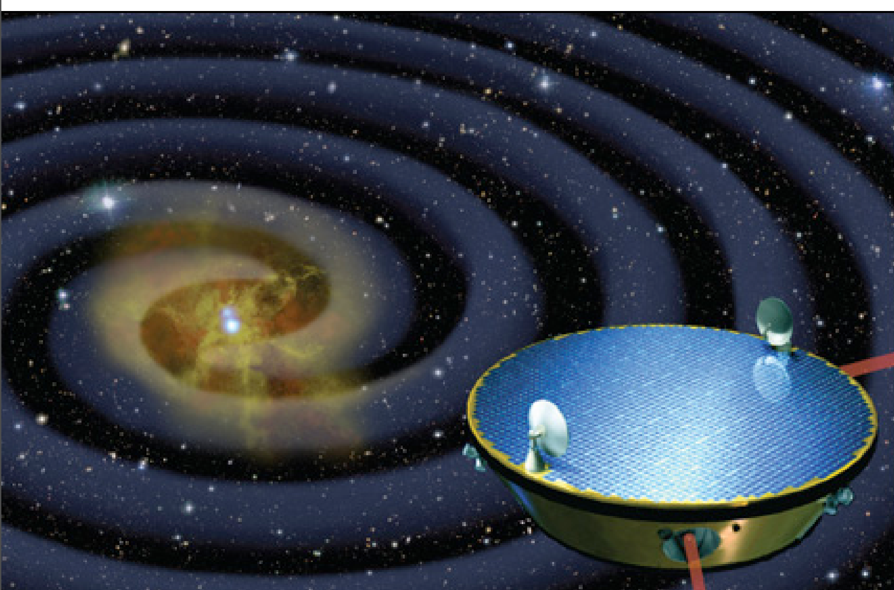
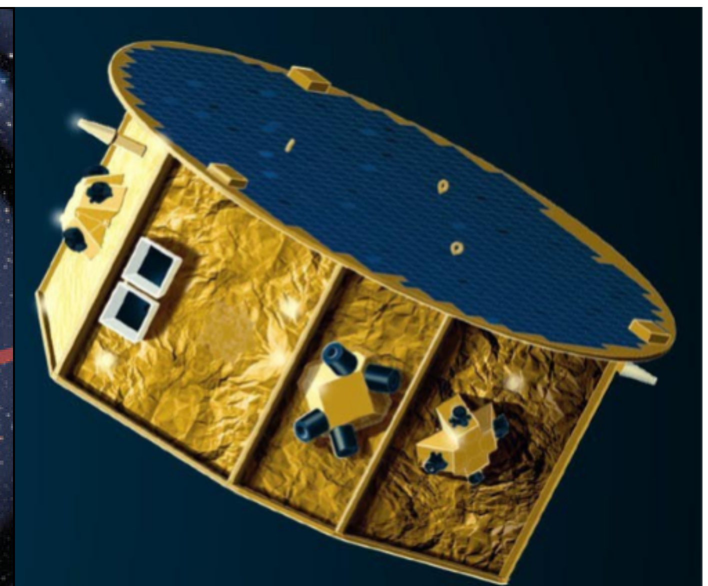
Attometer Astrophysics
News of Gravitational Wave Detectors

Sam Waldman
June 25, 2009
Recontres de Blois



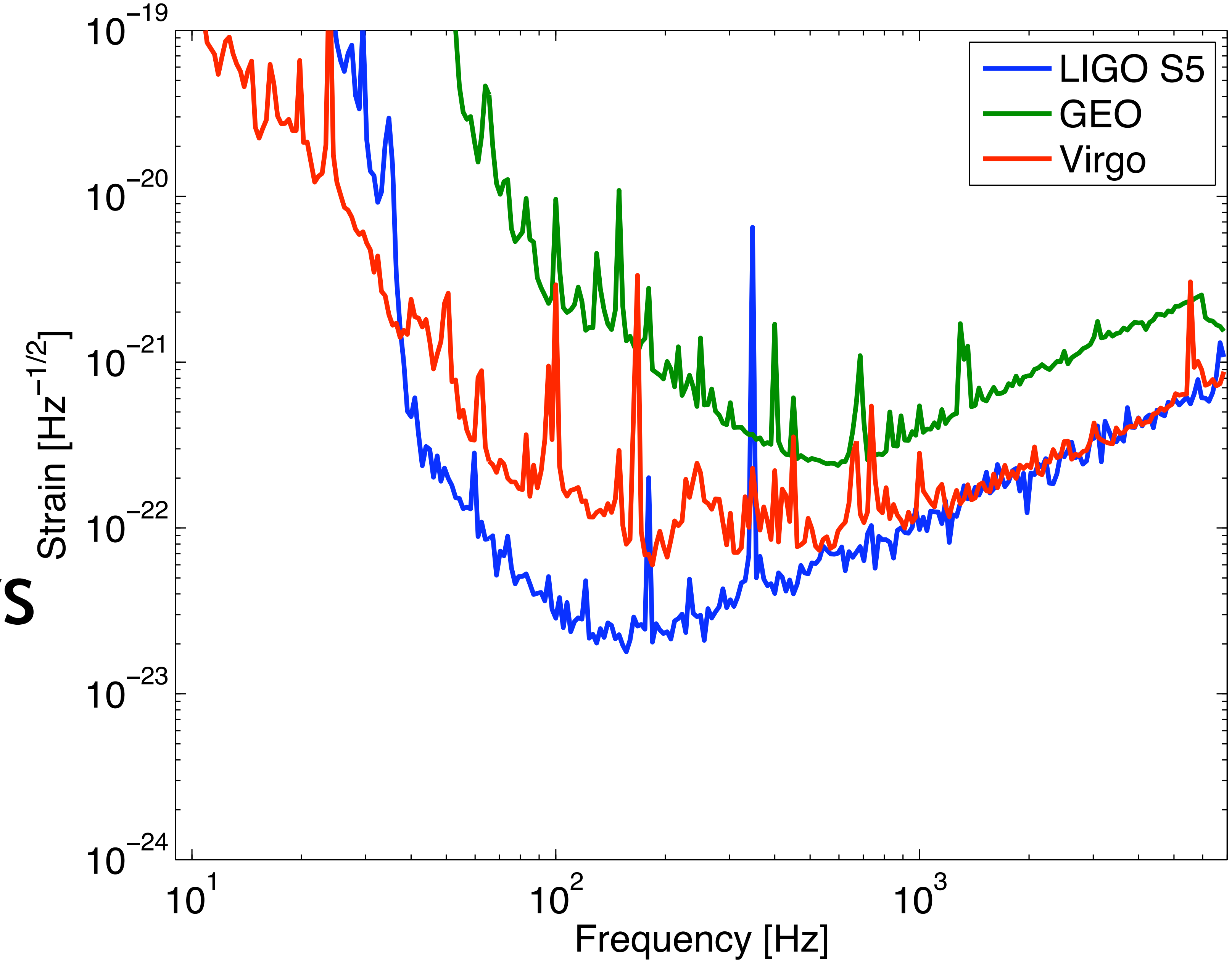
- GW astronomy sensitive to new phenomena in pulsars, GRBs, supernovae, and general relativity
- Kilometer scale interferometers have demonstrated NS/NS sensitivity to Virgo cluster with 1 year of data
- Upgraded instruments ~factor 2 improvement starting July '09

- **Advanced Detectors on schedule for science in 2013 at 10x NS/NS sensitivity**

