Meet GW230529: the gravitational wave from the merger of a ~3.6 Compact Object and a Neutron Star

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April 18 2024 | Artemis Seminar

LIGO VIRGO KAGRA

LAGRANGE

ARTEMIS

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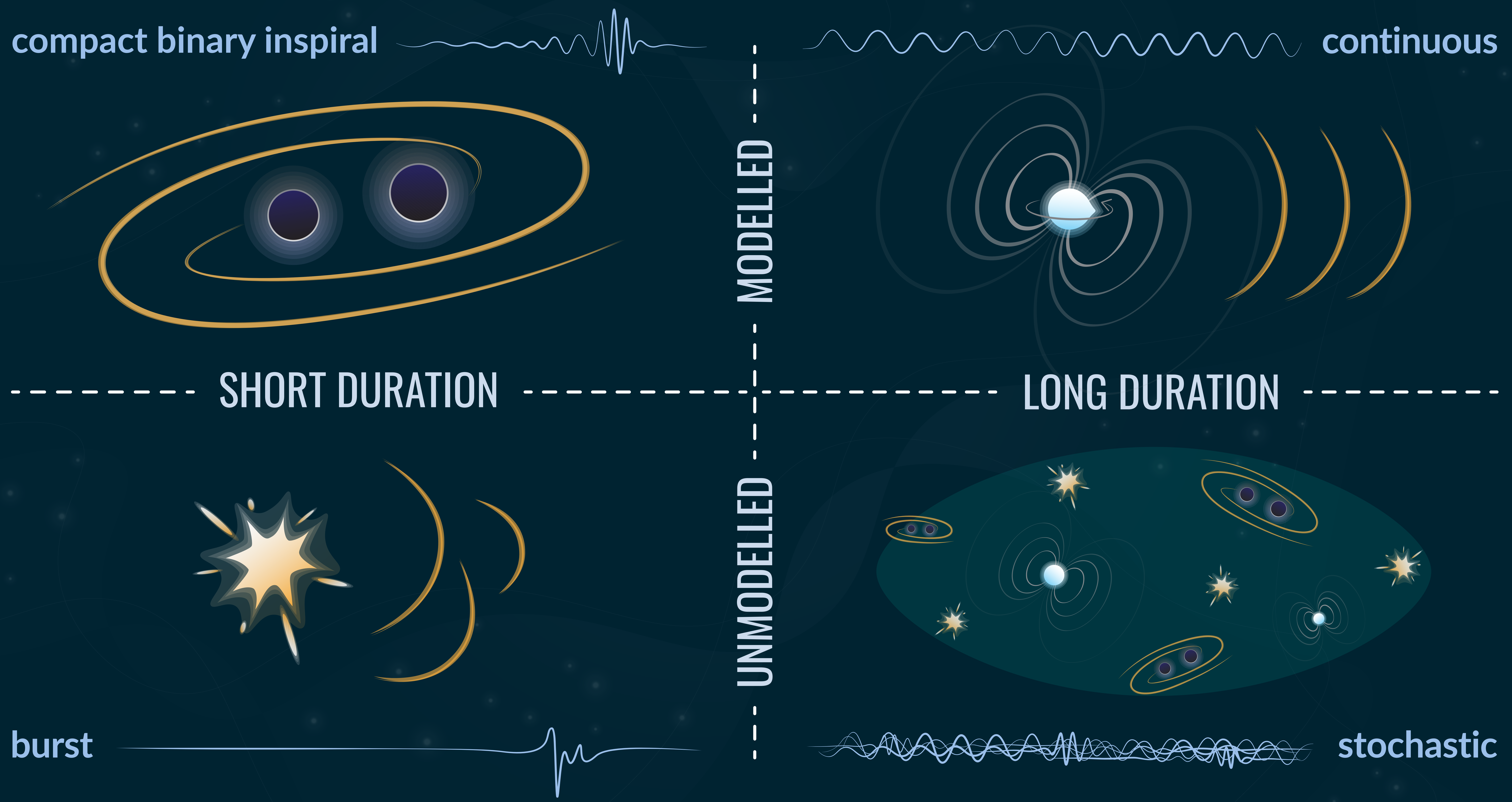
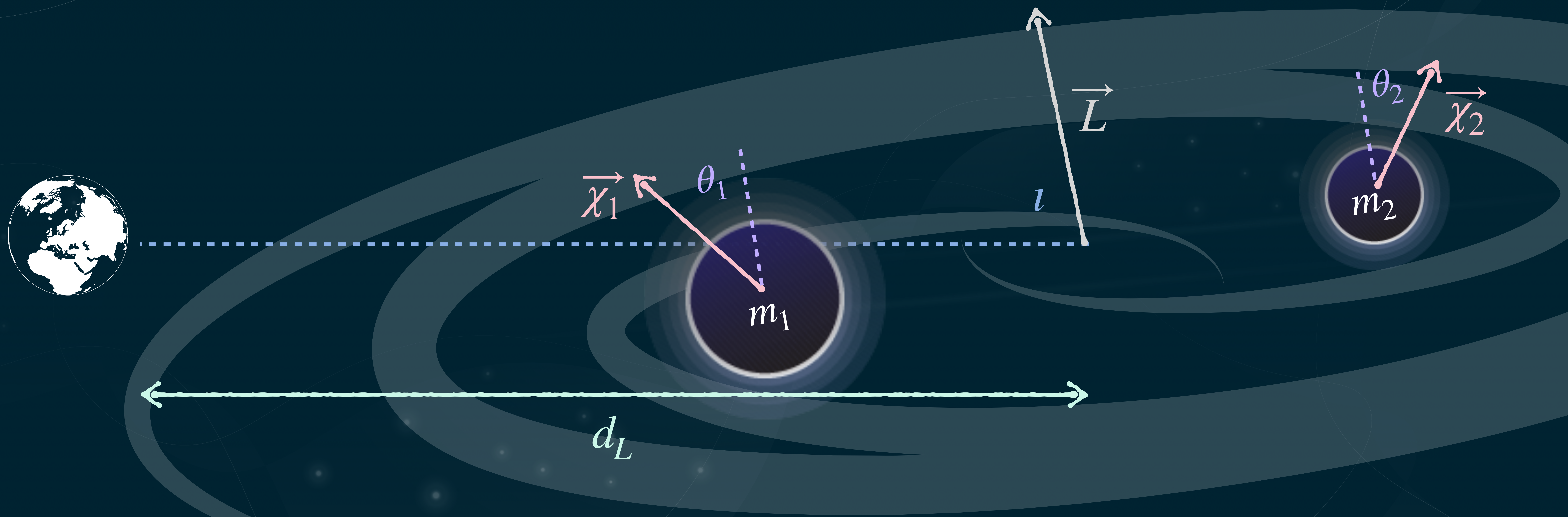

