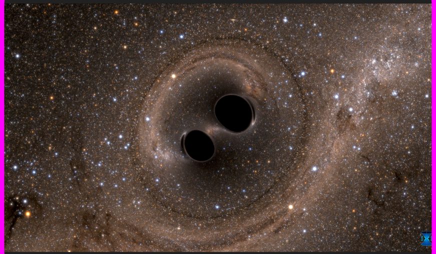
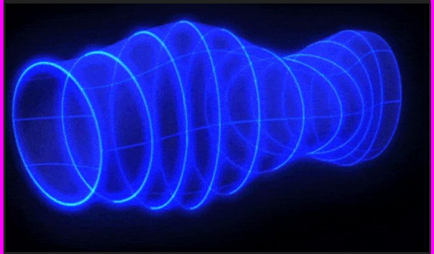
Gravitational wave astronomy: a very quick overview

Ansel Neunzert
GWANW June 2024 student workshop

sources → waves → detectors → analysis





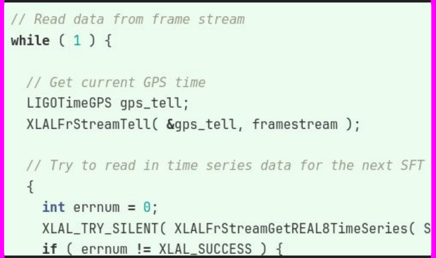


Image credits: SXS collaboration; European Space Agency; LIGO laboratory; LIGO algorithms library (LALsuite)

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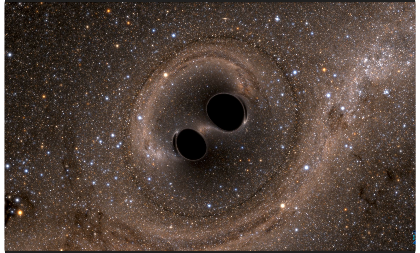

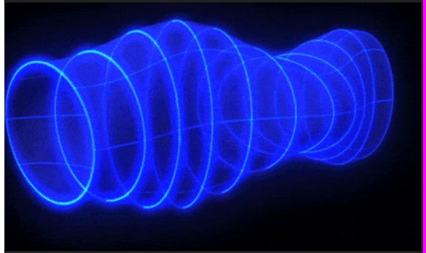

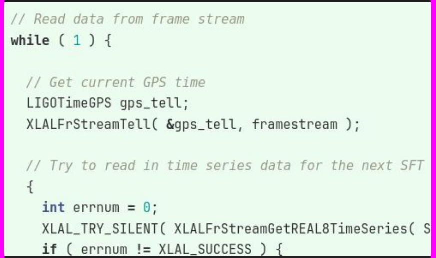

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What makes gravitational waves?

Technical: you need to have a mass quadrupole moment that is changing in time.

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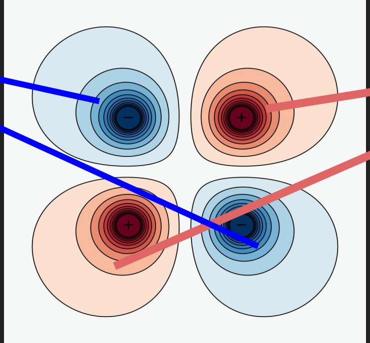
Reminder: what's a quadrupole?

Less stuff



More stuff (mass, charge, etc)

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What to remember: if it rotates and it's not symmetrical about the spin axis, you can get gravitational waves.

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Perfect sphere: ???

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Two spheres orbiting: ???

What makes gravitational waves?

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Perfect sphere: No GWs

Ellipsoid rotating: GWs

Two spheres orbiting: GWs

What makes gravitational waves?

Technical: the amplitude of the gravitational wave is related to the second time derivative of the mass quadrupole moment

Conceptual: in order to make a large gravitational wave, the system needs to move very fast and be very massive and compact.

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Technical: the amplitude of the gravitational wave is related to the second time derivative of the mass quadrupole moment

Conceptual: in order to make a large gravitational wave, the system needs to move very fast and be very massive and compact (like black holes and neutron stars, for example).

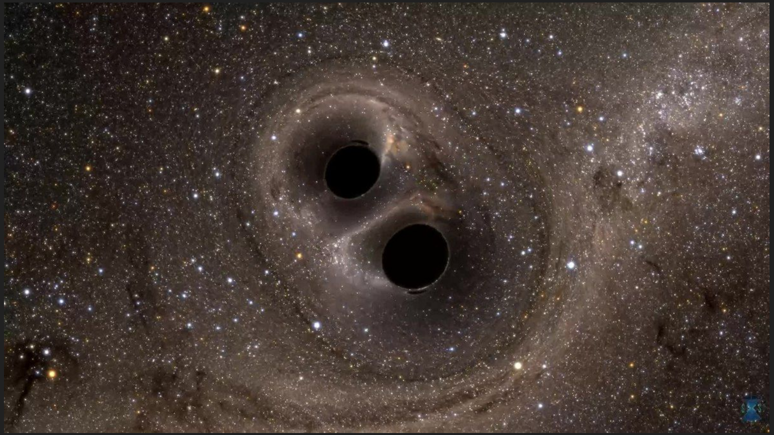


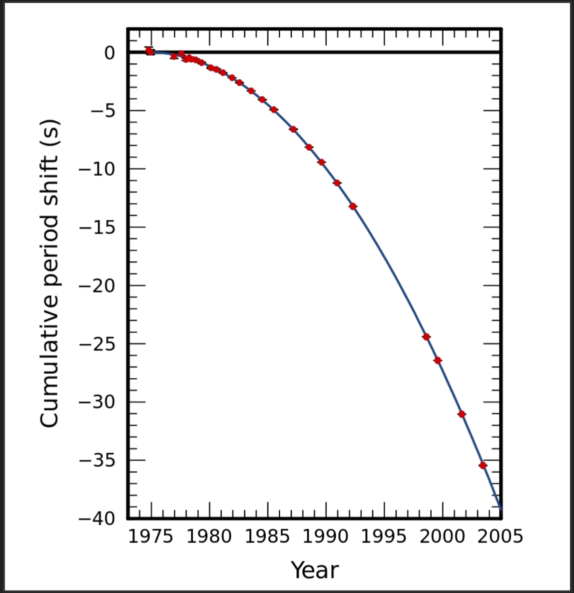
Image credit: SXS collaboration

Sources evolve as they emit gravitational waves

Gravitational waves carry energy.

So if a system is emitting gravitational waves, it must be losing energy. That energy loss affects the system.

Historical example: the Hulse-Taylor binary (1993 Nobel prize)



Sources evolve as they emit gravitational waves

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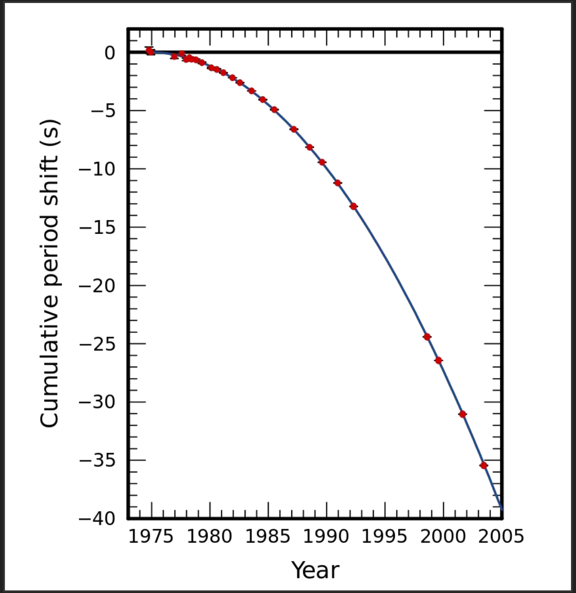
So if a system is emitting gravitational waves, it must be losing energy! That energy loss affects the system.

Is its orbital frequency increasing (more rotations per fixed time) or decreasing (fewer rotations per fixed time)?

Is the binary orbit getting tighter or wider?

Will the objects eventually collide or fly apart?



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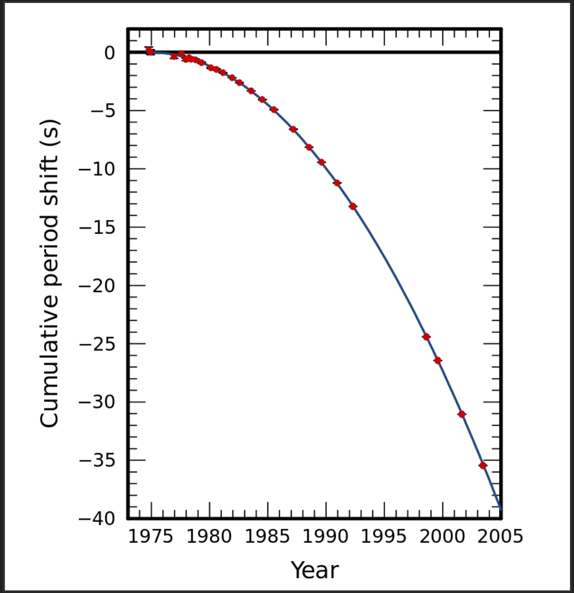

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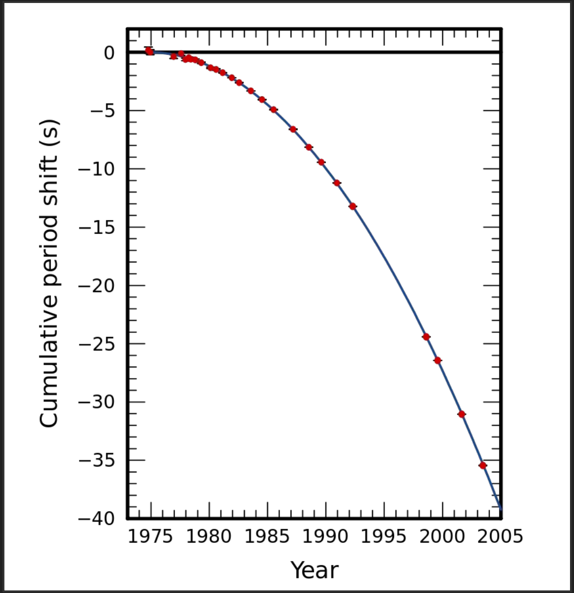
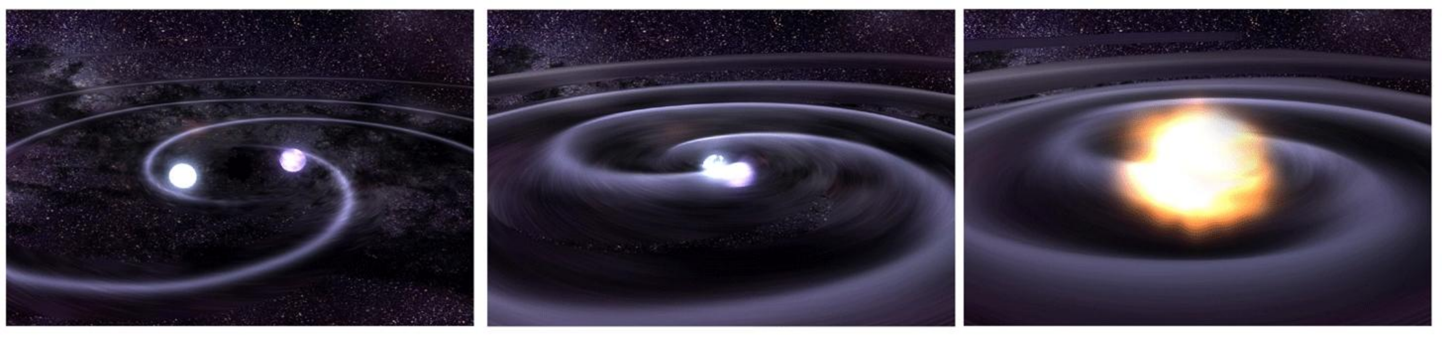
- Frequency and amplitude for this system would still be low for this system
- Wait about 300 million years…



Binaries → inspirals!