GW astrophysics

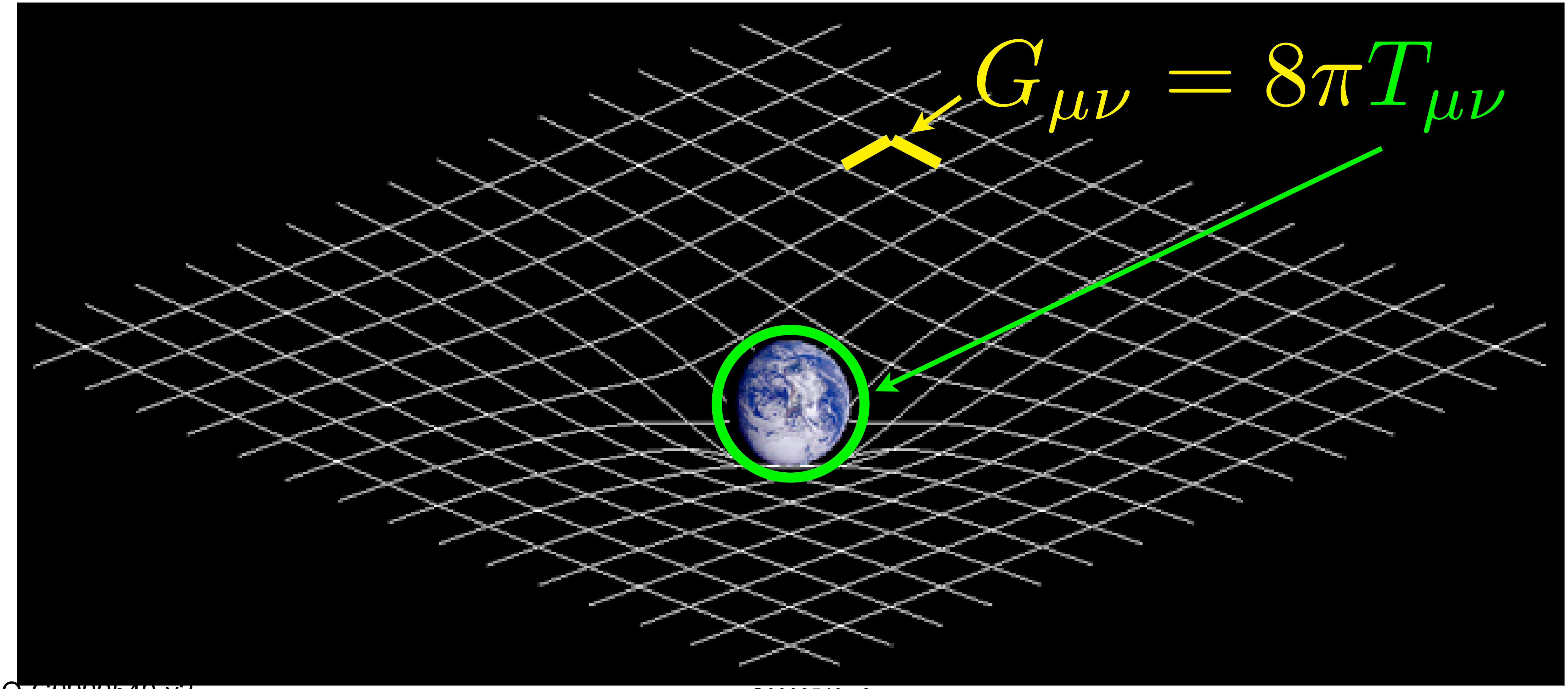
GW detectors

Advanced detectors



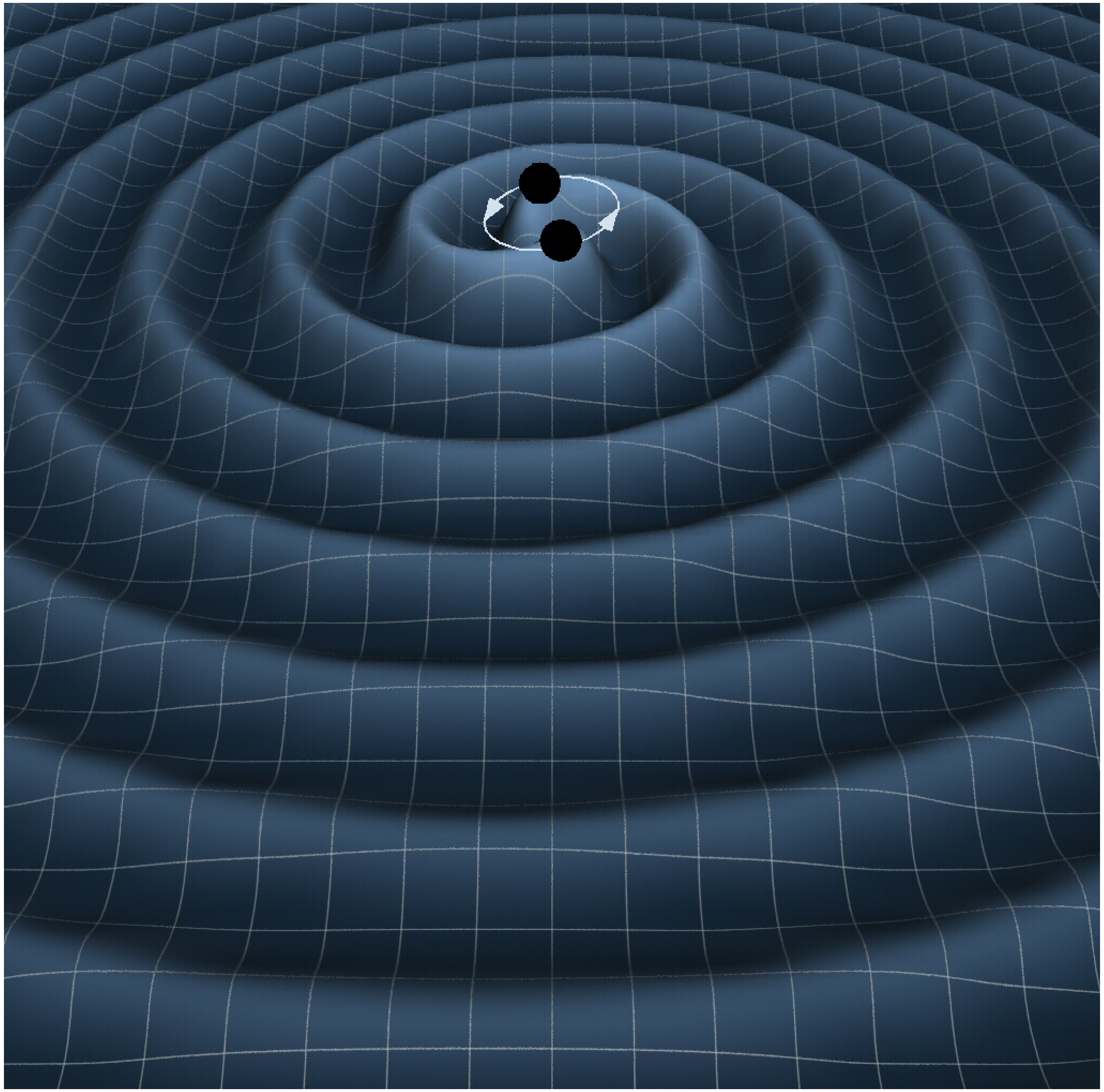
GR is curvature

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



Ripples in Space Time

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



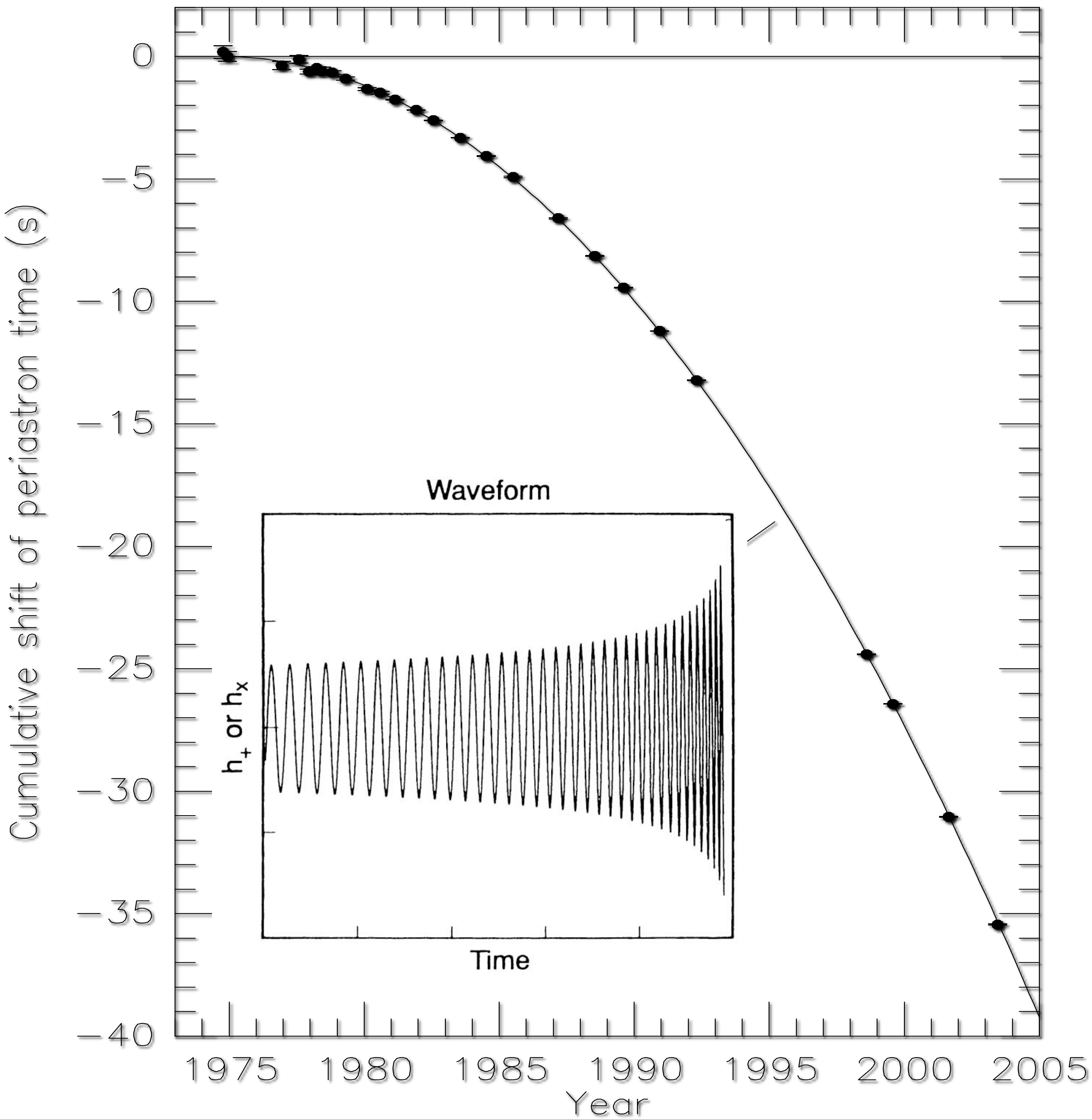
two polarizations for $h_{\mu\nu}$ propagate at c

$|h| = \delta L / L$

peak binary inspiral luminosity = c^5/G

= 10^{52} W

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

Matches GR 3mm/orbit

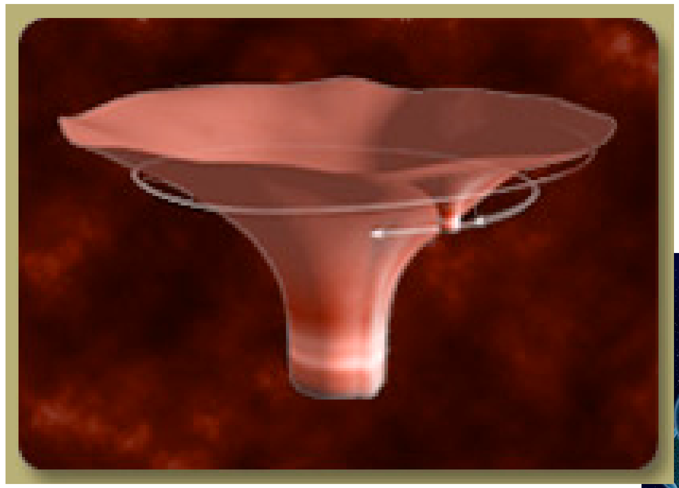
$dx/x \sim 1.5 \times 10^{-23}$

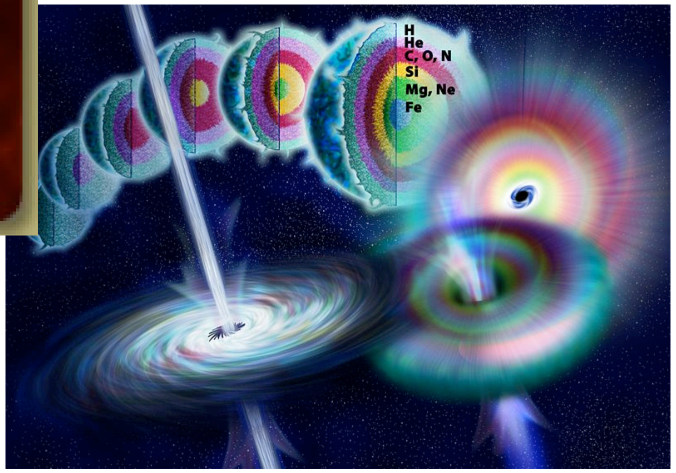
10^{-4} inspirals / MW yr

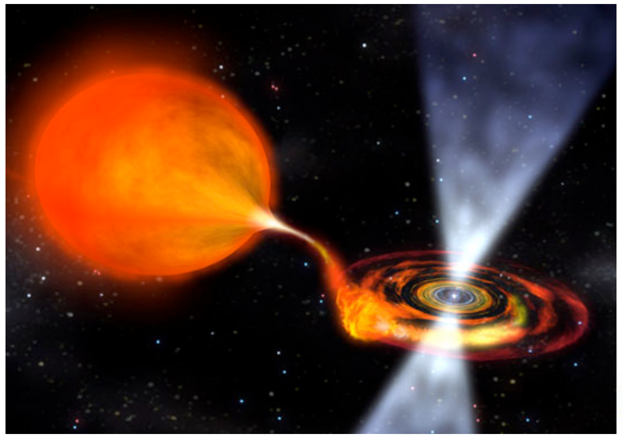
Einstein's messengers

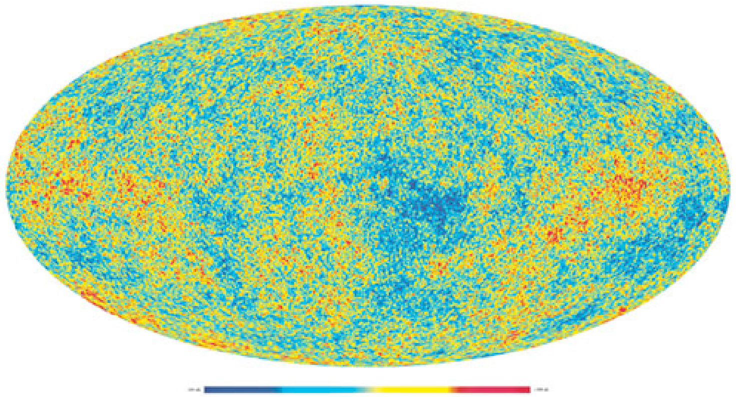
Gravitational waves propagate without absorption or dispersion through normal matter

- Core collapse supernova
- Standard candle
- Inflation era stochastic background
- Neutron star Equation of State
- No-hair theorem
- ...

