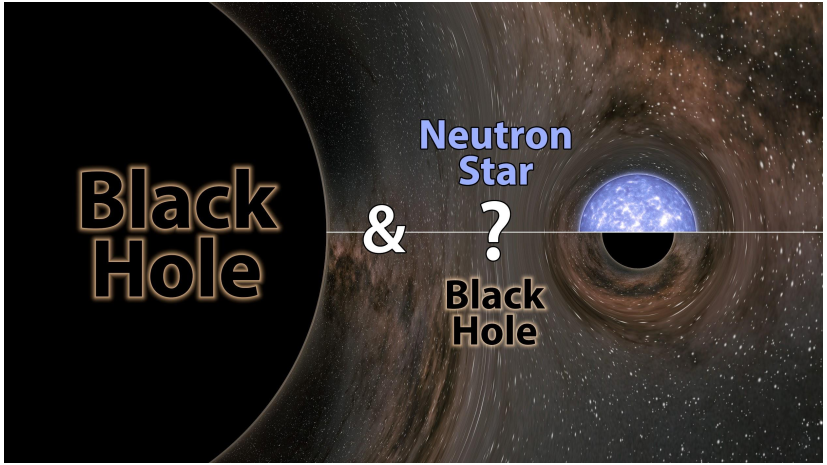
GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object

LIGO Scientific Collaboration and Virgo Collaboration

https://dcc.ligo.org/G2000963



R. Hurt

https://iopscience.iop.org/article/10.3847/2041-8213/ab960f

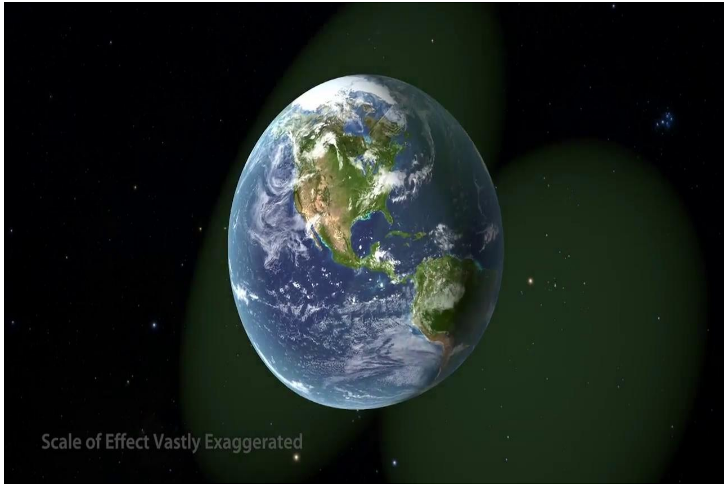
GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object

LIGO Scientific Collaboration and Virgo Collaboration

ABSTRACT

We report the observation of a compact binary coalescence involving a $22.2-24.3\,M_\odot$ black hole and a compact object with a mass of $2.50-2.67\,M_\odot$ (all measurements quoted at the 90% credible level). The gravitational-wave signal, GW190814, was observed during LIGO's and Virgo's third observing run on August 14, 2019 at 21:10:39 UTC and has a signal-to-noise ratio of 25 in the three-detector network. The source was localized to 18.5 deg^2 at a distance of 241^{+41}_{-45} Mpc; no electromagnetic counterpart has been confirmed to date. The source has the most unequal mass ratio yet measured with gravitational waves, $0.112^{+0.008}_{-0.009}$, and its secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system. The dimensionless spin of the primary black hole is tightly constrained to ≤ 0.07. Tests of general relativity reveal no measurable deviations from the theory, and its prediction of higher-multipole emission is confirmed at high confidence. We estimate a merger rate density of 1–23 Gpc^{-3} yr^{-1} for the new class of binary coalescence sources that GW190814 represents. Astrophysical models predict that binaries with mass ratios similar to this event can form through several channels, but are unlikely to have formed in globular clusters. However, the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models for the formation and mass distribution of compact-object binaries.

Gravitational waves

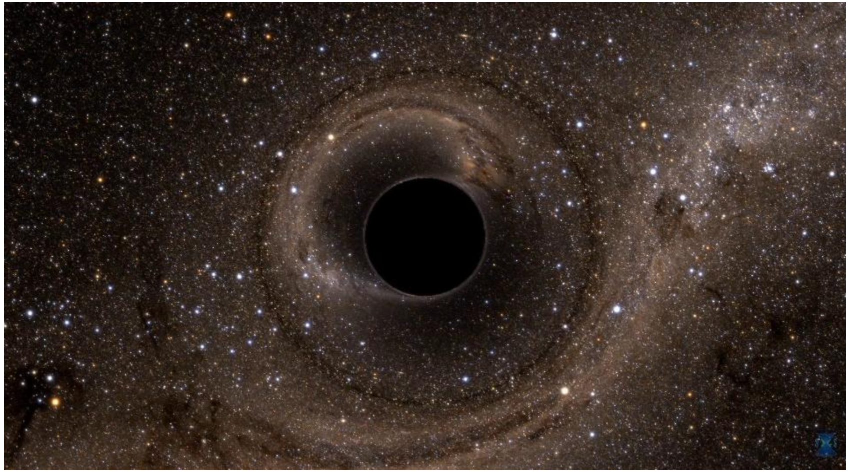


LIGO/R. Hurt

When massive, asymmetric objects move the curvature of spacetime changes

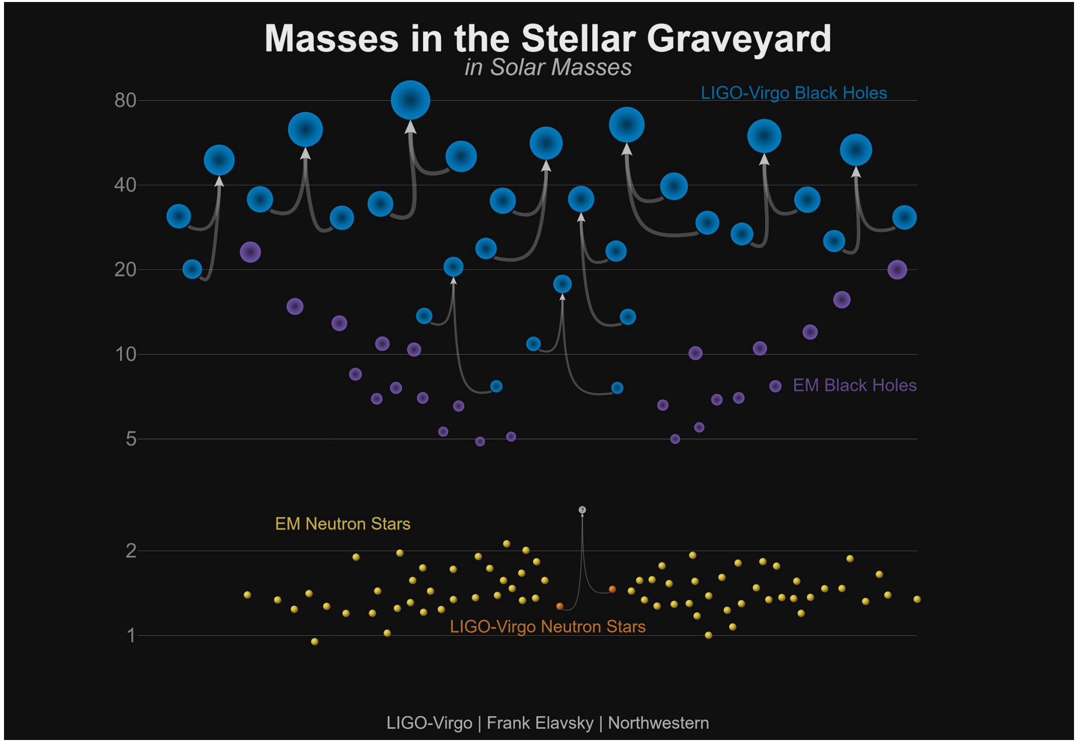
This change travels at the speed of light and are known as gravitational waves

Colliding black holes and neutron stars are the best sources of detectable gravitational waves


SXS

Where are we?

