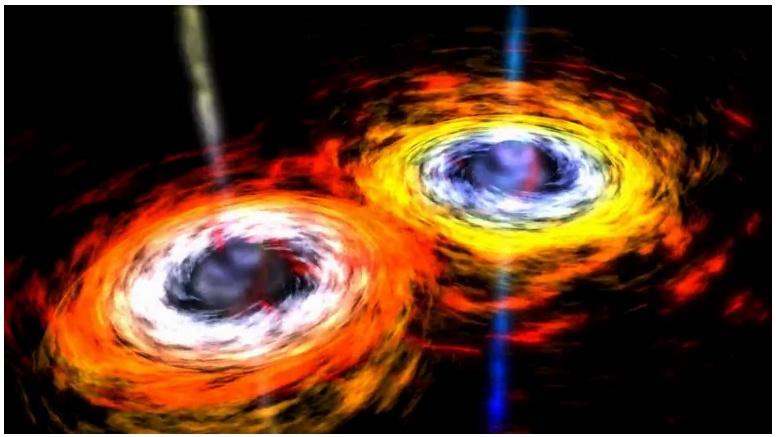
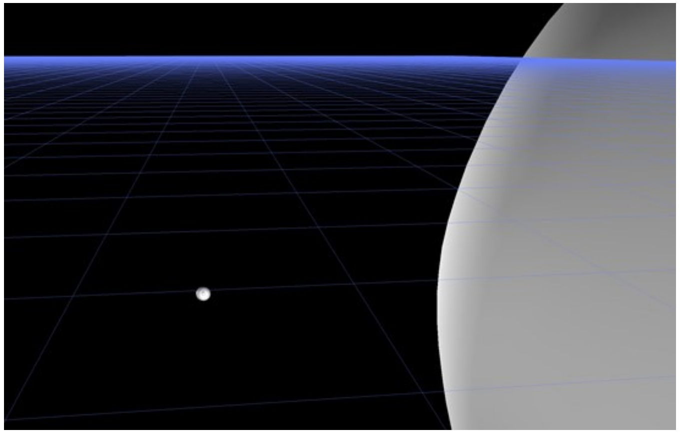
Gravitational Waves – Sources and Detectors



Orbiting Massive Bodies

Supernova, NGC7293-Helix Nebula

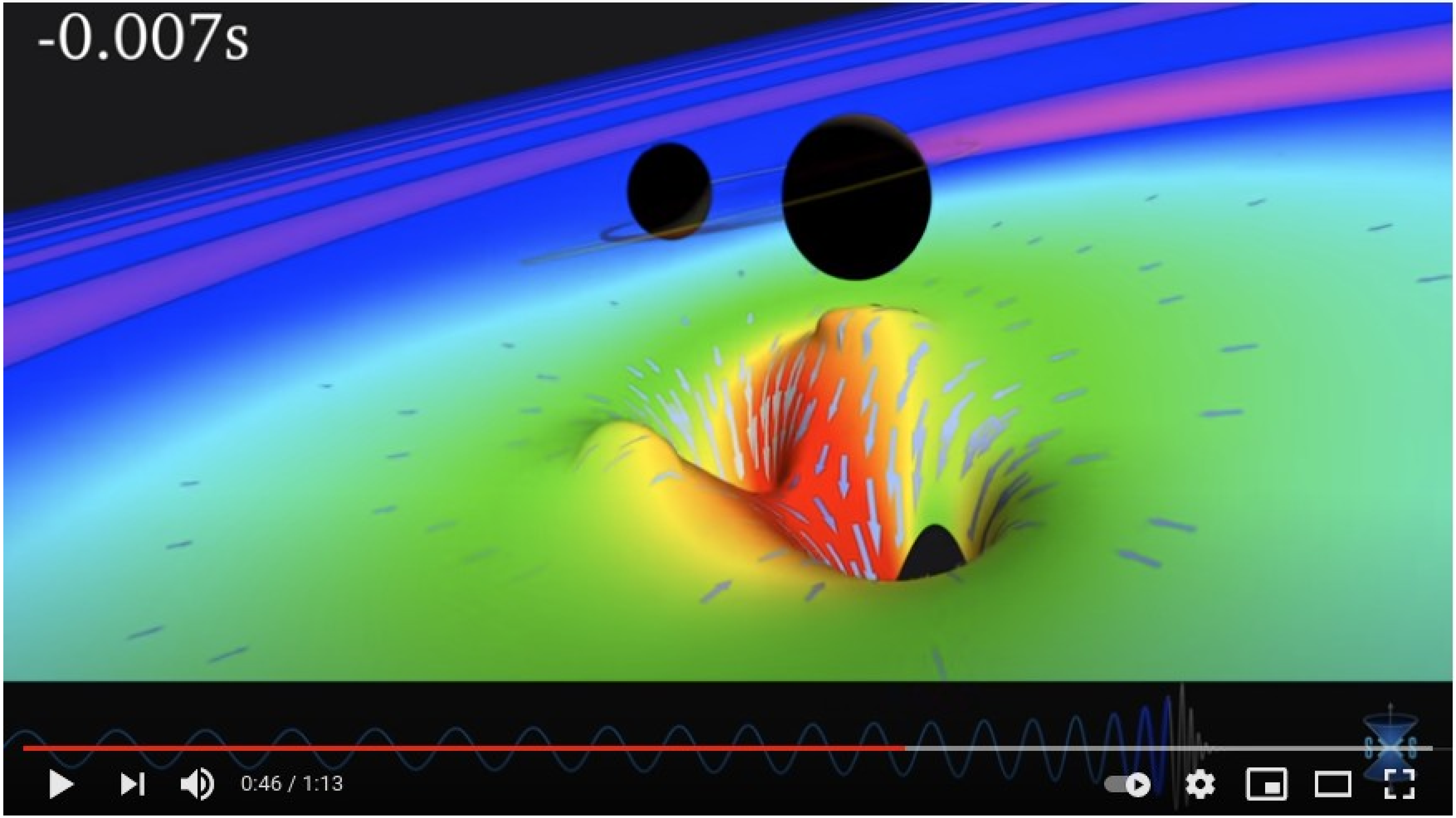


Extreme Mass Ratio Blackhole Mergers

Credit: https://www.rit.edu/news/story.php?id=47936

Sources, Binary Black Holes

- **Binary Black Holes** inspiral, merger, and ringdown. First **GW150914**.



https://youtu.be/1agm33iEAuo 1m13s, no matter around, GW150914 paramerters

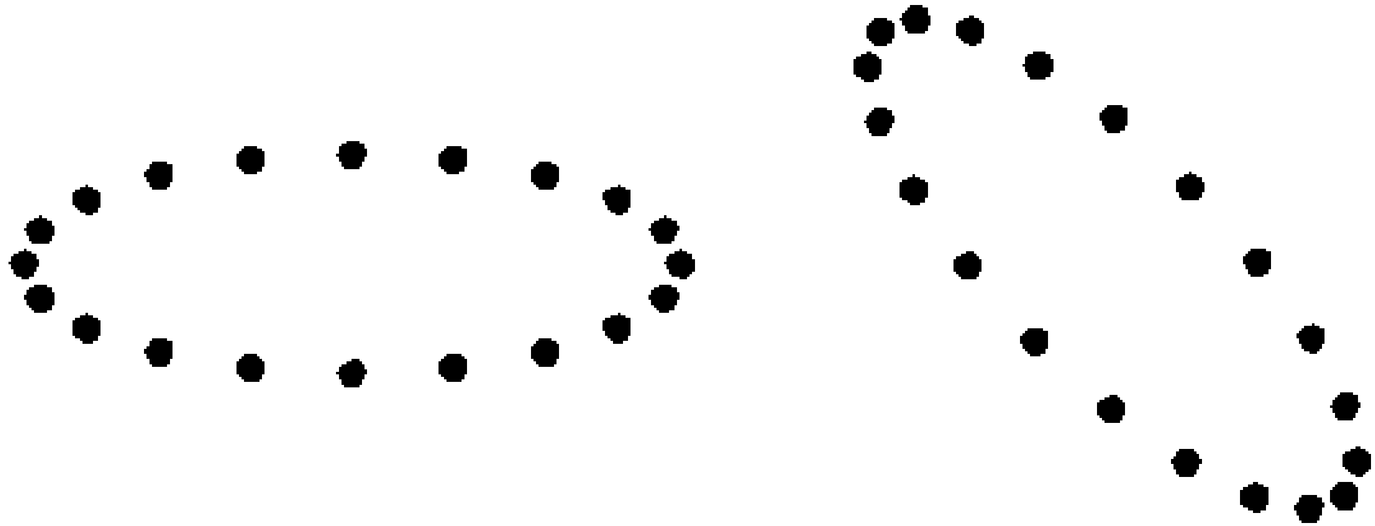
Sources, Binary Neutron Stars

- **Binary Neutron Stars** inspiral, merger, and ringdown. First **GW170817** . Seen in all optical and other EM bands.

https://youtu.be/y8VDwGi0r0Ehttps://youtu.be/1agm33iEAuo 48s, matter around, kilonova, heavy elements created.

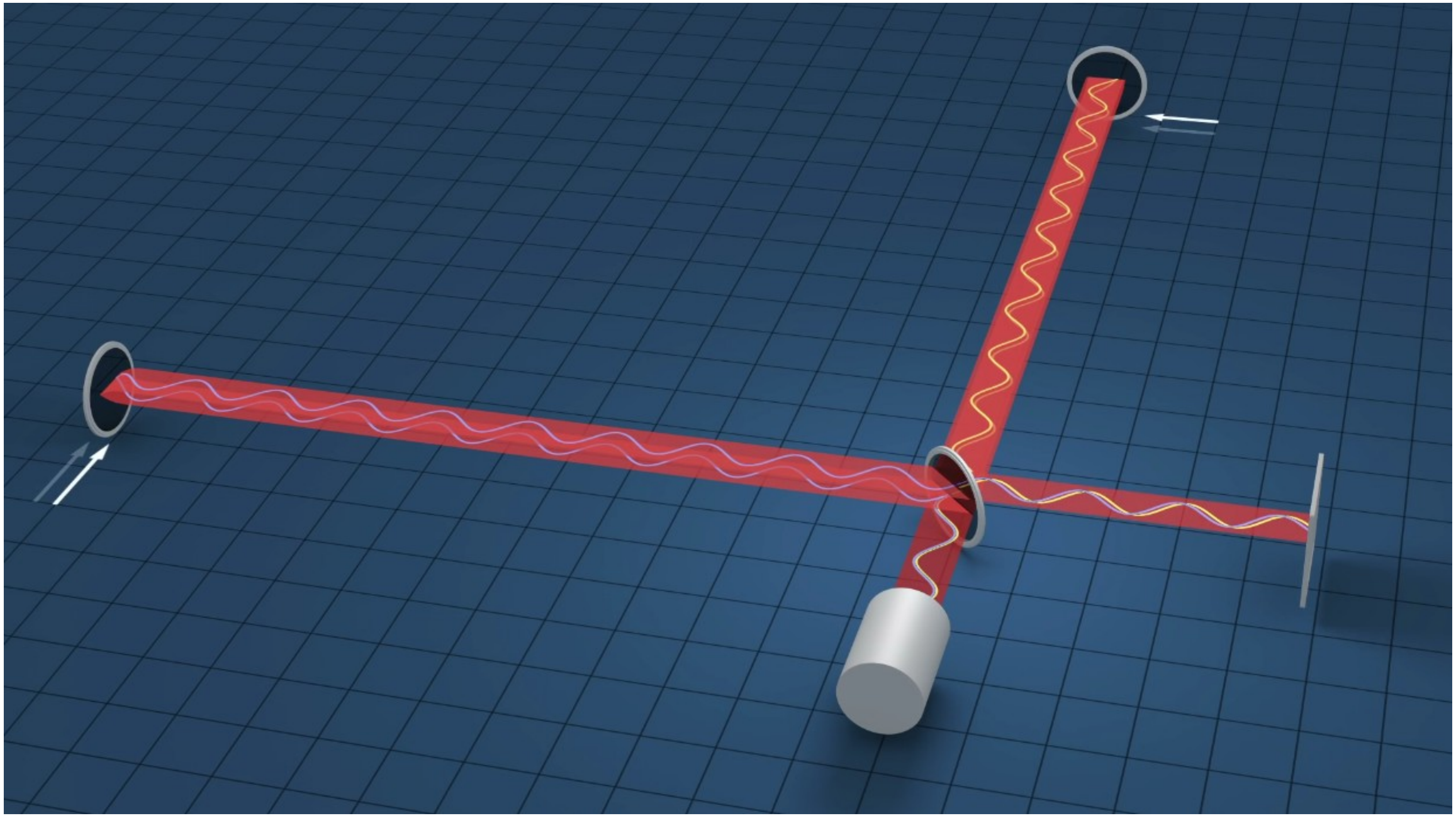
Sources, Waveforms – In a Picture

- Two modes, + and X
- Dots are masses hanging out in space with little self-attraction. They are NOT a metal ring! That is bound by atomic forces and the effect of the GW is miniscule.