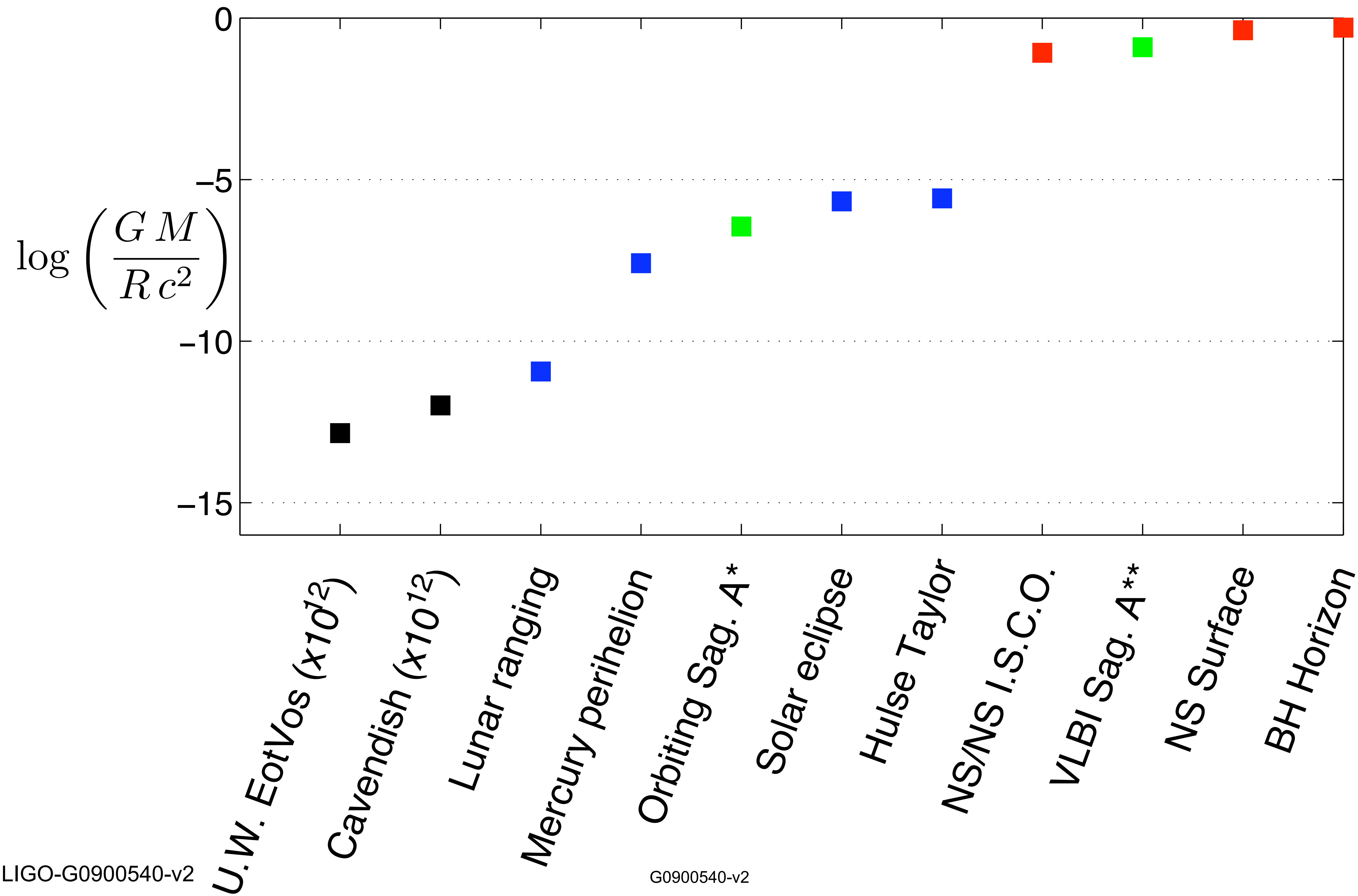








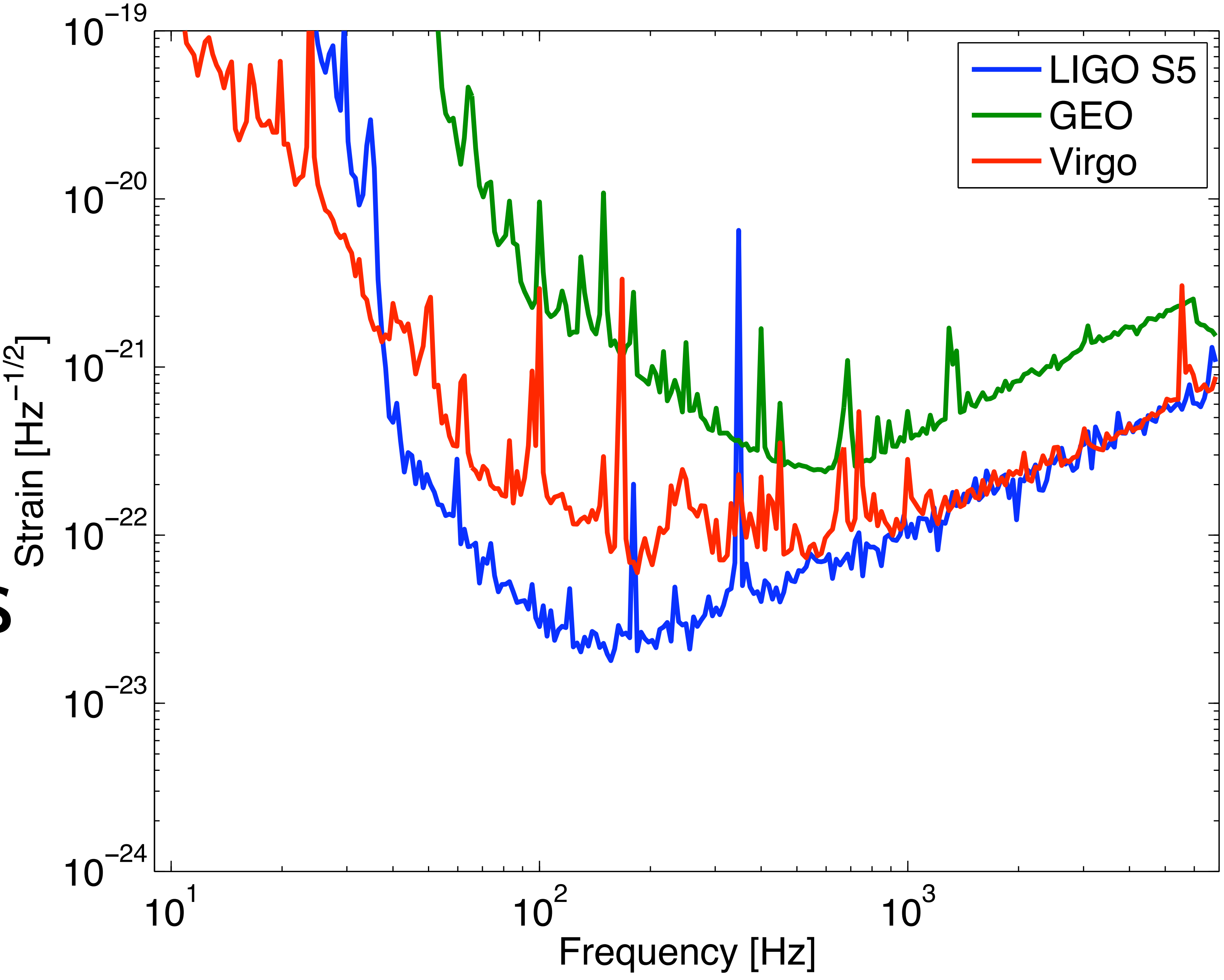
Probe GR physics



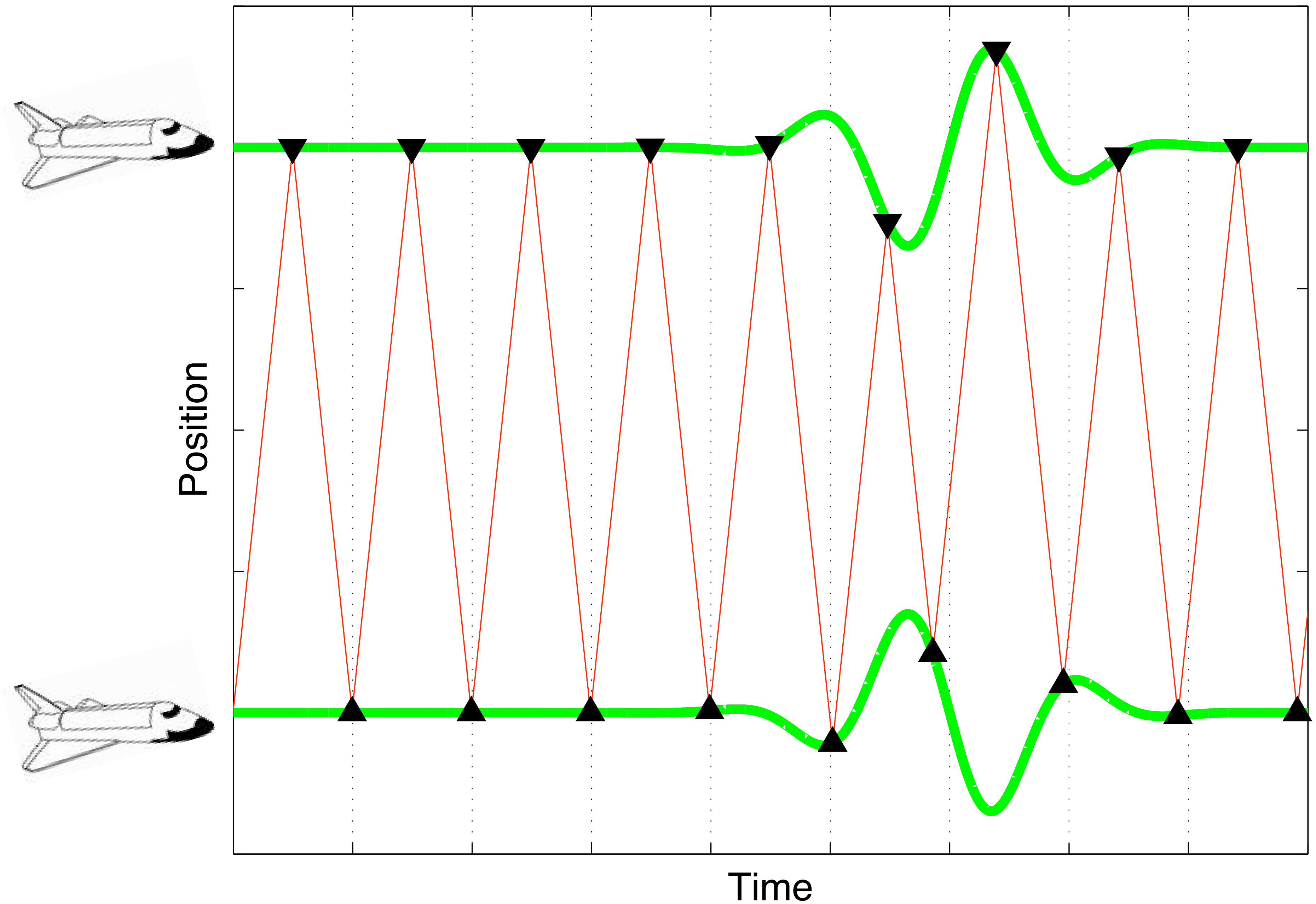
GW astrophysics

GW detectors

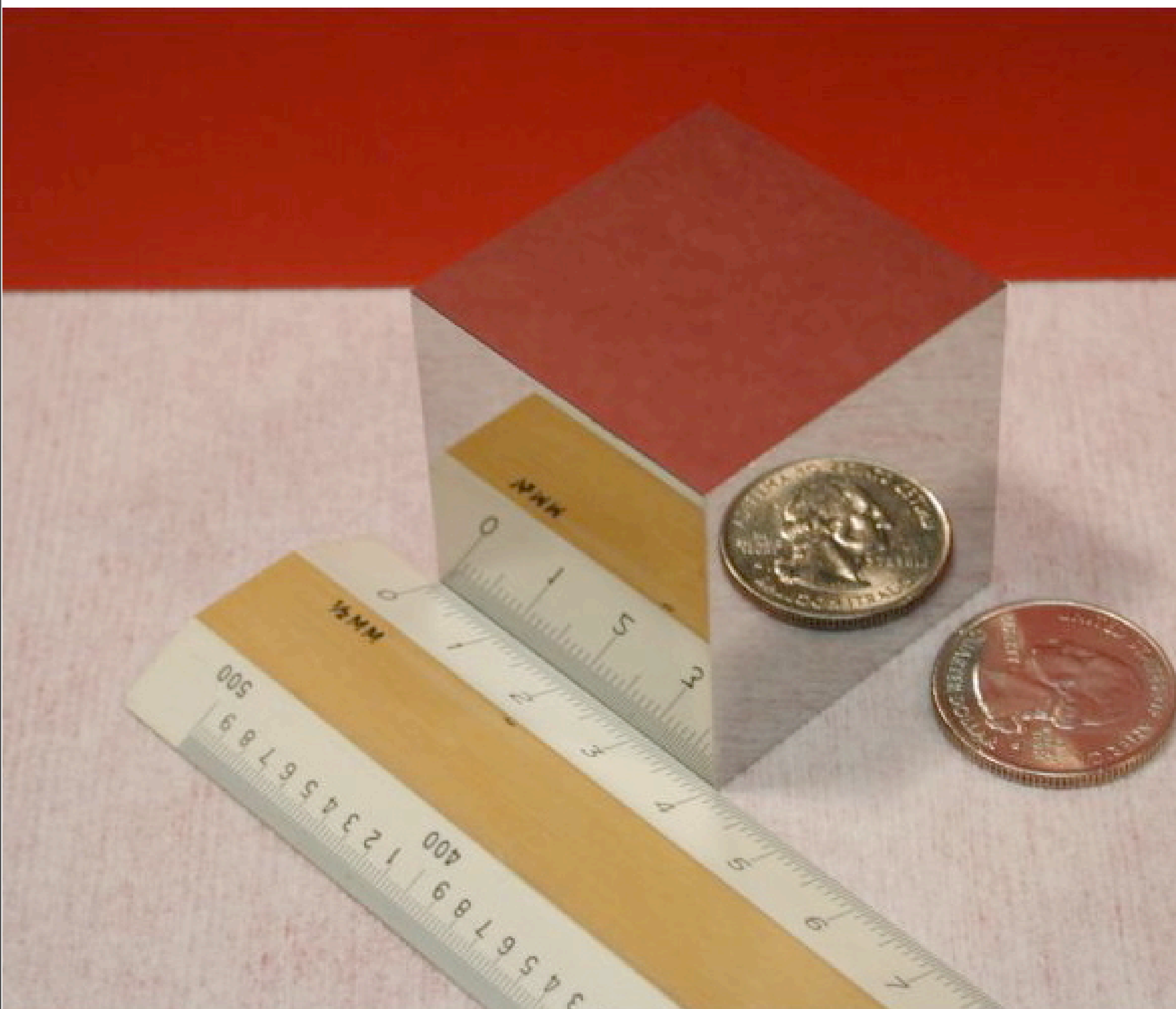
Advanced detectors

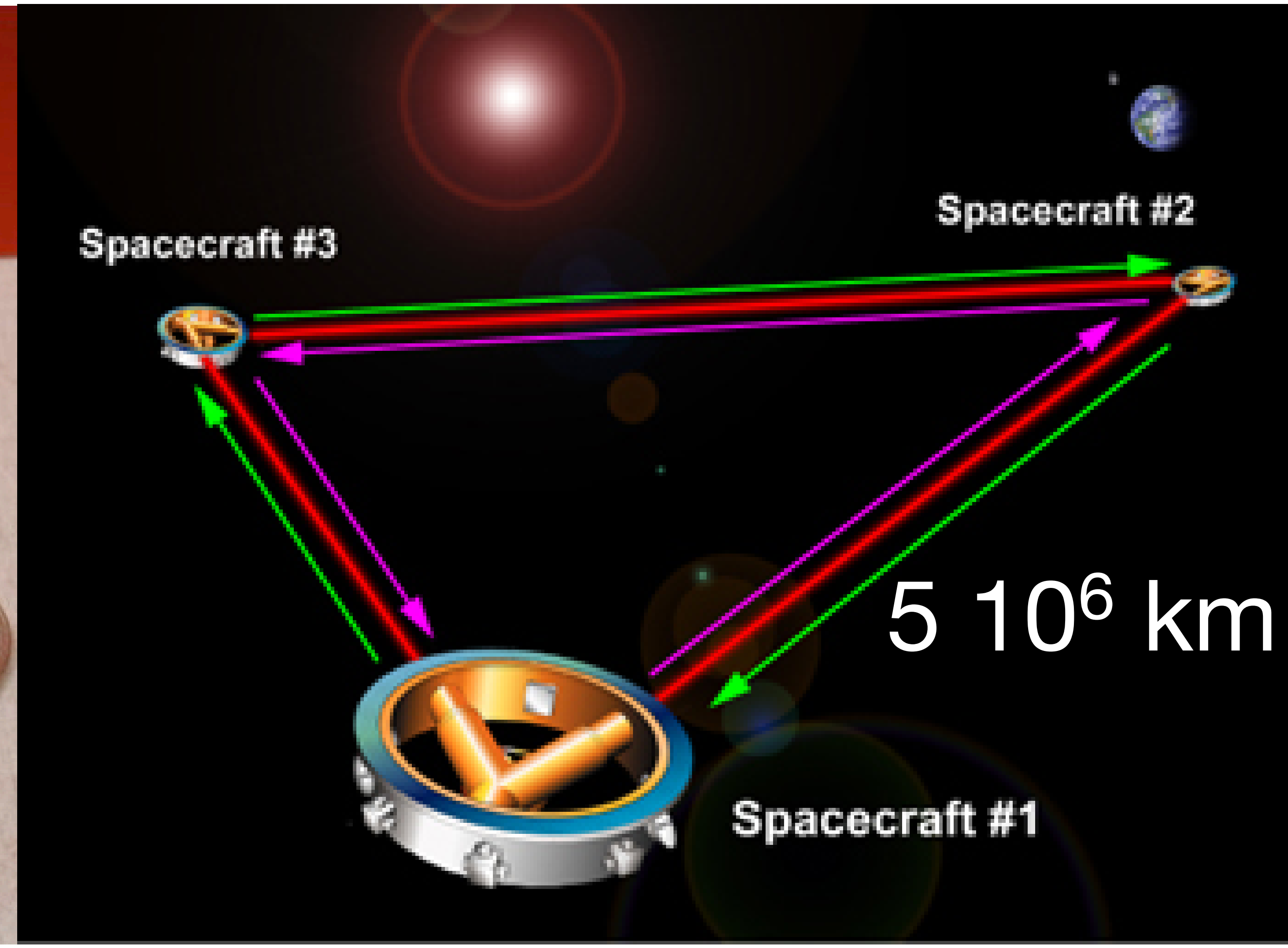


Detecting GWs



LISA

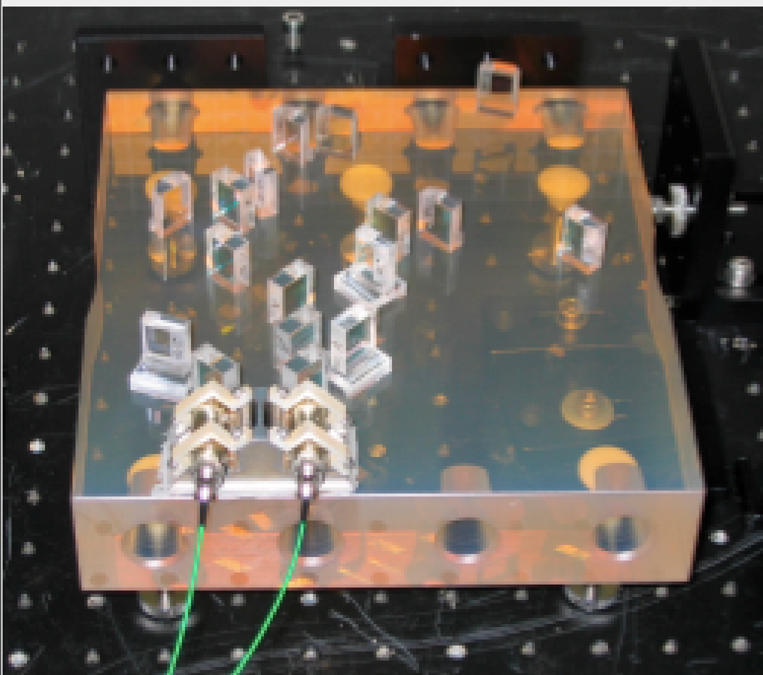




"LISA promises to open a completely new window into the heart of the most energetic processes in the universe, with consequences fundamental to both physics and astronomy." -National Academy

Waldman
Recontres de Blois
June 2009

LISA Pathfinder



Mission goals:

1. Verify that a test mass can be put in gravitational free-fall with residual acceleration noise less than

$$S_a^{1/2}(f) \leq 3 \times 10^{-14} \left[1 + \left(\frac{f}{3\mathrm{mHz}} \right)^2 \right] \frac{\mathrm{m\,s}^{-2}}{\sqrt{\mathrm{Hz}}}$$

2. Demonstrate on-orbit laser metrology with freely falling mirrors with displacement sensitivity less than

$$S_{\delta x}^{1/2}(f) \leq 9 \times 10^{-12} \left[1 + \left(\frac{3\mathrm{mHz}}{f} \right)^2 \right] \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

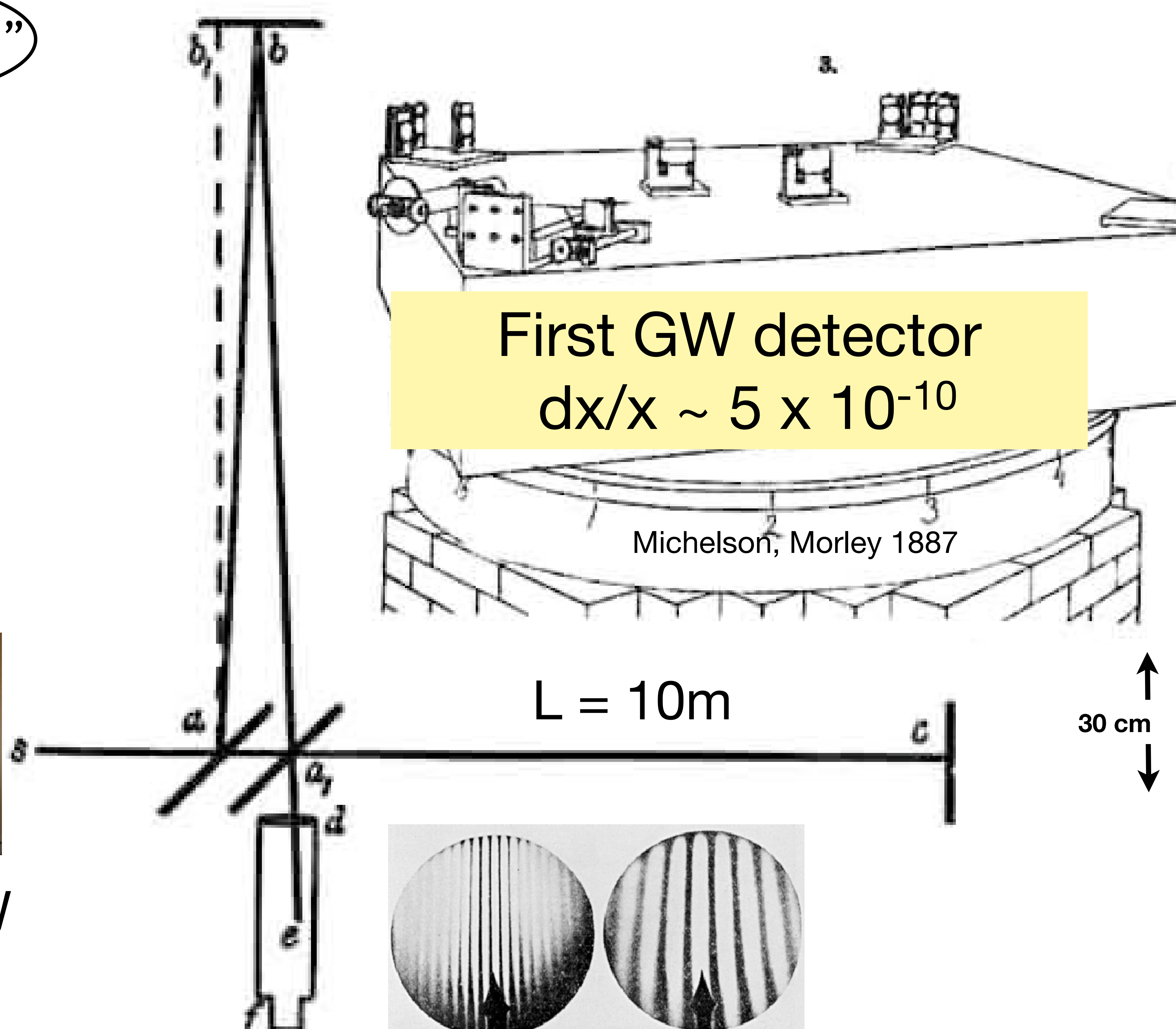
Scheduled launch mid-2011

GW observatory 0.01

“0.01 λ = 5 nm”


