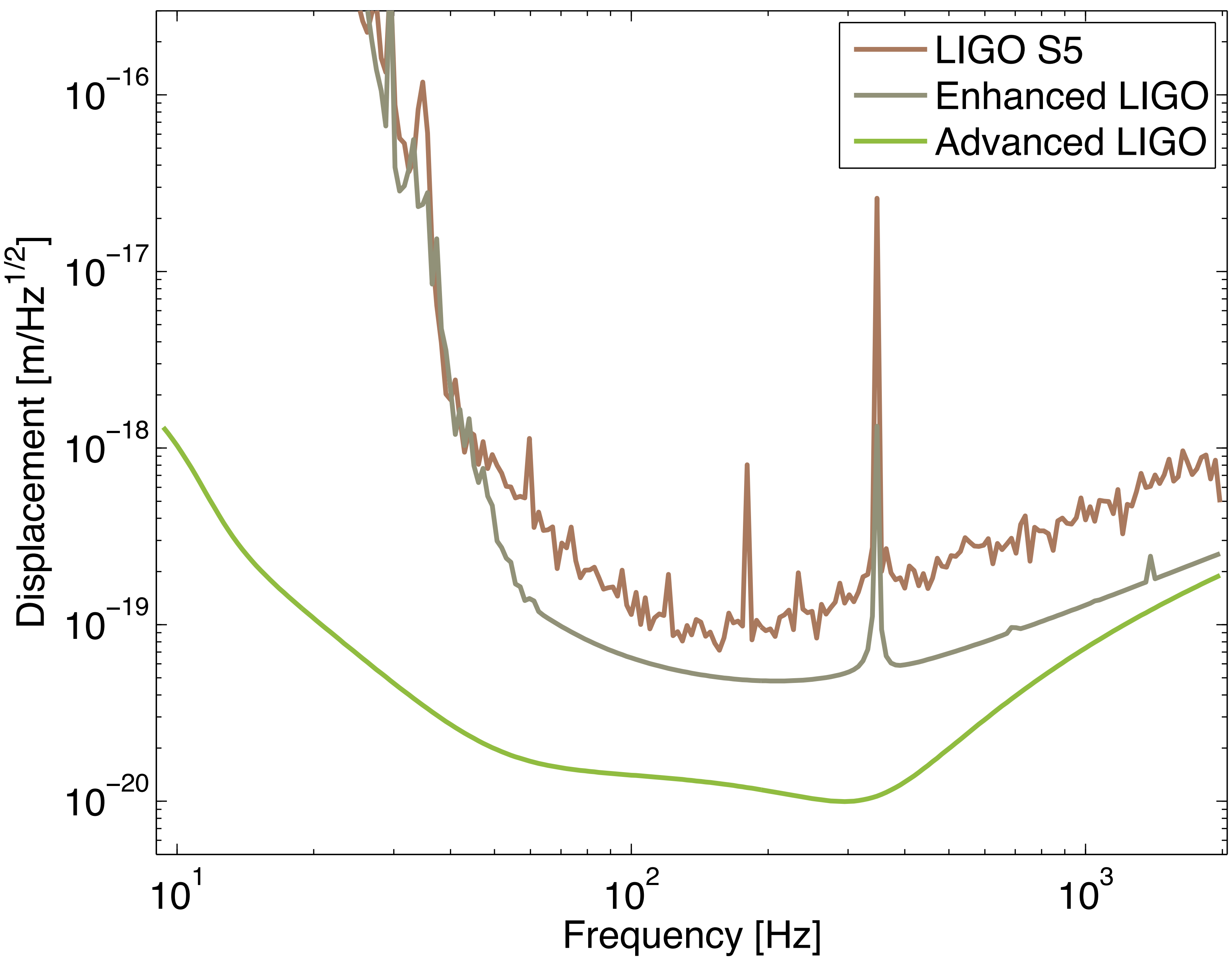
Enhancing & Advancing LIGO
4 years of Detector upgrades

Sam Waldman
Feb 28, 2008
University of Maryland

LIGO-G080420-00-0

Outline

- GW Detectors
- Initial LIGO
- Advanced LIGO
- Enhanced LIGO

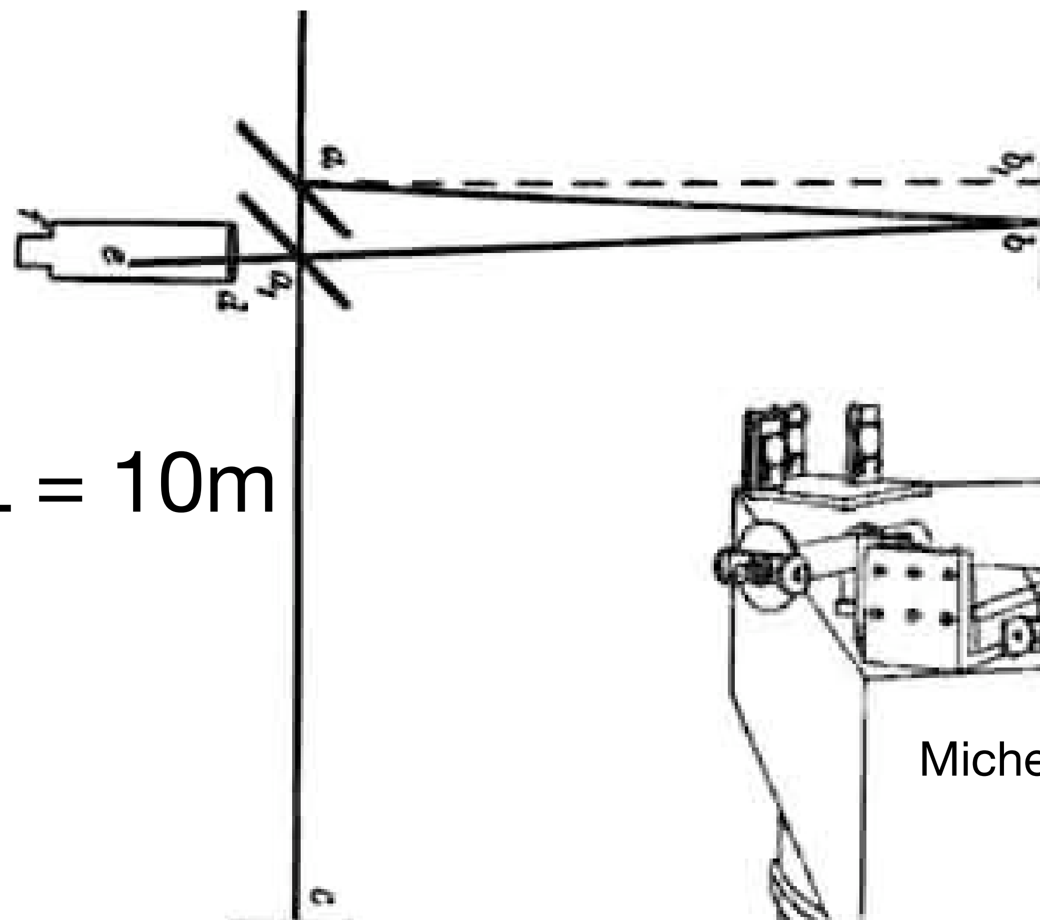


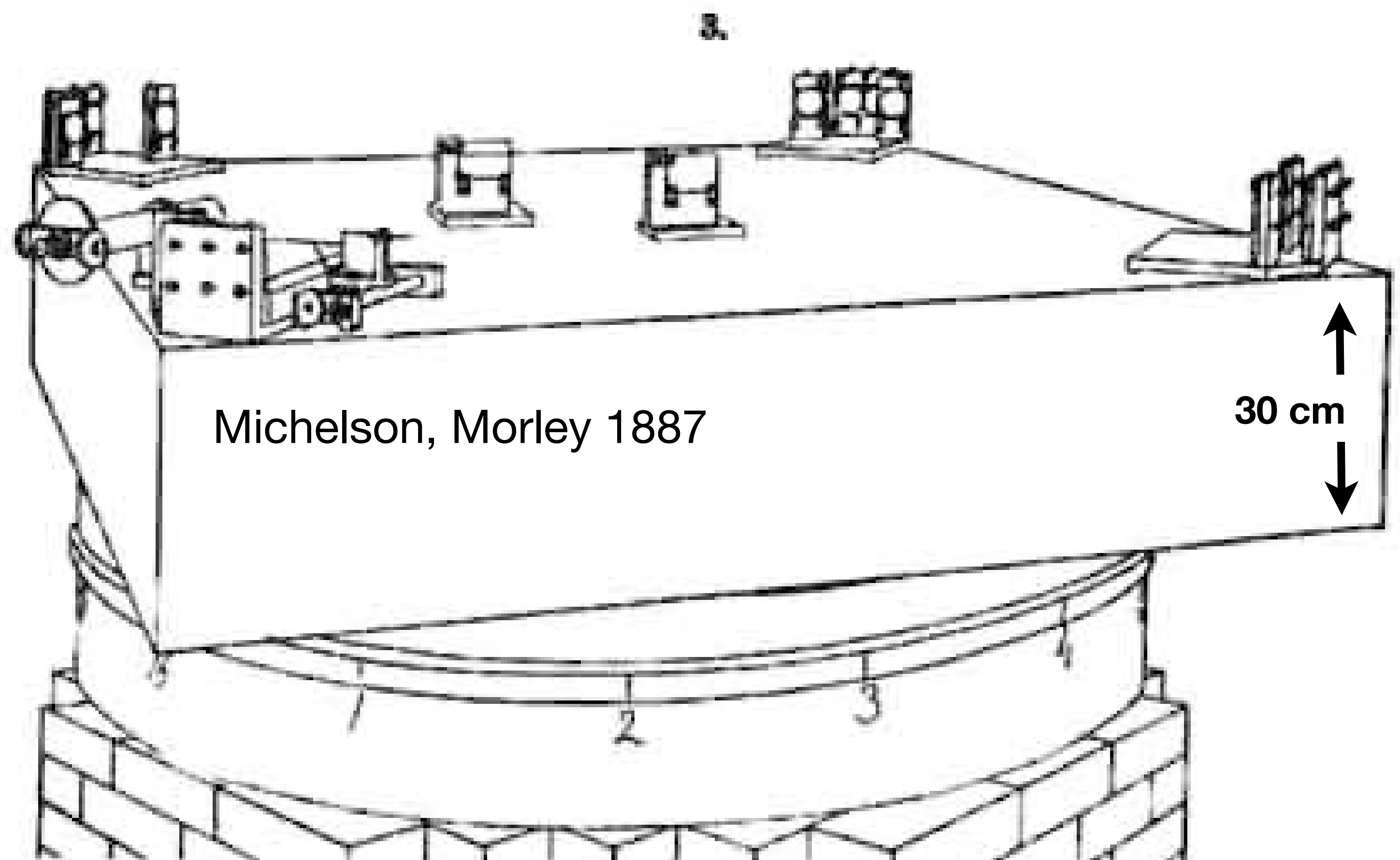
LIGO 0.1

> First GW detector
> $h \sim 5 \times 10^{-10}$

"0.01 λ = 5 nm"

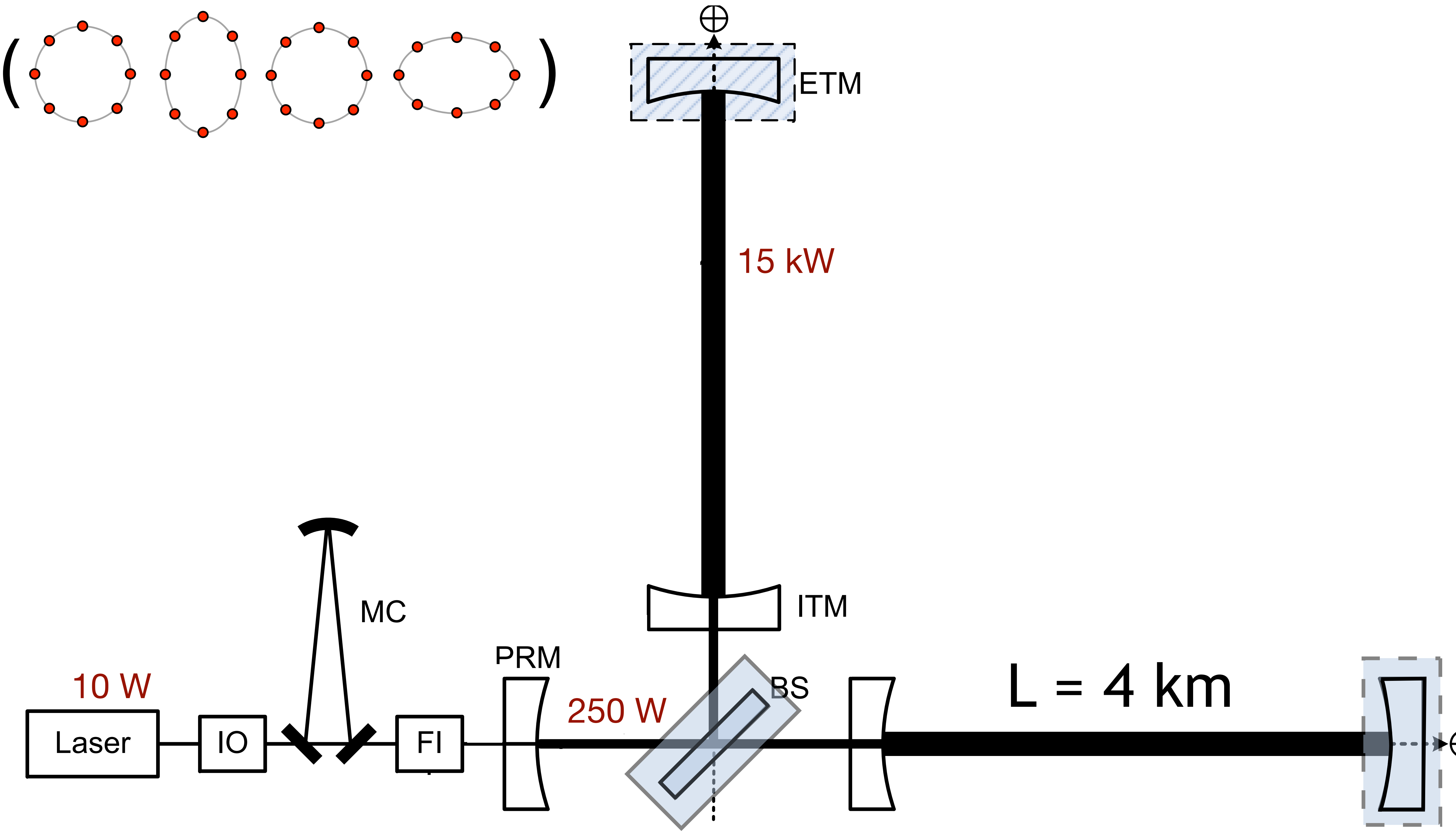

Albert A. Michelson





(Incidentally disproved the existence of the ether)

Initial LIGO



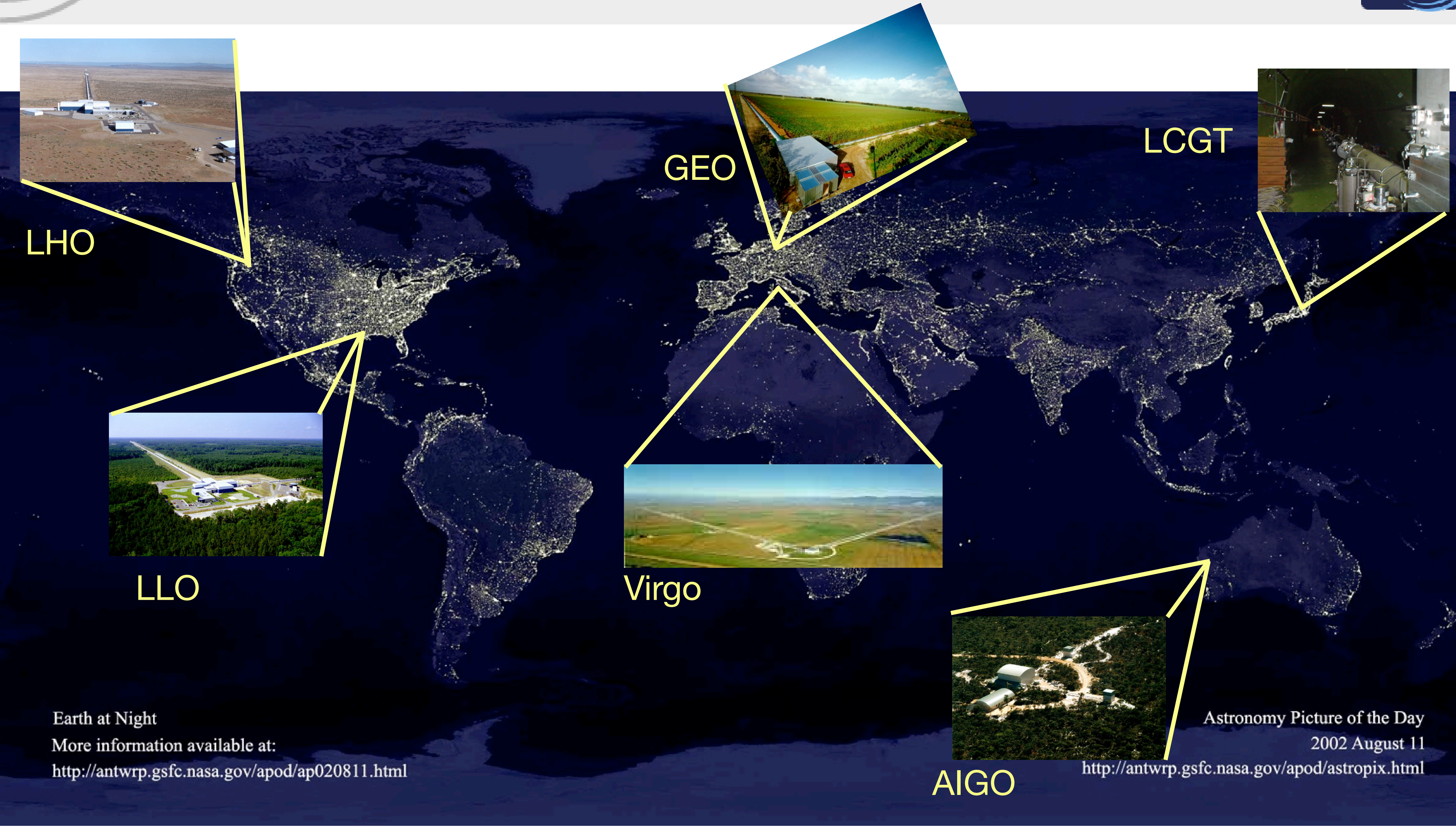
$10^{-12}\ \lambda = 10^{-18}$ m

LIGO detectors

LIGO Collaborations

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

Worldwide network



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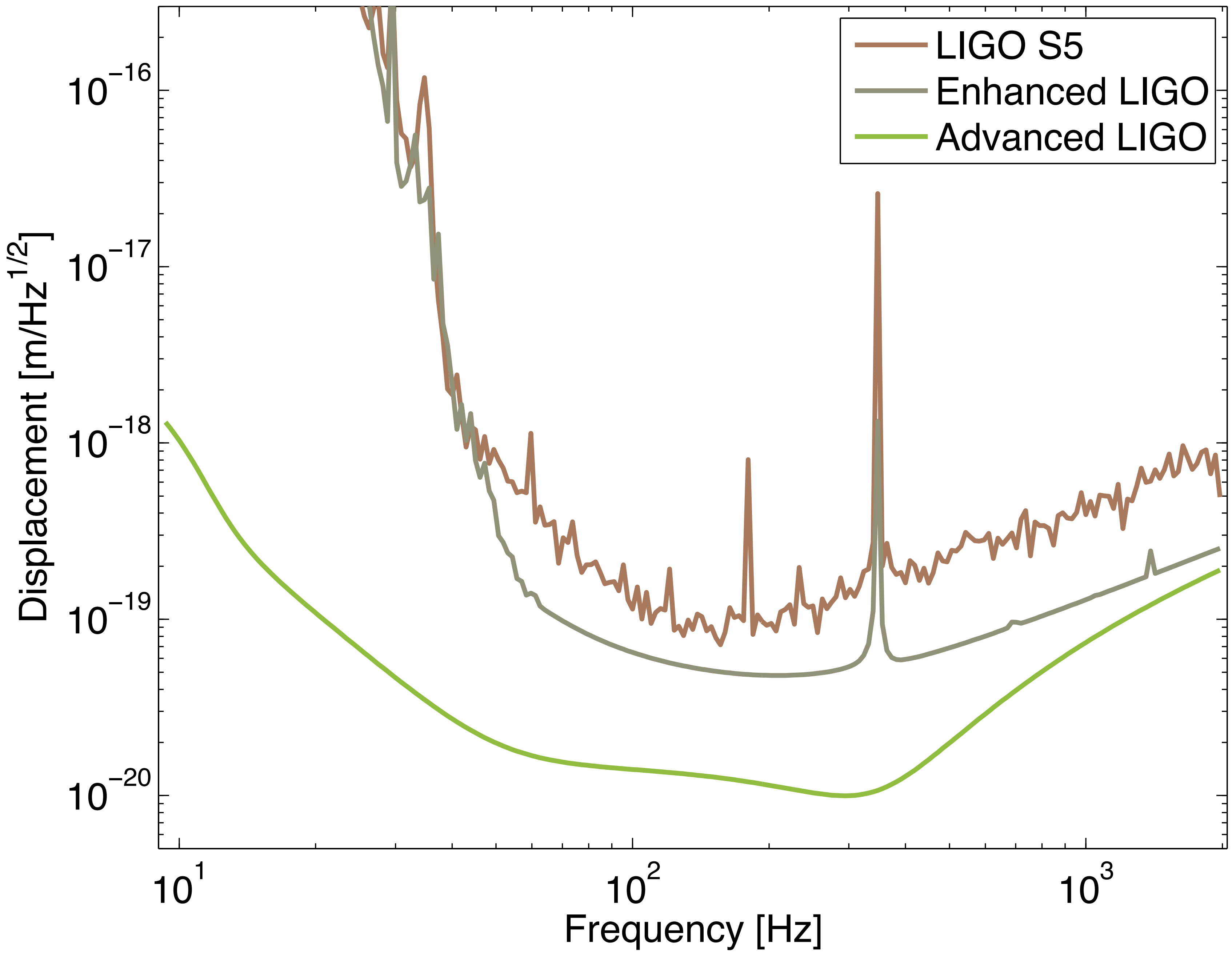
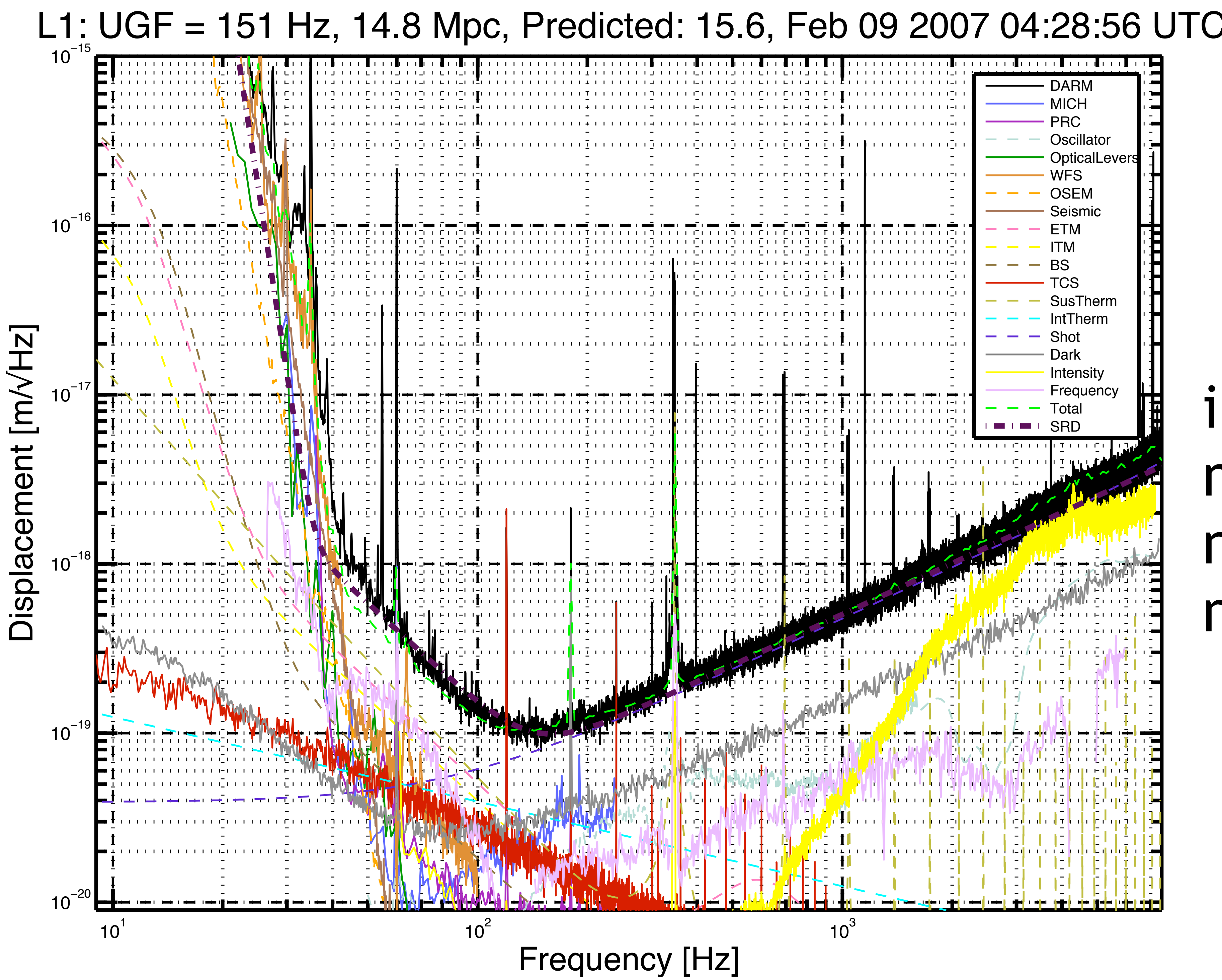