From O1 and O2:



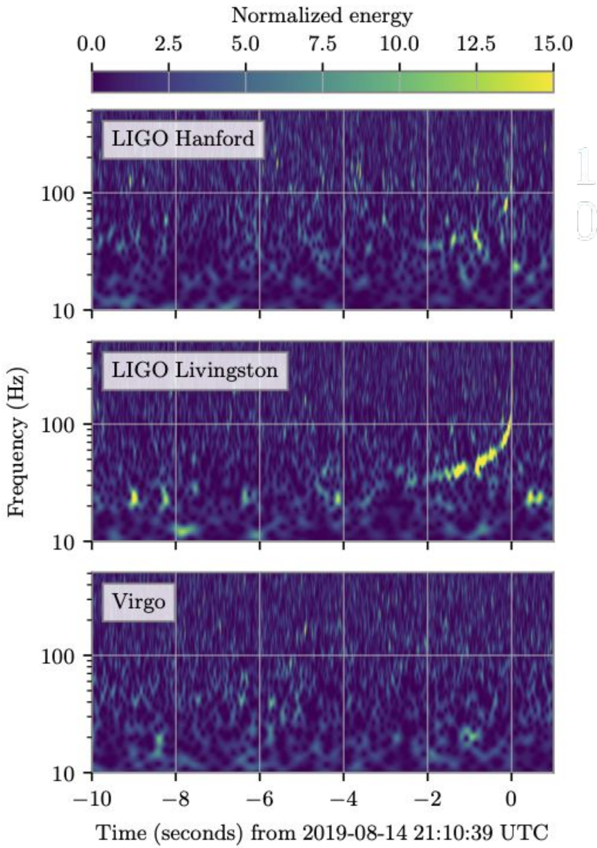
O3 (Apr 2019 - Mar 2020):

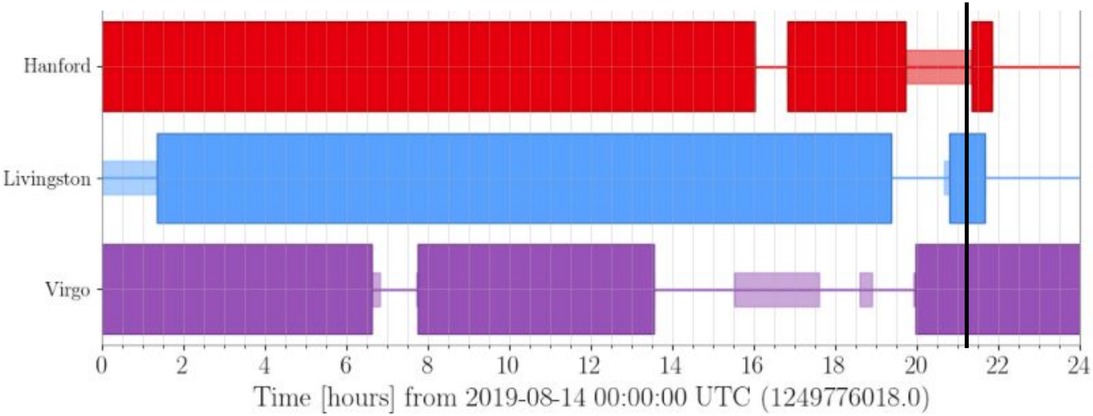
GW190425: Likely BNS with component masses between: 1.12-2.52 $M_\odot$

GW190412: BBH with component masses ~30 $M_\odot$ and ~8$M_\odot$

~50 candidate events from the O3 public alerts

At the time of GW190814...





- +/- 5 minutes around GW190814 no commissioning activities were taking place at Hanford
- We find no evidence instrumental or environmental disturbances could account for GW190814
- Note: there is some low-frequency transient noise due to scattered light in Livingston caused by thunderstorms

Detecting GW190814

14th Aug 2019
21:11 UTC

Loud 2-detector event by low latency GstLAL

~21:30 UTC

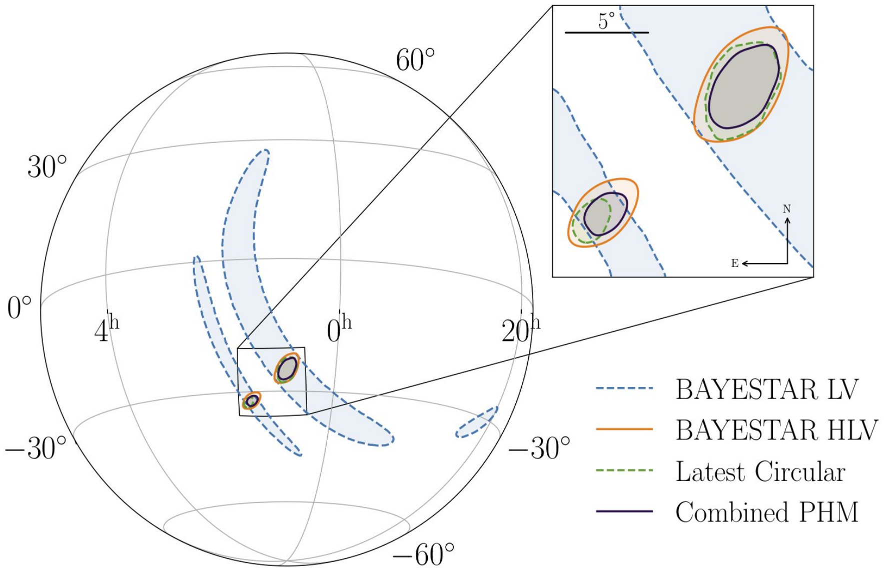
GCN issued:
- Blue skymap
- Classification = Mass Gap

~23:30 UTC

- GstLAL & PyCBC reanalysed data with 3 detectors
- SNR: Hanford 10.6, Livingston 21.6, Virgo 4.5
- GCN circular issued:
  - orange skymap (38 deg^2)

15th Aug 2019
~10:41 UTC

GCN circular:
- Green skymap (23 deg^2)
- Classification = NSBH



No electromagnetic or neutrino counterpart has been reported

Detecting GW190814

14th Aug 2019
21:11 UTC

Loud 2-detector event by low latency GstLAL

~21:30 UTC

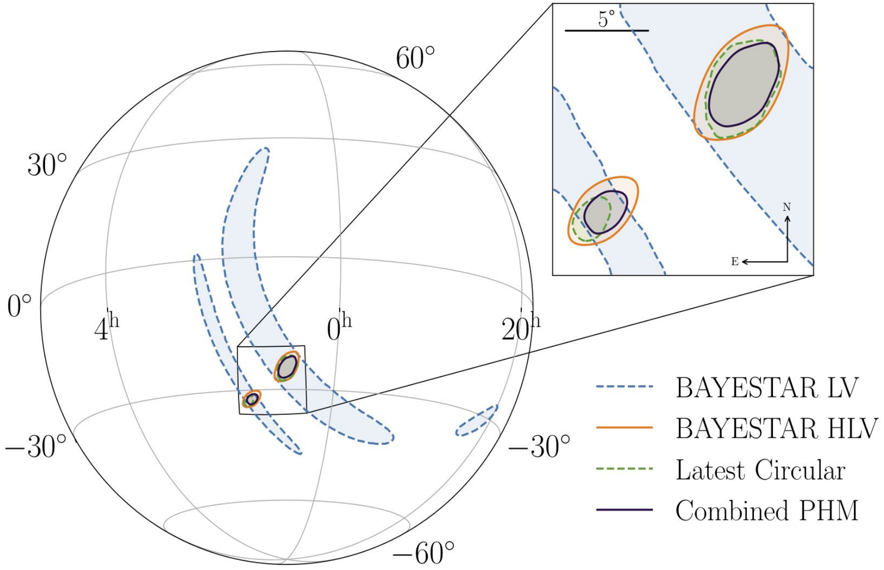
GCN issued:
- Blue skymap
- Classification = Mass Gap

