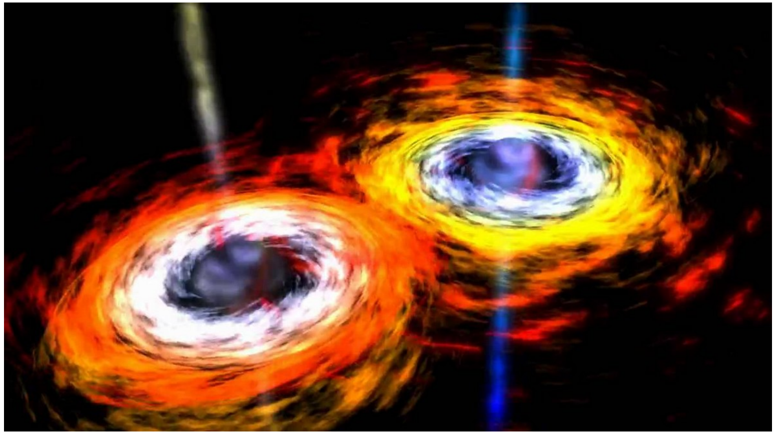
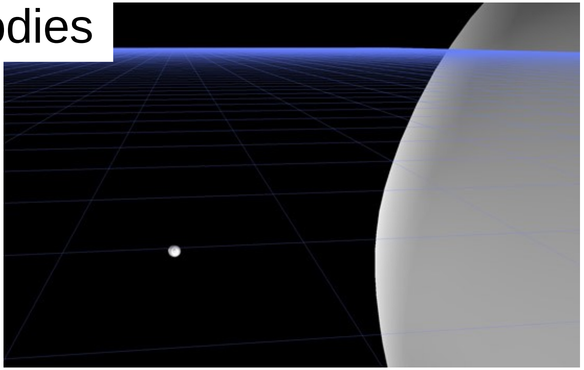
# Gravitational Waves – Sources and Detectors



Orbiting Massive Bodies

Supernova, NGC7293-Helix Nebula



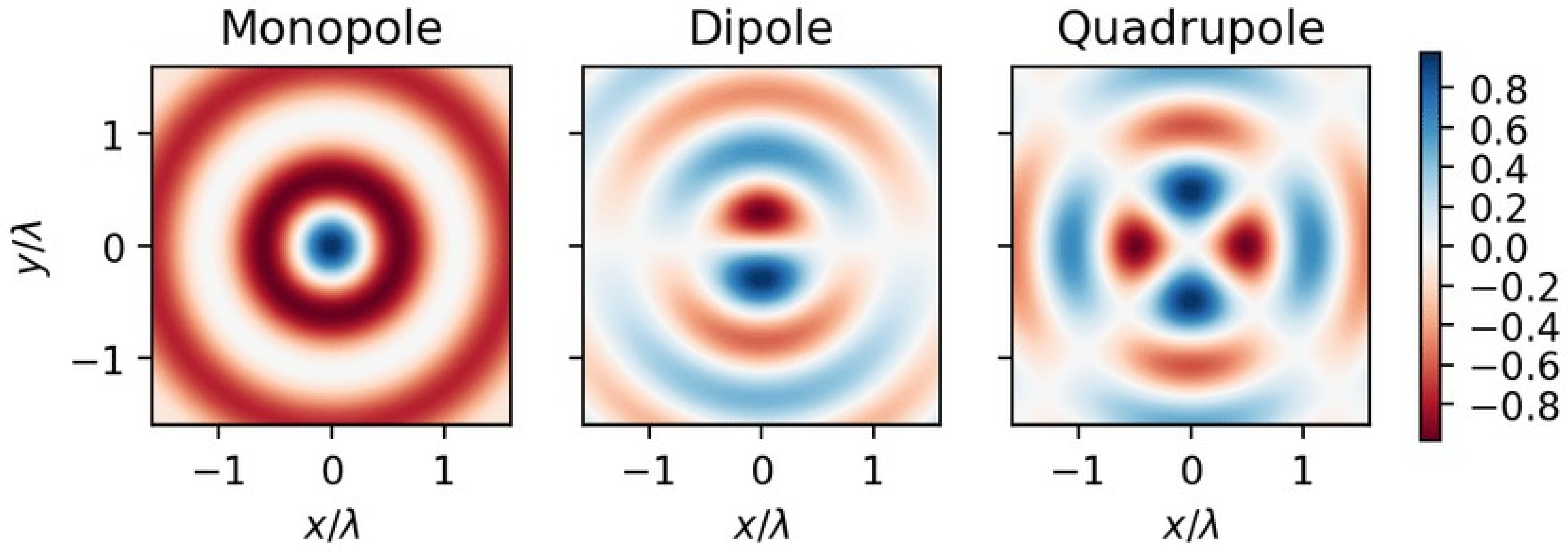
Extreme Mass Ratio Black hole Mergers

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

# Gravitational Waves are “ripples in spacetime.”

- **Ripples in space time**...hard to do, spacetime is very “rigid” or “stiff.”
- Need **matter in motion** to create Gravitational Waves, recall charges in motion create electromagnetic waves.
- The motion **cannot be spherically symmetric**.  Conservation of mass and conservation of linear momentum (of the mass) means the first “moment of the mass distribution” that can cause GWs is “quadrupole.”
- **Large masses and fast changes in time** create stronger GWs.
  - Black holes are small and massive.  In binary orbits with another black hole, orbital speeds can reach more than 30% the speed-of-light!  Small is good because they can get very close before they “touch” or “merge.”

# The Moments of a (Mass) Distribution

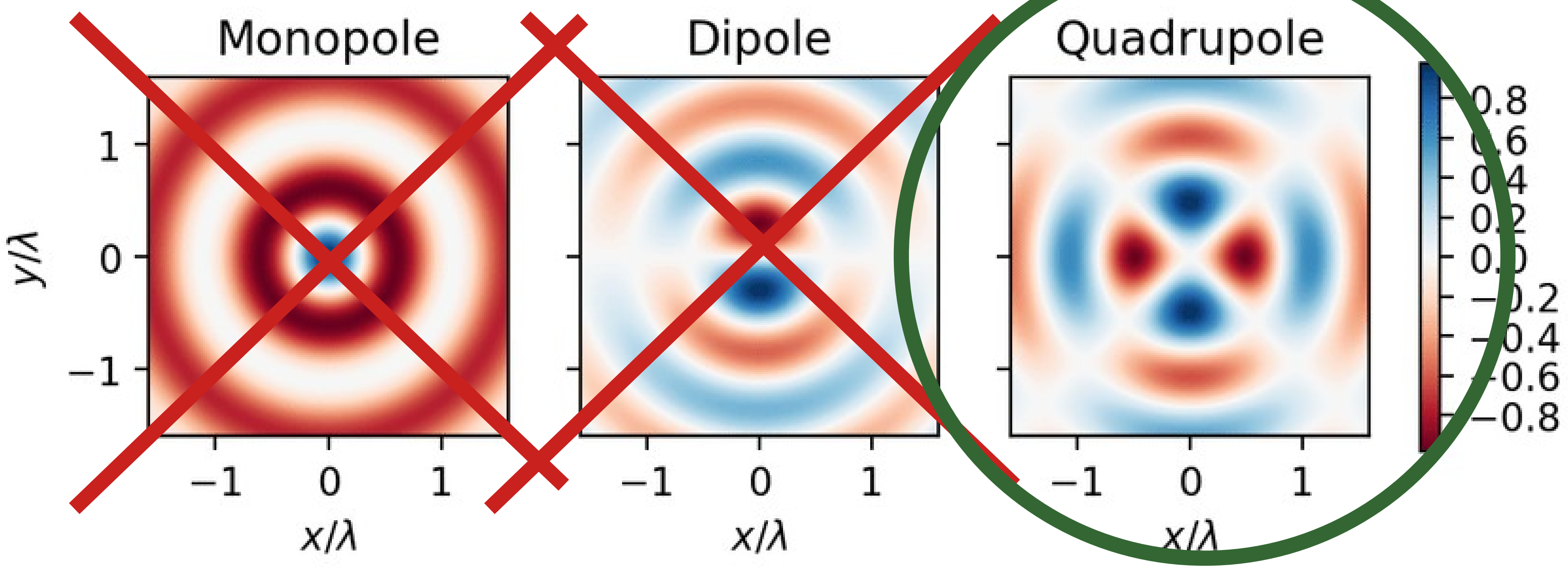



Like a pulsing mass / star.

A mass moving back and forth.

Mass in complicated motion, or it turns out orbiting each other.

# Quardrupole is the first to give GWs




Like a pulsing mass / star.

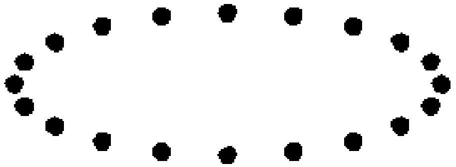
A mass moving back and forth.

Mass in complicated motion, or it turns out orbiting each other.

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

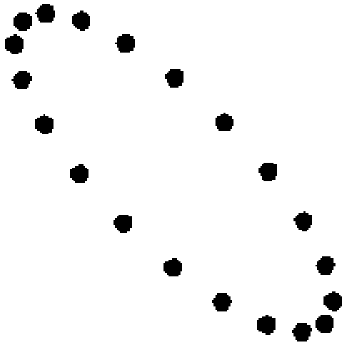
Of all 10 possible components to h, it simplifies to two polarizations. One with a motion that shrinks (grows) in one direction while growing (shrinking) in the other direction. The other polarization is just rotated by 45 degrees.

$h_+(t)$



hplus polarization

$h_\times(t)$



hcross polarization

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

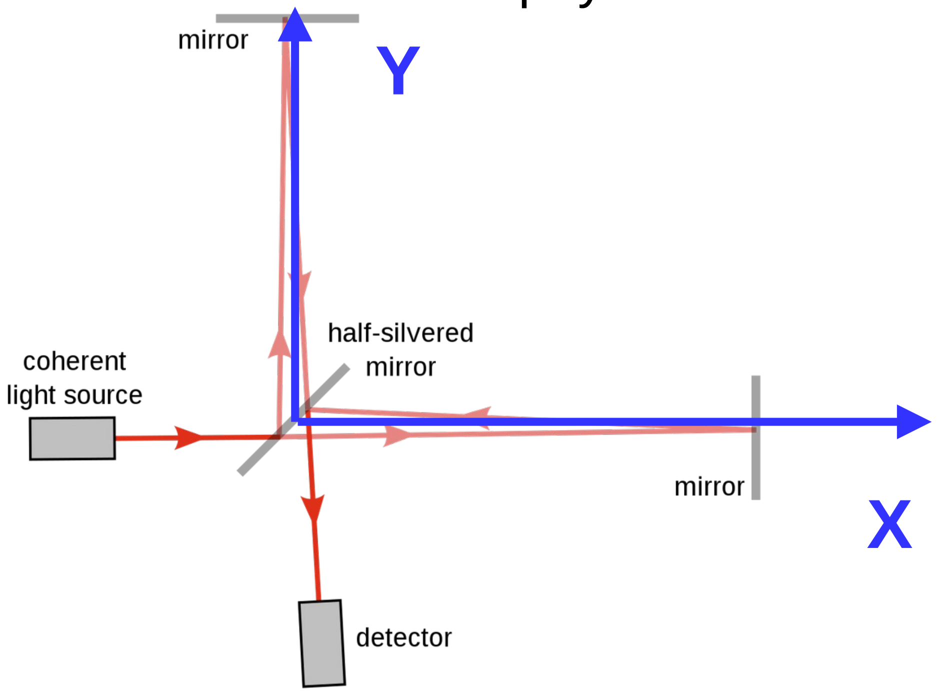
# The strain is

For ideal “test masses” the Gravitational Waves manifests as a physical “strain,” a change in length over length.

$$h = \frac{\Delta L}{L}$$

$h_{+}(t)$ ?

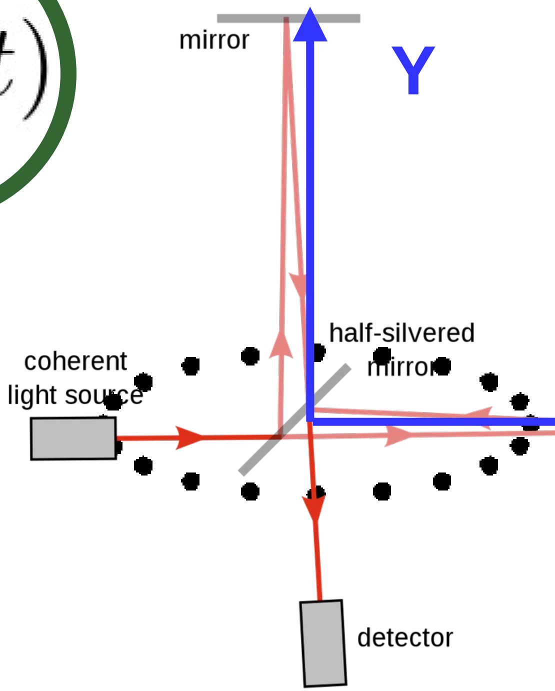
$h_{\times}(t)$ ?

