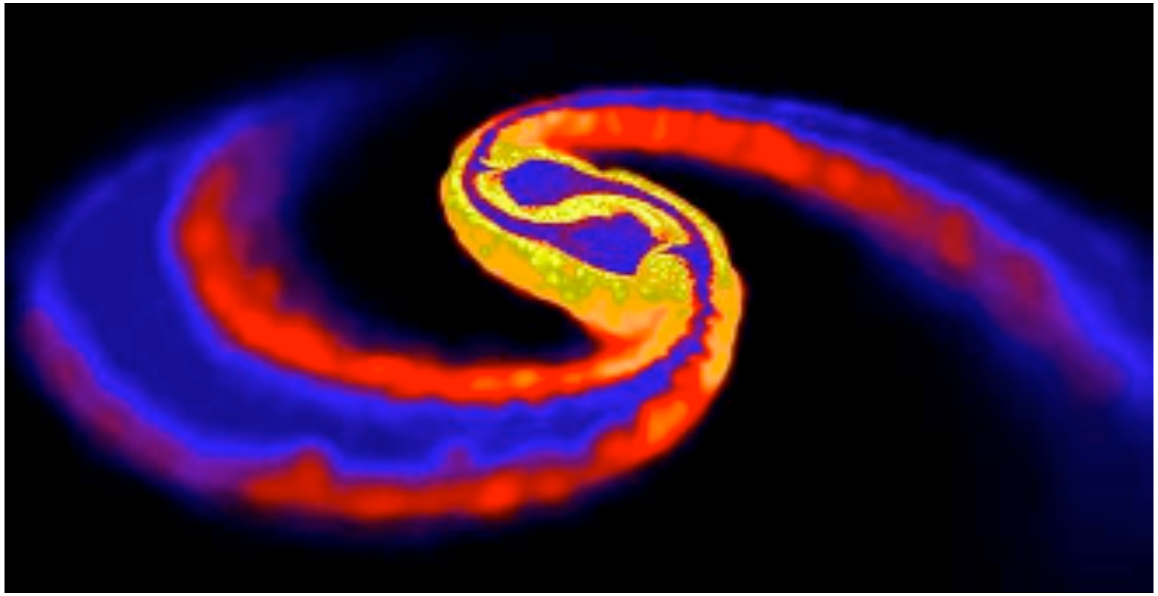
Searches for Gravitational Waves

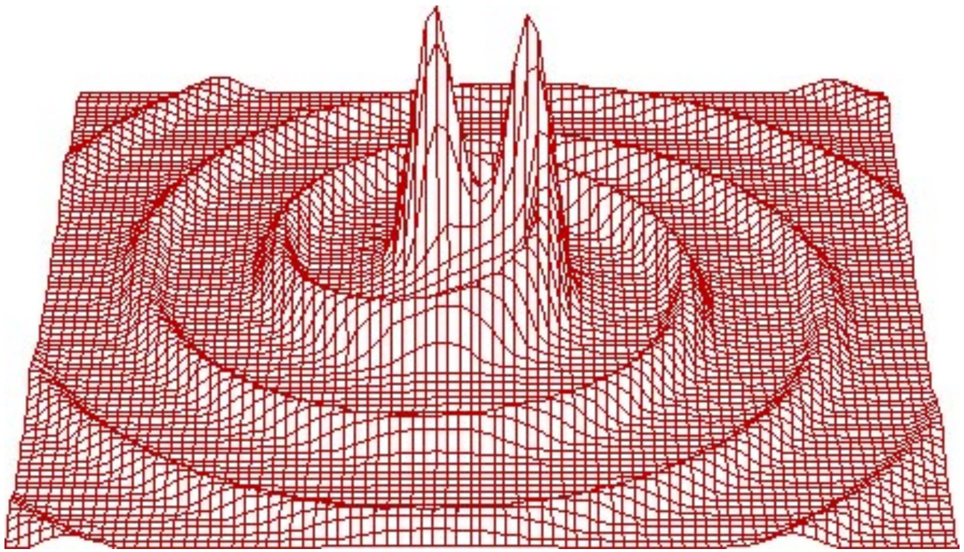


"Merging Neutron Stars" (Price & Rosswog)

Barry Barish
Caltech
IPA London – Aug 2014

Einstein's Theory of Gravitation

- a necessary consequence of Special Relativity with its finite speed for information transfer



- gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light

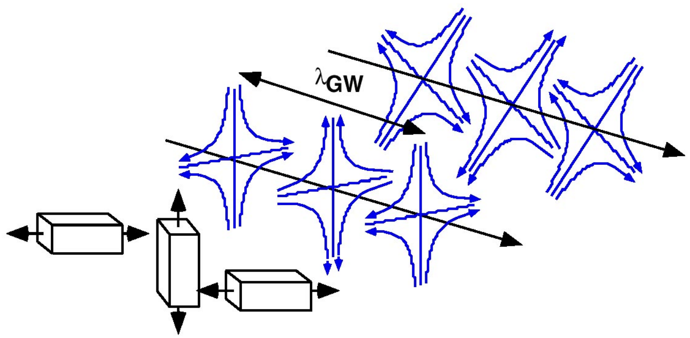
gravitational radiation
binary inspiral
of
compact objects

Einstein's Theory of Gravitation
gravitational waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

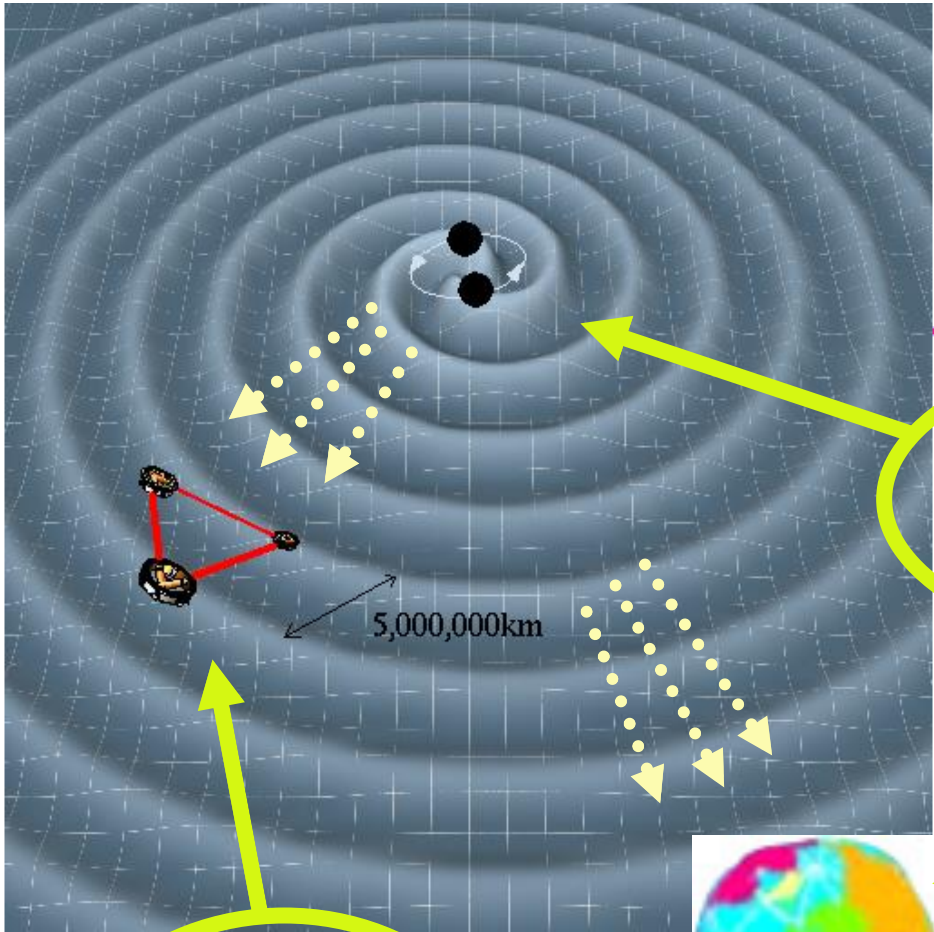
• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).



