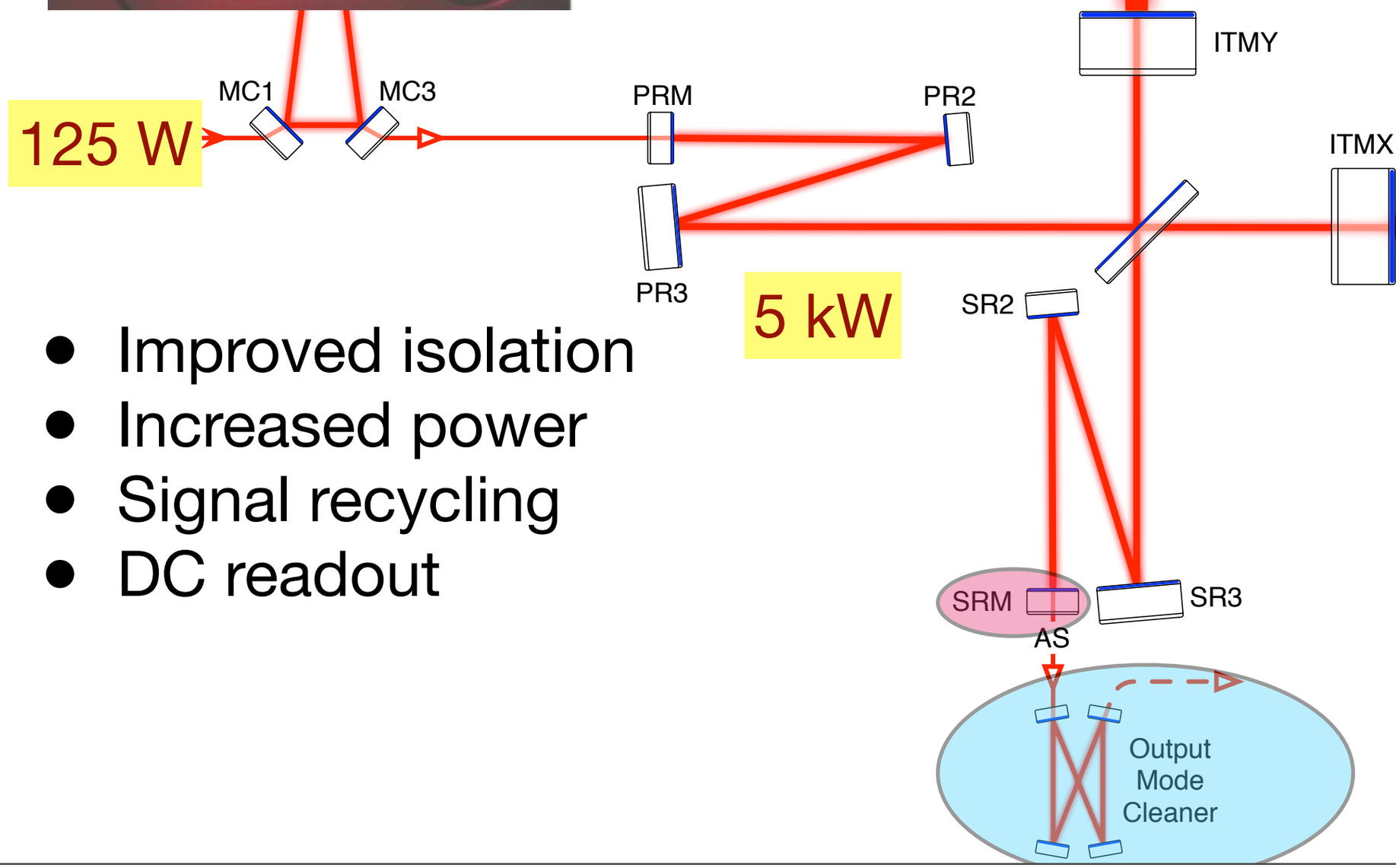


Active isolation &
quad pendulum

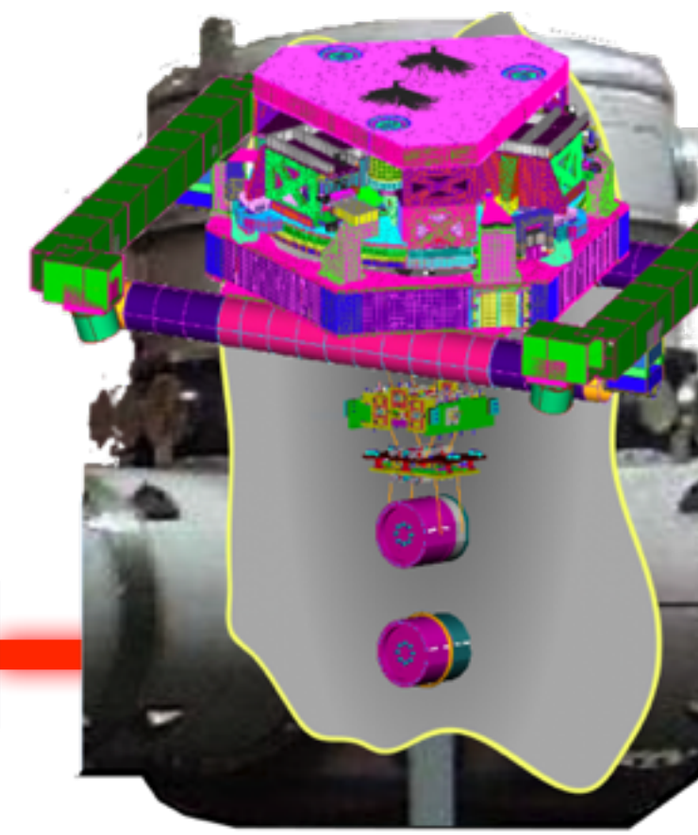


- Improved isolation
- Increased power
- Signal recycling

Advanced LIGO

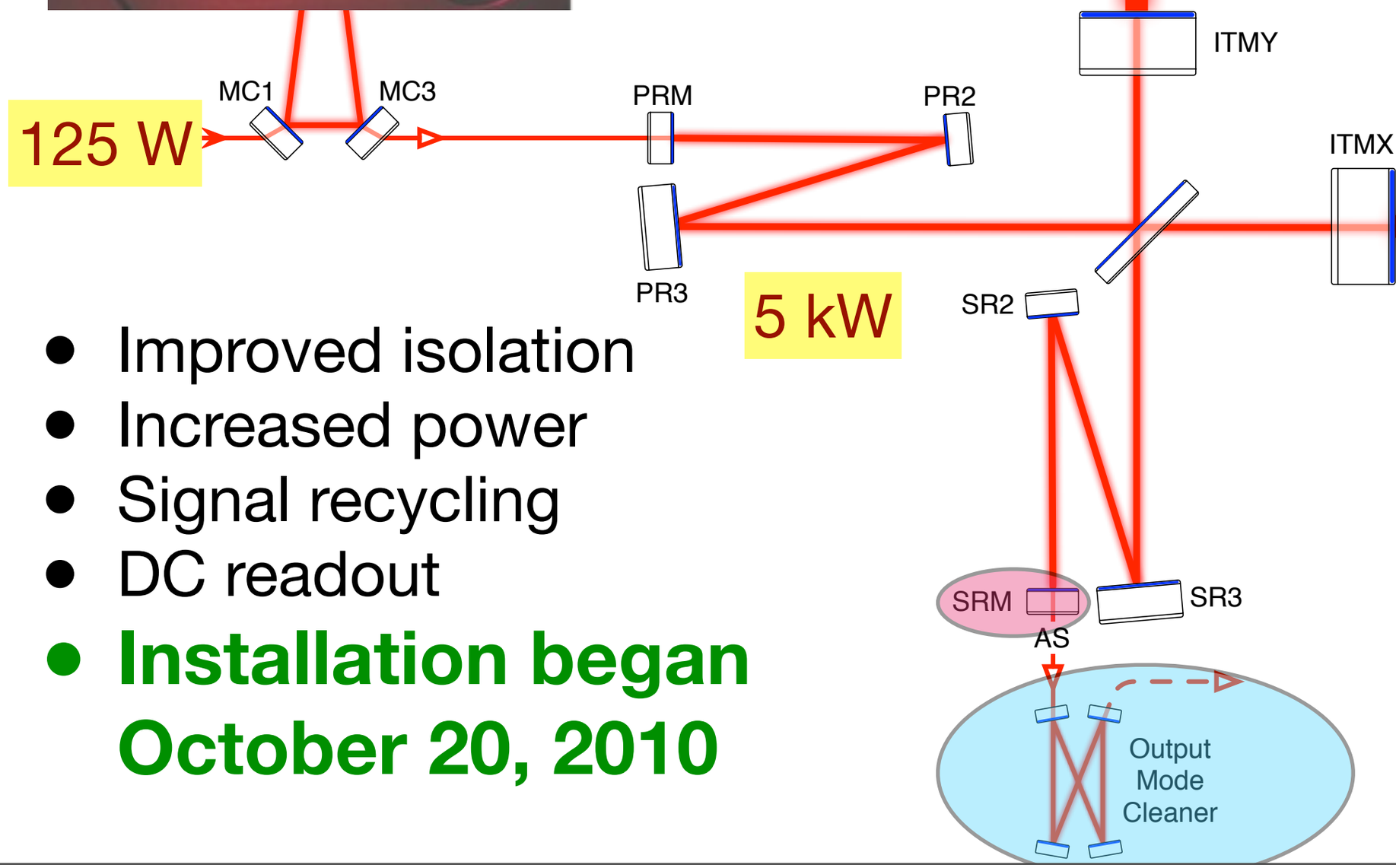


Active isolation &
quad pendulum

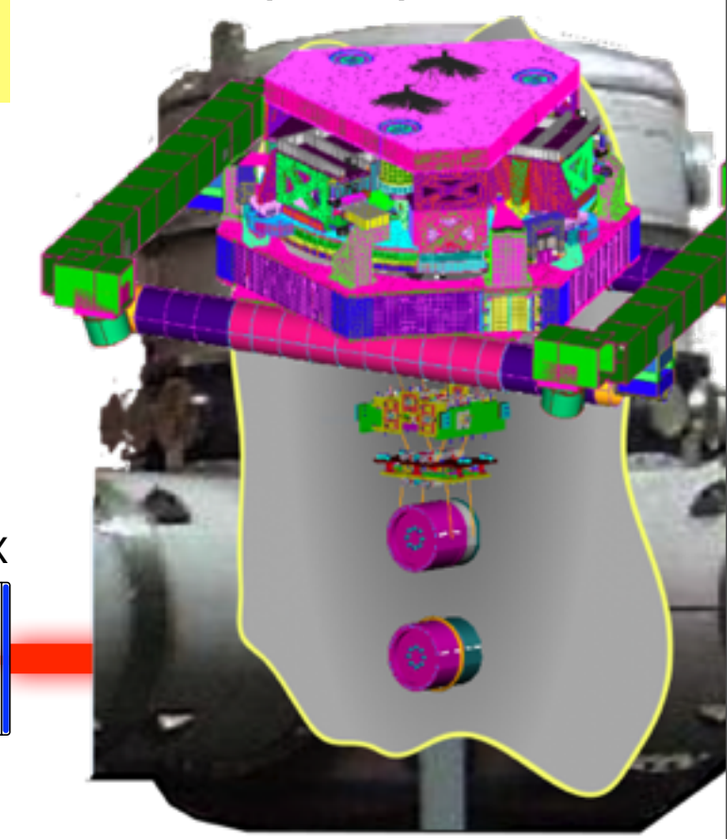


- Improved isolation
- Increased power
- Signal recycling
- DC readout

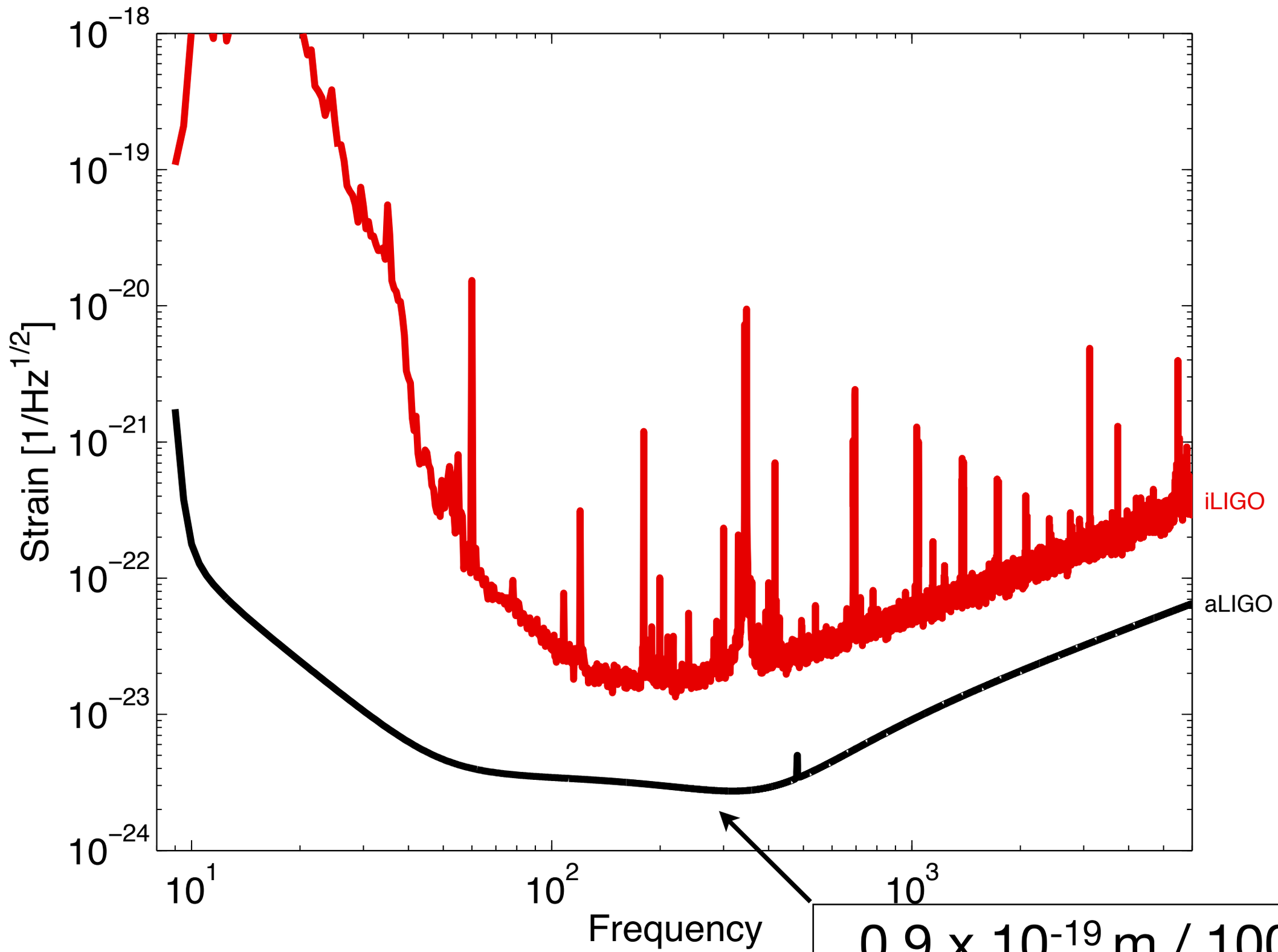
Advanced LIGO



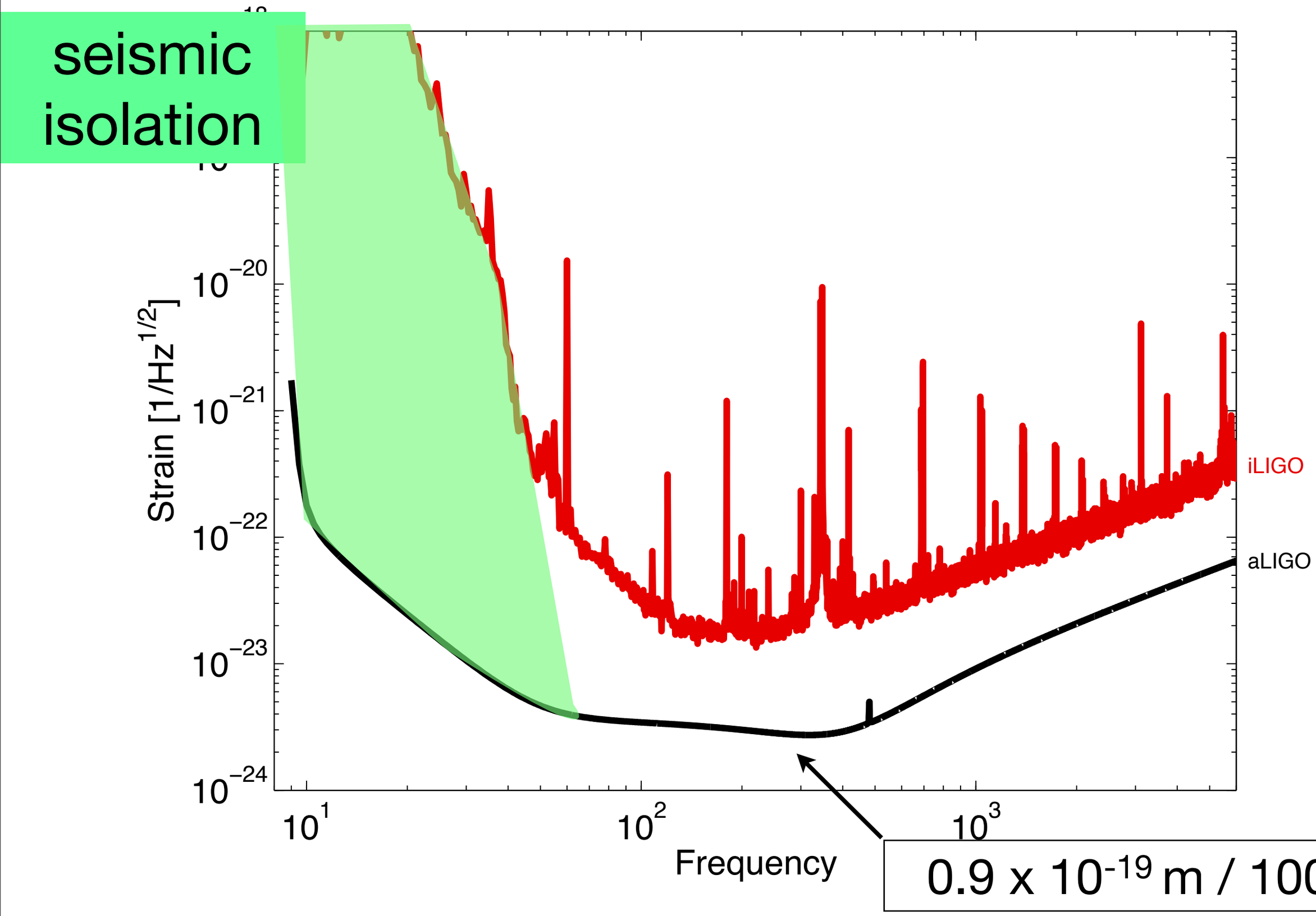
Active isolation &
quad pendulum

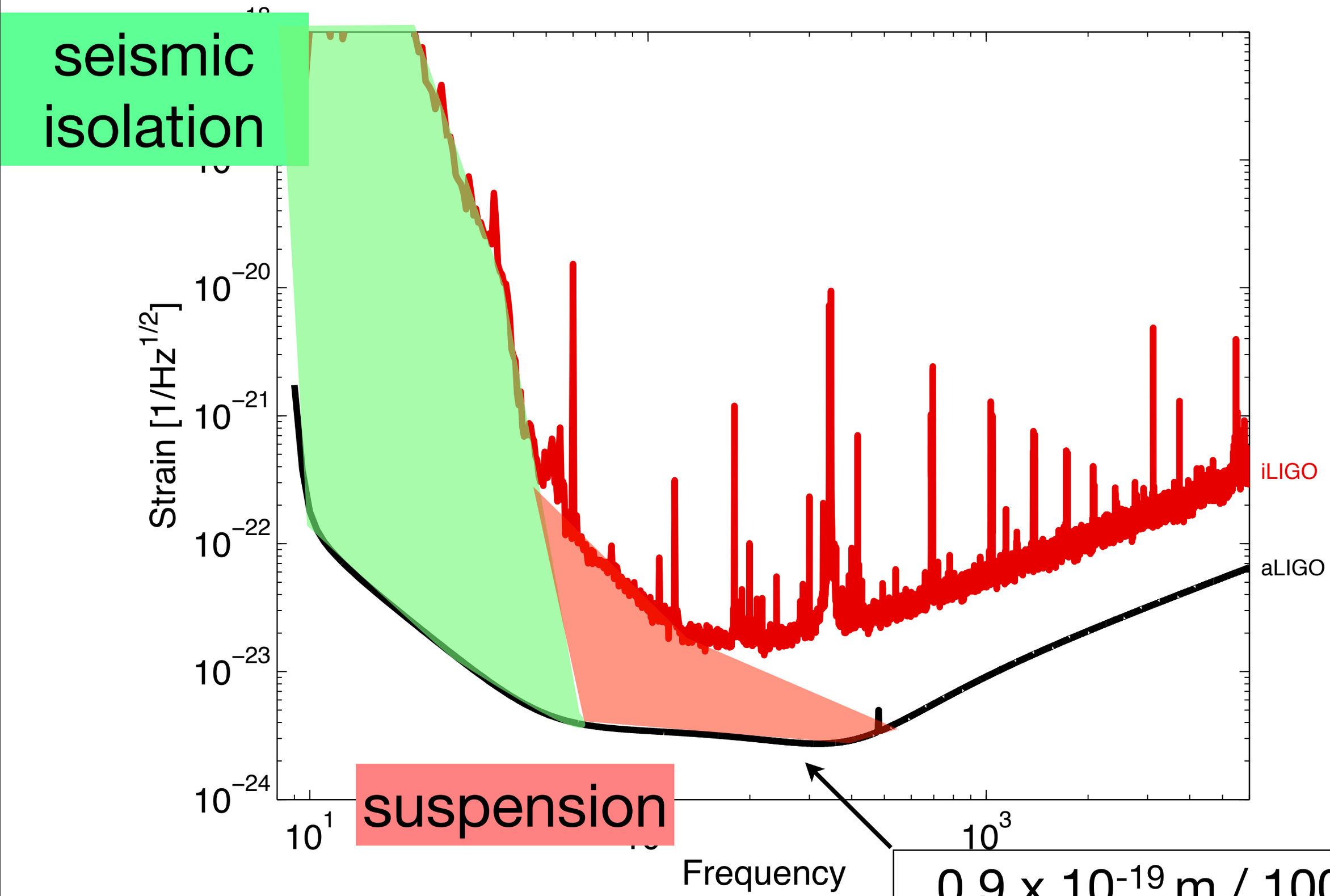


- Improved isolation
- Increased power
- Signal recycling
- DC readout
- **Installation began October 20, 2010**

