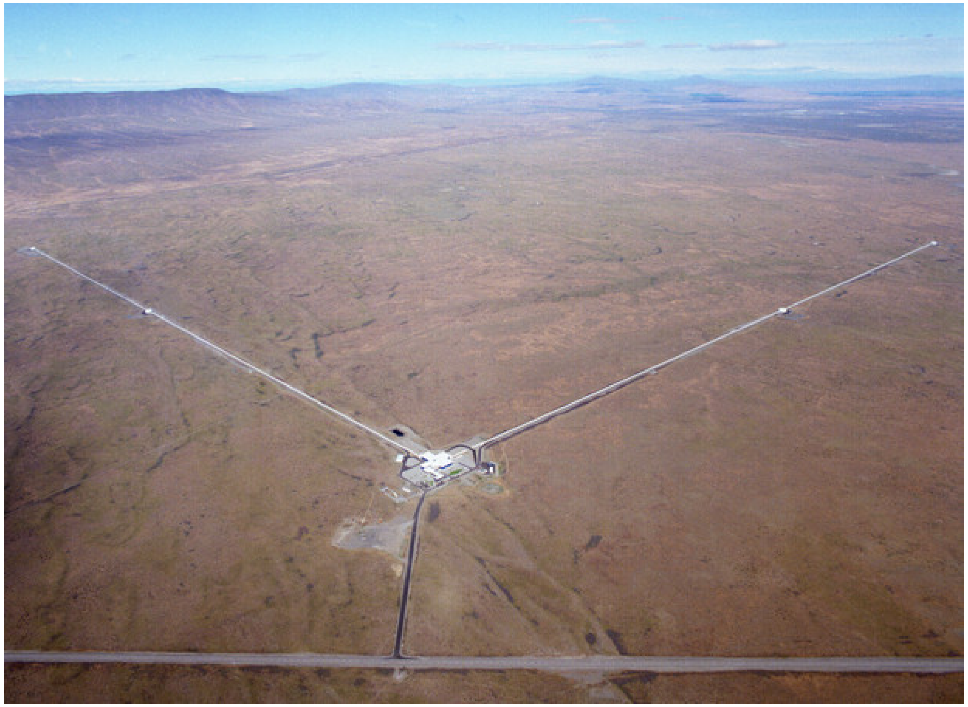
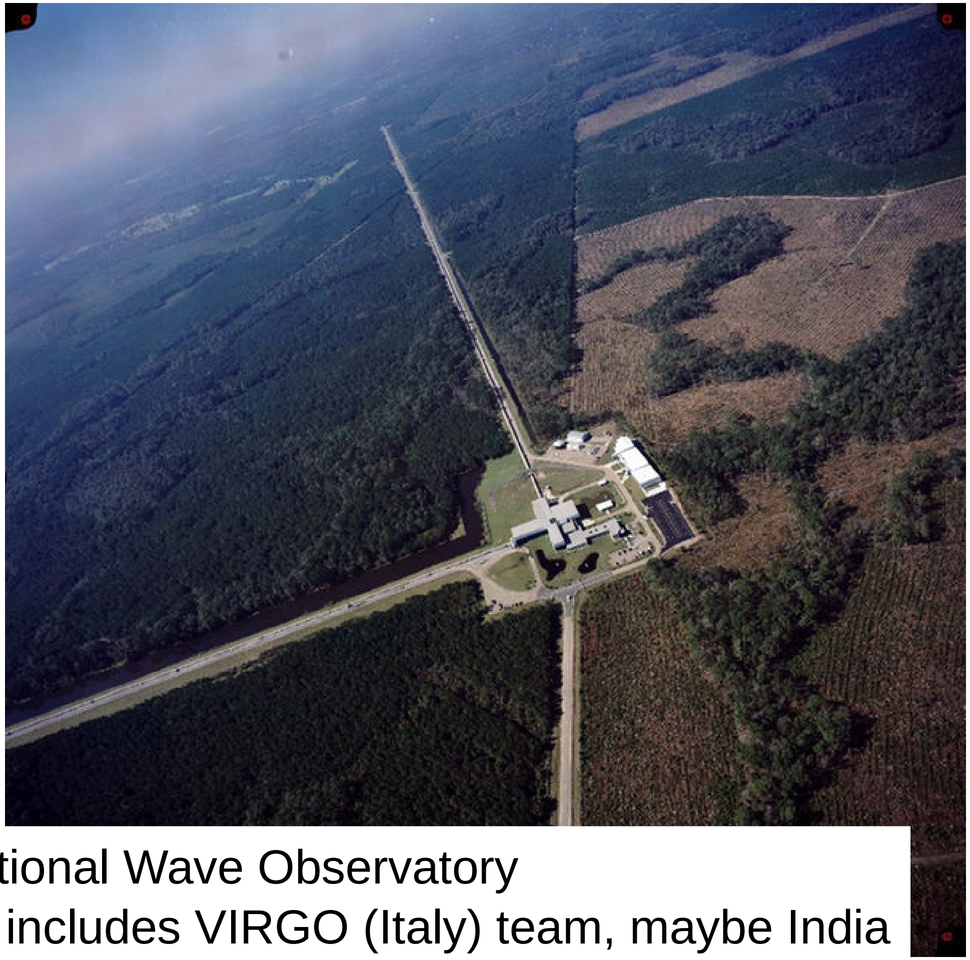
LIGO, ground-based Gravitational Wave Detectors



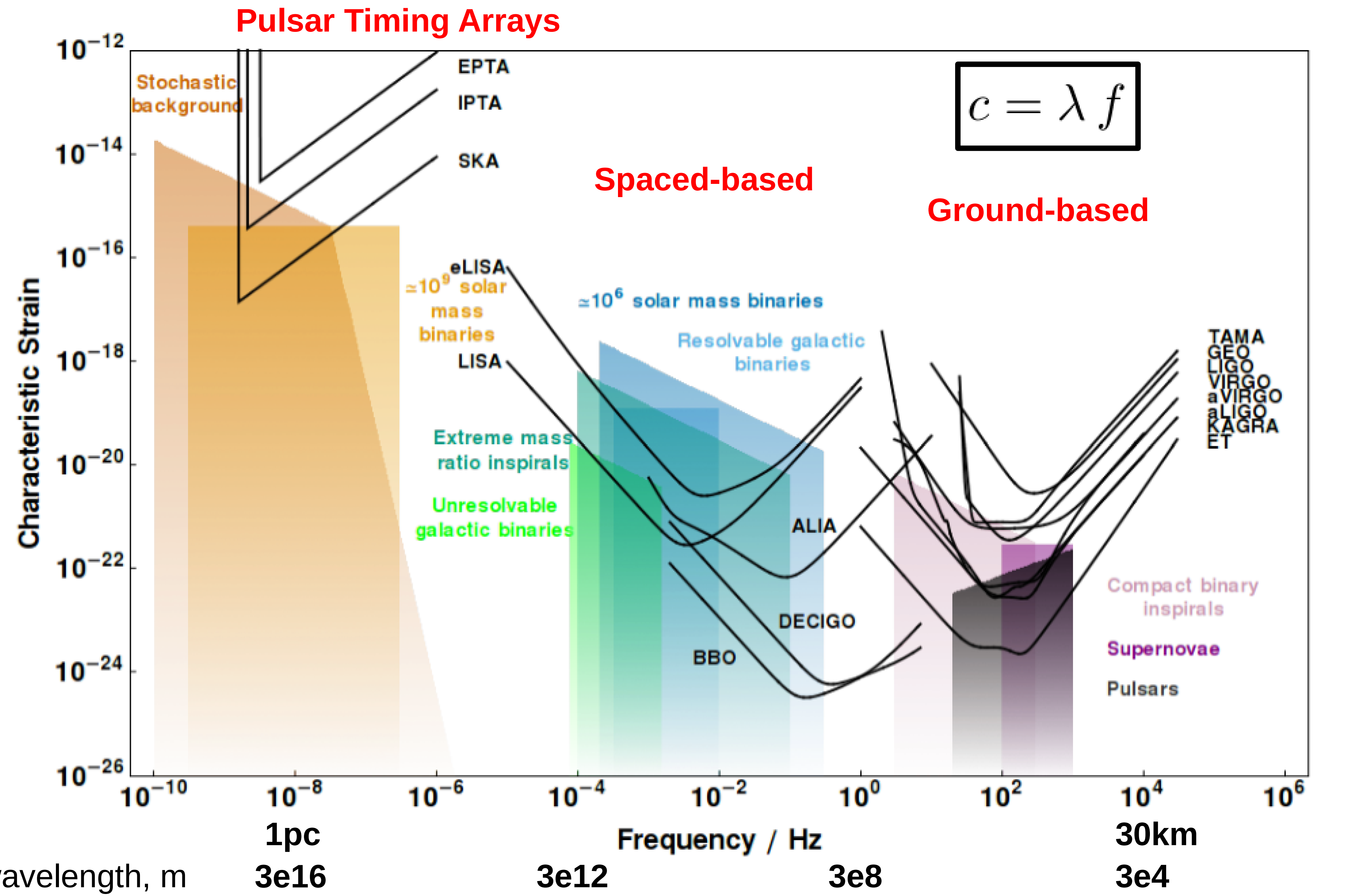
LIGO Hanford, WA (LHO)

LIGO Livingston, LA (LLO)

