LIGO
VIRGO
KAGRA

CBC Science

GW Open Data Workshop
April 18-20, 2024

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Gravitational Wave Sources in LIGO

Short duration transient signals

Long duration persistent signals

Modelled sources

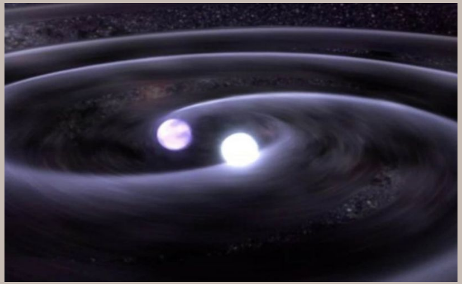


Image credit: NASA Goddard

CBCs

Continuous waves from spinning neutron stars

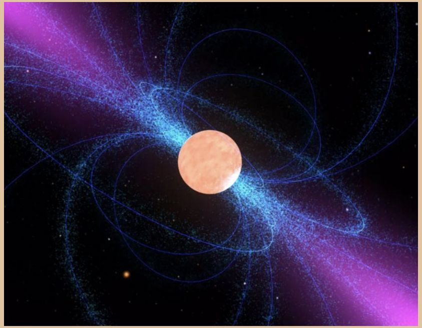


Image credit: NASA

Unmodelled sources

Image credit: NASA

Other unmodelled burst sources, eg. supernovae

Stochastic gravitational wave background

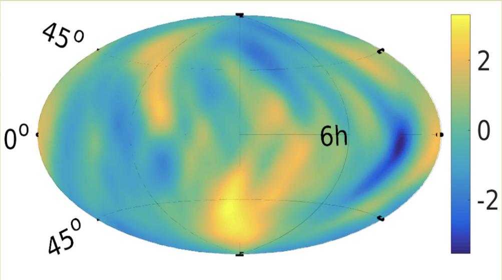


Image credit: Phys. Rev. Lett. 118, 121102

Gravitational Wave Sources in LIGO

	Short duration transient signals		Long duration persistent signals	
Modelled sources	Only sources detected by LIGO so far, and the focus of this talk	CBCs	Continuous waves from spinning neutron stars	Takahiro Yamamoto's lecture
Unmodelled sources	Marek Szczepanczyk's lecture	Other unmodelled burst sources, eg. supernovae	Stochastic gravitational wave background	Guo-Chin Liu's lecture

CBCs = Compact Binary Coalescences

Compact objects, dense astrophysical objects

Two of them

Merging

In This Talk

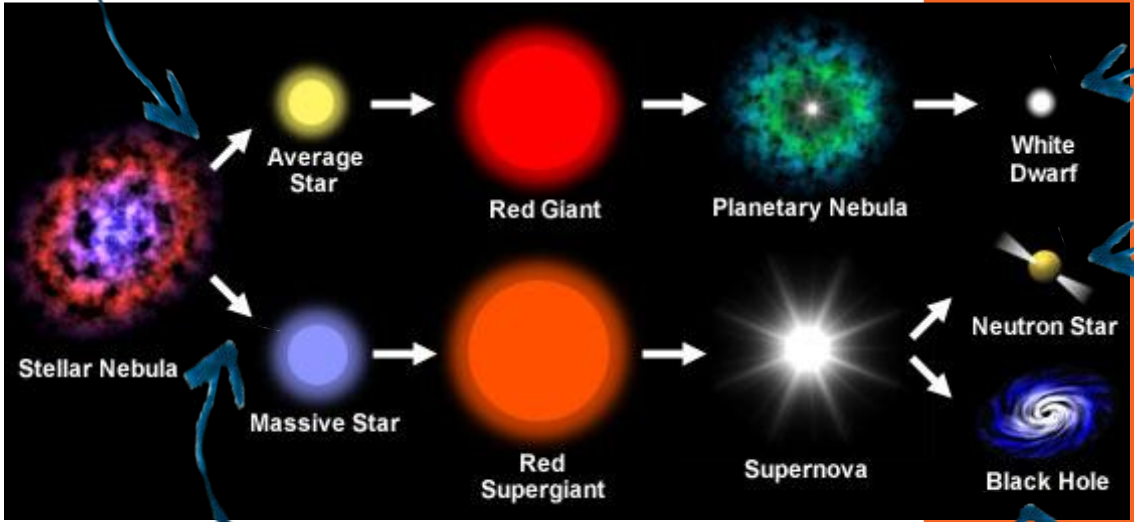
- **Part 1:** What are compact objects?
- **Part 2:** How do CBCs produce gravitational waves?
- **Part 3:** CBC gravitational wave detections made by LIGO so far
- **Part 4:** What can we learn about our universe using gravitational wave detections from CBCs?

Part 1: What are compact objects?

What are compact objects?

Less massive stars

Star's death



Lightest

Heavier

Heaviest

More massive stars

- Compact objects are dead stars
- The mass of the star determines the type of compact object it will become: black hole, neutron star, or white dwarf

Image credit: NASA

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Black Holes

- Densest objects in universe
- Not even light can escape
- Expected to be between 5 and 100,000,000,000 times the mass of our sun (very uncertain!)

Stellar mass black holes

- Between 5 and ~100 times the mass of our sun
- Formed by dying massive stars in core collapse supernovae

Intermediate mass black holes

- Between 100 and 1000 times the mass of our sun
- Too heavy to be formed by single dying star
- Can be formed by smaller black holes merging together (eg. GW190521)