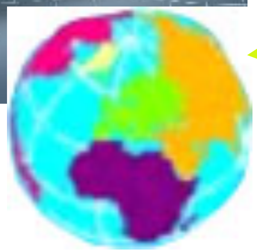
• Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

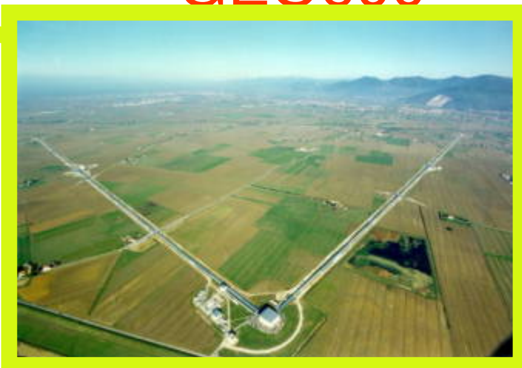
Direct Detection of Gravitational Waves



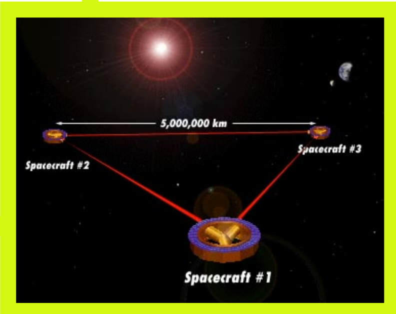
Gravitational Wave
Astrophysical Source



Terrestrial detectors
Virgo, LIGO, KAGRA,
GEO600

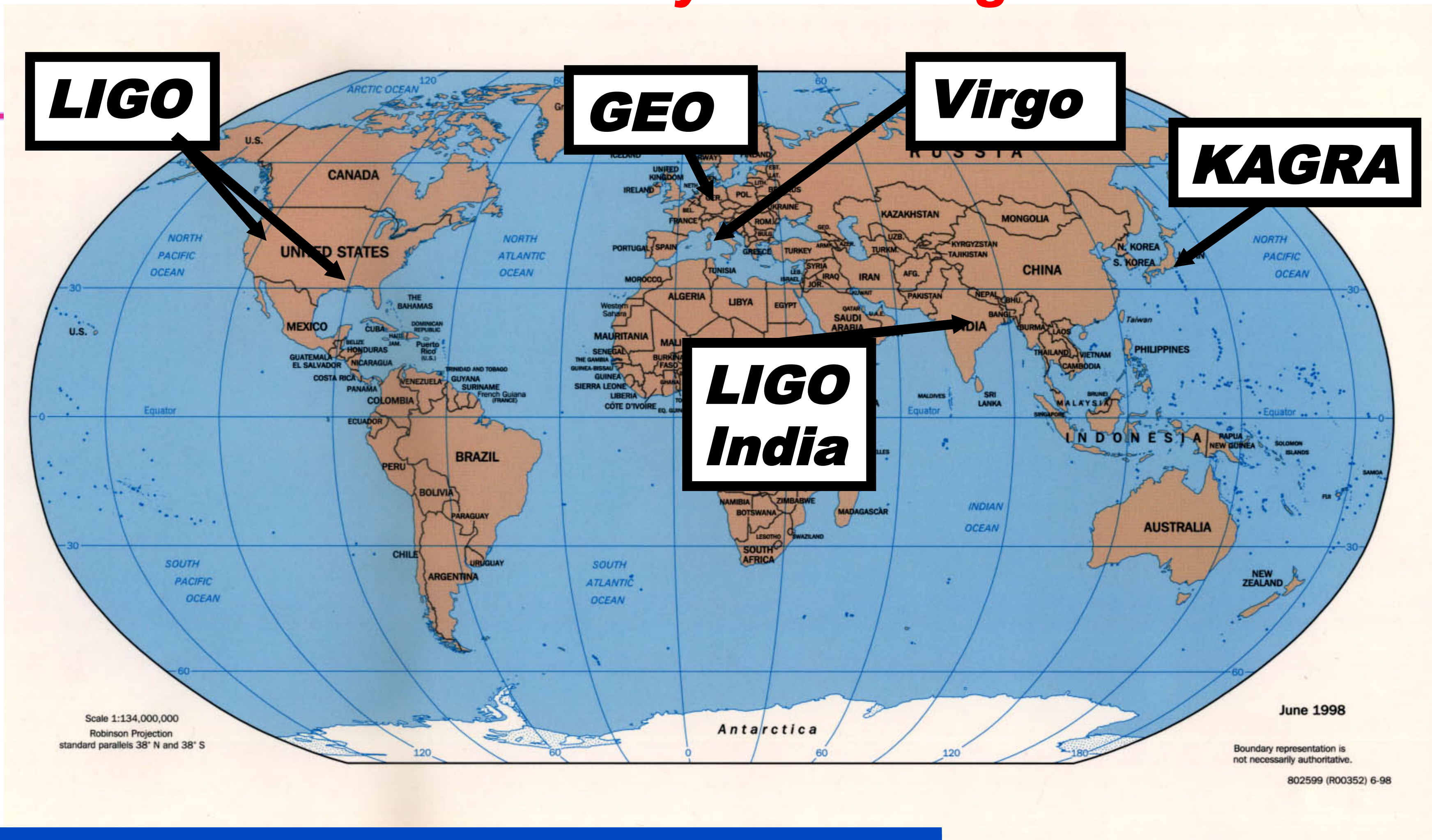


Detectors in
space
LISA



International Network on Earth

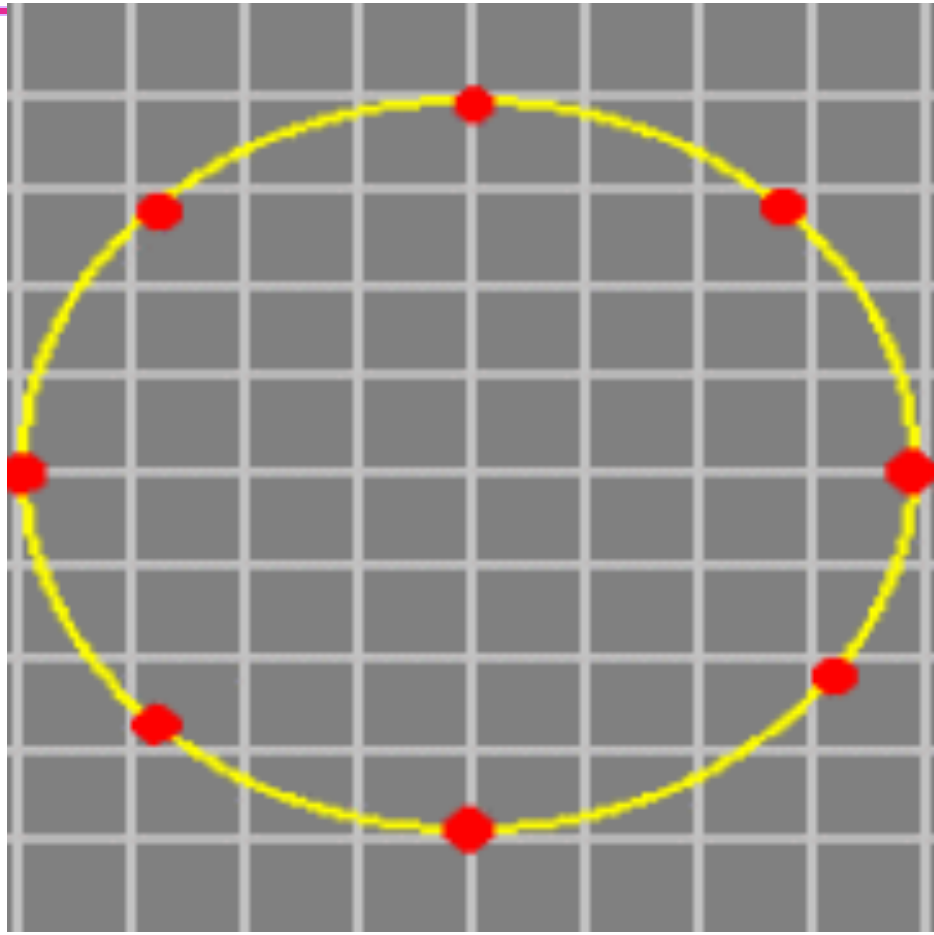
simultaneously detect signal



decompose the polarization of gravitational waves

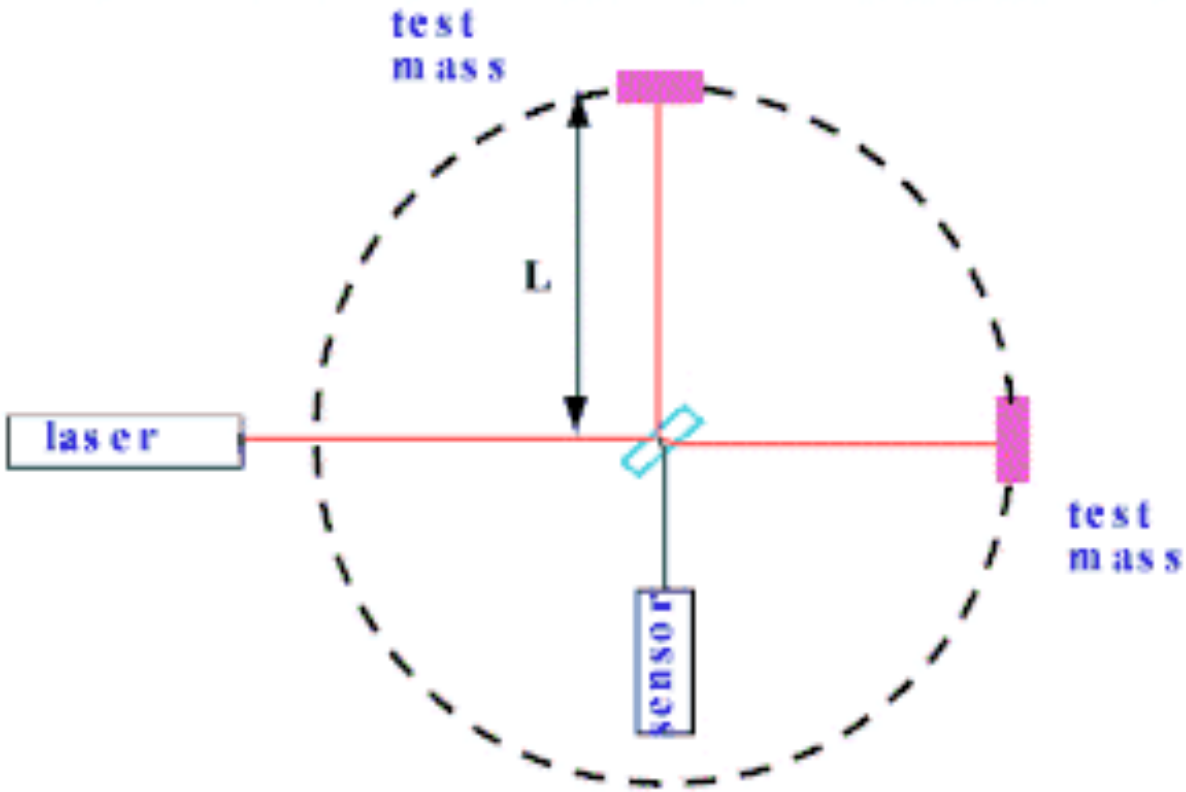
Detecting a passing wave ....