compact binary inspiral
continuous
MODELLED
SHORT DURATION
LONG DURATION
UNMODELLED
burst
stochastic

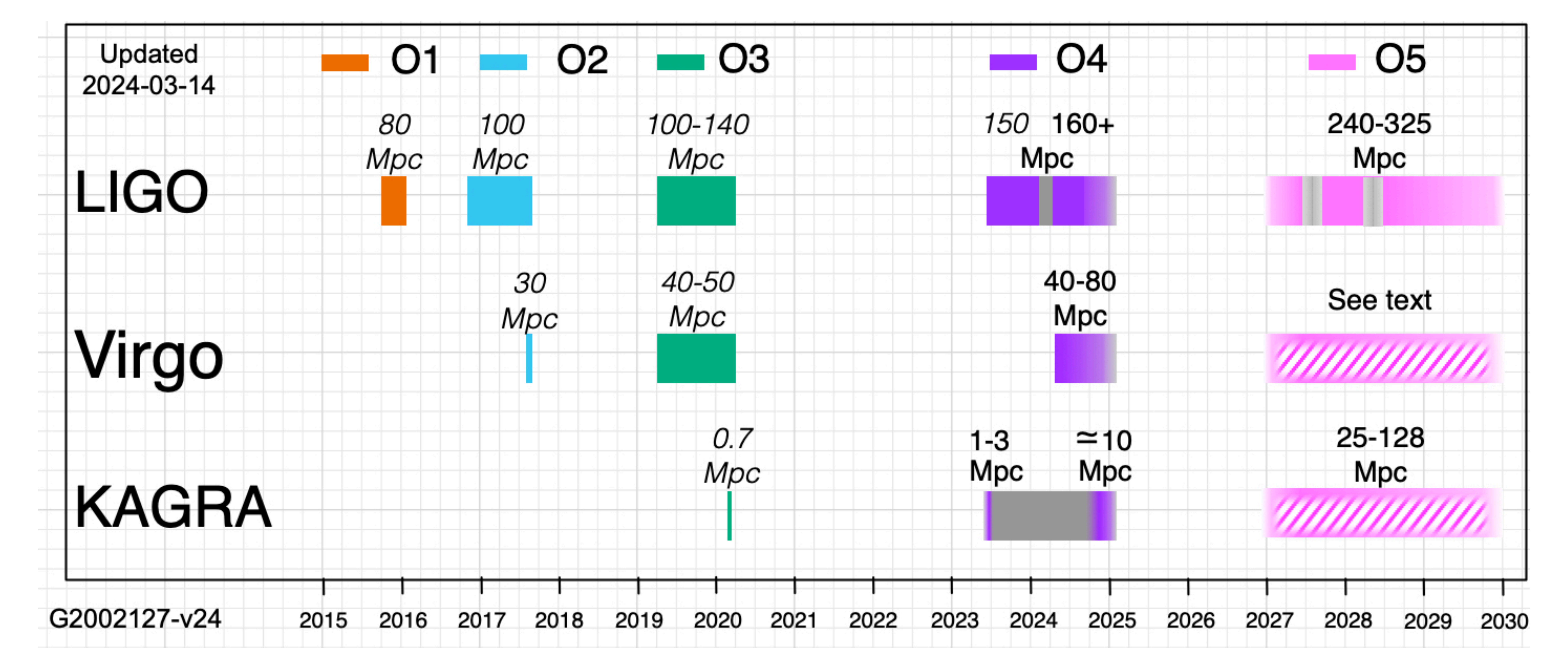
Compact binary mergers

The gravitational-wave (GW) signal carries information about the properties of the binary system (e.g. mass and spin).