An artist's impression of two stars orbiting each other and progressing (from left to right) to merger with resulting gravitational waves. [Image: NASA/CXC/GSFC/T.Strohmayer]

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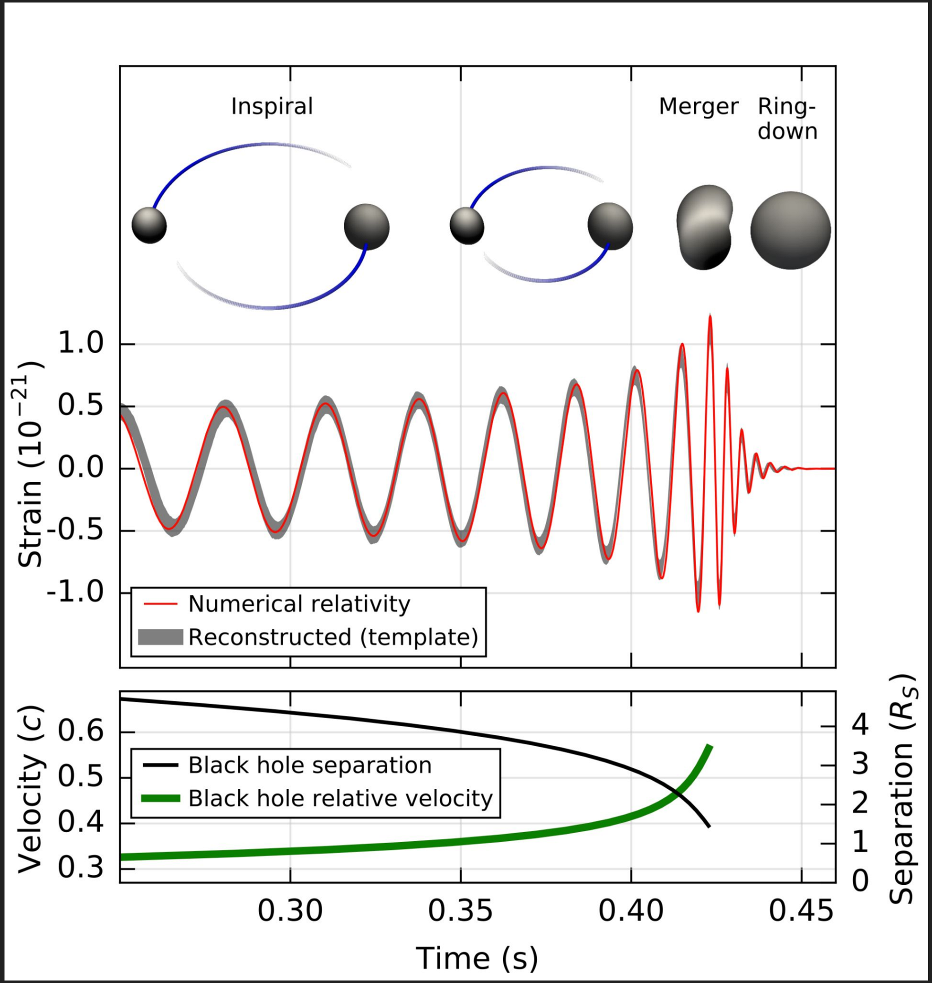
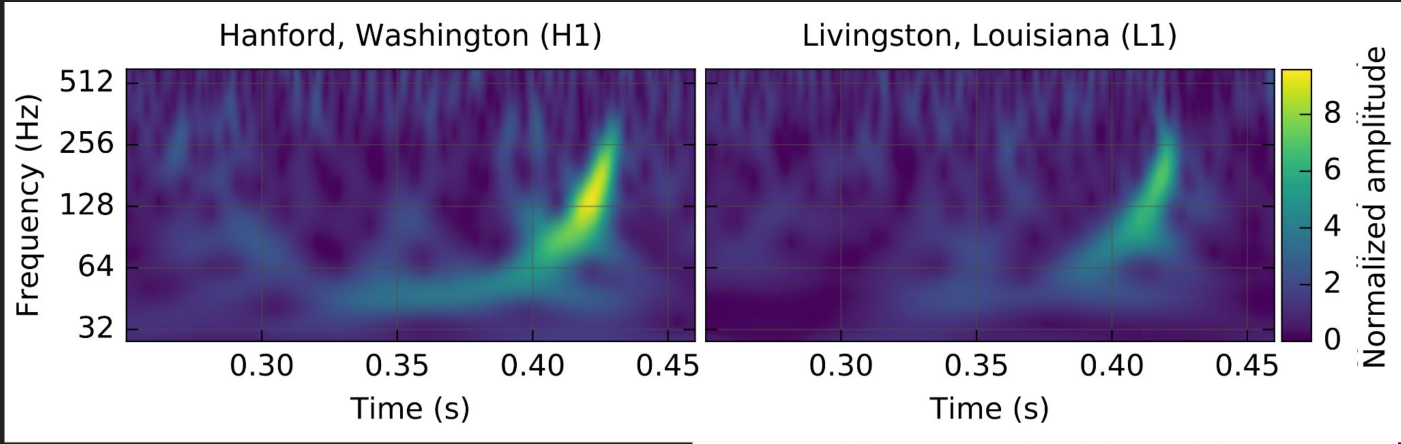


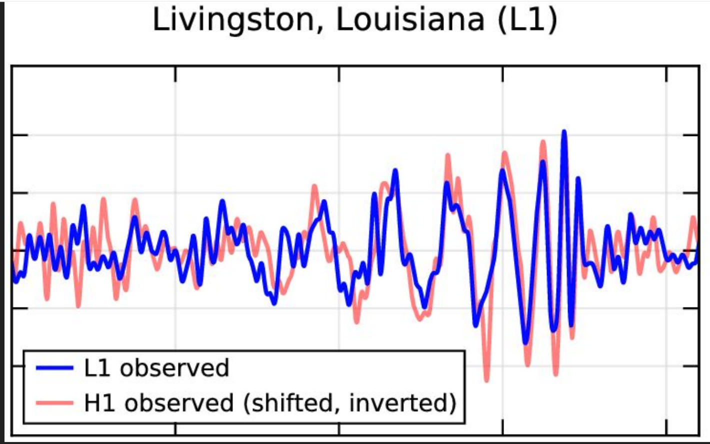
Diagram of a compact binary coalescence (LIGO Scientific Collaboration)

GW150914: first direct detection

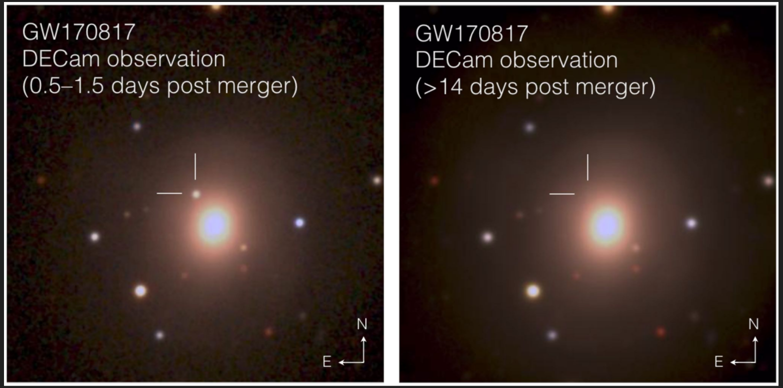


Binary black hole (BBH) coalescence - Sept 2015

"Observation of Gravitational Waves from a Binary Black Hole Merger", LIGO Scientific Collaboration and Virgo Collaboration, 2016



GW170817: first multi-messenger detection



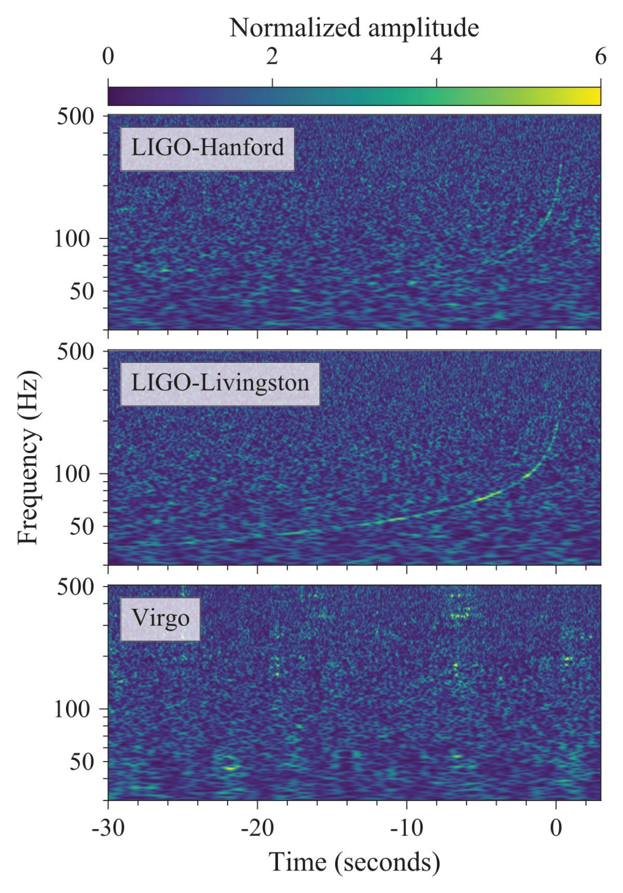


Image credits: DECam, LVK collaborations

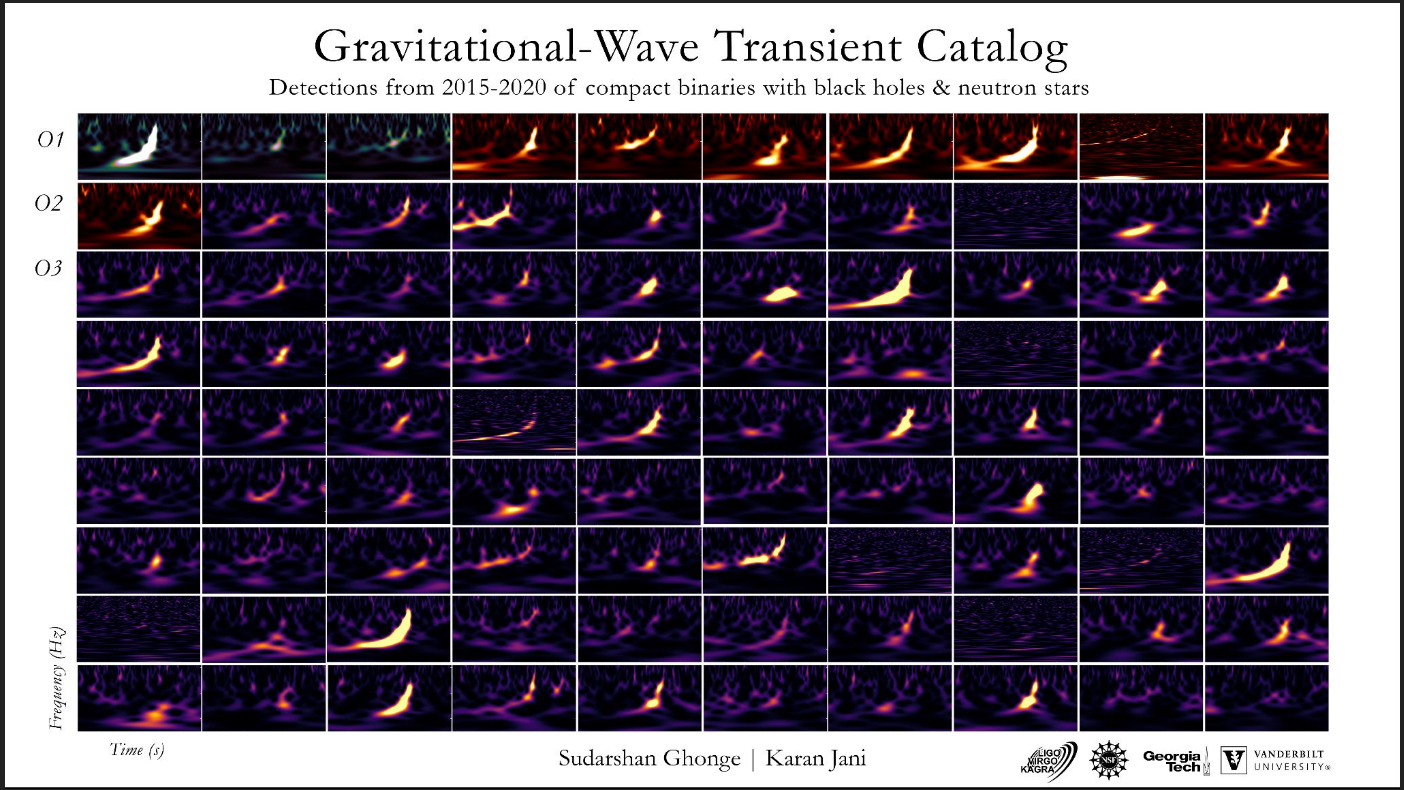
> sources

waves

detectors

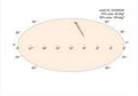
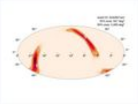
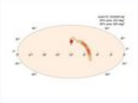
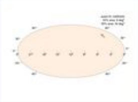
analysis

… and many detections since



… and many detections since

O4 Significant Detection Candidates: **112** (127 Total - 15 Retracted)

S240622h	BBH (99%), Terrestrial (1%)	Yes	June 22, 2024 00:40:08 UTC	GCN Circular Query Notices | VOE		1 per 2.6326 years
S240621em	BBH (96%), Terrestrial (4%)	Yes	June 21, 2024 21:40:41 UTC	GCN Circular Query Notices | VOE		2.1306 per year
S240621eb	BBH (>99%)	Yes	June 21, 2024 20:09:35 UTC	GCN Circular Query Notices | VOE		1.3595 per year
S240621dy	BBH (>99%)	Yes	June 21, 2024 19:50:59 UTC	GCN Circular Query Notices | VOE		1 per 7.9146e+11 years
S240618ah	BBH (96%), Terrestrial (4%)	Yes	June 18, 2024	GCN Circular Query		2.0533 per year

https://gracedb.ligo.org/superevents/public/O4/ public LVK alerts page

But wait! That’s not all!

Remember the criteria for a system that emits gravitational waves:

- Fast
- Massive
- Compact
- Non-axisymmetric

Are inspirals really the only thing that fit these criteria?