Free masses



Detecting a passing wave ....

Interferometer

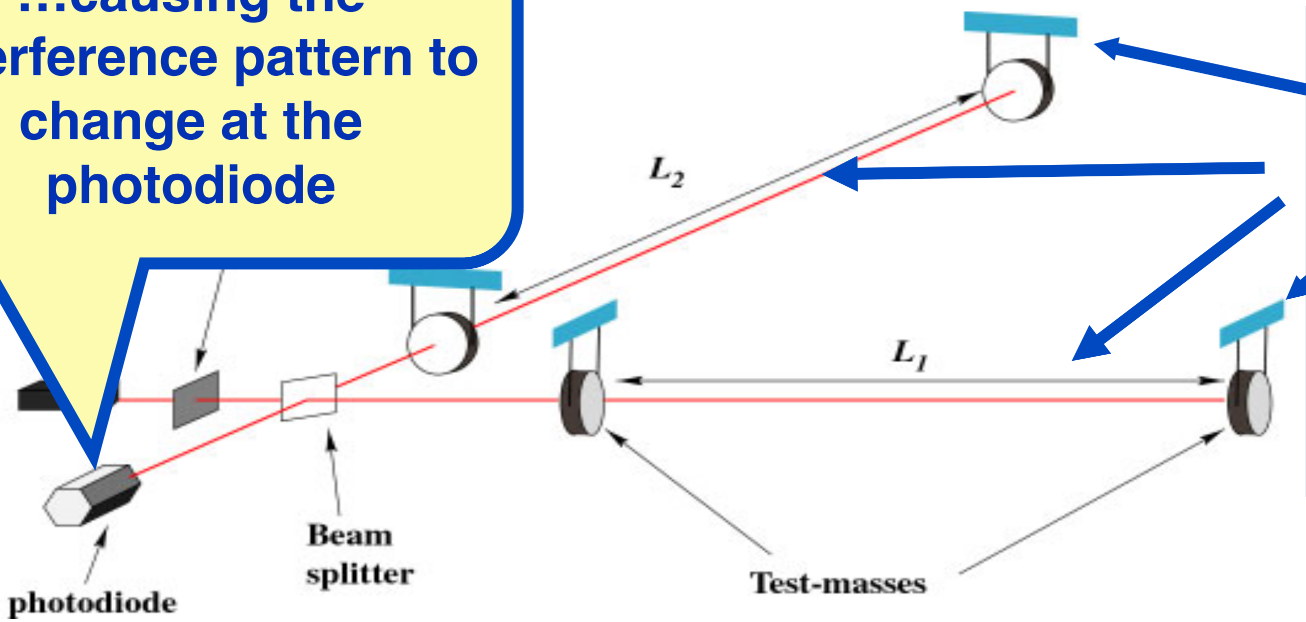


Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

- Arms in LIGO are 4km
- Measure *difference in length to one part in 10^{21} or 10^{-18} meters*

…causing the interference pattern to change at the photodiode



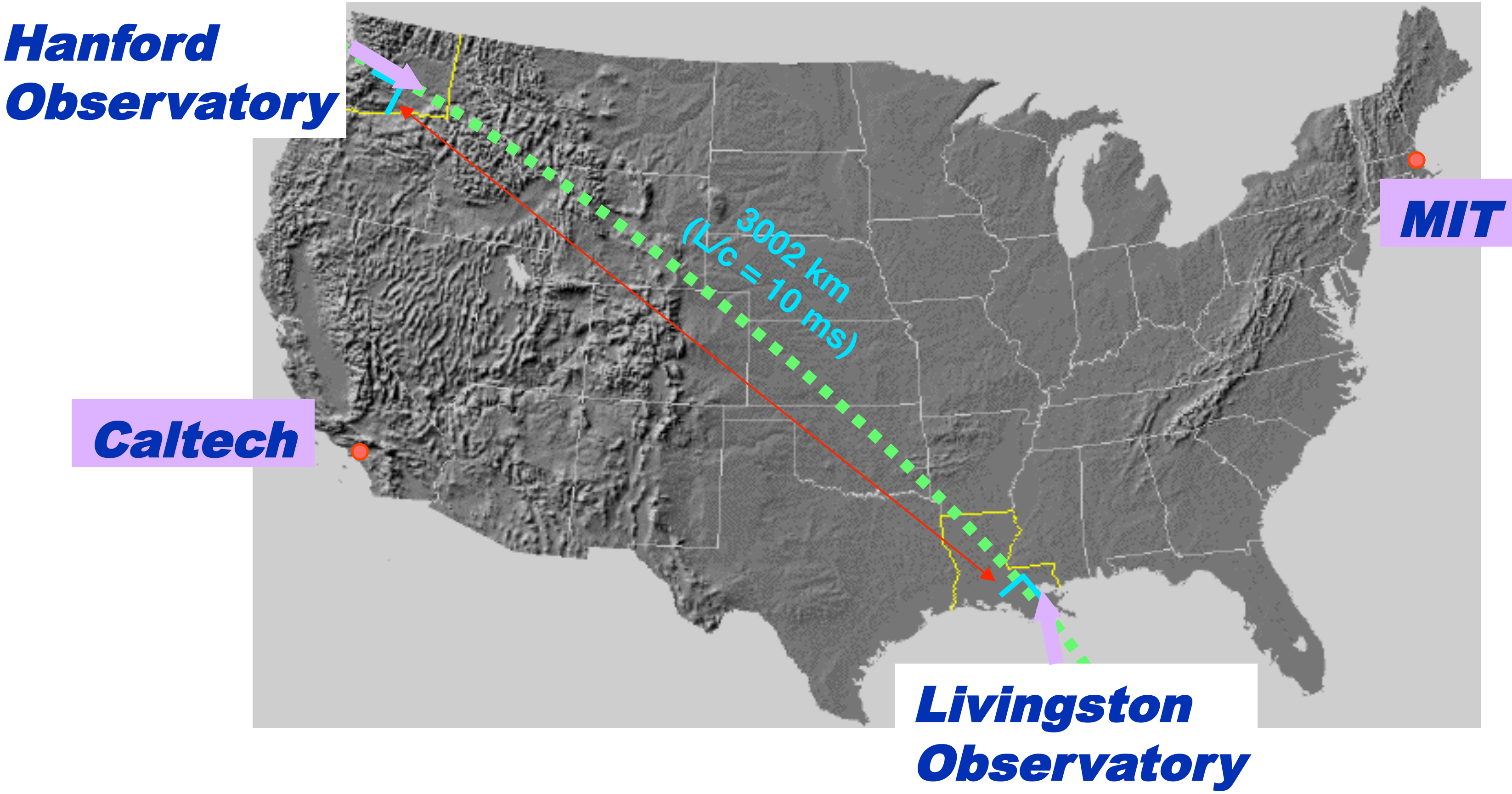
As a wave

Suspended Masses

change in different ways….