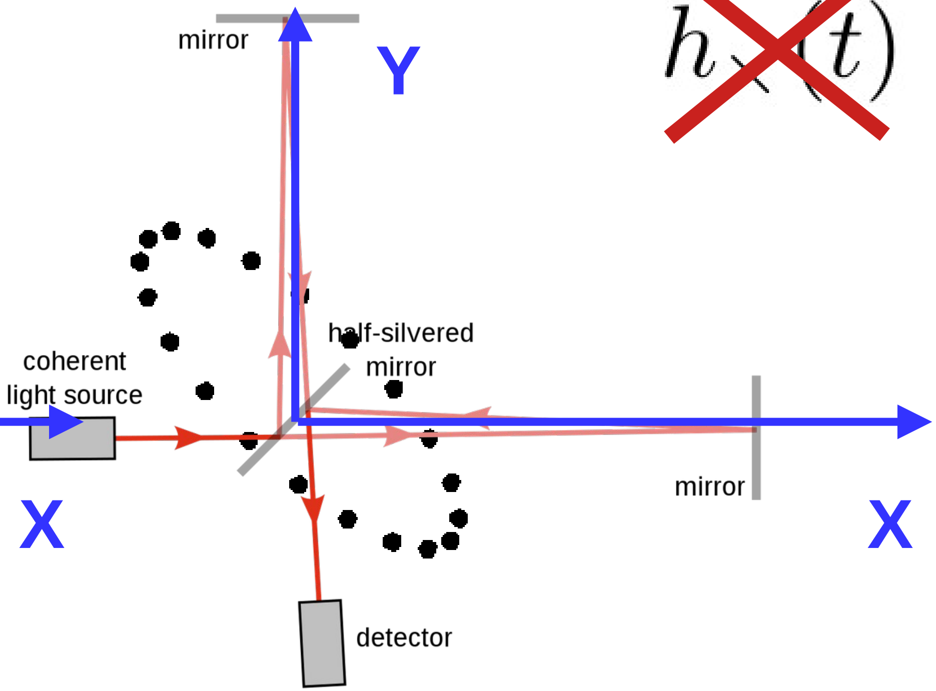



Interferometer is natural detector (though not easy).

$$h = \frac{\Delta L}{L}$$

$h_+(t)$

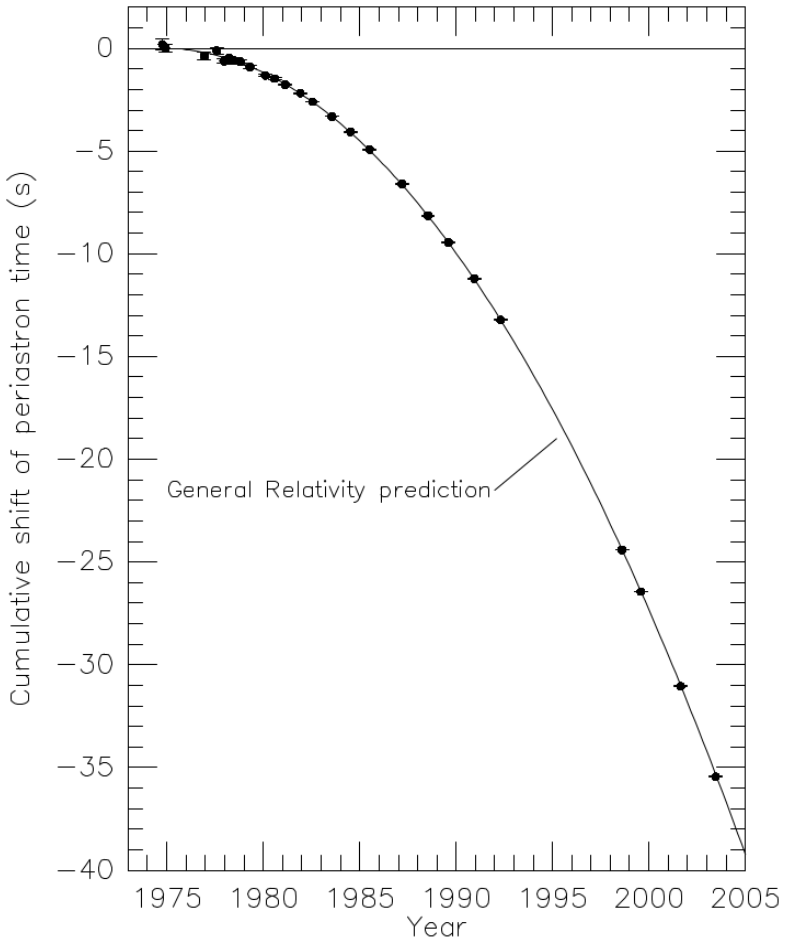



$\cancel{h_\times(t)}$

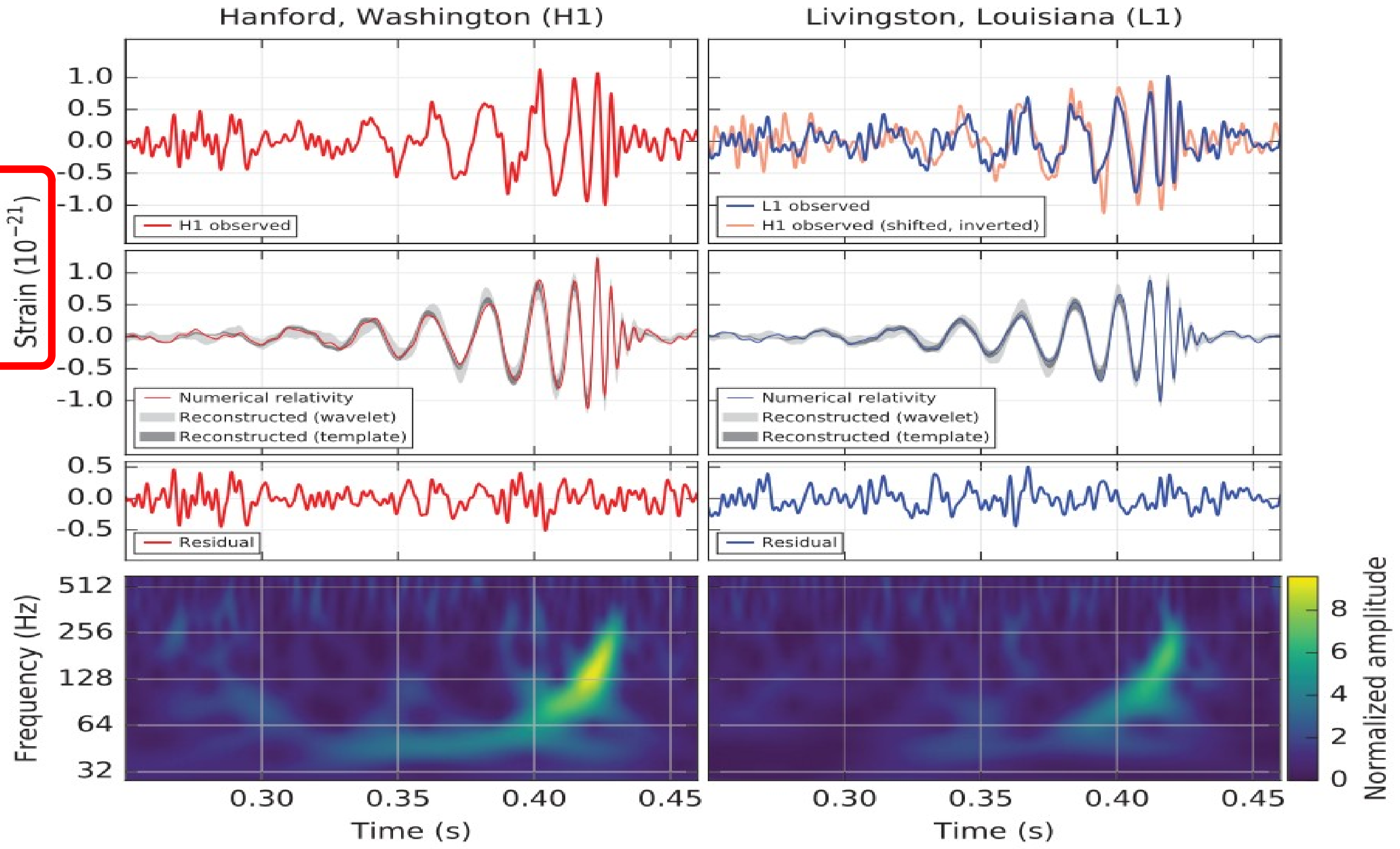
# Hulse-Taylor Pulsar gave strong evidence for GWs

- Pulsar mass 1.44 Msol, companion 1.39 Msol.
- The orbital change in the pulsar PSR B1913+16 (Hulse-Taylor Pulsar) could be explained by energy loss from gravitational waves.




Weisberg and Taylor, “Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis” arXiv 0407149

# LIGO first direct observation, 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.

# LIGO, ground-based Gravitational Wave Detectors

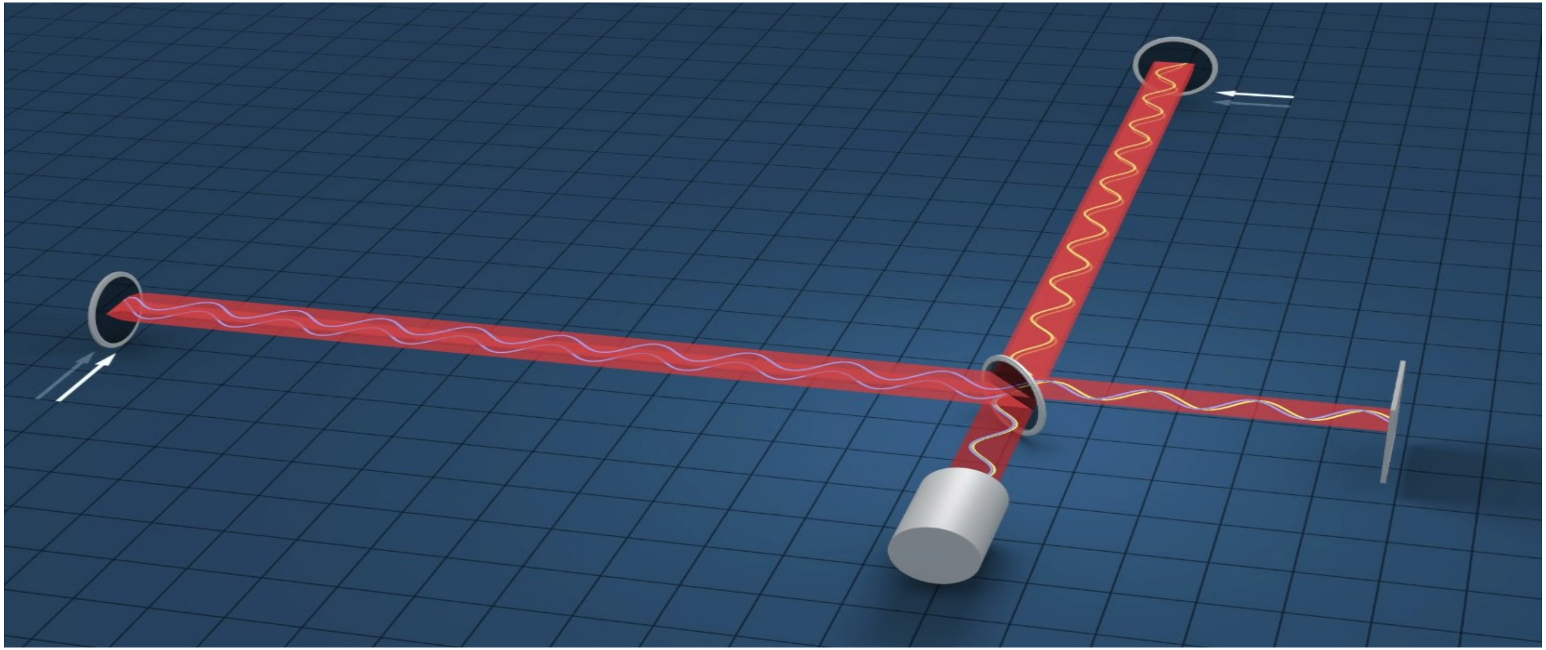
LIGO Livingston, LA (LLO)