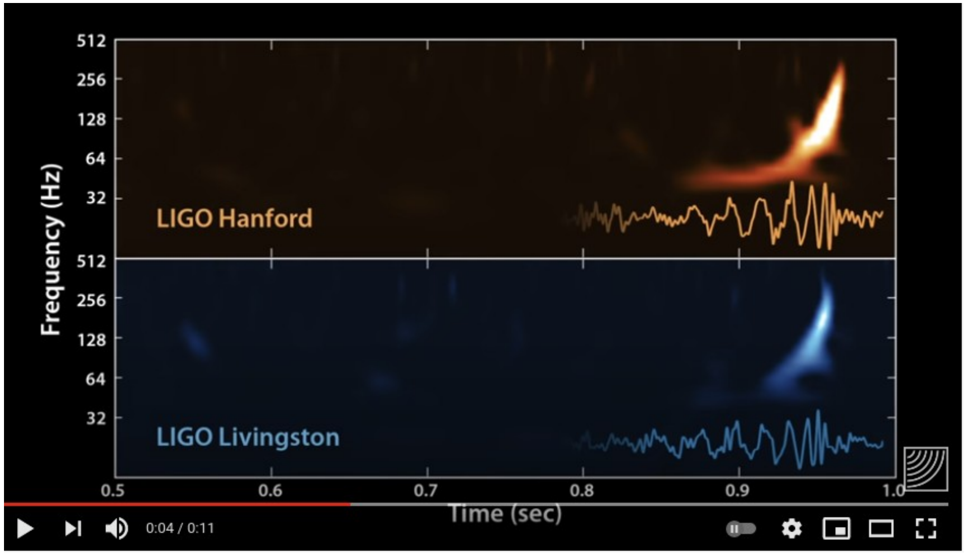
Big Michelson Interferometer, 4 km arms

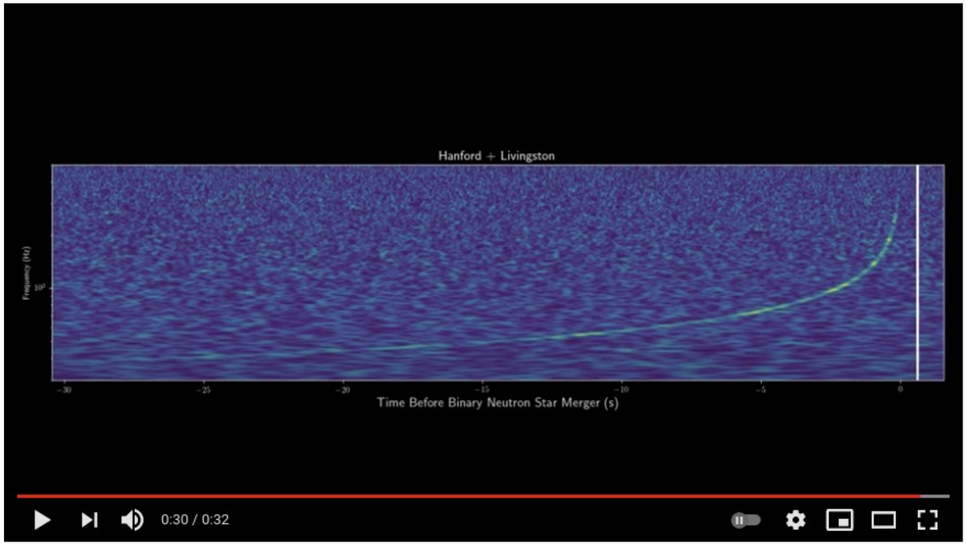
- YouTube link https://youtu.be/tQ_teIUb3tE



Sources, Waveforms---The Strain

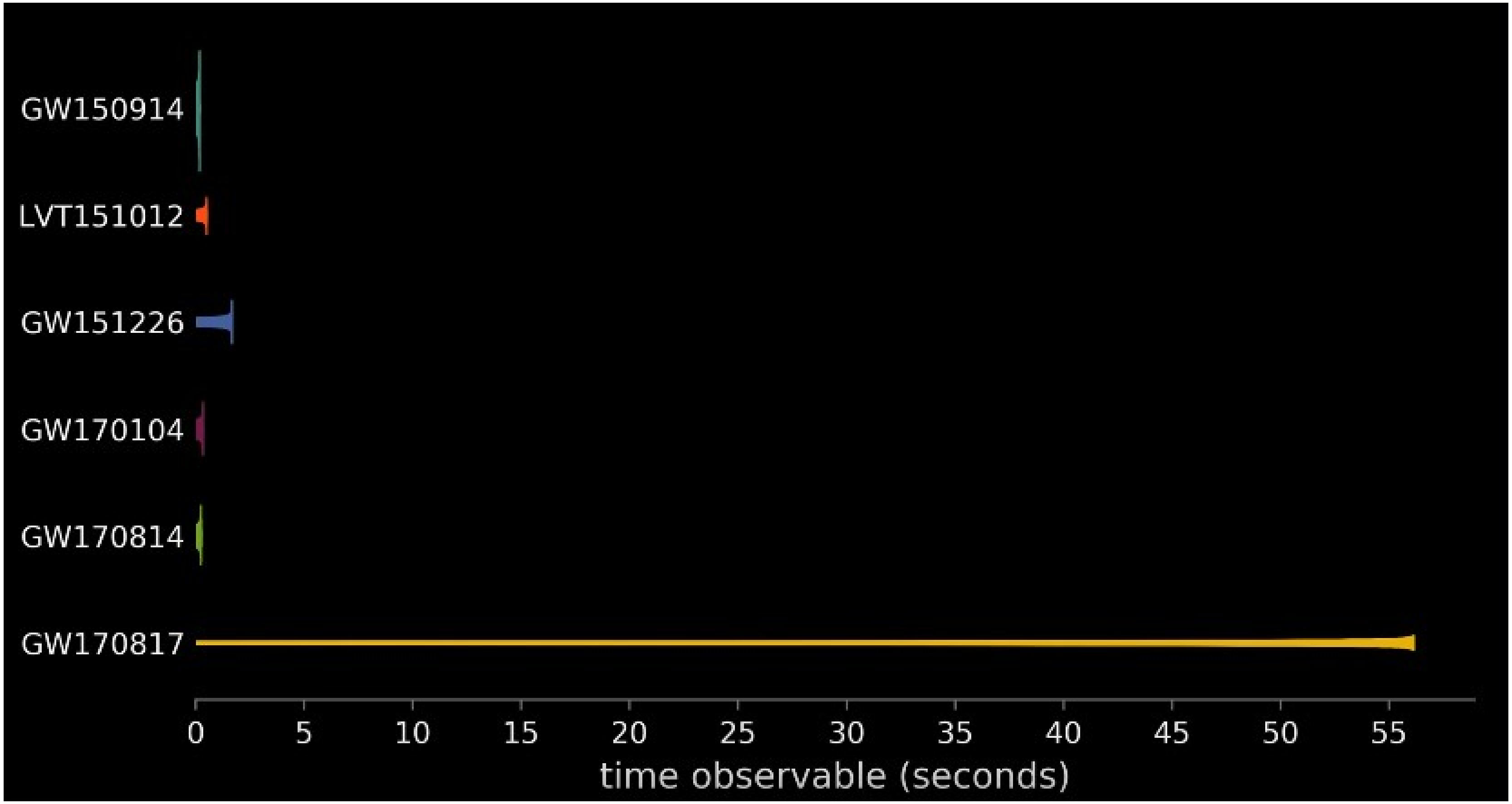
- **Waveforms**, the strain in the interferometer(s)
- Binary Black Holes, GW150914, here





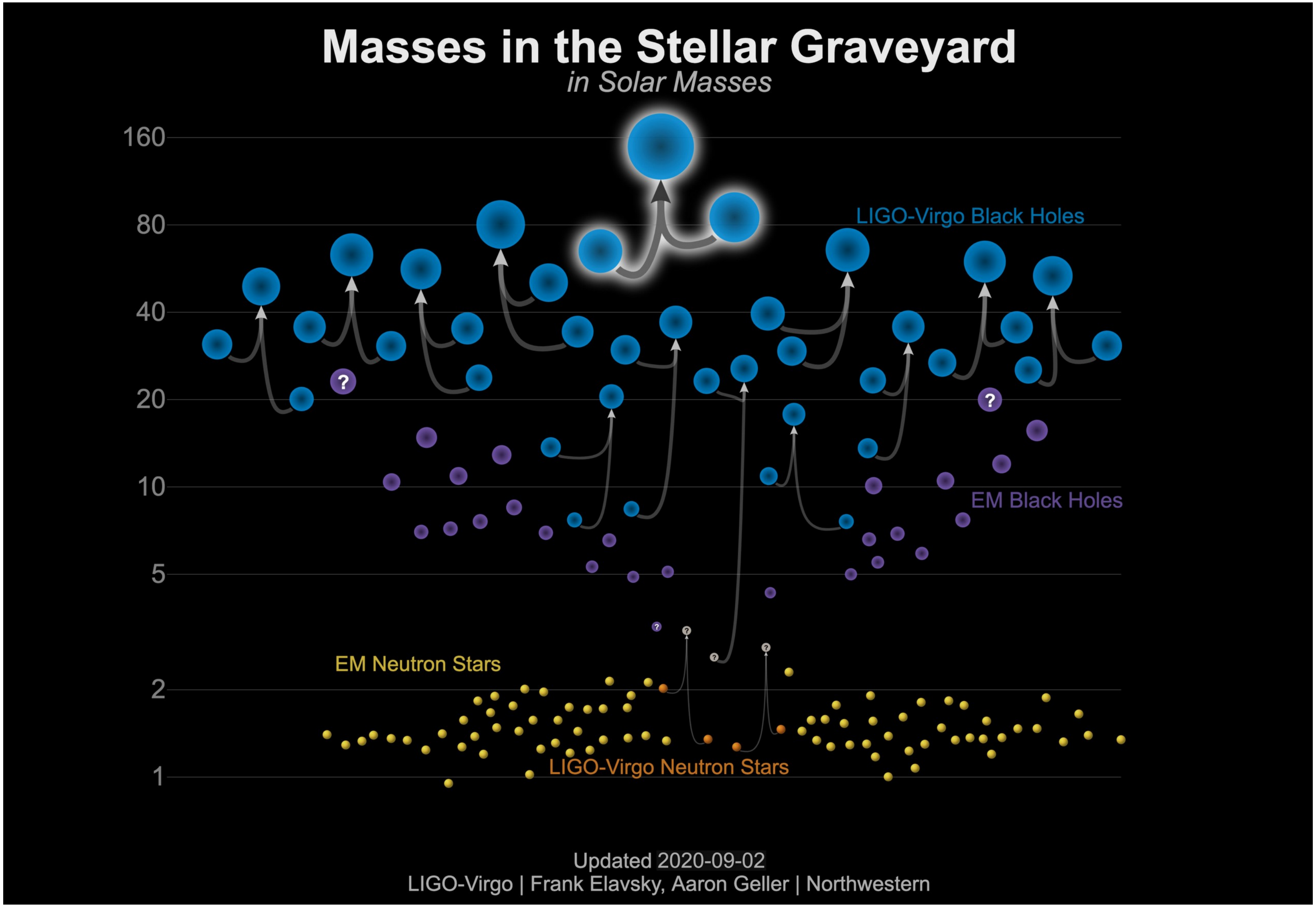
- Binary Neutron Stars, GW170817, here

GW170817 with other BH GW Sources



YouTube video, animated waveforms, here

Population of Black Holes and Neutron Stars



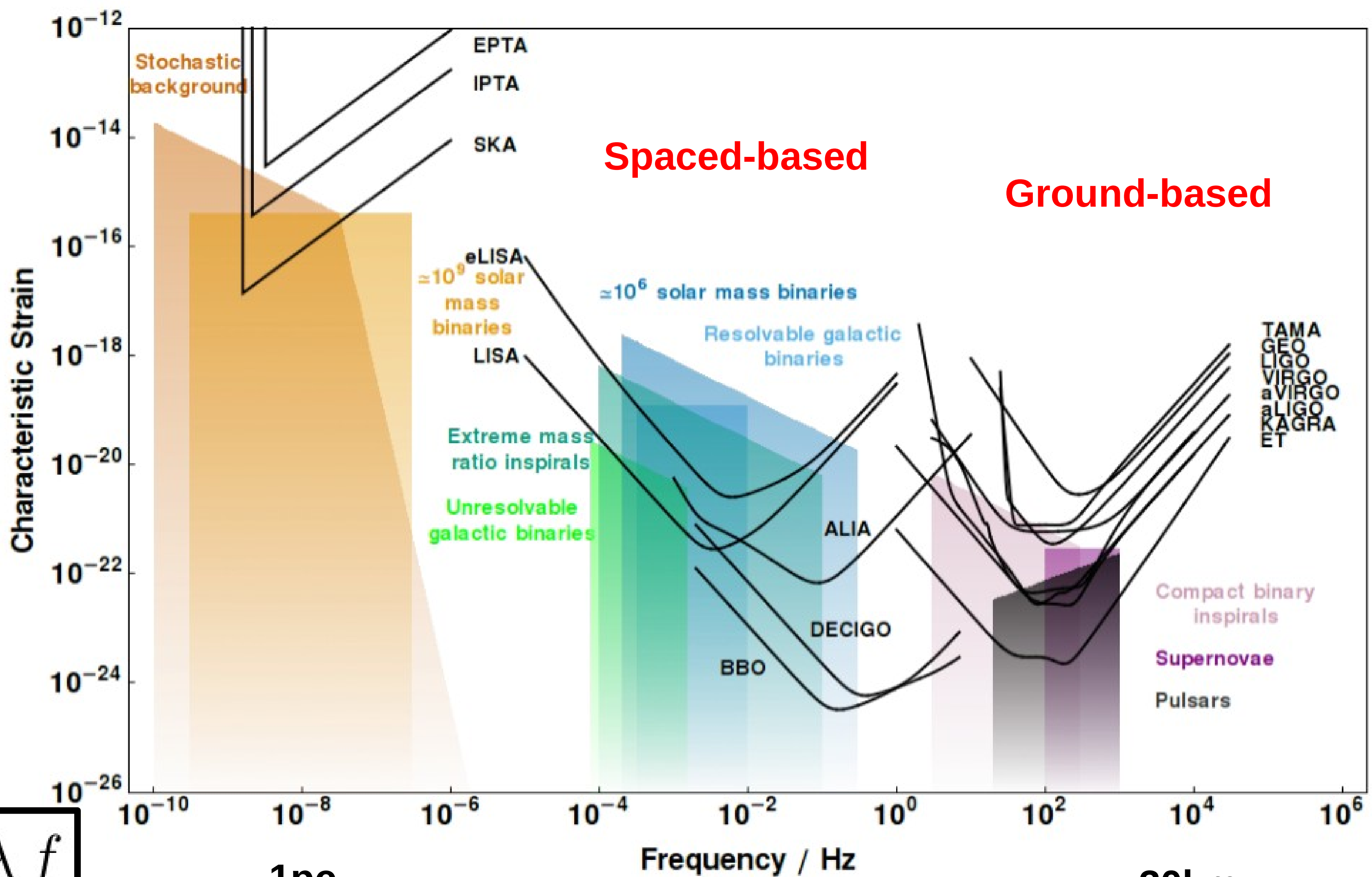
Reference

above in 20190521

Strain Curves from Moore et al.

Pulsar Timing Arrays

http://gwplotter.com/

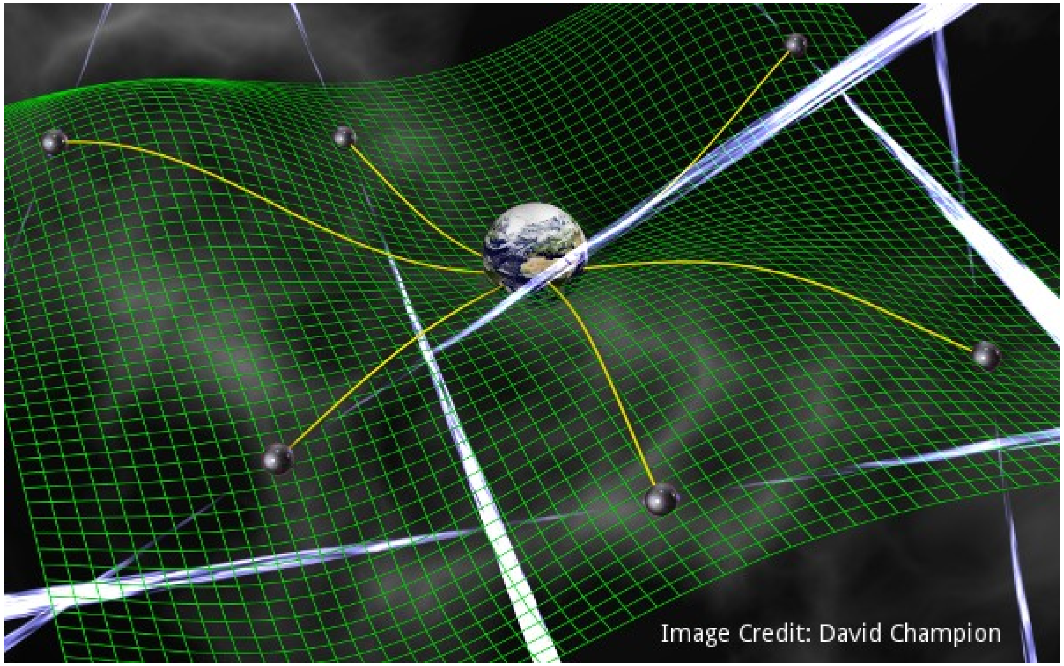


$$\boxed{c = \lambda f}$$

	1pc			**30km**
wavelength, m	**3e16**	**3e12**	**3e8**	**3e4**

Pulsar Timing Arrays

- Millisecond pulsars are very good clocks scattered around the Universe.
- By measuring them once in a while, you can detect a hiccup in the reception of the pulse at Earth. With enough “clocks” you can decide if there was a gravitational wave and from where it may have come.
- See chart, sensitive to very, very long wavelengths, and thus very, very small frequences. Size of the Universe sort of waves!



