An Introduction to Advanced LIGO and the Test Mass Mirror Coatings

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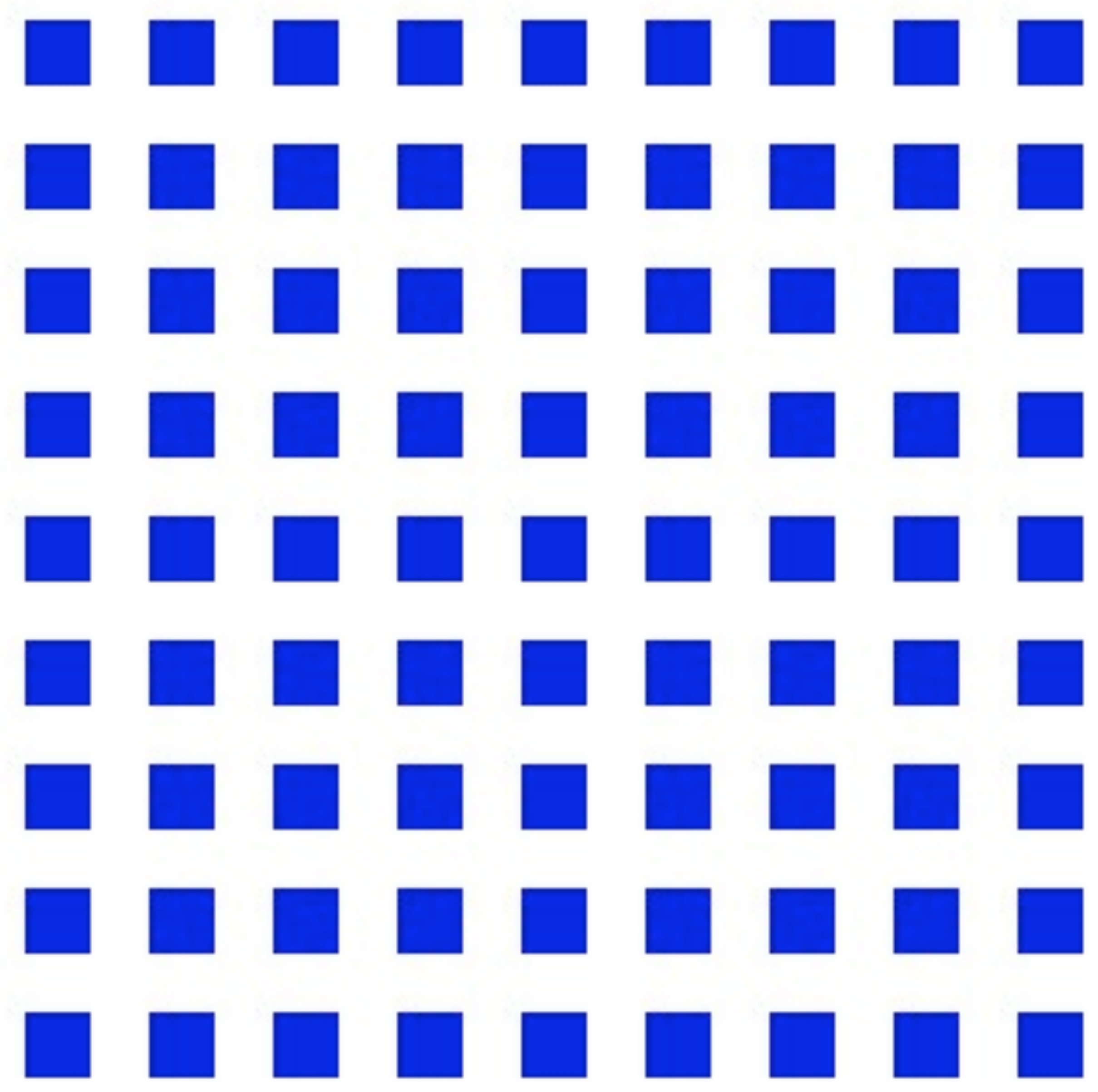
LIGO DCC: LIGO-G080303-00-Z

Why look for Gravity Waves?

- Gravity Waves important test of General Relativity
  - Test the Speed of Gravity Waves
  - Test GR in the Strong field limit
- Many GW sources not well understood with EM telescopes
  - Black Holes
  - Neutron Stars
  - Supernovae
  - Early Big Bang
  - New Window on Universe = Expect Surprises
- Difficult Challenge: BNS Inspiral in Virgo Cluster produces a strain on Earth of only 10^{-21}

Gravity wave moves masses in quadrapole



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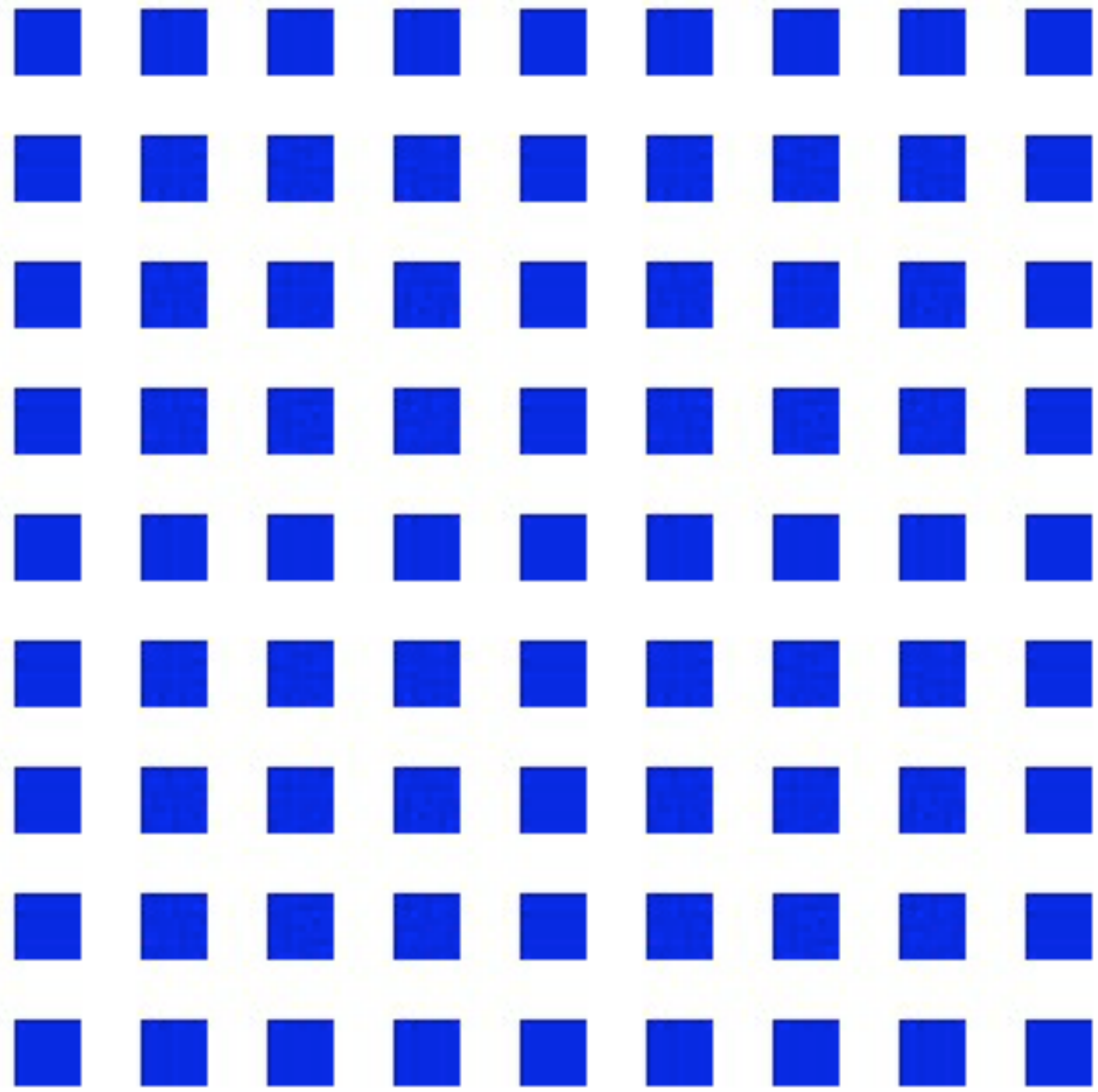
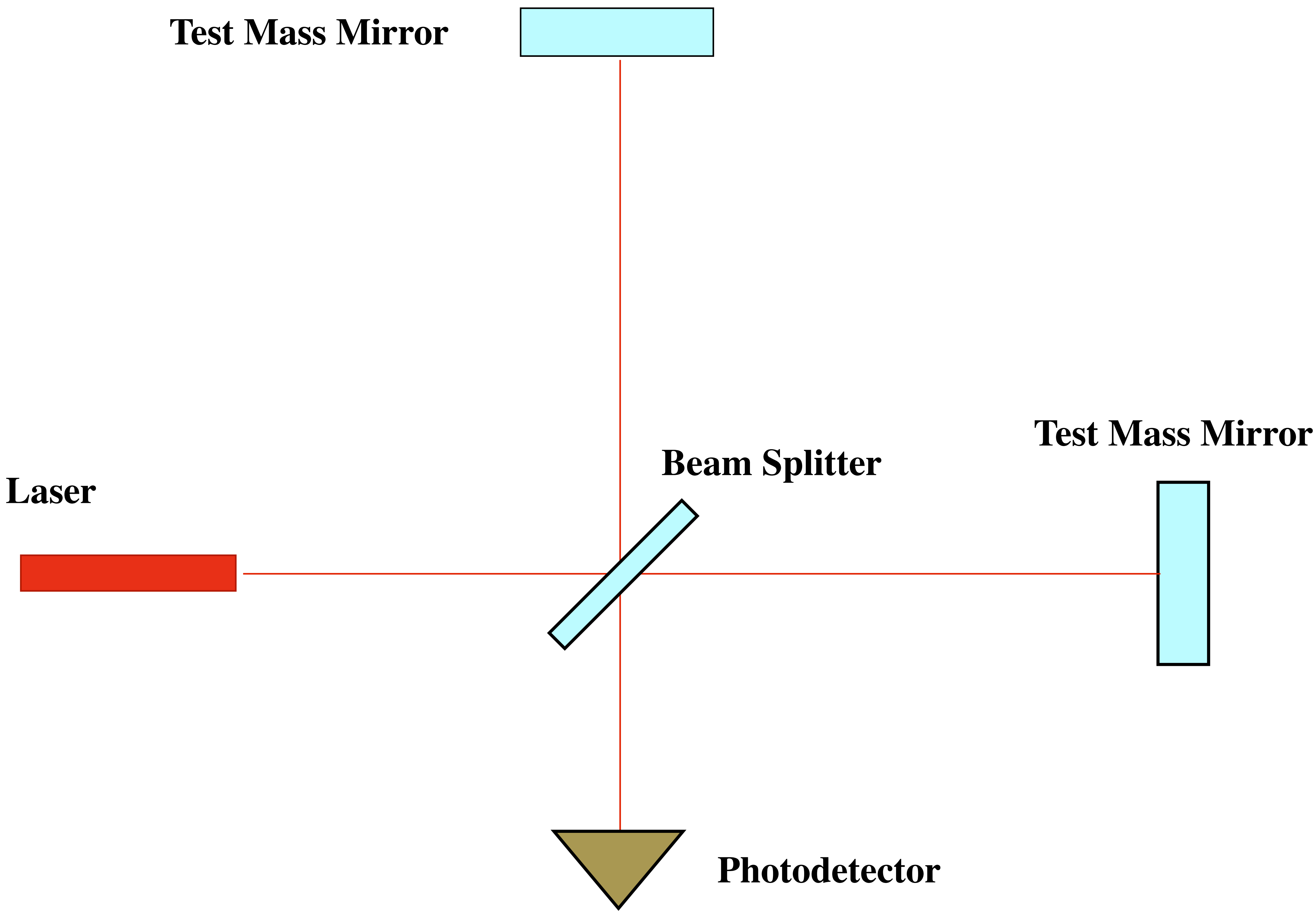
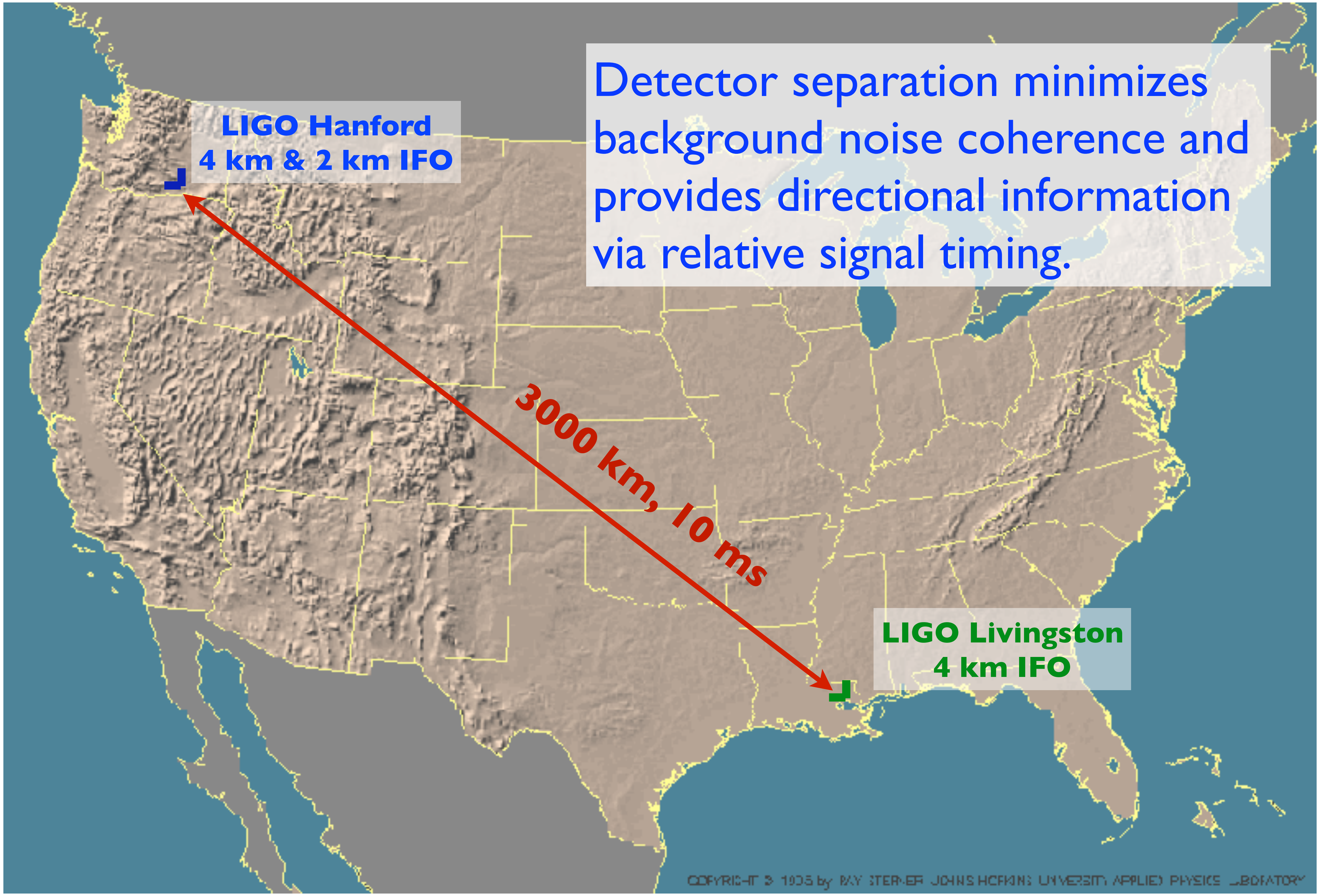


