Looking Towards Gravitational Wave Astronomy with LIGO

Sam Waldman
March 4, 2008
Stanford University

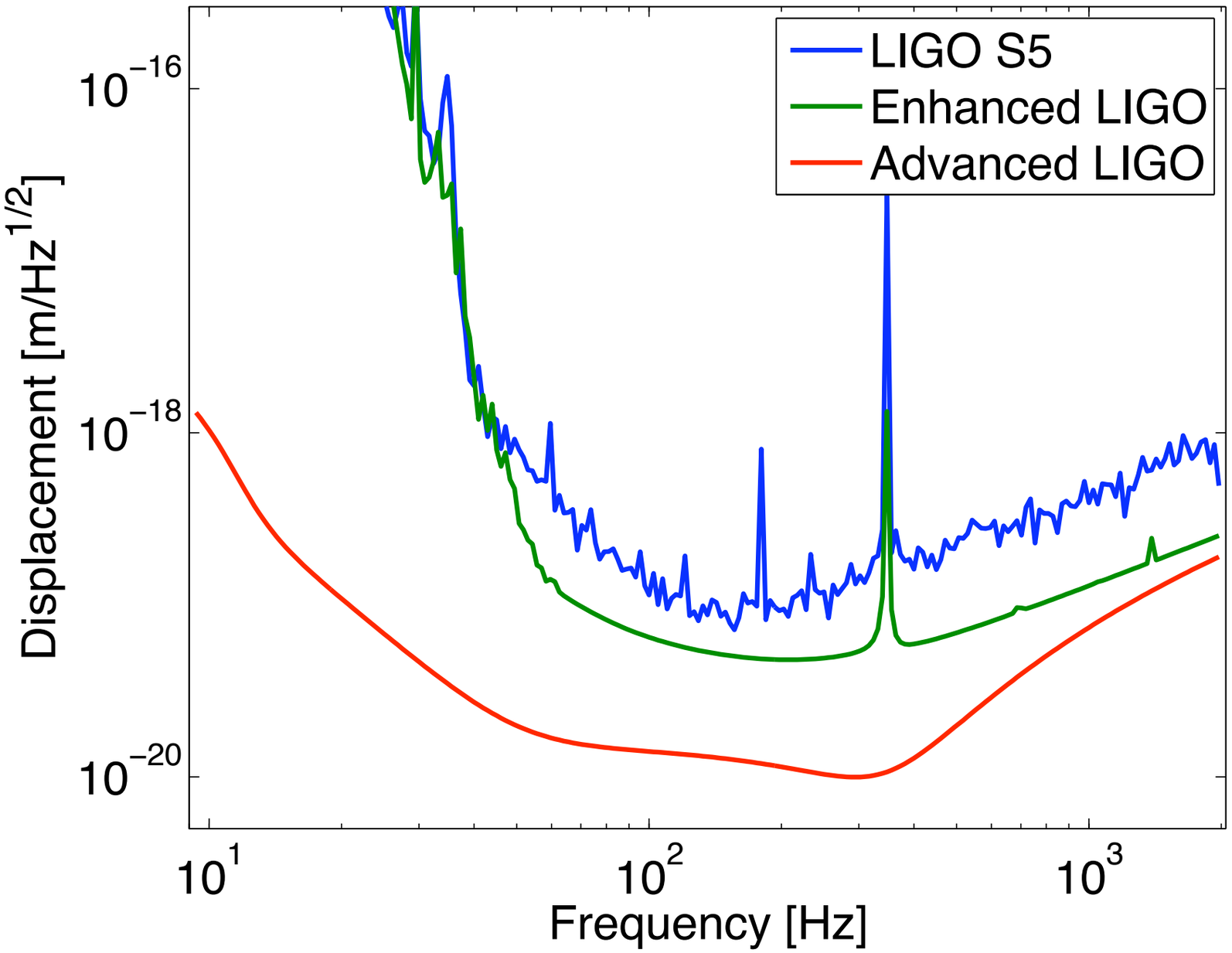
Outline

GW Detectors

Initial LIGO

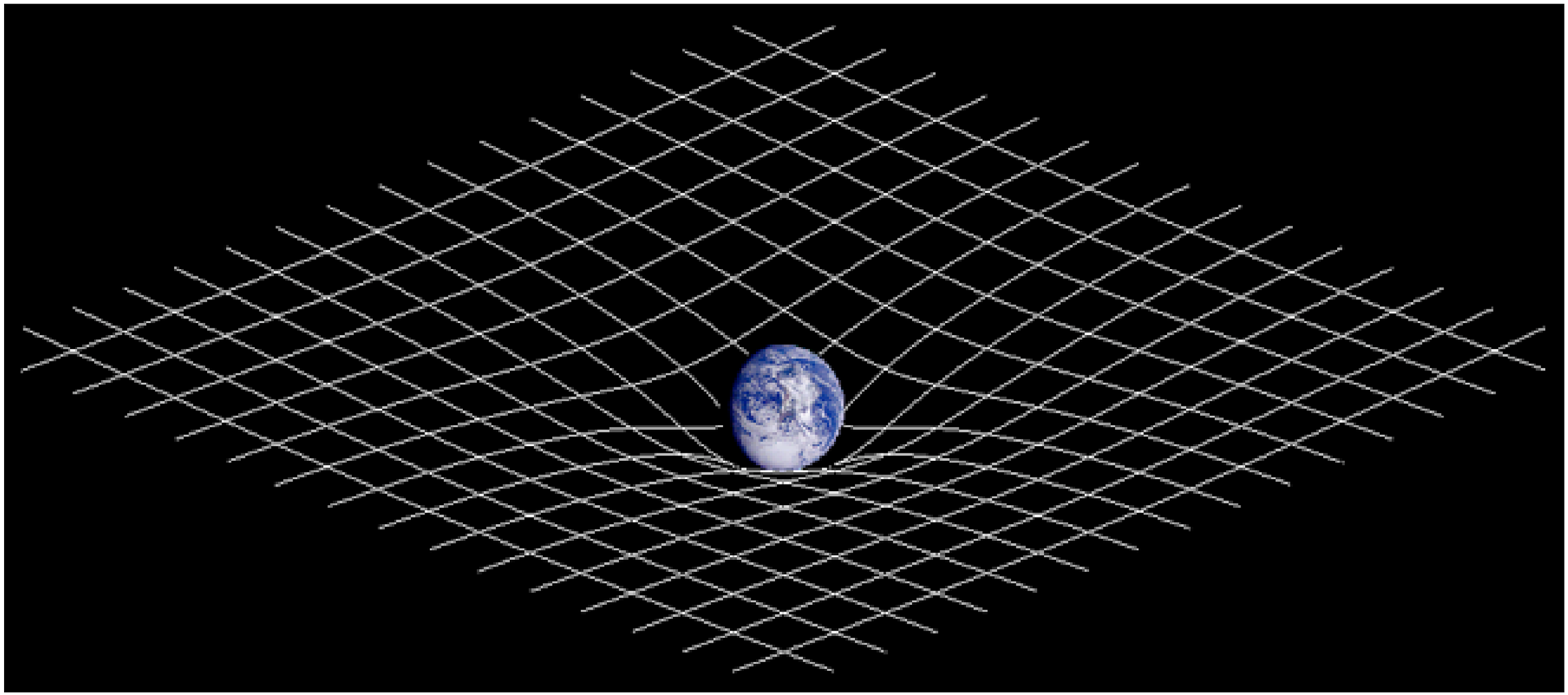
GW Astrophysics

Advanced LIGO



GR as curvature

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



Ripples in Space Time

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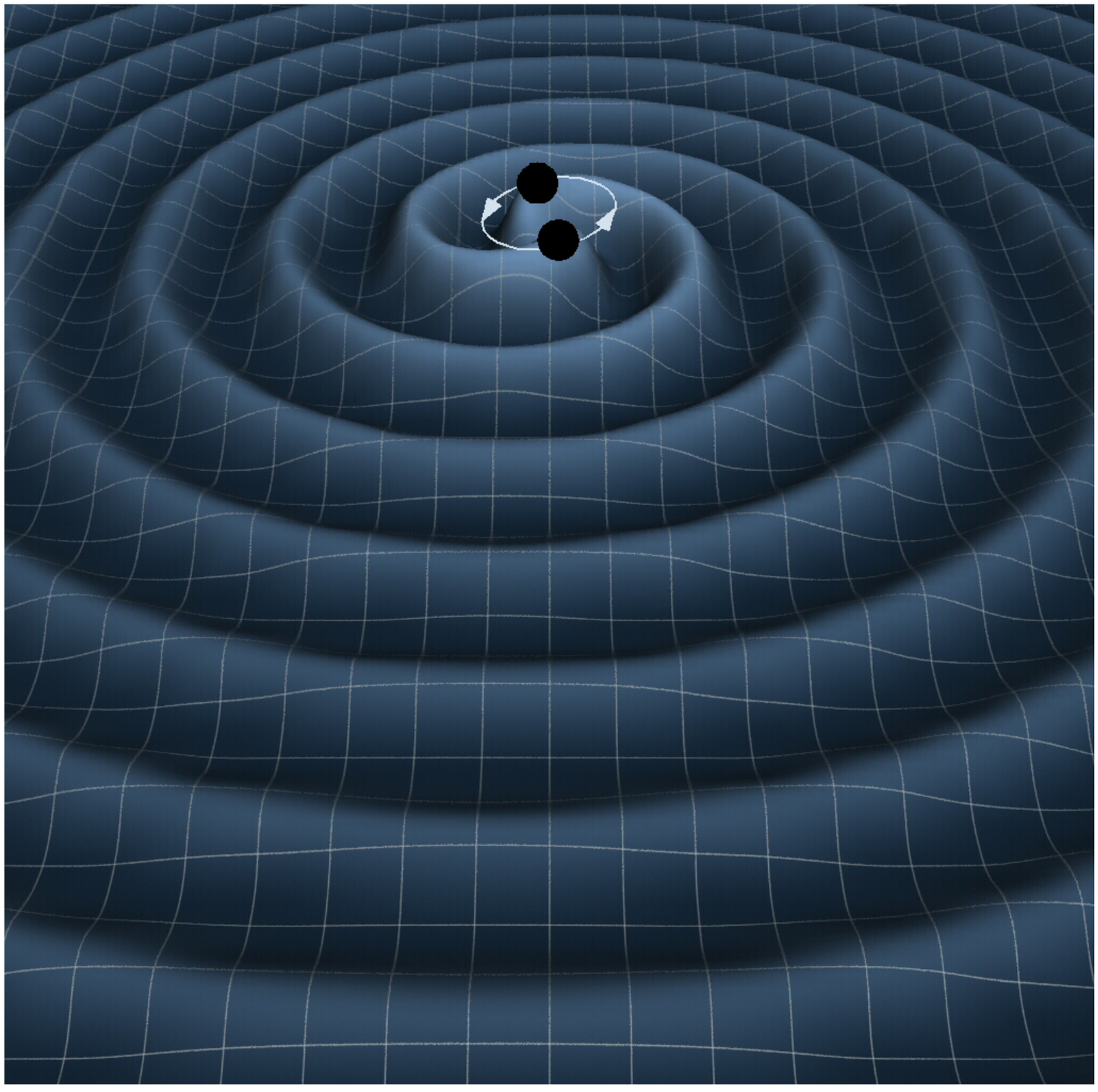


$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

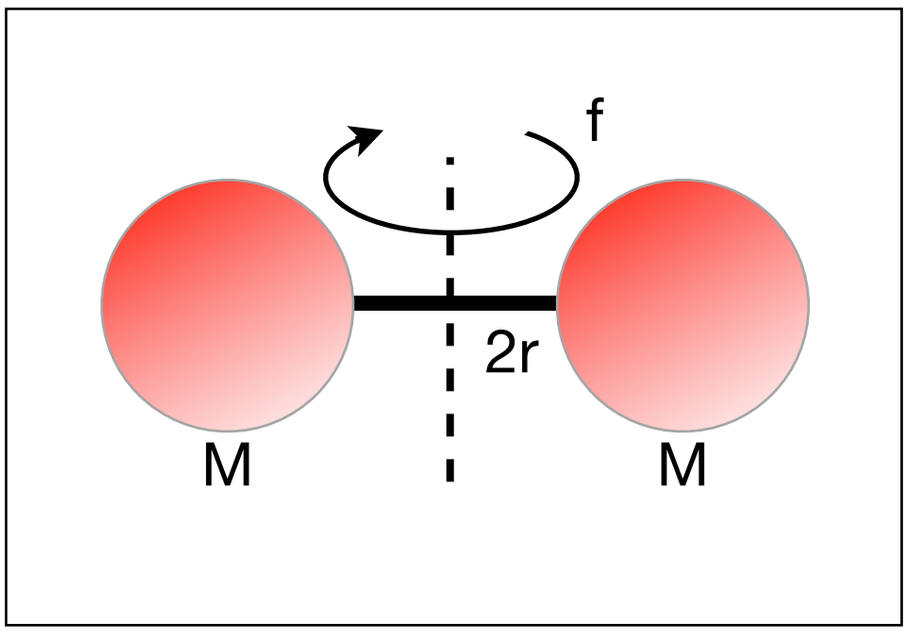
two plane wave solutions for $h_{\mu\nu}$ propagate at c

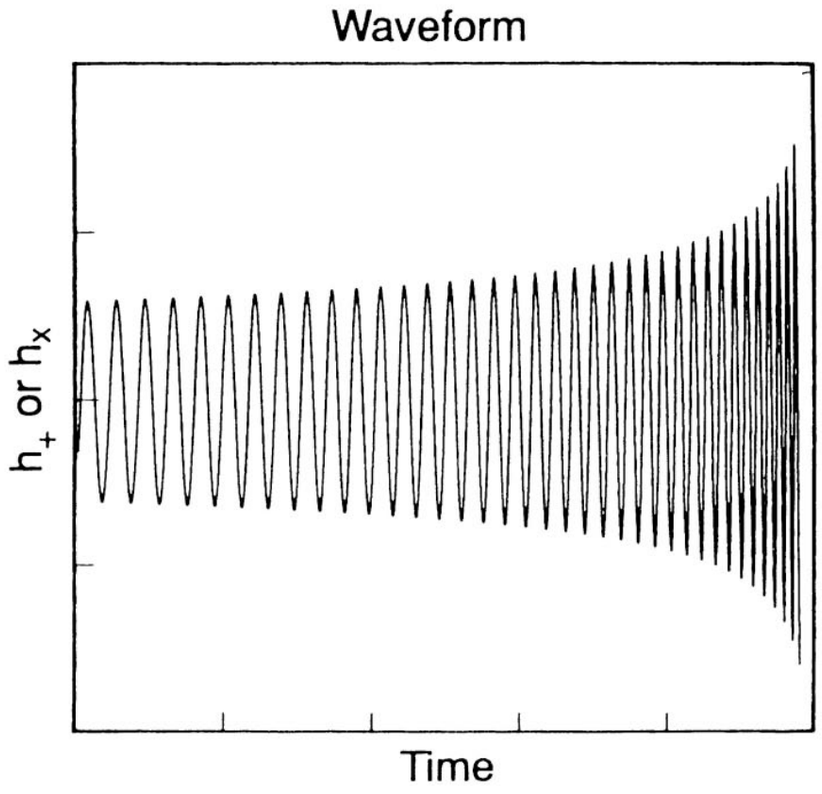
$|h| = \delta L / L$

Radiating GWs

Quadrupole moment: accelerating mass asymmetry

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





Saulson 1994

Indirect GWs

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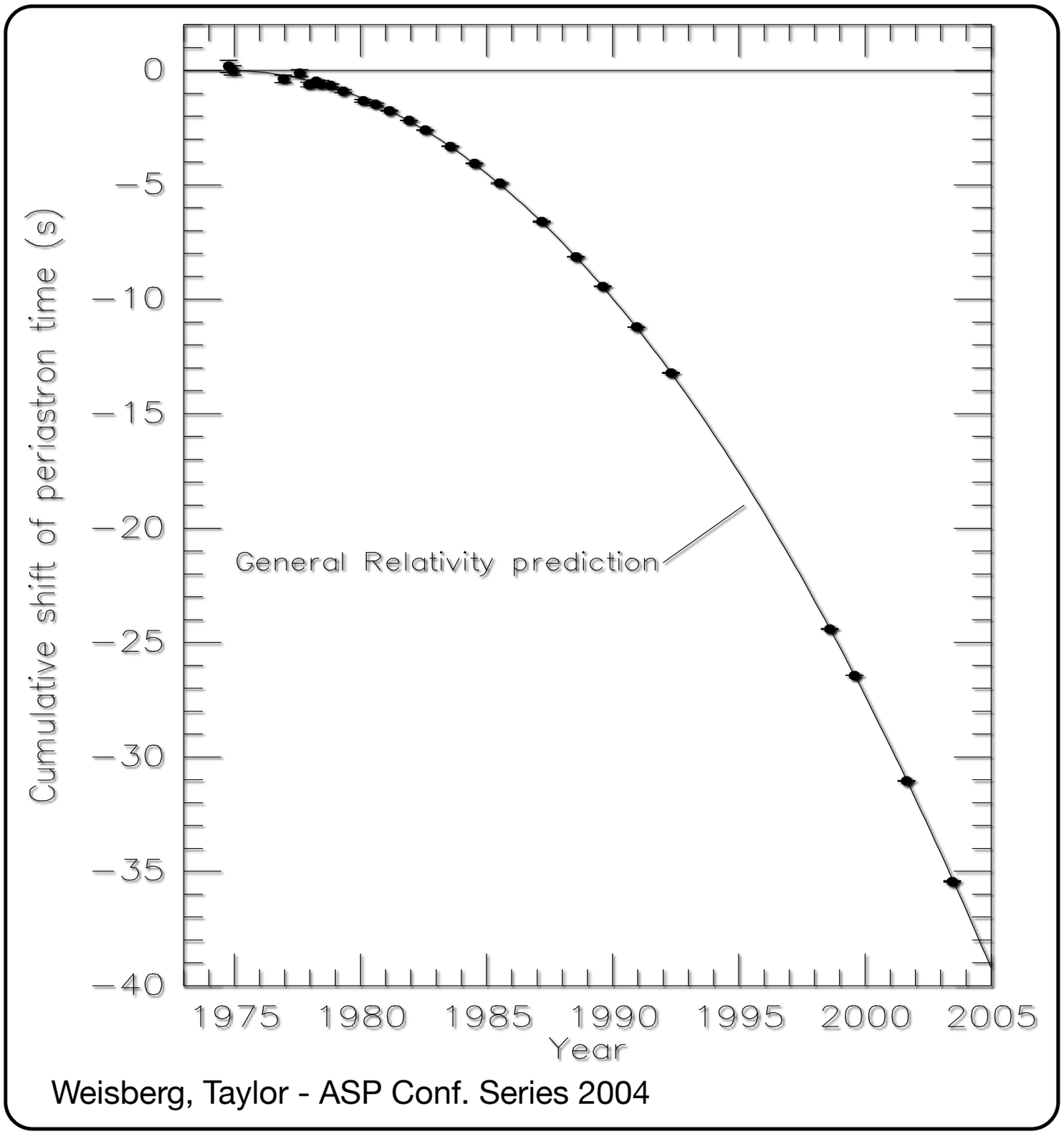


Weisberg, Taylor - ASP Conf. Series 2004

Hulse & Taylor

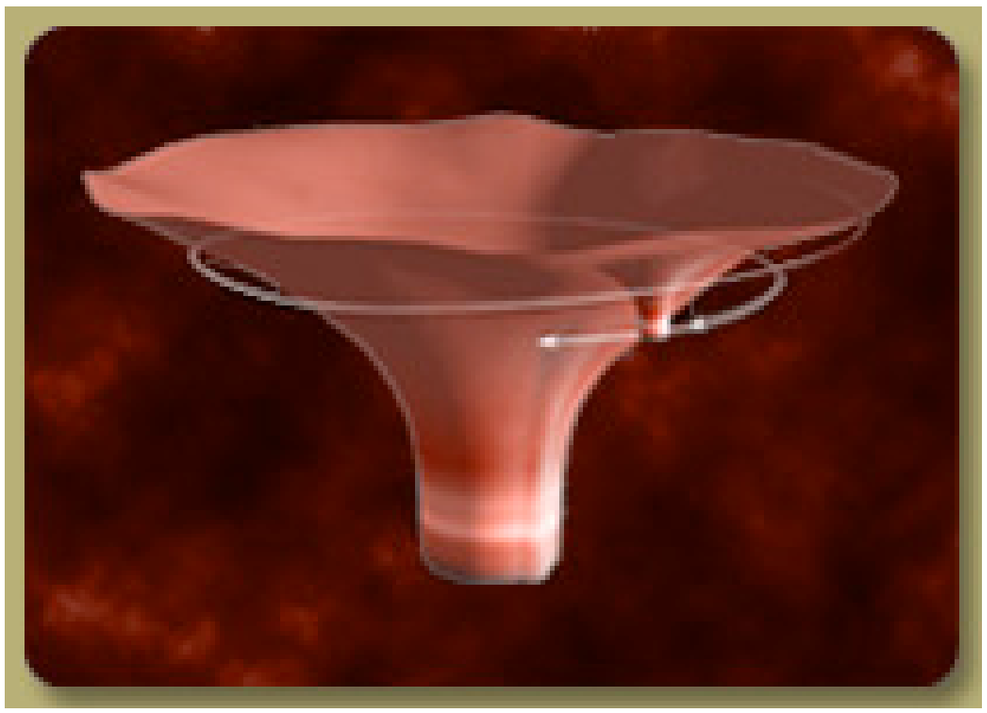
Binary NS system

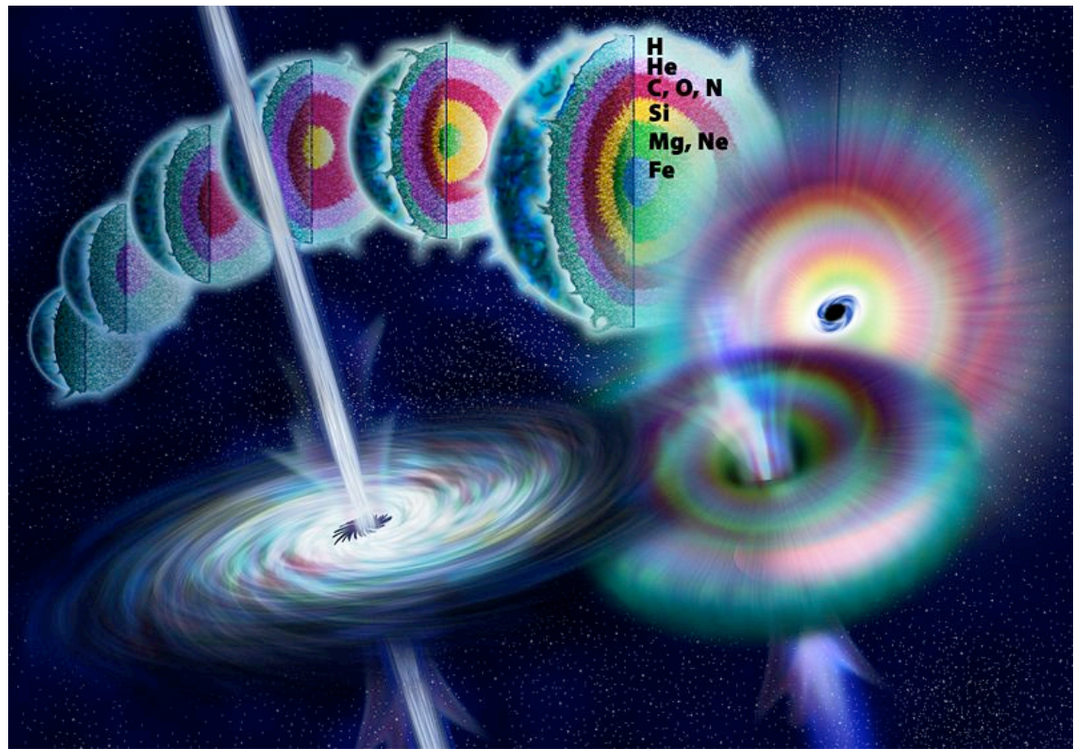
- $r = 1.6 \times 10^9$ m
- $m_1 \sim m_2 \sim 1.4\ M_\odot$
- 8 hr orbit
- 7.5 kpc from Earth

GR predicts 3mm/orbit

$dx/x \sim 1.5 \times 10^{-23}$

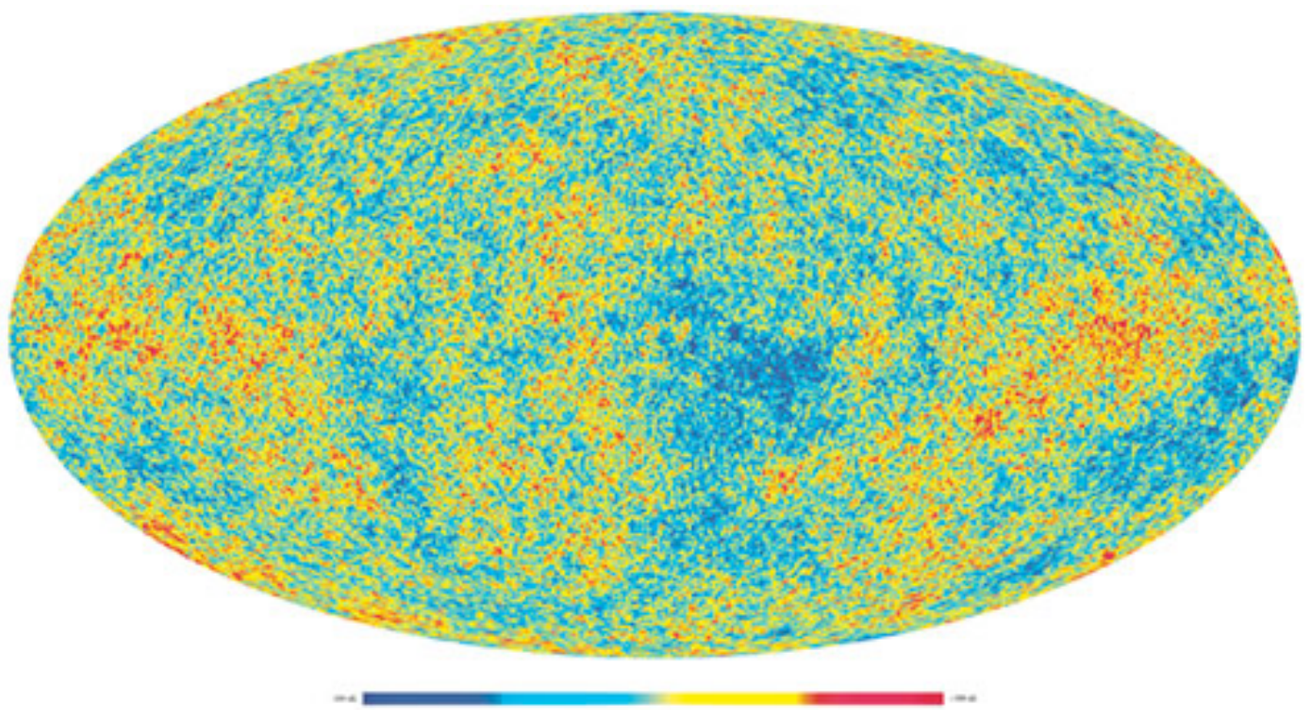
GW astronomy





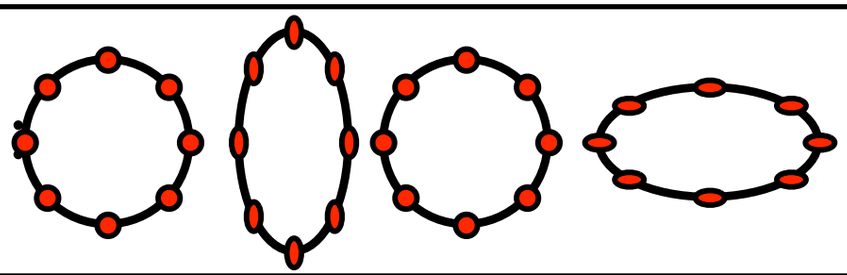
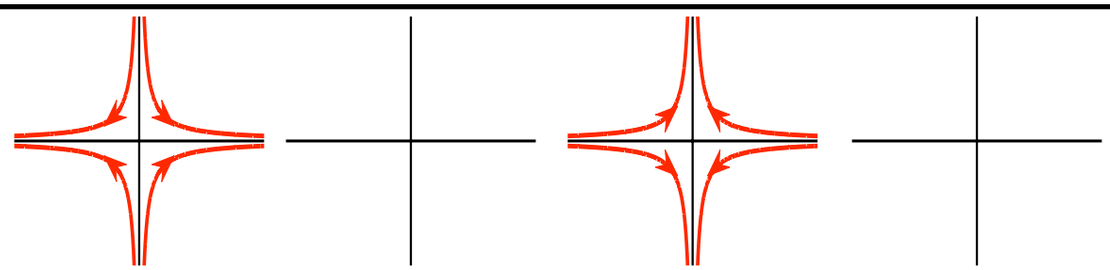
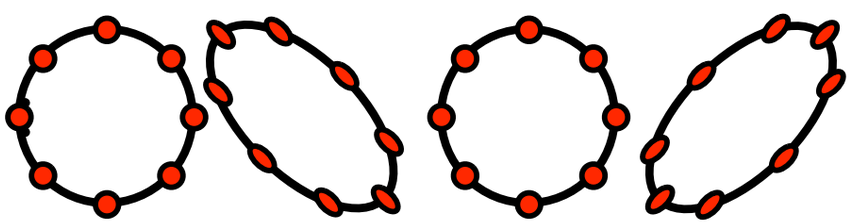
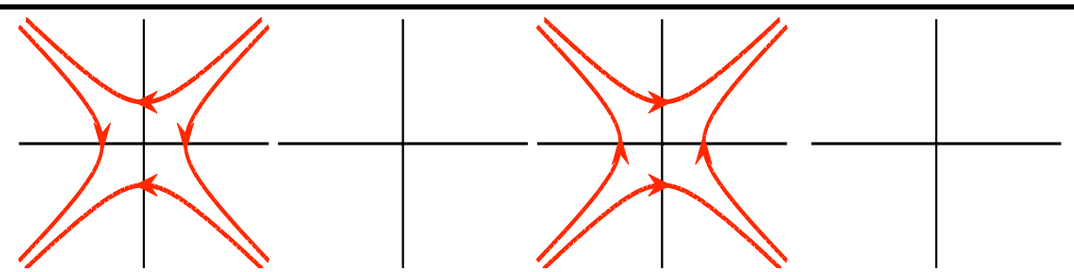
Strong field GR