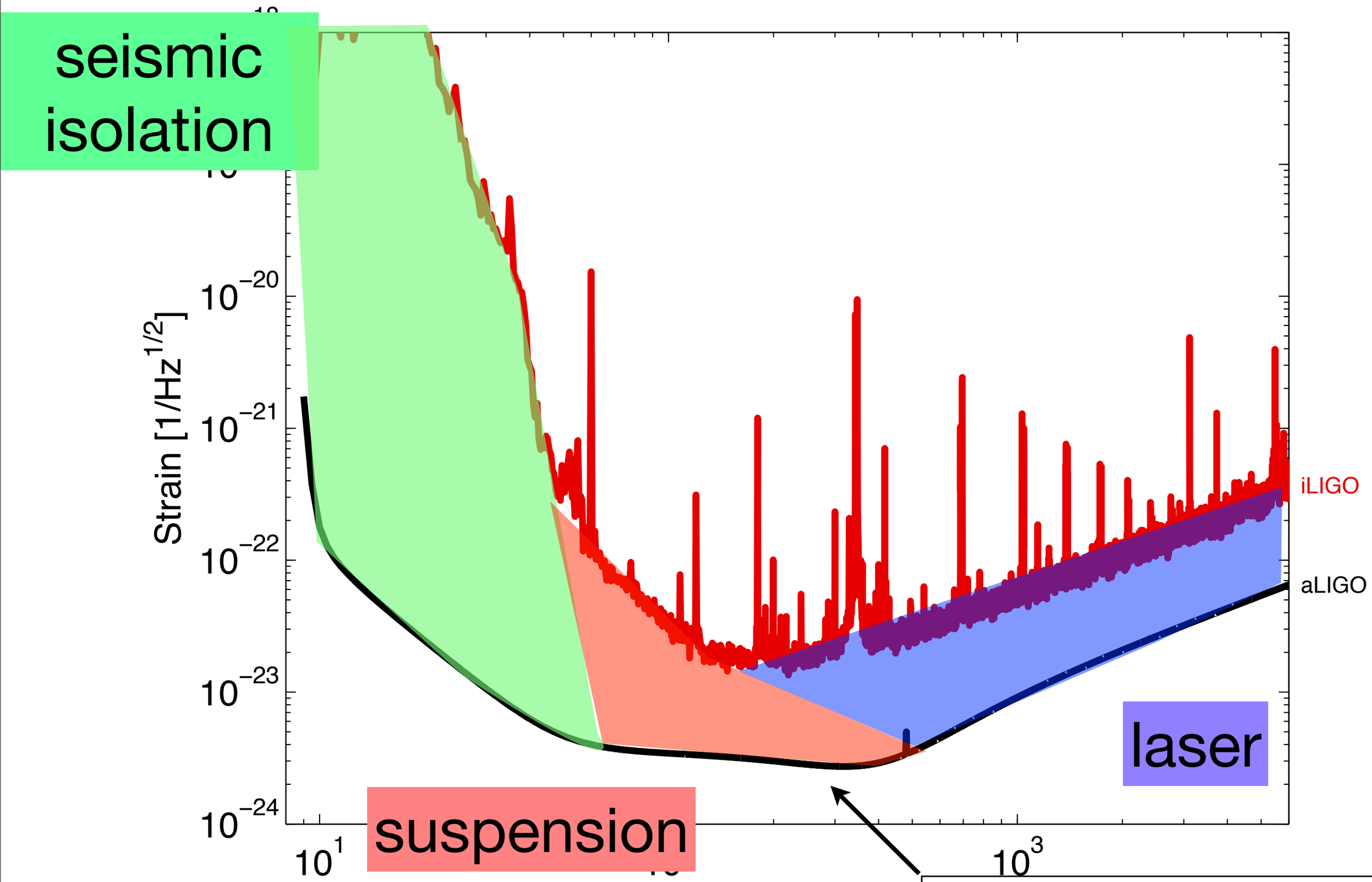


0.9×10^{-19} m / 100 Hz


seismic isolation
Strain [1/Hz^1/2]
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3
Frequency
iLIGO
aLIGO
0.9 x 10^-19 m / 100 Hz



0.9×10^{-19} m / 100 Hz



0.9 x 10^{-19} m / 100 Hz

Active seismic isolation

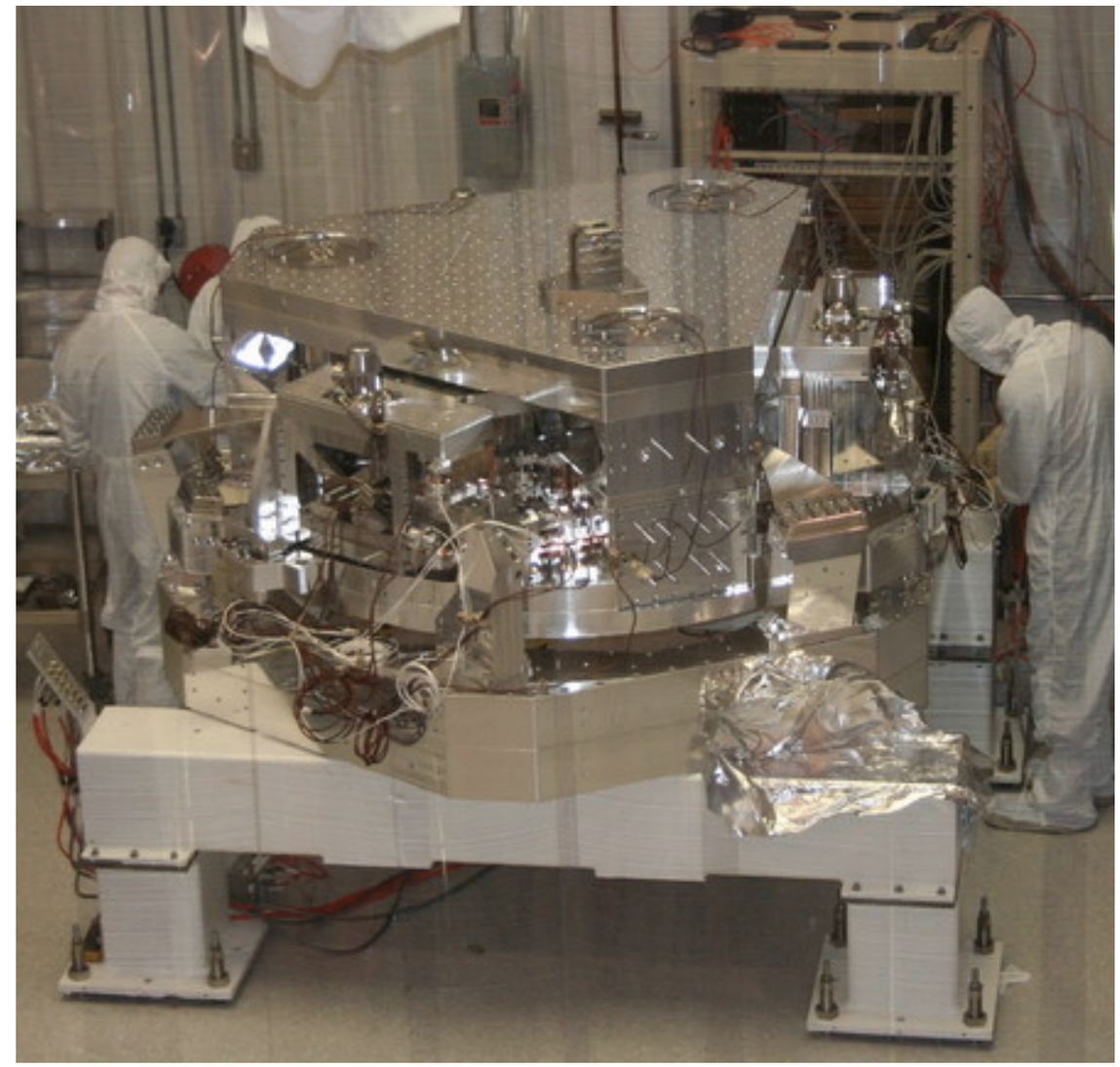
Two-stage, 12 DOF isolation system

24 sensors, 12 actuators

Mechanical resonance ~1 Hz

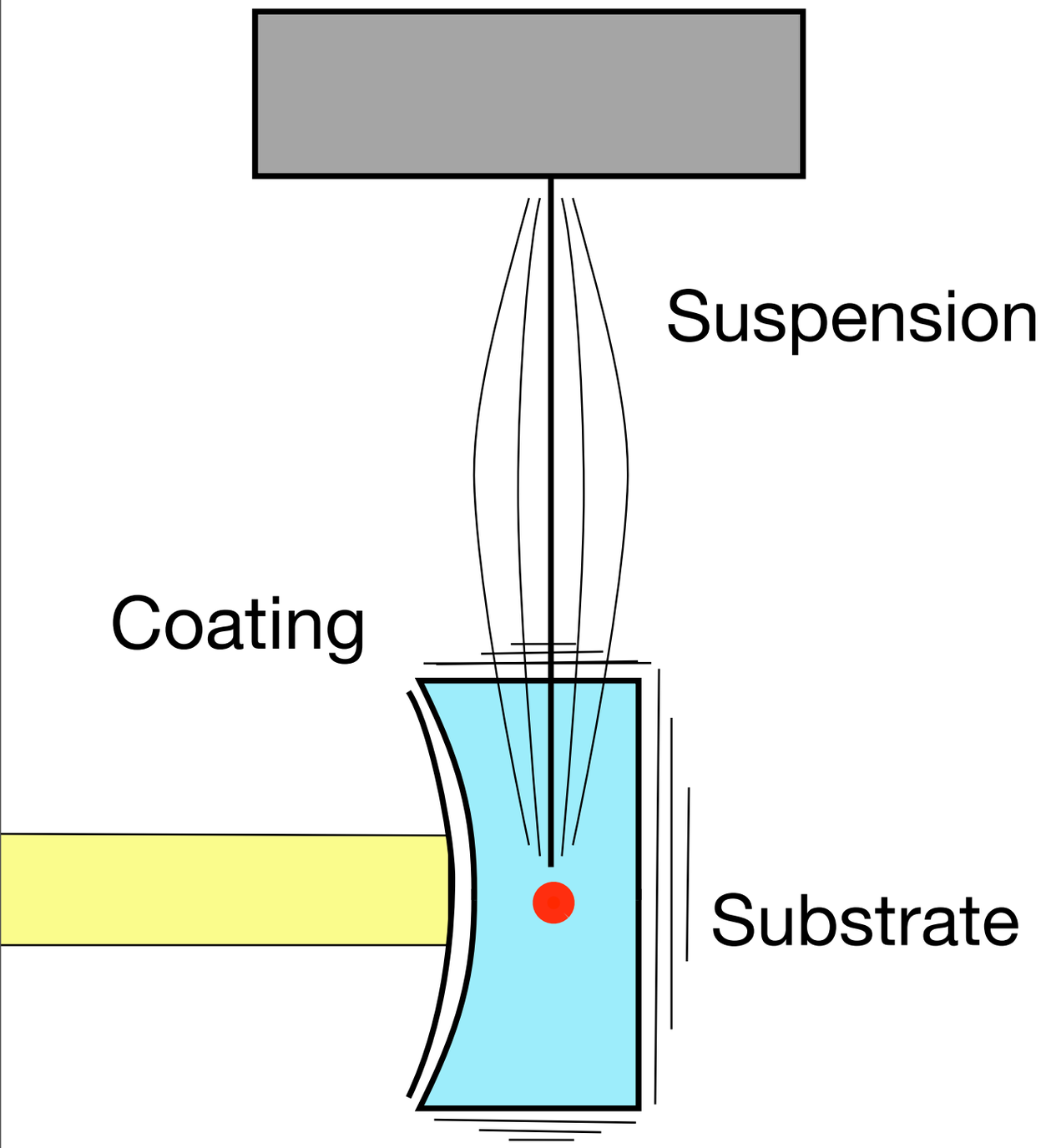
700 kG payload

~ 1 pm / $Hz^{1/2}$ at 10 Hz



(led by B. Lantz of Stanford)