Image credit: NASA Goddard

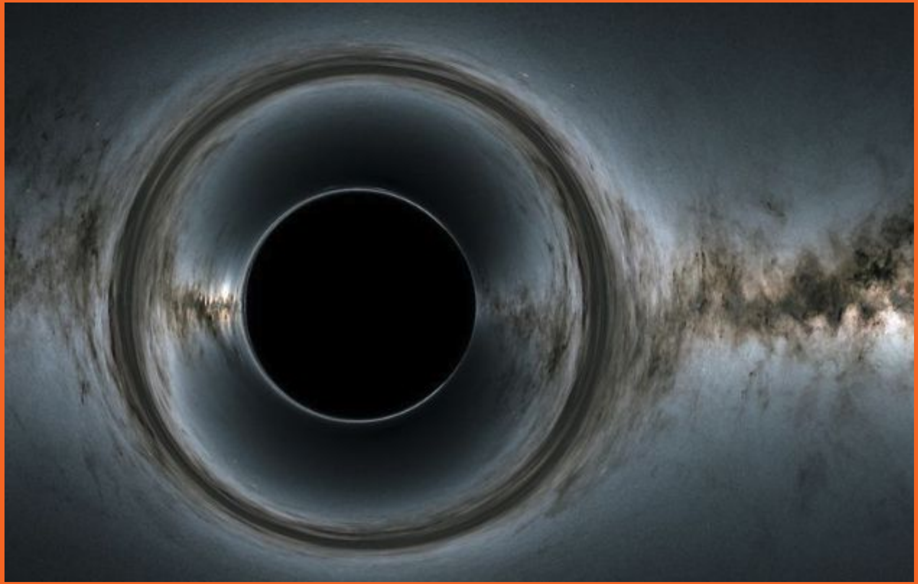


Image credit: NASA

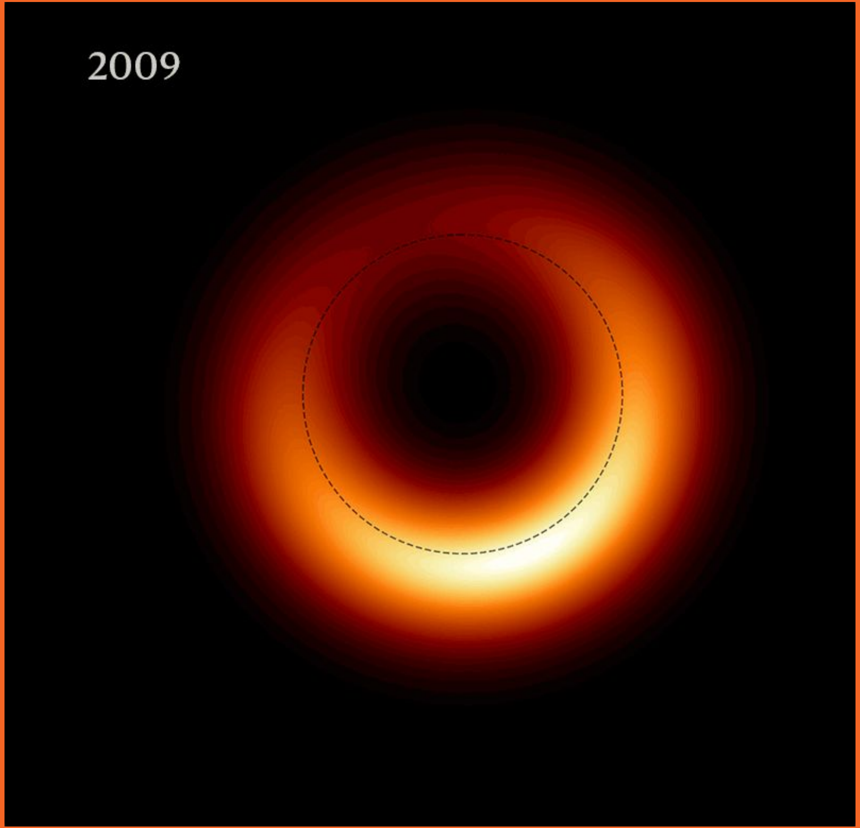
Black Holes

Supermassive black holes

- Between 1,000,000 and 100,000,000,000 times the mass of our sun
- Lie at the centre of galaxies
- Uncertain formation mechanism: formed with the galaxy? Mergers of smaller black holes?

Primordial black holes

- Hypothetically formed soon after Big Bang
- Huge potential mass range
- Dark matter candidates
- Not yet observed



Radio frequency images of M87*.
Image credit: Event Horizon Telescope, Nature

Neutron Stars

Image credit: Mark Garlick

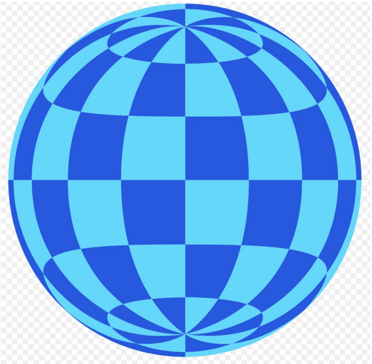


Image credit: Corvin Zahn

- Still extremely dense but not completely dark like a black hole
- Weighs between around 1.4 to 2.9 times our sun (very uncertain!)
- Extreme state of matter, in the core of a neutron star all protons and electrons are squished together to make neutrons
- Weird facts:
  - One teaspoon of neutron star weighs 10 million tons!
  - Some neutron stars are so compact and lens photons so much that you can see the whole neutron star surface at once!
- Inner structure of neutron stars theorised but unknown, including relation between mass and density (equation of state), and how deformable neutron star matter is

White Dwarfs

Image credit: K Miller

- Most common remnant for a dead star
- Mass less than 1.4 times our sun, radius comparable to Earth
- Very dense (though not as dense as neutron star or black hole), supported by electron degeneracy pressure
- Not detectable by LIGO, as binary orbits are too low in frequency

The focus of this talk will be on compact binaries containing combinations of black holes and neutron stars.

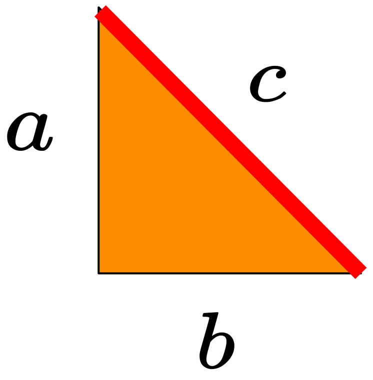
Part 2: How do CBCs produce gravitational waves?

Gravitational Waves

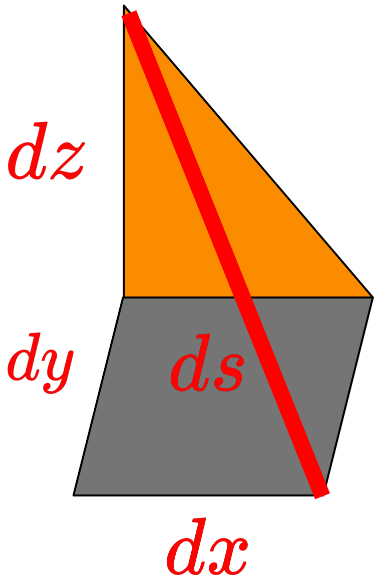
~~Gravitational Waves~~

Pythagoras' Theorem

Pythagoras’ Theorem



$$a^2 + b^2 = c^2$$



$$ds^2 = dx^2 + dy^2 + dz^2$$

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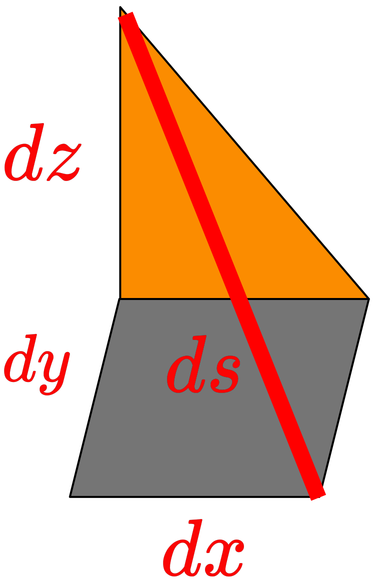
Metrics and Measuring Distances

$dx = dx^1$ $\quad dy = dx^2$ $\quad dz = dx^3$

$$ds^2 = 1 \times dx^1 \times dx^1 + 1 \times dx^2 \times dx^2 + 1 \times dx^3 \times dx^3$$

$$ds^2 = g_{11} \times dx^1 \times dx^1 + g_{22} \times dx^2 \times dx^2 + g_{33} \times dx^3 \times dx^3$$

$$ds^2 = \sum_{\mu=1,\nu=1}^{\mu=3,\nu=3} g_{\mu\nu} \times dx^\mu \times dx^\nu$$



$$ds^2 = dx^2 + dy^2 + dz^2$$

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

This is a metric!