Gravitational astrophysics



Cosmology

Strain and Gauge

Transverse Traceless	**Locally Lorentz**
Induced strain	Induced acceleration
$h = \frac{\delta l}{l}$	$\frac{d^2x}{dt^2} = \frac{1}{2}\left(\ddot{A}_+ x\,\hat{x} + \ddot{A}_\times y\,\hat{y}\right)$
A_+ 	
$A_\times$ 	

GW in Space

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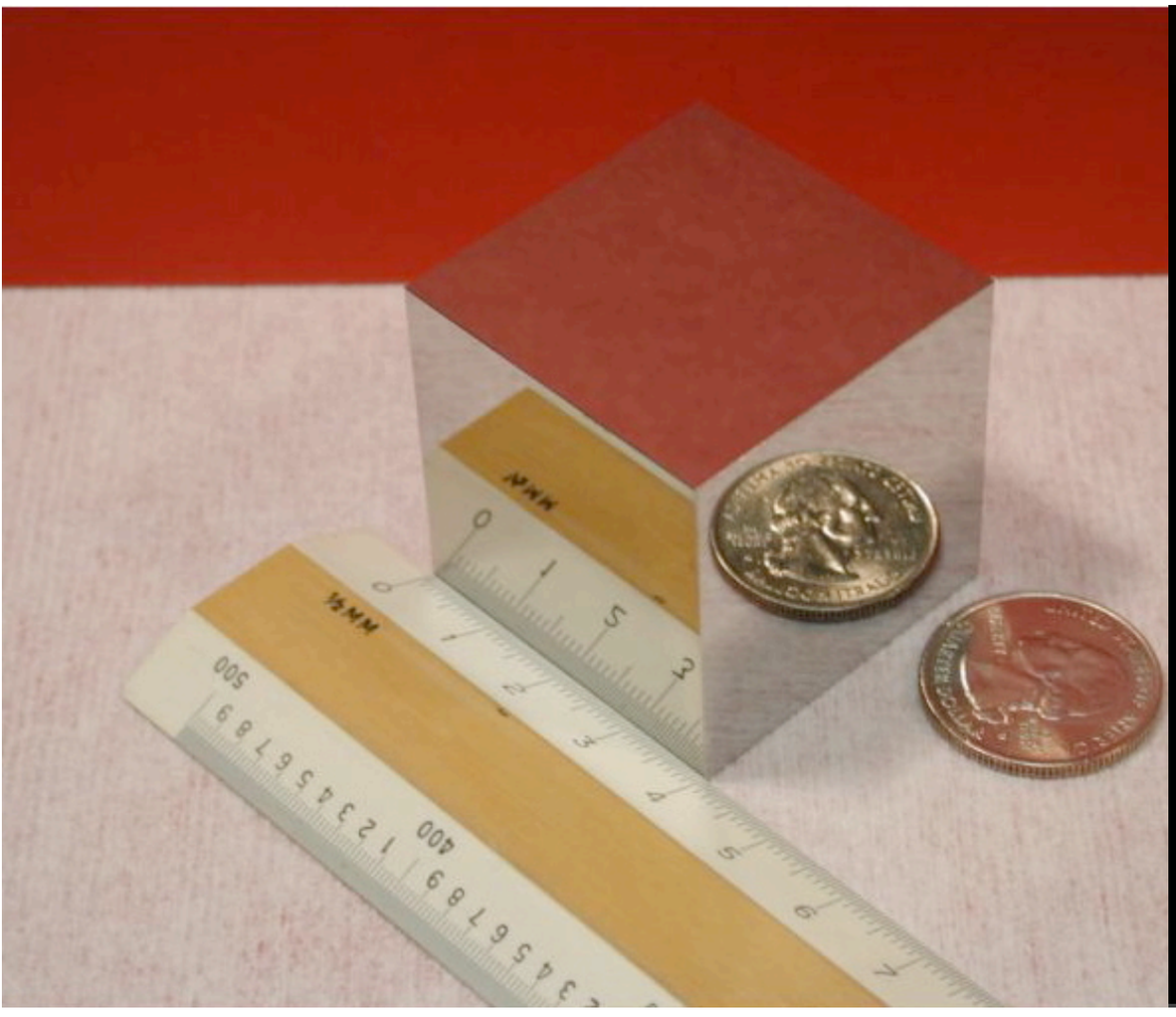

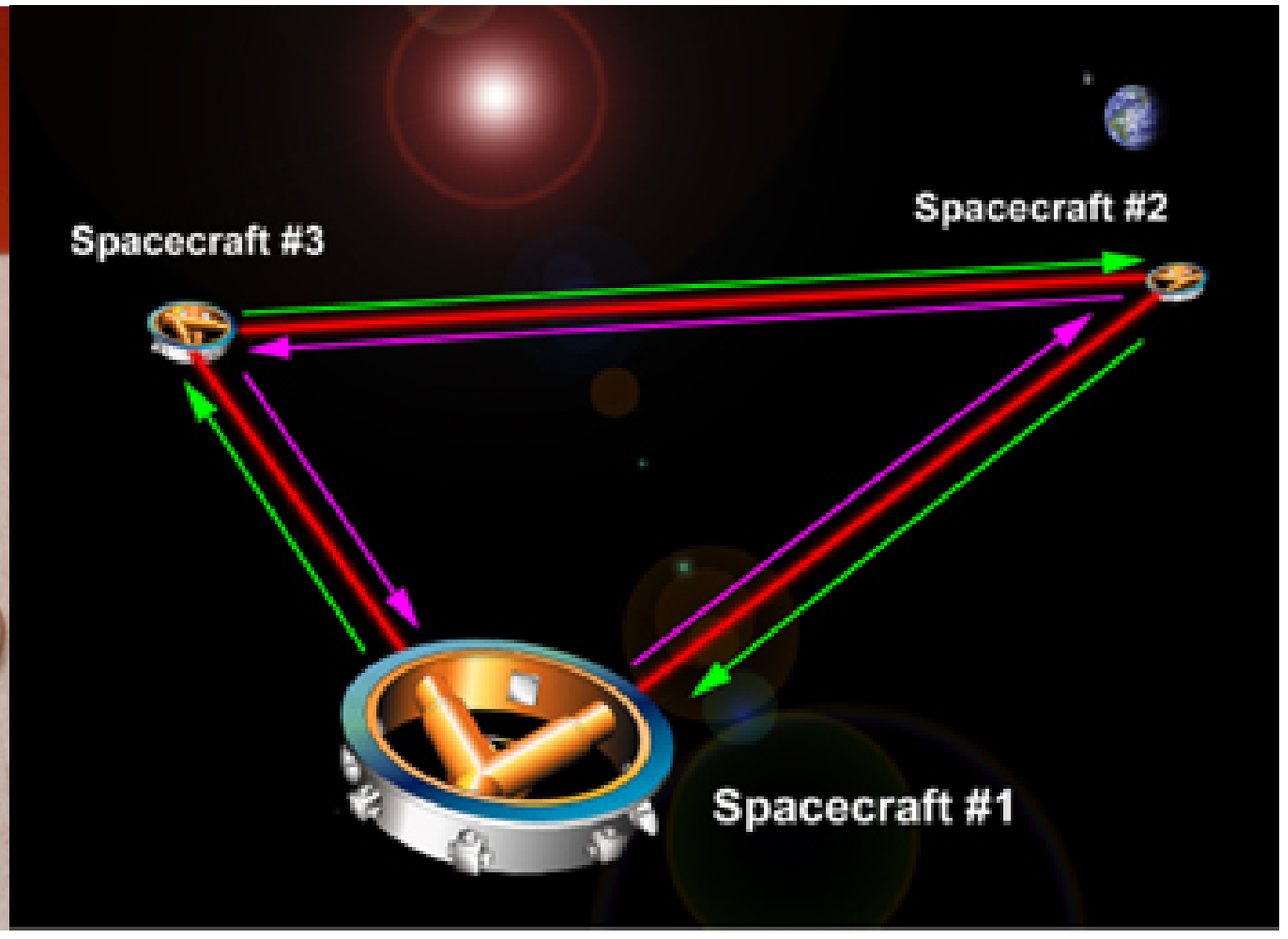

"LISA promises to open a completely new window into the heart of the most energetic processes in the universe, with consequences fundamental to both physics and astronomy." -National Academy

LIGO 0.01

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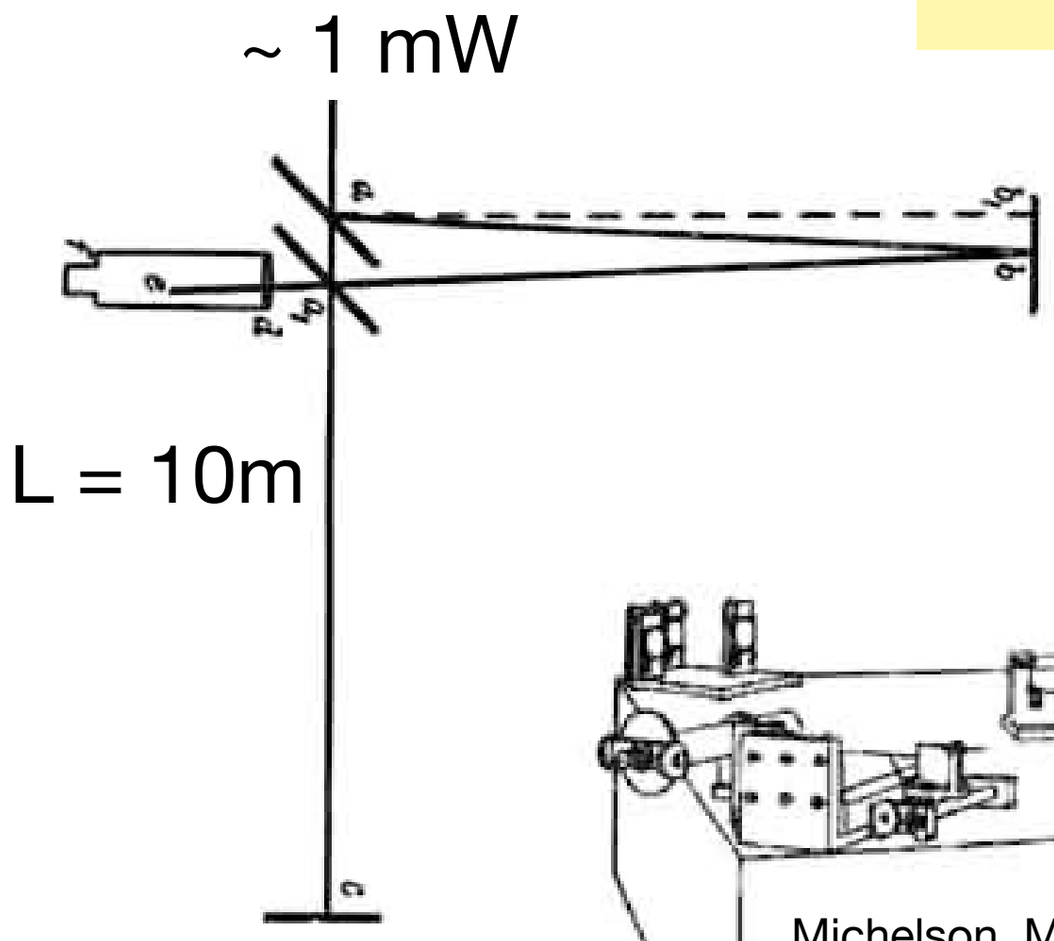
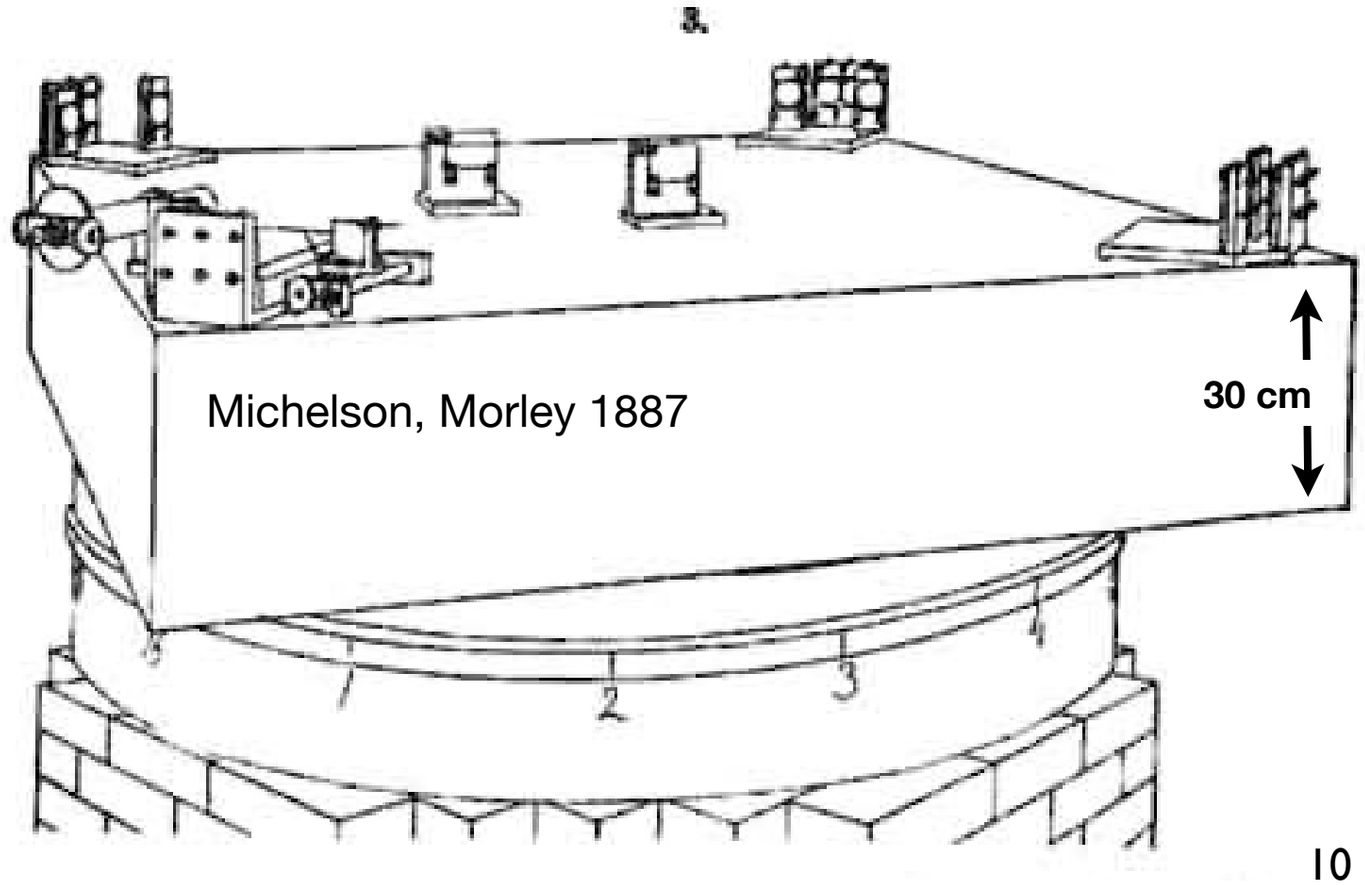
First GW detector
$dx/x \sim 5 \times 10^{-10}$





(Incidentally disproved the existence of the ether)

Outline

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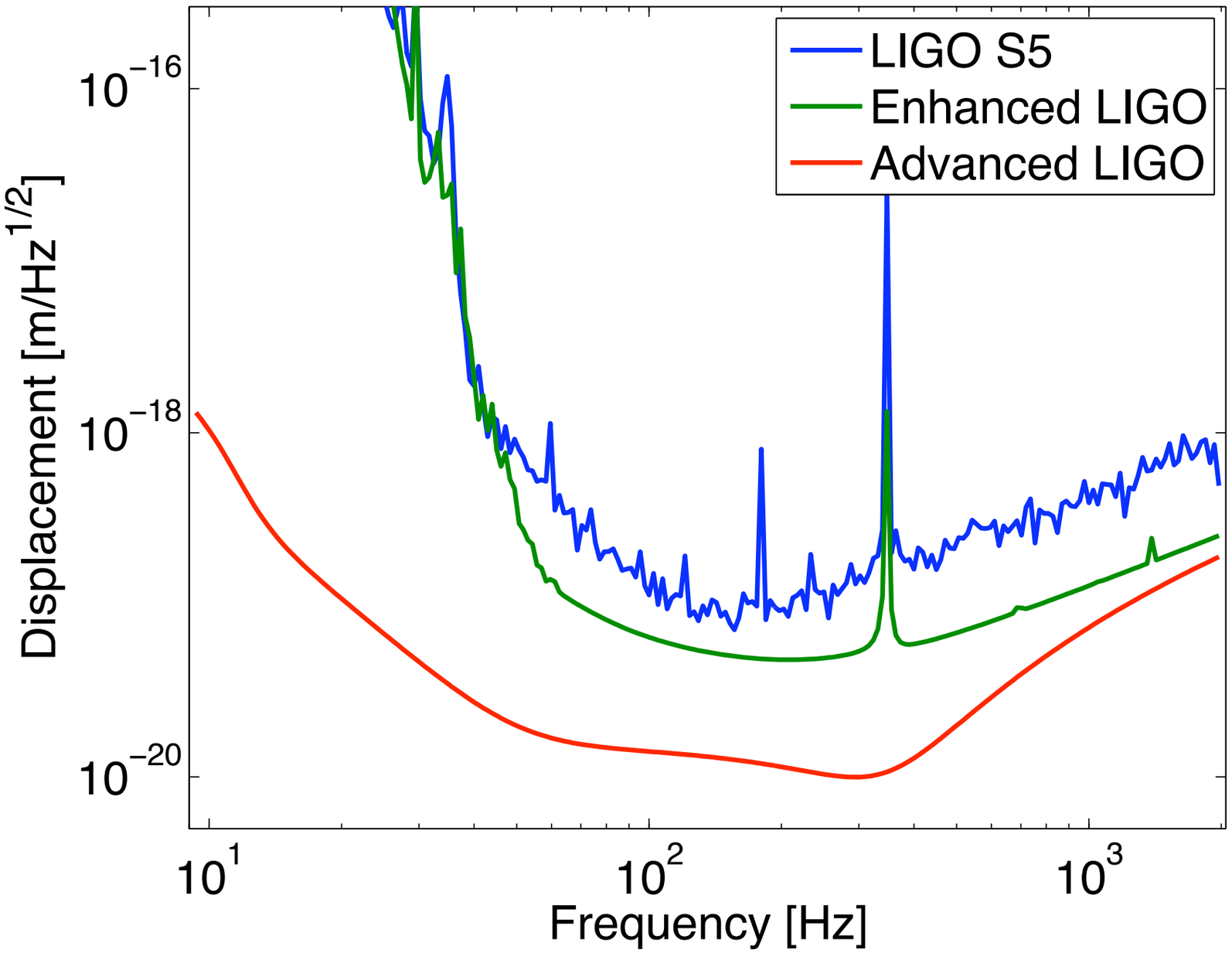
Initial LIGO

GW Astrophysics

Advanced LIGO



Initial LIGO

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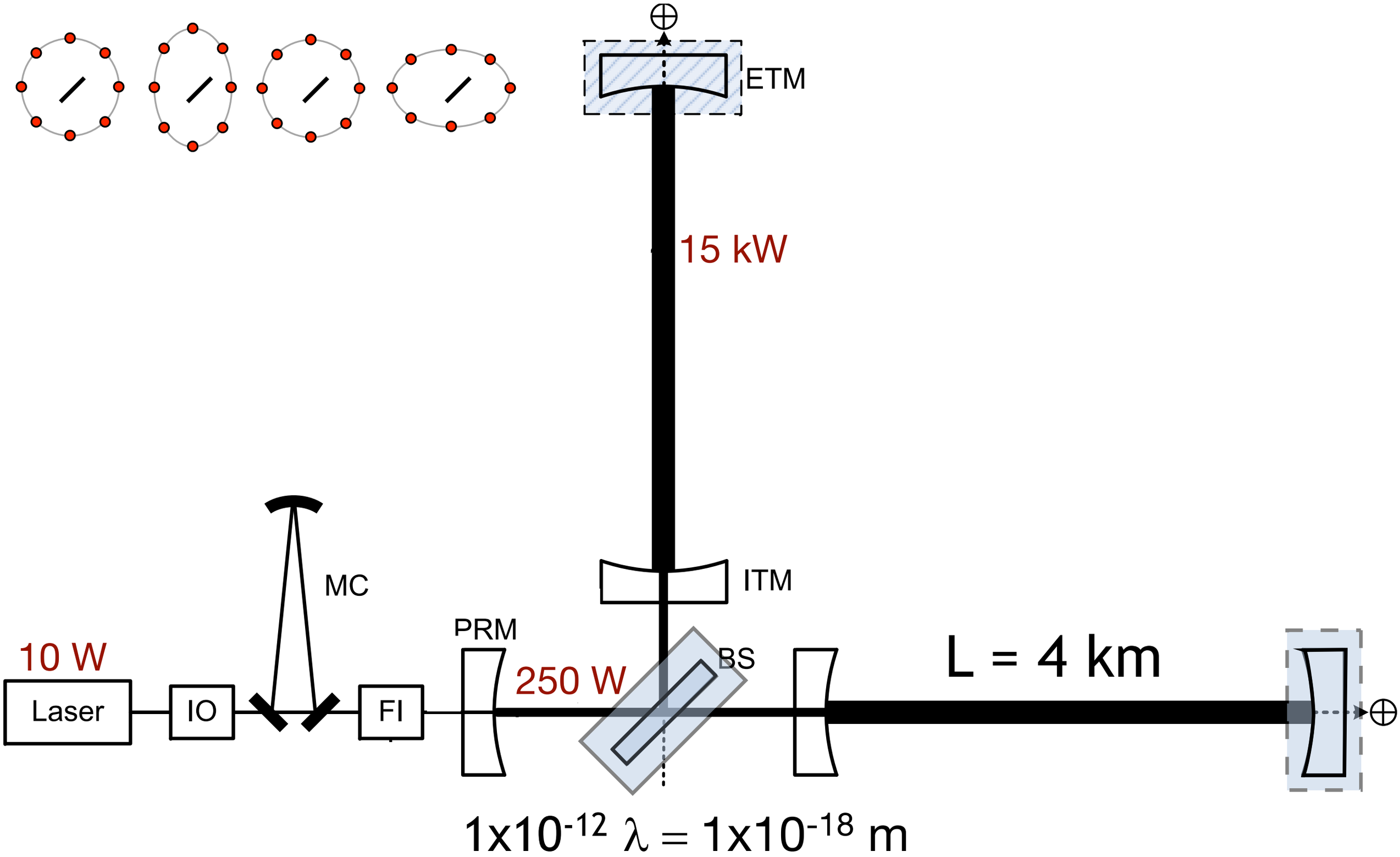

LIGO detectors

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Hanford History

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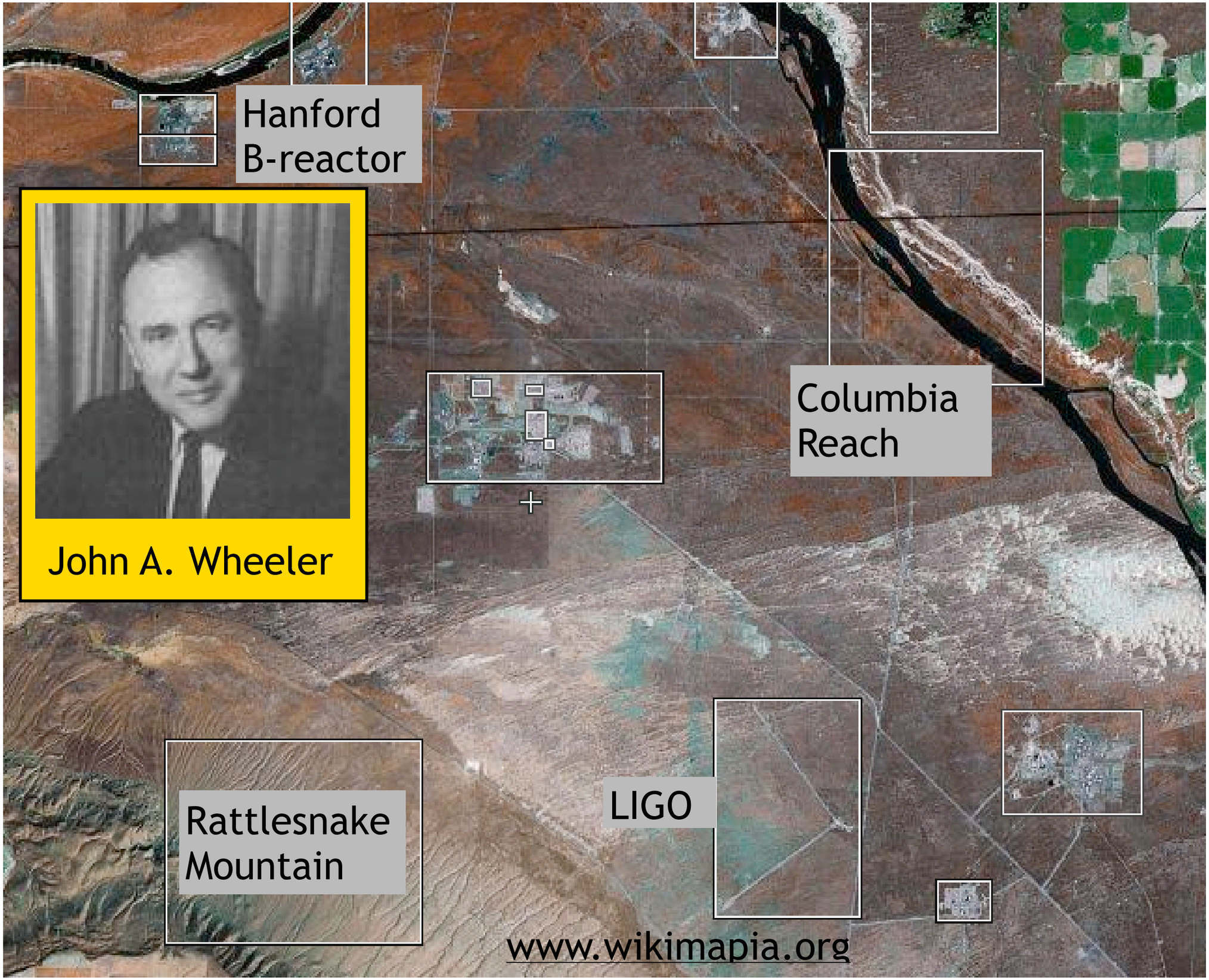

LIGO Collaborations

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LSC

- 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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LHO

GEO

LCGT

LLO

Virgo

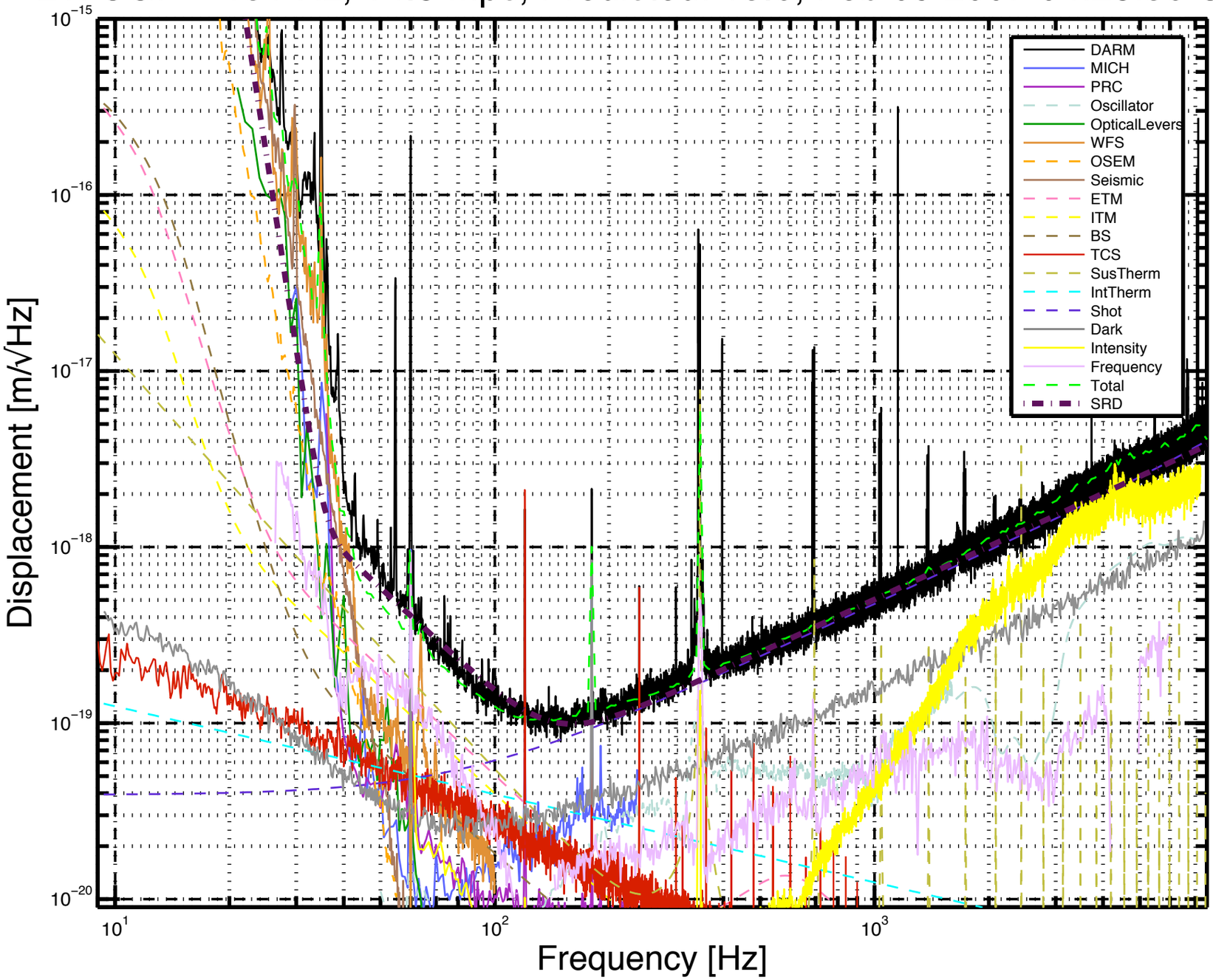
AIGO

Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap020811.html

Astronomy Picture of the Day
2002 August 11
http://antwrp.gsfc.nasa.gov/apod/astropix.html