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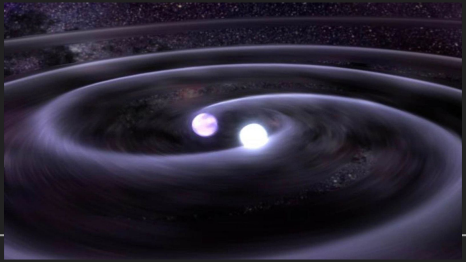
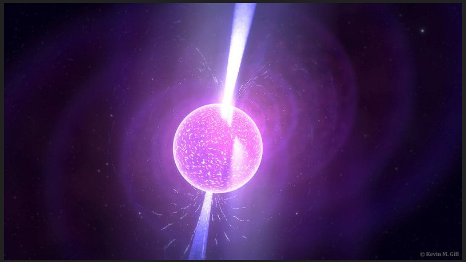
… many others

LIGO searches for many other types of signals

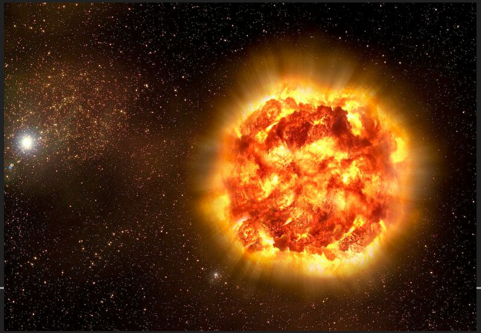
Compact binary coalescence (CBC)



Continuous wave (CW)



Burst



Stochastic background

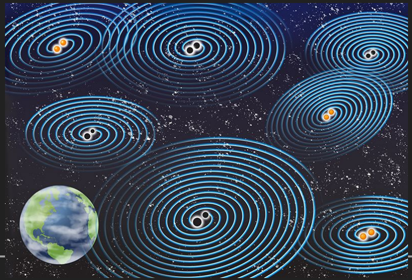


Image credits: NASA/CXC/GSFC/T.Strohmayer; Kevin Gill; European Southern Observatory; APS/Carin Cain

… and LIGO is searching just one part of the GW spectrum

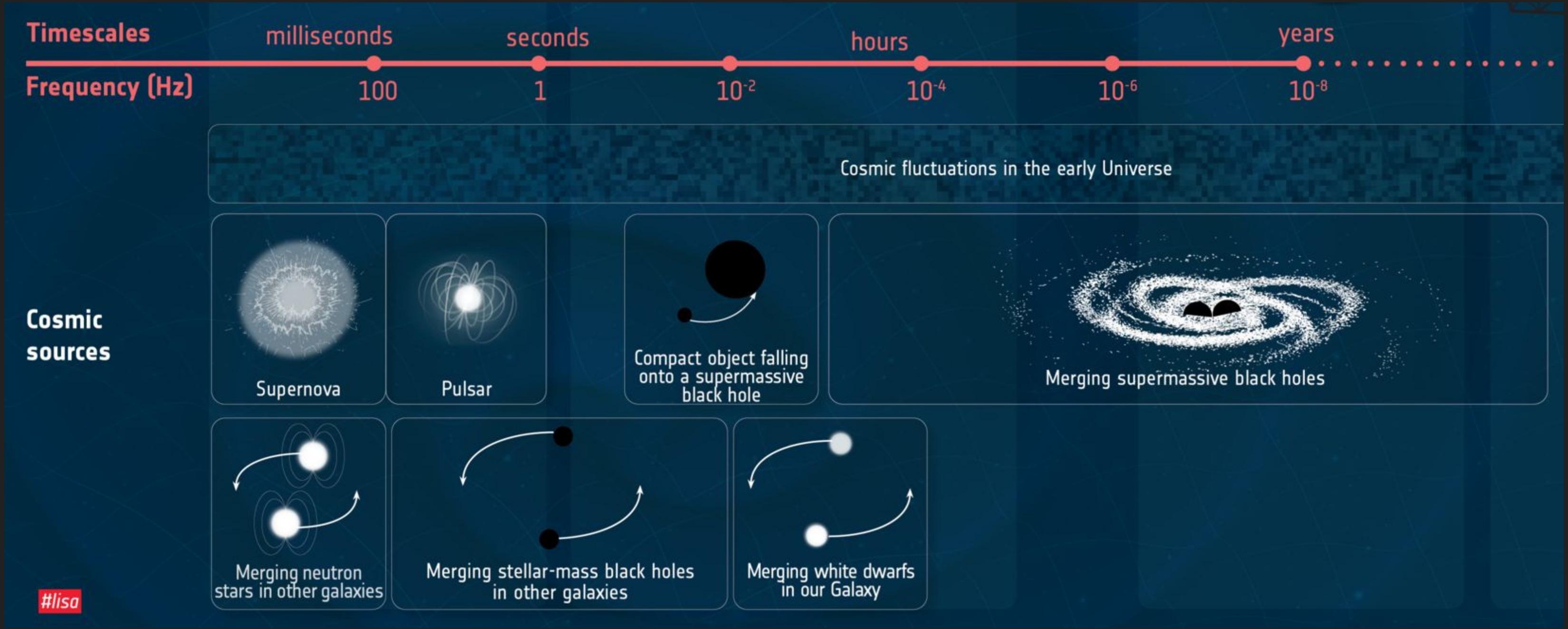
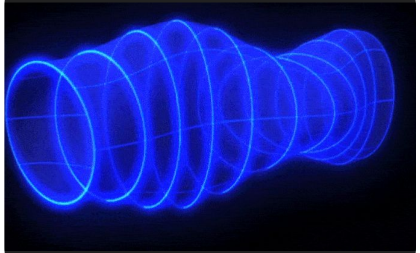


Image credit: ESA

sources → waves → detectors → analysis



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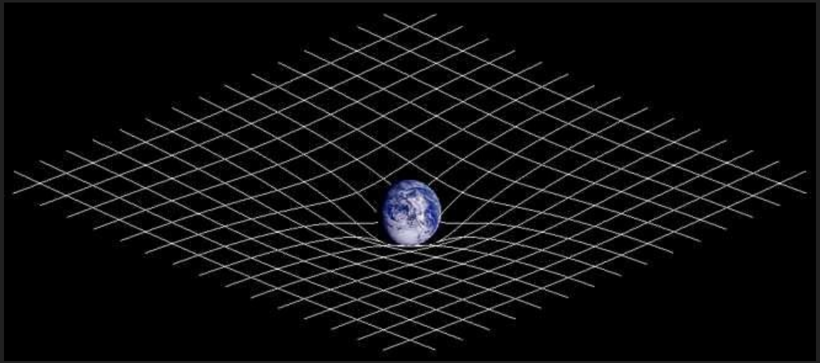
General relativity concepts



Spacetime curvature is described by a 4-dimensional (x, y, z, t) tensor called the **metric**

Image credit: NASA

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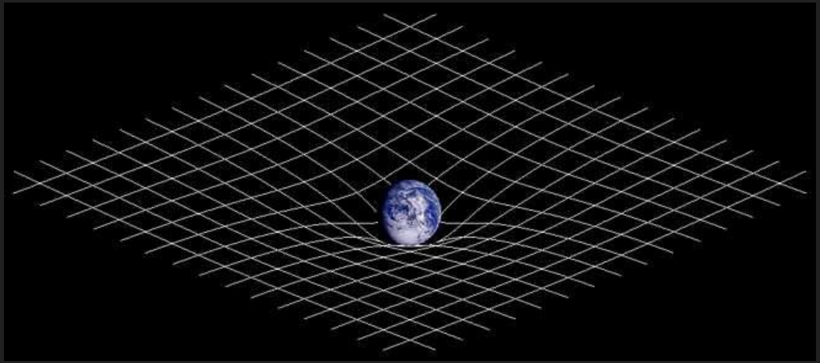
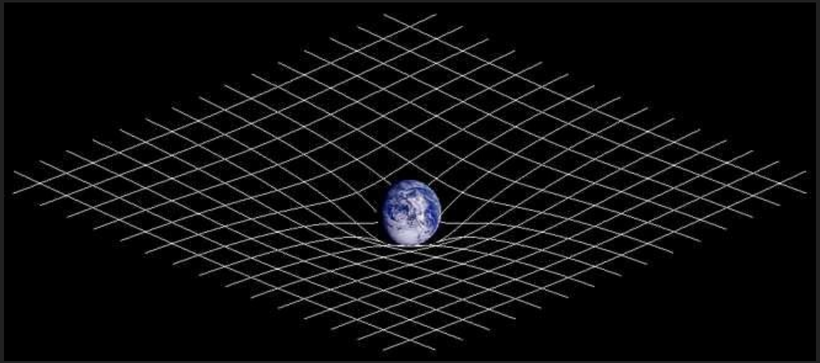


Spacetime curvature is described by a 4-dimensional *(x, y, z, t)* tensor called the **metric**

What does the word “metric” mean?

Image credit: NASA

General relativity concepts



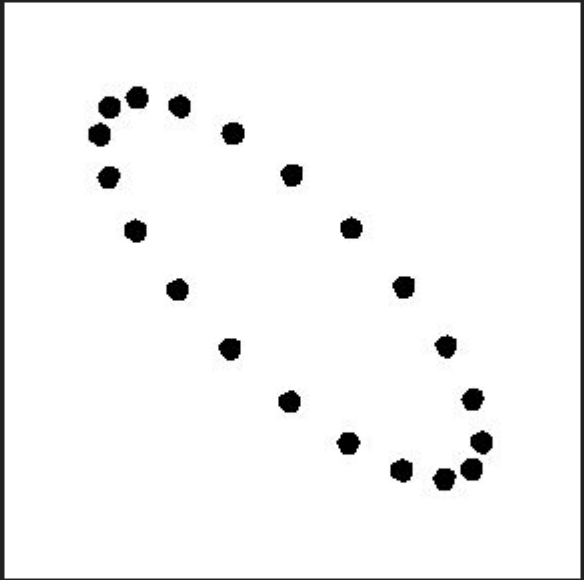
Spacetime curvature is described by a 4-dimensional (x, y, z, t) tensor called the **metric**

A “metric” generally defines the distance between points. In this case, the “distance” is actually the “spacetime interval” which also involves time.

spacetime curvature ~ separation between points

Image credit: NASA

What does a gravitational wave do?



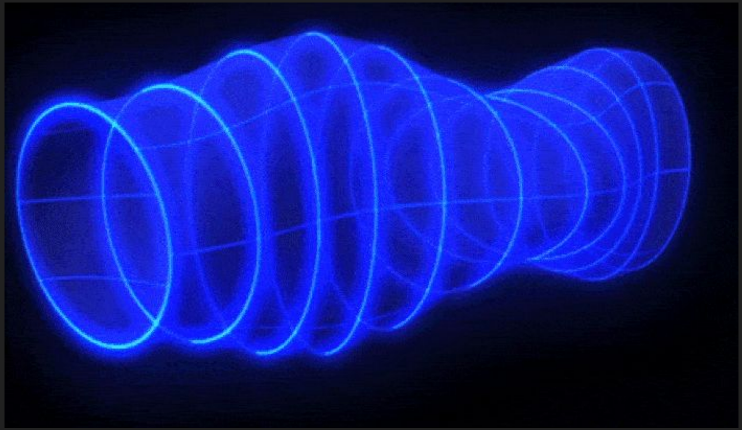


Image credit: wikipedia user MOBle; ESA

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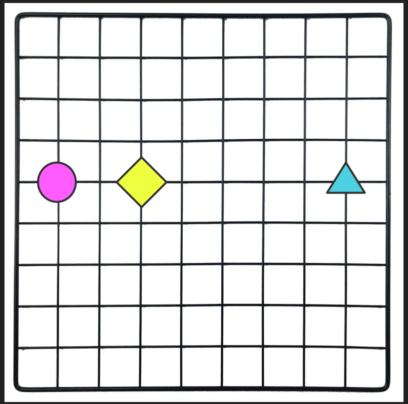

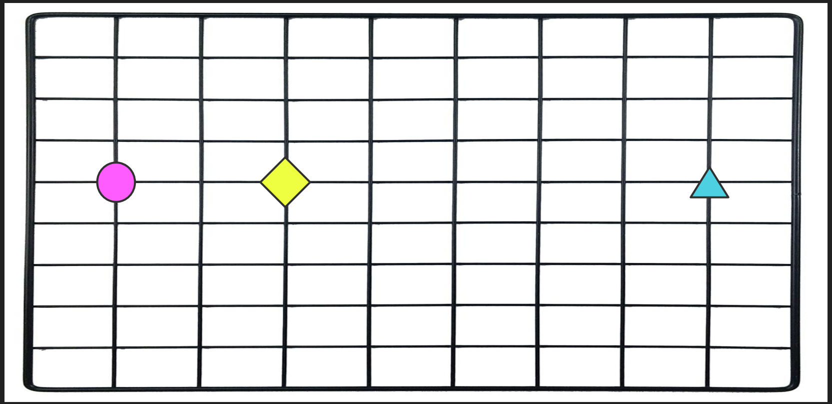

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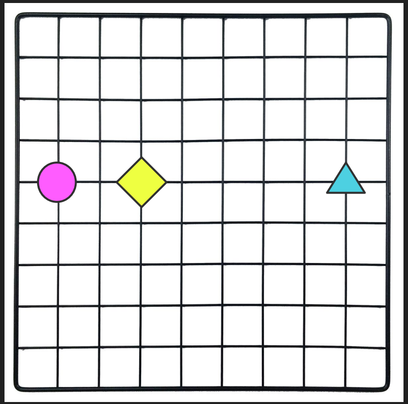

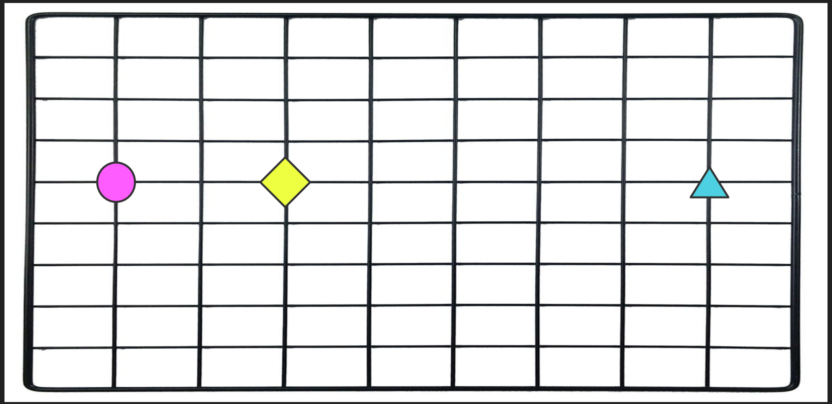

“strain”: $h = \Delta L / L$

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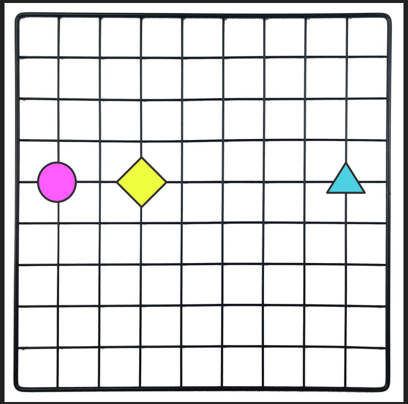