Metrics tell us how to measure distance in a space

Metrics in Flat (Minkowski) Spacetime

- Special relativity says that nothing can travel faster than the speed of light

- So we have to include this 'travel time' as part of our distance measurement in spacetime

- We now have 3+1 dimensions, 1 time and 3 space

$$g_{\mu\nu} = \begin{pmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \eta_{\mu\nu}$$

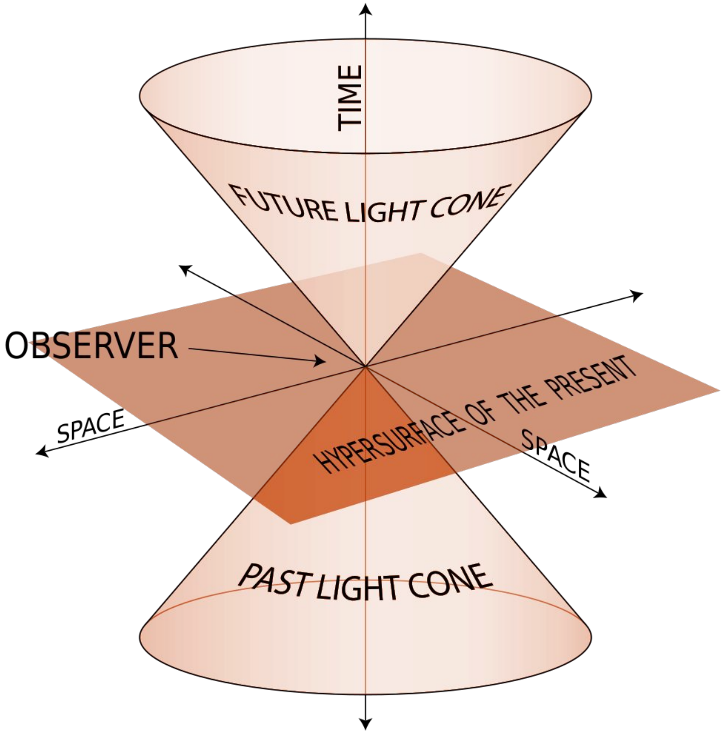


Image credit: Wikipedia

Black Holes: Schwarzschild Metric

$$g_{\mu\nu} = -c^2\left(1 - \frac{r_s}{r}\right) dt^c + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 sin^2\theta\, d\phi^2$$

$$r_s = 2GM/c^2$$

Schwarzschild radius, metric only makes sense outside this radius, there must be a black hole inside!

Kinetic energy of particle mass m: $mv^2/2$

Potential energy of particle mass m near large mass M, distance R away: GMm/R

$$v = \sqrt{2GM/R}$$

Setting escape velocity v = c, we obtain

$$r_s = 2GM/c^2$$

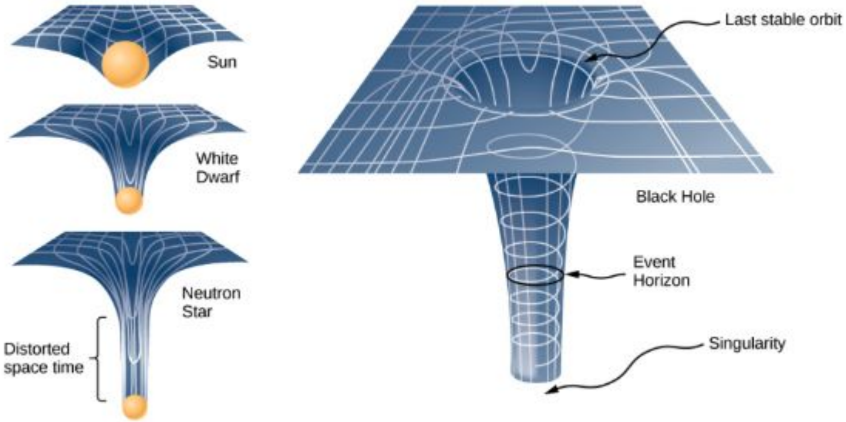


Image credit: NASA

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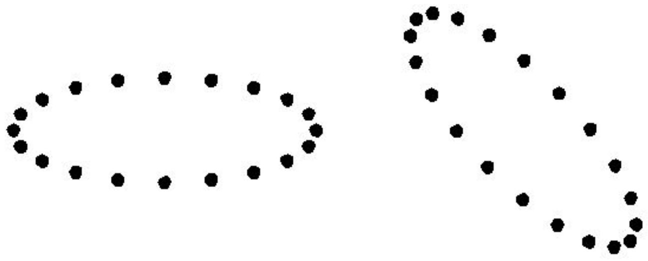
Einstein's General Relativity

Einstein tensor: spacetime curvature

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Energy-momentum tensor: matter



Cross and plus GW polarisations. Image credit: Wikipedia

Spacetime tells matter how to move, and matter tells spacetime how to curve.

Linearising:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1.$$

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_x & 0 \\ 0 & h_x & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Gravitational waves are a prediction of General Relativity, and are caused by acceleration of mass.

Heavier masses, faster movements = stronger waves.

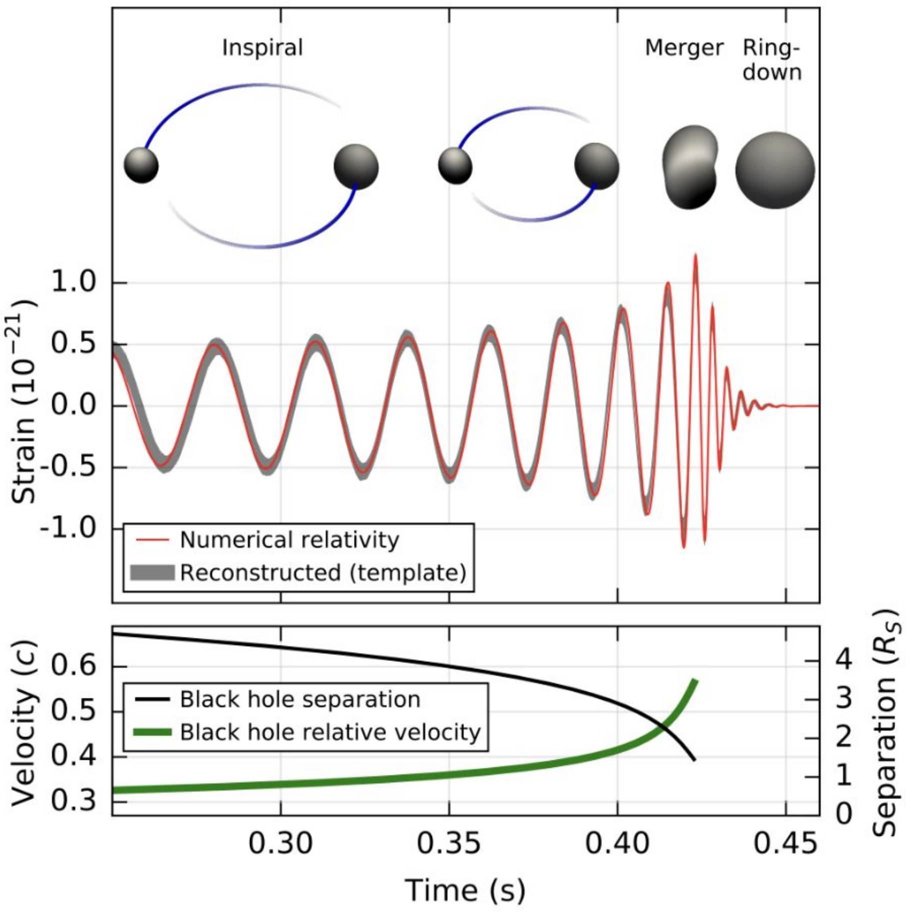


Image credit: LIGO

Features of a CBC Signal

- Inspiral in which objects spiral in towards each other with increasing frequency, giving off gravitational waves of increasing frequency and energy
- Merger, where most energy is released and two objects become one black hole or neutron star
- Ringdown, where final object settles into equilibrium state, releasing gravitational waves
- If the final remnant object is a neutron star, the ringdown will be longer and include features from the star's internal oscillations