~23:30 UTC

- GstLAL & PyCBC reanalysed data with 3 detectors
- SNR: Hanford 10.6, Livingston 21.6, Virgo 4.5
- GCN circular issued:
    - orange skymap (38 deg^2)

15th Aug 2019
~10:41 UTC

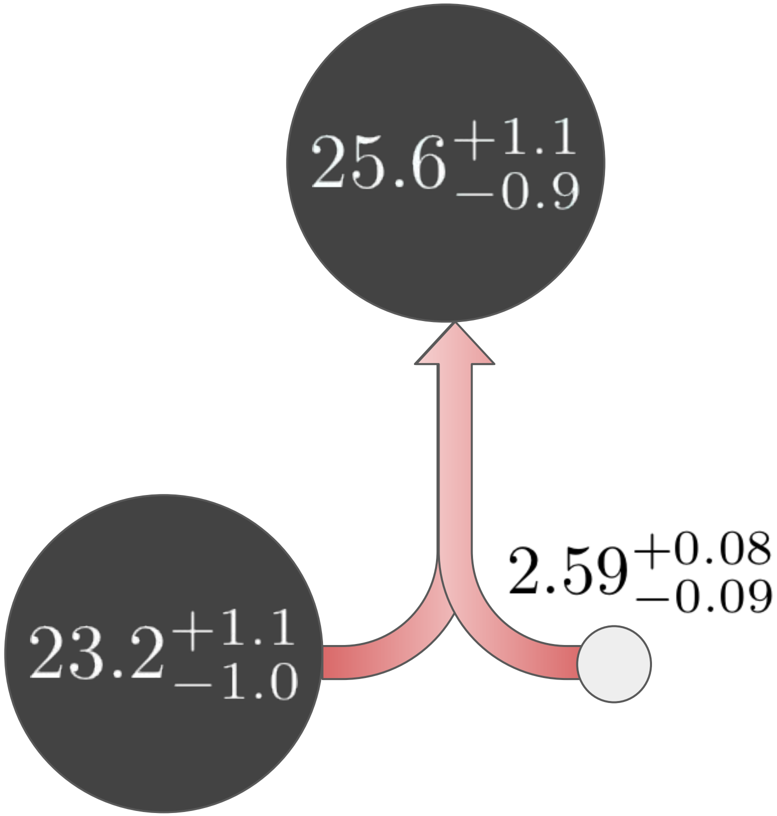
GCN circular:
- Green skymap (23 deg^2)
- Classification = NSBH

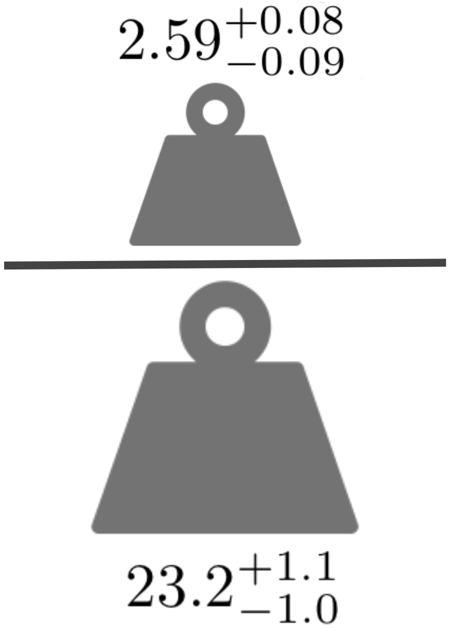


Significance:

- False alarm rate of < 1 in 42,000 years by matched-filtering searches.
  GW190814 is more significant than any event in background
- False alarm rate < 1 in 1000 years by unmodelled search