LIGO – Laser Interferometric Gravitational Wave Observatory

LVK – LIGO, Virgo (Italy), KAGRA (Japan) collaboration, sometimes LSC

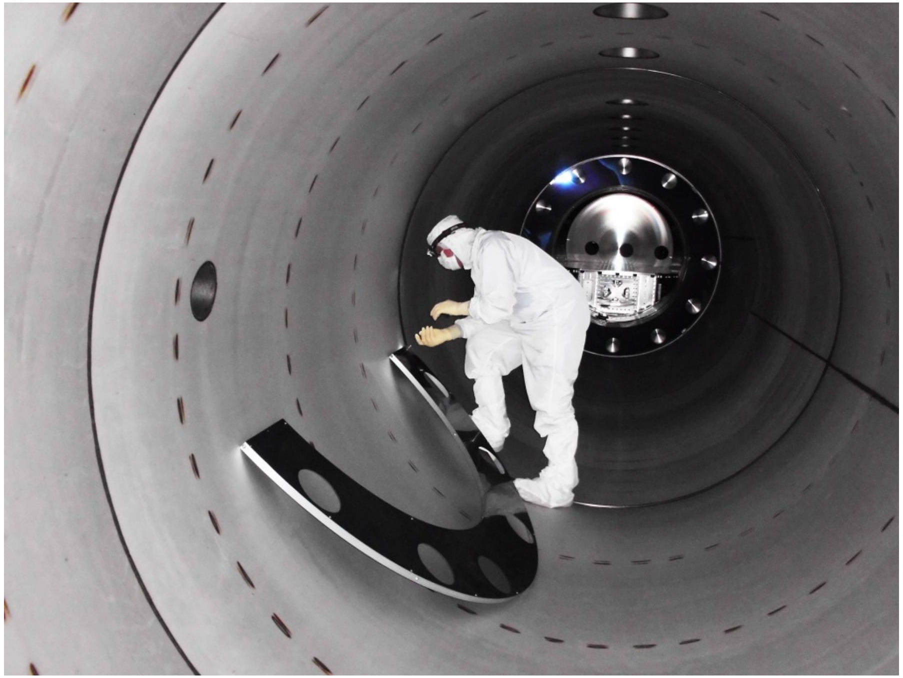
# Big Michelson Interferometer, 4 km arms

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



# LIGO Hardware

- LIGO “Test Mass” in 4-element suspension

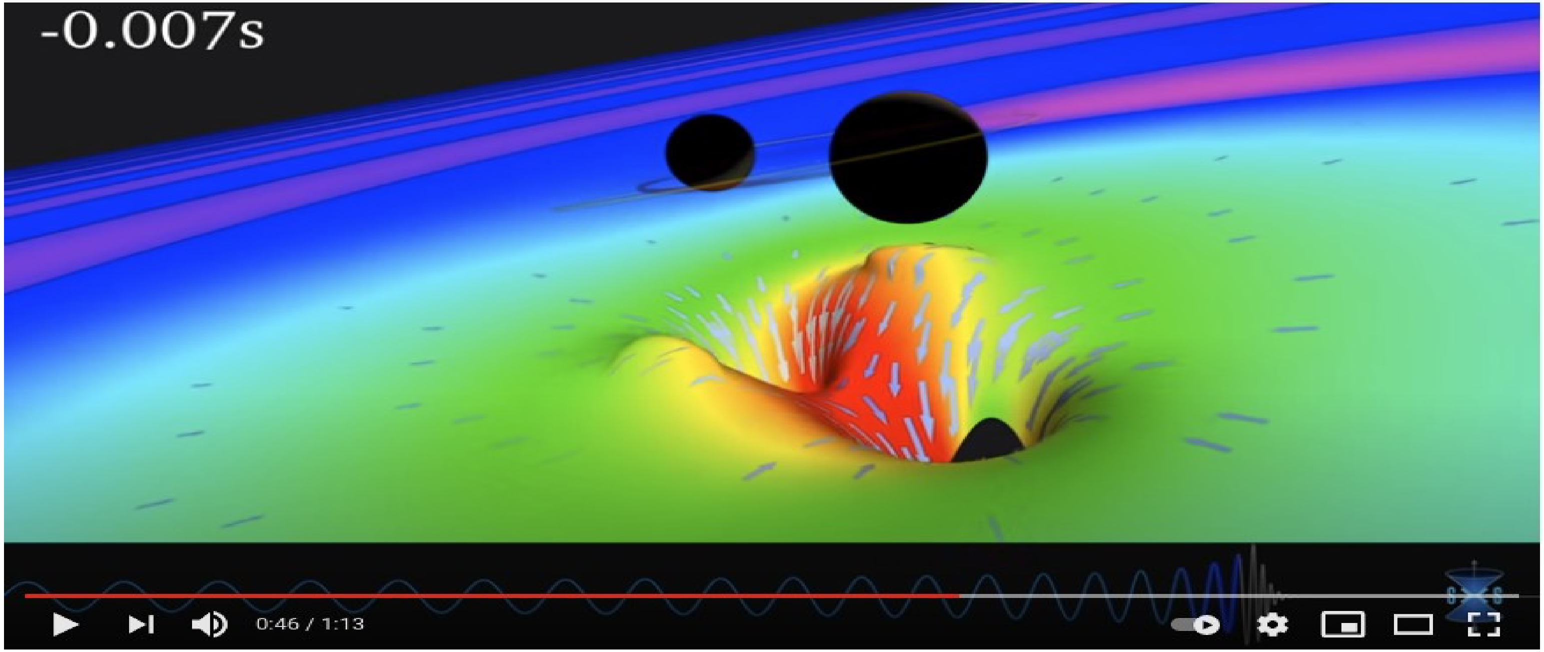



- LIGO Vacuum Tube

Ref: some hardware images

# Sources, Binary Black Holes

- **Binary Black Holes** inspiral, merger, and ringdown.  First discovered/seen **GW150914**, announced April 2016.




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

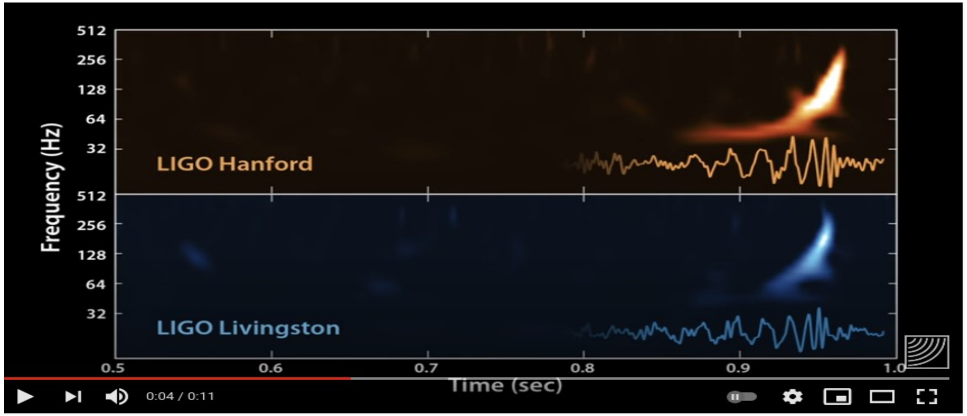
# Sources, Binary Neutron Stars

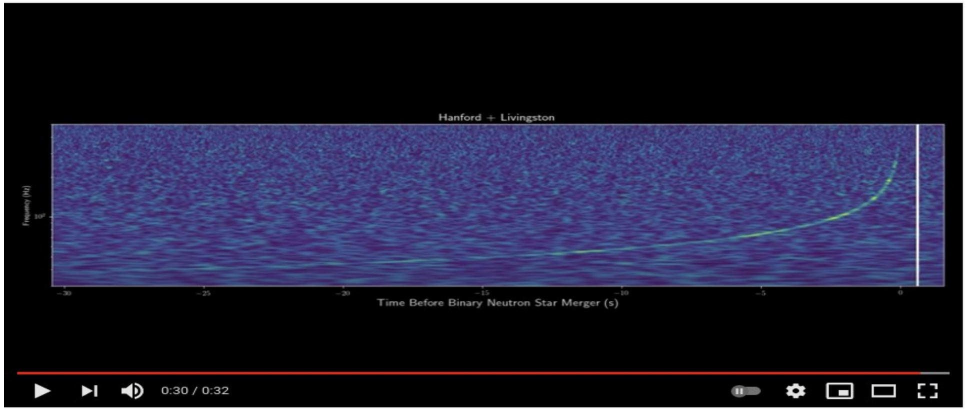
- **Binary Neutron Stars** also inspiral, merger, and ringdown.  First **GW170817** .  Seen in all optical and other EM bands.


https://youtu.be/bBCArmUPgCw 48s, matter around, kilonova, heavy elements created.

# Sources, Waveforms---The Strain

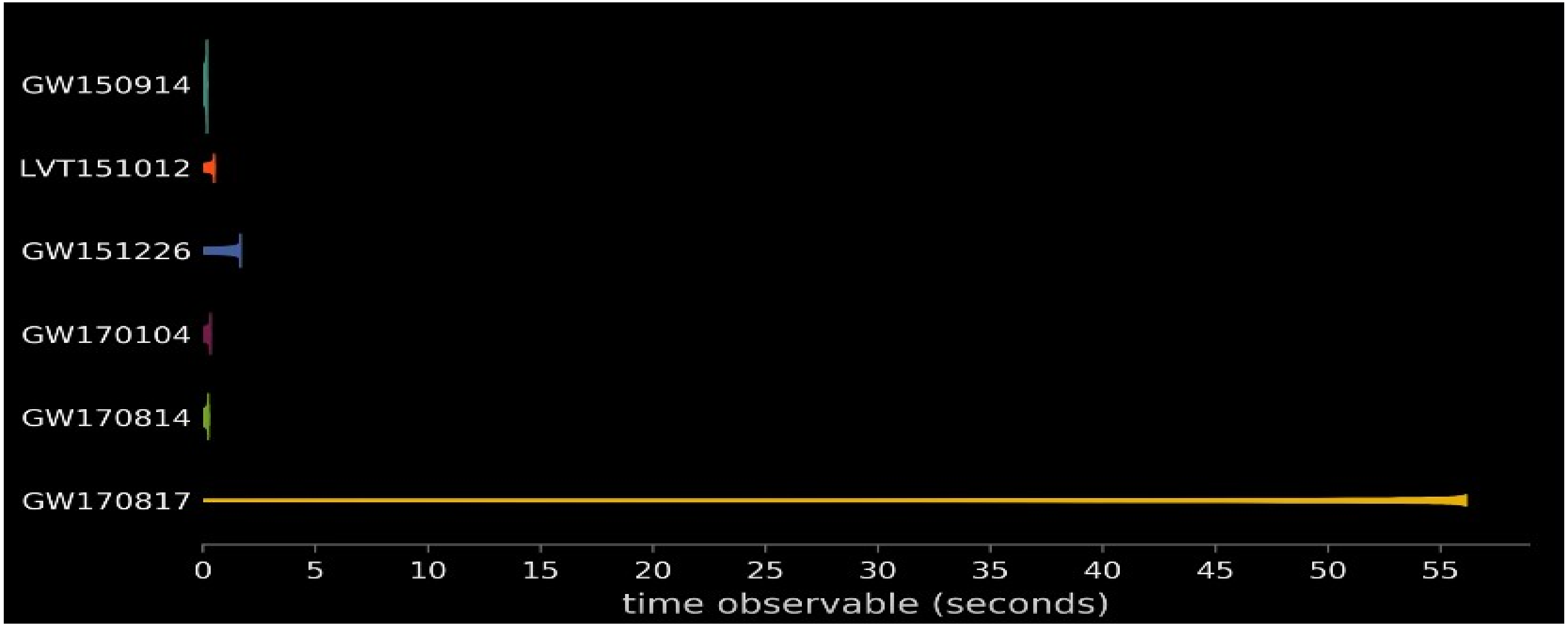
- **Waveforms**, the strain in the interferometer(s)
- Binary Black Holes, GW150914, here