Features of a CBC Signal

Video credit: SXS Collaboration

Part 3: CBC gravitational waves detections made by LIGO so far

CBC Detections So Far

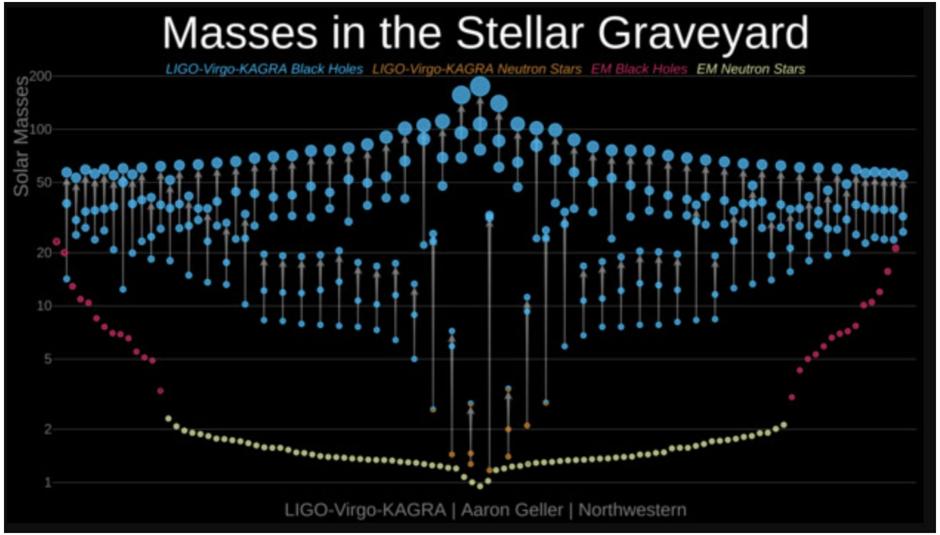
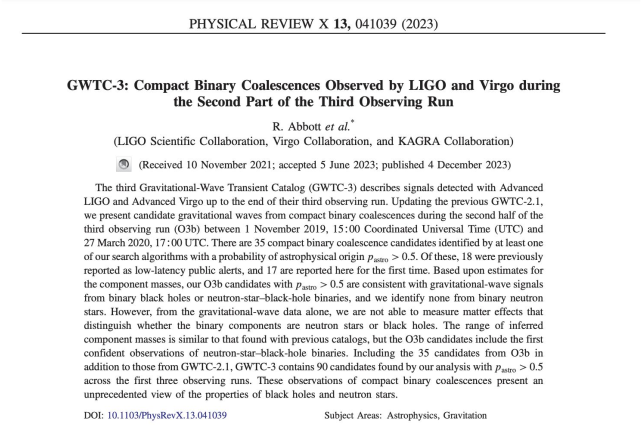


Image credit: LIGO

- CBC detections are becoming routine!
- 90 gravitational wave events from GWTC-3 + 83 detection candidates so far in fourth observing run
- Wide range of properties



PHYSICAL REVIEW X **13**, 041039 (2023)

GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run

R. Abbott *et al.**
(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

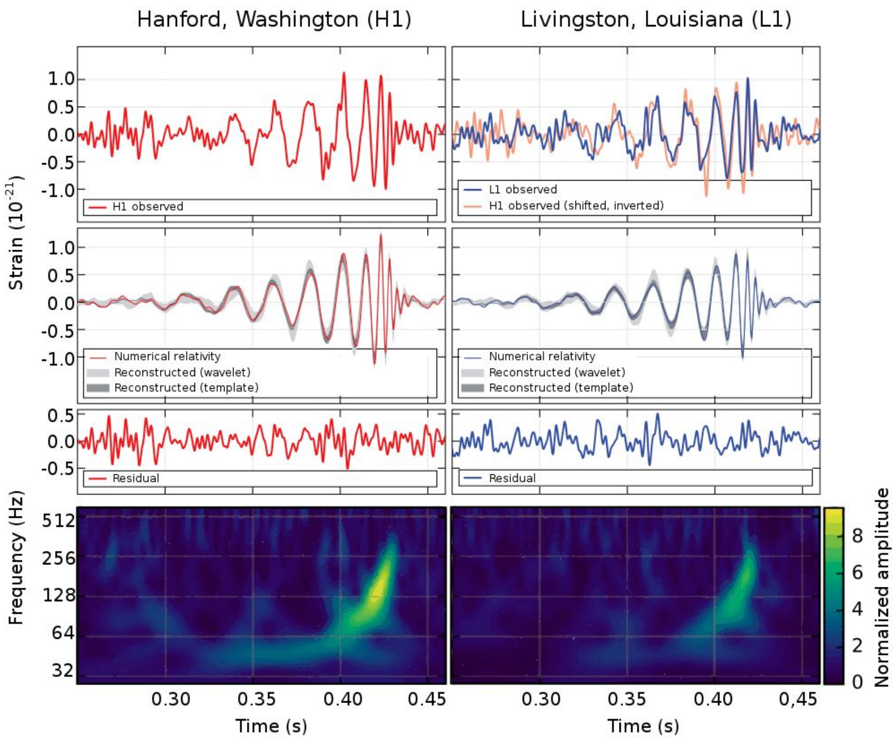
(Received 10 November 2021; accepted 5 June 2023; published 4 December 2023)

The third Gravitational-Wave Transient Catalog (GWTC-3) describes signals detected with Advanced LIGO and Advanced Virgo up to the end of their third observing run. Updating the previous GWTC-2.1, we present candidate gravitational waves from compact binary coalescences during the second half of the third observing run (O3b) between 1 November 2019, 15:00 Coordinated Universal Time (UTC) and 27 March 2020, 17:00 UTC. There are 35 compact binary coalescence candidates identified by at least one of our search algorithms with a probability of astrophysical origin $p_{astro} > 0.5$. Of these, 18 were previously reported as low-latency public alerts, and 17 are reported here for the first time. Based upon estimates for the component masses, our O3b candidates with $p_{astro} > 0.5$ are consistent with gravitational-wave signals from binary black holes or neutron-star–black-hole binaries, and we identify none from binary neutron stars. However, from the gravitational-wave data alone, we are not able to measure matter effects that distinguish whether the binary components are neutron stars or black holes. The range of inferred component masses is similar to that found with previous catalogs, but the O3b candidates include the first confident observations of neutron-star–black-hole binaries. Including the 35 candidates from O3b in addition to those from GWTC-2.1, GWTC-3 contains 90 candidates found by our analysis with $p_{astro} > 0.5$ across the first three observing runs. These observations of compact binary coalescences present an unprecedented view of the properties of black holes and neutron stars.