Ref: NANOGrav collaboration

Pulsar Timing Arrays

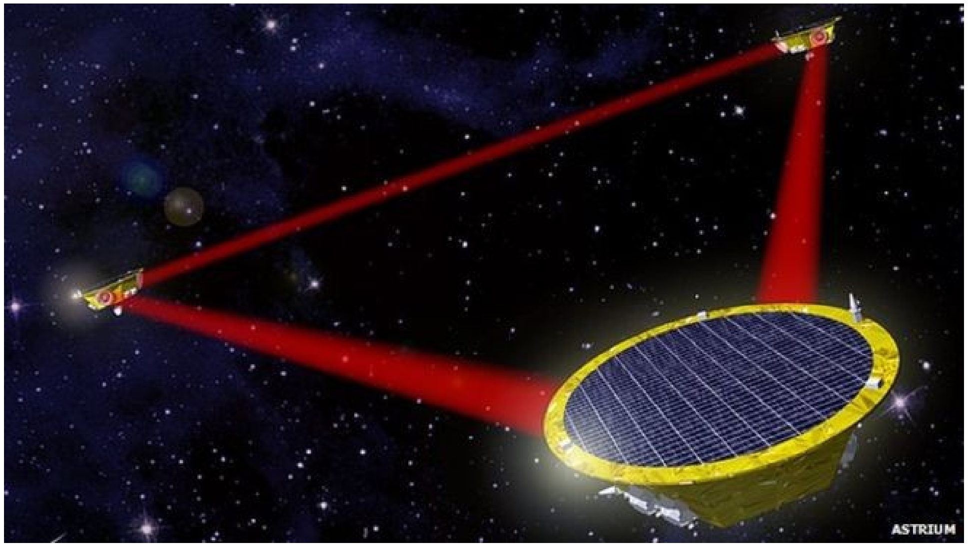
- Several collaborations working at radio astronomy facilities to measure millisecond pulsars:
- NANOGrav, US and NASA, using ~~Arecibo and~~ Green Bank.
- The International Pulsar Timing Array uses many radio telescopes.
- The European Pulsar Timing Array
- The Parkes Pulsar Timing Array (part of the IPTA)
- and others.

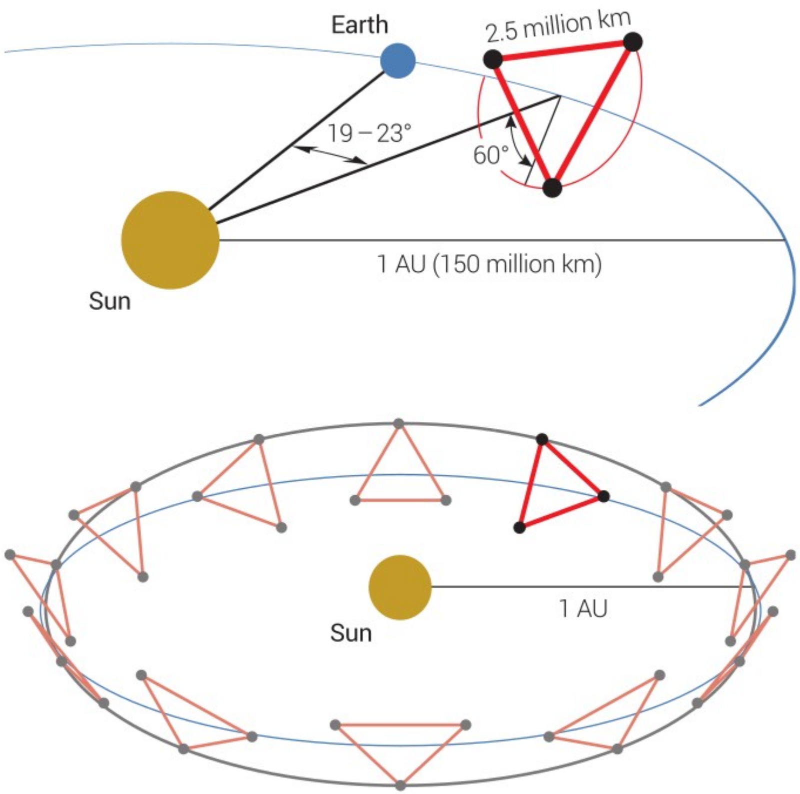
Space-Based

- **Laser Interferometer Space Antenna, LISA**, is a set of satellites with lasers bouncing in a triangle arrangement.
  - No seismic effects!
  - Very long baseline, 2.5e9 m each leg.
  - Control of craft suble, “drag-free flying” with free test masses inside as reference.
- Currently mostly European LISA Mission with NASA/US support. LISA could launch in 2032.
  - In the hardware testing/development and design phase, soon to choose the aerospace company that will build the spacecraft.
- LISA Pathfinder satellite experiment tested several components for eLISA, early 2016.

LISA

- LISA has a full equilateral triangle of lasers and baseline of 2.5e9 m. ESA mission with NASA participation.

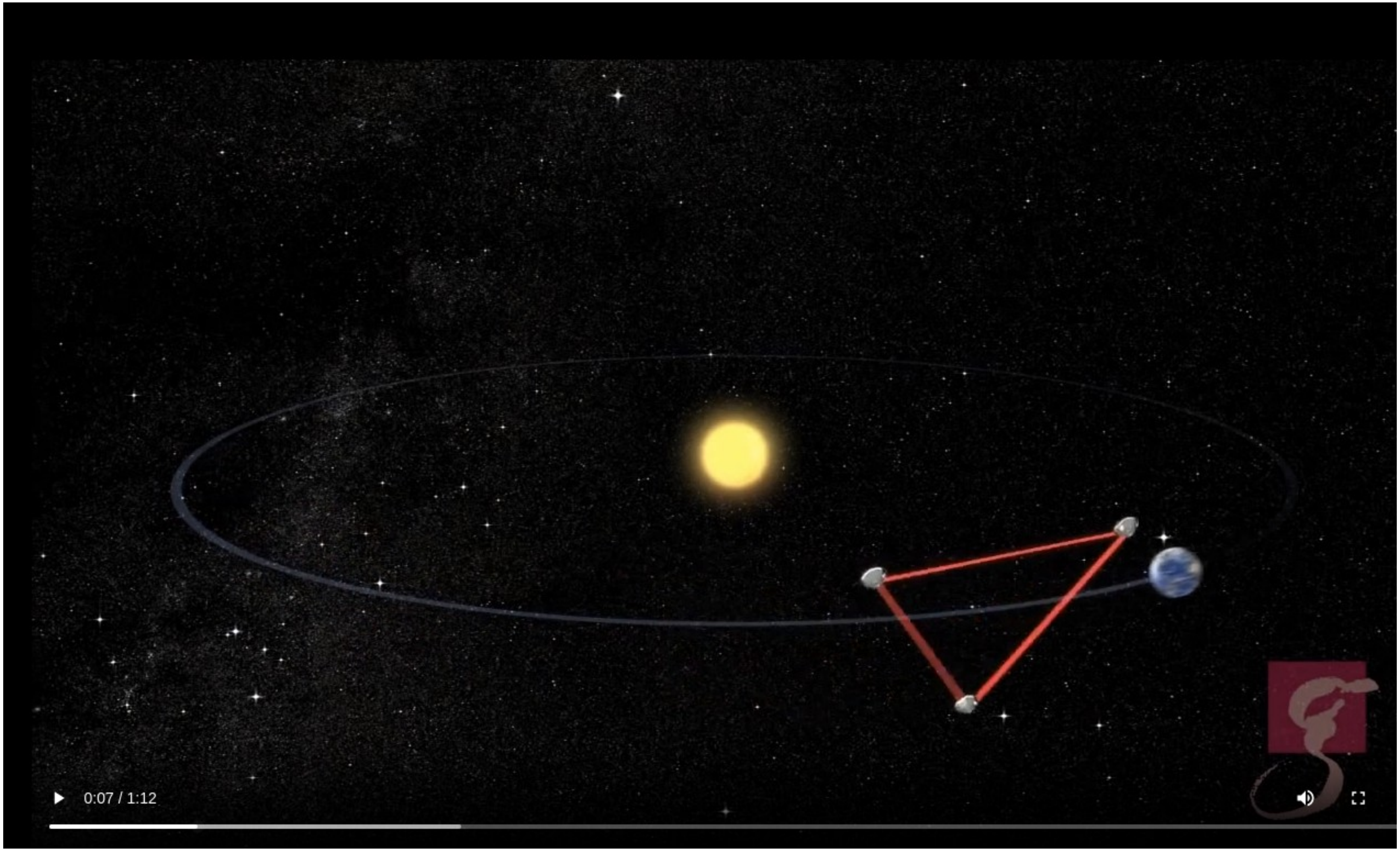




- Chinese have two groups working on this idea:
  - TianQin
  - TAIJI

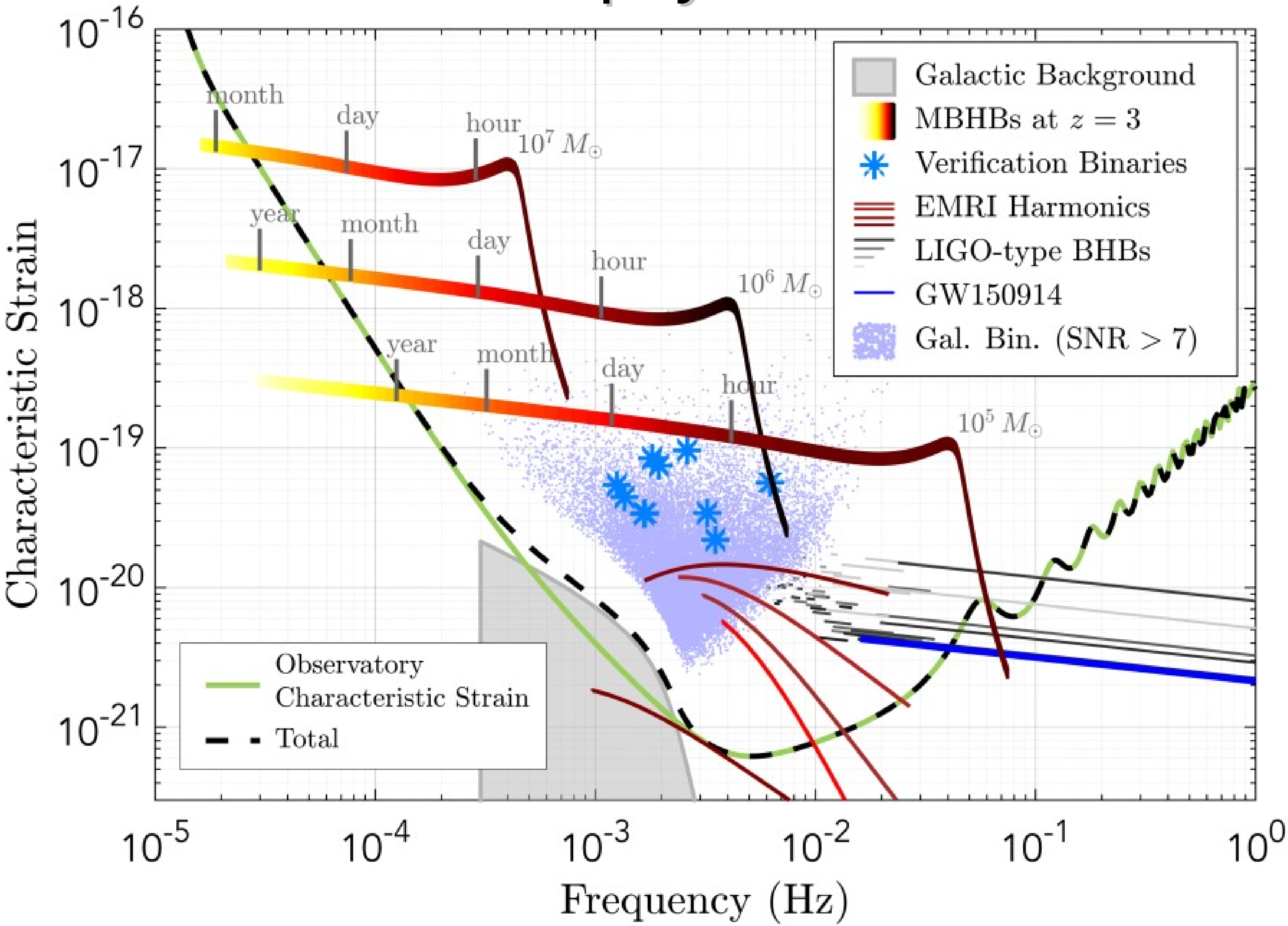
Credit

LISA Orbit



https://svs.gsfc.nasa.gov/vis/a030000/a030500/a030569/slide_09-A1_LISA_orbits2.mp4