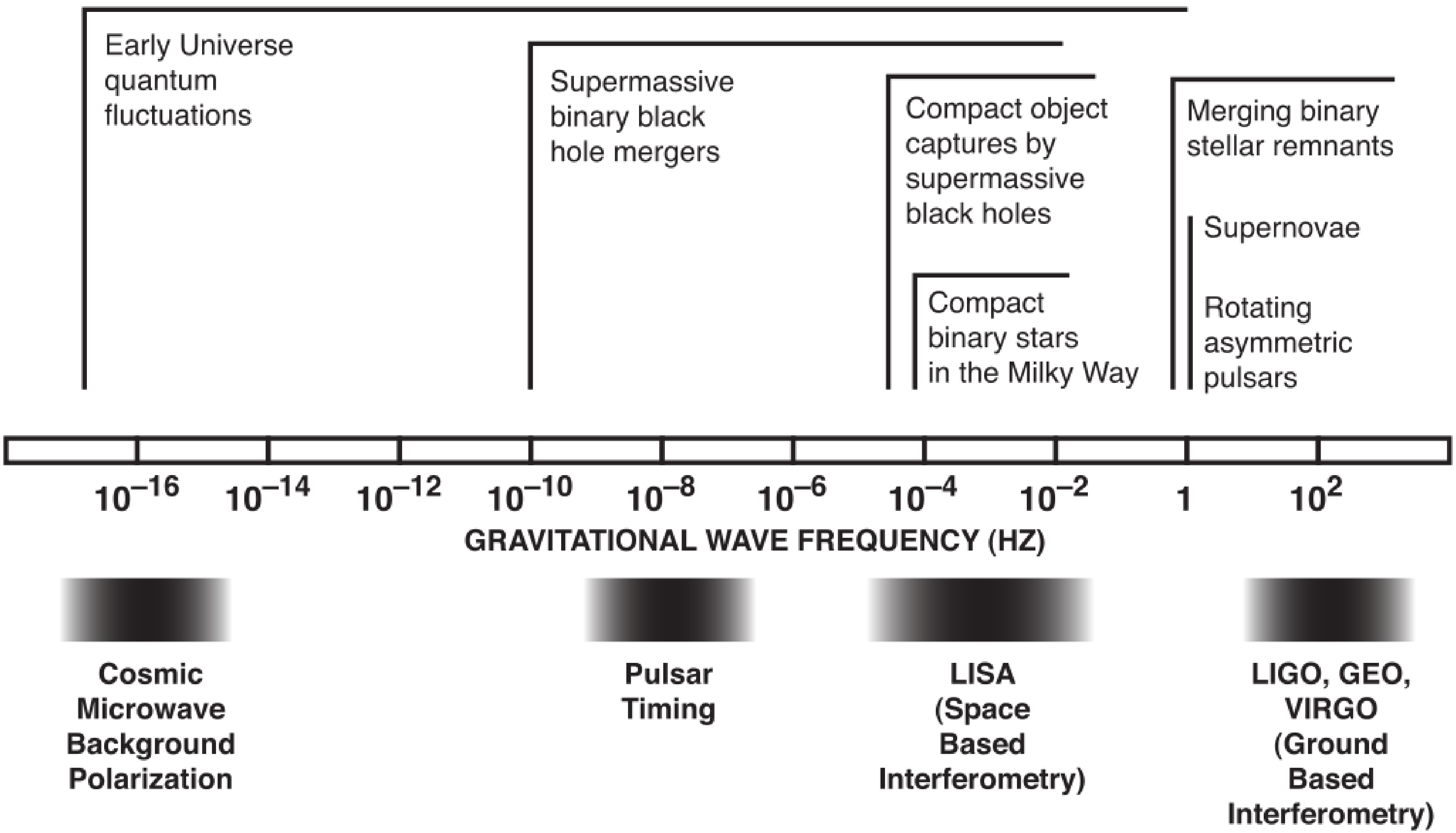


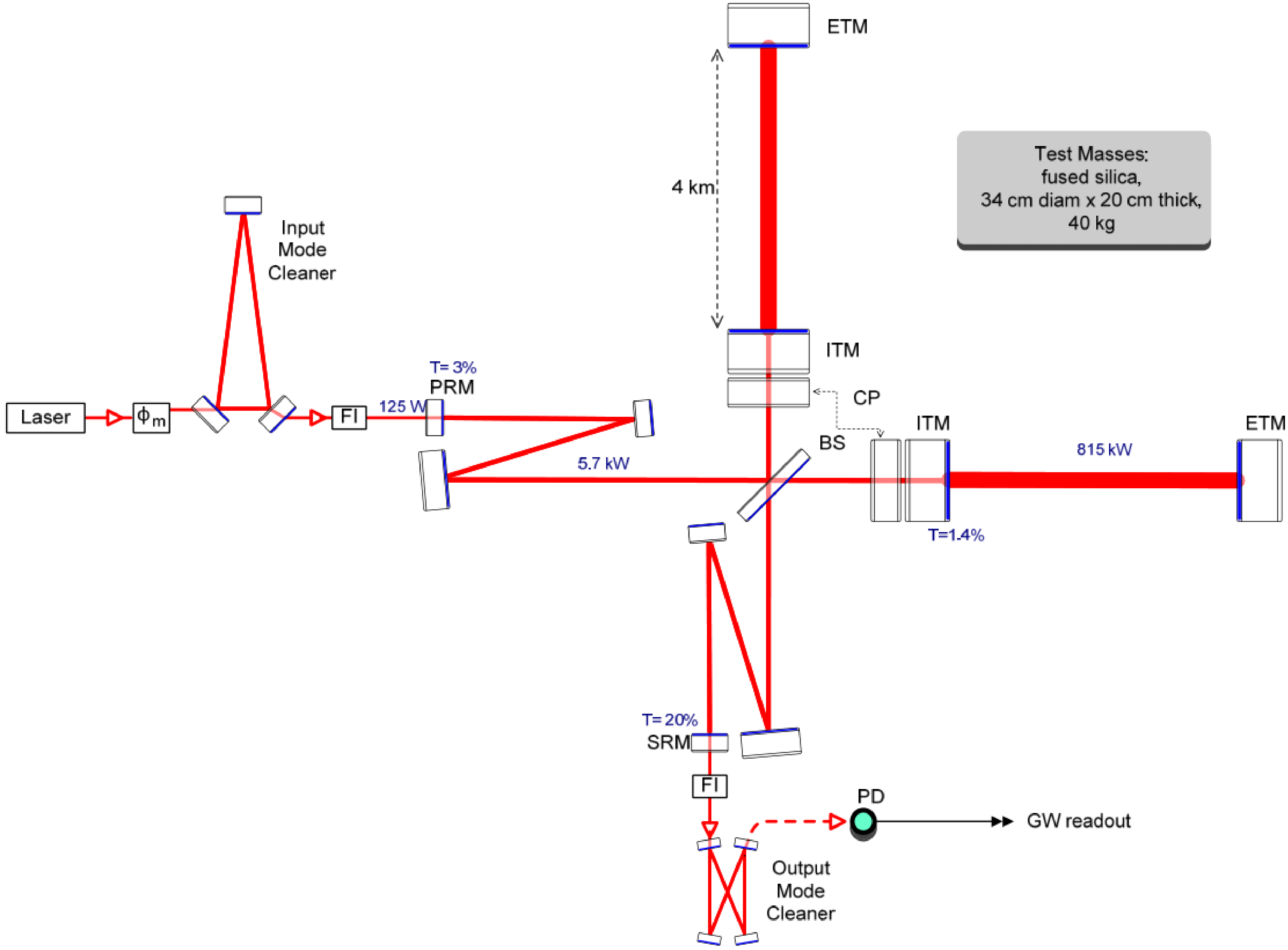
LIGO – Laser Interferometric Gravitational Wave Observatory
LSC – LIGO Scientific Collaboration, includes VIRGO (Italy) team, maybe India

Strain Curves from Moore et al.



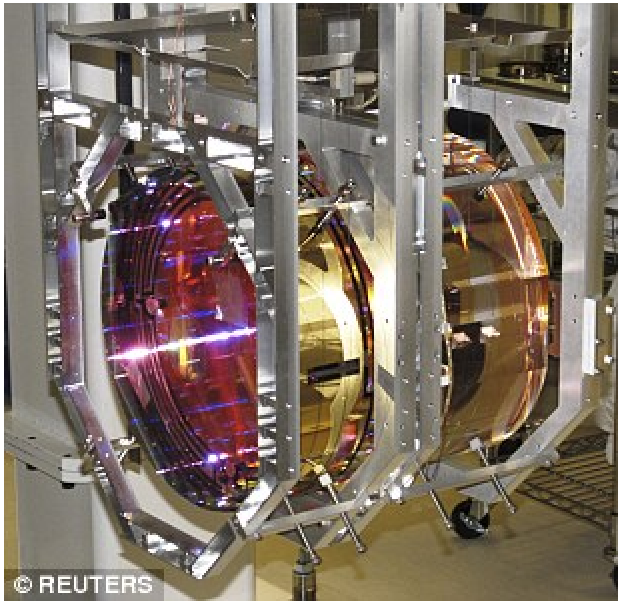
Gravitational Wave Spectrum

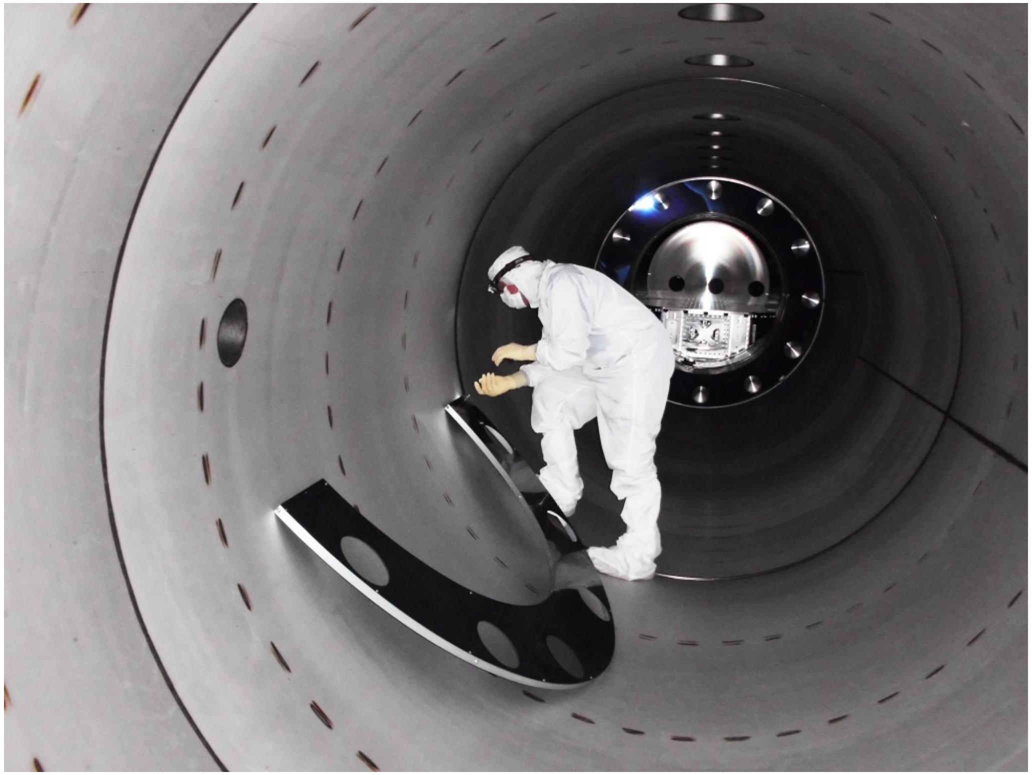



ETM
4 km
Test Masses:
fused silica,
34 cm diam x 20 cm thick,
40 kg
Input
Mode
Cleaner
ITM
CP
T= 3%
PRM
Laser
ϕm
FI
125 W
ITM
ETM
BS
815 kW
5.7 kW
T=1.4%
T= 20%
SRM
FI
PD
GW readout
Output
Mode
Cleaner