LIGO

Simultaneous Detection



LIGO Livingston Observatory

LIGO Hanford Observatory

LIGO Facilities
beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

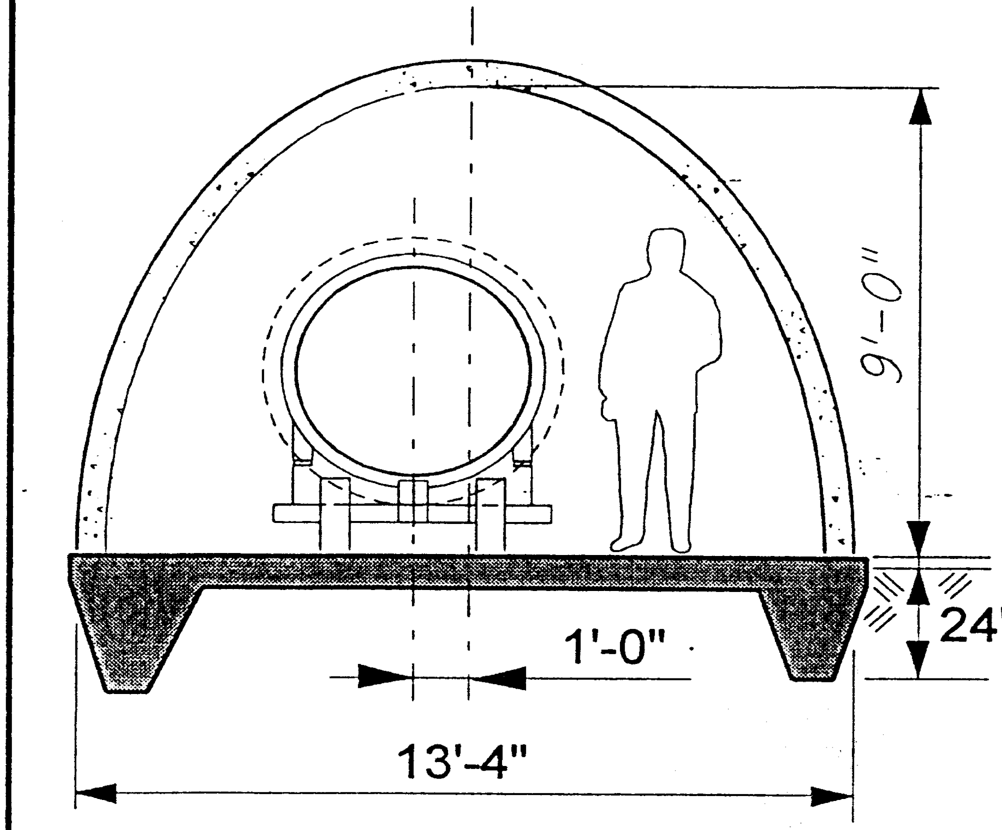


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

LIGO

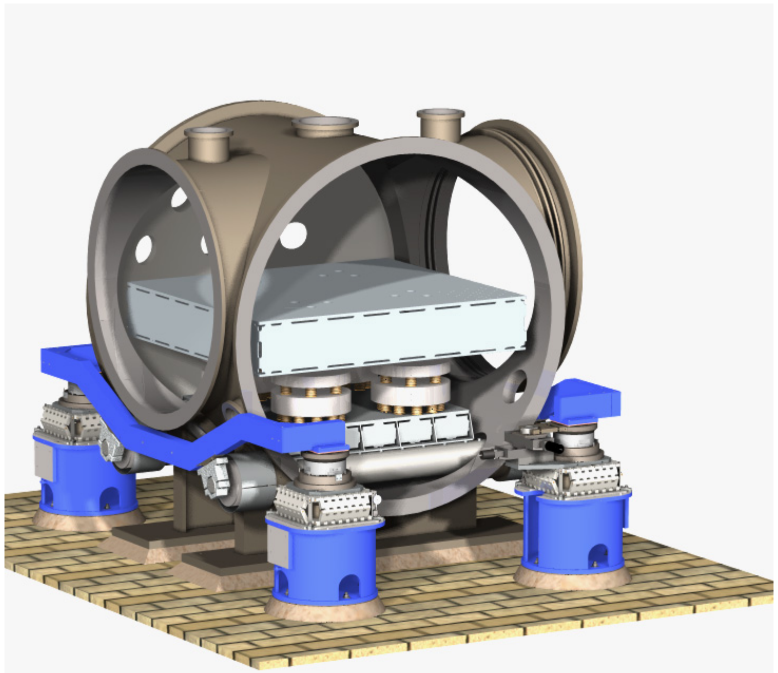
beam tube

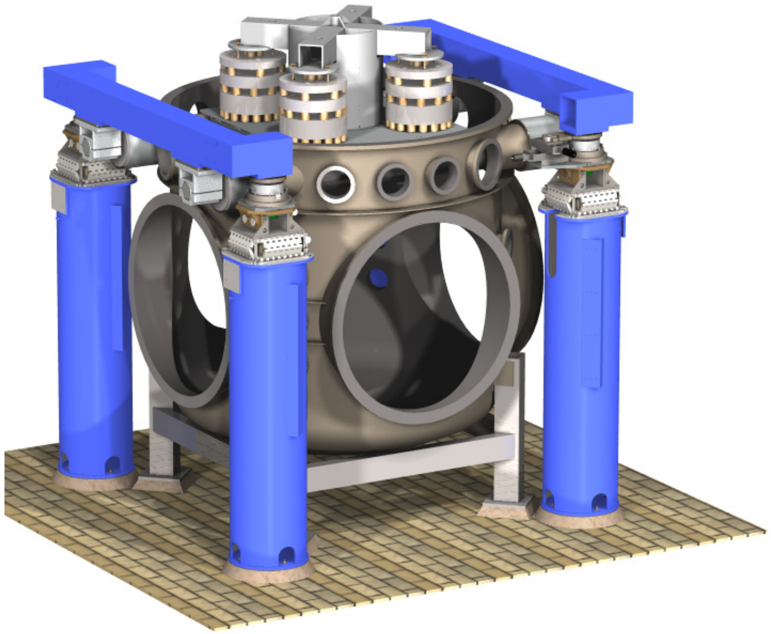
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

Vacuum Chambers
vibration isolation systems

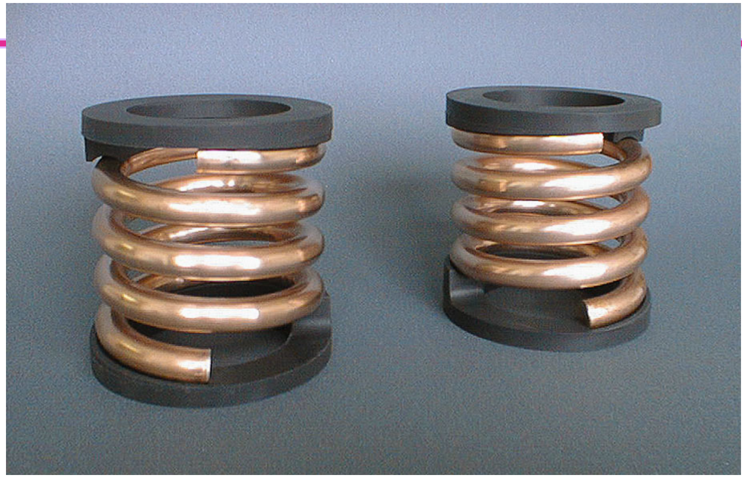
- » Reduce in-band seismic motion by 4 - 6 orders of magnitude
- » Compensate for microseism at 0.15 Hz by a factor of ten
- » Compensate (partially) for Earth tides