Gravity wave moves masses in quadrapole

Basic Interferometer



LIGO Observatory Sites



LIGO Livingston


LIGO Livingston
End Station

LIGO

LIGO Observatory Sites


LIGO
Hanford

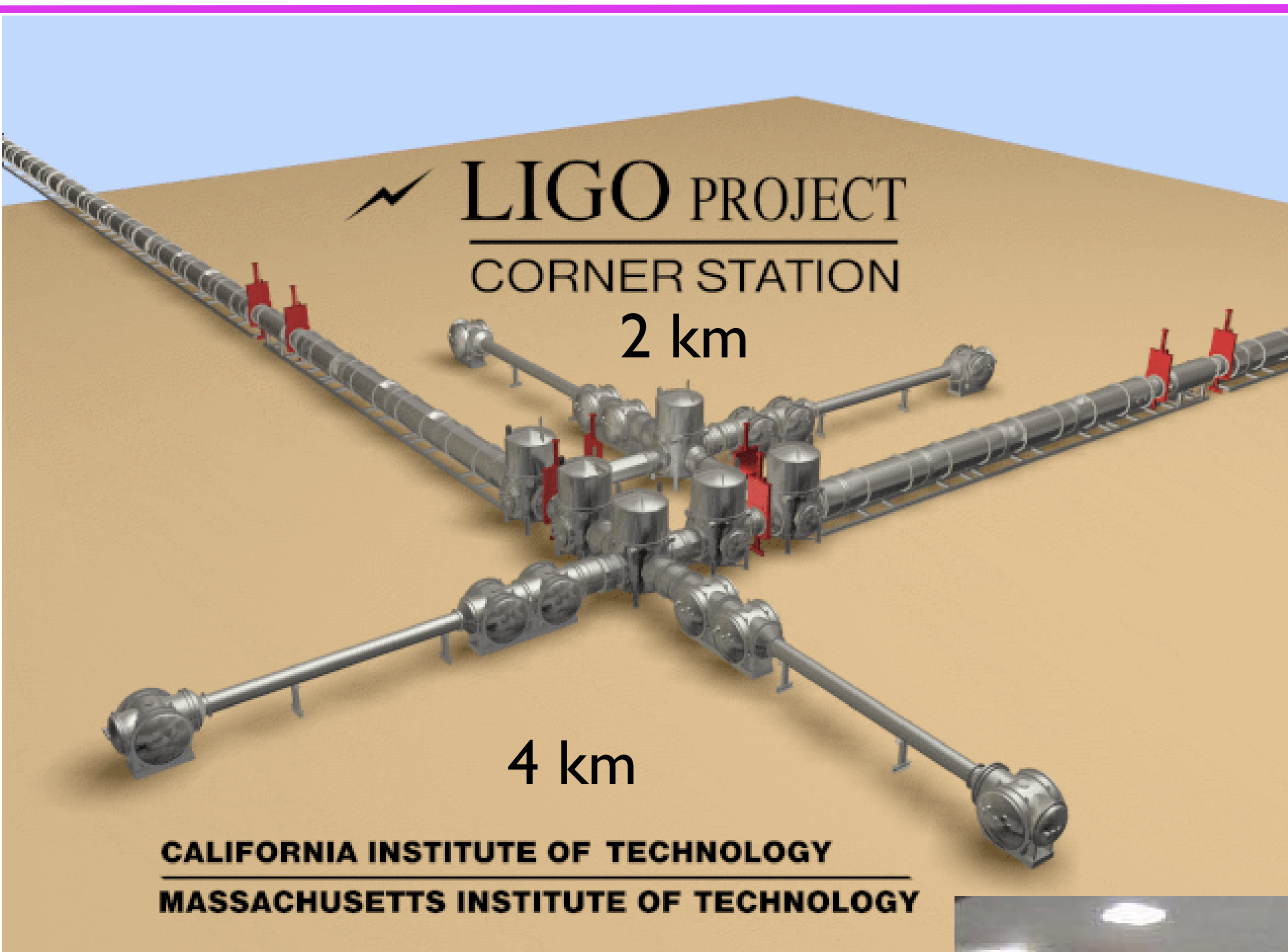
LIGO

GW Interferometers

LSC

LIGO

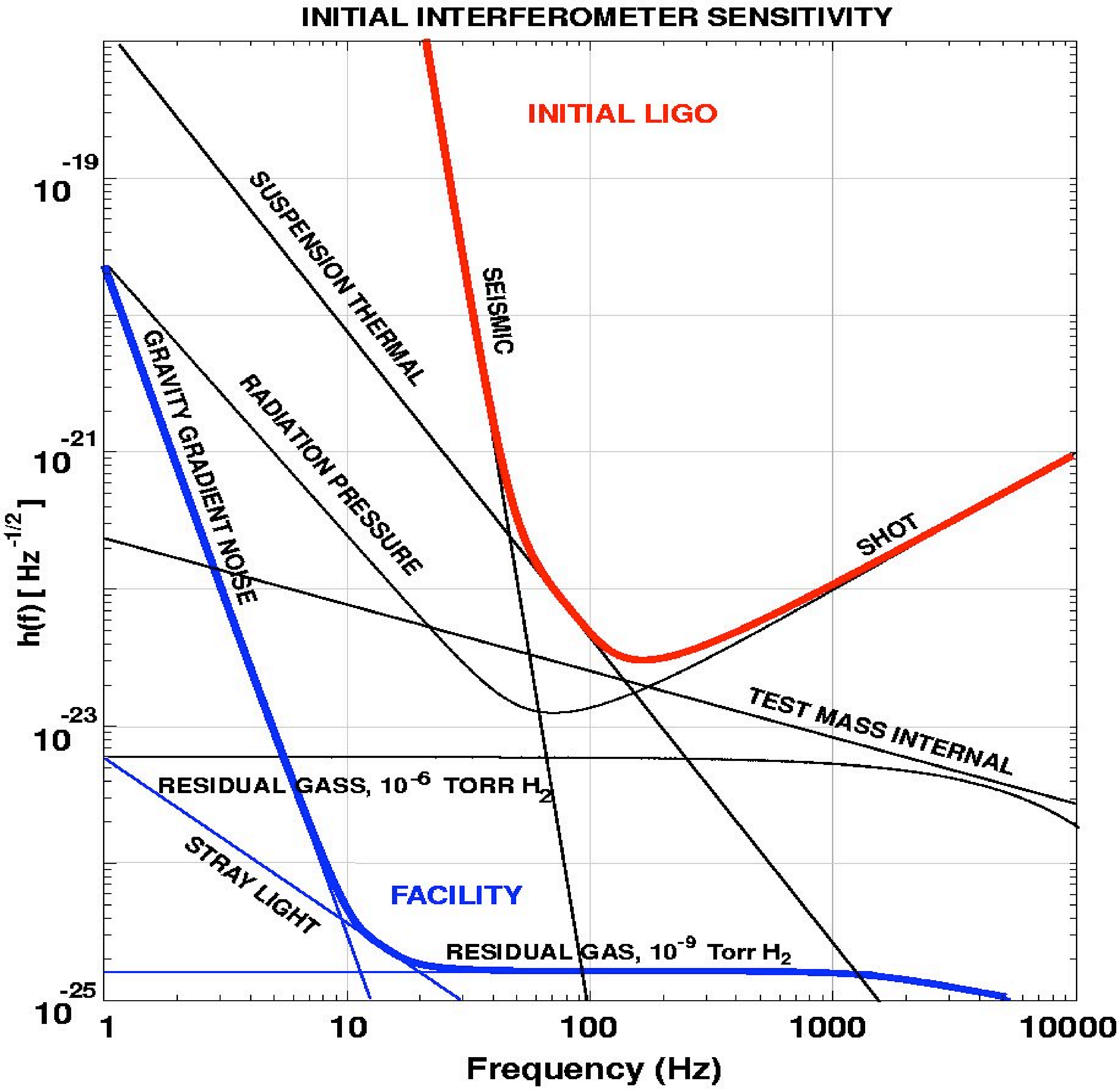
Design Layout of LIGO



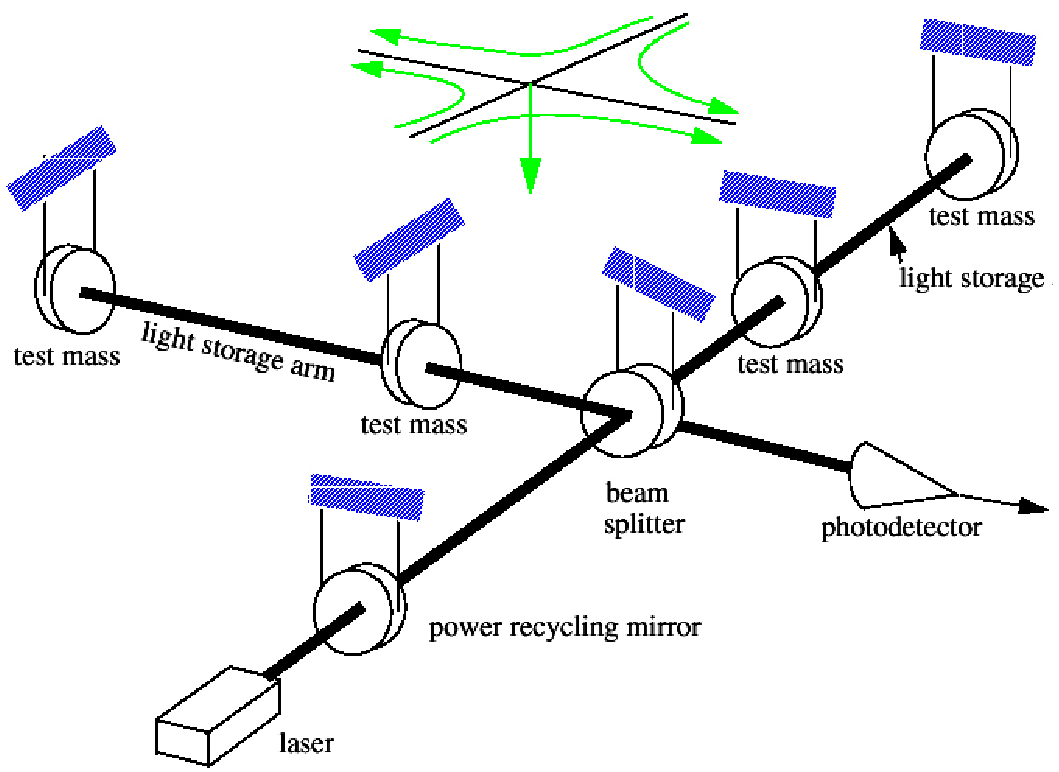
- The Corner Station houses the laser, detector, and all of the optics except the End Test Masses.
- Each vacuum chamber has an independently supported, seismically isolated table on which the optics are mounted.
- The beam tubes are 1.2 m diameter, low oxygen stainless steel.