Latest observing run of LIGO-Virgo-KAGRA

- Currently in second half (O4b) with Virgo joining!
- ~80 significant alerts so far in O4



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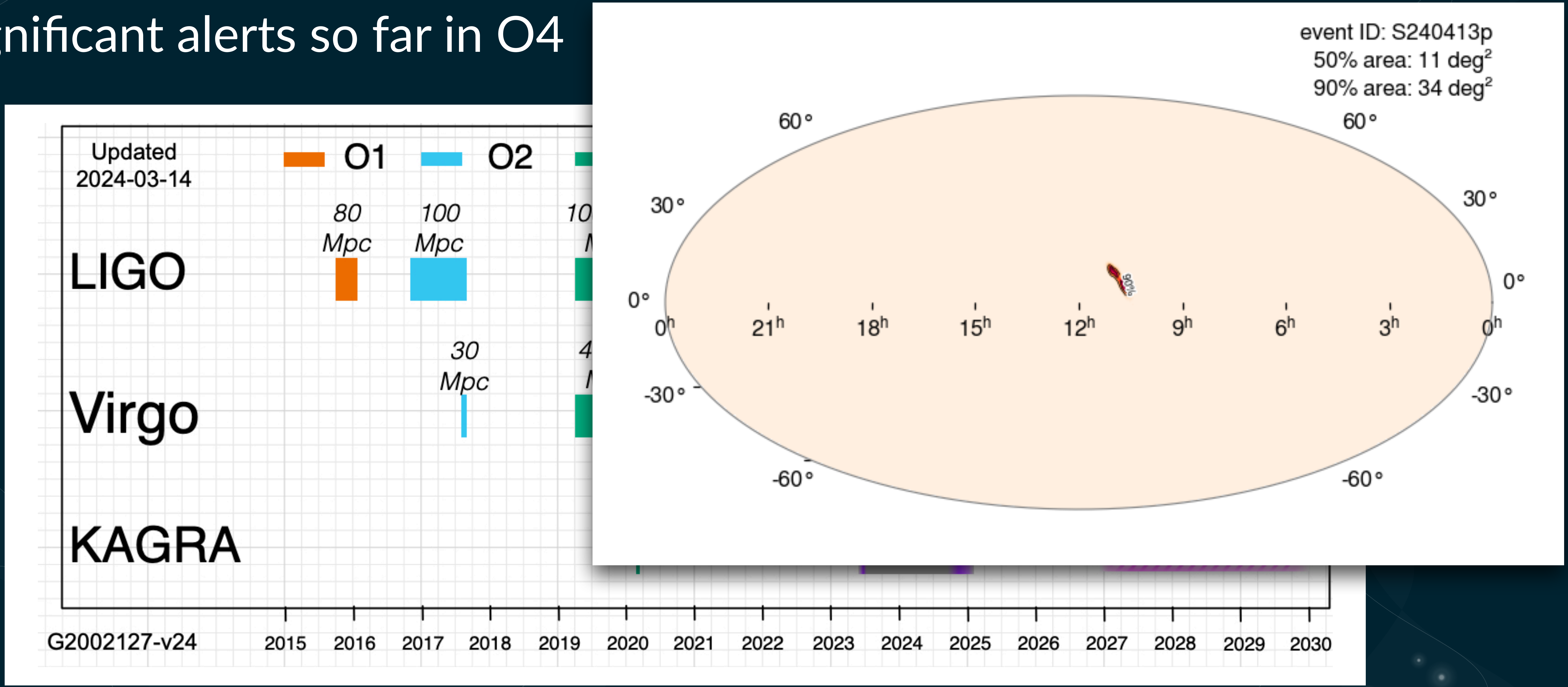
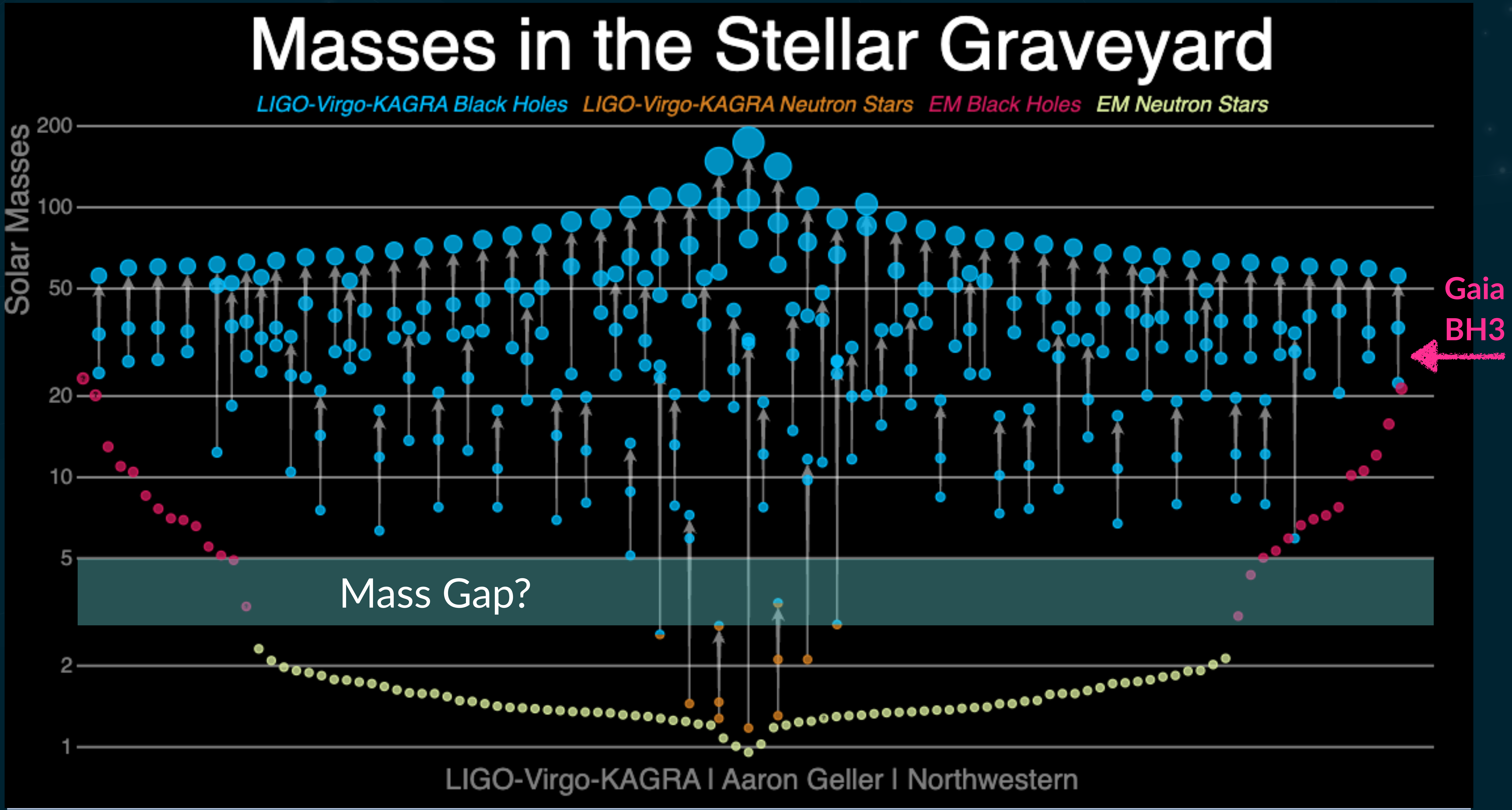


