The Hunt for Gravitational Waves

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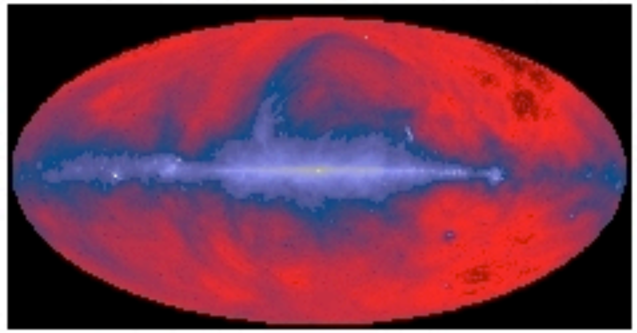
on behalf of the LIGO scientific collaboration

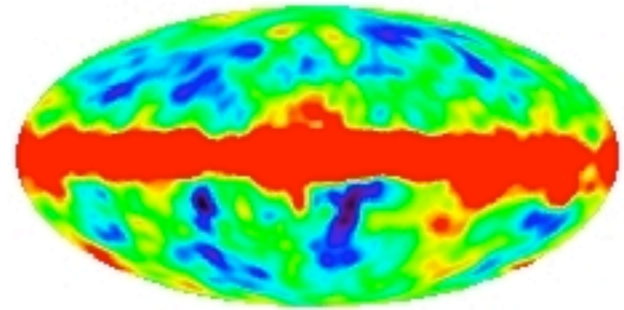
LIGO-G080032-00-K

Why is it so important to detect gravitational waves and study their properties ?

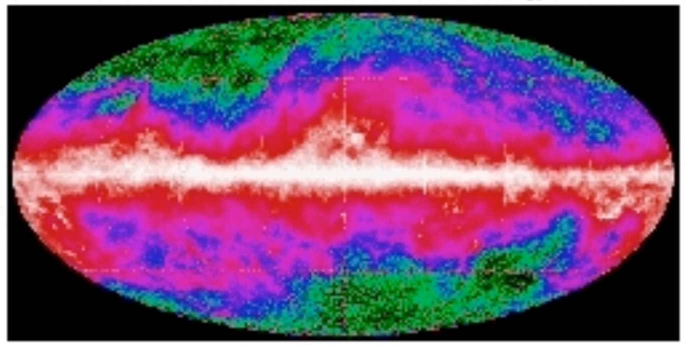
RADIO 408MHz, Jodrell Bank, Effelsburg, Parkes



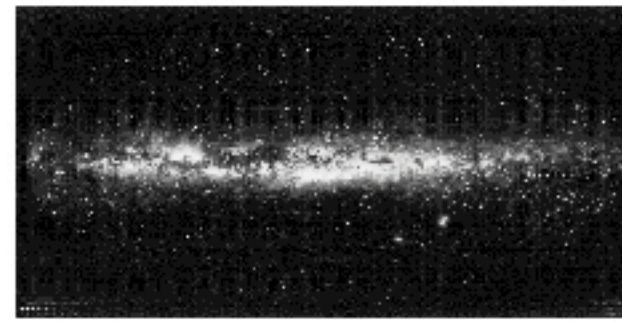
COBE 53 GHz Microwave



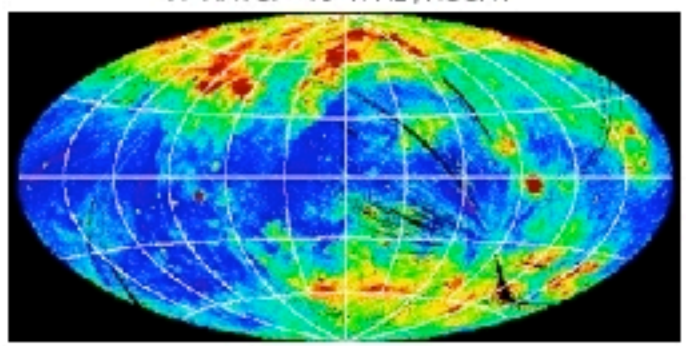
COBE 1.25THz Diffuse Infra-red Background



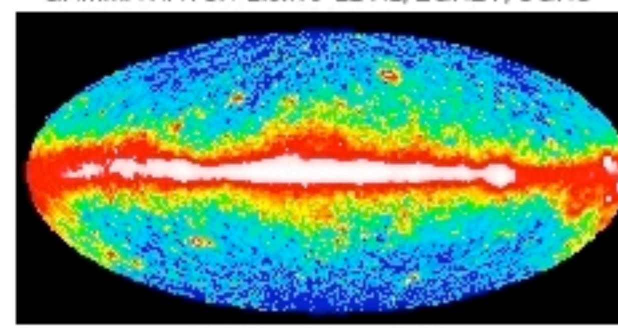
VISIBLE: ~5x10^14 Hz, Lund Observatory



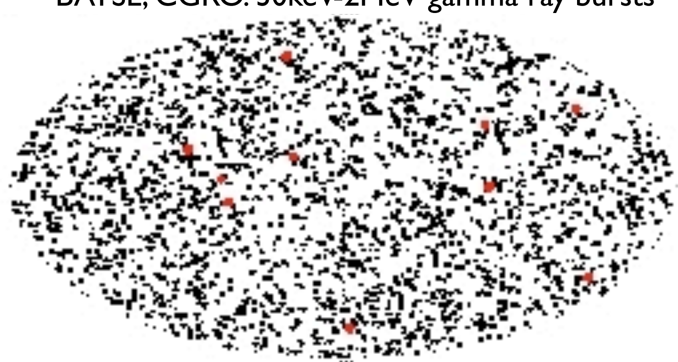
X-RAYS: ~ 10^17Hz , ROSAT

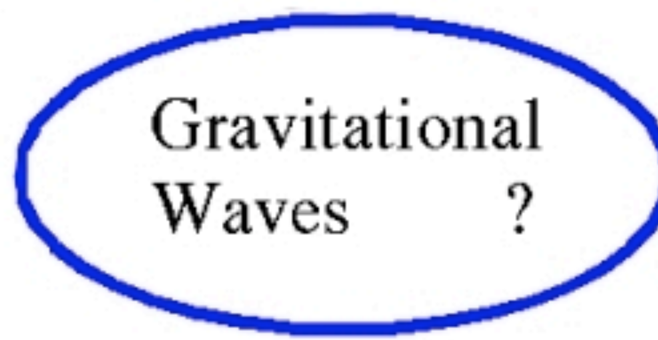


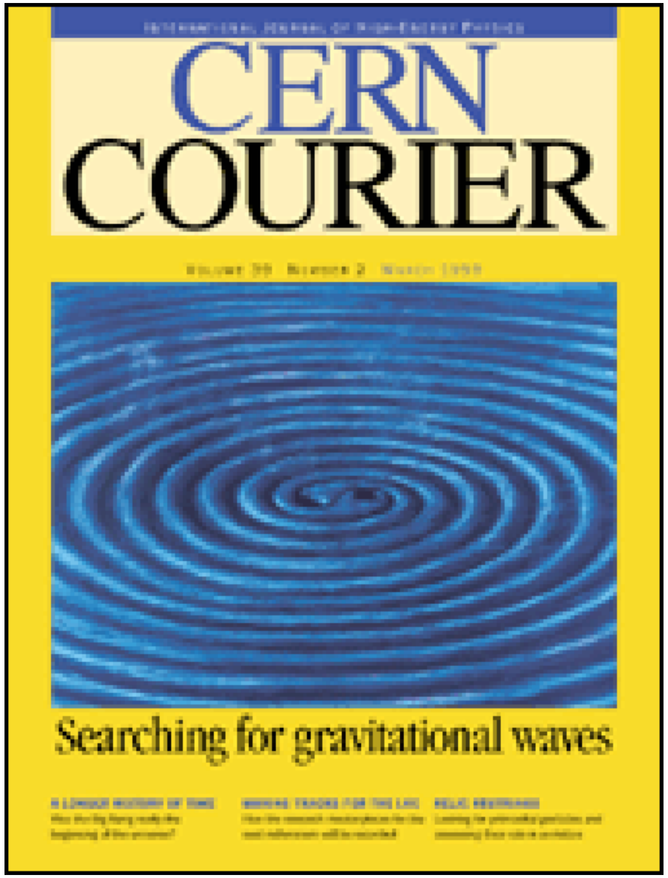
GAMMA RAYS: >2.5x10^22 Hz, EGRET, CGRO



BATSE, CGRO. 30keV-2MeV gamma ray bursts





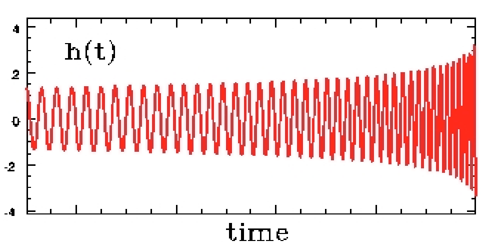


Possibly the first detections of LIGO/GEO/Virgo:

...will be of binary systems of compact objects

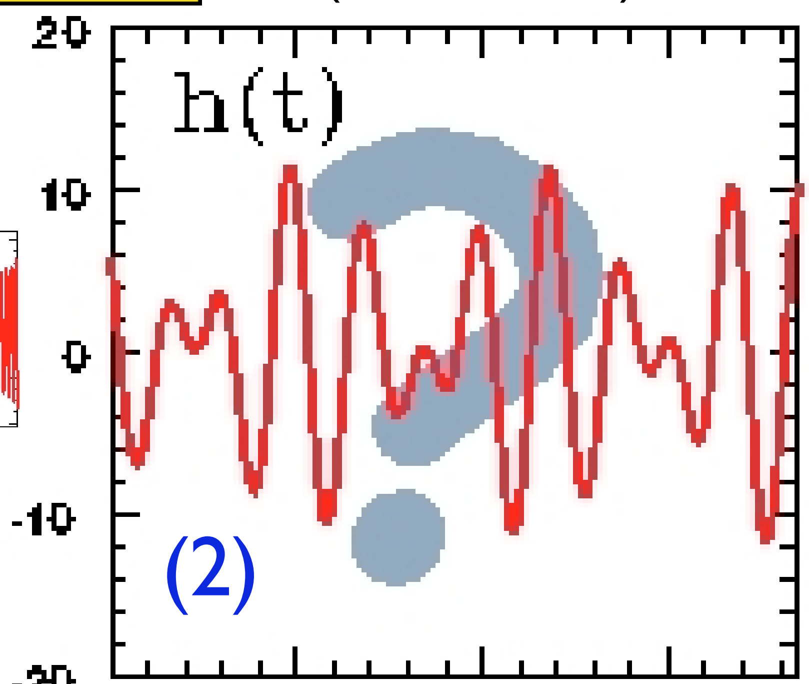
(1) Inspiral, (2) Coalescence, (3) Ringing

20 mins

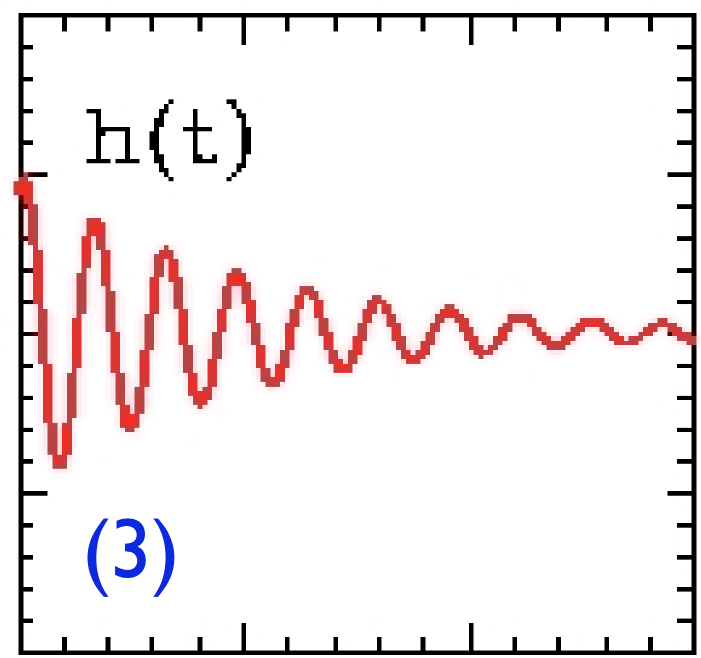


(1)

(Uncertain)



10 msec

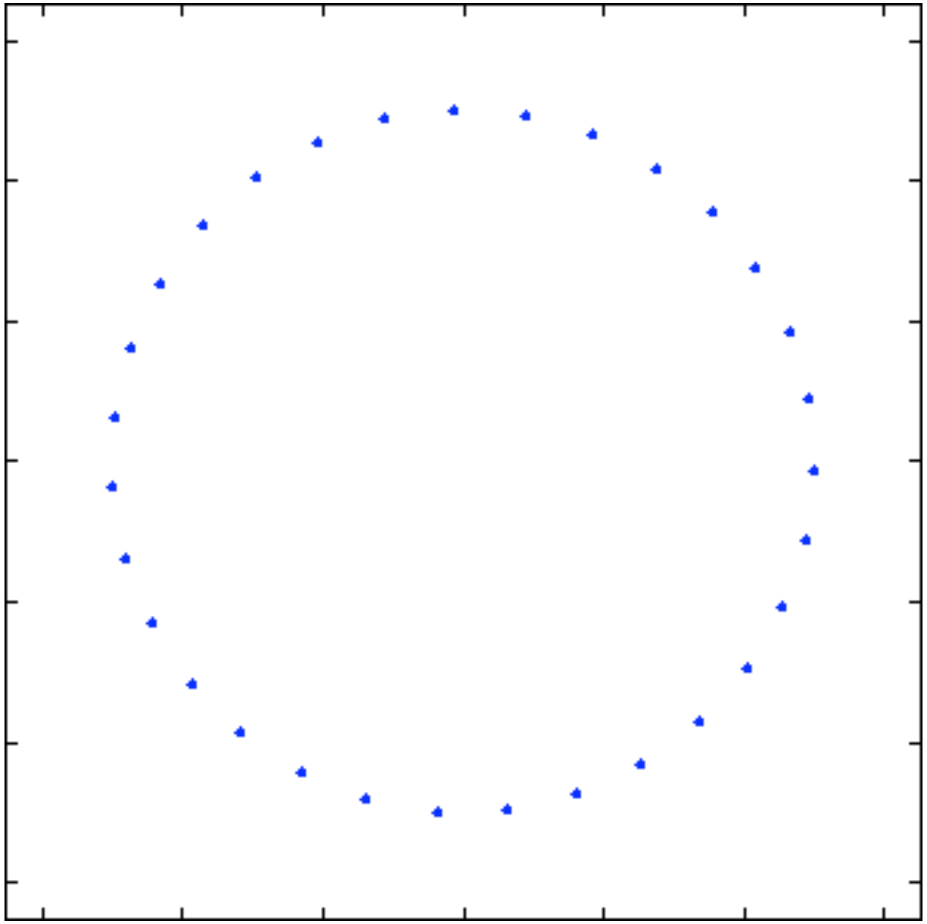


What Are Gravitational Waves ?

Oscillations in the geometry of space propagating at the speed of light. Amplitude is STRAIN h(t) where

$h(t) = \delta L/L$ =extension/original length

+ polarization



x polarization

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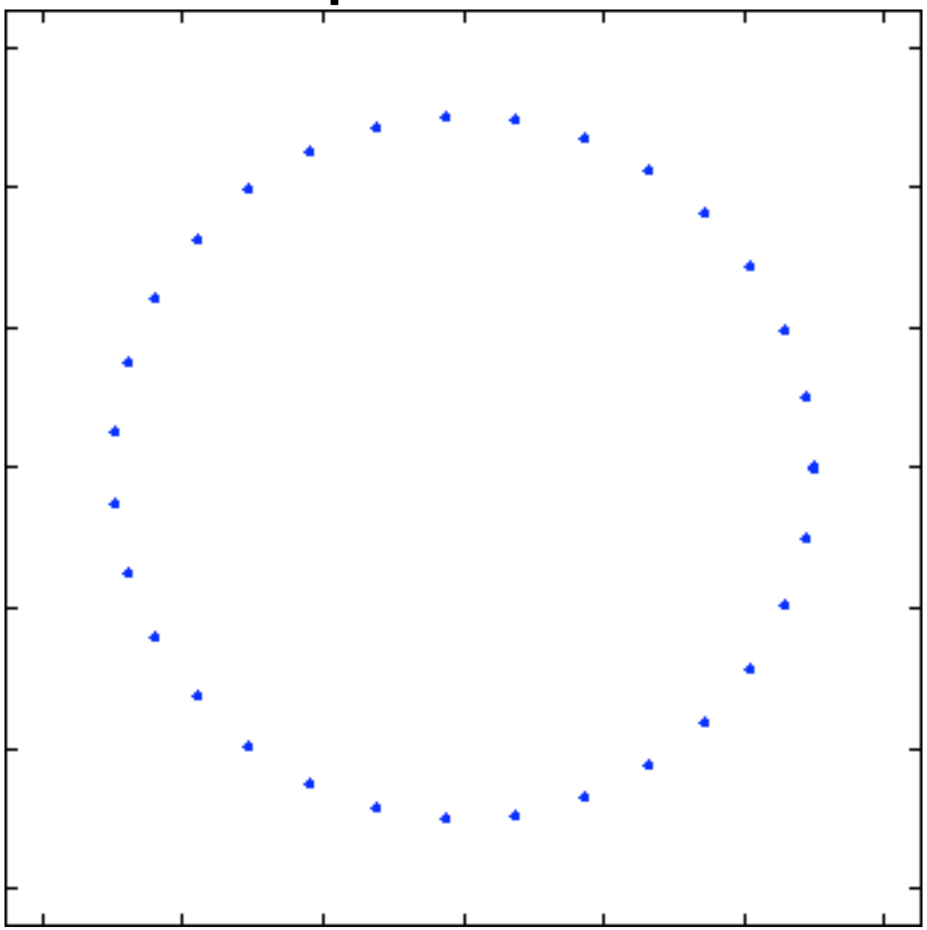

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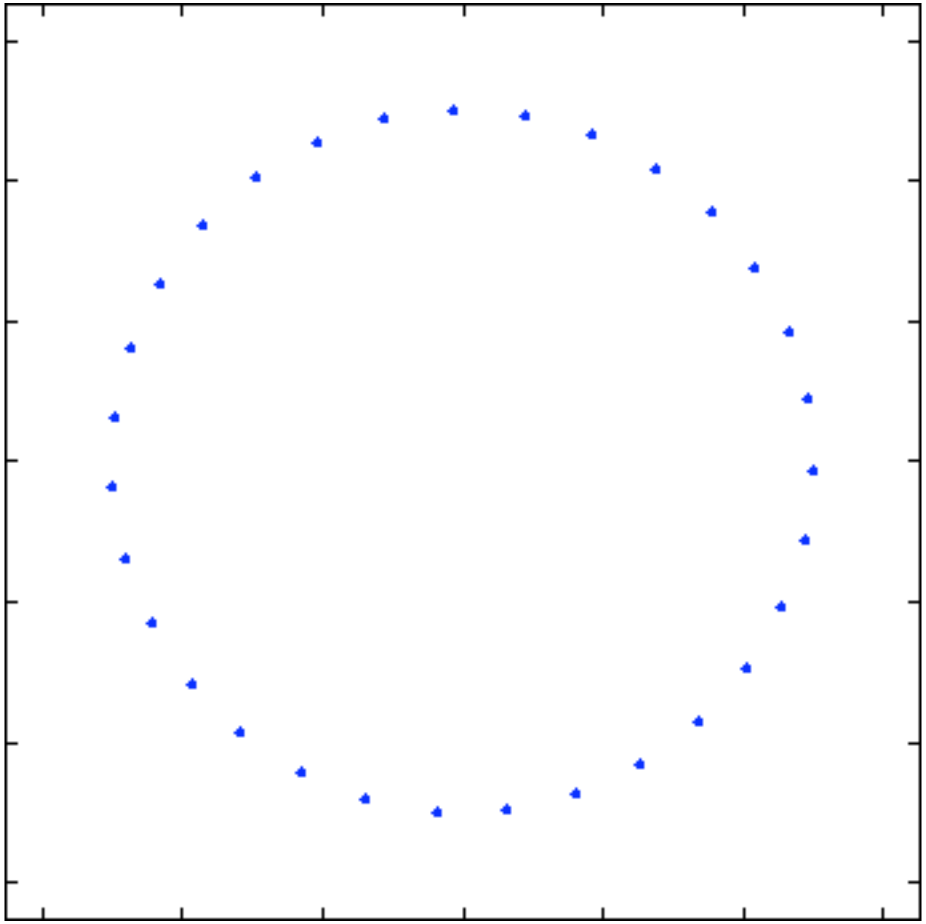

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Question: In what sense are these two polarizations orthogonal to each other ?