Noise Budget

L1: UGF = 151 Hz, 14.8 Mpc, Predicted: 15.6, Feb 09 2007 04:28:56 UTC



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

Noise Budget

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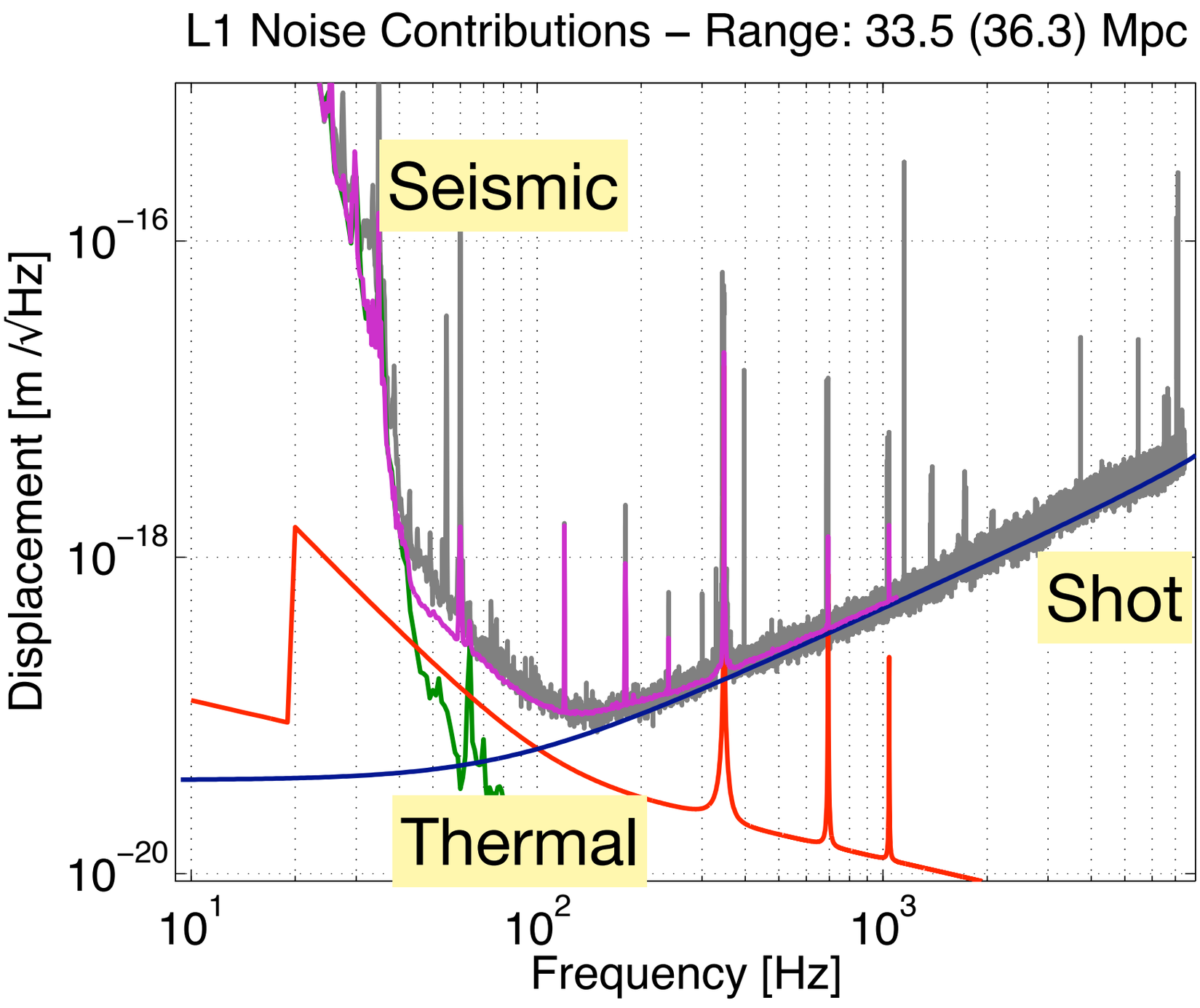

injection/response measurements of noise couplings to test mass displacement

LIGO Facilities

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10^{-9} torr UHV
50 km of spiral weld
10,000 m^3 per site

Seismic isolation

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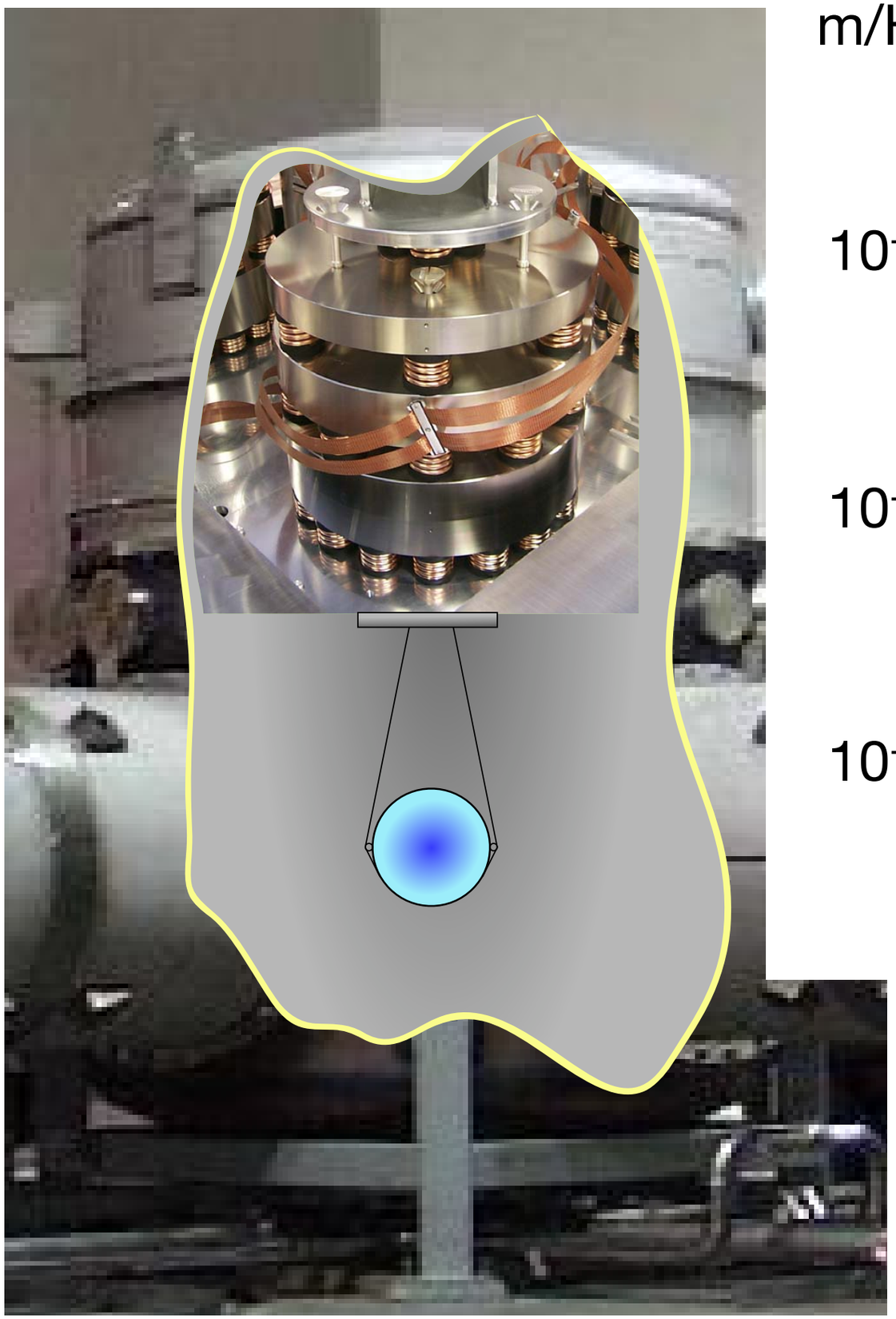
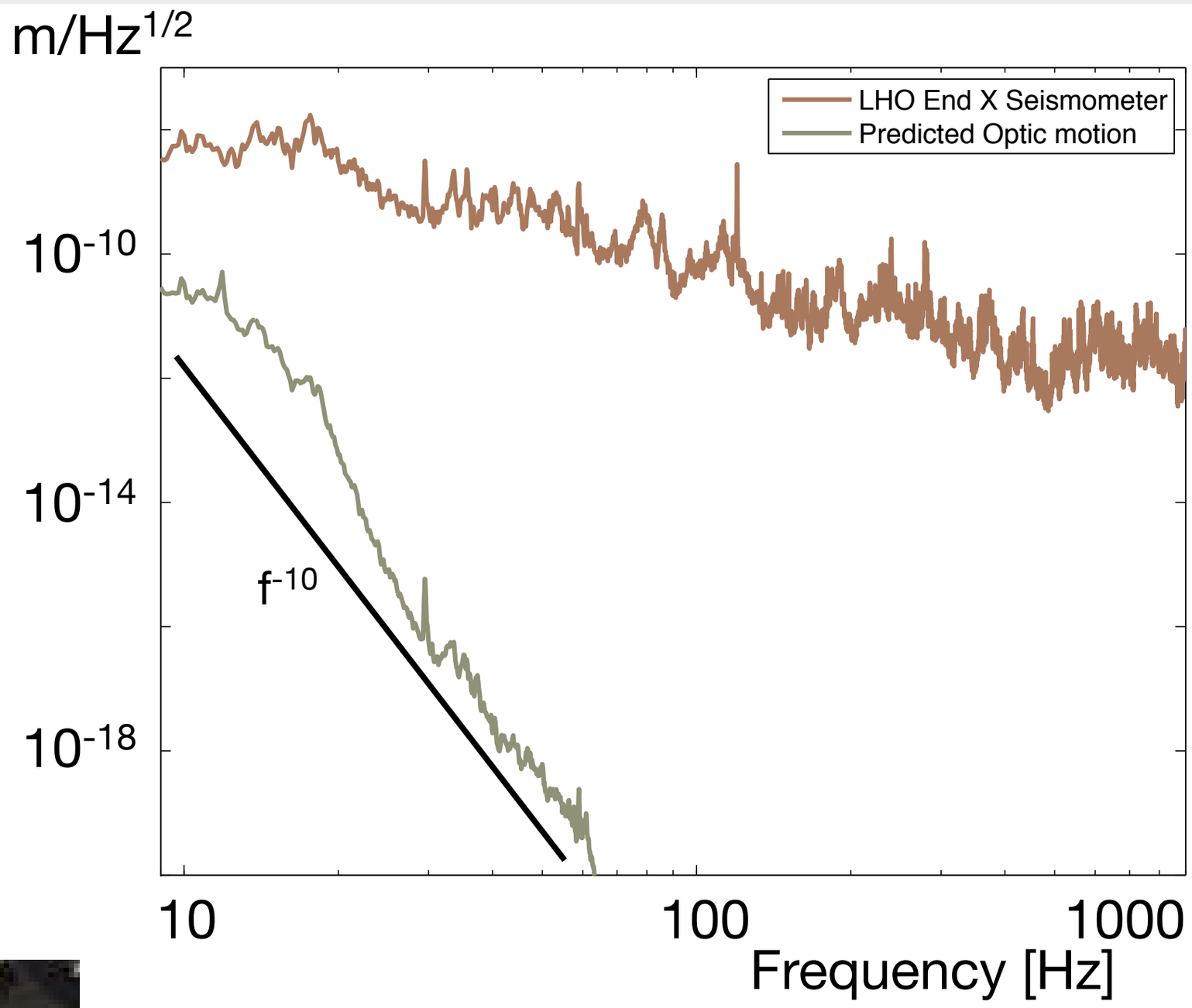
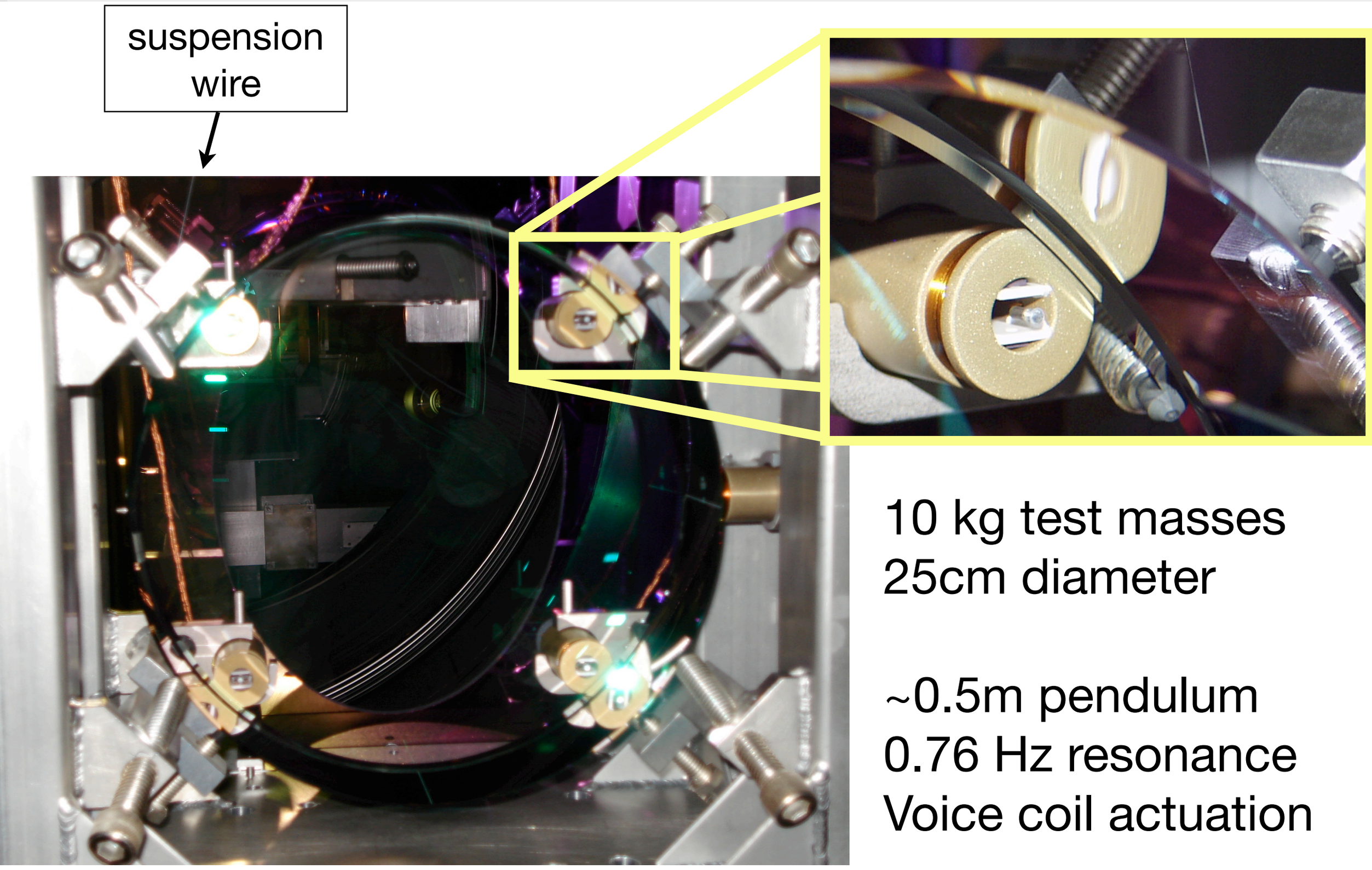




$$\frac{x_2(\omega)}{x_1(\omega)} = \frac{1}{1 - \omega^2/\omega_0^2}$$

Free masses



10 kg test masses
25cm diameter

~0.5m pendulum
0.76 Hz resonance
Voice coil actuation

Thermal noise

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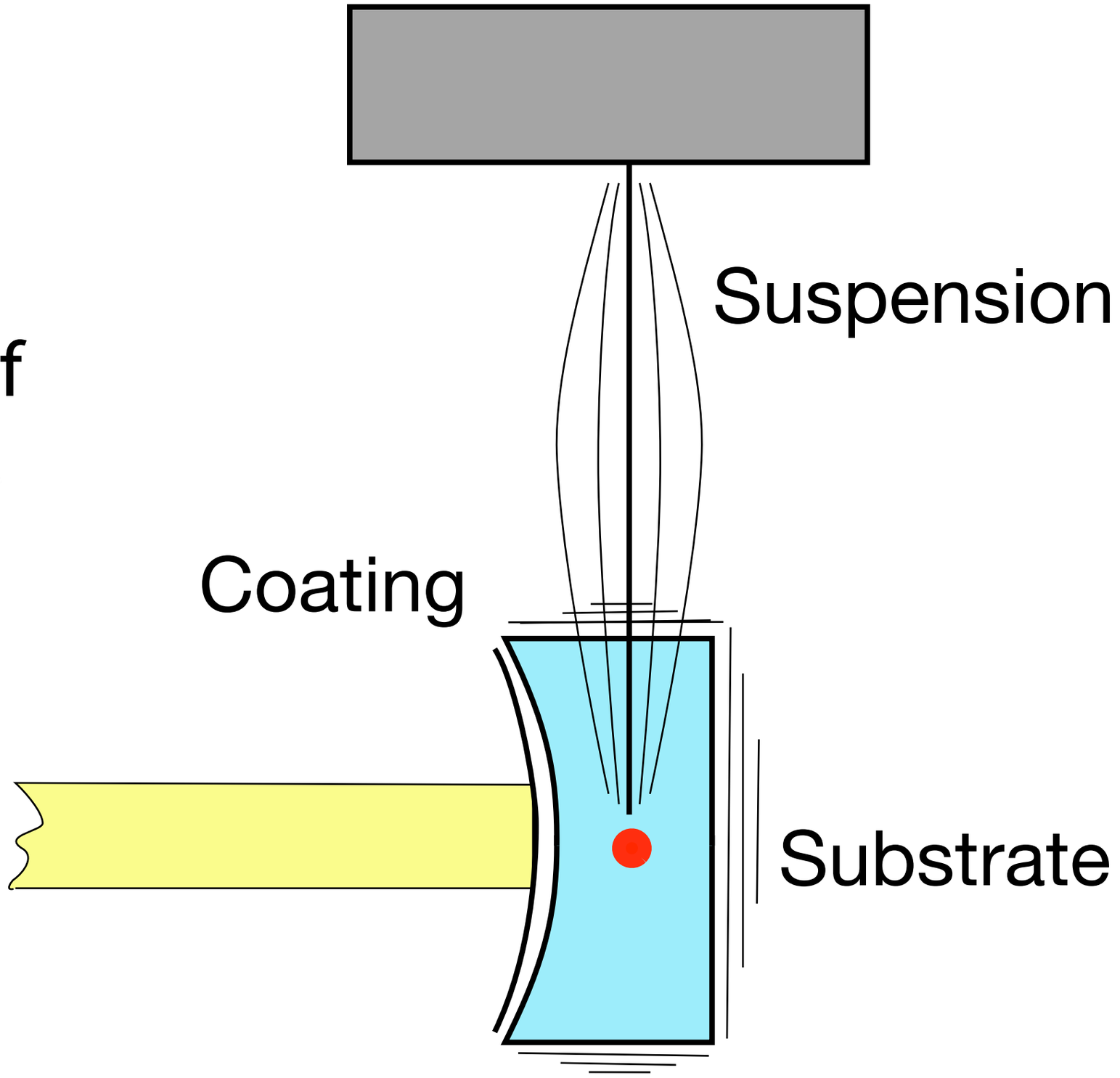
Dissipation in lossy materials causes fluctuations in the measured center of mass displacement

May be limiting noise 40-100 Hz



Shot Noise

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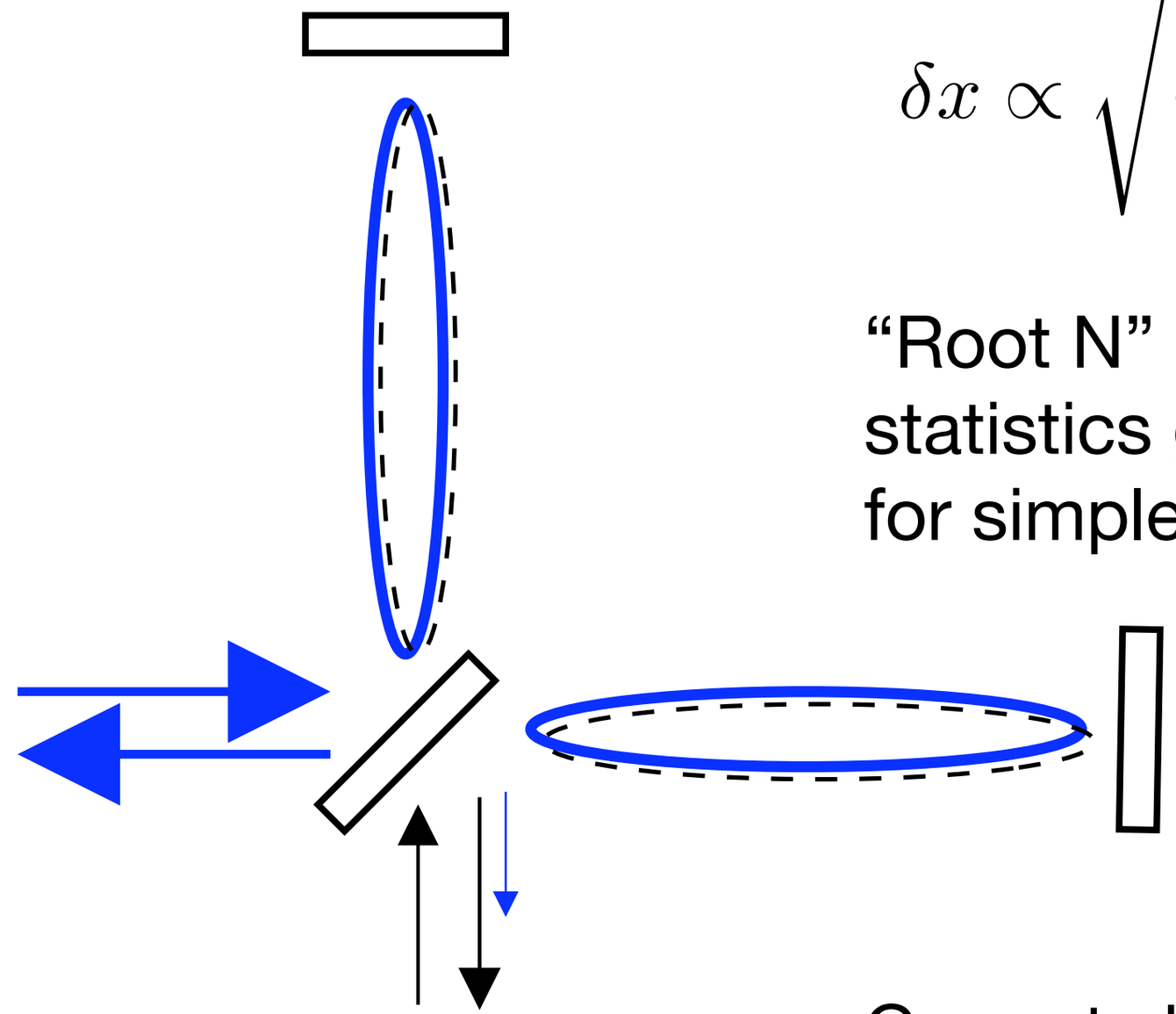
$$\delta x \propto \sqrt{\frac{1}{N_{photons}}} = \sqrt{\frac{1}{P_{BS}}}$$

"Root N" photon counting statistics gives correct answer for simple interferometers

Input laser field



Correct shot noise includes the vacuum fields entering the interferometer

CM Caves, PRD23, 1981

Arm response

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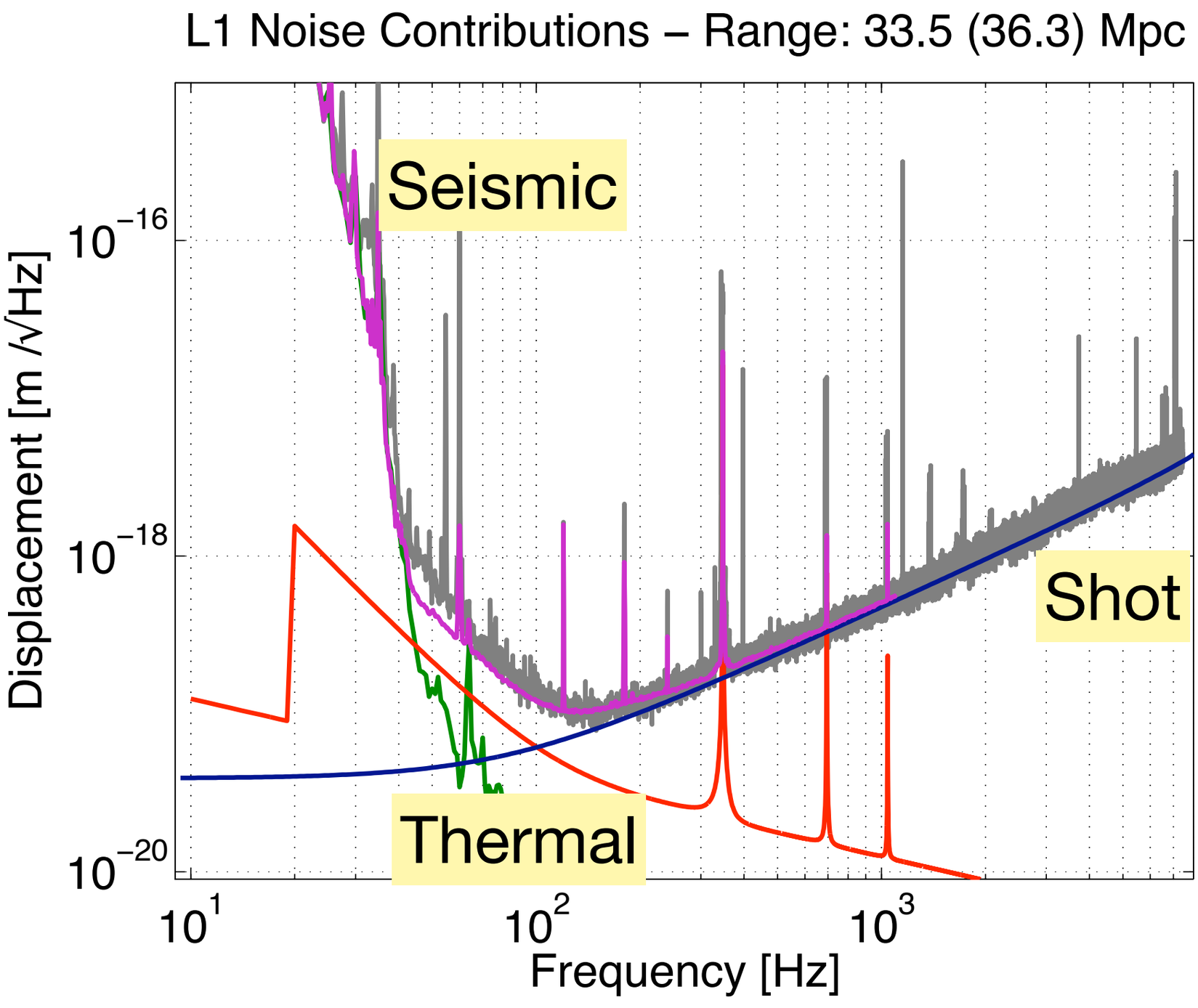