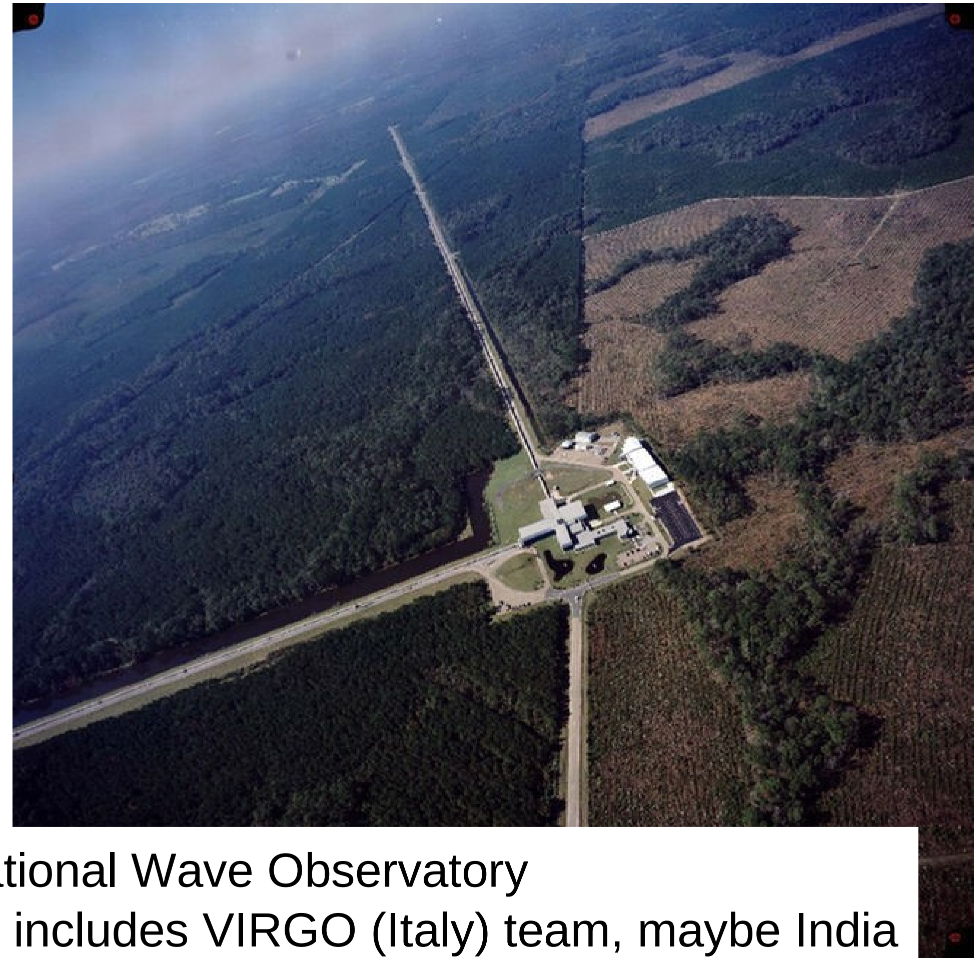
LISA Astrophysical Sources



LIGO, ground-based Gravitational Wave Detectors

LIGO Hanford, WA (LHO)

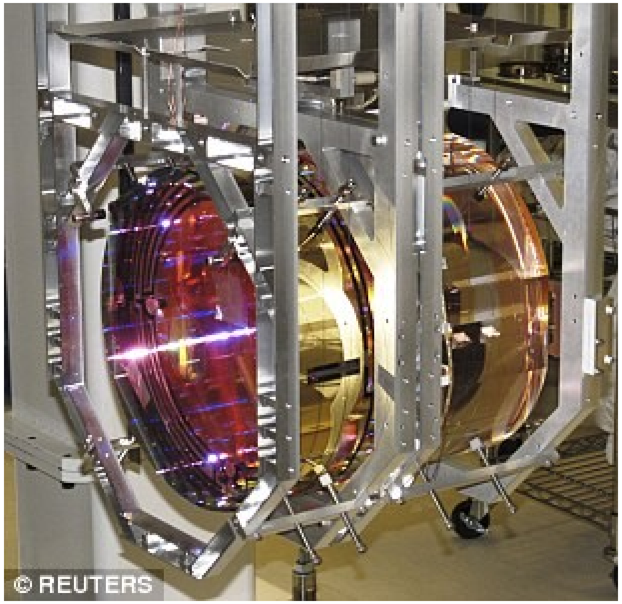
LIGO Livingston, LA (LLO)

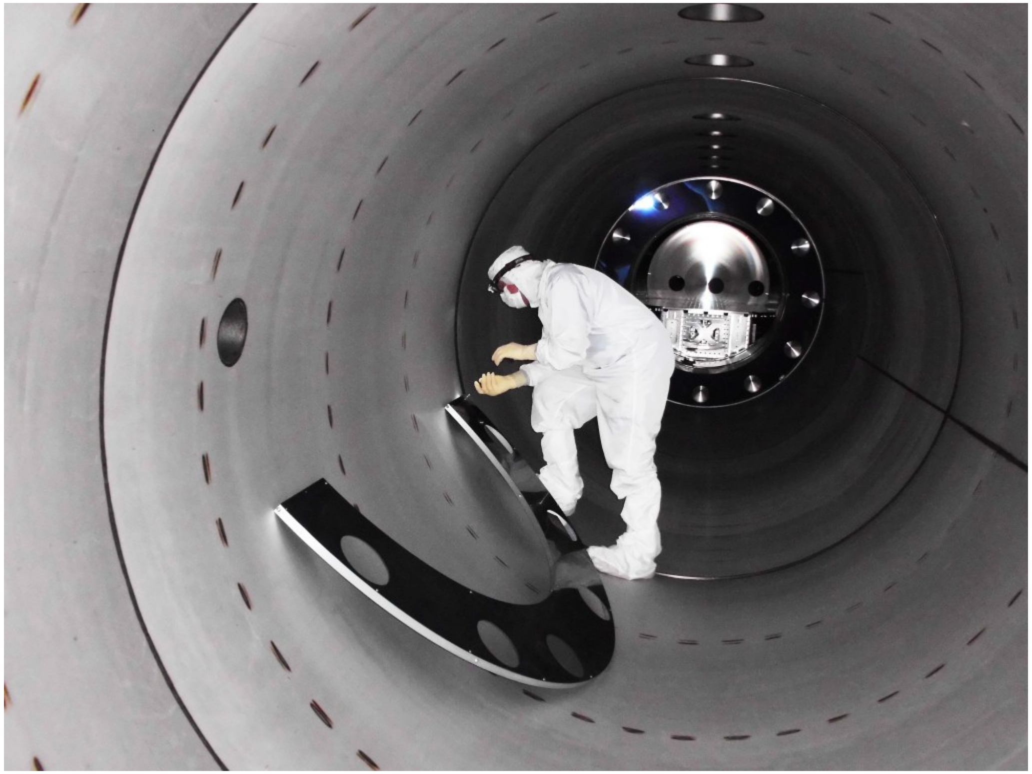


LIGO – Laser Interferometric Gravitational Wave Observatory
LSC – LIGO Scientific Collaboration, includes VIRGO (Italy) team, maybe India

LIGO Hardware

- LIGO “Test Mass” in 4-element suspension



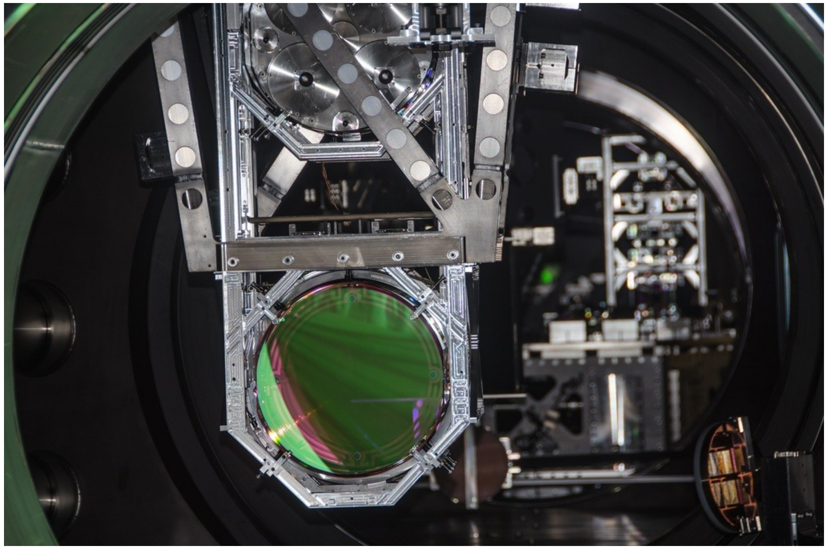


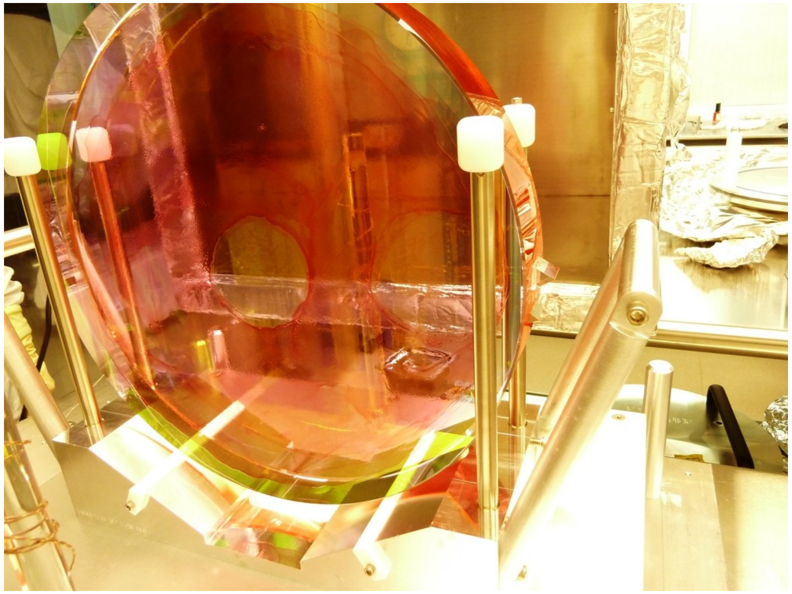
- LIGO Vacuum Tube

Ref: some hardware images

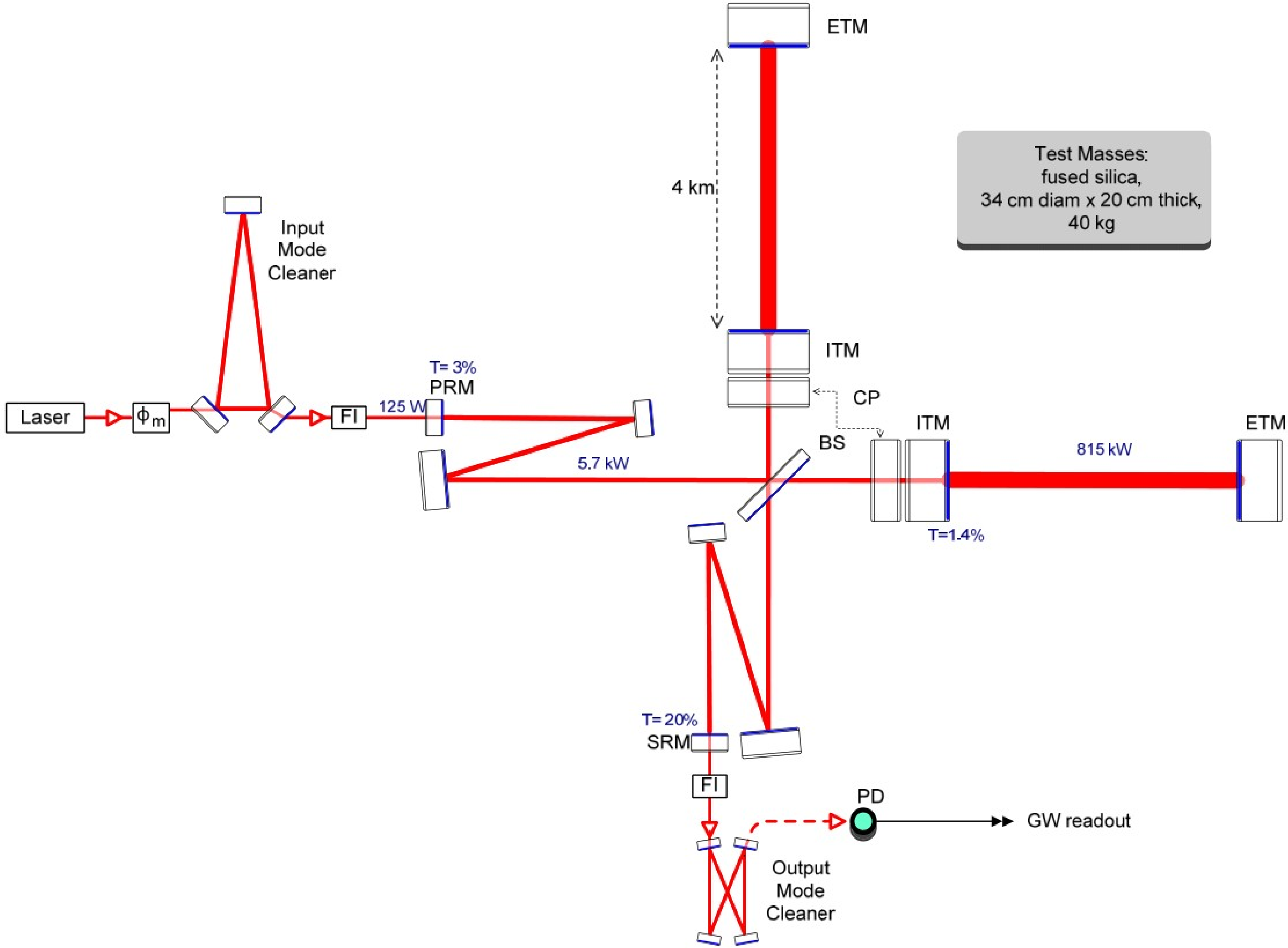
LIGO Hardware

- LIGO “Test Mass” in suspension

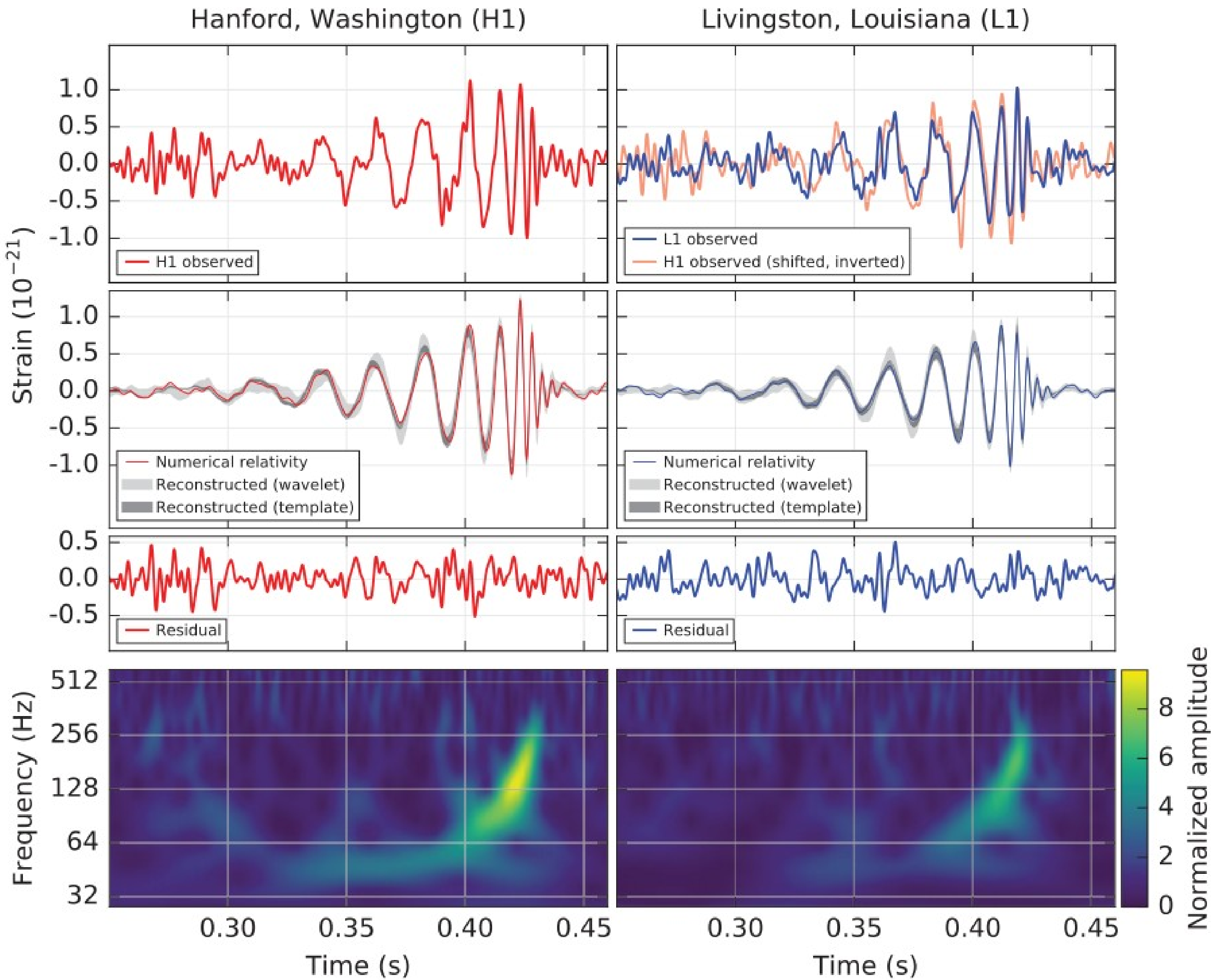




- Beam Splitter


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

Gravitational Wave GW150914



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

SNR = 24, so a greatre than **5 sigma** detection!