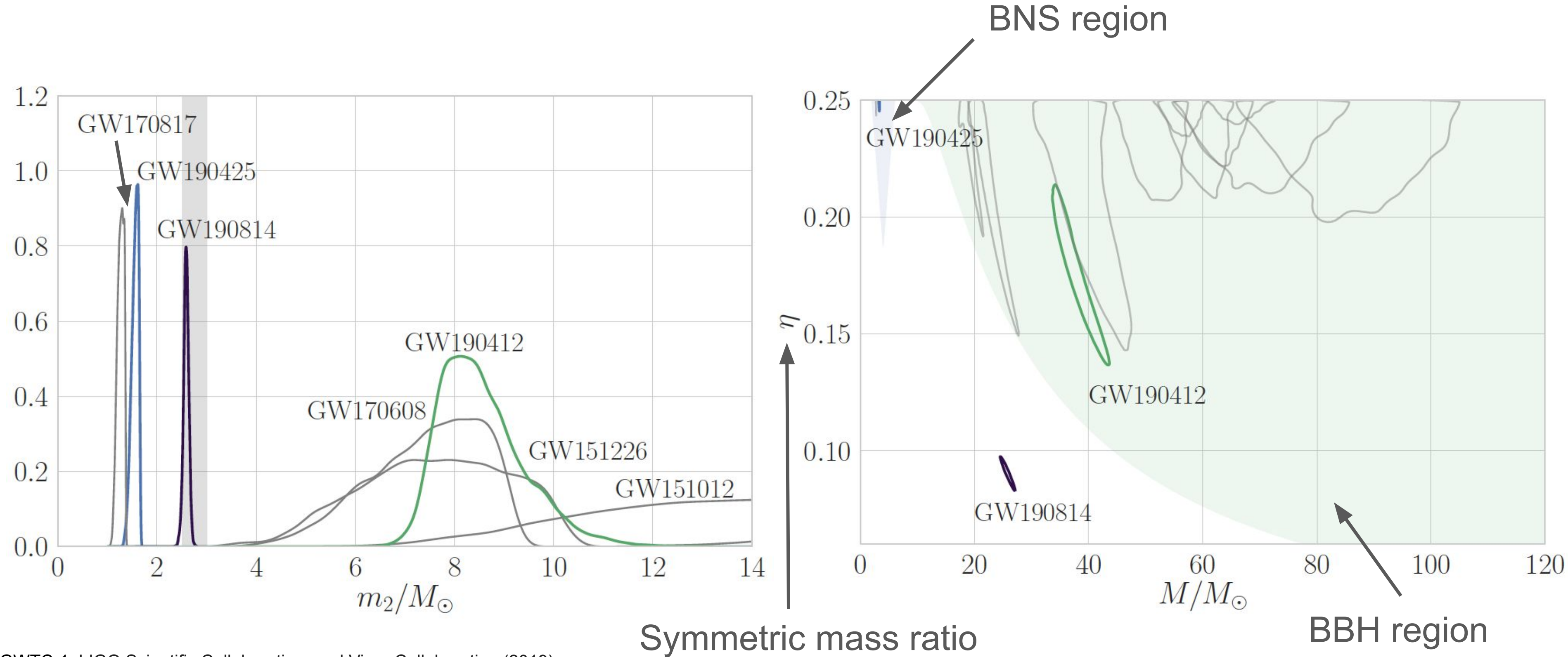
GW190814 - Source frame masses





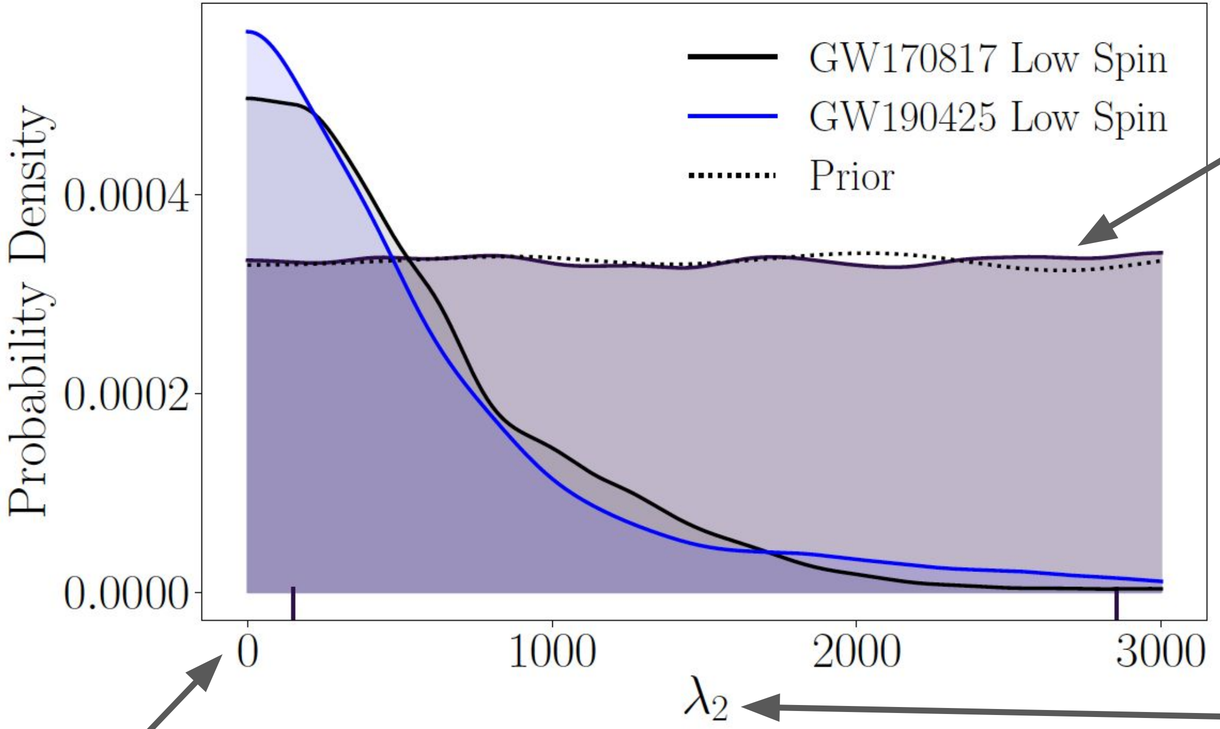
$$= 0.112^{+0.008}_{-0.009}$$

GW190814 - Source frame masses



GWTC-1: LIGO Scientific Collaboration, and Virgo Collaboration (2019)
GW190425: LIGO Scientific Collaboration, and Virgo Collaboration (2020)
GW190412: LIGO Scientific Collaboration, and Virgo Collaboration (2020)

GW190814 - Searching for tidal signatures



For GW190814, we recover no information about the tidal deformability of the secondary object.