Thermal noise



~ mechanical Johnson noise

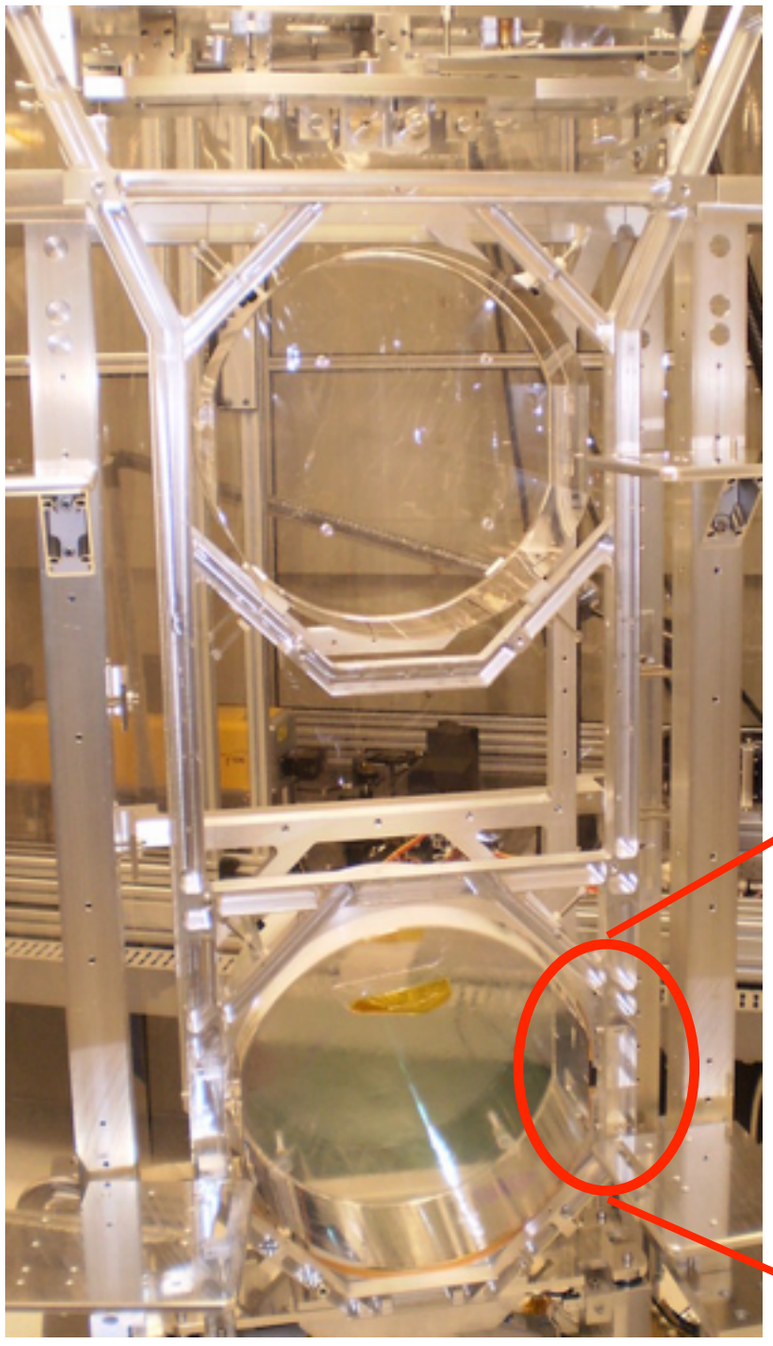
$$v_n(f) = \sqrt{4\pi kTR}$$

Brownian motion of the lossy mechanical system

Dominated by the multi-layer dielectric coating

Monolithic suspension

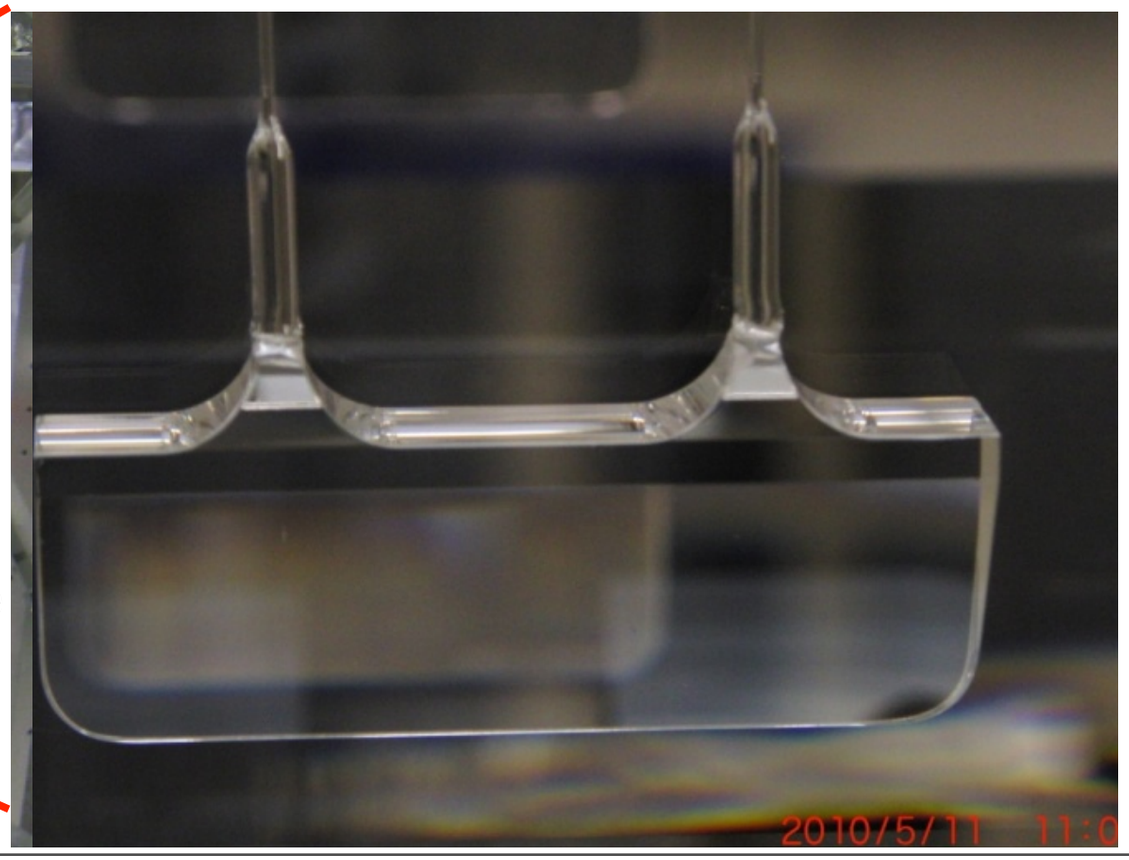
welded fused silica fibers



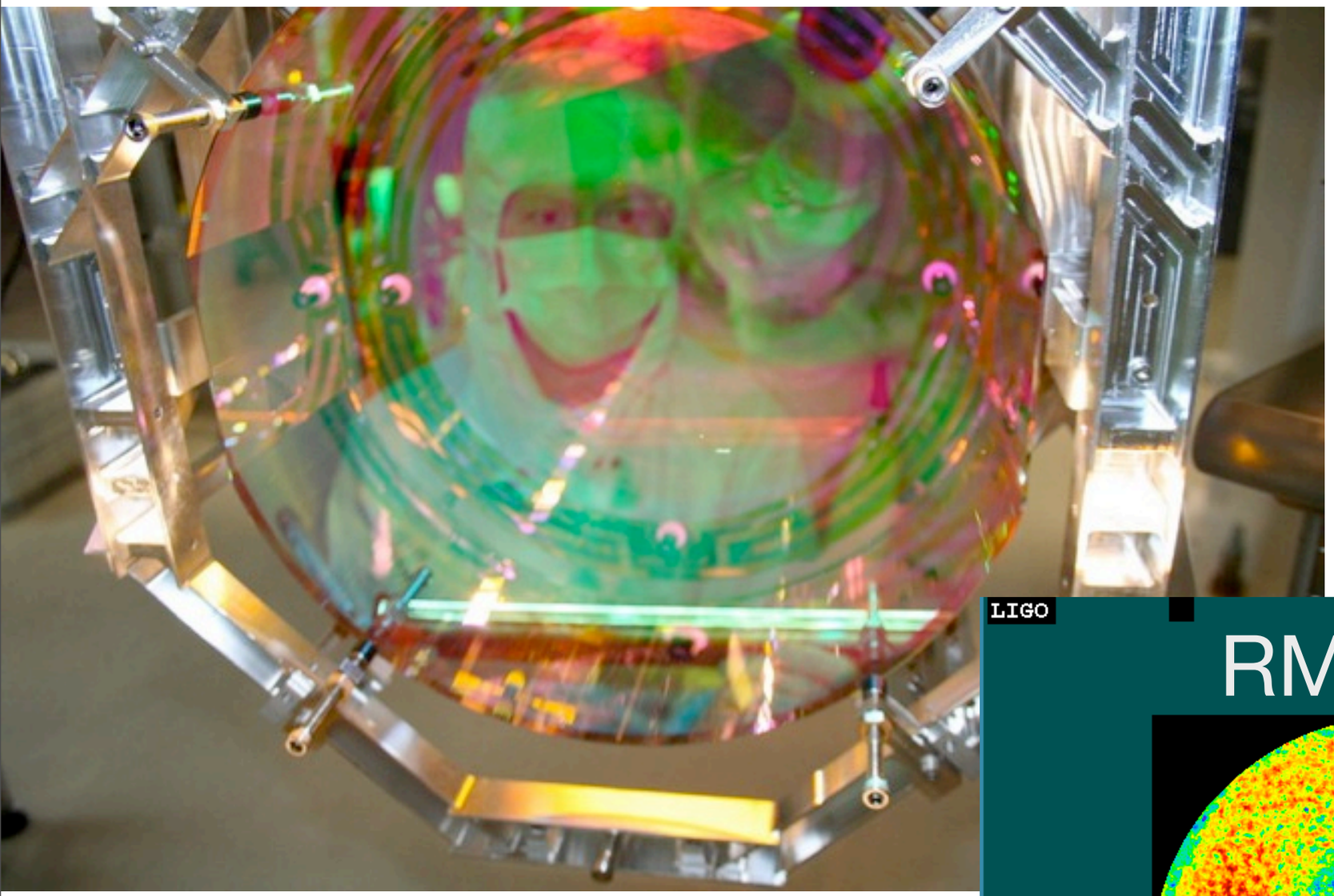
LASTI Monolithic suspension 2010

- Reduce suspension thermal noise ~10x
- 40 kg test mass
- 4 stages

Silicate bonding



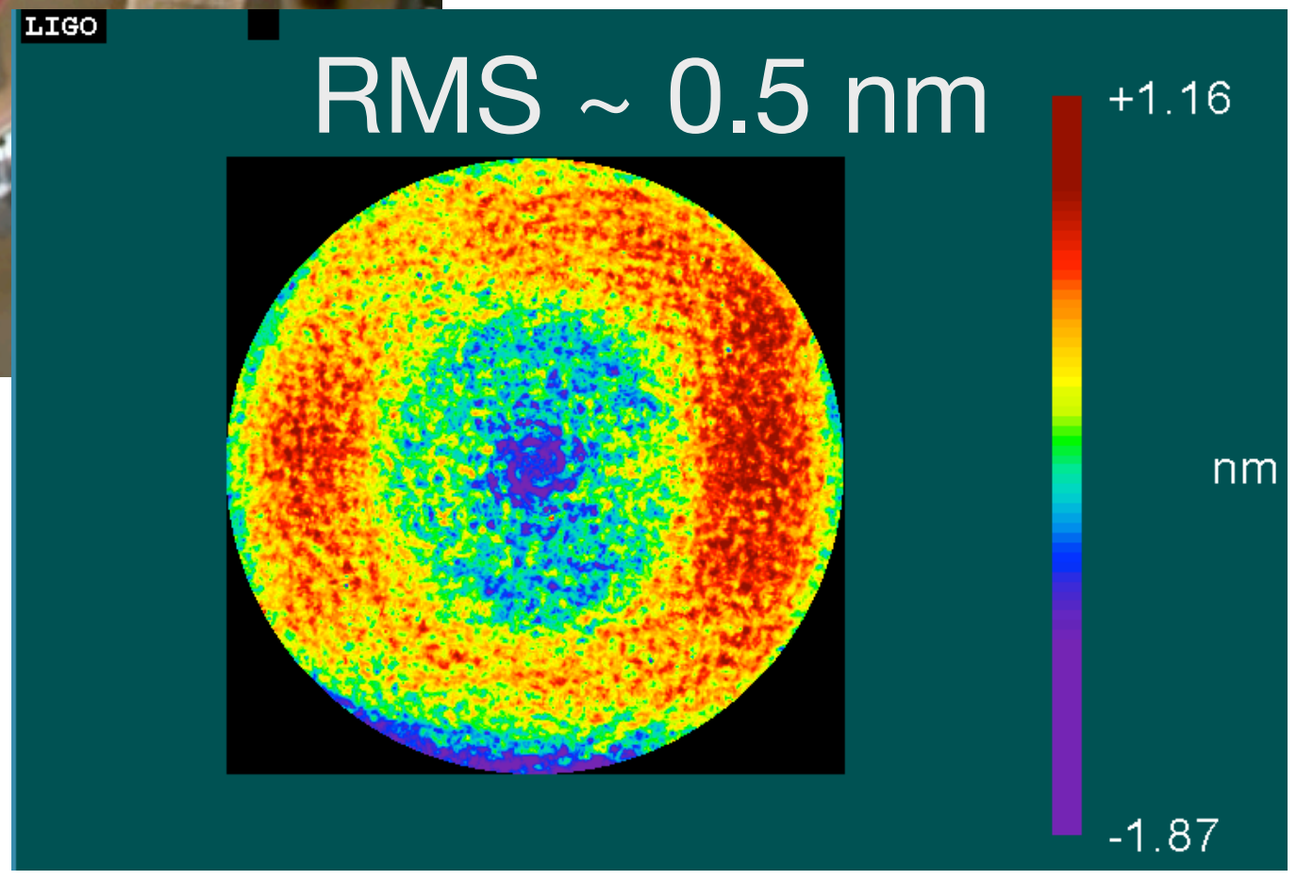
Monolithic suspension



ϕ34cm, 40 kg

Monolithic fiber suspension

Electrostatic actuation

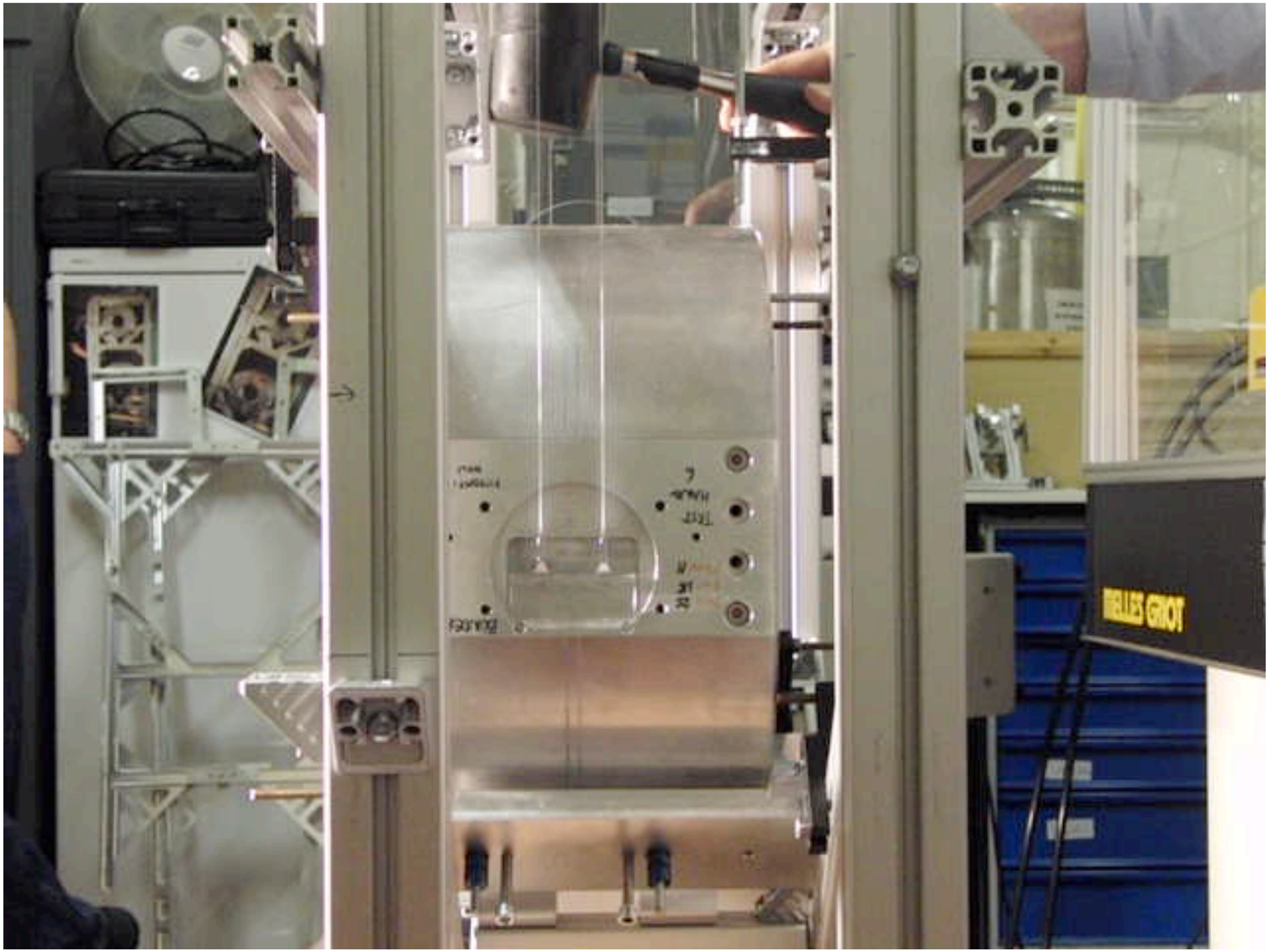


First installed test mass at LHO, Jan 2012

Robust?

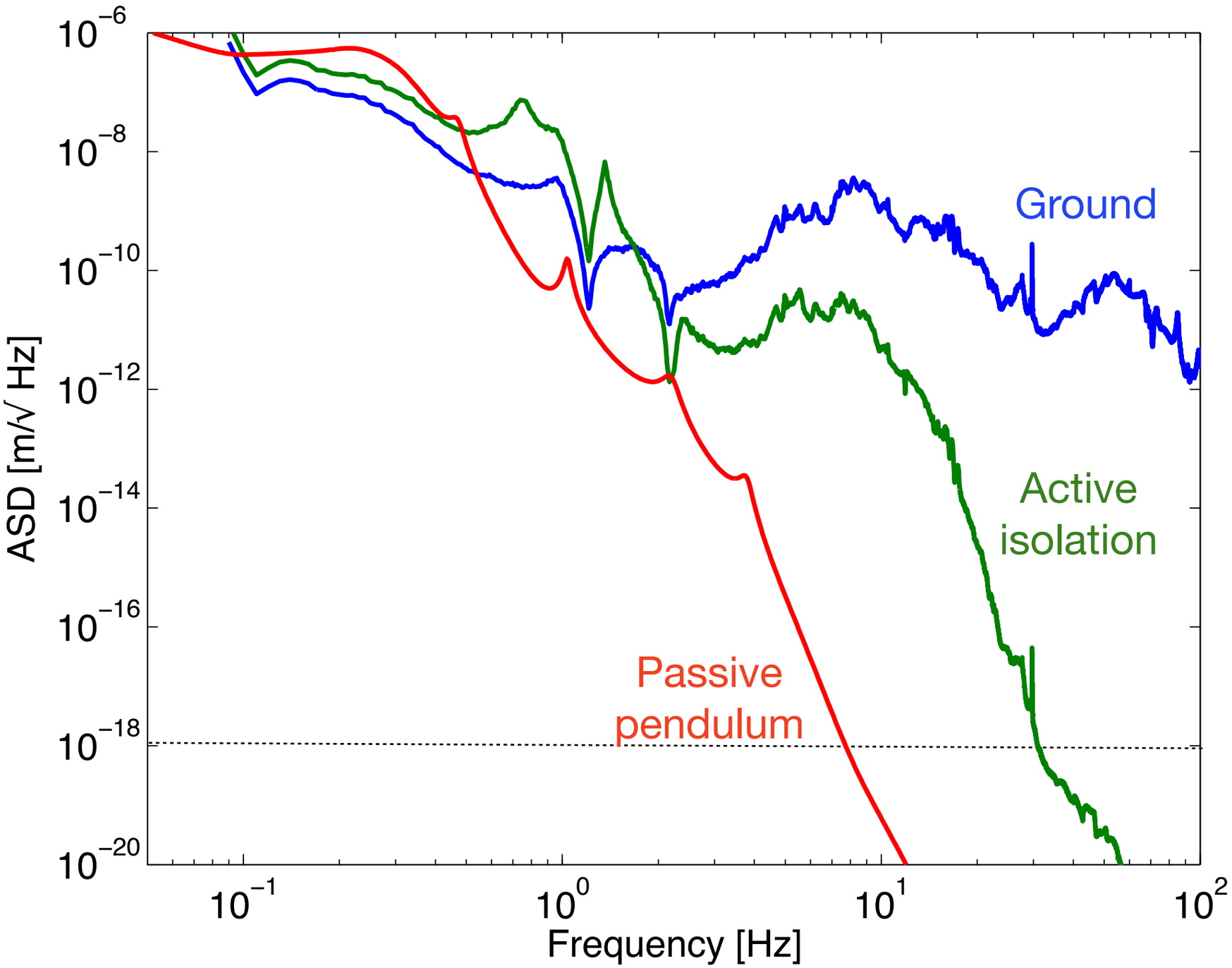
Glasgow fiber test 2010

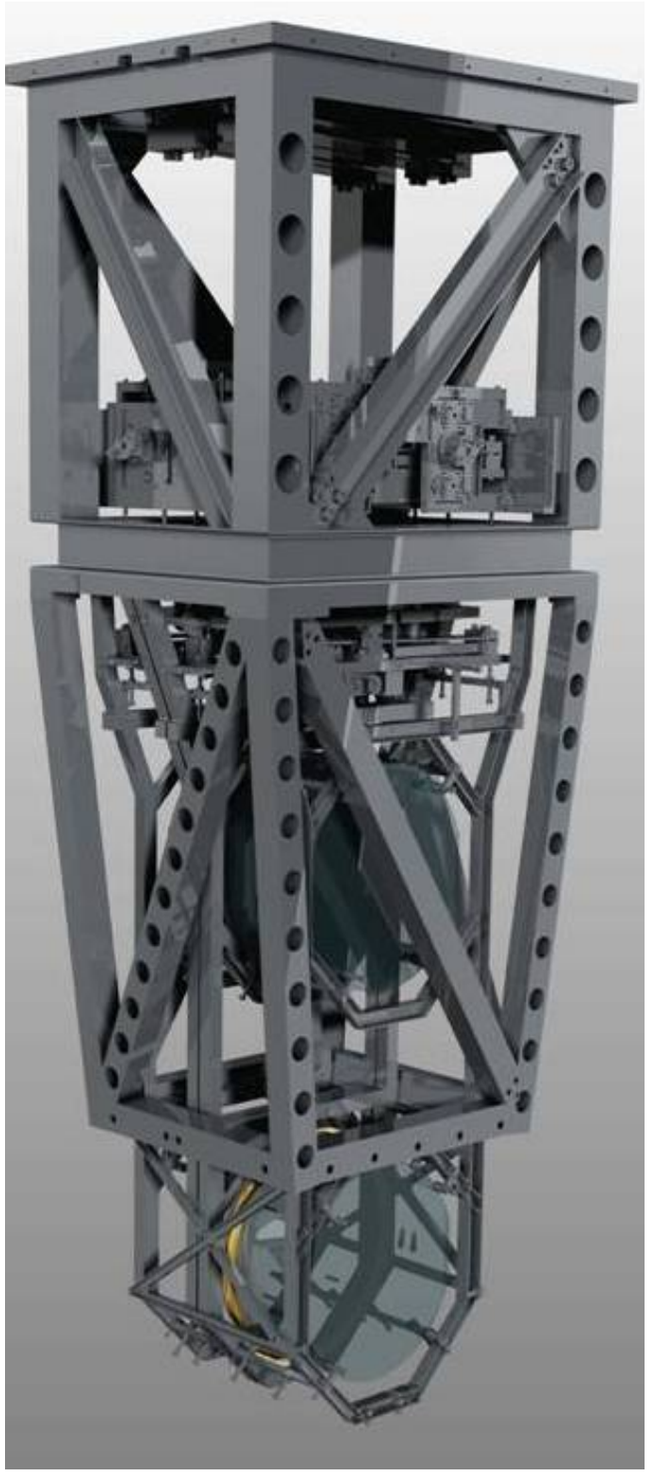
Robust?



