Astrophysical Implications of Compact Binary Observations with Gravitational Waves

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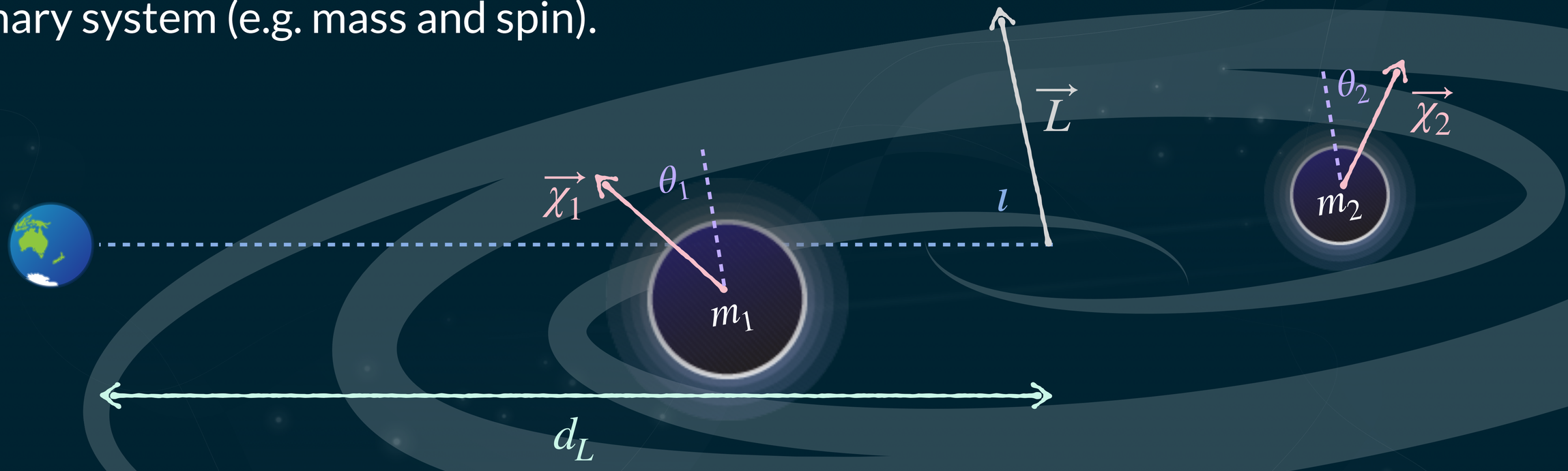
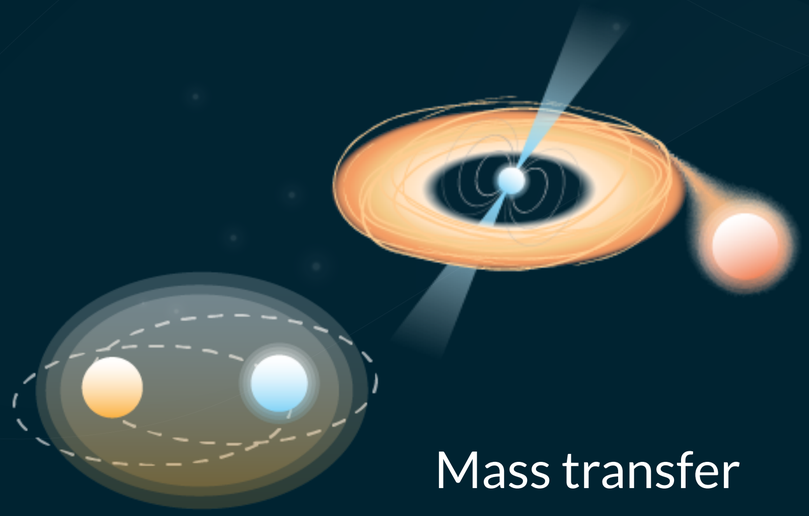
Compact binary mergers

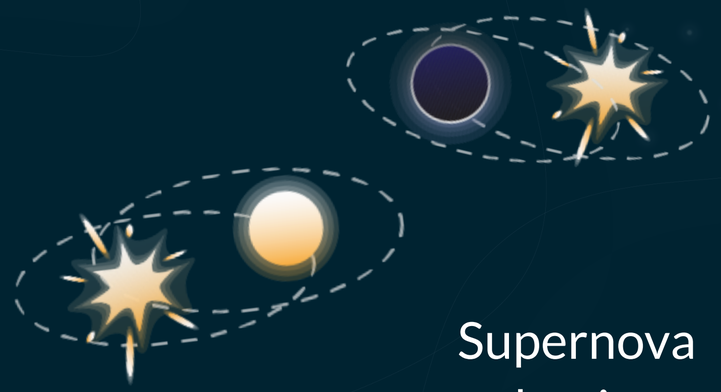
LIGO-Virgo-KAGRA (LVK) observes mergers of binary black holes (BBH) binary neutron stars (BNS) and neutron star-black hole (NSBH) systems. The gravitational-wave (GW) signal carries information about the properties of the binary system (e.g. mass and spin).



