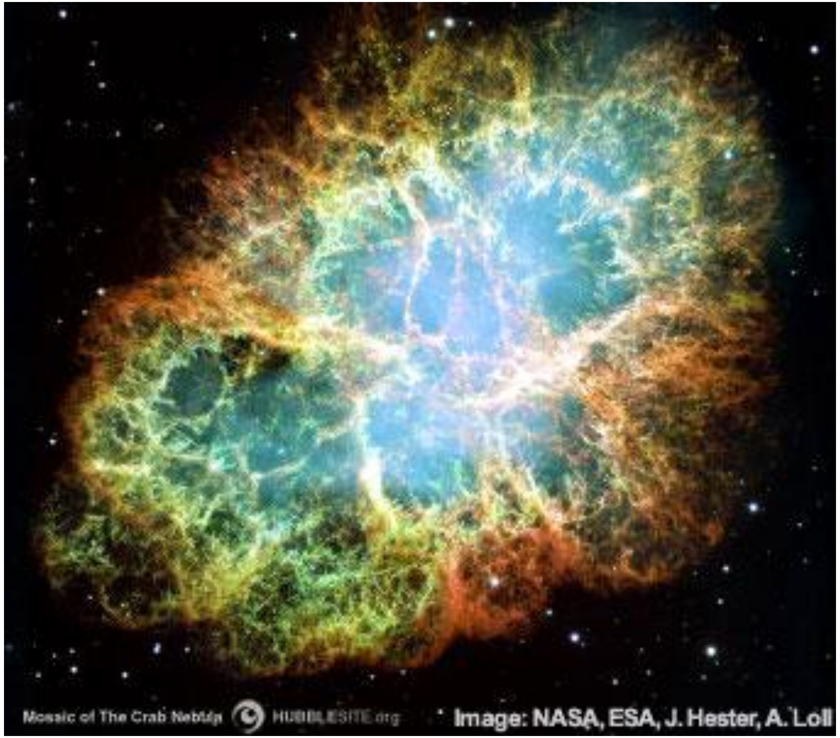
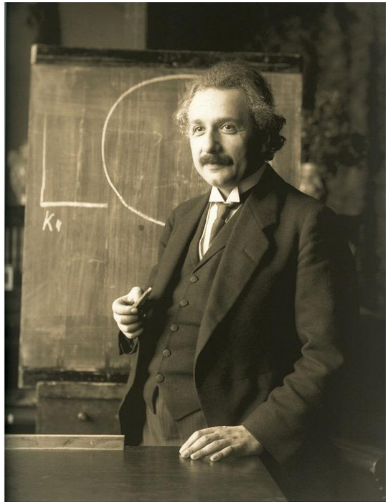
Cosmic Tag Team:

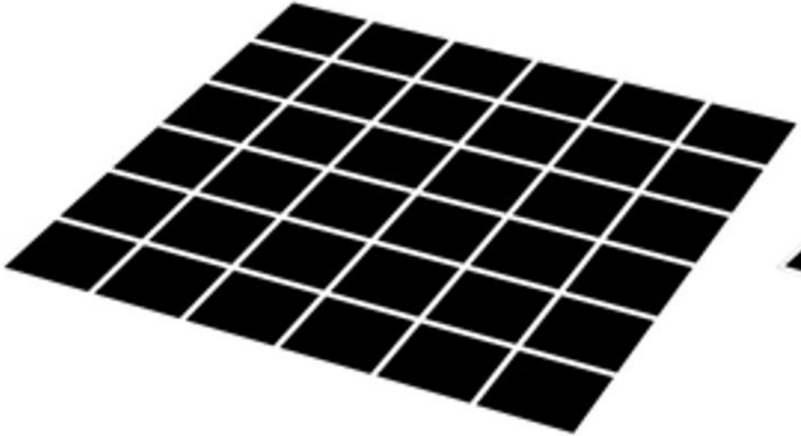
How LIGO and Gravitational Waves
“Wrestle” with the Universe

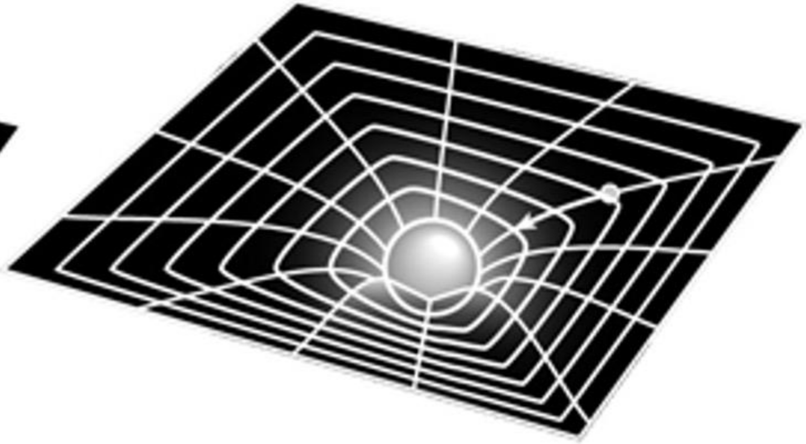

Mosaic of The Crab Nebula
HUBBLESITE.org
Image: NASA, ESA, J. Hester, A. Loll

What are Gravitational Waves?



"Space-time tells matter how to
move; matter tells space-time how to curve."
-Dr. John Wheeler