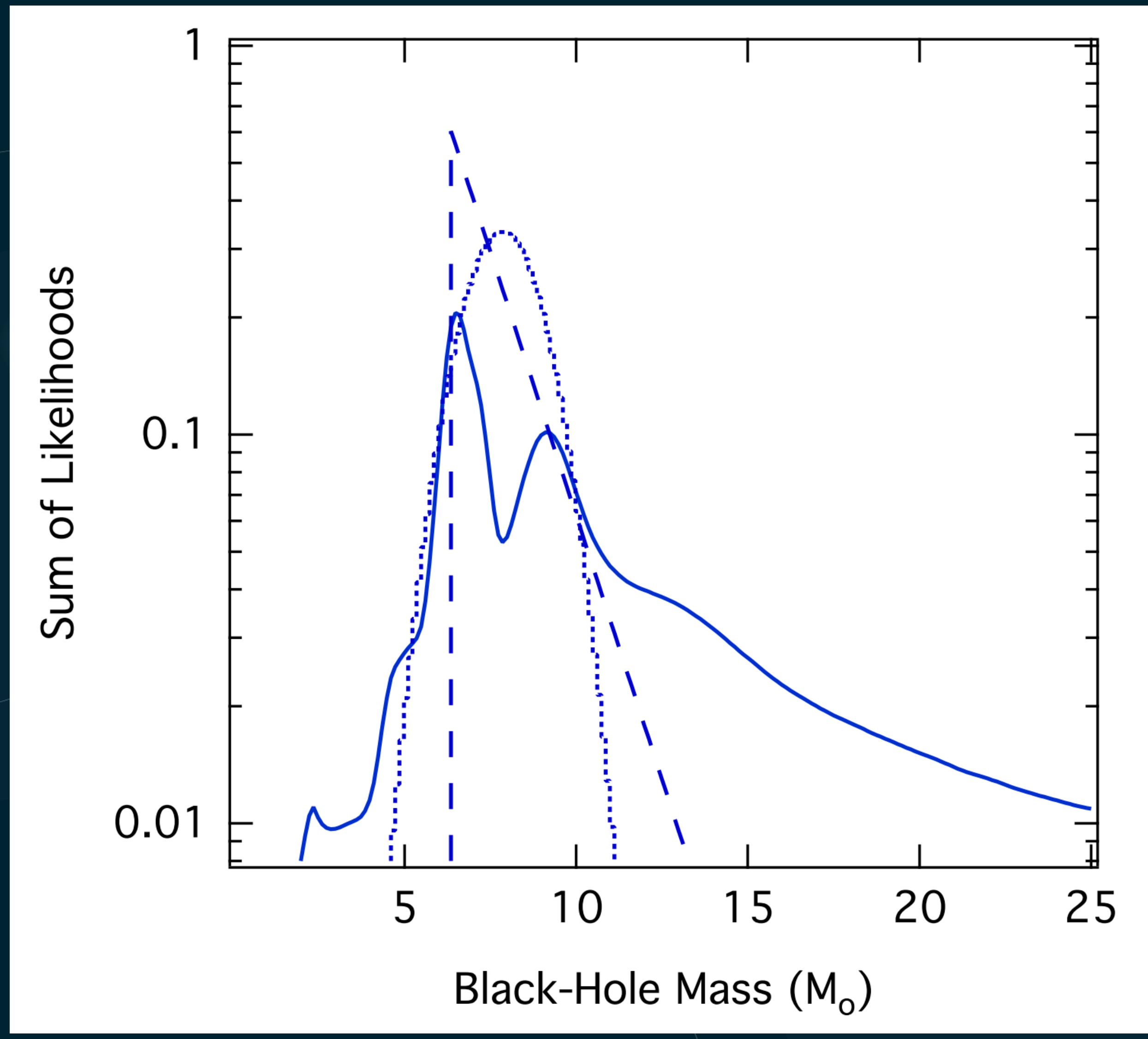


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
Mass Gap?
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern
Gaia BH3