Tidal deformability of the secondary object

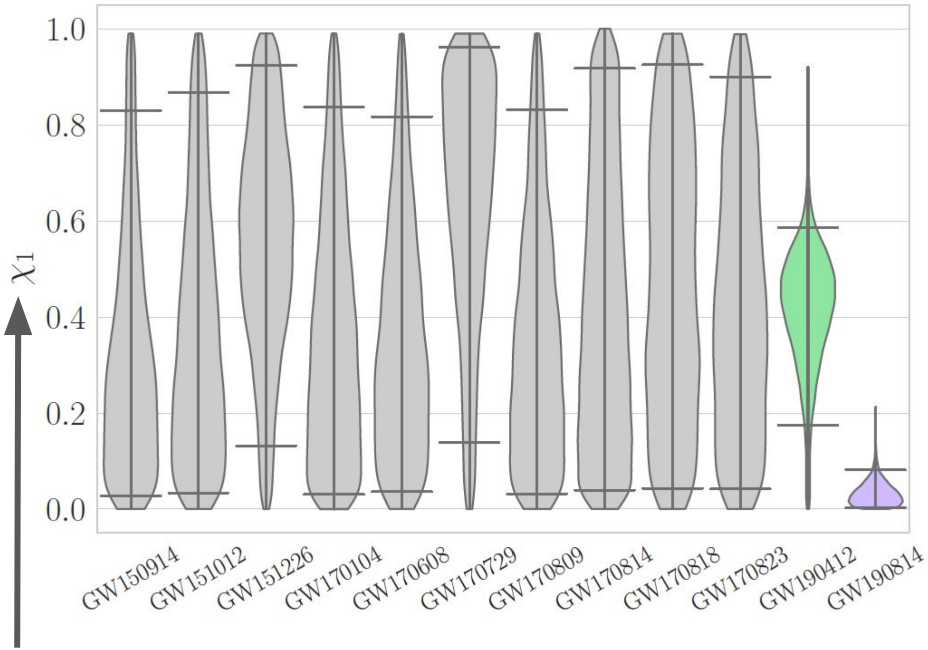
BH regime

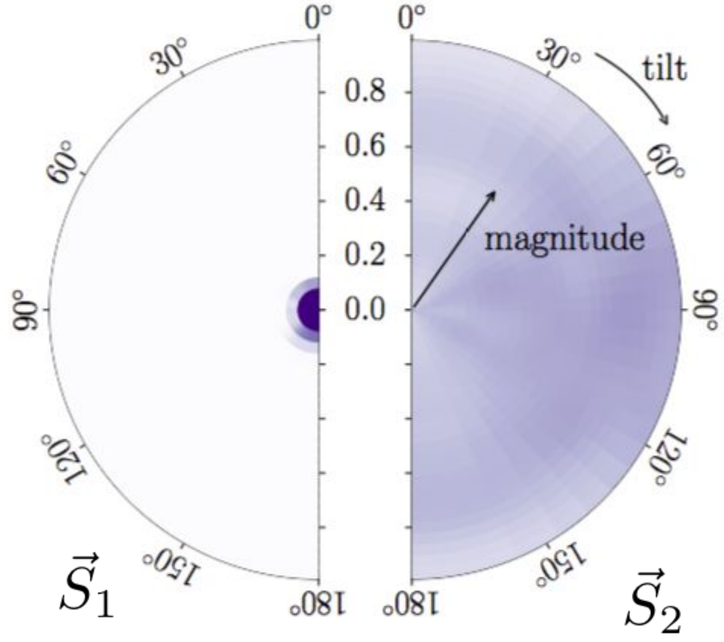
GW190814 - Spins

Upper bound on primary spin magnitude χ_1 : 0.07

Effective inspiral spin parameter $\chi_{\rm eff}$: $-0.002^{+0.060}_{-0.061}$

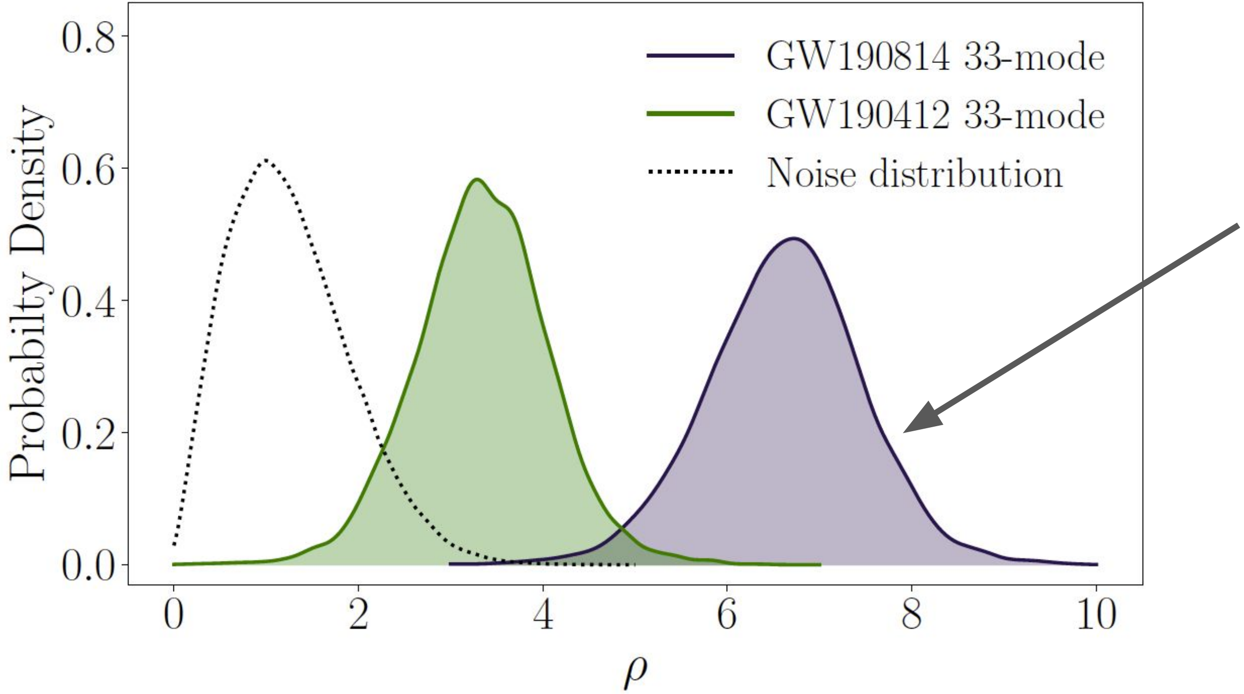
Upper bound on effective precession parameter $\chi_{\rm p}$: 0.07





Primary spin magnitude

Higher order multipoles



GW190814 has the strongest evidence for Higher order multiples that we have ever detected.

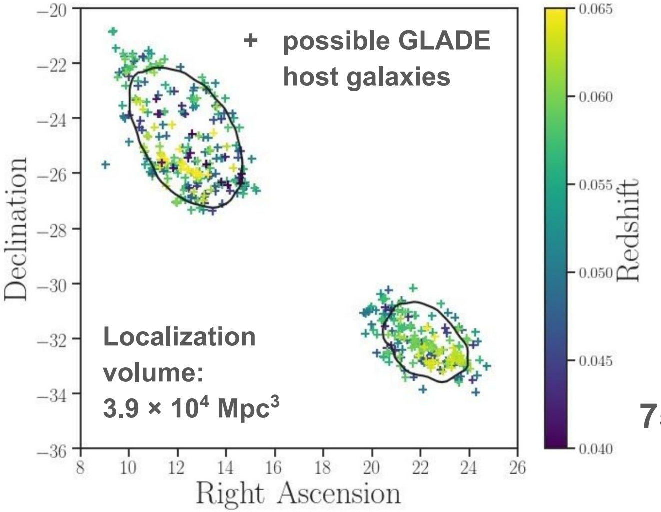
SNR in 33 multipole nearly as high as the total SNR of GW151012

Validating Einstein and Hubble

GW190814 enables tests of gravity in the highly unequal mass-ratio regime.

- Spin-induced quadrupole test
- Parameterized inspiral test
- Residuals analysis

General relativity validated by all three tests



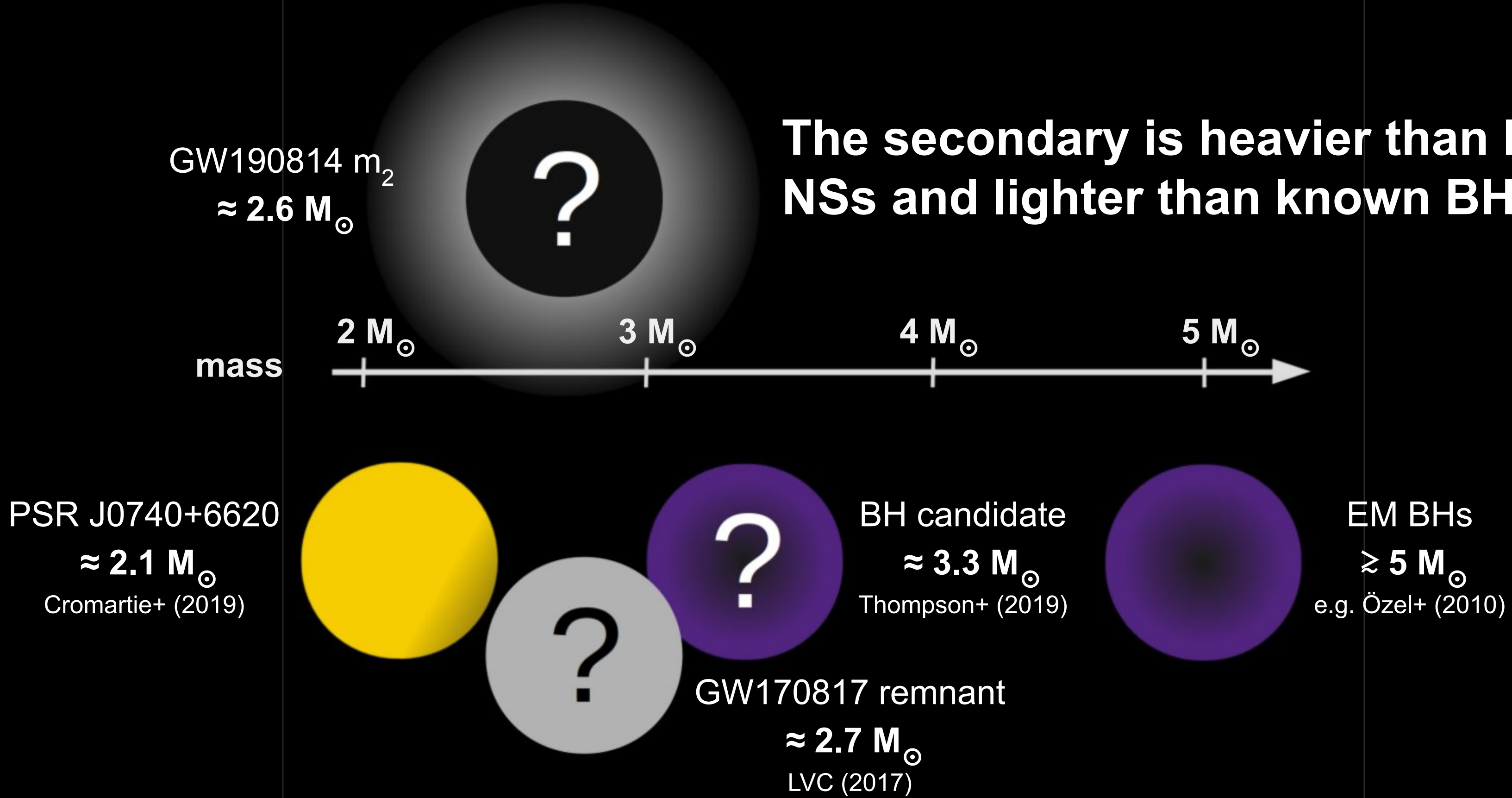
GW190814 is the best dark siren to date.