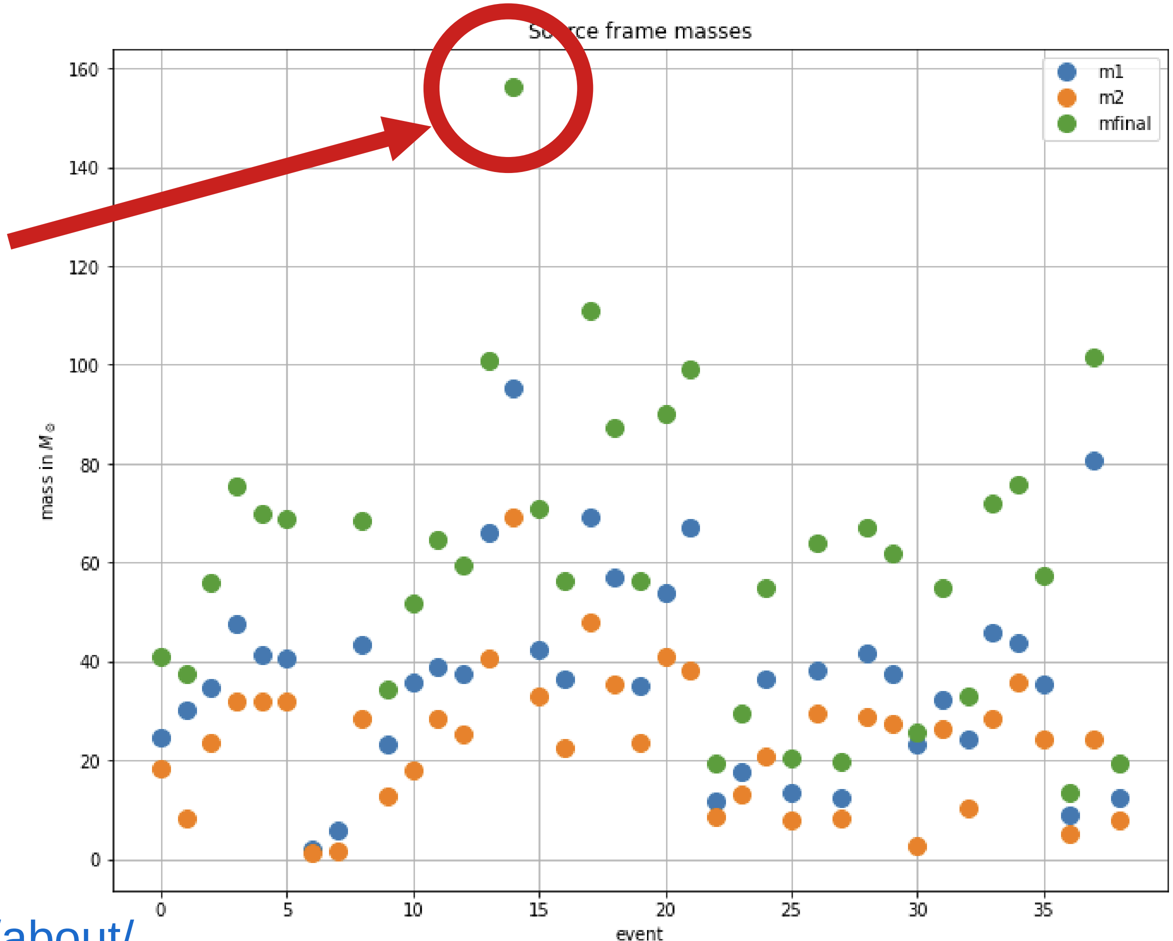
Pretty after filtering out the known seismic noise frequencies.

First at L1 and 6.9ms later at H1.

Catalog GWTC-2

The publicly released table of gravitational wave events, see the page
https://www.gw-openscience.org/eventapi/html/GWTC-2/

Event **GW190521_v3**, first Intermediate Mass Black Hole (IMBH)

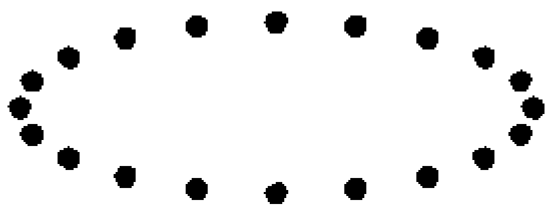


https://www.gw-openscience.org/about/

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

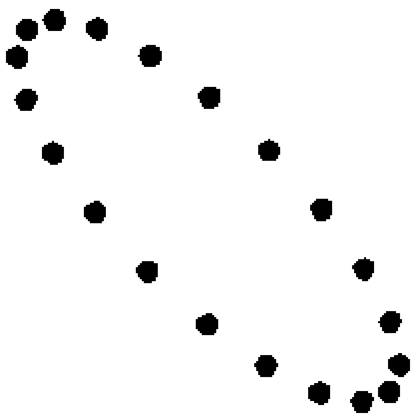
Of all 10 possible components to h, it simplifies to two polarizations. One with a motion that shrinks (grows) in one direction while growing (shrinking) in the other direction. The other polarization is just rotated by 45 degrees.

h_+



hplus polarization

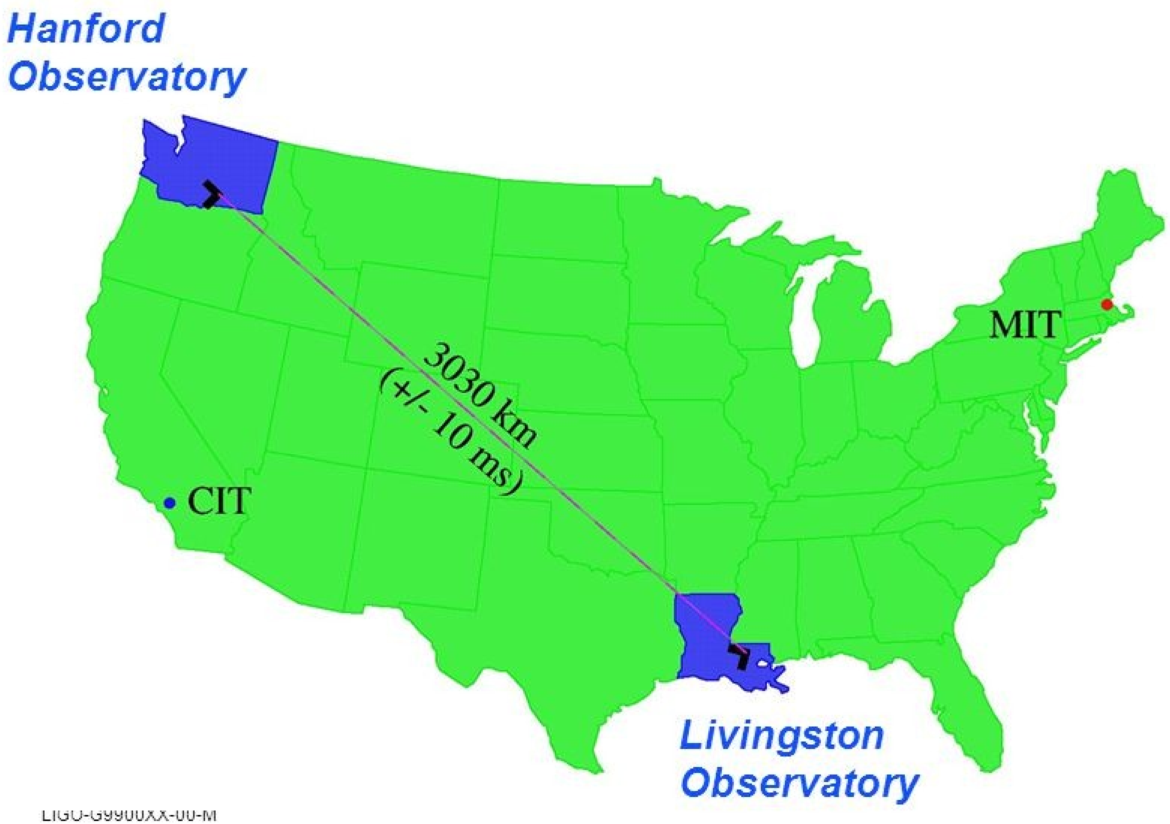
$h_\times$



hcross polarization

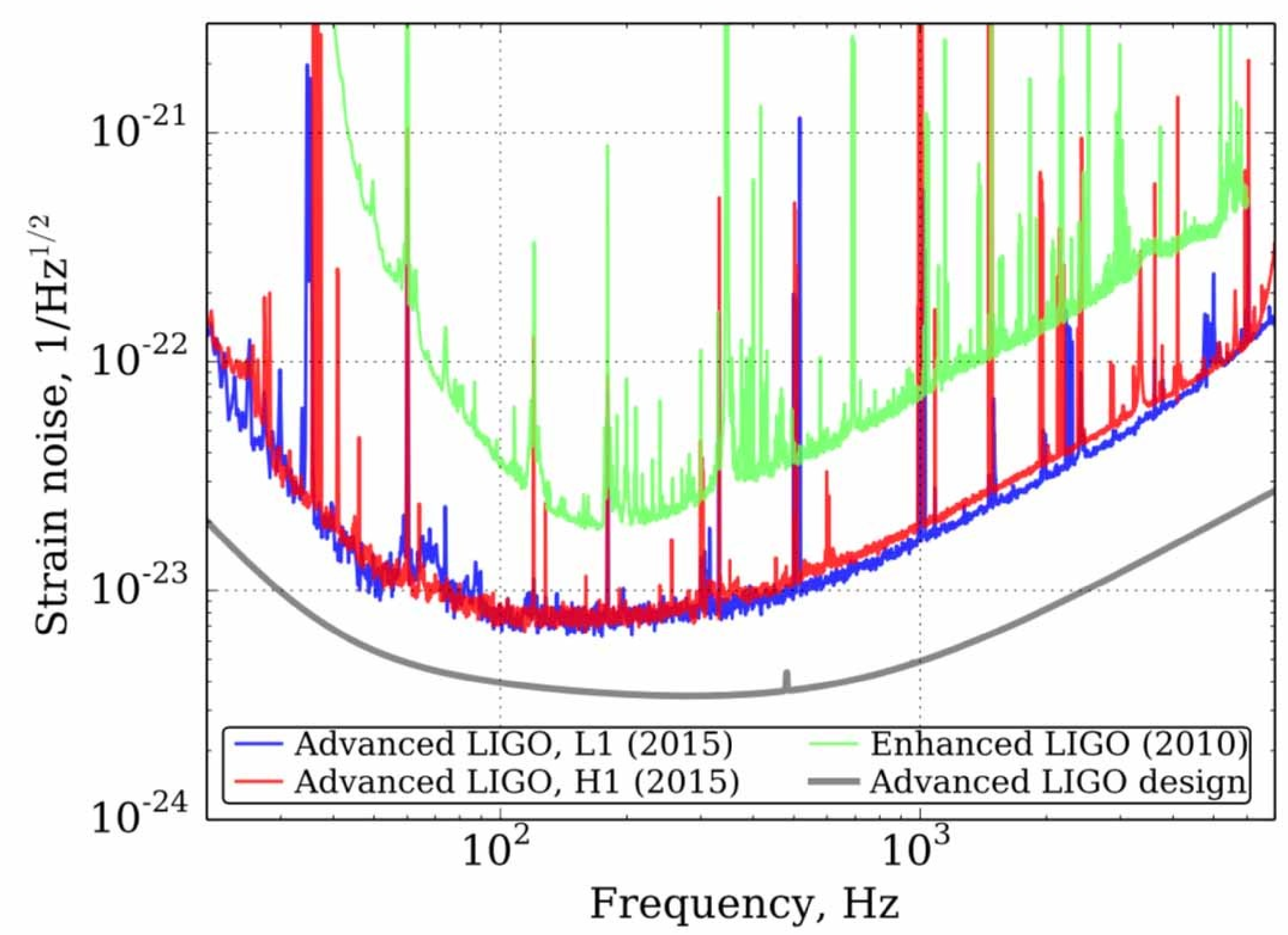
Wave headed into the page, Y up, X right.