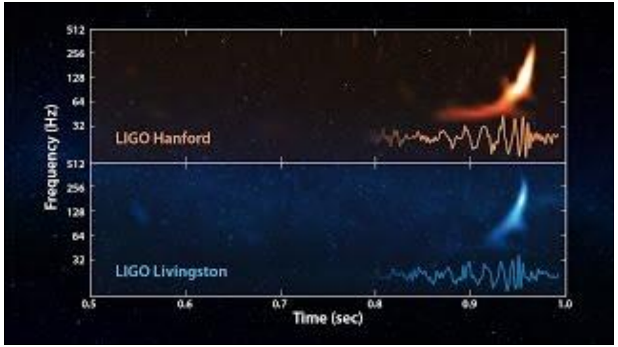
DOI: 10.1103/PhysRevX.13.041039 Subject Areas: Astrophysics, Gravitation

GW150914: A Merger of Two Black Holes

Images credit: LIGO



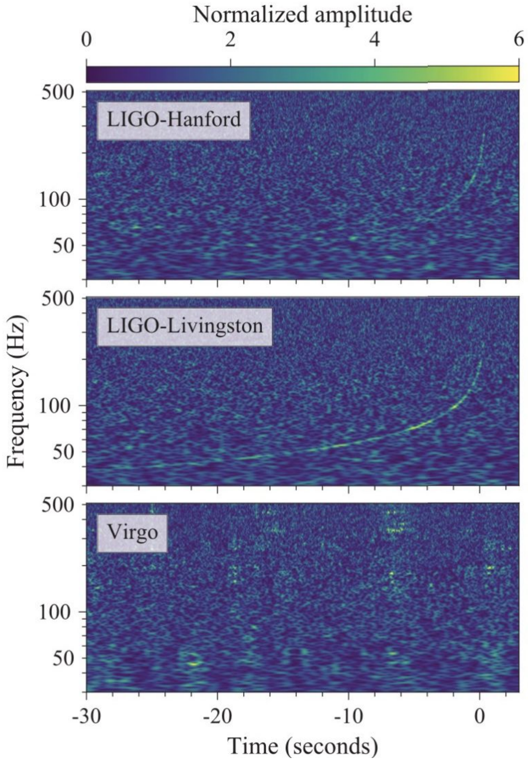
- First gravitational wave signal detected from merger of two black holes on September 14th 2015
- Comparison of signal to computational models showed the signal was from a merger event
- Einstein's prediction confirmed after 99 years!



Video credit: Georgia Tech YouTube

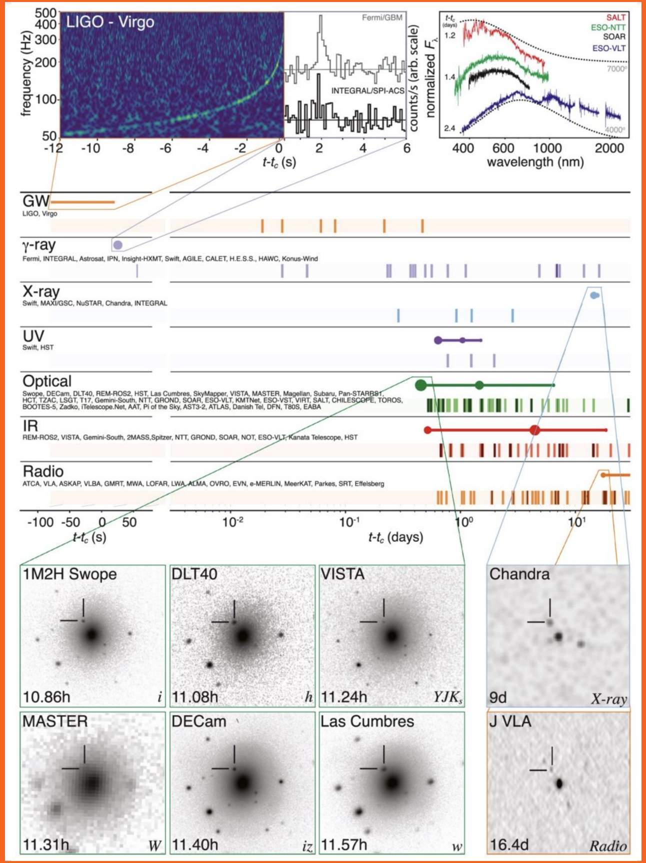
GW170817: Binary Neutron Star with EM Counterpart

- Virgo joins the observing run, three detectors means better sky localisation - EM counterpart!



- Observed in many EM bands, multimessenger observation
- New insights on heavy element creation

[Phys Rev Lett 119, 161101](), [ApJL 848 L12]()



Images credit: LIGO

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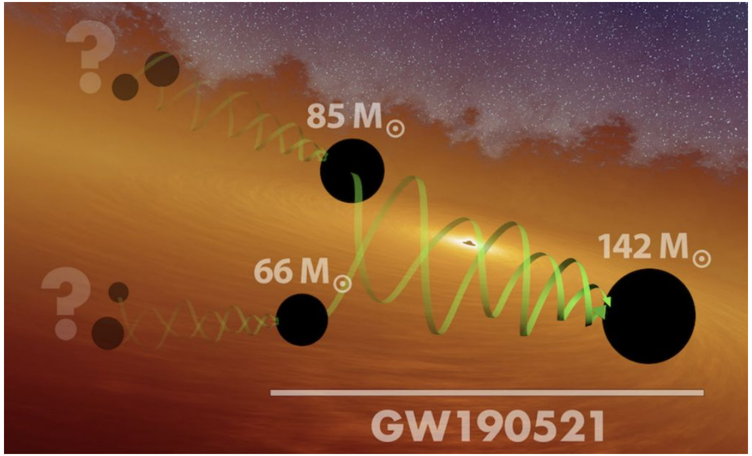
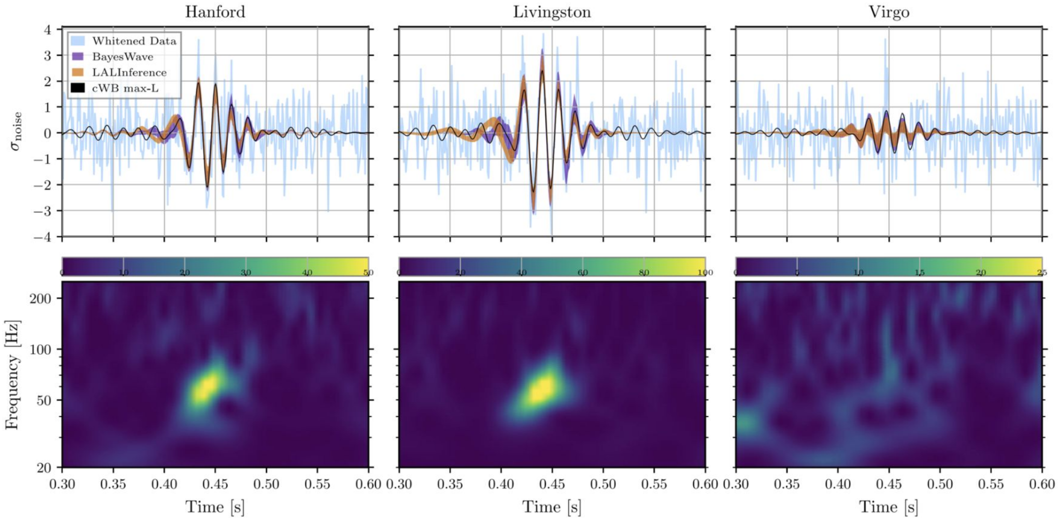
GW190521: First Intermediate-Mass Black Hole

- Observation of a binary black hole merger of 66 and 85 times the mass of our sun, first direct observation of intermediate mass black hole
- Direct evidence of hierachical mergers as formation channel of IMBHs

[Phys Rev Lett 125, 101102](), [ApJL 900 L13]()

Image credit: LIGO





GW200105 and GW200115: Neutron Star-Black Hole Mergers

- Observation of two NSBH mergers
- Thought to be very rare events: two detected within ten days of each other!