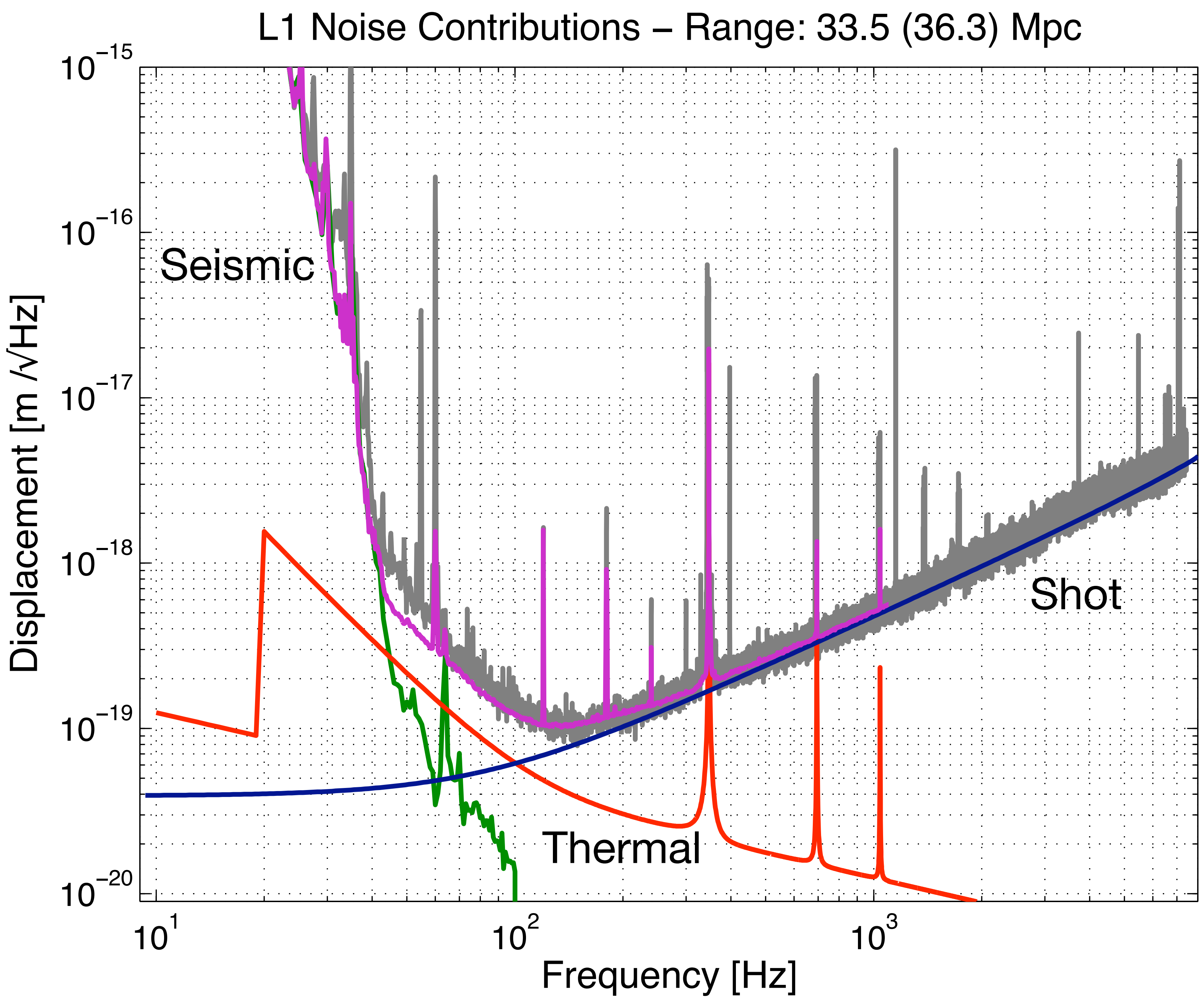
Noise Budget



injection/response measurements of noise couplings to test mass displacement

L1 Noisebudget Feb 9, 2007 04:28 UTC

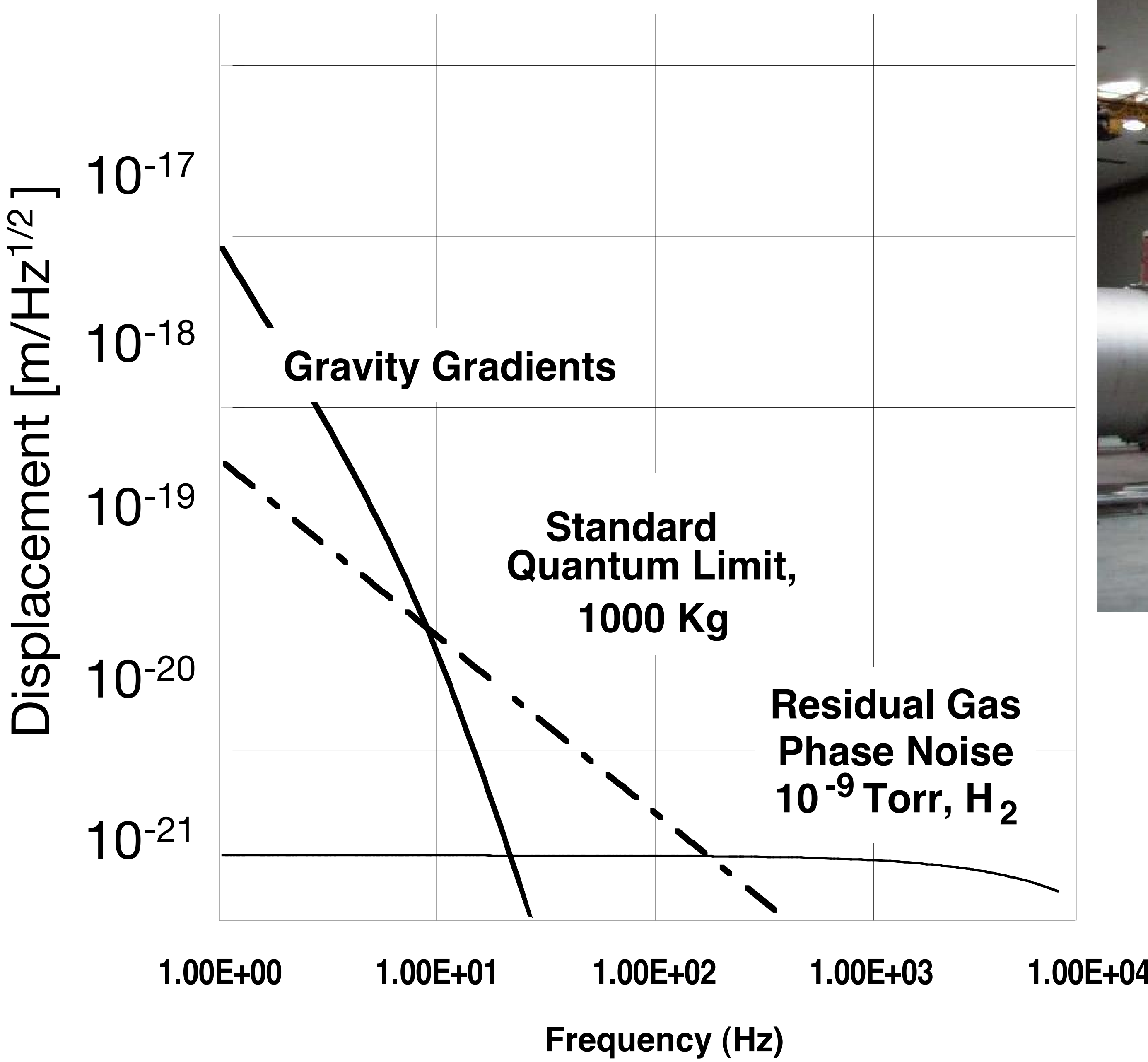
Noise Budget

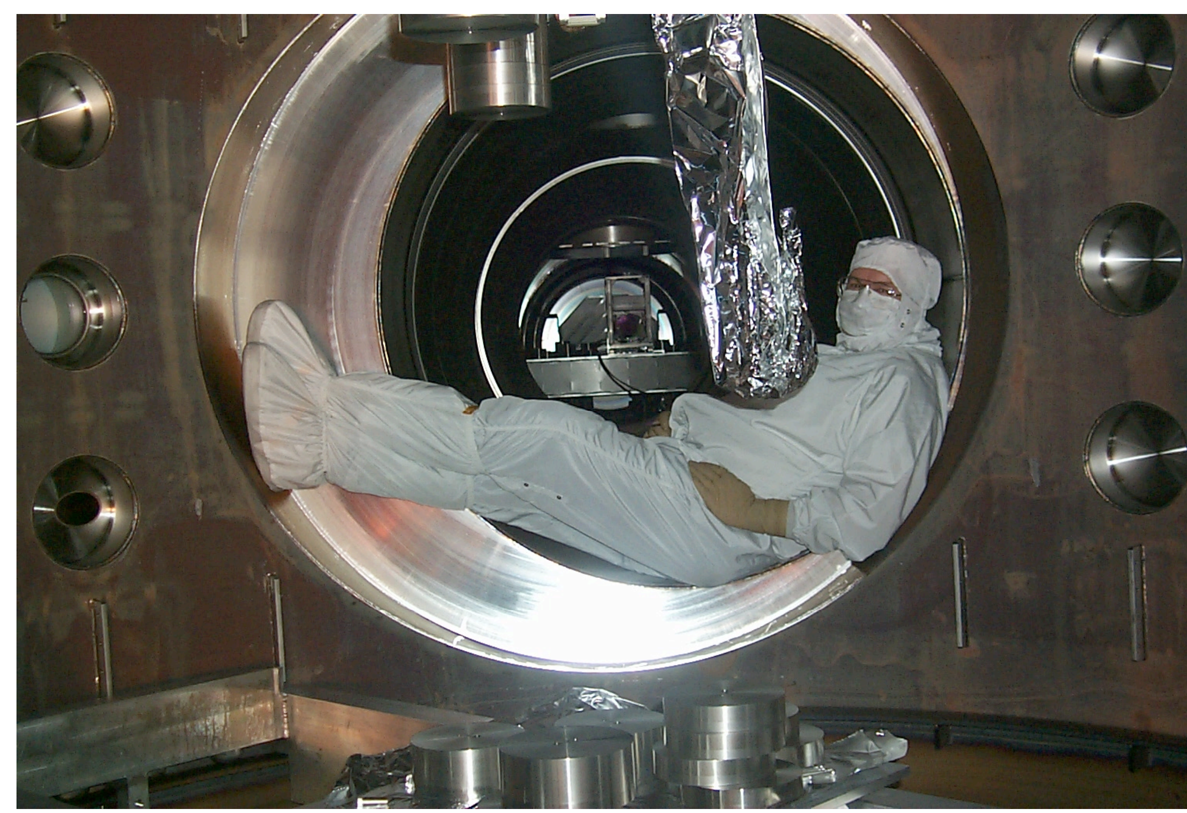


injection/response measurements of noise couplings to test mass displacement

L1 Noisebudget Feb 9, 2007 04:28 UTC

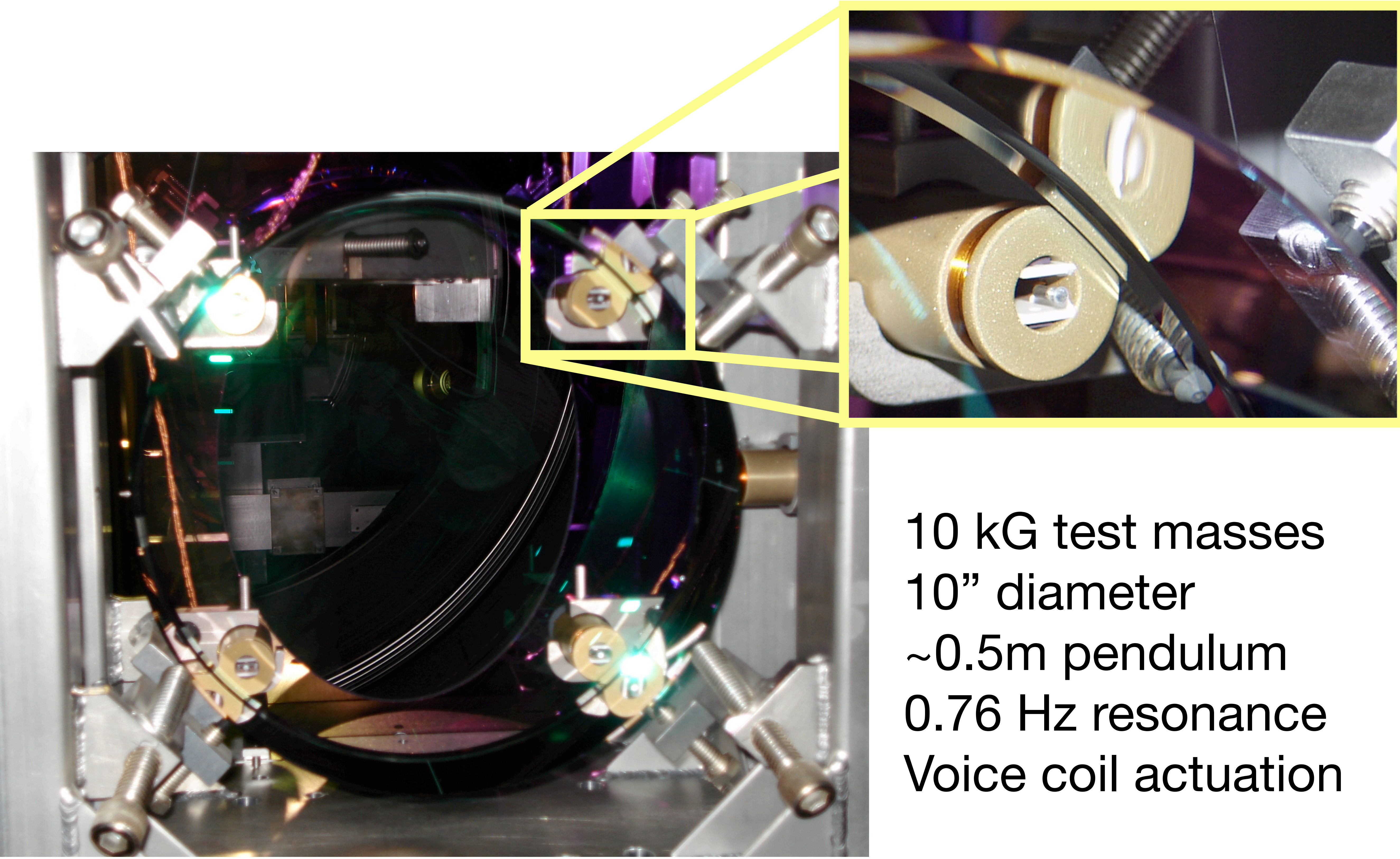
Facility limits





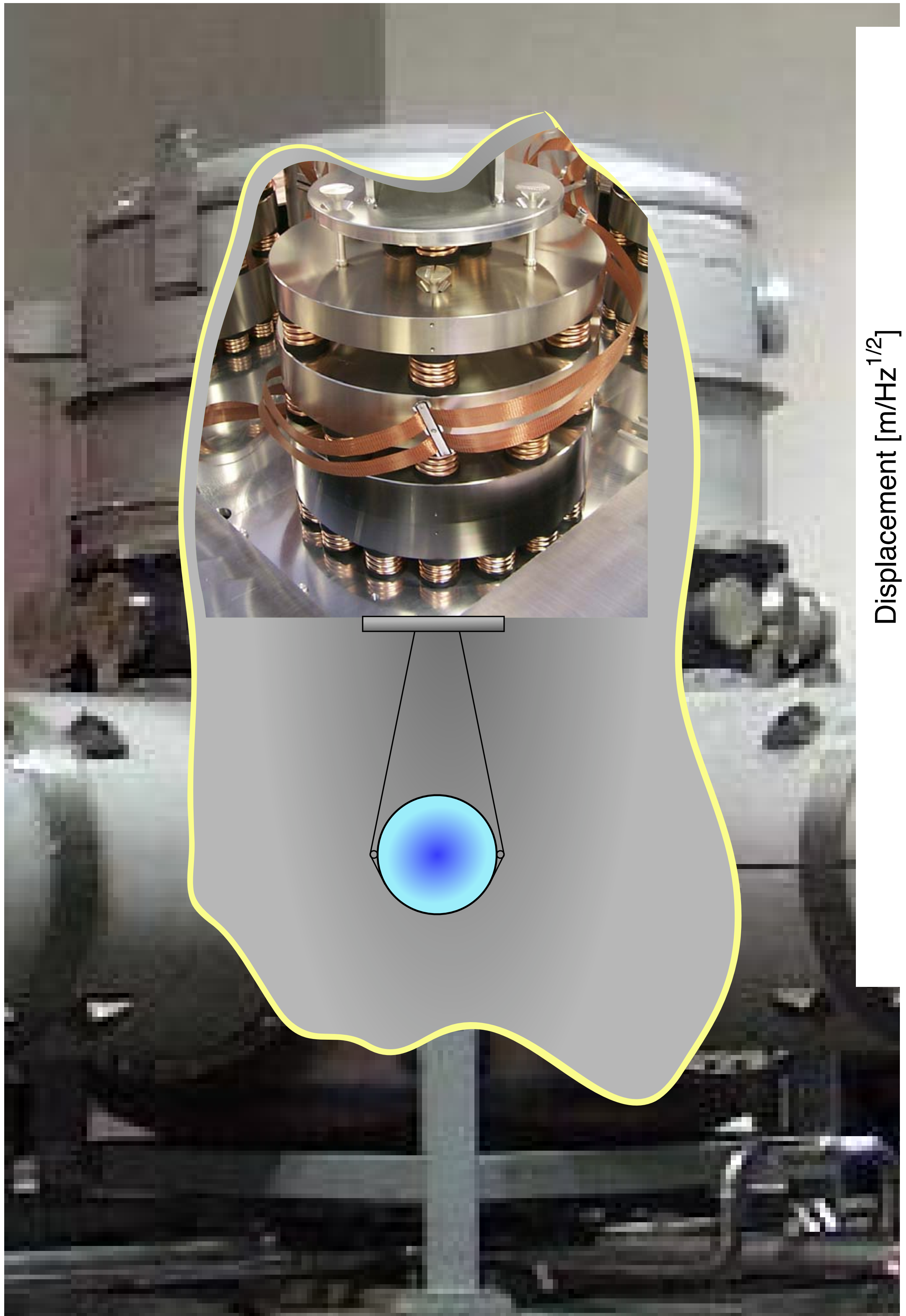
Lazzarini, Weiss LIGO E950018

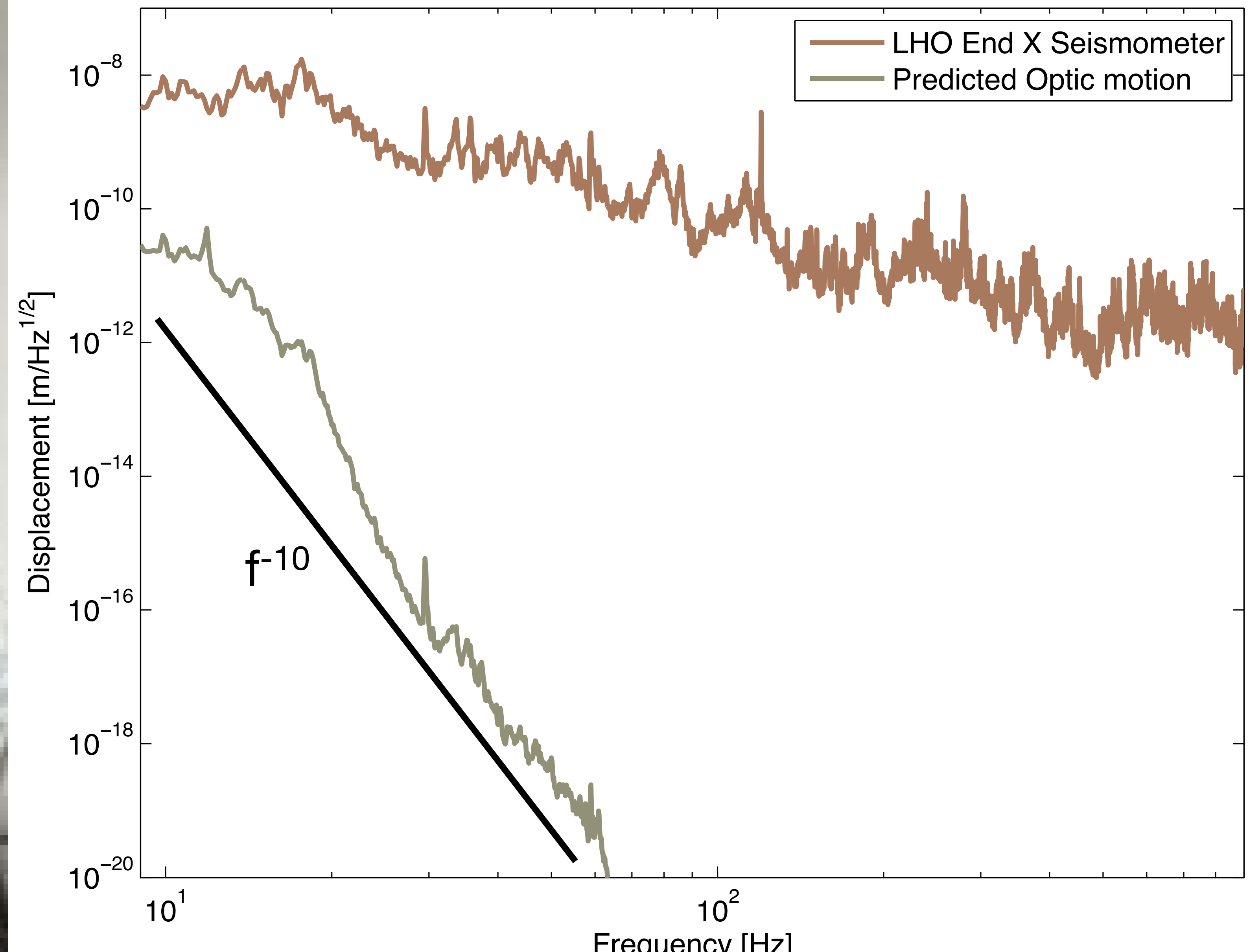
Suspended mirrors



10 kG test masses
10" diameter
~0.5m pendulum
0.76 Hz resonance
Voice coil actuation

