Compact Binary Coalescences Observed by the LIGO-Virgo-KAGRA Collaboration during the First Three Observing Runs

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17Th Marcel Grossmann Meeting 2024

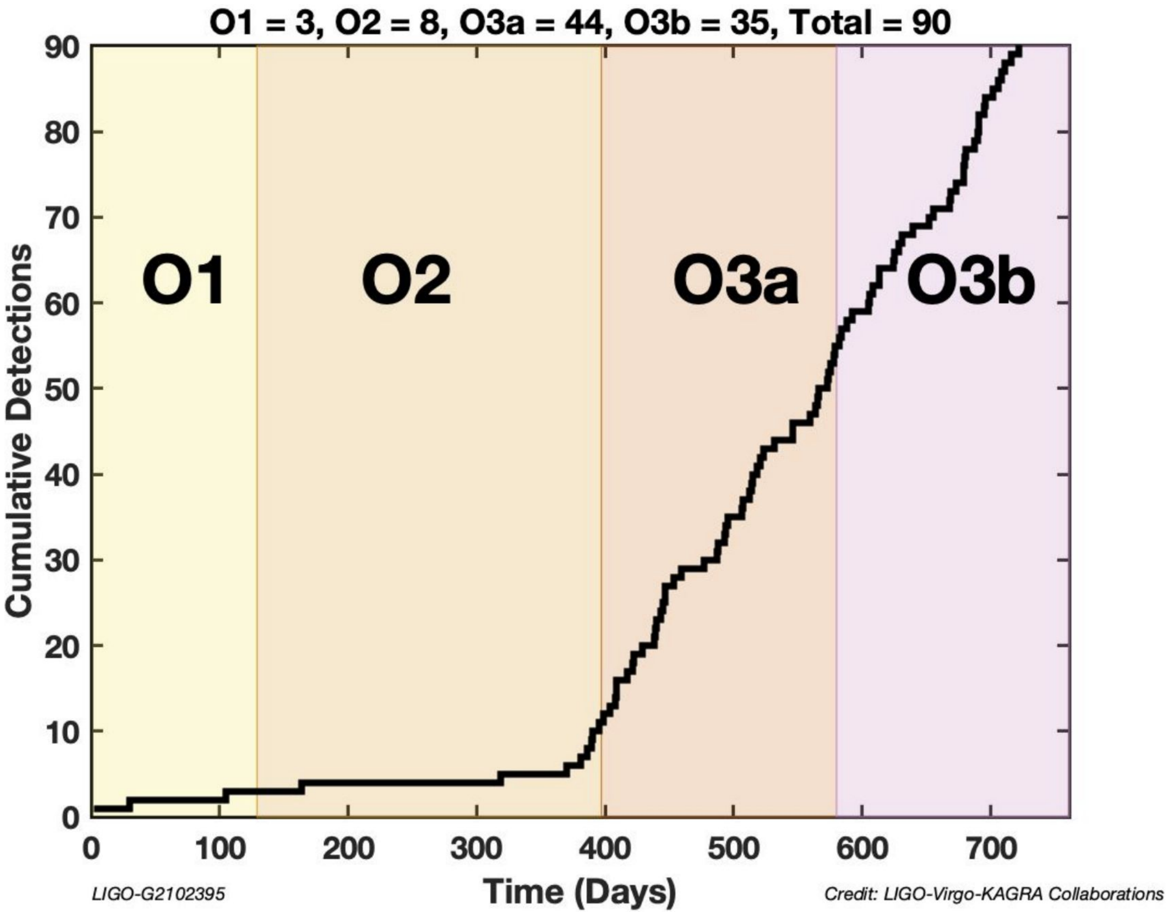
A century-long story

Gravitational Waves are ripples in the fabric of spacetime

Predicted by A. Einstein in **1916**

Directly detected in **2015** by the LIGO-Virgo-KAGRA Collaboration detectors

All the observed signals are emitted by merging binaries of compact objects, a.k.a. **Compact Binary Coalescences** (CBCs)