LIGO Sites

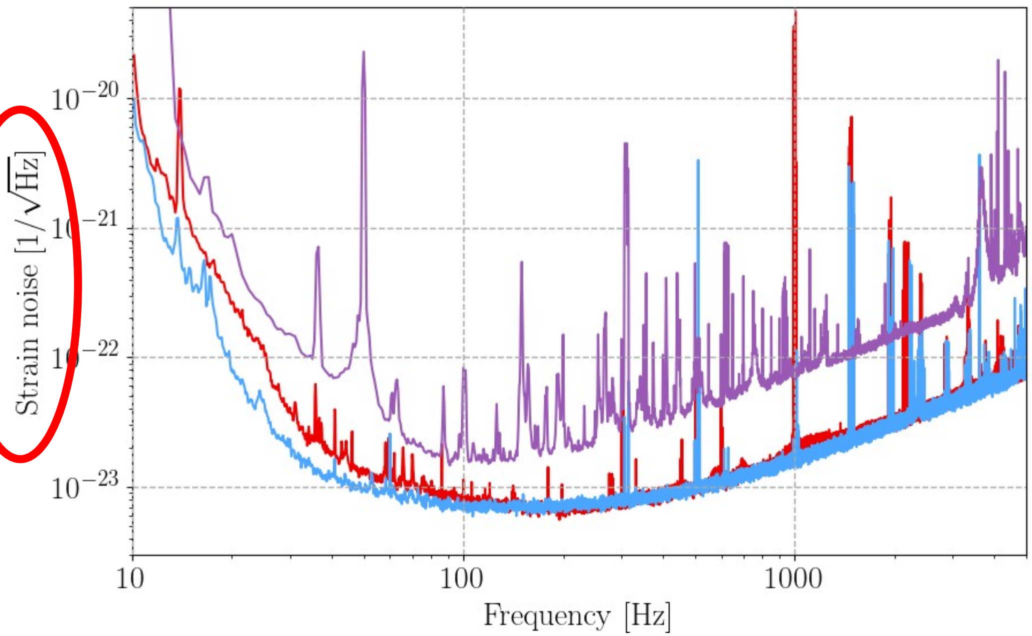


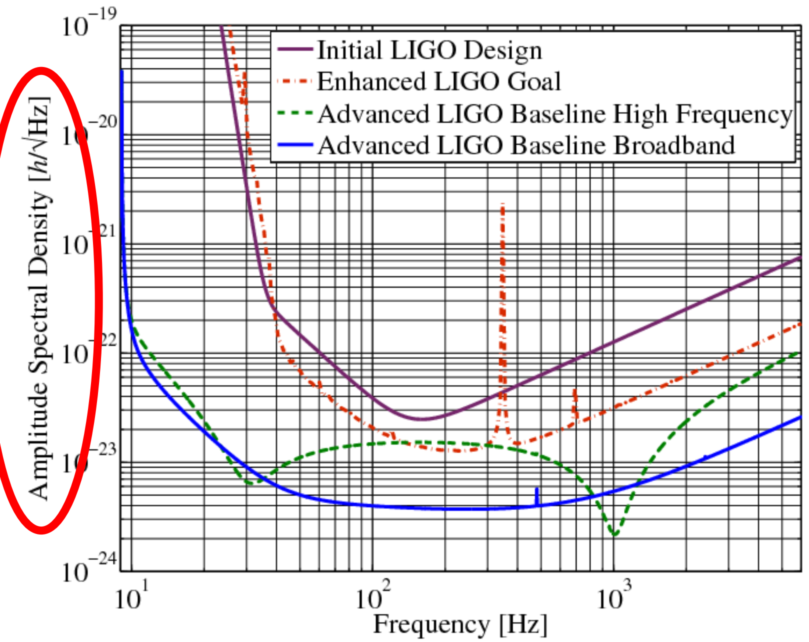
Also Virgo, Cascina, Italy and KAGRA, Japan

Seismic Noise aLIGO and initial



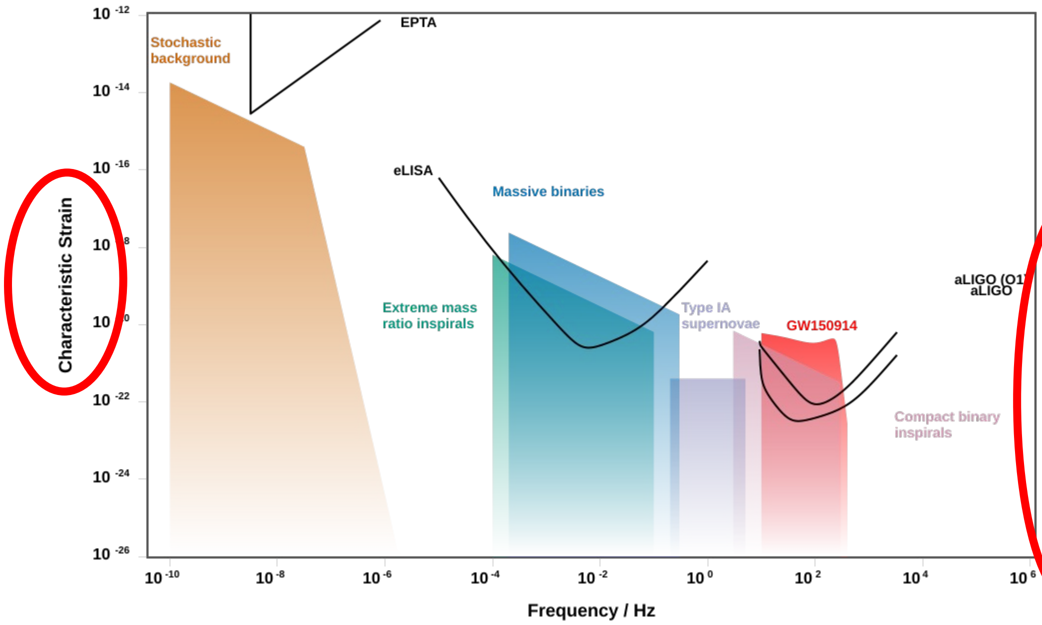
Strain Curve, Strain Sensitivity, Amplitude Spectral Density, Power Spectral Density...OH MY!



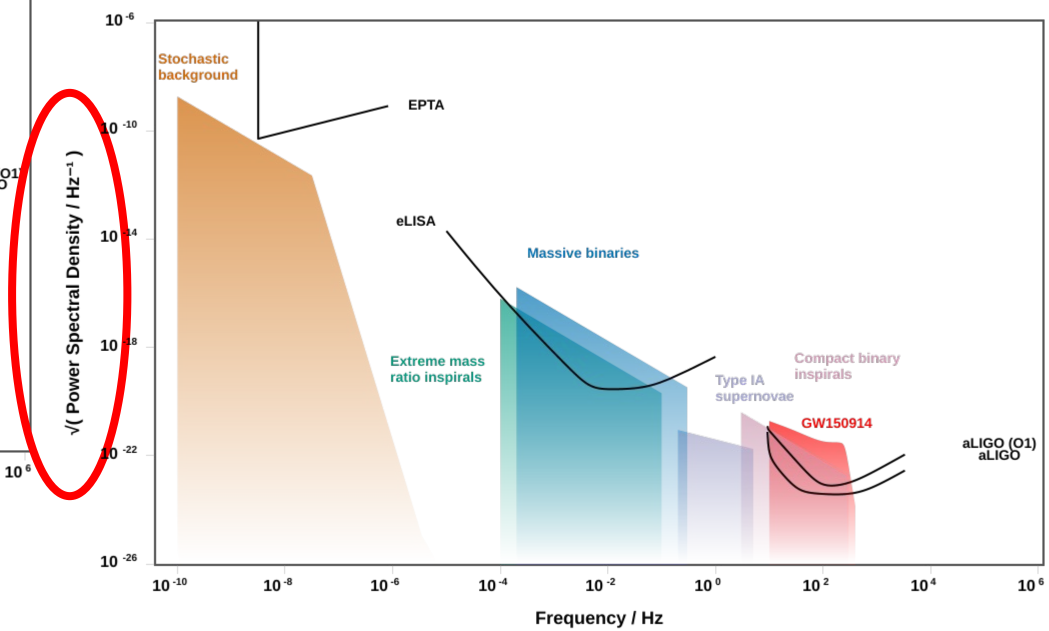


"per root Hz" is usually called the *strain sensitivity*, or sometimes *amplitude spectral density*

Strain Curve, etc...



Characteristic Strain



square root of *Power Spectral Density* is the *amplitude spectral density*

Ref: Cole,s online app .

Summary

- Vanderbilt University (Kelly Holley-Bockelmann and group) was accepted into LIGO September 2020.
  - Led by Karan Jani, researching Intermediate Mass Black Holes.
- LIGO should start taking data again mid-2022.
  - Analyzing the second half of “O3,” Sept 2018 to March 2019.
- LISA should launch around 2032.
- Nanograv PTA announced in the latest data release, 13 years, that they see statistical evidence of low-frequency GWs.
  - Arecibo Observatory had a catastrophic failure.

Thank you for your Attention!

Links

- LIGO Teacher’s page here
- LIGO Student’s page here
- LIGO CalTech Educational Resources here
- 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

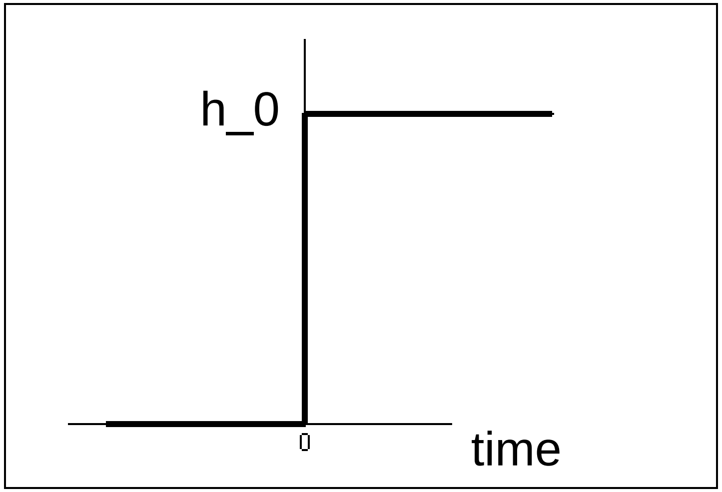
Backup

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.



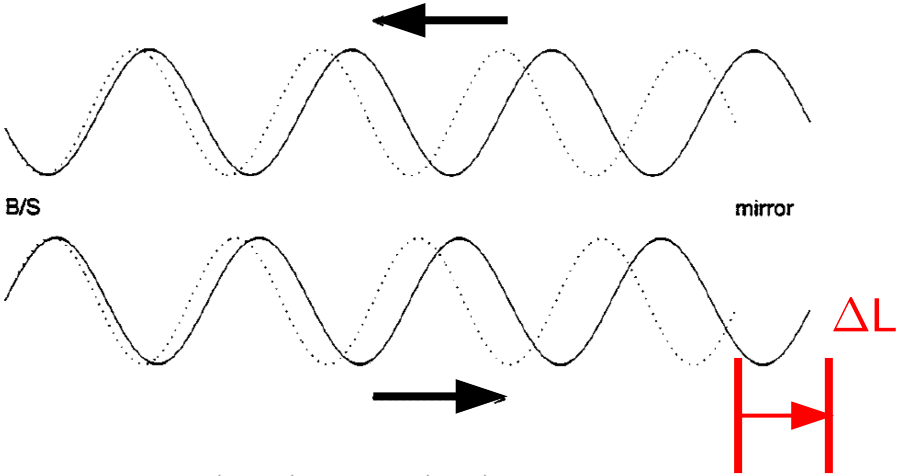
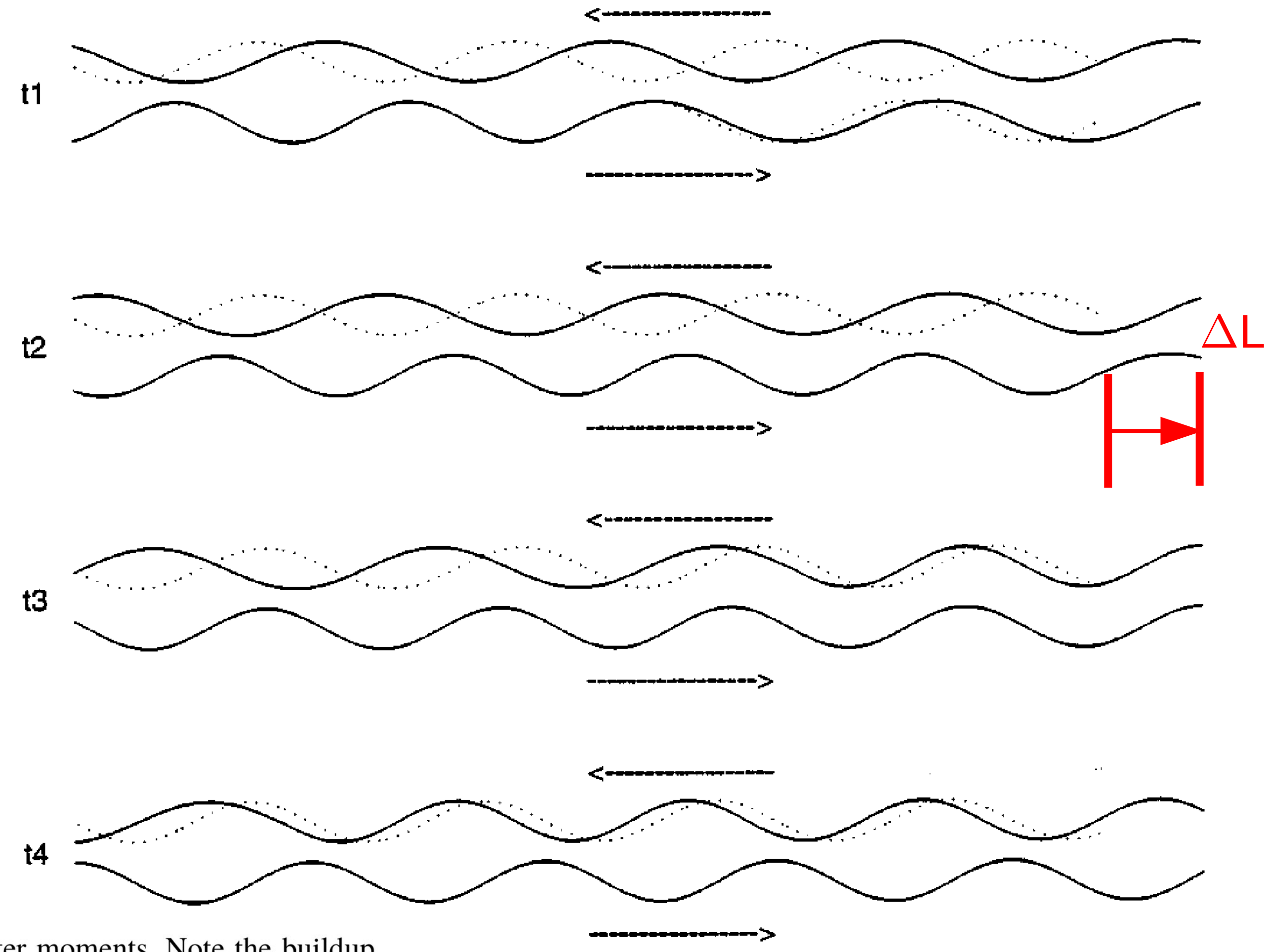


Fig. 2. Light before (dotted) and after (solid) the arrival of a gravitational wave. The beamsplitter is at left, end mirror at right. Outbound light is shown at the bottom, returning light at the top.