LIGO Hardware

- LIGO "Test Mass" in 4-element suspension



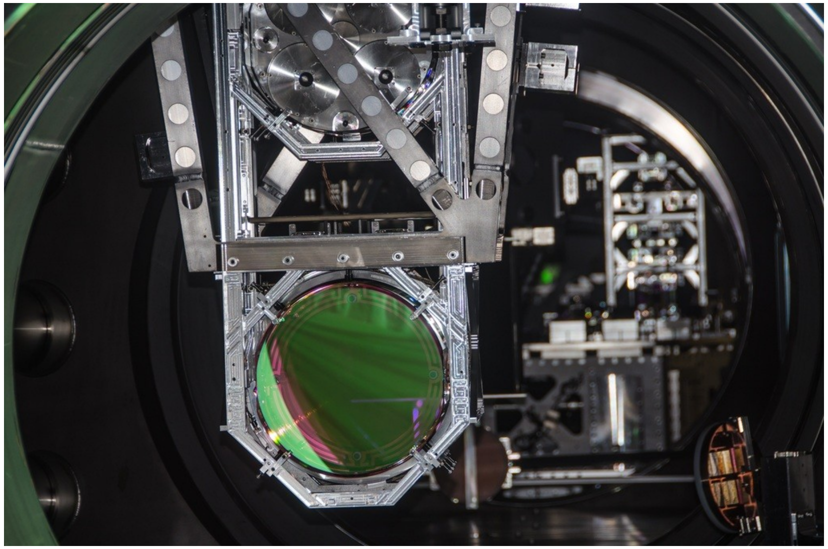


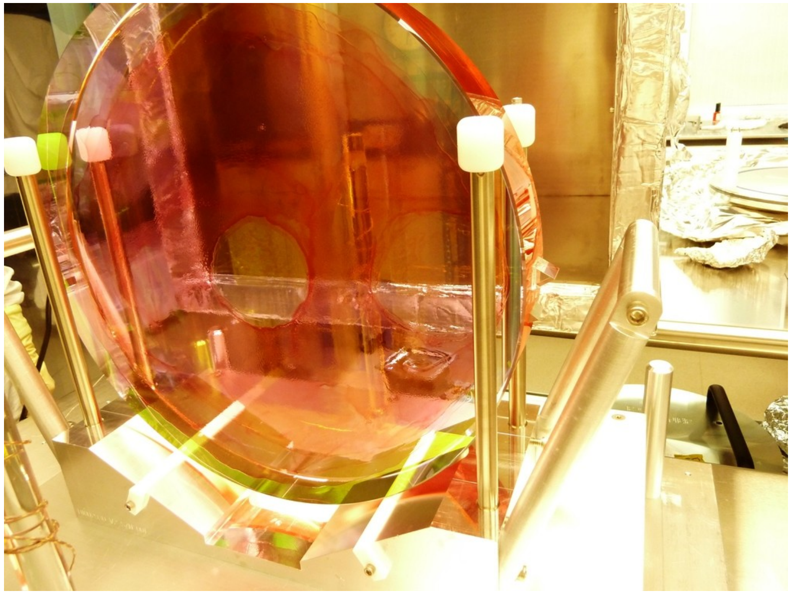
- LIGO Vacuum Tube

Ref: some hardware images

LIGO Hardware

- LIGO “Test Mass” in suspension

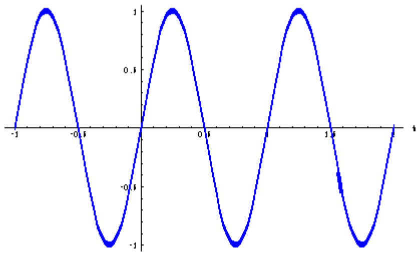




- Beam Splitter

Interference

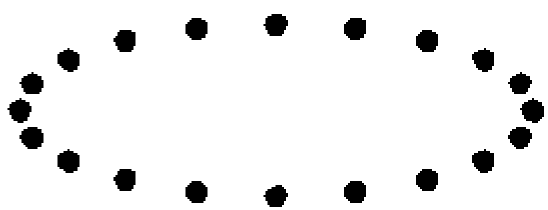
- Two arms, slightly different lengths, L and L+ΔL, consider the **amplitudes** coming together.
- Single amplitude like $e^{i\,kL}$
- Sum them together for $e^{i\,kL} + e^{i\,k(L+\Delta L)}$



Nature of Gravitational Waves, and $h_{\mu\nu}$

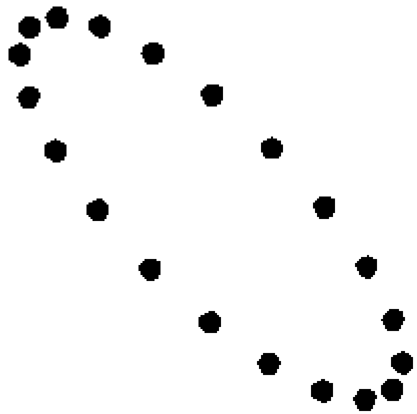
Of all 10 possible components to h, it simplifies to two polarizations. One with a motion that shrinks (grows) in one direction while growing (shrinking) in the other direction. The other polarization is just rotated by 45 degrees.