Hubble constant estimated via statistical cross-correlation with possible host galaxies

GW190814 H_0	GW170817 + GW190814 H_0	Planck 2018 H_0
75^{+59}_{-13} km s^{-1} Mpc^{-1}	**70^{+17}_{-8} km s^{-1} Mpc^{-1}**	**$67.4^{+0.5}_{-0.5}$ km s^{-1} Mpc^{-1}**

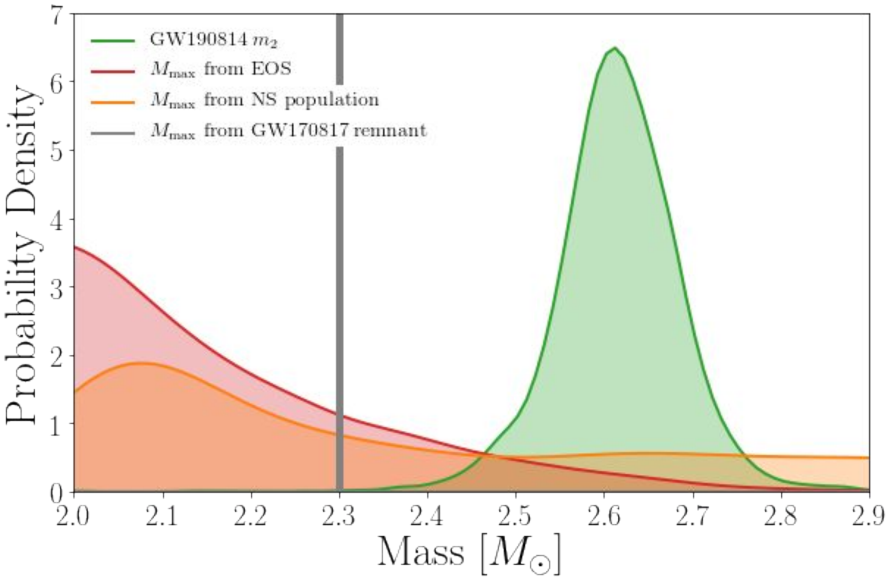
Compact object from the mass gap

The secondary is heavier than known NSs and lighter than known BHs.



Heavy neutron star or light black hole?

The secondary mass is above typical estimates of the maximum NS mass.



M_{max} from EOS (LVC 2018): spectral EOS analysis of GW170817, $M_{max} \lesssim 2.4\ M_\odot$ (90% CL)

$P(m_2 \leq M_{max}) \approx 3\%$

M_{max} from NS pop (Farr+Chatziioannou 2020): fit to Galactic NS population, $M_{max} \lesssim 3.1\ M_\odot$ (90% CL)

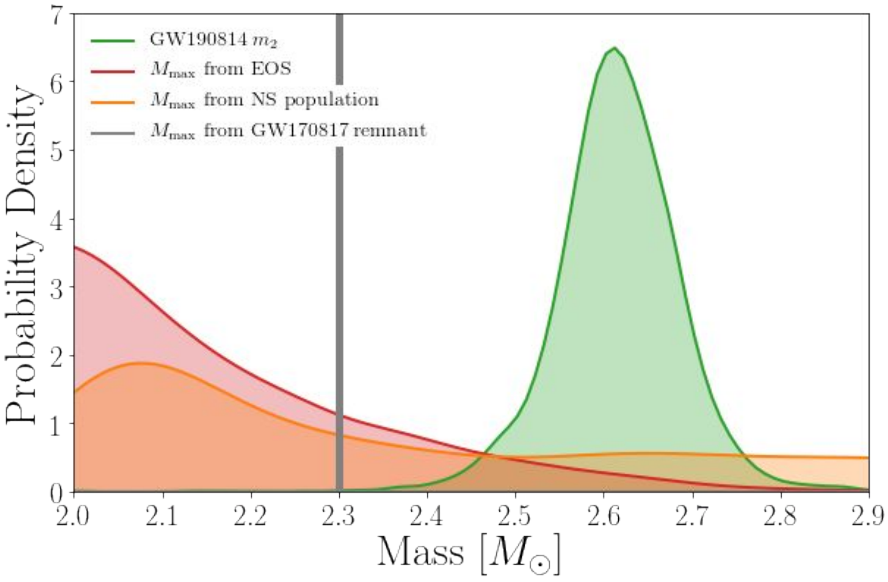
$P(m_2 \leq M_{max}) \approx 29\%$

M_{max} from GW170817 remnant (e.g. LVC 2020): map threshold for collapse of rotating remnant to nonrotating maximum mass, $M_{max} \lesssim 2.3\ M_\odot$

$P(m_2 \leq M_{max}) \ll 1\%$

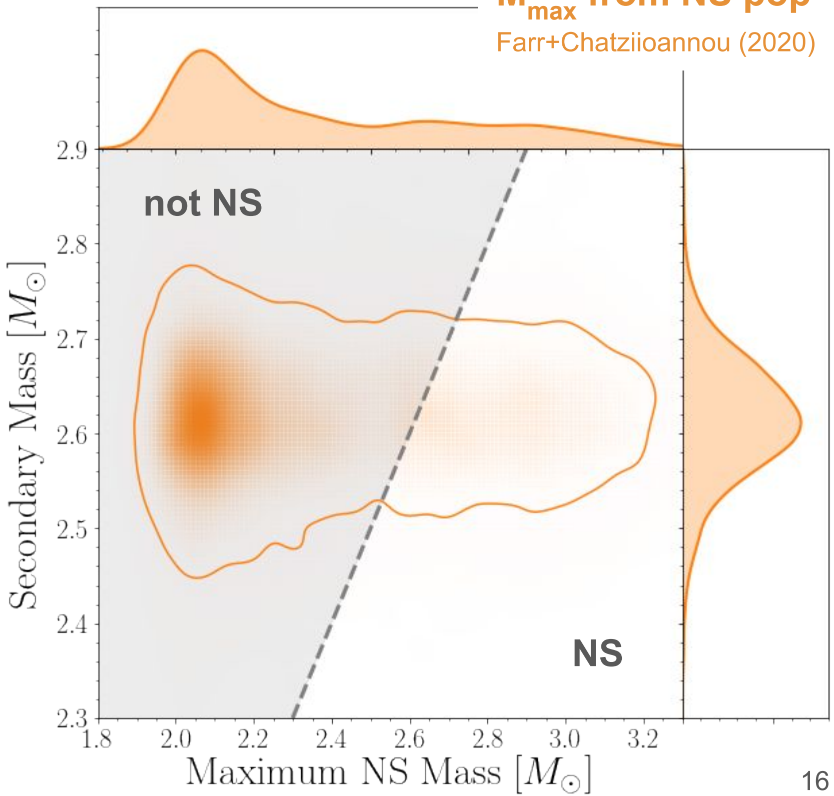
Heavy neutron star or light black hole?

The secondary mass is above typical estimates of the maximum NS mass.



M_{max} from NS pop

Farr+Chatziioannou (2020)



Rate of GW190814-like mergers

GW190814 represents a new class of compact binary mergers.

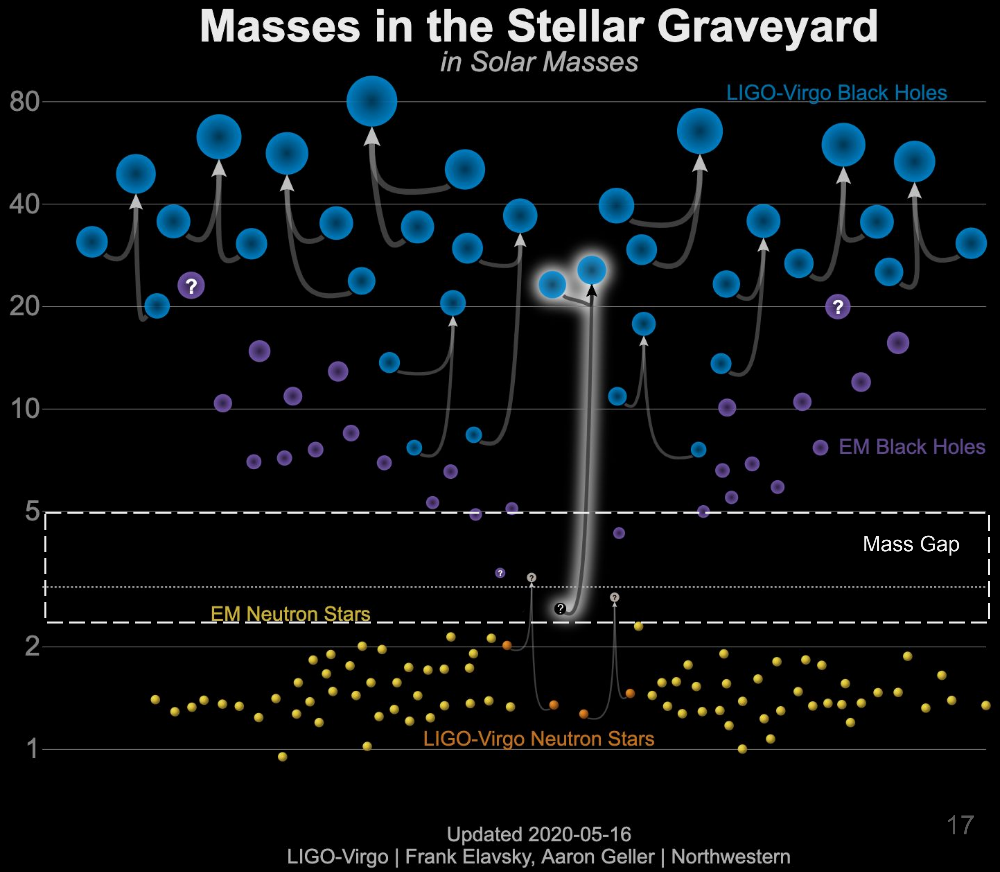
Astrophysical merger rate density estimated as