LIGO Livingston Observatory Corner Station Chambers

Initial LIGO Noise Spectrum

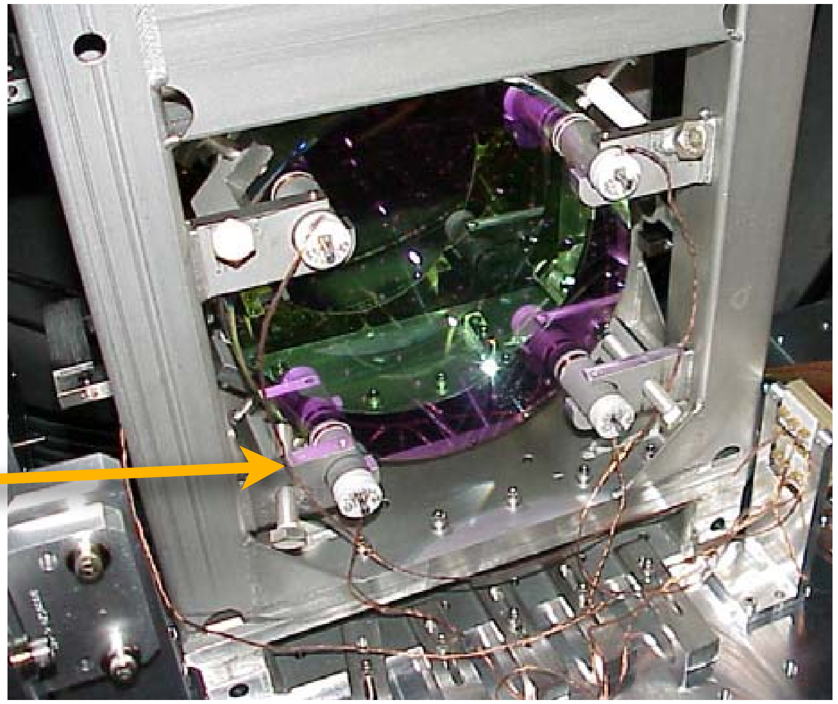


LIGO's Main Optics



- The large optics are suspended on a single wire loop and are free to move (in "free fall") in the plane of the interferometer. The fused silica optics are 25 cm in diameter, 10 cm thick and have a 10 kg mass.
- Fast servo controls adjust all the optics positions and the laser wavelength to keep the interferometer locked. Slower servos correct for land tide drifts and temperature dependent changes in mirror curvature.
- Each optic's position is controlled by 5 sensor/actuators which maintain the optics relative position to 10^{-13} m and angular orientation to 10^{-8} radians.