h_{+}



hplus polarization

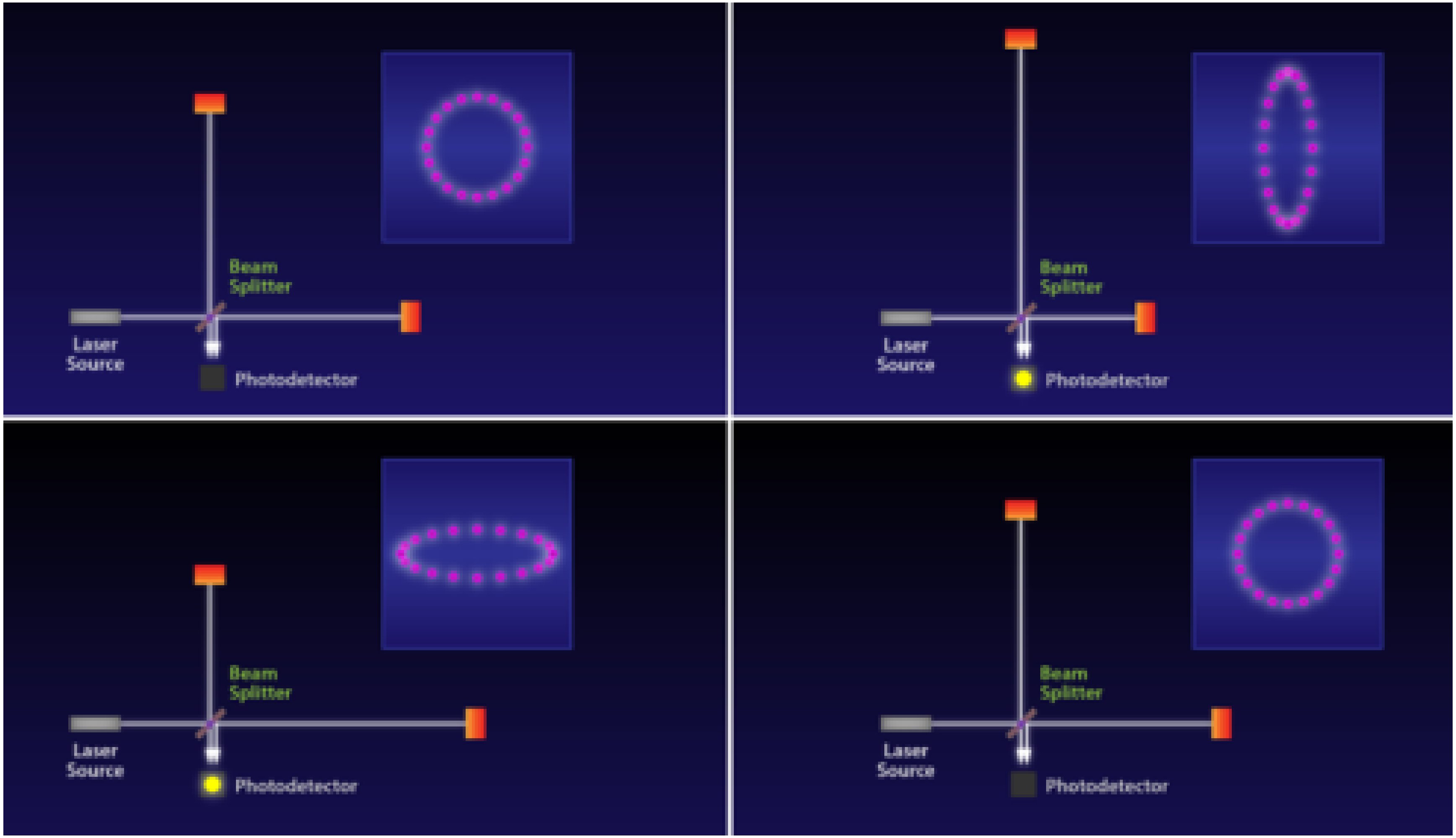
$h_{\times}$



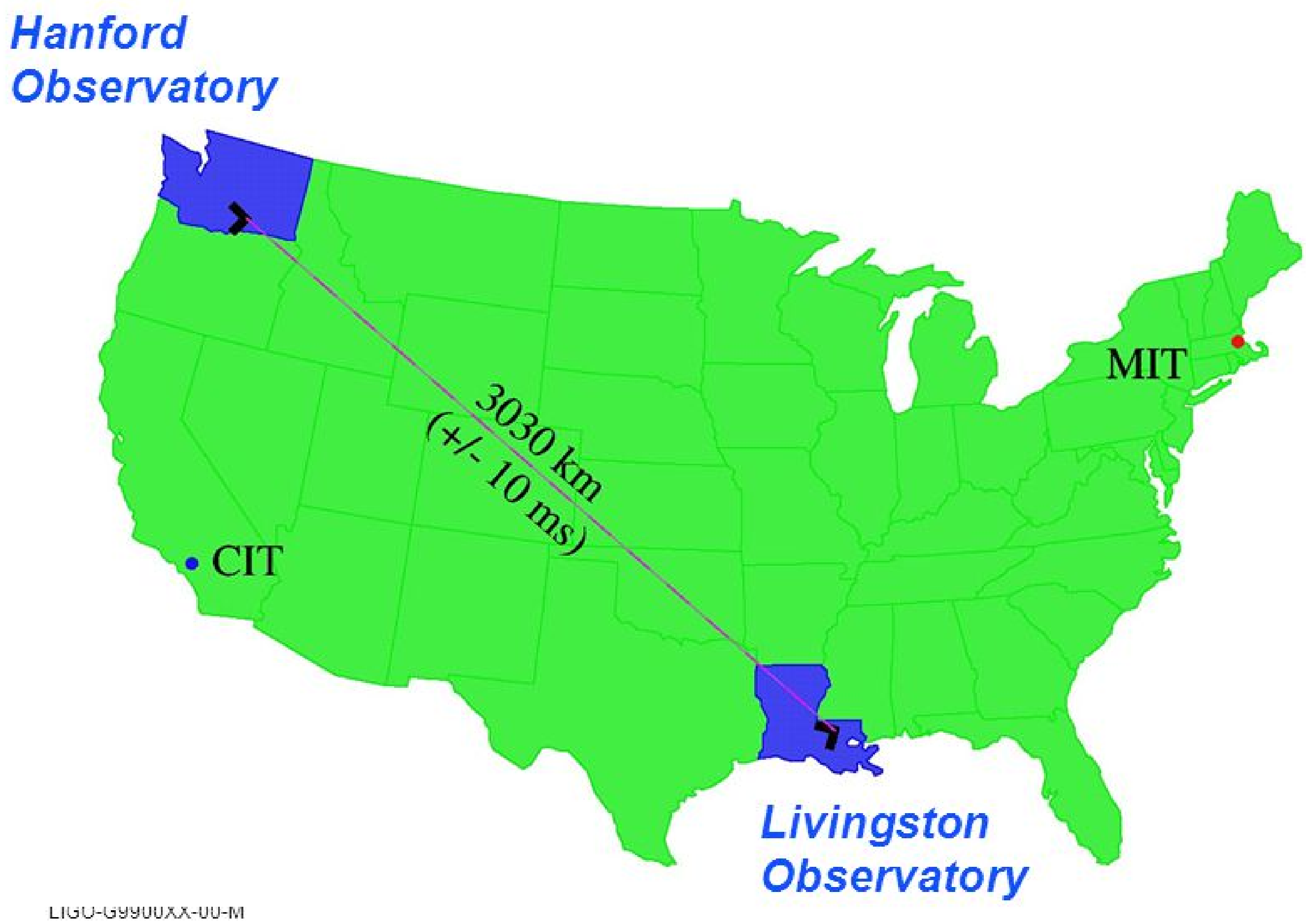
hcross polarization

Wave headed into the page, Y up, X right.

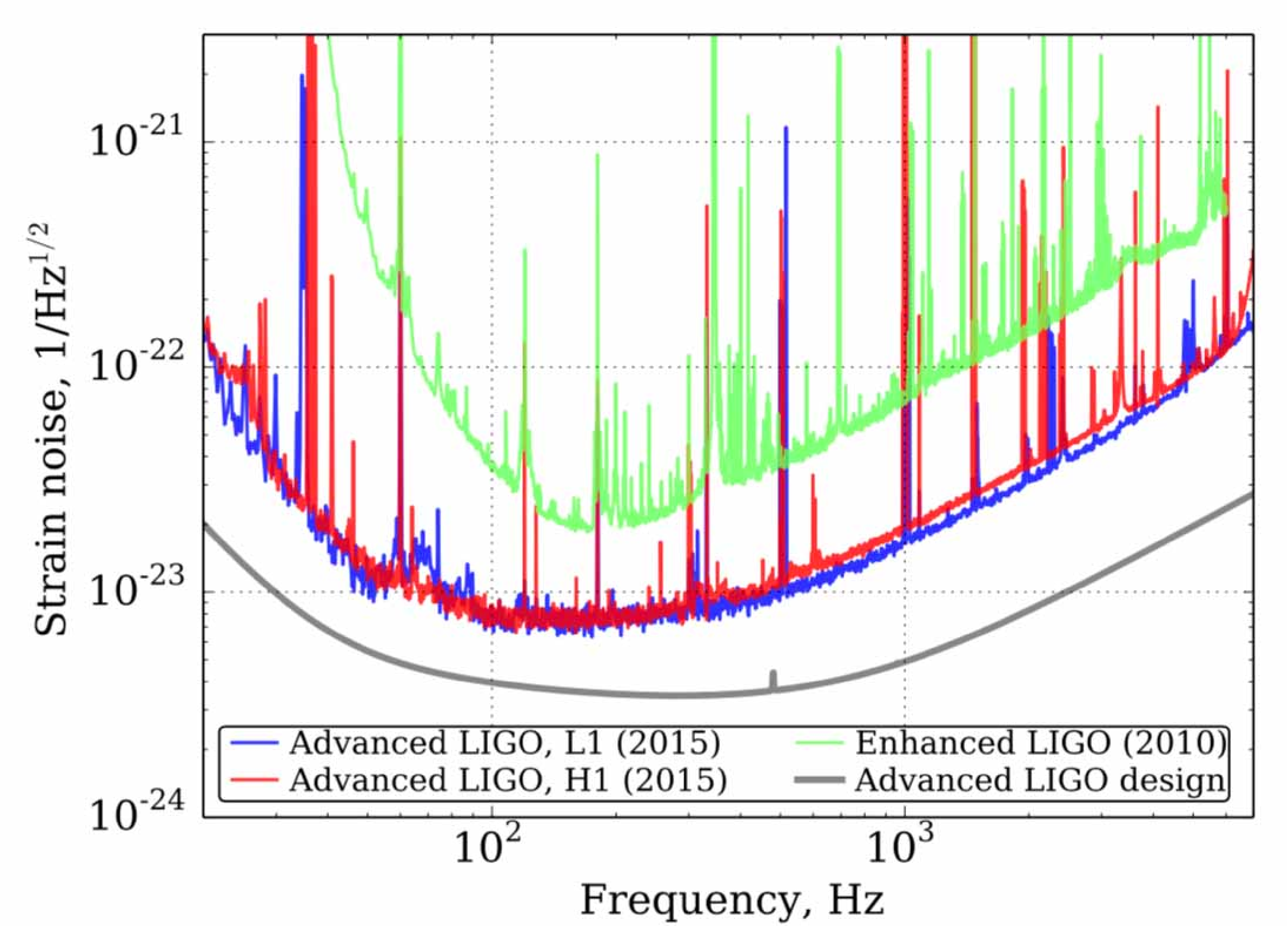
Effect of a perfectly aligned wave on LIGO



LIGO Sites


Hanford
Observatory
3030 km
(+/- 10 ms)
CIT
MIT
Livingston
Observatory
LIGO-G9900XX-00-M

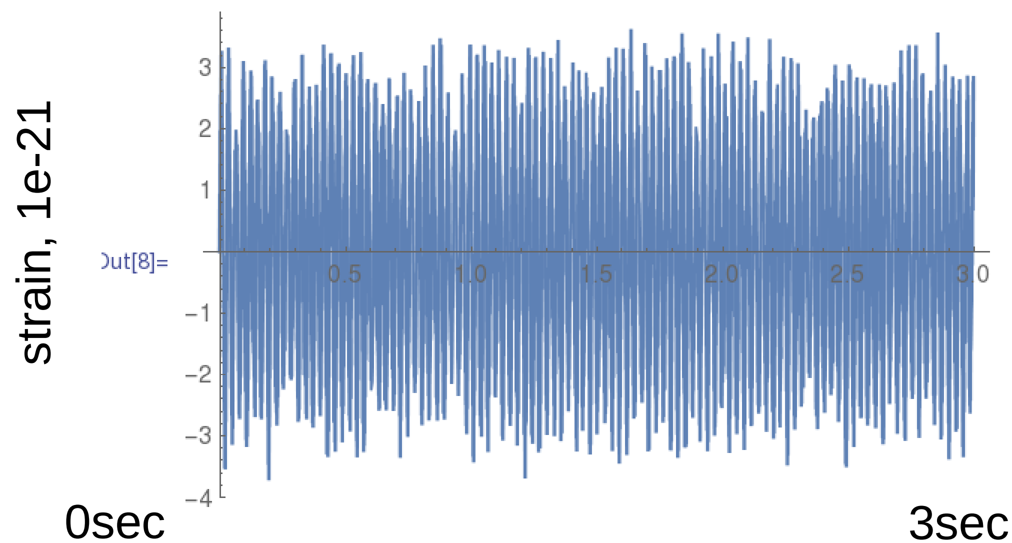
Seismic Noise aLIGO and initial



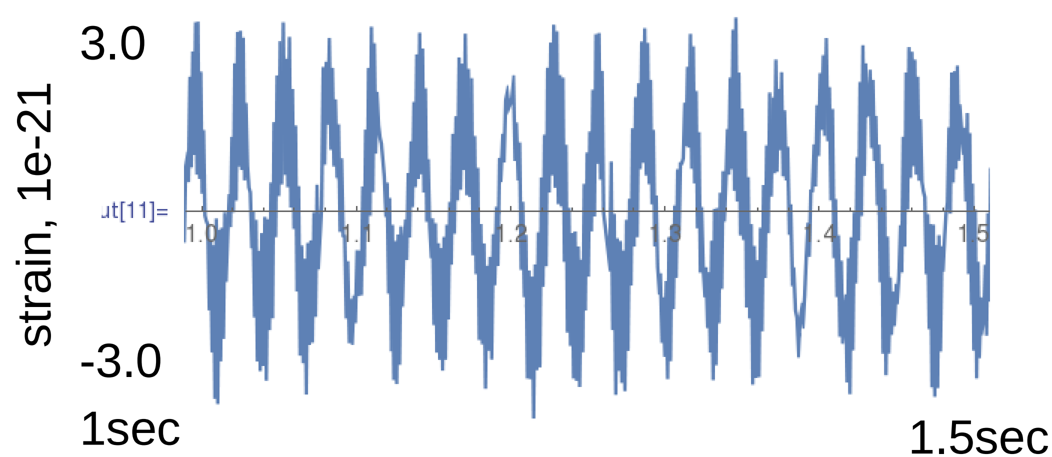
Pick out the Livingston Peaks in Above

Pick out the largest peaks, reconstruct the possible noise. Assumed at t=0 all the modes are in phase.

```
In[8]:= aplot = Plot[ total, {t, 0, 3}]
```




```
In[11]:= Show[aplot, PlotRange → {{1.0, 1.5}, {-4, 4}}]
```

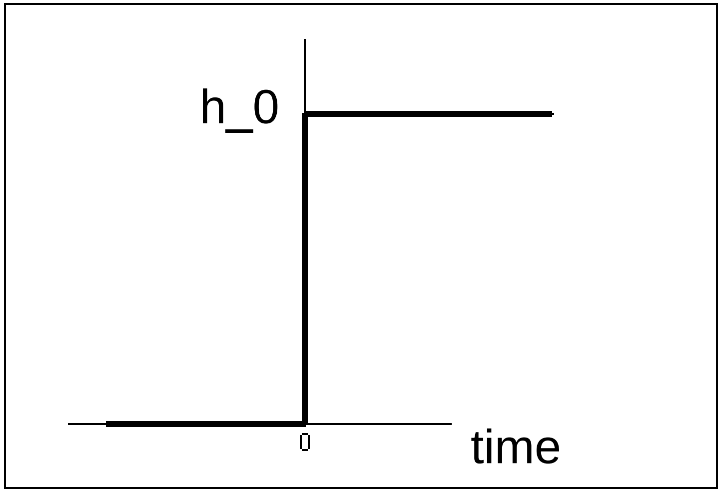


Saulson, *If Light Waves…*

- Argues that in the expanding Universe, light continuously experiences the increase in scale by expanding continuously itself.

$$\frac{\lambda_1}{\lambda_0} = \frac{R(t_1)}{R(t_0)}$$

- **NOT** the case for a light wave in LIGO...
  - The wave filling the cavity **IS** stretched by the sudden onset of the gravitational wave.
  - Light travel time, 2x4km is 27μs, but GW oscillates at 20 Hz, 50ms.