[ApJL 915, L5]

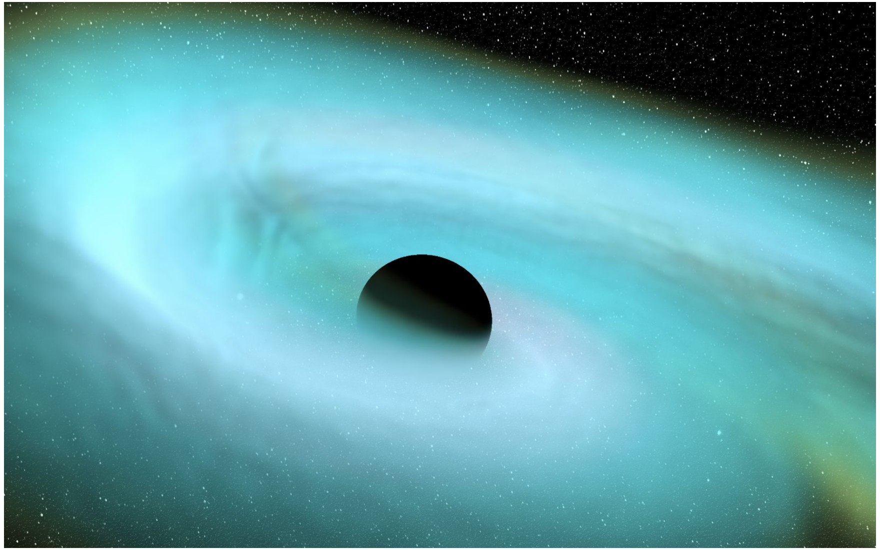


Image credit: Deboard Ferguson (UT Austin), Bhavesh Khamesra (Georgia Tech), Karan Jani (Vanderbilt)

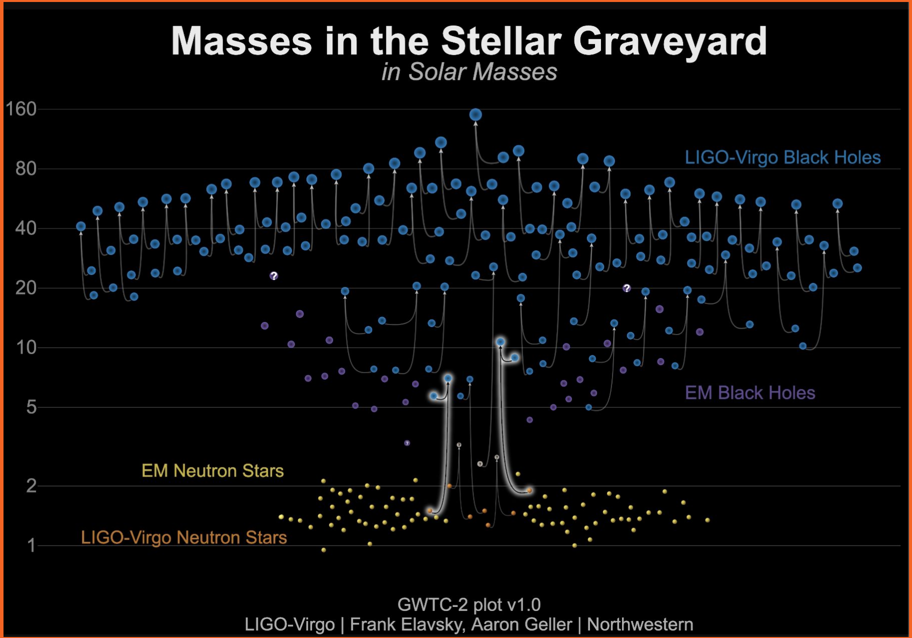
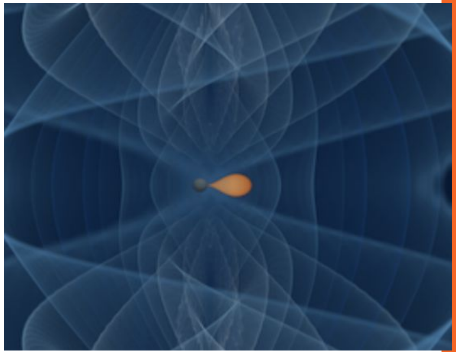
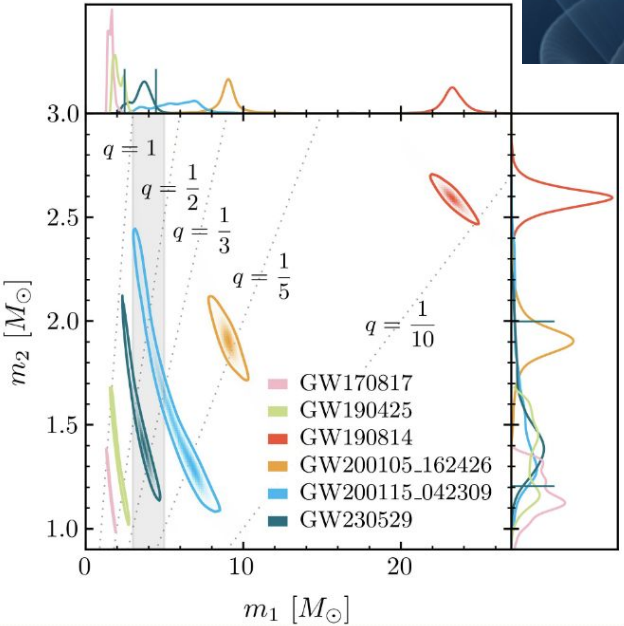