Albert A. Michelson

~ 1 mW



L = 10m

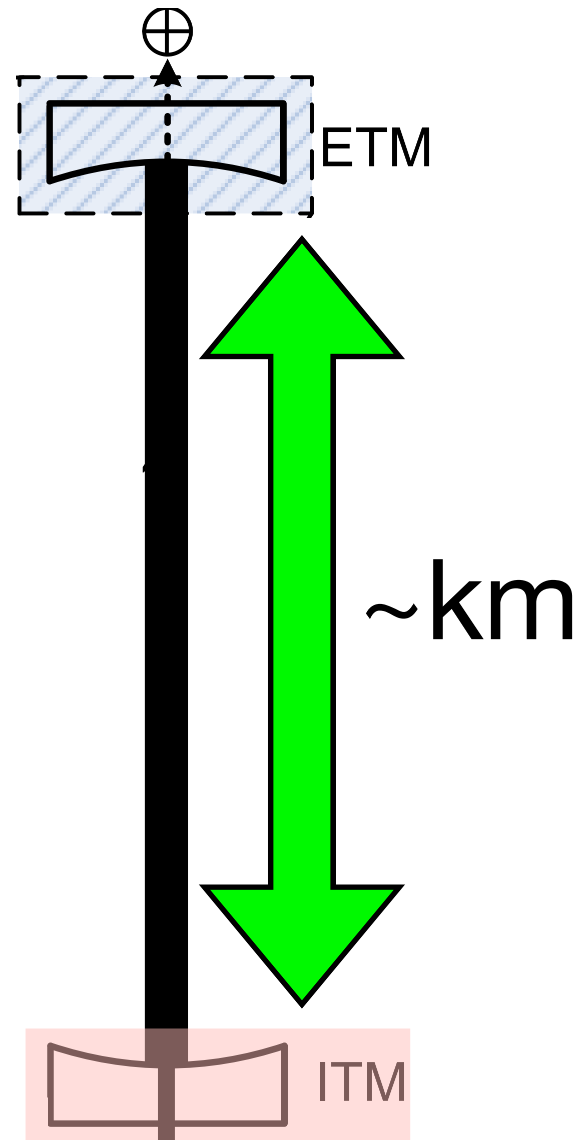
30 cm

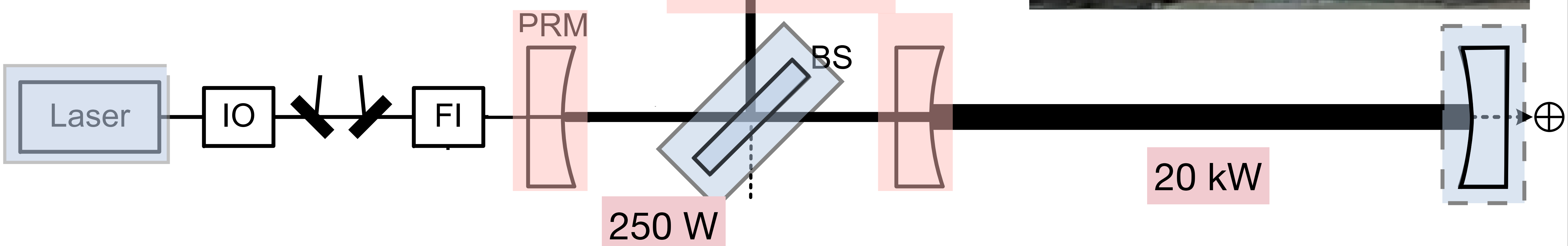
First GW detector
dx/x ~ 5 x 10^{-10}

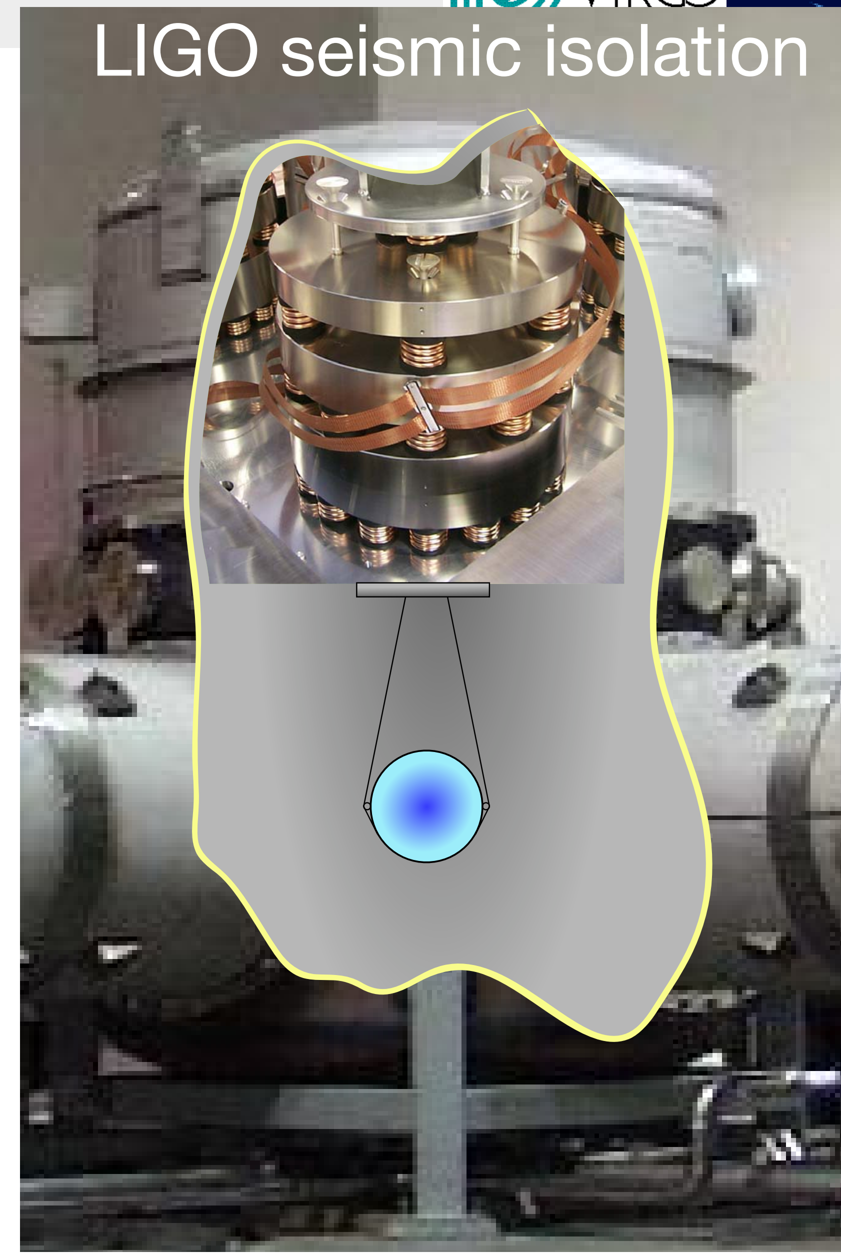
Michelson, Morley 1887

Modern interferometer

10 W Nd:YAG
laser @ 1064nm

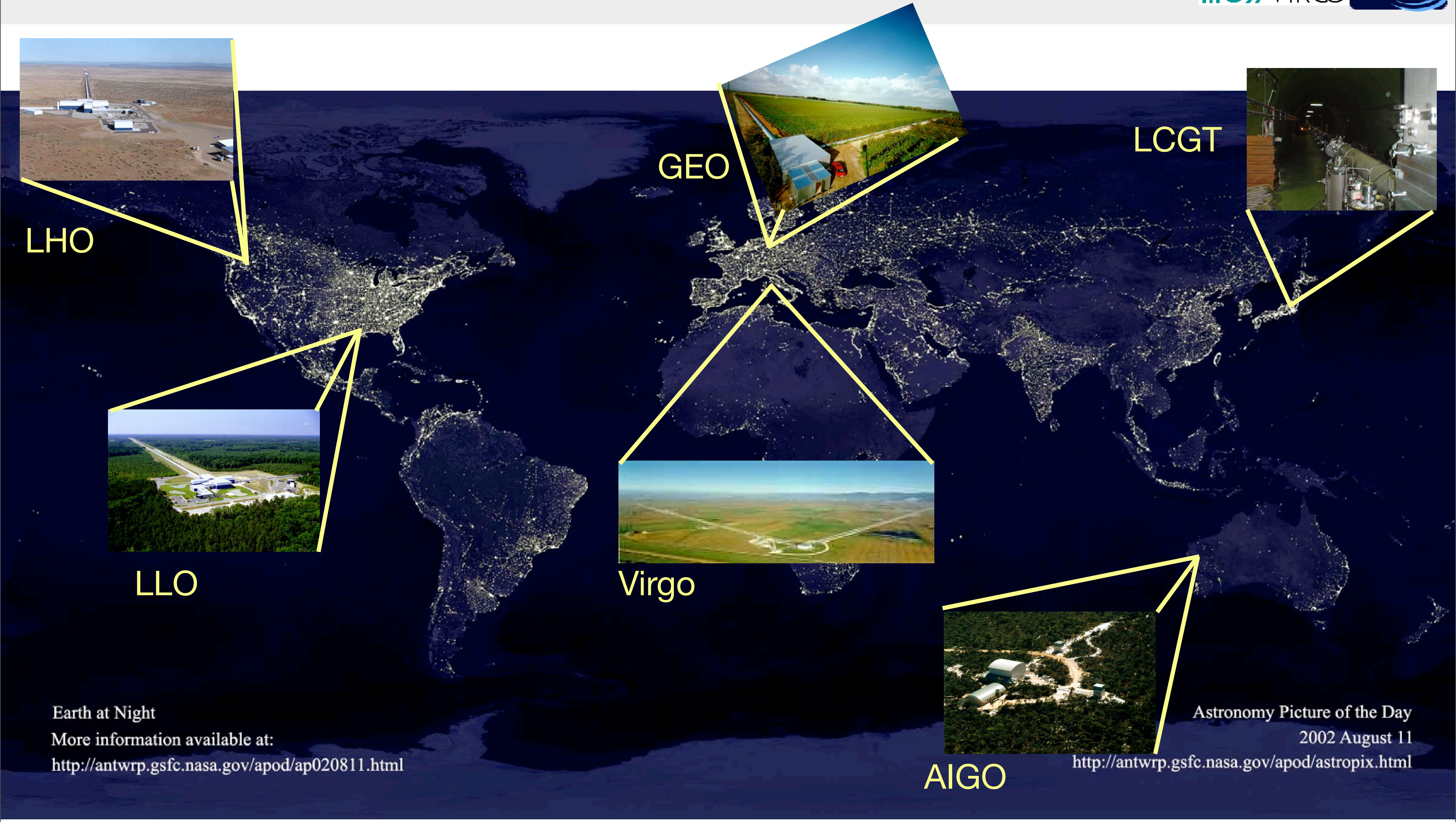






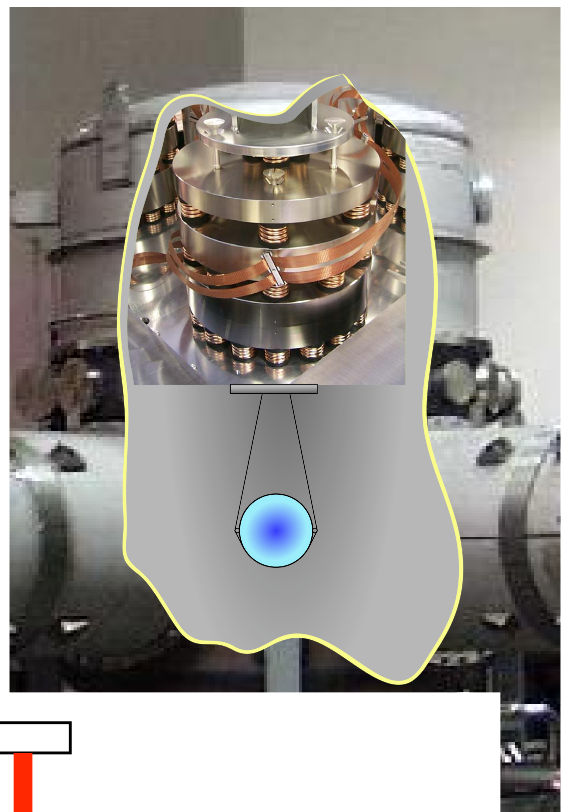
arXiv:0711.3041 LIGO: The Laser Interferometer Gravitational-Wave Observatory