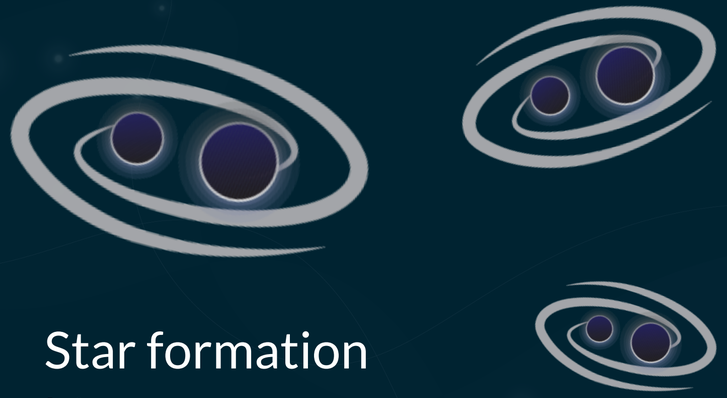


Mass transfer

Heavy element production

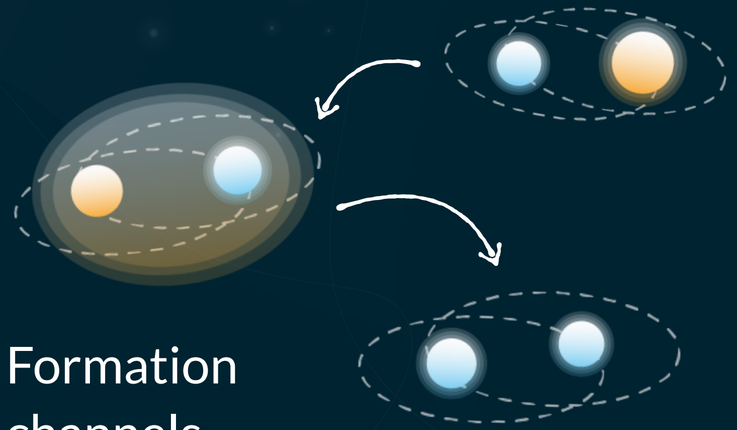


Supernova mechanisms



Star formation history

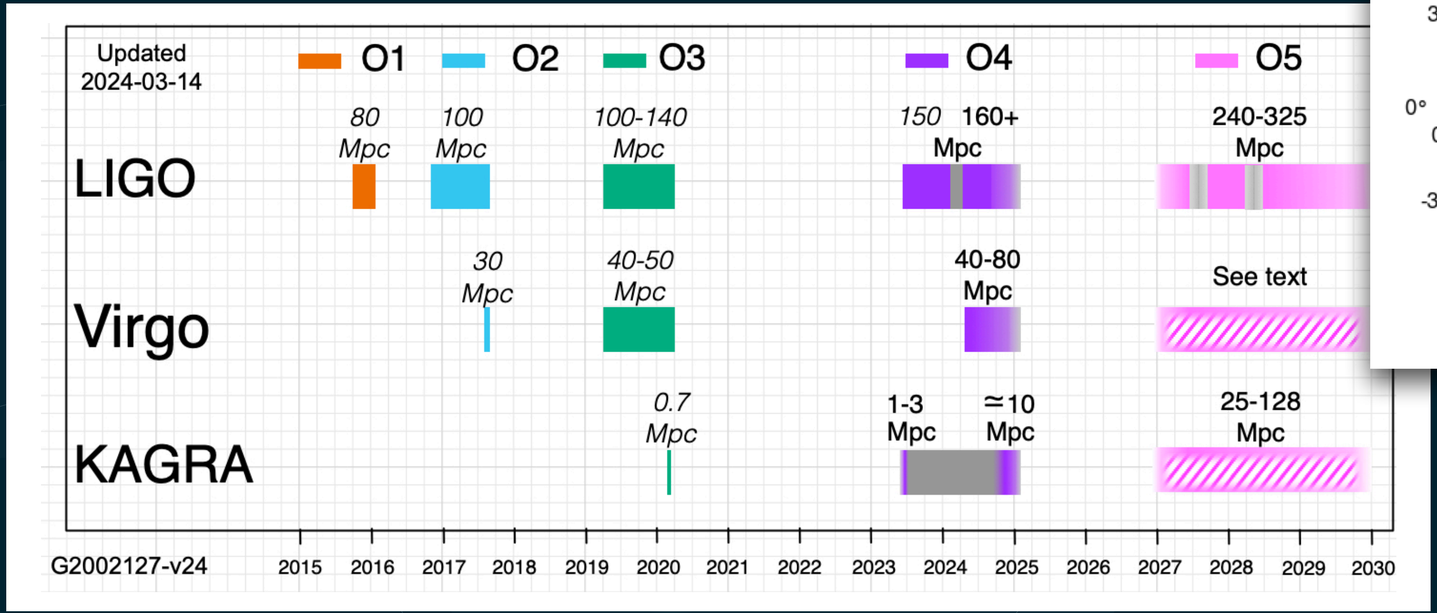
Maximum BH mass from stellar collapse

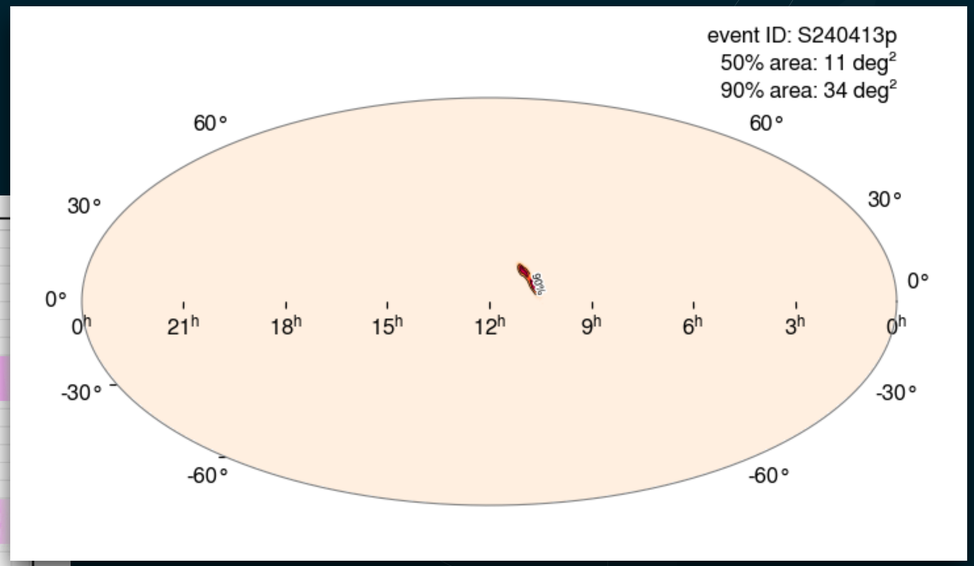


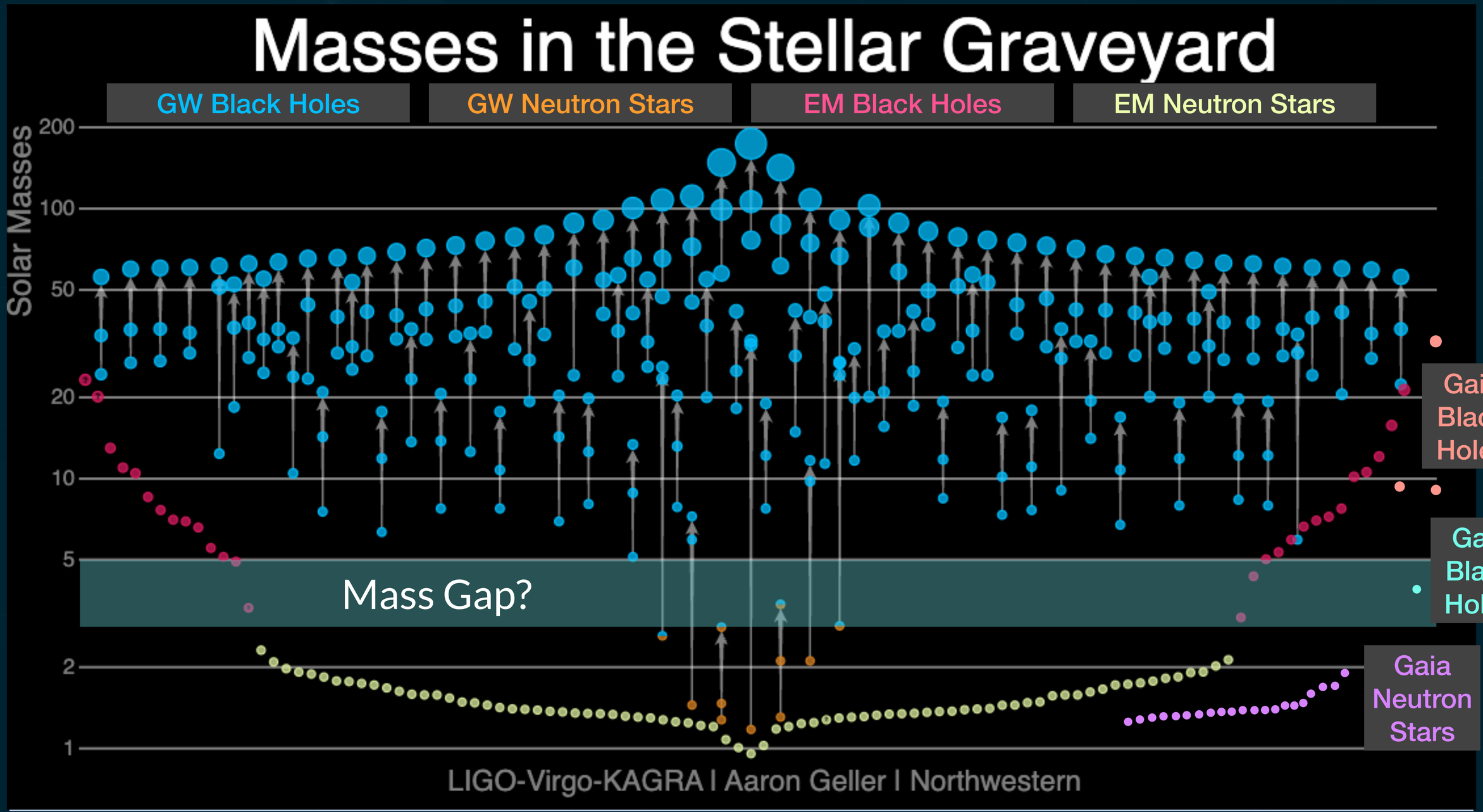
Formation channels

Latest observing run of LIGO-Virgo-KAGRA

- Currently in second half (O4b) with Virgo joining!
- ~131 significant alerts so far in O4