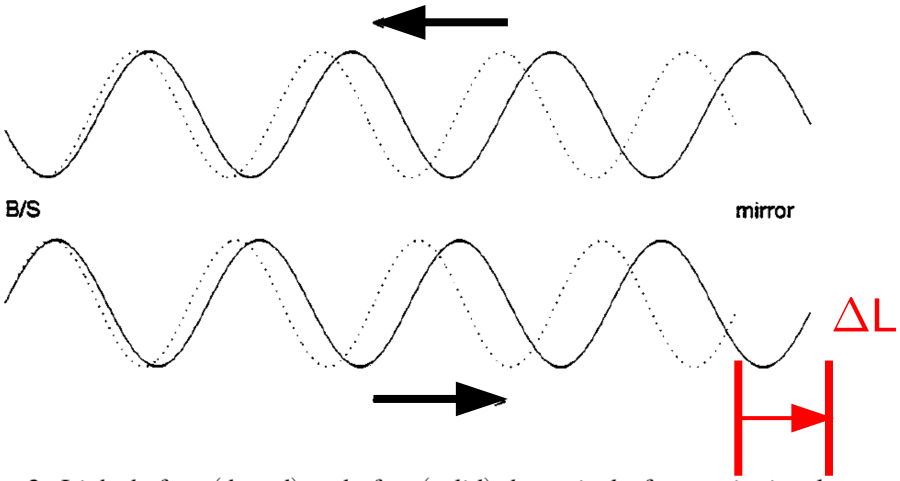
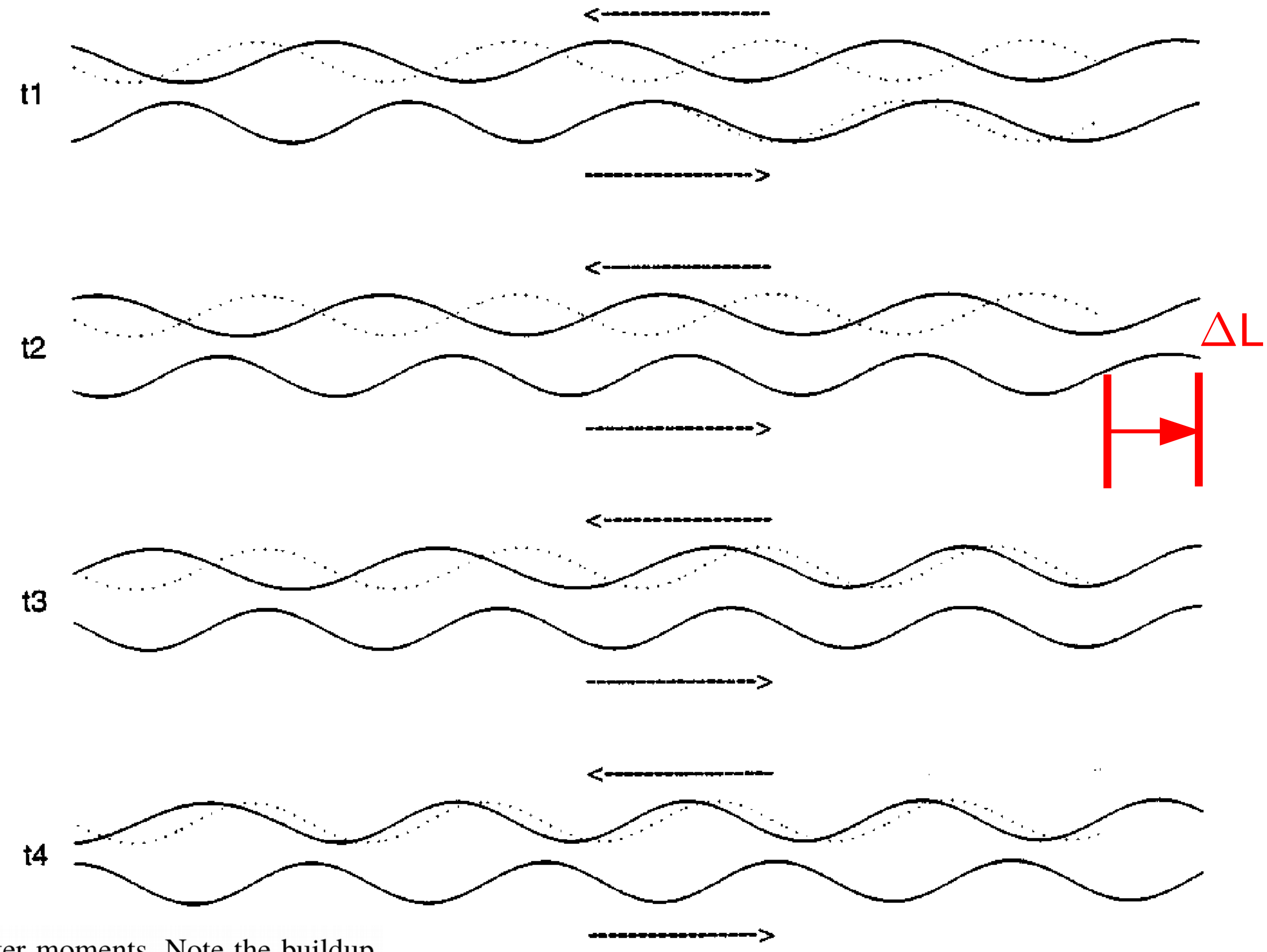


Fig. 2. Light before (dotted) and after (solid) the arrival of a gravitational wave. The beamsplitter is at left, end mirror at right. Outbound light is shown at the bottom, returning light at the top.

Ref: Saulson, *If Light Waves…*, AmJPhys **65**, 501 (1997)

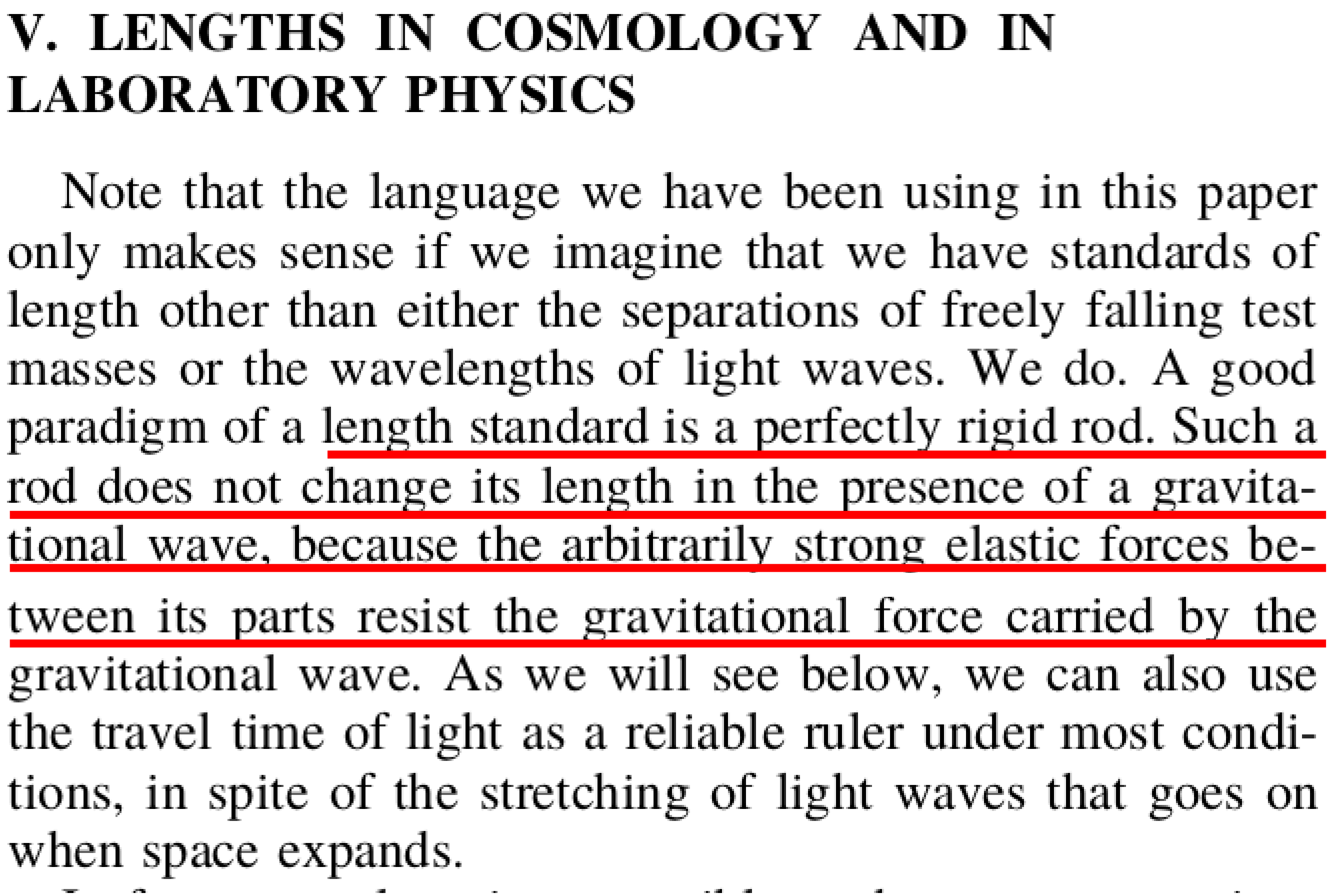
As the Wave runs through...