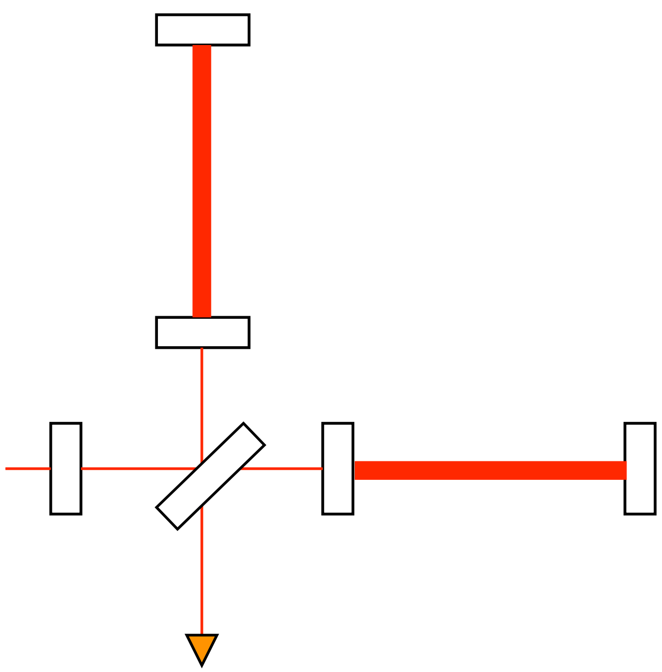
Worldwide network



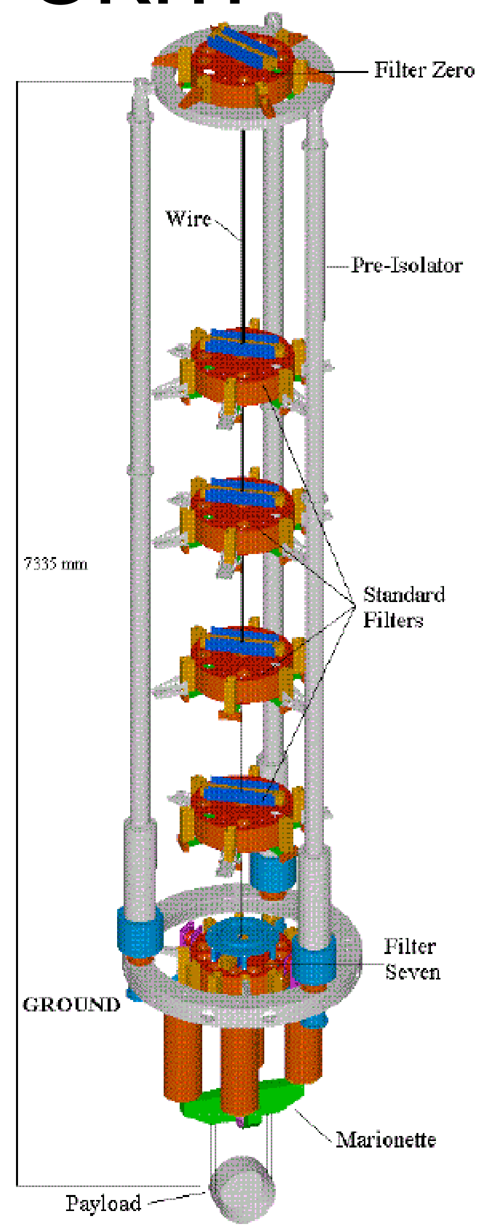
Detector menagerie

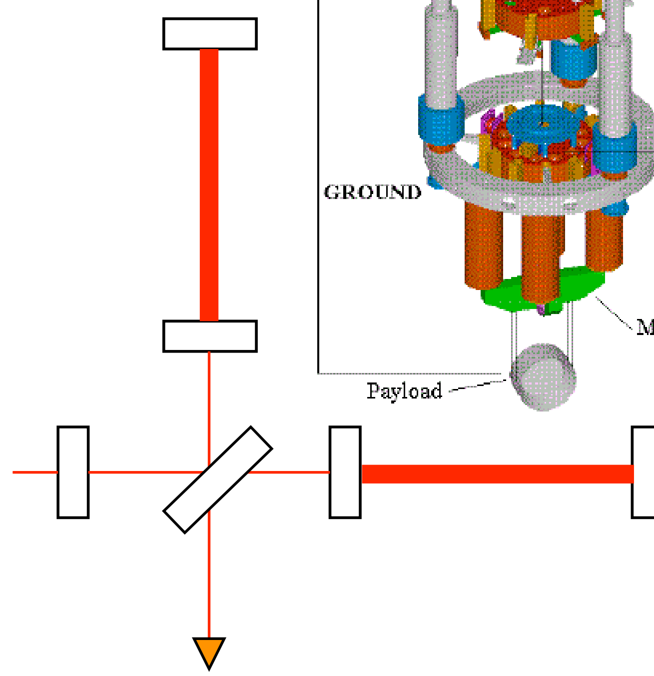
LIGO 2km, 4km



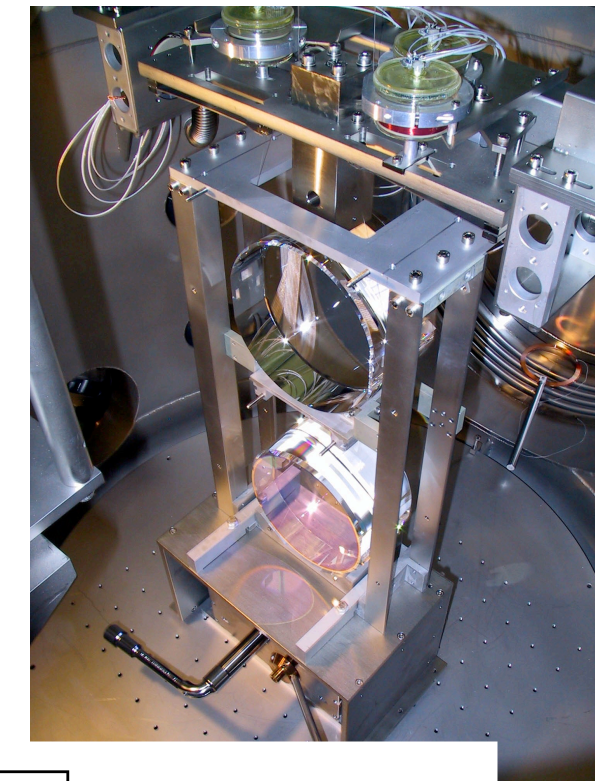


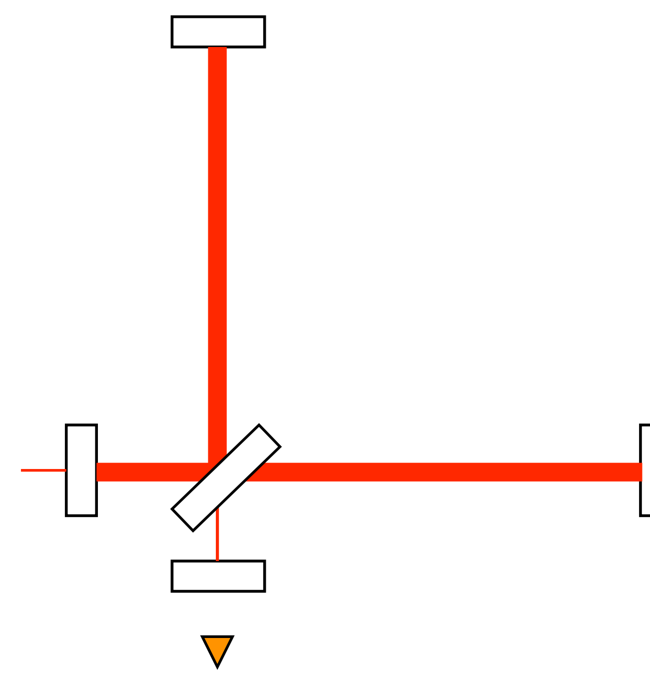
Virgo 3km



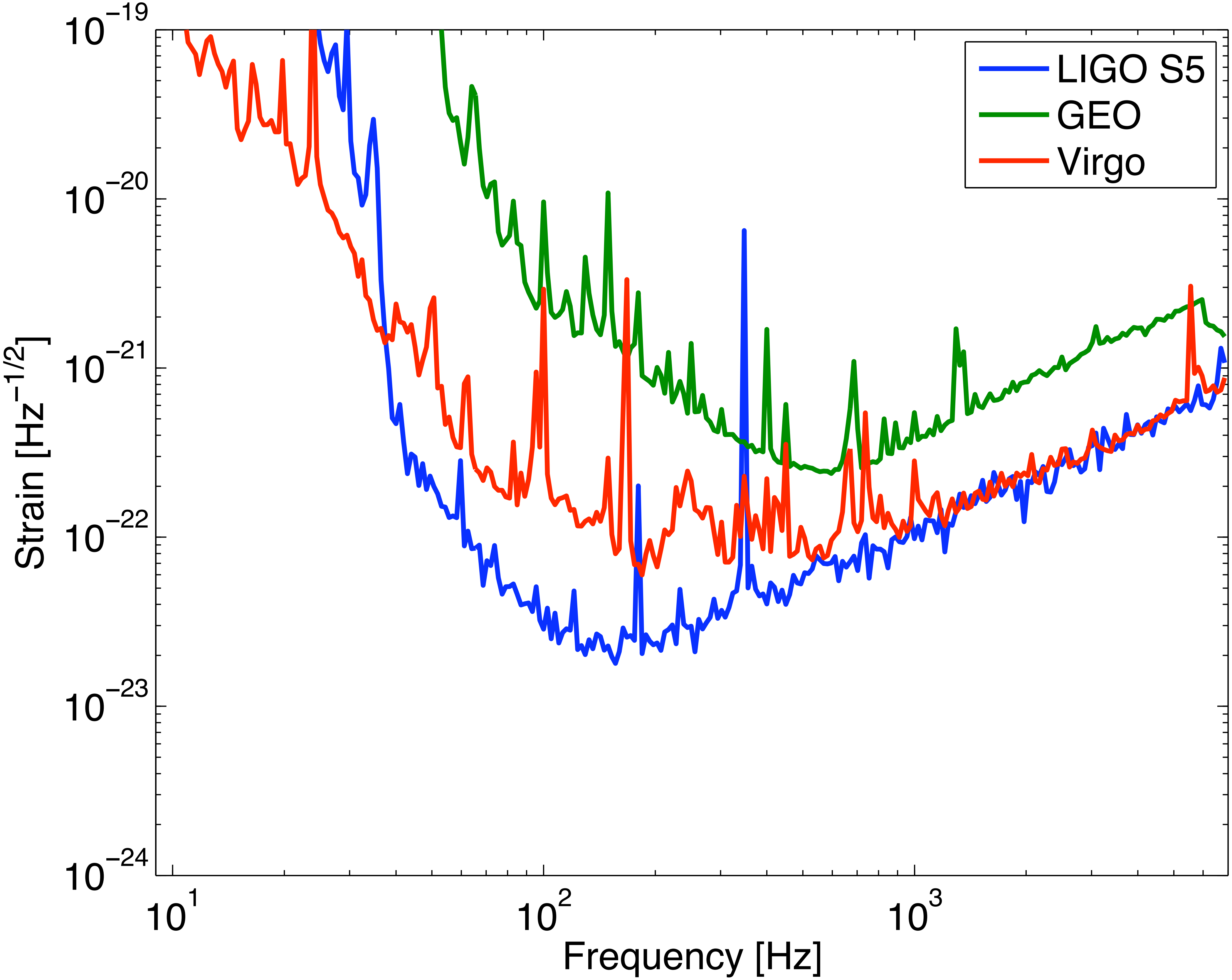


GEO 600m

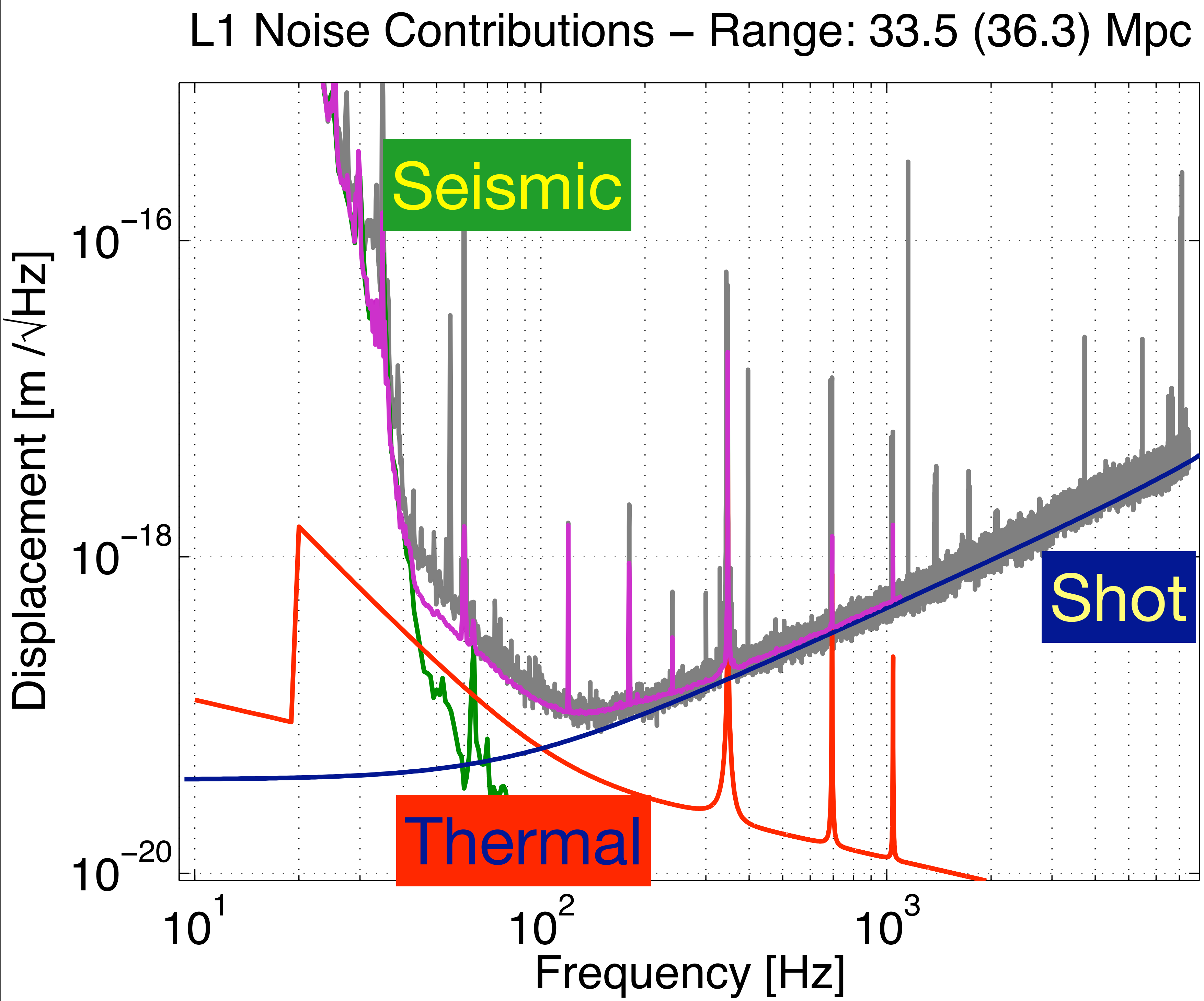




Detector sensitivities



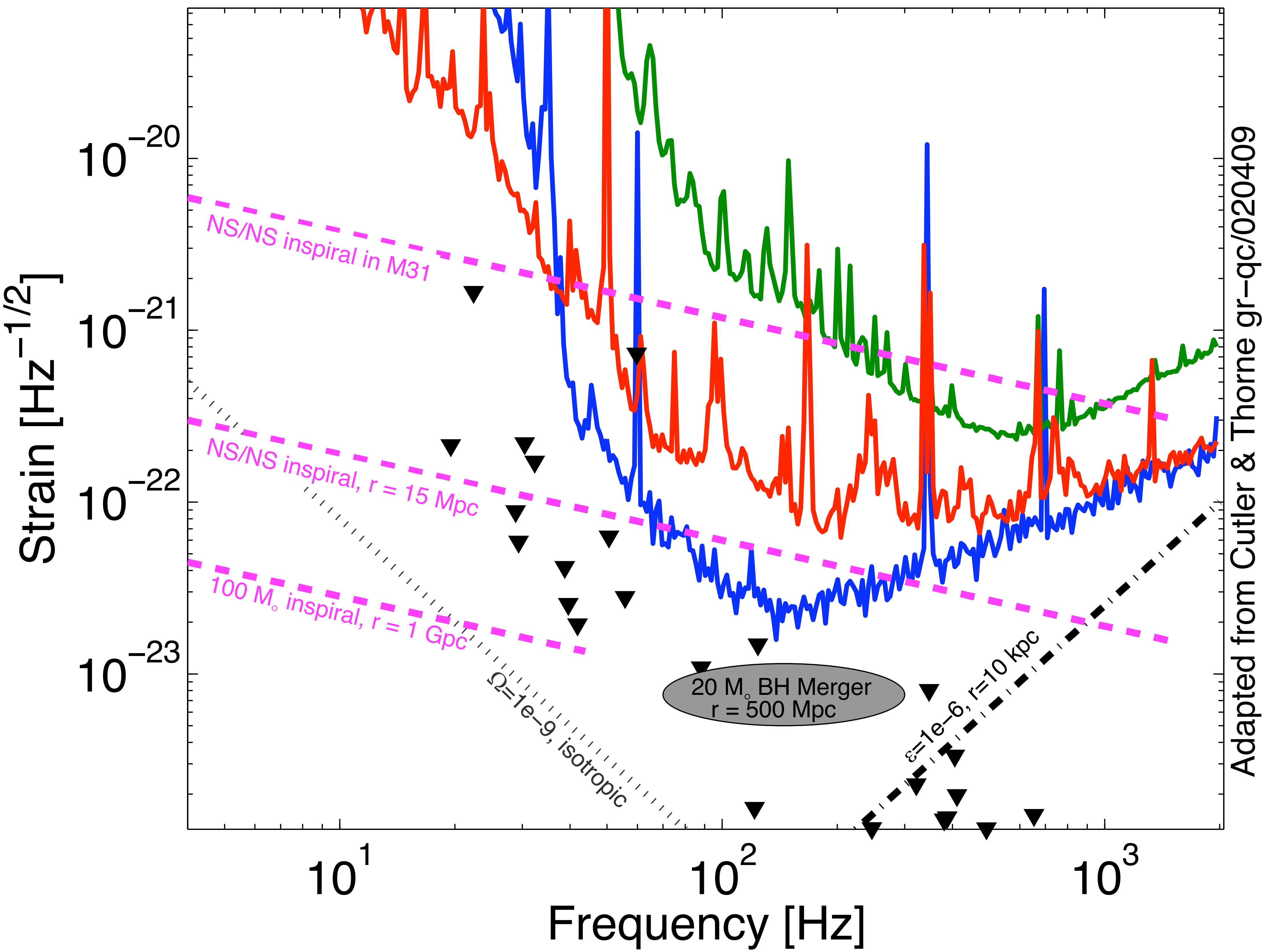
Noise contributions



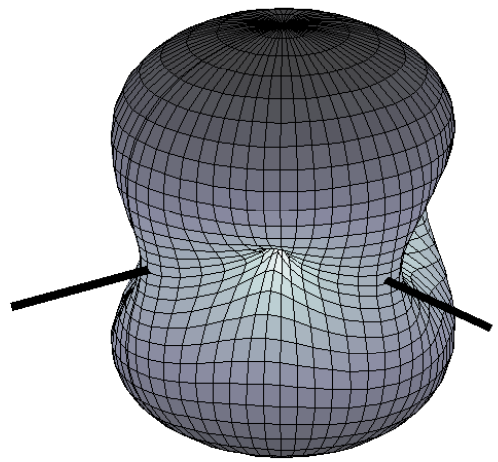
injection/response measurements of noise couplings to test mass displacement