$$1 - 23\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

based on

- One detection so far
- Surveyed spacetime volume V × T

BNS	BBH
110 - 3840 Gpc^{-3} yr^{-1}	**10 - 101 Gpc^{-3} yr^{-1}**
LVC GWTC-1 (2019)	LVC GWTC-1 (2019)

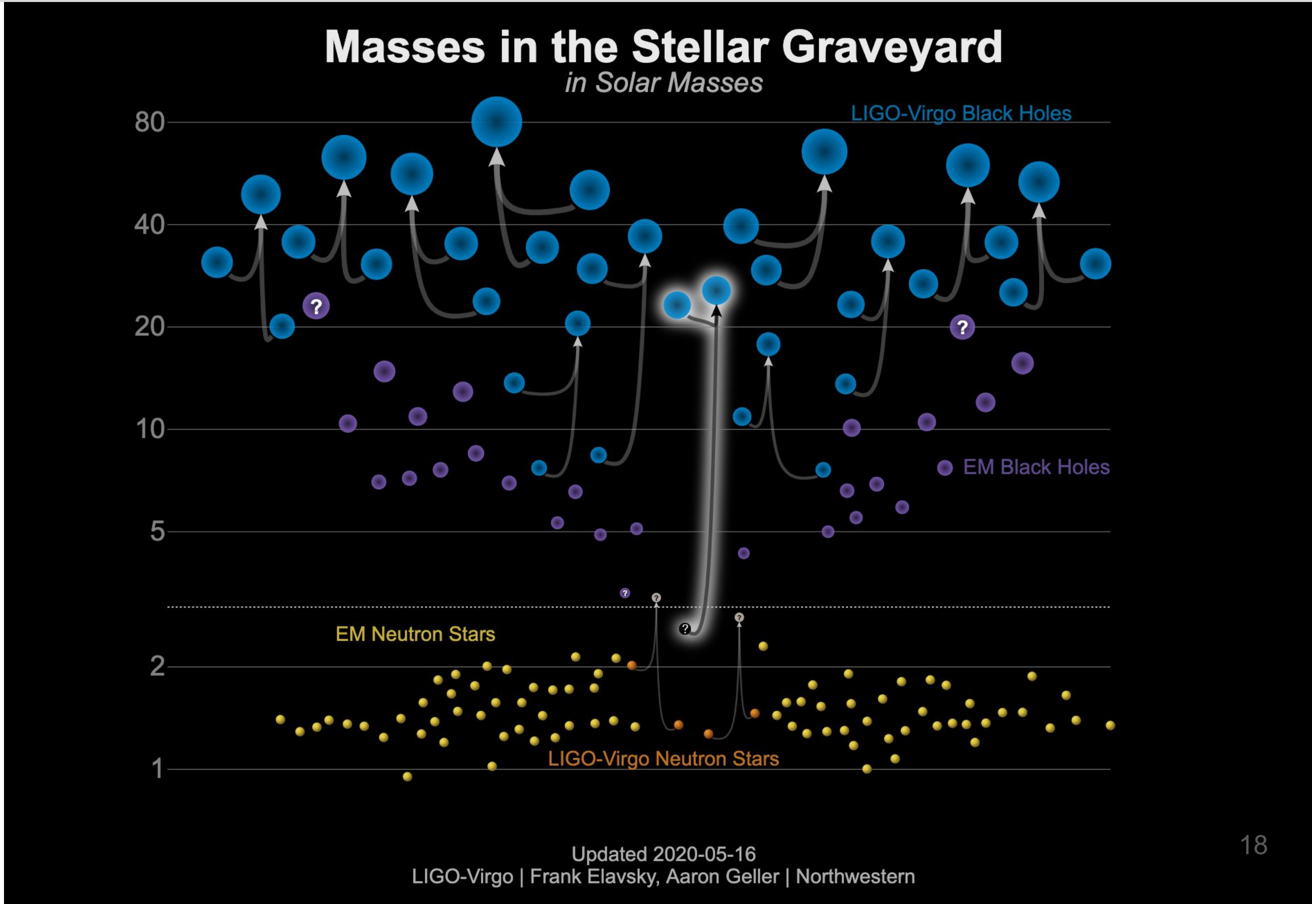


Astrophysical implications and formation channels

GW190814: quite different from other LIGO-Virgo and EM Black Holes

Possibly, a previously undetected class of coalescences

Crucial implications for astrophysics



Astrophysical implications and formation channels

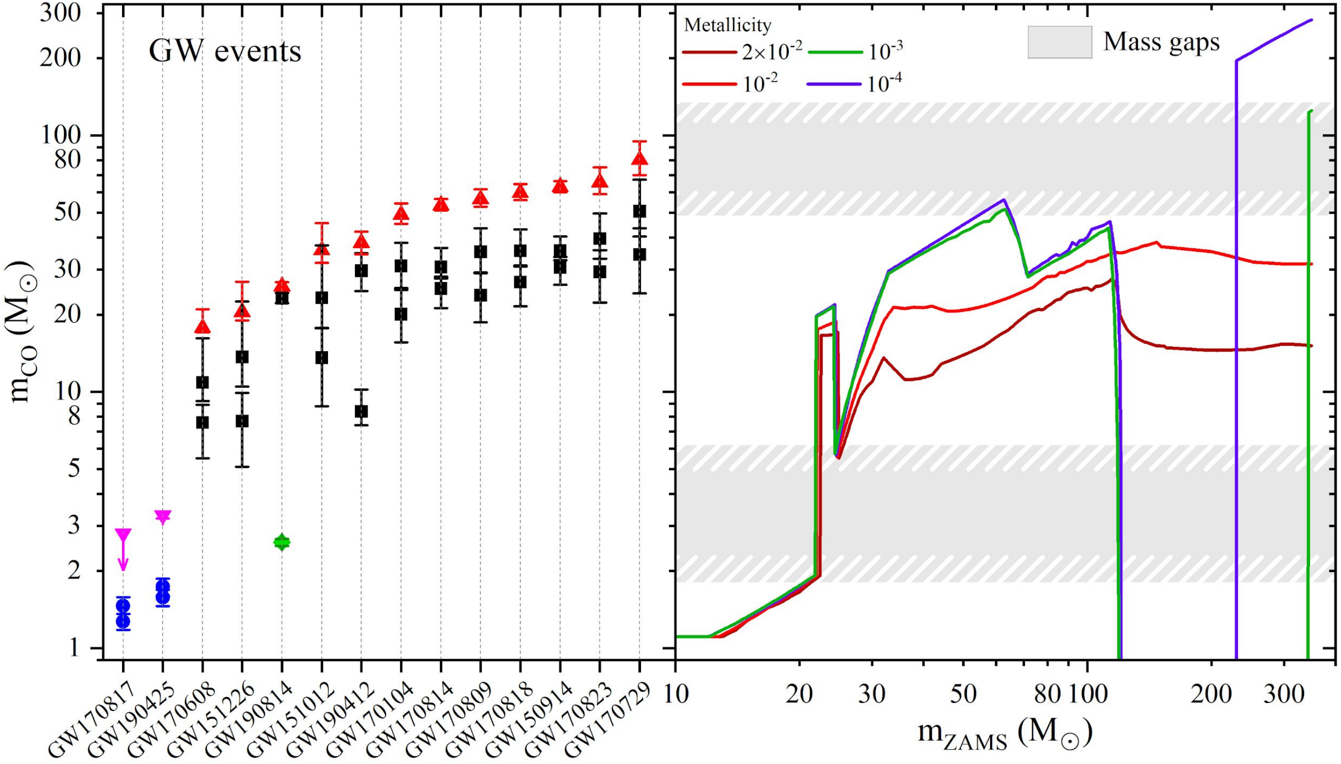
Robust mass measurement

$$2.59^{+0.08}_{-0.09}\ \mathrm{M}_{\odot}$$

Implications on

- Supernova explosion mechanism
- Existence of the lower mass gap

Adapted from Abbott B.~P., et al., 2019, ApJL, 882, L24



Astrophysical implications and formation channels

Robust mass measurement

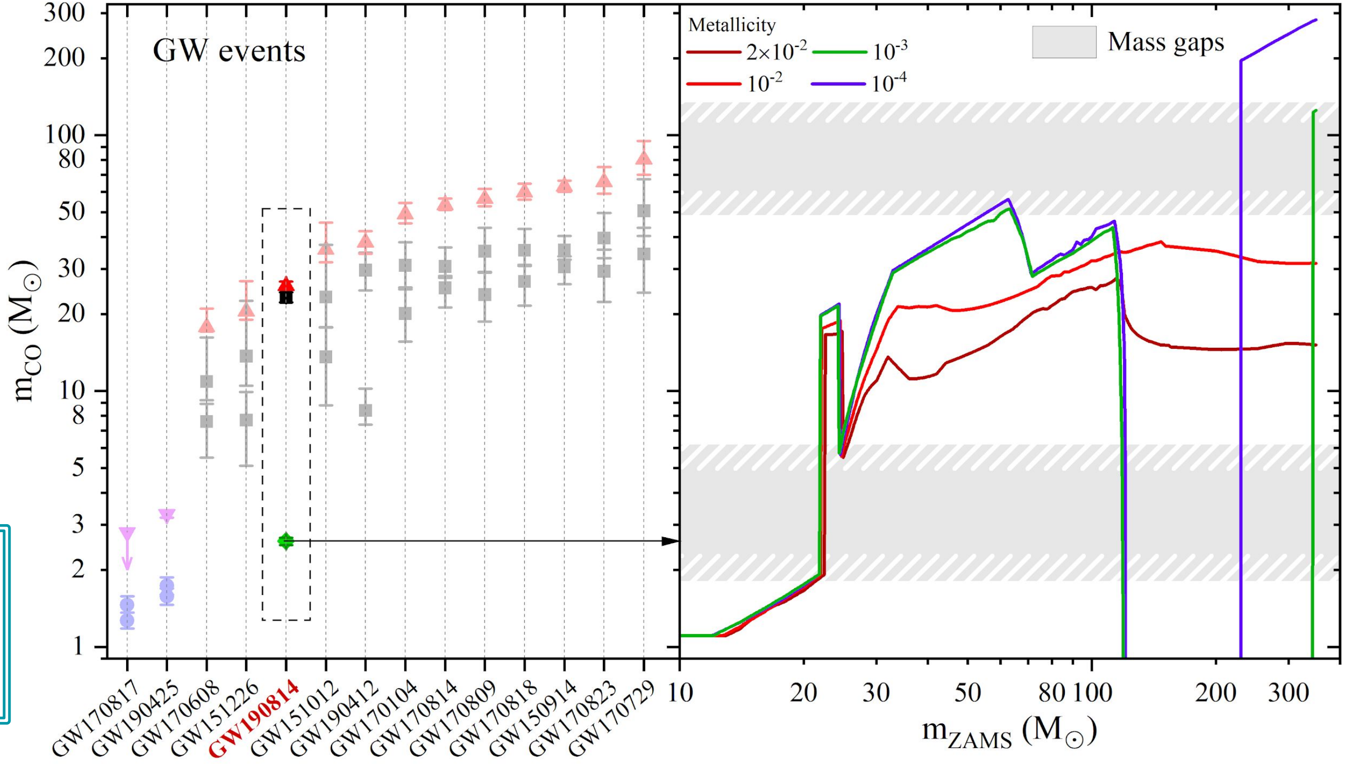
$$2.59^{+0.08}_{-0.09}\ M_{\odot}$$

Implications on

- Supernova explosion mechanism
- Existence of the lower mass gap

However, GW190814 **challenges** all astrophysical models

Adapted from Abbott B.~P., et al., 2019, ApJL, 882, L24



Astrophysical implications and formation channels

Secondary mass (~2.6 $M_\odot$)

Mass ratio (~0.1)

Inferred merger rate (1 - 23 Gpc^{-3} yr^{-1})

GW190814 is challenging to explain

Astrophysical models

- Parameter space for GW190814 is **unexplored**
- Adopt a **mass threshold** to distinguish BHs and NSs (range 2 - 3 $M_\odot$)
  - ➢ *GW190814-like merger labeled as either a BBH or a NSBH*

Astrophysical implications and formation channels

Isolated binary channel

- q (BBH) $\gtrsim$ 0.5 and q (NSBH) $\gtrsim$ 0.15
- **disfavor** mergers with highly asymmetric masses
- dependence on poorly constrained assumptions

Dynamical channel

Globular clusters

- q (BBH) $\gtrsim$ 0.5
- formation of NSBH highly suppressed