$$T_{arm} \approx \frac{2L}{c} N = .01\ sec$$

round trip time in 4km arm cavity limits the interferometer frequency response

Real world problems

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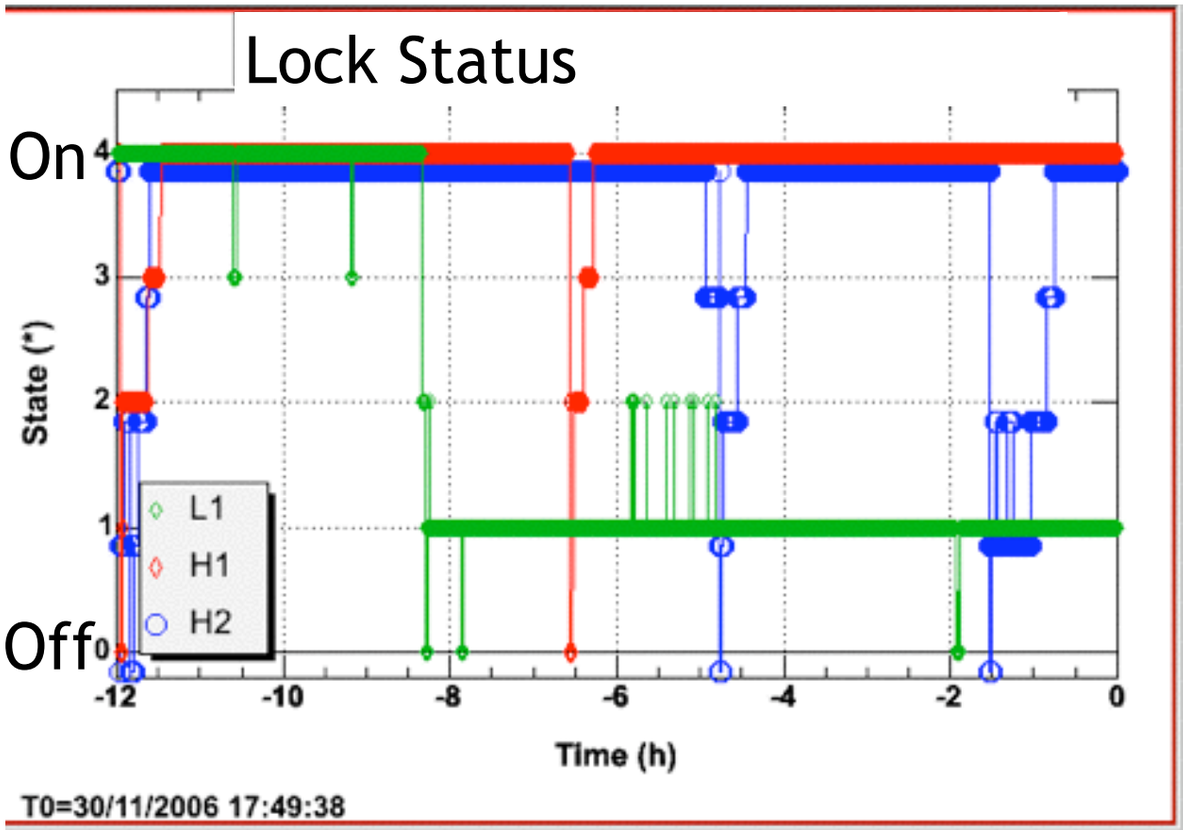
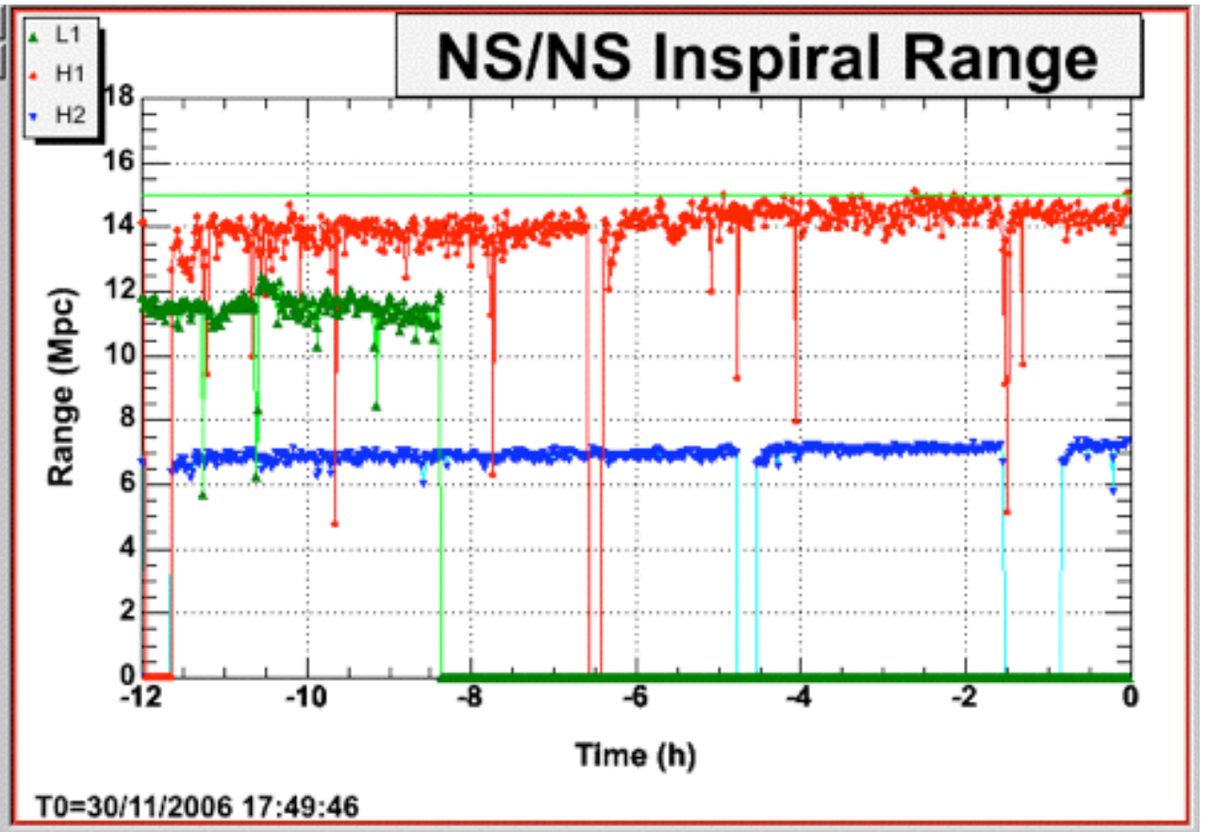
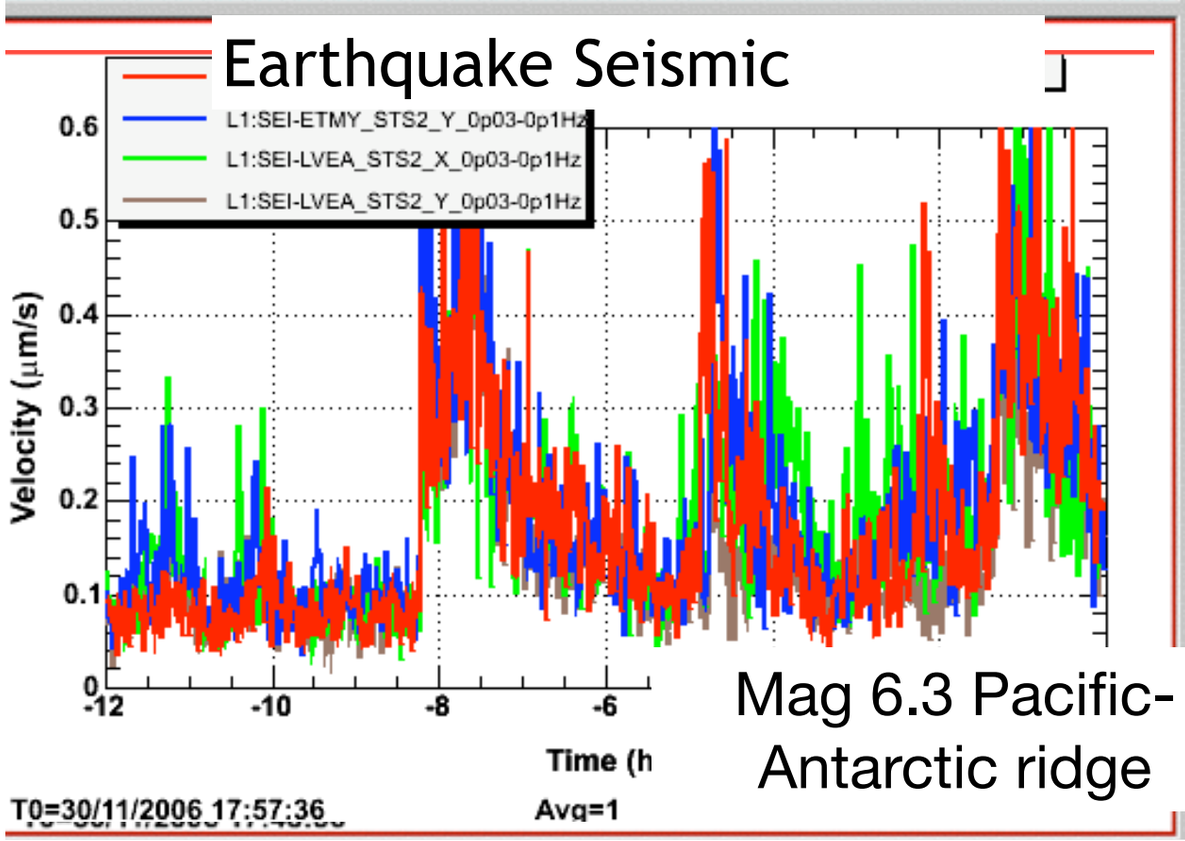
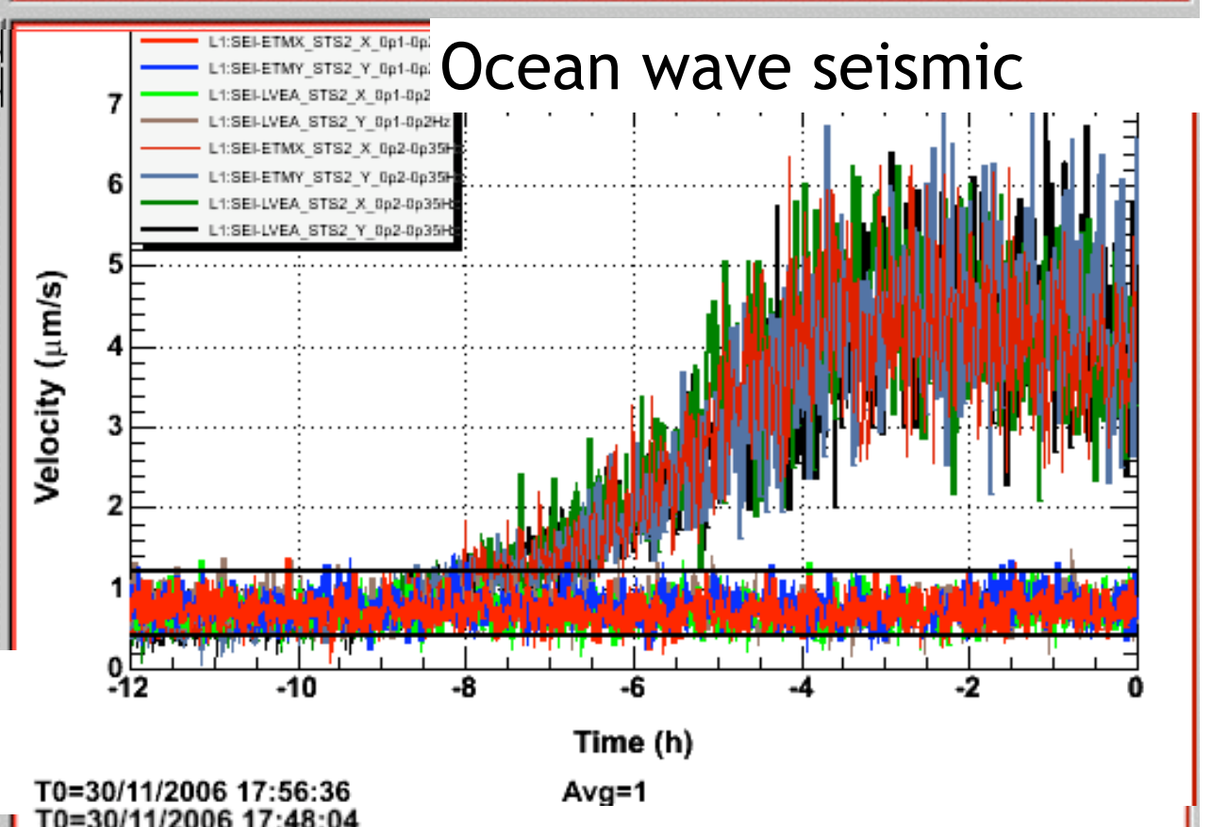


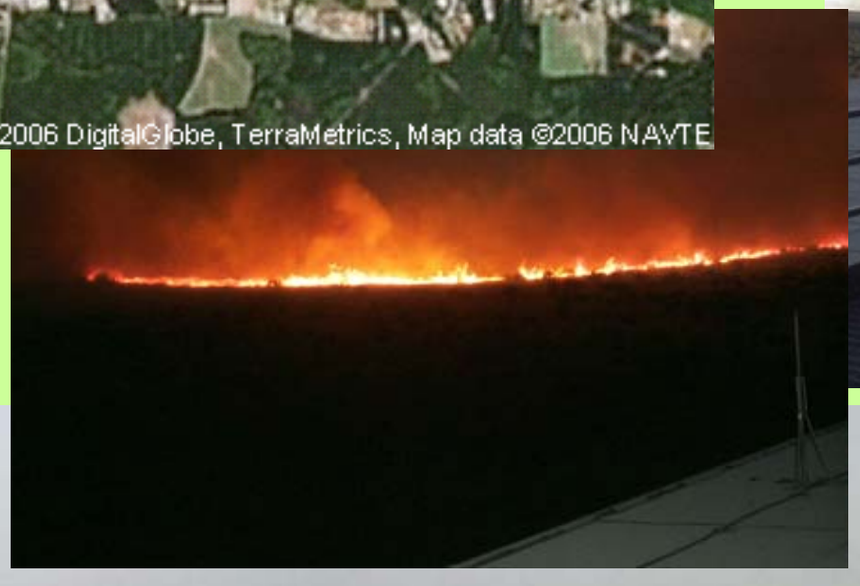




Mag 6.3 Pacific-Antarctic ridge

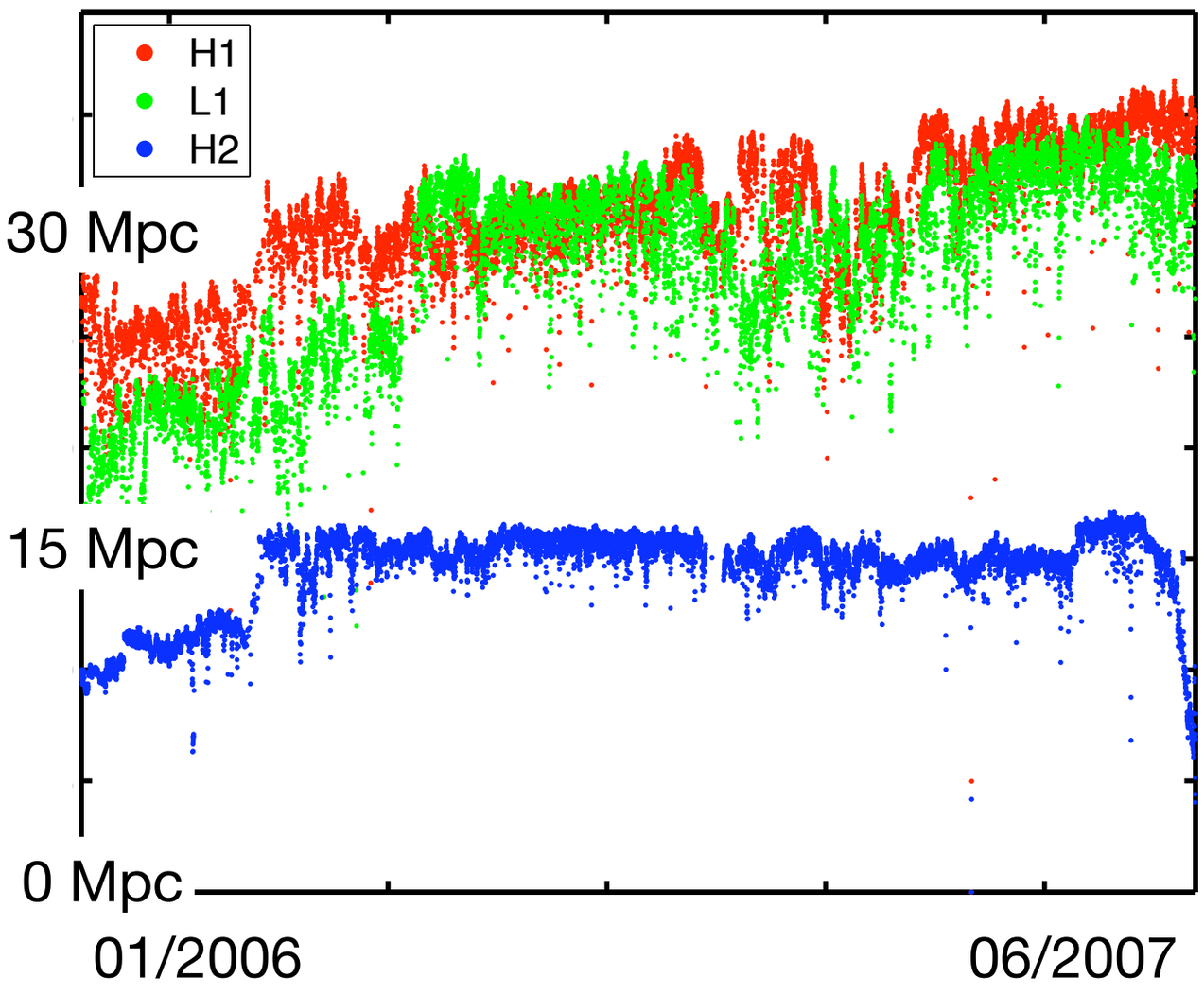


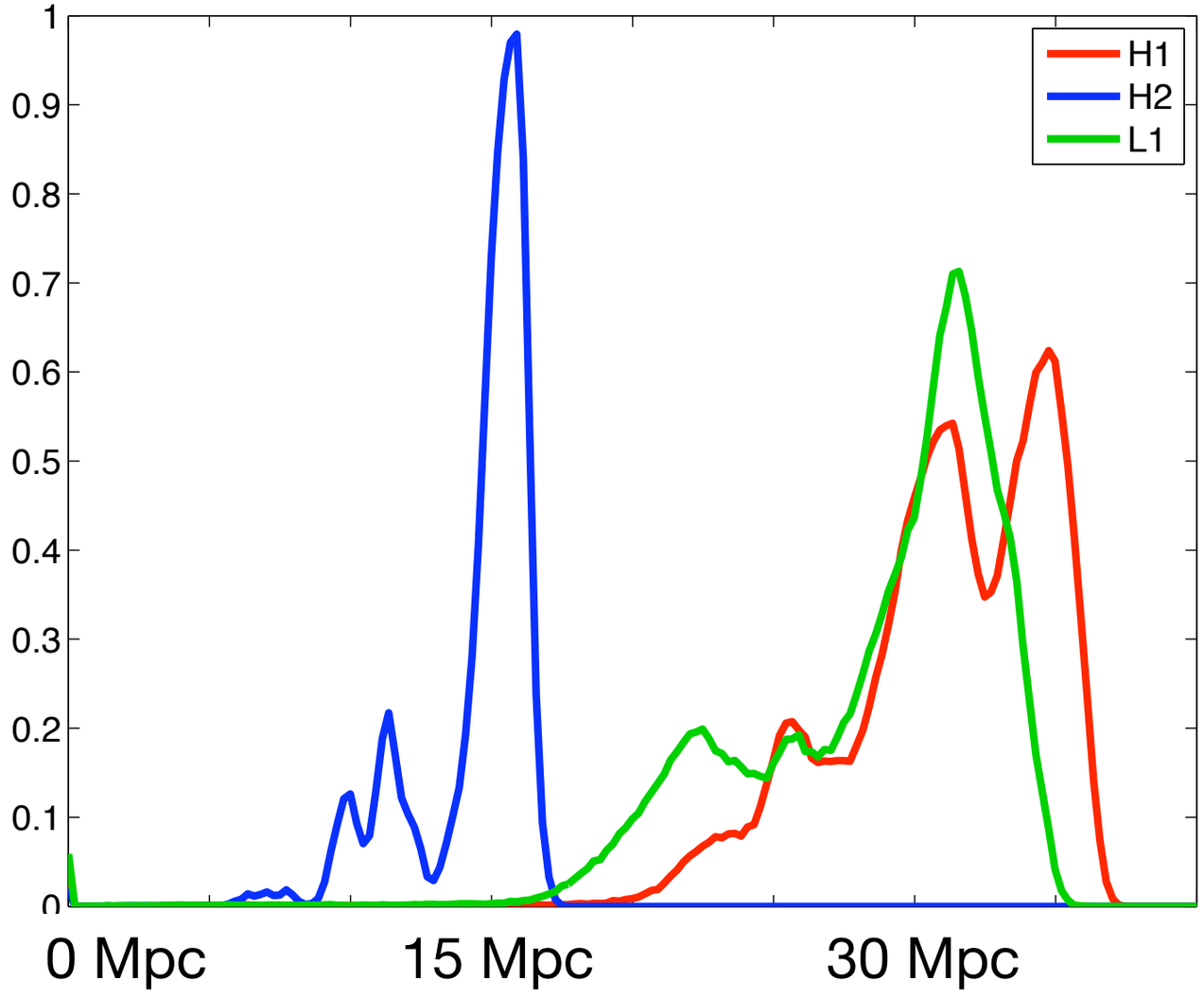
More problems



NS/NS range

~70% duty factor





1.4/1.4 M_0 Horizon Distance

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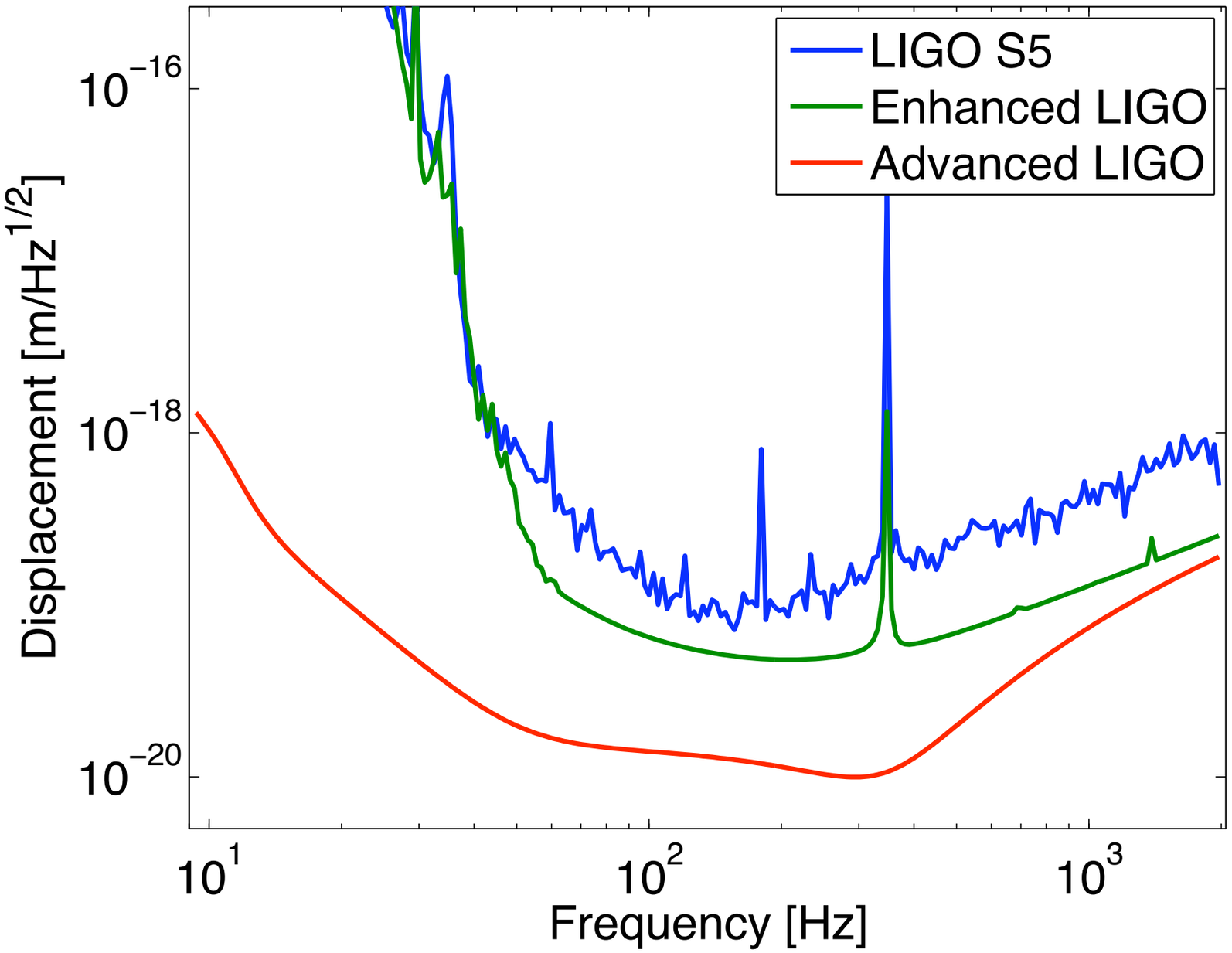

GW sources

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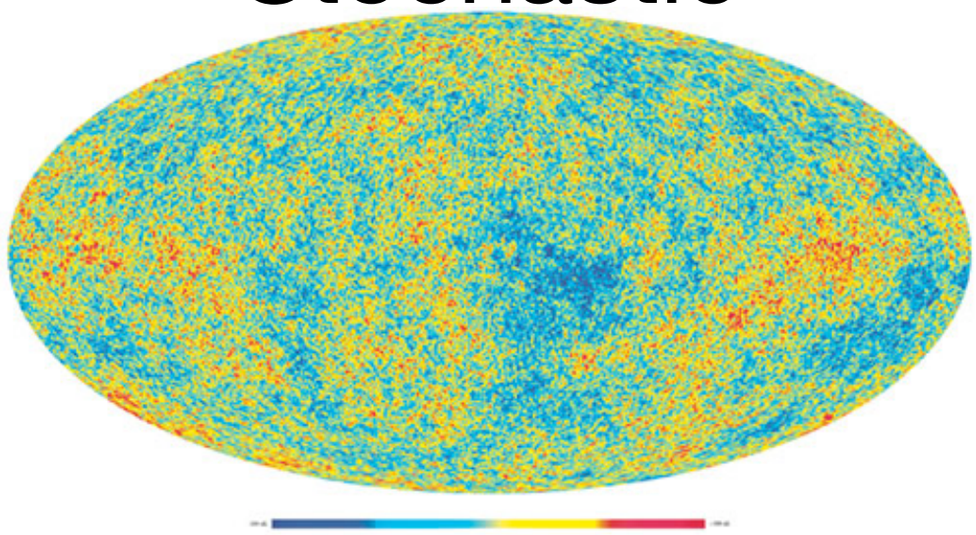
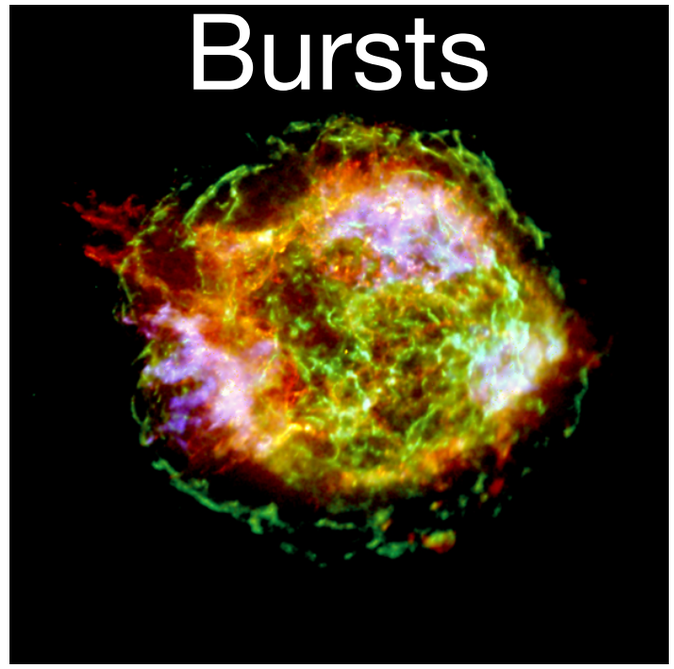
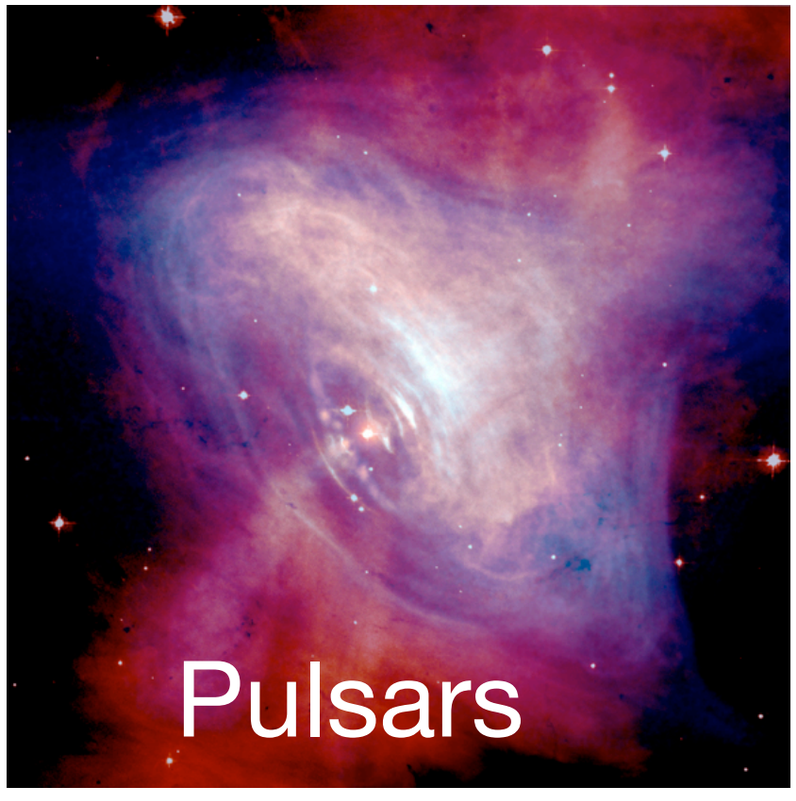
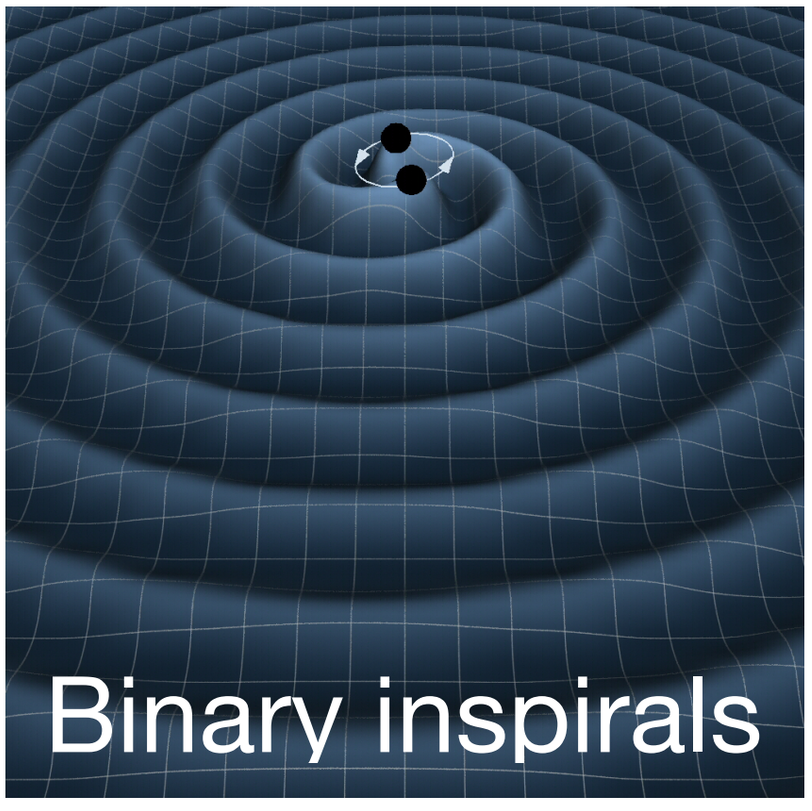
	Continuous	Short
Unmodeled	Stochastic 	Bursts 
Template	Pulsars 	Binary inspirals 