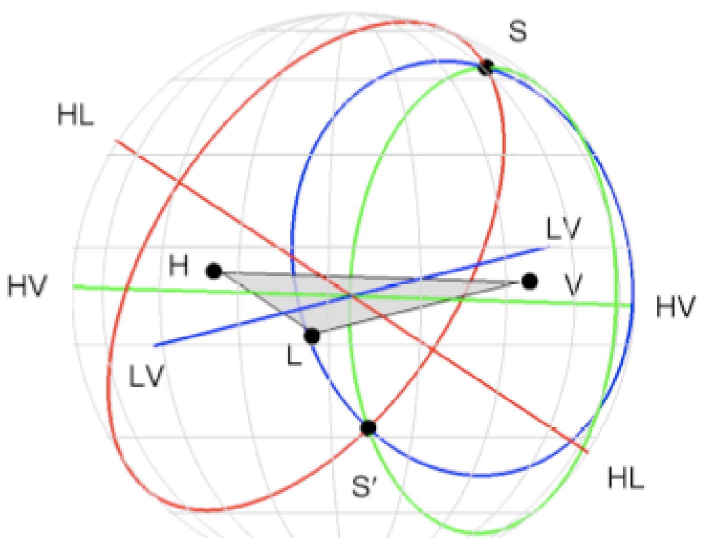
Signals vs. spectrum

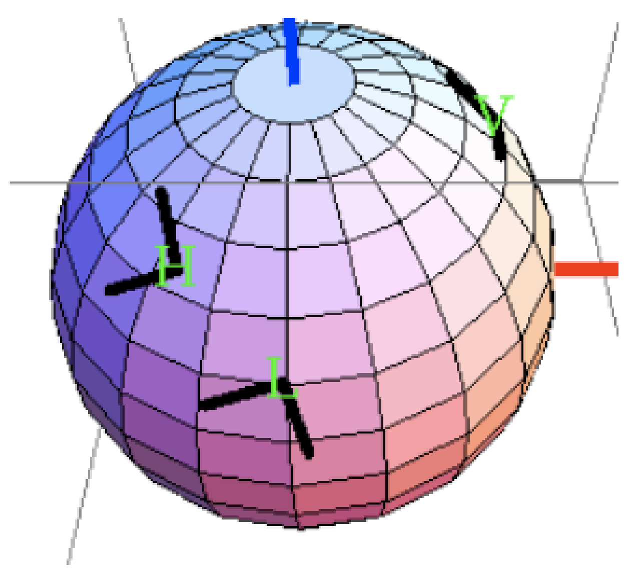
Waldman
Recontres de Blois
June 2009



LIGO + Virgo + GEO





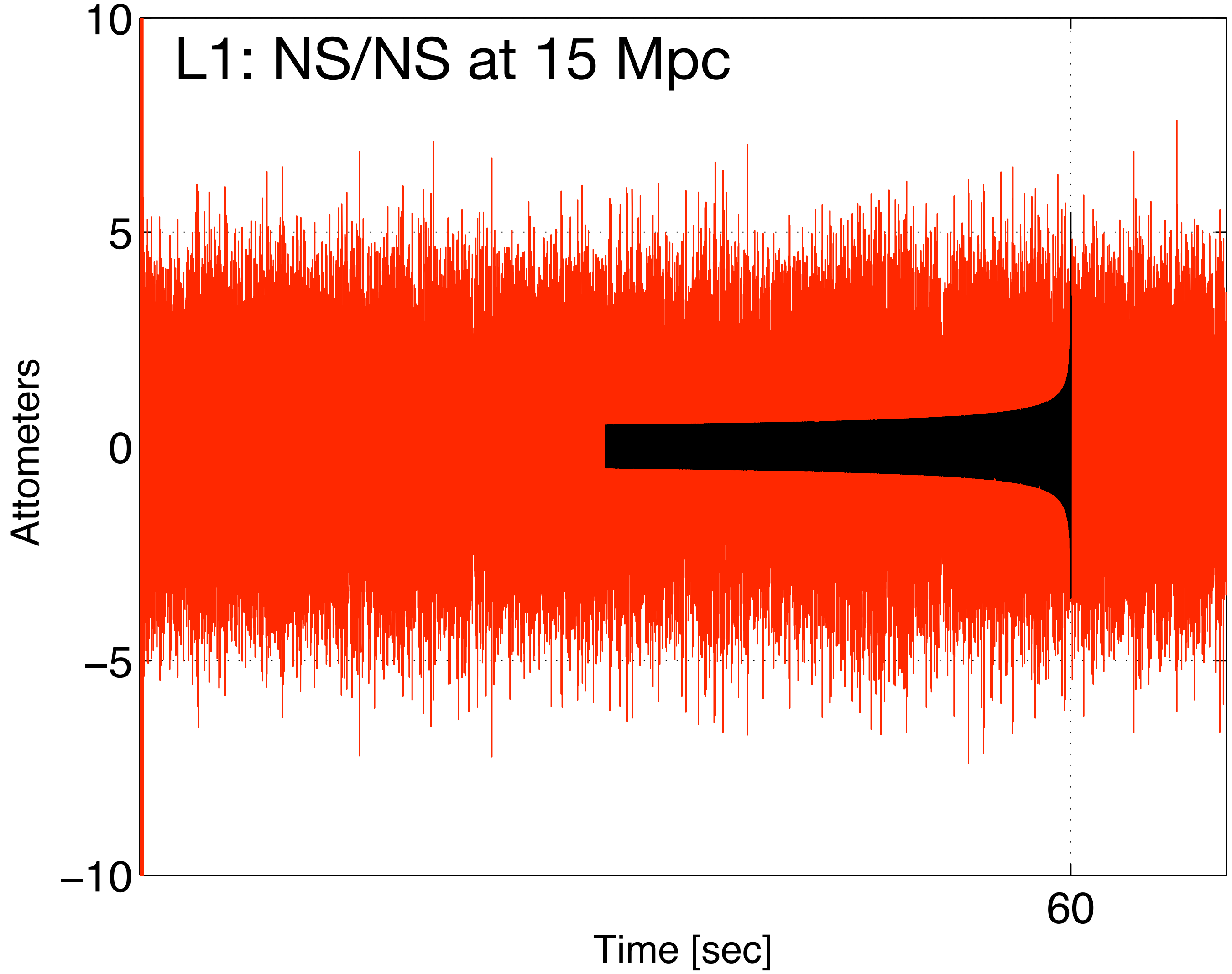


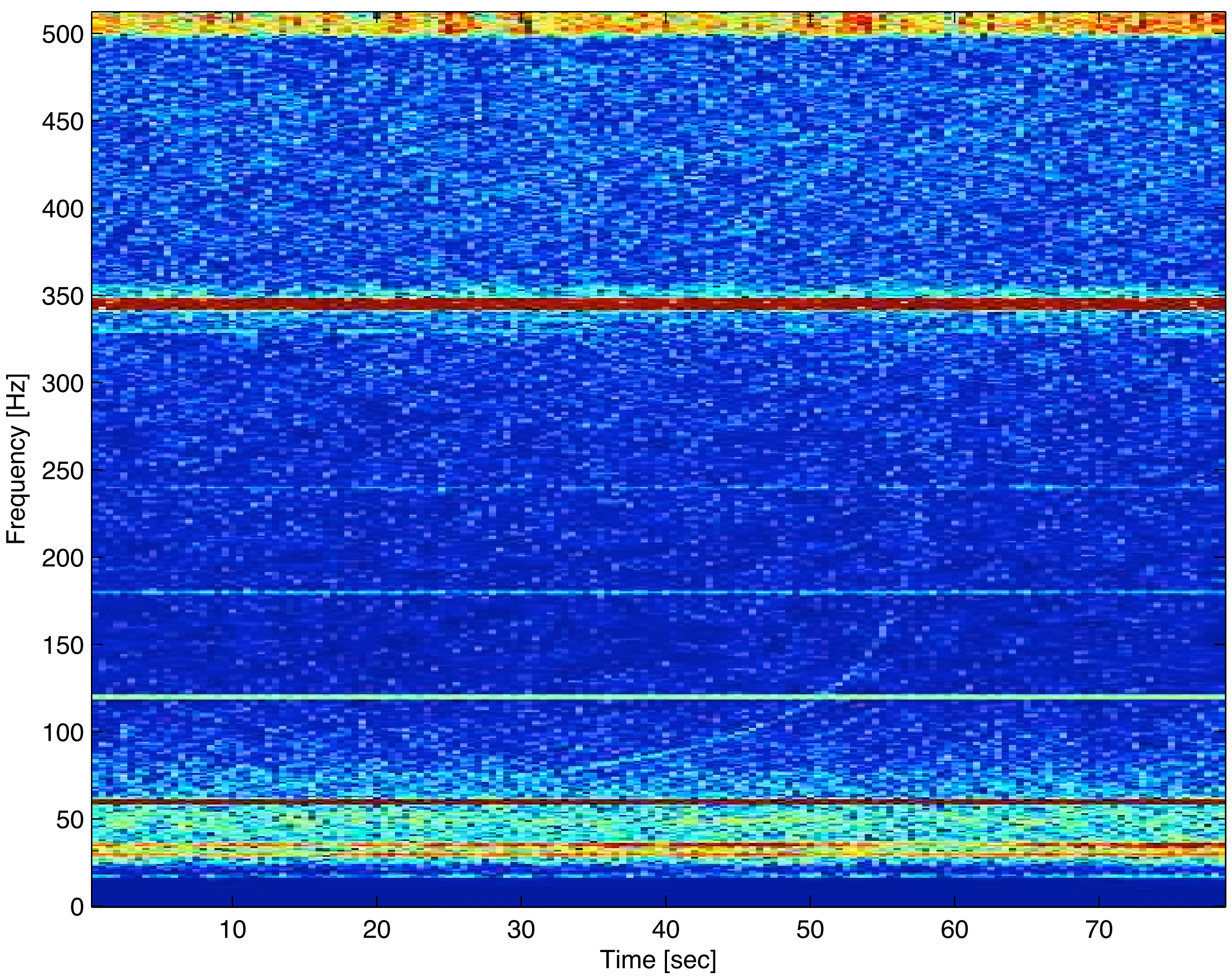
LIGO/GEO and Virgo began data sharing May 18, 2007

- Sky localization with 3 site coincidence
- Improved rejection of non-Gaussian noise
- LVC network delivers 40% more events over LIGO alone
- LVC coherent analysis provides 90% more events

Signal injections

Inject "realistic" waveforms into detectors in coincidence to measure analysis efficiency





More interesting: "blind" hardware injections test entire detection pipeline.

LIGO 5th Science Run

LIGO: 1 year triple coincidence operation at design sensitivity

LIGO/Virgo: 4 months coincident operation and data sharing

Astrophysical Journal 681 Implications for the Origin of GRB 070201 from LIGO Observations

ApJ Letters 683 Beating the spin-down limit on gravitational wave emission from the Crab pulsar

Phys. Rev. Letters 101 Search for Gravitational Wave Bursts from Soft Gamma Repeaters

Phys. Rev. Letters 102 All-sky LIGO Search for Periodic Gravitational Waves in the Early S5 Data

arXiv 0711.3041 LIGO: The Laser Interferometer Gravitational-Wave Observatory

arXiv 0901.0302 Search for Gravitational Waves from Low Mass Binary Coalescences in the First Year of LIGO's S5 Data

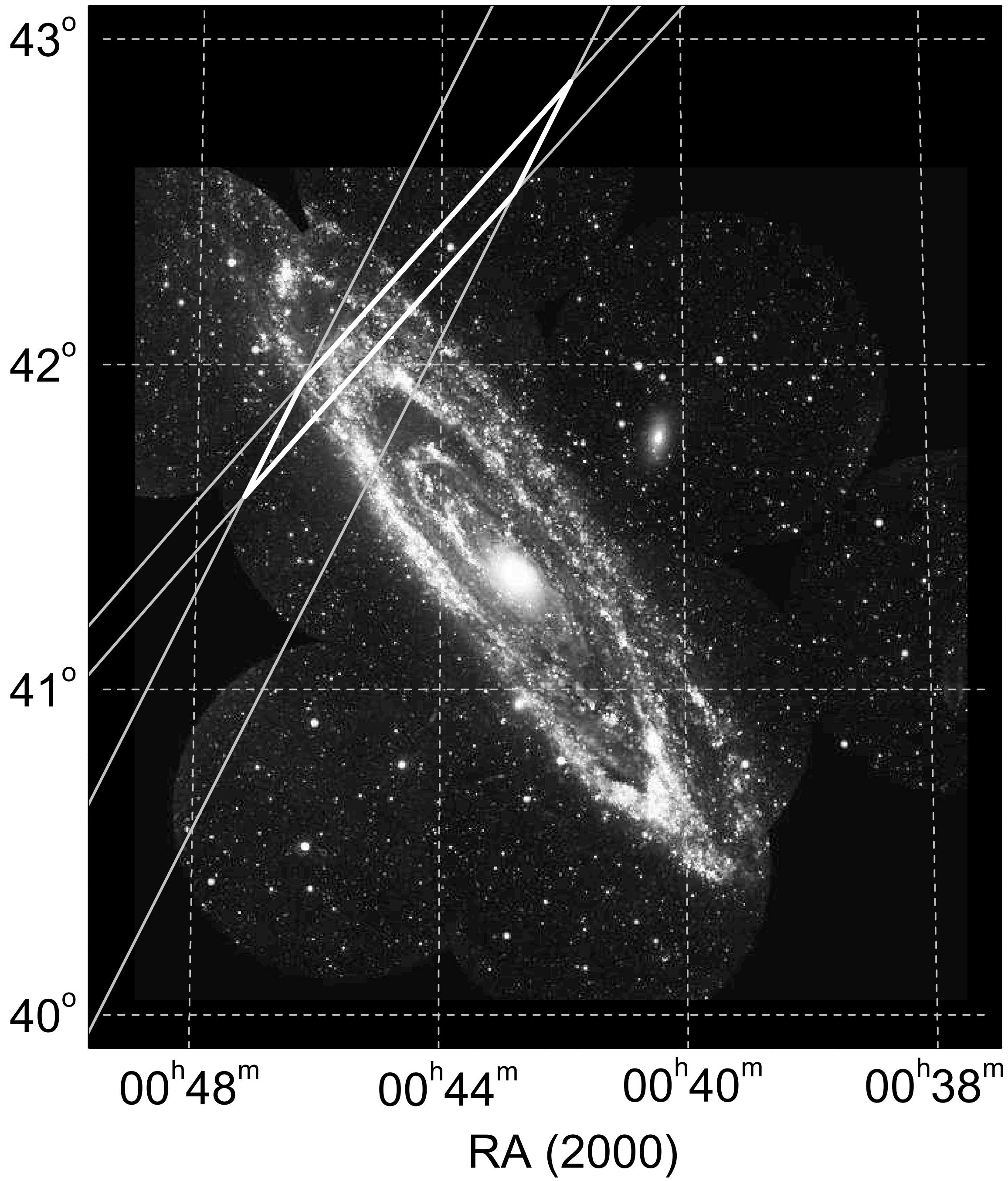
arXiv 0905.0005 Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm

arXiv 0905.0020 Search for gravitational-wave bursts in the first year of the fifth LIGO science run

arXiv 0905.1654 Search for gravitational wave ringdowns from perturbed black holes in LIGO S4 data

arXiv 0905.1705 Einstein@Home search for periodic gravitational waves in early S5 LIGO data