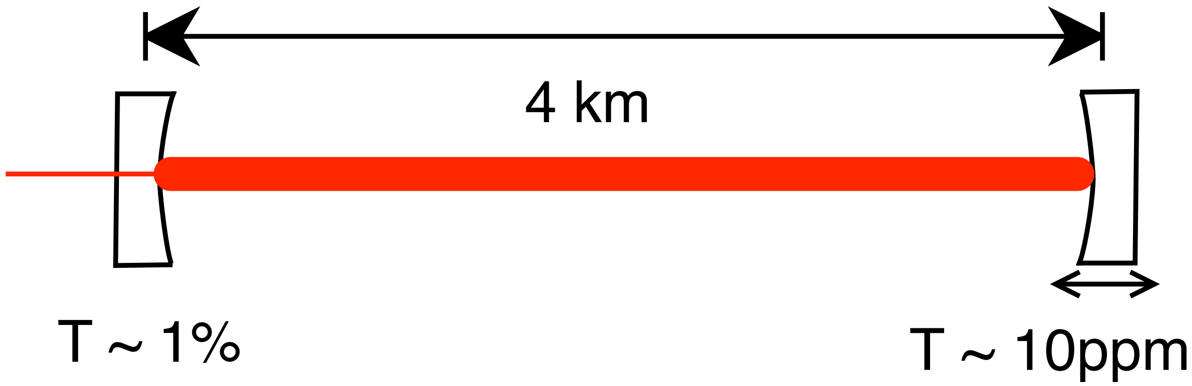
Seismic isolation

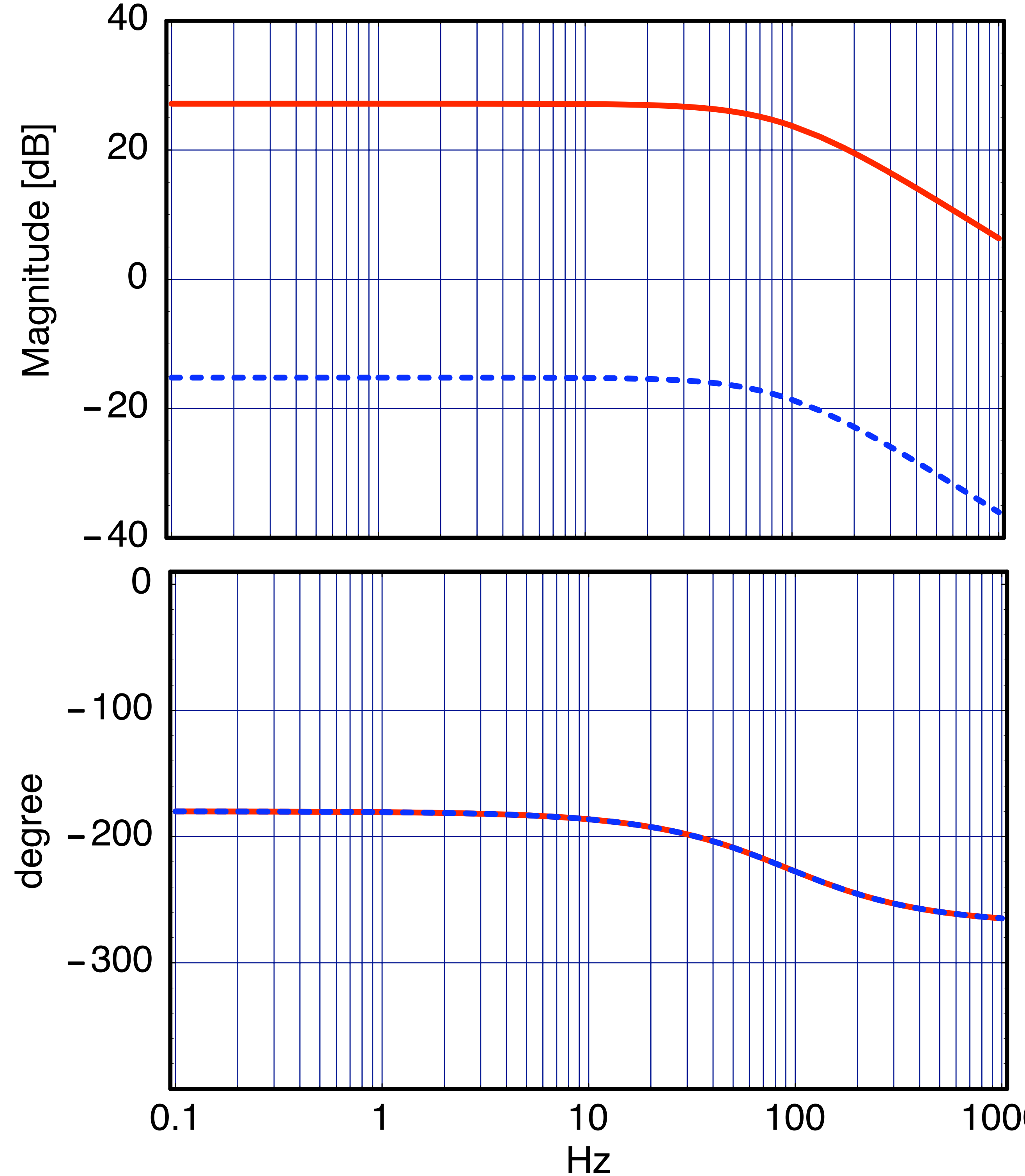




$$\frac{x_2(\omega)}{x_1(\omega)} = \frac{1}{1-\omega^2/\omega_0^2}$$

Arm cavity response



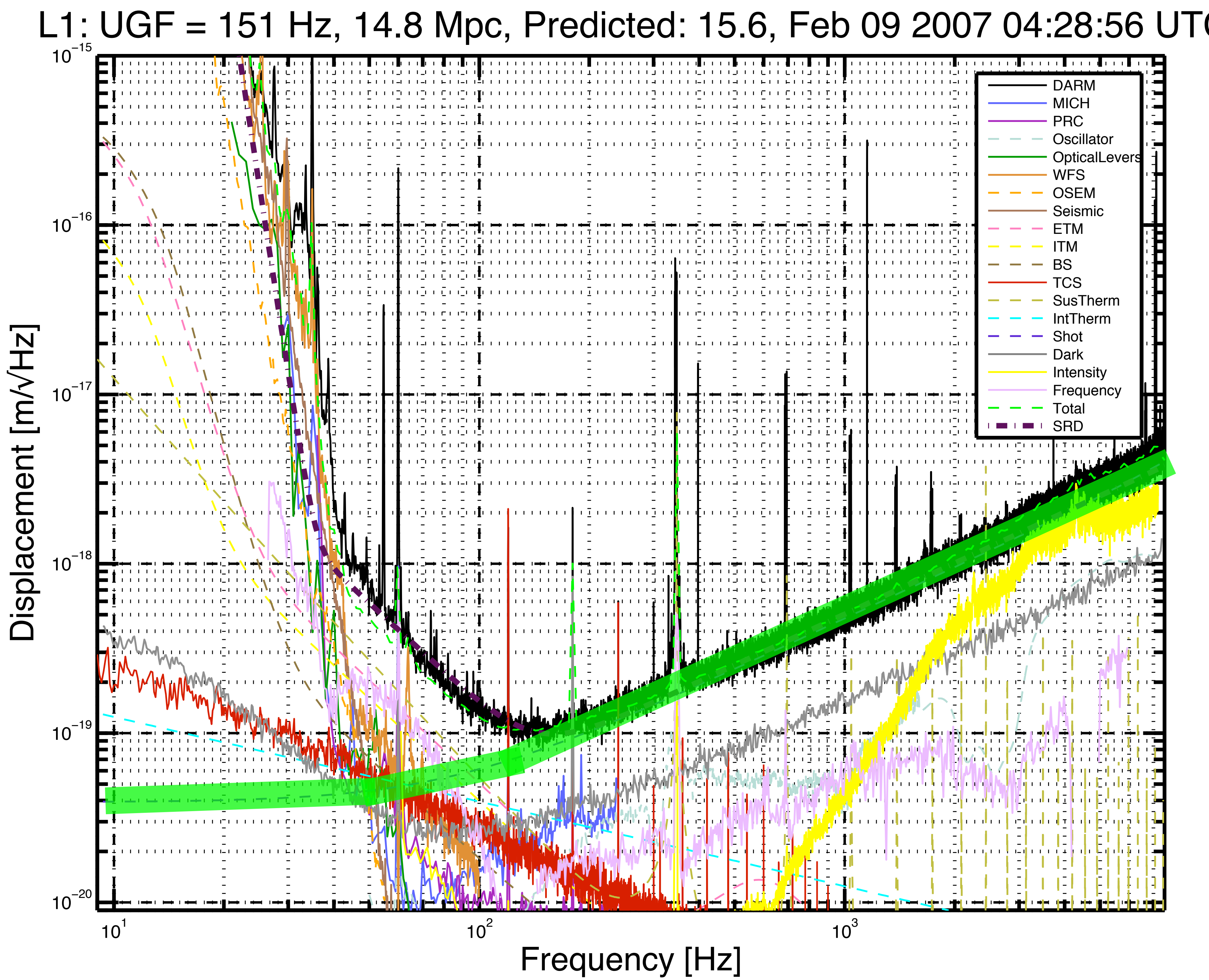


- Arm cavity storage time acts as a single-pole low-pass filter

$$\omega_p = \frac{c}{L}\frac{\pi}{\mathcal{F}}$$

Shot noise limit

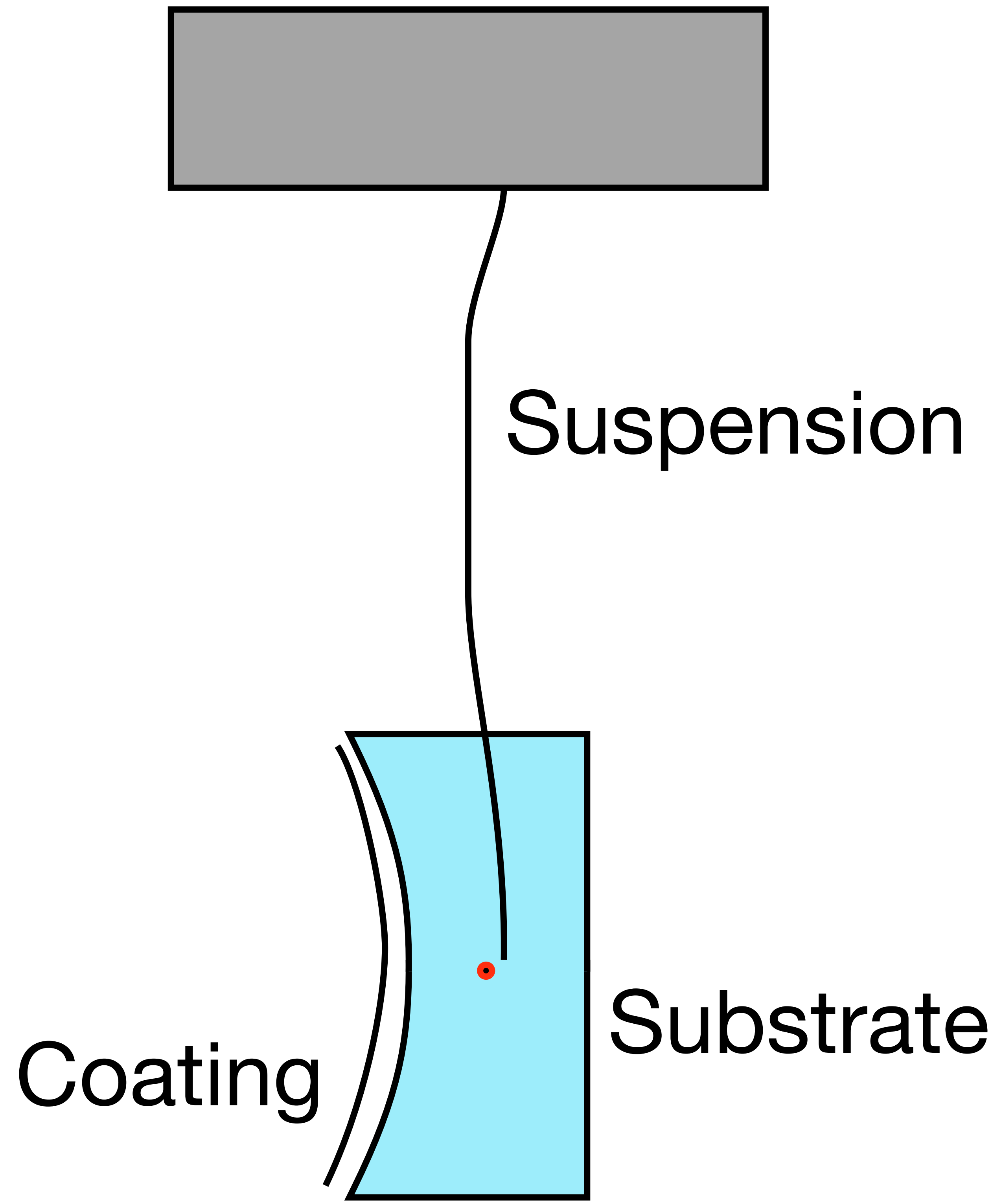
White shot noise with arm cavity response gives high frequency sensitivity limit



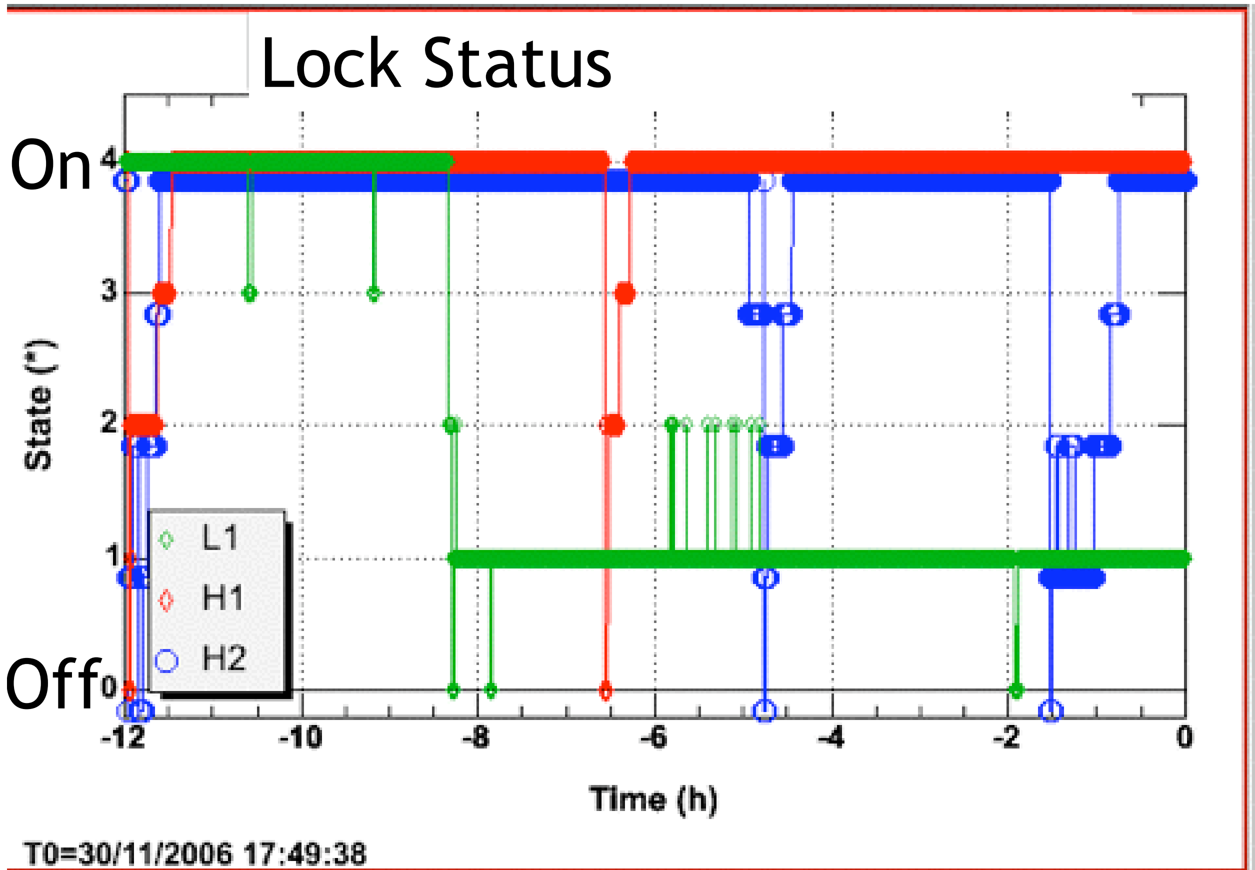
Thermal noise

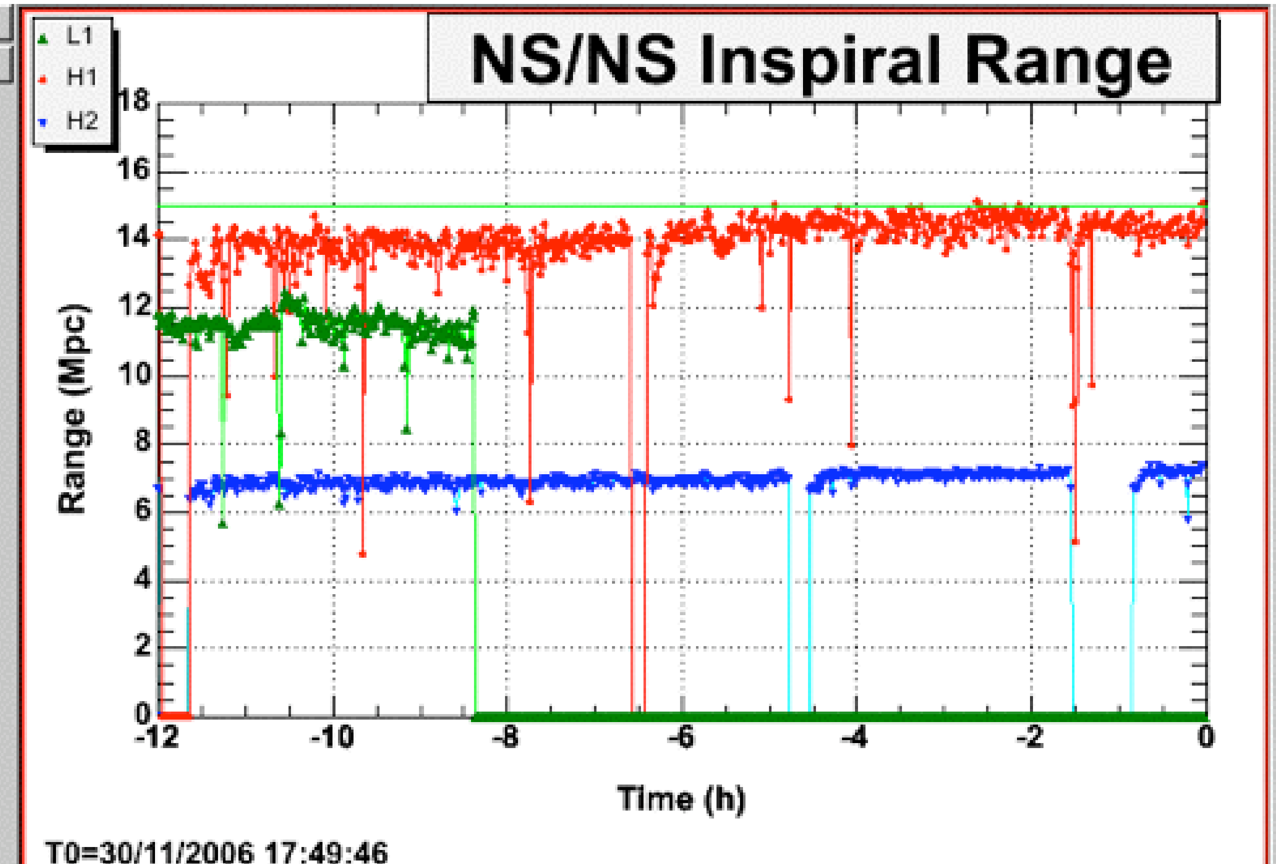
Dissipation in lossy materials (wire, substrate, coating) causes fluctuations in the measured displacement