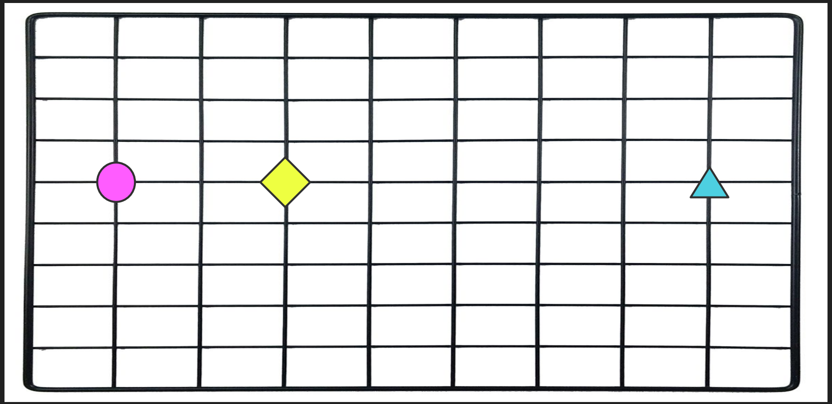

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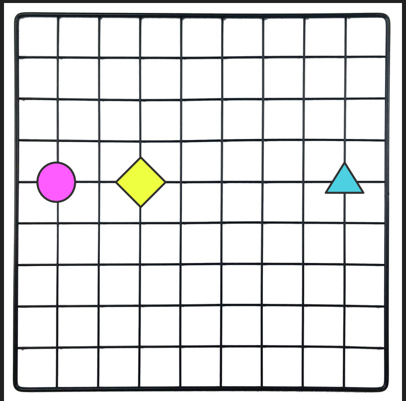
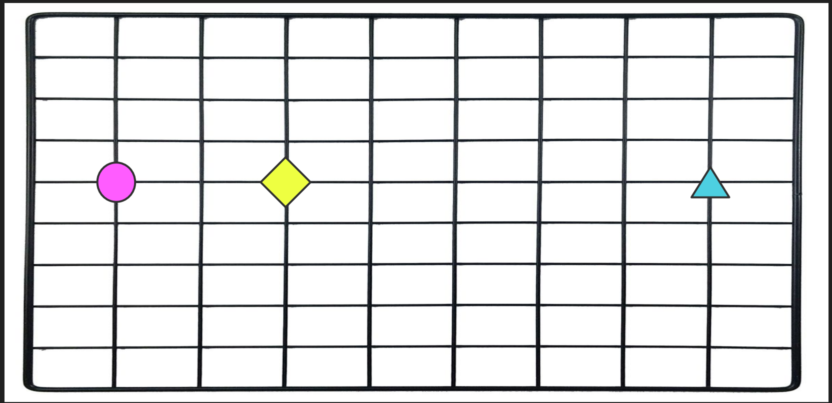
$h_{●◆}$ vs $h_{●▲}$?

$\Delta L_{●◆}$ vs $\Delta L_{●▲}$?

What does a gravitational wave do?





“strain”: $h = \Delta L / L$

$$h_{\bullet\blacklozenge} = h_{\bullet\blacktriangle}$$

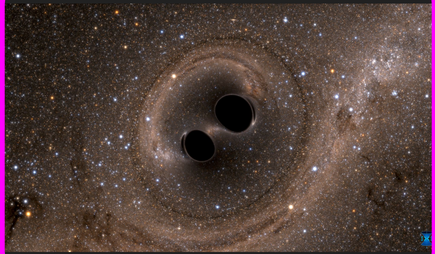
$$\Delta L_{\bullet\blacklozenge} < \Delta L_{\bullet\blacktriangle}$$

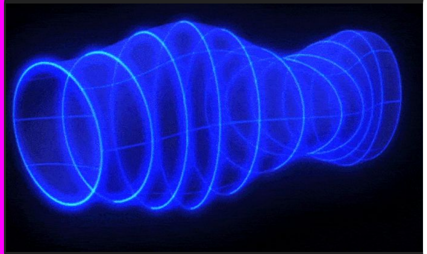
Spacetime does not bend easily

- It's possible to calculate an effective "stiffness" for spacetime (frequency dependent). At 100 Hz it's about 10^{20} times more stiff than steel.
  (http://kirkmcd.princeton.edu/examples/stiffness.pdf)

- GW150914, for example, released 3 solar masses of energy in the form of gravitational waves, in a fraction of a second - yet it was only observed with a strain amplitude of about 10^{-21} !

sources → waves → detectors → analysis





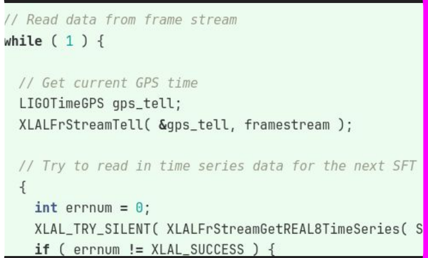


Image credits: SXS collaboration; wikimedia commons; LIGO laboratory; LIGO algorithms library (LALsuite)

Interferometry

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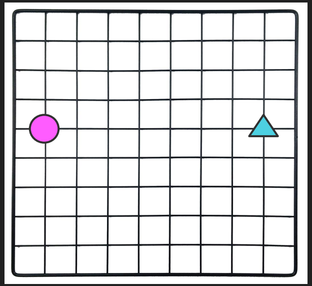

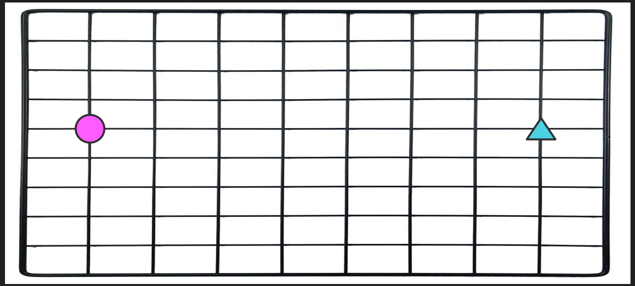

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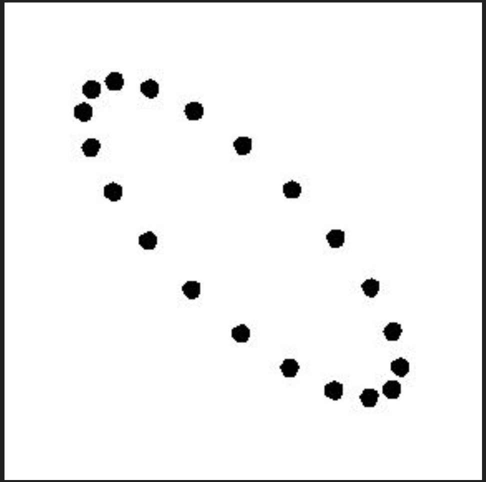
$h(t)$



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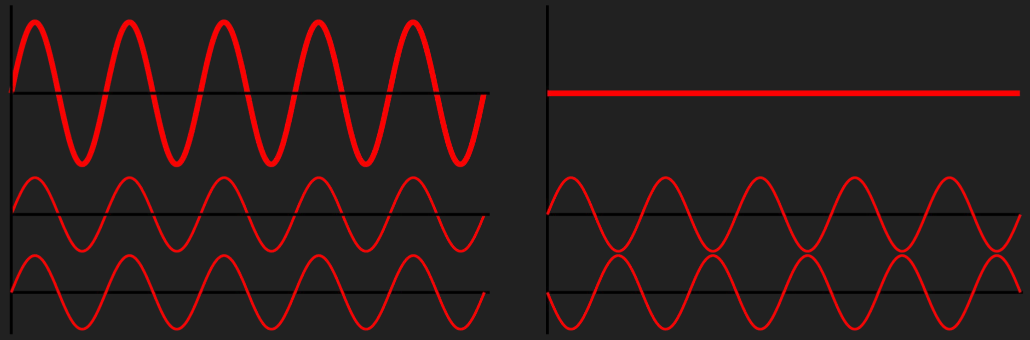

Image credit: wikipedia users Haade and Quibik

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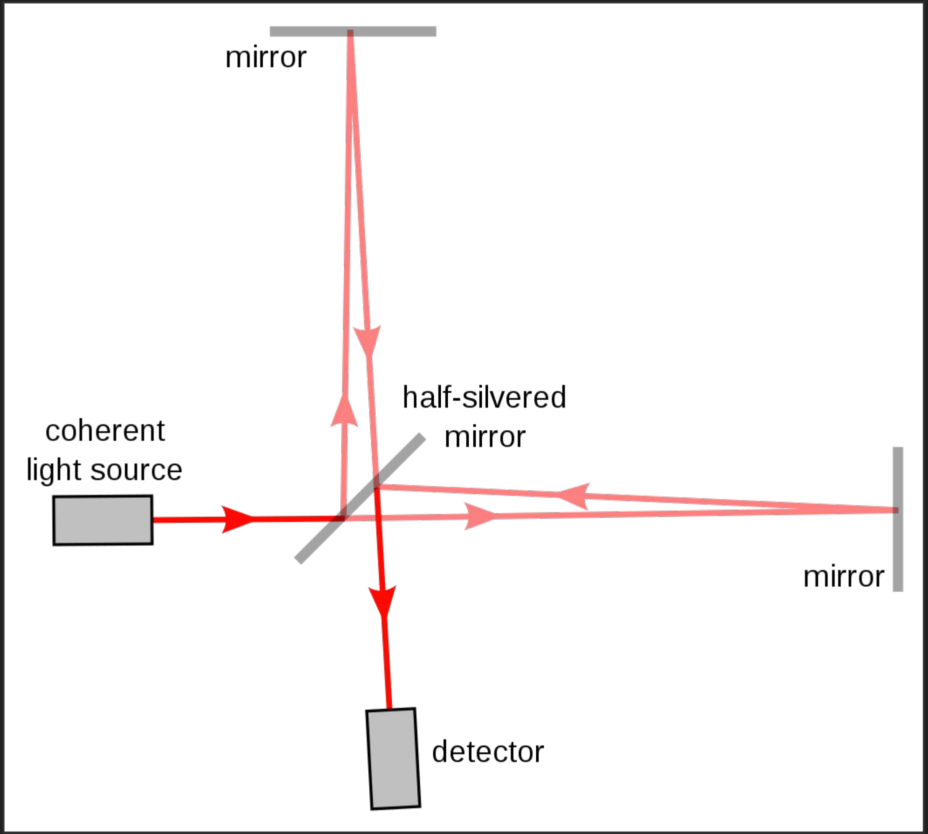