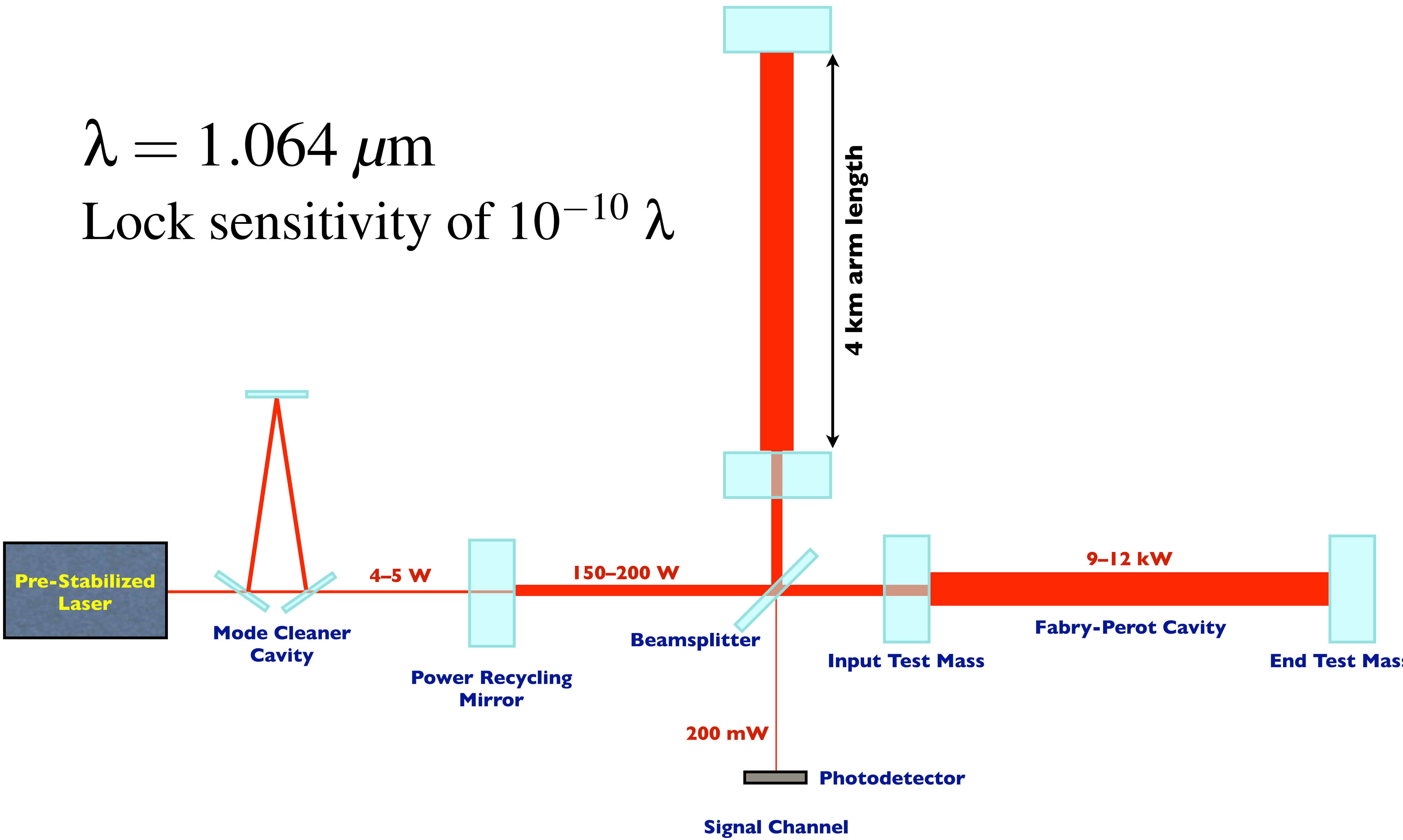
OSEM sensor-actuators



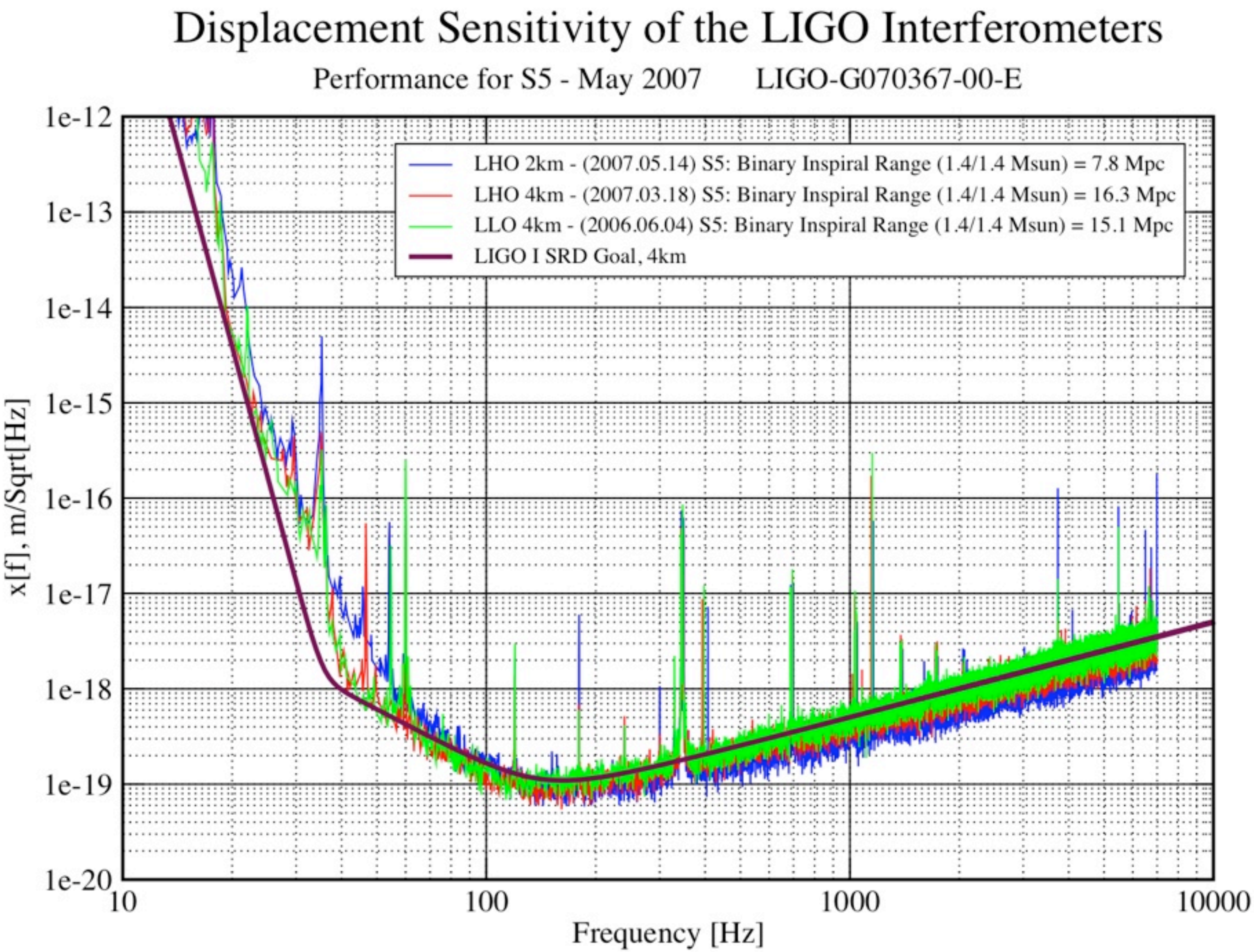
LIGO Laser System

$\lambda = 1.064\ \mu m$

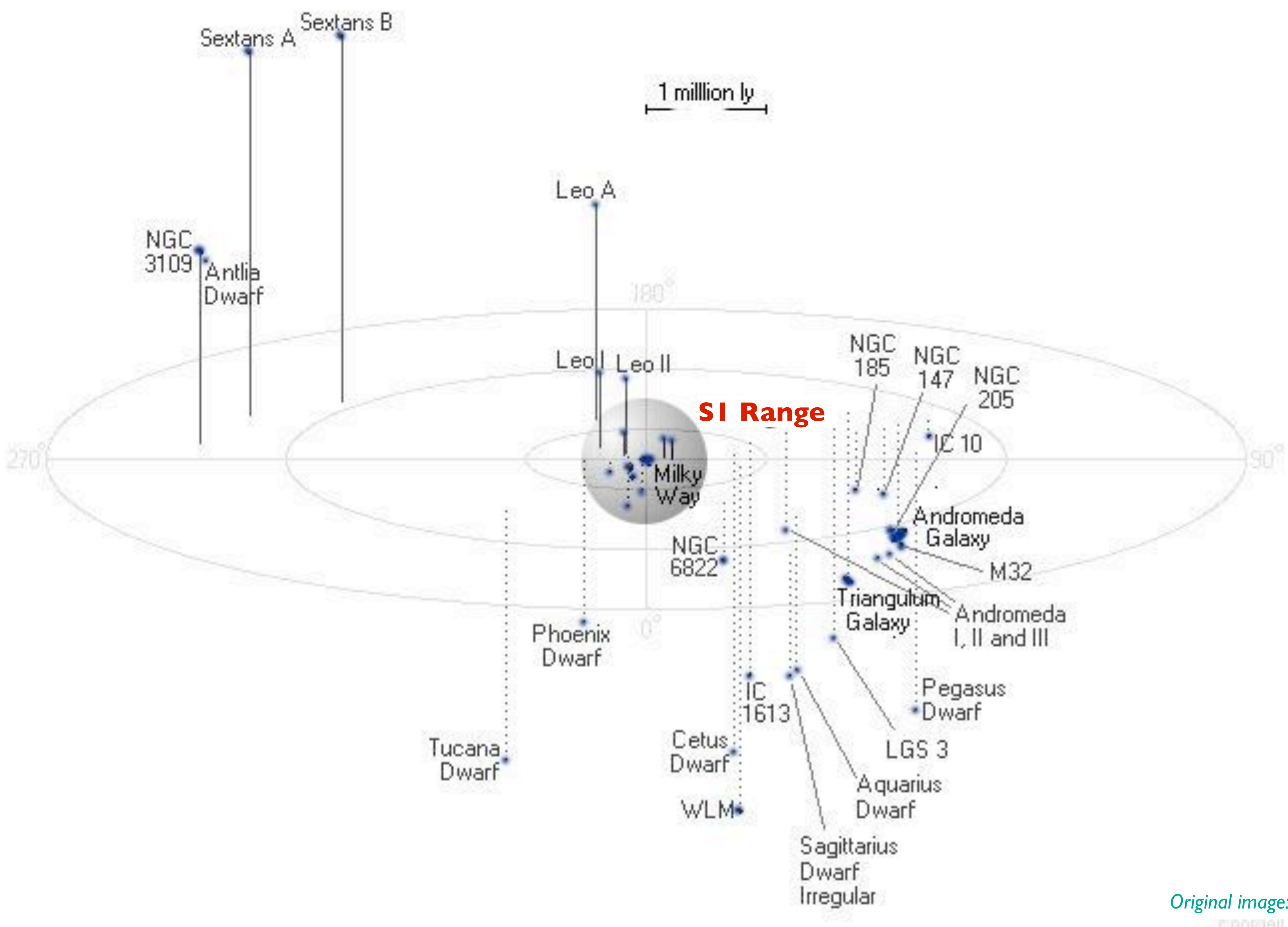
Lock sensitivity of $10^{-10}\ \lambda$



Current Displacement Sensitivity

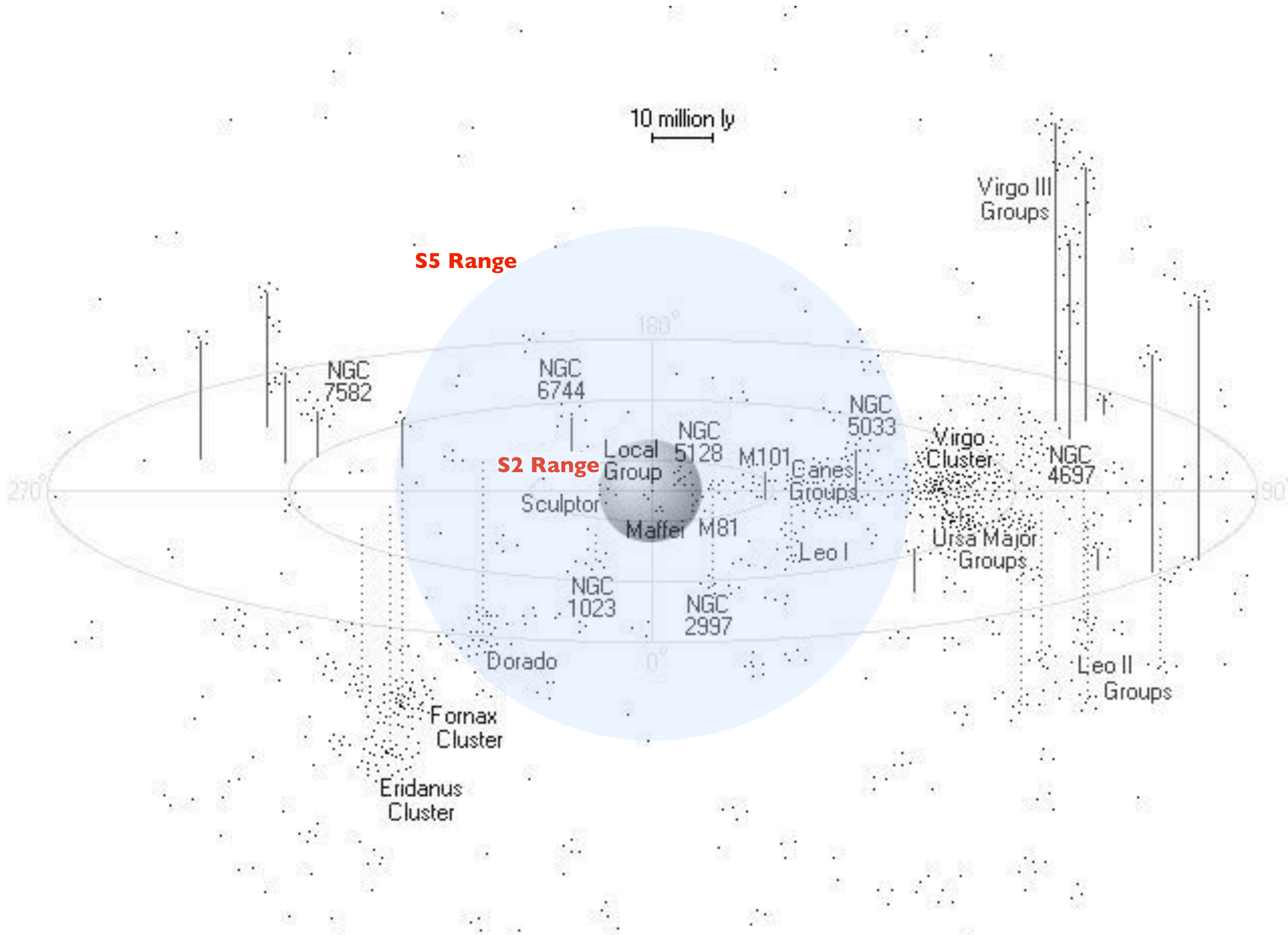


Initial LIGO Range for BNSI: S1



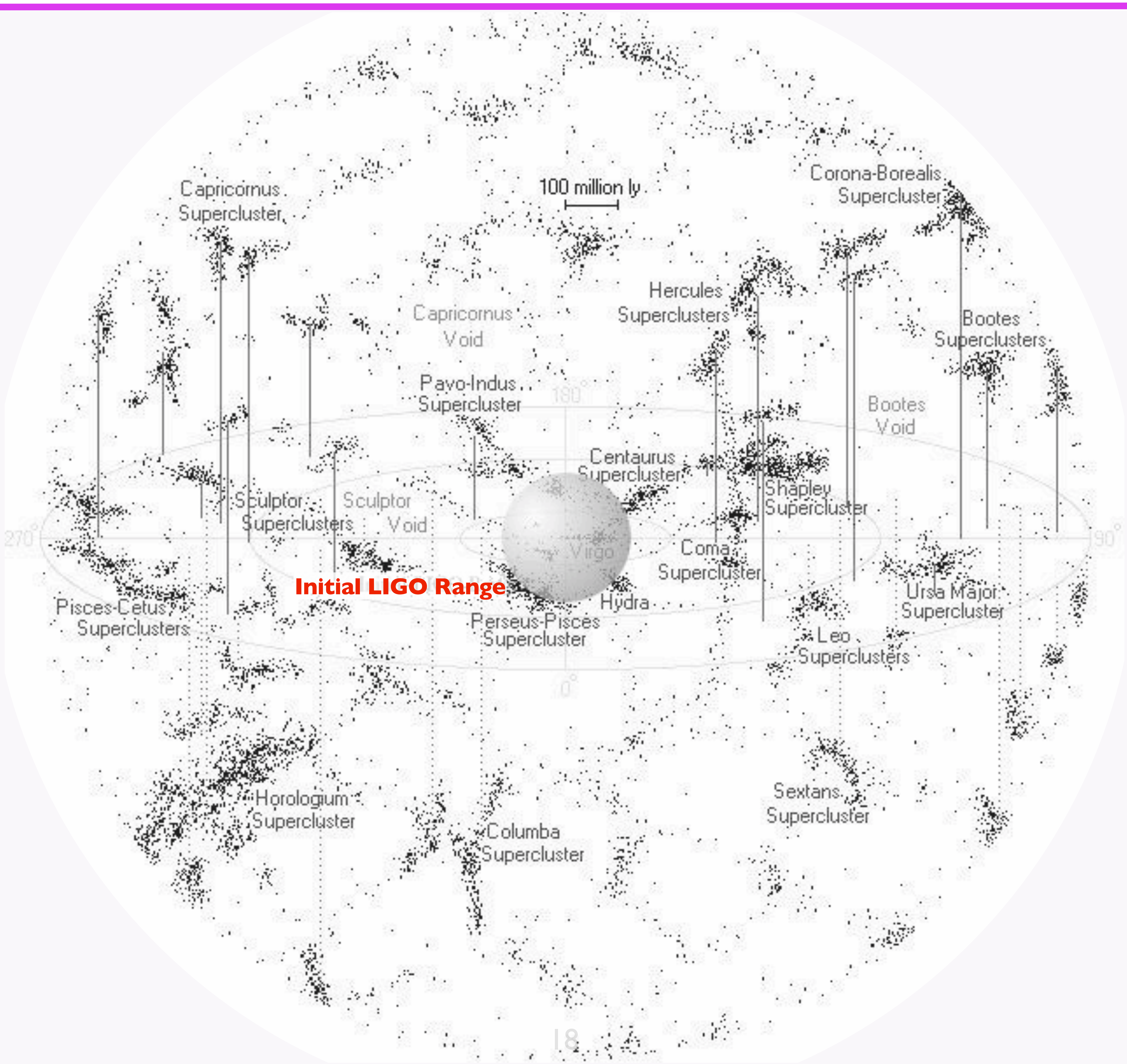
Original image: R. Powell

Initial LIGO Range for BNSI: S5



Original image: R. Powell

Adv. LIGO Range for BNSI



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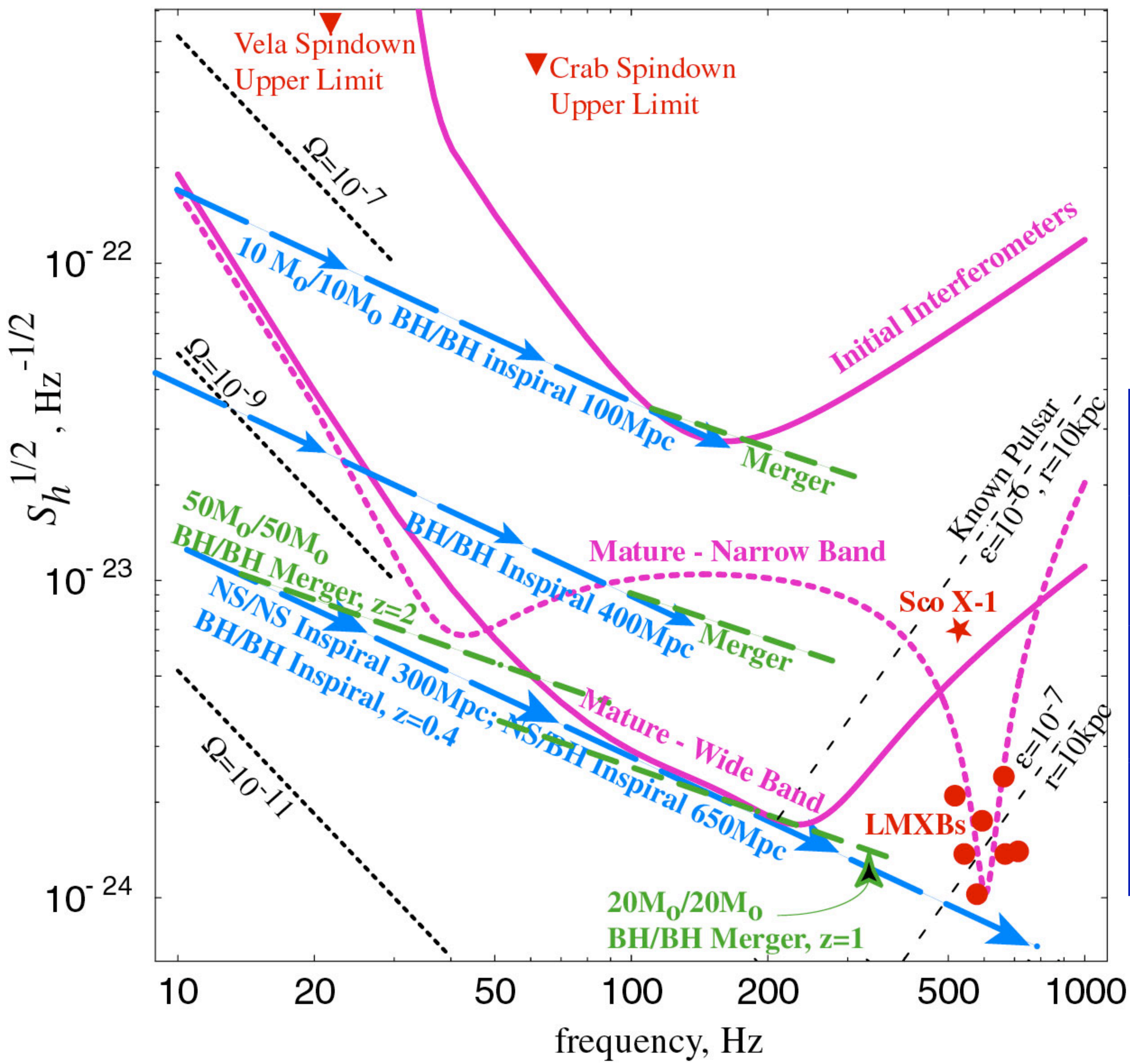
Advanced LIGO Sources