"**<u>Space-time tells matter how to move</u>**; matter tells space-time how to curve."
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“Space-time tells matter how to move; **matter tells space-time how to curve**.”
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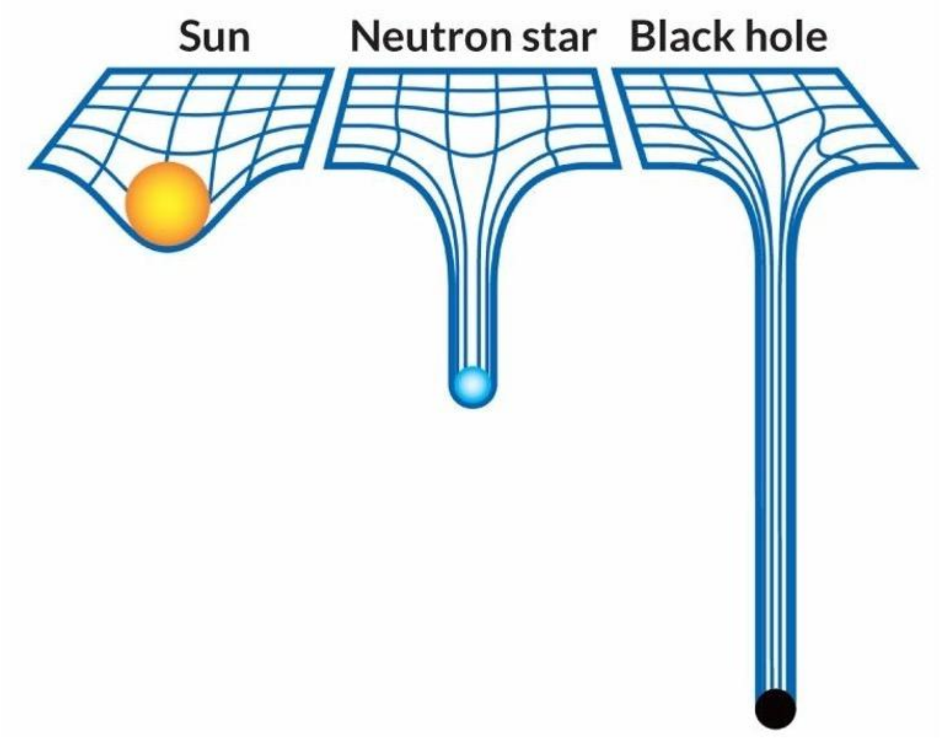
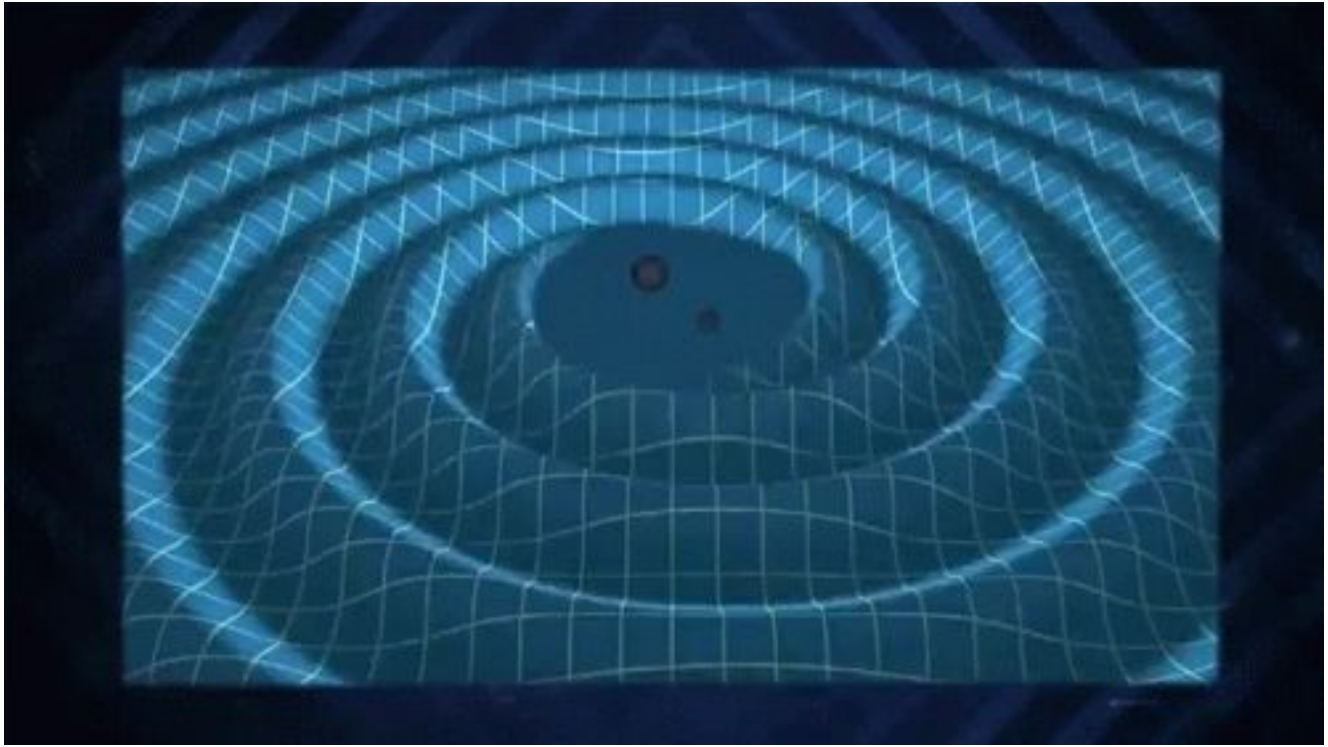
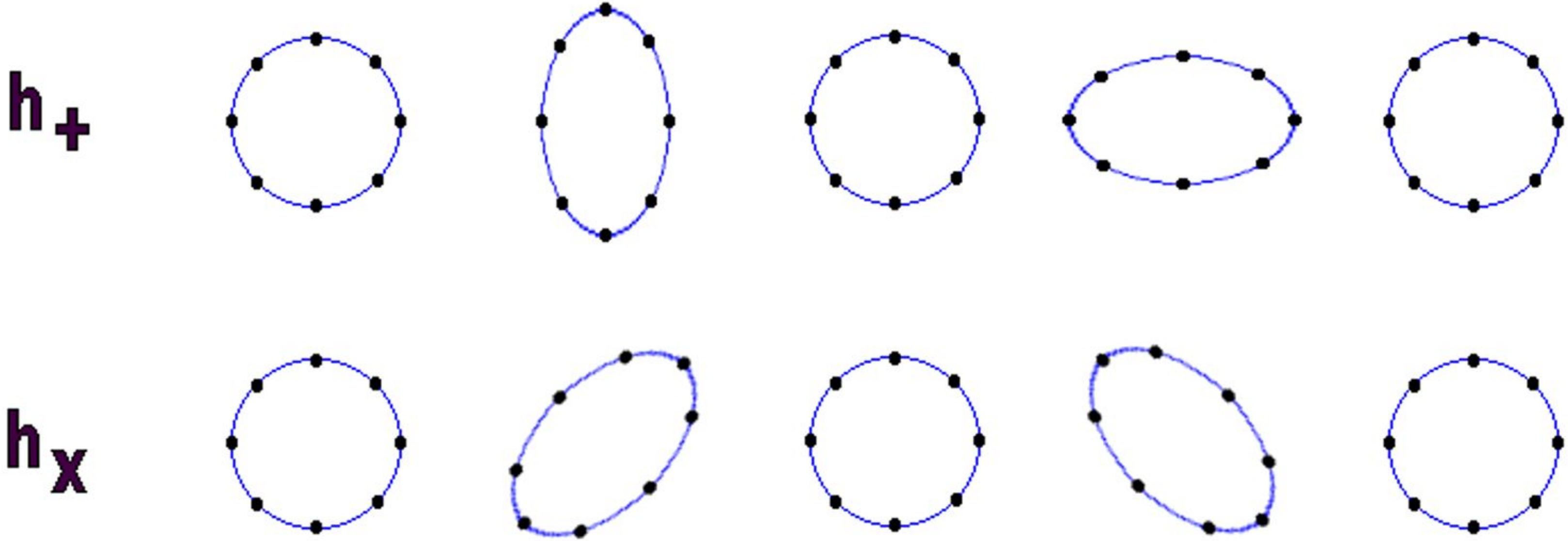


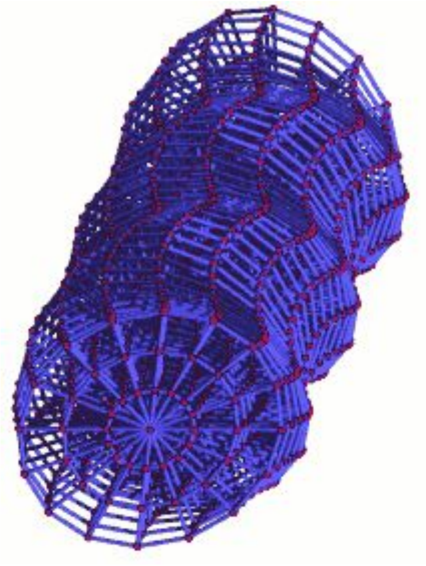
When objects accelerate through space



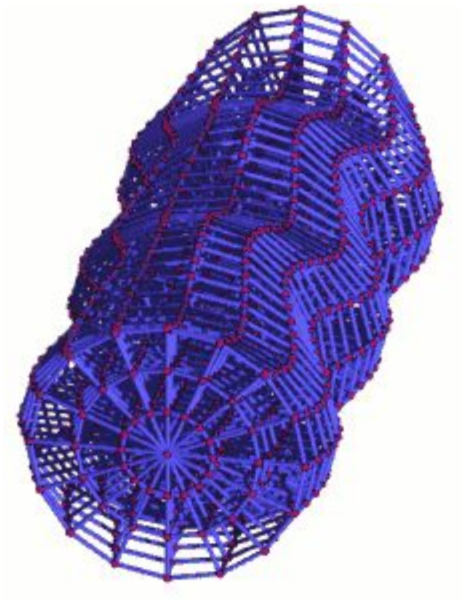
How matter respond to Gravitational Waves- Stretching and Squishing



How matter respond to Gravitational Waves- Stretching and Squishing



h_x

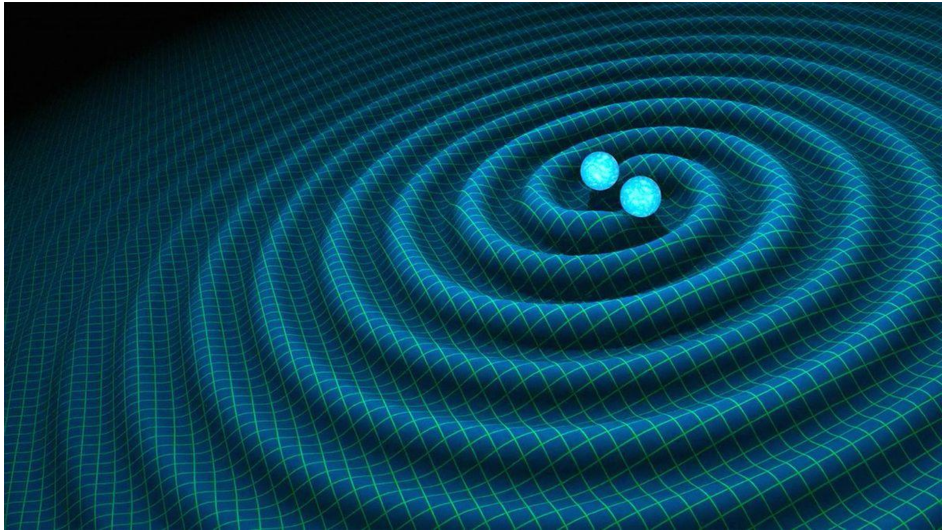


h_+

What creates a Gravitational Wave?