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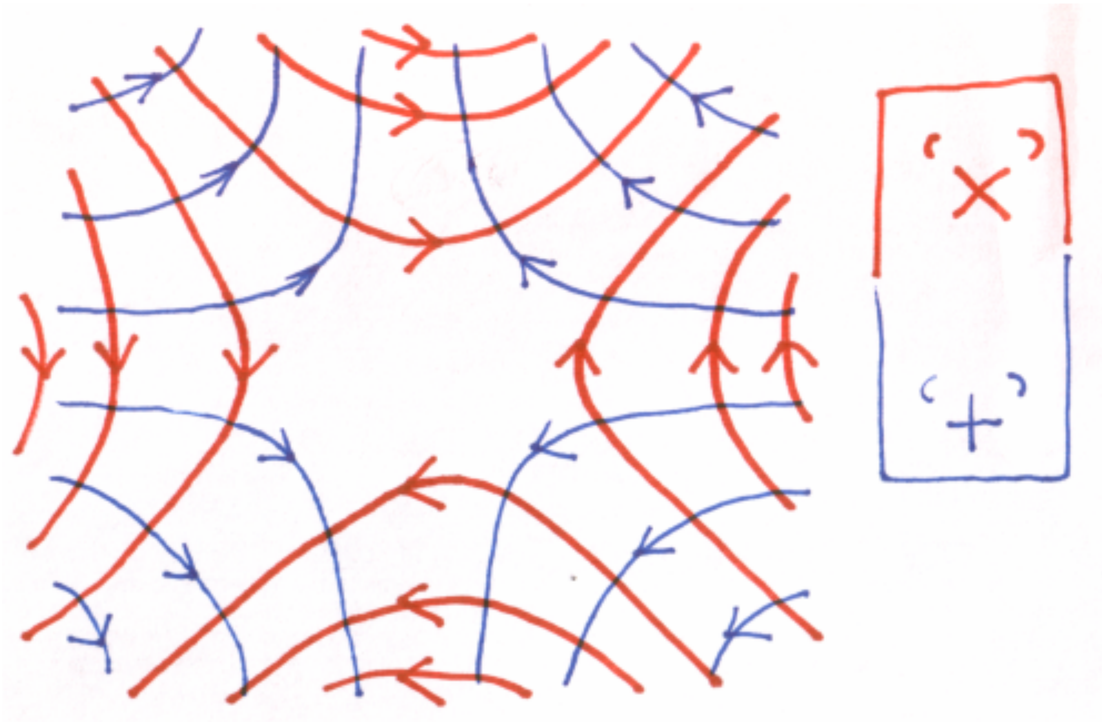
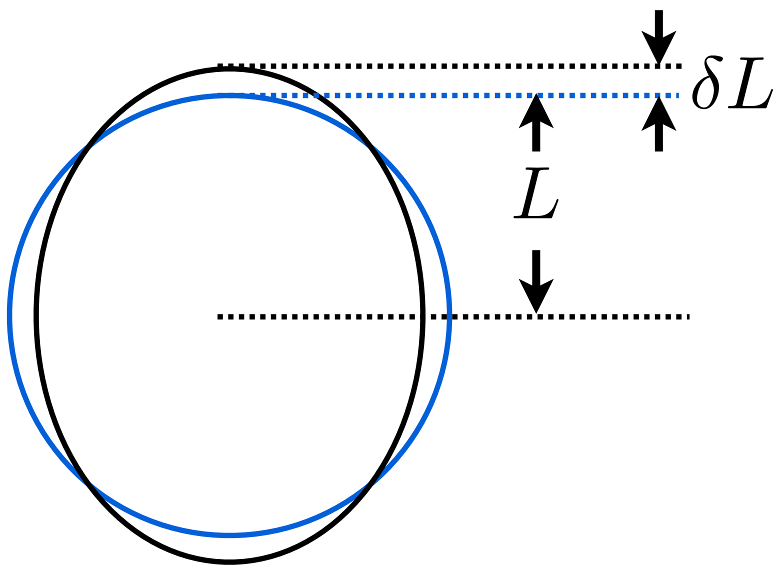


Anticipated Signal Strength



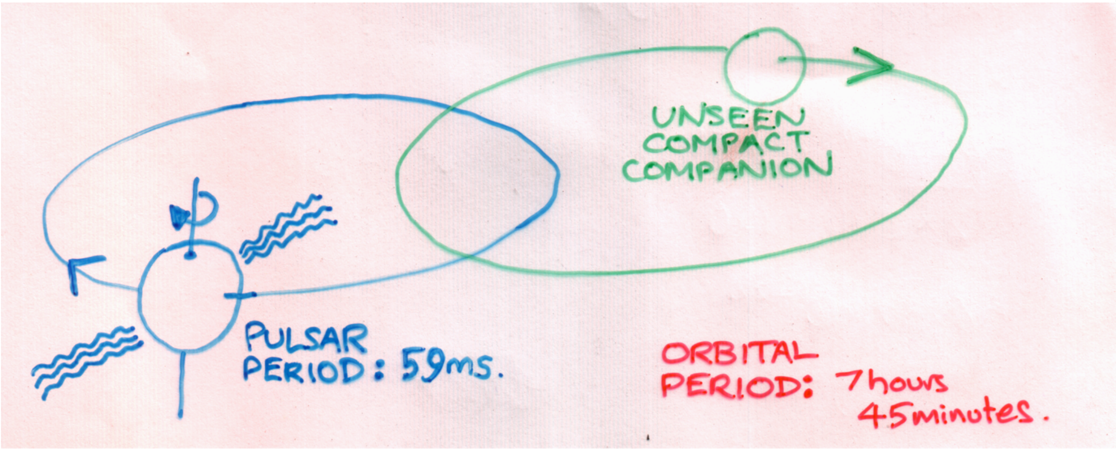
For an optimistic source, like a neutron star pair inspiral in the Virgo cluster, 20 Mpc from here,

$$\frac{\delta L}{L} \sim 10^{-21}$$

At LIGO Hanford, each arm length is distorted by about 1/250 of a proton diameter !

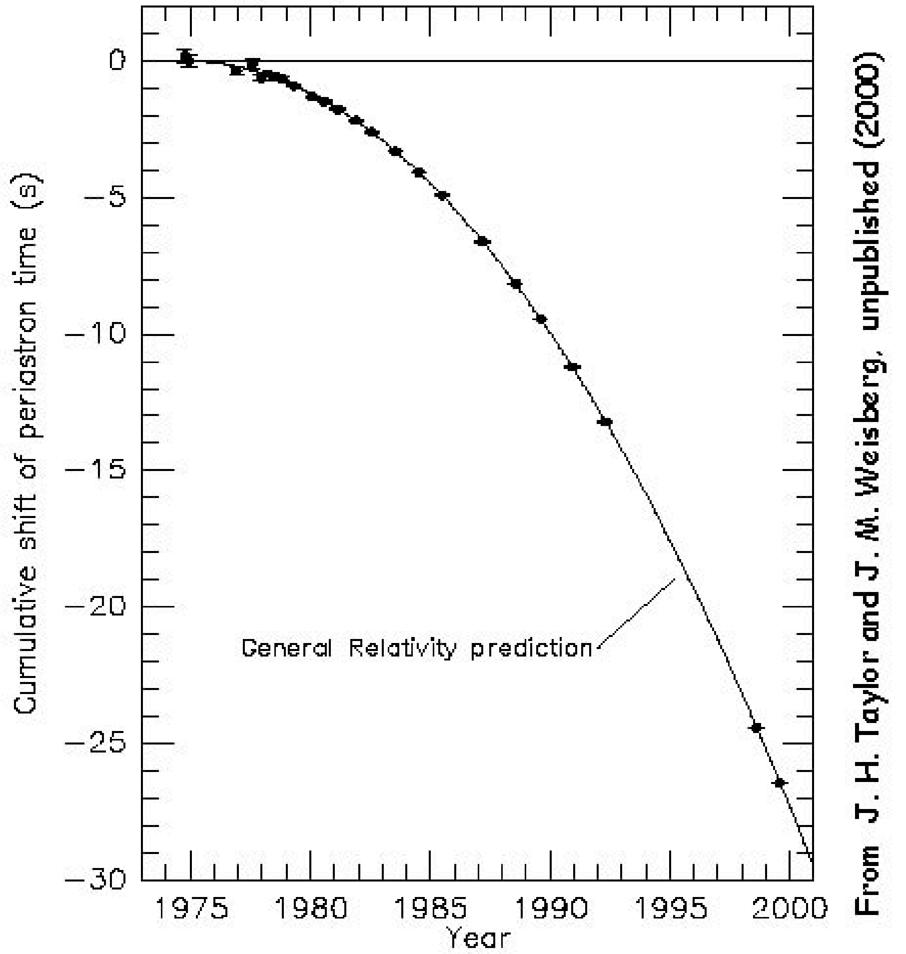
Indirect evidence for gravitational radiation

Binary pulsar PSR1913+16, Hulse and Taylor, 1976

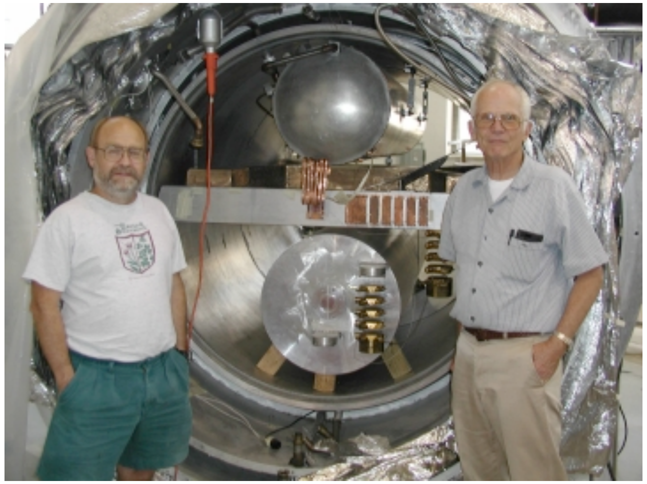


Doppler shift of millisecond pulses gives a measure of the orbital period. Orbital period decreases with time as system radiates energy in gravitational waves.

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

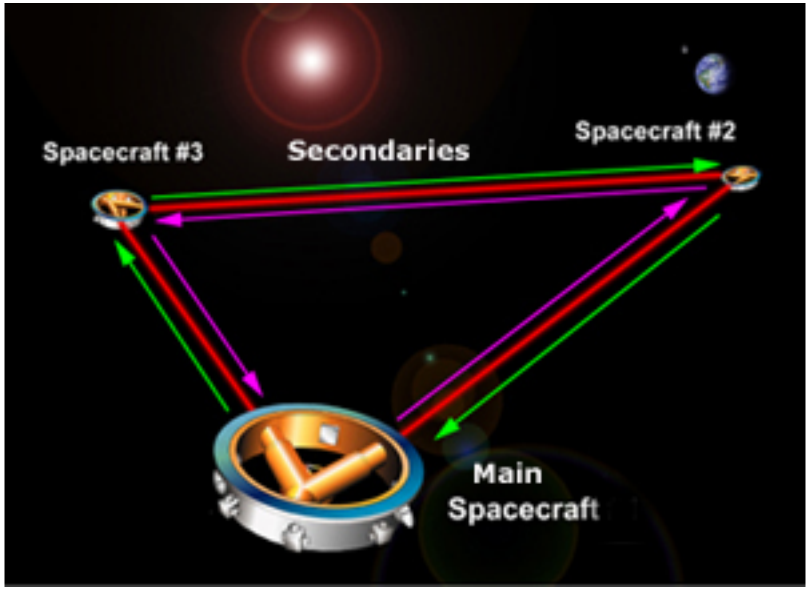


Search Instrument Types



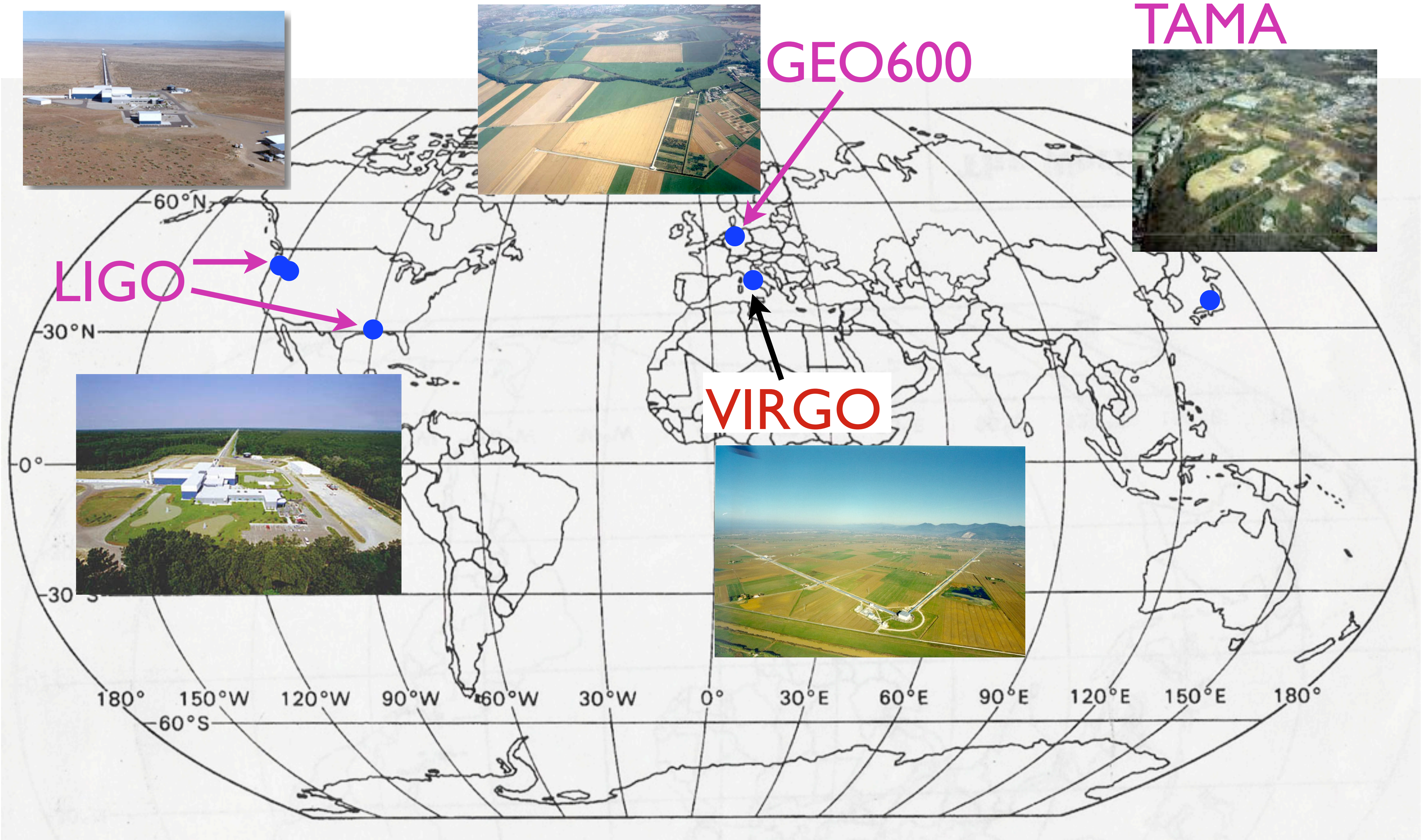
Resonant Bars
(eg: Allegro, Louisiana State University)
1kHz - 10kHz

Ground-Based Interferometers
(eg: LIGO Hanford 2km and 4km instruments)
1Hz - 8kHz



Space-Based precision metrology
(NASA/ESA LISA planned 3 satellite constellation)
0.1mHz - 0.1Hz

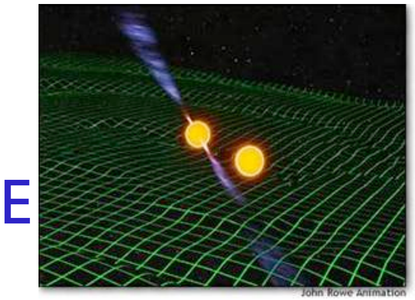
Interferometric Gravitational Wave Detectors World-Wide

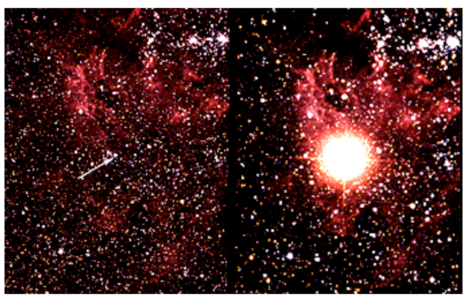


Some sources in the interferometer frequency band

BINARY INSPIRALS
- NS-NS
- NS-black hole
- black hole - black hole

MATCHED FILTERING + COINCIDENCE



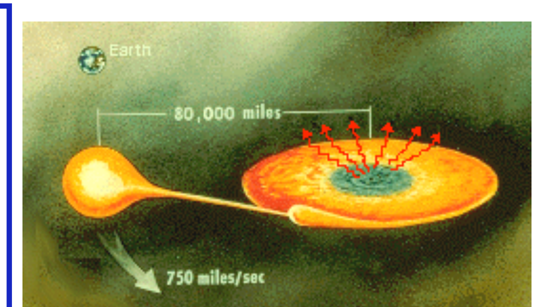


UNMODELED BURSTS
- core-collapse supernovae
- accreting/merging black holes
- gamma ray burst engines

TIME / TIME FREQUENCY / WAVELET BASED SEARCHES FOR EXCESS POWER. COHERENT TIME DOMAIN SEARCHES.