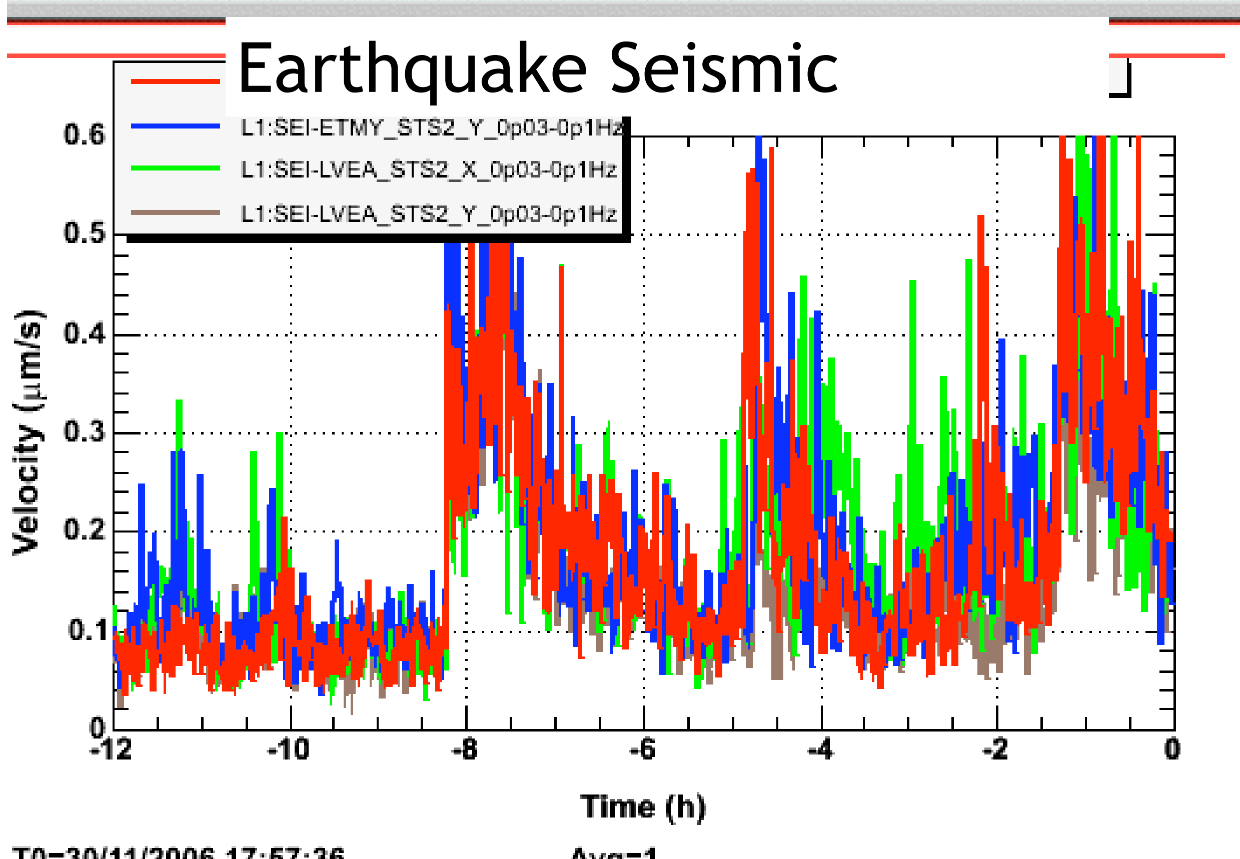
May be limiting noise 40-100 Hz

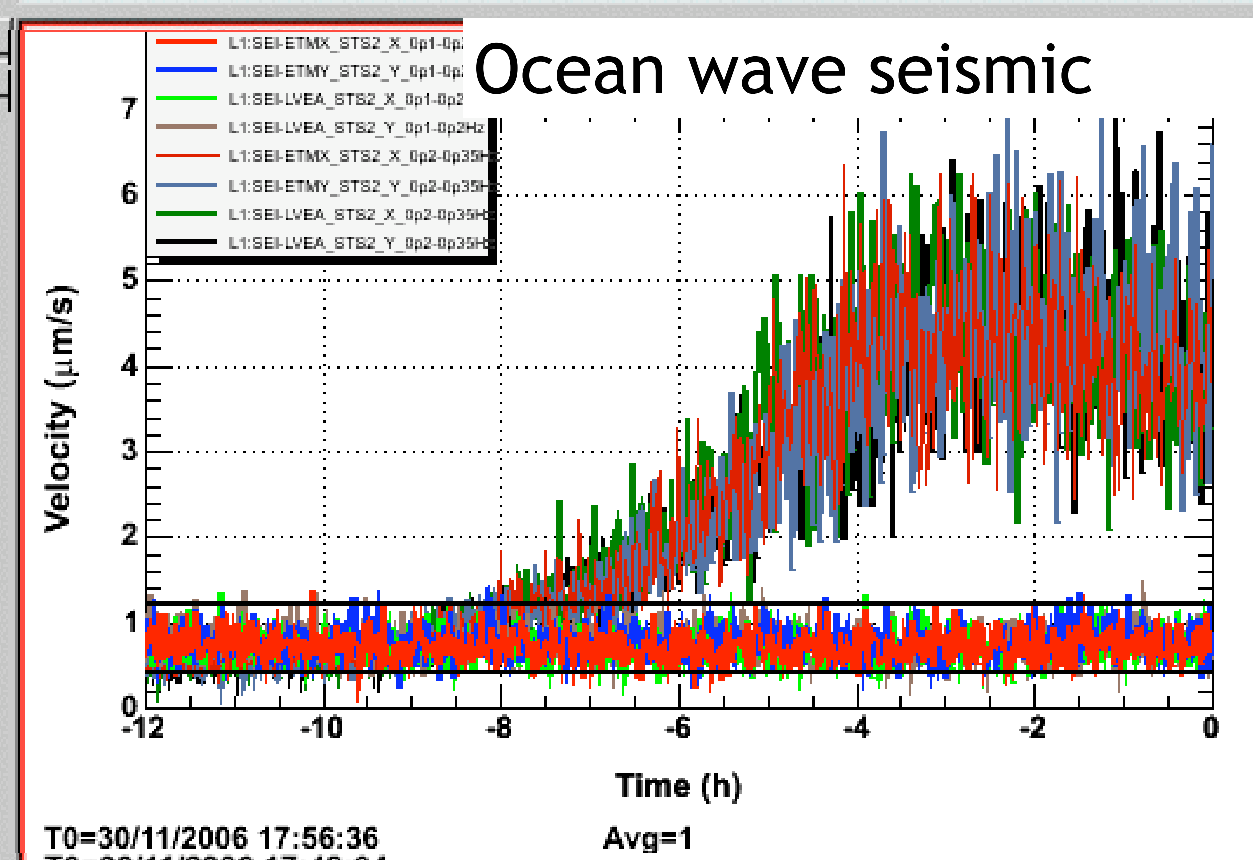


Real world problems

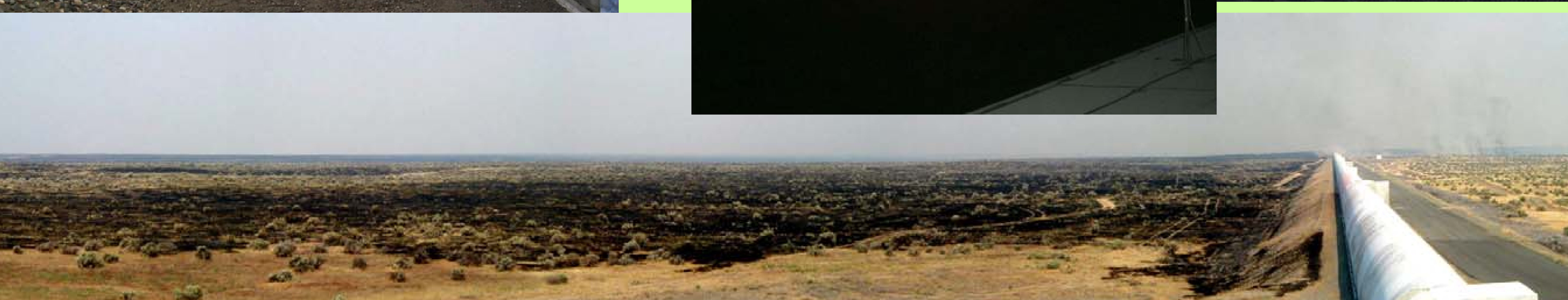




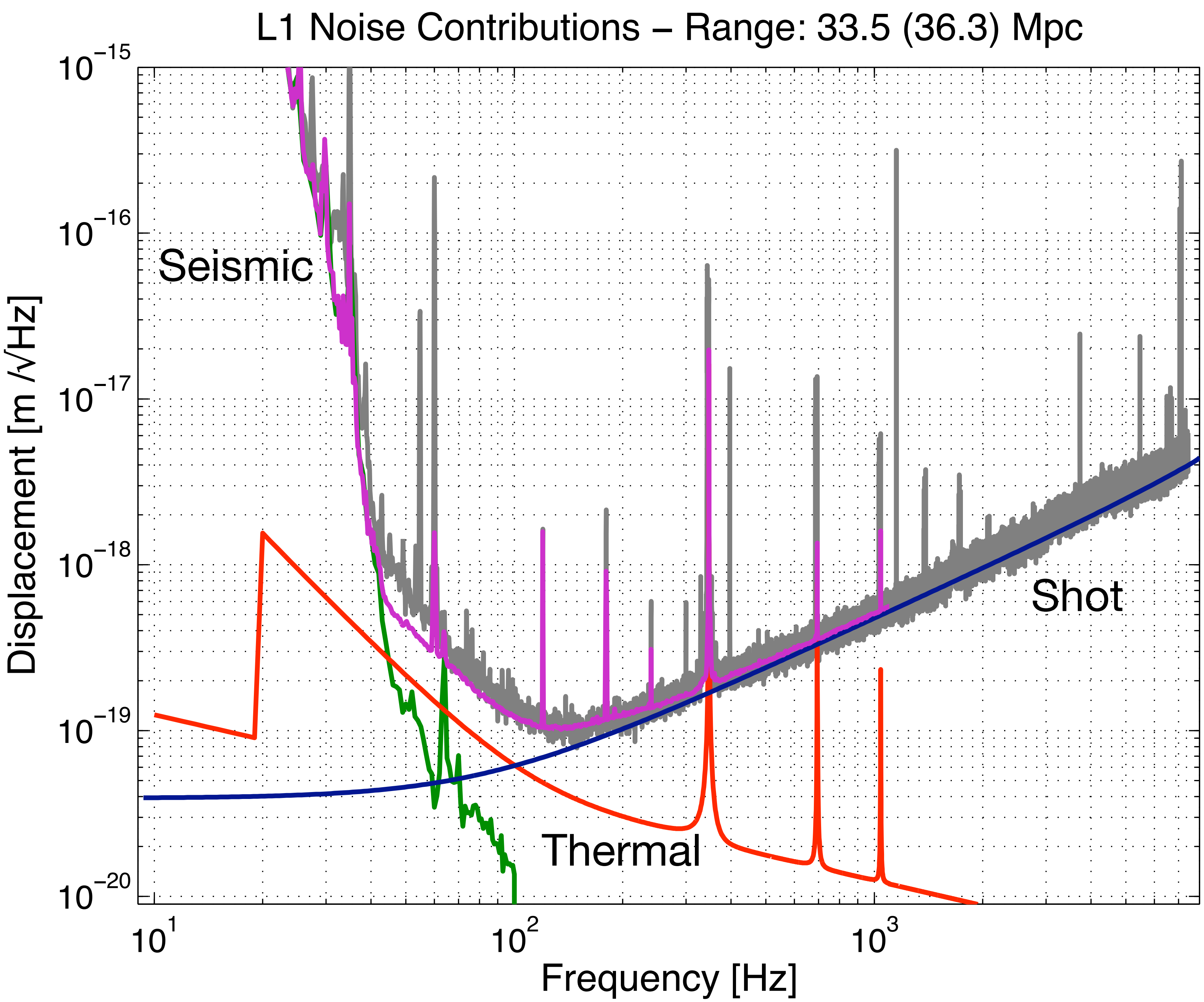




More problems



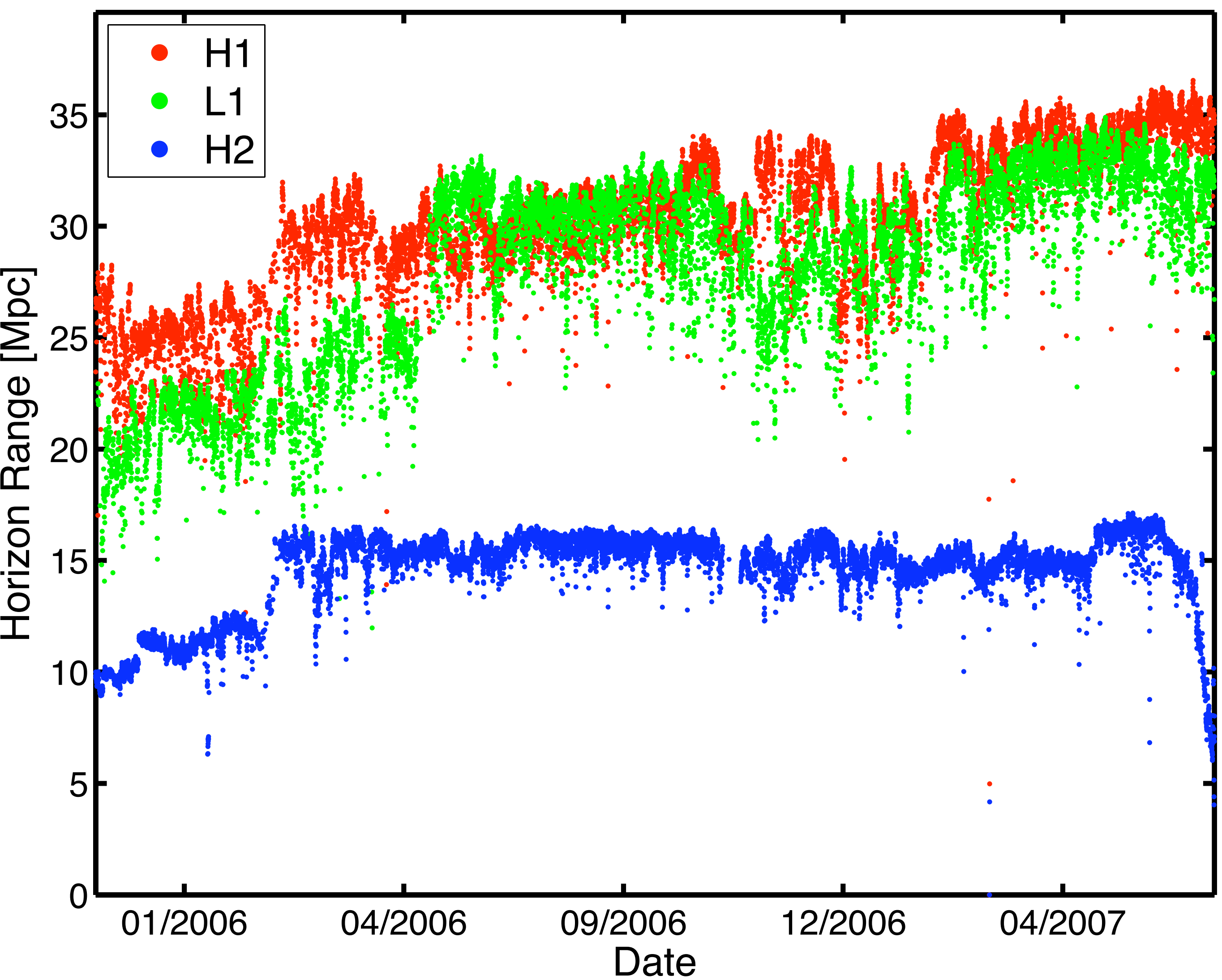
Noise Budget

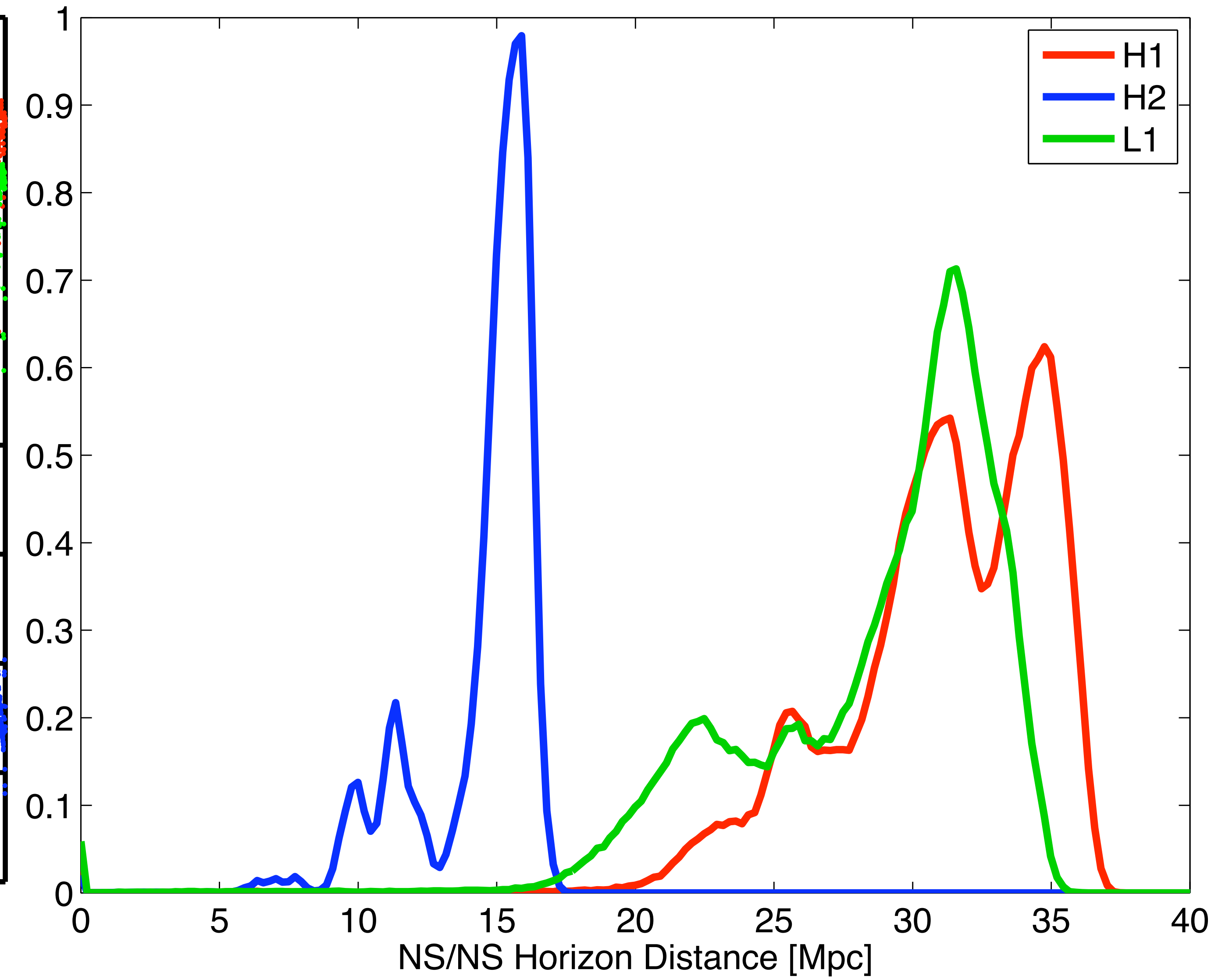


injection/response measurements of noise couplings to test mass displacement

L1 Noisebudget Feb 9, 2007 04:28 UTC

NS/NS range





~70% duty factor

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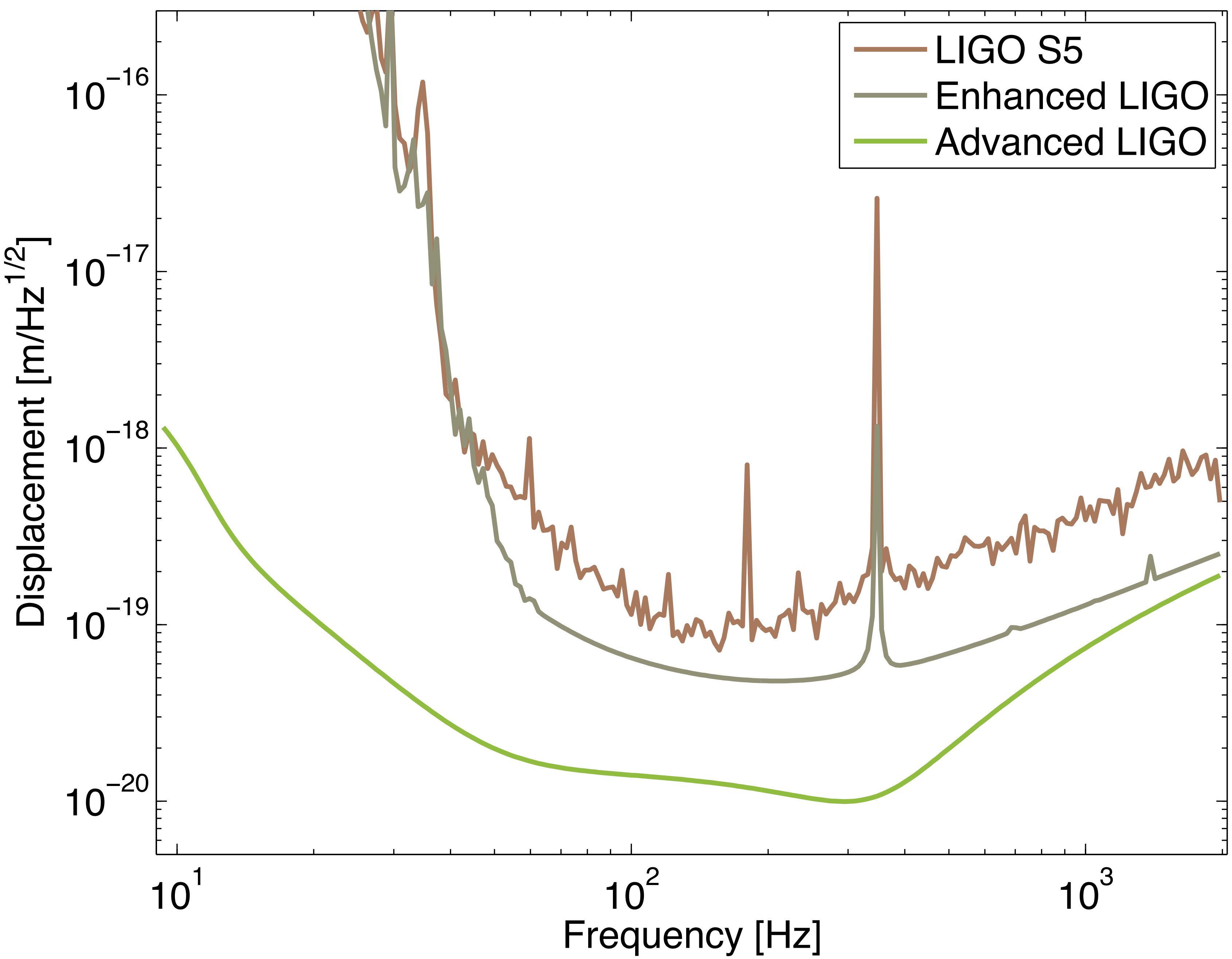
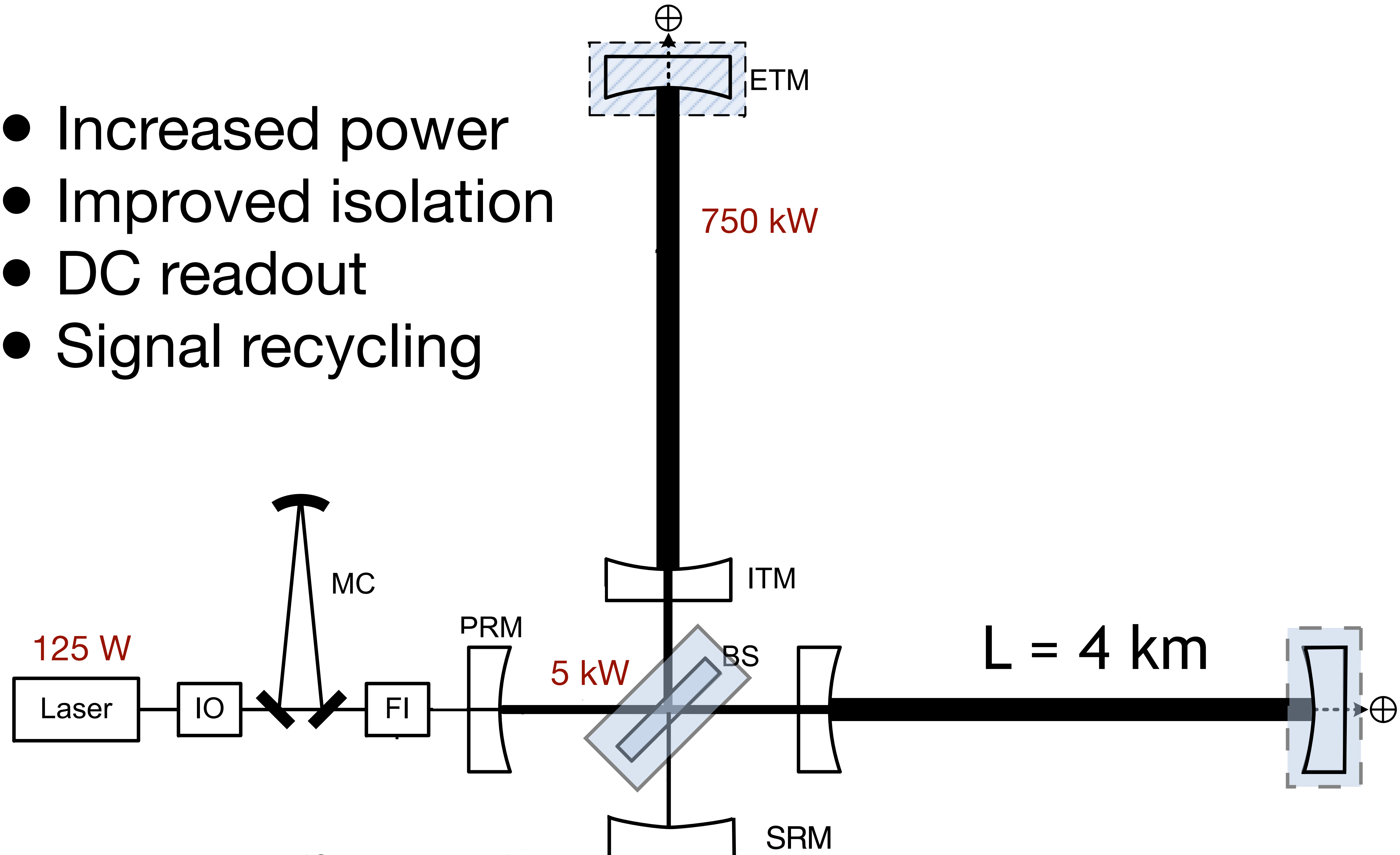