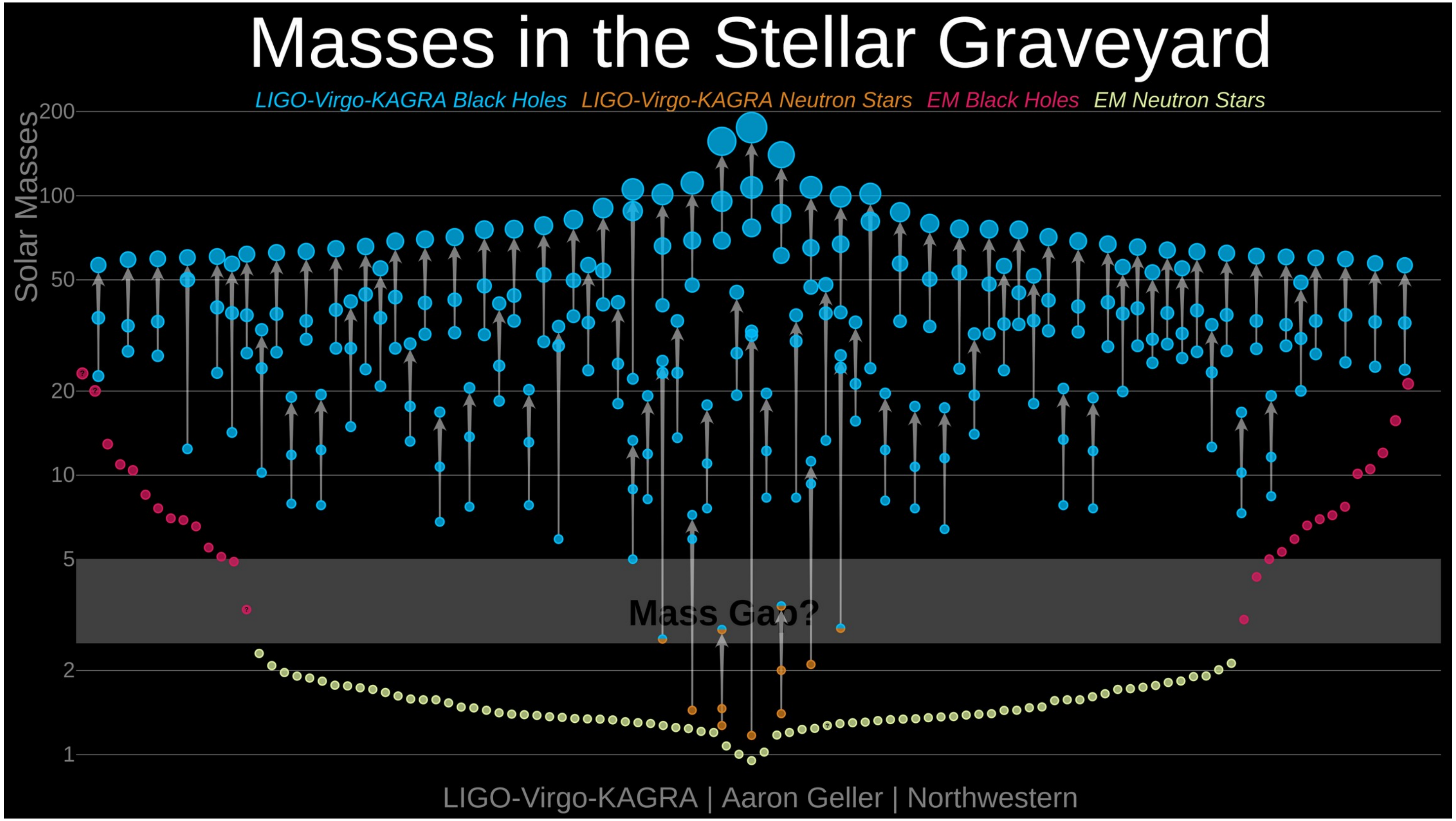

- Binary Neutron Stars, GW170817, here

# GW170817 with other BH GW Sources




YouTube video, animated waveforms, here

# Population of Black Holes and Neutron Stars




above in 2022

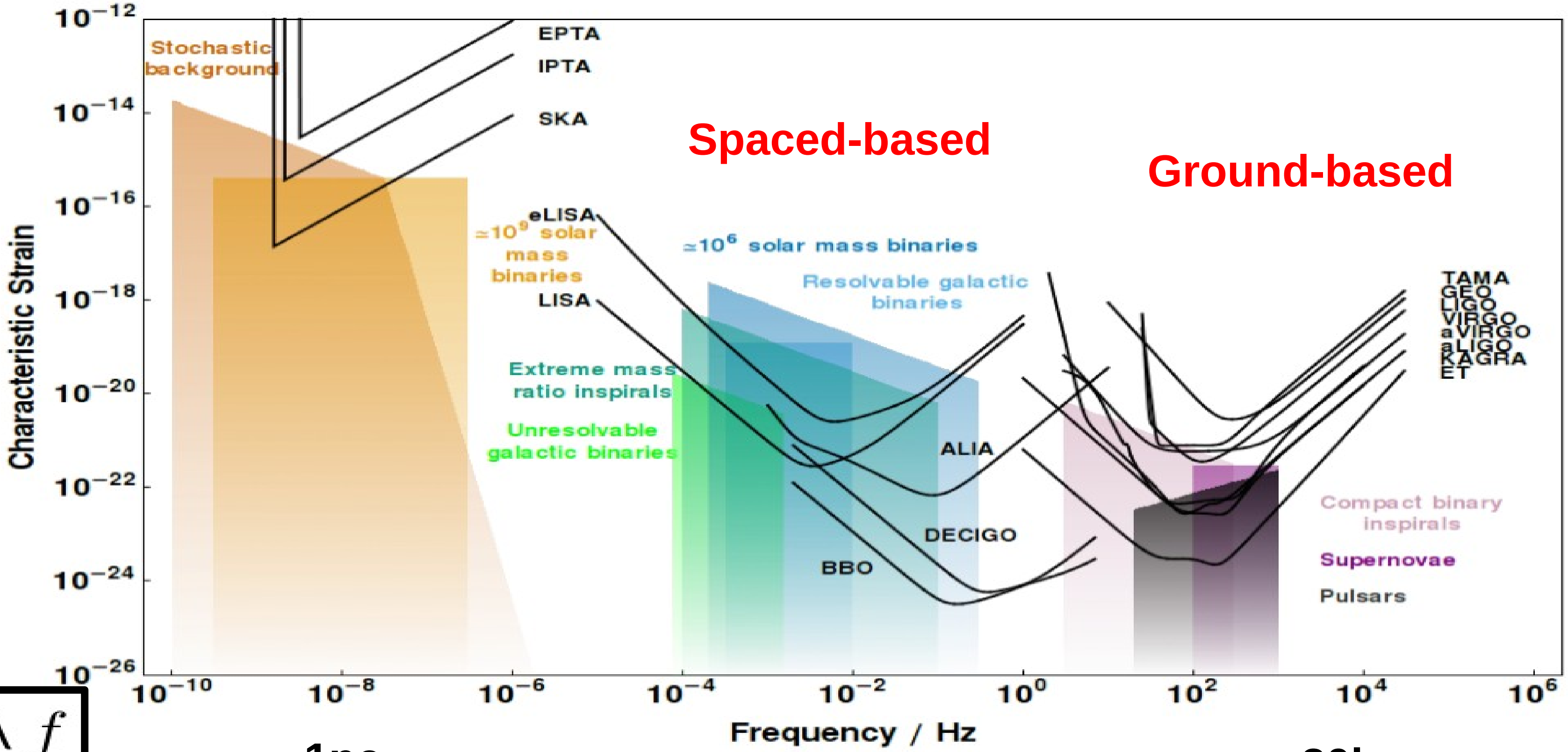
https://media.ligo.northwestern.edu/

Reference to 2020 Image

# Strain Curves from Moore et al.

http://gwplotter.com/

**Pulsar Timing Arrays**




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

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

# Summary

- Gravitational Waves are ripples in spacetime, caused by massive objects moving fast.
  - Have to have a Quadrupole Moment or higher—and orbits do.
  - Most observed events are form Binary Black Holes losing energy and merging, but also from binary neutron stars, and neutron star-black hole binaries.
- LIGO had a direct detection in 2015 and with Virgo (Europe) and KAGRA (Japan) continue to operate.
  - In previous runs, O1-3, the group has announced 93 events.
  - LIGO and KAGRA started data taking in May 2023, O4; Virgo will join later.
  - Seeing a great many (more) candidates each day.

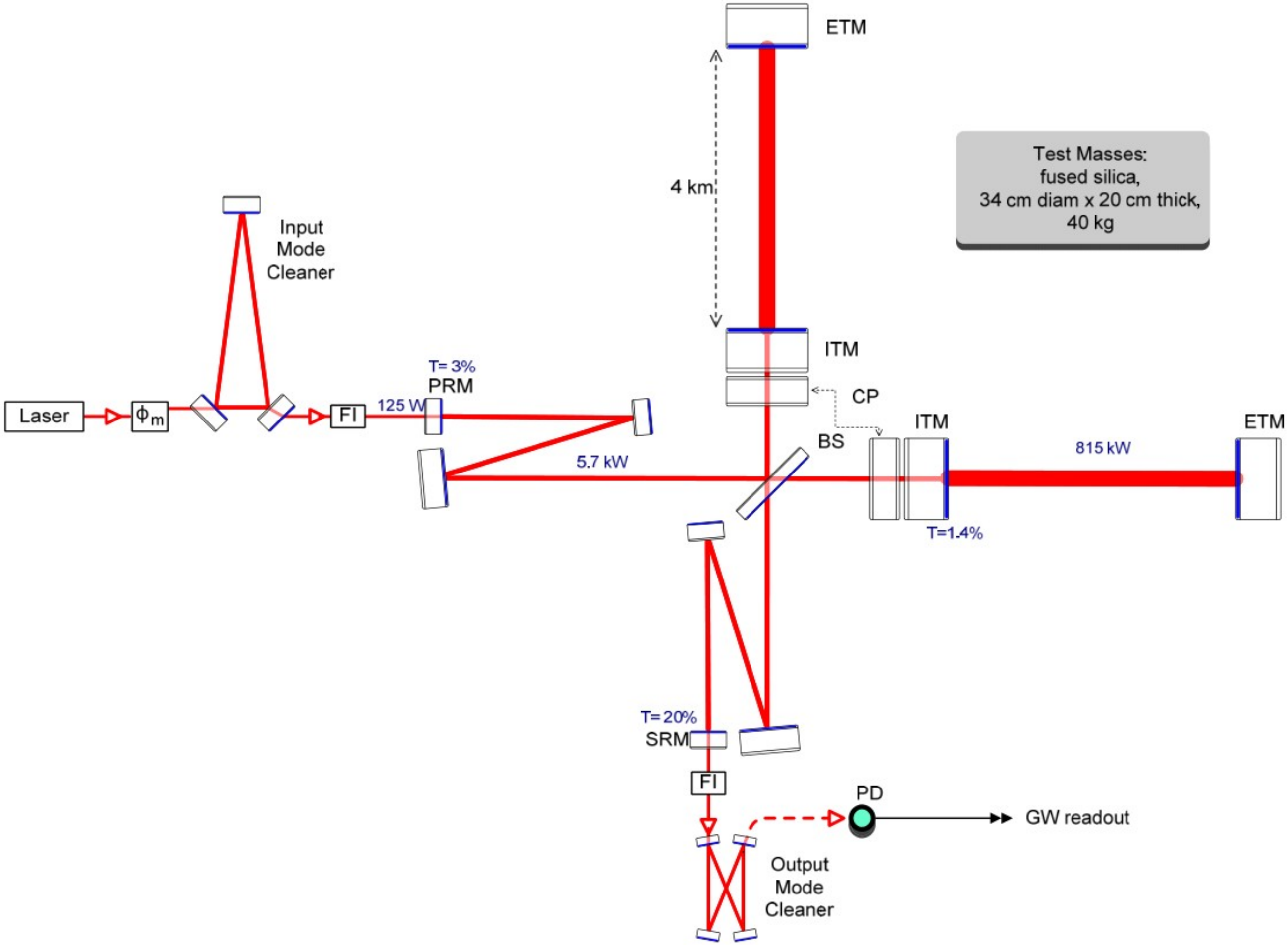
# Vanderbilt Connection

- Kelly Holley-Bockelmann and Karan Jani and group are members of LIGO, since September 2020.
  - Led by Karan Jani, newly hired assistant professor at Vanderbilt, researching Intermediate Mass Black Holes and Lunar based GW detectors.
- LISA is the space-based detector being built by ESO with NASA contributing. Kelly is chair of the NASA LISA Study team.
- PTAs/Pulsar Timing Arrays uses the pulsars in the Milky Way as good clocks to detect GWs passing by...long time scales, data taking for 15 years. Steve Taylor is the spokesperson for the Nanograv collaboration, the US PTA effort.