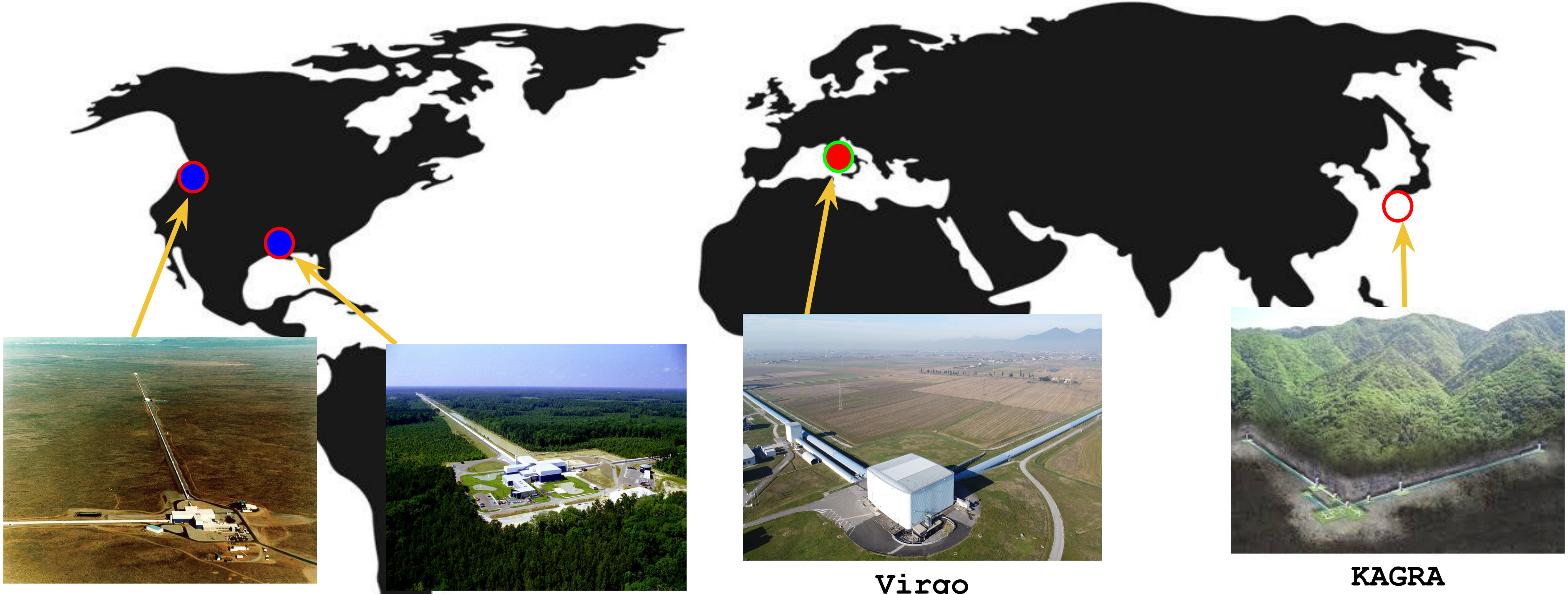
Sep 2015
Jan 2016

Nov 2016
Aug 2017

Apr 2019
Oct 2019

Nov 2019
Mar 2020

The LIGO-Virgo-KAGRA (LVK) Detector Network



LIGO
Hanford
(Washington)

LIGO
Livingston
(Louisiana)

Virgo
Cascina
(Italy)

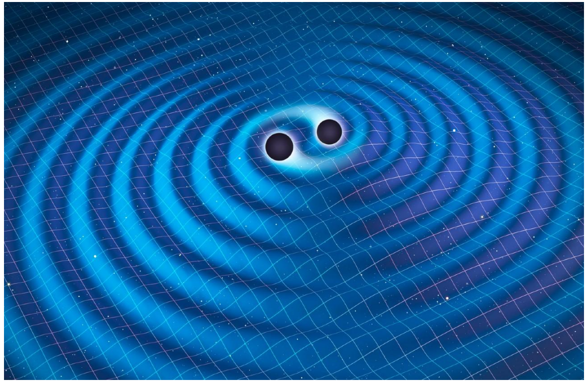
KAGRA
Kamioka mine
(Japan)