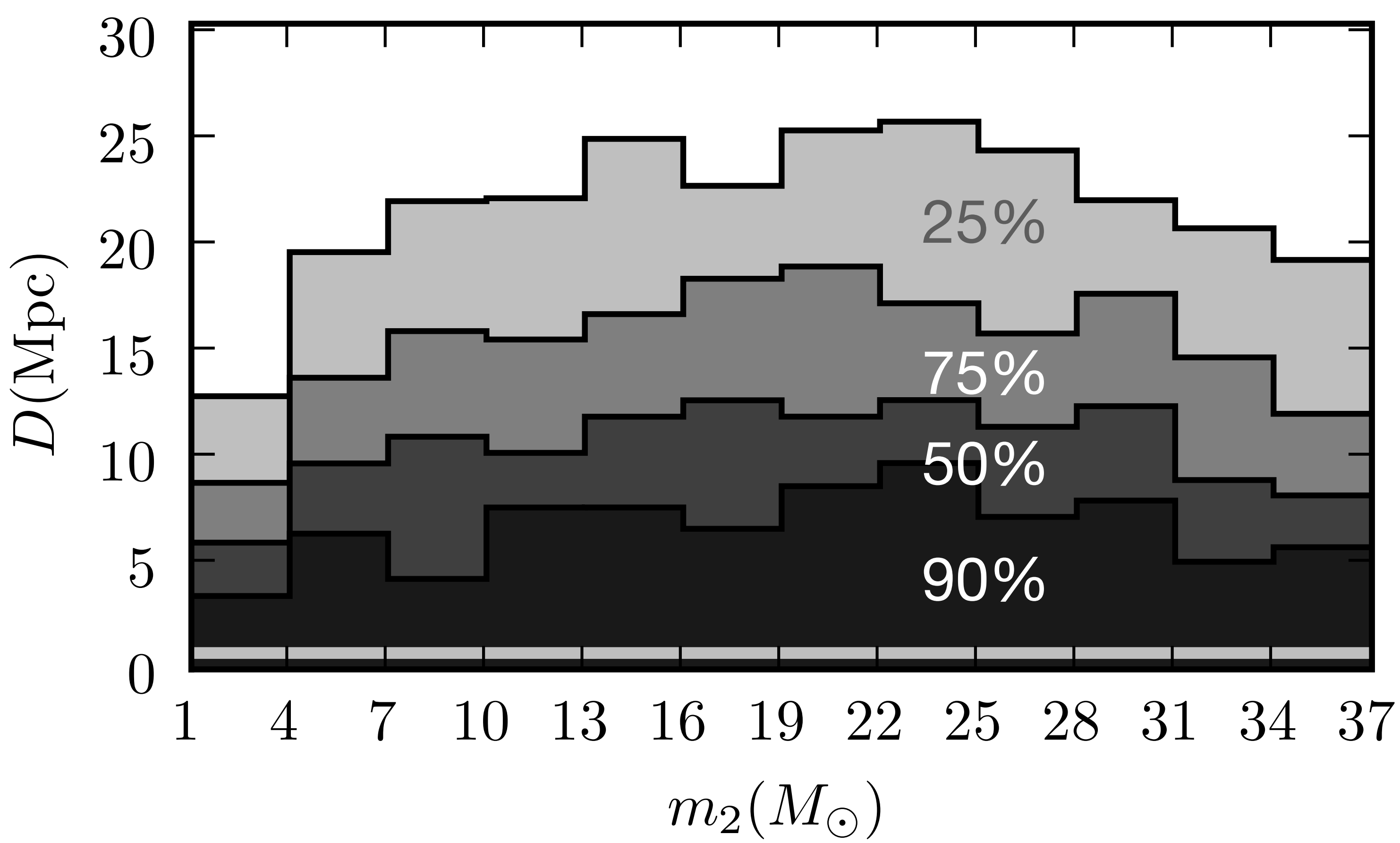
GRB 070201 w/ LIGO



Short GRB (NS/NS?)

Position consistent with M31

No GW counterpart



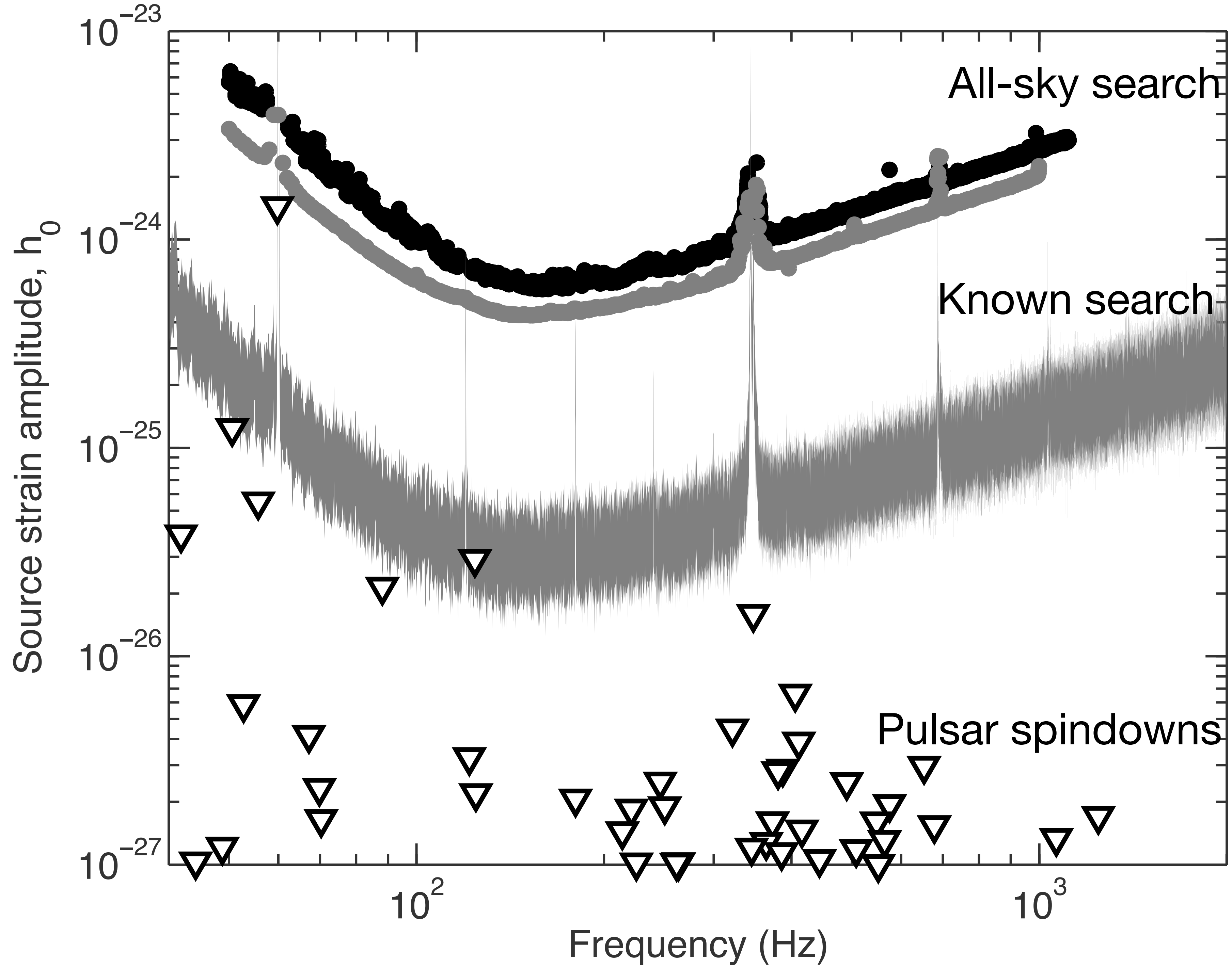
Astrophysical Journal 681 Implications for the Origin of GRB 070201 from LIGO Observations

Crab Pulsar

Limits on (un)known pulsars

Crab spindown not GW

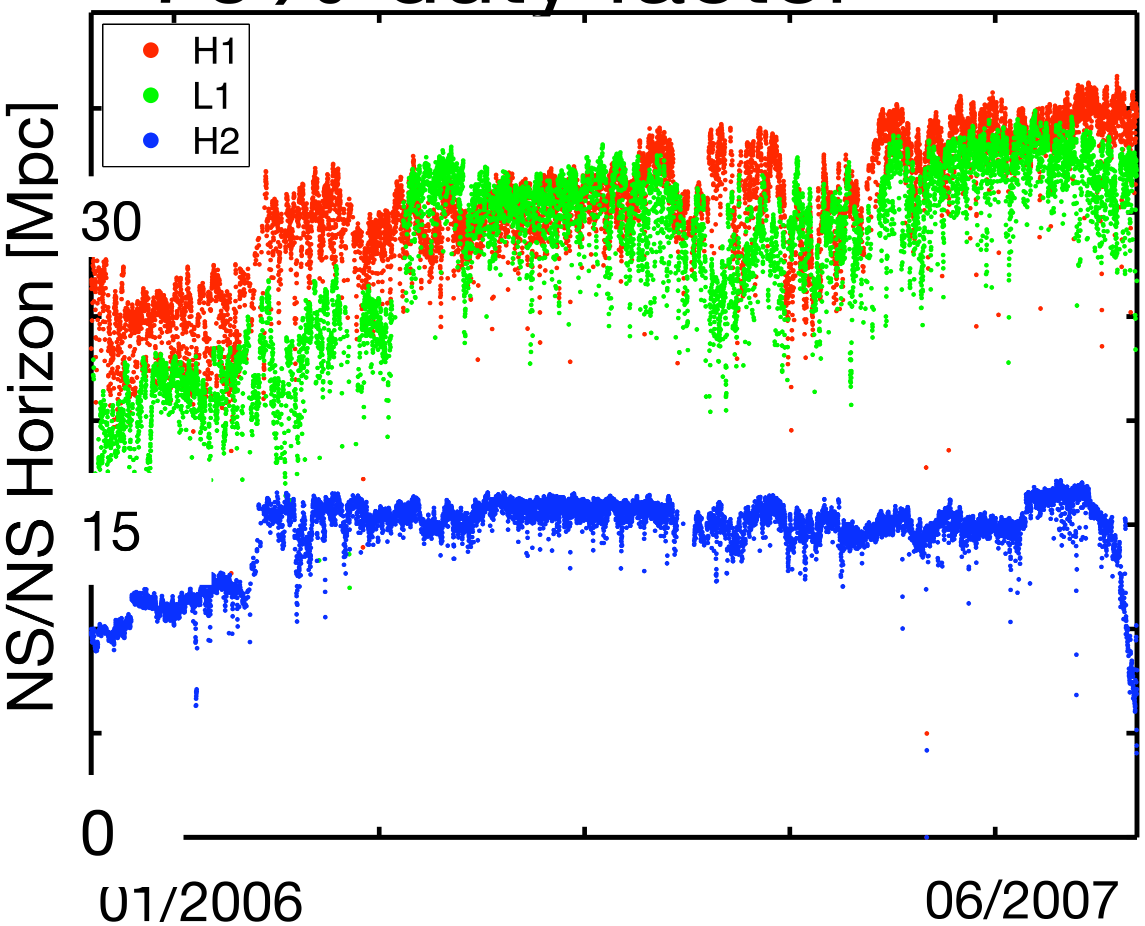
Expected S5 ellipticity limit $\varepsilon \sim 10^{-7}$

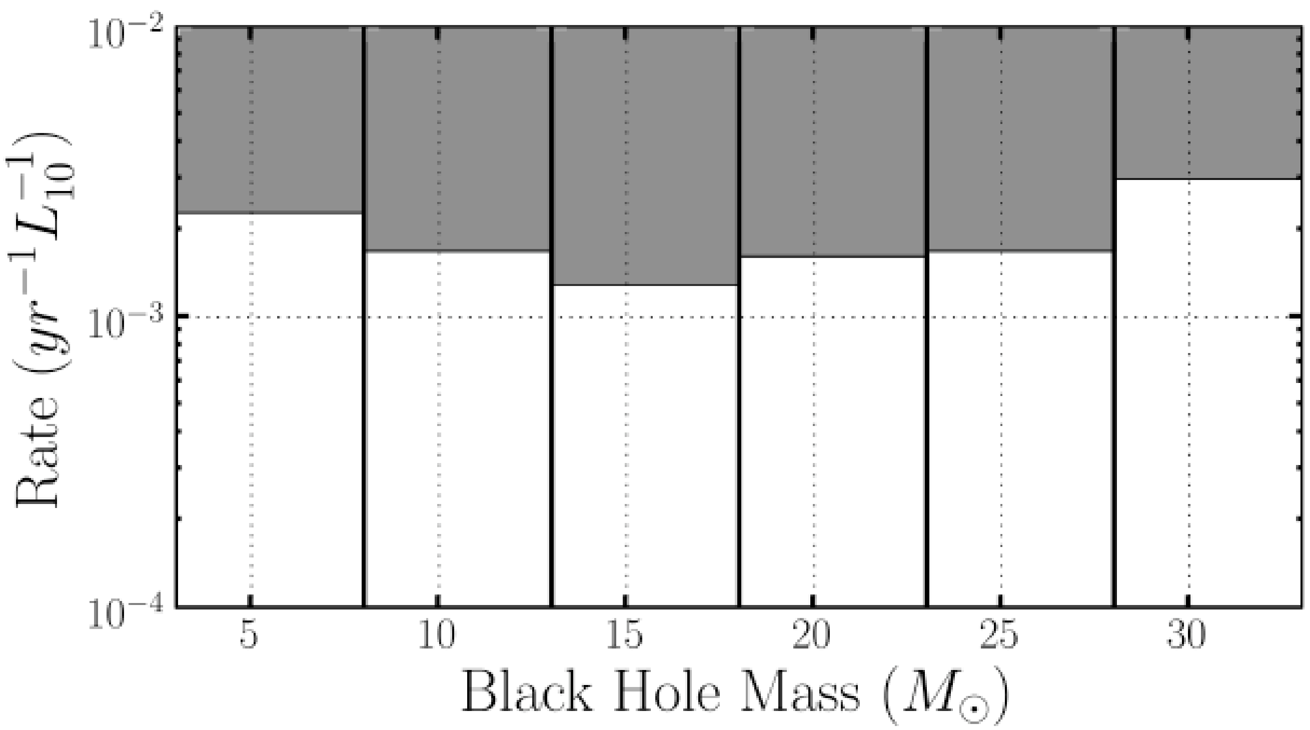


ApJ Letters 683 Beating the spin-down limit on gravitational wave emission from the Crab pulsar