# Thank you for your Attention!

# Questions?  Comments?

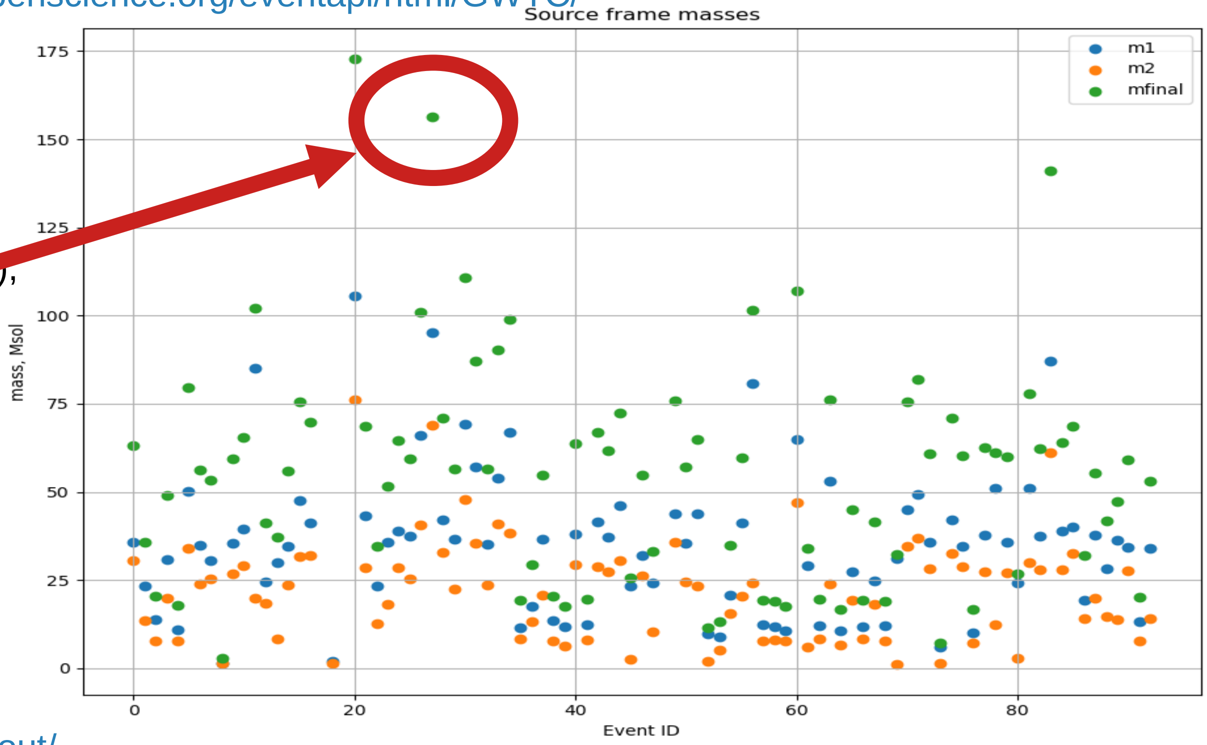
# Backup


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

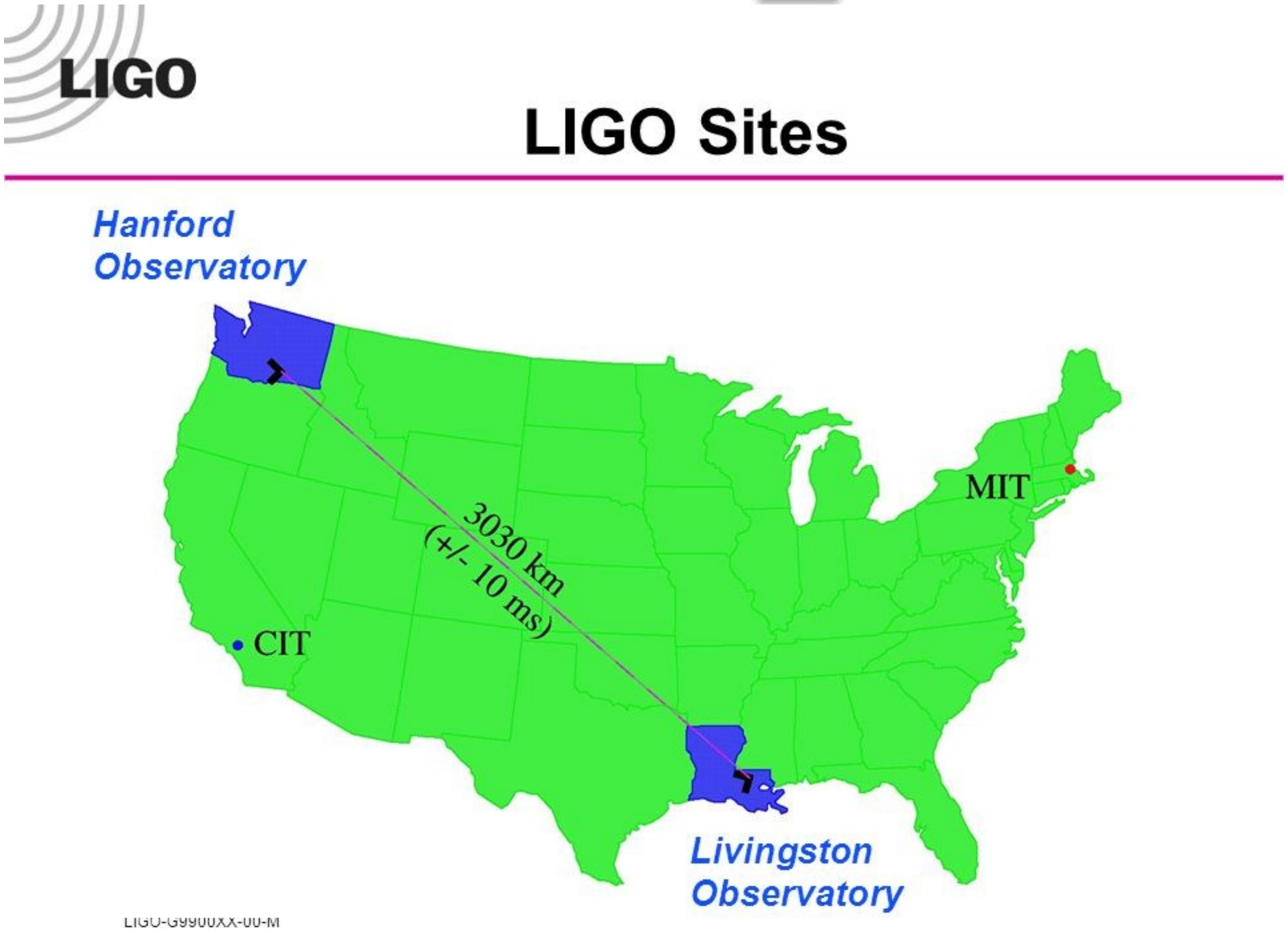
# Catalog GWTC-3

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

Event **GW190521_v3**, first Intermediate Mass Black Hole (IMBH), 156.3 Msol

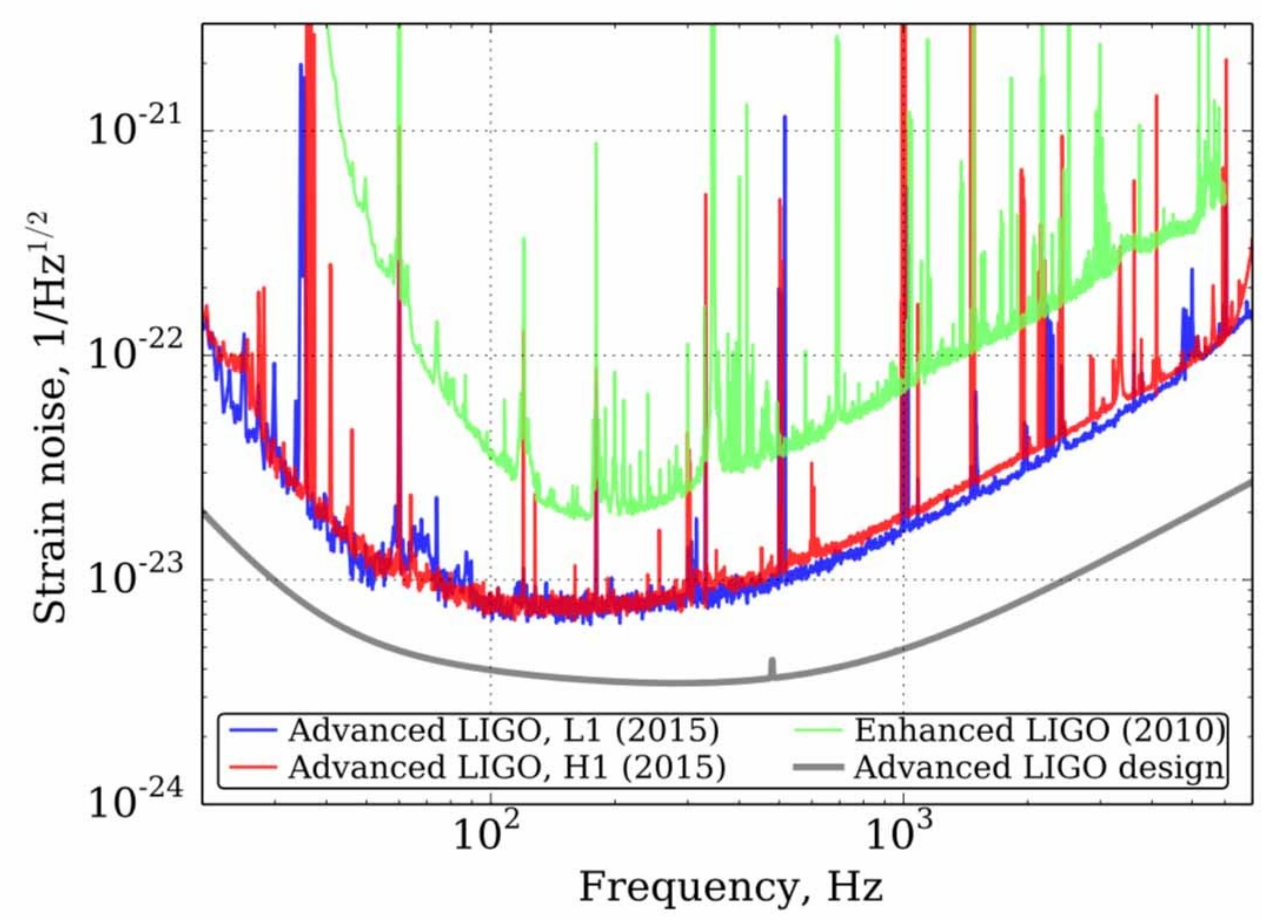



https://www.gw-openscience.org/about/




Also Virgo, Cascina, Italy and
KAGRA, Japan

# Seismic Noise aLIGO and initial




Above the background noise.

Below the noise.

# Links

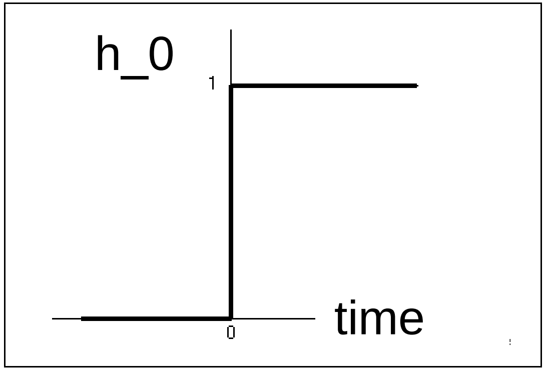
- LIGO Teacher's page here
- LIGO Student's page here
- LIGO CalTech Educational Resources here
- LIGO Scientific Collaboration, LSC
- LIGO Document Server
- CalTech GW media assets page.
- Kelly Holley-Bockelmann's TEDx Nashville Talk 2016 about GW150914.
- Pulsar timing array, Nanograv
- LISA Consortium, space-based GW detectors
- Gravitational Wave Open Science Center

# Saulson, *If Light Waves…*

- We know 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.



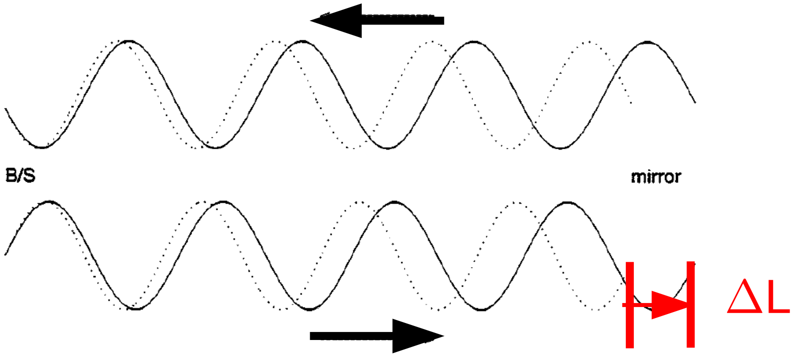




Fig. 2. Light before (dotted) and after (solid) the arrival of a gravitational wave. The beamsplitter is at left, end mirror at right. Outbound light is shown at the bottom, returning light at the top.

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

# As the Wave runs through...

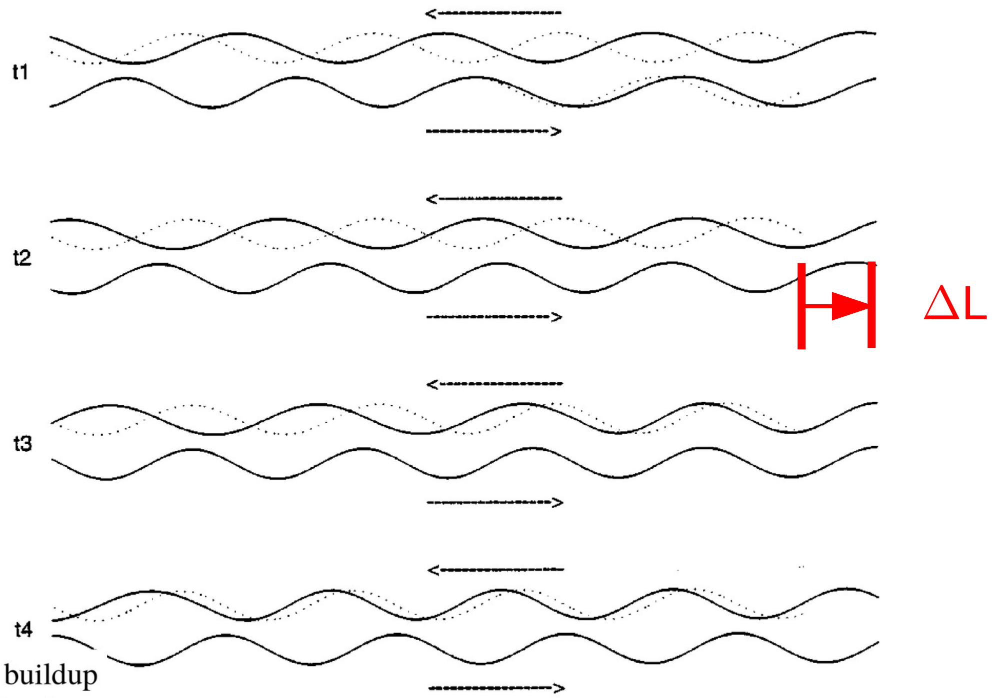



Fig. 3. Like Fig. 2, but at a succession of later moments. Note the buildup of phase shift between the light in the stretched arm (solid) compared to how it would have traveled through an unstretched arm.