Stochastic background

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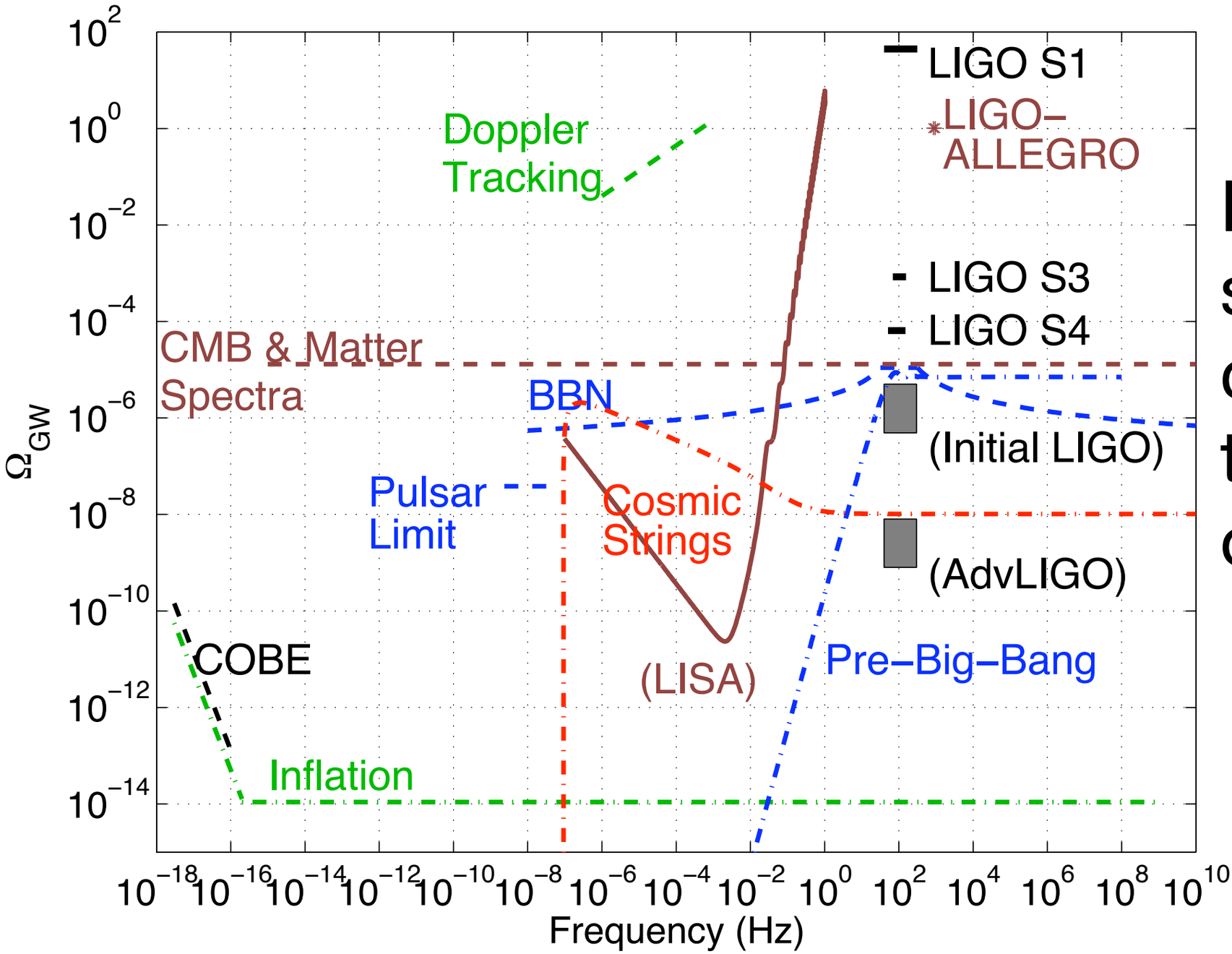
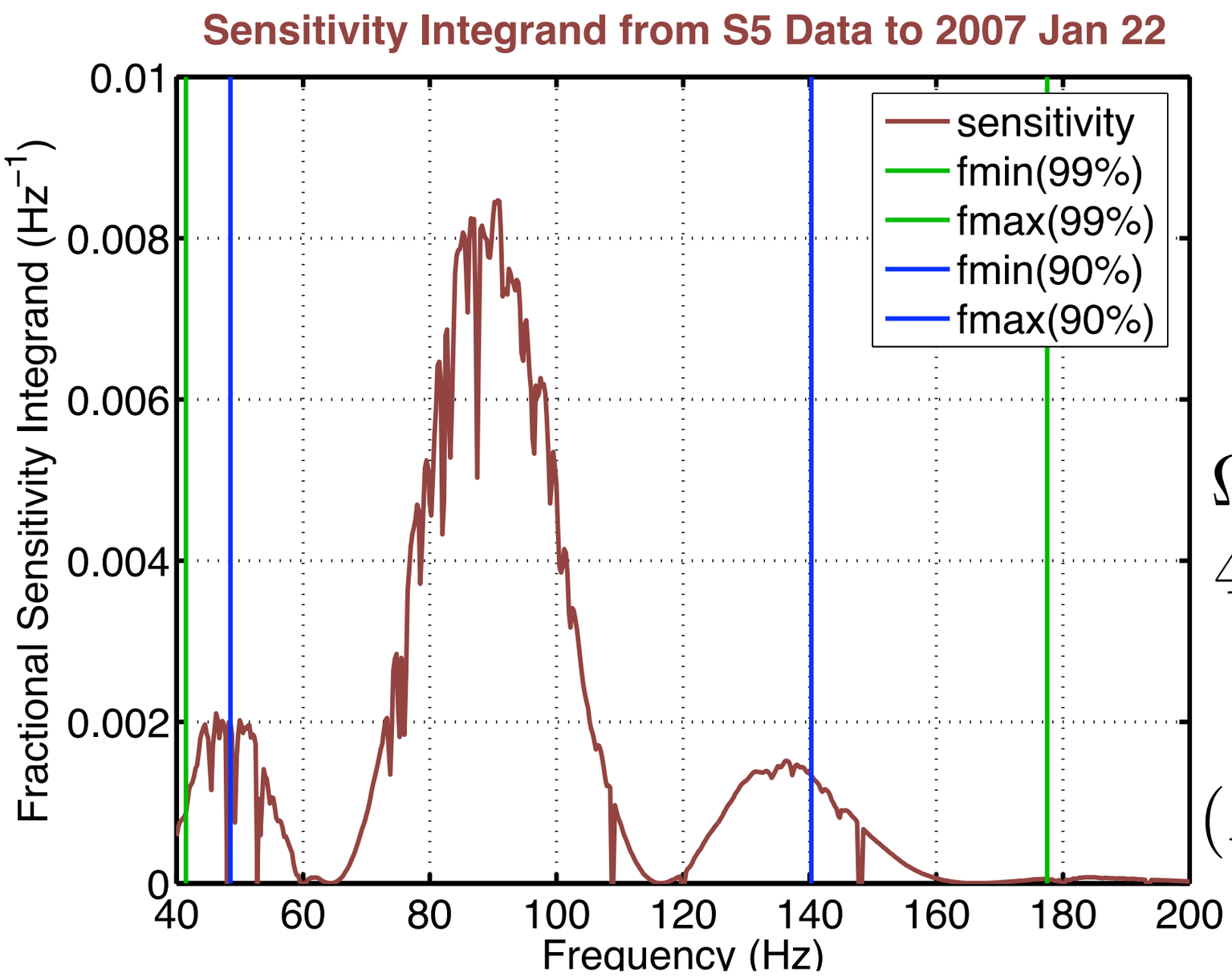


Measure stochastic BG by cross-correlating the output of two or more detectors

Stochastic results



$$\Omega_{GW} \leq 9.0 \times 10^{-6}$$

$$41.5\ Hz < f < 177.5\ Hz$$

$$(BBN: \quad \Omega \leq 1.1 \times 10^{-5})$$

Matched filtering

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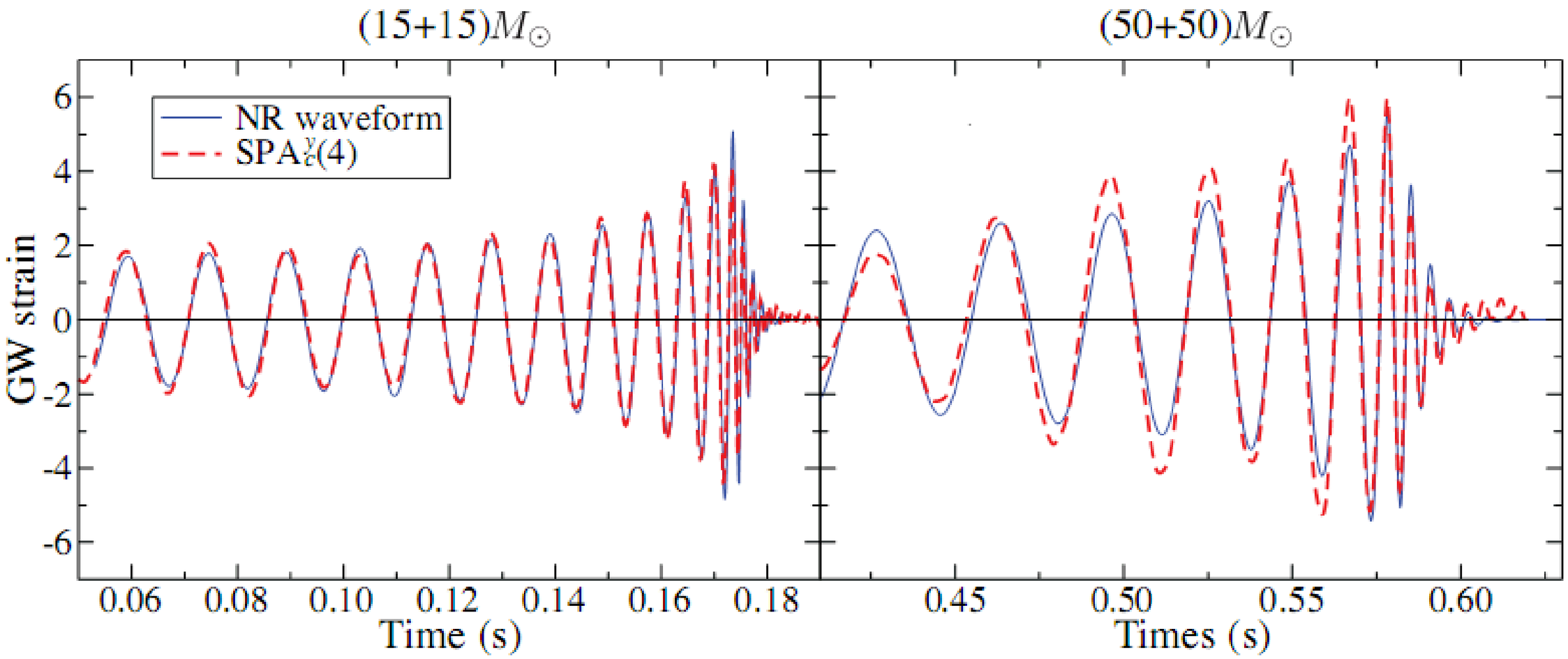

Detected waveform is a function of a few parameters:

non-spinning circular: 9
spinning circular: 15
spinning eccentric: 18

Buonanno et al., arXiv:0704.1964

Templates

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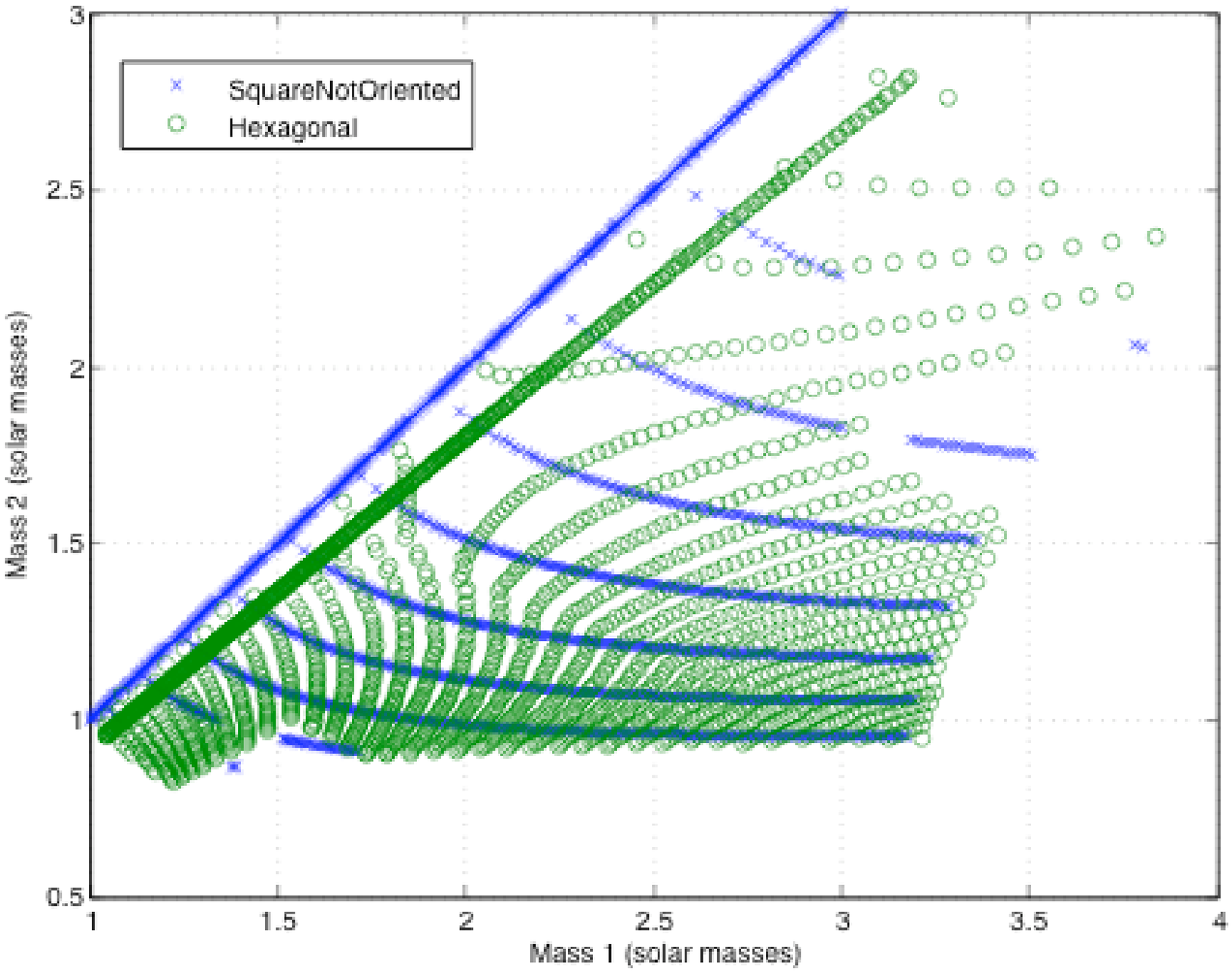
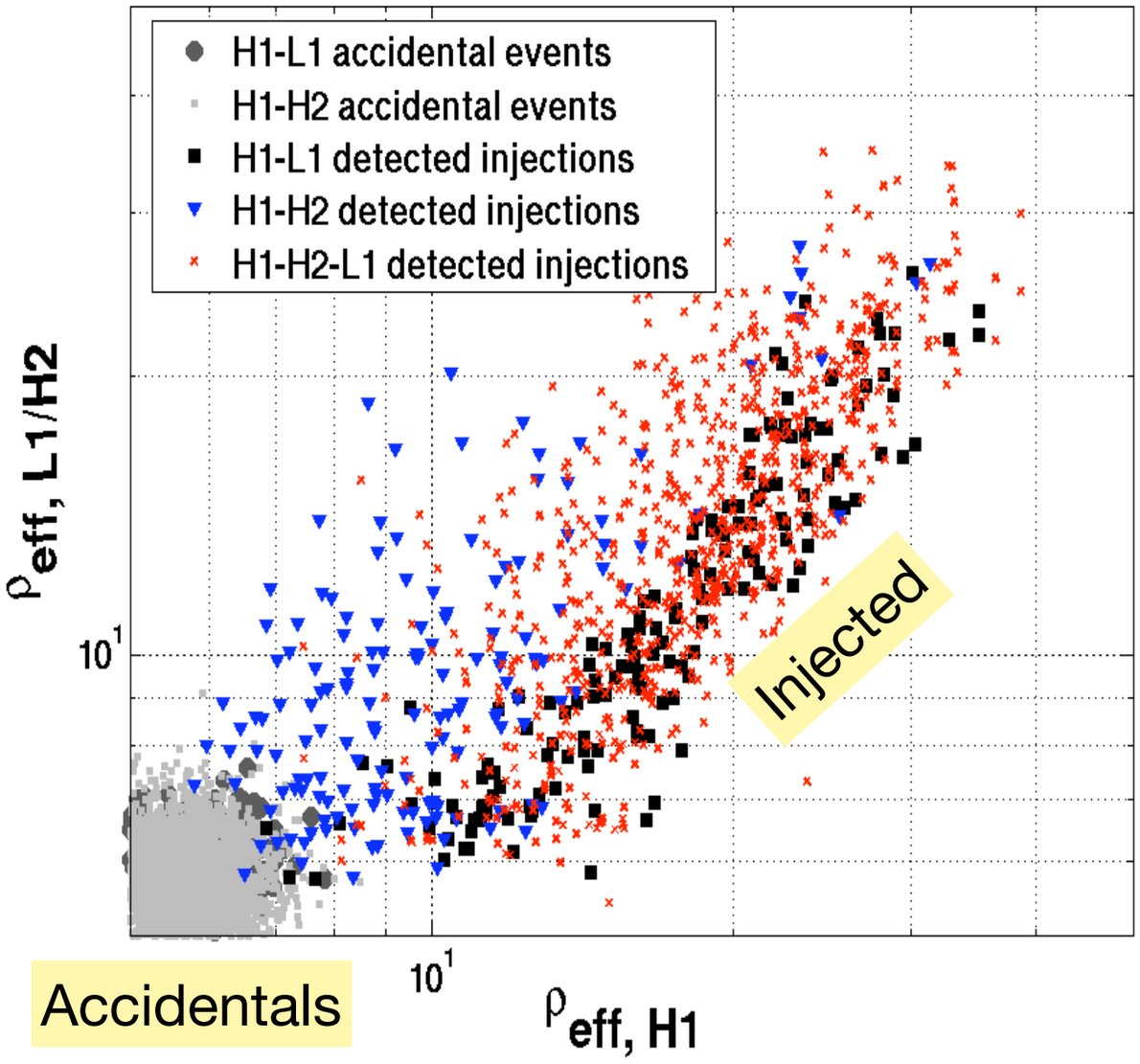
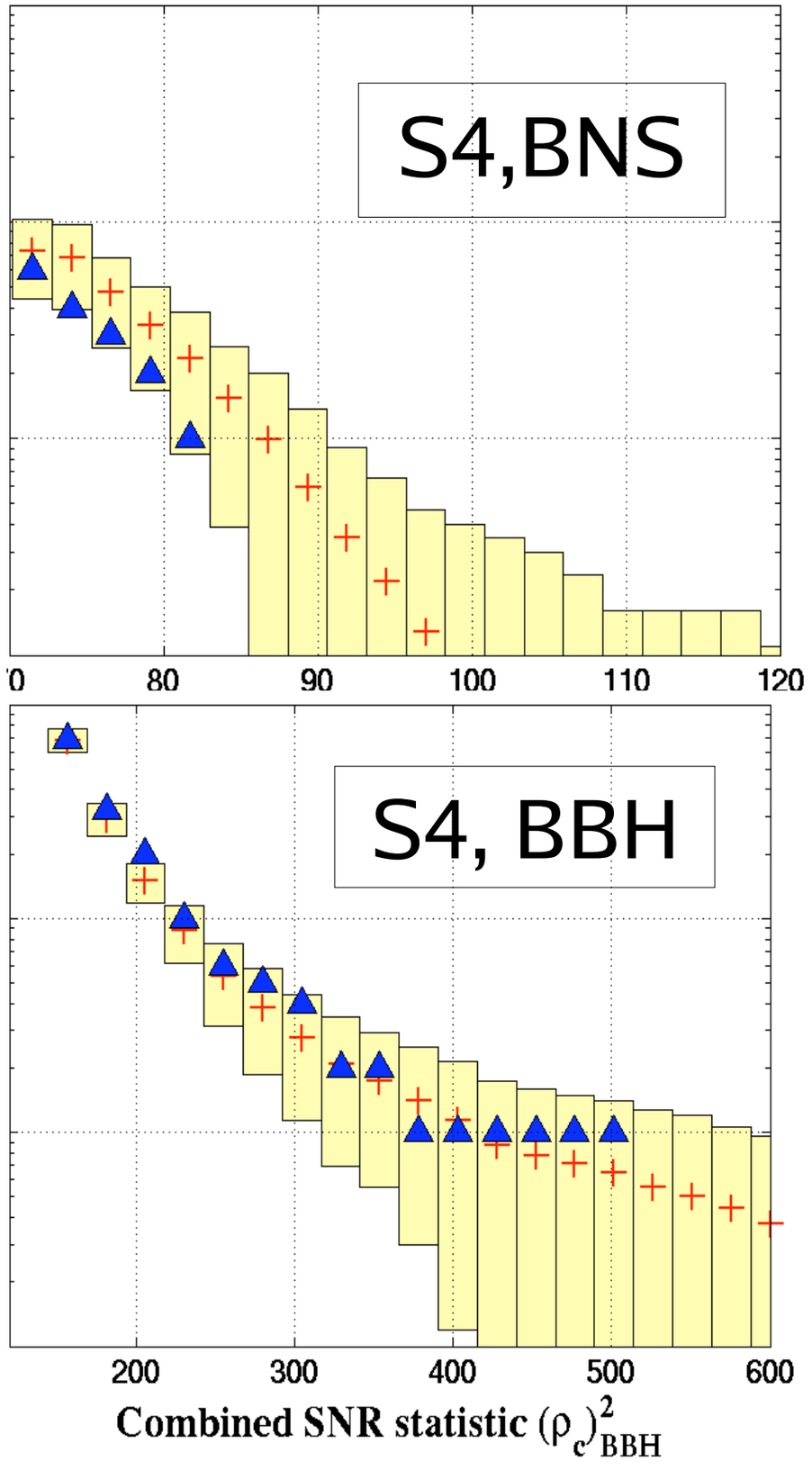
$$\rho_c^2(t) = \frac{1}{\sigma} \int_{f_{\rm low}}^{f_{\rm max}} \frac{\tilde{s}(f)\tilde{h}_c^*(f)}{S_n(f)} e^{2\pi i f t}\, dt$$



10^4 templates per search

S4 Results



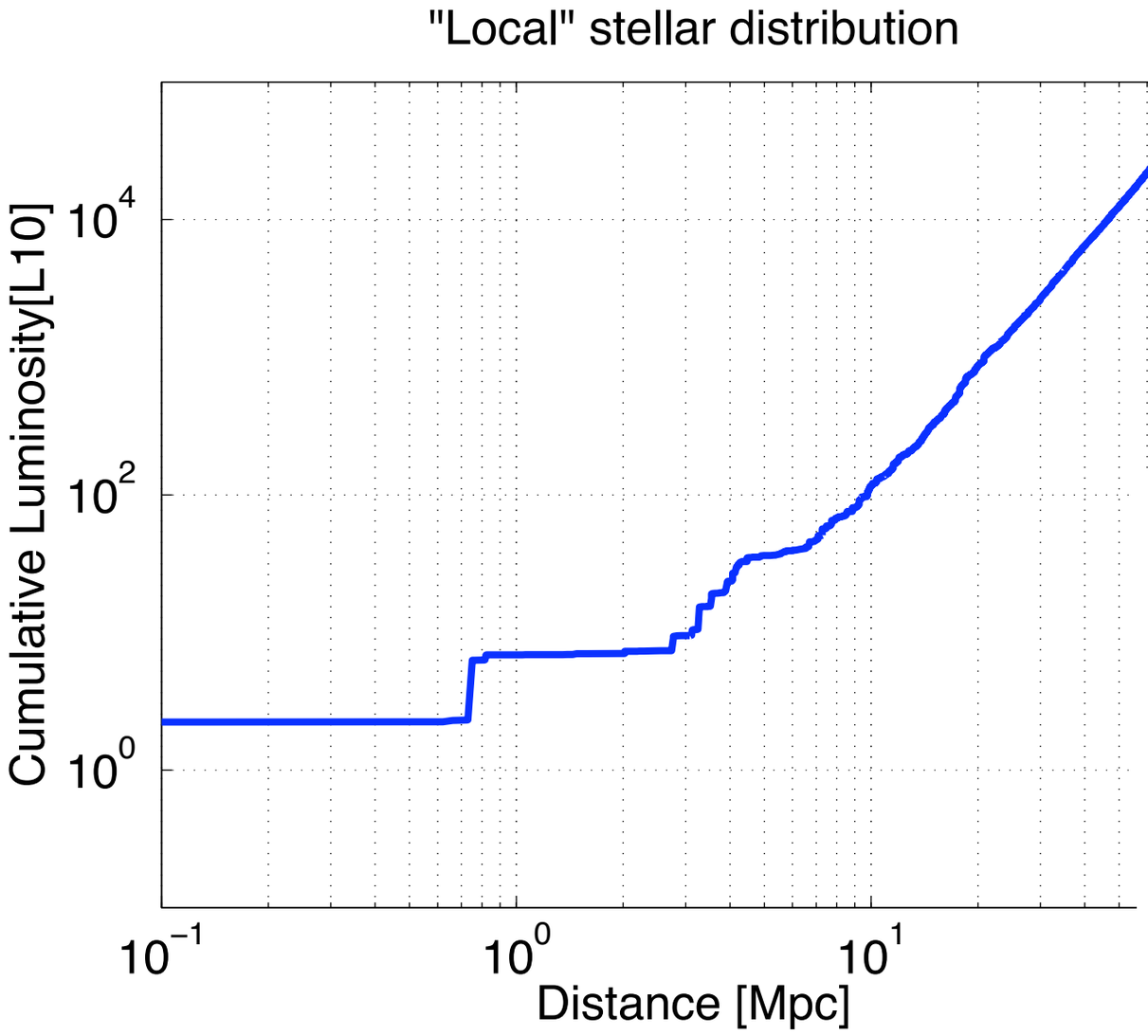


Binary Neutron Star ≤ 1.2 yr^{-1} $L10^{-1}$

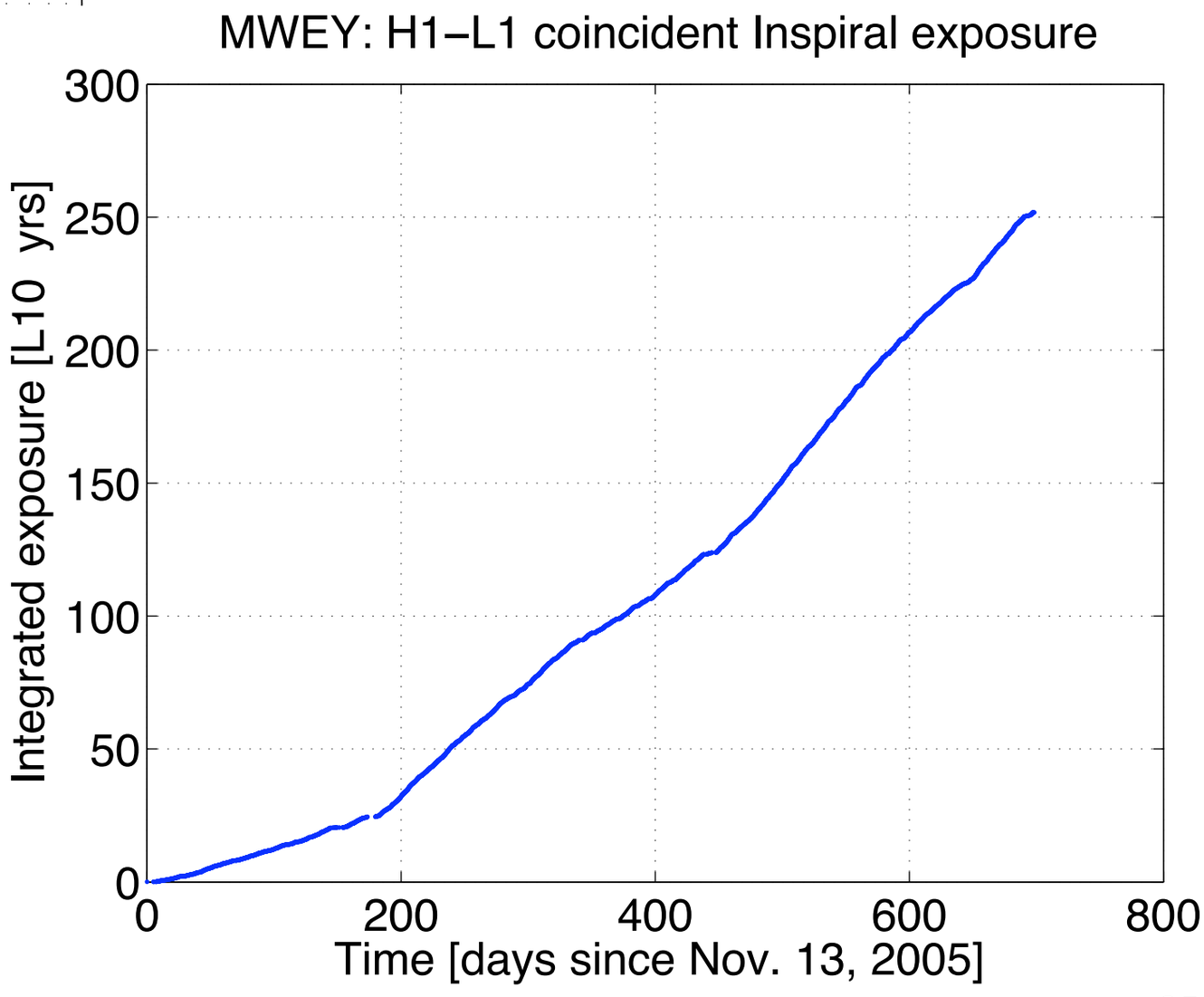
Binary Black Hole ≤ 0.5 yr^{-1} $L10^{-1}$