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.

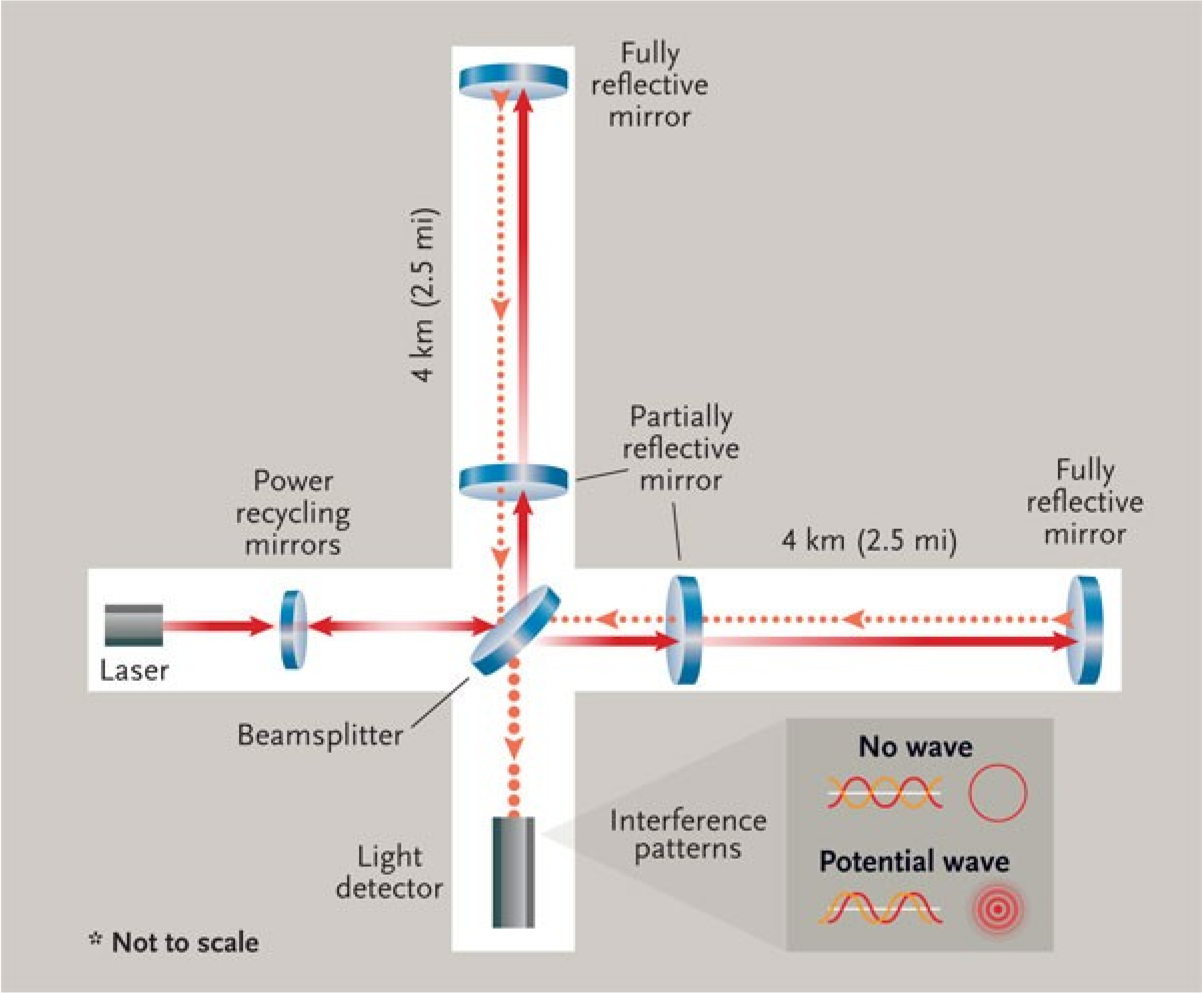
Saulson, *If Light Waves…*, says rods are still rigid!

V. LENGTHS IN COSMOLOGY AND IN LABORATORY PHYSICS

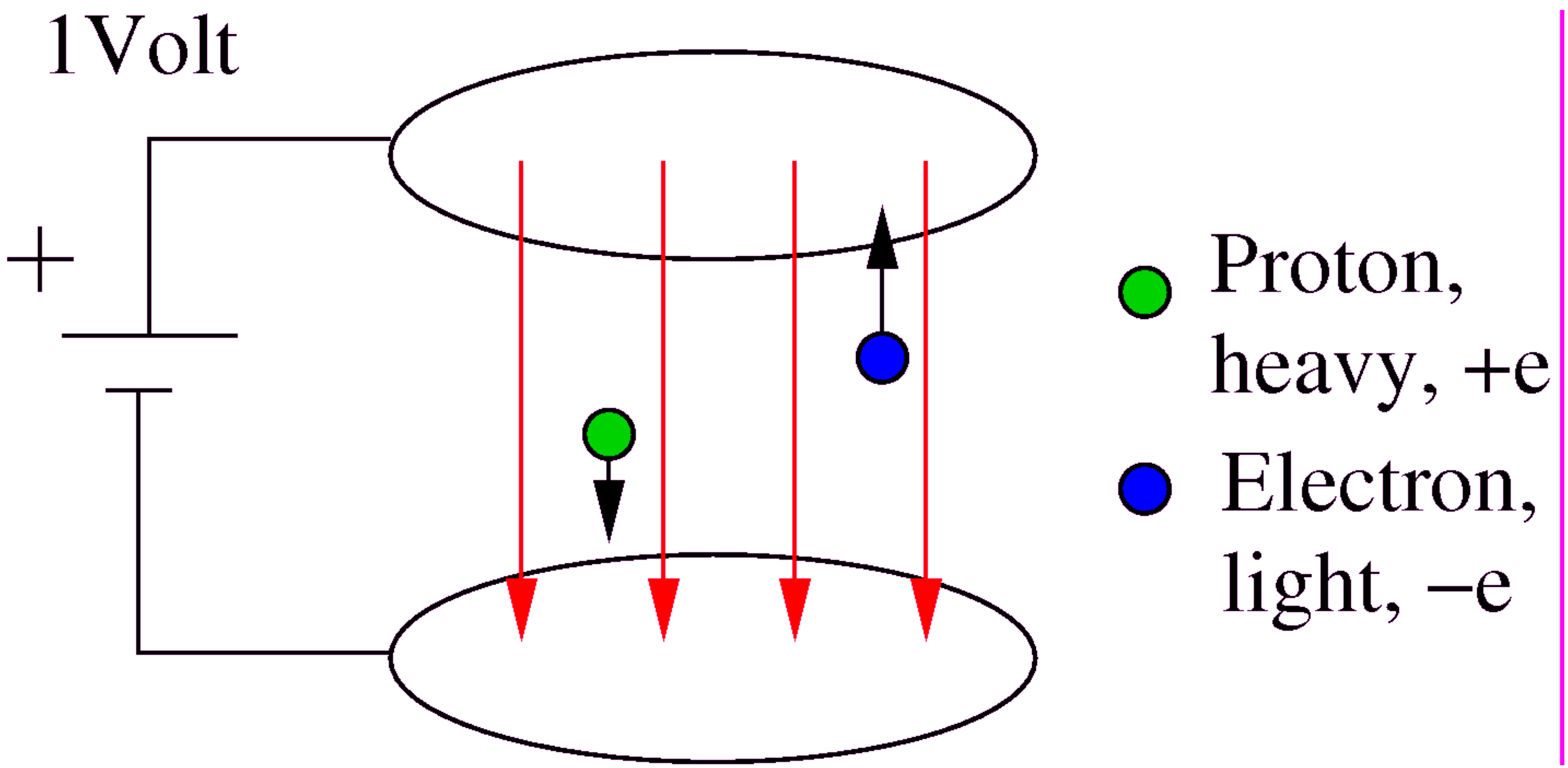
Note that the language we have been using in this paper only makes sense if we imagine that we have standards of length other than either the separations of freely falling test masses or the wavelengths of light waves. We do. A good paradigm of a length standard is a perfectly rigid rod. Such a rod does 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.

LIGO Inteferometer

- 4km long



Units?

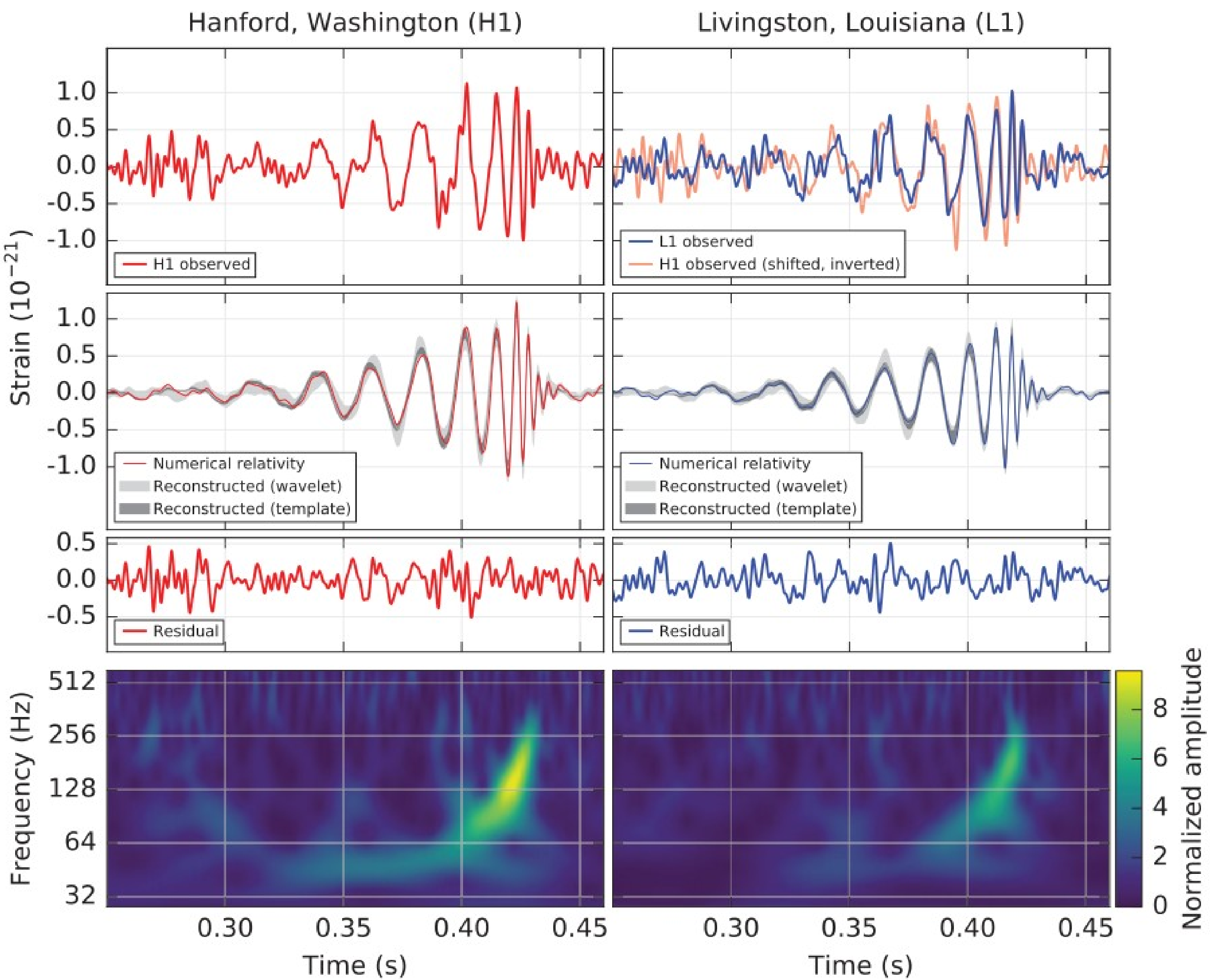


SI Prefixes

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.

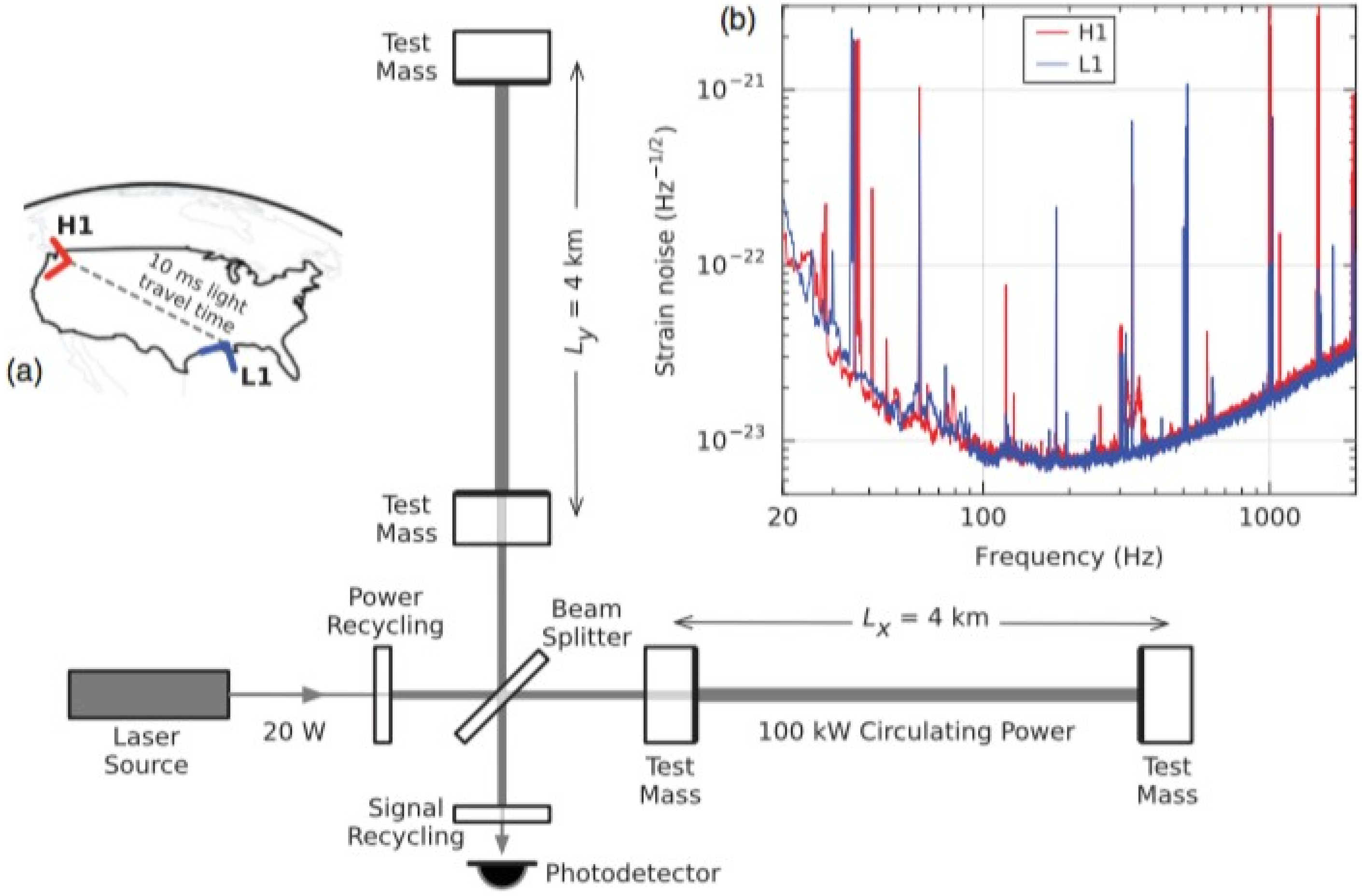
SNR = 24, 5 sigma detection!