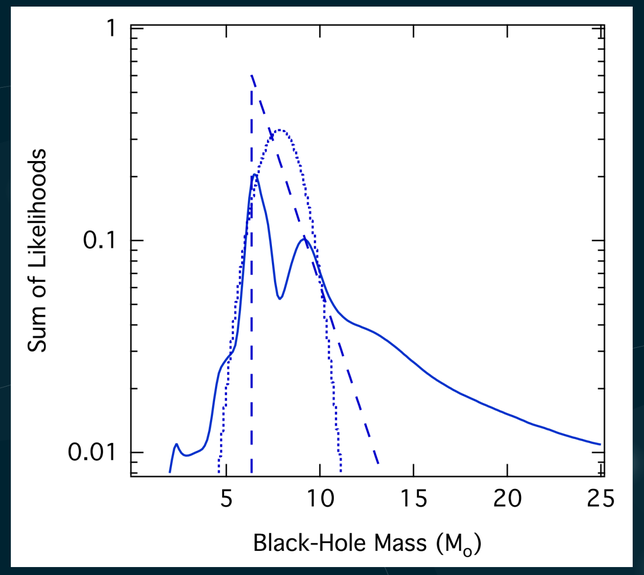



Masses in the Stellar Graveyard
GW Black Holes
GW Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
Mass Gap?
Gaia Black Holes
Gaia Black Hole?
Gaia Neutron Stars
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Is there a gap between masses of NS and BH?

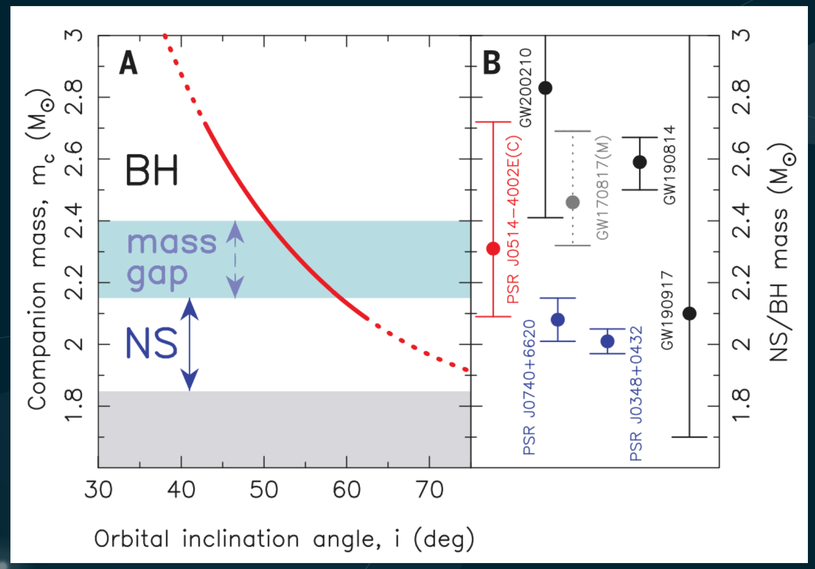
- Dearth of compact objects observed in the Milky Way between $\sim$ 3-5 $M_\odot$ (from observations of X-ray binaries)