Is there a gap between masses of NS and BH?

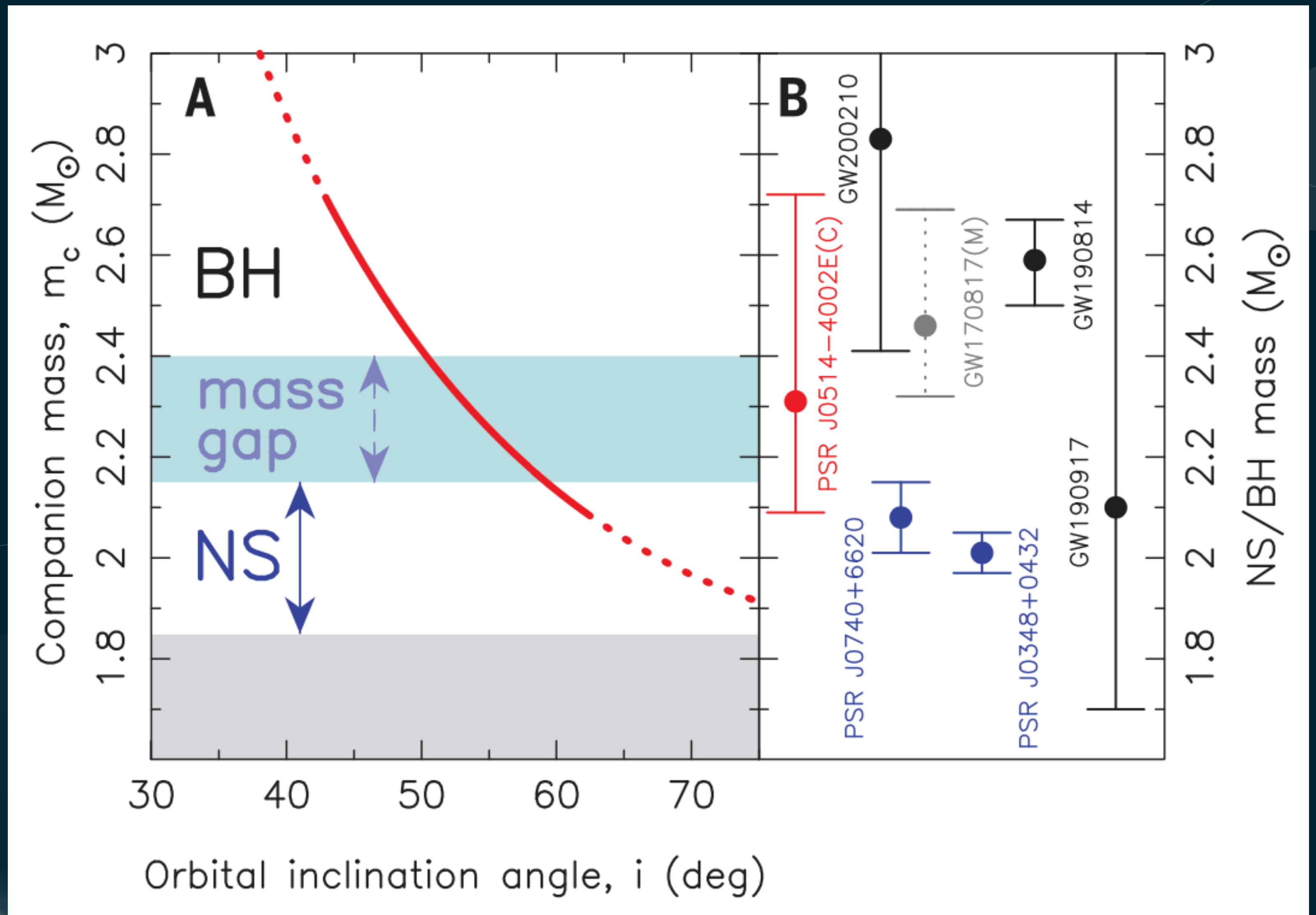
- Dearth of compact objects observed in the Milky Way between $\sim$ 3-5 $M_\odot$ (from observations of X-ray binaries)