Image credit: wikipedia user Stannerd

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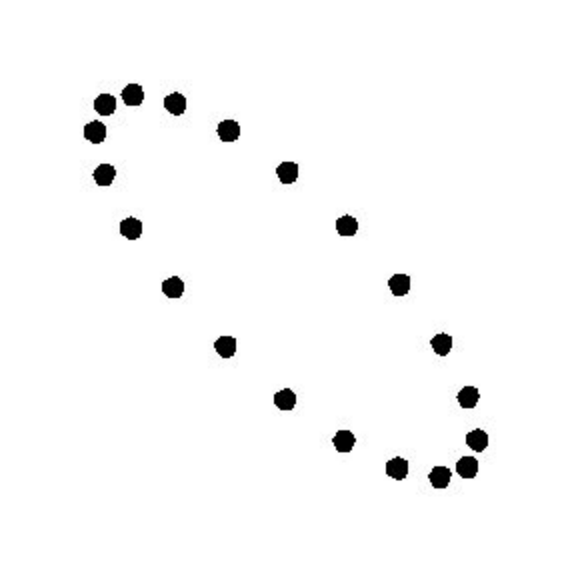
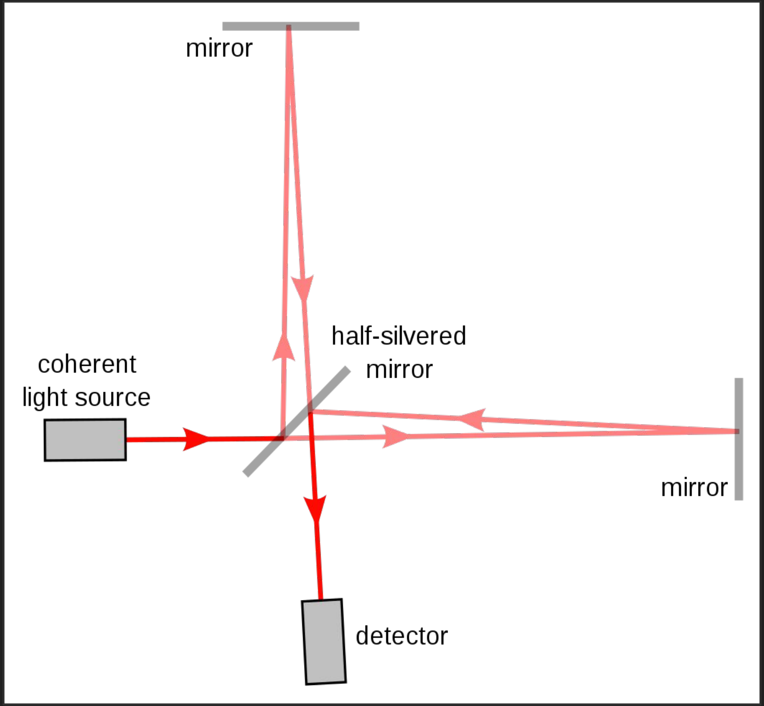
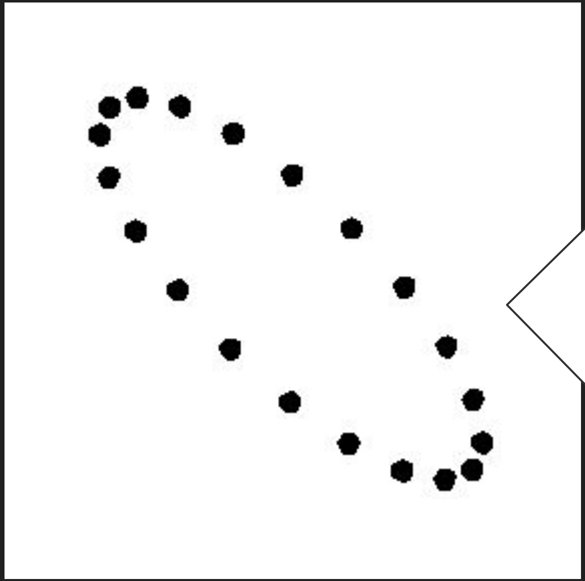
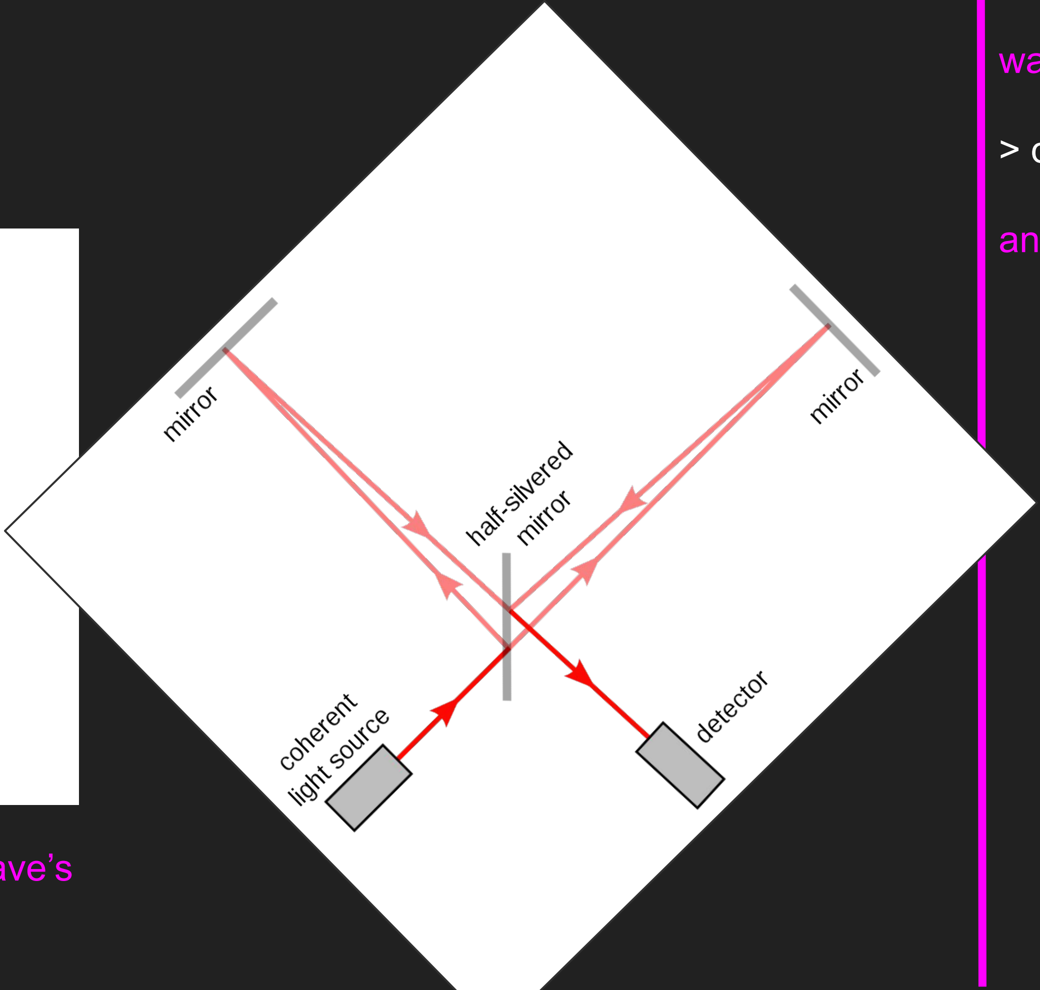




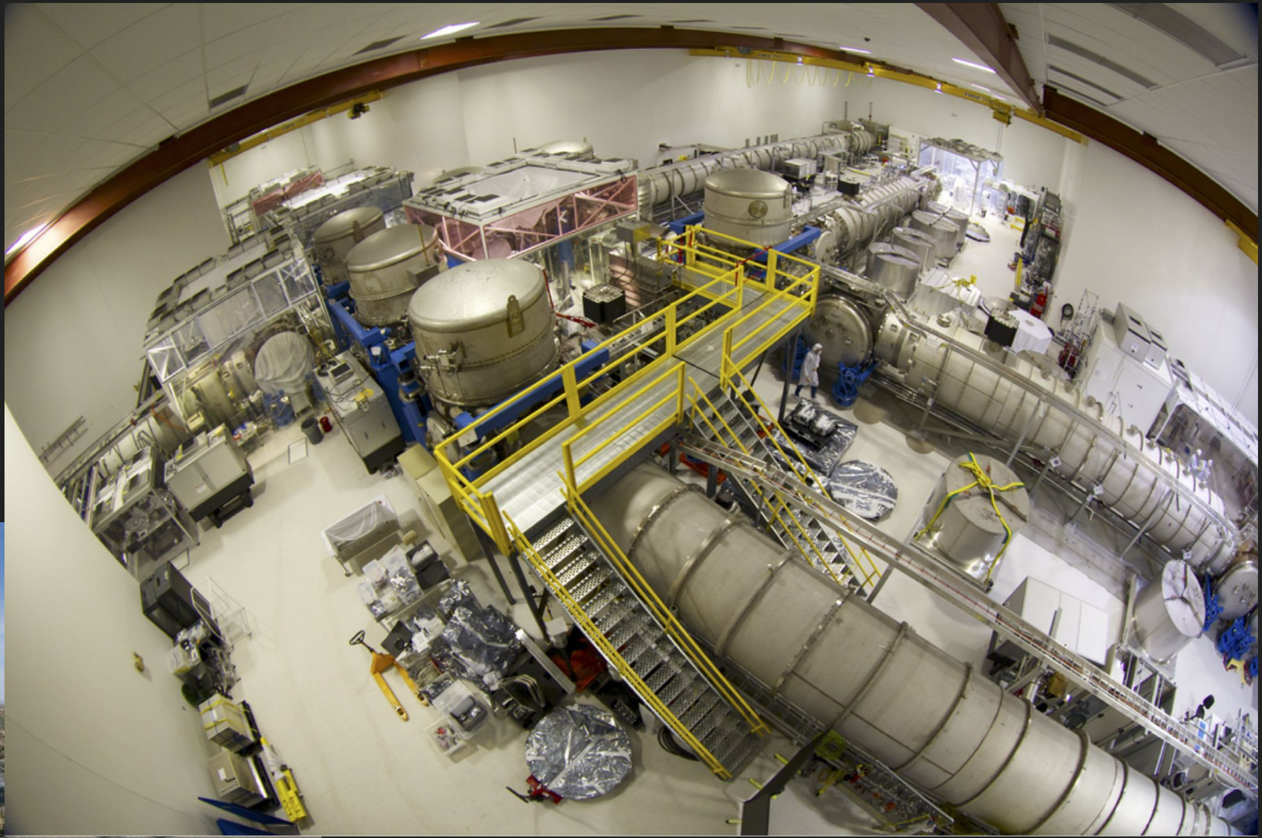
Interferometry





Detector response depends on the wave's polarization (+ or x)

LIGO



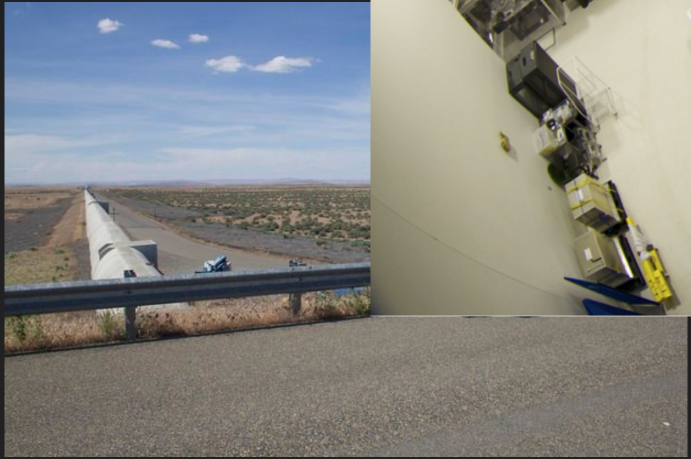


Image credit: LSC

See more on the tour!

LIGO

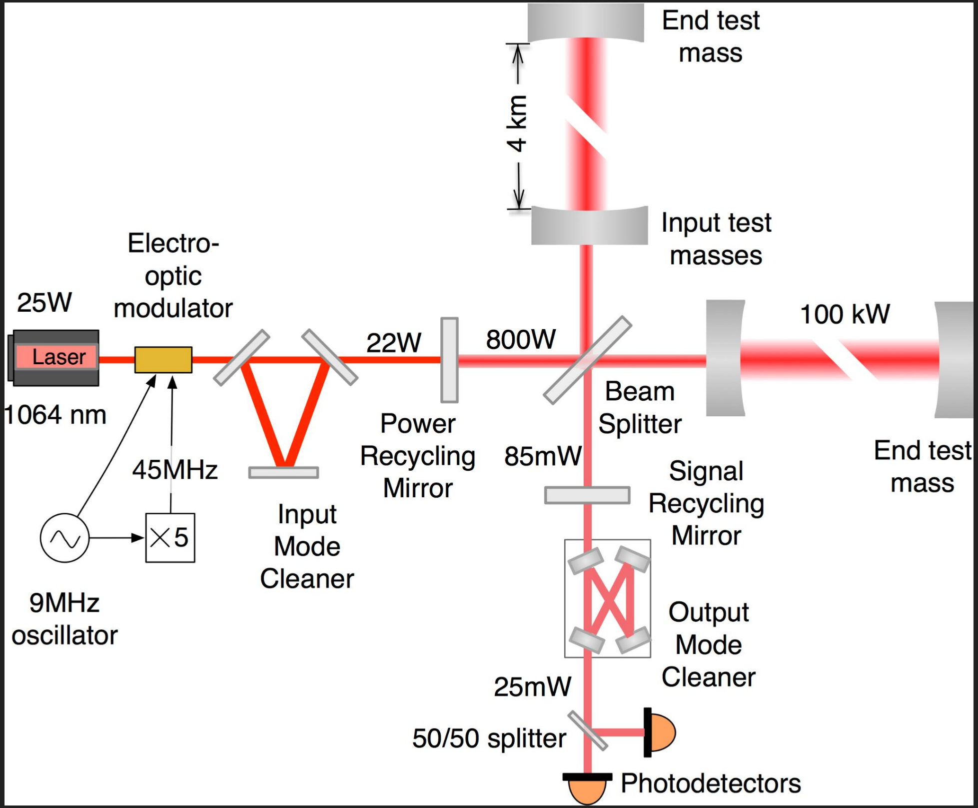


Image credit: LSC

LIGO

How much are the mirrors moving?

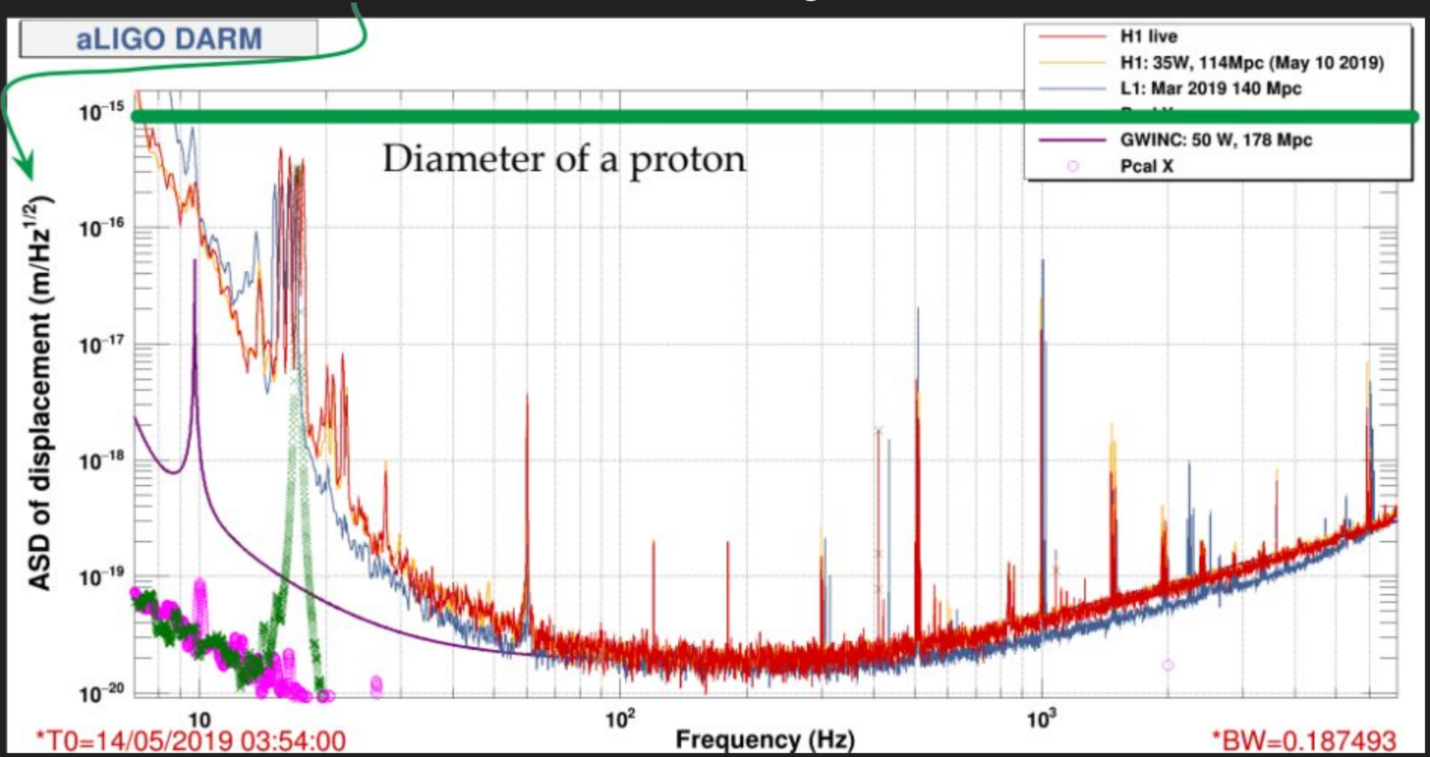


Image credit: LIGO / Jenne Driggers

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LIGO Hanford site - regional context