- Most things can produce gravitational waves
  - May be too small to be detected

- What can potentially be detected
  - Black hole binary
  - Neutron star binary
  - Supernovae



- Most things can produce gravitational waves
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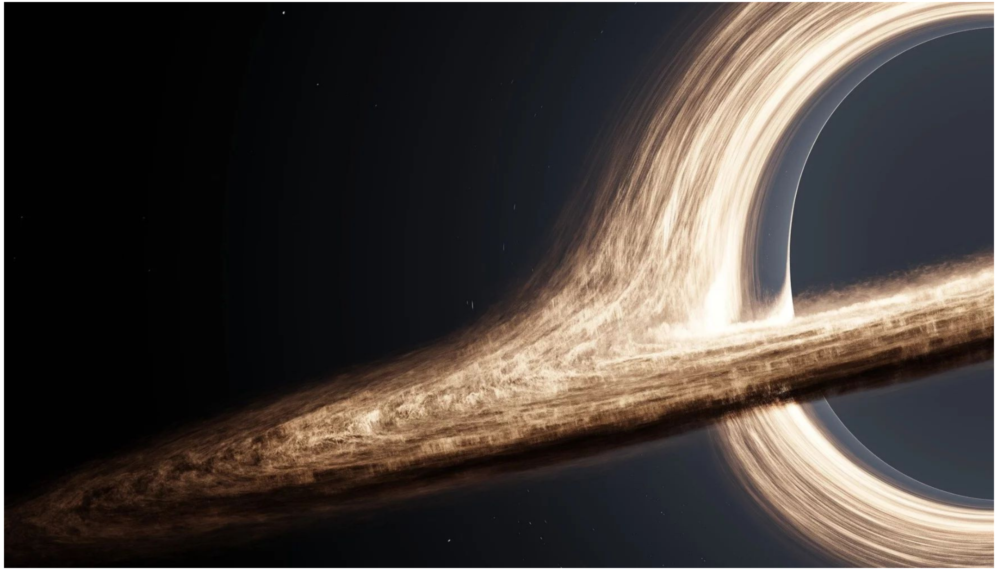
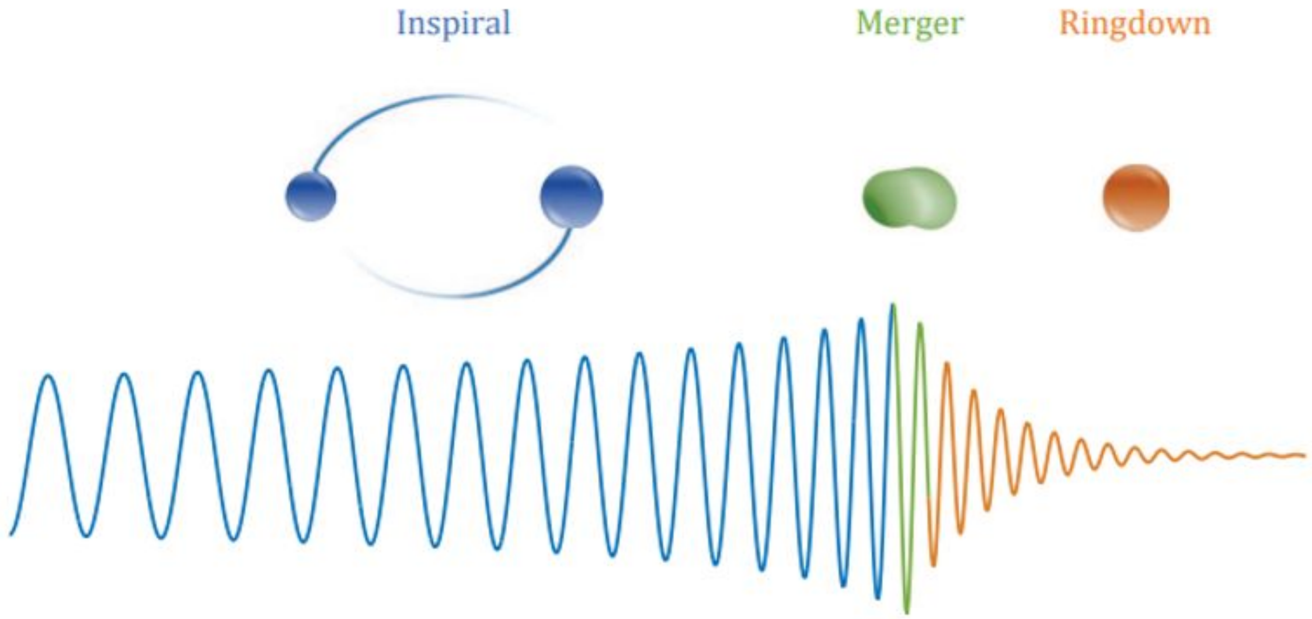
- What can potentially be detected
    - **Black hole binary**
    - Neutron star binary
    - Supernovae

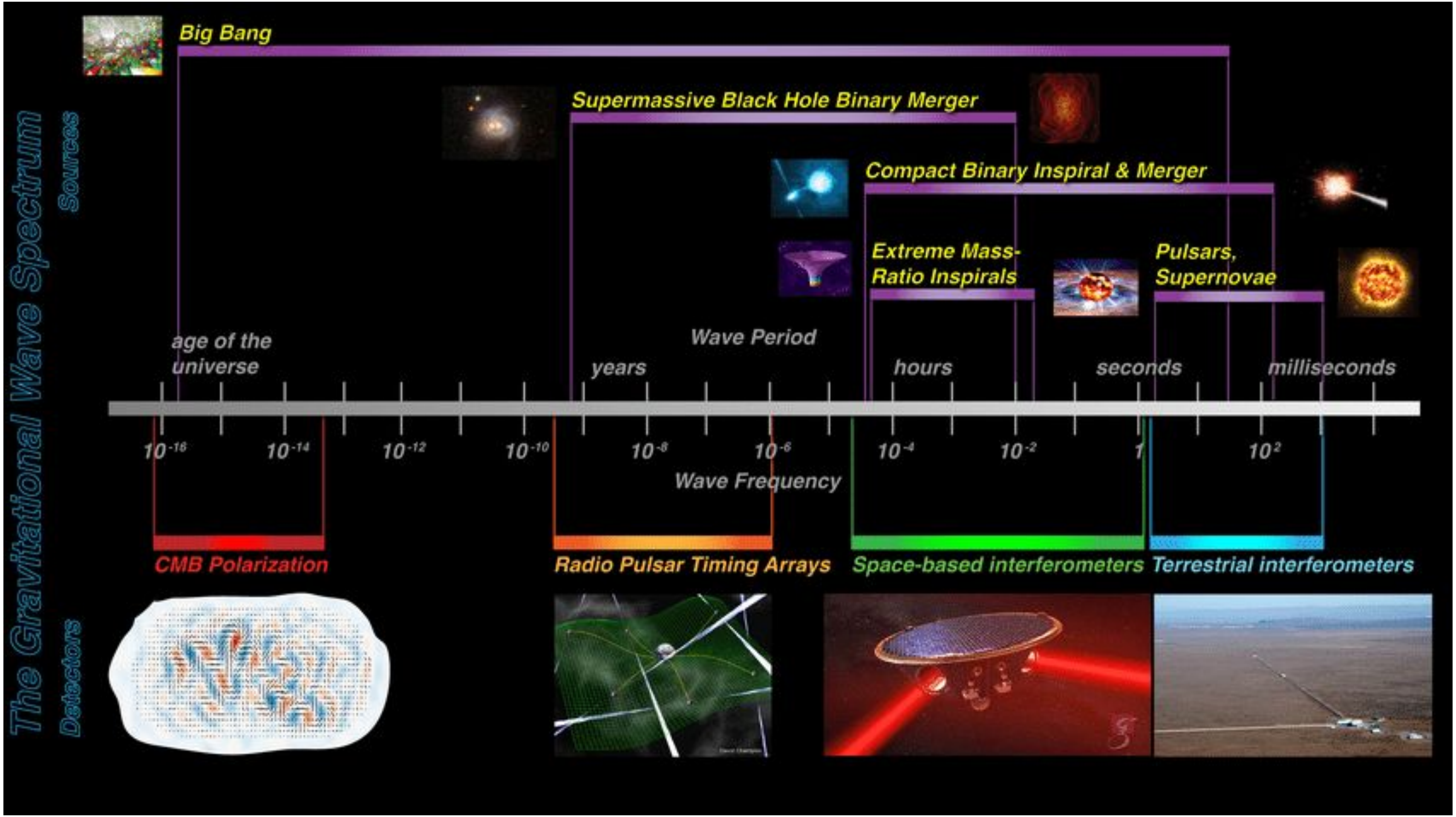
Types of Black Holes

- Stellar Origin Black Holes
  - 2 - 100$M_\odot$
- Intermediate Mass Black Holes
  - 100-10^5 $M_\odot$
- Supermassive Black Holes
  - 10^5-10^{10} $M_\odot$