LONG TIME DURATION AVERAGING / COINCIDENCE

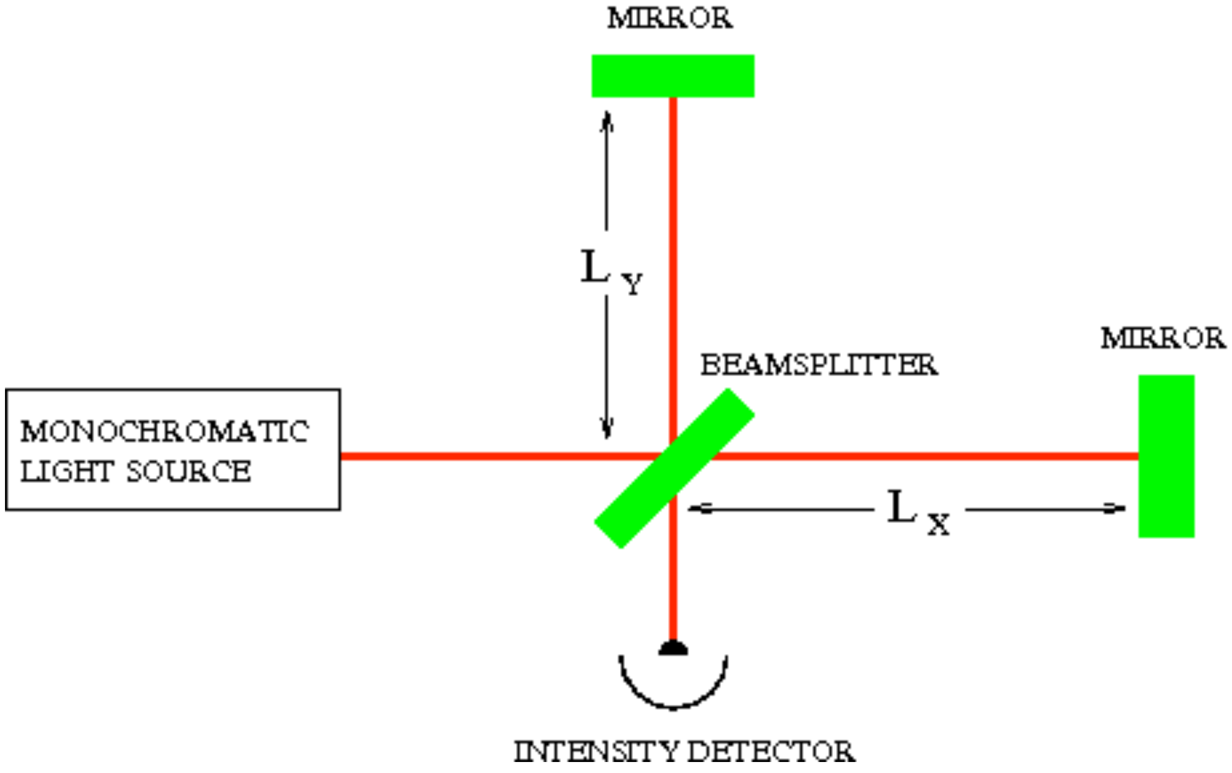
CONTINUOUS WAVE SOURCES
- non-axisymmetric neutron stars
- pulsars with precessing spin axis
- low mass x-ray binaries



MULTI-INTERFEROMETER CROSS CORRELATION

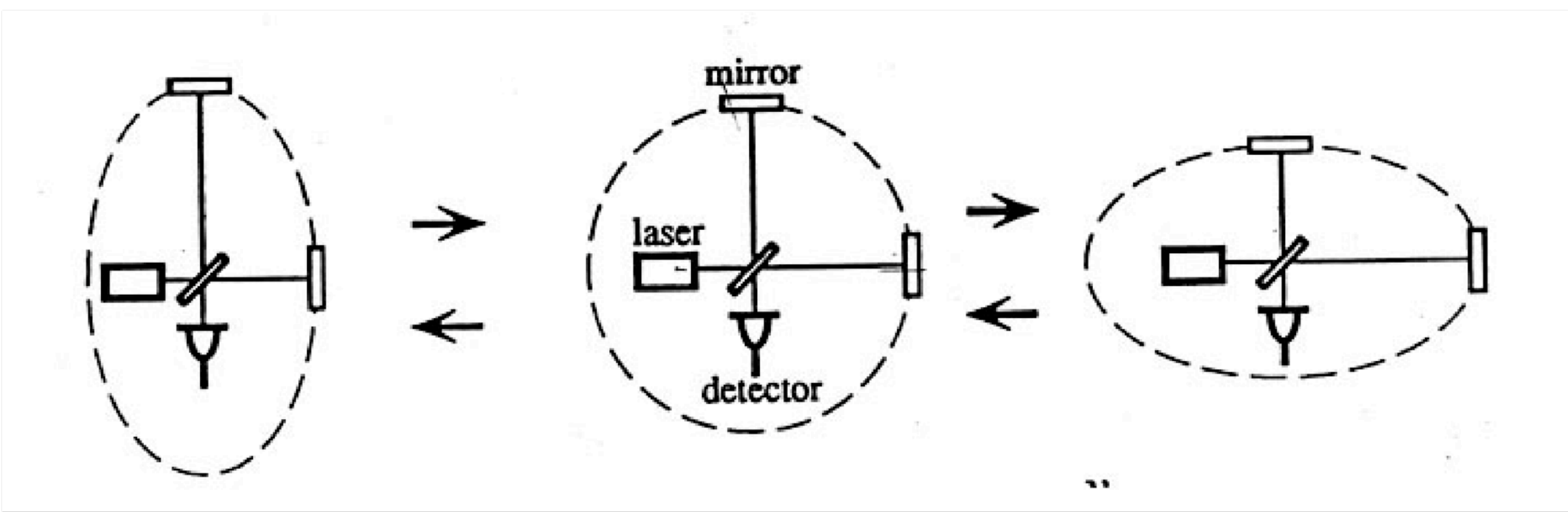
STOCHASTIC
- cosmic gravitational wave background.
- unresolved astrophysical sources.

The Michelson Interferometer

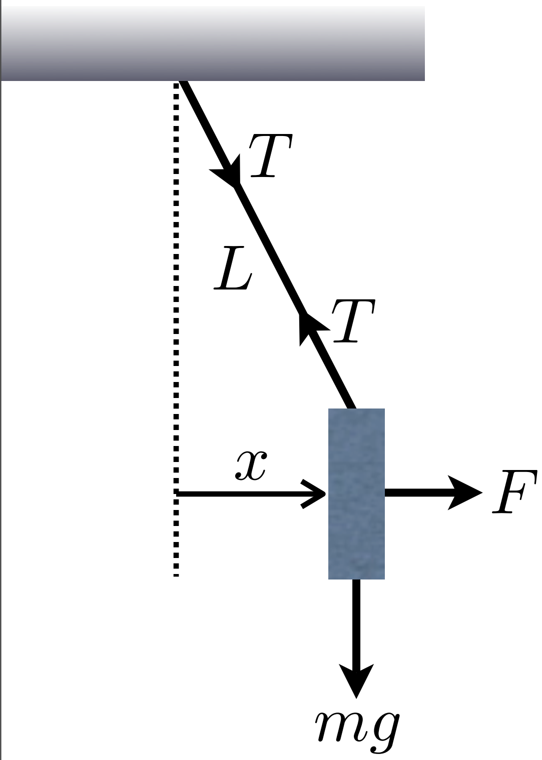


strain changes the differential length:

$$\delta = \frac{L_x - L_y}{2}$$



Test masses, pendulum suspensions



$$F(t) - \frac{mgx(t)}{L} = m\ddot{x}(t)$$

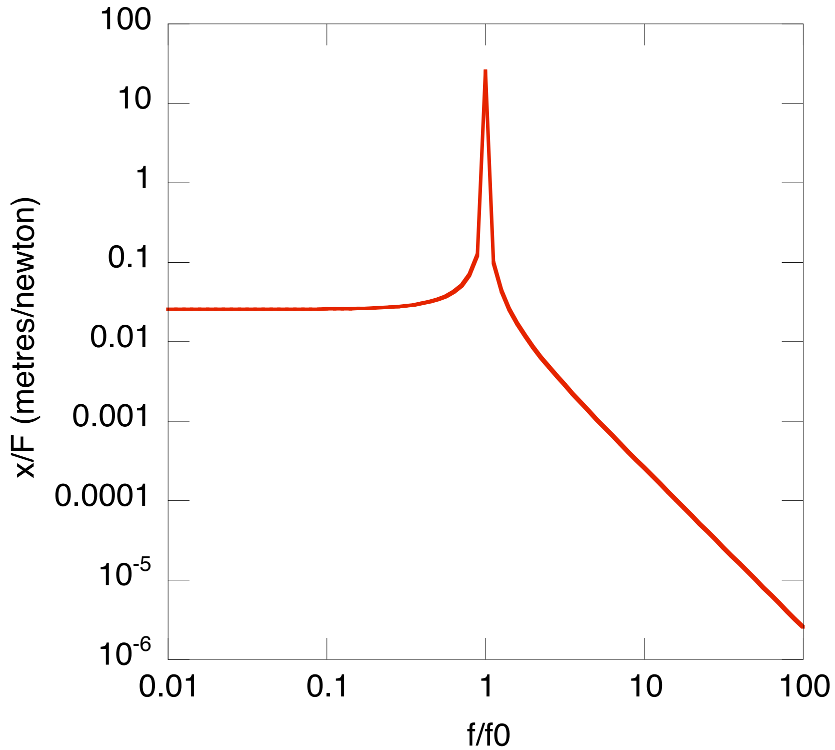
$$\tilde{F}(\omega) = -m\omega^2\tilde{x}(\omega) + \frac{mg\tilde{x}(\omega)}{L}$$

$$\omega^2 \gg \frac{g}{L} :$$

$$\tilde{F}(\omega) \approxeq -m\omega^2\tilde{x}(\omega)$$

$$F(t) \approxeq m\ddot{x}(t)$$

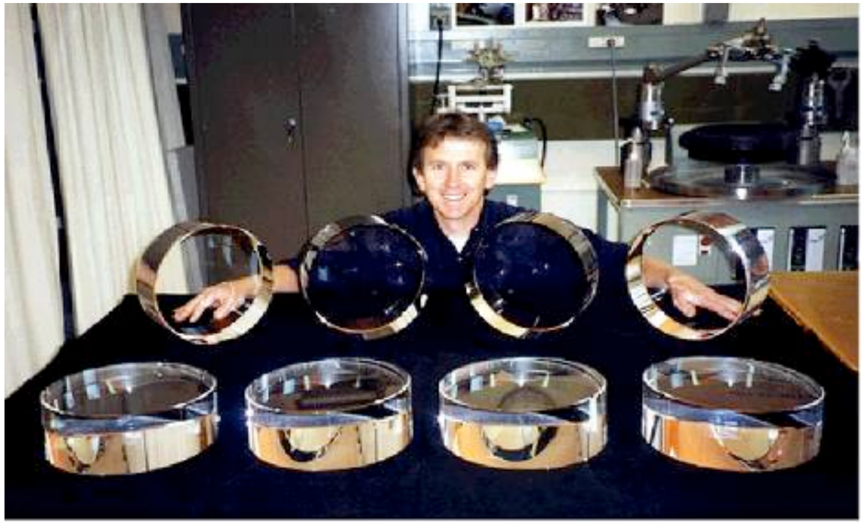
The suspension acts as a low pass filter between the mass and support.

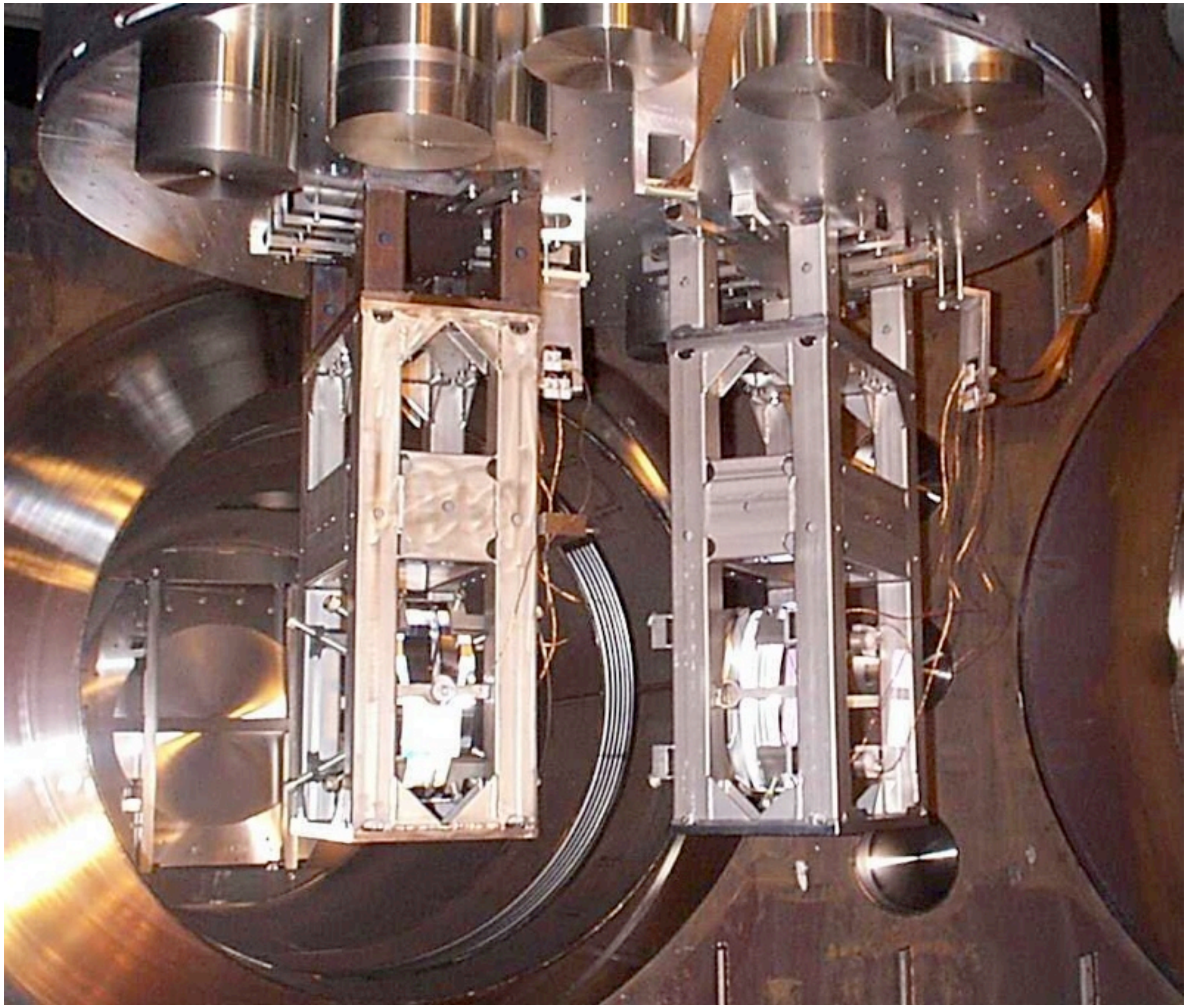


Well above the resonant frequency of the pendulum, the suspended mass has the equation of motion of a free particle.