X-ray Binaries



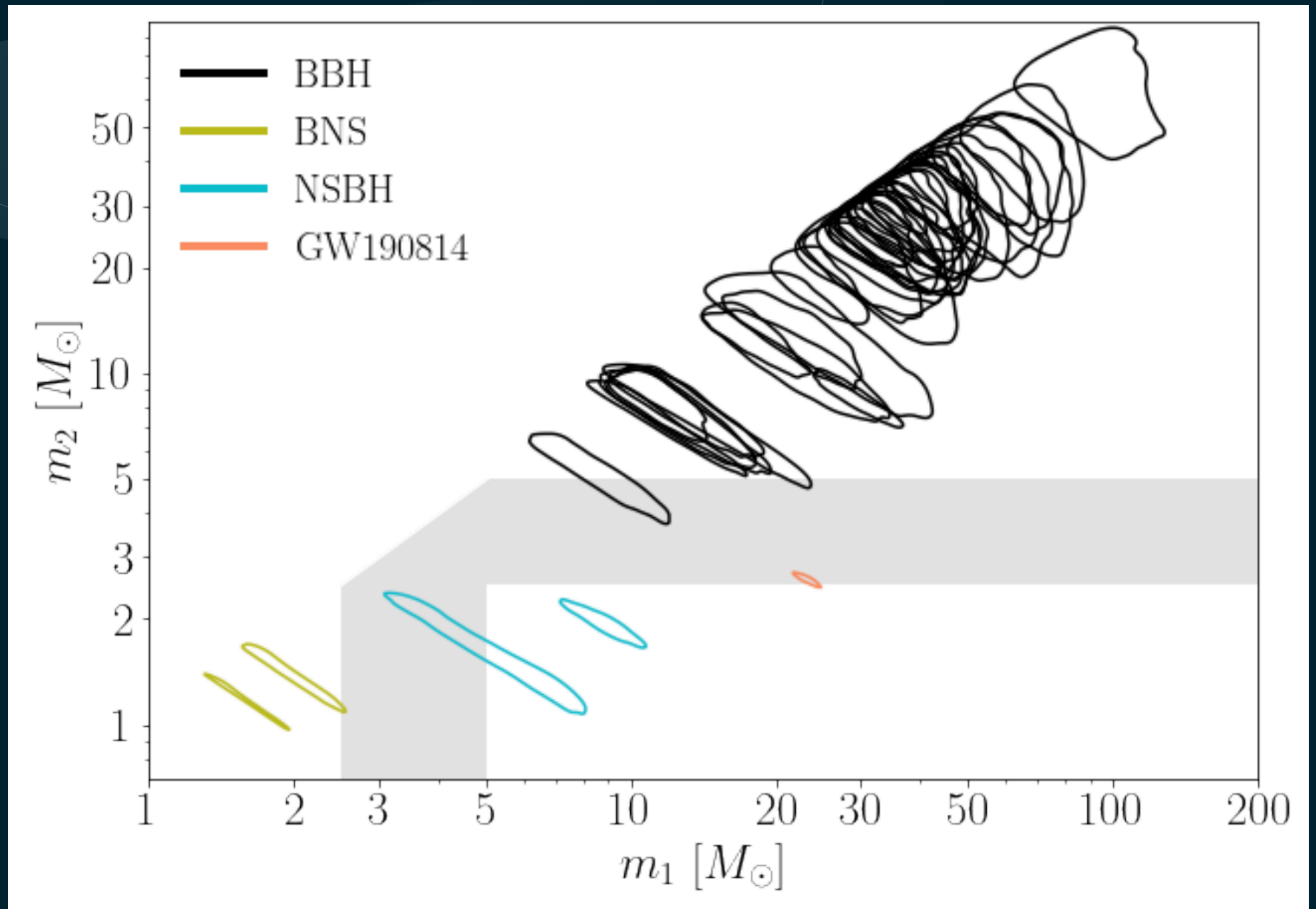
Özel+2010 arXiv:1006.2834

Detached Galactic Binaries



Barr+2024 arXiv:2401.09872

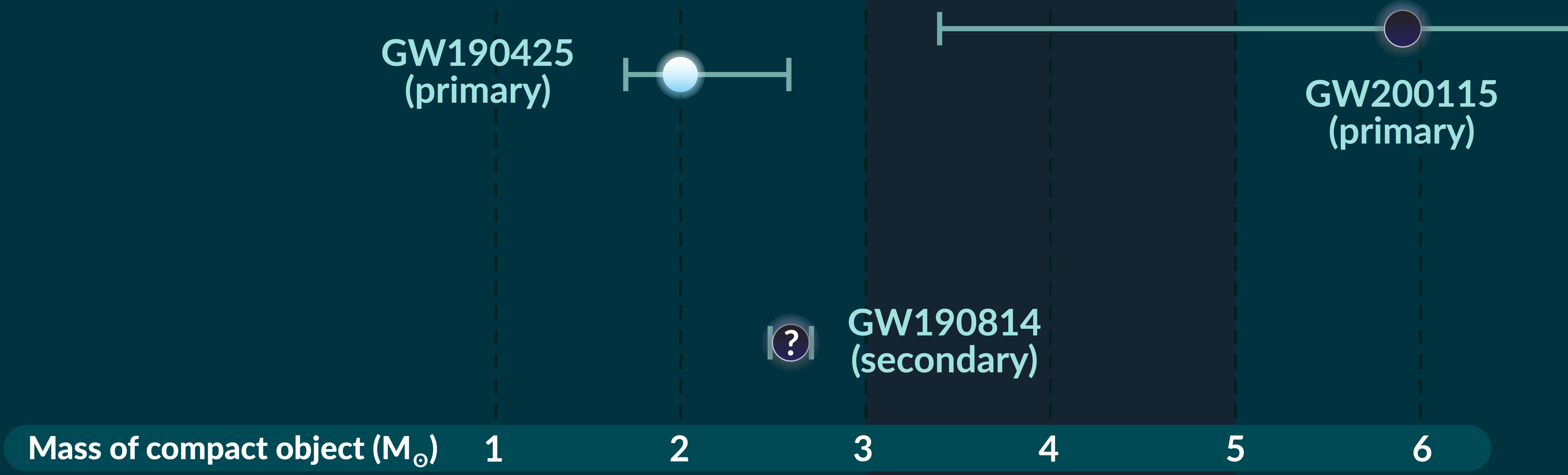