X-ray Binaries



Özel+2010 arXiv:1006.2834

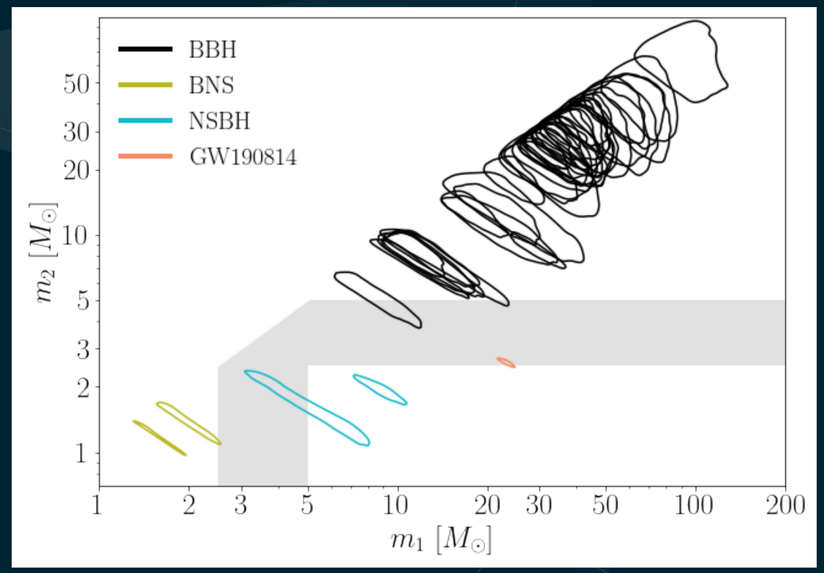
Detached Galactic Binaries



Barr+2024 arXiv:2401.09872

See Paulo Freire's talk

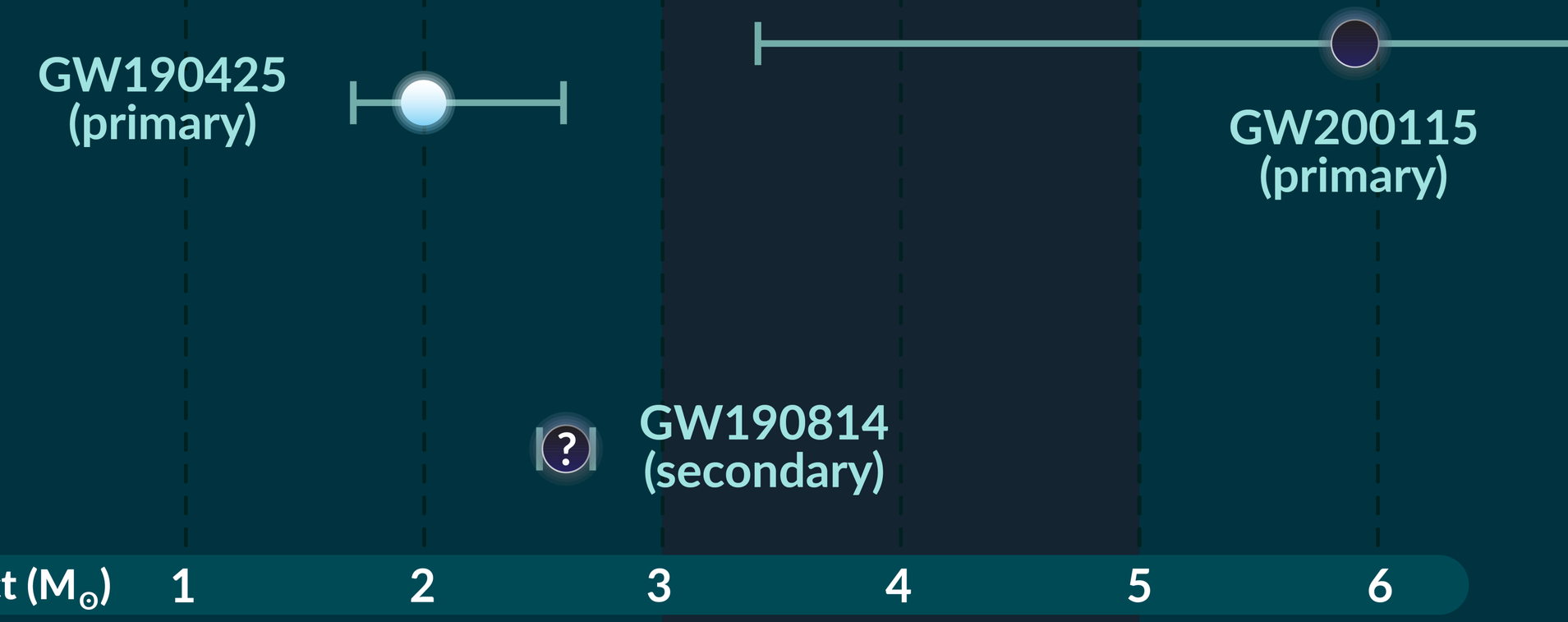
Gravitational Waves



Farah+2021 arXiv:2101.02212

FILLING THE MASS ⟷ GAP

with observations of compact binaries from gravitational waves



Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

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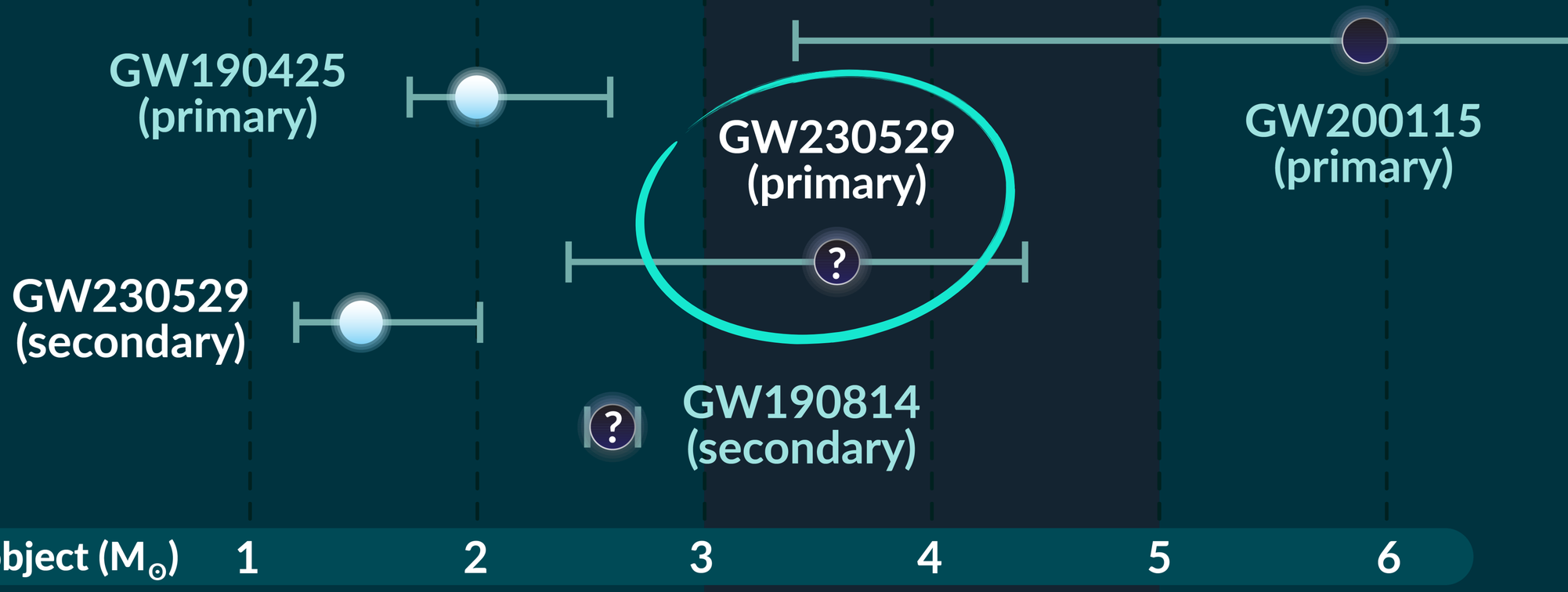


Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

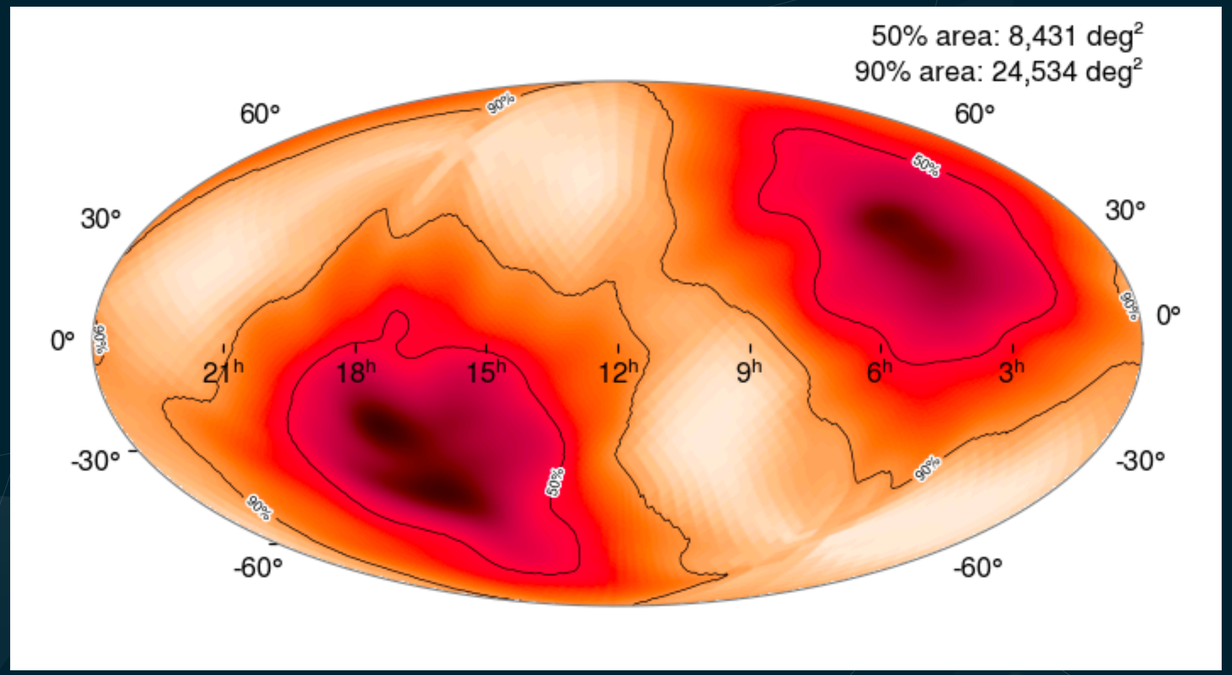
Discovery of GW230529

- Observed on 29 May 2023 at 18h15 UTC
- Seen only by LIGO Livingston
- LIGO Livingston operationally stable for $\simeq 66$ hours with binary neutron star range of $\simeq 150$ Mpc
- Poor sky localization ($\sim 25{,}000$ deg^2)