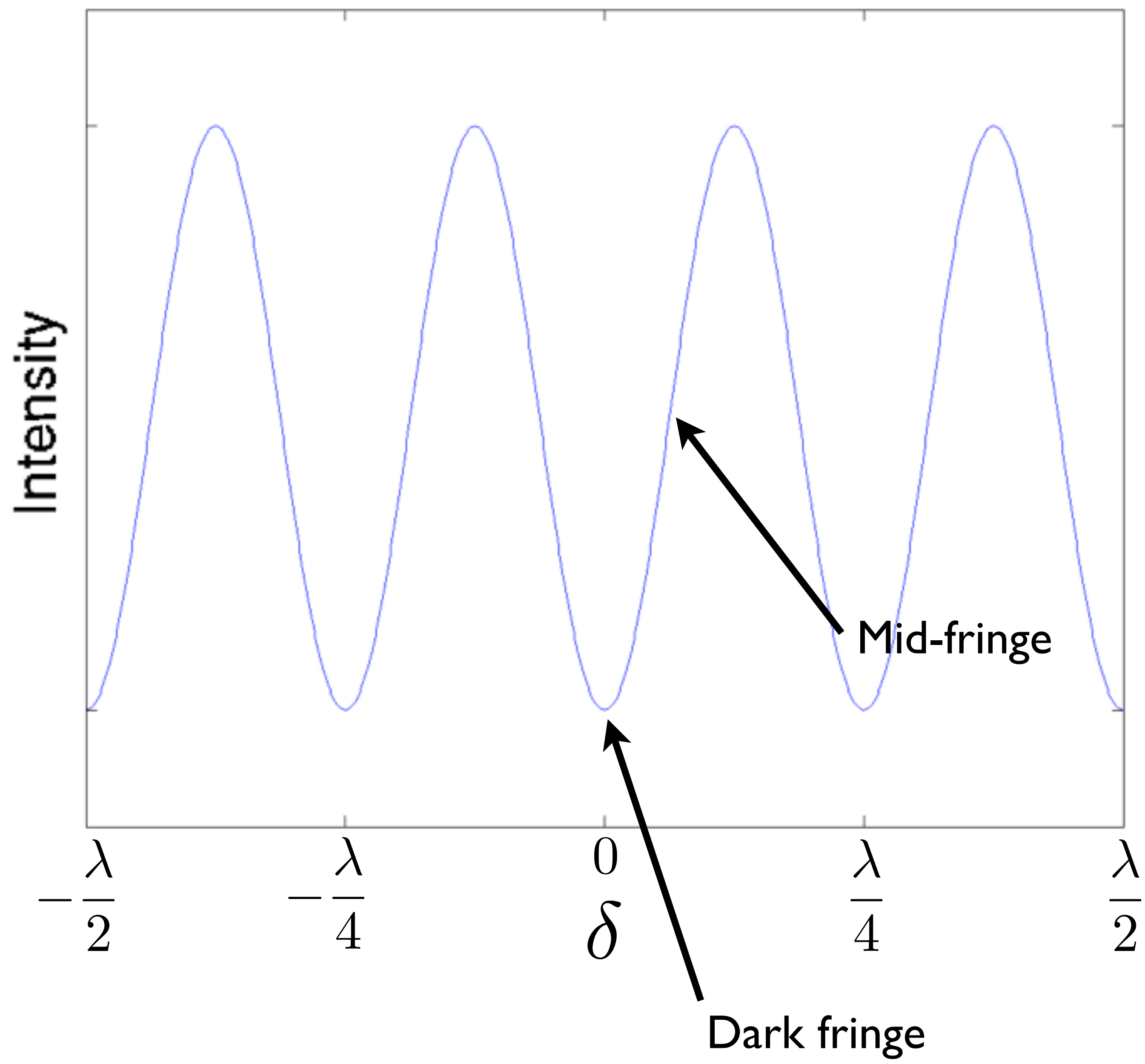
LIGO

Suspended test masses





Where to 'Bias' the Michelson?



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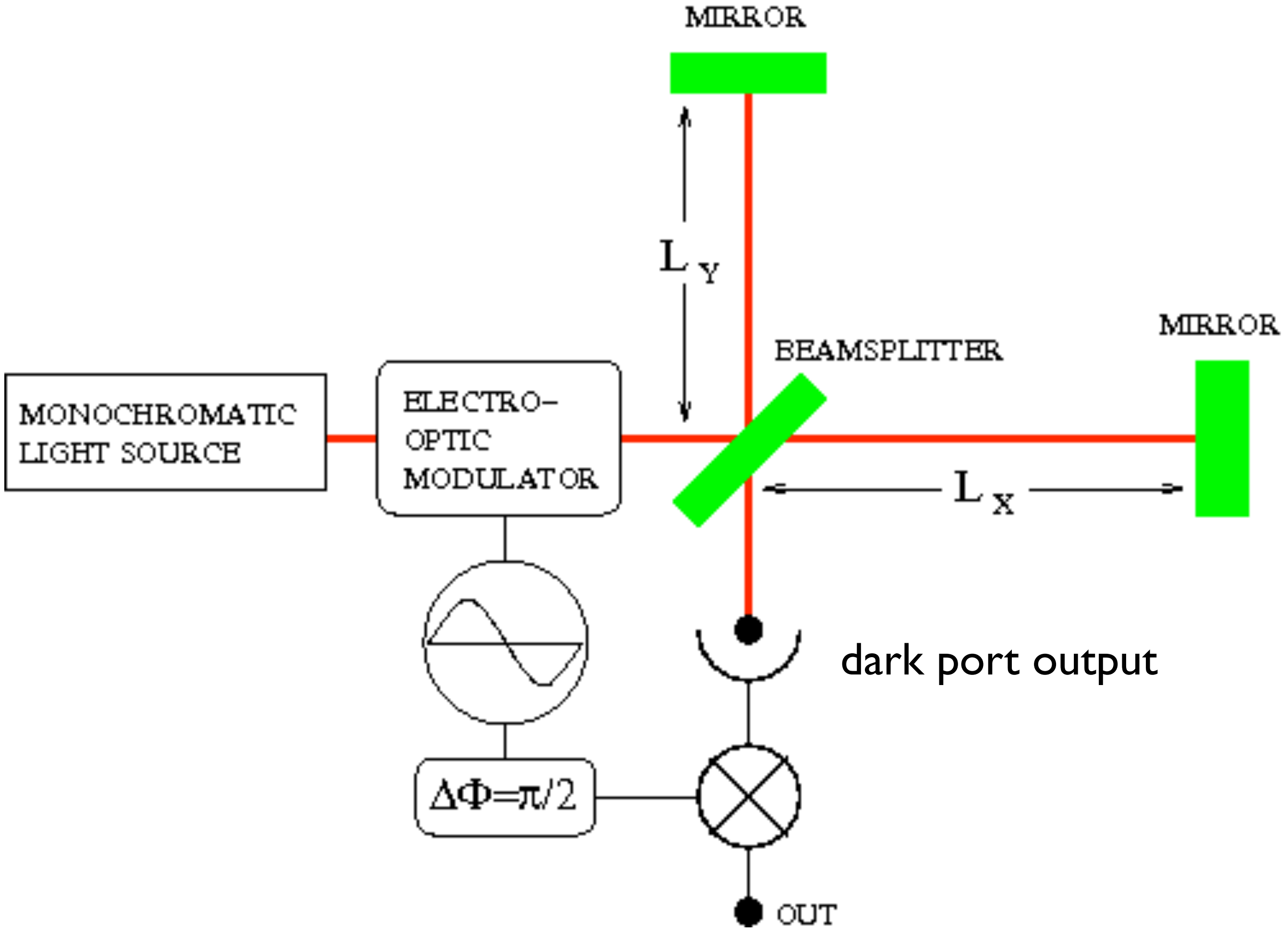
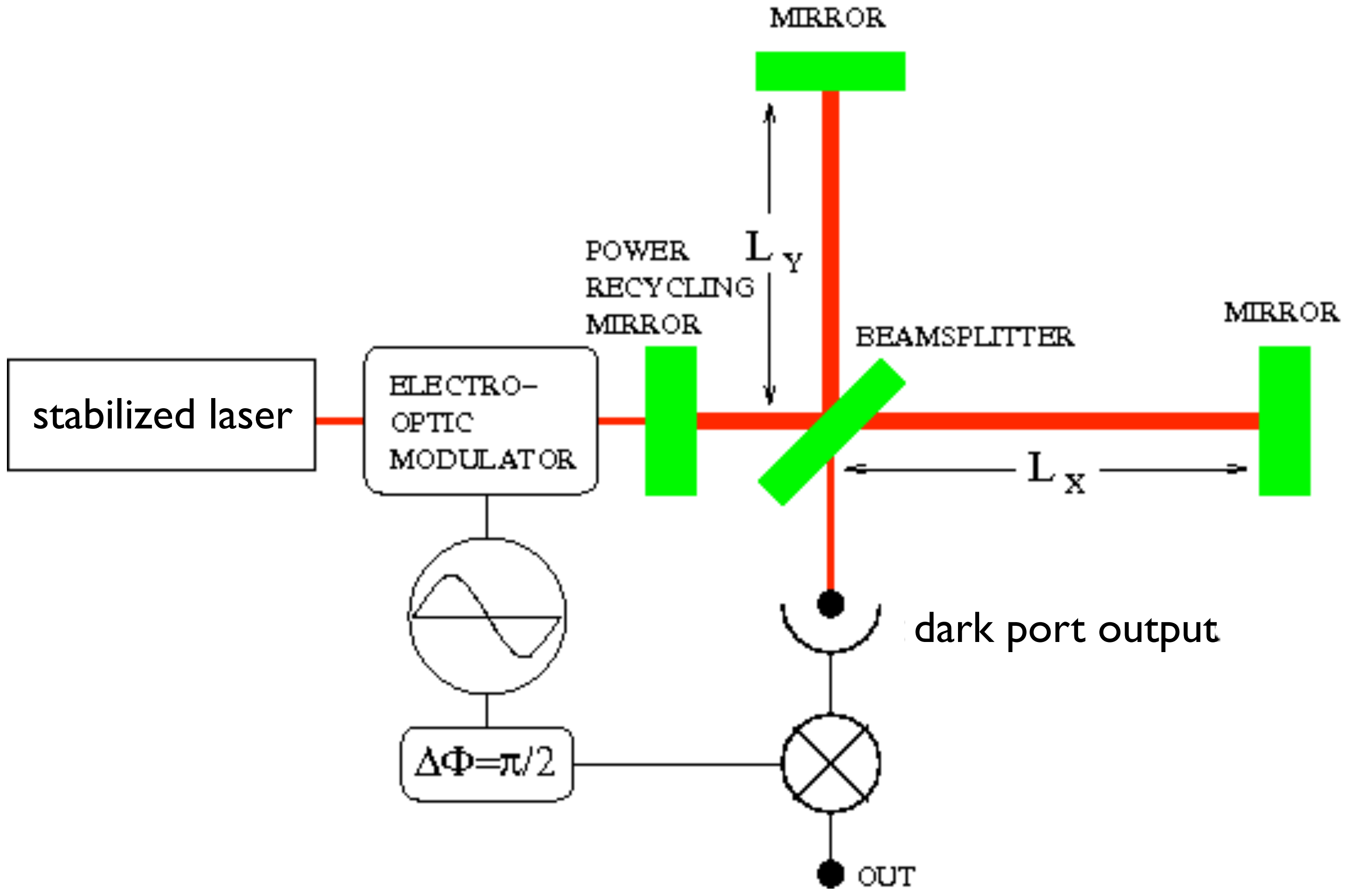
Schnupp modulation

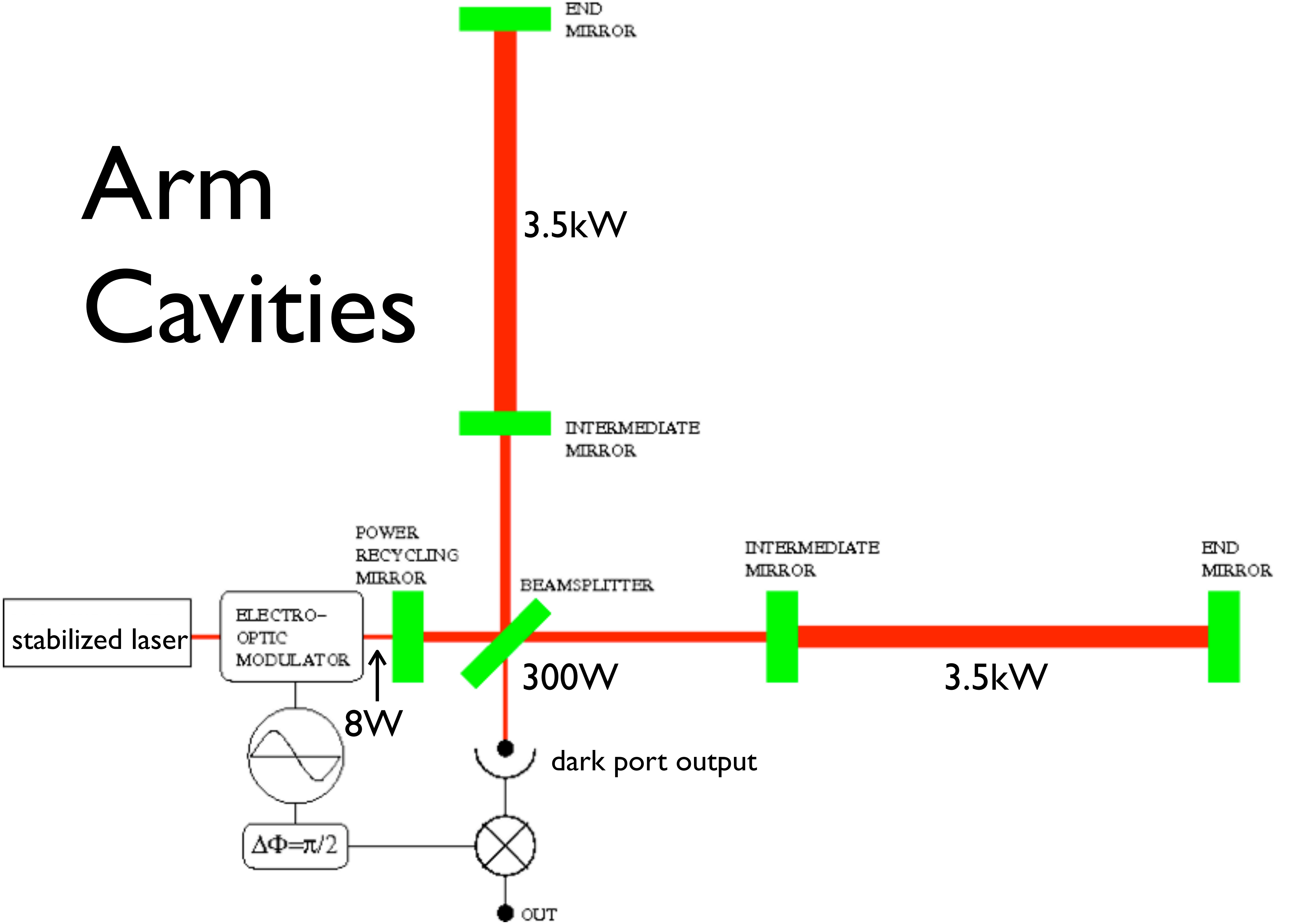
Lise Schnupp



Power Recycling



Arm Cavities



Interferometers

Interferometers

Interferometers

Vacuum Systems

Beam Splitter Chambers

Livingston Corner Station Lab

Back-of-the-Envelope Strain Sensitivity

Noise Limit: Uncertainty in phase σ_ϕ of each light beam re-combining at the beam splitter. Assume quantum limited.

$$\sigma_n \sigma_\phi \sim 1$$

Power at beam splitter is 300W.

Photon flux in each beam is $n = \frac{300 \text{ W}/2}{\text{hc}/\lambda} = 7 \times 10^{20}$

$$\sigma_n = \sqrt{n} = 3 \times 10^{10}$$

$$\sigma_\phi = 1/\sigma_n = 4 \times 10^{-11} \text{ rad}$$

Noise in inferred arm length difference

$$\sigma_L = \frac{\sigma_\phi \lambda}{2\pi n_b} = 5 \times 10^{-20} \text{ m}$$

Equivalent noise in strain

$$\sigma_h = \frac{\sigma_L}{L} \sim 10^{-23}$$

Vibration Isolation Stacks

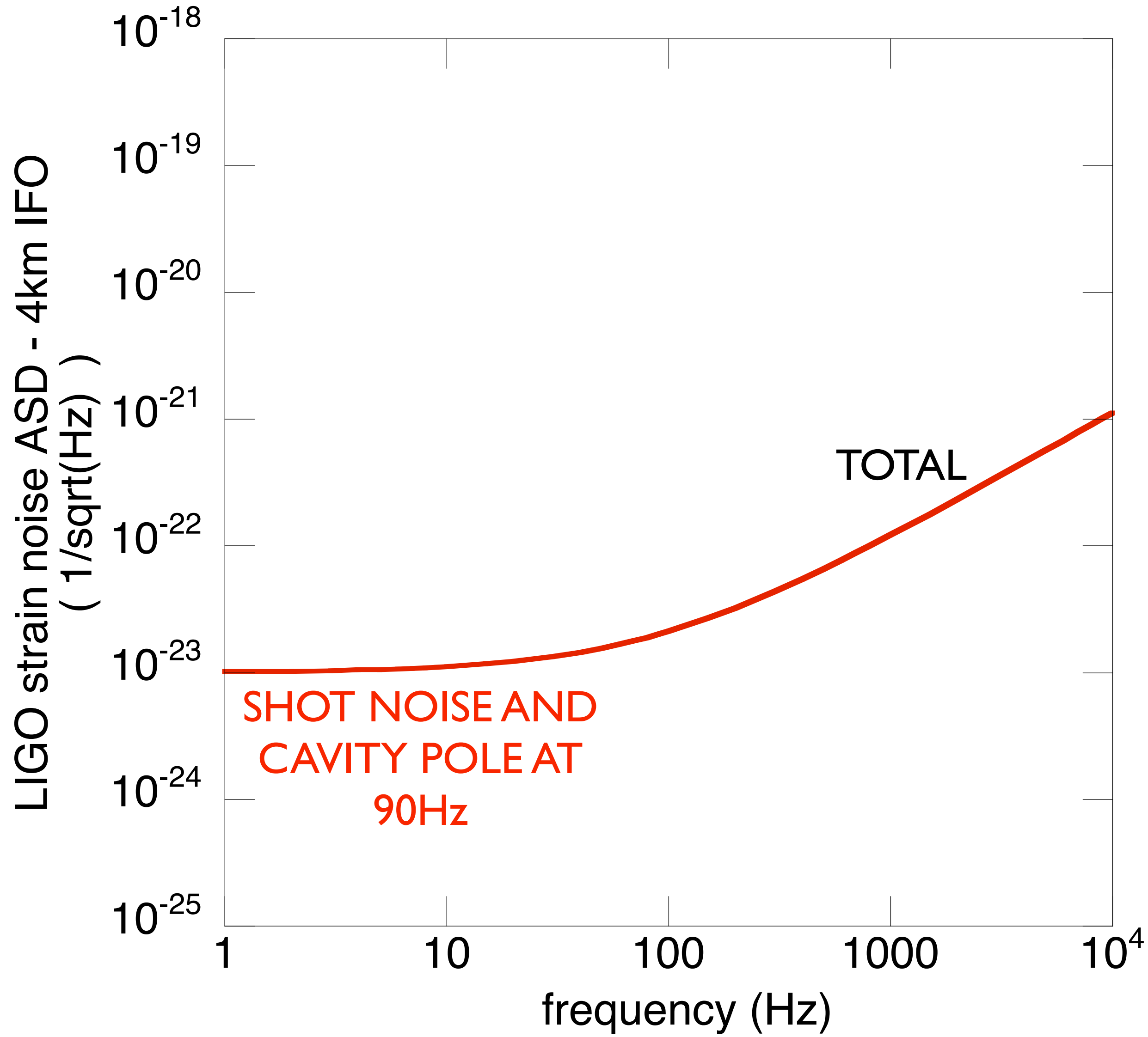
Initial LIGO uses passive stacks of masses and springs.