Strain sensitivity increase >≈ 10

Range increases >≈ 10

Rate increases as (Range)^3

SOURCE	RANGE	RATE
NS/NS	200–350 Mpc	2–1000 /yr
BH/BH	1.7 Gpc	10–10^4 /yr
BH/NS	750 Mpc	1–300 /yr

Adv. LIGO Laser System

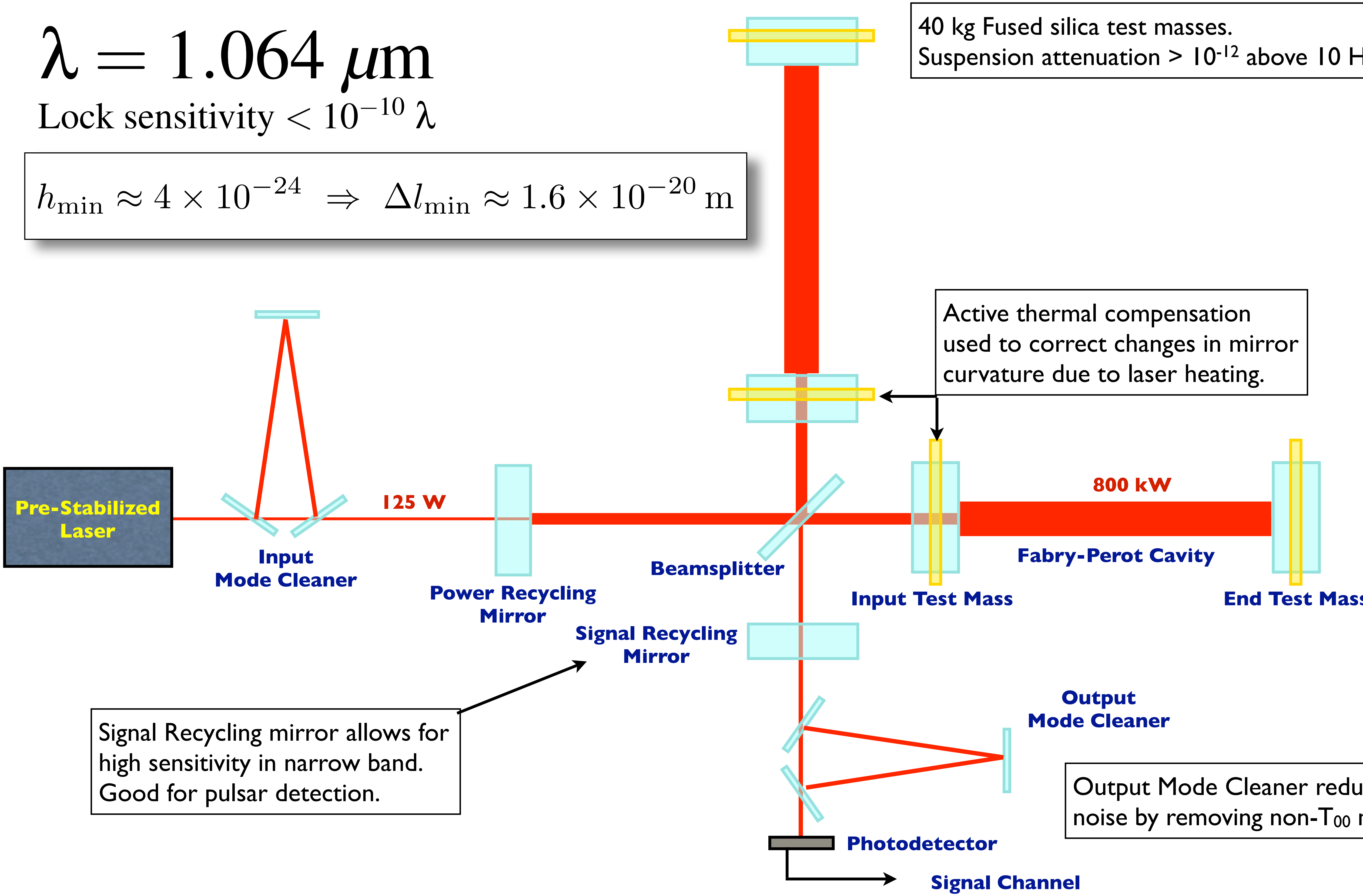
$$\lambda = 1.064\ \mu m$$

Lock sensitivity $< 10^{-10}\ \lambda$

$$h_{\min} \approx 4 \times 10^{-24} \;\Rightarrow\; \Delta l_{\min} \approx 1.6 \times 10^{-20}\ \mathrm{m}$$

40 kg Fused silica test masses.
Suspension attenuation > 10^{-12} above 10 Hz.

Active thermal compensation used to correct changes in mirror curvature due to laser heating.



Signal Recycling mirror allows for high sensitivity in narrow band. Good for pulsar detection.

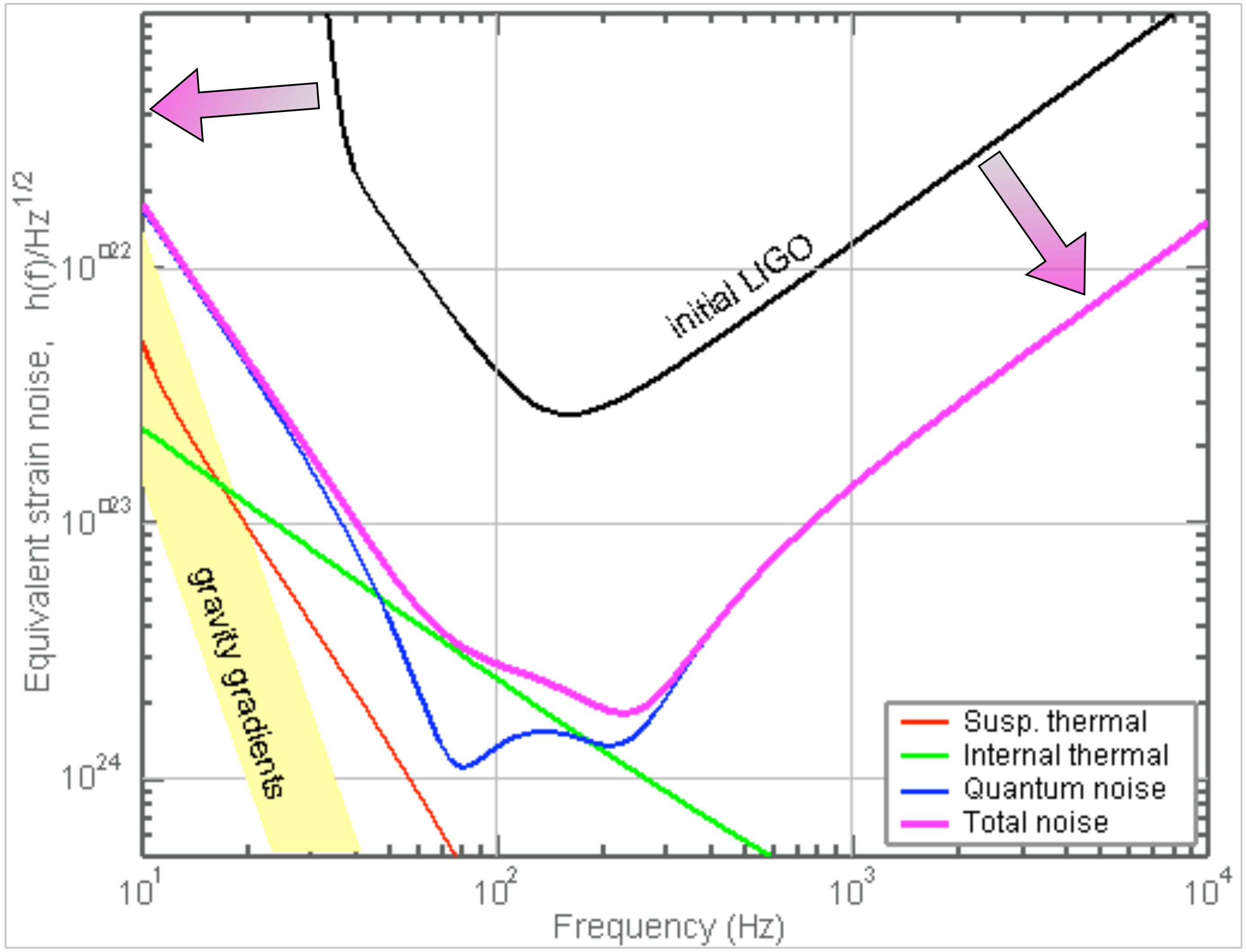
Output Mode Cleaner reduces noise by removing non-T_{00} modes.

Advanced LIGO Specs

Subsystem	Advanced LIGO	Initial LIGO
Strain sensitivity [rms, 100Hz band]	8×10^{-23}	10×10^{-21}
Displacement sensitivity [rms, 100Hz band]	8×10^{-20}	4×10^{-18}
Optical power at laser output	180 W	10 W
Optical power at IFO input	125 W	6 W
Optical power at test masses	800 kW	30 kW
Input mirror transmission	0.5%	3%
End mirror transmission	15 ppm	15 ppm
Arm cavity power beam size	6 cm	4 cm
Light storage time in arms	5.0 ms	0.84 ms
Test masses	Fused Silica, 40 kg	Fused Silica, 11 kg
Mirror diameter	35 cm	25 cm
Test mass pendulum period	1s	1s
Seismic isolation system	3 stage active, 4 stage passive	passive 5 stage
Seismic system horizontal attenuation	$>=10^{-12}$ (10 Hz)	$>=10^{-9}$ (100Hz)
Suspensions	Quad Pendulum, FS fibers	Single steel wire loop