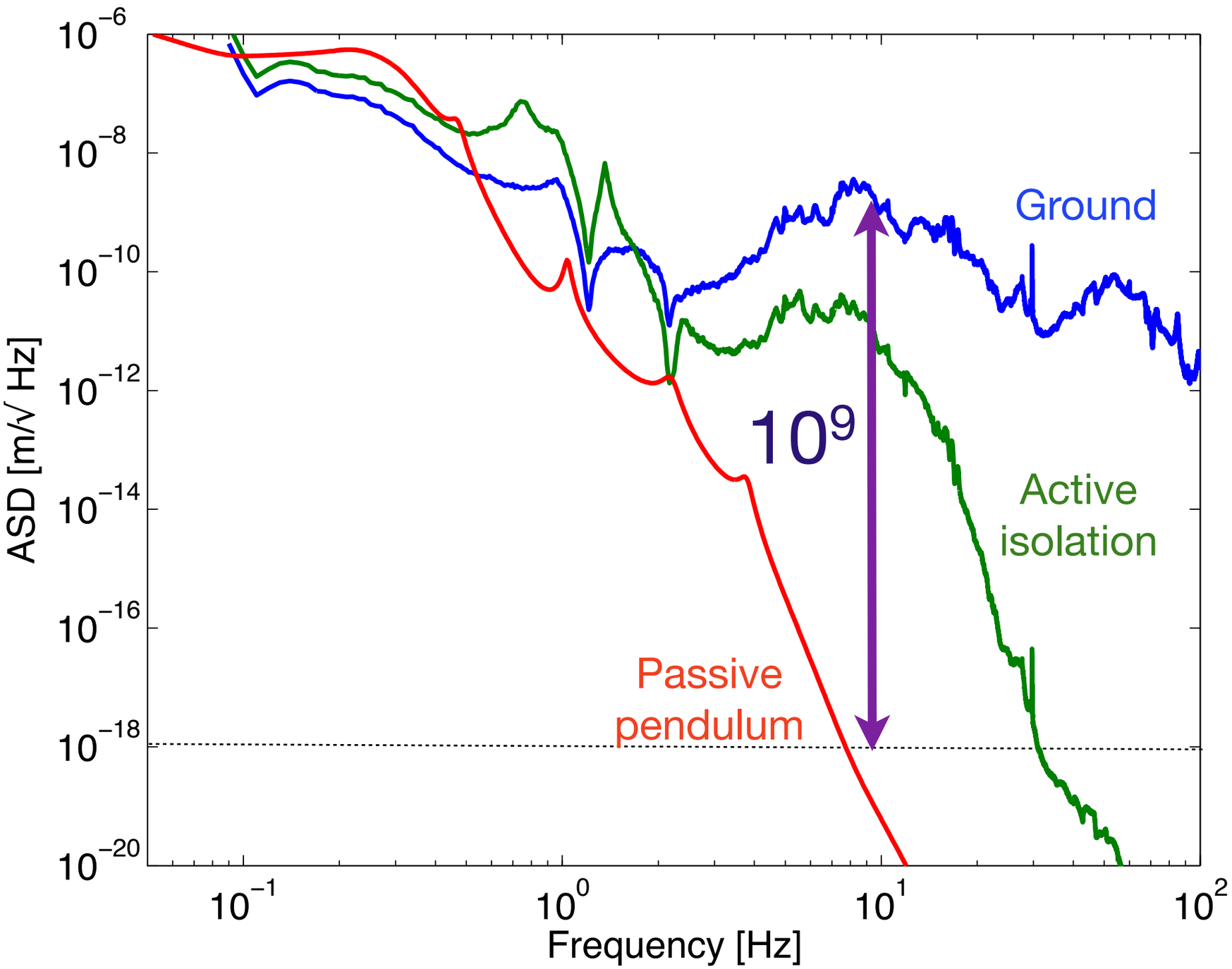
Glasgow fiber test 2010

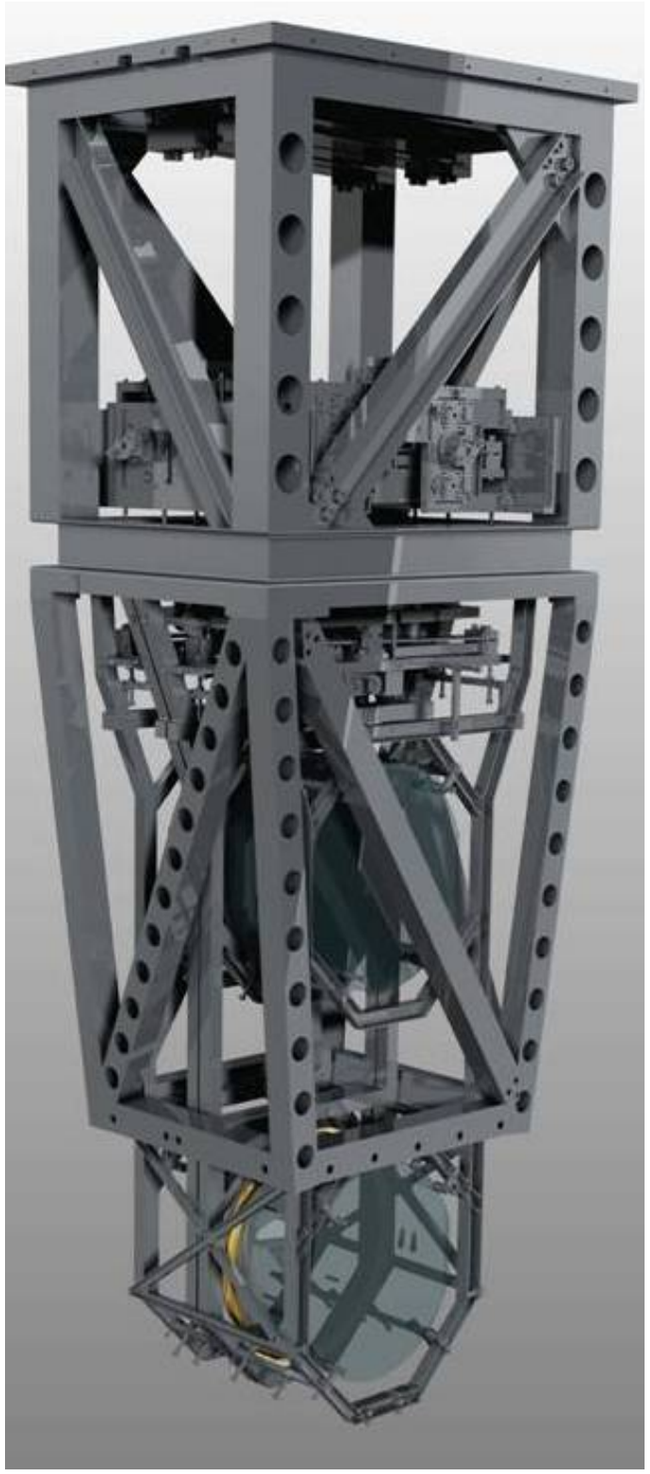
Active isolation



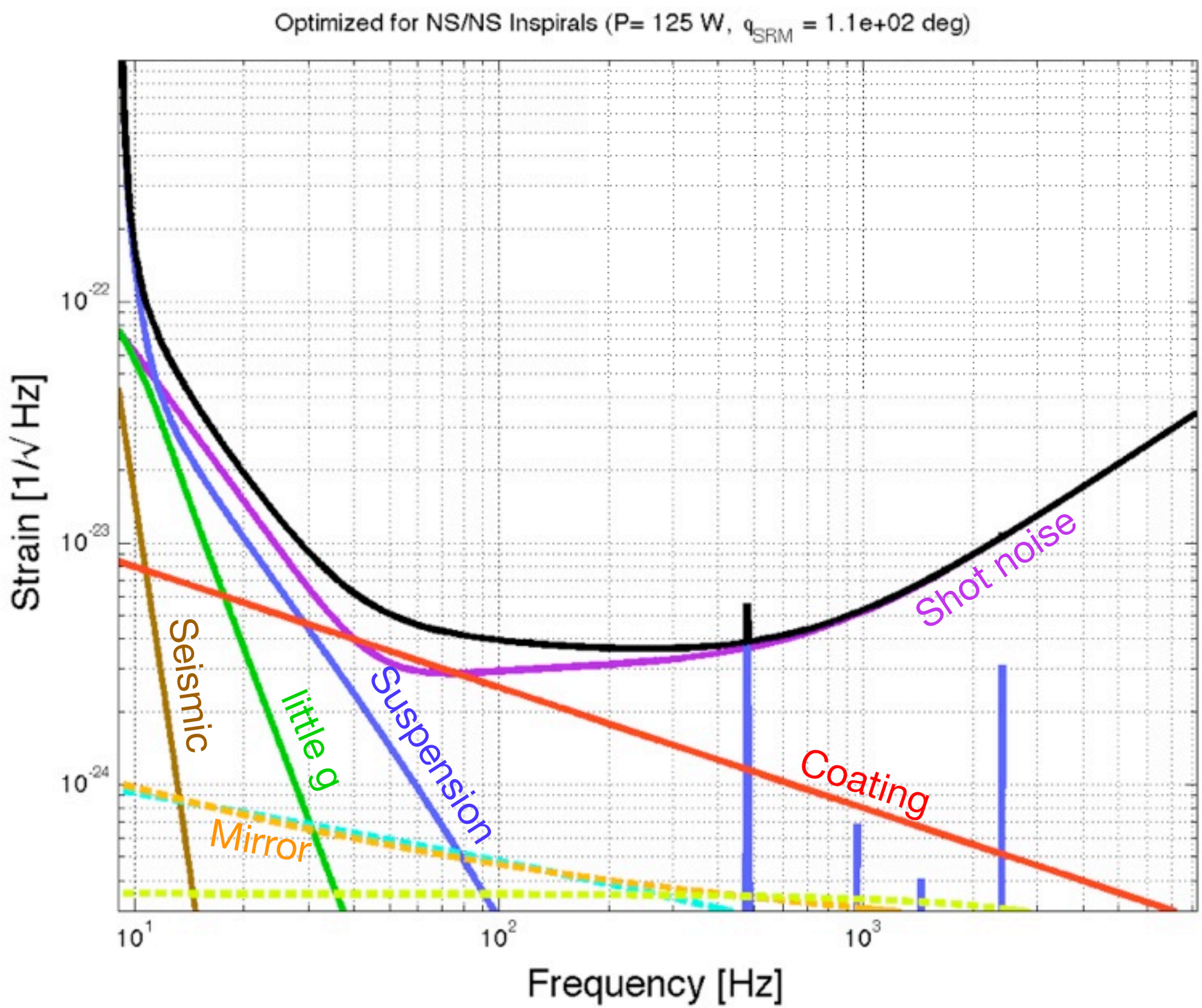


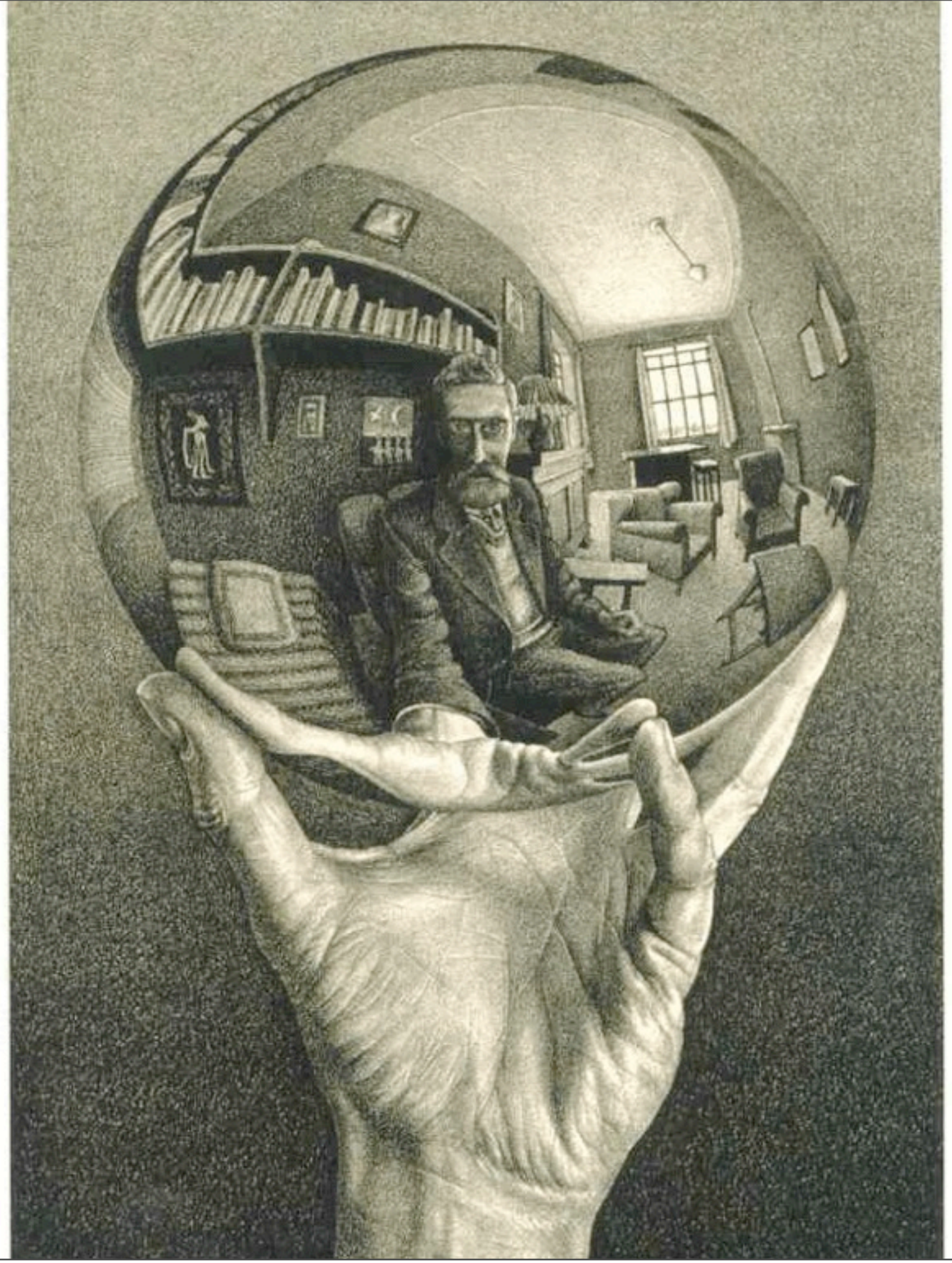
Active isolation





aLIGO Performance

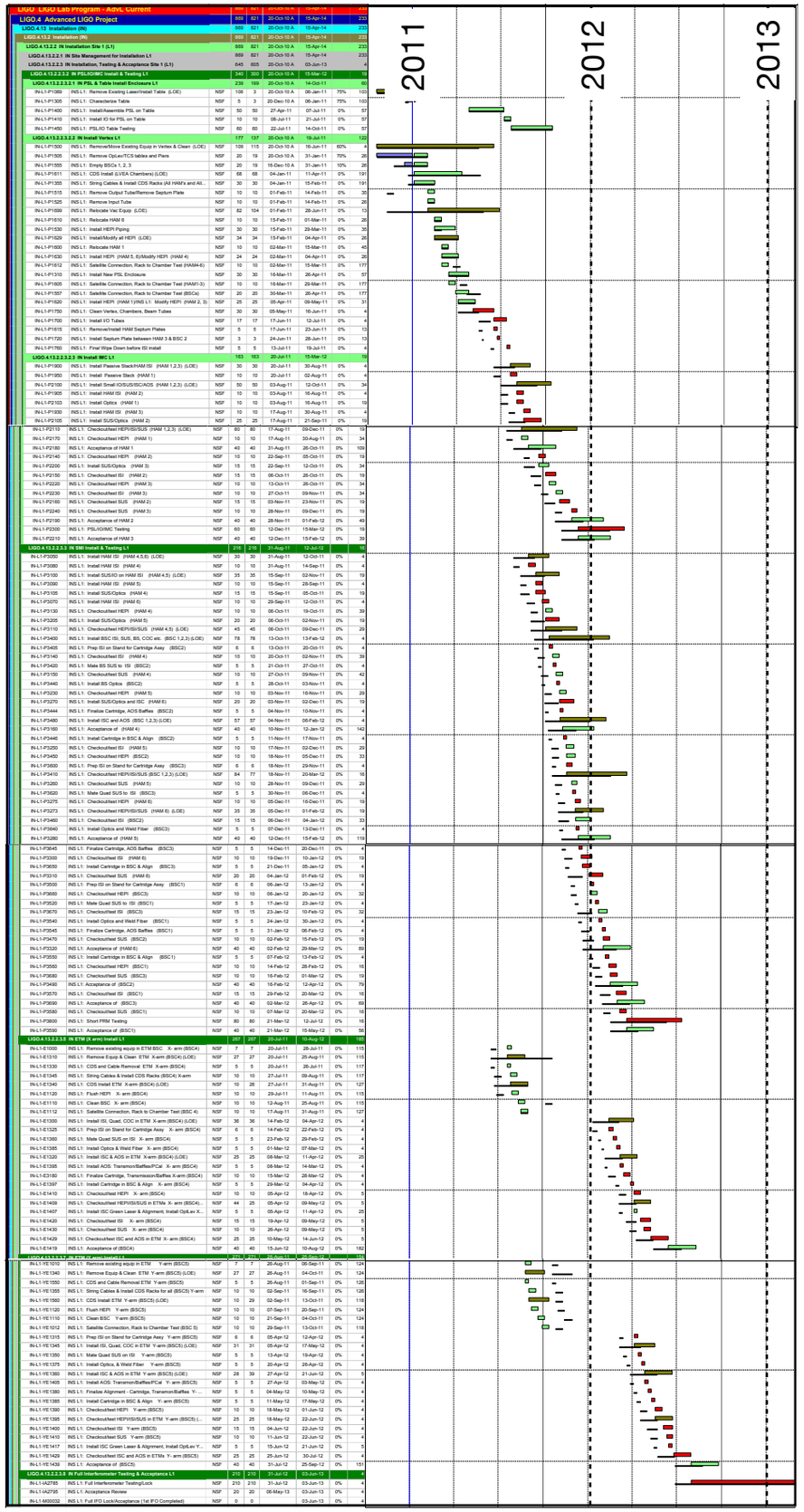


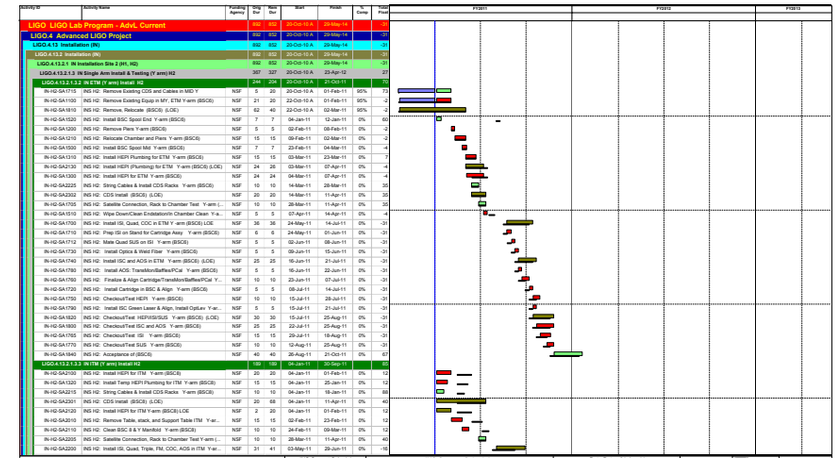


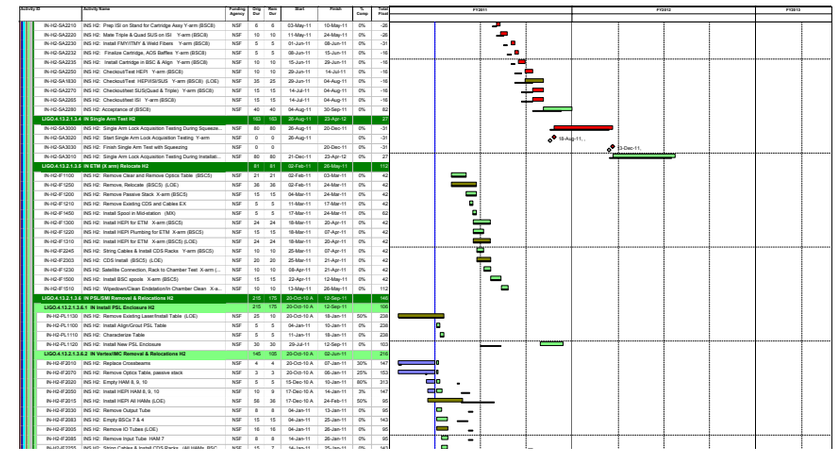
When does the science happen?

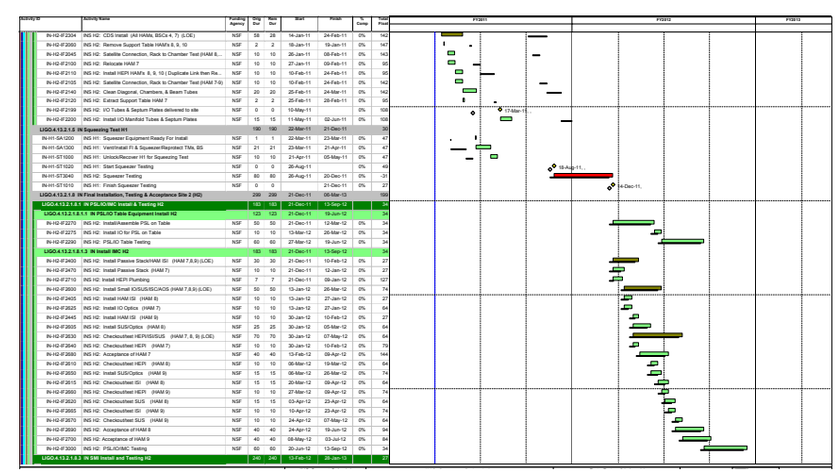
Waldman
LBL RPM
February 2012

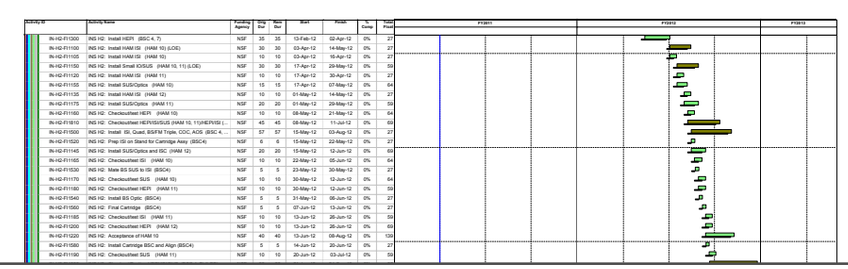
aLIGO Installation



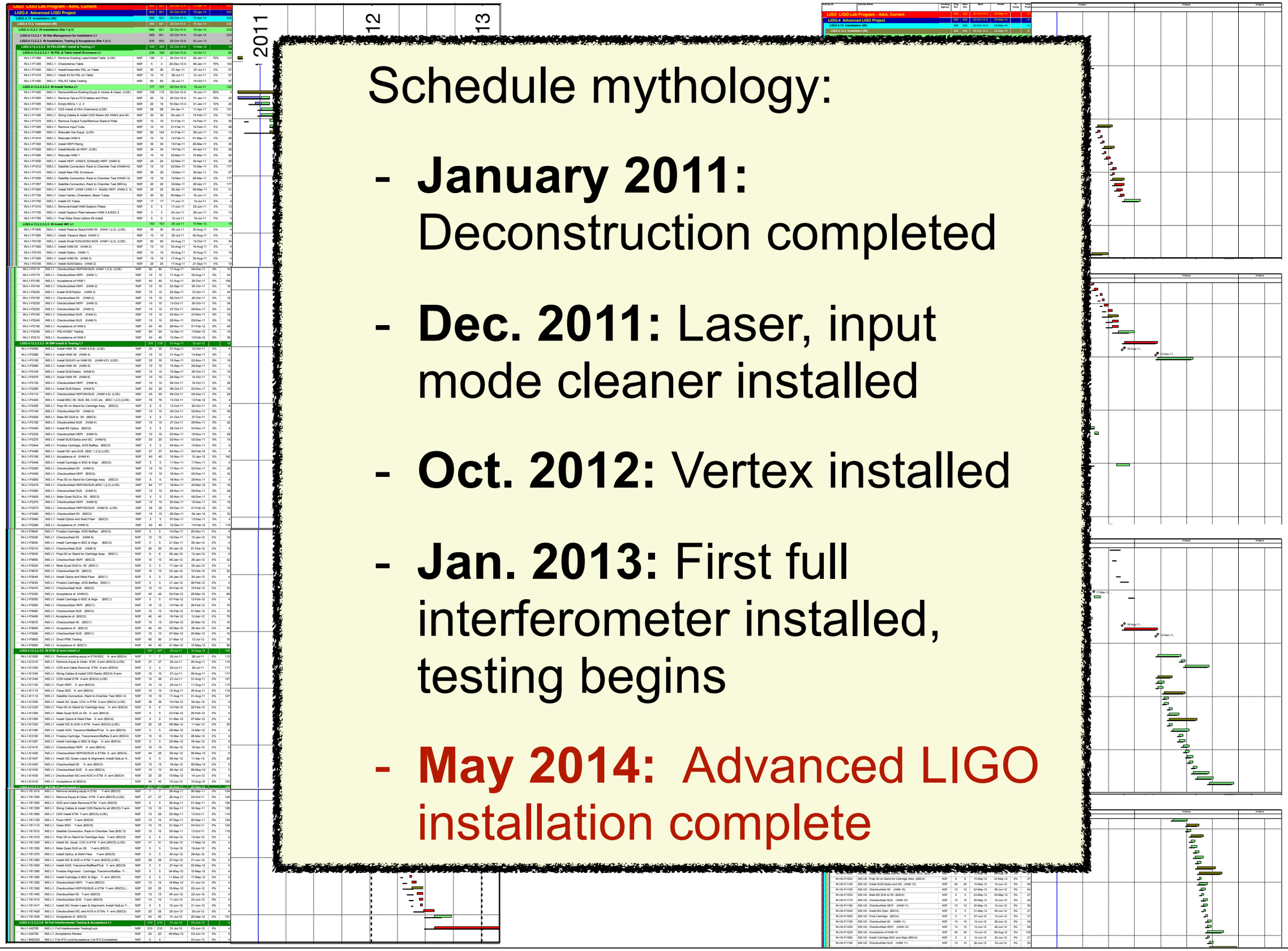








aLIGO Installation



Schedule mythology:

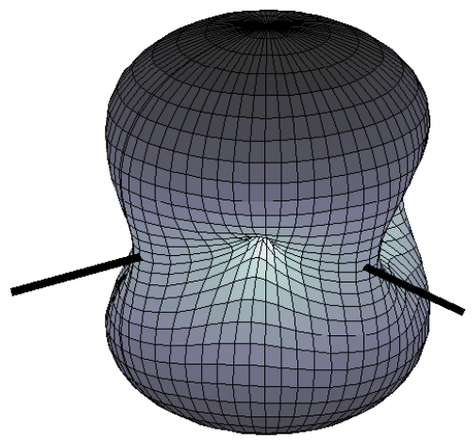
- **January 2011:** Deconstruction completed
- **Dec. 2011:** Laser, input mode cleaner installed
- **Oct. 2012:** Vertex installed
- **Jan. 2013:** First full interferometer installed, testing begins
- **May 2014:** Advanced LIGO installation complete

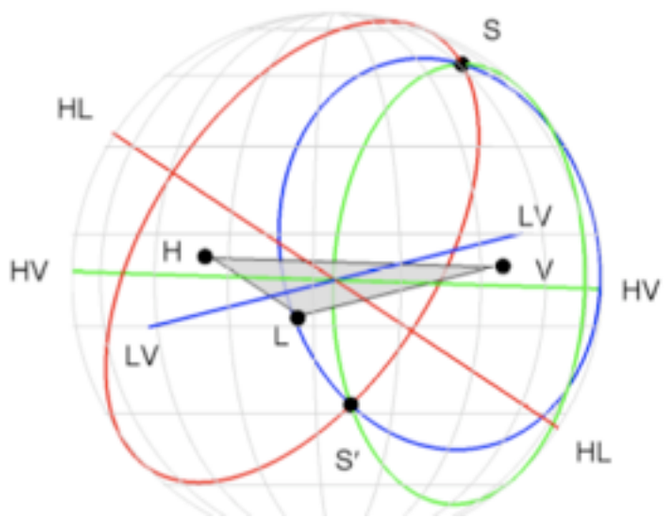
Rates

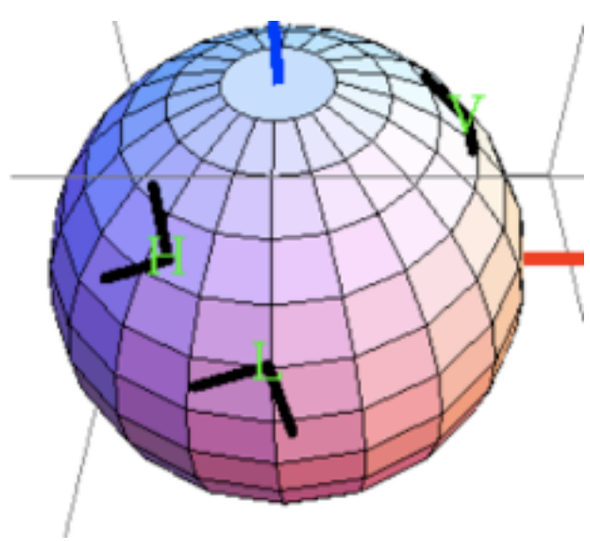
Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors
Classical and Quantum Gravity 27 (2010) 173001

	NS-NS	NS-BH	BH-BH
Rate ($\mathrm{MWEG}^{-1}\ \mathrm{yr}^{-1}$)	$100\,^{1000}_{1}$	$3\,^{100}_{0.05}$	$0.4\,^{30}_{0.01}$
iLIGO (yr^{-1})	$0.02\,^{0.2}_{2\times10^{-4}}$	$0.004\,^{0.1}_{7\times10^{-5}}$	$0.007\,^{0.5}_{2\times10^{-4}}$
aLIGO (yr^{-1})	$40\,^{400}_{0.4}$	$10\,^{300}_{0.2}$	$20\,^{1000}_{0.4}$

Parameter estimation

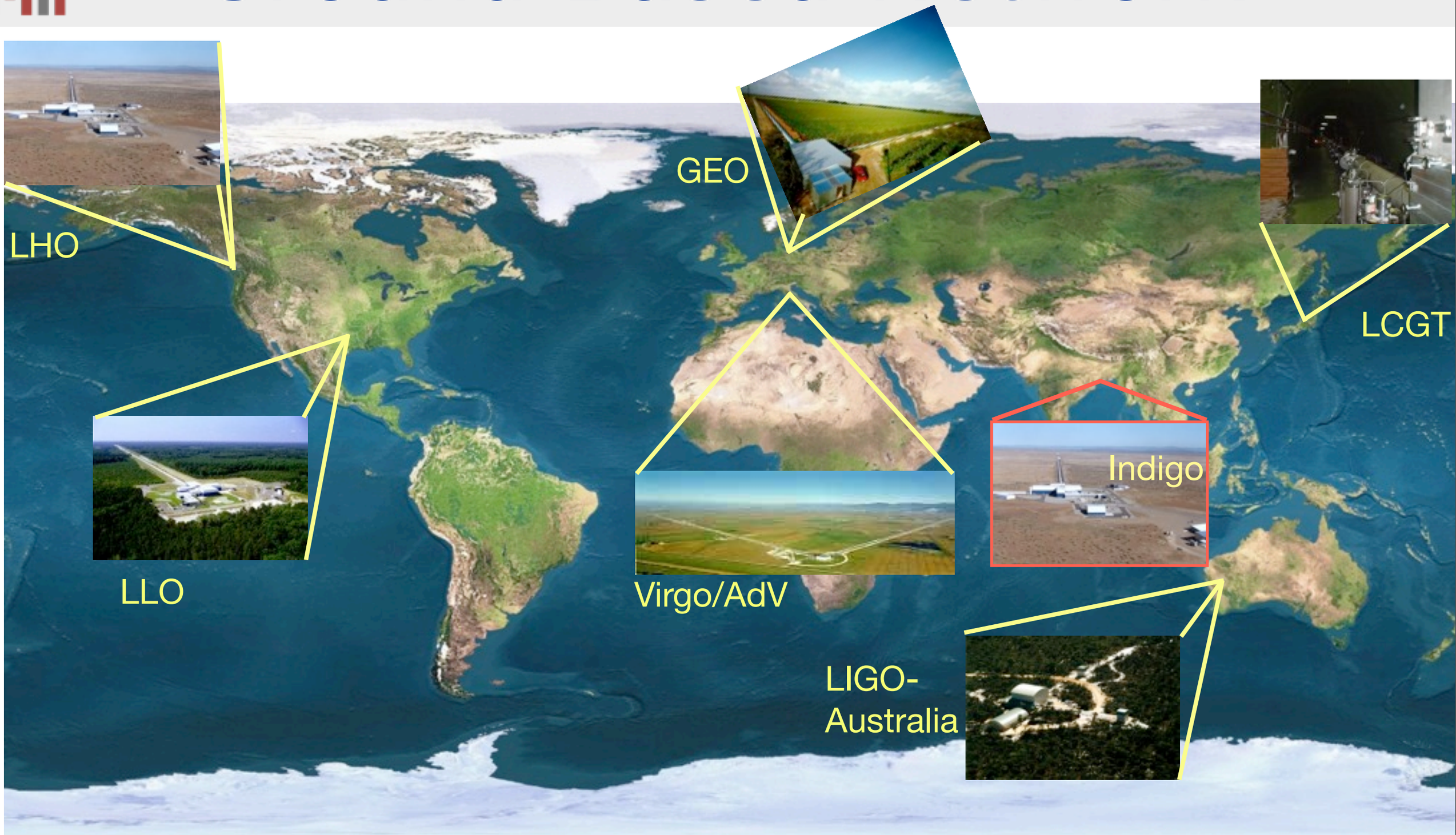




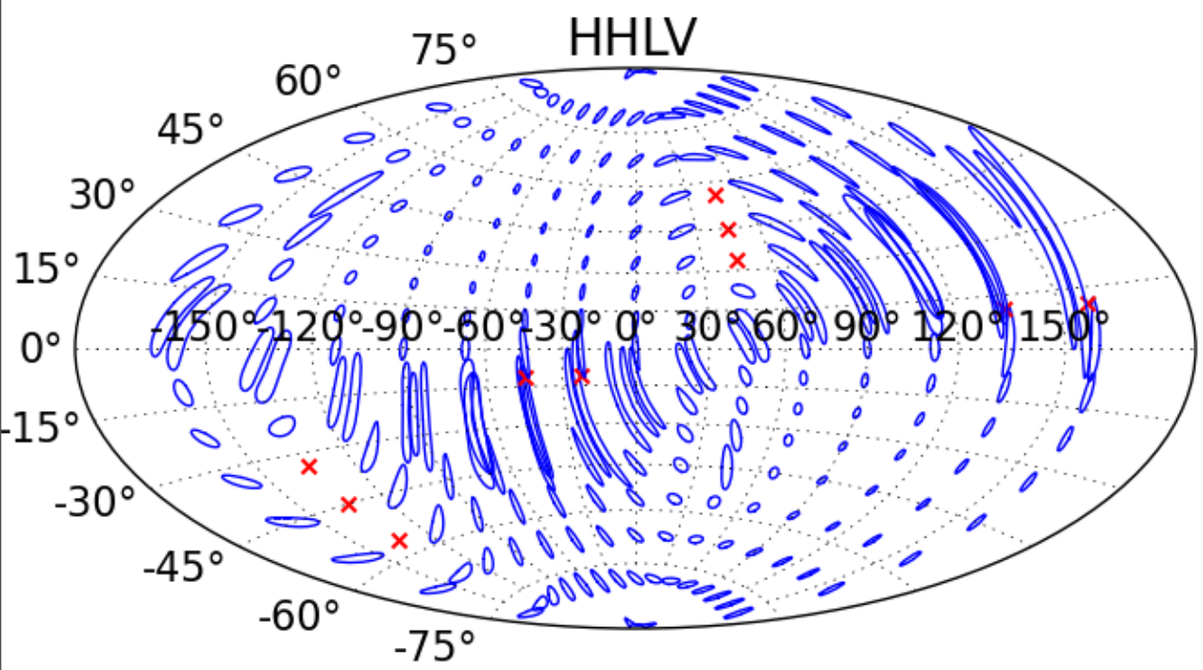


- 3 site detection determines sky location (~0.1 srad/SNR), polarization and amplitude
- For NS/NS inspirals, 2 or more sites give M1, M2, and h_0: *standard candle to 400 Mpc*
- EM / particle priors needed to invert the 12 parameters of spinning BH/BH waveforms: *standard candle to 4000 Mpc*

Ground Based Network



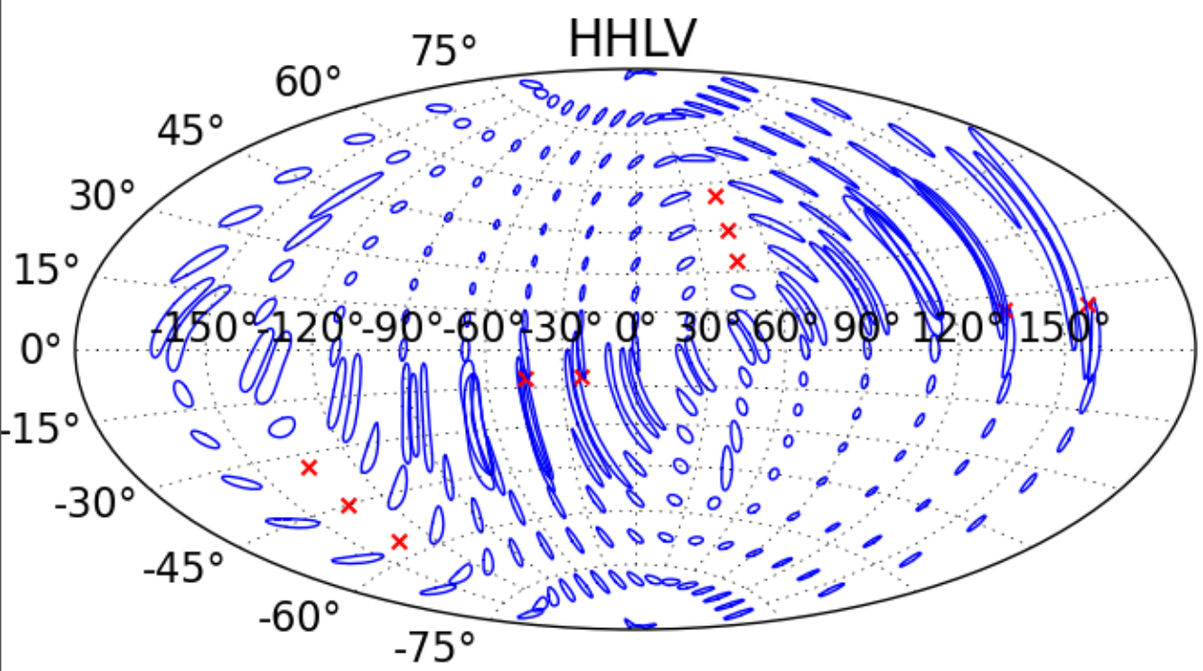
Source localization

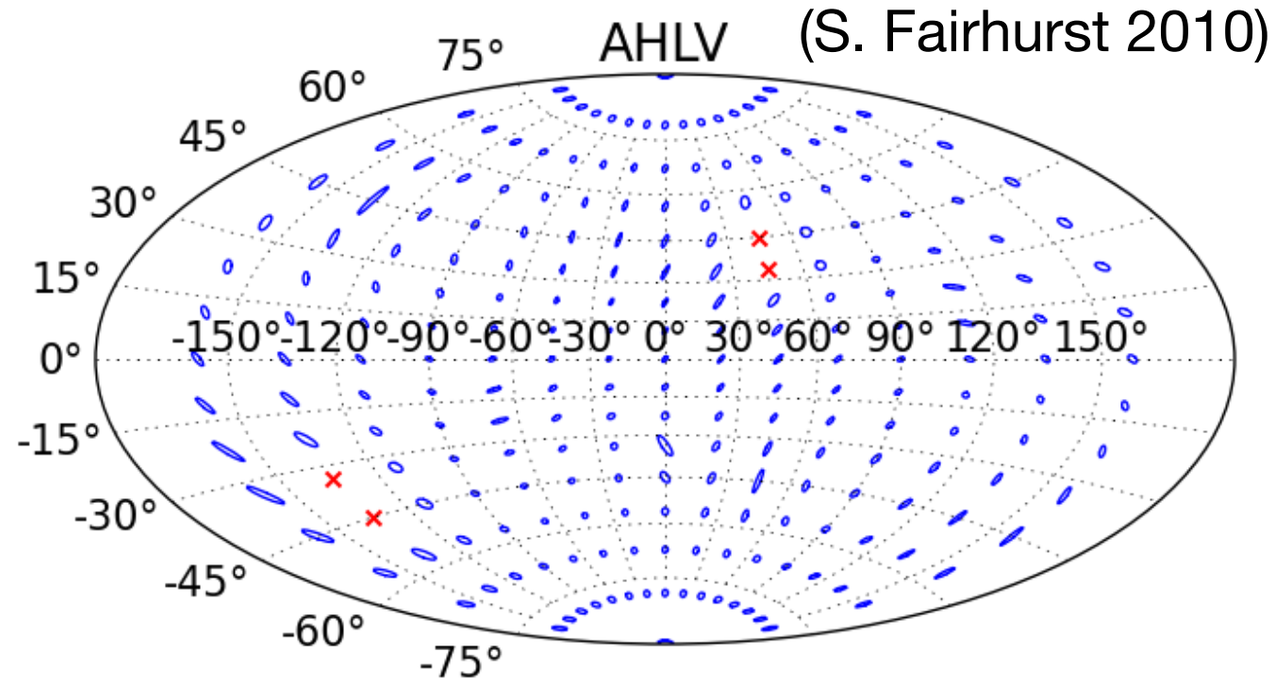


Detectors must be separated long baselines

eg. Hanford, Livingston, Virgo

Source localization





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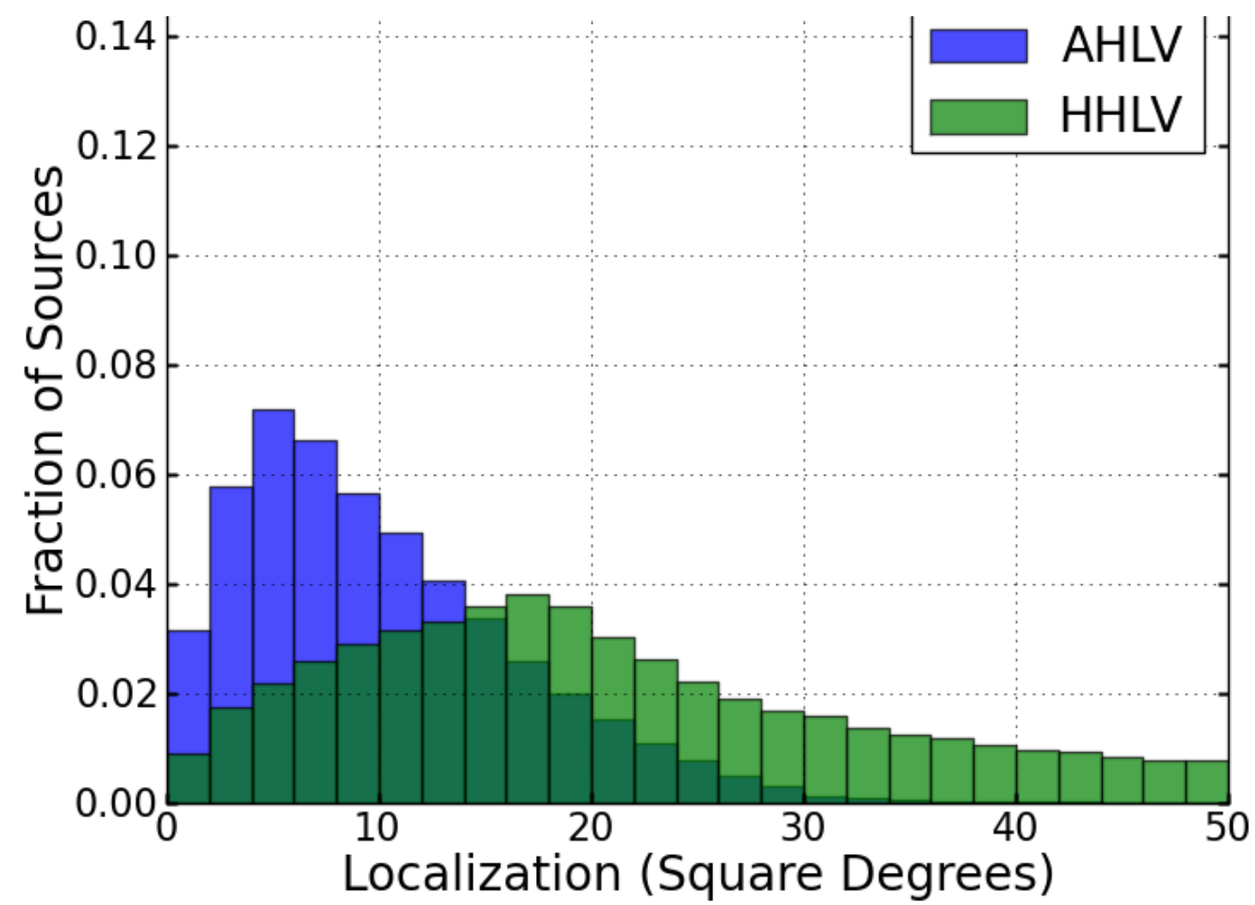


LIGO India

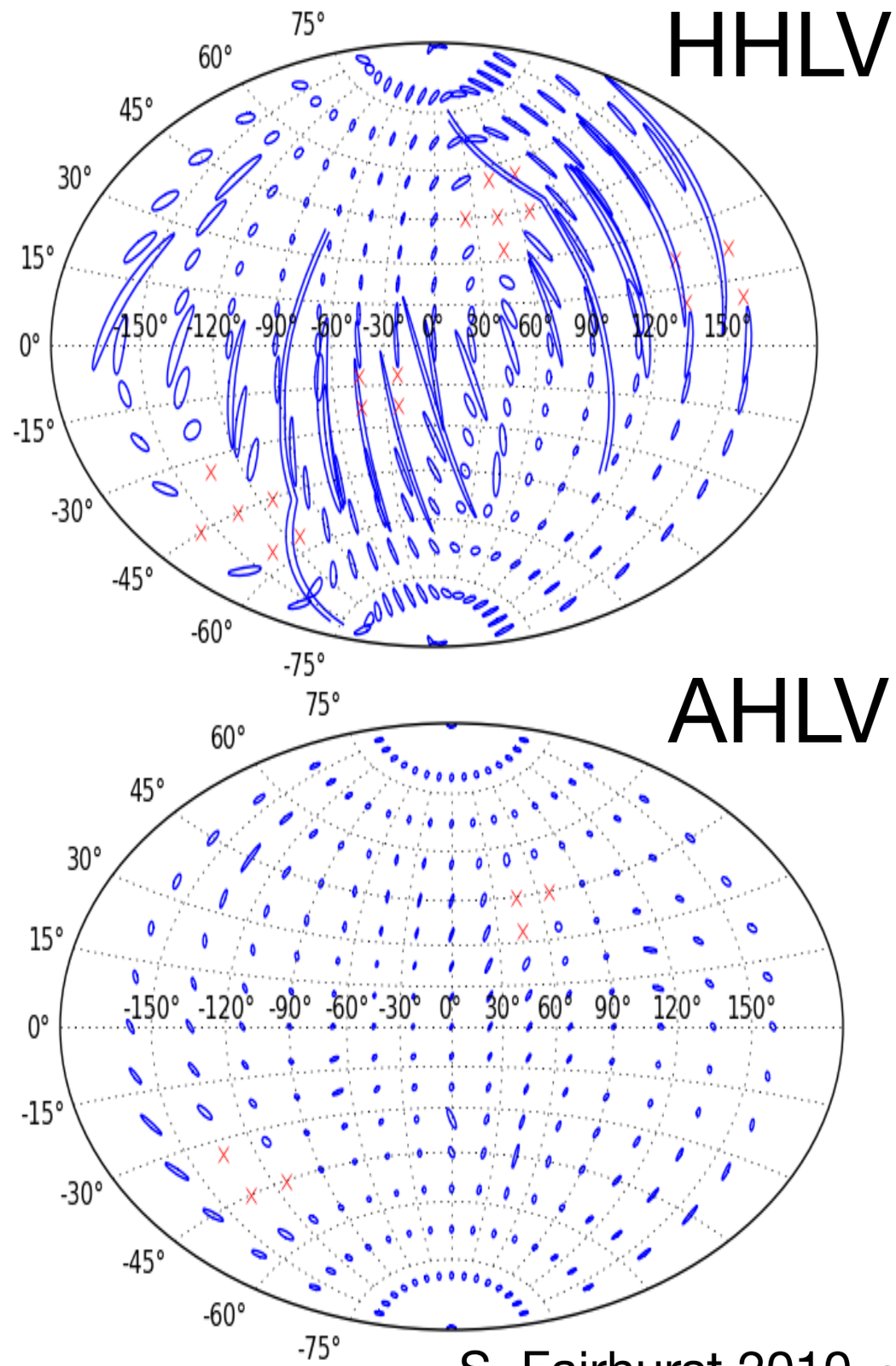
3rd aLIGO detector in India

India (Indigo) provides all the infrastructure - buildings, vacuum, clean rooms and staff