$1/f^2$ per layer, 4 layers

BUT only true above the resonant frequencies of the stack between 1 and 12 Hz, AND these vibrational modes that can get rung up !

Nonetheless, do expect $1/f^8$ drop-off in seismic noise at optics above 20Hz.

Initial LIGO sensitivity



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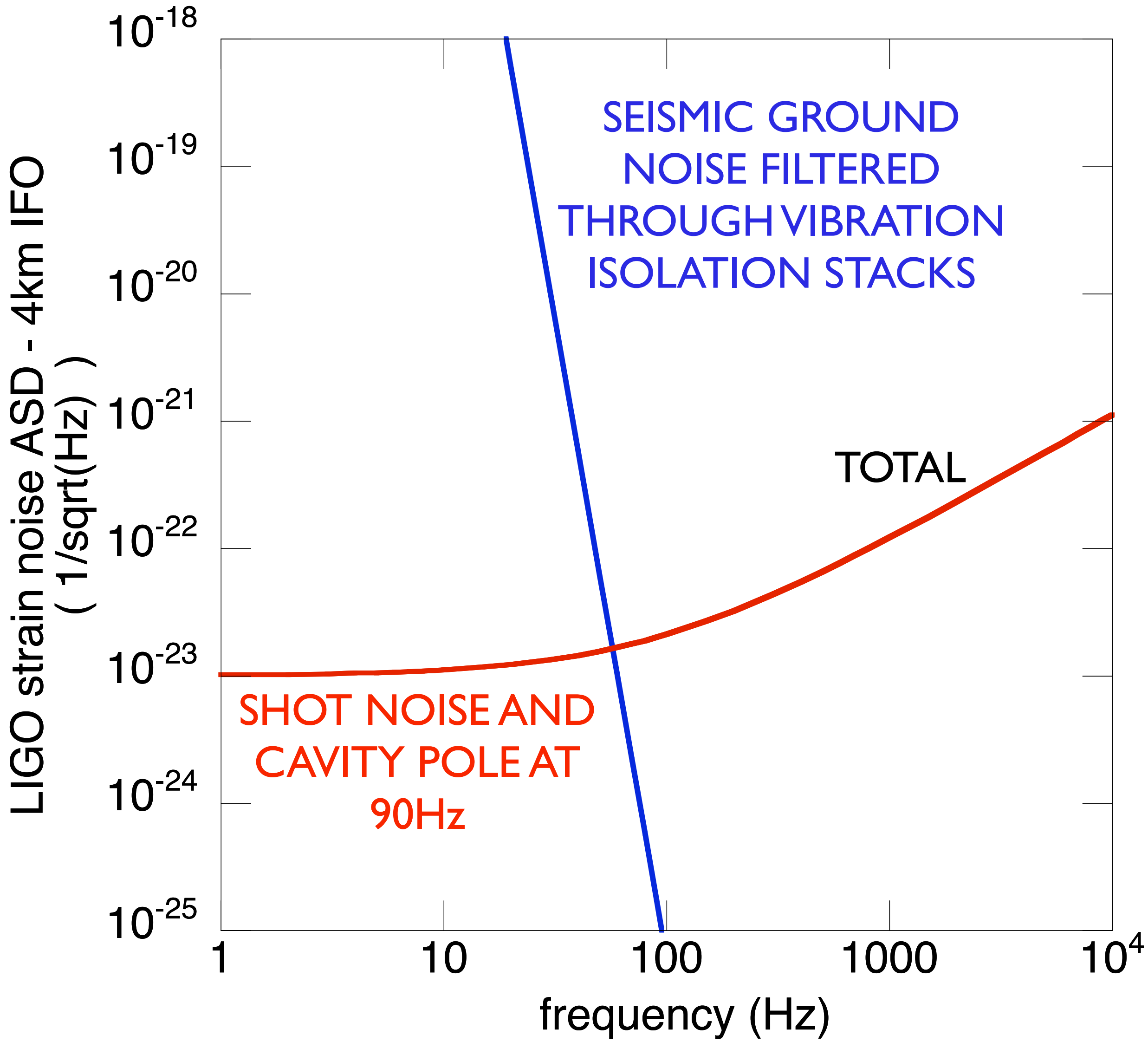
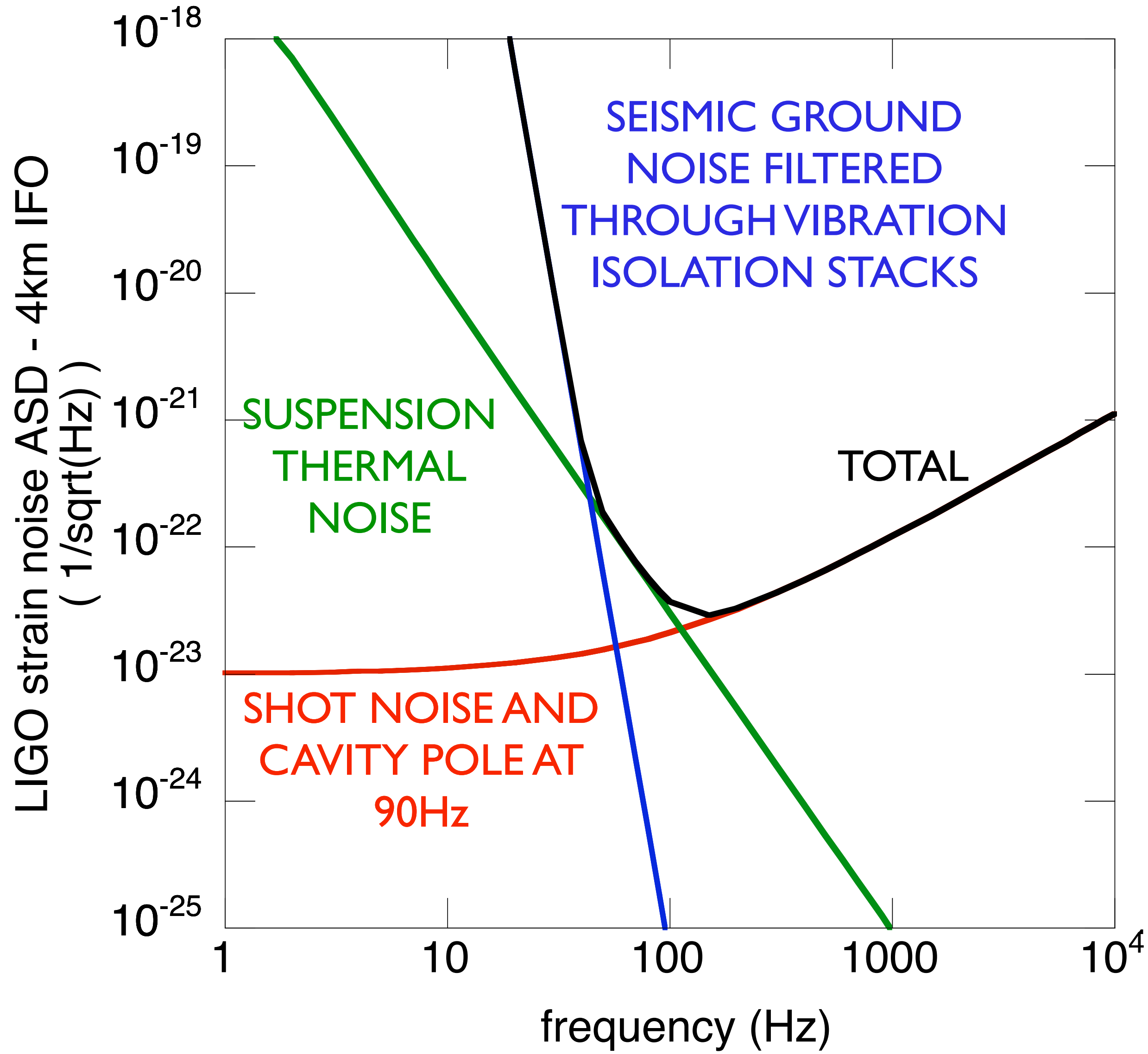
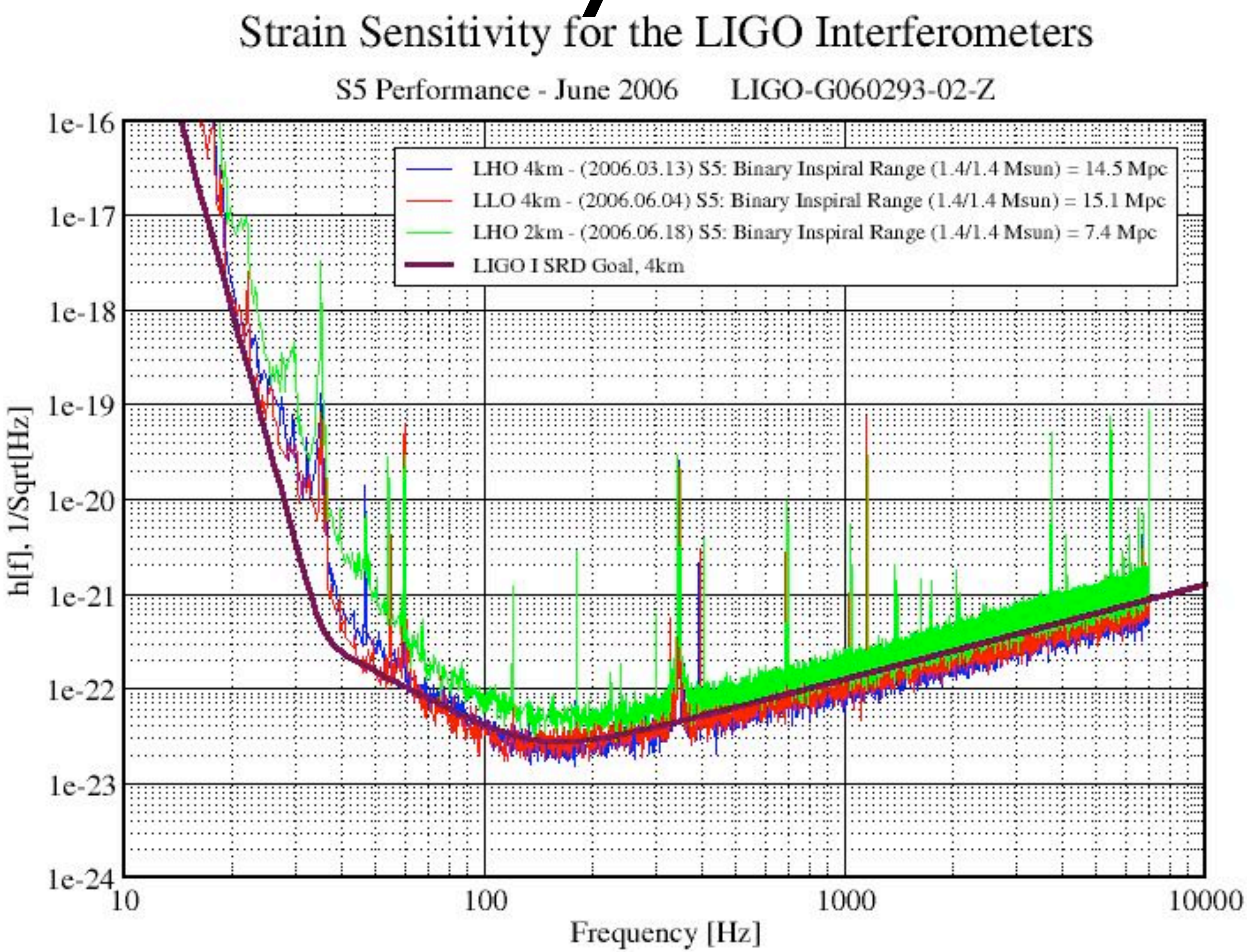


Initial LIGO sensitivity



LIGO 2 year S5 run



Initial LIGO operating at its design sensitivity above 70Hz

LIGO 2 year S5 run

Initial LIGO operating at its design sensitivity above 70Hz

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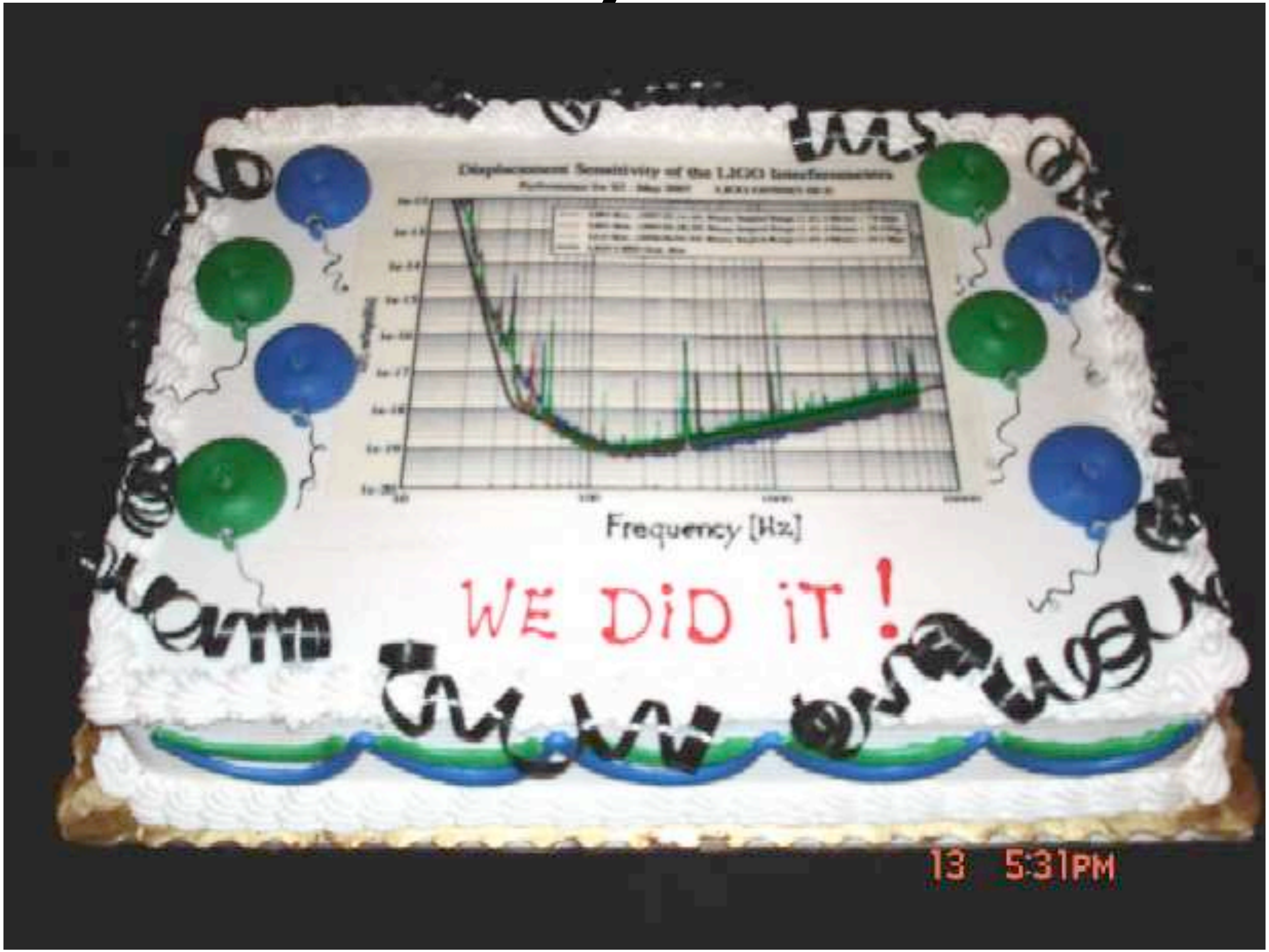
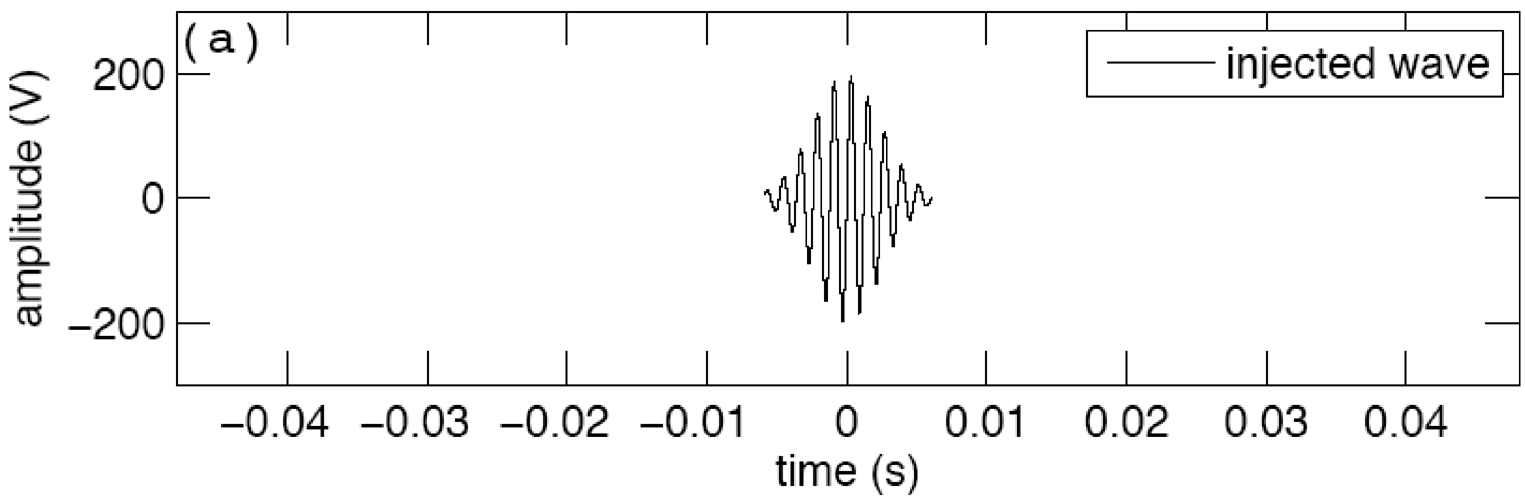


Initial LIGO operating at its design sensitivity above 70Hz

Unmodelled burst searches

My work as part of the LSC/Virgo science collaboration has recently been on methods for optimizing sensitivity to unmodelled bursts.