Inspiral rates

Waldman
Stanford '08



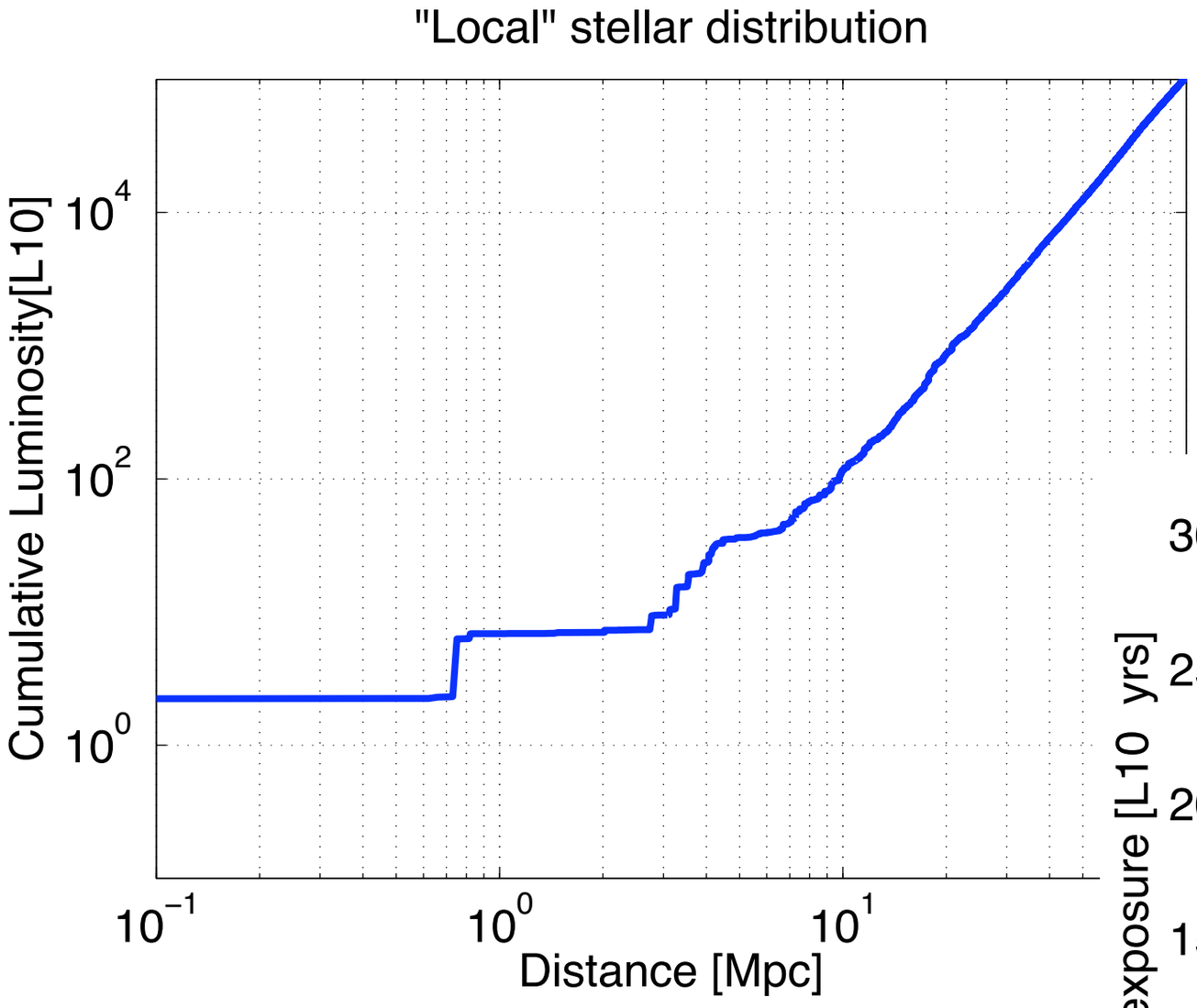
Single detector
SNR = 8
Average orientation



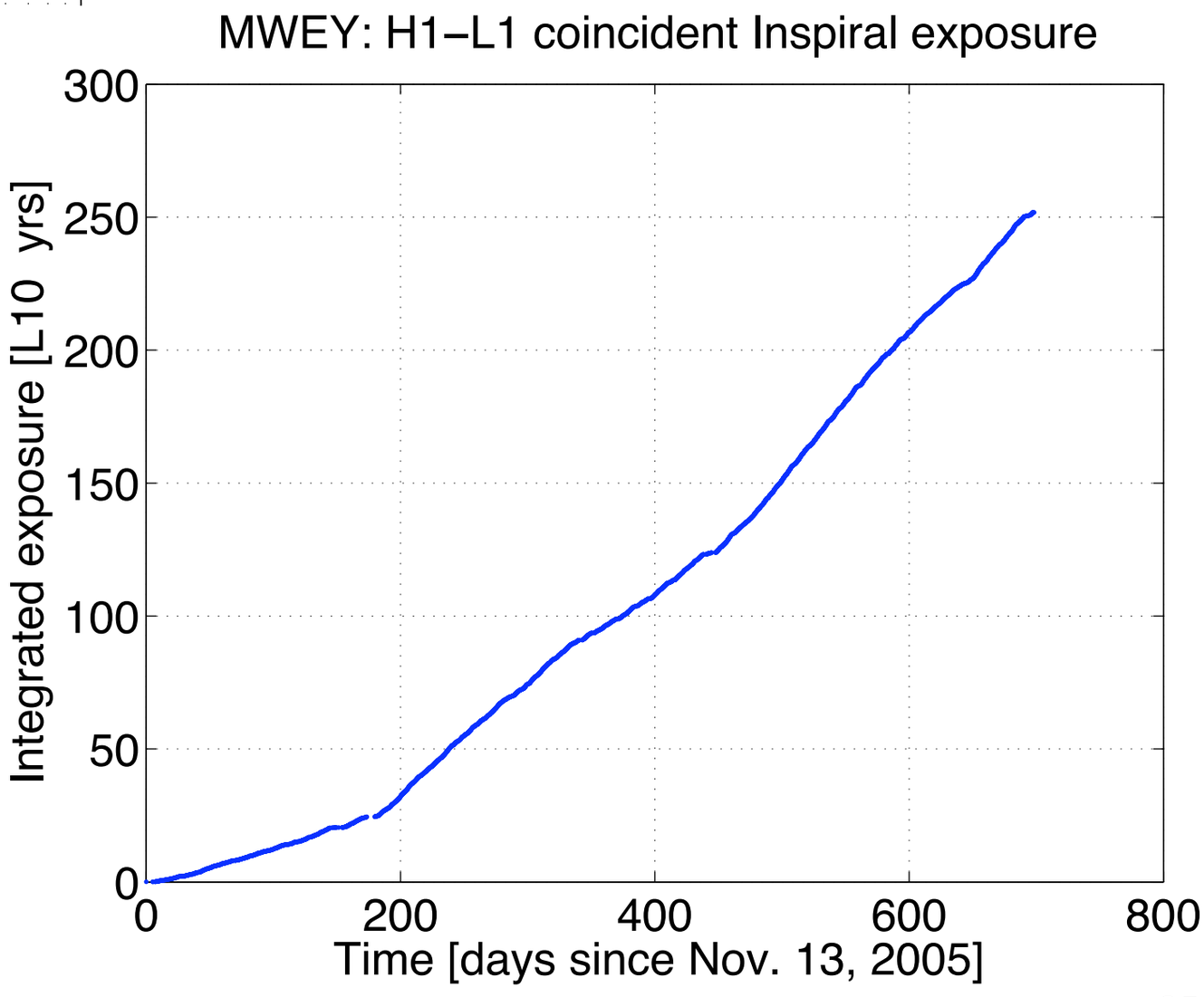
Not an analysis result!
Full analysis worth 4-5x more

Inspiral rates

Waldman
Stanford '08



Single detector
SNR = 8
Average orientation

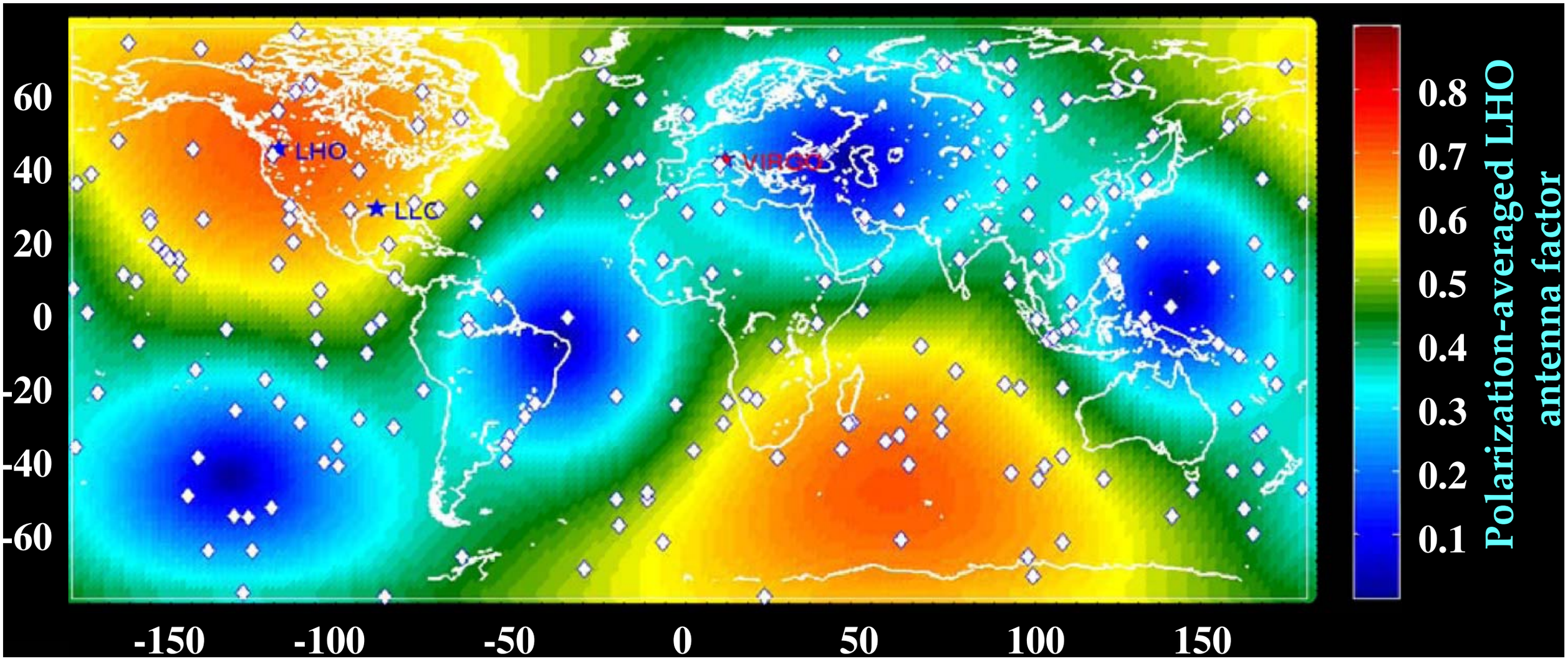


1 Inspiral / 10^4 L10 / year

Not an analysis result!
Full analysis worth 4-5x more

Triggered search

Waldman
Stanford '08



213 GRB triggers during S5

70% with double coincidence data

GRB 070201

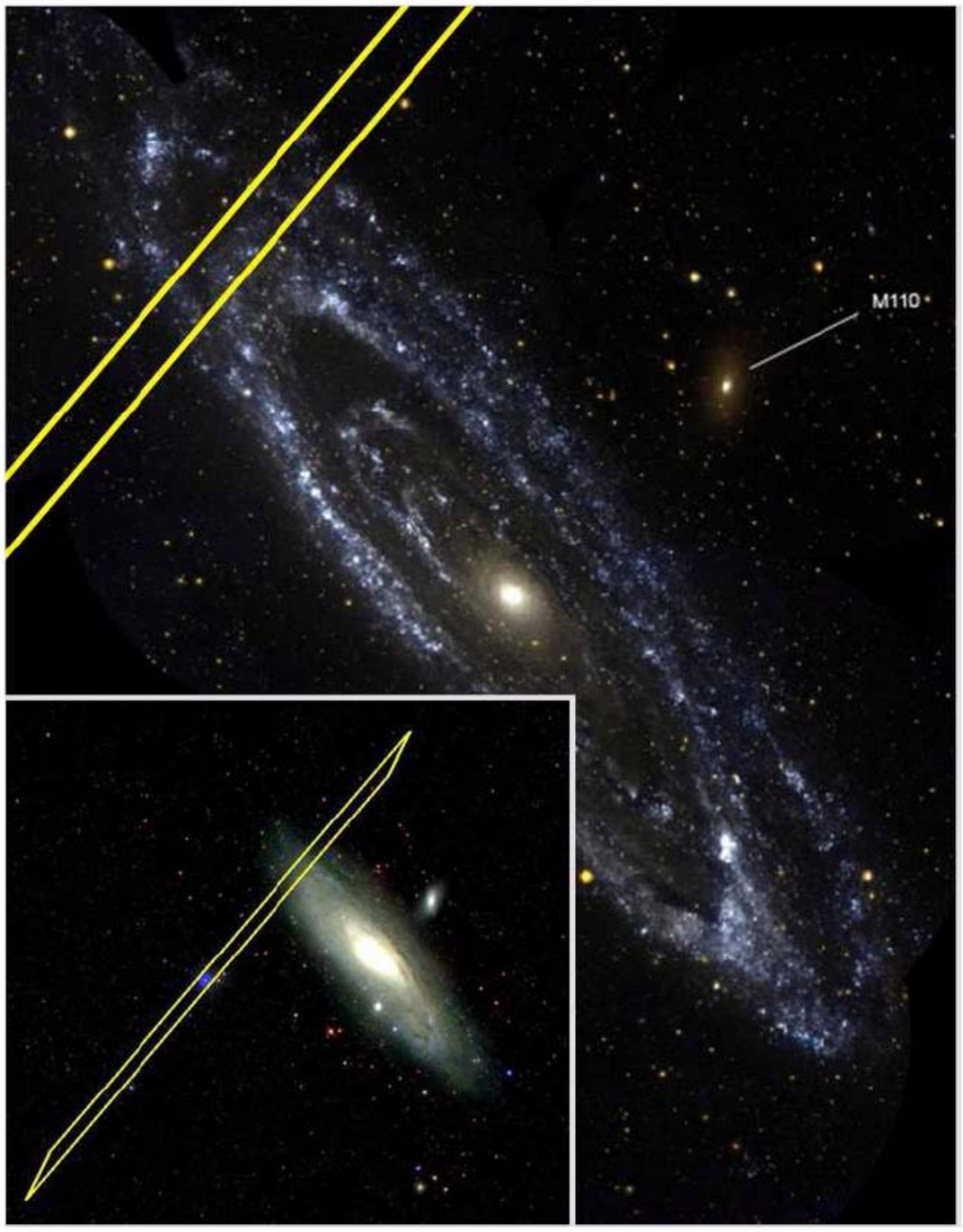
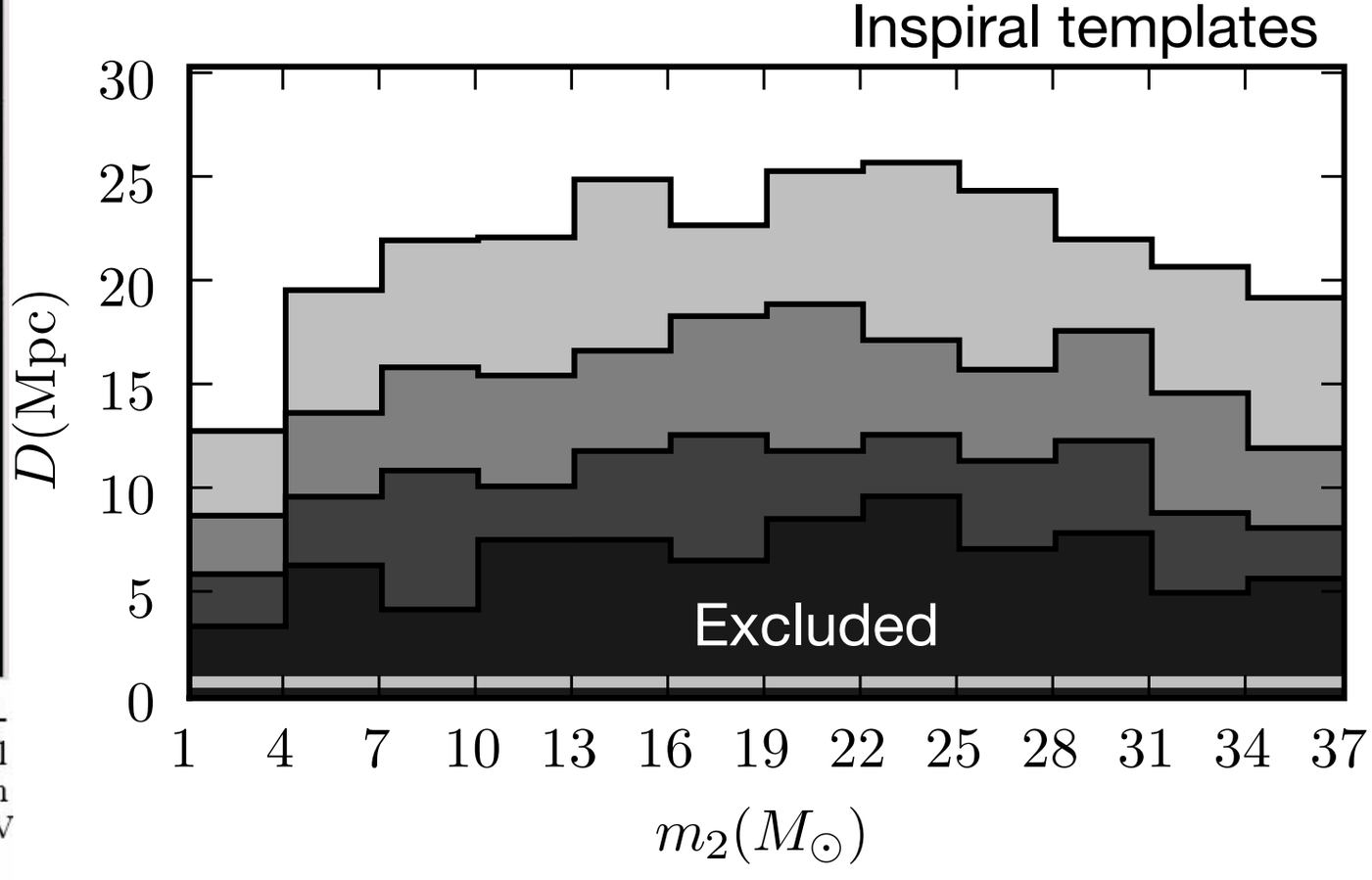


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

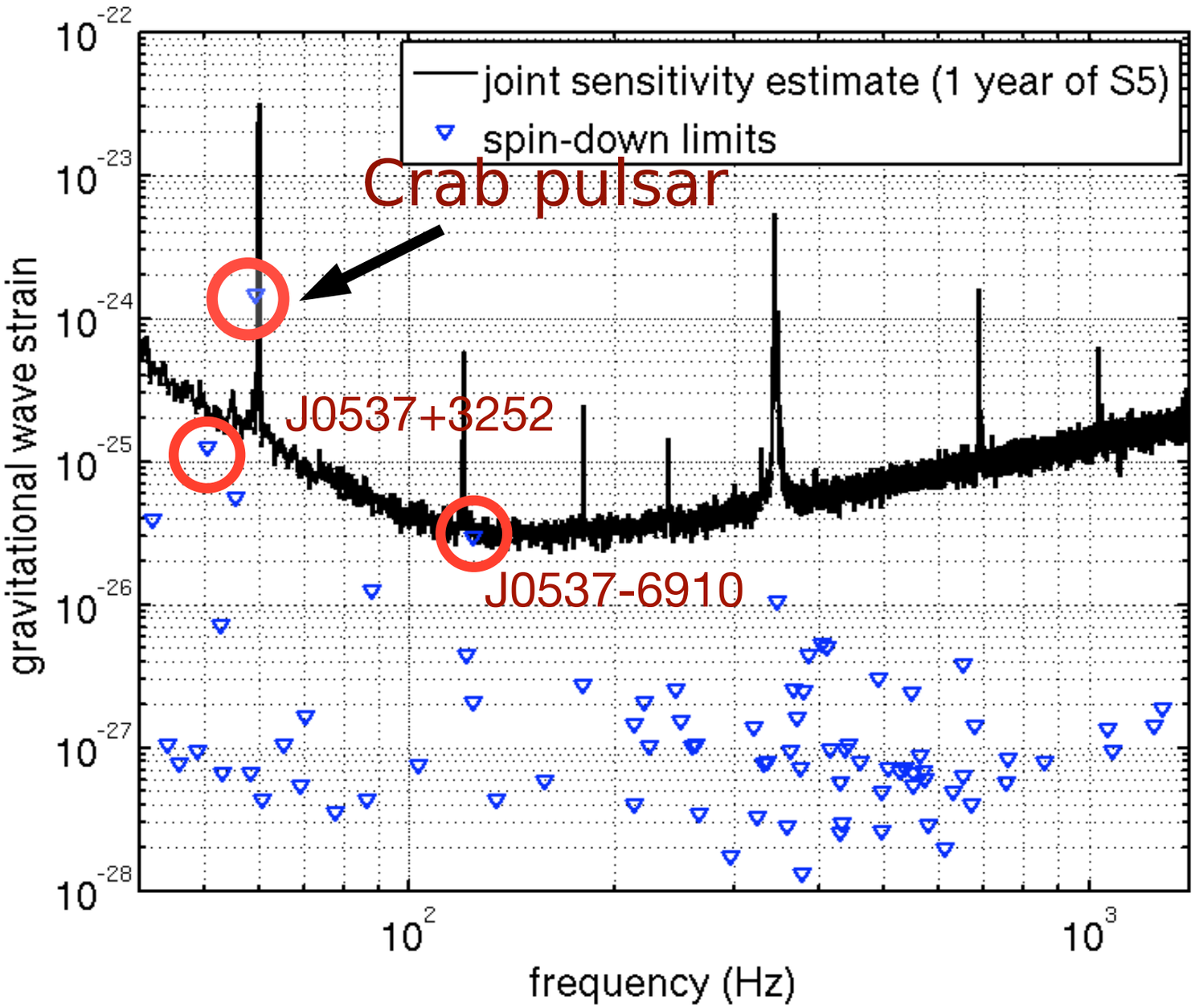
Short, hard gamma-ray burst (could be NS/NS inspiral)

Position consistent with M31



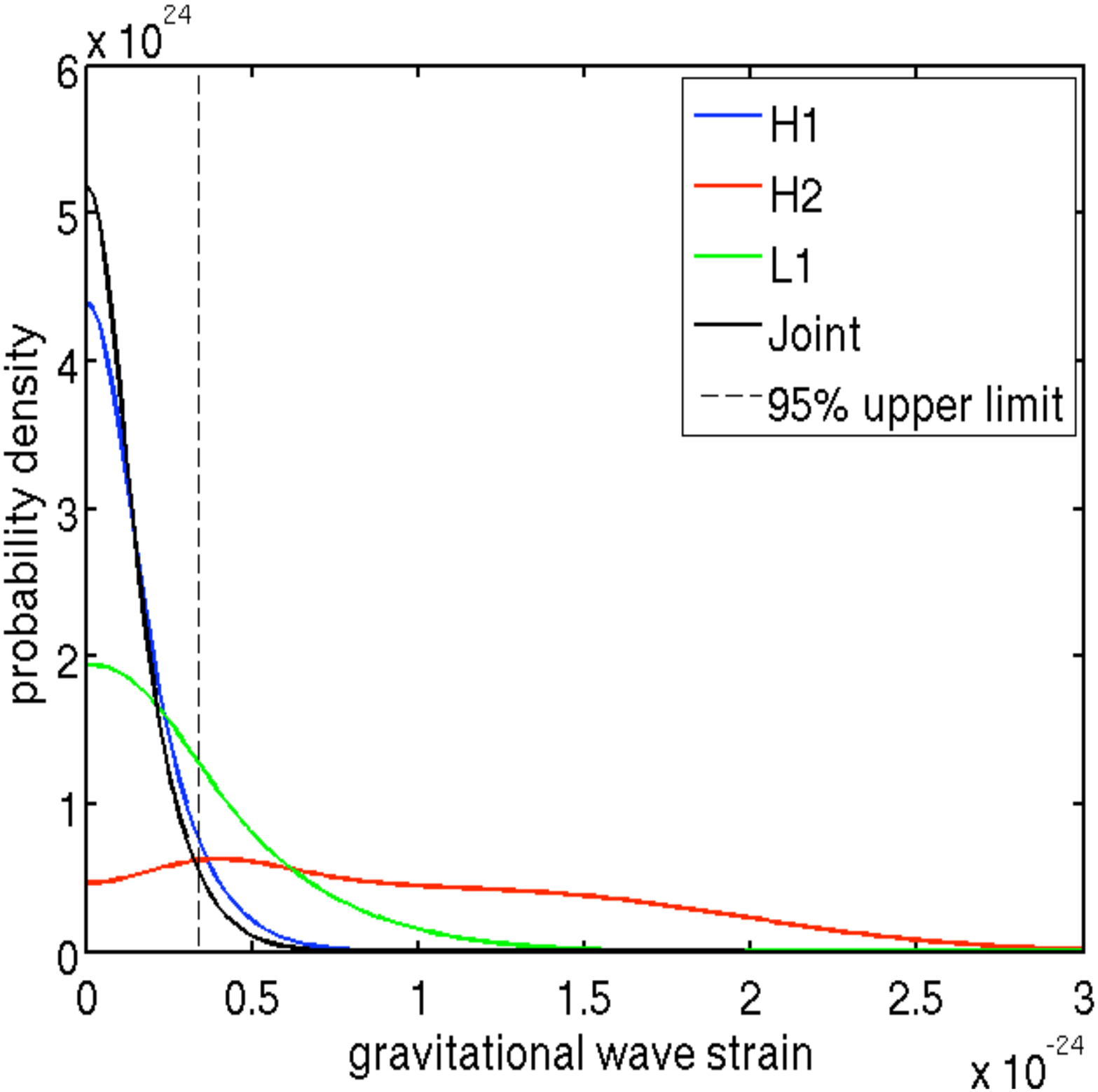
Pulsar ringdown

Waldman
Stanford '08



Use known millisecond pulsar ephemerides from radio observations for coherent search

Crab Spindown



No GWs observed at h ~ 3.4×10^{-25} (with uniform priors)

Beats the spin-down limit!