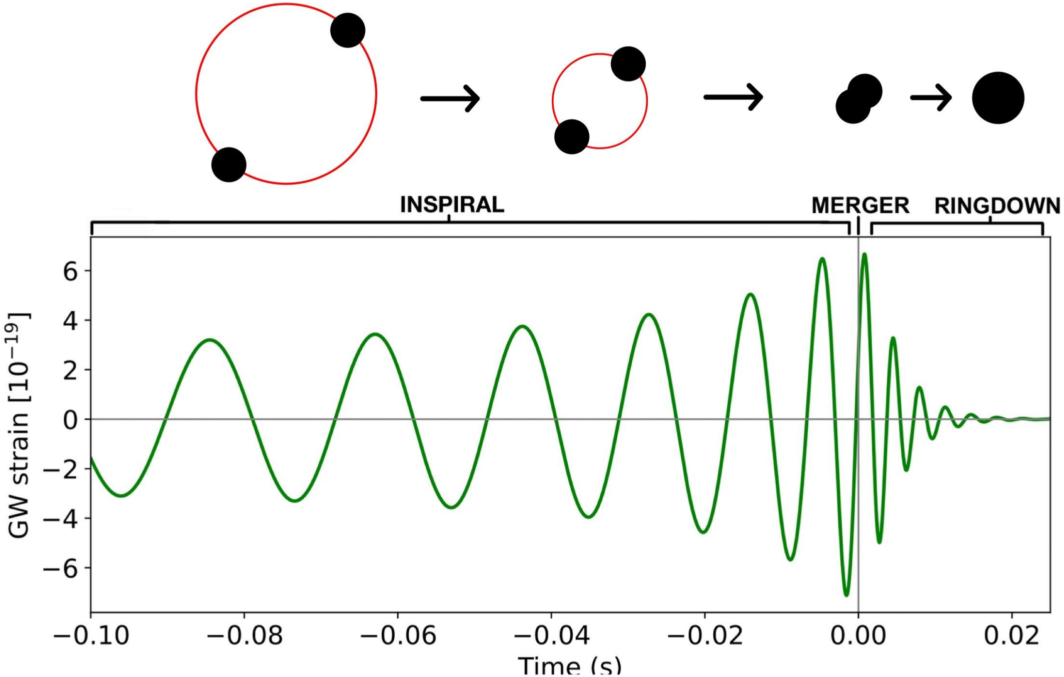
Compact Binary Coalescences (CBCs)

Compact Binary Coalescences (CBCs) are among the most relevant GW emitters in the Universe, they are the sources of all the GW signals detected so far by the LIGO-Virgo-KAGRA Collaboration network.

CBCs can be formed by:

- **Binary Black Holes** (BBH)
- **Binary Neutron Stars** (BNS)
- **Neutron Star - Black hole** systems (NSBH)