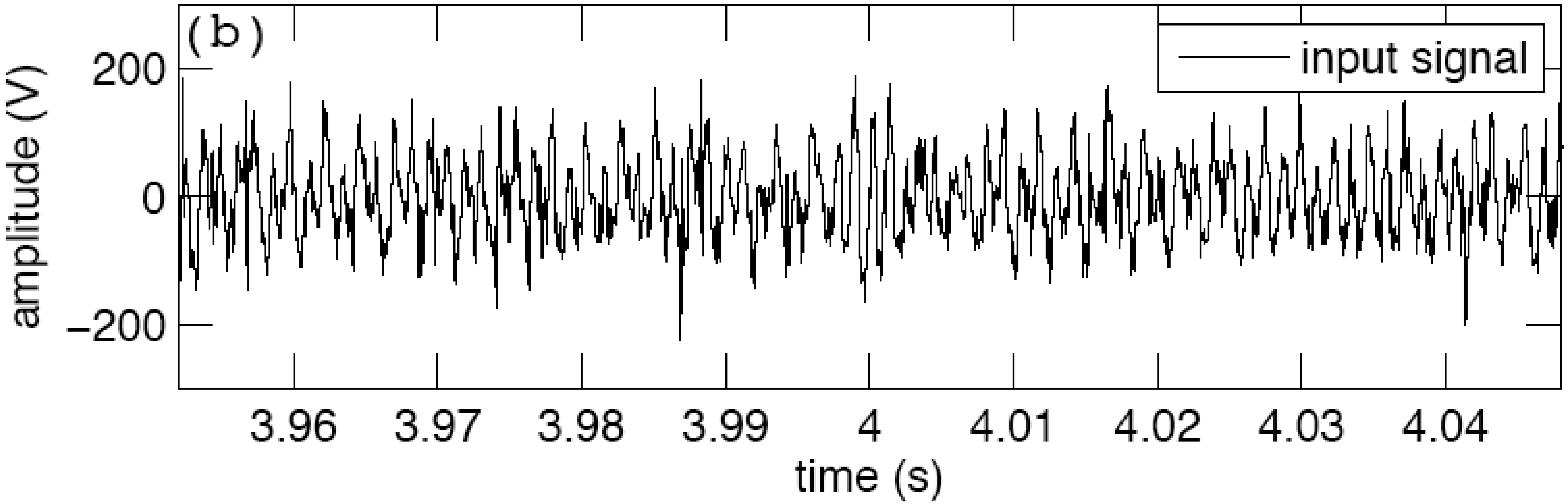
An unmodelled burst is a signal of short duration and poorly constrained shape. For example, perhaps some astrophysical source gives this signal:



How might you look for a signal like this ? Common sense suggests setting a threshold in amplitude, then looking for coincidence between signals at multiple instruments.

Lines and Line Subtraction

A problem here is that the data is polluted by coherent background - sine waves picked up from electromagnetic or mechanical background sources. When you add the above waveform to a background of this type, you might get:

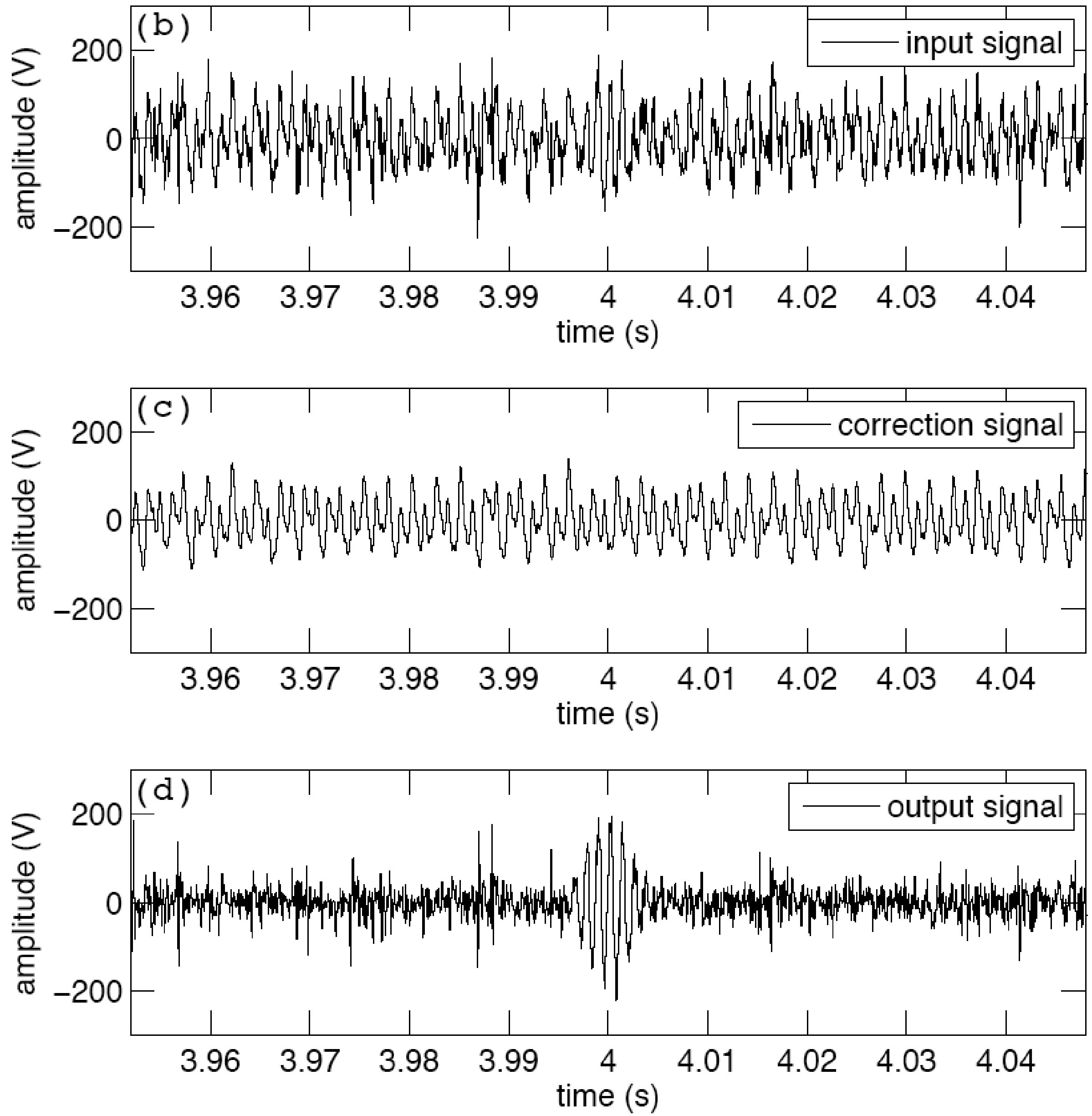


The signal has been added at 4 seconds. Could you pick this out ?
I doubt a thresholding algorithm in the time domain could either.

The trick is to either suppress the sources of the line noise (hard), or to subtract the lines in the data in a manner that doesn't throw out the signal.

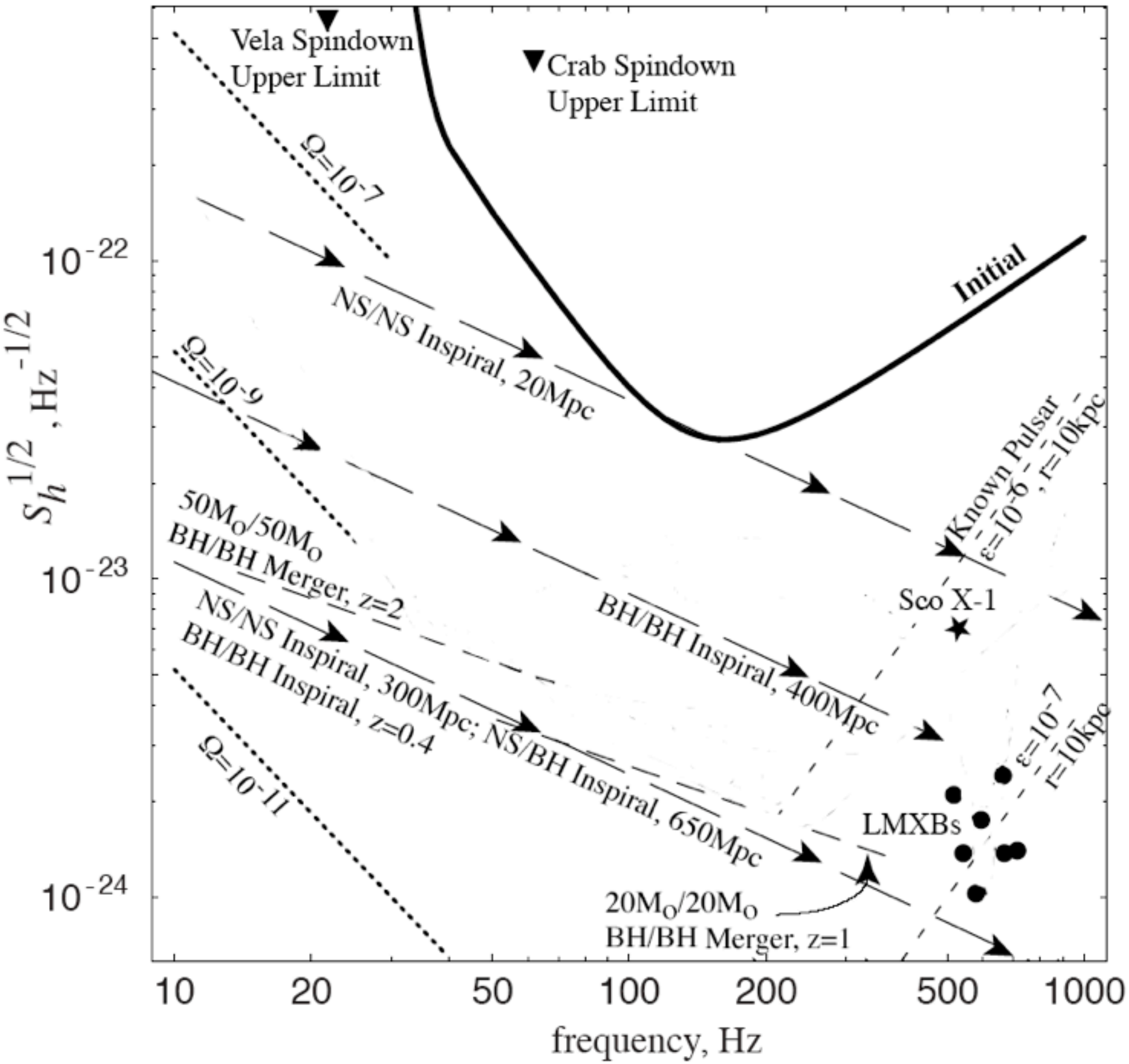
EFC line removal algorithm

We have developed an algorithm to monitor the parameters of the lines, averaged over a time duration much longer than the bursts, but shorter than the timescale for evolution of the parameters of the lines. It does quite well at removing the sine waves, without removing energy from bursts. It is much faster than real time.



Status: paper ready for submission to CQG, pending LSC/Virgo committee approval.

How Sensitive is Initial LIGO to these sources ?



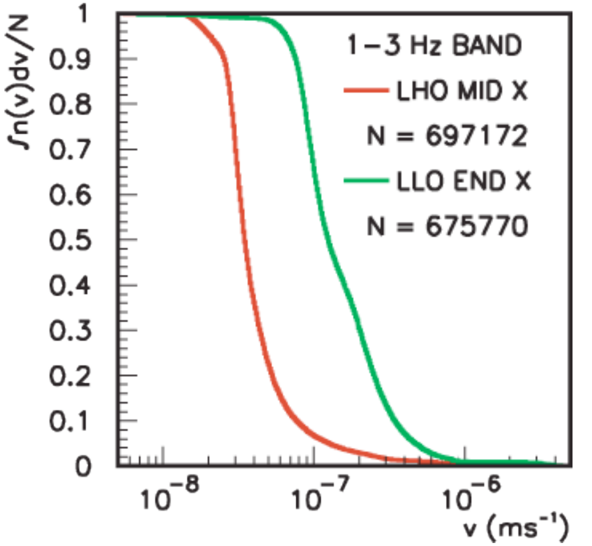
Where source has strain amplitude equal to or greater than IFO noise on this plot, source is detectable on background noise with a 1% false acceptance rate.

Adapted from K. Thorne, LIGO document P000024-A

Need to lower noise floor of the LIGO instruments

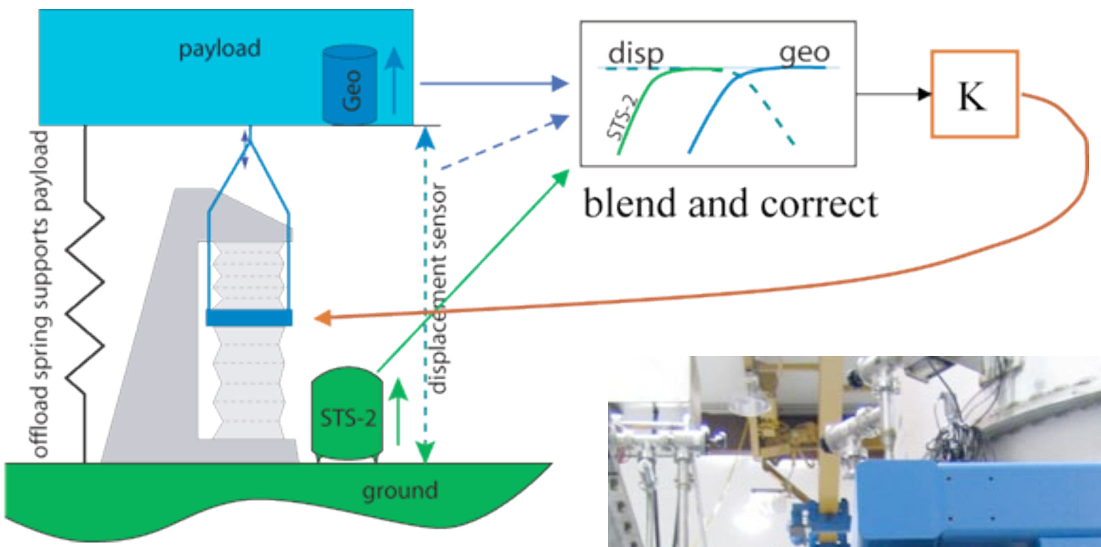
Active Seismic Isolation

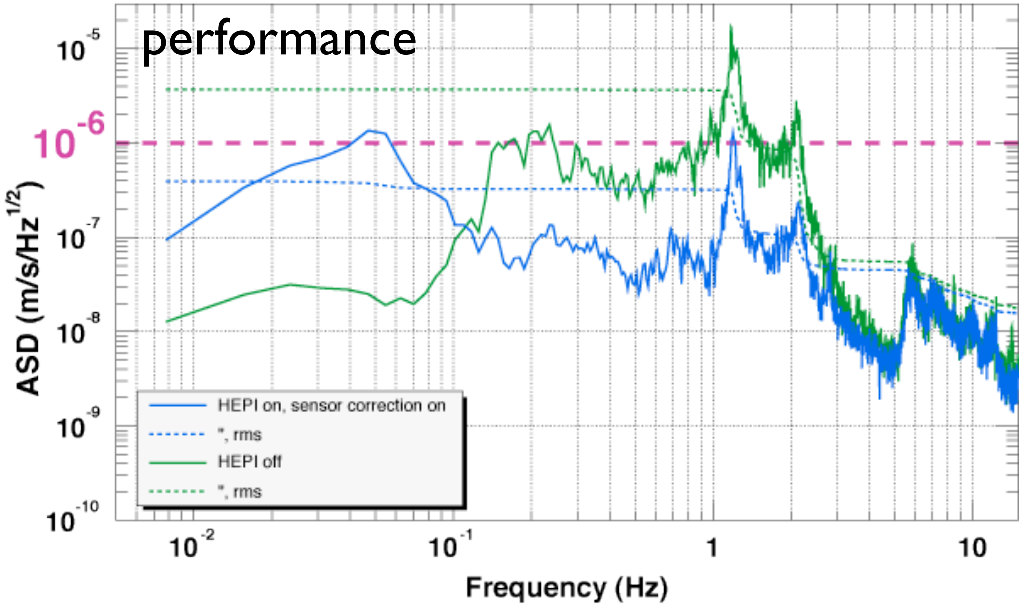
The problem: ground motion in 1-3Hz band.



Daw et al., Class. Quantum Grav, 21, 2255-2273 (2004)

Active vibration isolation based on feedforward from seismometers and feedback from accelerometers





Installation at Livingston

‘Enhanced LIGO’

Installation in progress

Phase I LIGO upgrade.
Commission some of the upgrade technologies
Increase LIGO’s search volume by a factor of 8.