Advanced LIGO

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



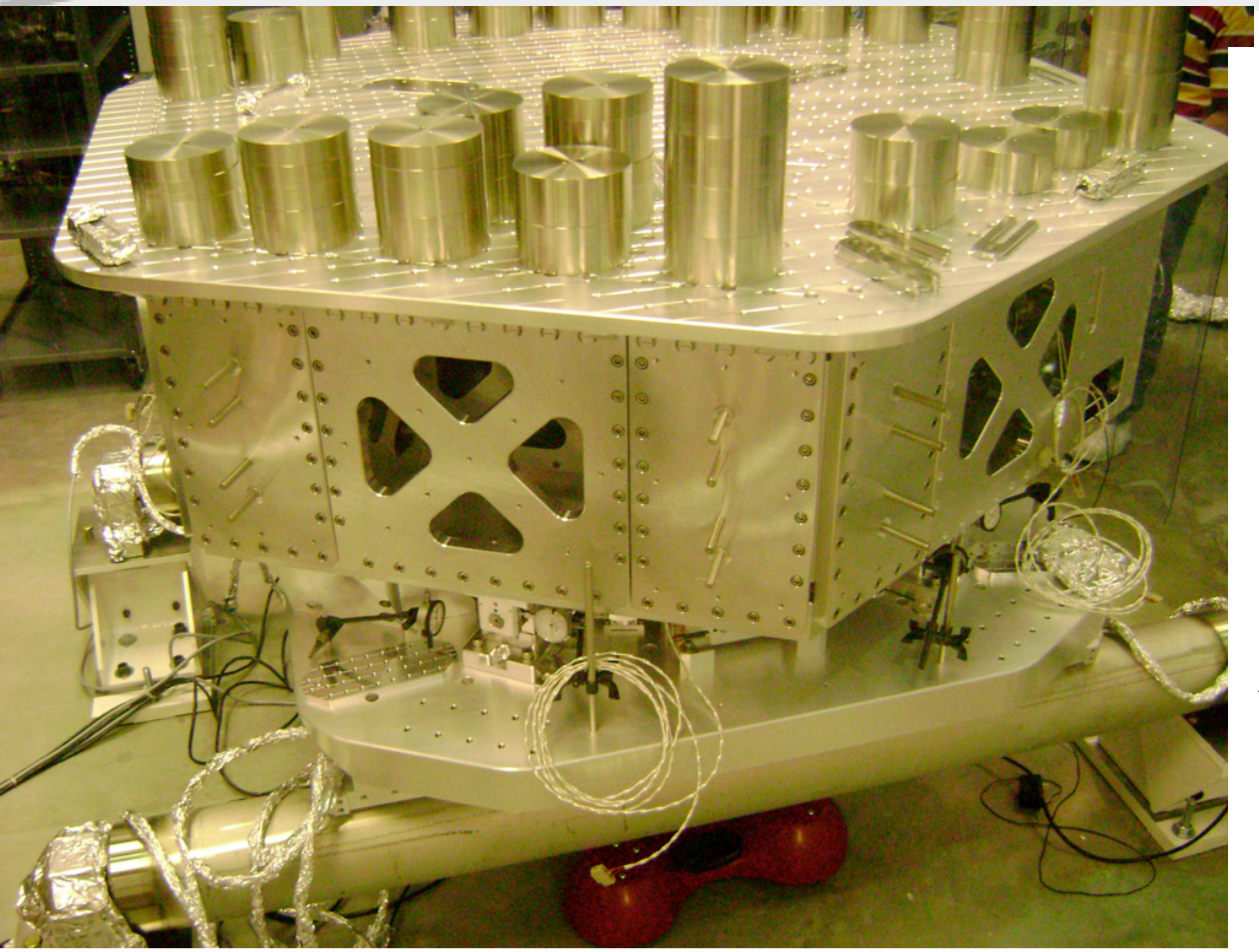
$10^{-13}\ \lambda = 10^{-19}$ m

Quadruple pendulum

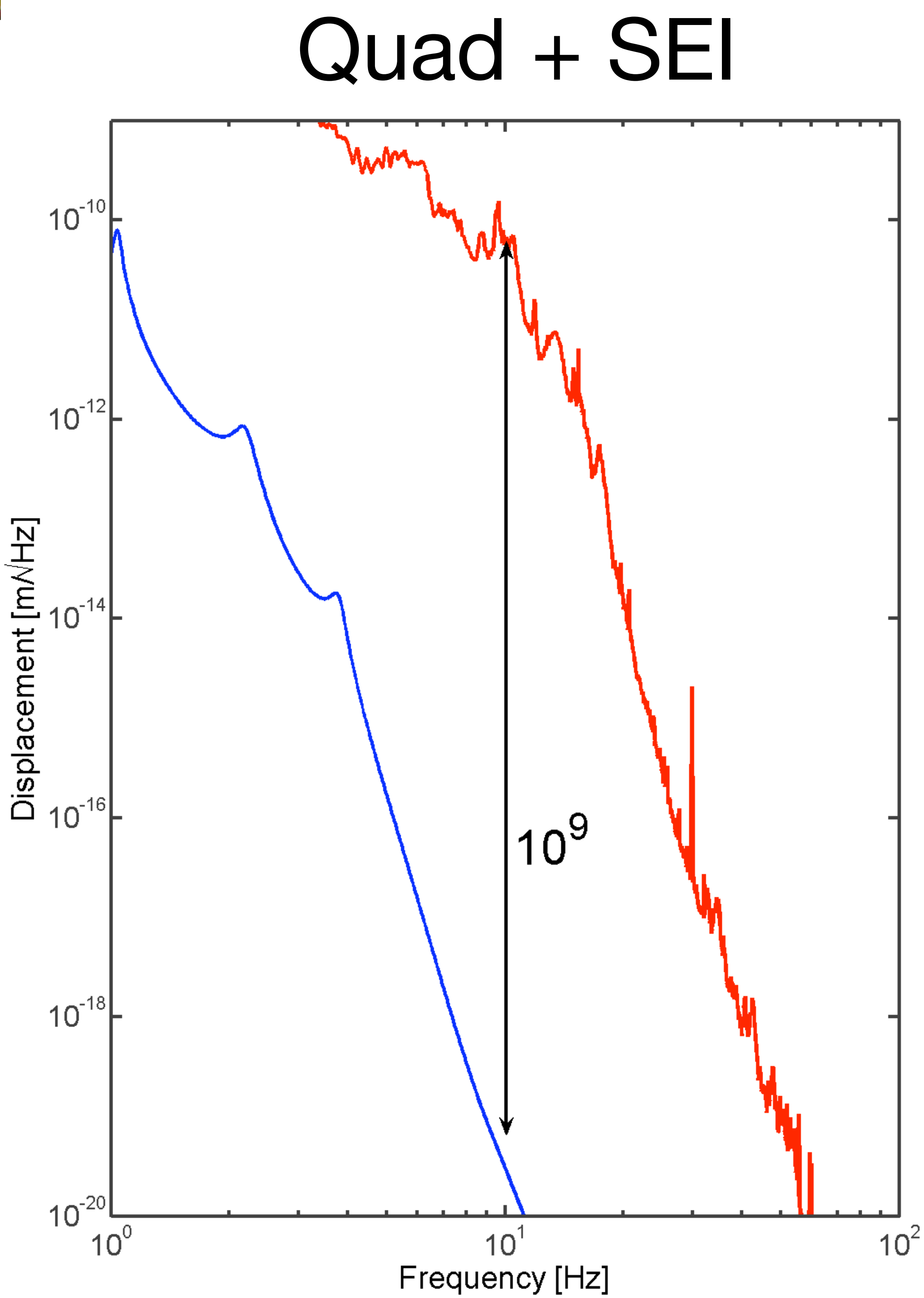
- isolation of f^{-8} above a few Hz
- f^{-2} filtering of actuator noise
- reaction mass
- fused silica suspension
- 40 kG test mass

Controls prototype @ CIT 2007

Active isolation



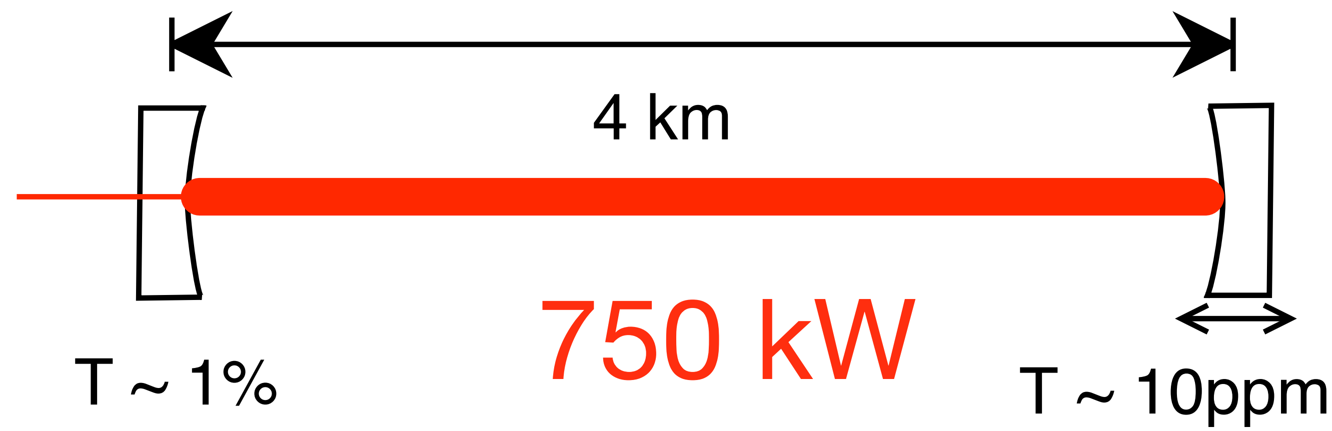
HAM ISI at Livingston Feb. 20, 2008

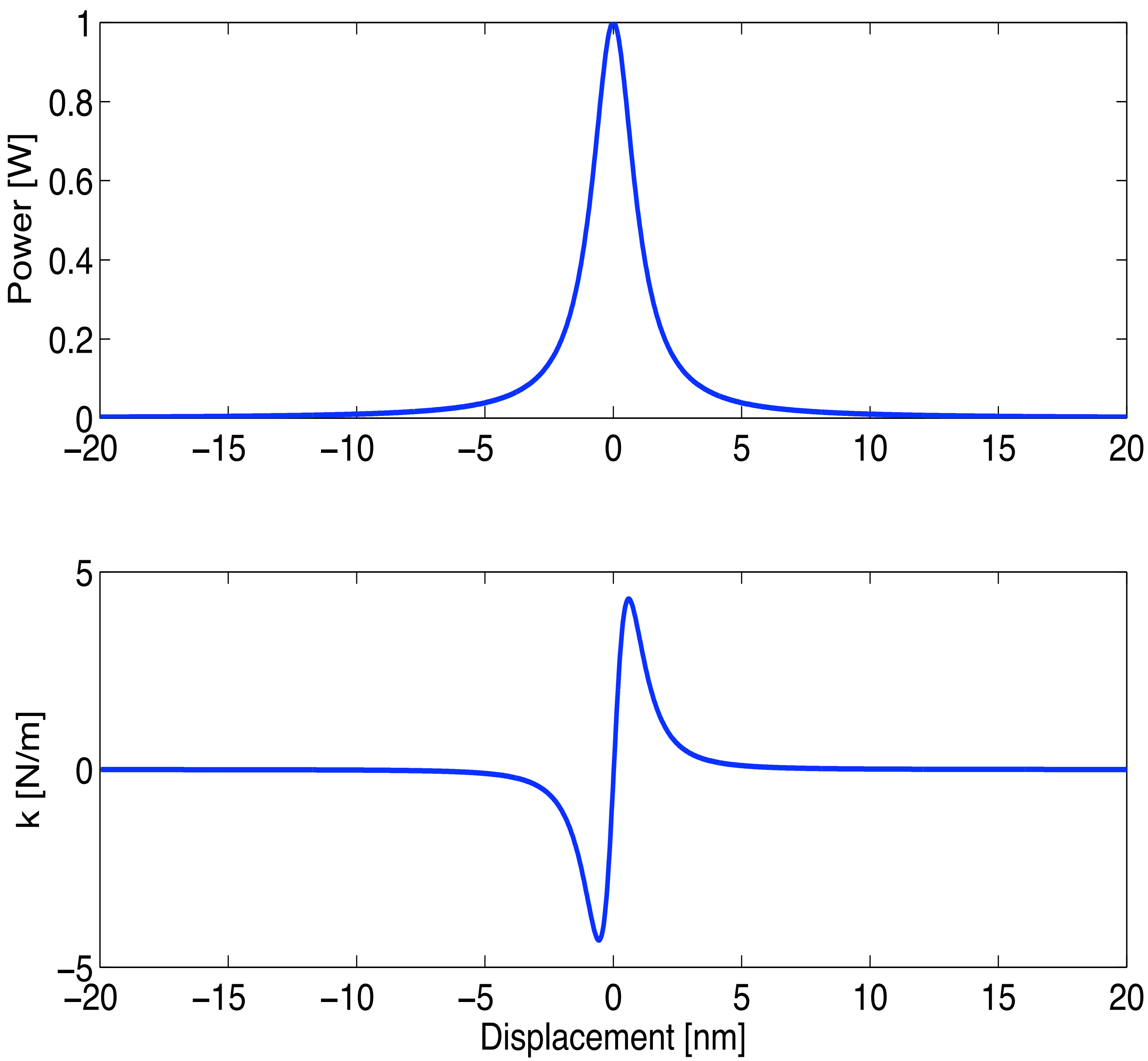


Optical spring

$$F_{rad} = \frac{2P}{c}$$

$$k_{rad} = -\frac{2}{c}\frac{dP}{dx}$$

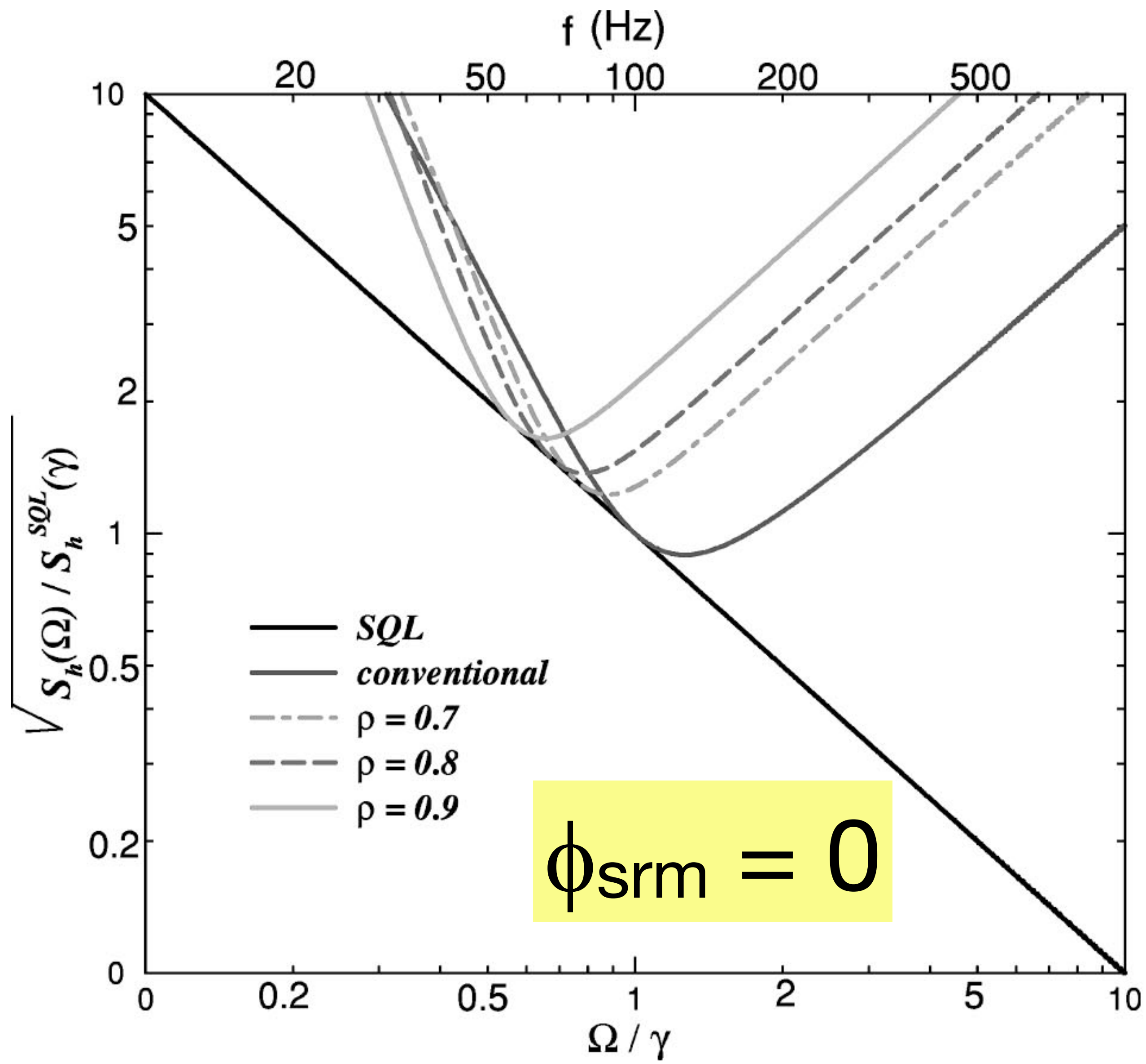




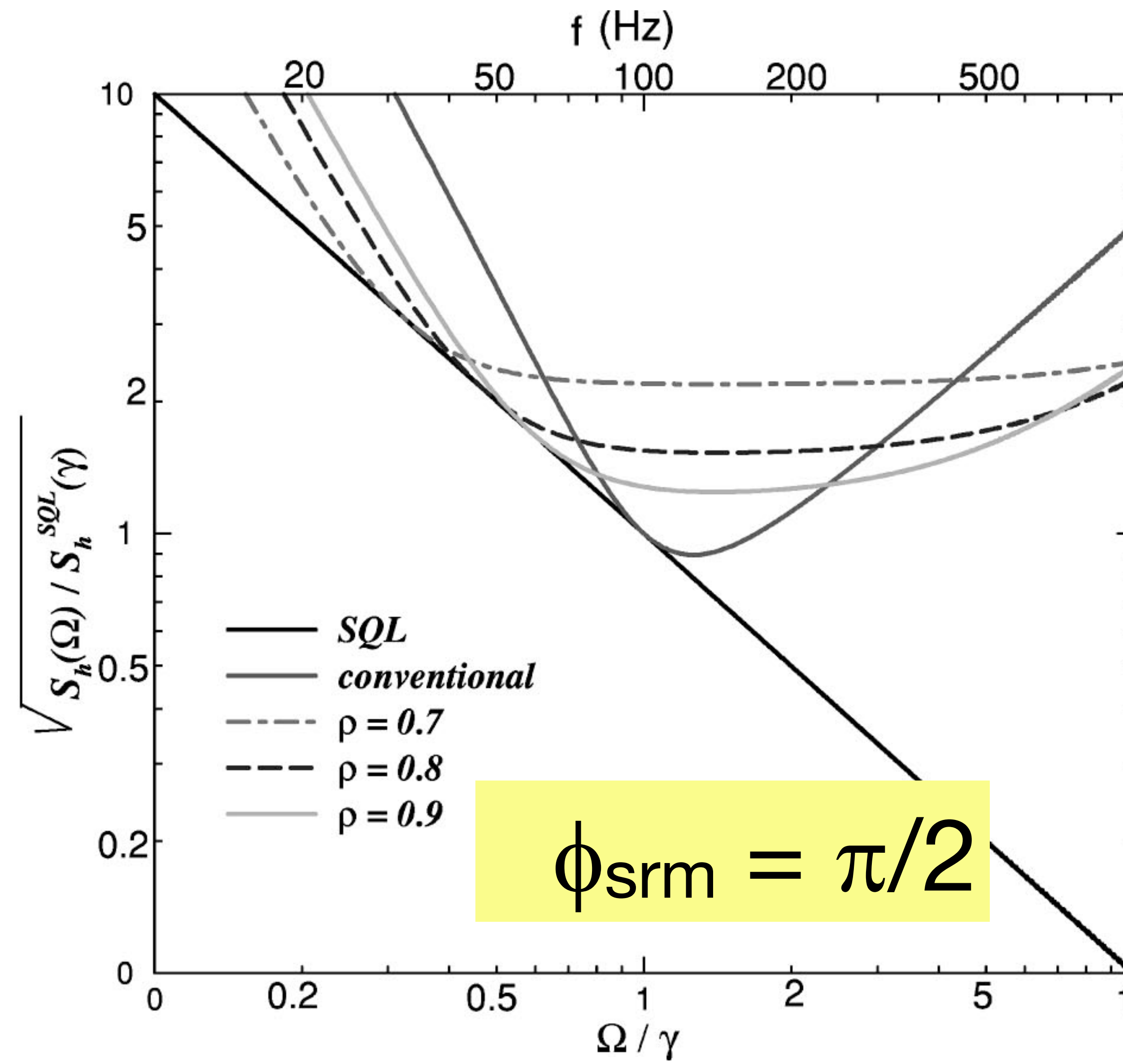
750 kW buildup
10 pm offset
Finesse = 500