Detectors

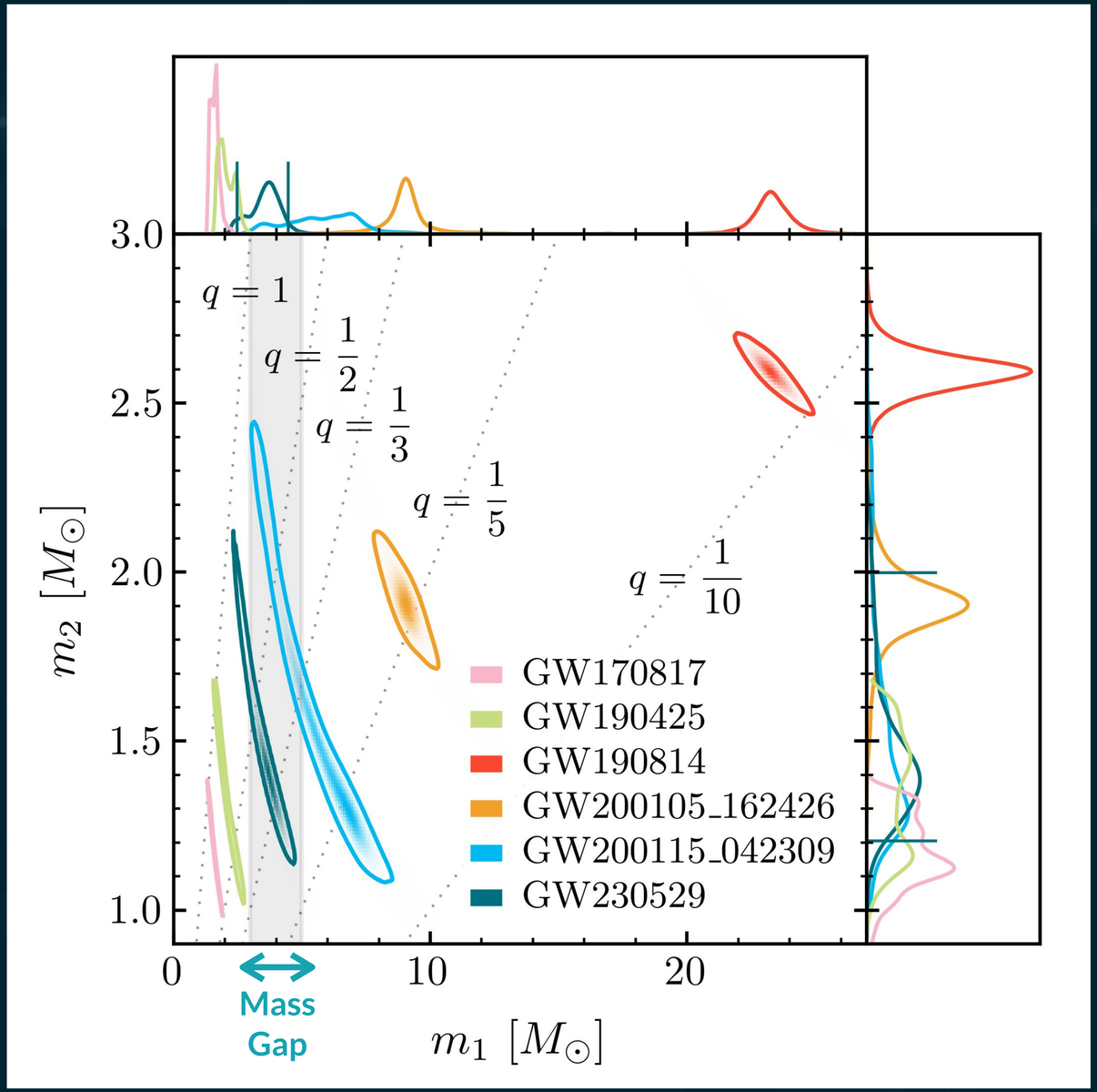
H L V K

- Offline OR not operational
- Online BUT not used for analysis
- Online AND used for analysis



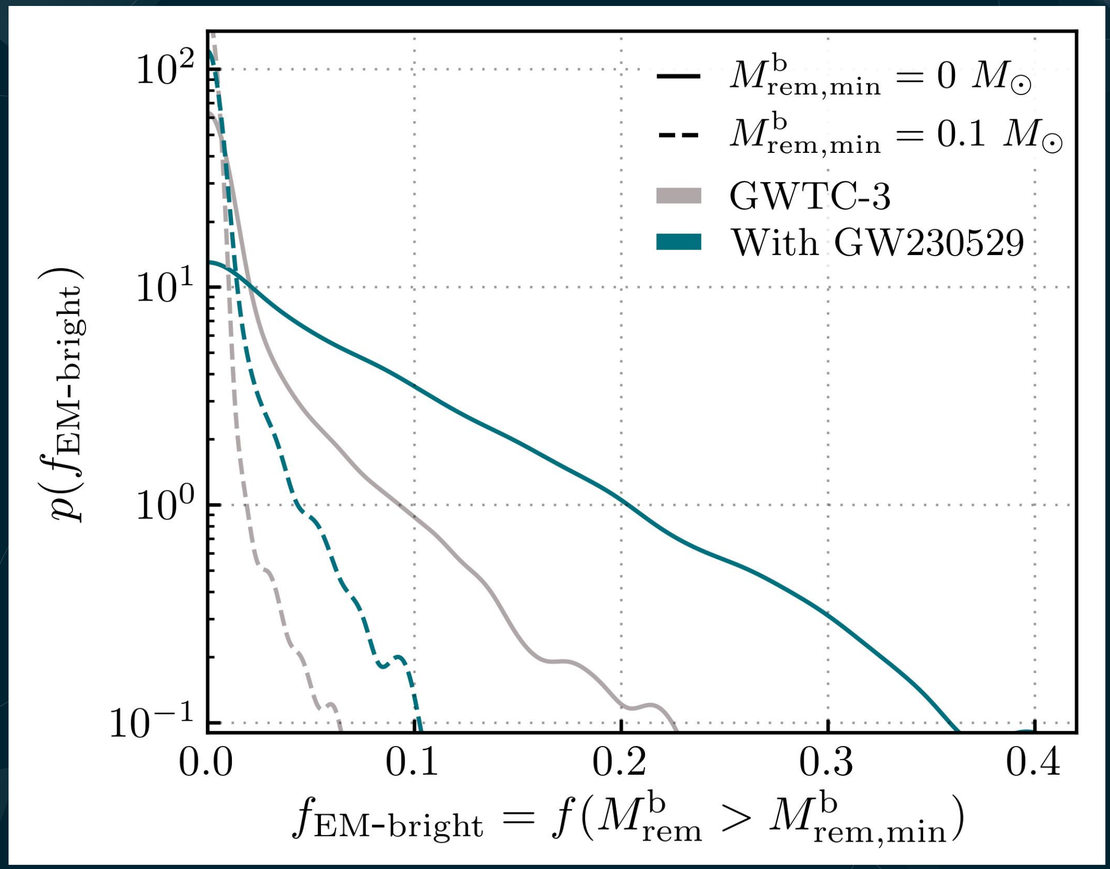
Source properties

- Primary (more massive component) in 2.5-4.5 $M_\odot$ range ($< 5\ M_\odot$) at 99% credibility
- Most likely a black hole paired with a neutron star of $\sim 1.4\ M_\odot$
- However, some support for GW230529 source being merger of two $\gtrsim 2\ M_\odot$ compact objects