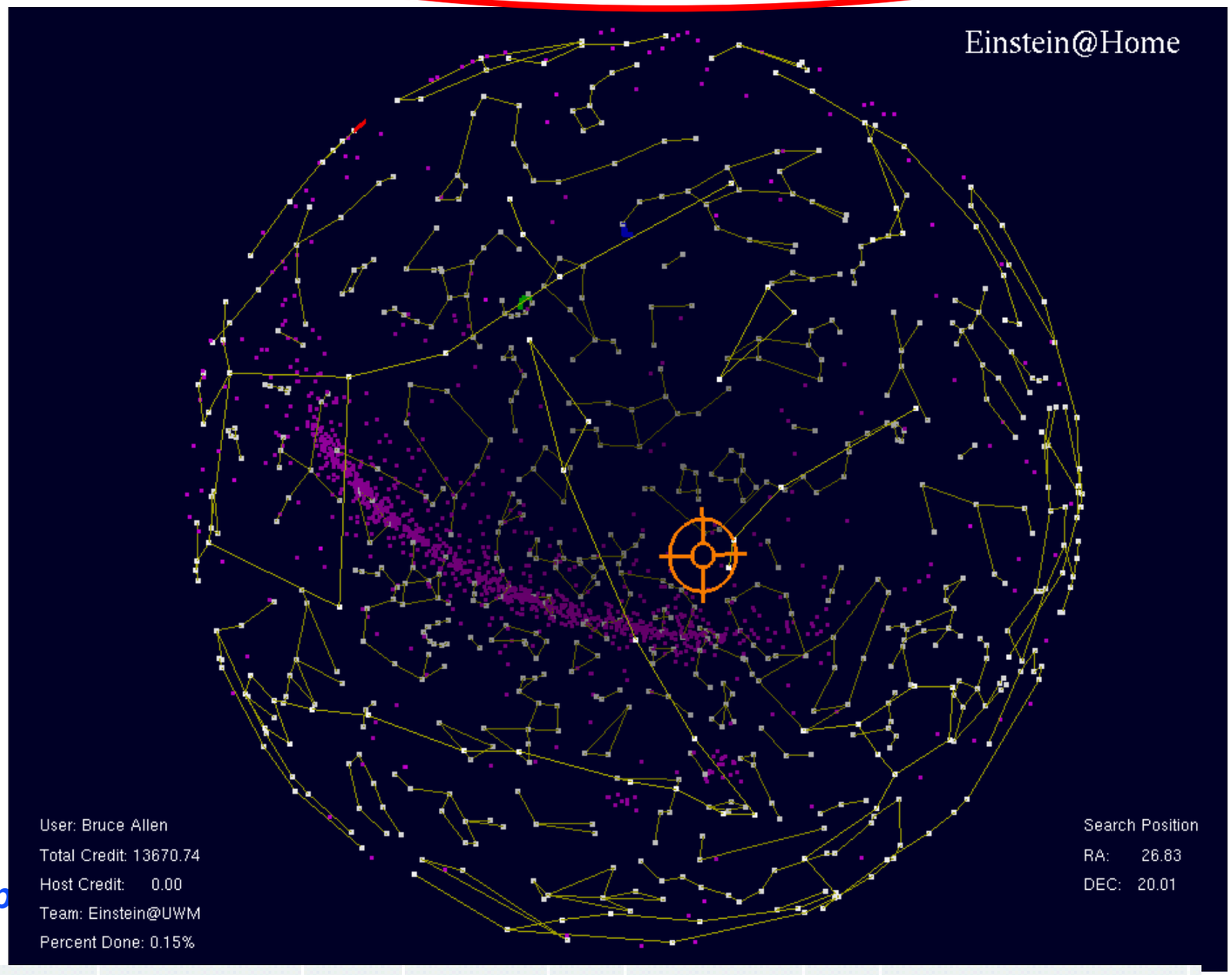
Eccentricity limit of 1.8×10^{-4}

Einstein@Home

Waldman
Stanford '08

- Like SETI@home, but for LIGO/GEO data
- Goal: pulsar searches using ~1 million clients. Support for Windows, Mac OSX, Linux clients
- From our own clusters we can get thousands of CPUs. From Einstein@home hope to many times more computing power at low cost

http://einstein.phys.uwm.edu/



Einstein@Home	148,596	+155	308,921	+446	6,243	+9	195	D	2,633,550,524

Users Machines Countries

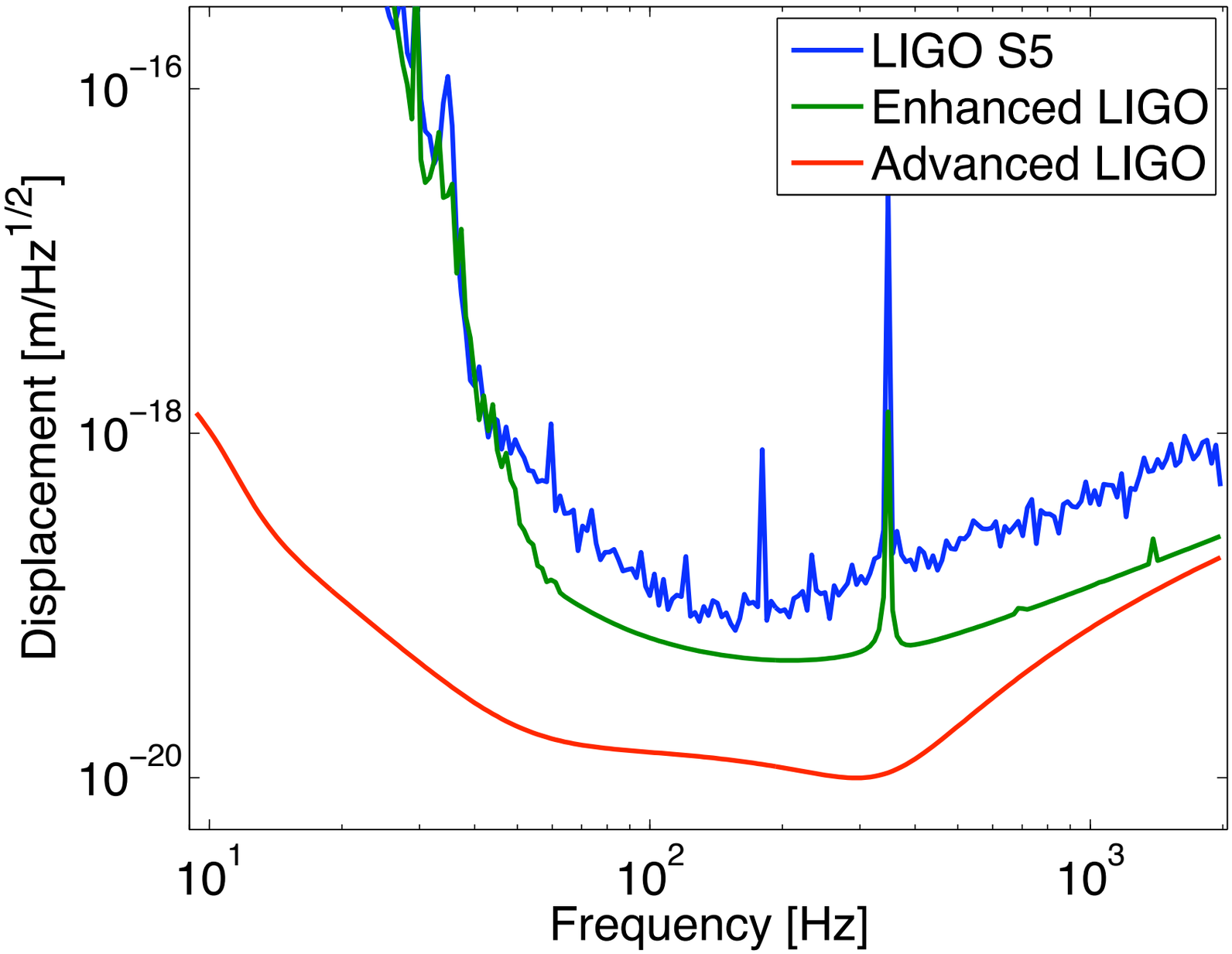
Outline

GW Detectors

Initial LIGO

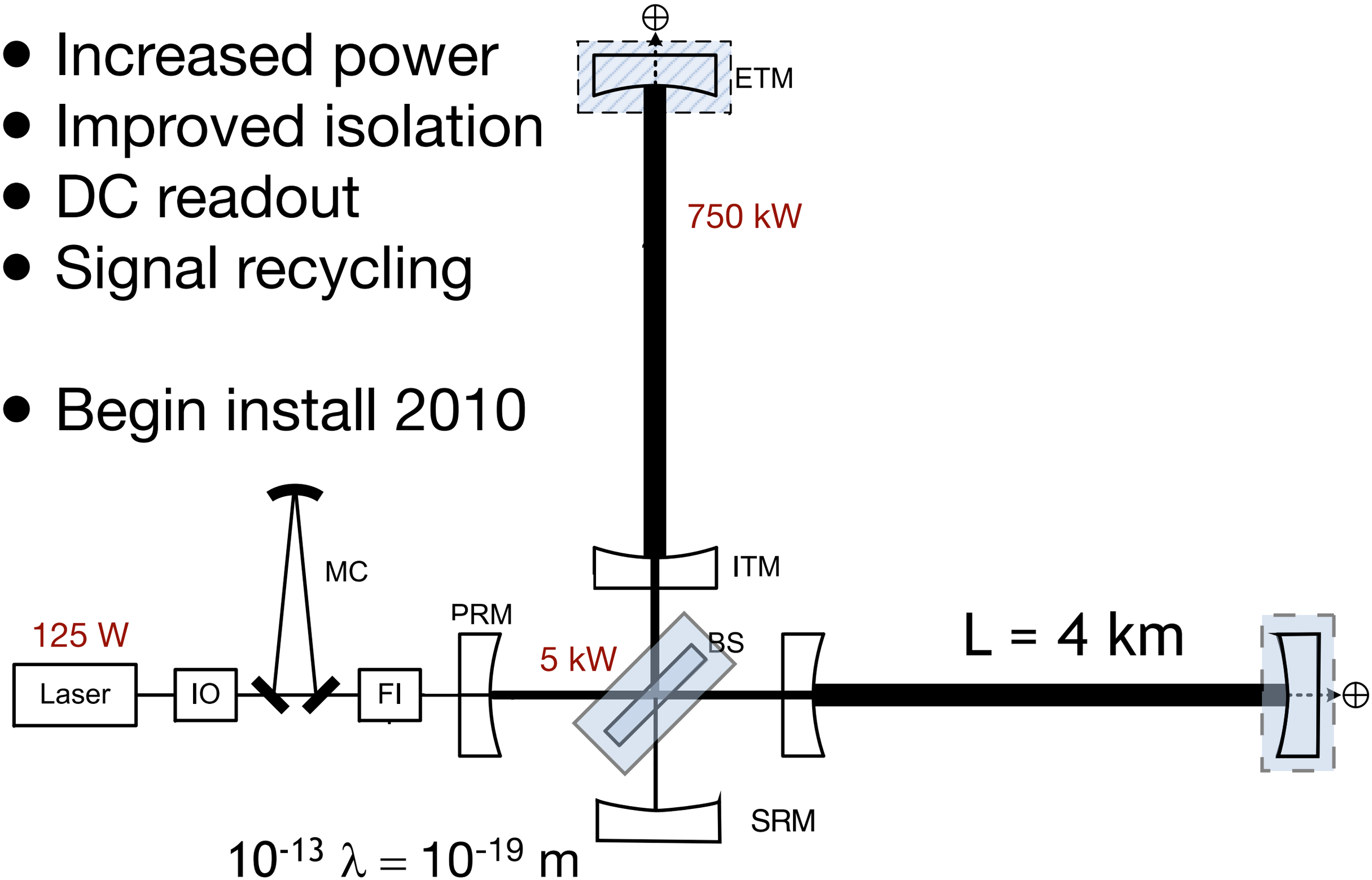
GW Astrophysics

Advanced LIGO



Advanced LIGO

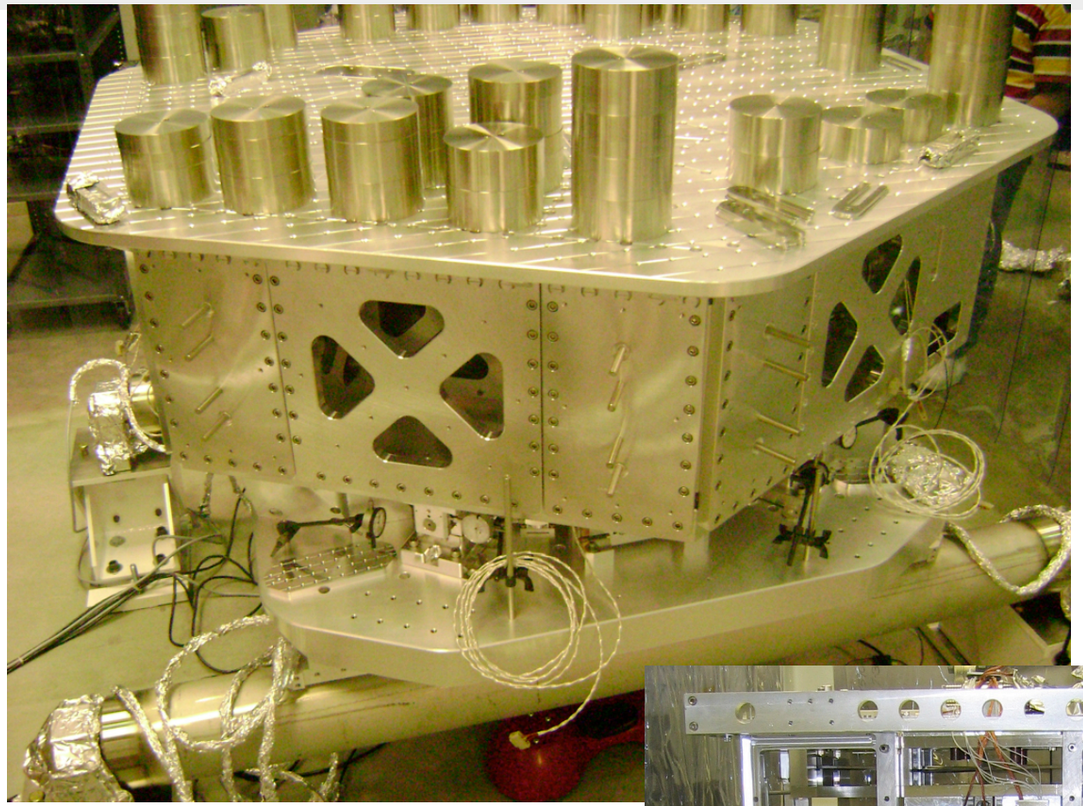
- Increased power
- Improved isolation
- DC readout
- Signal recycling



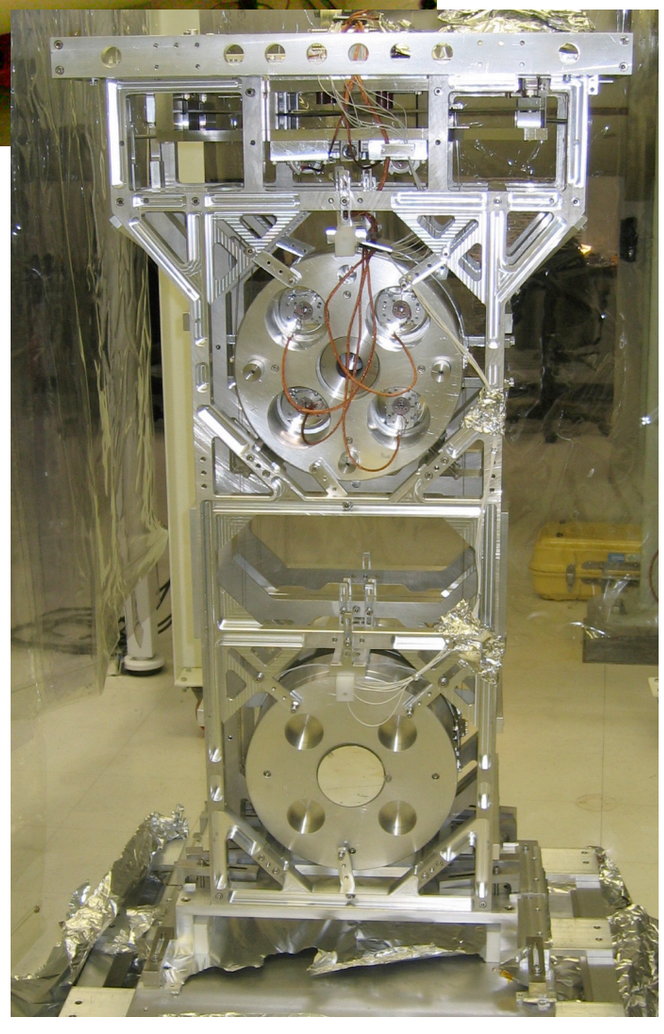
- Begin install 2010

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

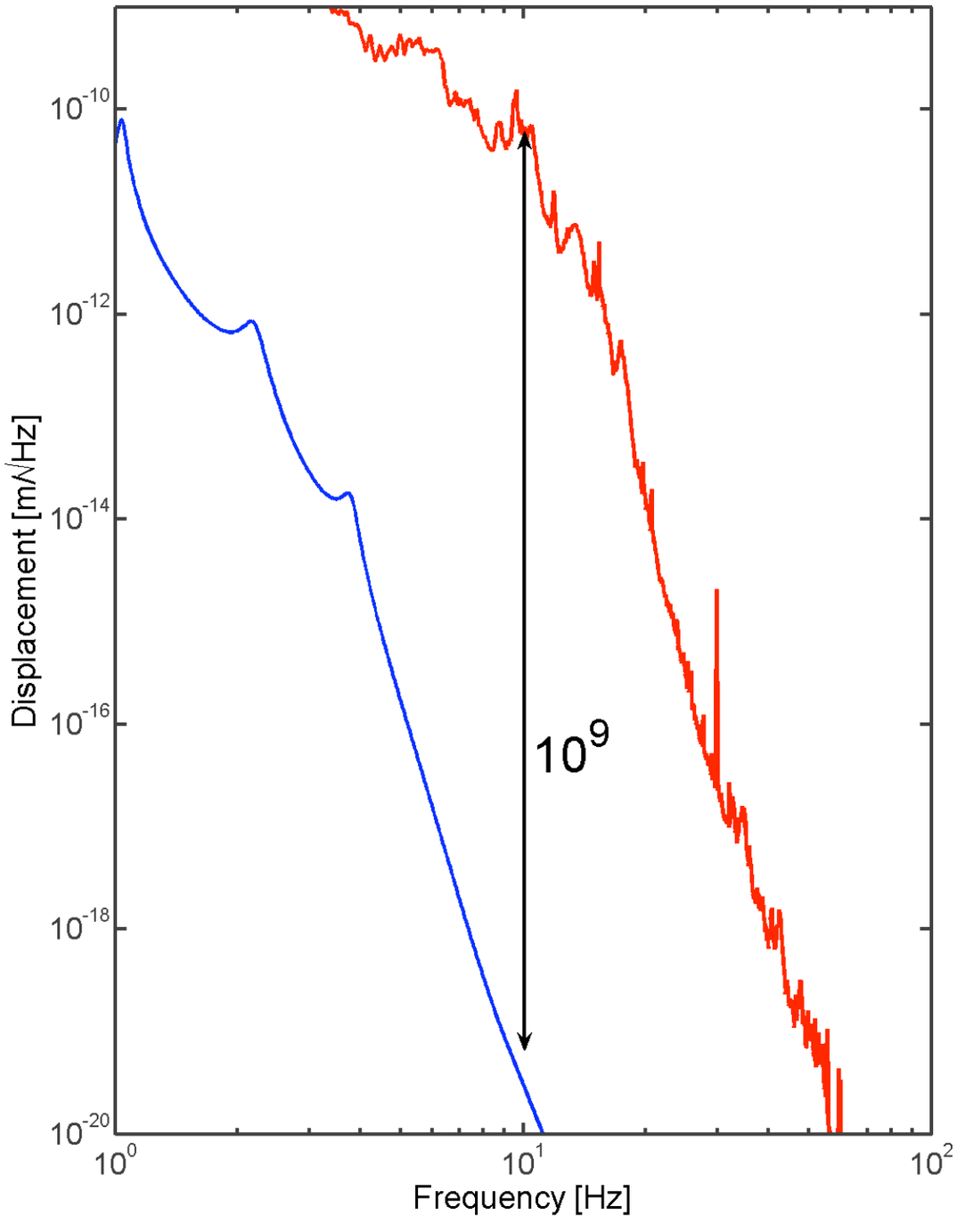
Active isolation



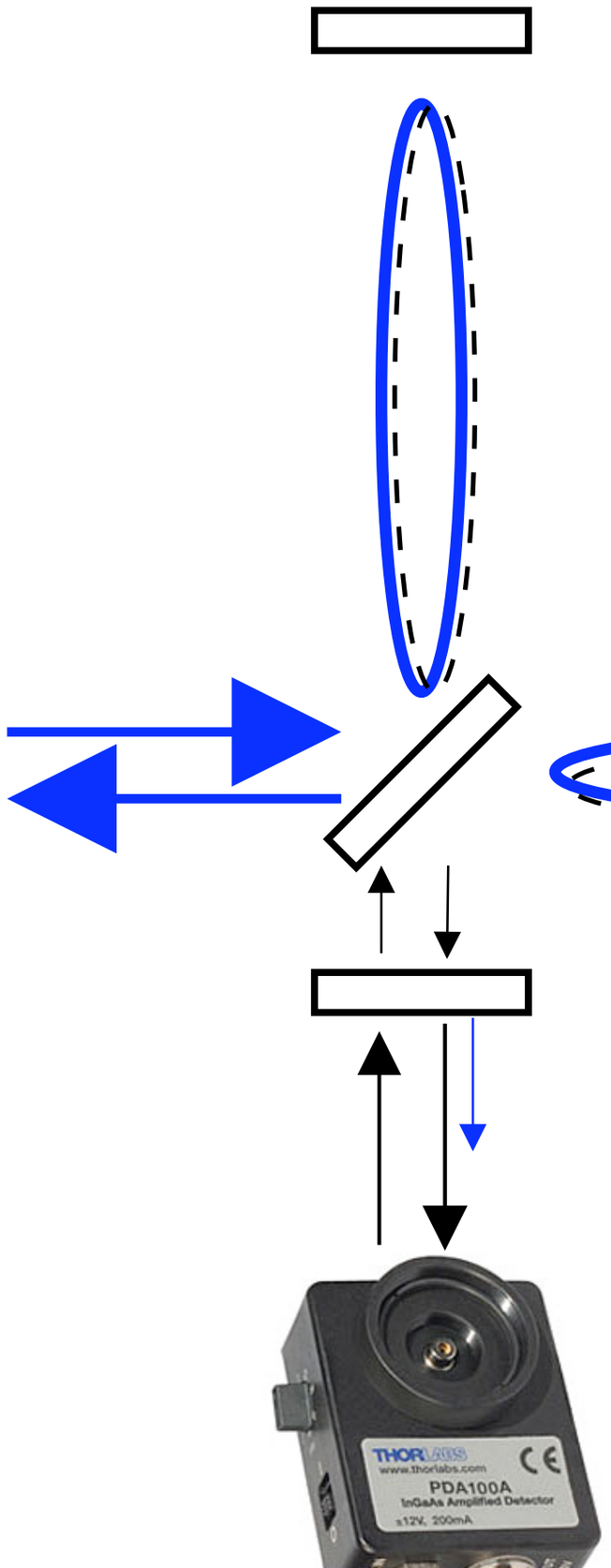
HAM ISI at Livingston
Feb. 20, 2008
Stanford Ginzton Group



Quad + SEI



Quantum Noise



"Root N" photon counting statistics does not give correct answer for SRM interferometers

SRM allows "tuning" of the noise

$$\delta x \neq \sqrt{\frac{1}{N_{photons}}} \neq \sqrt{\frac{1}{P_{BS}}}$$

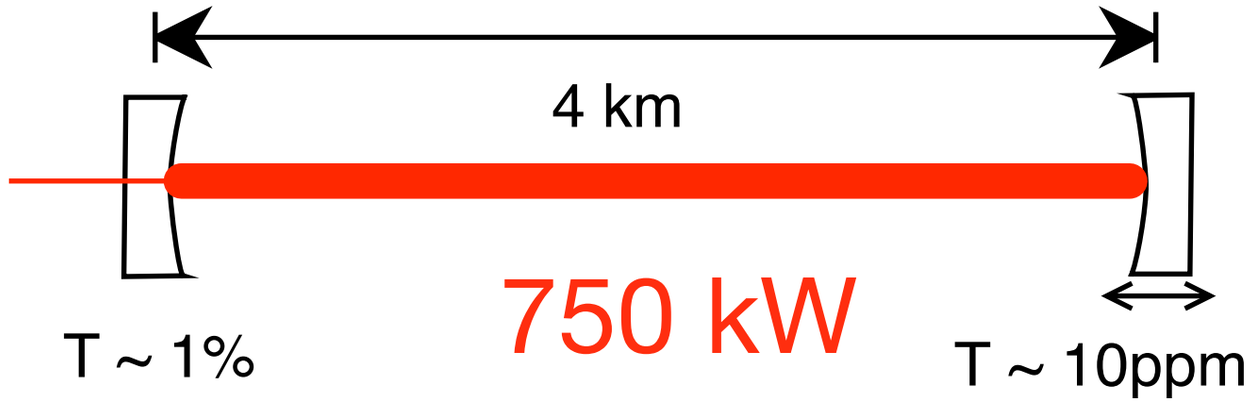
CM Caves, PRD23, 1981

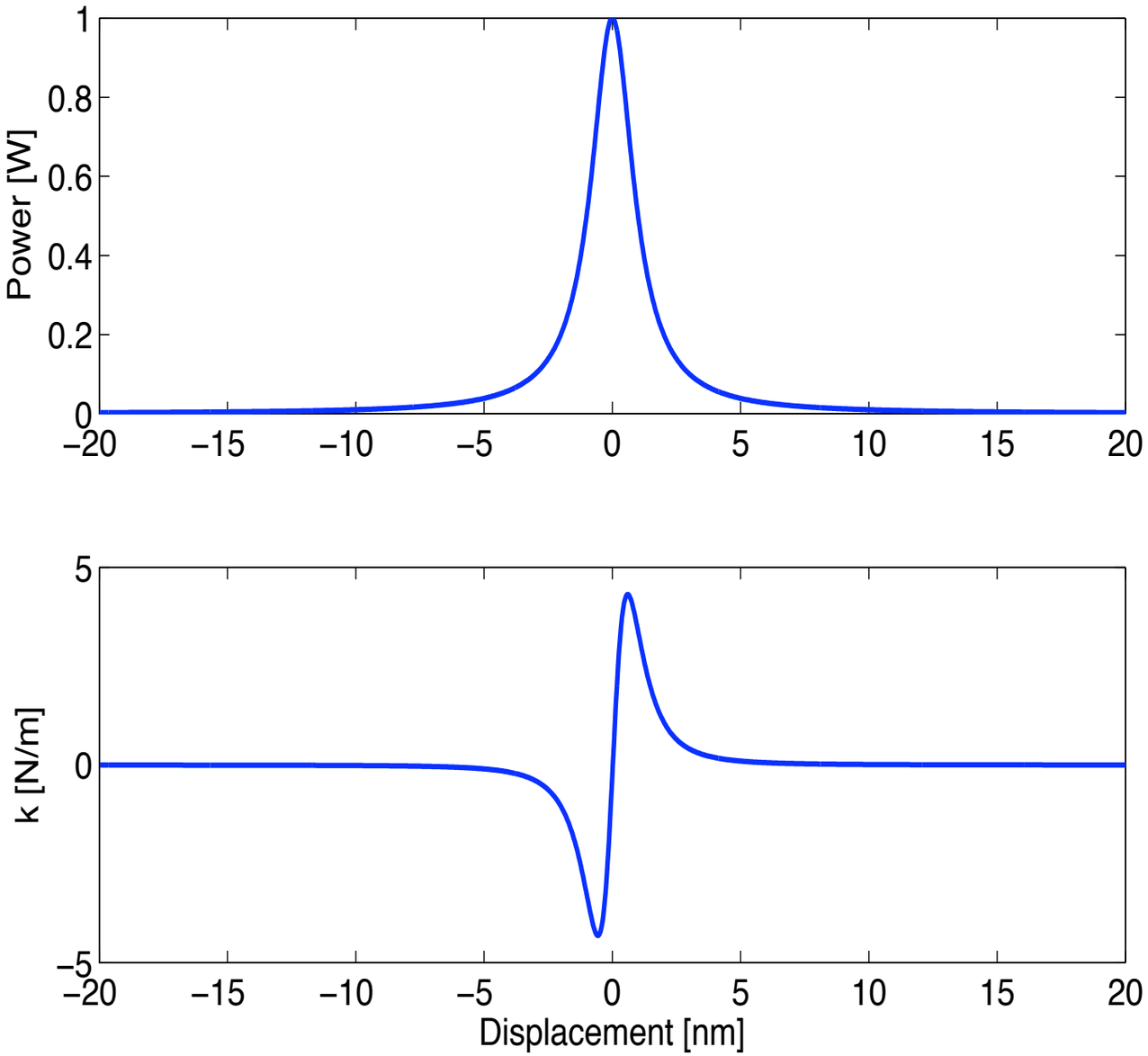
Optical spring

Waldman
Stanford '08

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

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





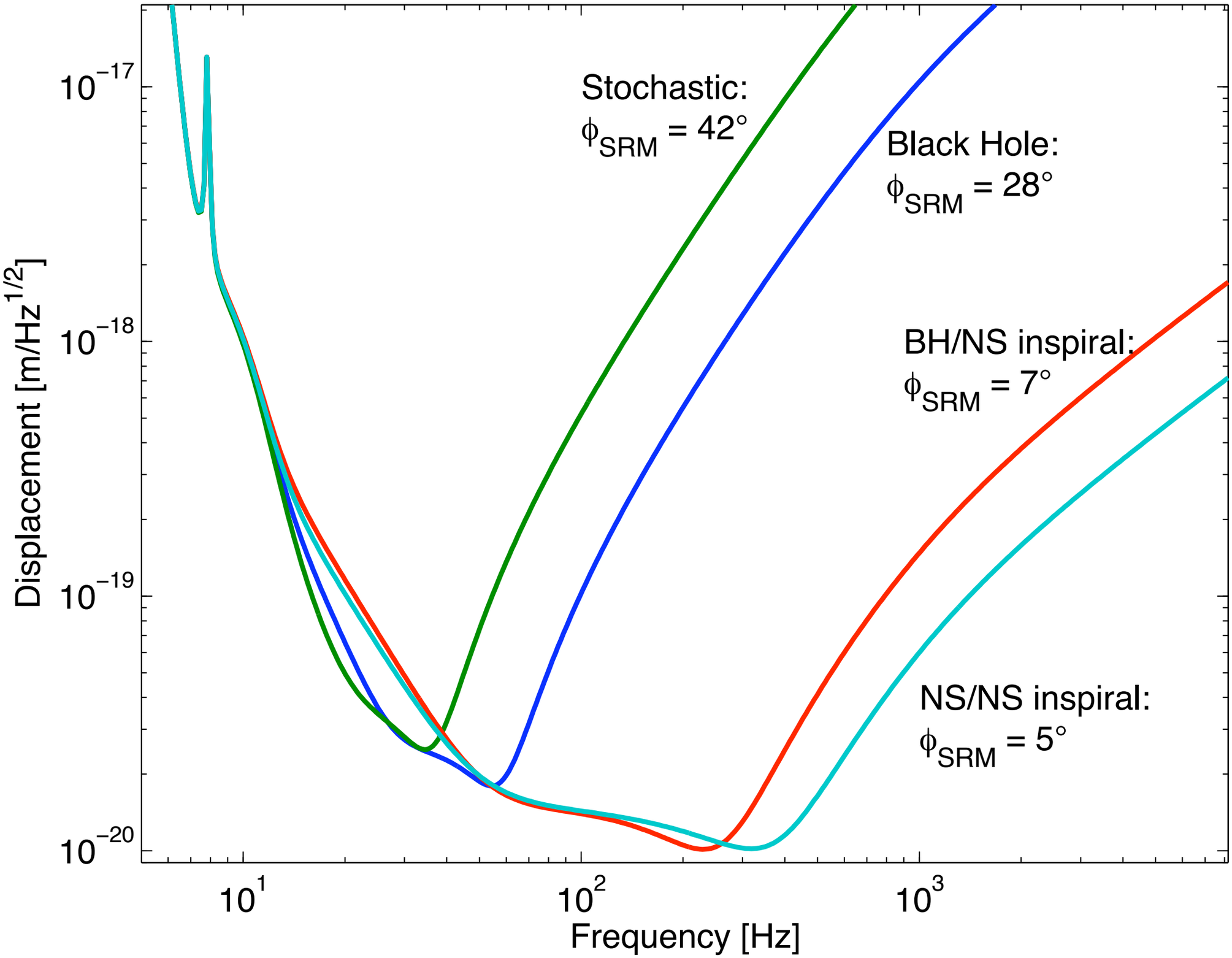
750 kW buildup
10 pm offset
Finesse = 500