k = 10^5 N/m
ω = 50 Hz

Signal recycling



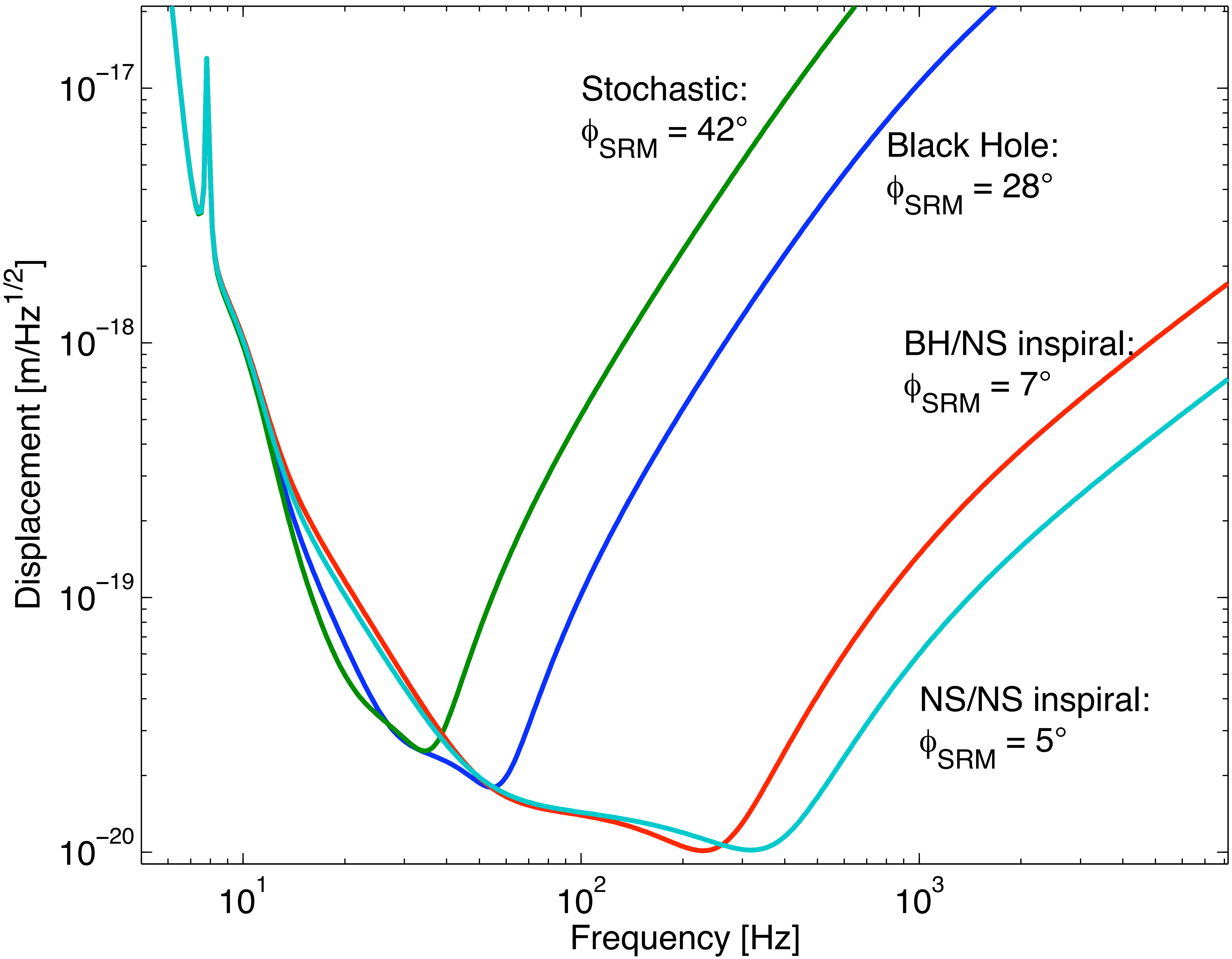
Signal recycling



Resonant sideband extraction

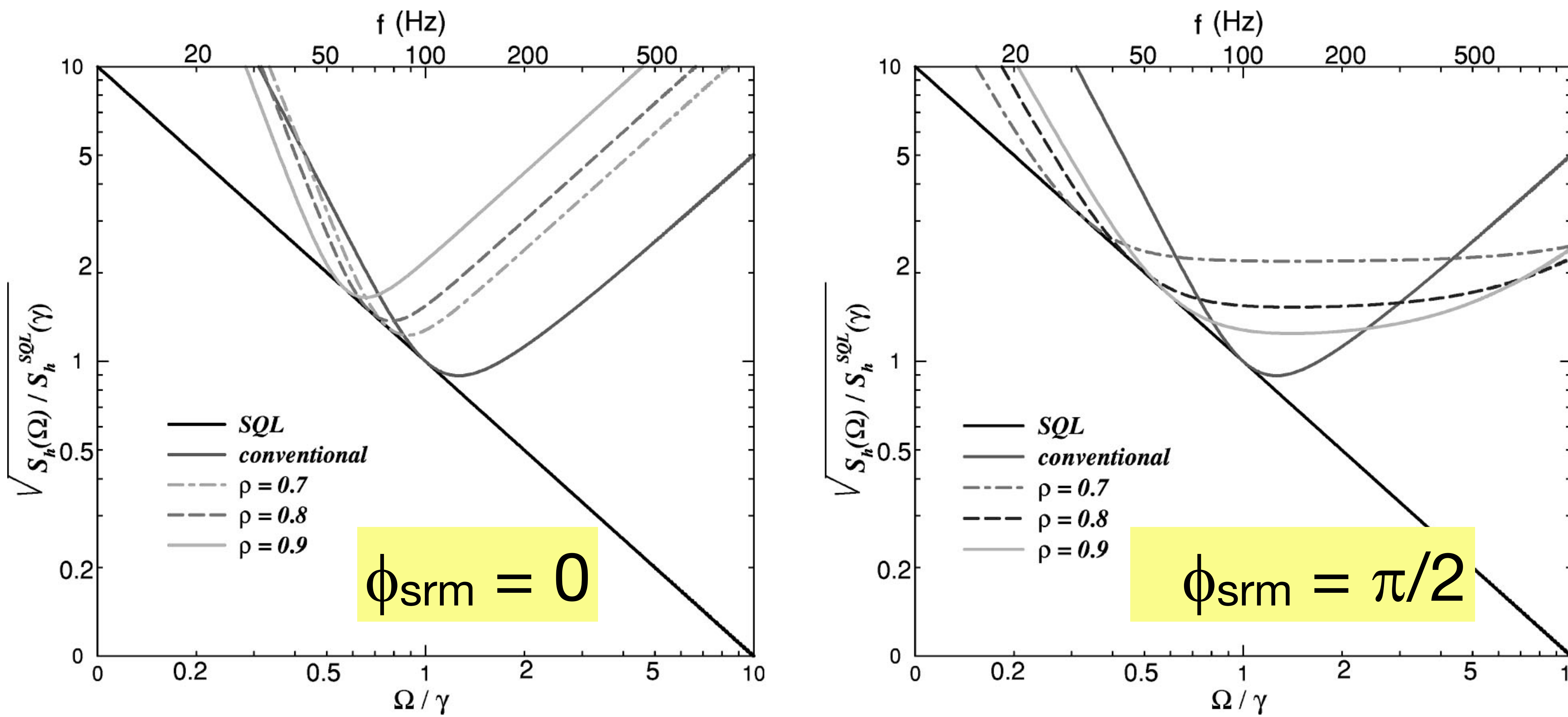
Buonanno & Chen, PRD64 2001

Tailor made response



Advanced LIGO Design Team, M060056

Signal recycling



Signal recycling

Resonant sideband extraction

Buonanno & Chen, PRD64 2001

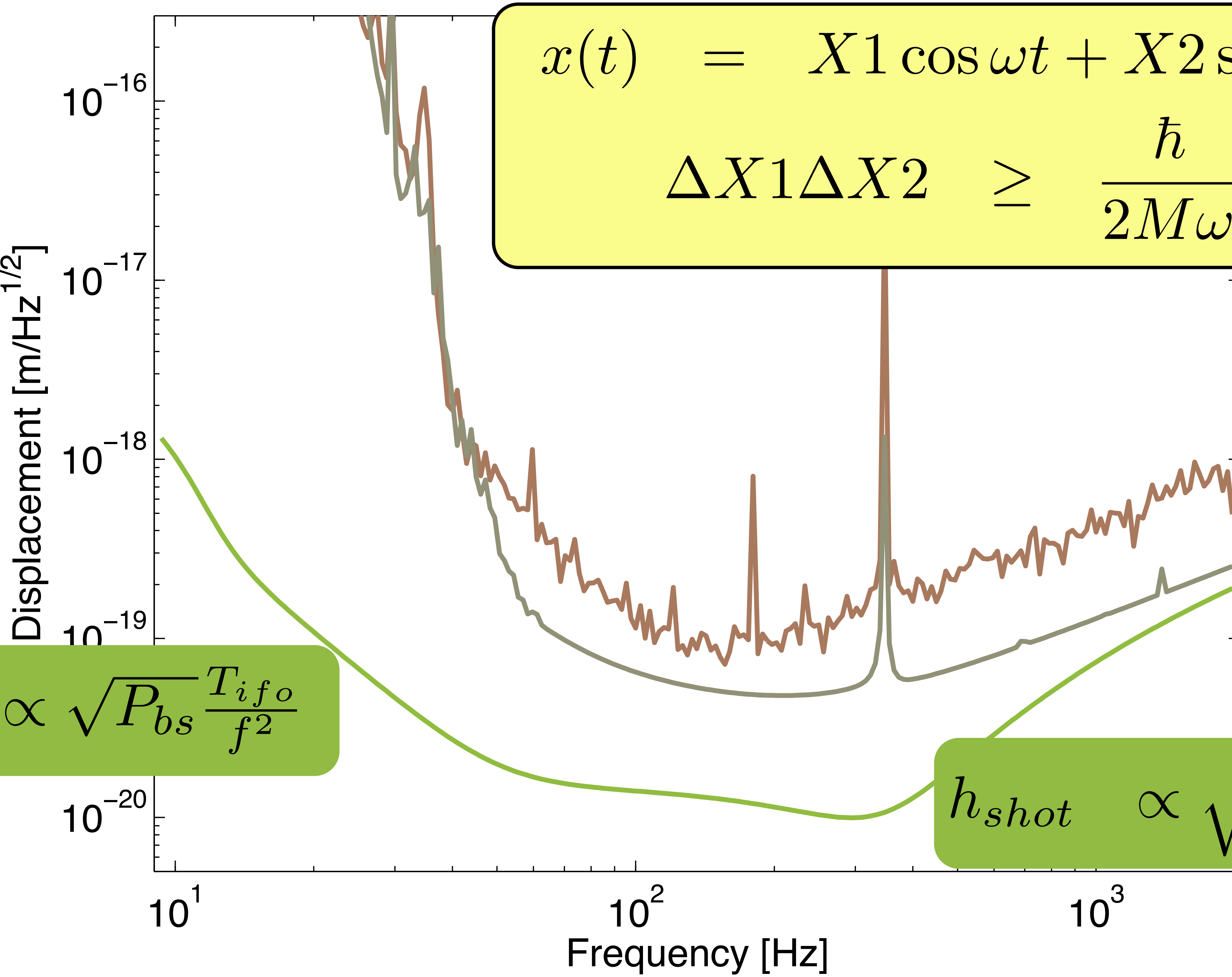
Standard Quantum Limit

Waldman
Maryland '08

"Light enforced quantum uncertainty"

$$x(t) = X1\cos\omega t + X2\sin\omega t$$

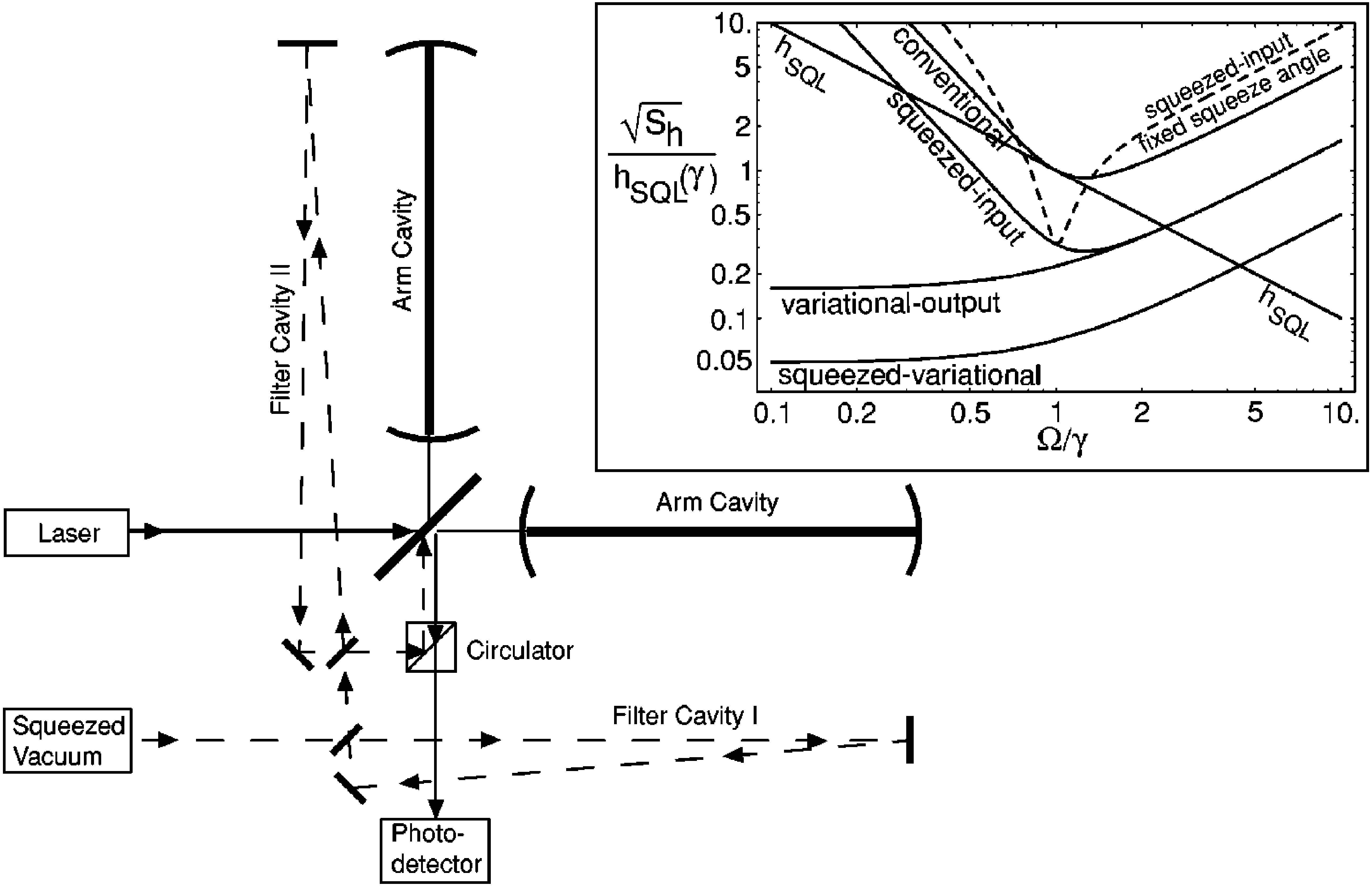
$$\Delta X1 \Delta X2 \geq \frac{\hbar}{2M\omega}$$



$$h_{rad} \propto \sqrt{P_{bs}}\frac{T_{ifo}}{f^2}$$

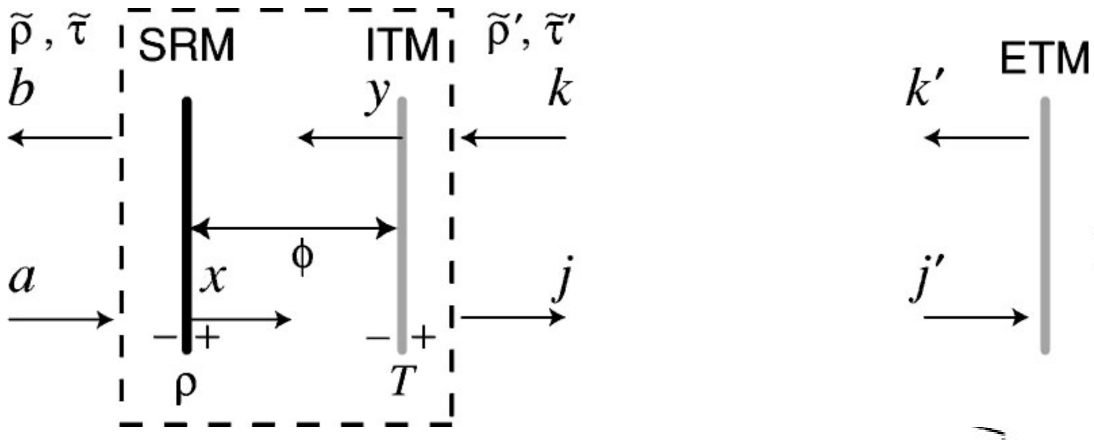
$$h_{shot} \propto \sqrt{\frac{1}{P_{BS}}\frac{1}{T_{ifo}}}$$

Quantum measurement



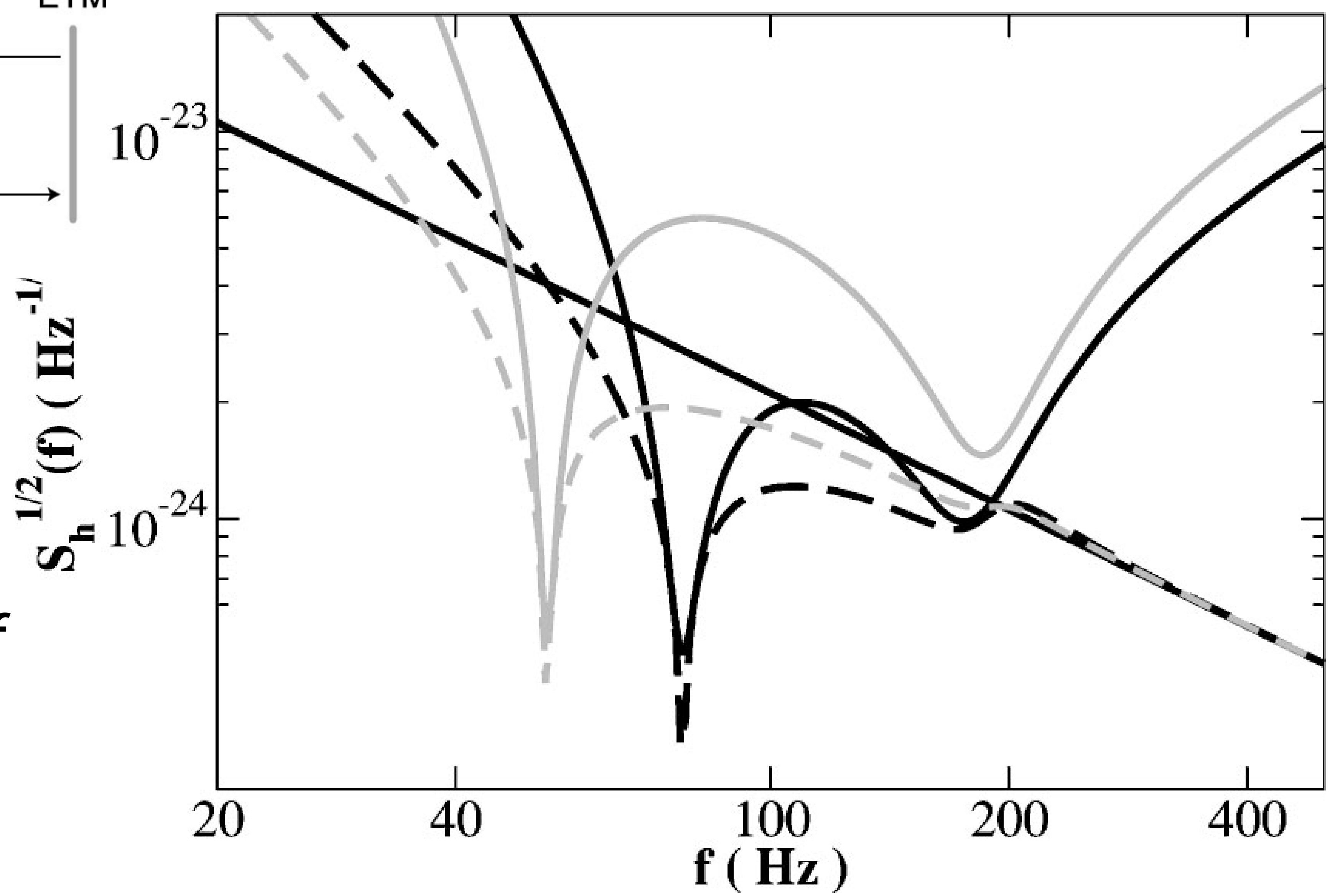
Kimble et al., PRD65 2001

Back action evading



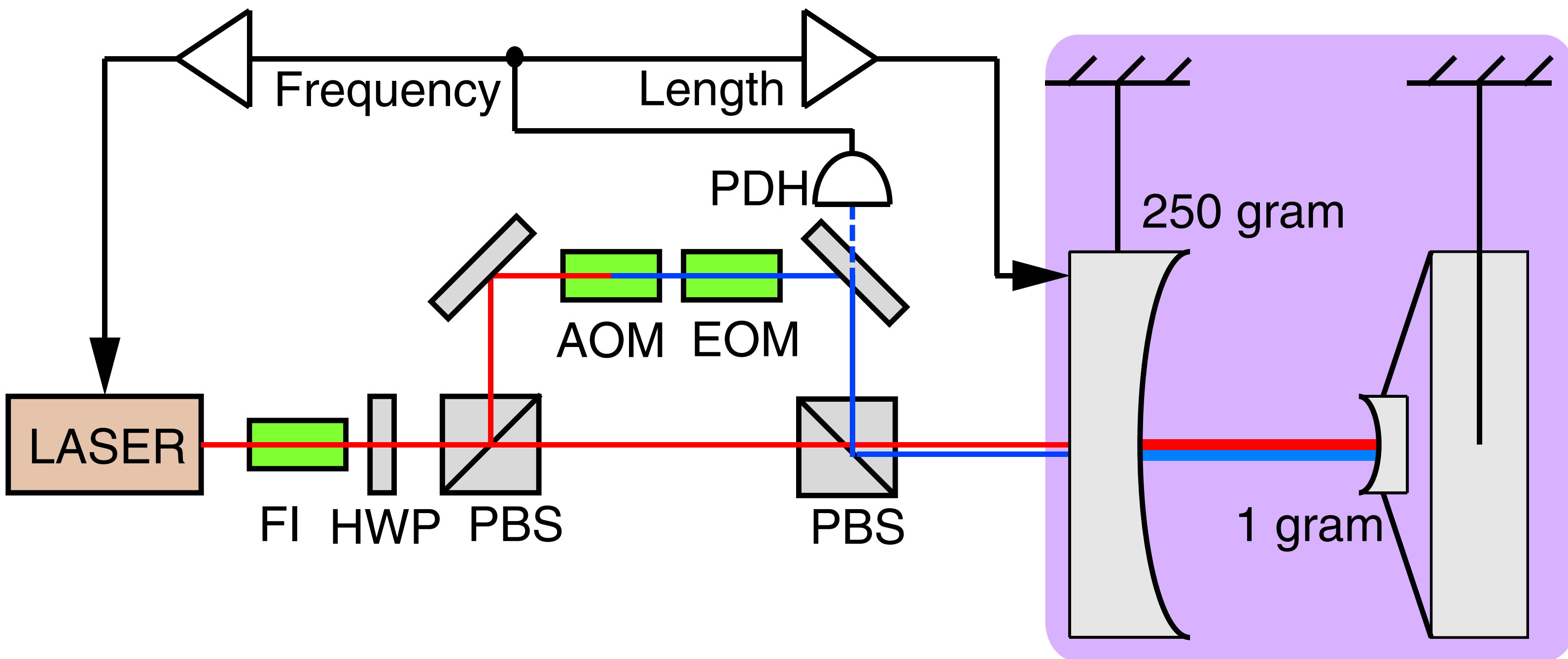
For a given frequency, the measurement of a specific quadrature of the light at *b*, doesn't perturb the measurement