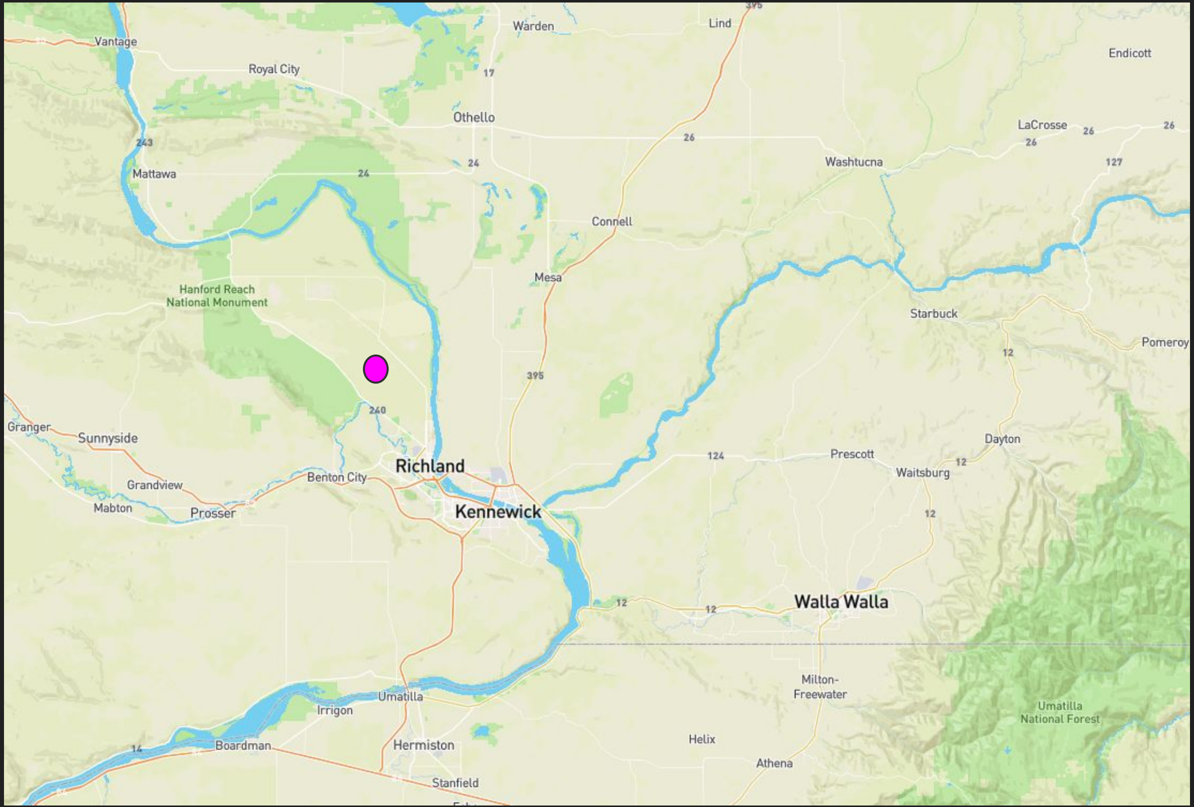

Image credit: https://native-land.ca/

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LIGO Hanford site - regional context

Image credit: https://native-land.ca/

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LIGO Hanford site - regional context

Traditional inhabitants and caretakers of this land include the Walla Walla, Umatilla, Yakama, Wanapum, Cayuse, Palouse and Nez Perce.

- https://www.yakama.com/about/
- https://nezperce.org/about/
- https://ctuir.org/about/
- https://wanapum.org/about/

LIGO Hanford is located on the Hanford nuclear site, which was acquired by the federal government in 1943 under the Second War Powers act for use by the Manhattan project. Plutonium from the site was used in the bombing of Nagasaki in 1945.

Image credit: Atomic Heritage Foundation

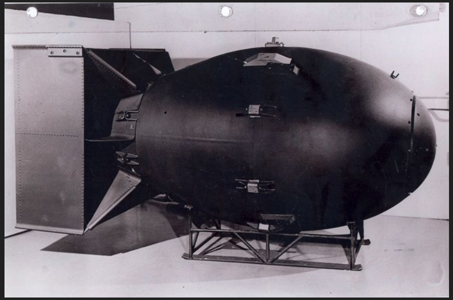

Image credit: U.S. National Archives, RG 77-AEC

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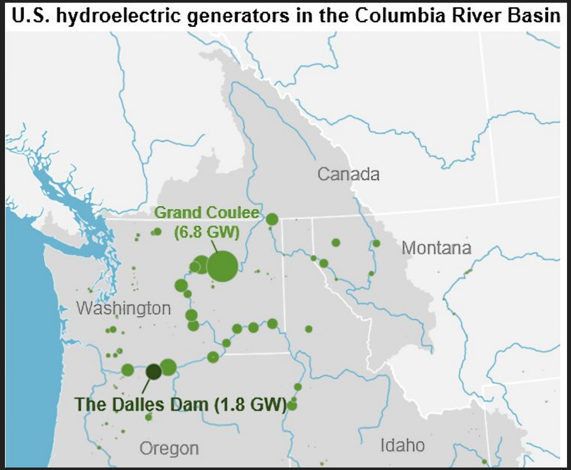
LIGO Hanford site - regional context

LHO energy usage: about ~80% hydroelectric, ~10% nuclear, and ~5% wind



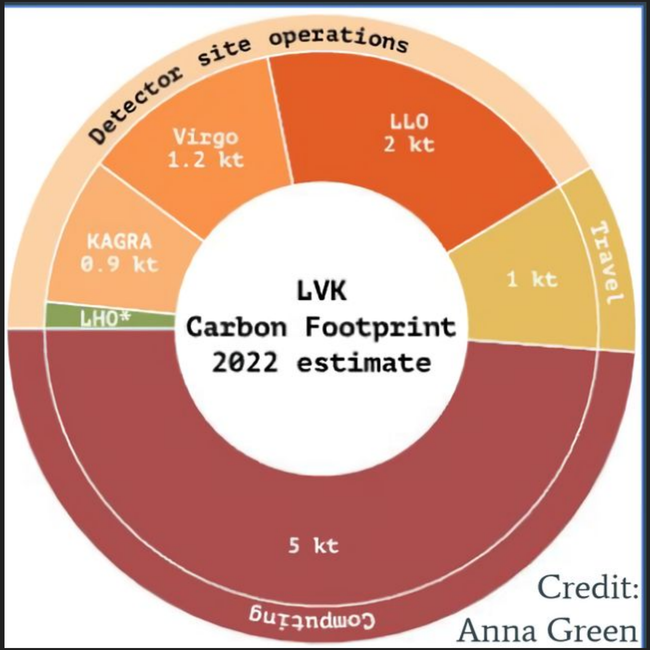


Image credits:
https://www.eia.gov/todayinenergy/detail.php?id=37152; LIGO magazine issue 22

LIGO Hanford site - regional context

LHO energy usage: about ~80% hydroelectric, ~10% nuclear, and ~5% wind

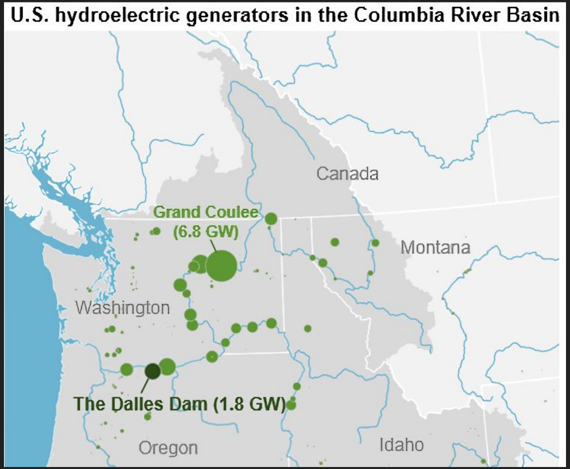


Image credit: https://native-land.ca/

Global context - LIGO, Virgo, KAGRA

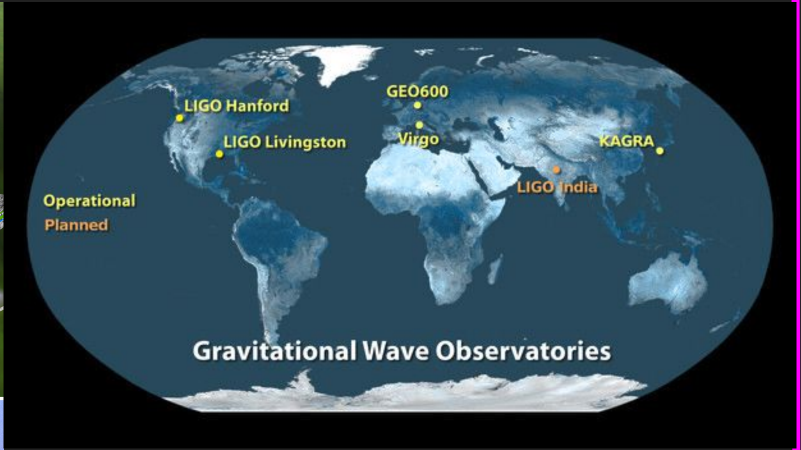


Image credits: LIGO-Virgo-KAGRA

LVK observing runs

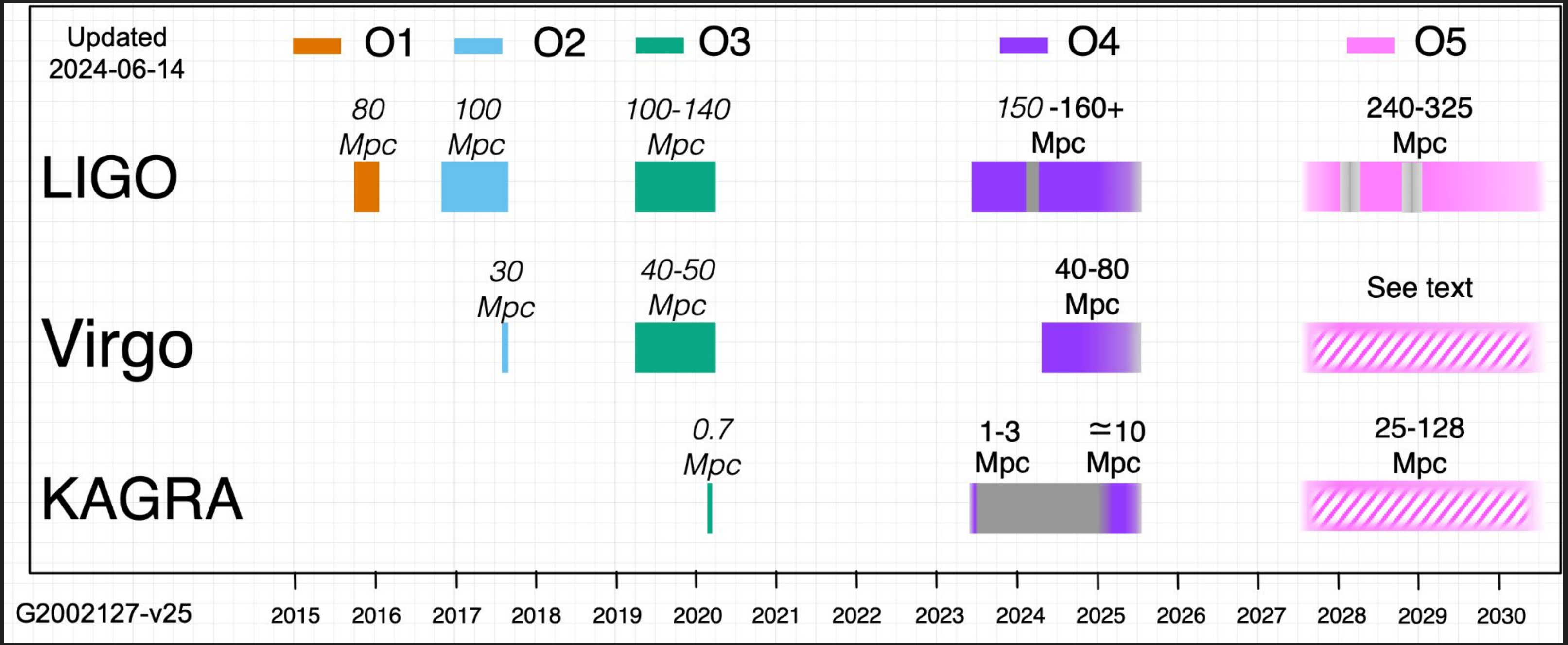
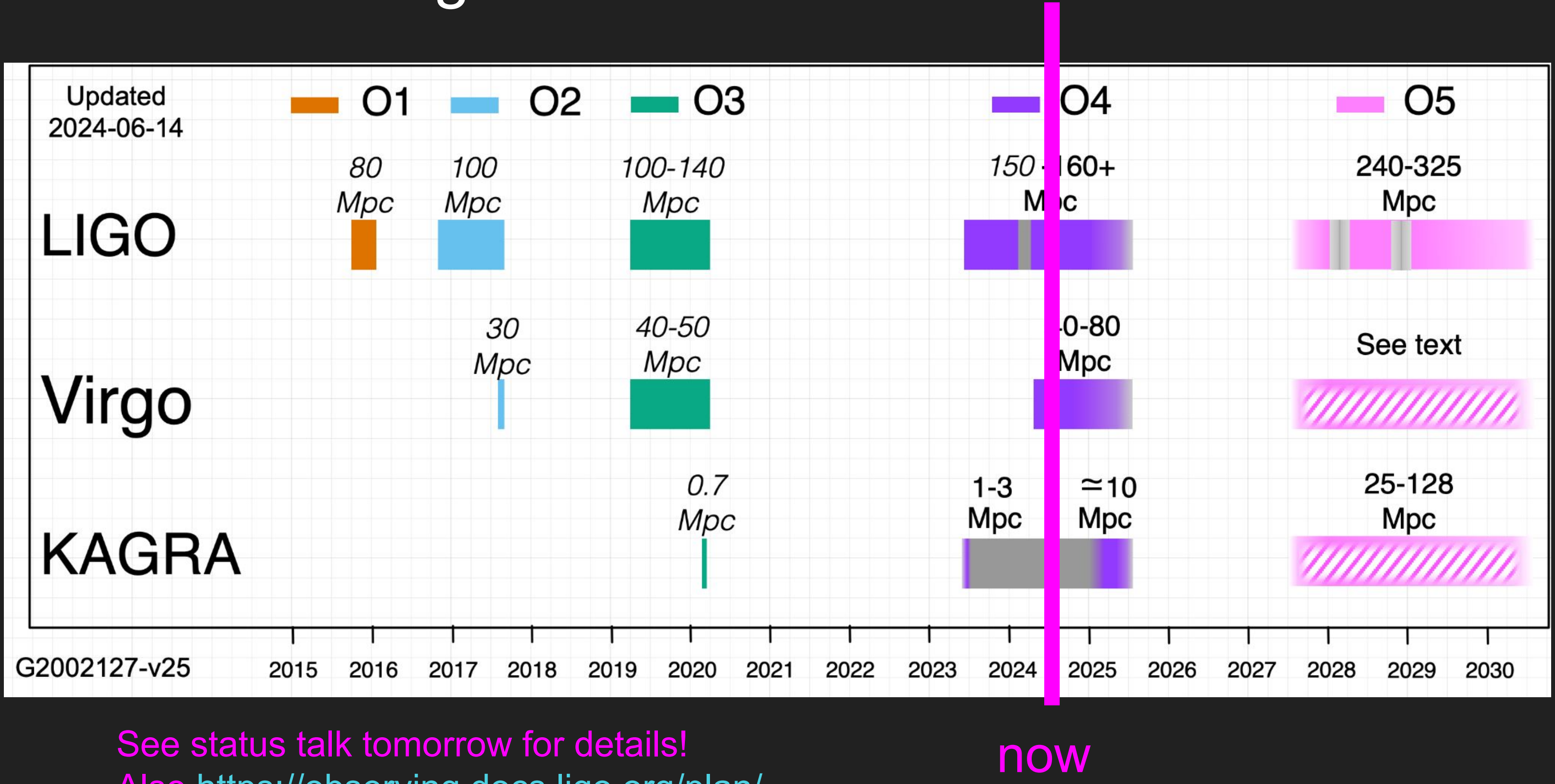