Inspiral
Merger
Ringdown

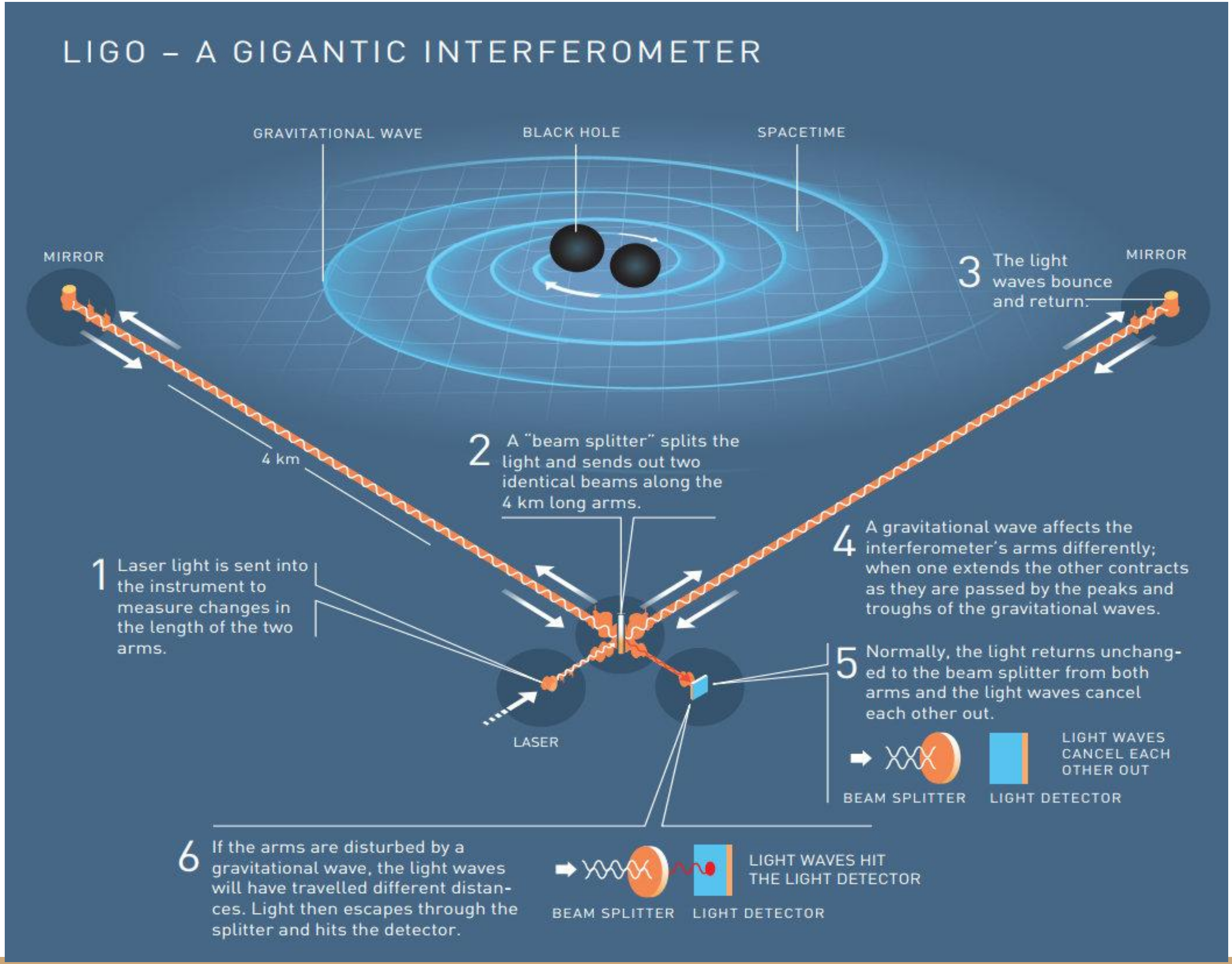
Detecting Gravitational Waves



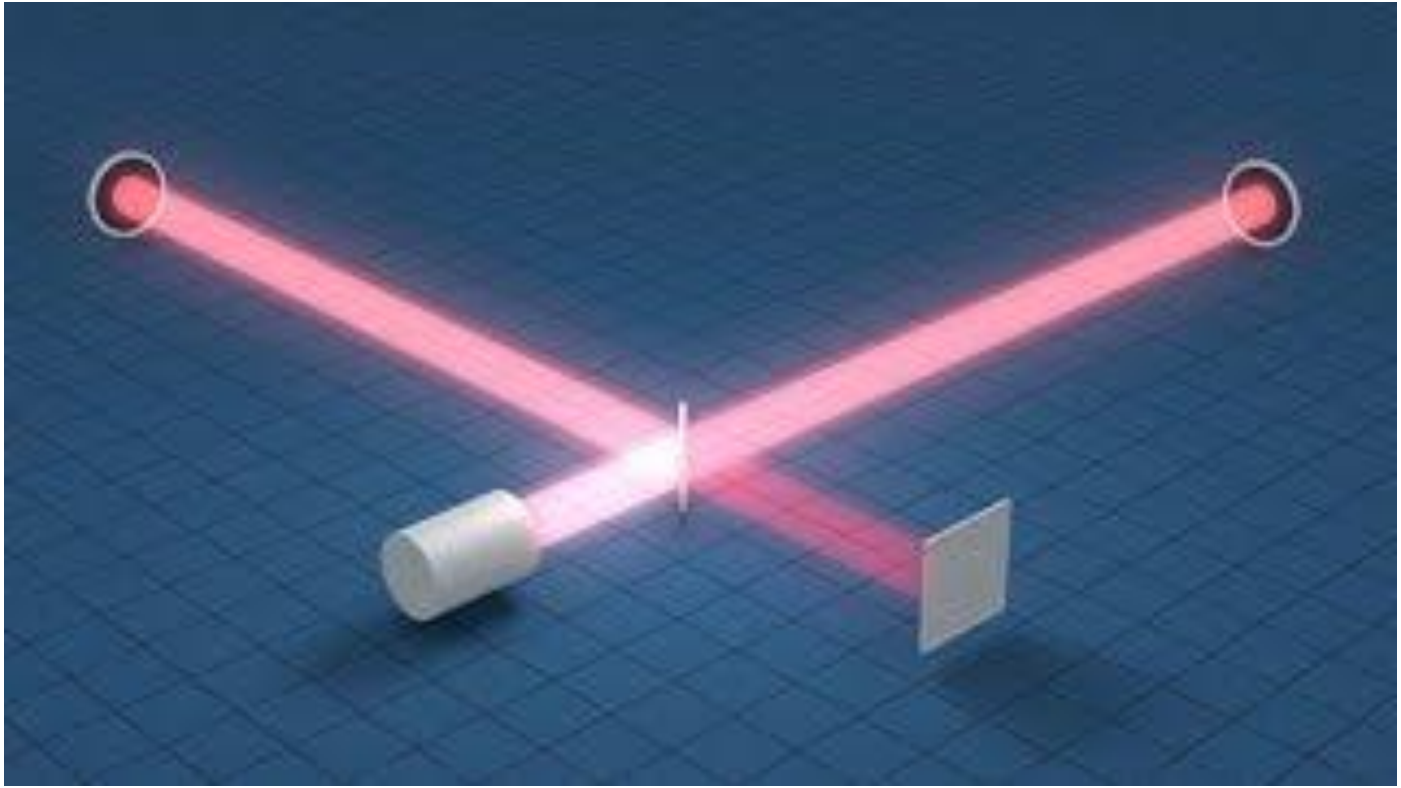
The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
Wave Period
age of the universe
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers

LIGO

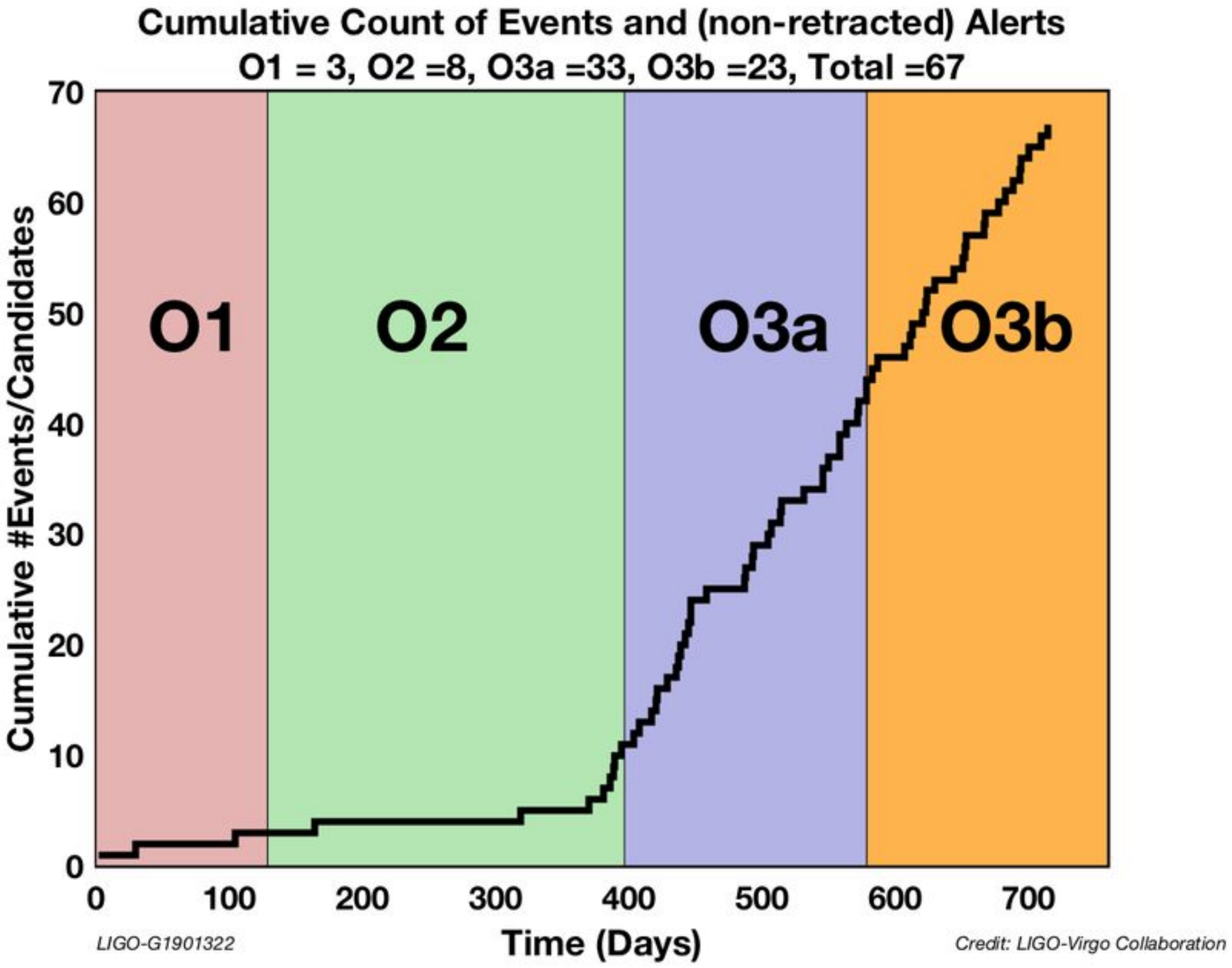
LIGO


LIGO – A GIGANTIC INTERFEROMETER
GRAVITATIONAL WAVE
BLACK HOLE
SPACETIME
MIRROR
MIRROR
3 The light waves bounce and return.
4 km
2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.
4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.
1 Laser light is sent into the instrument to measure changes in the length of the two arms.
5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.
LASER
LIGHT WAVES CANCEL EACH OTHER OUT
BEAM SPLITTER
LIGHT DETECTOR
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.
LIGHT WAVES HIT THE LIGHT DETECTOR
BEAM SPLITTER
LIGHT DETECTOR

LIGO



What has LIGO Detected?


Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67
Cumulative #Events/Candidates
Time (Days)
O1
O2
O3a
O3b
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
LIGO-G1901322
Credit: LIGO-Virgo Collaboration

GRAVITATIONAL WAVE **MERGER** DETECTIONS

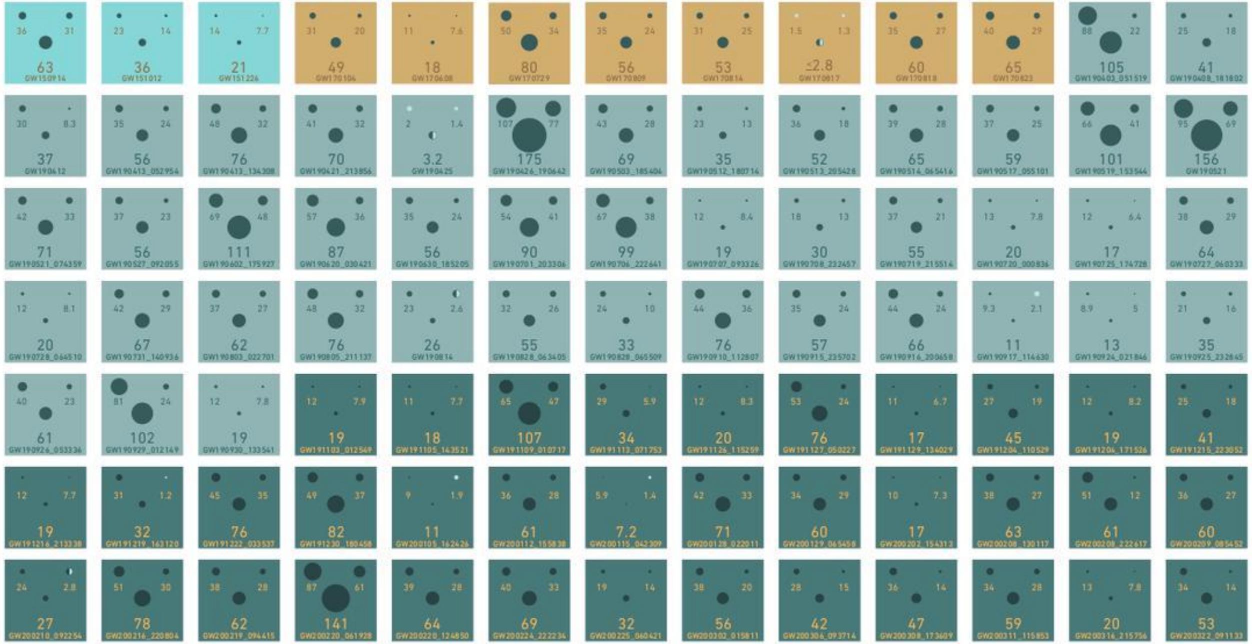
SINCE 2015

OBSERVING RUN

01 2015-2016

02 2016-2017

03a+b 2019-2020



KEY

BLACK HOLE

PRIMARY MASS

FINAL MASS

NEUTRON STAR (SHOWN AT X10 SCALE)

UNCERTAIN OBJECT

SECONDARY MASS

DATE(_TIME)

31 1.2 32 GW191219_163120

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

OzGrav

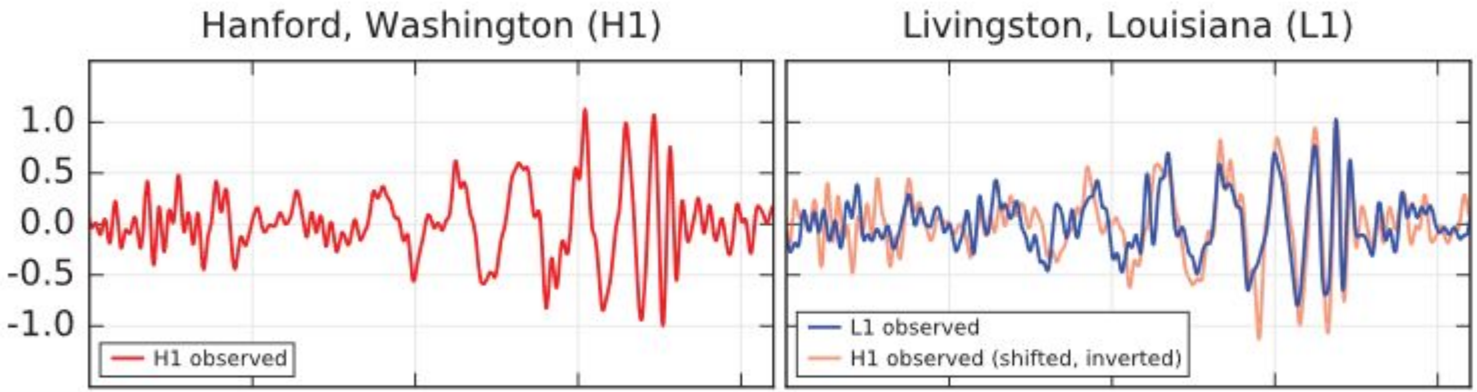
ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

Notable Events

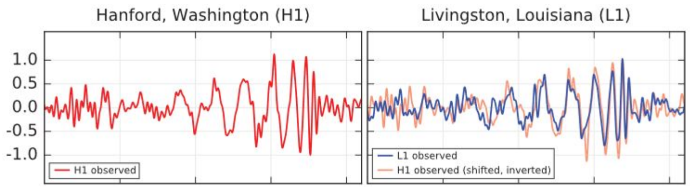
- GW150914: First GW event detected
- GW170817: First Binary Neutron Star
- GW190521: First GW with a remnant in the IMBH mass range

How does LIGO extract information from a signal?