Multimessenger prospects

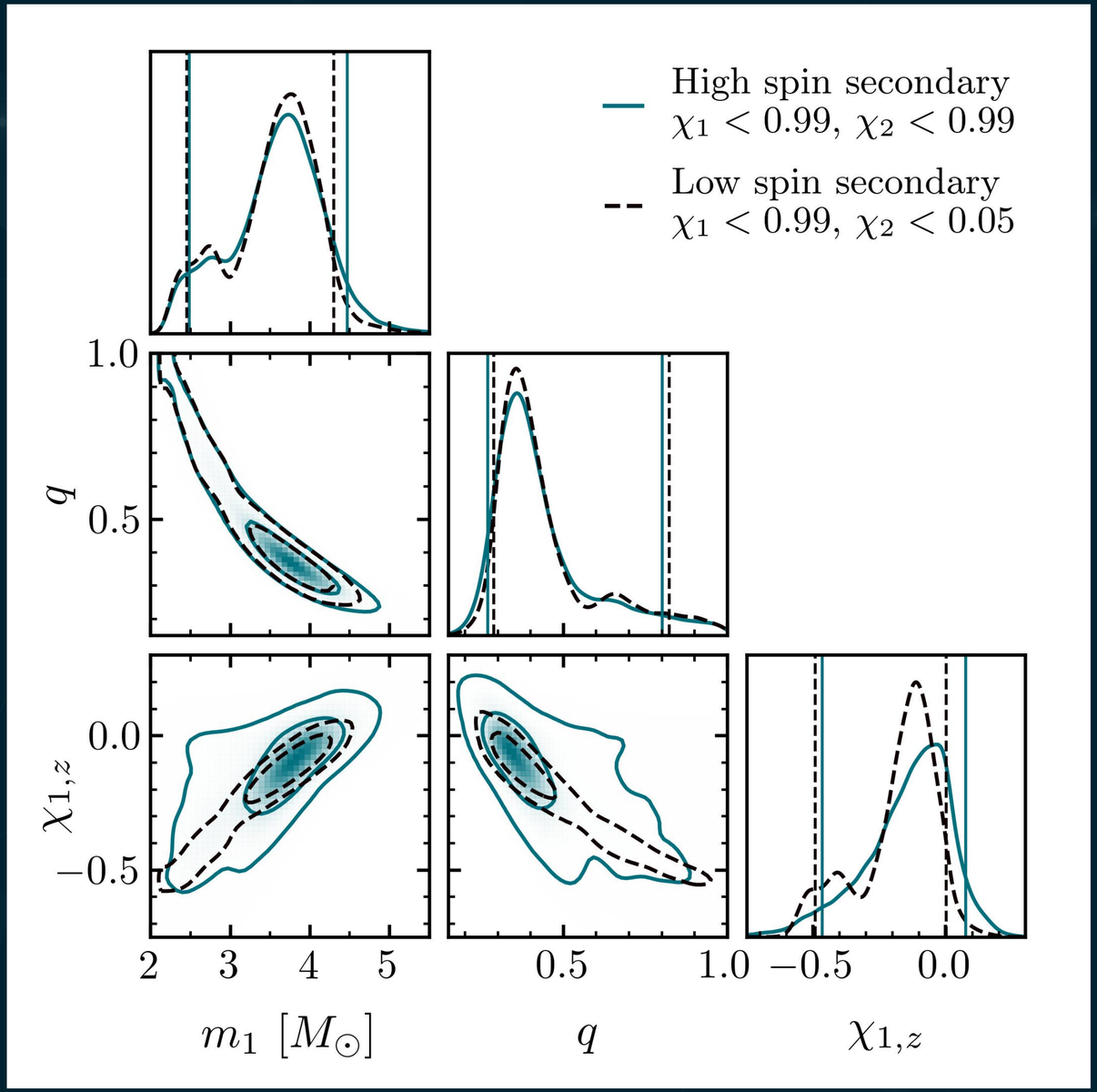
- Increases upper limits on fraction of EM-bright NSBH mergers from $\leq 6\,\%$ to $\leq 18\,\%$
- At most $1.1\ M_\odot\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ contributes to heavy element production, and rate of gamma-ray bursts with NSBH progenitors is at most $23\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Note, model dependant.



Source properties

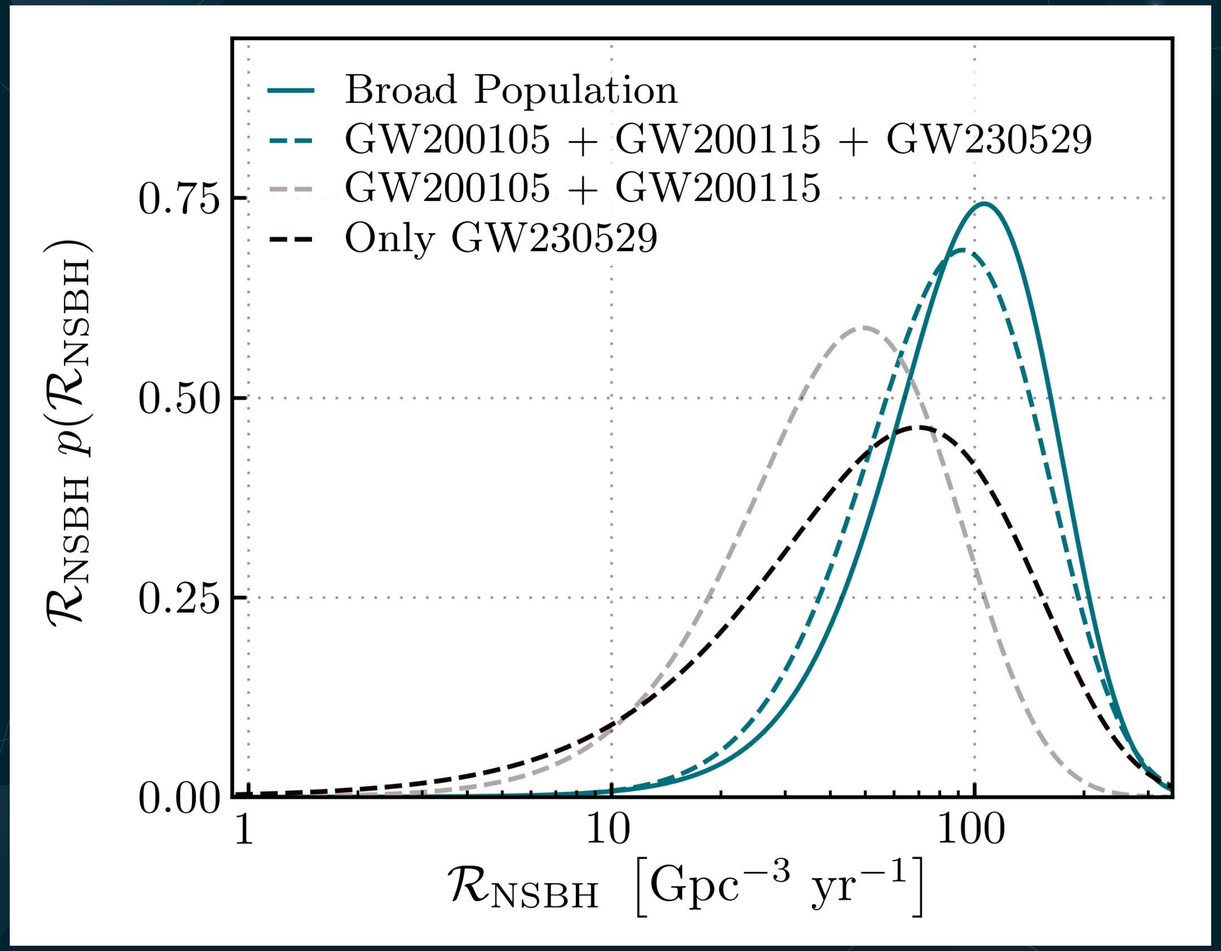
- Primary component consistent with non-spinning or anti-aligned spin ($\chi_{1,z} < 0$ at 83% credibility)
- Correlation between mass ratio ($q = m_2/m_1$) and spin components parallel to orbital angular momentum ($\chi_{1,z}$)