Seismic Isolation

springs and masses



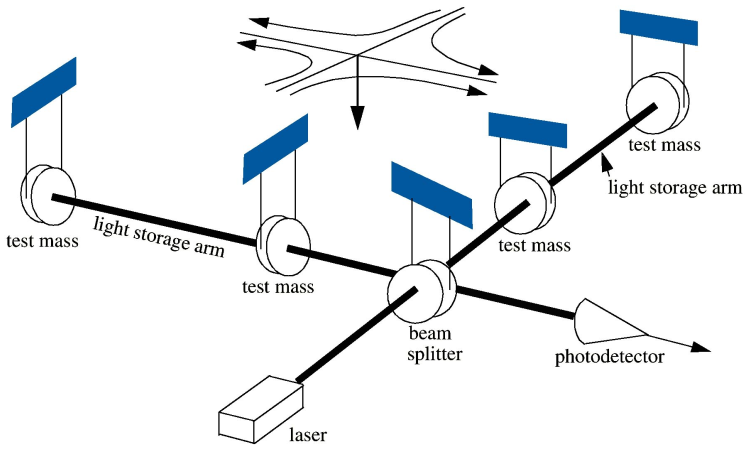
Constrained Layer damped spring

LIGO

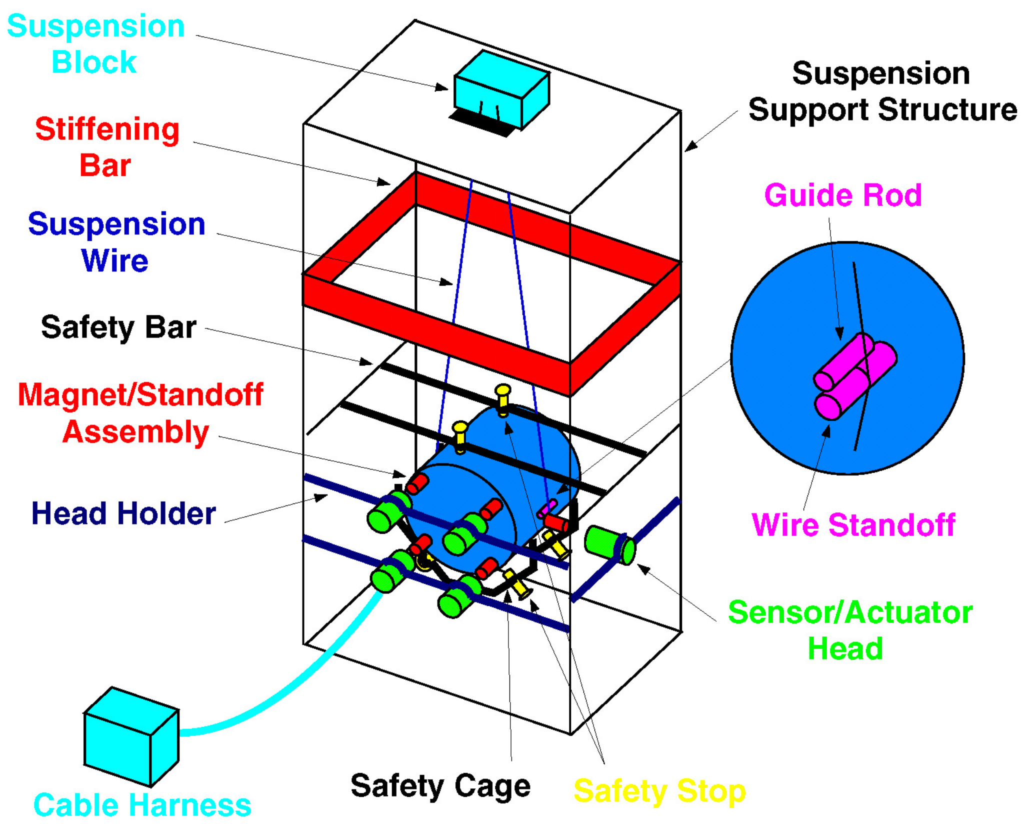
vacuum equipment

Seismic Isolation

suspension system



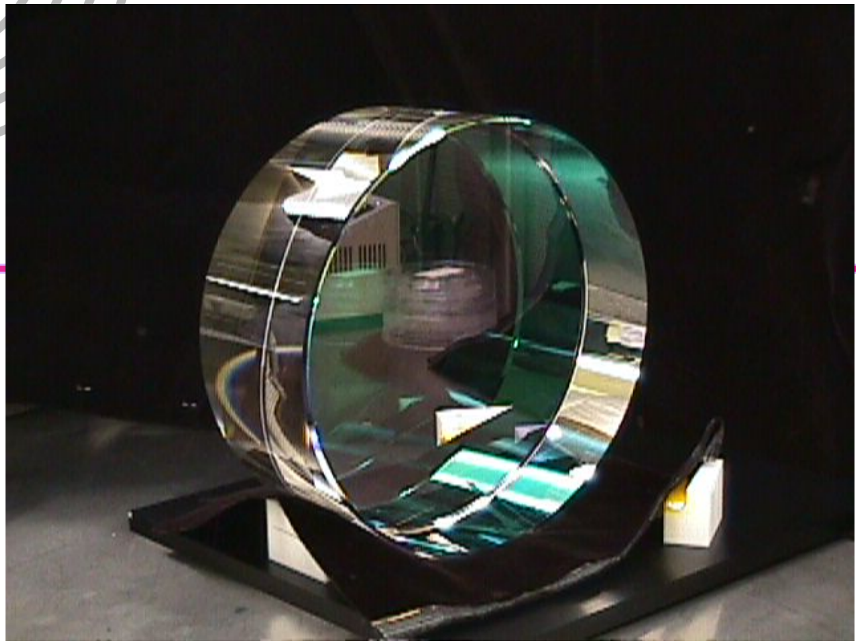
suspension assembly for a core optic



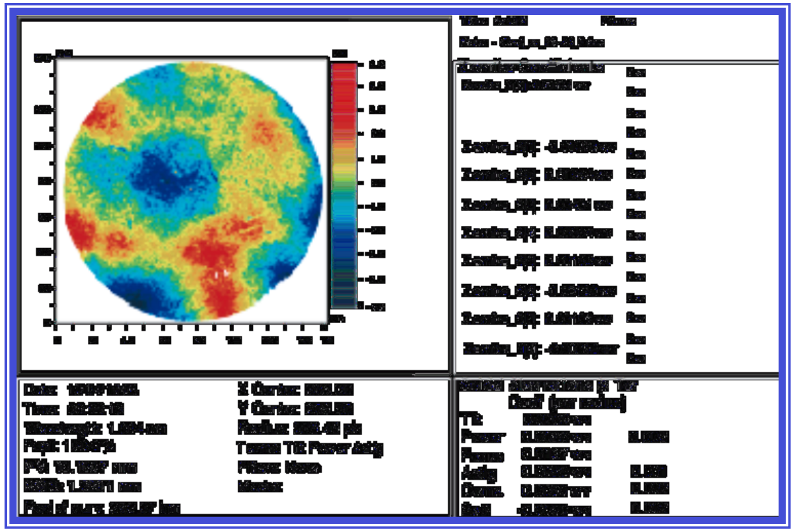
- **support structure is welded tubular stainless steel**
- **suspension wire is 0.31 mm diameter steel music wire**
- **fundamental violin mode frequency of 340 Hz**