Image credit: LSC

LVK observing runs



See status talk tomorrow for details!
Also https://observing.docs.ligo.org/plan/

Image credit: LSC

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Interferometry in space

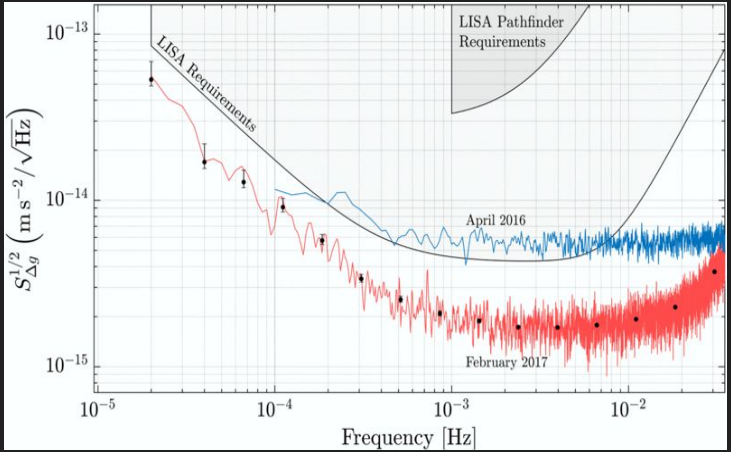


Image credit: Armano et al 2018, PRL "Beyond the Required LISA Free-Fall Performance"

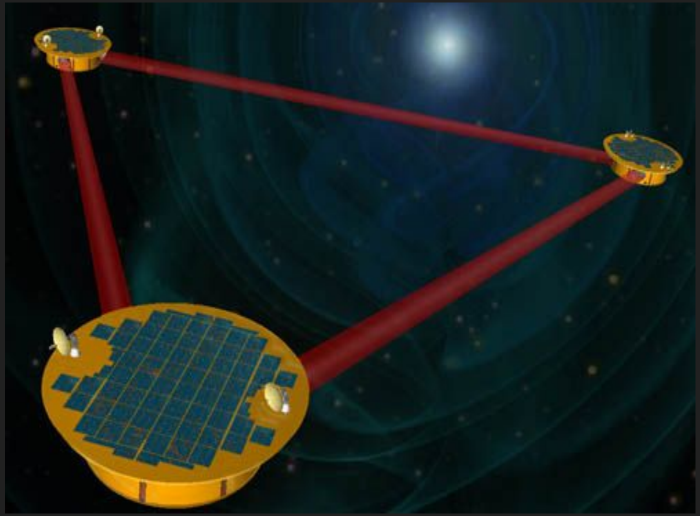
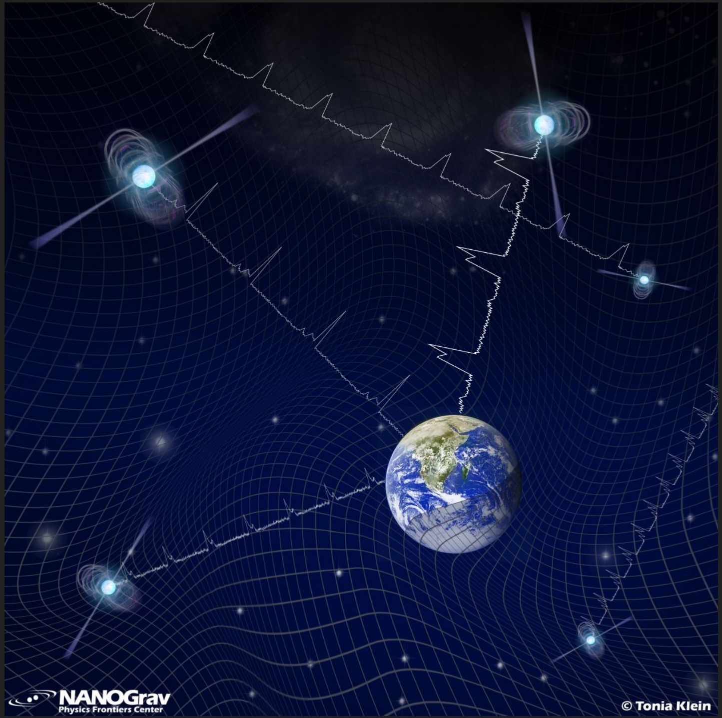


Image credit: NASA / LISA project

Pulsar timing arrays (NANOGrav, EPTA, PPTA, …)

Images: Green Bank Telescope, Very Large Array, Arecibo Observatory, Canadian Hydrogen Intensity Mapping Experiment - https://nanograv.org/science/telescopes



Pulsar timing arrays (NANOGrav, EPTA, PPTA, …)

“The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background” (2023)

“We report multiple lines of evidence for a stochastic signal that is correlated among 67 pulsars from the 15 yr pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. The correlations follow the Hellings-Downs pattern expected for a stochastic gravitational-wave background.”

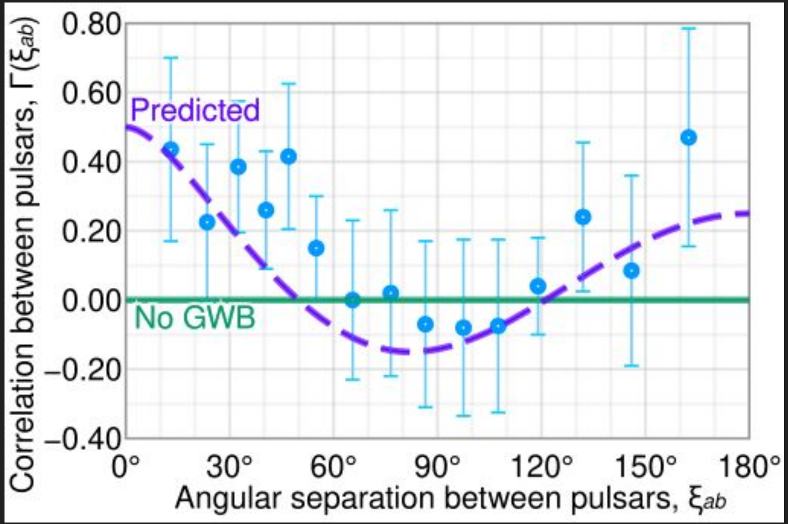
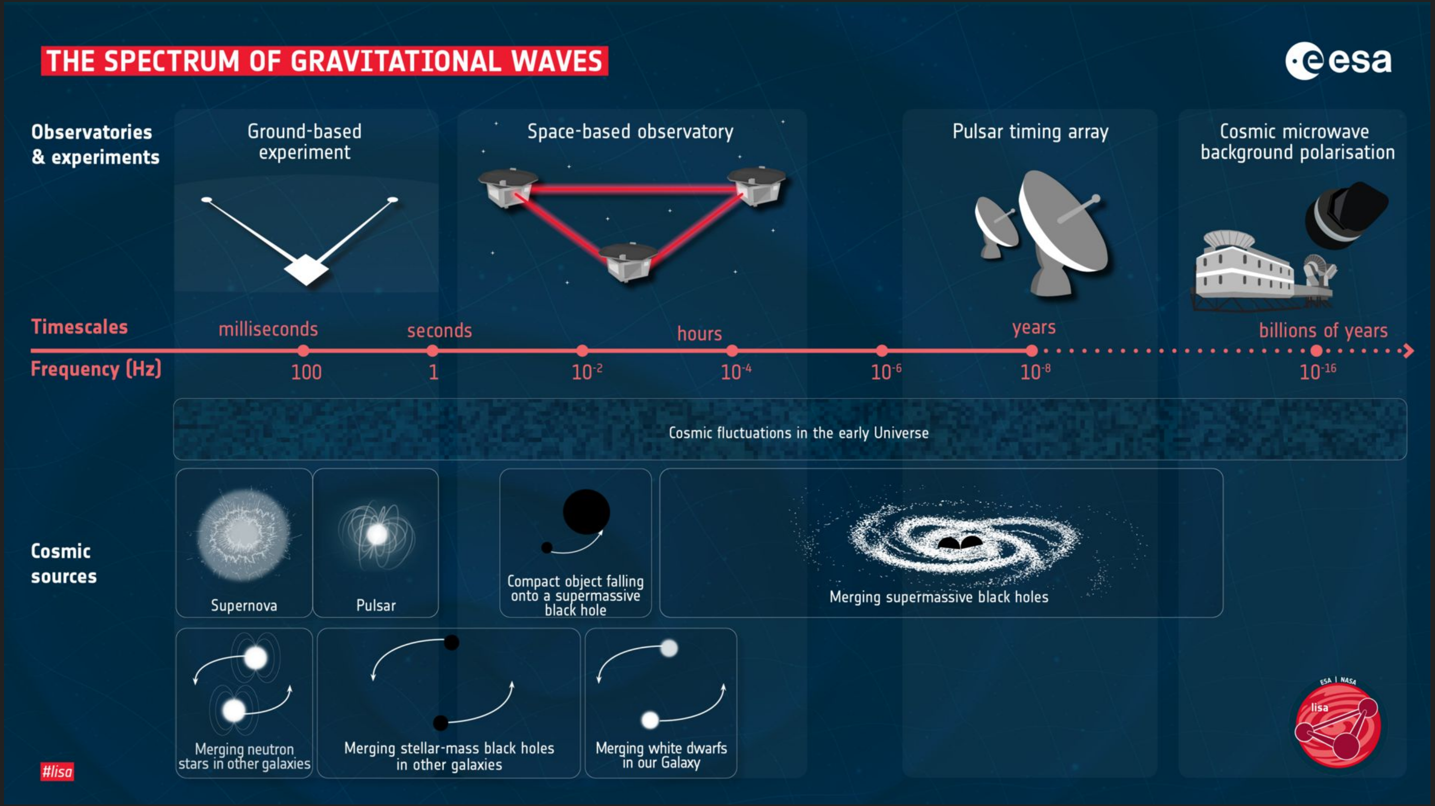


Image credit: NANOGrav Collaboration, CMG Lee

The gravitational wave spectrum



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The gravitational wave spectrum