Note, the misalignment could actually be a result of an NSBH with nonspinning components while assuming the priors used in the LVK analysis, see Mandel & Smith arXiv:2109.14759



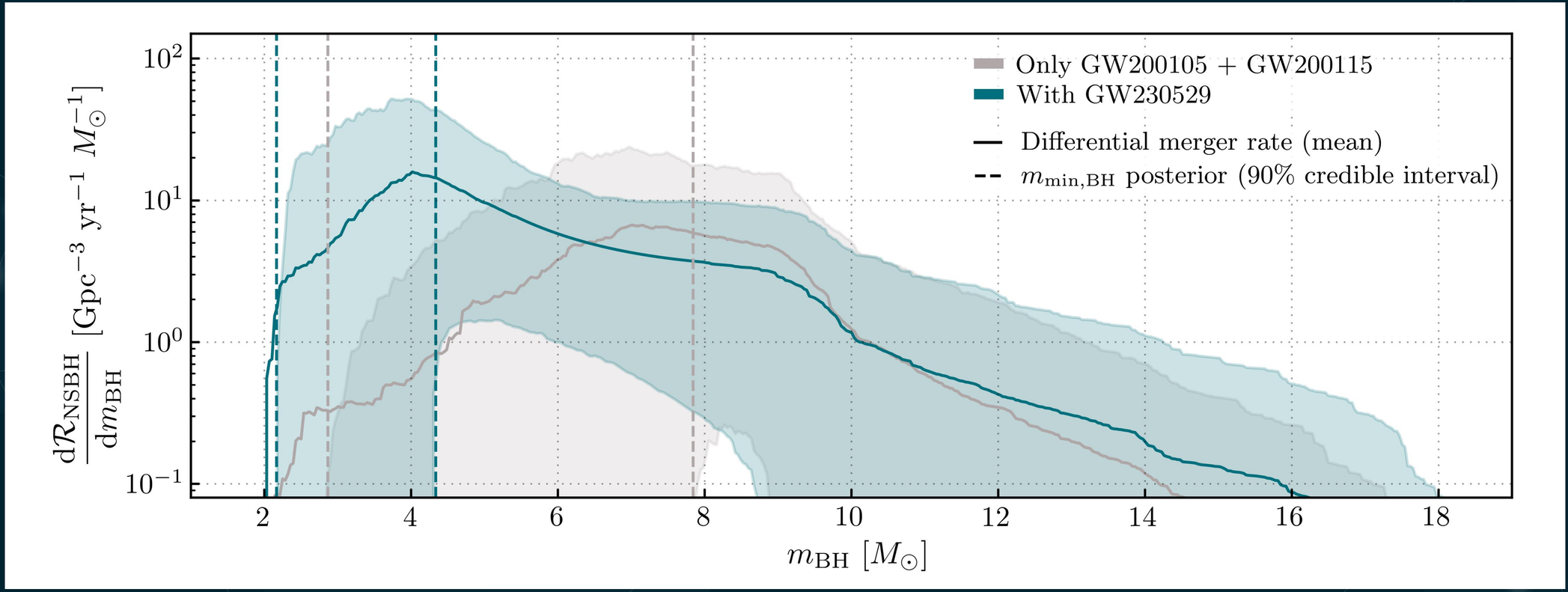
What is the NSBH merger rate?

- Updated NSBH merger rate
  $30\text{-}200\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (90% credible)
- Two methods:
  1. population-based = all NSBH same class of events
  2. event-based = GW230529 is a different class of event.
- GW230529-like events have similar or higher merger rates than other NSBH events we have seen.



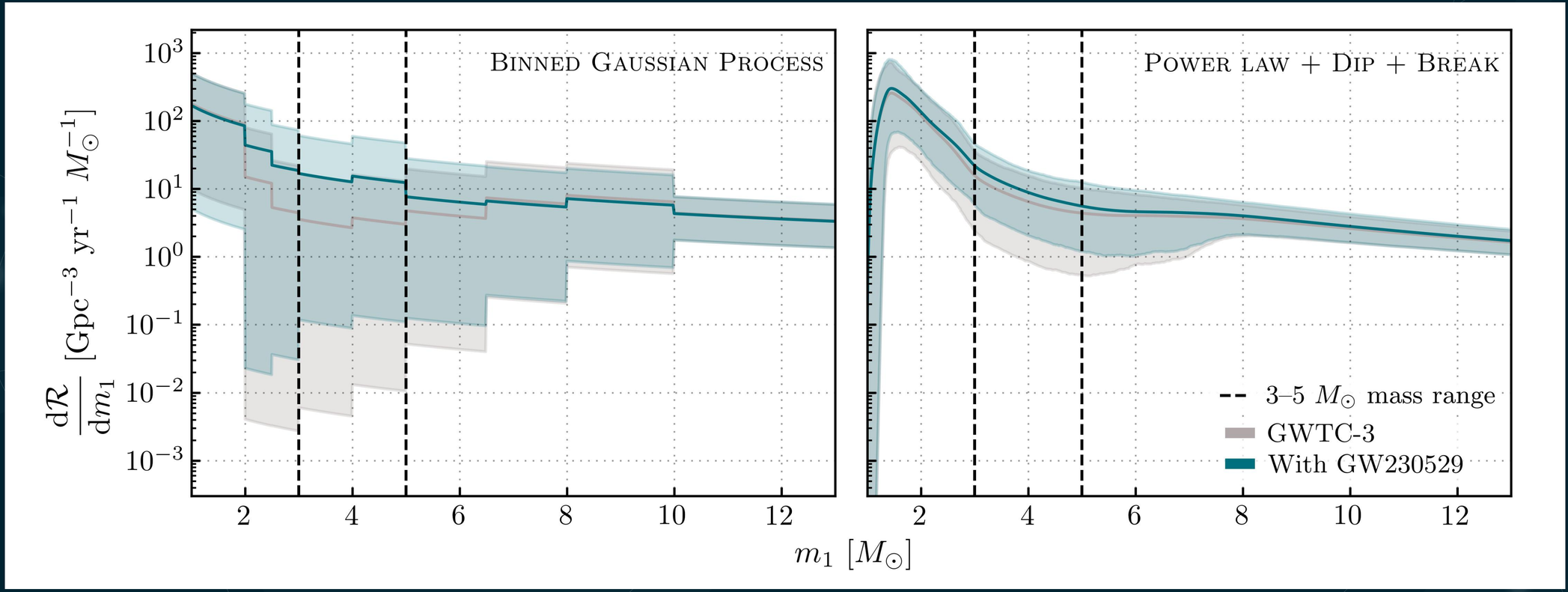
Mass distribution of NSBH population

Assuming the source is a NSBH, minimum black hole mass is smaller than previously inferred for NSBH systems.