LIGO Optics

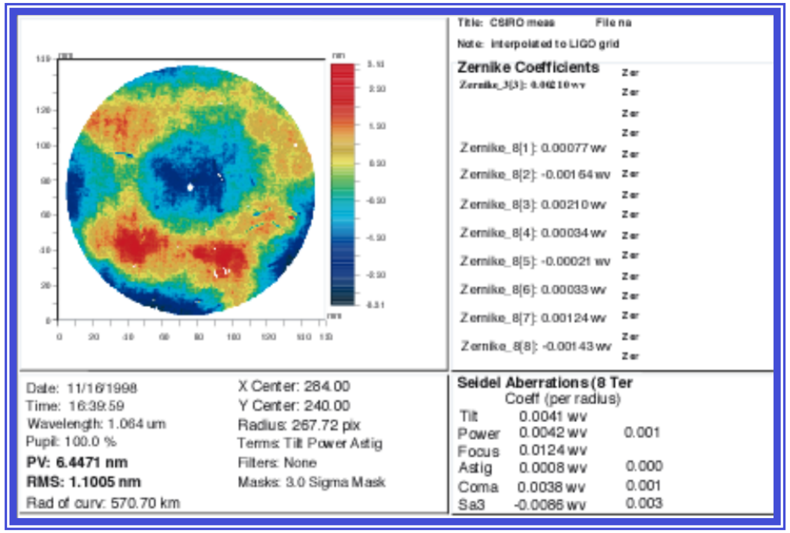
fused silica



- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q's > 2 x 10^6



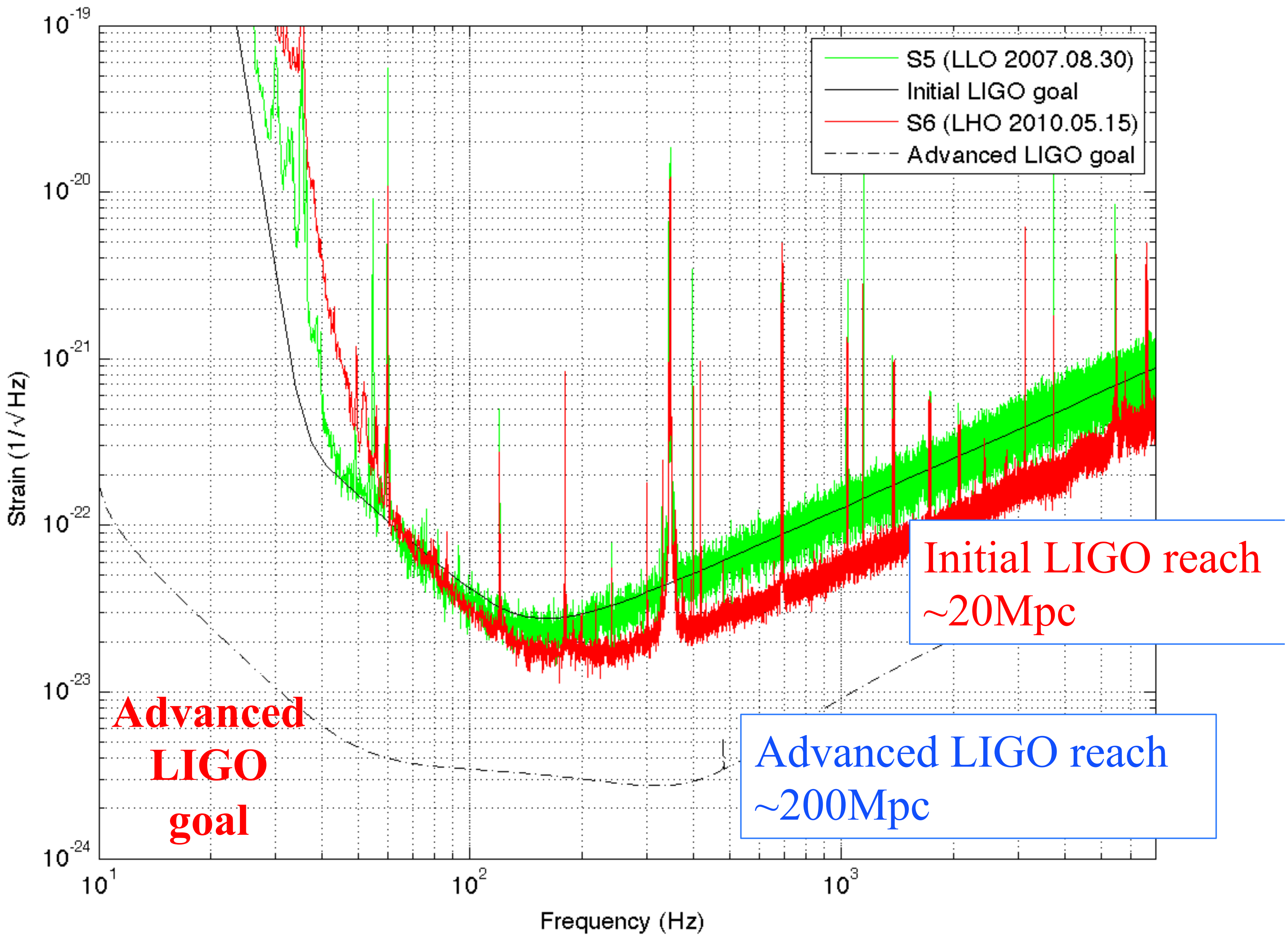
Caltech data



CSIRO data

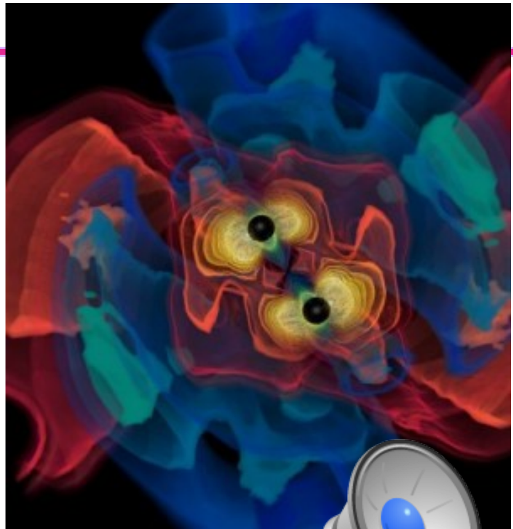
Core Optics

installation and alignment



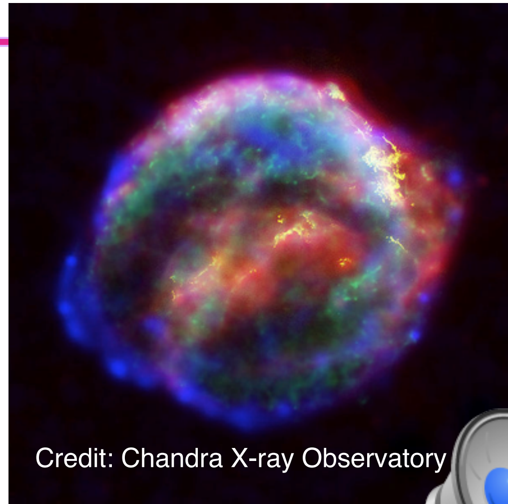
S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3
Initial LIGO reach
~20Mpc
Advanced LIGO reach
~200Mpc
Advanced
LIGO
goal

Astrophysical Sources of Gravitational Waves


Credit: AEI, CCT, LSU

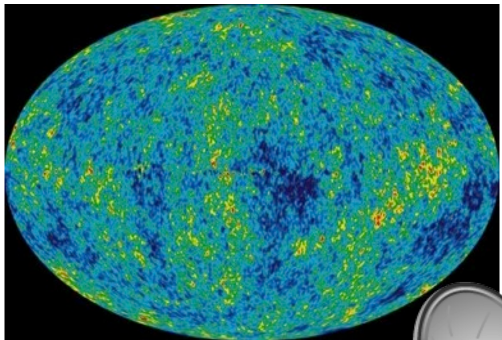
Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,
- (effectively) transient


Credit: Chandra X-ray Observatory

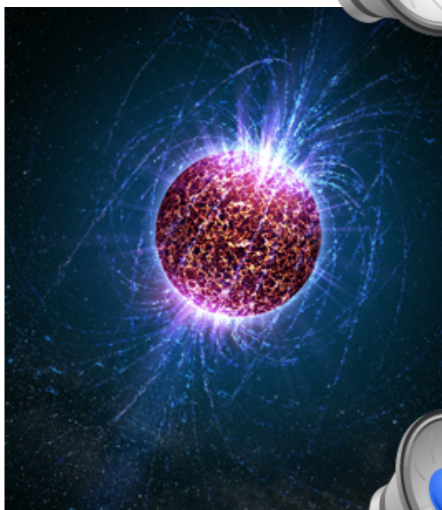
Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient


NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang
- Long duration, stochastic background

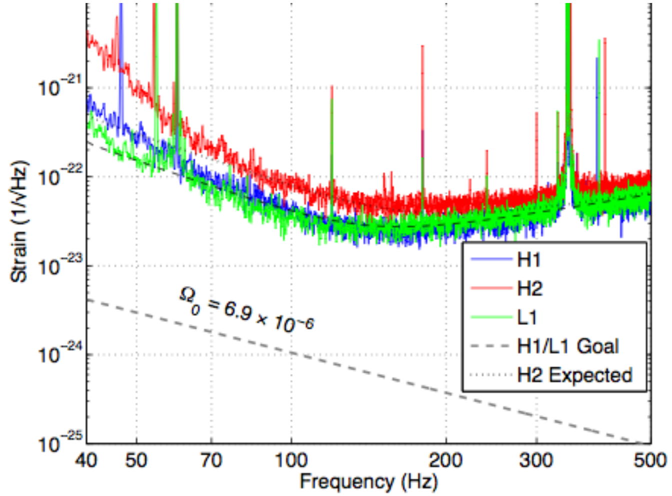

Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform
- Long duration

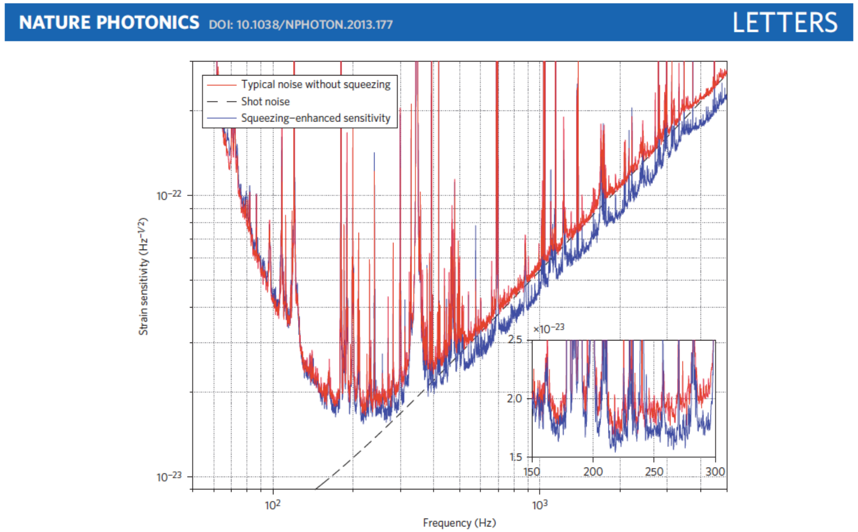
Some other LVC Results

Upper limit on GW stochastic background

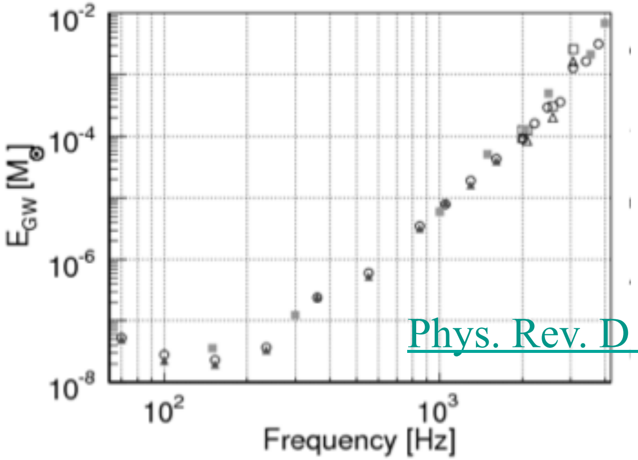


Nature **460** (2009) 990

Quantum-enhanced sensitivity!