Compact binaries

~70% duty factor





Matched filtering for NS/NS coalescence

First seven months LIGO S5

Total mass 2-35 $M_\odot$, BH/NS coalescence < 2 x 10^{-3} / yr / L_{10}

Predicted rate 5 to 50 x 10^{-5} / yr / L_{10}

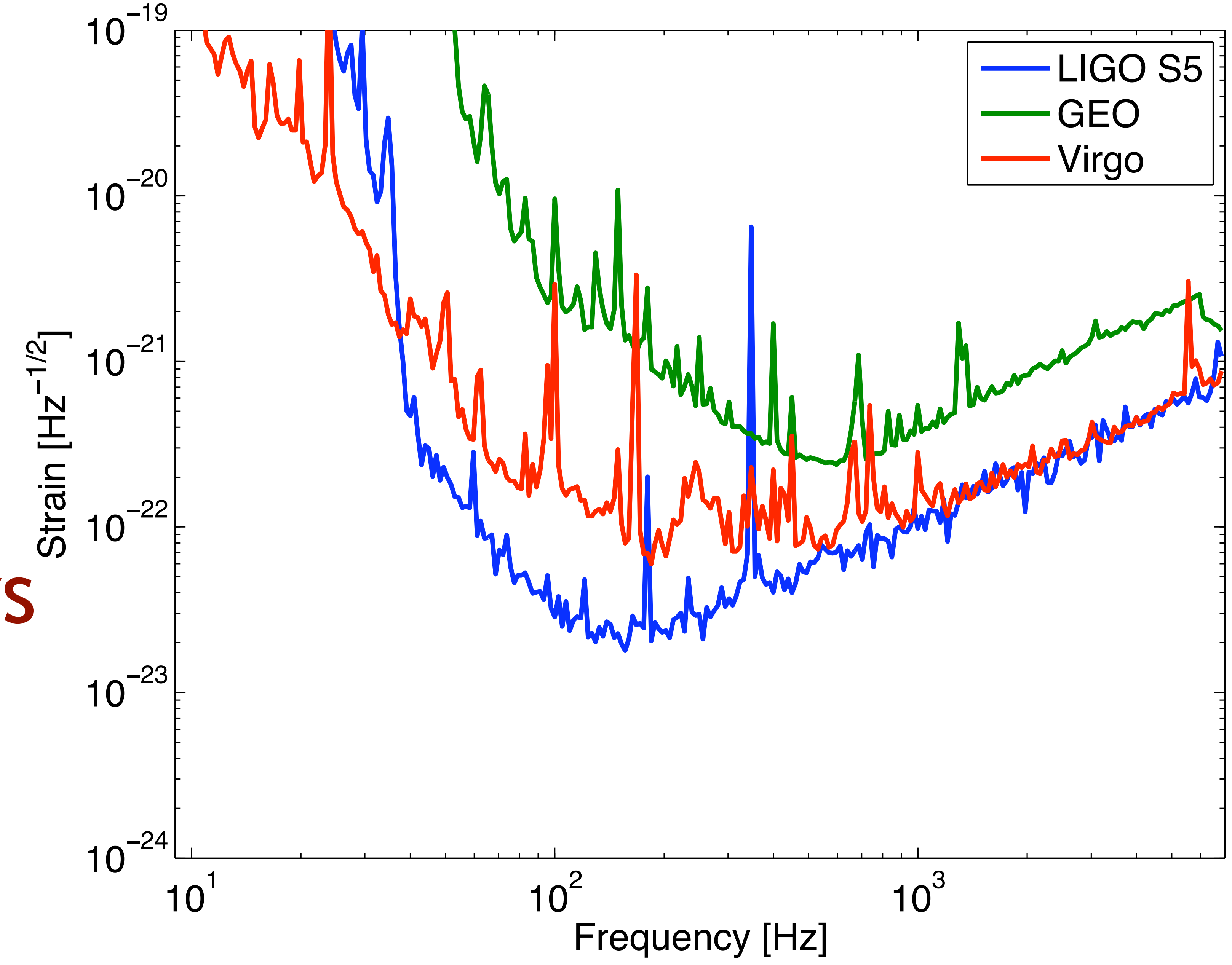
arXiv 0901.0302 Search for Gravitational Waves from Low Mass Binary Coalescences in the First Year of LIGO's S5 Data

Real world experience

GW astrophysics

GW detectors

Advanced detectors

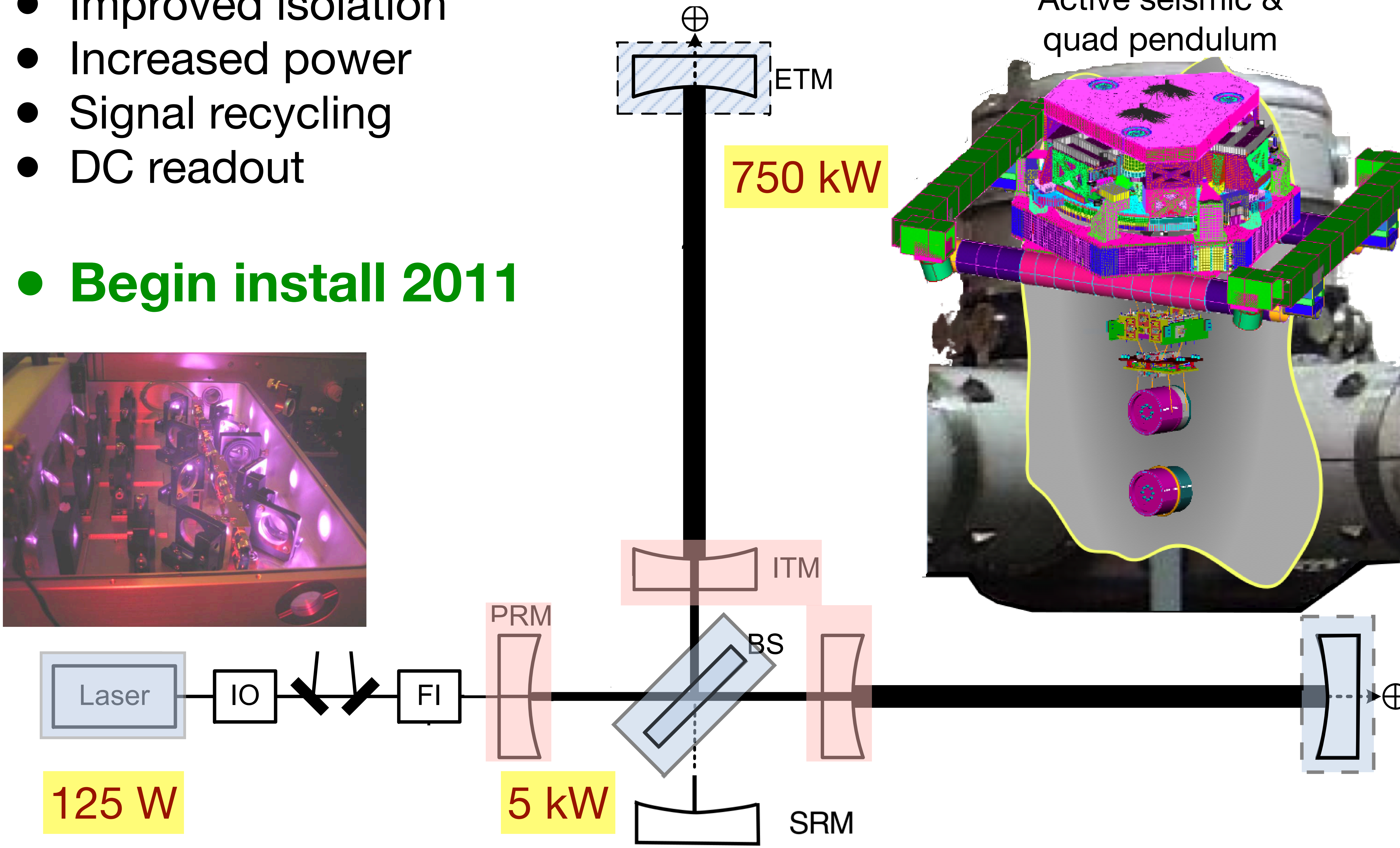


Advanced Detectors

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

- **Begin install 2011**

Active seismic & quad pendulum



Advanced Virgo:

- Monolithic fused silica suspensions w/ rxn mass
- Increased laser power, 100 to 200 W
- Signal recycling and modified optics

(see E. Tournier in parallel session)

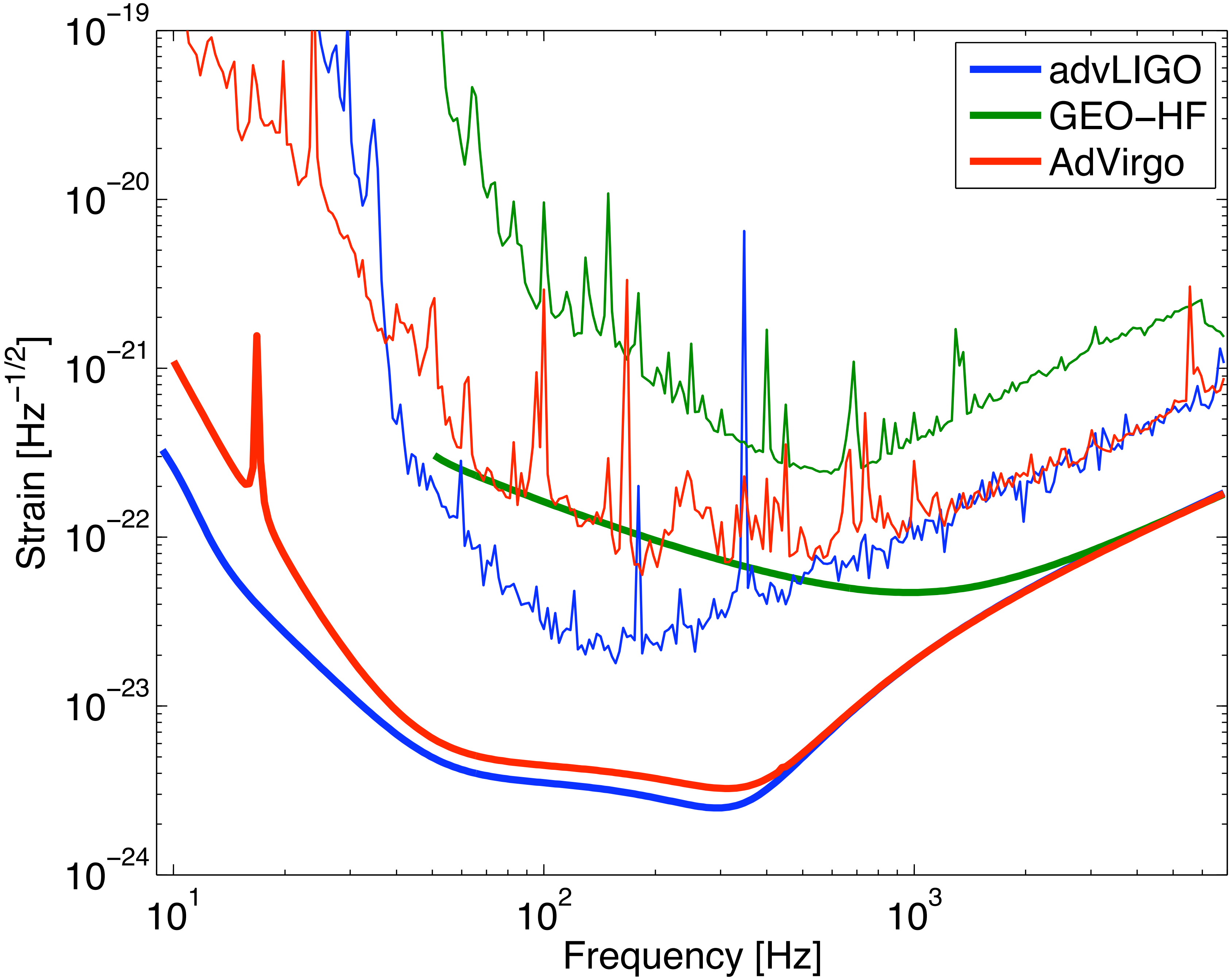
GEO-HF:

- High Frequency, 1 kHz tuning
- Increased laser power
- Squeezed vacuum to improve shot noise

Advanced LIGO:

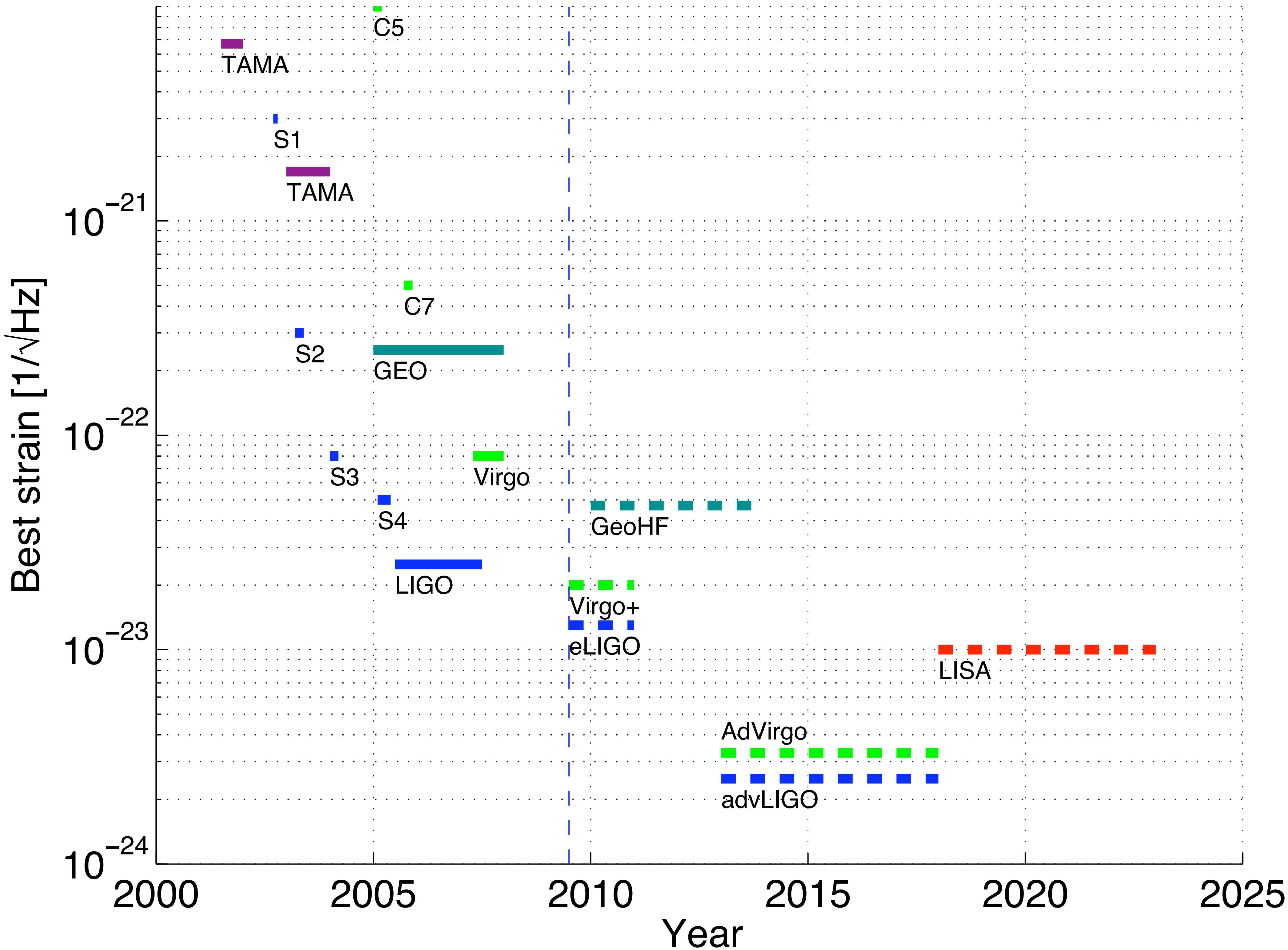
- Multi-stage, active seismic isolation
- Quadruple pendulum, monolithic suspensions
- Increased laser power to 120 W
- Signal recycling and modified optics

Advanced Sensitivities



- Quantum limited in detection band
- 10-15x sensitivity improvement
- Larger bandwidth
- Worldwide network complementary in time and location
- advLIGO program since 2008, first detector mid-2013

Past & future detectors



(note detectors' differing frequency bands)

Signals vs. spectrum

- GWs probe astrophysics invisible to EM & particle messengers; qualitatively new information
- Direct detection of GWs is the best way to test strong field general relativity
- Initial detectors NS/NS ~30 Mpc
- Advanced detectors science 2013 @ 15x S5 sensitivity