bb

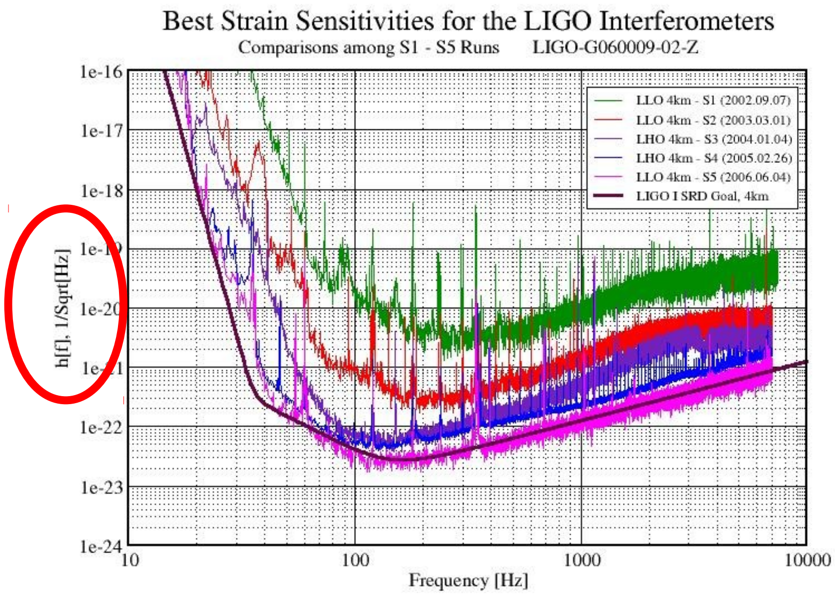
Fig. 3. Like Fig. 2, but at a succession of later moments. Note the buildup of phase shift between the light in the stretched arm (solid) compared to how it would have traveled through an unstretched arm.

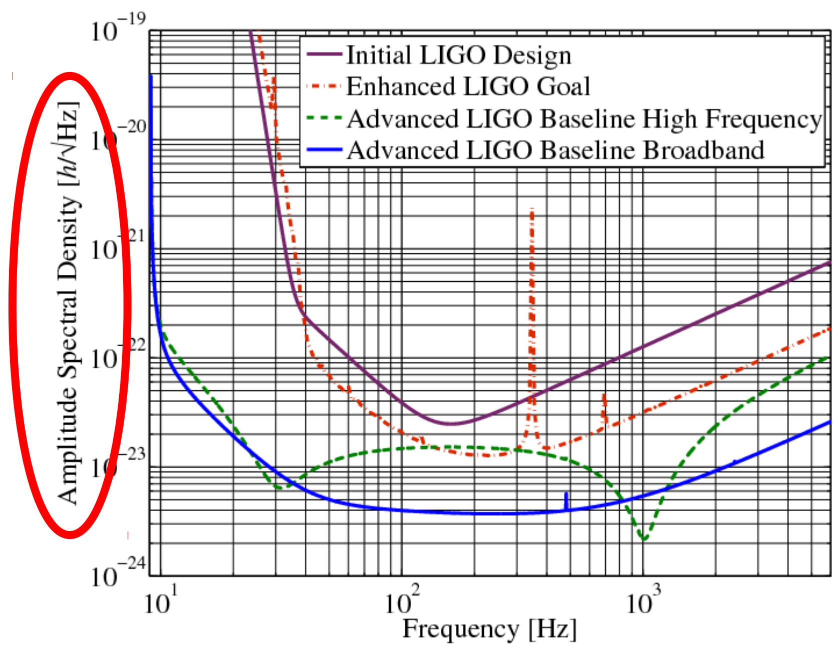
Saulson, *If Light Waves…*, says rods are still rigid!


V. LENGTHS IN COSMOLOGY AND IN LABORATORY PHYSICS

Note that the language we have been using in this paper only makes sense if we imagine that we have standards of length other than either the separations of freely falling test masses or the wavelengths of light waves. We do. A good paradigm of a length standard is a perfectly rigid rod. Such a rod does not change its length in the presence of a gravitational wave, because the arbitrarily strong elastic forces between its parts resist the gravitational force carried by the gravitational wave. As we will see below, we can also use the travel time of light as a reliable ruler under most conditions, in spite of the stretching of light waves that goes on when space expands.

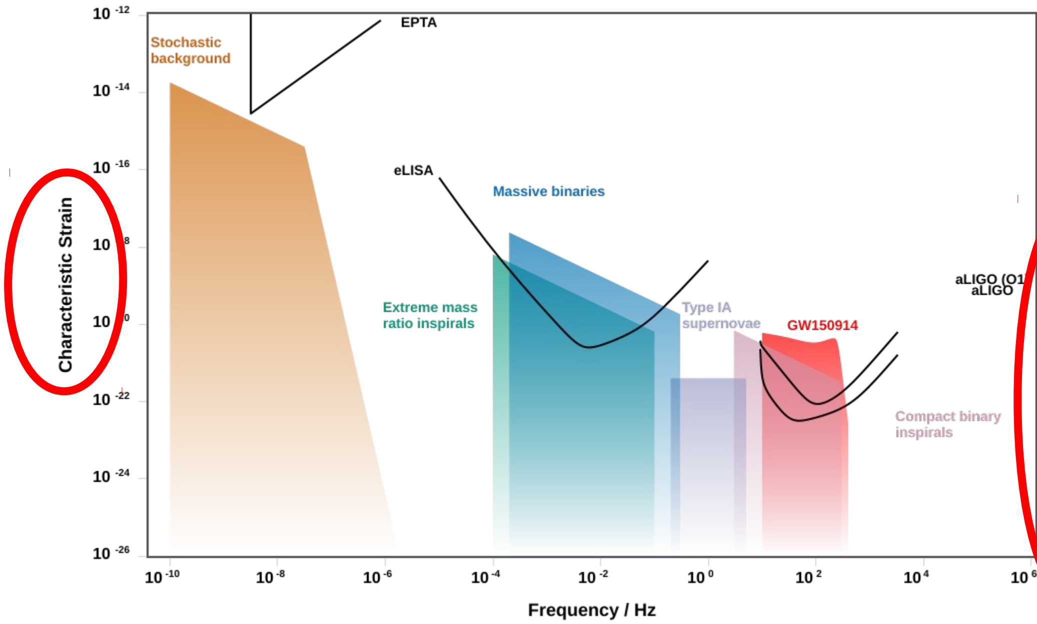
Strain Curve, Strain Sensitivity, Amplitude Spectral Density, Power Spectral Density...OH MY!



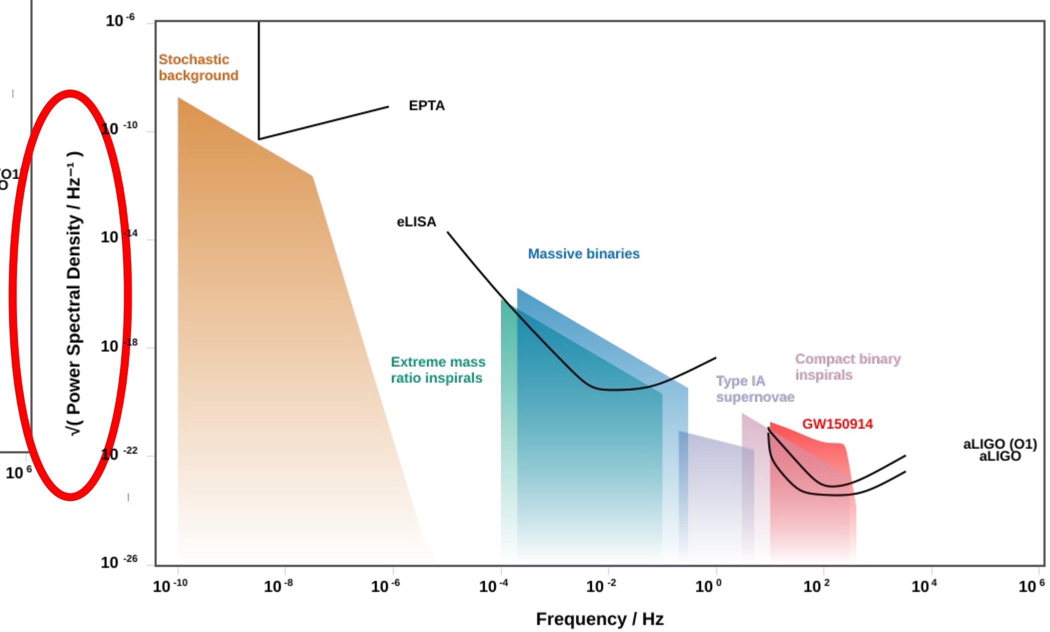


“per root Hz” is usually called the *strain sensitivity*, or sometimes *amplitude spectral sensitivity*

Strain Curve, etc...



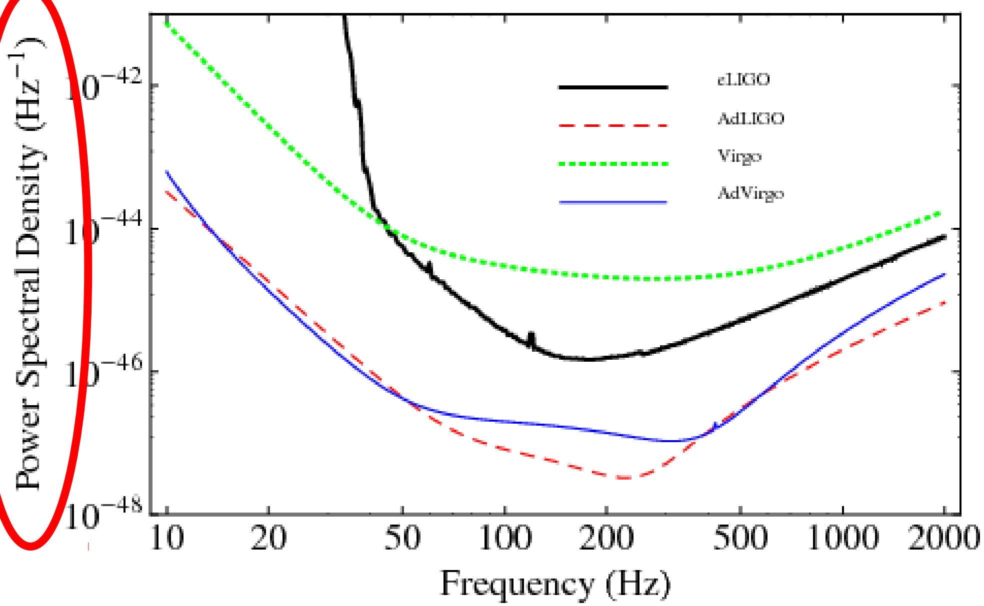
Characteristic Strain, just h



square root of *Power Spectral Density*, really *amplitude spectral density*

Ref: Cole,s online app .