Advanced LIGO Improvements

Seismic Noise Wall:
$h < 10^{-22}$ for f > 10 Hz



Limited by Thermal Noise in Test Mass Mirrors
≈ 4 – 40 Hz band

Shot Noise:
Stored laser power to increase 25x

Noise approaches Quantum Limit across most of band

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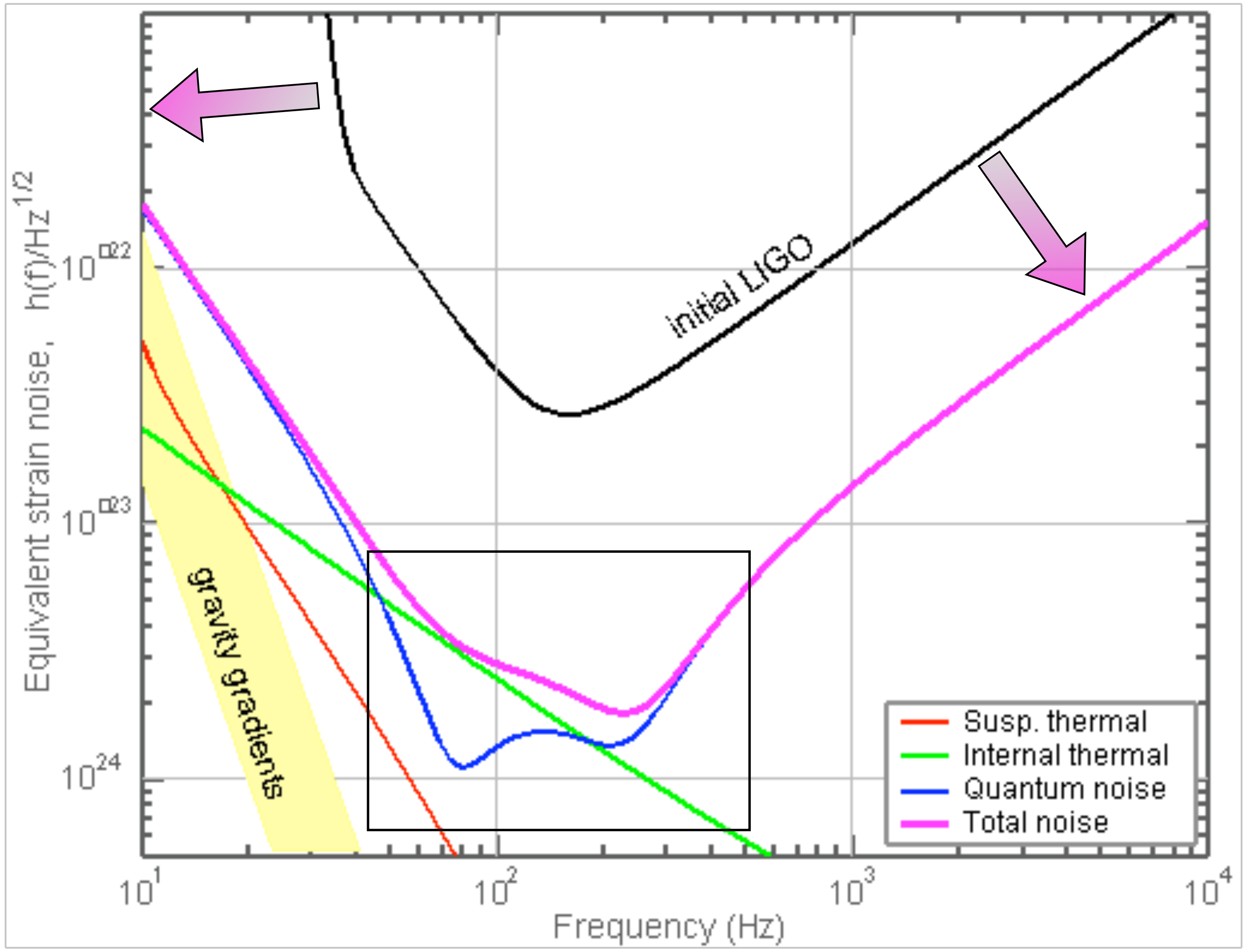

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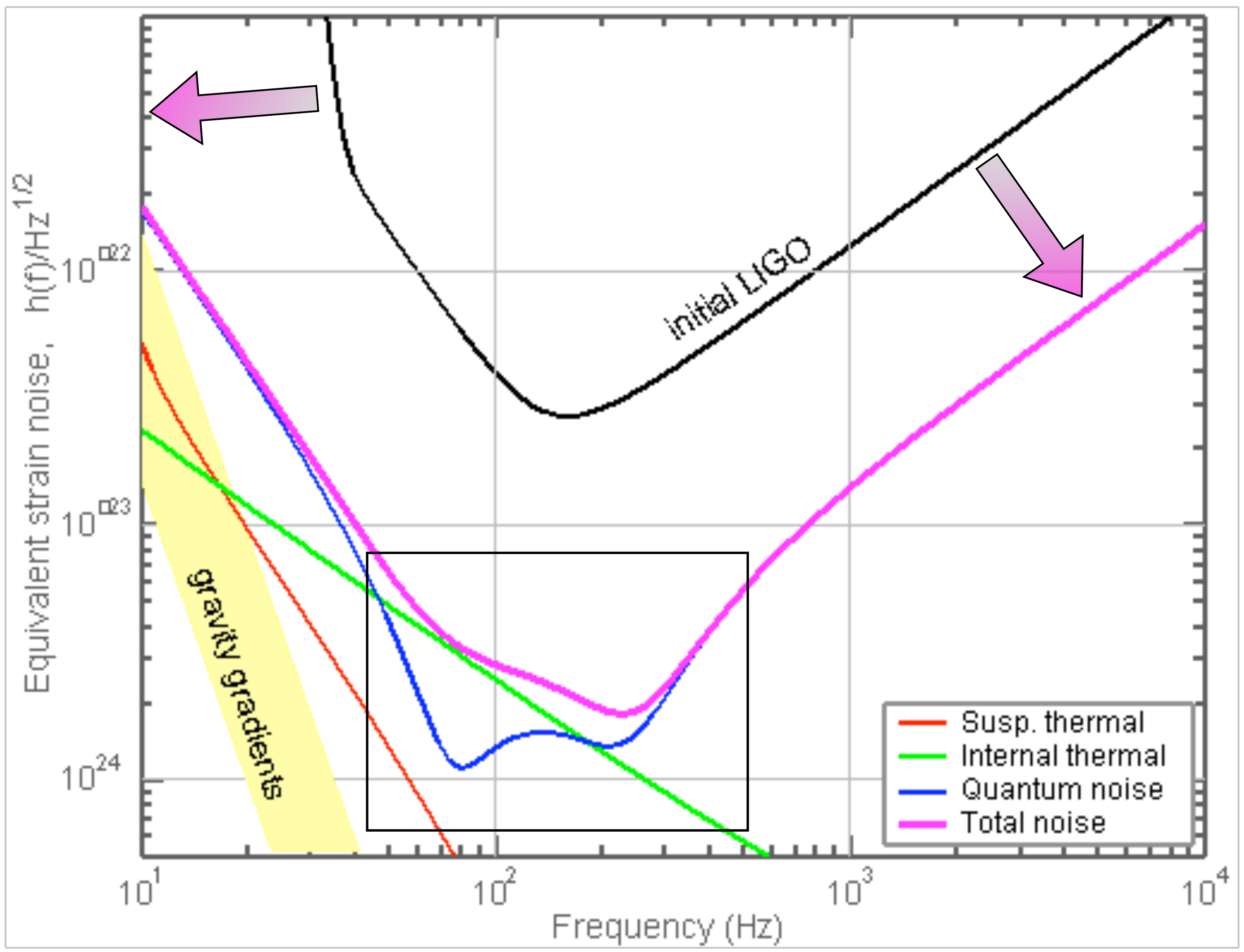

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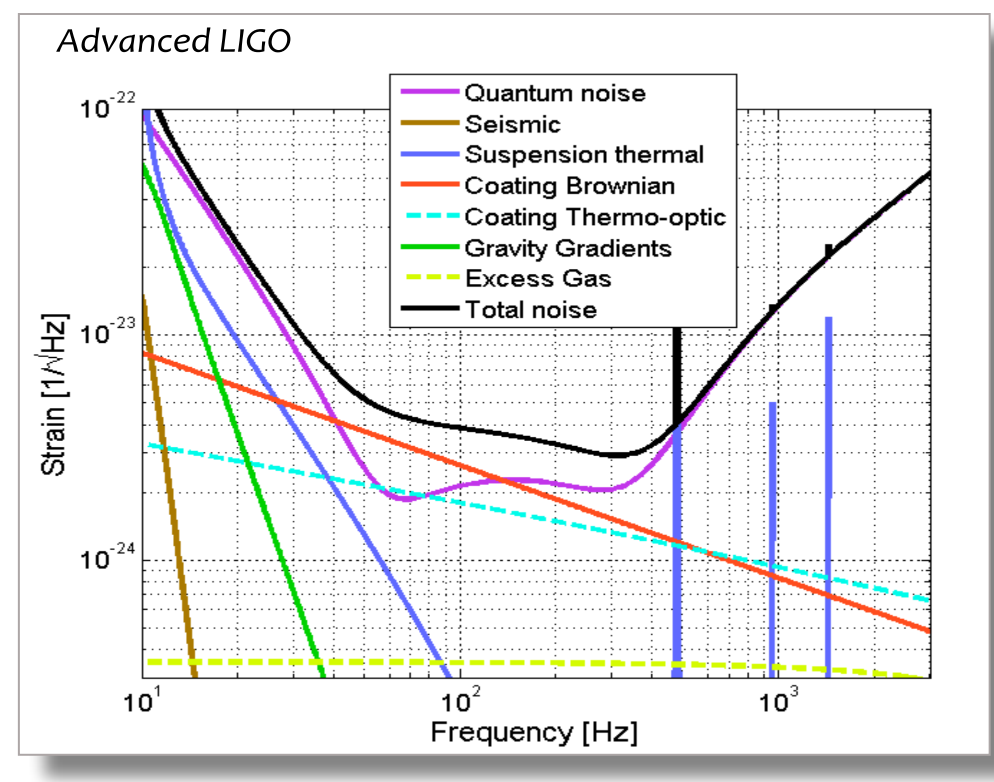

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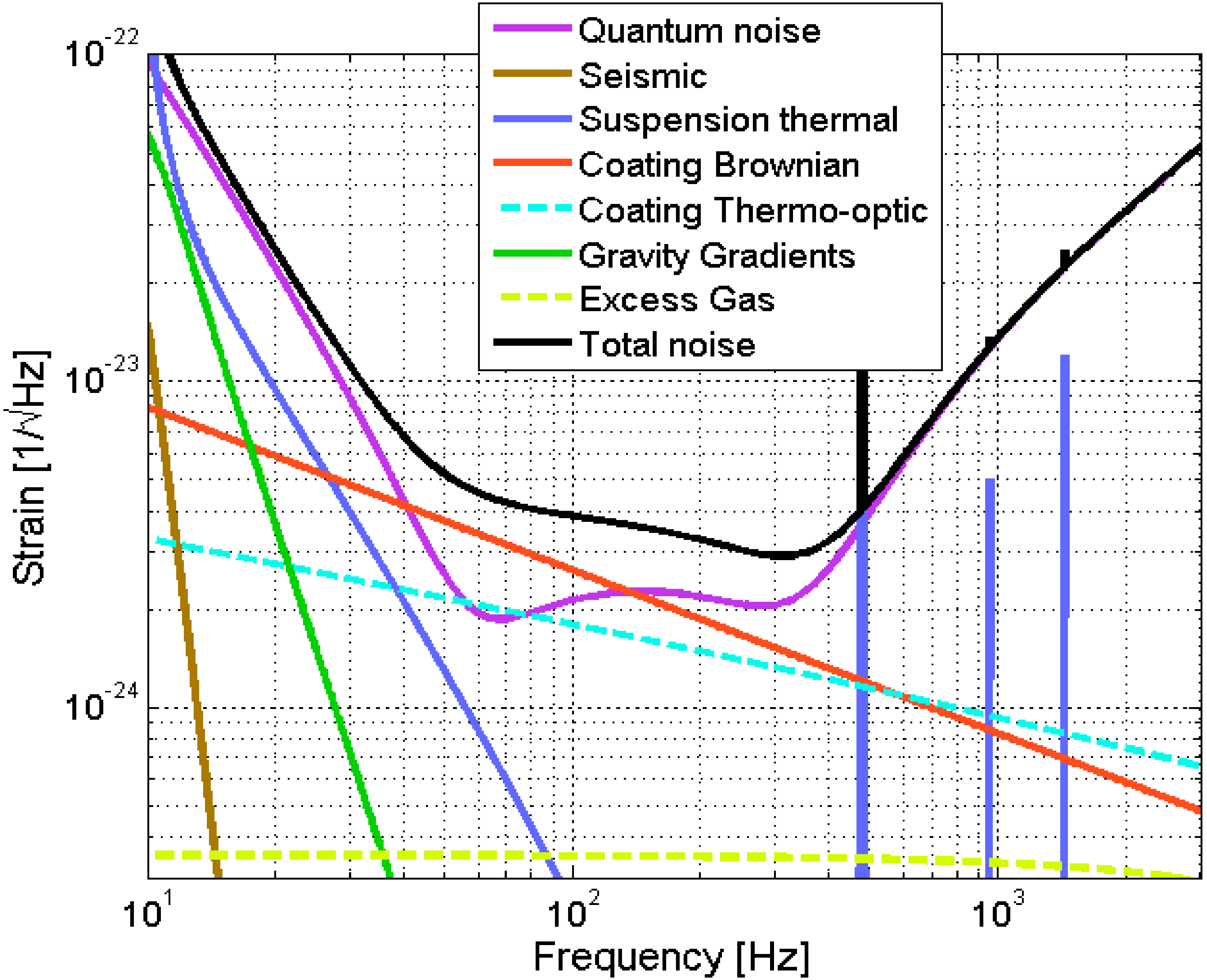
LIGO