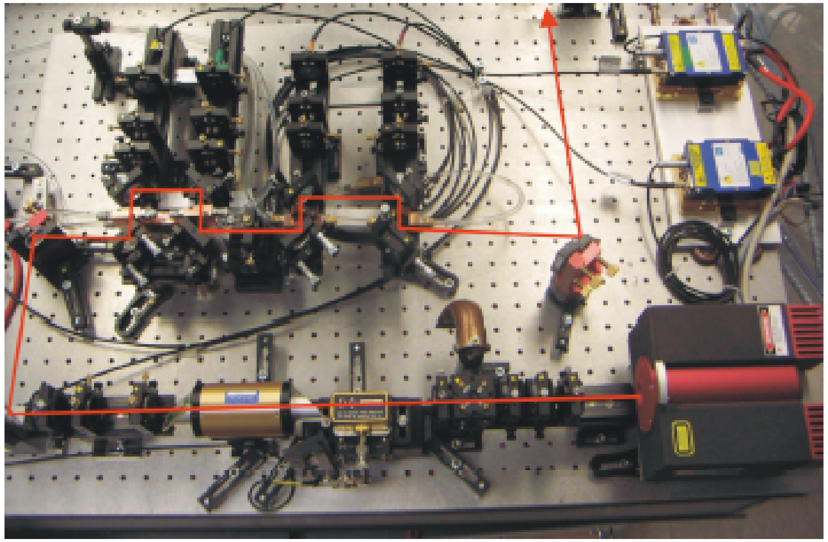
30-35W laser power

DC readout of photodiode

Output mode cleaner

Photodiode table under vacuum

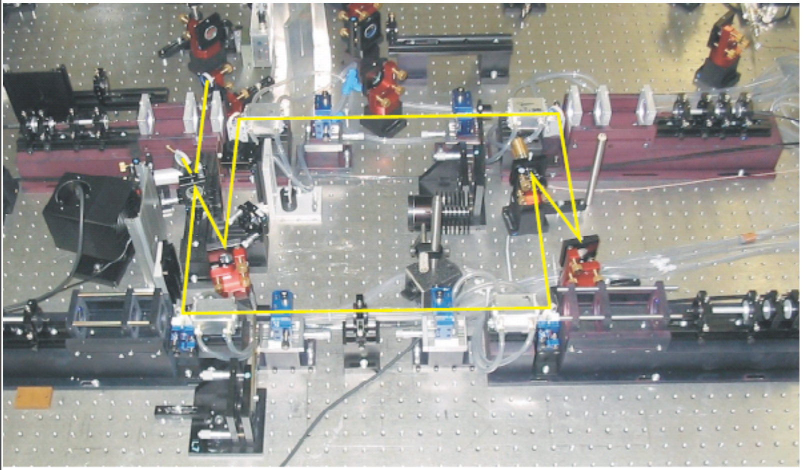
Upgrade thermal lensing compensation

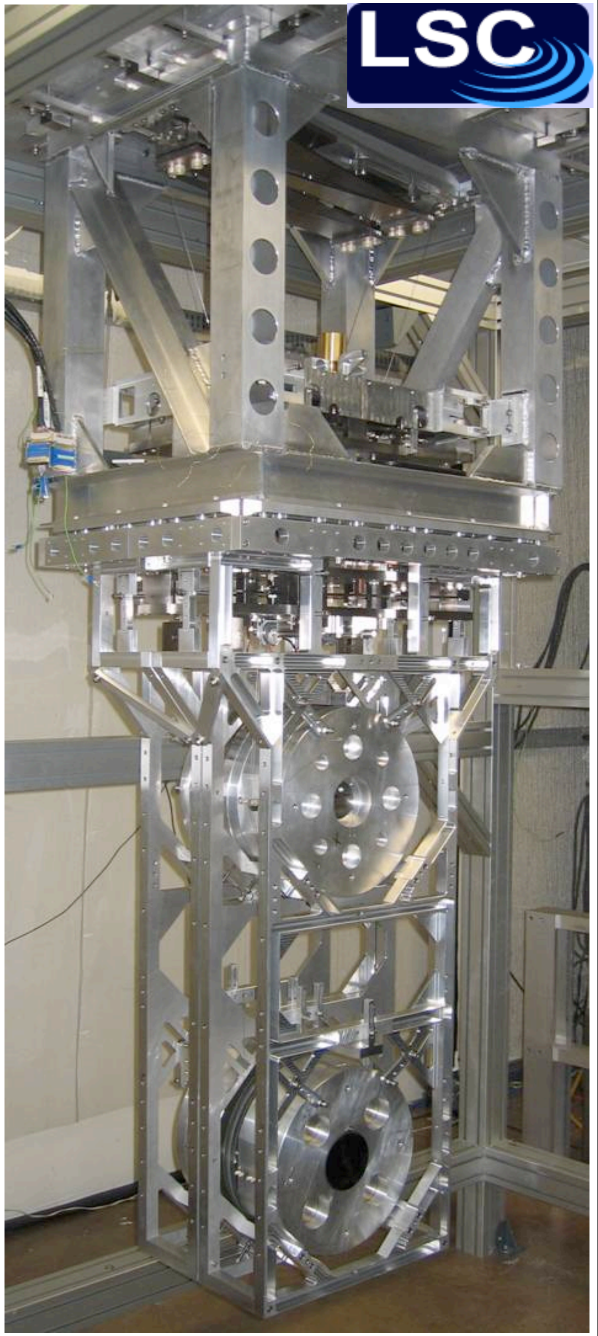


‘Advanced LIGO’

Phase 2 of upgrade plan. Factor of 10-15 improvement in sensitivity over initial LIGO.

- 180W laser power
- HEPI active vibration isolation at both sites
- High Q compound pendulum suspensions
- 40kg optics to reduce radiation pressure noise
- Signal recycling mirror for narrowbanding

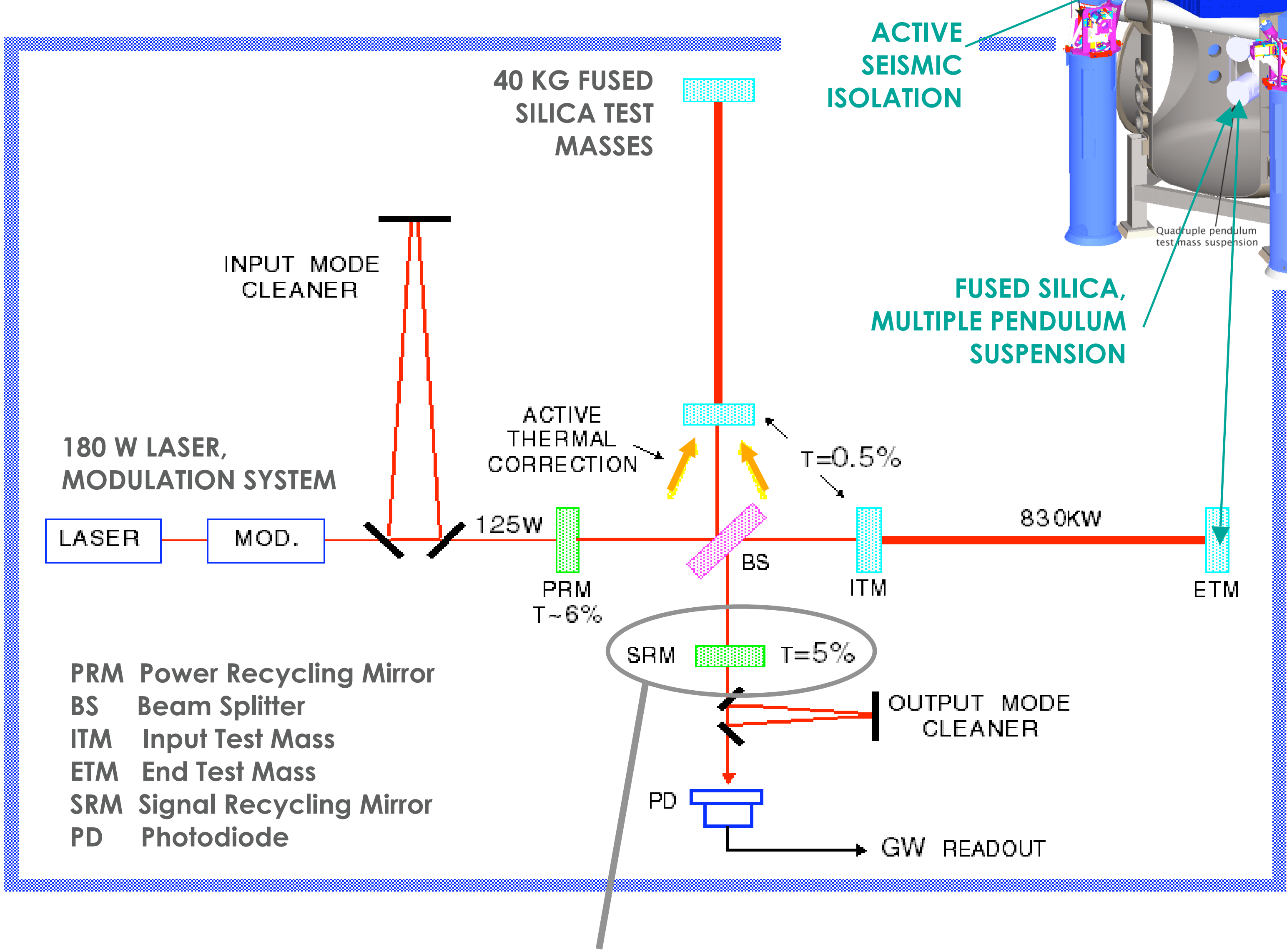


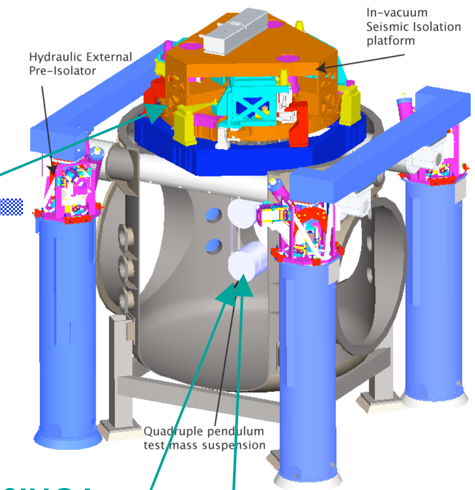


2011 scheduled installation start

LIGO

Advanced LIGO Optical Configuration

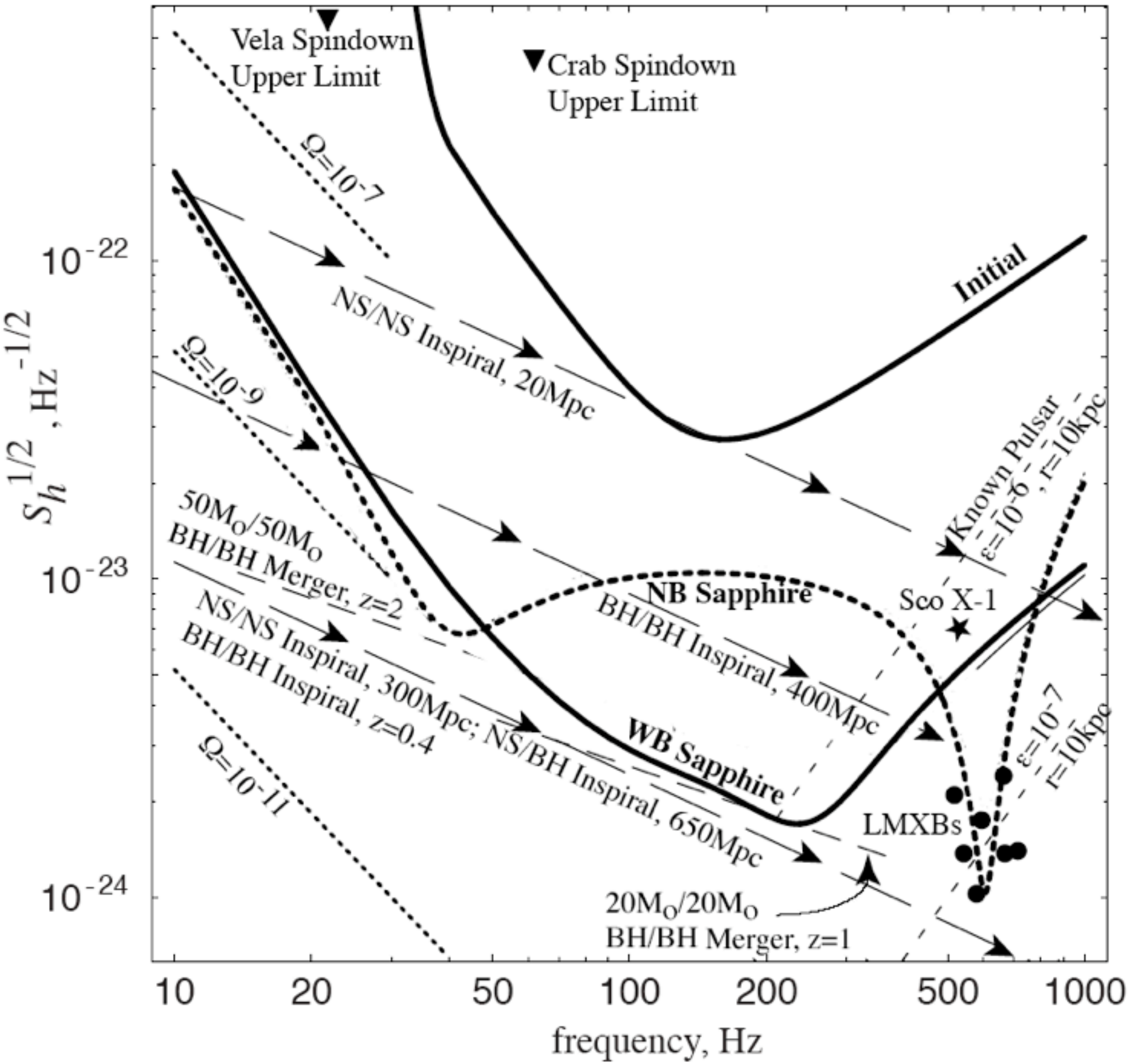




Signal recycling mirror

LSC

Sensitivity of advanced LIGO



Strain vs. source distance

LIGO signals are proportional to gravitational wave AMPLITUDE.

Strain is proportional to $\frac{1}{r}$, not $\frac{1}{r^2}$.

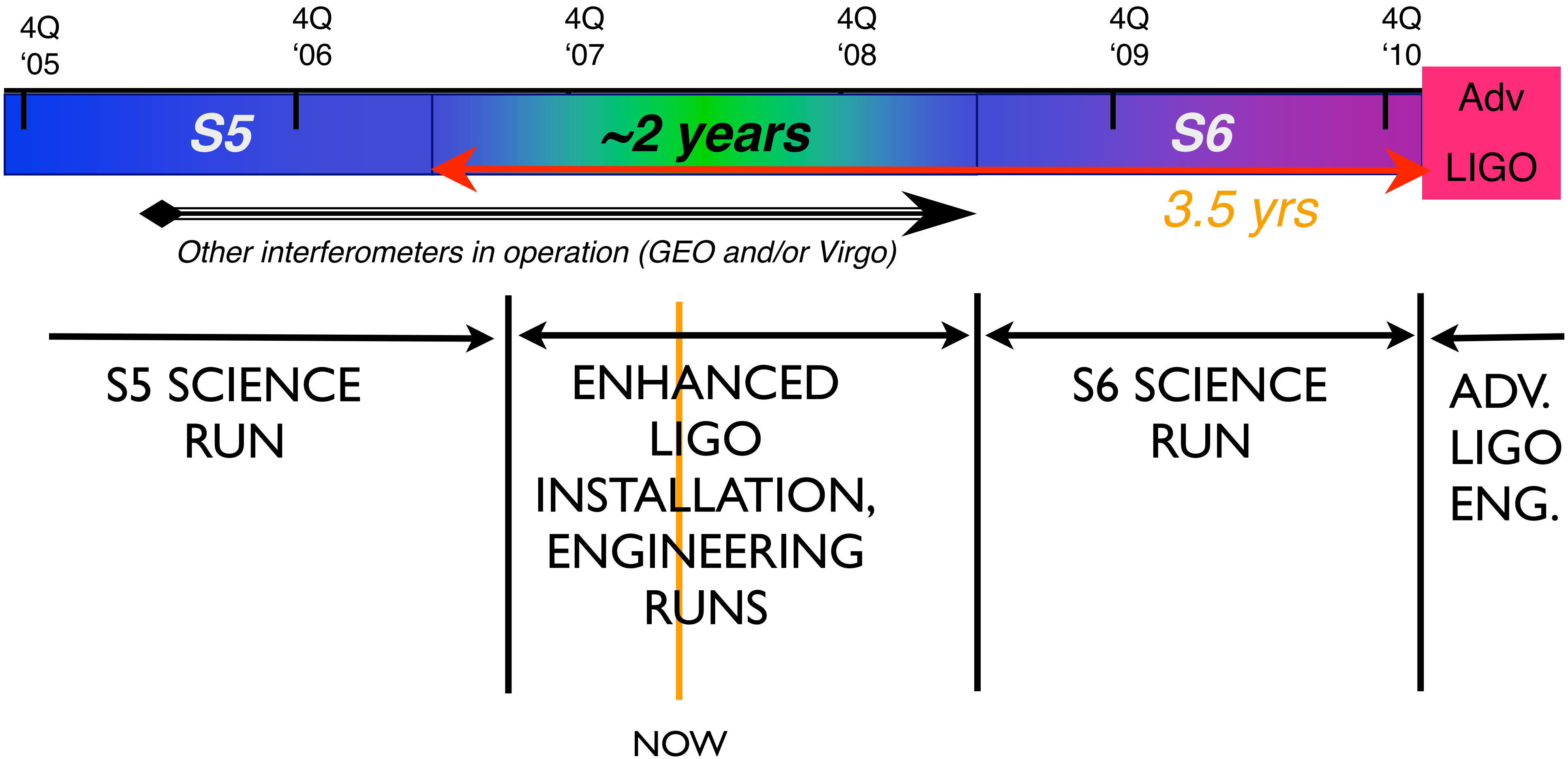
So dividing the noise level by 10, for example, would increase the range by a factor of 10.

....which increases the search volume, or the rate for a given source, by a factor of roughly 1000.

	ESTIMATED RATE (per year)		
	initial LIGO	enhanced LIGO	advanced LIGO
NS-NS	0.0002-0.01-0.7*	(0.002-0.1-6)	1-60-400*
NS-black hole	0.002-0.02-0.07*	(0.02-0.2-0.6)	9-80-400*
BH-BH	0-0.8-2*	(0-6-16)	0-2000-8000*

*Belczynski, Kalogera, Bulik - Ap.J., 572: 407-431

LIGO upgrade timeline



Laser Interferometric Space Antenna

Seismic and gravitational gradient noise limits ground-based detectors to f > 1Hz.

For sources below this frequency, we must build space-based gravitational wave detectors.