Strain Curve, etc...



Power spectral Density

bb

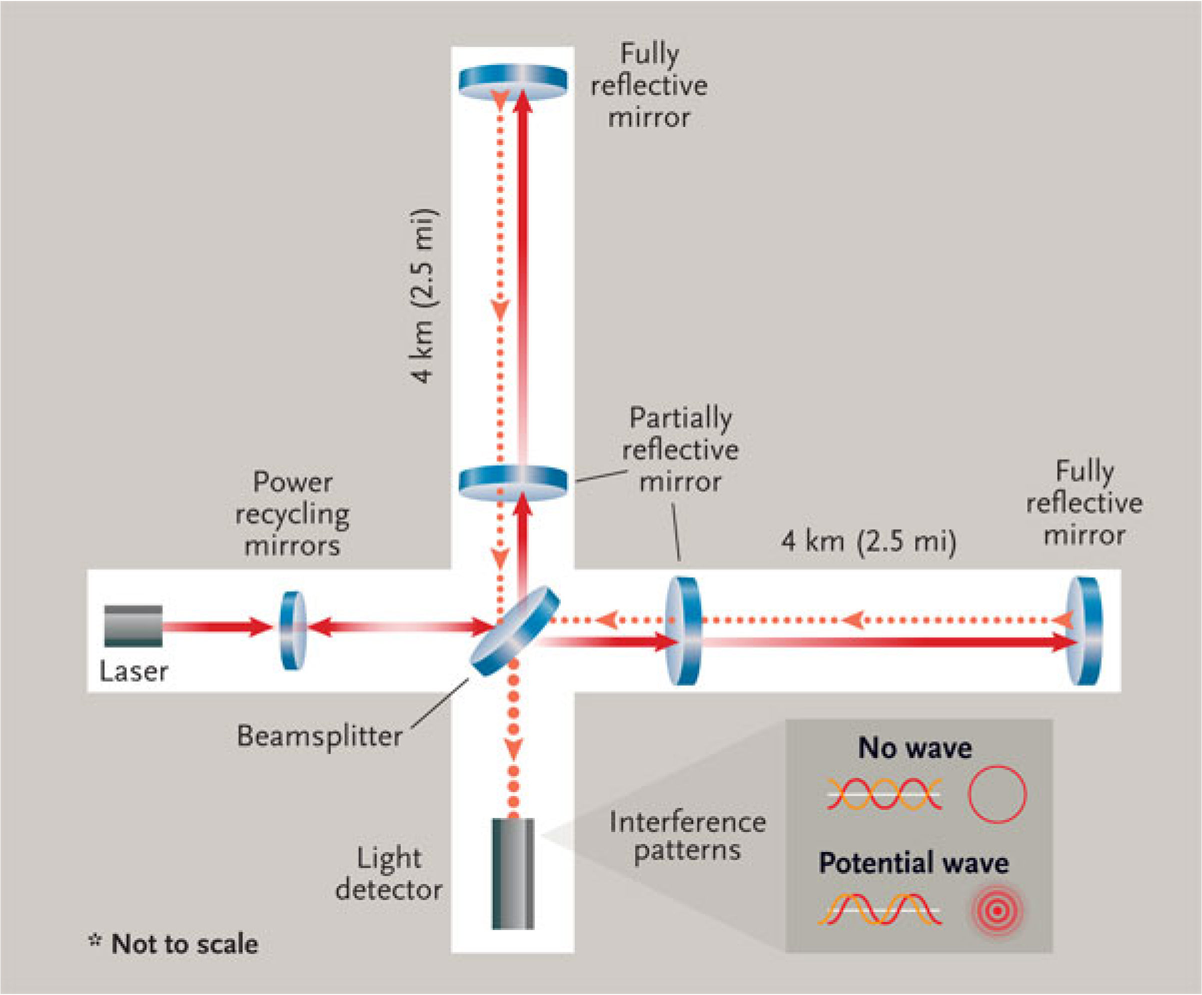
Links

- LIGO Scientific Collaboration, LSC
- LIGO Document Server
- CalTech GW media assets page.
- Kelly Holley-Bockelman's TEDx Nashville Talk 2016 about GW150914.
- Pulsar timing array, Nanograv

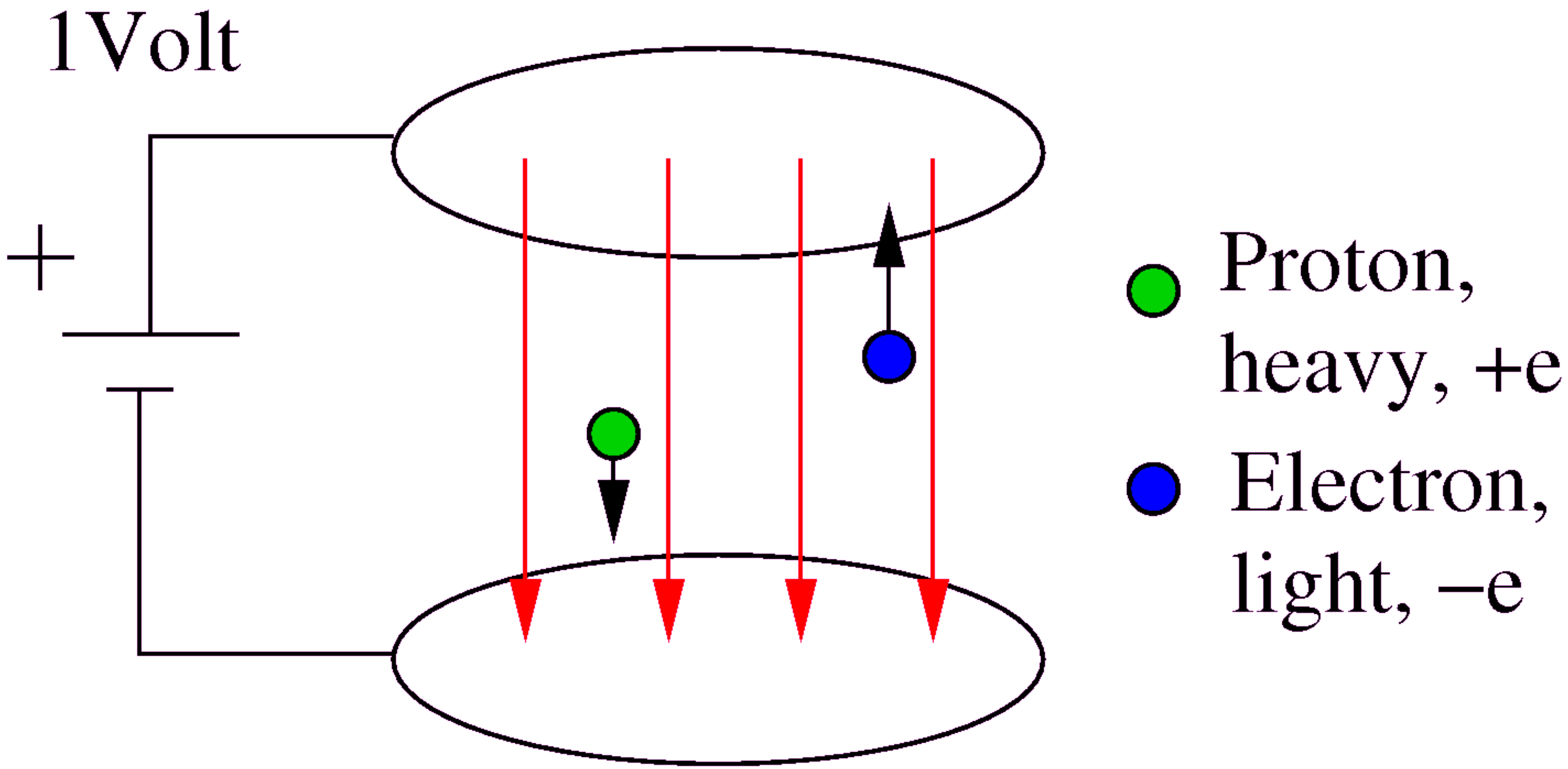
Backup

LIGO Inteferometer

- 4km long



Units?

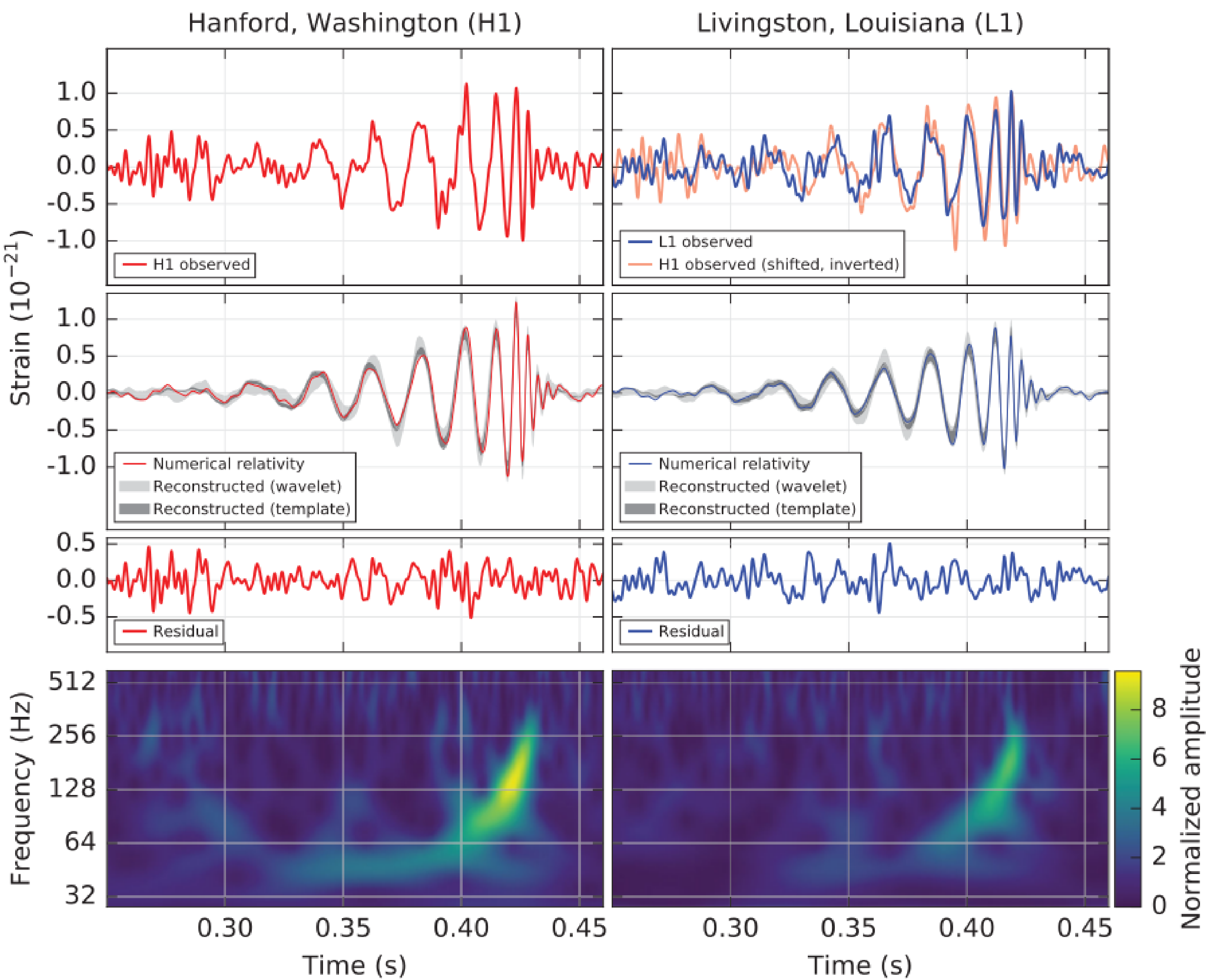


SI Prefixes

Table 5. SI prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Gravitational Wave GW150914