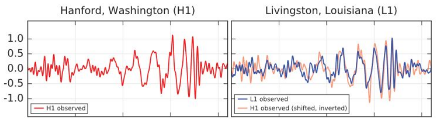
Hanford, Washington (H1)
Livingston, Louisiana (L1)
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)

GW Signal

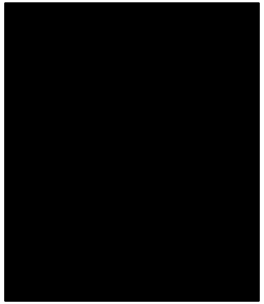


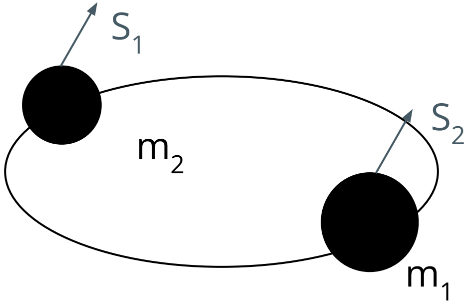
Parameter Estimation

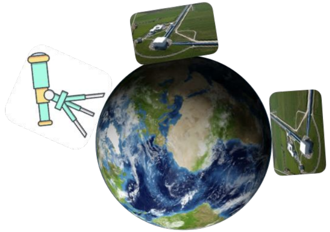
GW Signal



Parameter Estimation

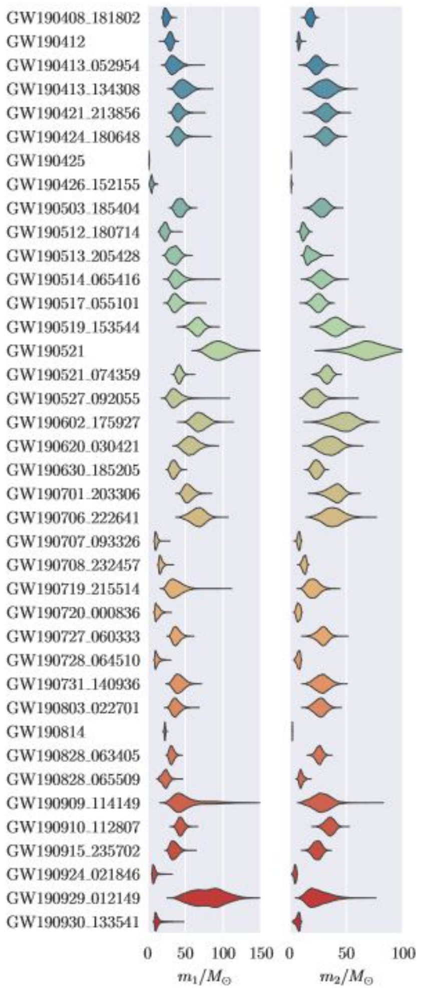






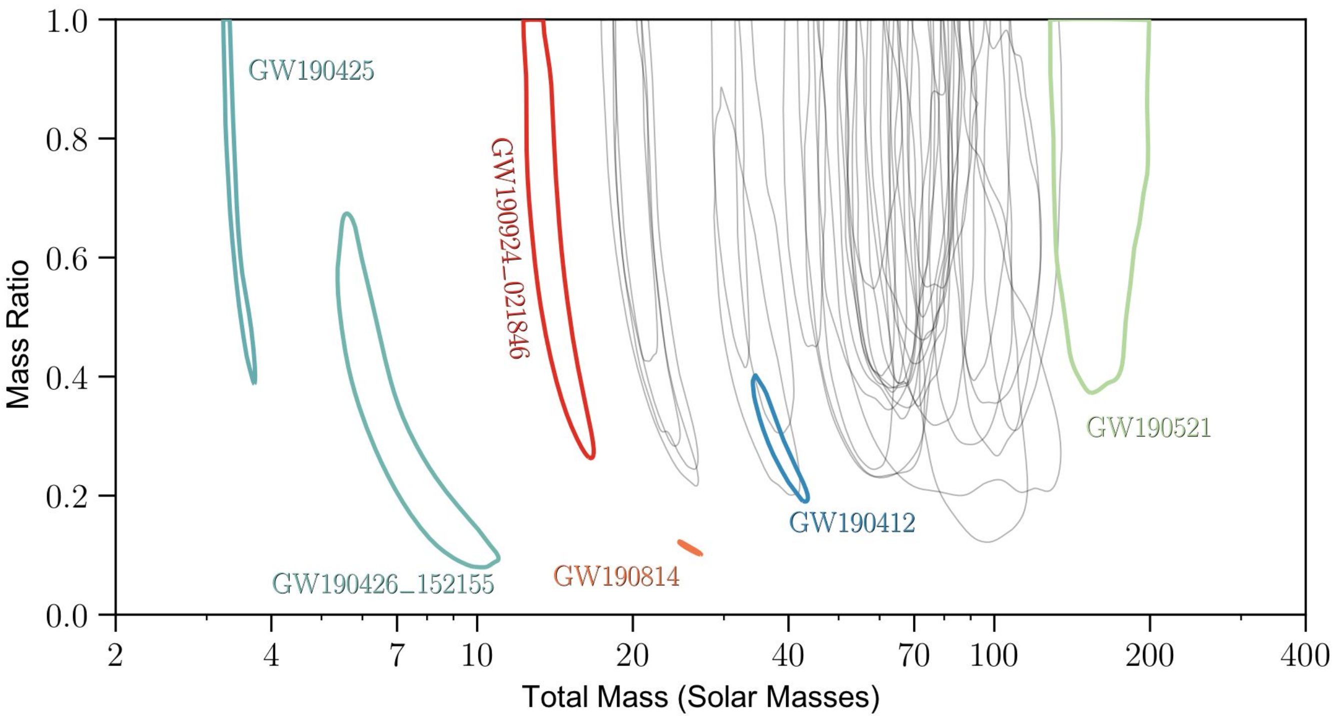
i, RA, Dec, distance, ...

03 Results



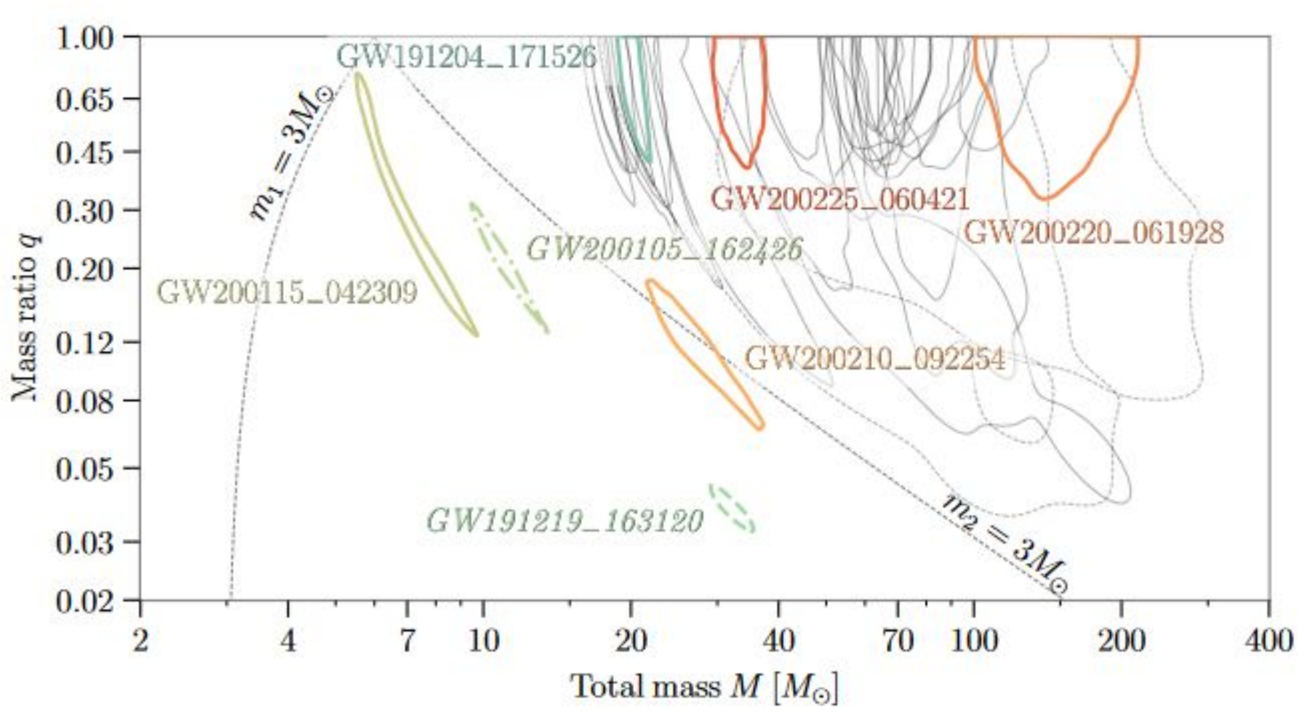
GW190408_181802
GW190412
GW190413_052954
GW190413_134308
GW190421_213856
GW190424_180648
GW190425
GW190426_152155
GW190503_185404
GW190512_180714
GW190513_205428
GW190514_065416
GW190517_055101
GW190519_153544
GW190521
GW190521_074359
GW190527_092055
GW190602_175927
GW190620_030421
GW190630_185205
GW190701_203306
GW190706_222641
GW190707_093326
GW190708_232457
GW190719_215514
GW190720_000836
GW190727_060333
GW190728_064510
GW190731_140936
GW190803_022701
GW190814
GW190828_063405
GW190828_065509
GW190909_114149
GW190910_112807
GW190915_235702
GW190924_021846
GW190929_012149
GW190930_133541
0 50 100 150
$m_1/M_\odot$
0 50 100
$m_2/M_\odot$