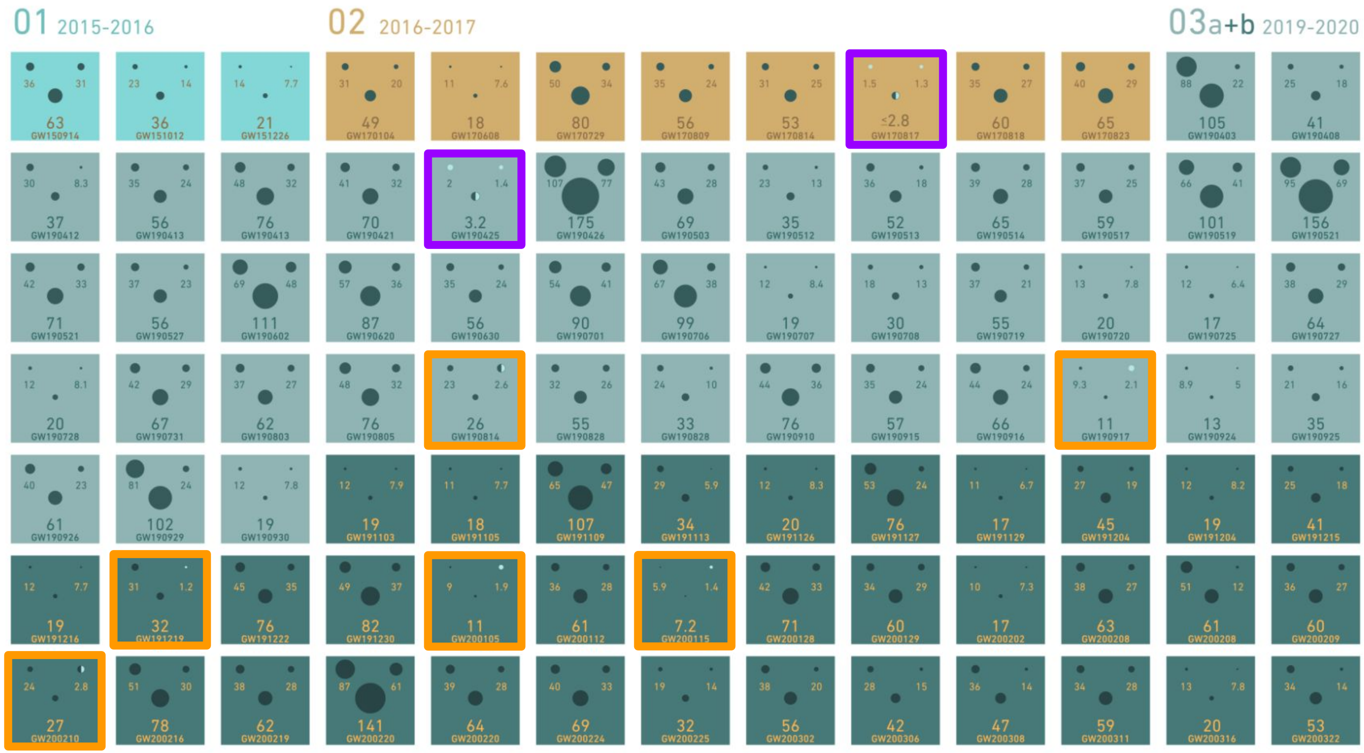
The Gravitational-wave Transients Catalog (GWTC)

The 90 events confidently-detected by the LVK Collaboration are collected in the **Gravitational-wave Transients Catalog** (GWTC)

Among them we have:

- **2** Binary Neutron Stars
- **2** Neutron Star - Black Hole systems (plus 4 potential ones)

All the others are confidently stellar- mass black hole binaries



https://www.ligo.org/news.php

Strain data for GWTC events are publicly downloadable from **GWOSC** website

GW150914 - The First Historical Detection

Discovery paper

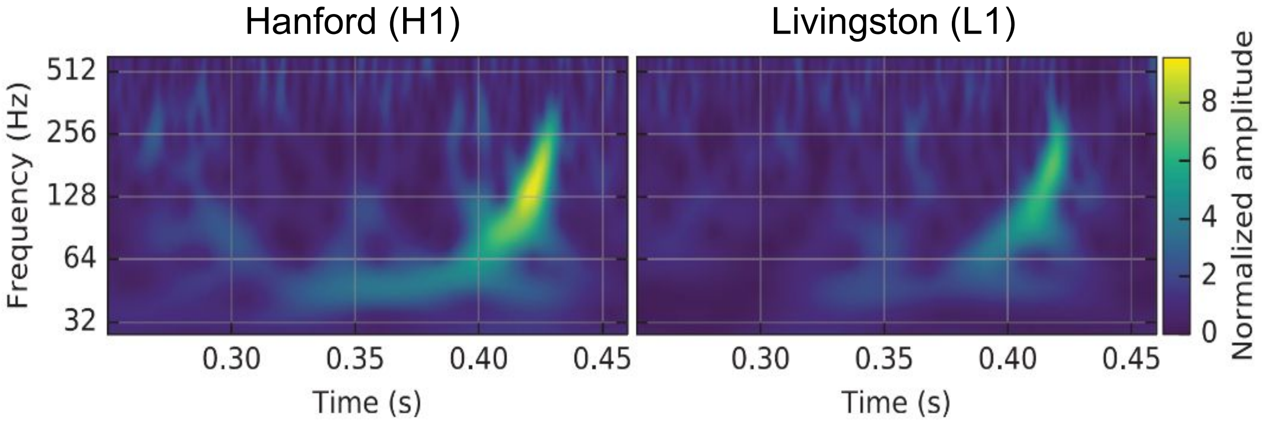
Source: **Binary Black Hole**

Component masses:

- ➔ m1 = $\mathbf{35^{+5}_{-3}\,M_\odot}$
- ➔ m2 = $\mathbf{30^{+3}_{-4}\,M_\odot}$

Mass of the final product:

- ➔ M_{fin} = $\mathbf{63^{+3}_{-3}\,M_\odot}$



Final black hole was more massive than any other previously measured with X-ray binaries

First observational evidence that BBH actually form in nature, with properties such that they merge in the local universe.