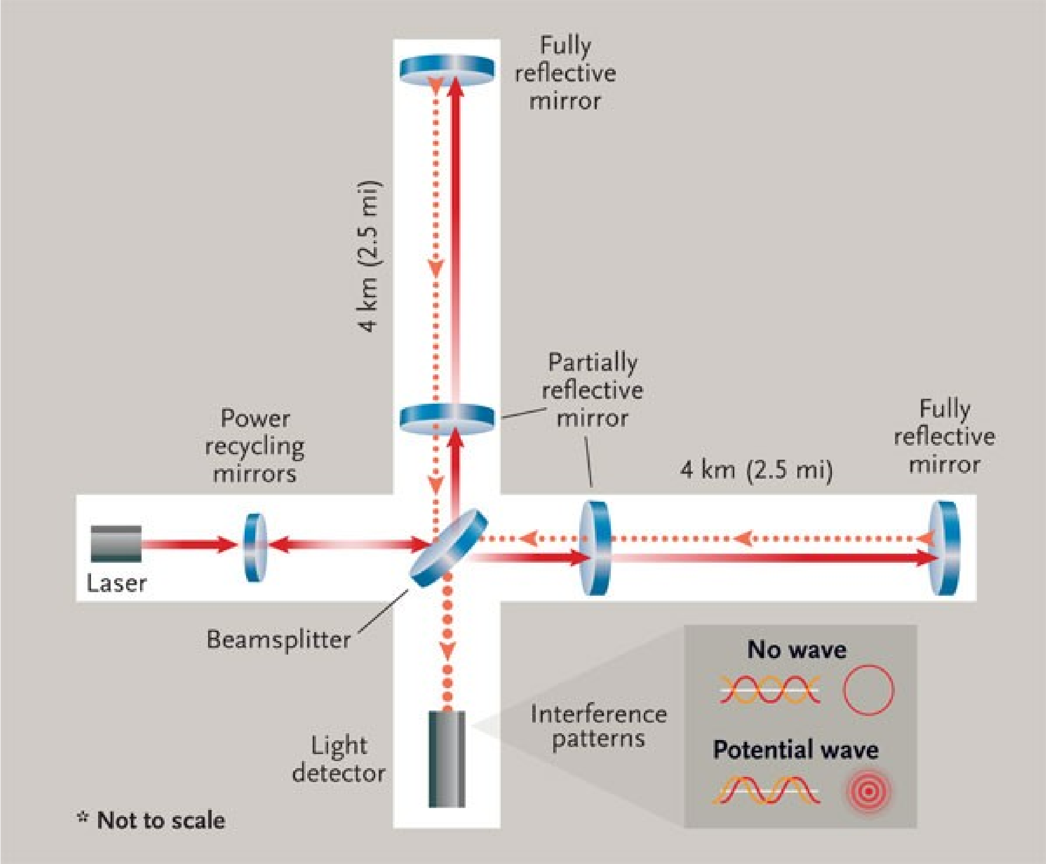
# Saulson, *If Light Waves…*, says rods are still rigid!

## V. LENGTHS IN COSMOLOGY AND IN LABORATORY PHYSICS

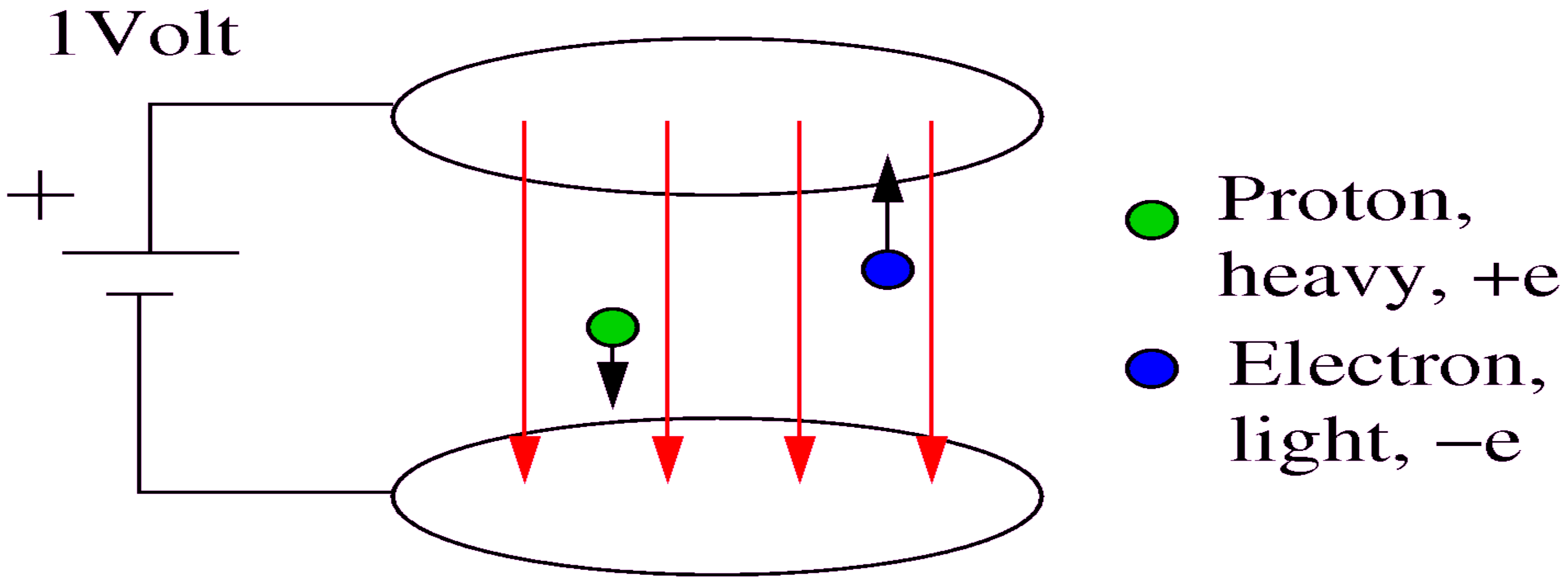
Note that the language we have been using in this paper only makes sense if we imagine that we have standards of length other than either the separations of freely falling test masses or the wavelengths of light waves. We do. A good paradigm of a length standard is a perfectly rigid rod. Such a rod does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

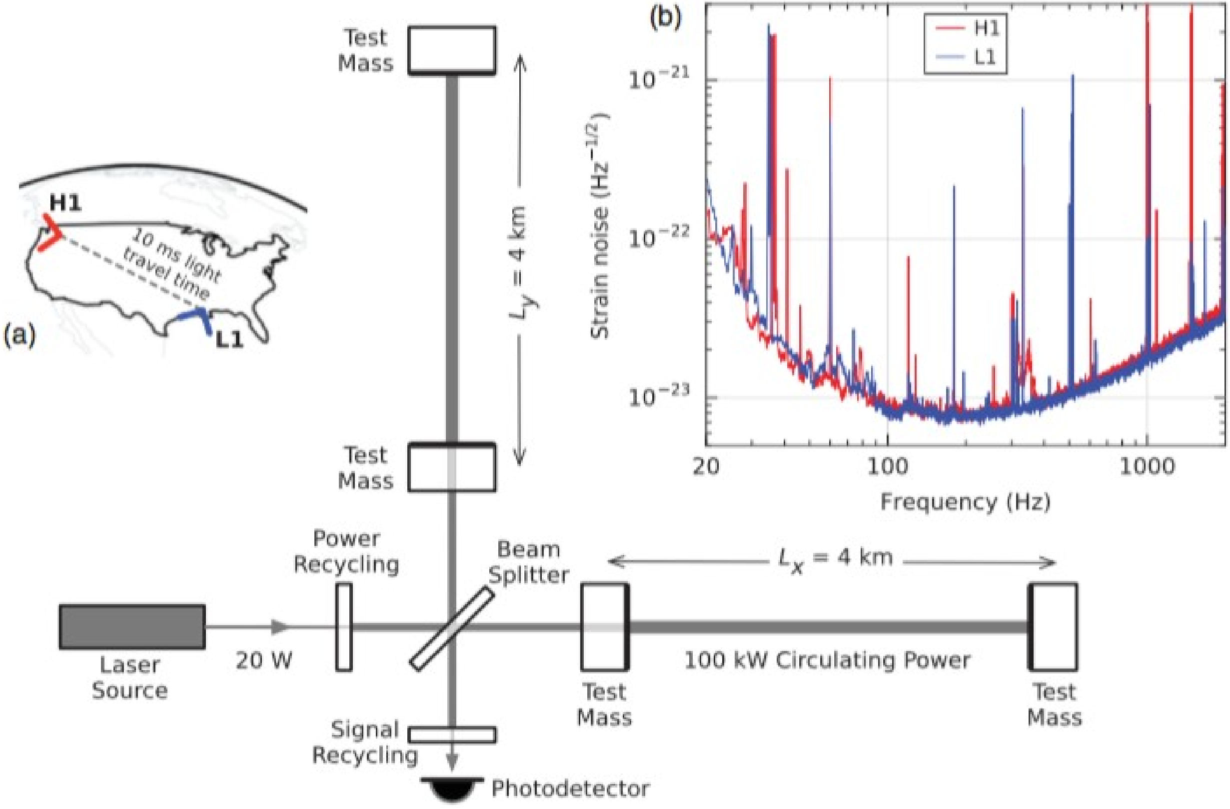
**Table 5. SI prefixes**

| 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 |

# 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

$$h_0 = \frac{r_{s1} \cdot r_{s2}}{r \cdot R} \qquad \frac{\omega_s^2}{c^2} = \frac{(r_{s1} + r_{s2})}{2\, R^3}$$

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

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

- 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.