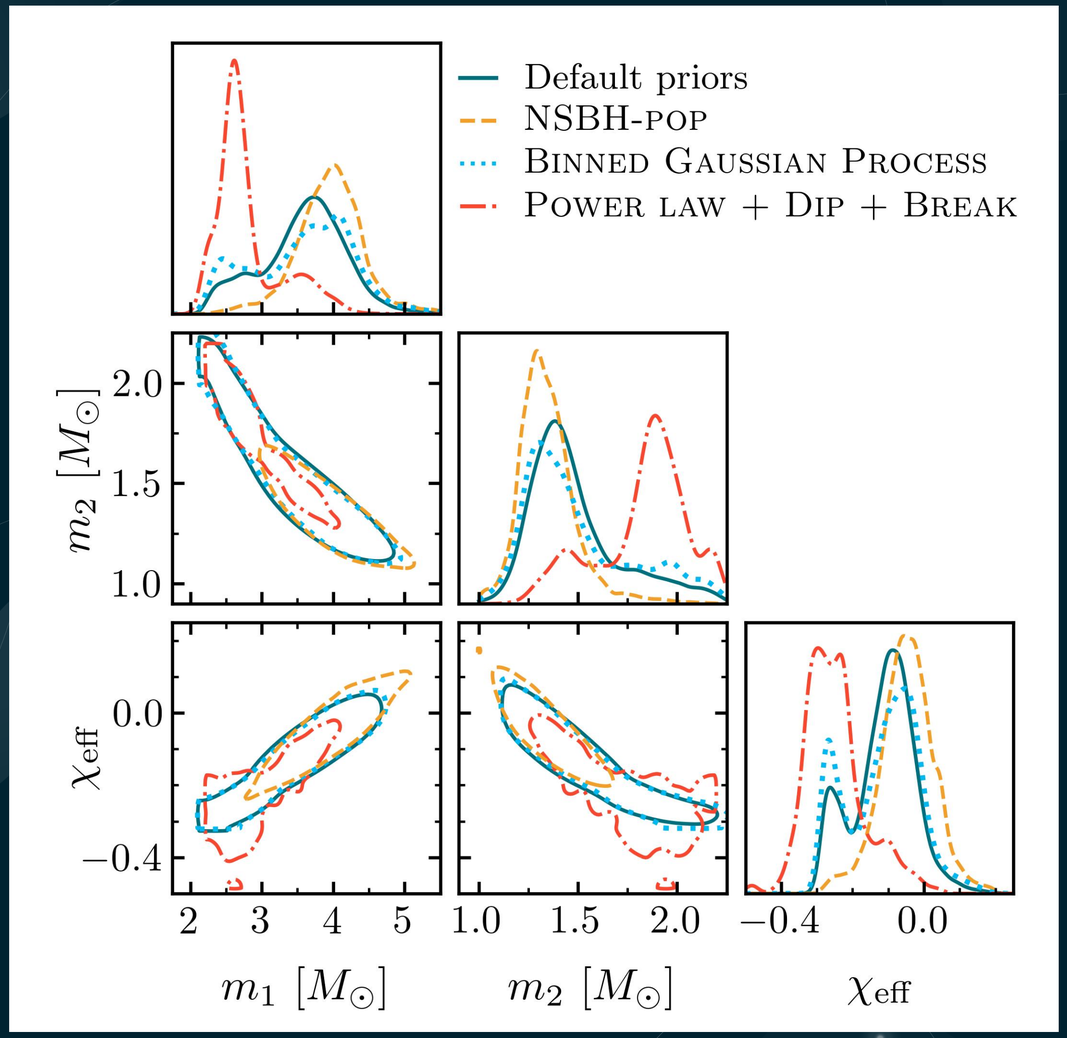
Mass distribution of CBC population

- GW230529 is consistent with the full compact binary population observed with gravitational waves



Is the source an NSBH?

- Most likely, yes!
- We use population-informed priors to reweight distributions, varying conclusions from different models.
- Combining population models and equation-of-state constraints we can get up to ~10% chance of the source being a heavy binary neutron star.

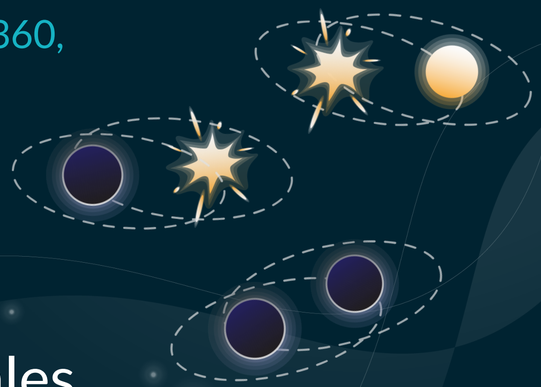


How did GW230529 form?

Isolated binary evolution

From current understanding, unlikely that the BH formed via direct collapse, but:

- stochasticity in remnant masses (Mandel & Müller 2020 arXiv:2006.08360, Antoniadis+2022 arXiv:2110.01393)
- supernova fallback (Sukhbold+2016 arXiv:1510.04643, Ertl+2020 arXiv:1910.01641)
- delayed explosion timescales (Fryer+2012 arXiv:1110.1726, Zevin+2020 arXiv:2006.14573, Zhu+2024 arXiv:2404.10596)



Dynamical assembly

BH possibly formed in dense stellar environment or triple system:

- product of a merger b/w two NS (Fragione+2020 arXiv:2002.11278, Gupta+2020 arXiv:1909.05804, Tagawa+2021 arXiv:2012.00011)
- but rates expected to be too low (Ye+2020 arXiv:1910.10740)

O4 is HERE!

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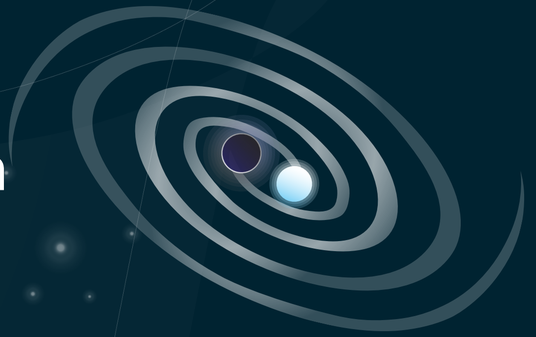
- We have seen all three ‘flavours’ of compact binaries with gravitational waves; now we can probe deeper questions, e.g. is there a gap between NS and BH?
- GW230529, most symmetric NSBH so far, with mass gap object.
- #O4IsHere with 131 events as of this afternoon! Follow along on gracedb: https://gracedb.ligo.org/superevents/public/O4/



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