GW170817 - The Birth of GW Multi-Messenger Astronomy

Discovery paper

The **first** Binary Neutron Star detected by the LVK Collaboration

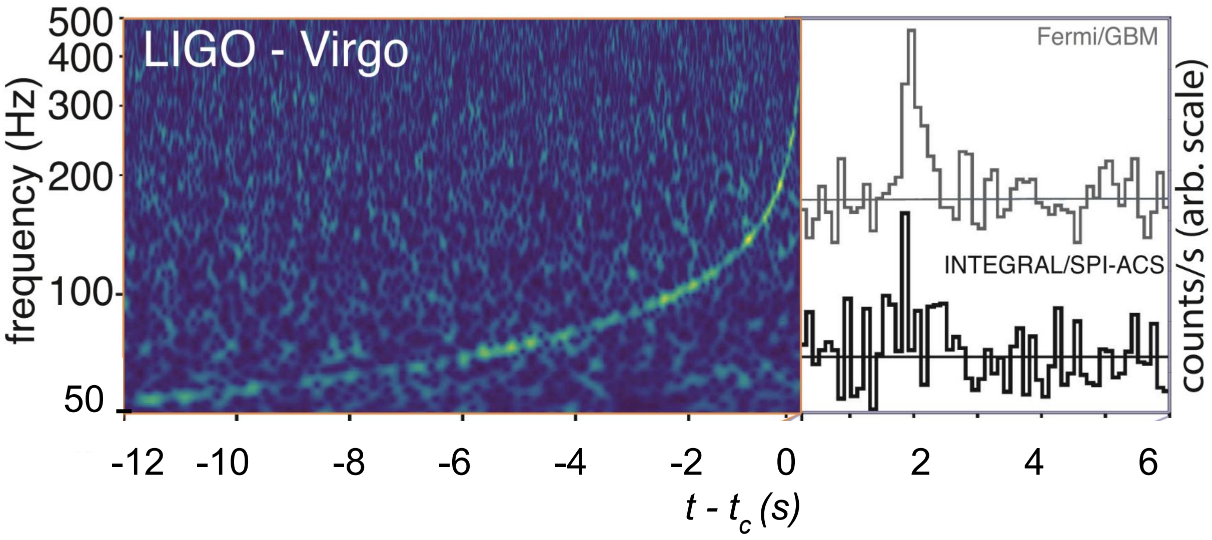
Component masses:

➔ m1 = **[1.36 , 1.89] $M_\odot$**

➔ m2 = **[1.00 , 1.36] $M_\odot$**

Electromagnetic counterparts were jointly detected:

- **Short Gamma Ray Burst** and its delayed **Afterglow** (γ-rays, X-rays, Radio)
- **Kilonova** (UV, Optical, IR)



LVK Collab. (2017)

Insights on short Gamma Ray Bursts (sGRBs) and Kilonovae

The first evidence that binary neutron stars are progenitors of such events

Constraints on central engine and jet structure of sGRBs

Evidence that BNS produce r-process heavy nuclei

Hubble constant measurement

Luminosity distance d_L is measured from the GW signal

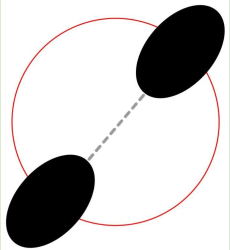
EM counterpart allowed to identify the host galaxy: NGC 4993;

➔ Estimation of the redshift z

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

Constraints con NSs equation of state

Tidal deformations of NSs in the binary has a direct imprint on the gravitational signal emitted by the systems



NSs deformability is heavily dependent on the equation of state of matter in its inside