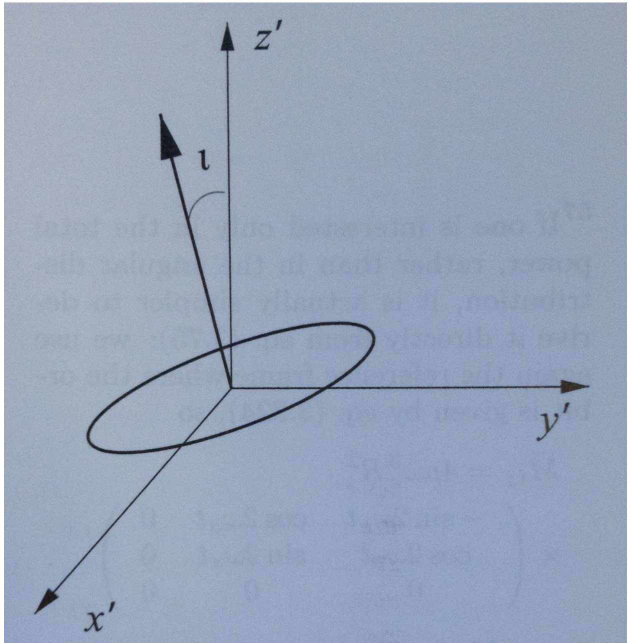


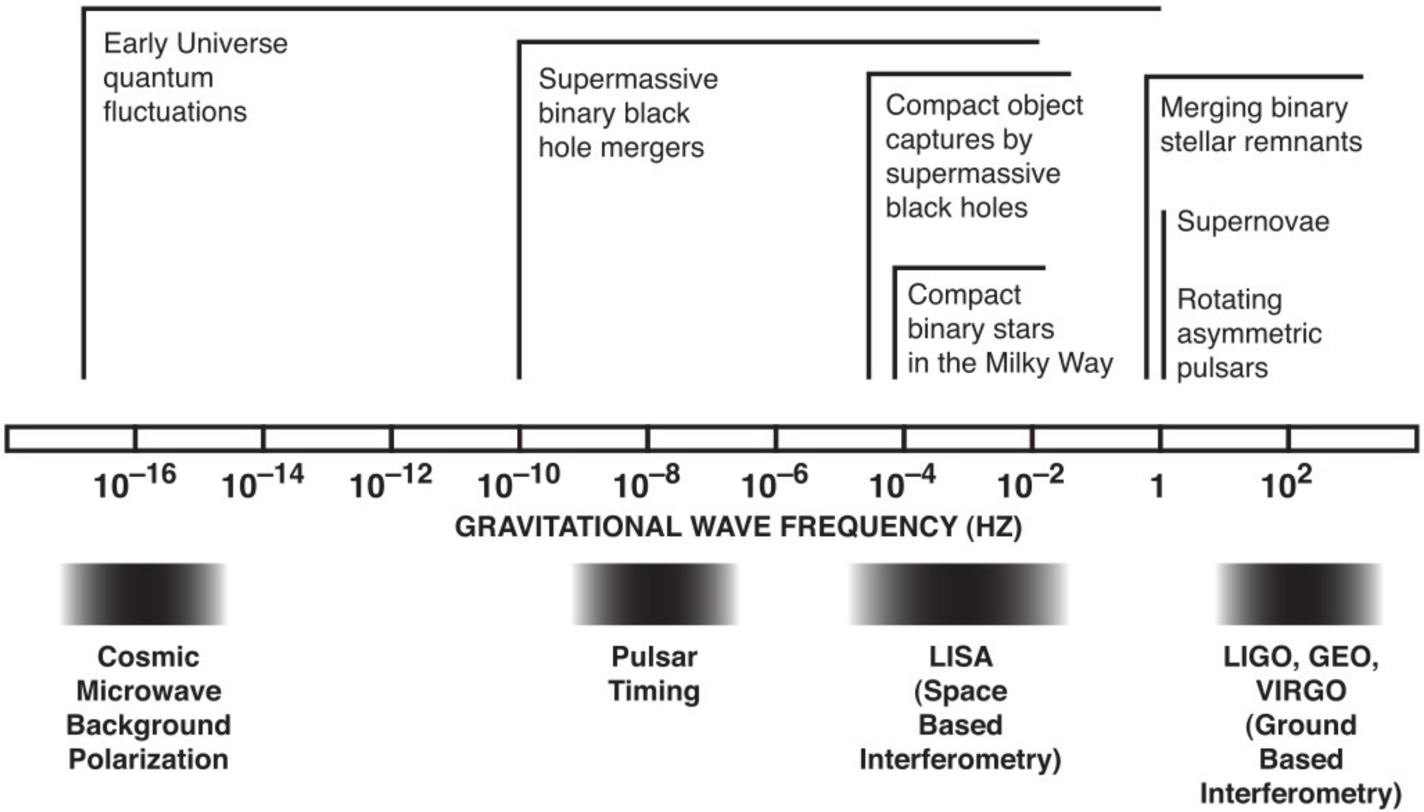

**Fig. 3.6** The geometry of the problem in a frame $(x', y', z')$ where a fixed observer is at large distance along the positive $z'$ axis. The normal to the orbit makes an angle $\iota$ with the $z'$ axis.

ref: Maggiore around Eqn. 3.332.

# Some Constants

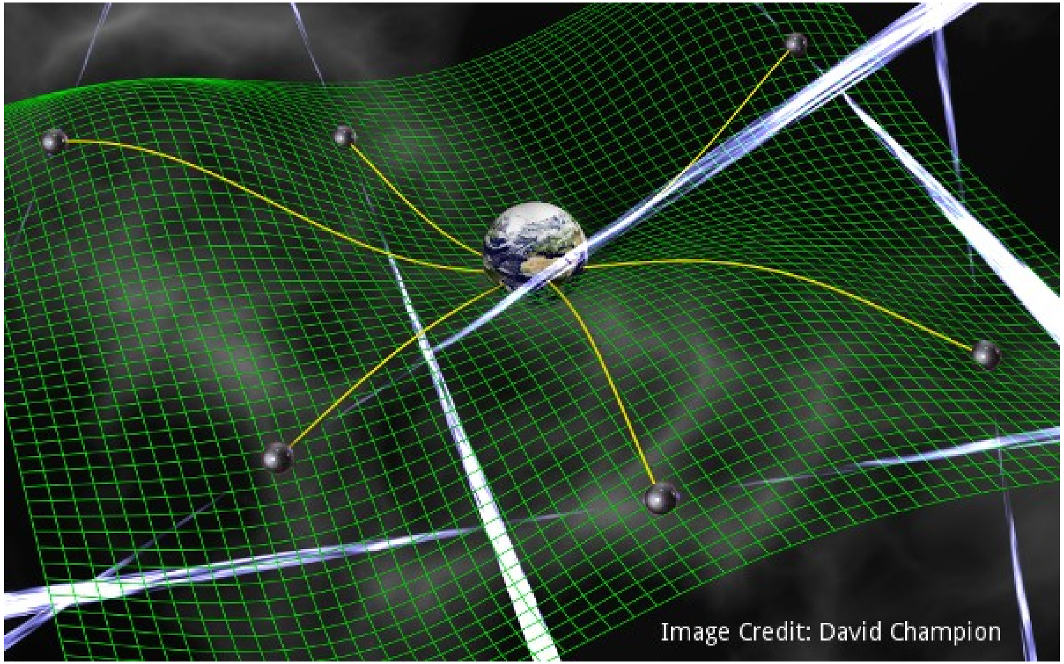
| | | |
|---|---|---|
| Schwarzschild radius | 2GM/c^2 | 2953 m for Msun |
| GR Units, Mass | GM/c^2 | 1477 m for Msun |
| GR Units, Power | c^5/G | 3.628e52 W |
| GR Units, Energy | c^4/G | 1.210e44 J/m |
| parsec, pc | | 3.09e16 m = 3.262 ly |
| astronomical unit, au | | 149.6e9 m |
| light-year, ly | | 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, 1.24 GeV fm |

# Gravitational Wave Spectrum



# 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 frequencies. Size of the Universe sort of waves!




Ref: NANOGrav collaboration

# Pulsar Timing Arrays

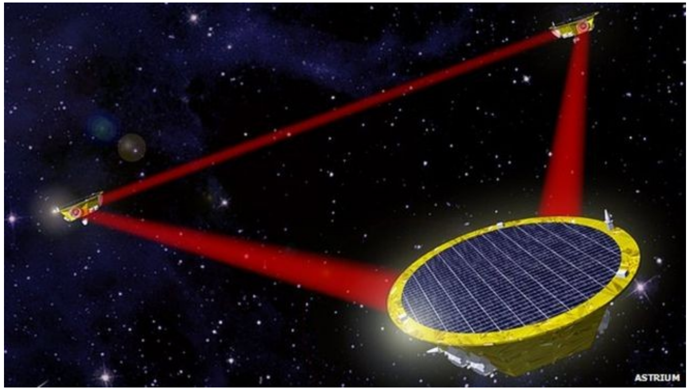
- Several collaborations working at radio astronomy facilities to measure millisecond pulsars:
- NANOGrav, US and NASA, using ~~Arecibo and~~ Green Bank.
- The International Pulsar Timing Array uses many radio telescopes.
- The European Pulsar Timing Array
- The Parkes Pulsar Timing Array (part of the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

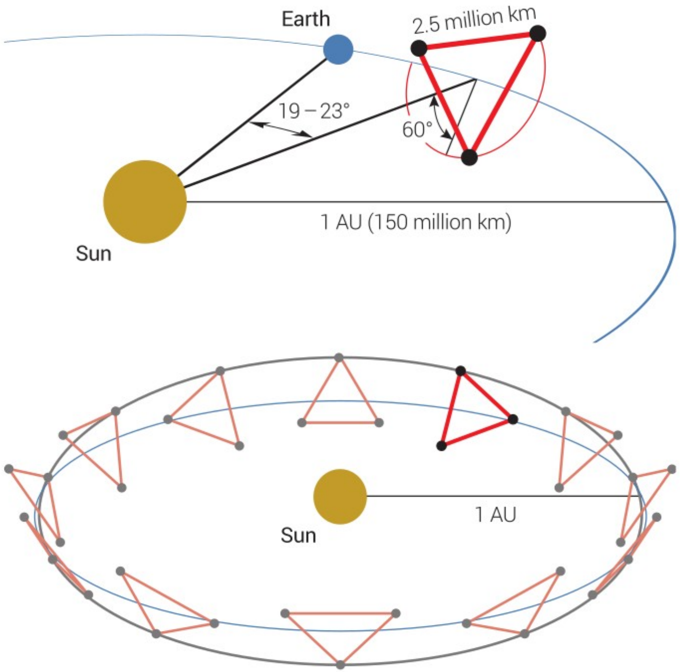
# Space-Based

- **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 subtle, “drag-free flying” with free test masses inside as reference.
- Currently mostly European LISA Mission with NASA/US support. LISA could launch in 2037 (factsheet).
  - 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.