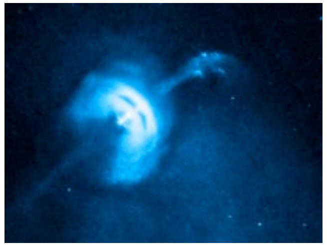


Upper limit on GW energy emitted by generic sources at 10 kpc



Phys. Rev. D **81** (2010) 102001

Upper limits on GW emissions from Crab and Vela pulsars

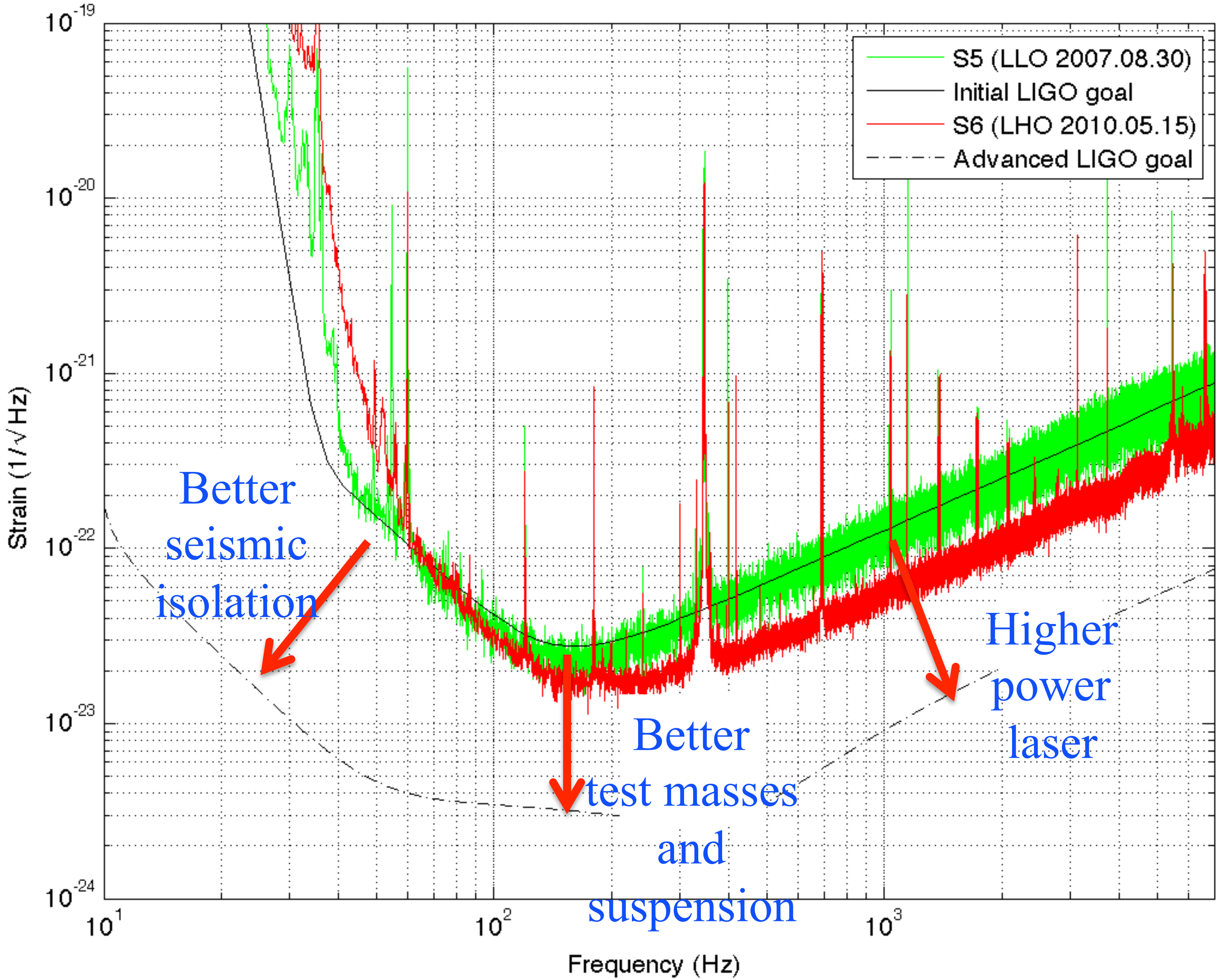


(X-ray: NASA/CXC/Univ of Toronto/M.Durant et al; Optical: DSS/Davide De Martin);

NASA/CXC/ASU/J Hester *et al.* (Chandra); NASA/HST/ASU/J Hester *et al.* (Hubble)

Astrophys. J. **737** (2011) 93

Astrophys. J. **722** (2010) 1504

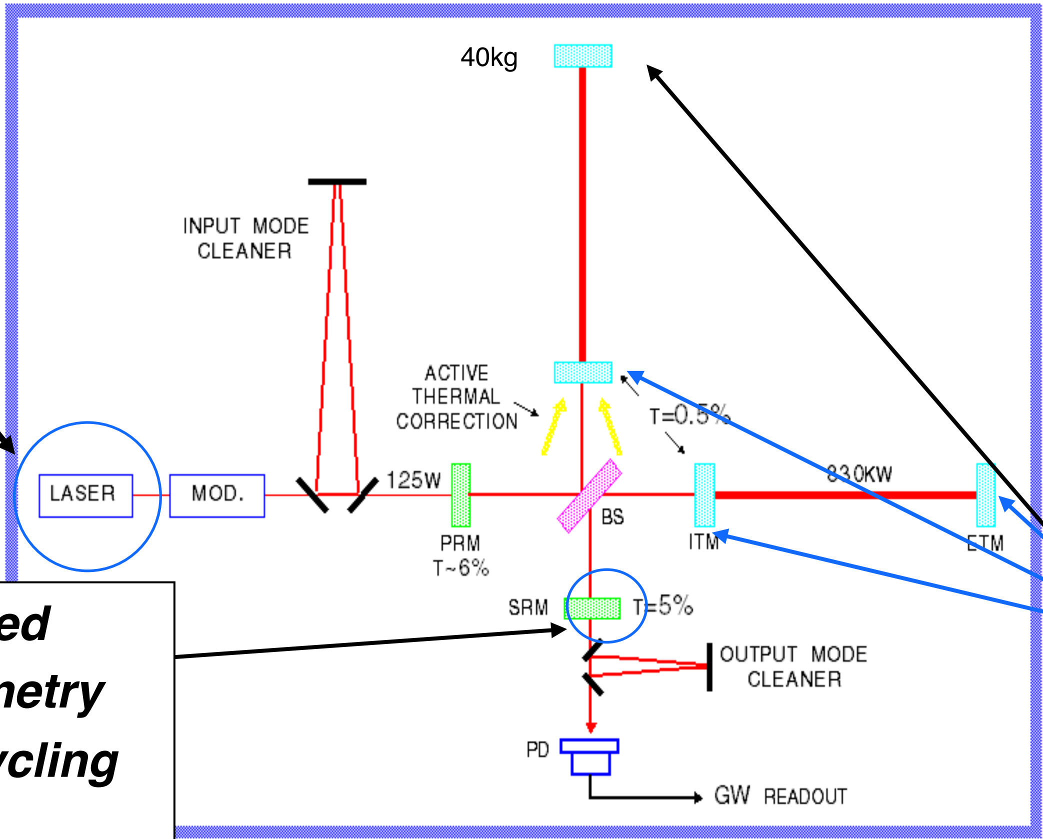

S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
Better seismic isolation
Better test masses and suspension
Higher power laser

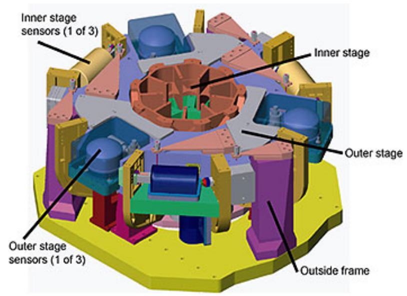
Advanced LIGO

Major technological improvements

High power laser (180W)

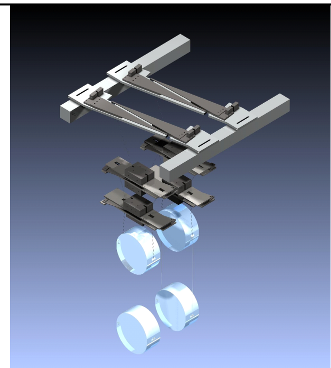
Advanced interferometry
Signal recycling