Some of stiffest EOS were ruled out

Speed of gravity test

EM theory minimally coupled to general relativity predicts that GWs and light propagate with identical speeds

Delay between GW and EM signal was (1.74 ± 0.05) s, across a distance greater than 100 million light years

➔ Stringent constraints on deviations from fundamental physics

GW190521: The Heaviest Merger Ever Detected

Discovery paper

The most massive Binary Black Holes detected so far:

Component masses:

➔ $m1 = \mathbf{85^{+21}_{-14}\ M_\odot}$

➔ $m2 = \mathbf{66^{+17}_{-18}\ M_\odot}$

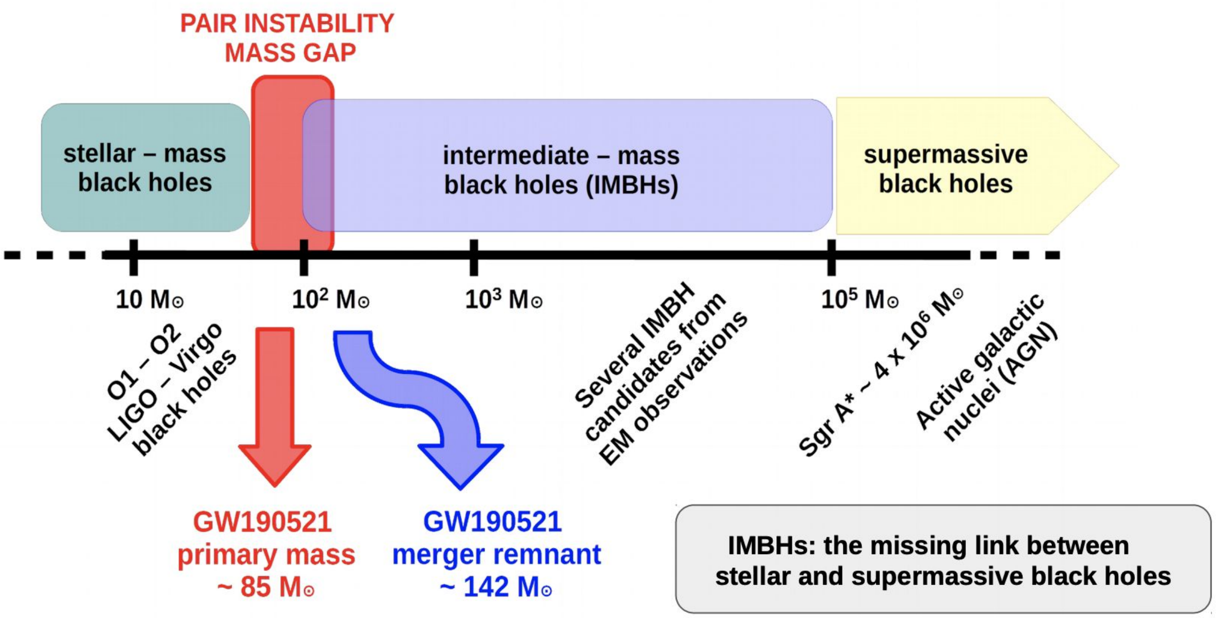
Mass of the merge product:

➔ $M_{fin} = \mathbf{142^{+28}_{-16} M_\odot}$

Challenges our understandings of black hole formation:

- The primary mass falls in the **Pair Instability mass gap**

- The final product falls in the **Intermediate Mass Black Holes** mass range



Other relevant events

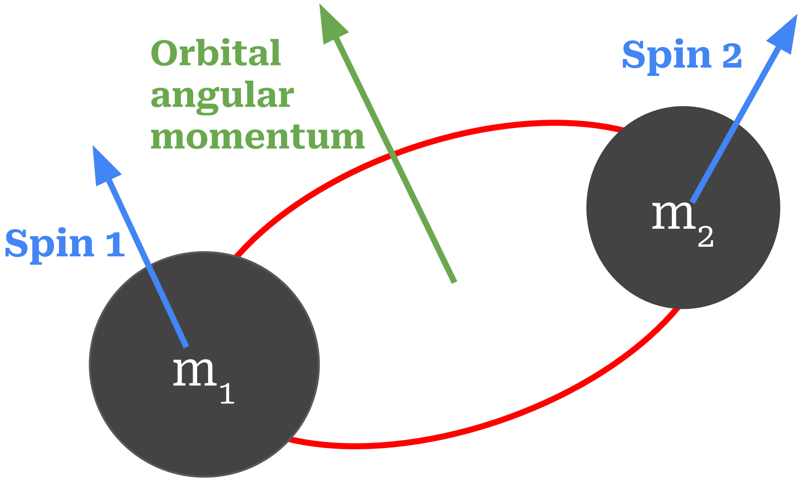
Other events containing Neutron Stars:

- **GW190425** → The only other binary neutron star:
    - Higher total mass ($3.4^{+0.1}_{-0.3}\,M_{\odot}$) than any other previously known BNS
    - No tidal effects or EM counterpart
- **GW200105** and **GW2001115** → The first confident detections of Neutron star - black hole systems
    - No tidal effects or EM counterpart

Have we seen spin-induced general-relativistic orbital precession?

Component spins misaligned with the orbital angular momentum generate precessing binaries

GW200129 in O3b showed evidence for it, but with a dependance on the waveform adopted to model the signal

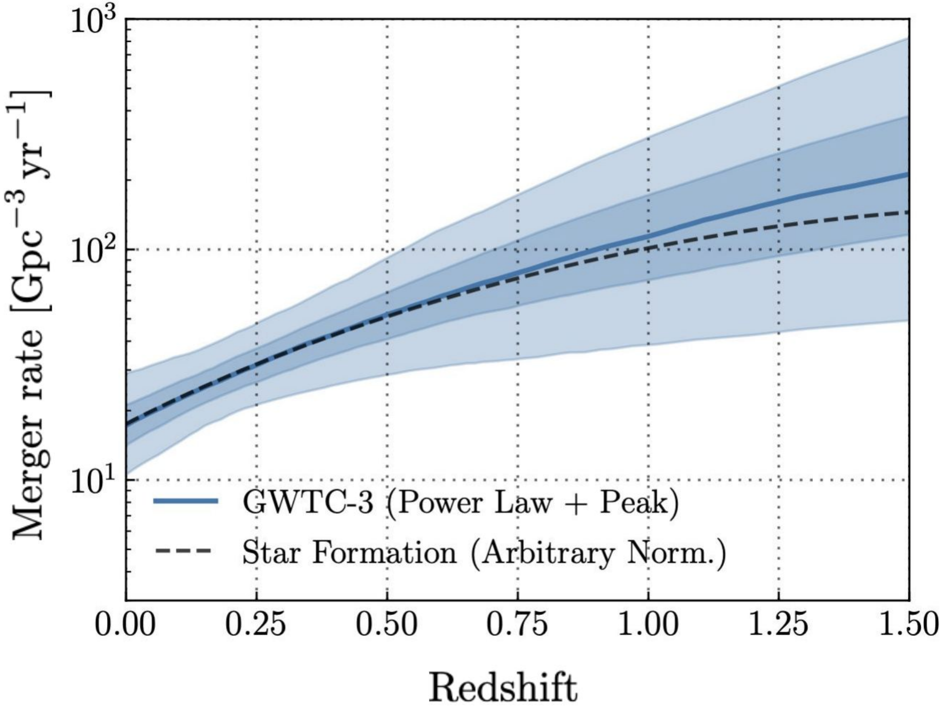


Exploiting the whole GWTC

We can take advantage of the full set of events in GWTC by means of **population studies**:

- Estimate merger rates
- Infer mass distributions to extract astrophysical properties

Cosmology:
We can measure the Hubble constant exploiting GW events as **Dark Sirens**



GWTC-3 Population studies, LVK Collab. (2023)

This is Not the End of the Story

- The nearly 100 detections performed by the LIGO-Virgo-KAGRA Collaboration in their first three observing runs have already provided unprecedented insights into several aspects of physics, from fundamental physics to astrophysics and cosmology.

- The fourth observing run (O4) of the LIGO-Virgo-KAGRA Collaboration is currently underway:

  → Exciting new events are waiting for us ... **Stay tuned!**

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THANKS
FOR THE
ATTENTION!

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