Direct Discovery by LIGO of a gravitational wave announced on 11 February 2016 for a wave on 14 September 2015---event labeled GW150914.

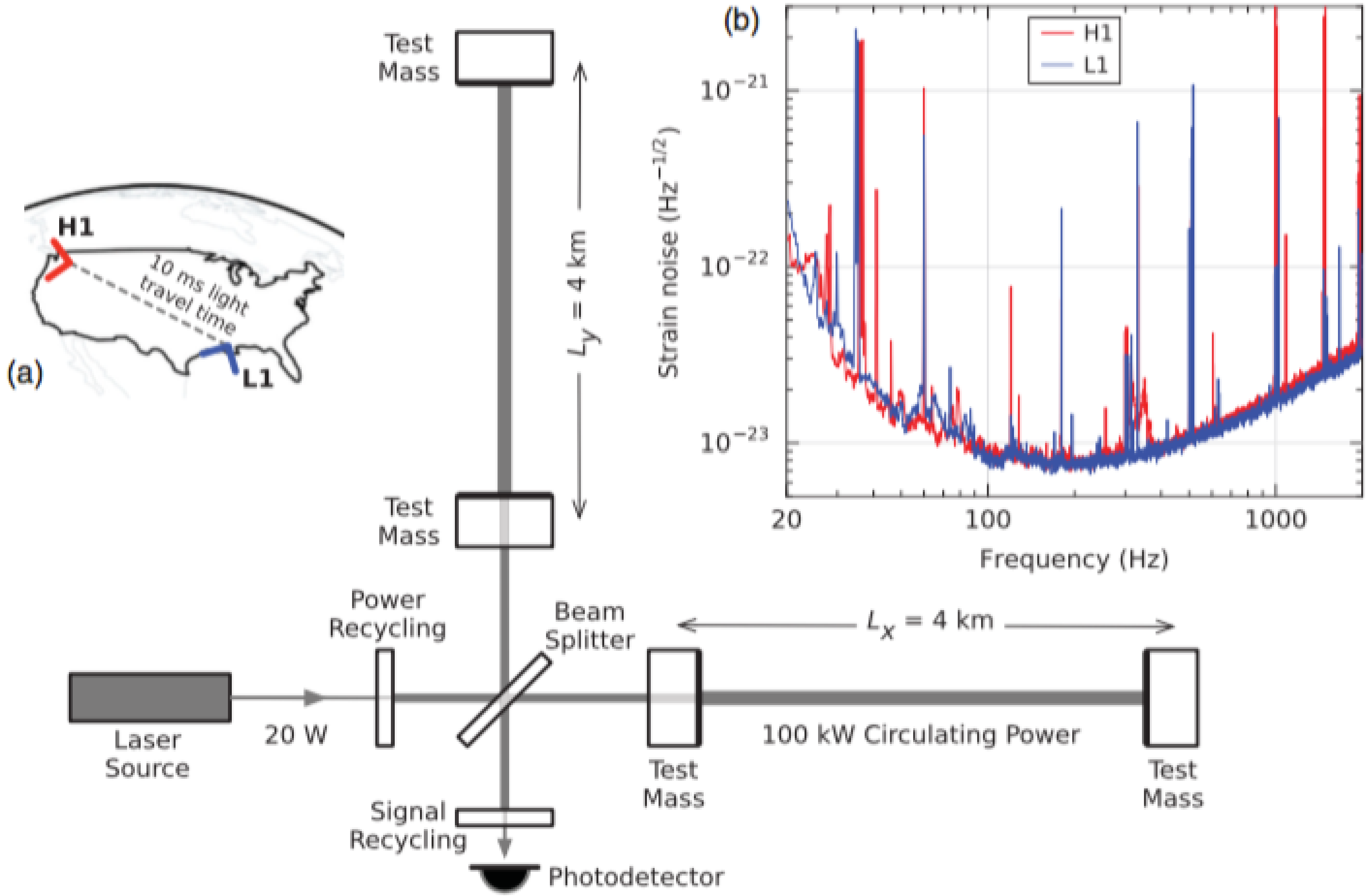
SNR = 24, 5 sigma detection!

Pretty after filtering out the known seismic frequencies.

Merging Black Holes

ref: http://www.techinsider.io/binary-black-holes-confirmed-gravitional-waves-2016-2

Schematic, Map, and Noise



GW strain for Circular Orbit

$$h_0 = \frac{r_{s1} \cdot r_{s2}}{r \cdot R}$$

$$\frac{\omega_s^2}{c^2} = \frac{(r_{s1} + r_{s2})}{2\, R^3}$$

$$h_+(t) \quad = \quad h_o\left(\frac{1 + \cos^2 i}{2}\right) \cos 2\omega_s t$$

$$h_\times(t) \quad = \quad h_o \, \cos i \, \sin 2\omega_s t$$

- rs1 is 2GM_1/c^2, Schwarzschild radius for mass M_1, etc.
- r is distance from Earth to system.
- R is the separation of the two bodies.

ref: Maggiore around Eqn. 3.332.

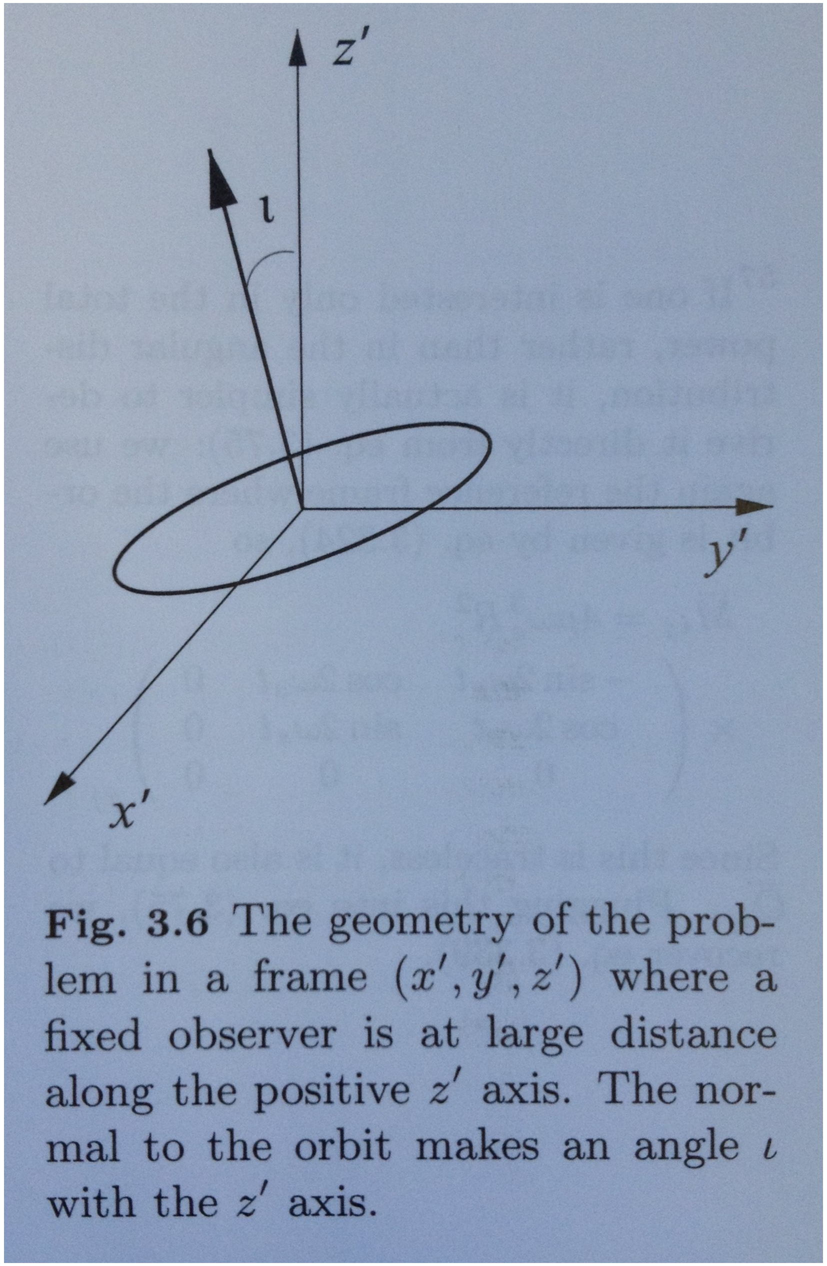


Fig. 3.6 The geometry of the problem in a frame (x', y', z') where a fixed observer is at large distance along the positive z' axis. The normal to the orbit makes an angle ι with the z' axis.

Some Constants

Schwarzschild radius	2GM/c^2	2953 m for Msun
GR Units, Mass	GM/c^2	1477 m for Msun
GR Units, Power	c^5/G	3.628e52 W
GR Units, Energy	c^4/G	1.210e44 J/m
parsec, pc		3.09e16 m = 3.262 ly
astronomical unit, au		149.6e9 m
light-year, ly		0.946e16 m = 0.307 pc
fine structure constant	e^2/(4pi eps0)/hbar c	0.00730 = 1/137.04
wavelength-energy	h c	1.24 eV µm