Image credit: LIGO

GW230529: Neutron Star-Black Hole (?) Merger



Images credit: LIGO

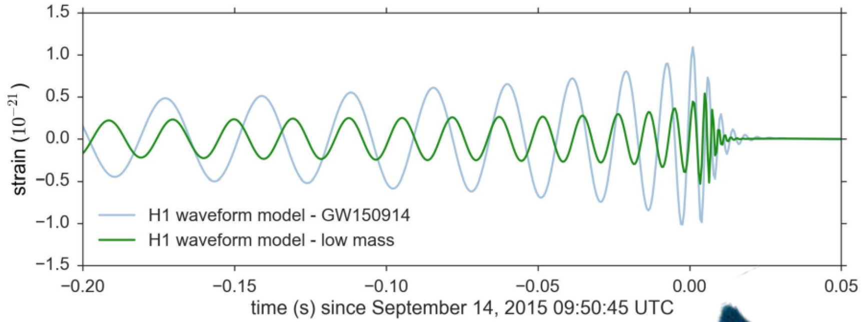


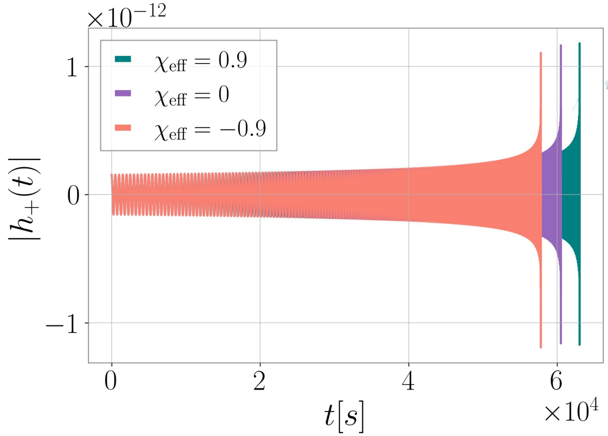
- Most recent LIGO publication, coalescence of a neutron star (between 1.2 and 2 times our sun's mass) and an object between 2.5 and 4.5 our sun
- Larger object lies within the mass gap between previously-thought maximum neutron star and minimum black hole mass, nature is uncertain
- Challenges our current understanding of how stellar black holes form from stars, and what the mass distribution of black holes is!

arXiv:2404.04248

Part 4: What can we learn about our universe using gravitational waves from CBCs?

Image credit: V Raymond





Masses

Spins

Soichiro Morisaki's lecture

Parameter Estimation

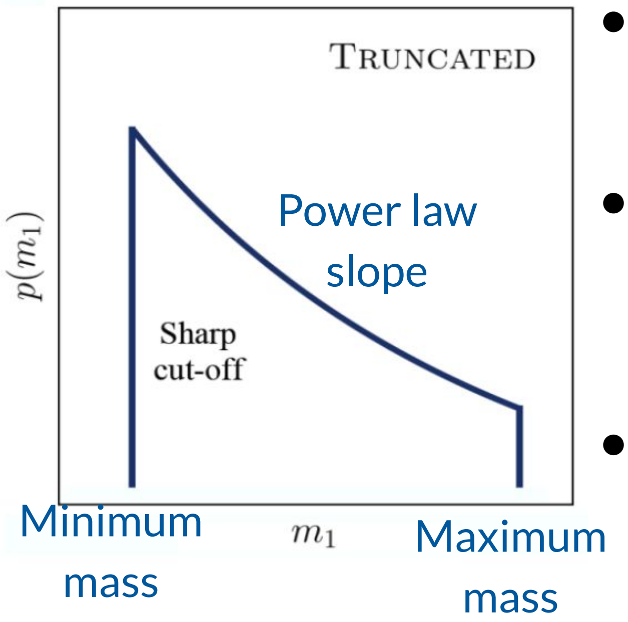
Properties of compact objects change the shape of the gravitational wave, so by analysing the signal we can infer:

- How heavy is each object?
- How fast are they spinning?
- Where and when did they merge?
- How deformable are the neutron stars?

We can use CBCs to infer the properties (masses, spins...) of the individual compact objects.

Rates and Populations

Image credit: GWTC-2 Population



- Given individual gravitational wave events, we can constrain the distribution of compact objection properties (masses, spins…) across a population.
- Example: fit a power law to black hole masses, population parameters are power law slope, minimum black hole mass, maximum black hole mass
- Use posteriors of individual events to constrain these population parameters

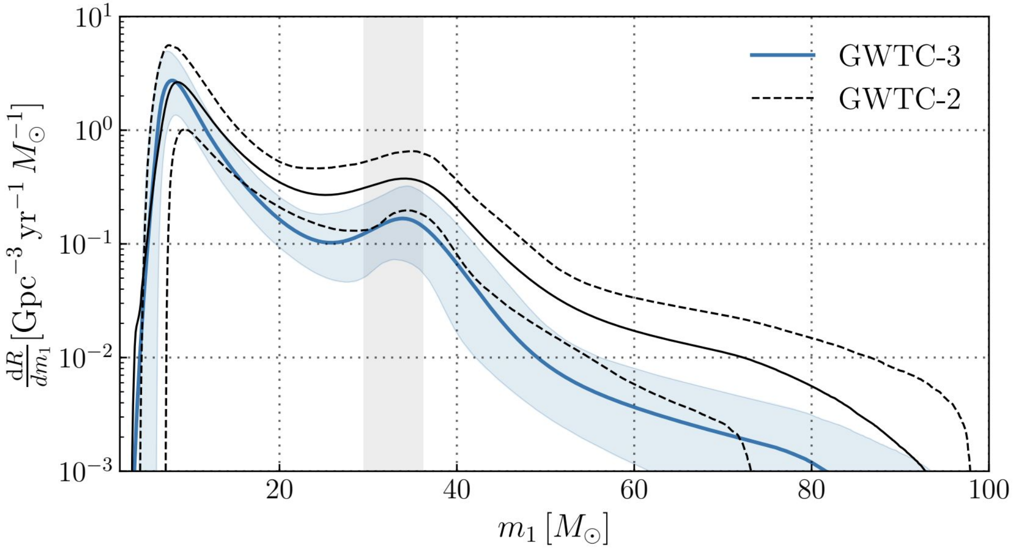
arXiv 2111.03634

We can use CBCs to infer the distributions of compact object properties in the Universe.

Rates and Populations

Population questions we can ask:

- What is the lightest black hole and heaviest neutron star mass? Is there a mass gap?
- Are there hints at multiple distinct binary formation pathways in the masses or spins?
- Does the distribution of black hole masses change with cosmic time?

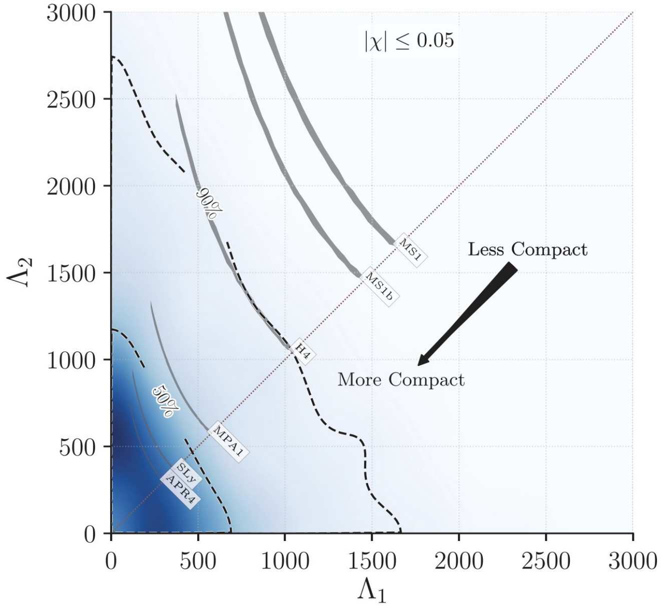


Most recent inferred primary mass distribution. Image credit: GWTC-3 Population

We can use CBCs to deduce how compact object binaries form, and how rare merger events are.

Extreme Matter

Image credit: GW170817 LIGO



We can use CBCs to constrain how matter behaves under extreme conditions.