O3a

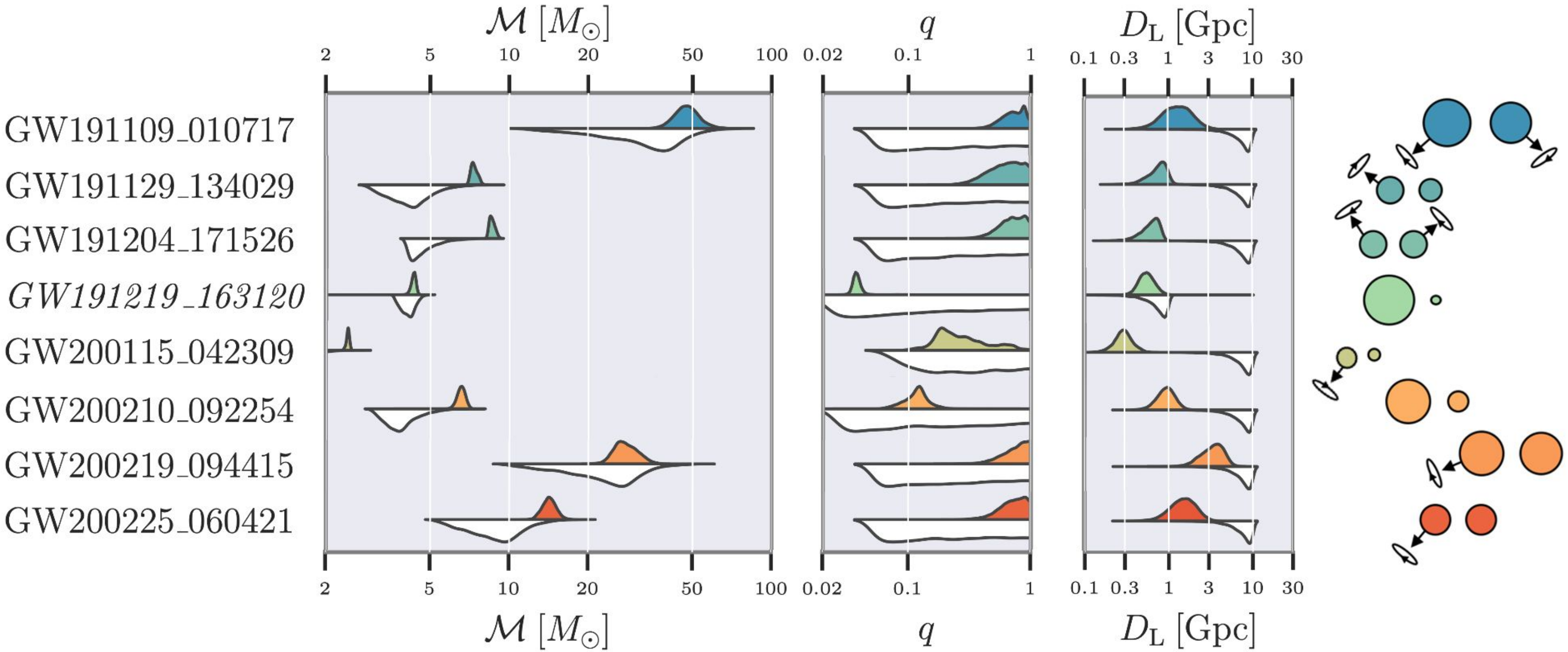


Mass Ratio
Total Mass (Solar Masses)
GW190425
GW190924_021846
GW190426_152155
GW190814
GW190412
GW190521
1.0
0.8
0.6
0.4
0.2
0.0
2 4 7 10 20 40 70 100 200 400

O3b

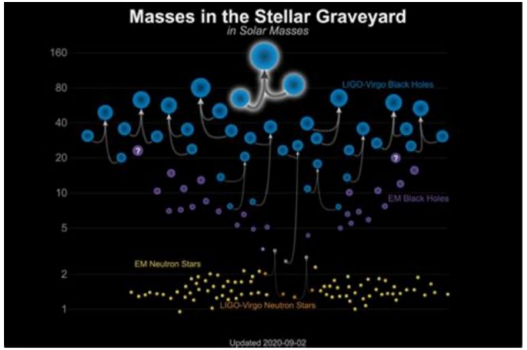


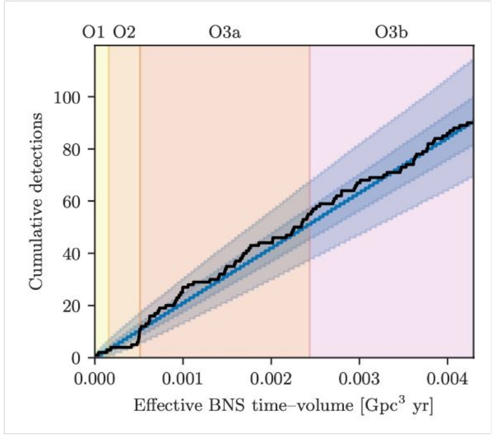
GW191204_171526
$m_1 = 3M_\odot$
GW200225_060421
GW200220_061928
GW200105_162426
GW200115_042309
GW200210_092254
GW191219_163120
$m_2 = 3M_\odot$
Mass ratio q
1.00
0.65
0.45
0.30
0.20
0.12
0.08
0.05
0.03
0.02
2
4
7
10
20
40
70
100
200
400
Total mass M $[M_\odot]$

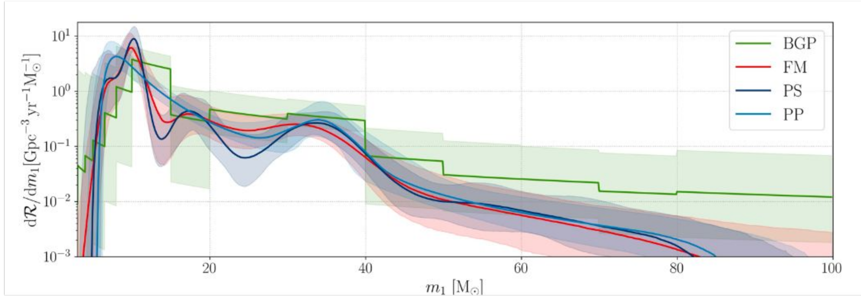


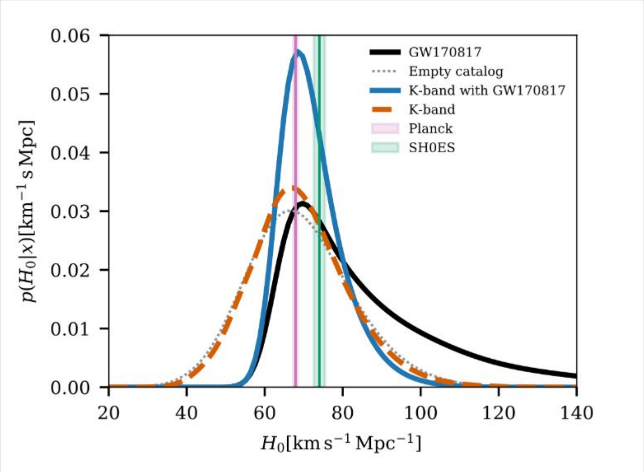
$\mathcal{M}\ [M_\odot]$
q
D_L [Gpc]
2
5
10
20
50
100
0.02
0.1
1
0.1
0.3
1
3
10
30
GW191109_010717
GW191129_134029
GW191204_171526
GW191219_163120
GW200115_042309
GW200210_092254
GW200219_094415
GW200225_060421

What astrophysics can we do with these gravitational waves?