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.

Gabella GravWaves

ref: Maggiore around Eqn. 3.332.

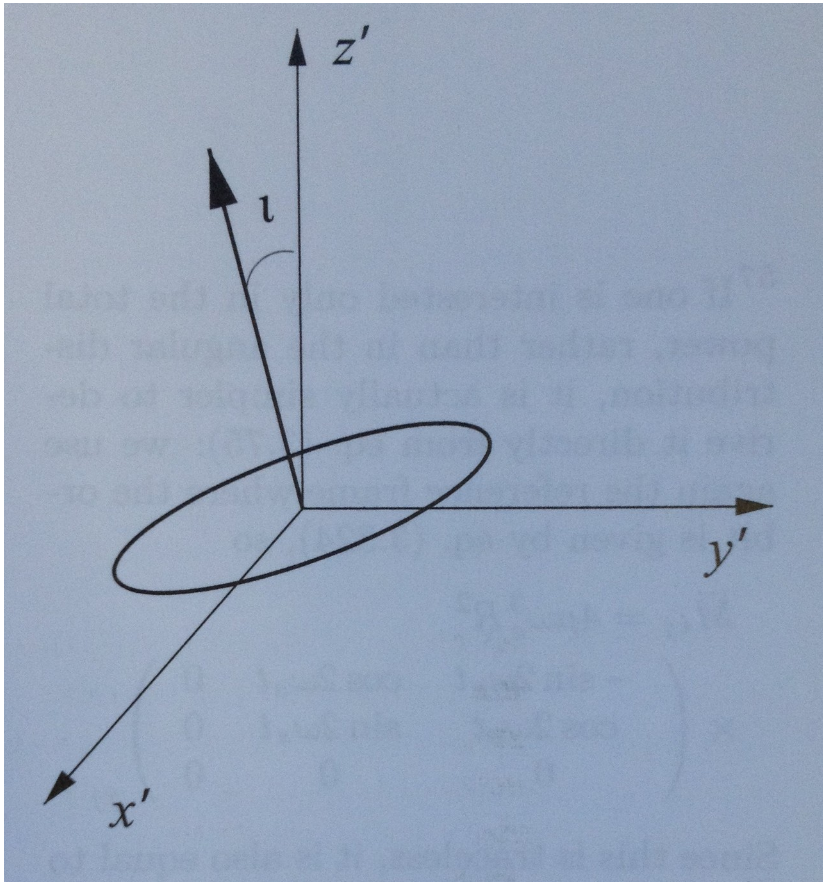


Fig. 3.6 The geometry of the problem in a frame (x', y', z') where a fixed observer is at large distance along the positive z' axis. The normal to the orbit makes an angle ι with the z' axis.

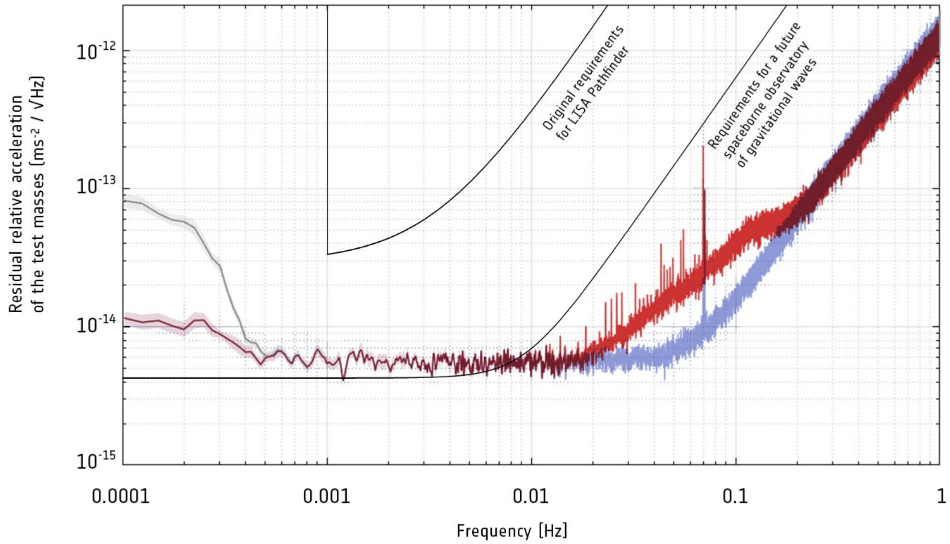
Some Constants

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

LISA Pathfinder

- LISA Pathfinder successfully demonstrated the technologies for “drag-free” flight of the eLISA space craft.
  - Orbit is *nearly* freely falling around the sun.
  - Microthrusters used to counter solar wind, etc, and allow a free mass inside to react only to gravity!

- Measured relative acceleration as good as 6e-15 m/s^2 per root Hz (tomorrow).



LISA Pathfinder

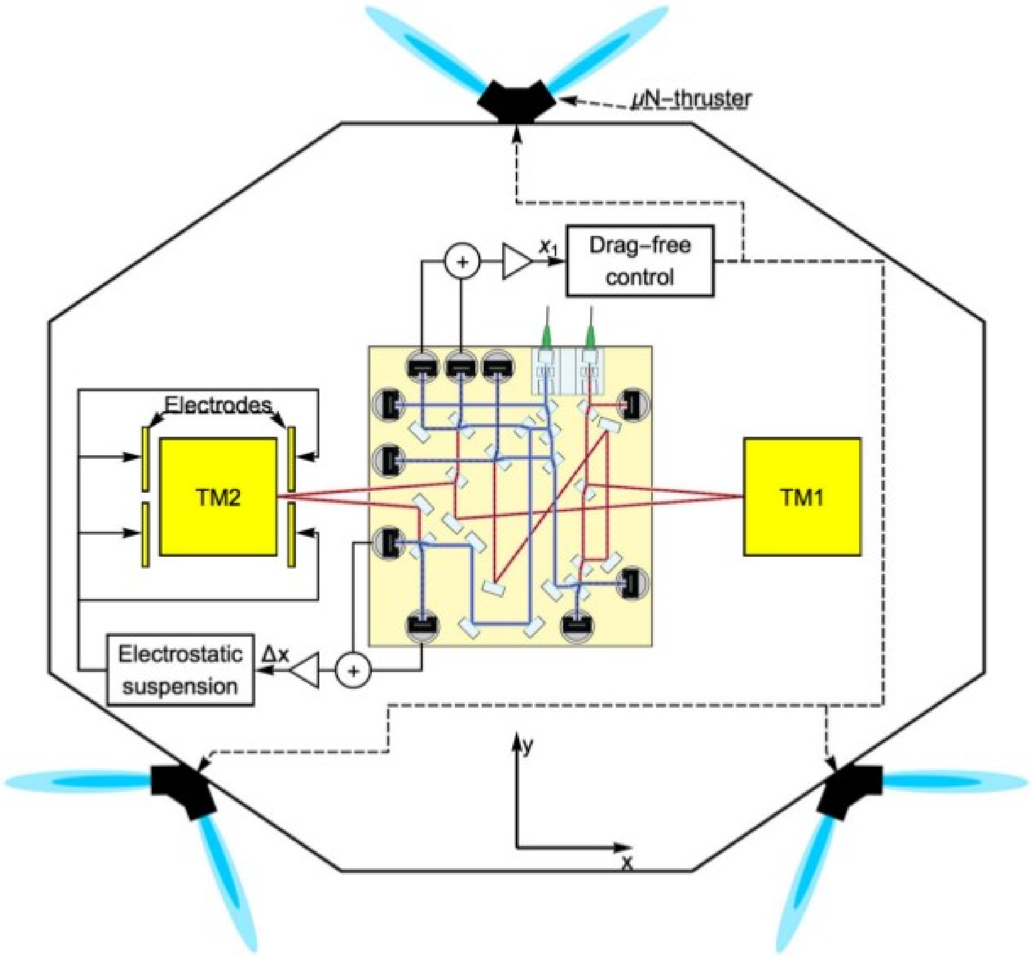
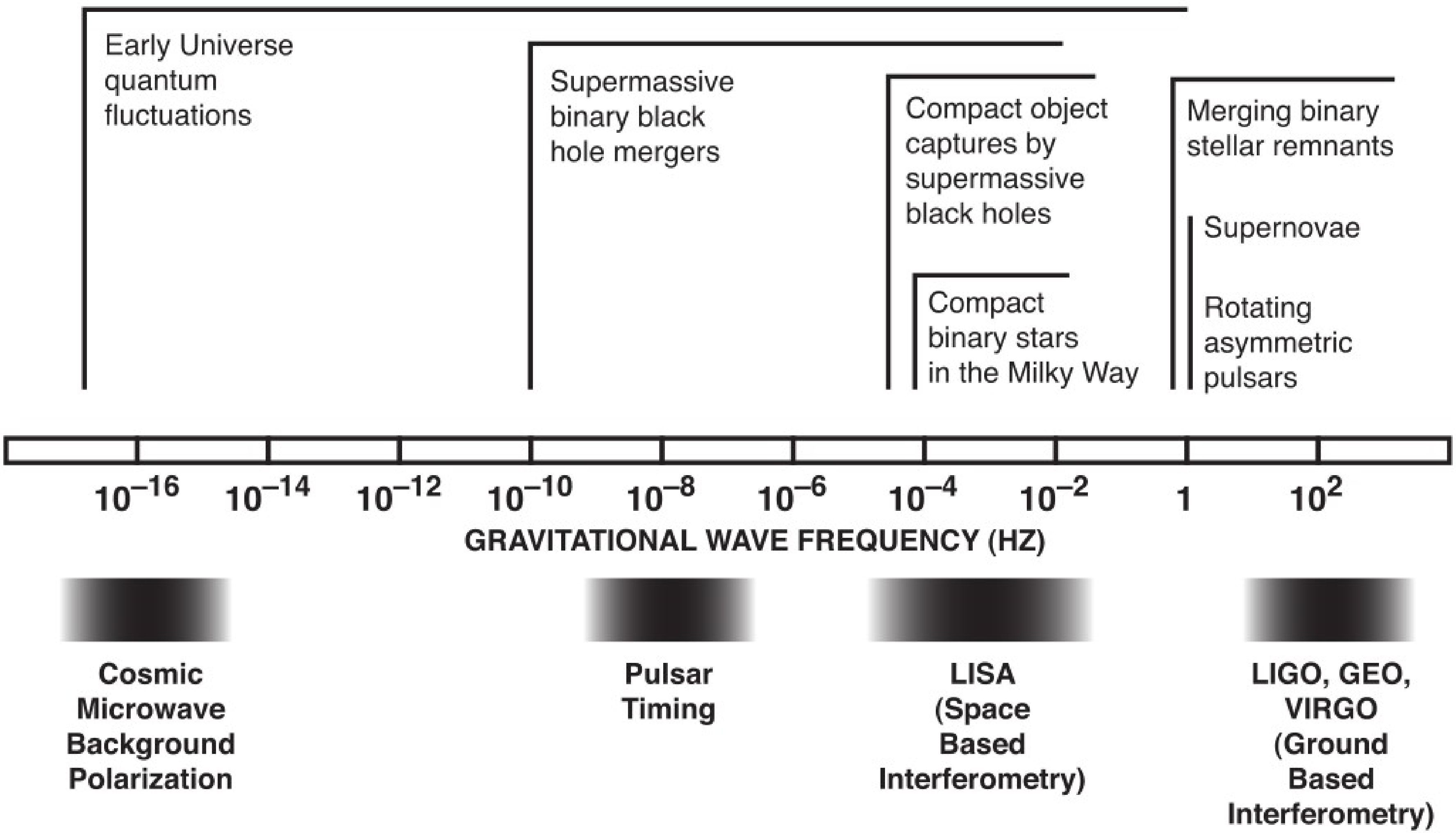


FIG. 2. A schematic of LPF. The figure shows TM1, TM2, and the optical bench beam paths for measuring Δx and x_1. The measurement of Δx drives the electrostatic suspension of TM2, which applies the necessary electrostatic forces by means of the electrodes represented by the four gold plates facing TM2. All other electrodes surrounding the TMs are not shown. The measurement of x_1 drives the drag-free control loop that uses the micronewton thrusters to exert forces on the spacecraft. The figure depicts the x and y axes we use in this Letter, while z is normal to the figure.

Ref: Armano et al., PRL 2016

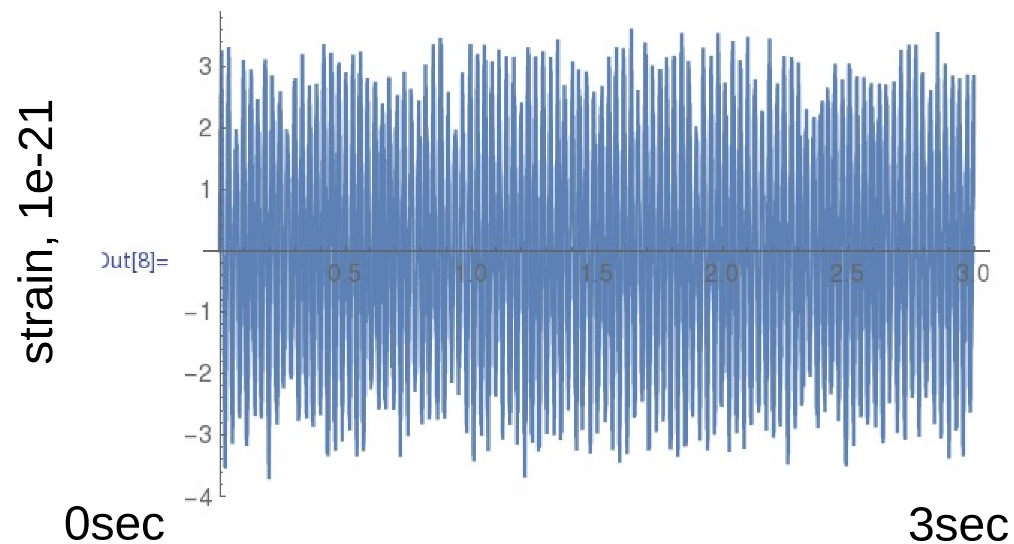
Gravitational Wave Spectrum



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}}]
```