- Neutron stars are invaluable laboratories for the most extreme matter in the universe
- Neutron star matter deforming will modify the signal during coalescence, in a way which we may be able to detect (parameterised by tidal deformabilities)
- With GWs we can measure NS tidal deformability and constrain equation of state
- GW170817 suggests neutron stars are 'soft', not very squishy!

—— Phys Rev X 9, 011101

Short GRBs and Kilonovae

- Both kilonovae and short GRBs associated with mergers of binary neutron stars
- When neutron stars merge, they form heavy elements through the r-process
- As the material is ejected in the merger event it produces radiation in the form of a kilonova
- With constraints on neutron star matter, can constrain the r-process in kilonovae and ask how many heavy elements neutron stars produce

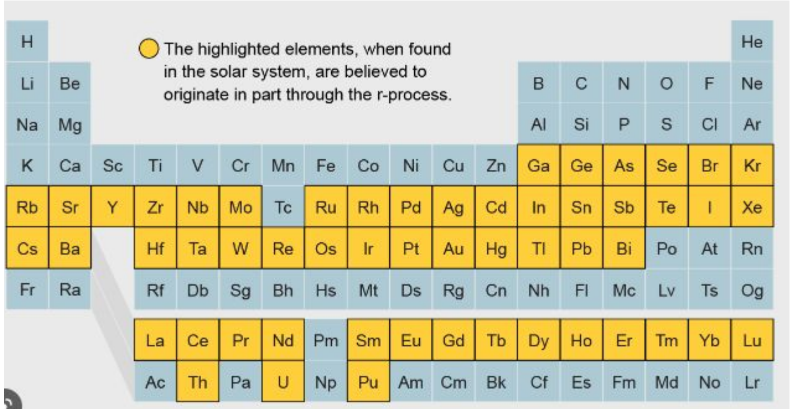


Image credit: Jen Christiansen

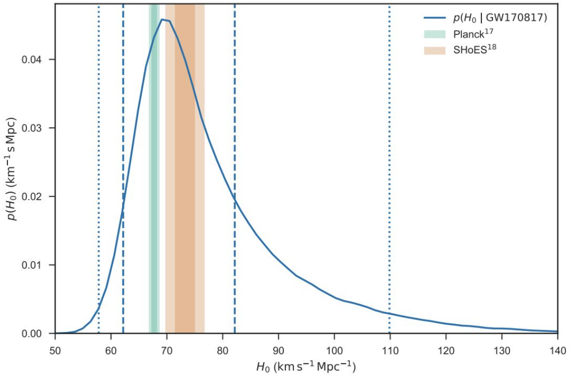
[Nature 551, 85–88 (2017)]

$$z = \frac{H_0}{c} d_L$$

Luminosity distance, from gravitational wave

Redshift, from electromagnetic counterpart or galaxy catalogue

- Universe is expanding, H_0 describes the rate at which the Universe is currently expanding
- If EM counterpart, can use redshift information to get H_0 ('bright siren')
- If no counterpart can compare redshift to galaxy catalogues to figure out probably host galaxies ('dark siren)



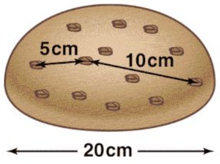
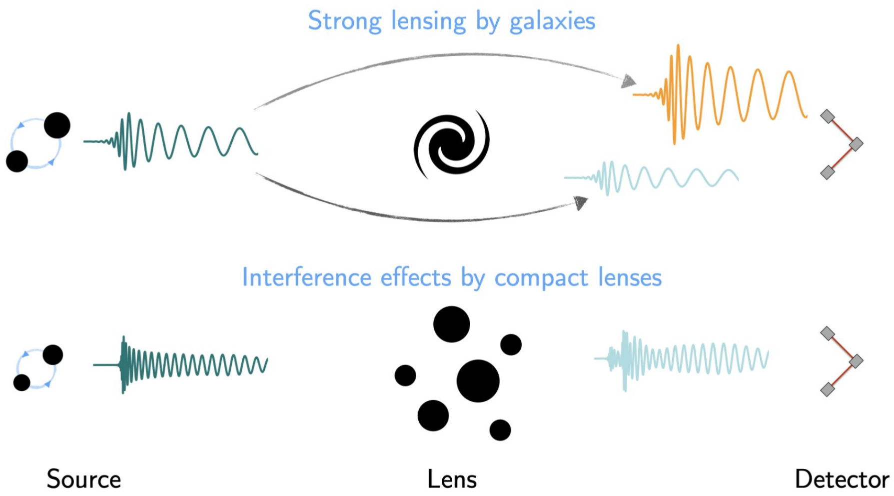


Image credit: LIGO Cosmology

We can use CBCs to infer how fast the Universe is expanding, and how old it is.

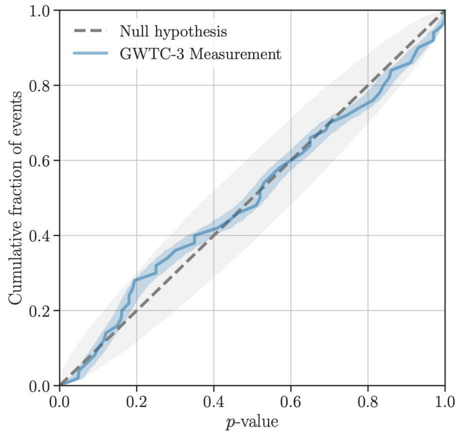
Testing General Relativity

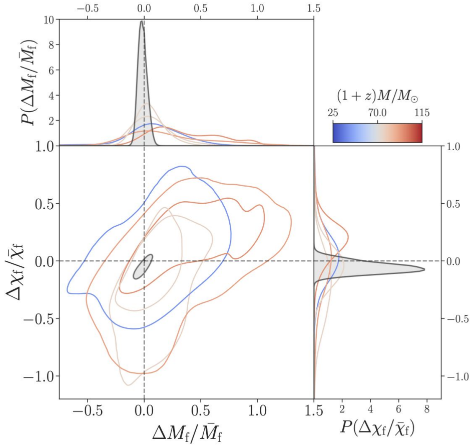


- Is general relativity the correct description of our universe?
- GW170817 GW+counterpart places constraints on GW propagation speed, so far consistent with General Relativity
- GR predicts the effect of gravitational lensing, if lensed signal found can test this predictions (no evidence yet)

arXiv 2112.06861

Image credit: LIGO





Testing General Relativity

- CBC waveforms assume General Relativity
- Can use tests of missing information in waveforms to constrain deviation from GR:
  - Residual tests look at coherent signal-to-noise ratio after subtracting best-fit waveform
  - IMR (inspiral-merger-ringdown) consistency checks to see if masses and spins from different parts of signal match
  - Modifications to inspiral of waveform to check for lost information
- No evidence yet for alternative theory of gravity!

We can use CBCs to test if General Relativity is the correct description of gravity.

Images credit: GWTC-3 Testing General Relativity

Summary

- Compact objects are dead stars, and can exist in binaries
- Many exciting mergers of CBCs including black holes and neutron stars have been detected in gravitational waves by LIGO, with a huge variety of astrophysical implications
- We can use gravitational waves from CBCs to infer populations, cosmology, neutron star matter, and test the nature of gravity
- We are just beginning the second half of the fourth observing run- many exciting discoveries to come!

Thank you for your attention!

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