No new cost or delay to NSF/ LIGO project

Improved performance for EM surveys

(analysis shown is for Australian site - similar improvement for Indian site)



S. Fairhurst 2010

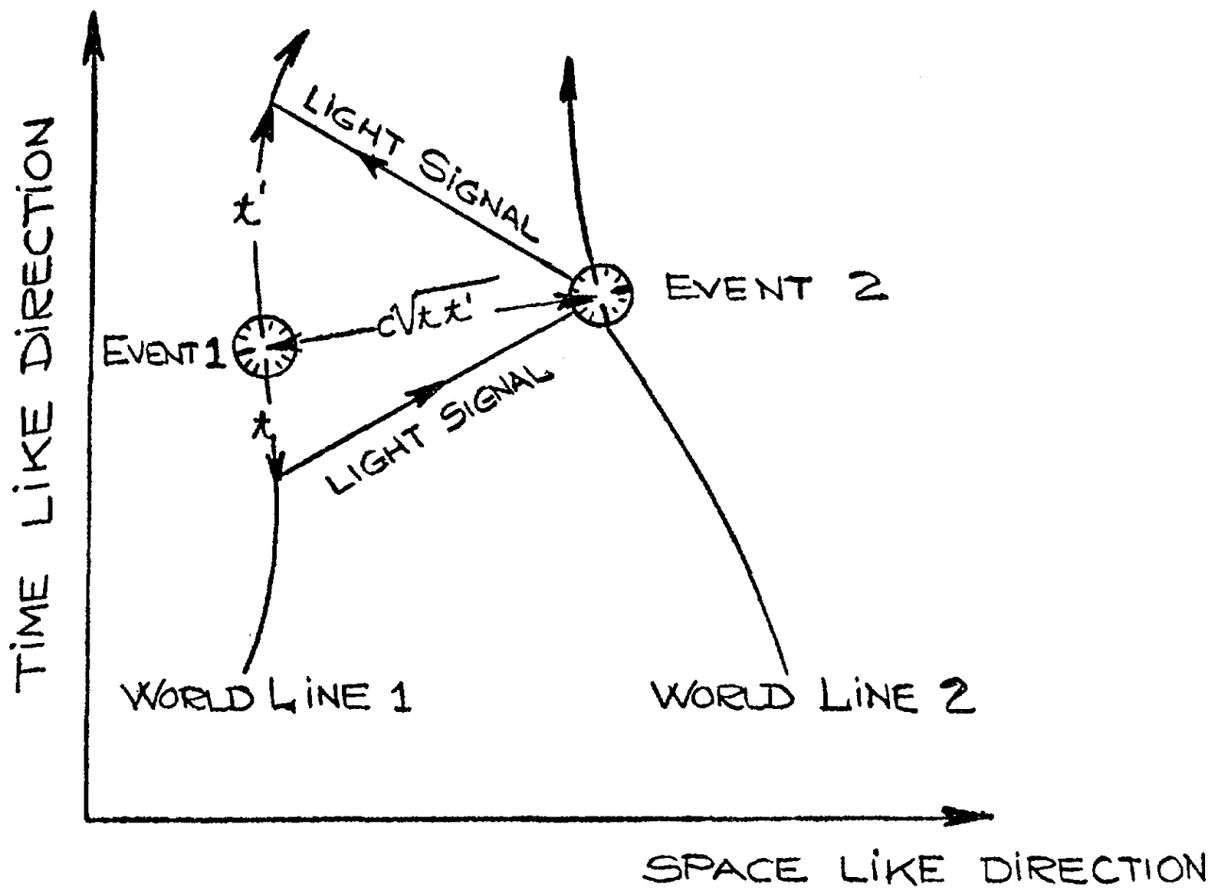
Initial LIGO

Advanced LIGO

Applied LIGO

Quantum + Gravity

Quantum events in a GR metric



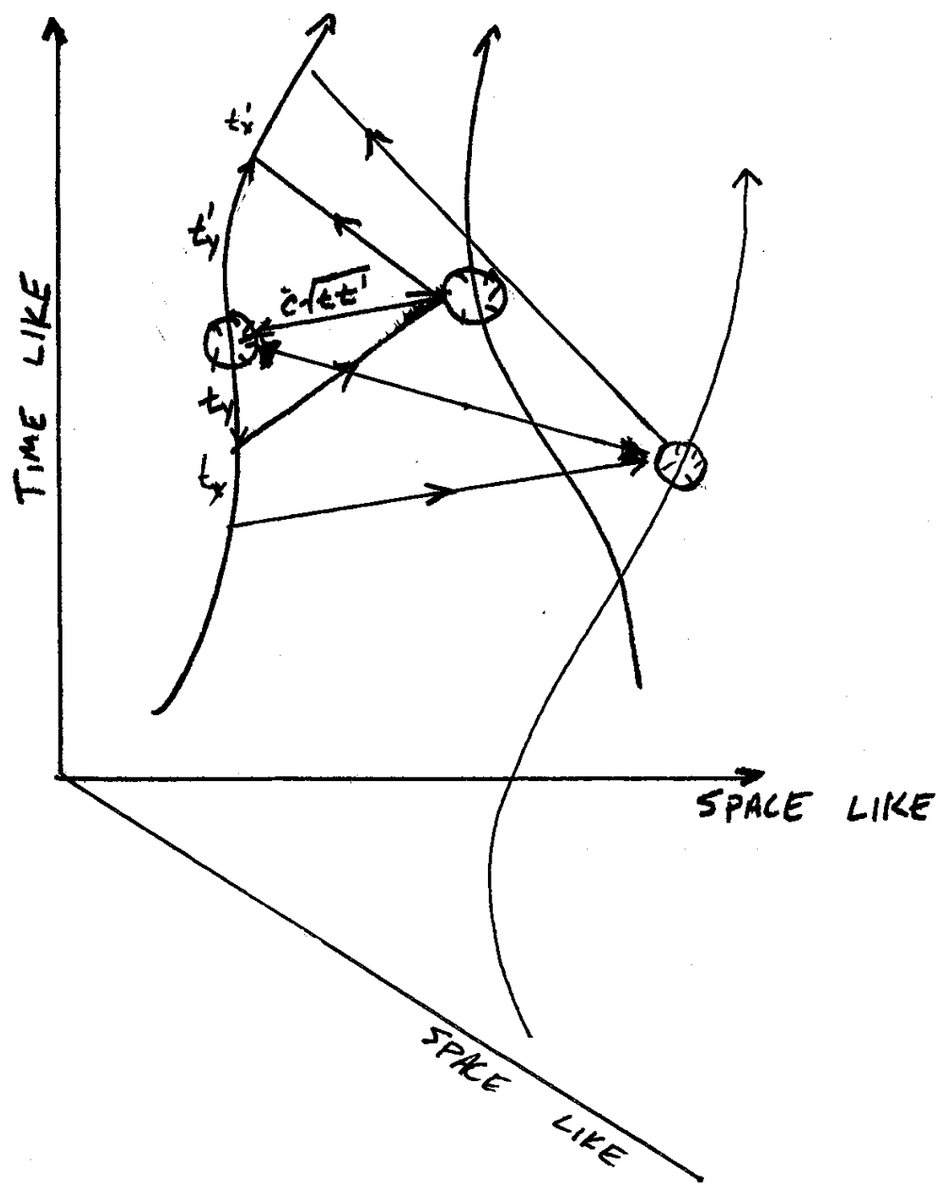
$$\lambda_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35} m$$

$$\tau_P = \sqrt{\frac{\hbar G}{c^5}} = 5.4 \times 10^{-44} s$$

Wigner; Rev. M. Phys. 1957

2-D Wigner measure

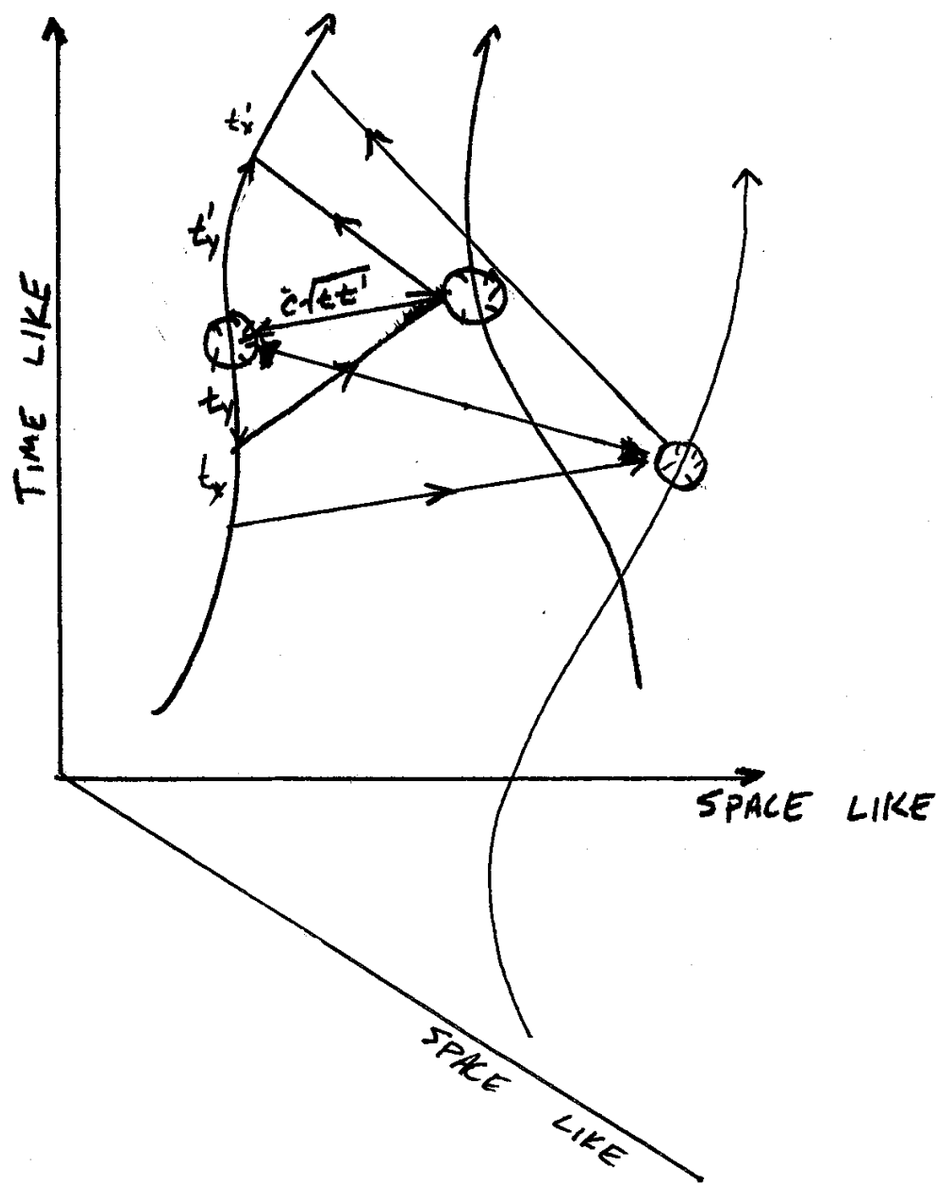
2-D quantum events in a GR metric



two measurements required to fix a two dimensional position

2-D Wigner measure

2-D quantum events in a GR metric

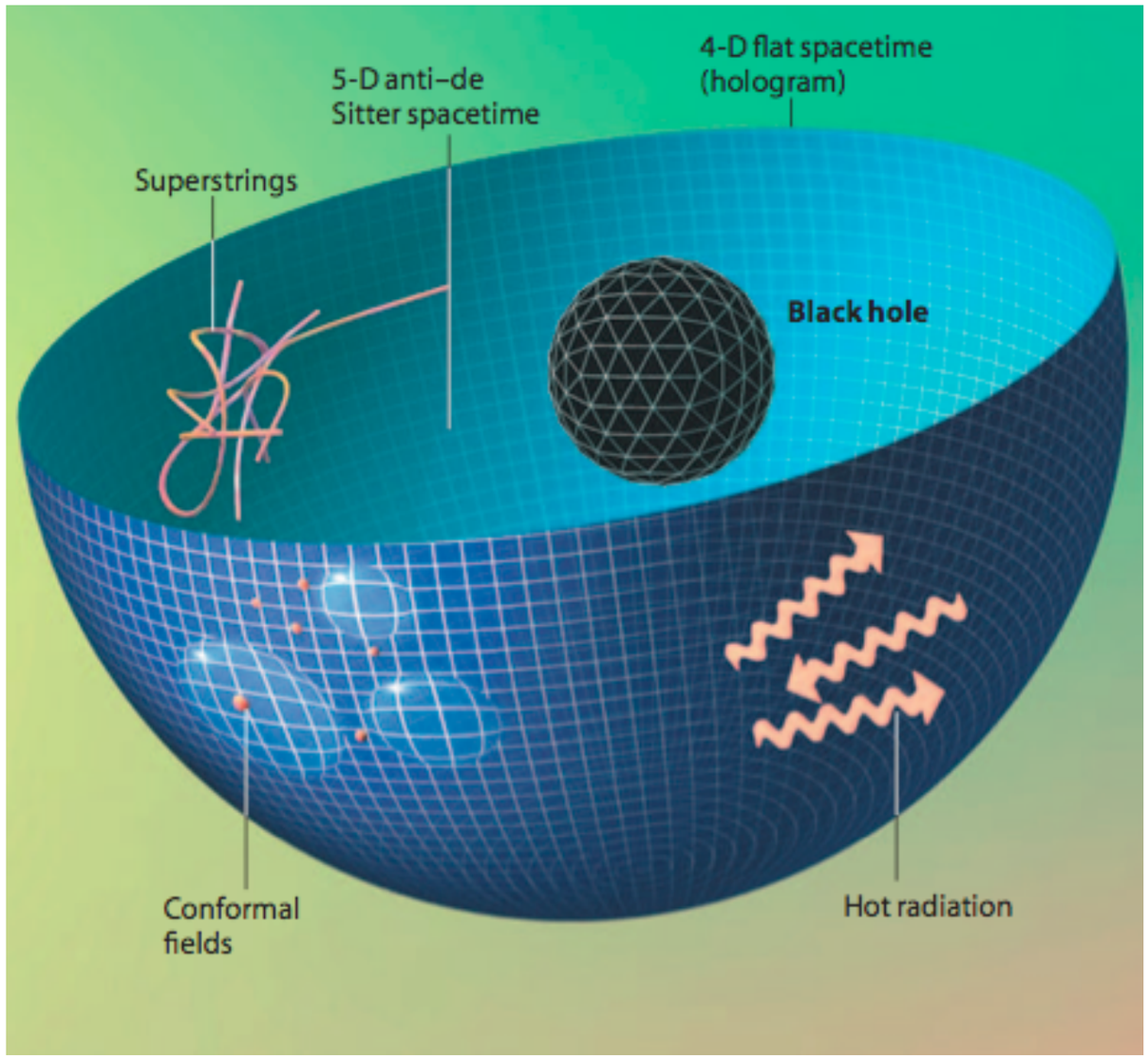


two measurements required to fix a two dimensional position

$$[\hat{X}, \hat{Y}] \neq 0$$

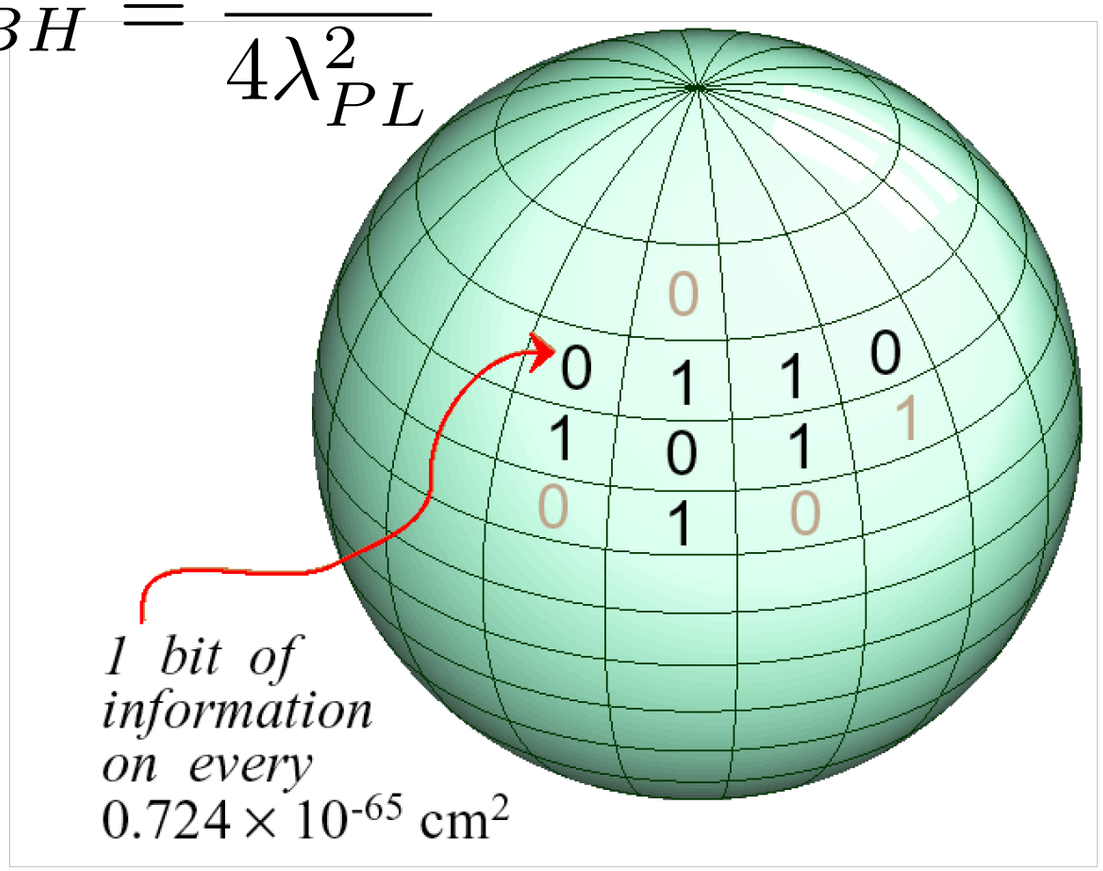
2-dimensional nature of BH entropy

AdS/CFT

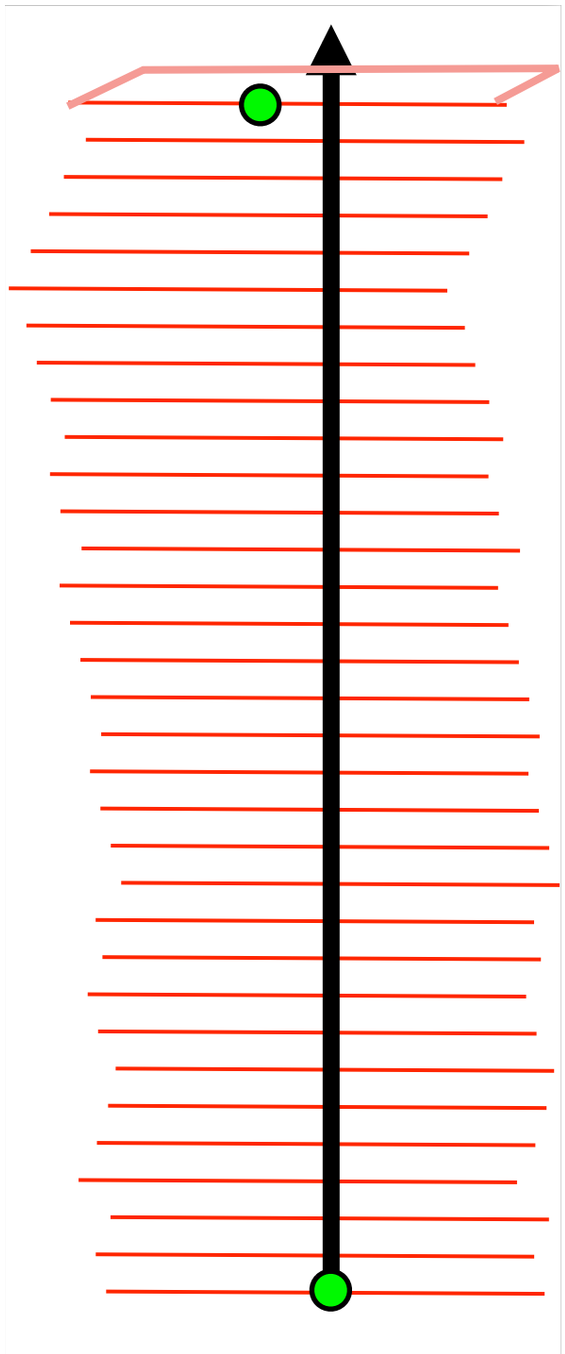


(Bekenstein 2007)