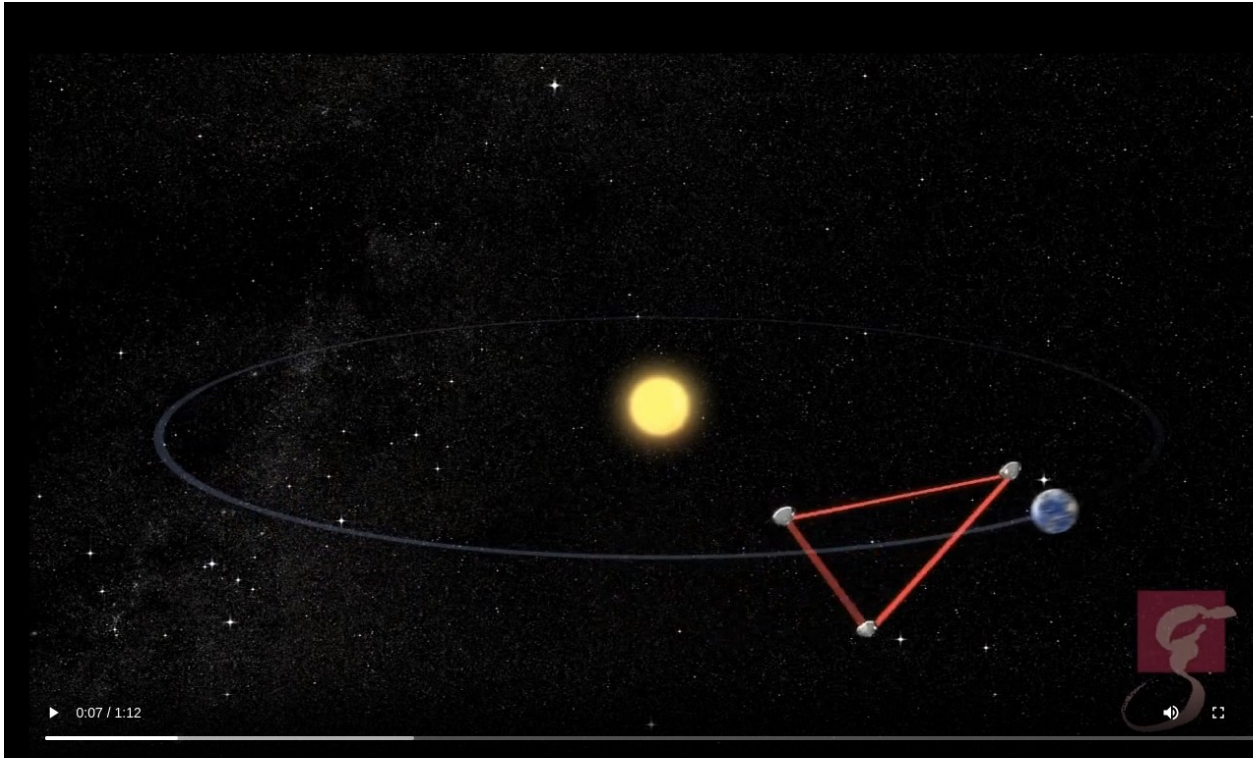



- Chinese have two groups working on this idea:
  - TianQin
  - TAIJI

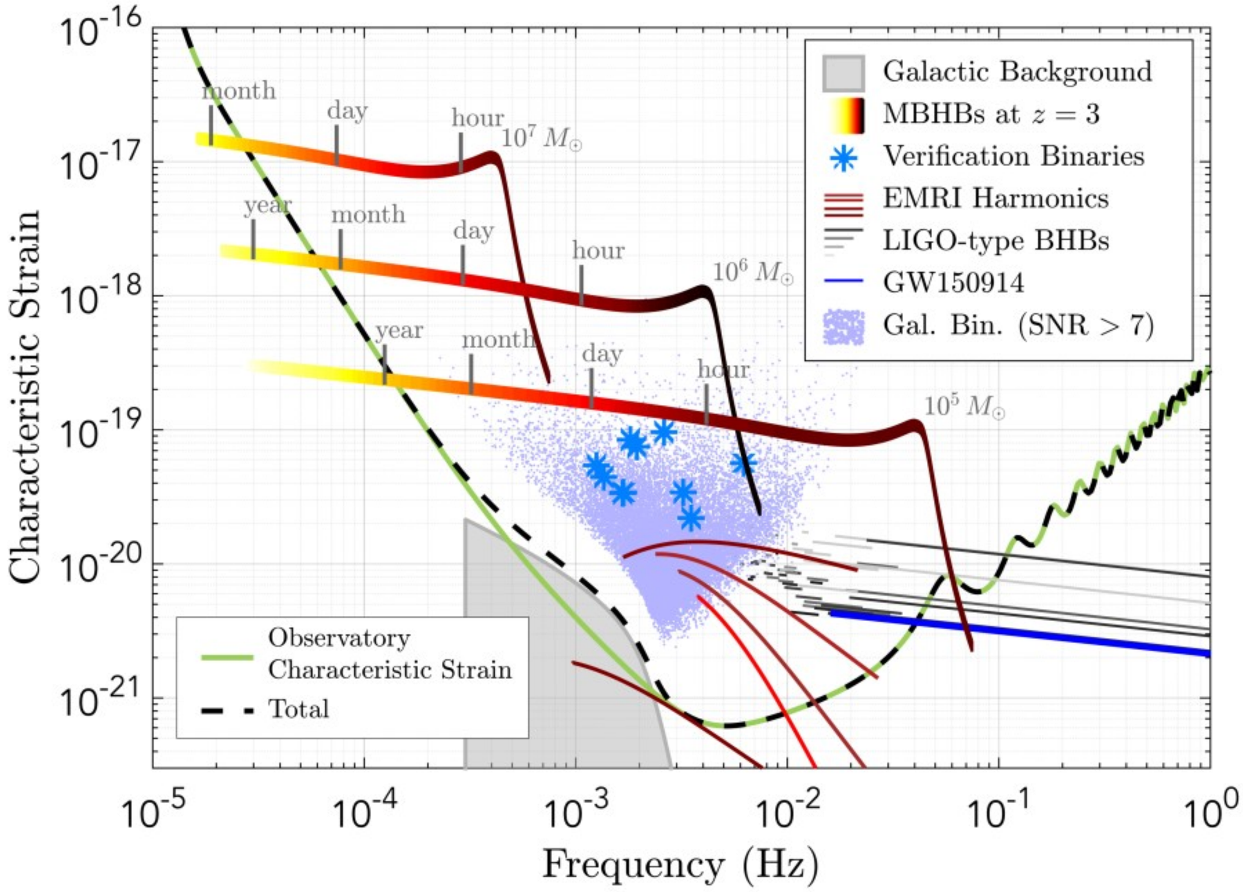
Credit

# LISA Orbit




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

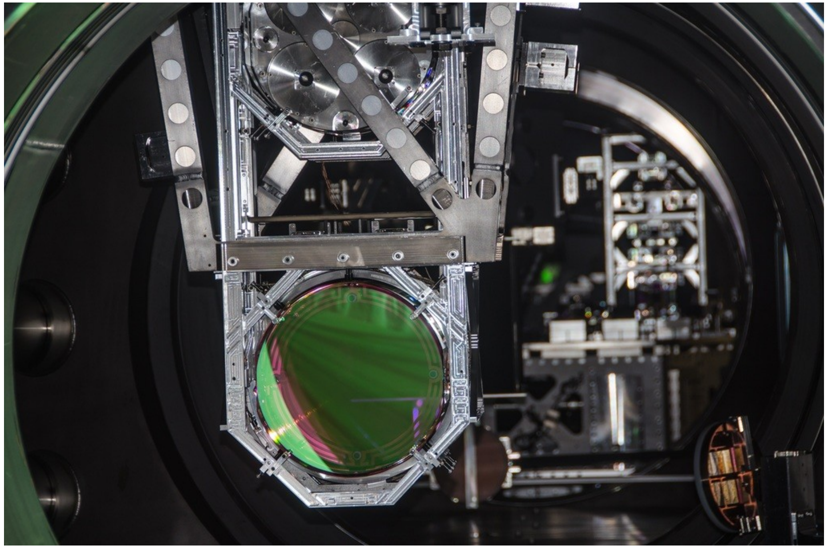
# LISA Astrophysical Sources

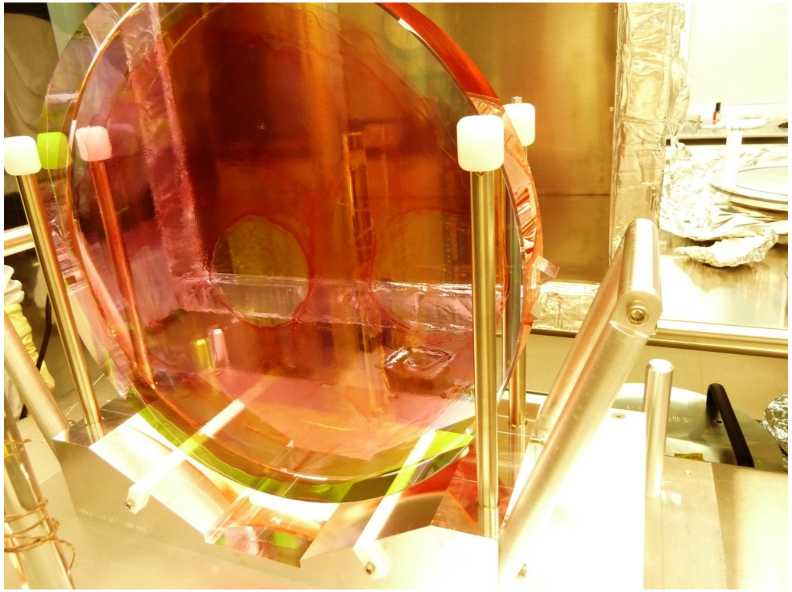



Credit

# LIGO Hardware

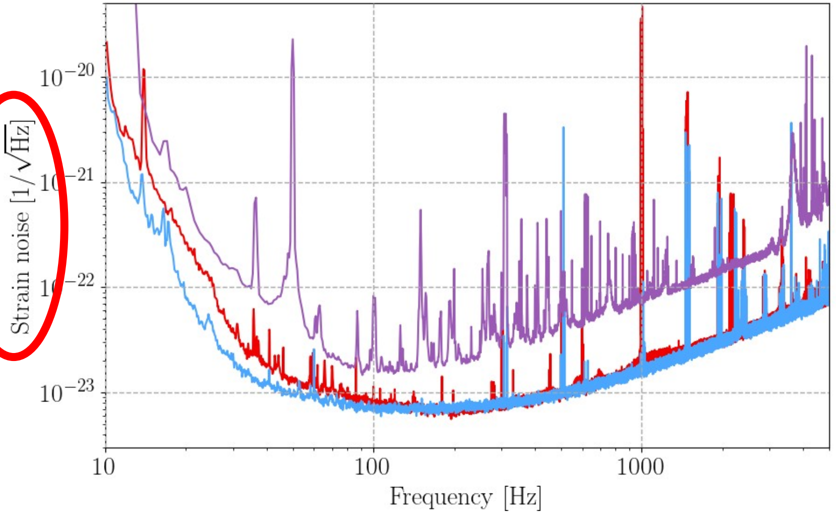
- LIGO "Test Mass" in suspension

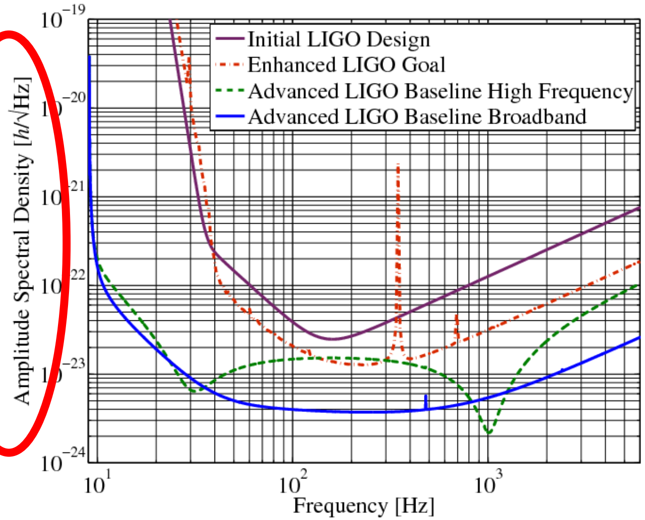




- Beam Splitter

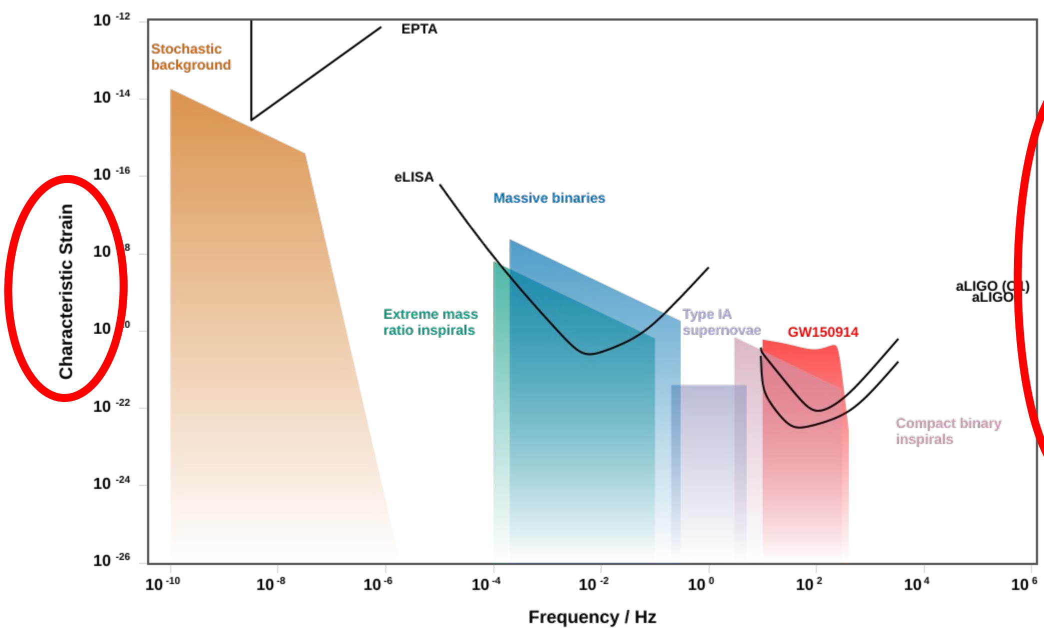
# Strain Curve, Strain Sensitivity, Amplitude Spectral Density, Power Spectral Density...OH MY!

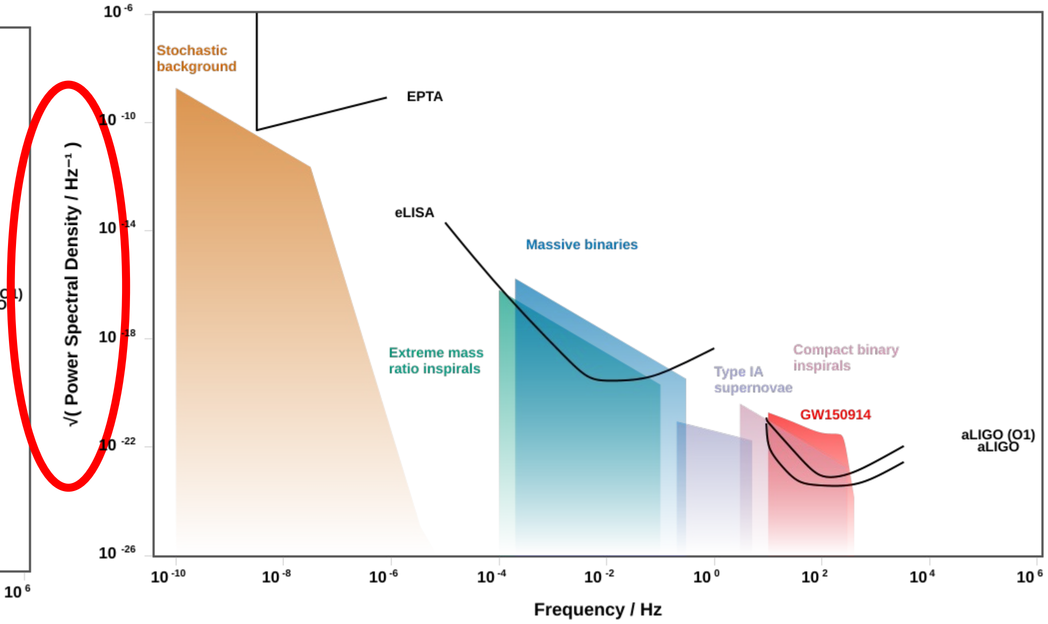



“per root Hz” is usually called the *strain sensitivity*, or sometimes *amplitude spectral density*

# Strain Curve, etc...




*Characteristic Strain*

Square root of *Power Spectral Density* is the *amplitude spectral density.*

Ref: Cole's online app .