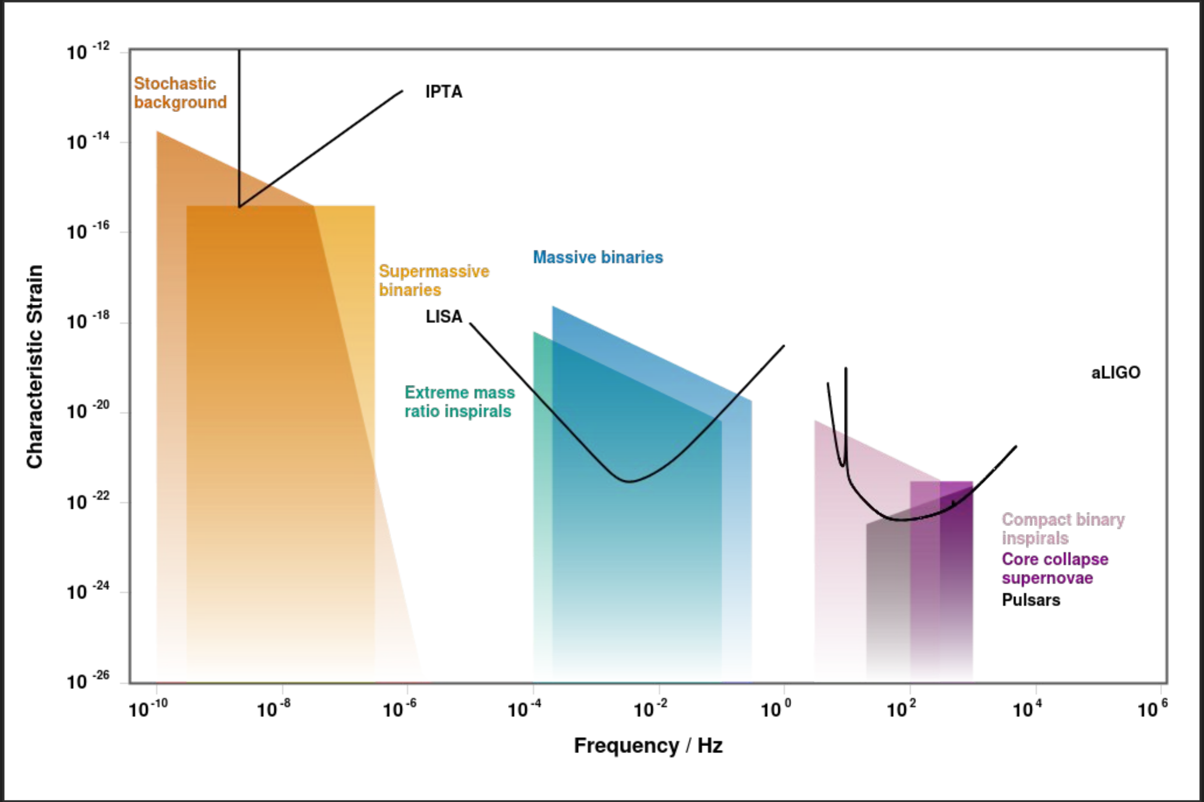
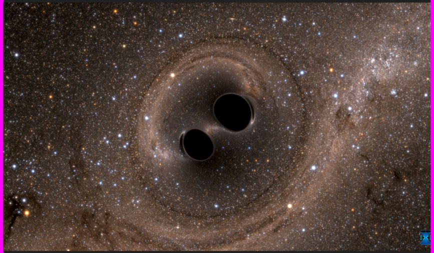
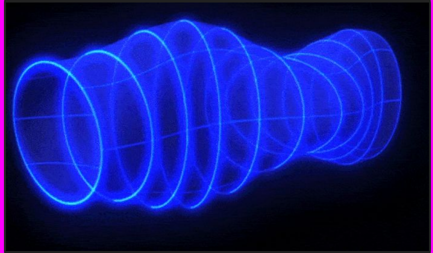


Image credit: http://gwplotter.com/ (C. Moore and C. Berry)

sources → waves → detectors → analysis





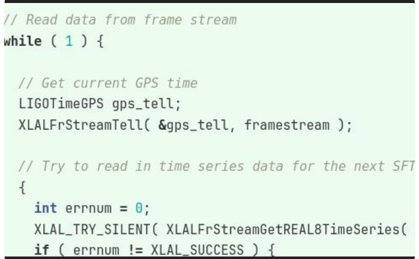


Image credits: SXS collaboration; wikimedia commons; LIGO laboratory; LIGO algorithms library (LALsuite)

What does GW data analysis need to do?

What does GW data analysis need to do?

- Find very weak signals
- Distinguish between signals and noise artifacts
- Rapidly alert EM observers when there's a chance of a multi-messenger detection
- Estimate source parameters (including sky location)
- Set upper limits when no signals are detected
- Regularly validate that detectors and search pipelines are working as intended
- Investigate the causes of noise artifacts or other problems
- … and more

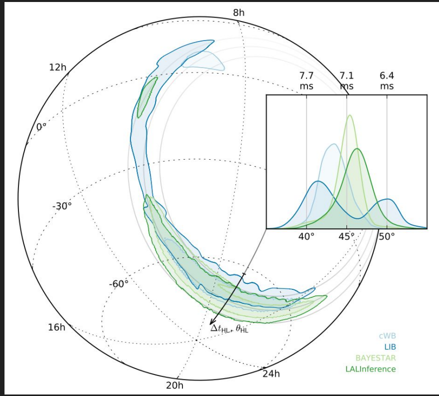
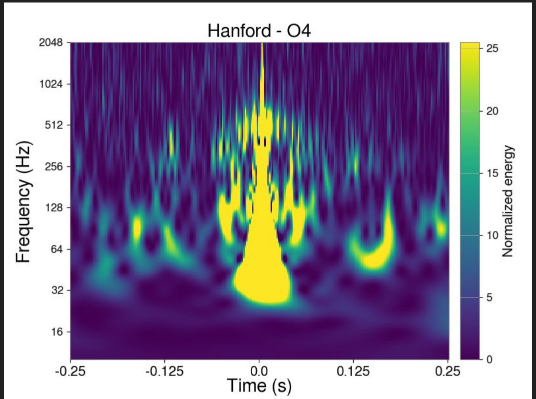


Image credits: GWOSC (left), GravitySpy (bottom)



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What does (LIGO) GW data analysis need to do?

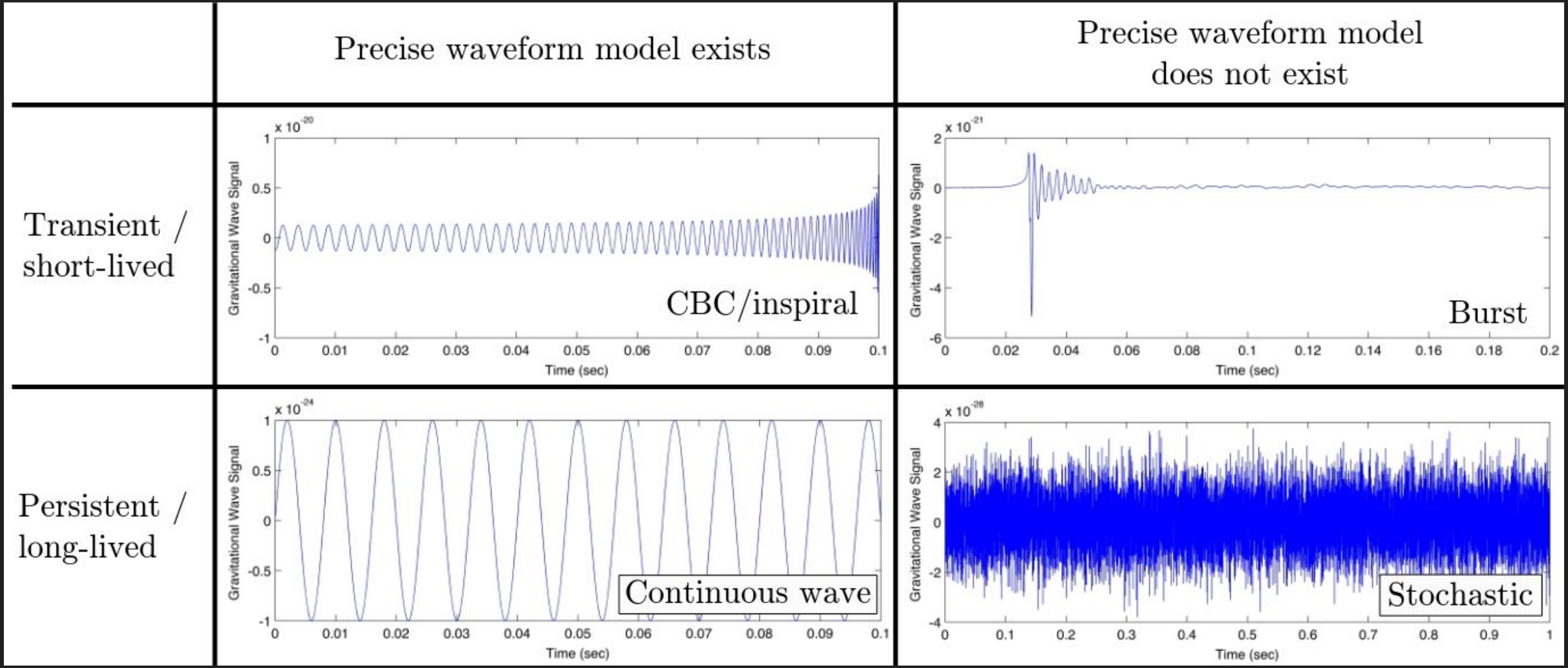


Image credits: A. Stuver / LIGO

And it's not just h(t)!

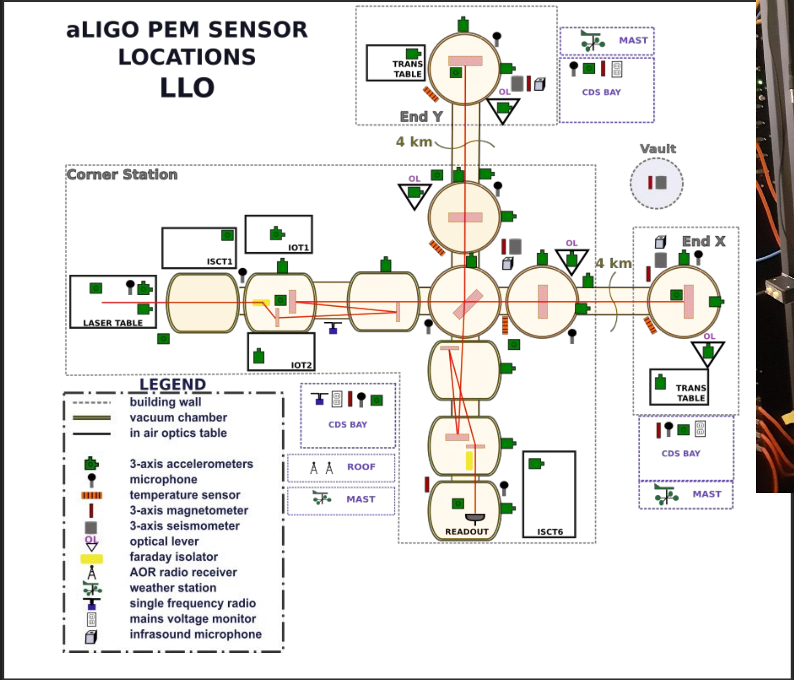
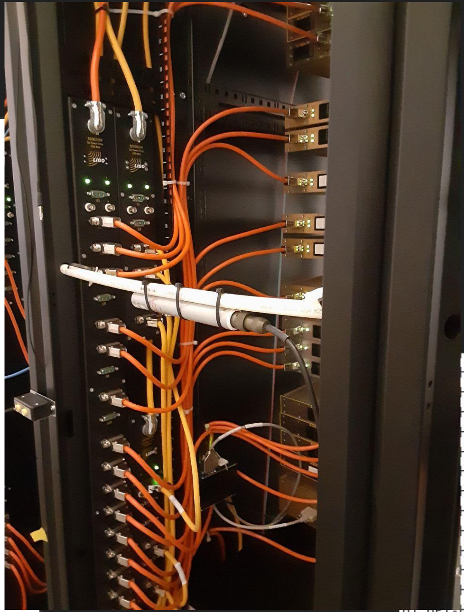


Image credit: pem.ligo.org



HAM6_BLND_L4C_HP_IN1_DQ 1024 safe clean
HAM6_BLND_L4C_RX_IN1_DQ 1024 safe clean
HAM6_BLND_L4C_RY_IN1_DQ 1024 safe clean
HAM6_BLND_L4C_RZ_IN1_DQ 1024 safe clean
HAM6_BLND_L4C_VP_IN1_DQ 1024 safe clean
HAM6_BLND_L4C_X_IN1_DQ 1024 unsafe clean
HAM6_BLND_L4C_Y_IN1_DQ 1024 safe clean
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H1:HPI-HAM4_BLND_L4C_HP_IN1_DQ 1024 safe clean
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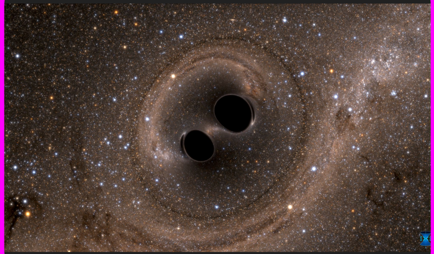
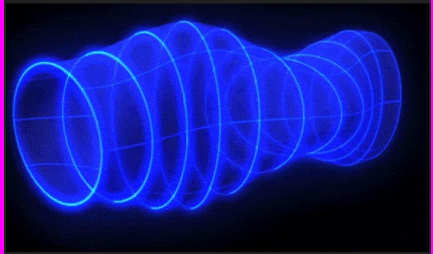
H1:HPI-HAM4_BLND_L4C_RY_IN1_DQ 1024 safe clean
H1:HPI-HAM4_BLND_L4C_RZ_IN1_DQ 1024 safe clean

Thank you!

sources → waves → detectors → analysis





```
// Read data from frame stream
while ( 1 ) {

  // Get current GPS time
  LIGOTimeGPS gps_tell;
  XLALFrStreamTell( &gps_tell, framestream );

  // Try to read in time series data for the next SFT
  {
    int errnum = 0;
    XLAL_TRY_SILENT( XLALFrStreamGetREAL8TimeSeries( S
    if ( errnum != XLAL_SUCCESS ) {
```

Image credits: SXS collaboration; wikimedia commons; LIGO laboratory; LIGO algorithms library (LALsuite)