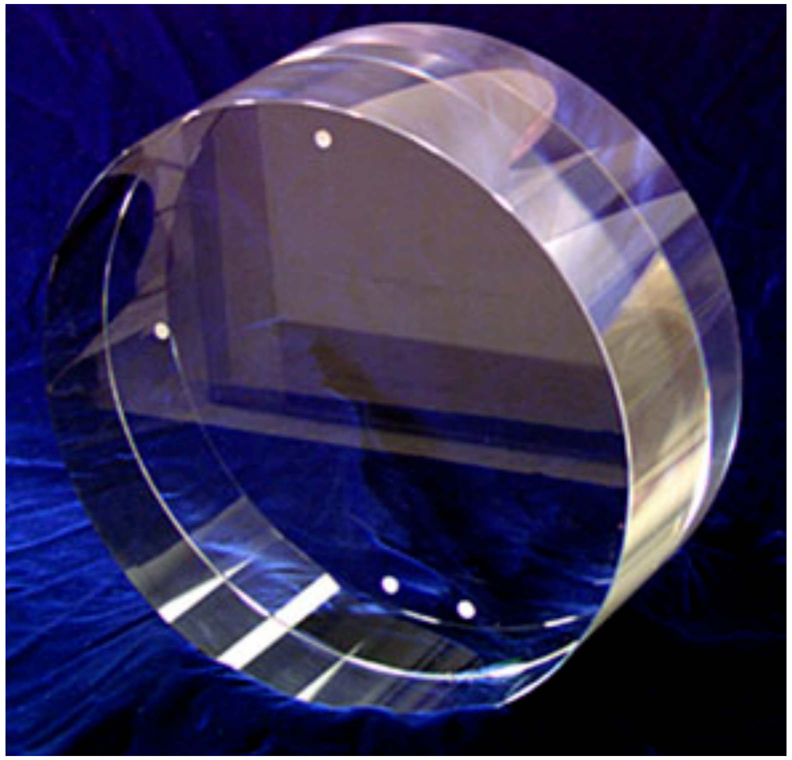
Adv. LIGO Thermal Noise



Adv. LIGO Thermal Noise

Test Mass: Fused Silica or Sapphire

Property	Best Material
Young's Modulus	Sapphire
Thermal Conductivity	Sapphire
Density	Sapphire
Optical Absorption	Fused Silica
Thermoelastic loss	Fused Silica
History as Optical Material	Fused Silica
Ability to Polish & Coat	Fused Silica
Mechanical Loss	???



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LSC

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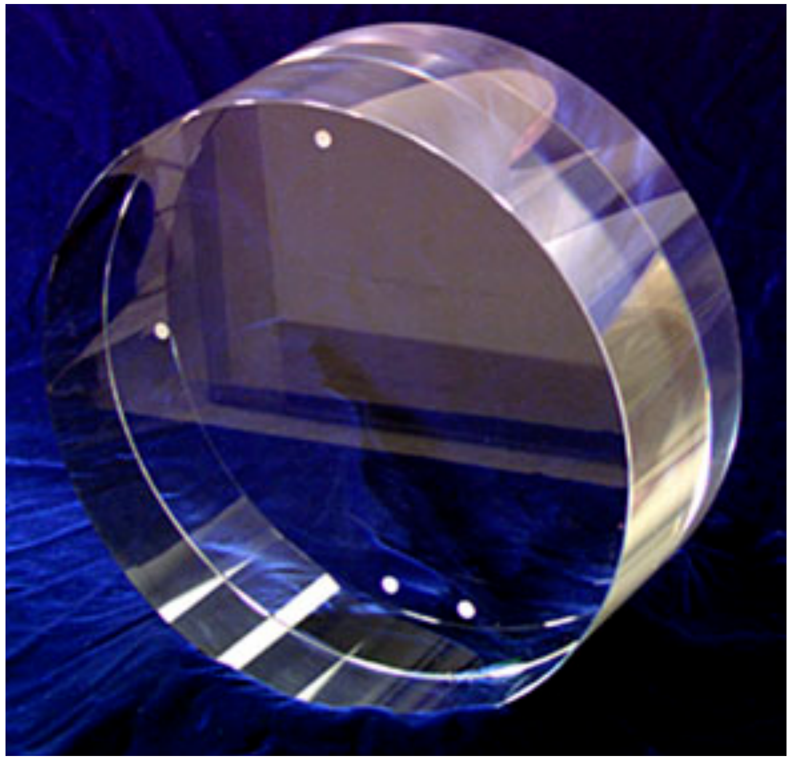
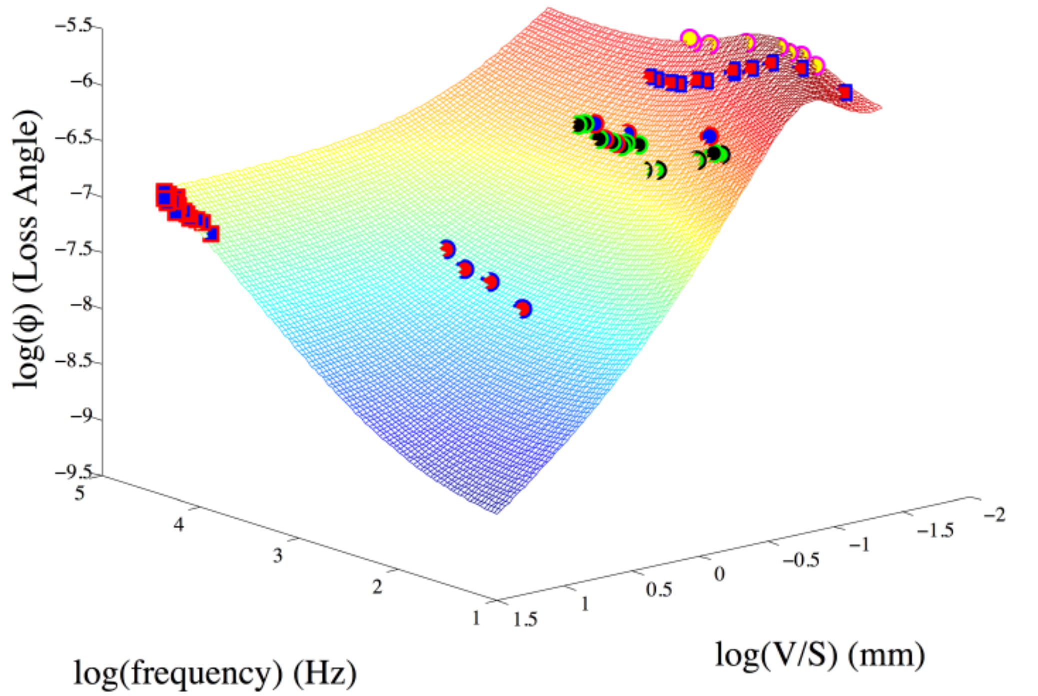


$$\phi = (8.55e{-09}\ S/V + 7.15e{-12}\ f^{0.822} + 1.02\ \phi_{th})$$



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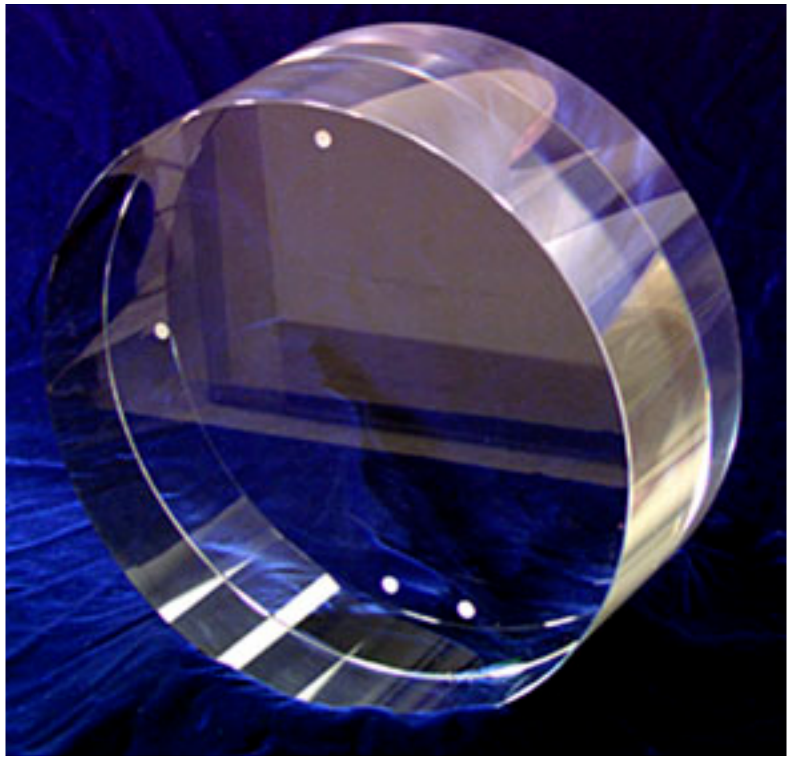

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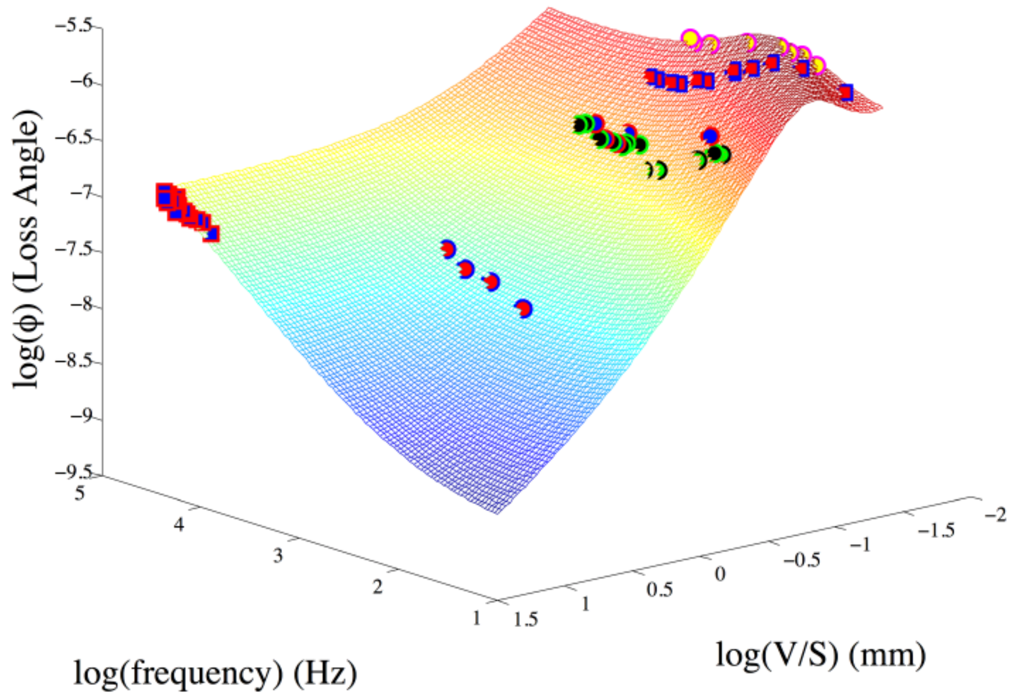