(at the expense of noise at other frequencies)

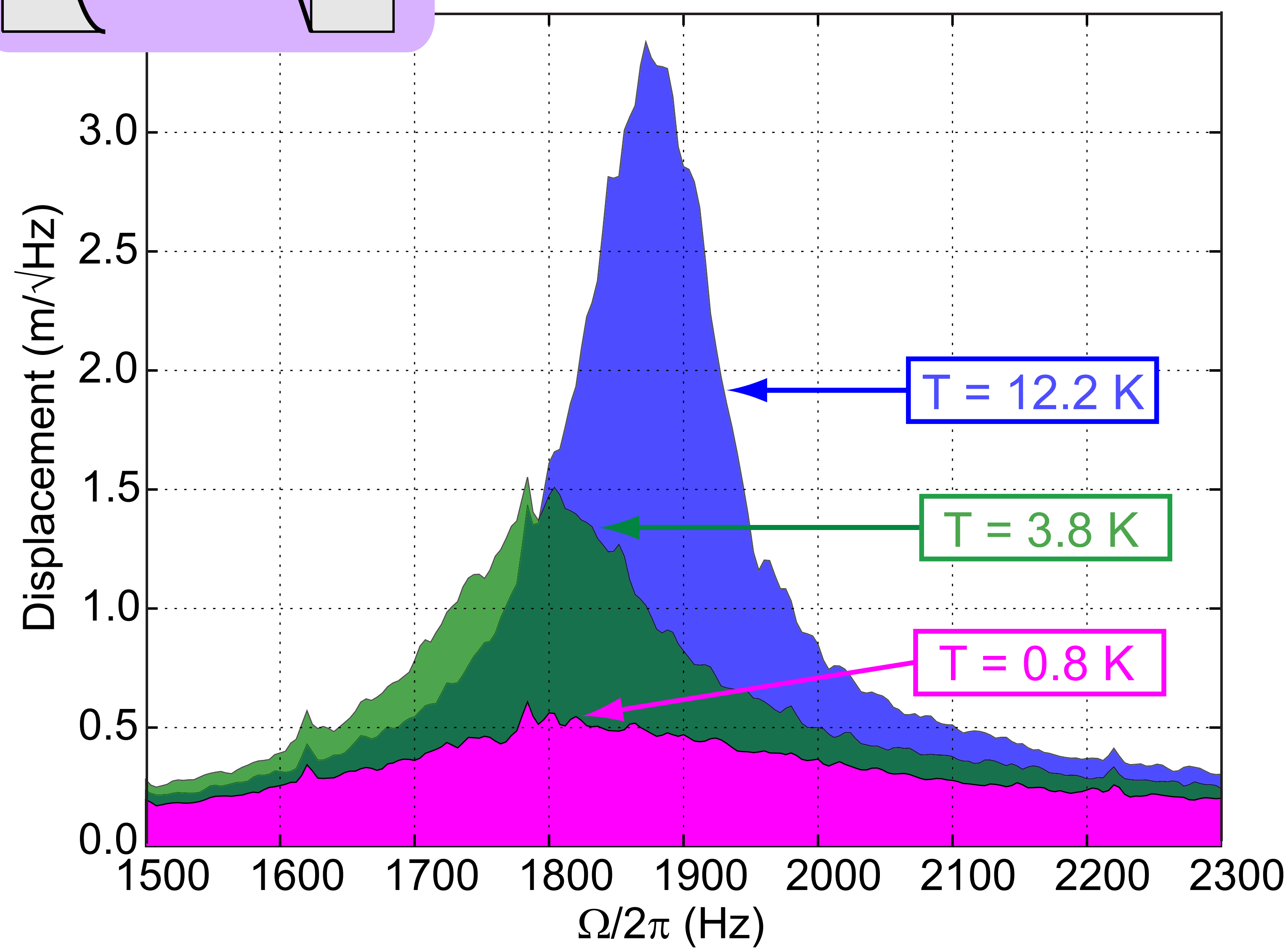


Buonanno & Chen, PRD67 2003

Optical Trapping

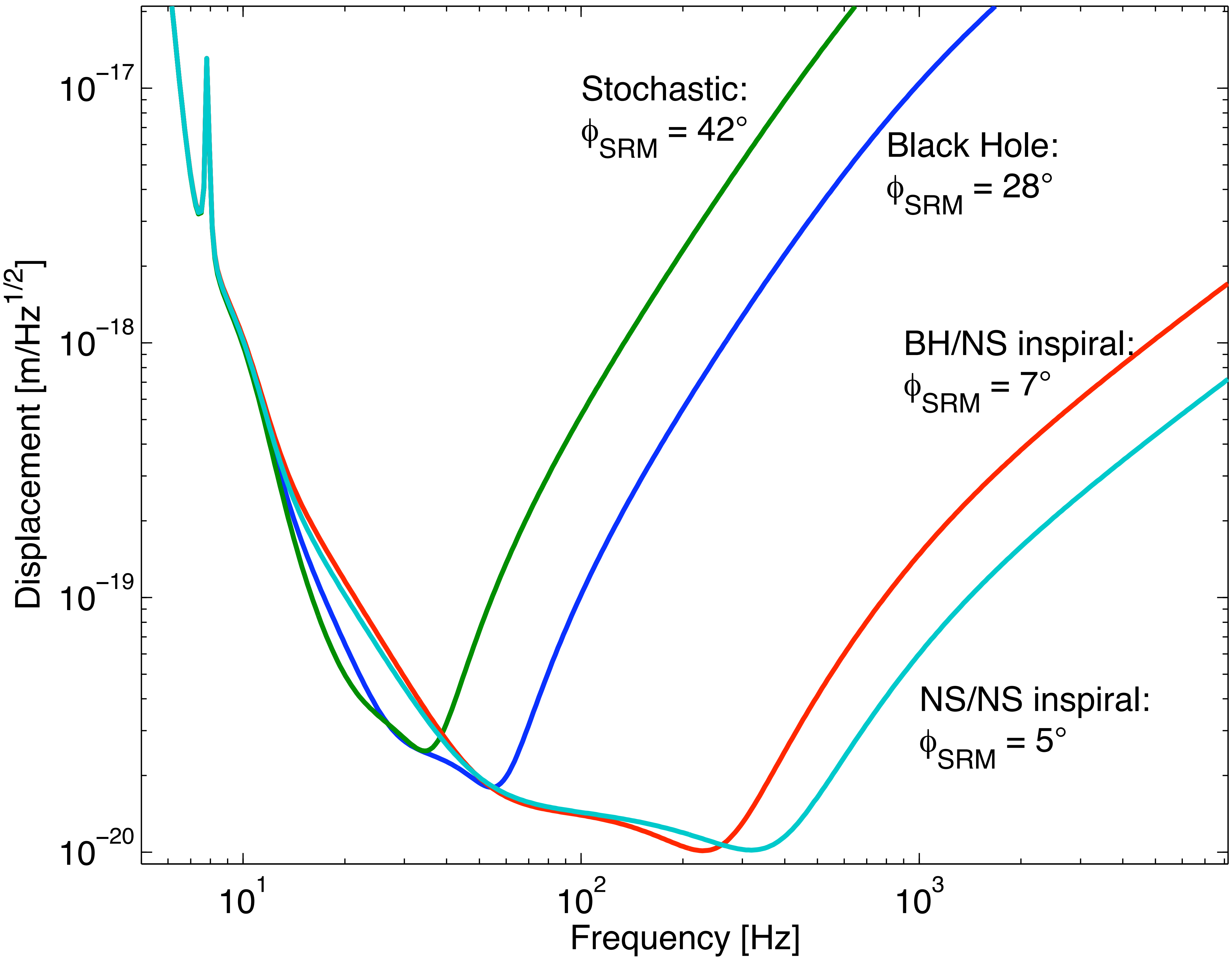


- Use optical spring to "trap" mirror
- Used on 1g optic



Corbitt et al. PRL98 2007

Tailor made response



Advanced LIGO Design Team, M060056

aLIGO Sensitivity

1.4 x 1.4 M_{sun}
NS/NS inspiral

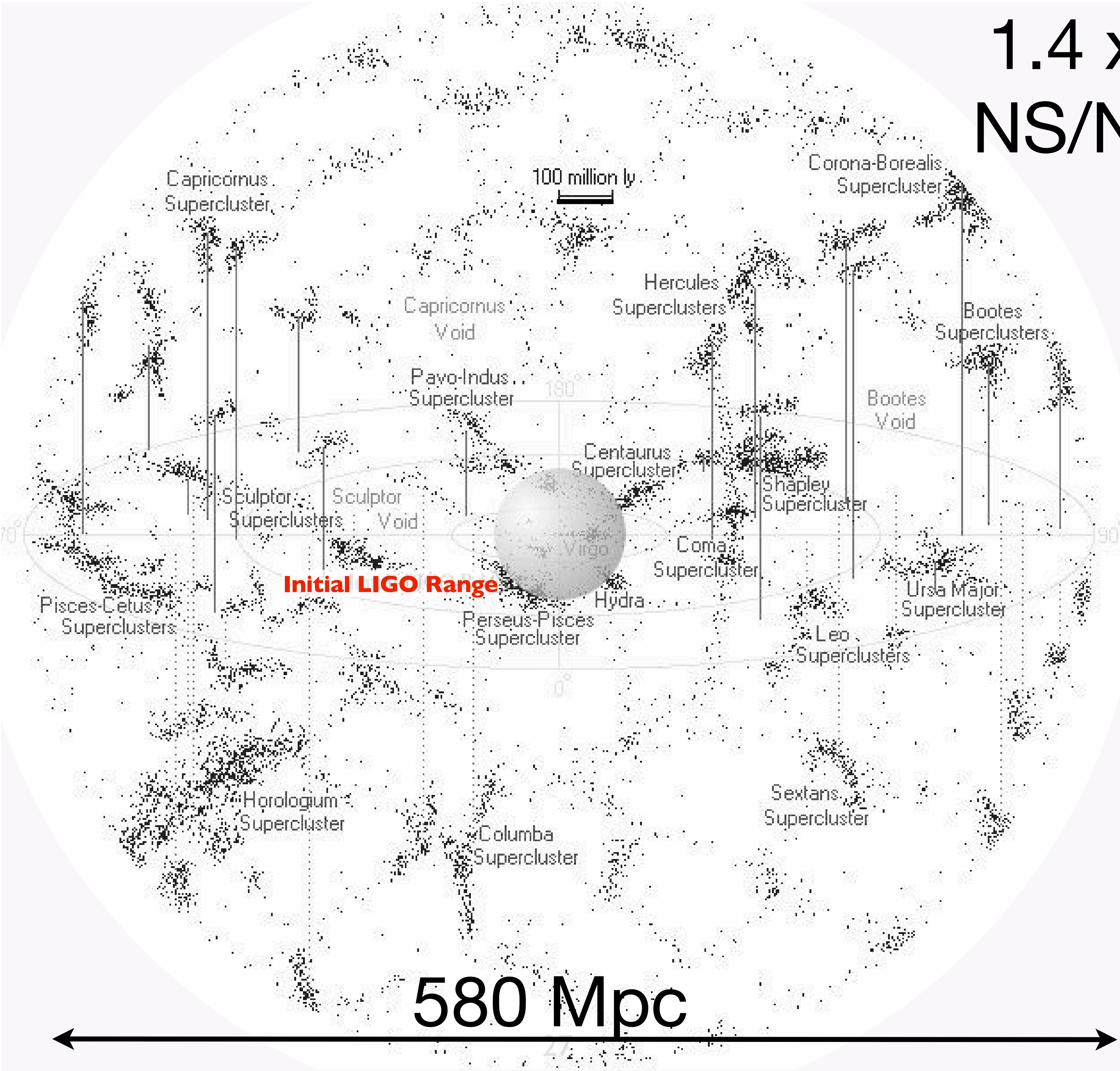
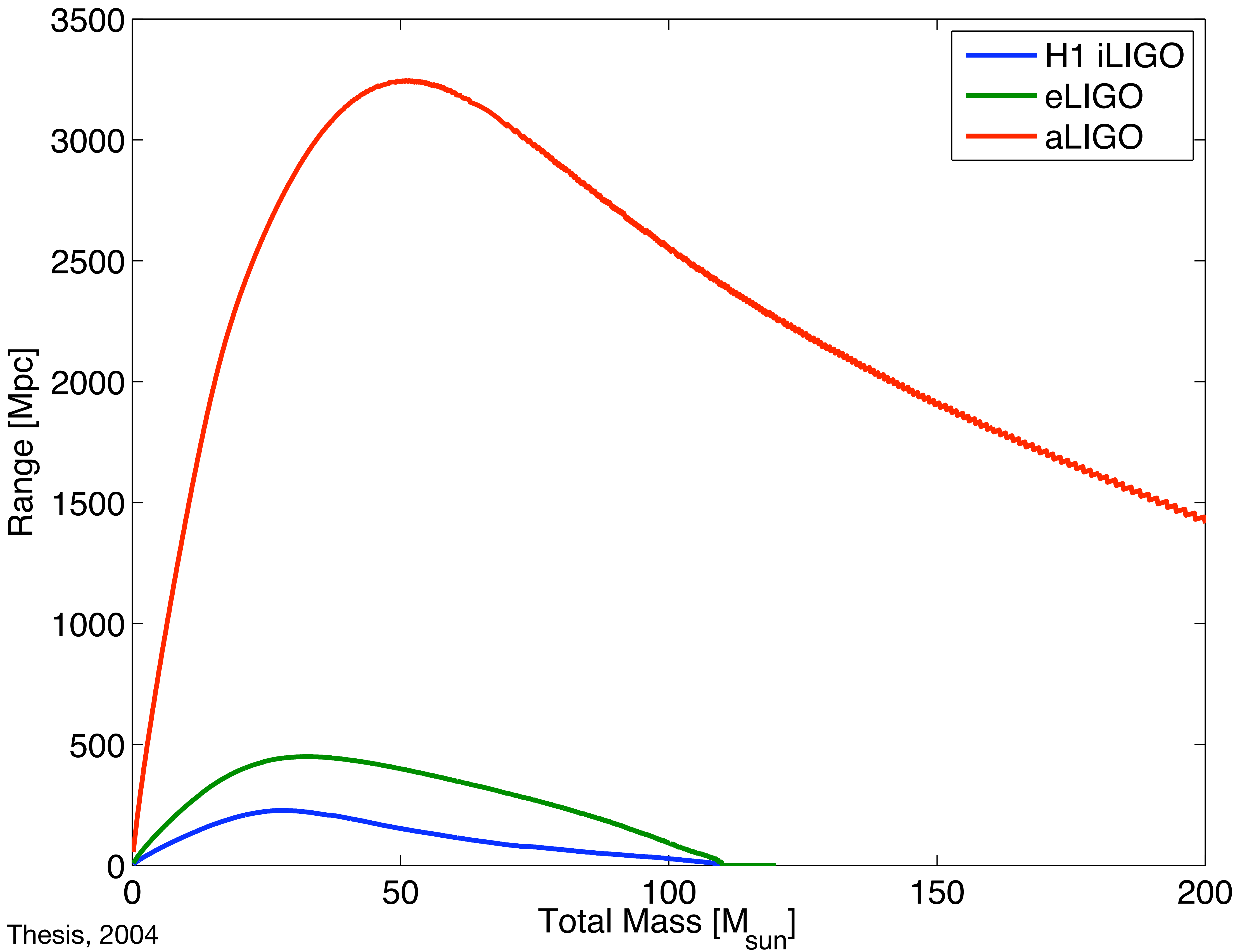


Image: R Powell

Range per Mass



D. Brown Thesis, 2004

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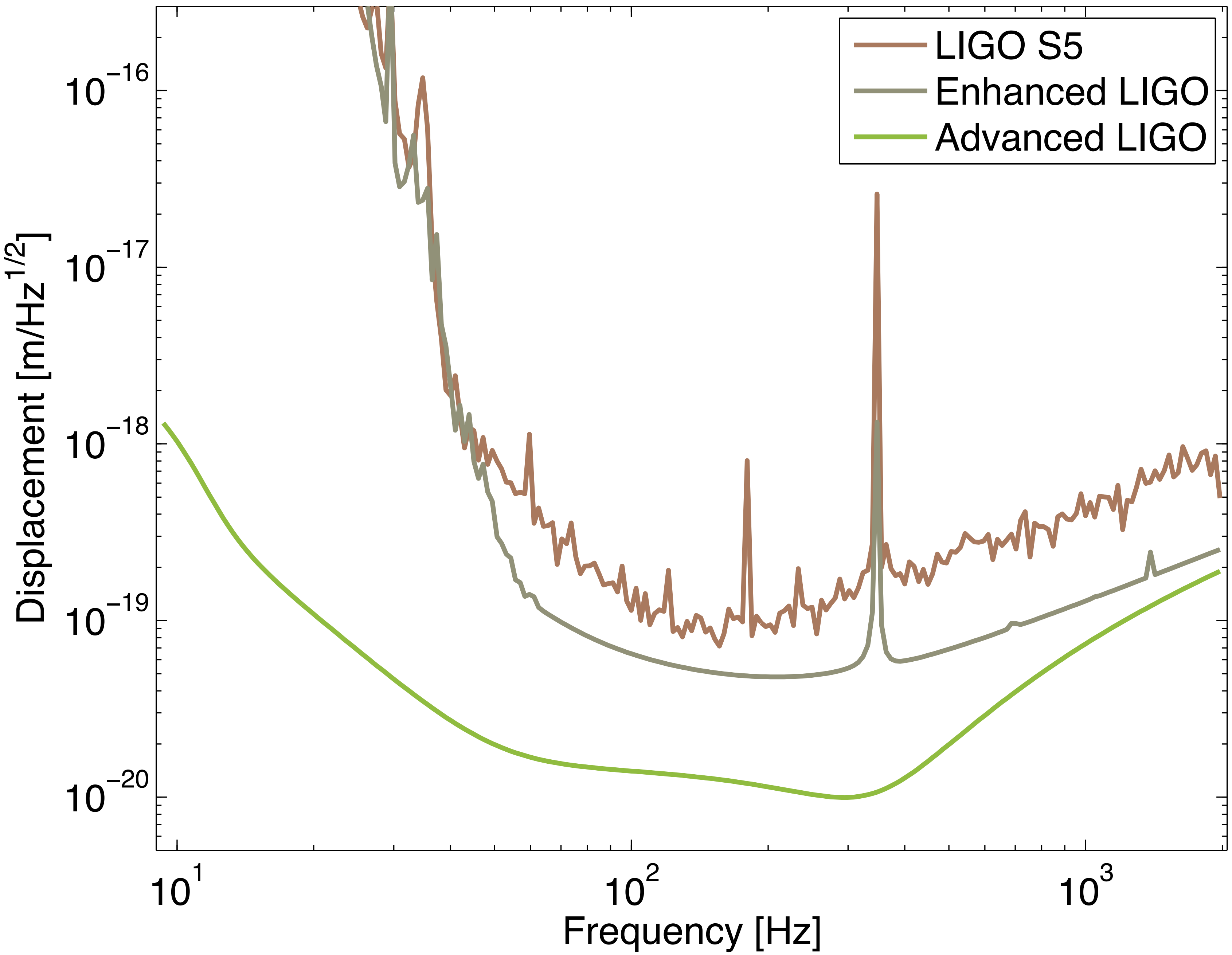
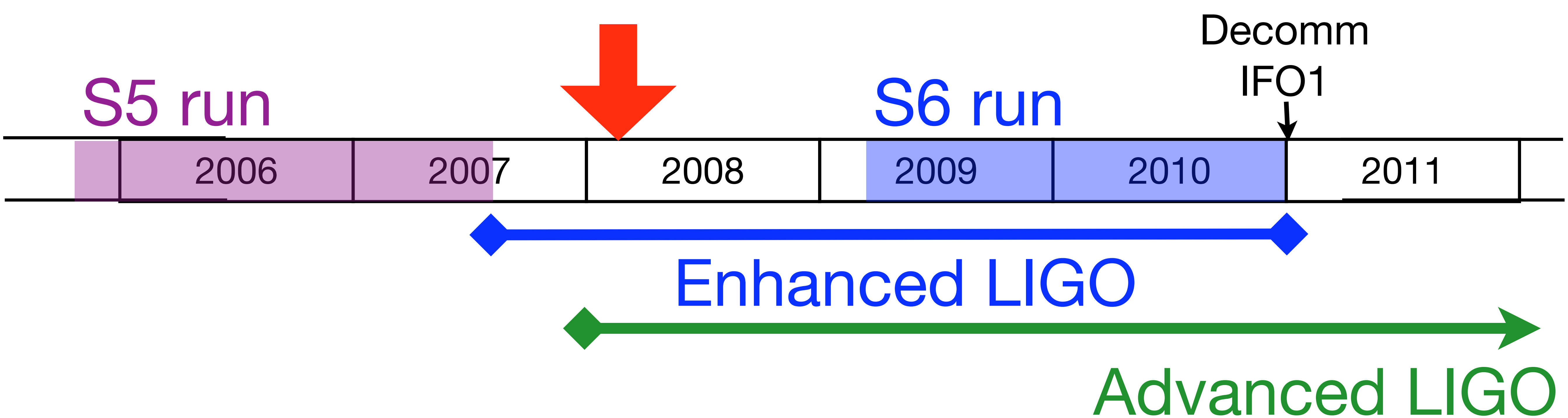
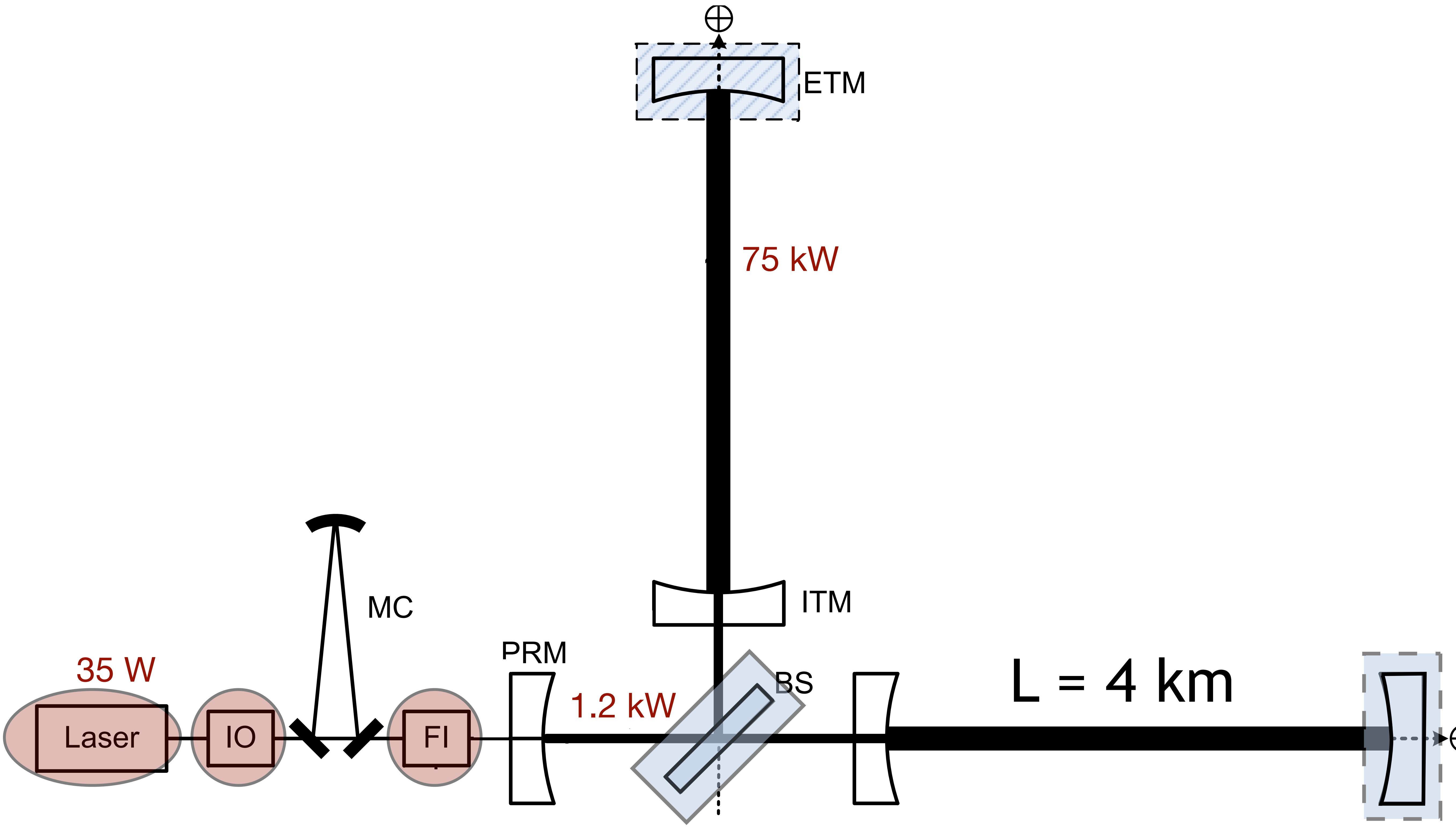