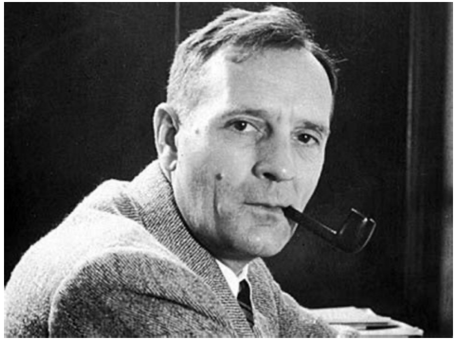








One example: Gravitational Waves and Cosmology



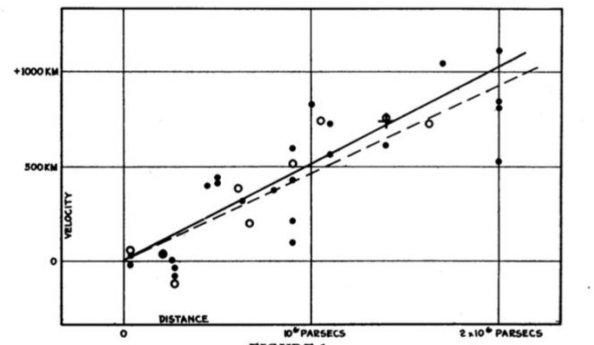
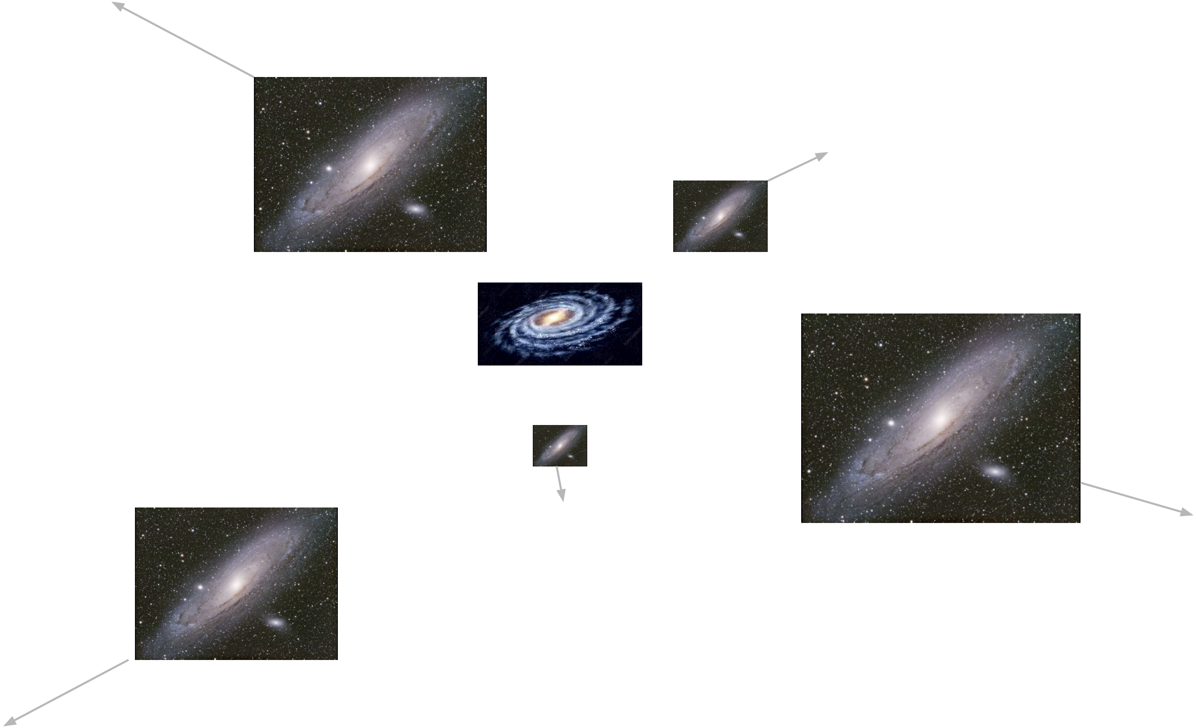
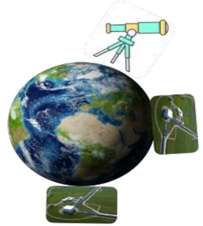


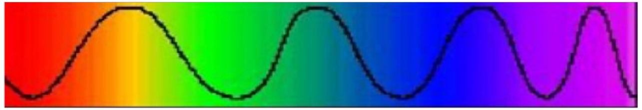
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.



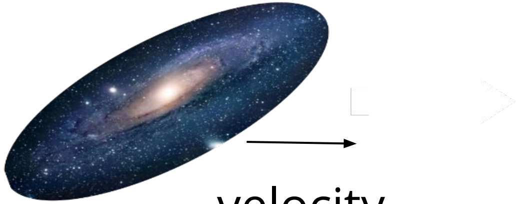
Cosmological inference is easy in theory

Cosmological inference - Measuring the Hubble constant is really easy (in theory)

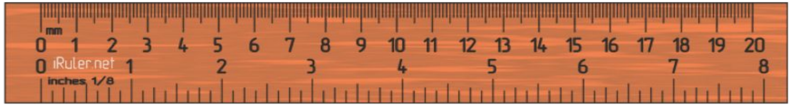


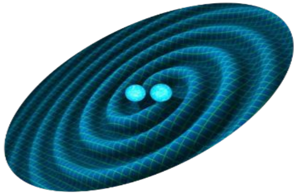


redshift



velocity

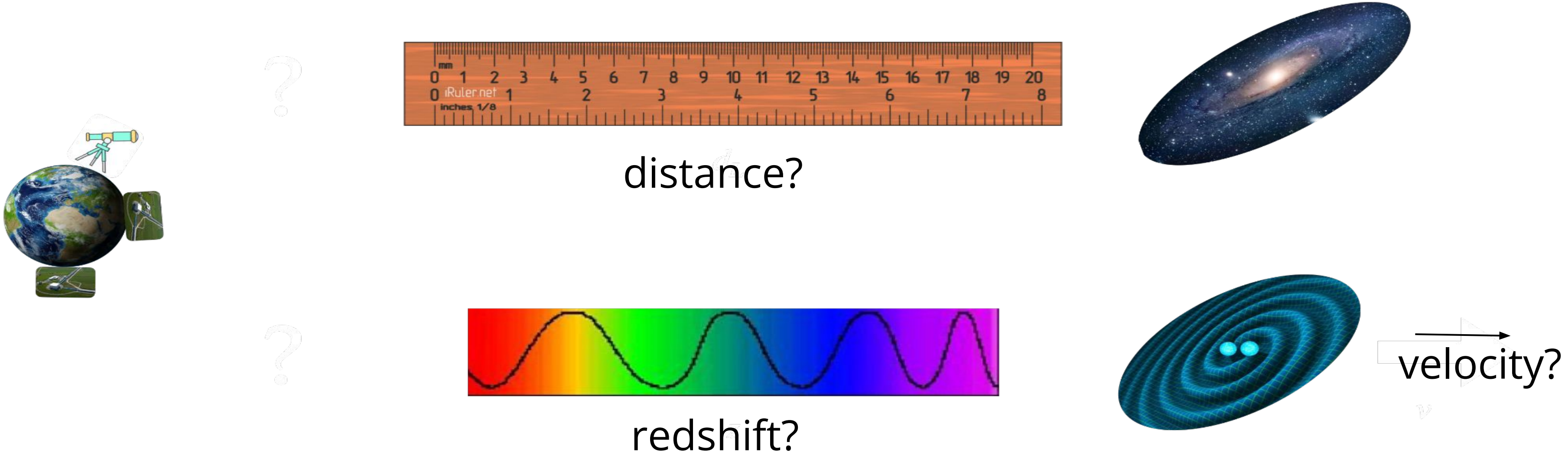




distance

Cosmological inference is not so easy in practice

Measuring the Hubble constant is not so easy…



Notable Events

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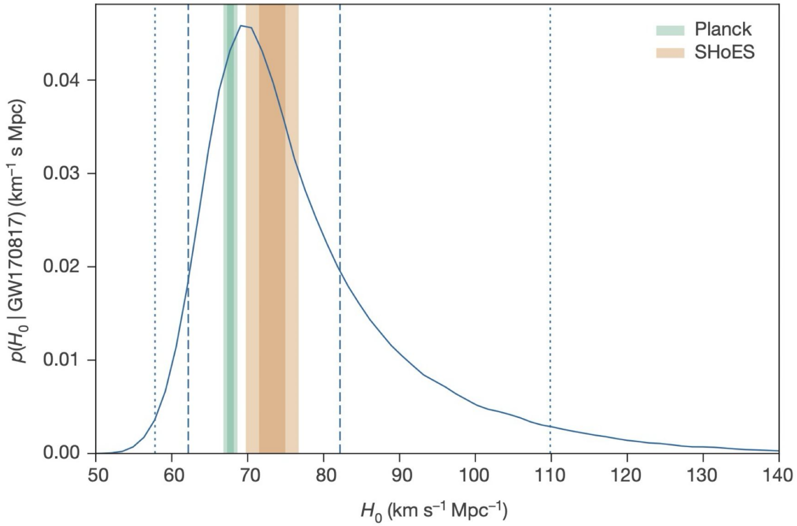

Summary

- Gravitational waves are ripples in spacetime caused by compact binary coalescences.
- We can detect gravitational waves using the advanced interferometry of the LIGO, Virgo, and KAGRA detectors, and determine the properties of these merging objects.
- The numbers and types of events observed give us a better astrophysical understanding of the universe writ large.