Active vibration isolation systems

Quadruple pendulum

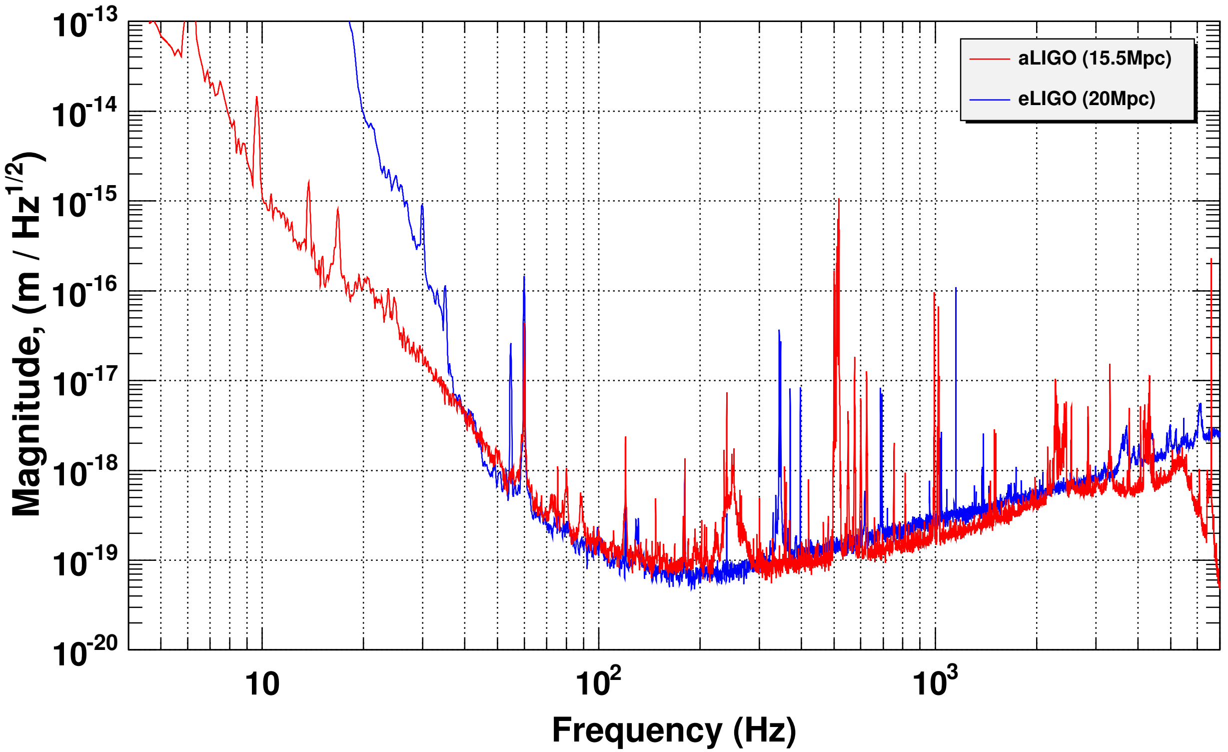


Advanced LIGO

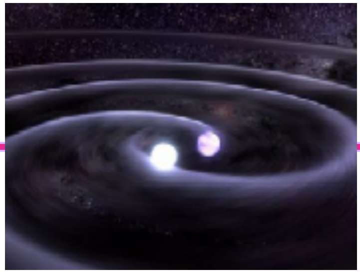
Parameter	*Initial LIGO*	*Advanced LIGO*
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	$f_{low} \sim 50$ Hz	$f_{low} \sim 13$ Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

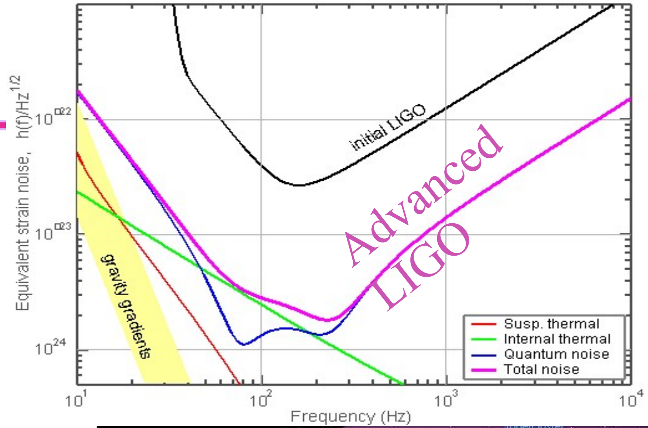
Sensitivity as of 23 July 2014

- The team is working on stability rather than sensitivity
- But present sensitivity is already similar (or better, at low frequencies) to the best sensitivity achieved with initial ‘enhanced’ LIGO
- Strain sensitivity is better after 3 months than after 6 *years* in iLIGO –



Predicted Rates – Adv LIGO





Neutron Star Binaries:

Initial LIGO:

Average BNS reach ~15 Mpc → rate ~1/50yrs

Advanced LIGO: ~ 200 Mpc

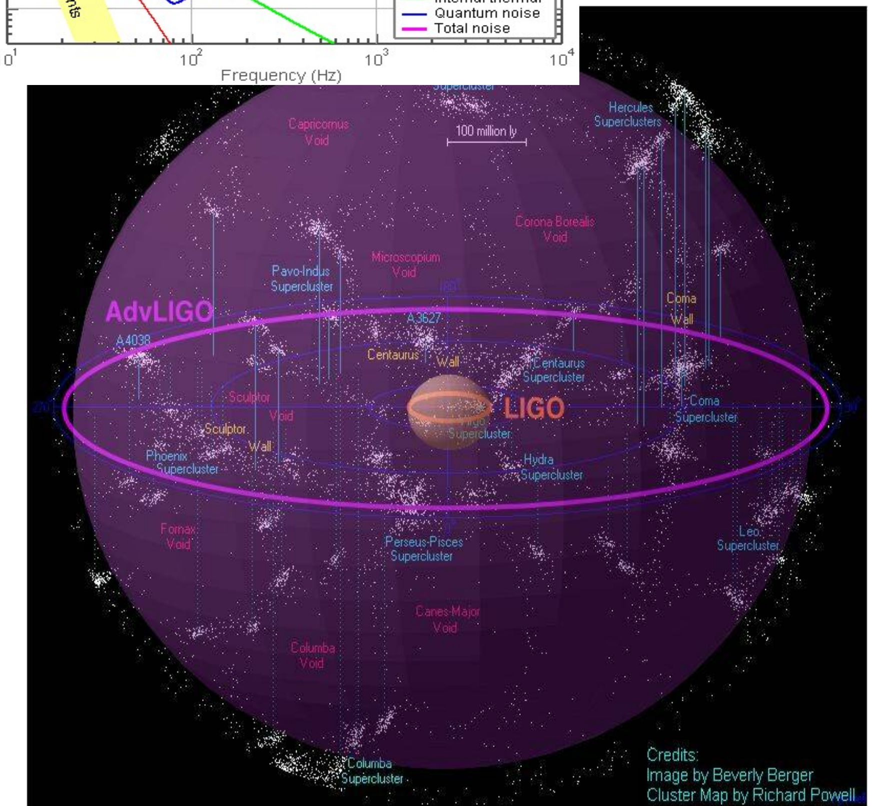
"Realistic rate" ~ 40/year (but can be 0.4-400)

Other binary systems:

NS-BH: 0.004/yr → 10/yr

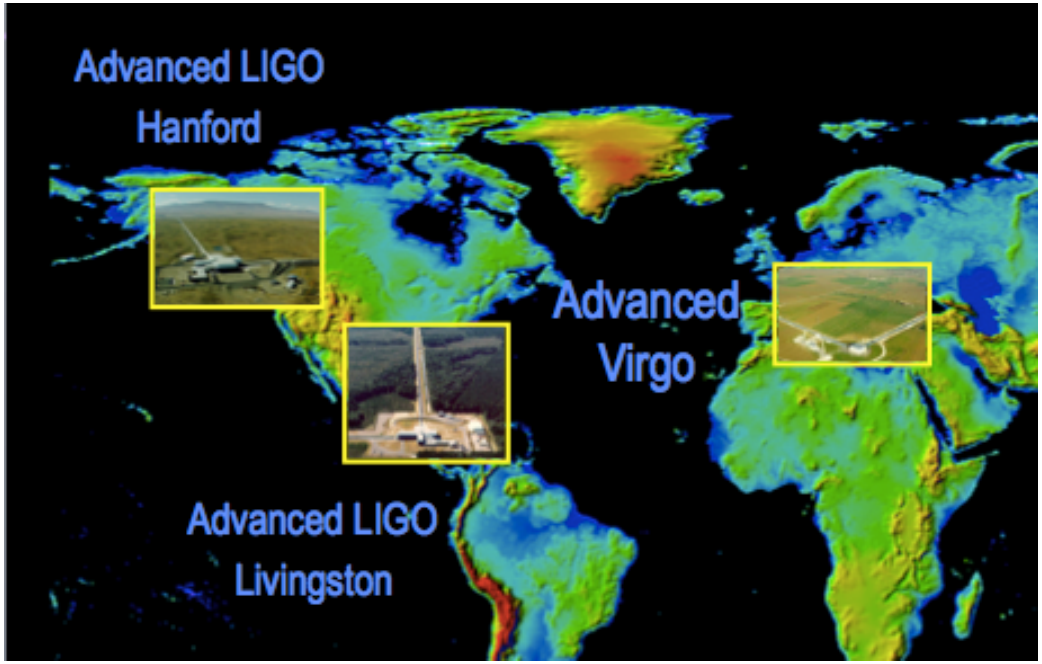
BH-BH: 0.007/yr→ 20/yr

Class. Quant. Grav. **27**, 173001 (2010)



Advanced GW Detectors run plan

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections
		LIGO	Virgo	LIGO	Virgo	
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100



Coming soon

Gravitational waves
a new window on the universe