The next 2 years

- Advanced LIGO start in mid-2008 (NSB meets end of March)
- First IFO decommissioned in 2010
- Use Enhanced LIGO to
  - Increase exposure 10x
  - Minimize aLIGO risk



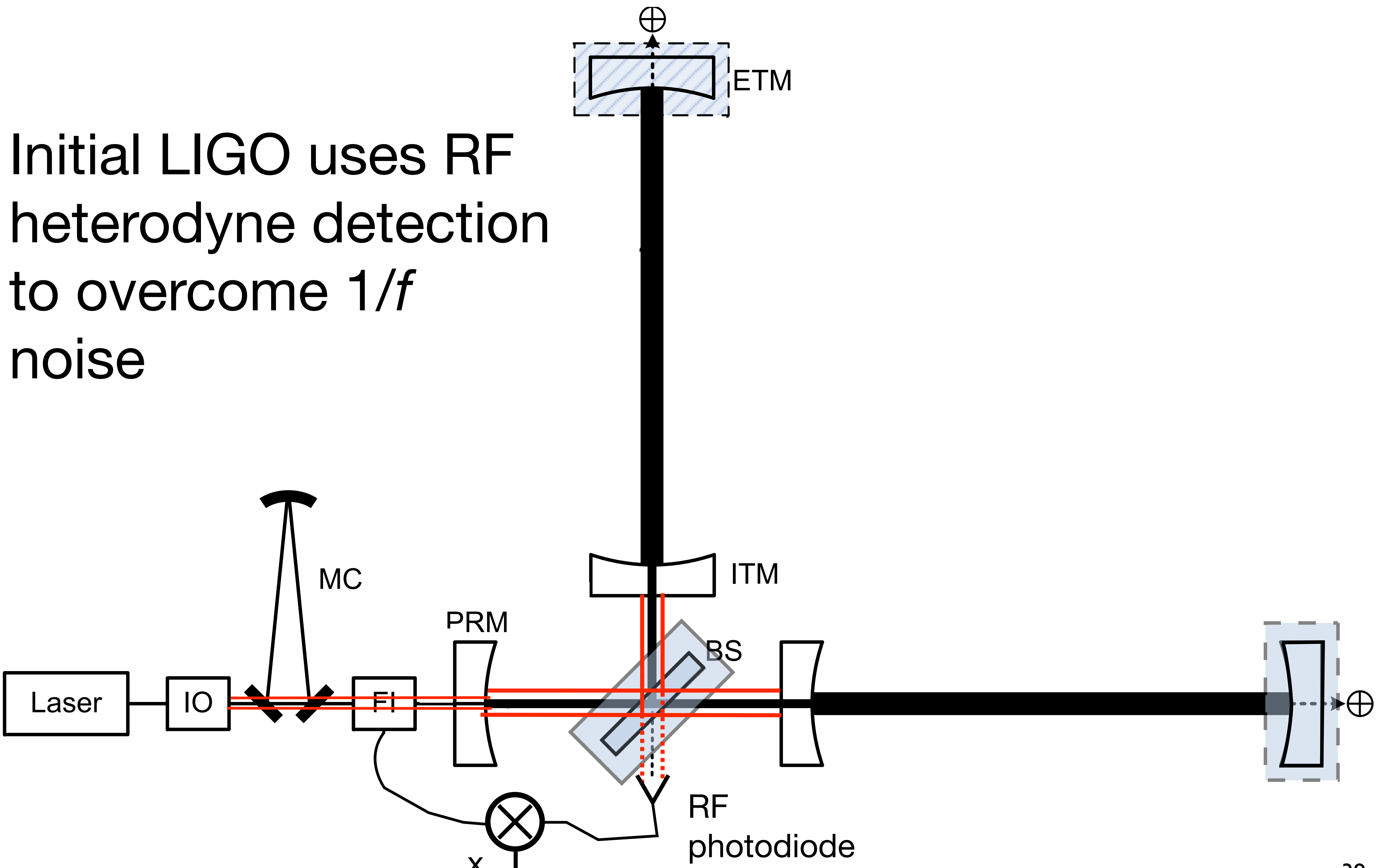
Enhanced LIGO



$5\times10^{-13}\ \lambda = 5\times10^{-19}$ m

RF readout

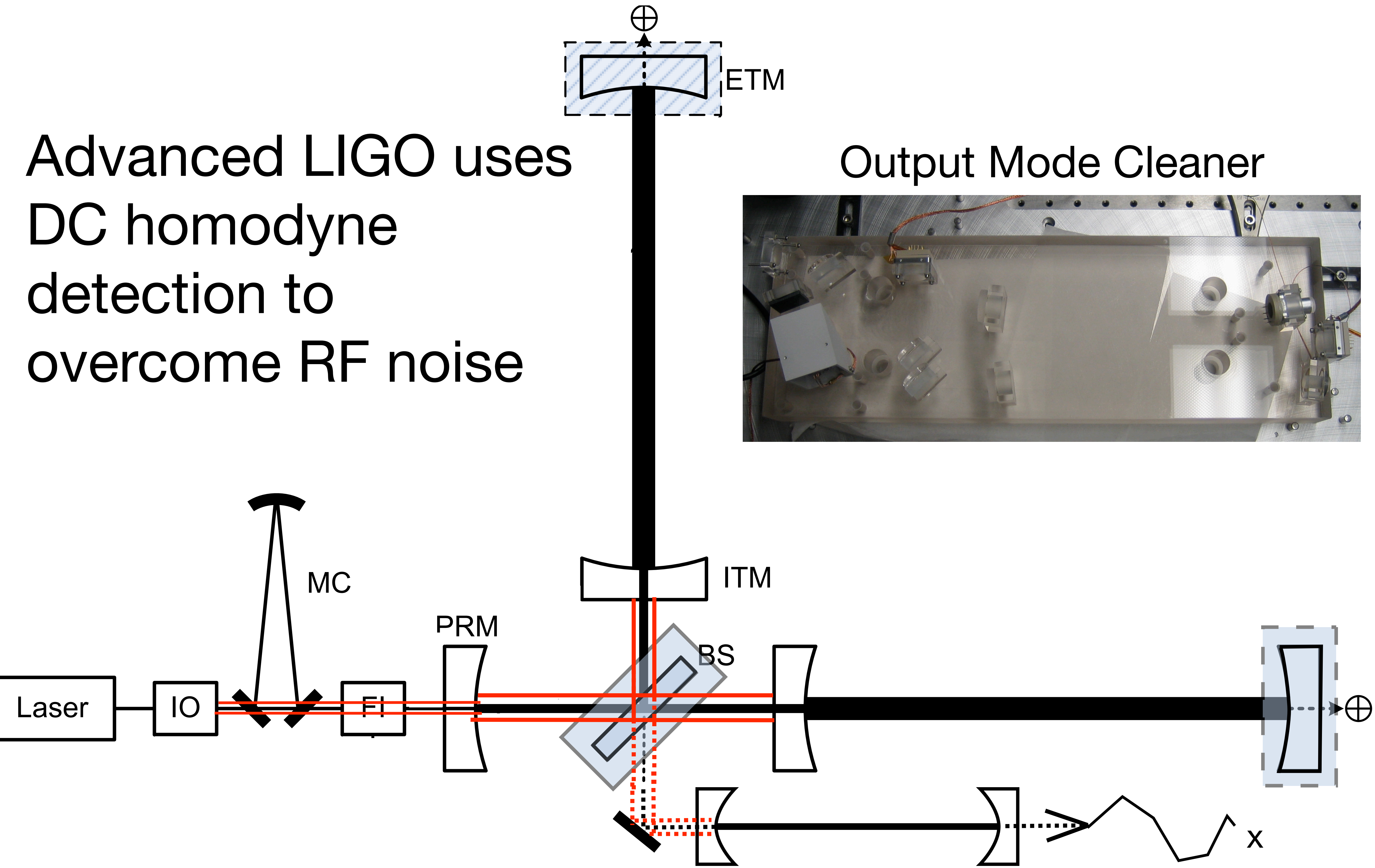
Initial LIGO uses RF heterodyne detection to overcome 1/*f* noise



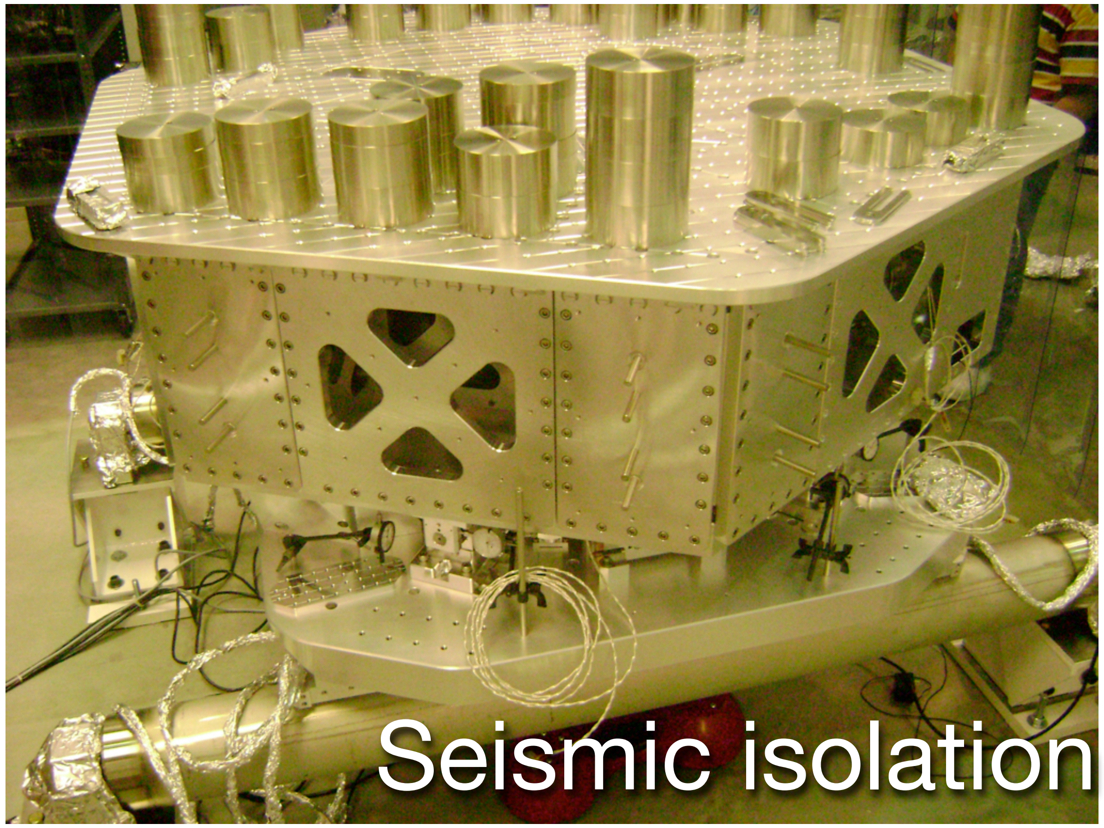
DC readout

Advanced LIGO uses DC homodyne detection to overcome RF noise

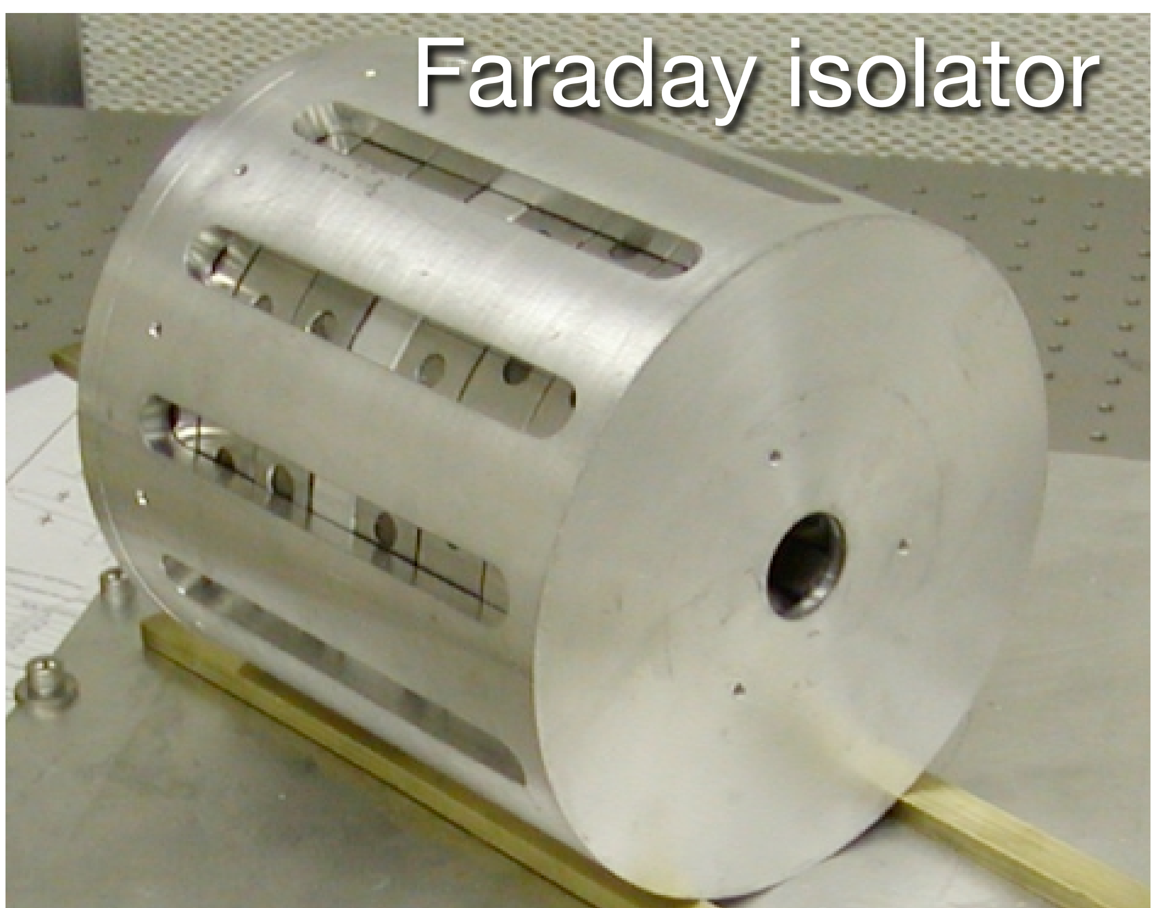
Output Mode Cleaner



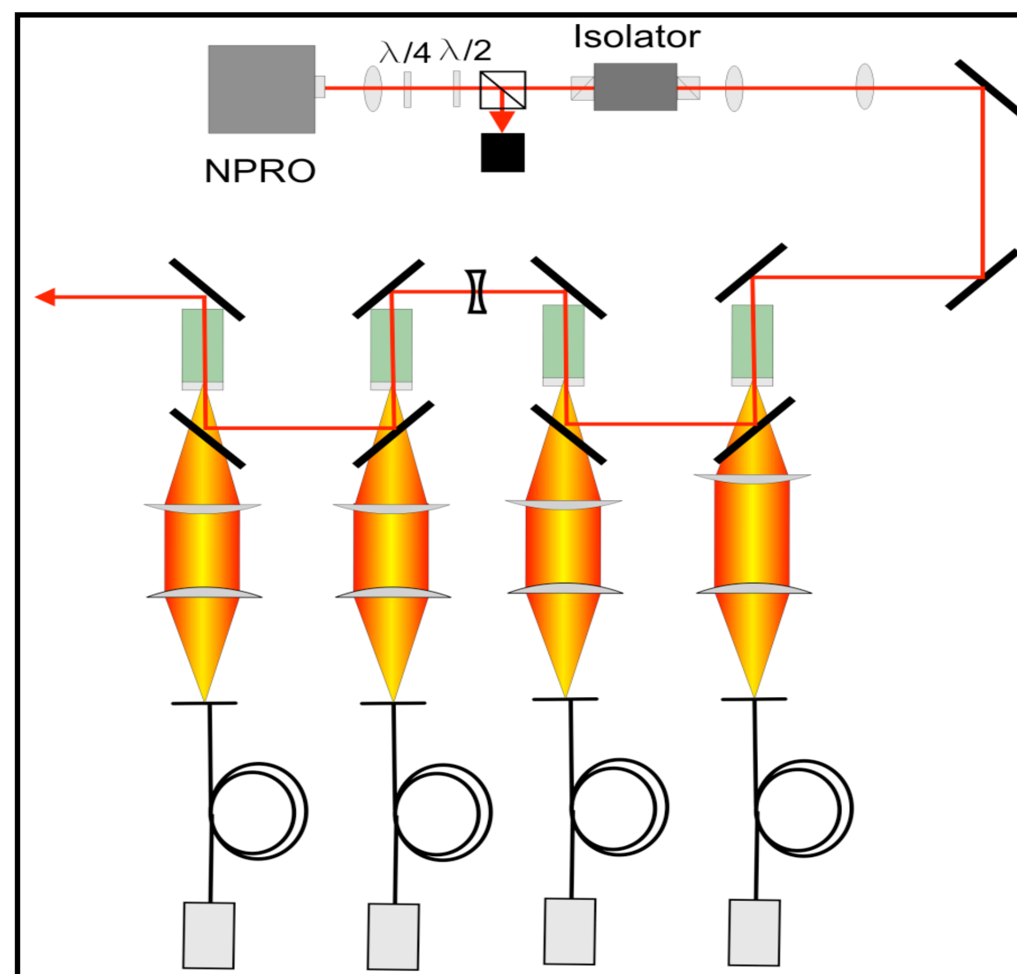
aLIGO prototype


Seismic isolation


Output mode cleaner


Faraday isolator

High power laser



eLIGO Range

1.4 x 1.4 M_{sun}
NS/NS inspiral
to 80 Mpc

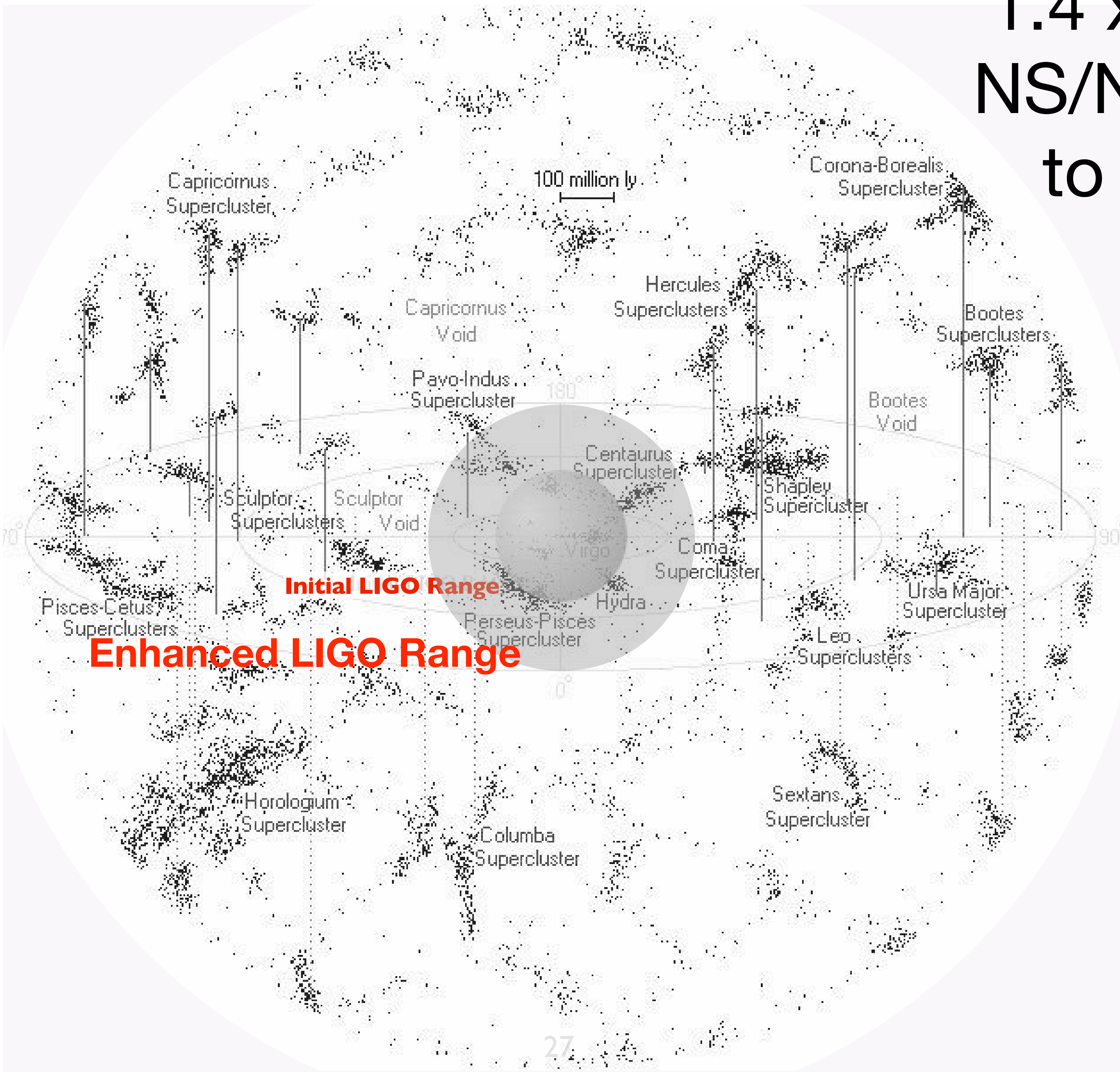


Image: R Powell