$$S_{BH} = \frac{k_B A}{4\lambda_{PL}^2}$$



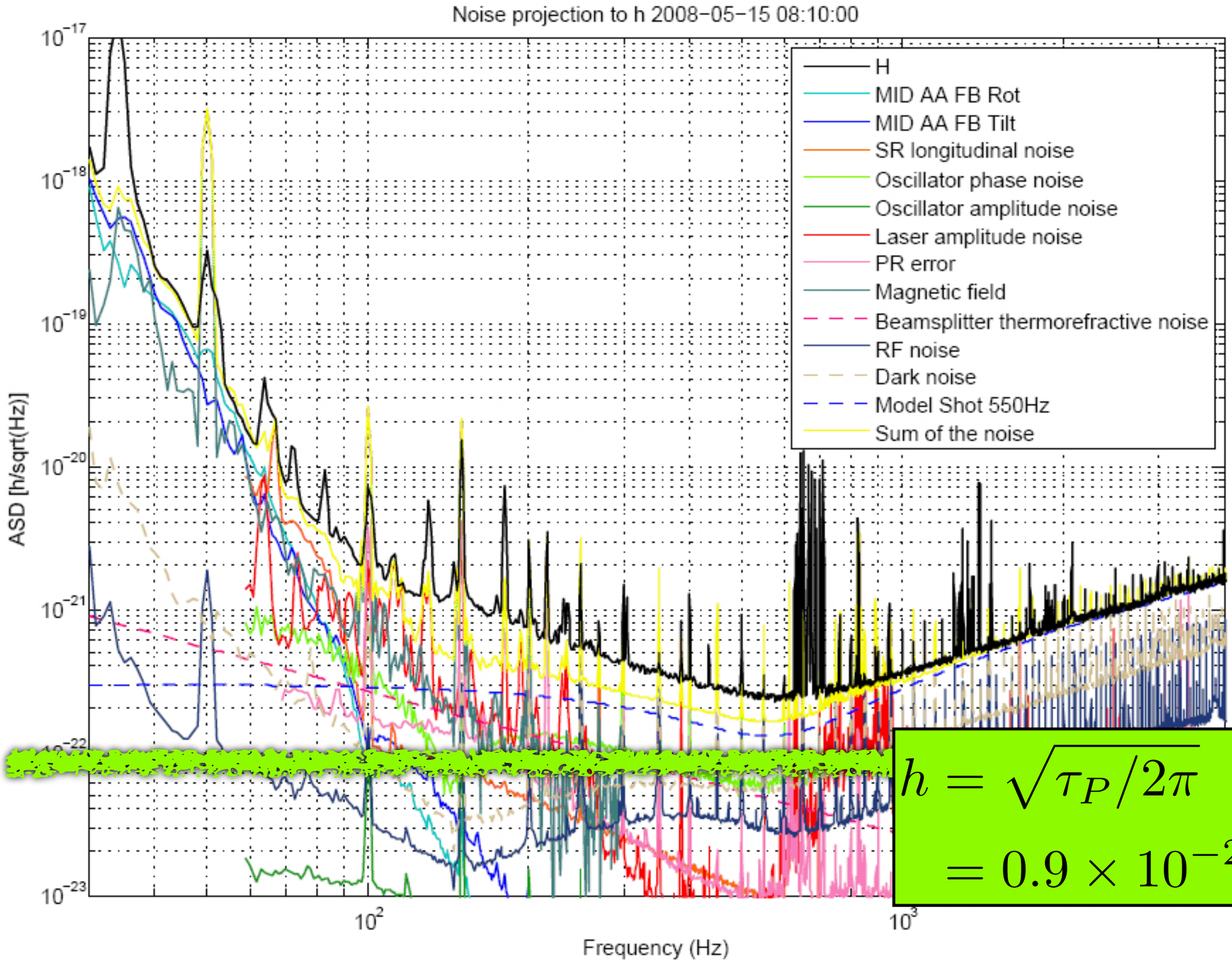
Conjecture:



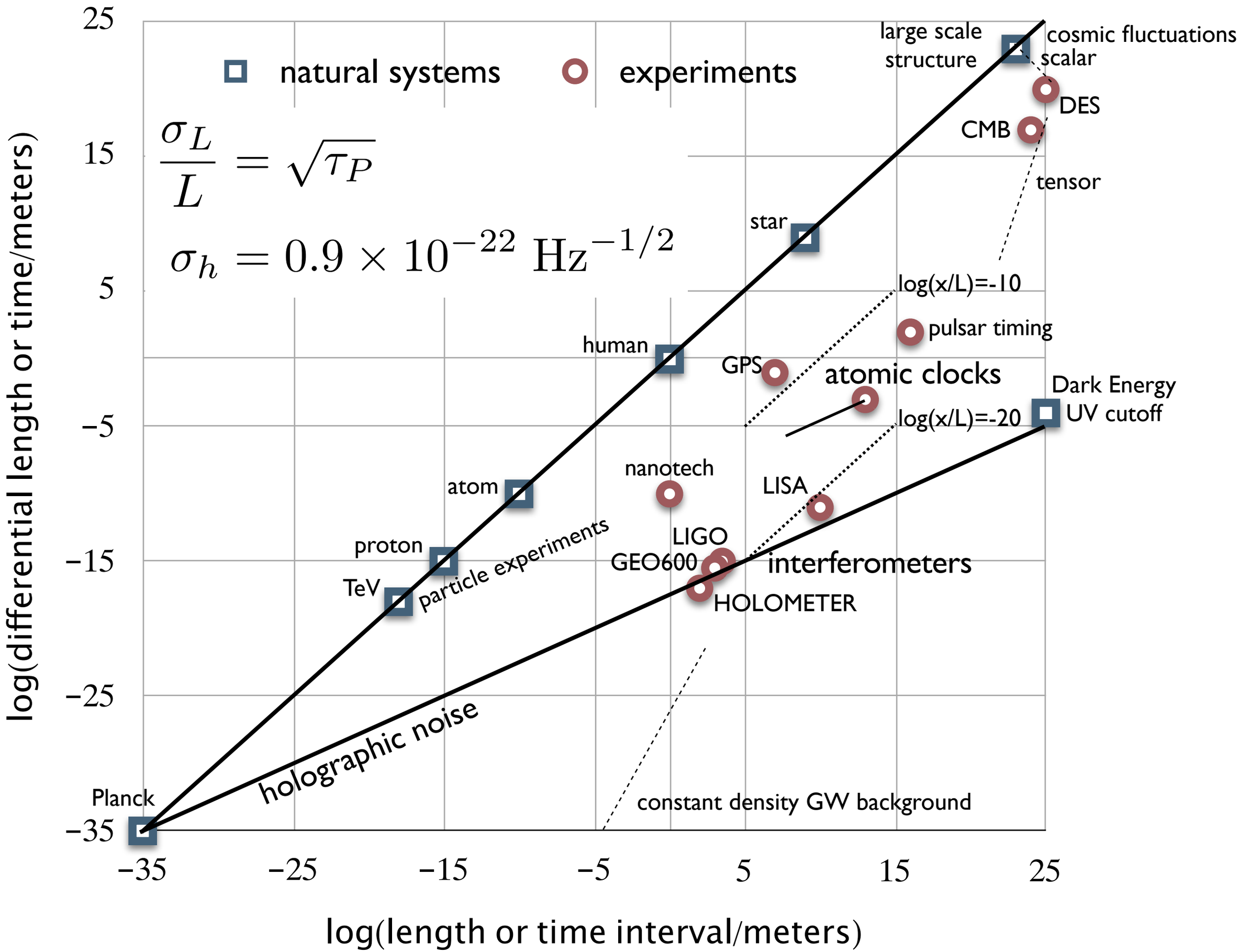
Position wave function has *transverse* uncertainty, coherent across a null surface, as a random walk with step size τ_P

$$[\hat{X}, \hat{Y}] = i\lambda_P^2$$

Claimed GEO600



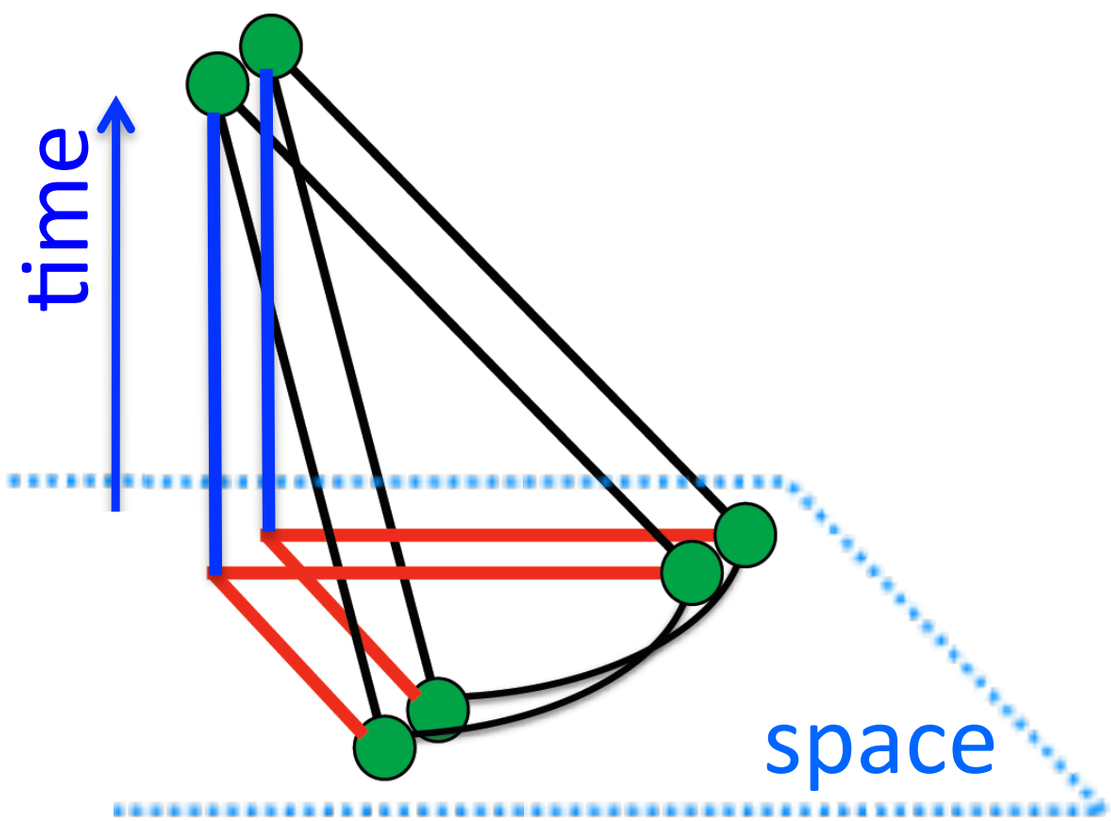
$$h = \sqrt{\tau_P / 2\pi}$$
$$= 0.9 \times 10^{-22}\ Hz^{-1/2}$$


natural systems
experiments
$$\frac{\sigma_L}{L} = \sqrt{\tau_P}$$
$$\sigma_h = 0.9 \times 10^{-22}\ \mathrm{Hz}^{-1/2}$$
large scale structure
cosmic fluctuations
scalar
DES
CMB
tensor
star
log(x/L)=-10
pulsar timing
human
GPS
atomic clocks
Dark Energy
UV cutoff
log(x/L)=-20
nanotech
LISA
atom
LIGO
proton
GEO600
interferometers
TeV
particle experiments
HOLOMETER
holographic noise
Planck
constant density GW background
25
15
5
−5
−15
−25
−35
−35
−25
−15
−5
5
15
25
log(differential length or time/meters)
log(length or time interval/meters)

Coherence

Coherent over a null surface

Correlation experiment eliminates technical noise, provides a difference measurement, and allows for modulation:



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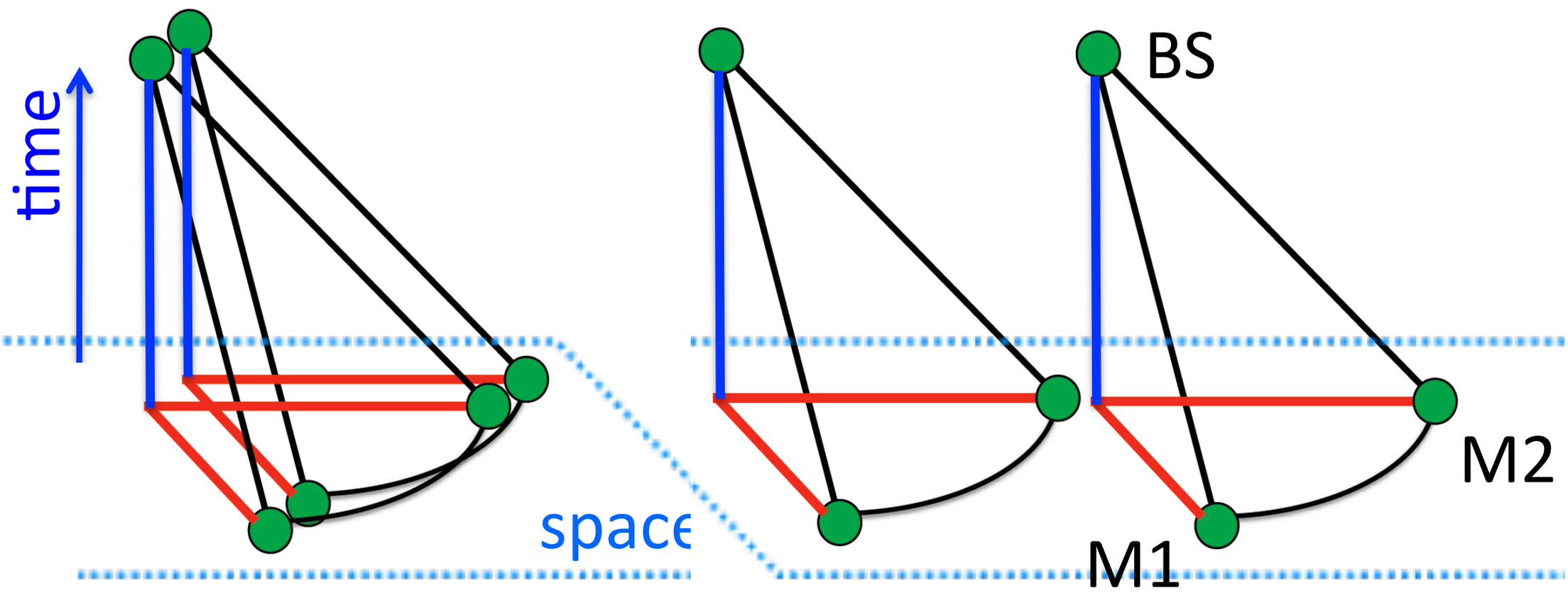
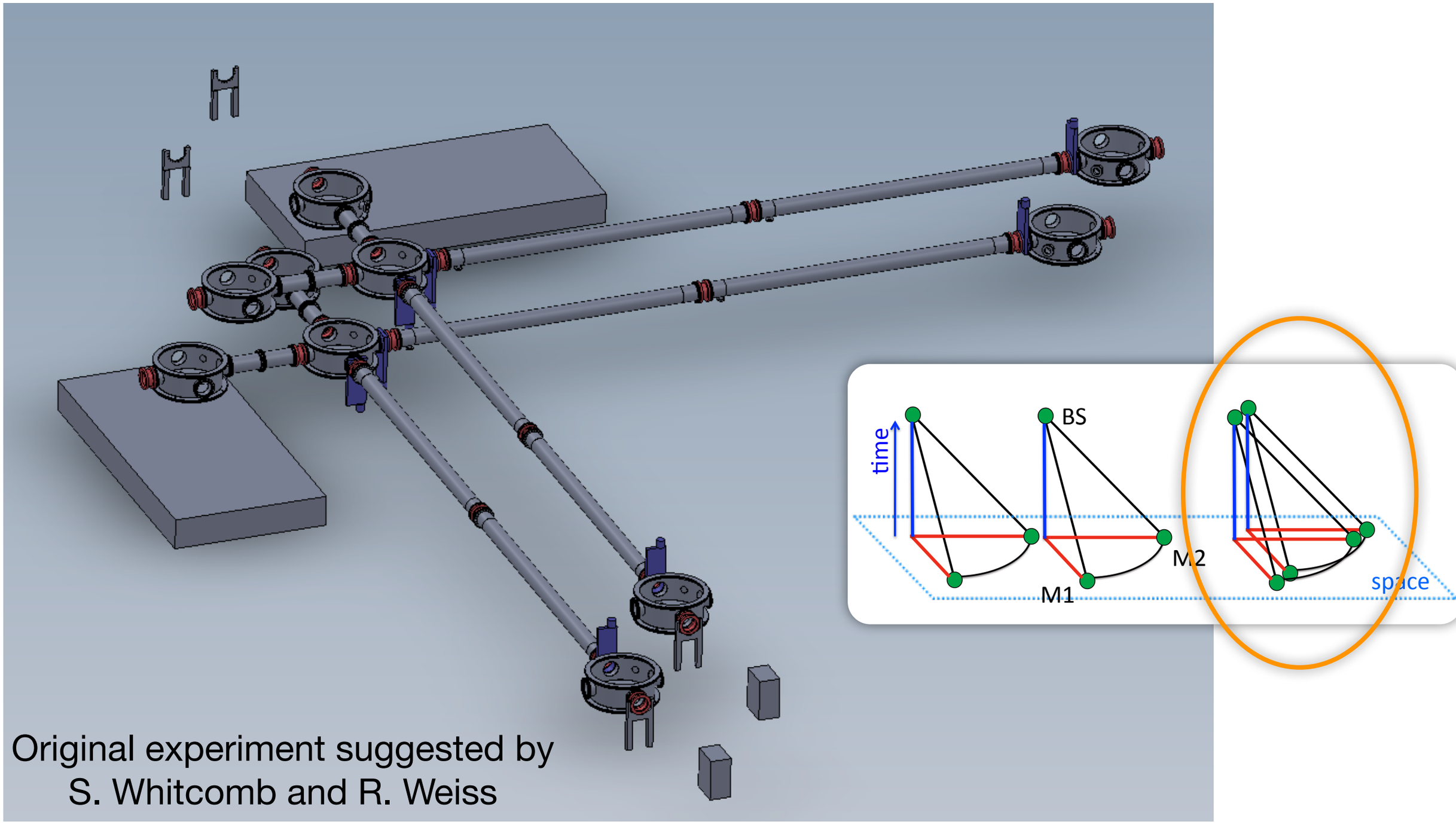