- local merger rate density (NSBH) $\lesssim$ 0.1 Gpc^{-3} yr^{-1}
- rates for GW190814-like systems $\ll$ 0.1 Gpc^{-3} yr^{-1}

Astrophysical implications and formation channels

Dynamical channel

Young star clusters

- number of mergers with $q \lesssim 0.2$ is **enhanced**
- merger rates as **high** as

  ~100 $Gpc^{-3}\ yr^{-1}$ (BBH) ~70 $Gpc^{-3}\ yr^{-1}$ (NSBH)
- rates for GW190814-like systems still **unexplored**

2nd-generation scenario

- secondary of GW190814 is a merger product *(dynamically acquire a ~23$M_\odot$ companion)*
- Exceedingly **rare** in young and globular clusters
- **Uninformative spin** posterior of the secondary of GW190814

Astrophysical implications and formation channels

Hierarchical systems (field or galactic centres)

Dynamical channel

- quadruples? {[NS+NS] + BH} + BH
- unclear if mergers with $q \lesssim 0.2$ are enhanced
- rates (NSBH - BBH) $\lesssim$ a few $\mathrm{Gpc^{-3}\ yr^{-1}}$
  (likely lower for GW190814-like mergers)

Active Galactic Nuclei

- median mass ratio q (NSBH) ~ **0.07**
- Rate (NSBH) ~ 100 $\mathrm{Gpc^{-3}\ yr^{-1}}$
- Dependence on poorly constrained AGN parameters

Astrophysical implications and formation channels

- GW190814 challenges all astrophysical models
- The parameter space relevant to explain GW190814 is still mostly unexplored
- No quantitative predictions for rates of GW190814-like systems (yet)
- Future GW detections of similar events: further insights on different formation channels

Summary

The GW190814 source is unlike any compact binary signal observed to date.

- Secondary is lightest BH or heaviest NS ever observed in a double compact-object system
- Most unequal mass ratio measured with GWs
- Tightest constraint on a primary spin

This event has exciting implications for the formation and mass spectrum of compact objects in the Universe.