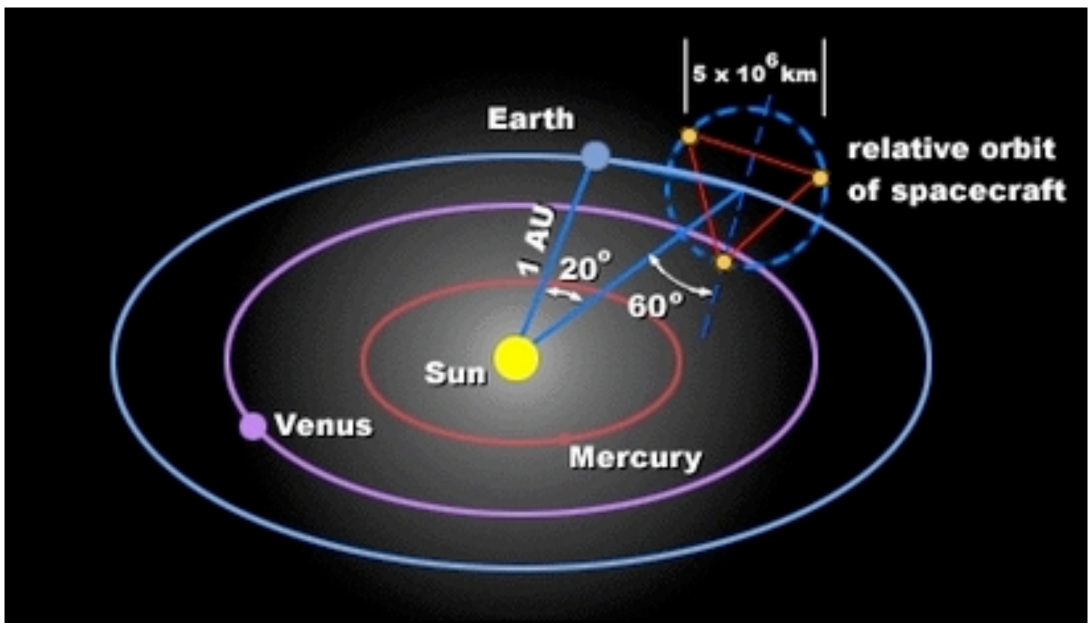
In space, it becomes much less practical to operate elaborate ‘fringe locked’ interferometers.

On the other hand, it becomes much more realistic to build very long baseline instruments.

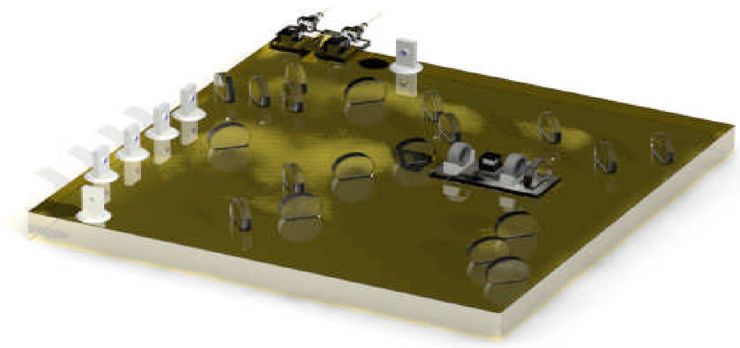
LISA Constellation

Baseline set by storage time of photons order of period of highest frequency gravitational waves in search.

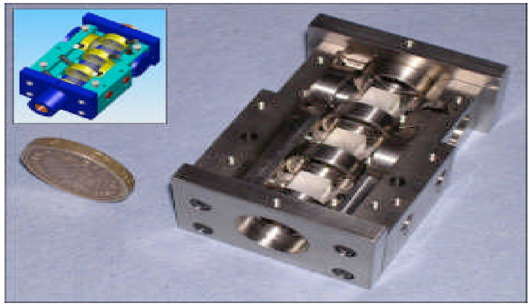
$$L = c\Delta t = \frac{c}{f} \quad \text{for f=0.1Hz,} \quad L = \frac{c}{0.1} = 3 \times 10^6 \text{km}$$



LISA technology

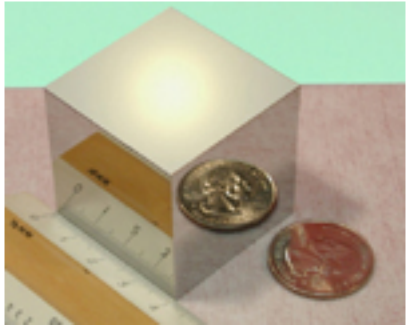


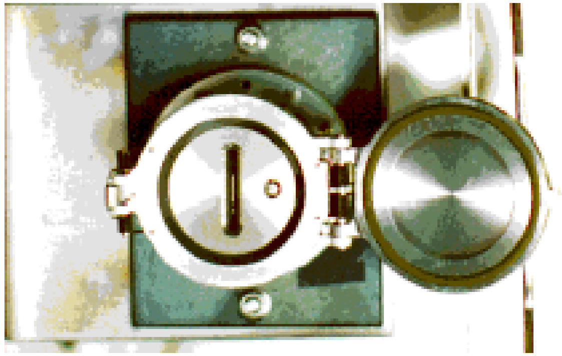
Laser power: 1W.
All except 100pW lost in transmission between satellites.

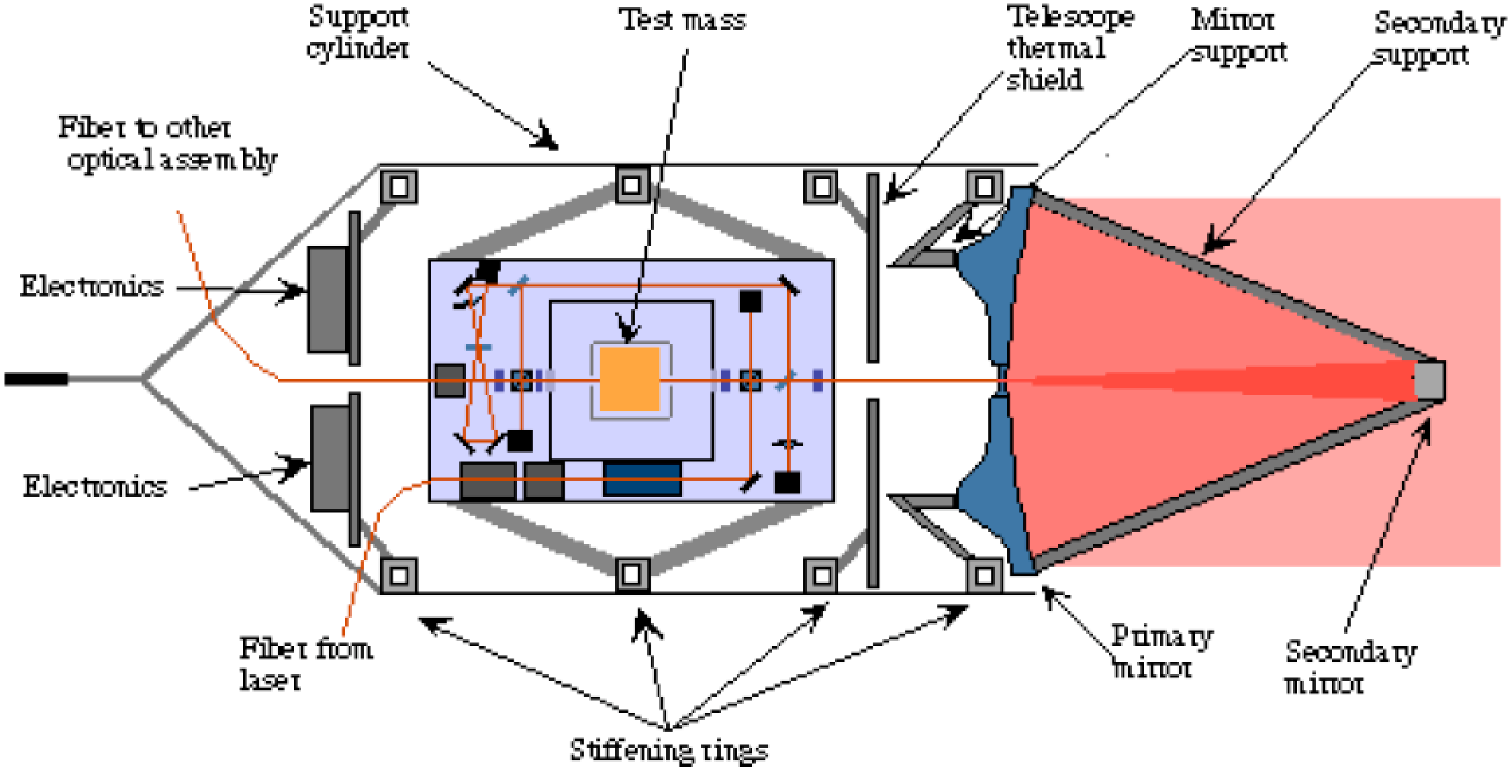


Problem -satellite subject to non-gravitational forces. It is not itself a suitable test mass.

LISA concept - the satellite body encloses test masses, and moves to track their motions,







Back of the Envelope Strain Sensitivity

Lasers are 1W, $\lambda = 1.06\mu\mathrm{m}$

Beam divergence over $5 \times 10^9\mathrm{m}$ $\quad \frac{\mathrm{P_{received}}}{\mathrm{P_{sent}}} \approxeq 2 \times 10^{-10}$

Number of photons in received beam is $n = \frac{2 \times 10^{-10}\lambda}{hc} = 10^9$

$$\sigma_n = \sqrt{n} \approxeq 3 \times 10^4$$

$$\sigma_\phi = \frac{1}{\sigma_n} = 3 \times 10^{-5}$$

$$\sigma_L = \frac{\lambda \sigma_\phi}{2\pi} = 5 \text{ pm}$$

$$\sigma_h = \frac{\sigma_L}{L} = 10^{-21}$$

But LISA sources last a long time, so can improve signal to noise ratio by averaging. for a signal at 0.01Hz that lasts a year, the background from averaged shot noise is:

[radiometer equation] $\quad \frac{\sigma_h}{\sqrt{Bt}} = \frac{\sigma_h}{\sqrt{0.01 \times 365 \times 86400}} = 2 \times 10^{-24}$

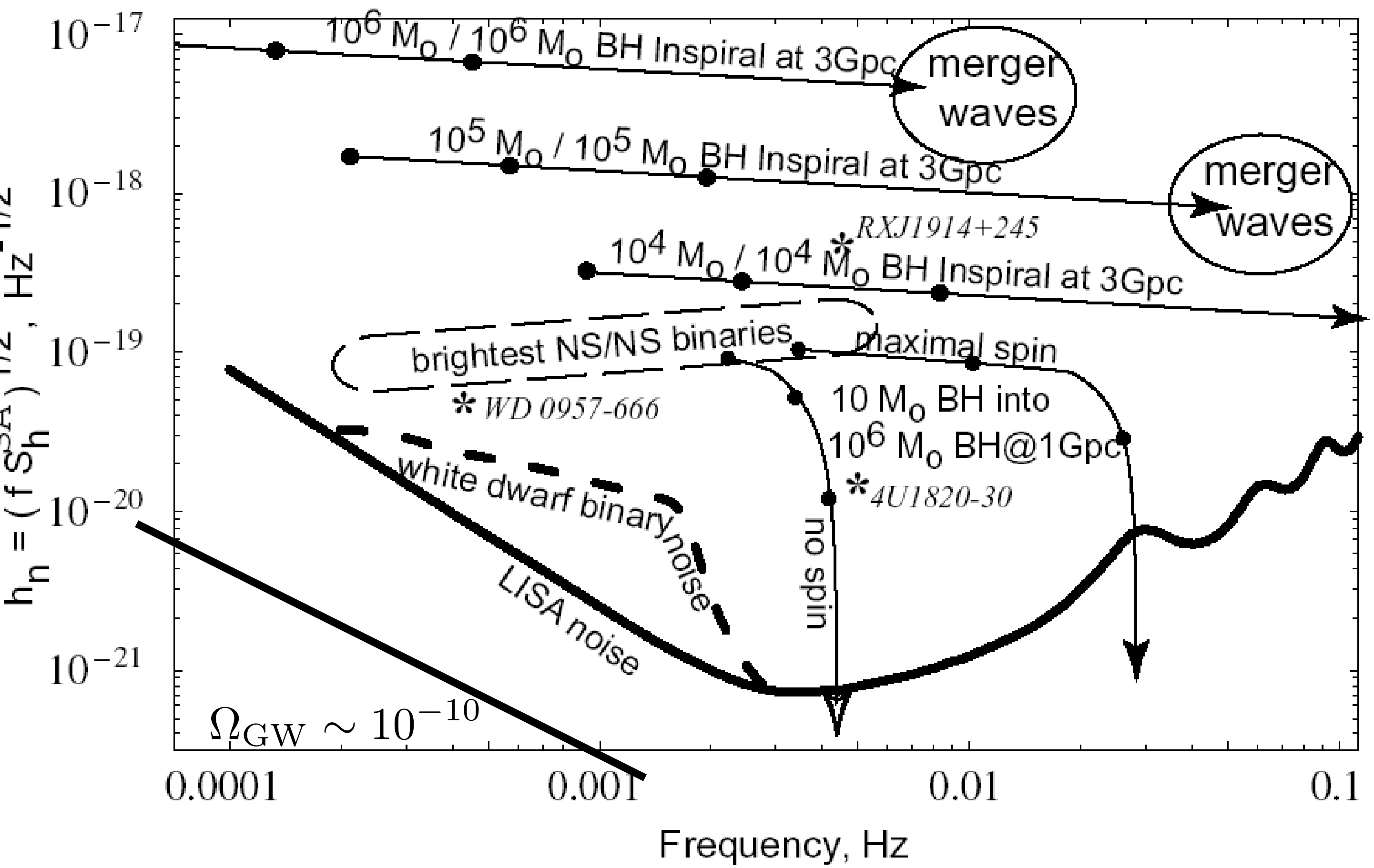
Some LISA sources

Galactic white dwarf binaries

Black hole binary inspirals

Neutron star binaries

supermassive BH infall

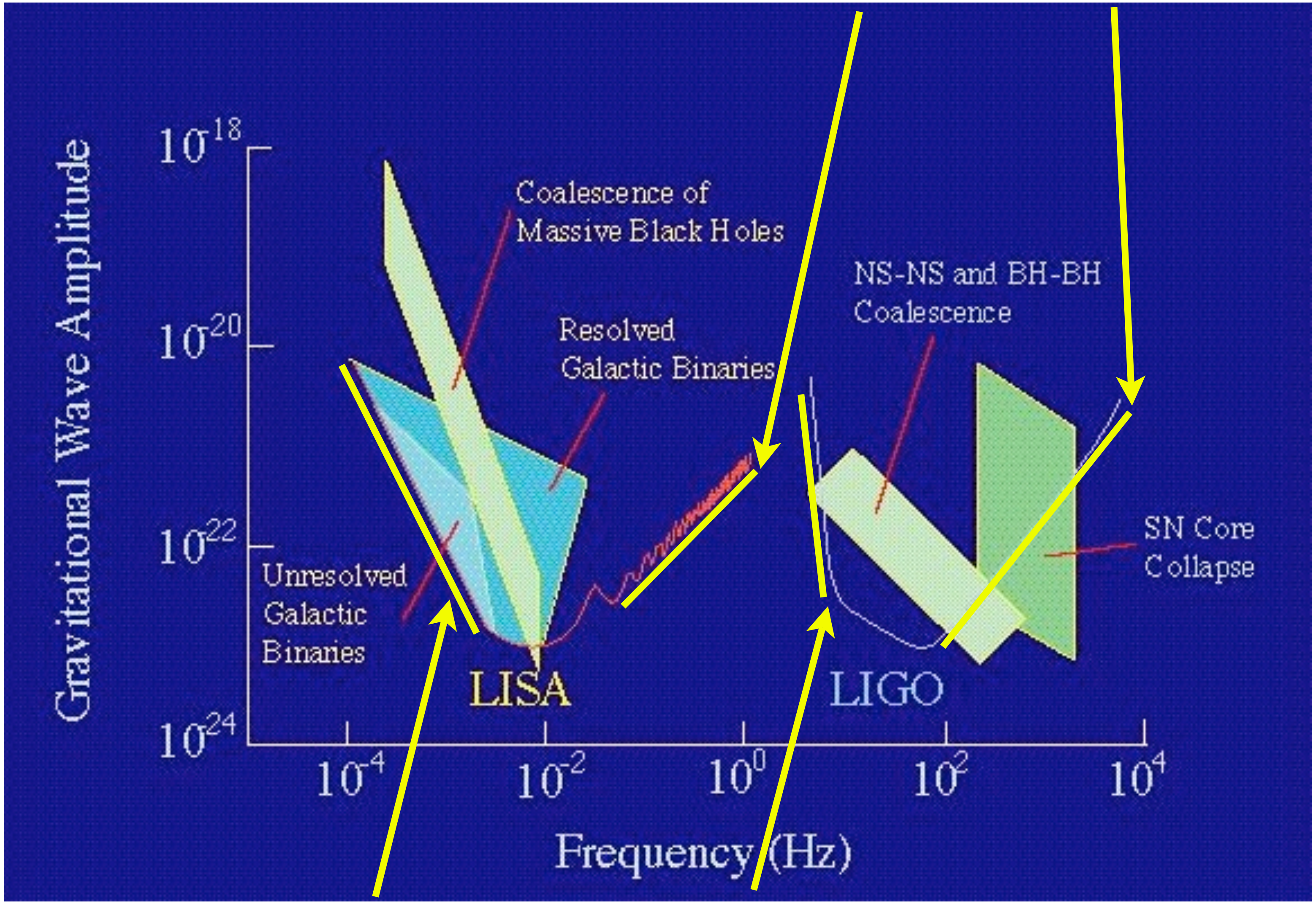


Cosmic gravitational-wave background hard:

slow rollover inflation suggests $\Omega_{\rm GW} \sim 10^{-15}$

LISA & LIGO Sensitivities

photon travel time in instrument > period



[LISA curve assumes a one year integration]

Thermal & charge fluctuations

Seismic wall

Conclusions

Initial LIGO has taken 2 years of data at its design sensitivity.

Initial sensitivity marginal for known astrophysical sources.

First upgrade phase is almost complete

Prospects for direct detection with advanced LIGO is excellent.

LISA - space based probe for sources at $f<0.1$Hz.
3 satellite constellation. Many sources at high SNR.

A very exciting time for the hard science of gravitational waves, and the perfect time to be involved!