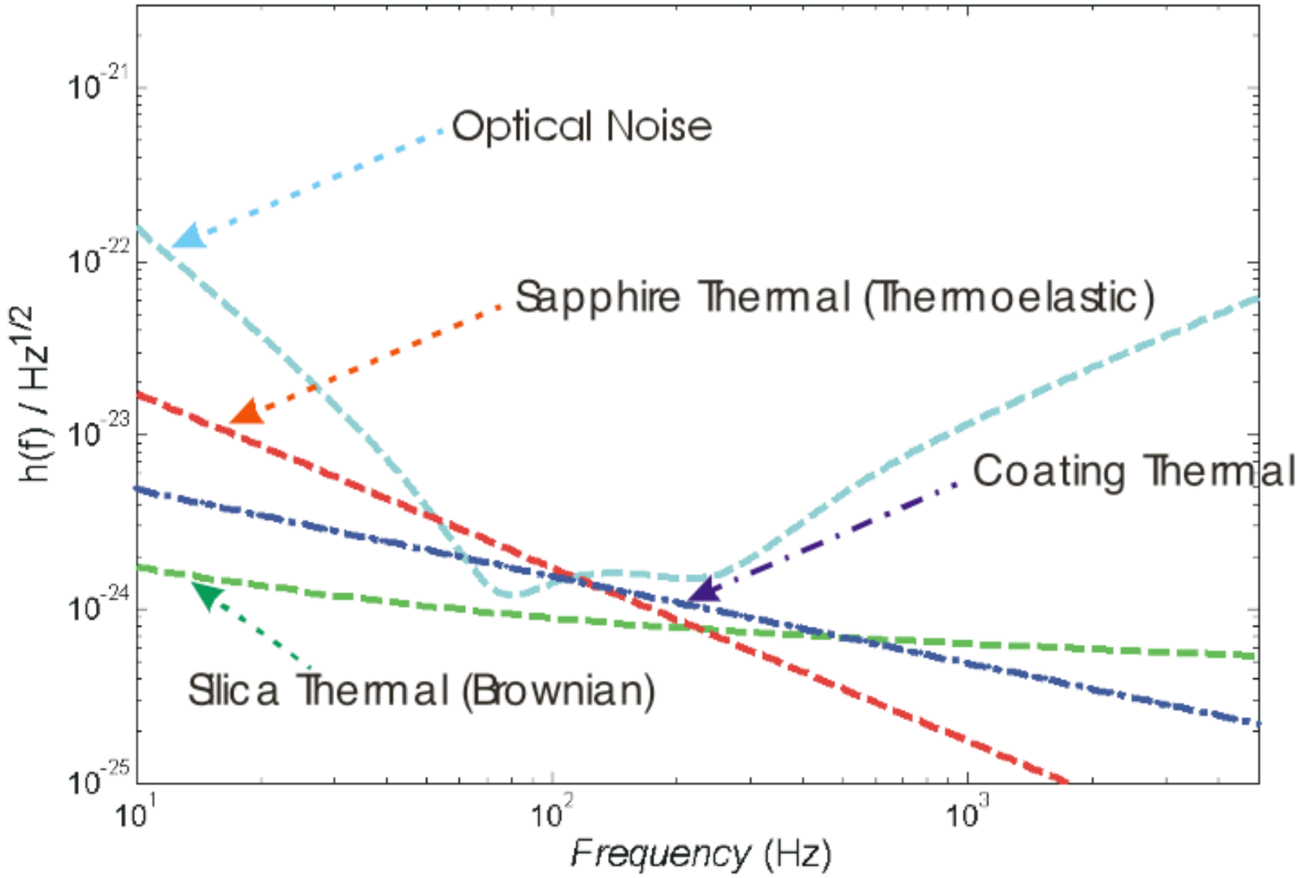

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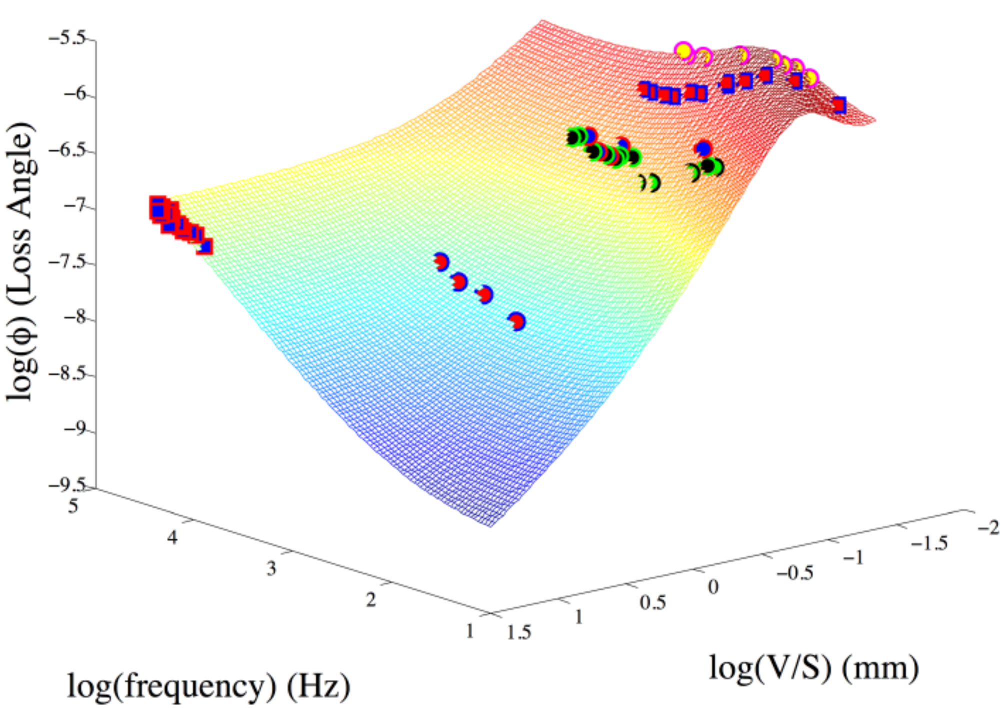
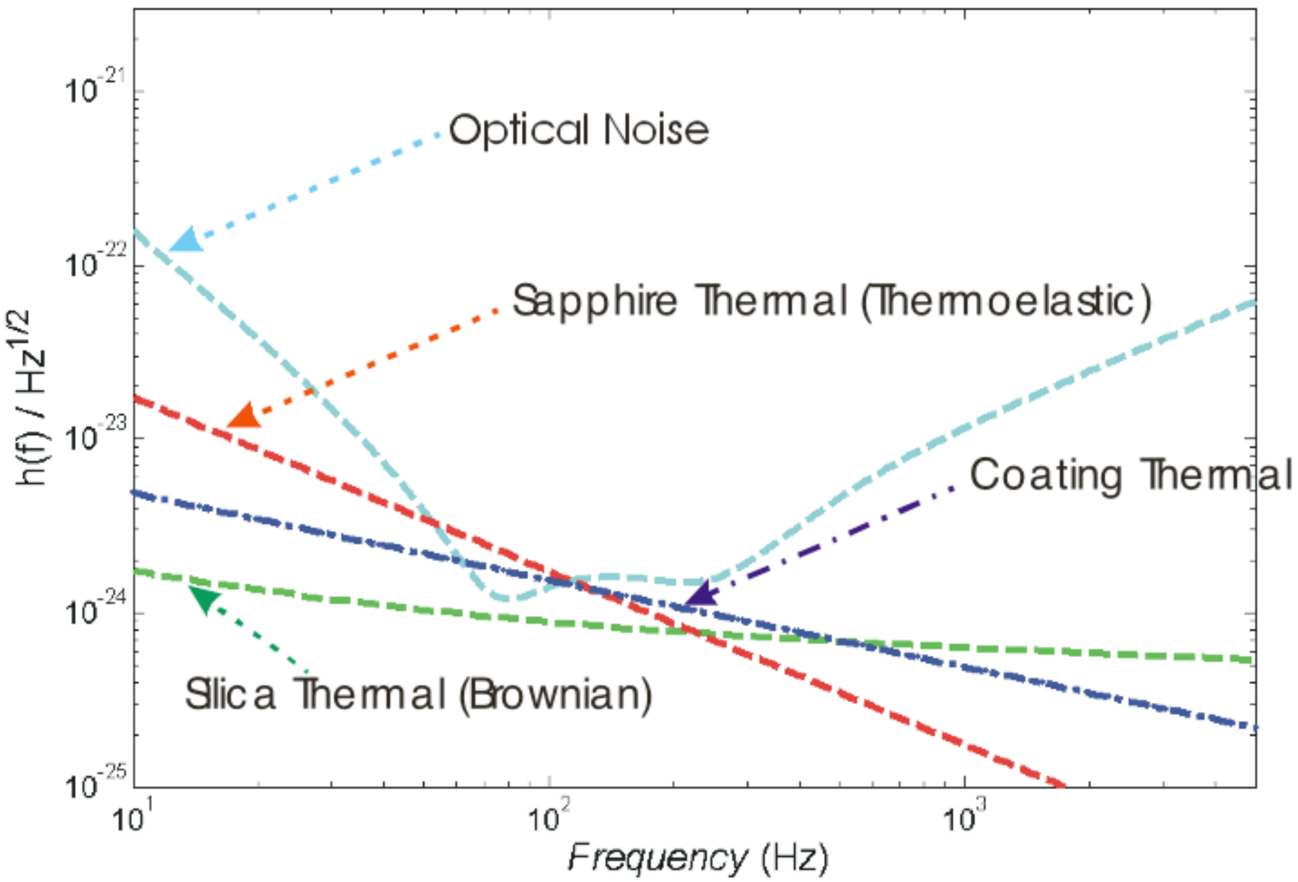


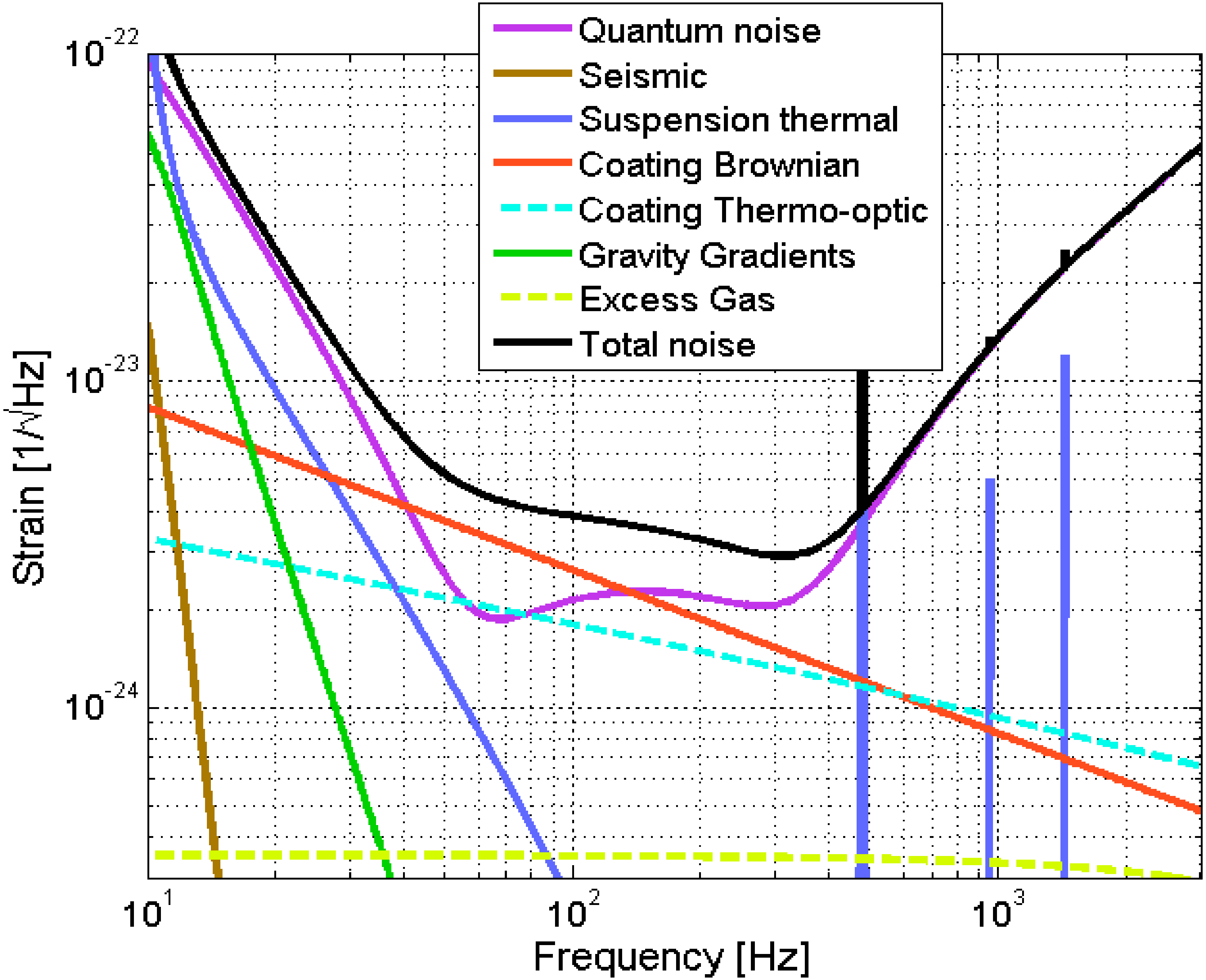
Fused Silica Chosen for Adv LIGO

- **Mechanical Loss is comparable with Sapphire.**
- **Extensive experience with producing, polishing, coating, and using high quality fused silica.**
- **Lower thermal conductivity requires uniform thermal compensation.**
- **Size for 40 kg fused silica optic will fit in suspension system.**



LIGO

Adv. LIGO Thermal Noise



Coating Research Issues

- Thermal Noise Issues
  - Fundamental Loss Mechanisms (Glasgow)
  - Mechanical Loss in Materials (HWS, ERAU, MIT)
  - Direct Measurement of Thermal Noise (Caltech)
  - Modeling Loss in Coatings (Florida)
  - Optimizing Coatings (Sannio)
- Thermal/Optical Issues
  - Thermorefractive & Thermoelastic noise (ERAU, Caltech)
  - Thermal Compensation of Absorptive Heating (Caltech)
- Optical Issues
  - Scatter in the Coatings (Syracuse, Caltech)
  - Mesa Beams Cavities (Caltech)
  - UV Irradiation (Stanford)
  - Coating Optical Damage (Florida)

Conclusions

- Advanced LIGO will increase our sensitivity by 10x and our rate by 1000x. Scheduled to be online by 2013.
- Coatings play a major role in setting the ultimate sensitivity level.
- Several important problems to solve to understand and lower the coating loss.
- Exciting and unexpected physics awaits us!