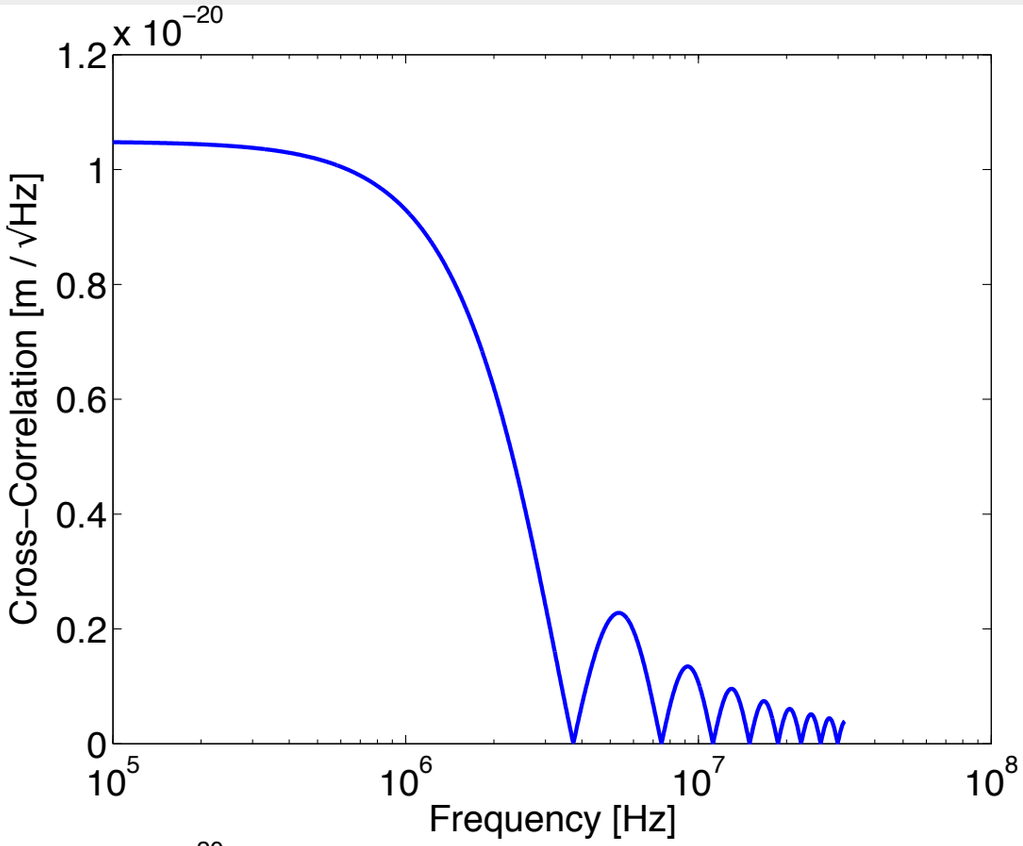
Holometer @ Fermilab

http://holometer.fermilab.gov



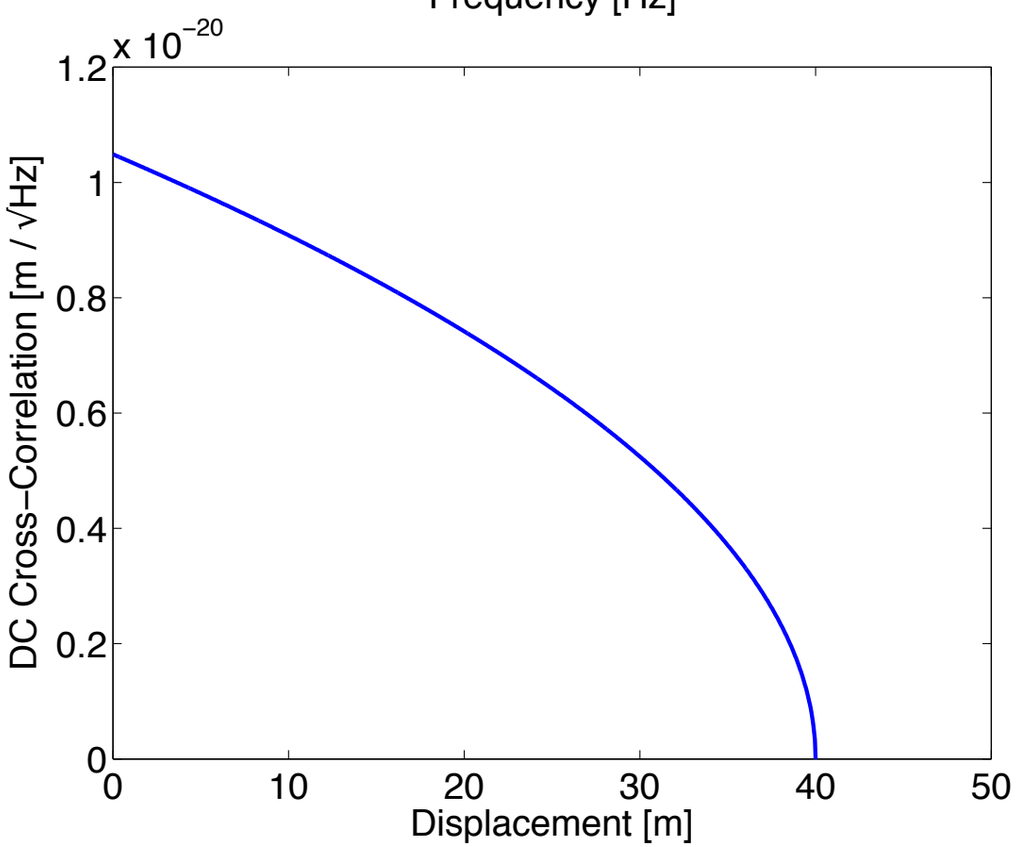
Original experiment suggested by
S. Whitcomb and R. Weiss

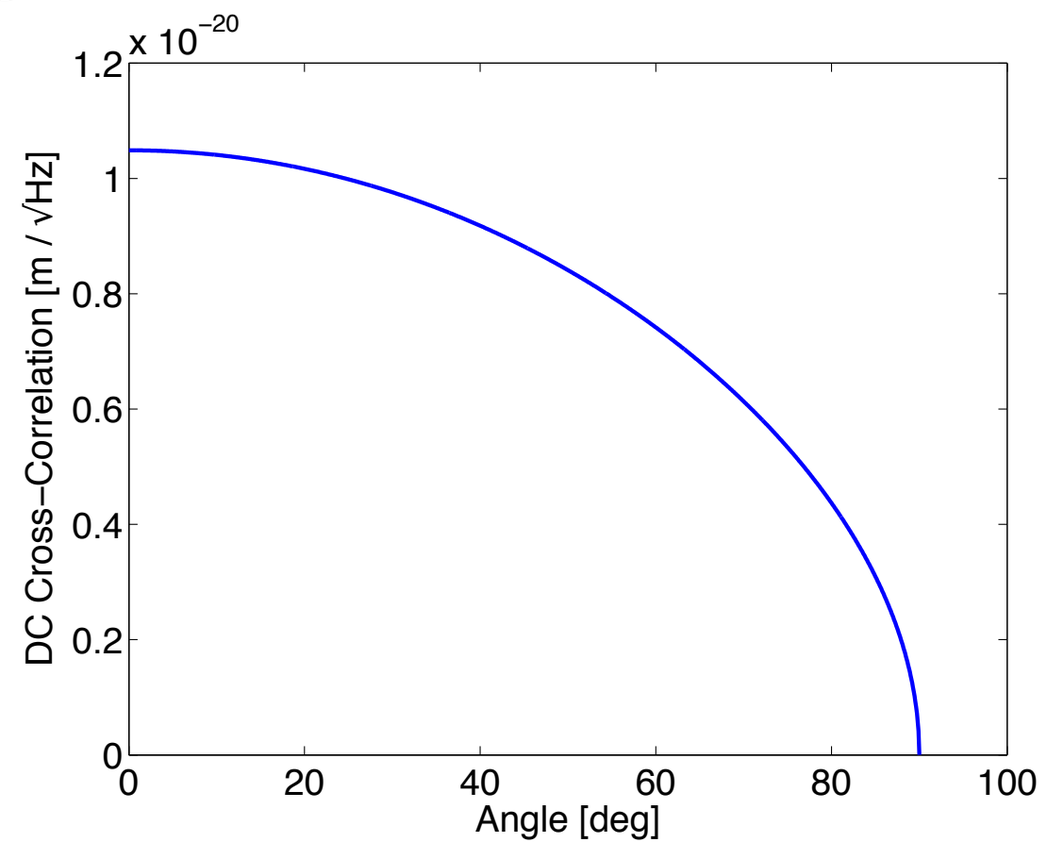
Signatures



Arxiv [1002.4880] Interferometers as Probes of Planckian Quantum Geometry

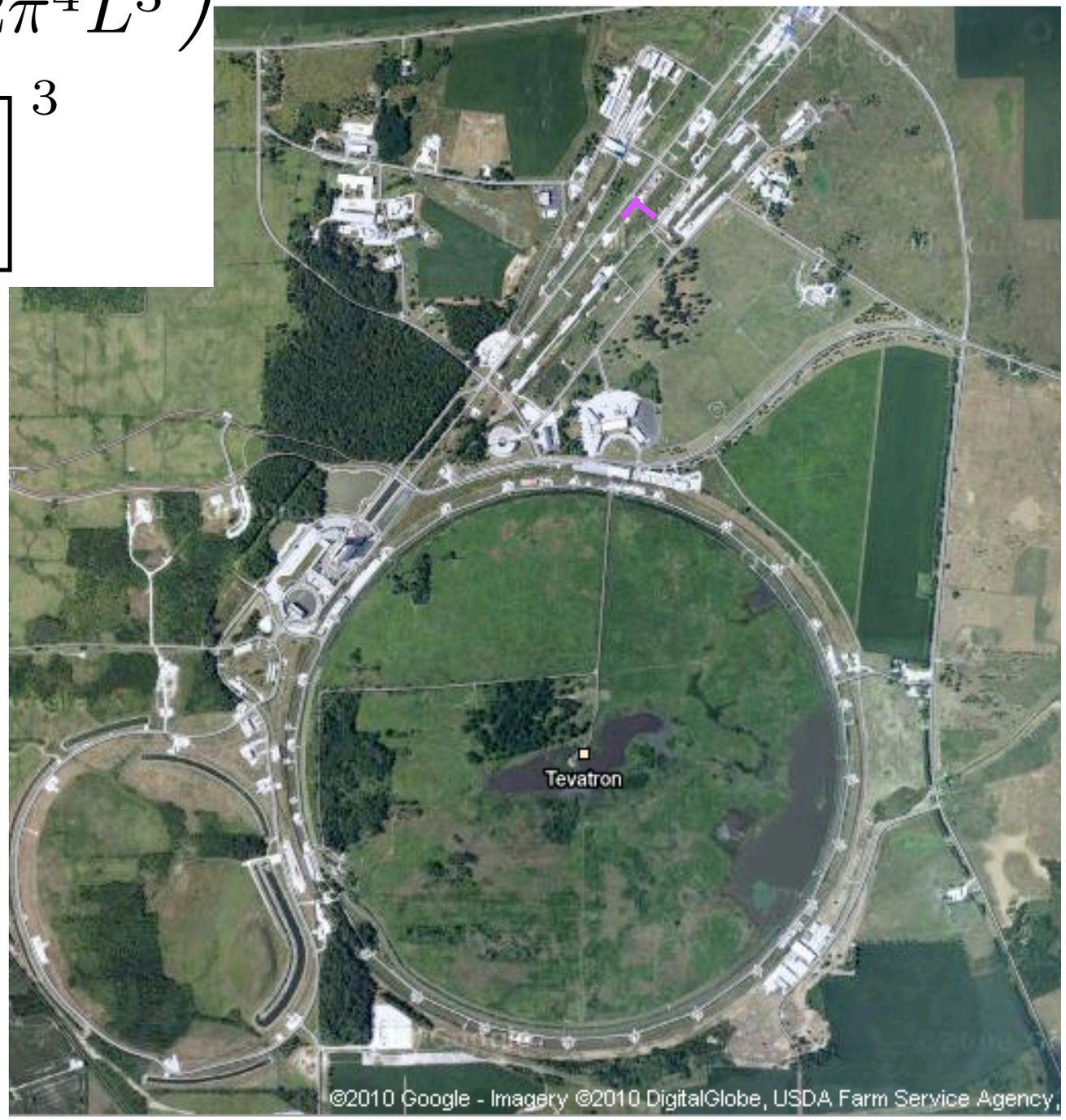
- Flat in frequency until FSR/2 @ 2 MHz
- Depends on interferometer separation
- Smoothly varying function of angle





$$t_{obs} > \left(\frac{h}{P_{BS}}\right)^2 \left(\frac{\lambda_{opt}}{\lambda_P}\right)^2 \left(\frac{c^3}{32\pi^4 L^3}\right)$$

$$= 5 \text{ min} \left[\frac{1 \text{ kW}}{P_{BS}}\right]^2 \left[\frac{40\ m}{L}\right]^3$$



Two independent interferometers

Colocated (~1 m)

Wide bandwidth (40 MHz)

40 m cavity test in meson tunnel

groundwork for full holometer Oct. ’11

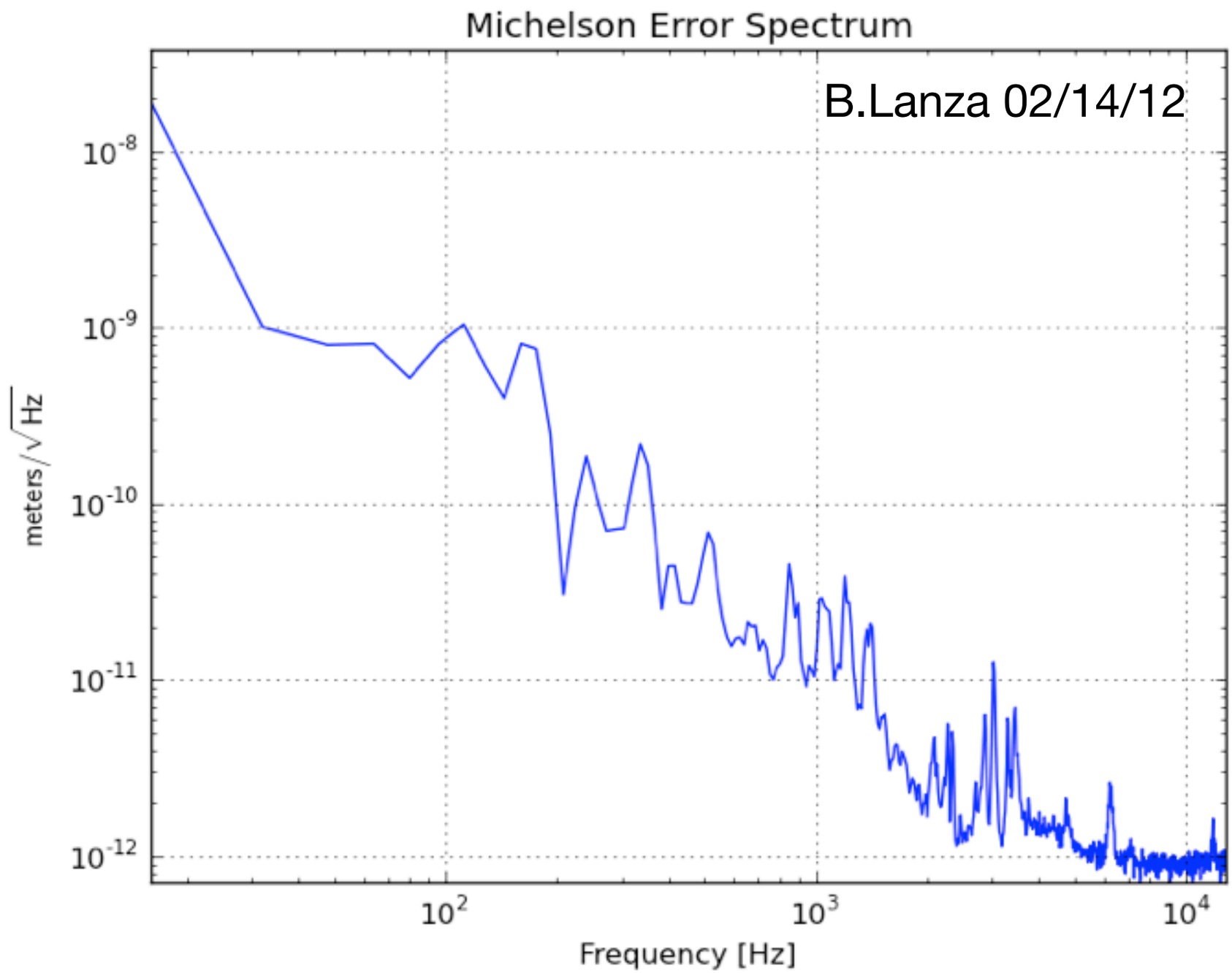
First Light

First vacuum tube installed Oct. 2011

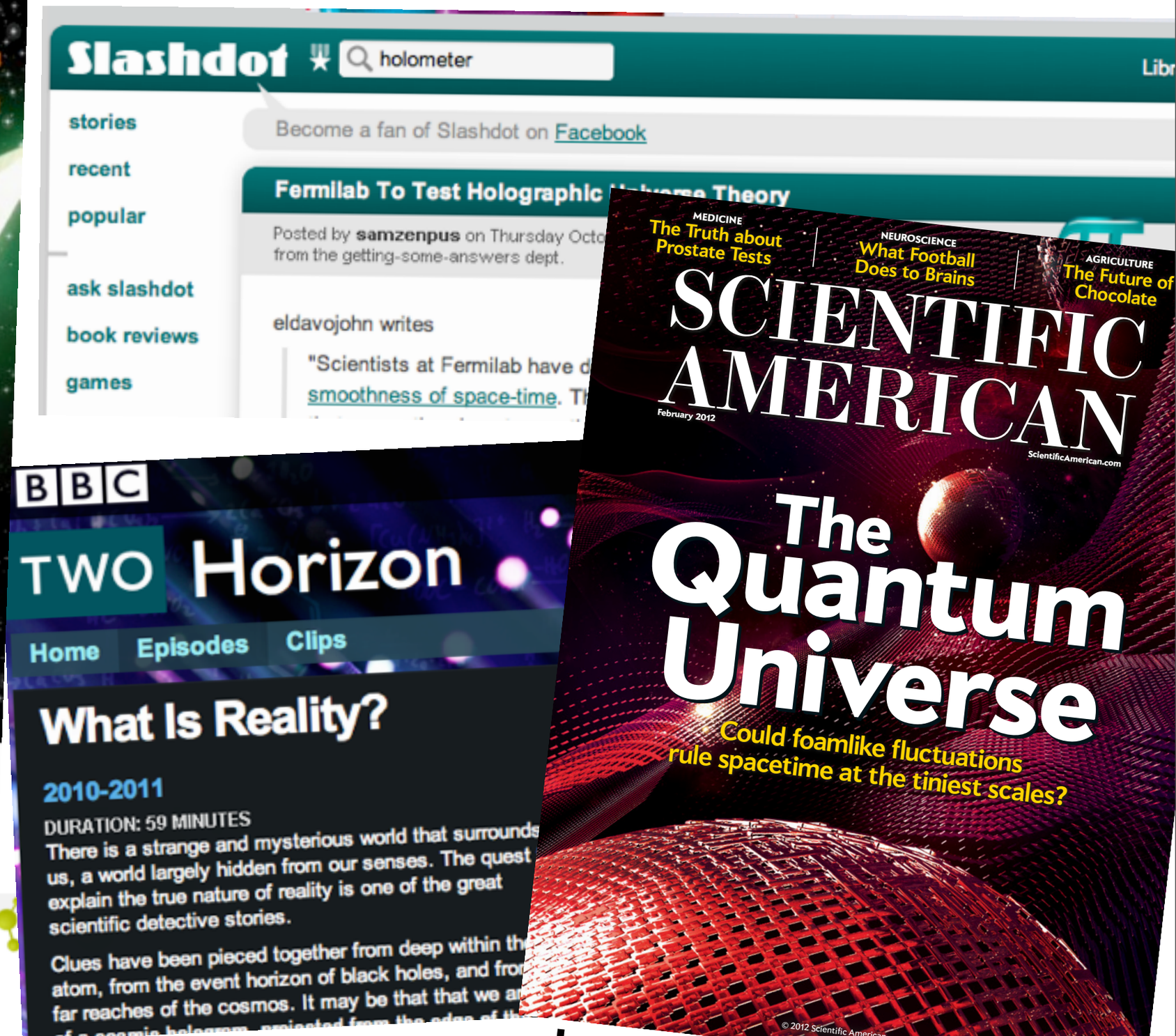
First light Feb. 2012

Second light April 2012

Coherent operation Sept. 2012

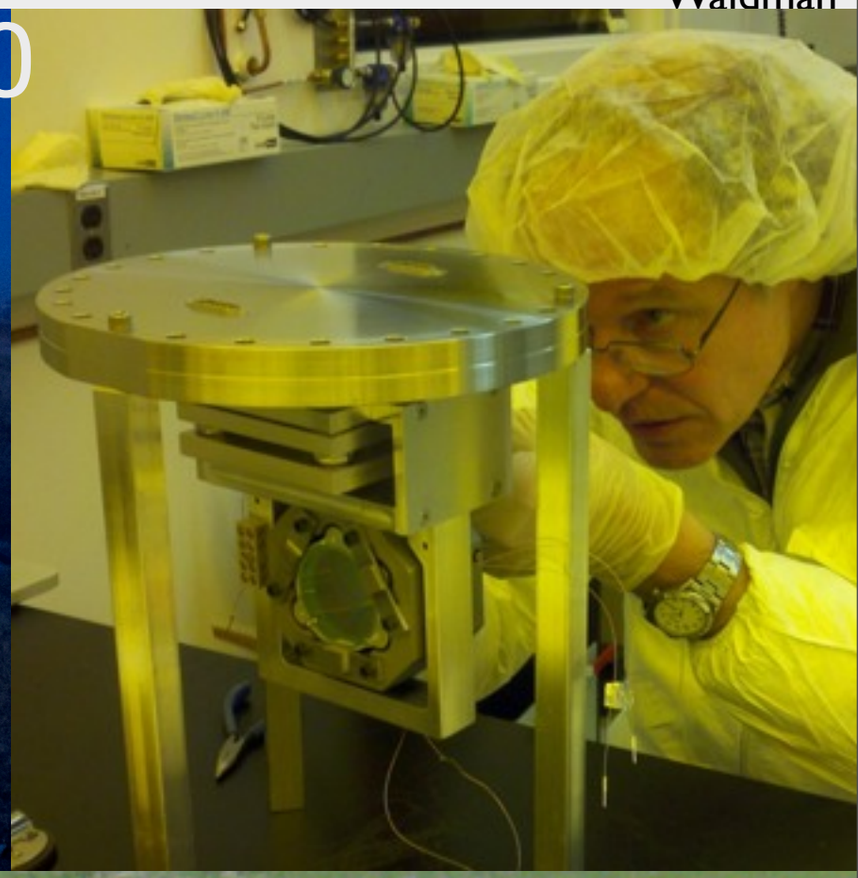


January 2009



January 2012

Fermilab E990



Historical aside

VOLUME LXI APRIL 1925 NUMBER 3

THE EFFECT OF THE EARTH'S ROTATION ON THE VELOCITY OF LIGHT

PART I

By A. A. MICHELSON

"Theory of the effect of the earth's rotation on the velocity of light as derived on the hypothesis of the fixed ether."

Review

- Initial LIGO recorded 2 years of data at $h \sim 10^{-23}$ with an expected rate of ~0.1/yr
- 100 Mpc detectors online in **2015**, first science data
- **First detections 2016-2017**
- **Design sensitivity by 2020**, dozens of GWs/yr

- Fermilab Holometer has installed first 40 m interferometer with First Light Februrary 2011
- Full experiment during the summer 2012