$k = 10^5$ N/m

$\omega = 50$ Hz

Tailor made response

Waldman
Stanford '08

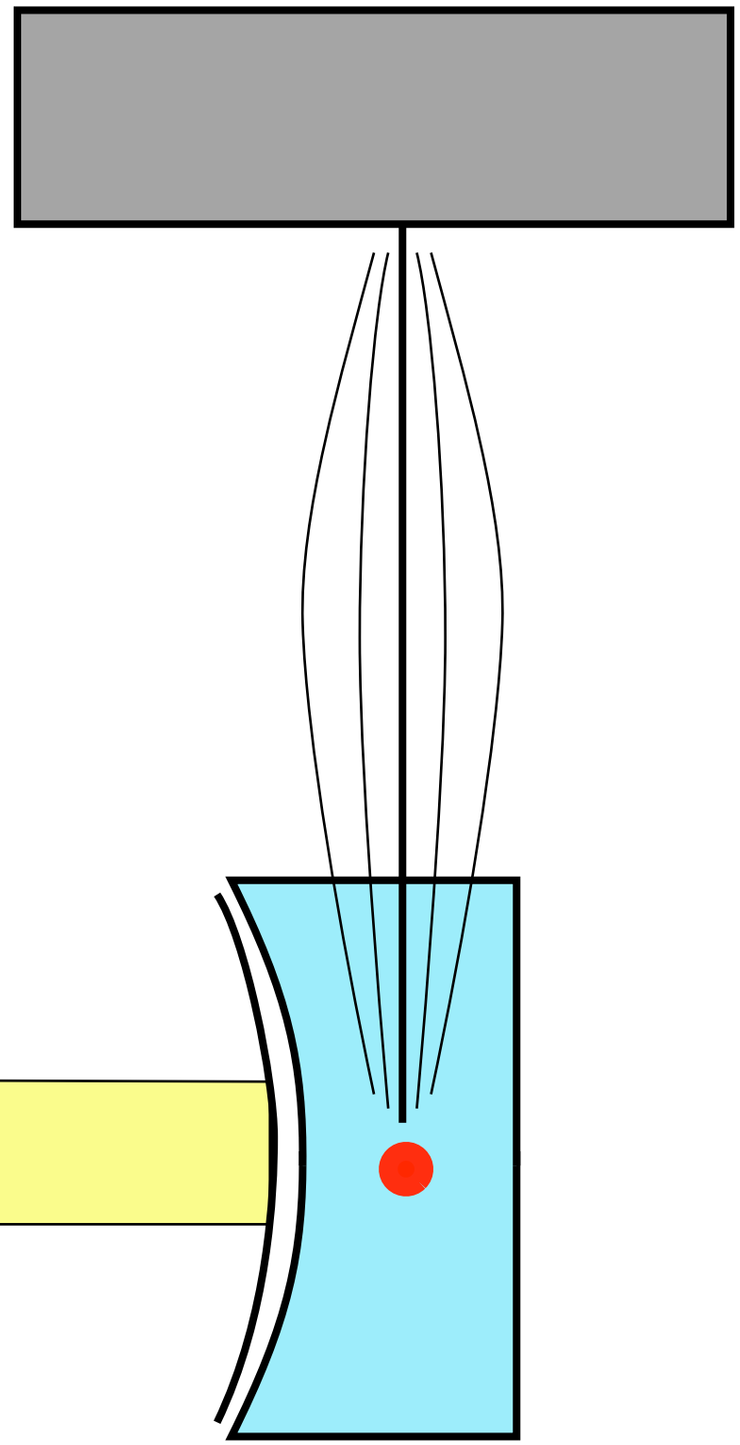


Heisenberg microscope

Waldman
Stanford '08

"Light enforced quantum uncertainty"

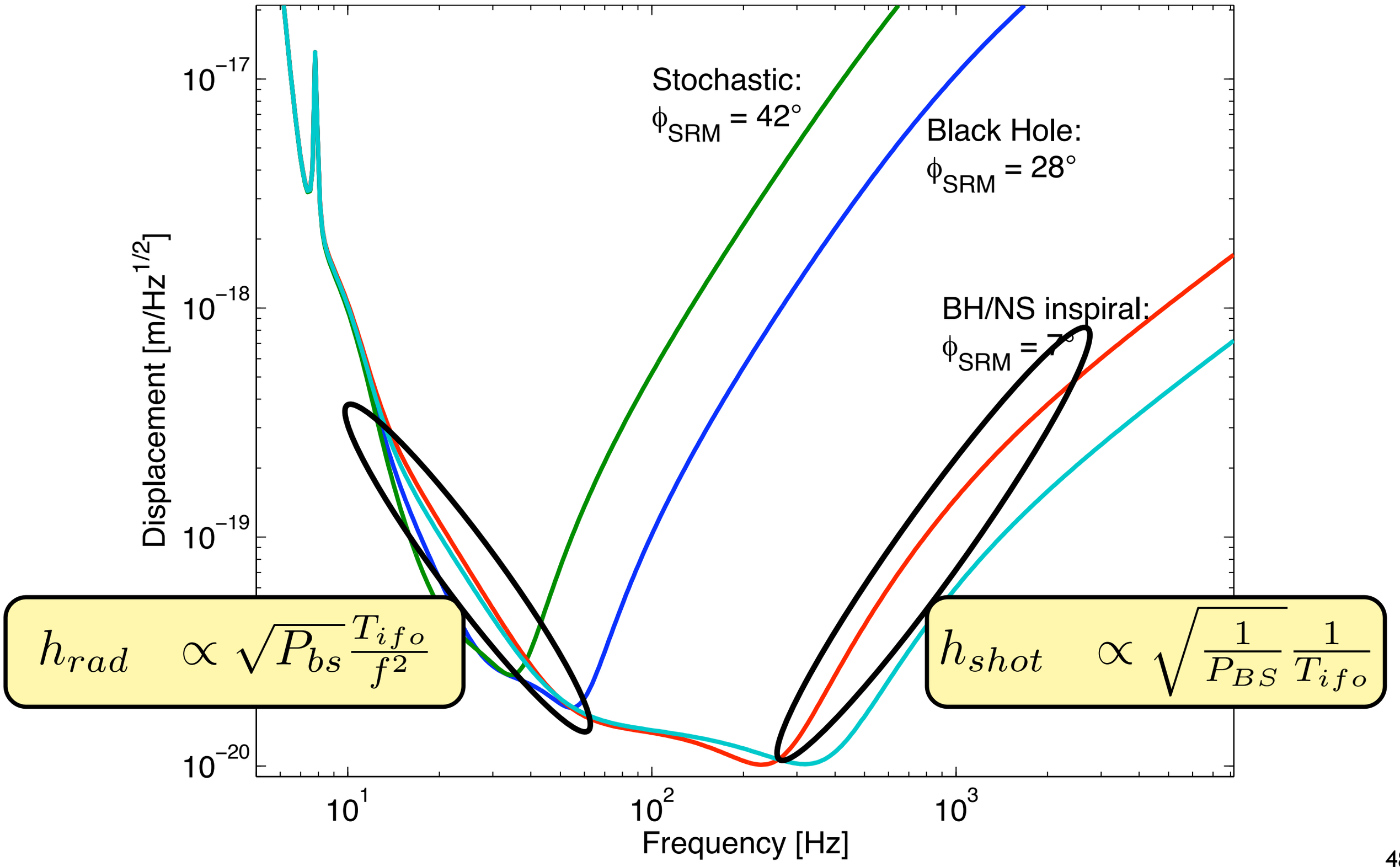
$$\delta x \geq \sqrt{\frac{\hbar}{2M\omega}}$$



Laser readout of the test mass position changes the test mass position

Macroscopic Quantum

Waldman
Stanford '08



aLIGO Sensitivity

Waldman
Stanford '08

1.4 x 1.4 M_{sun}
NS/NS inspiral

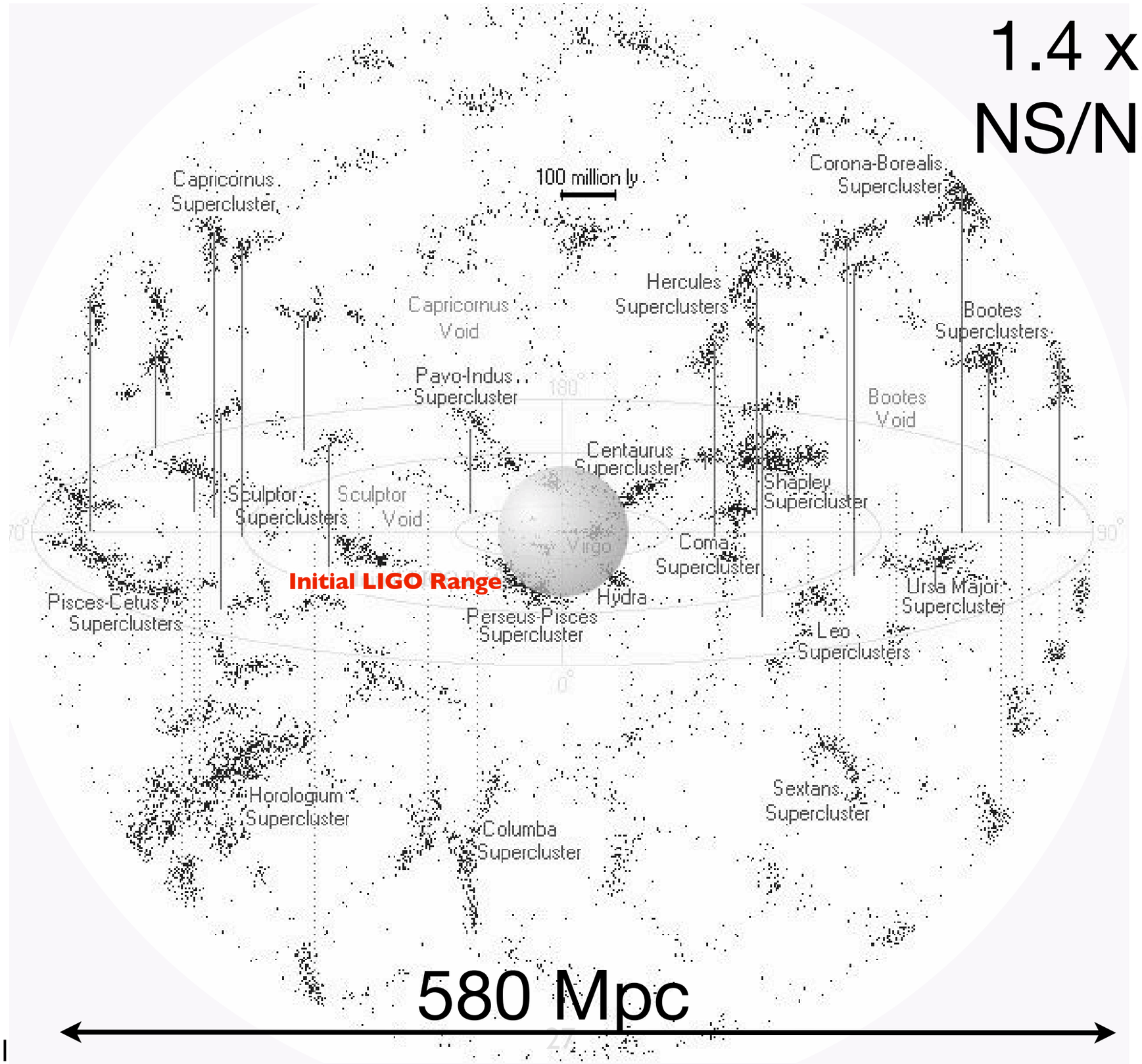
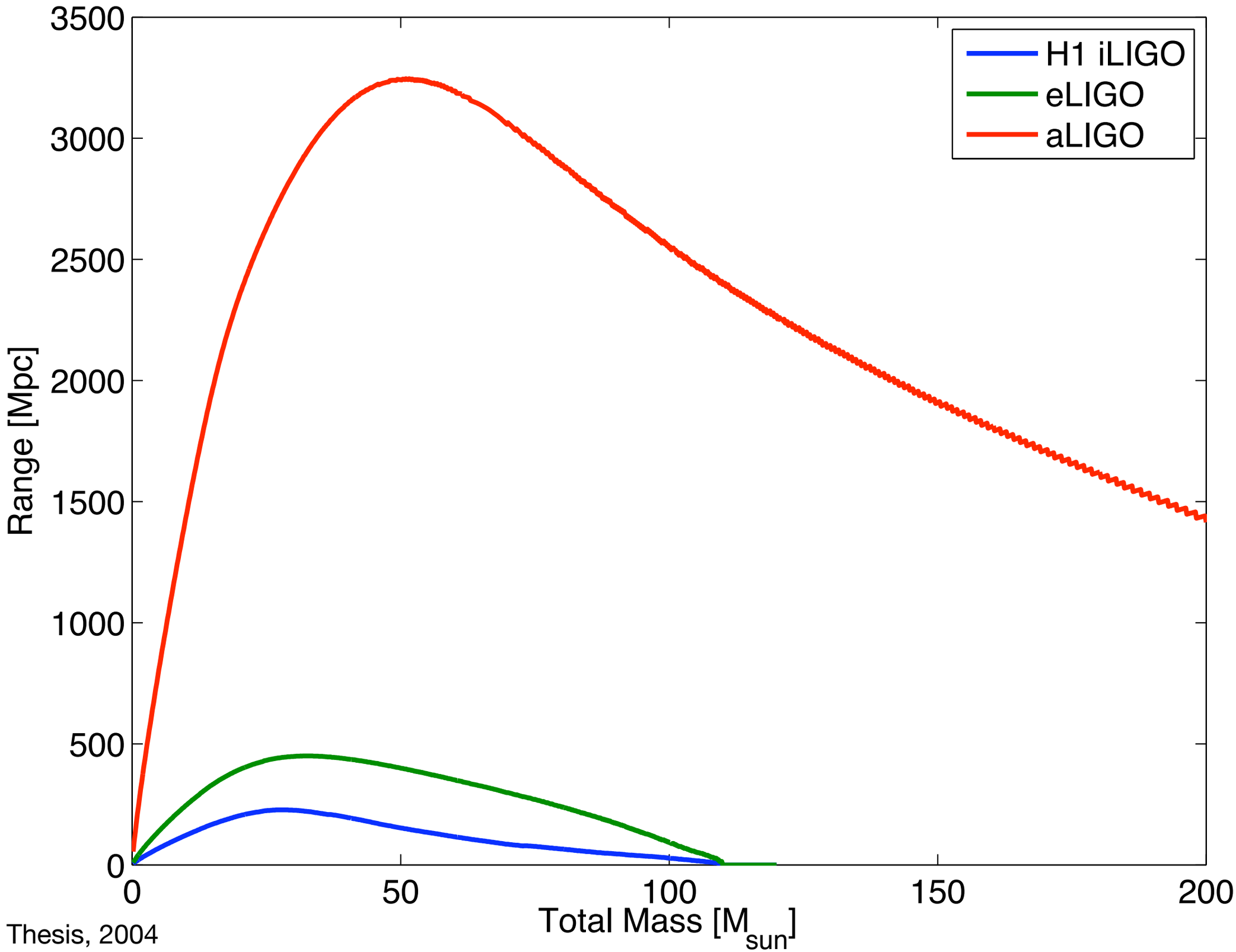


Image: R Powell

aLIGO inspiral range

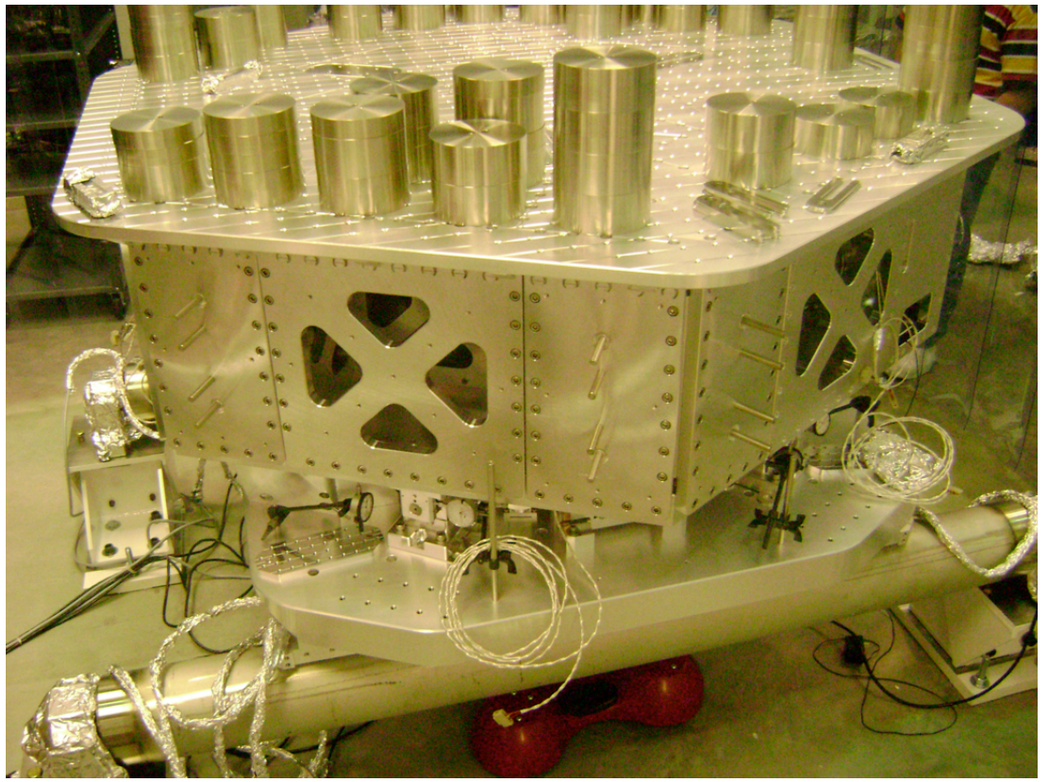
Waldman
Stanford '08



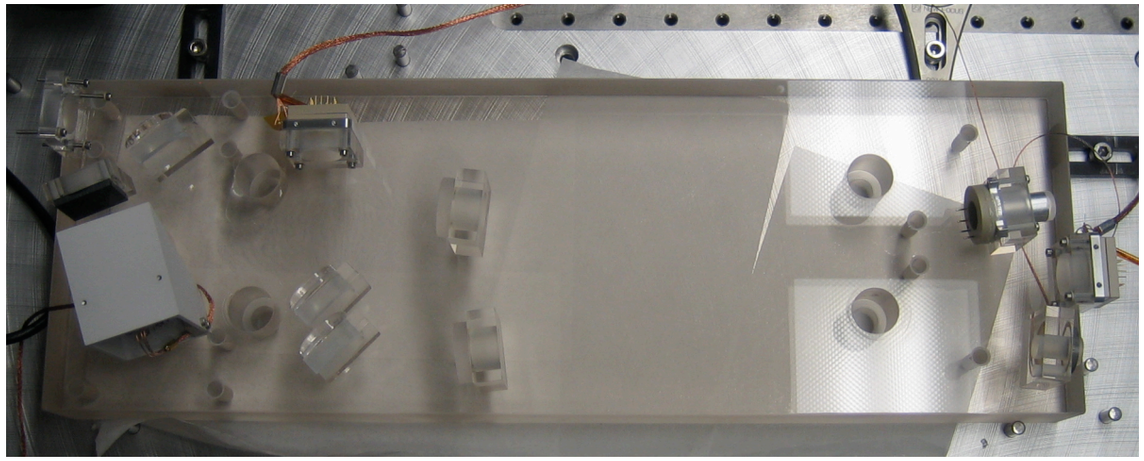
D. Brown Thesis, 2004

aLIGO prototype

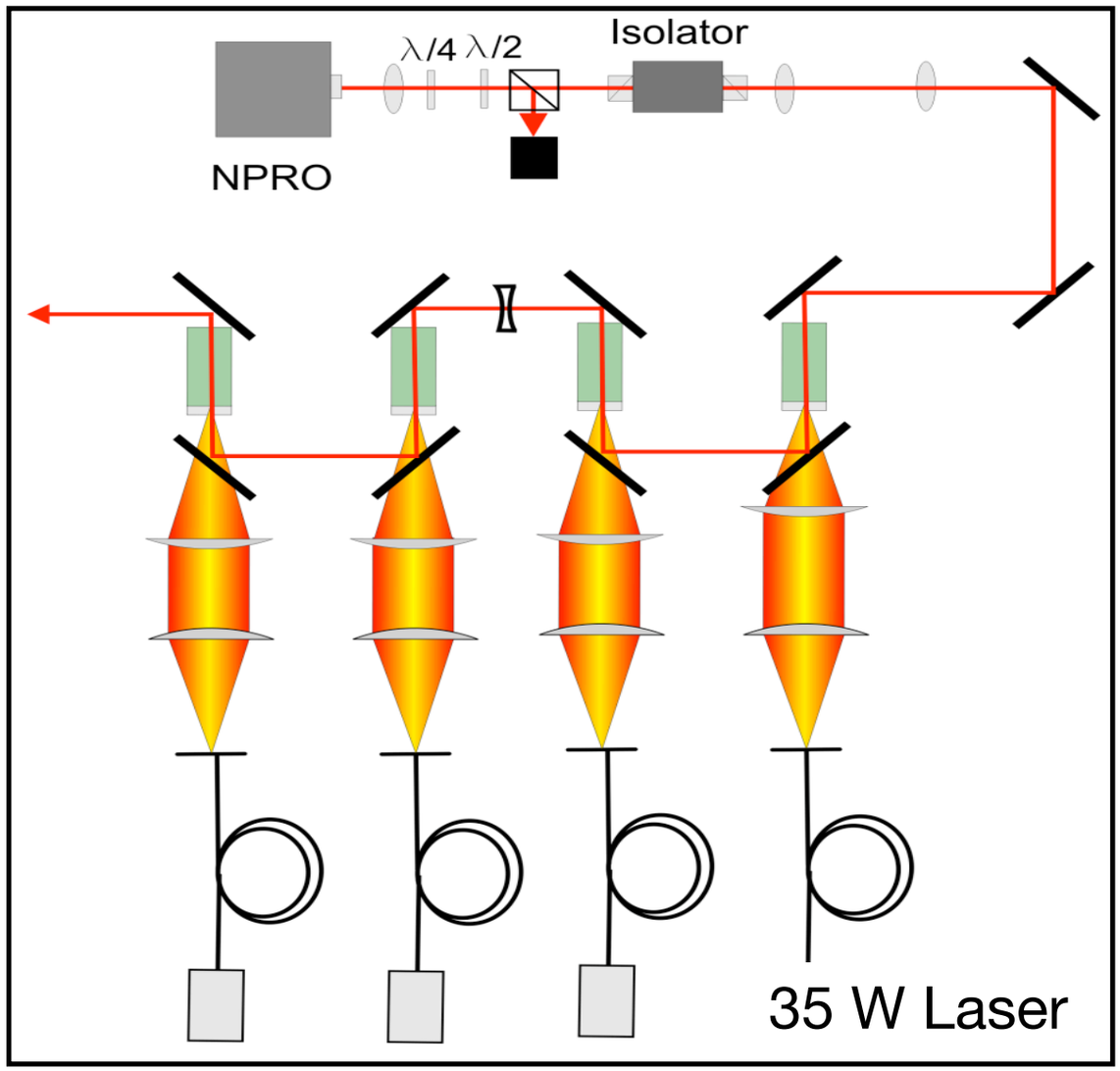
Waldman
Stanford '08



HAM ISI



DC Readout



- eLIGO validates key aLIGO technologies
- Factor of ~2x in sensitivity
- Factor of ~10x in rate

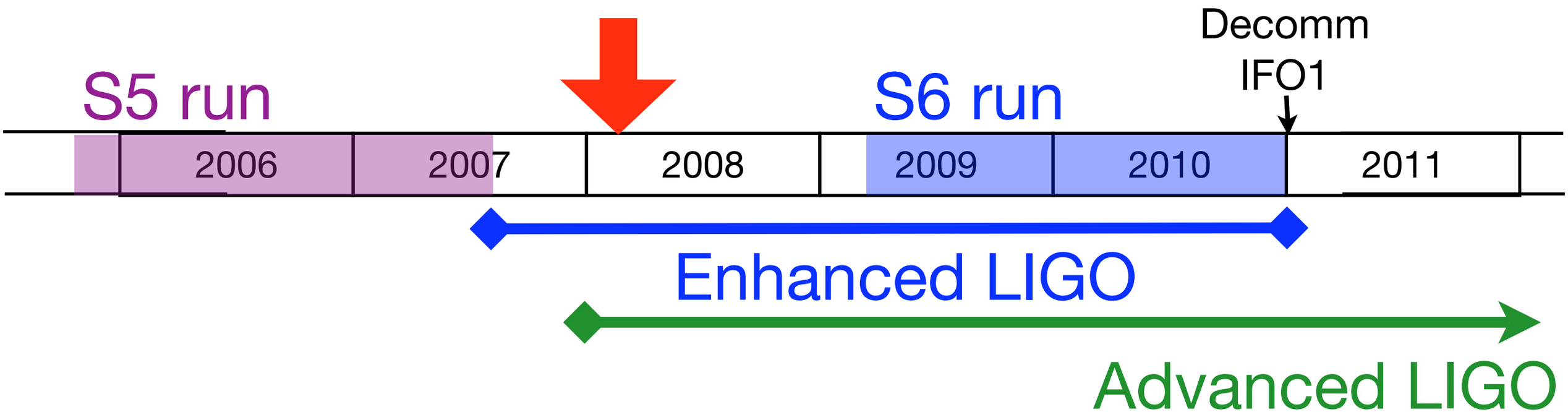
Future of LIGO

Enhanced LIGO upgrades underway for 2x sensitivity improvement

Advanced LIGO start in mid-2008

First IFO decommissioned in 2010

First aLIGO interferometry ~2012



LIGO Range

Waldman
Stanford '08

1.4 x 1.4 M_{sun}
NS/NS inspiral

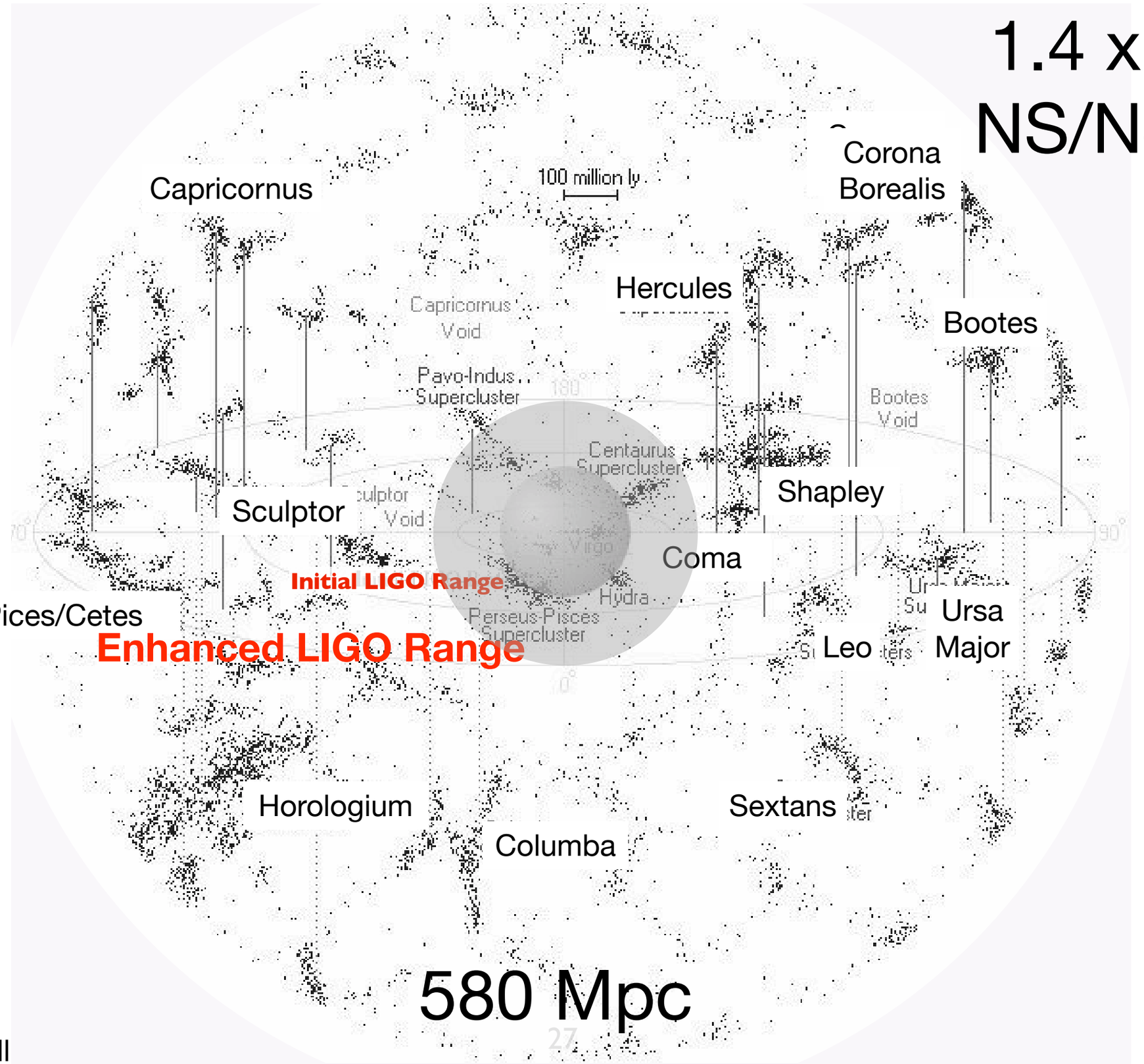


Image: R Powell