Gravitational Waves



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

FILLING THE MASS ⟷ GAP

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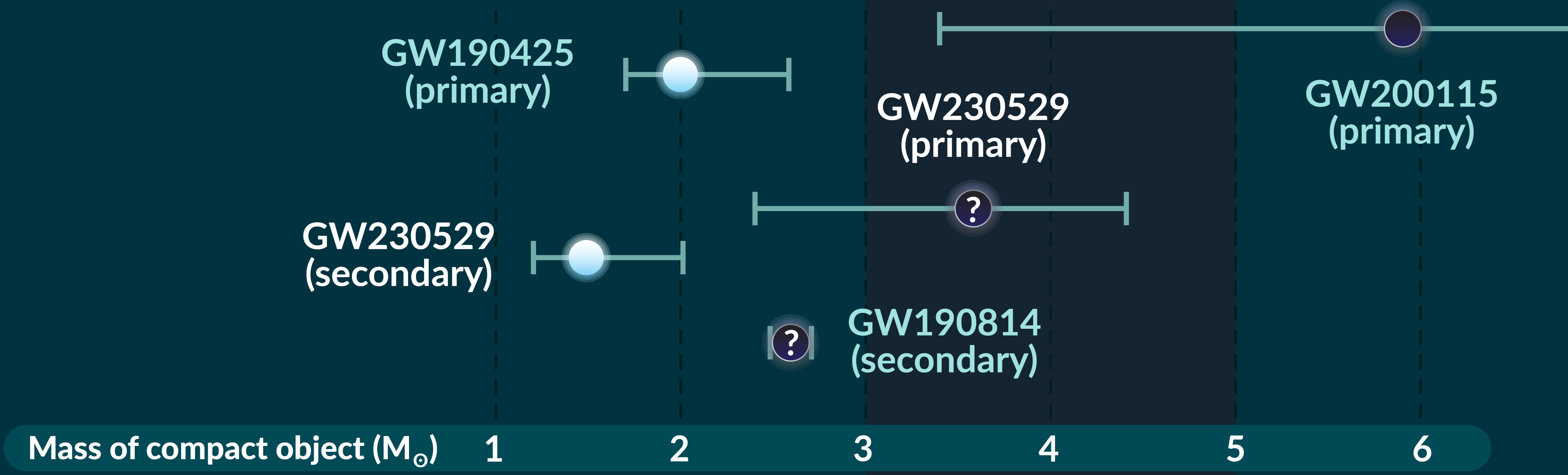


Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

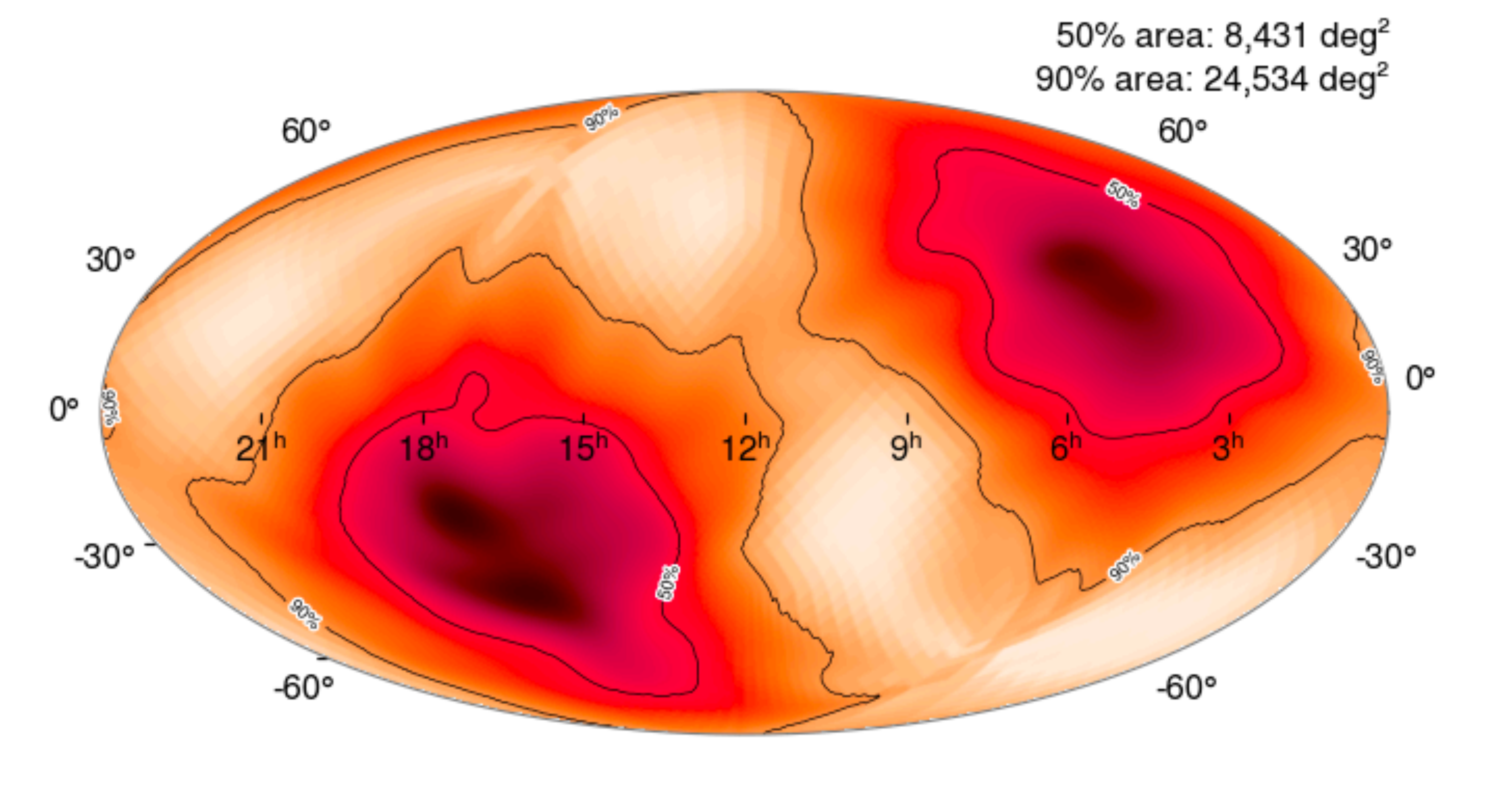
Discovery of GW230529

- 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

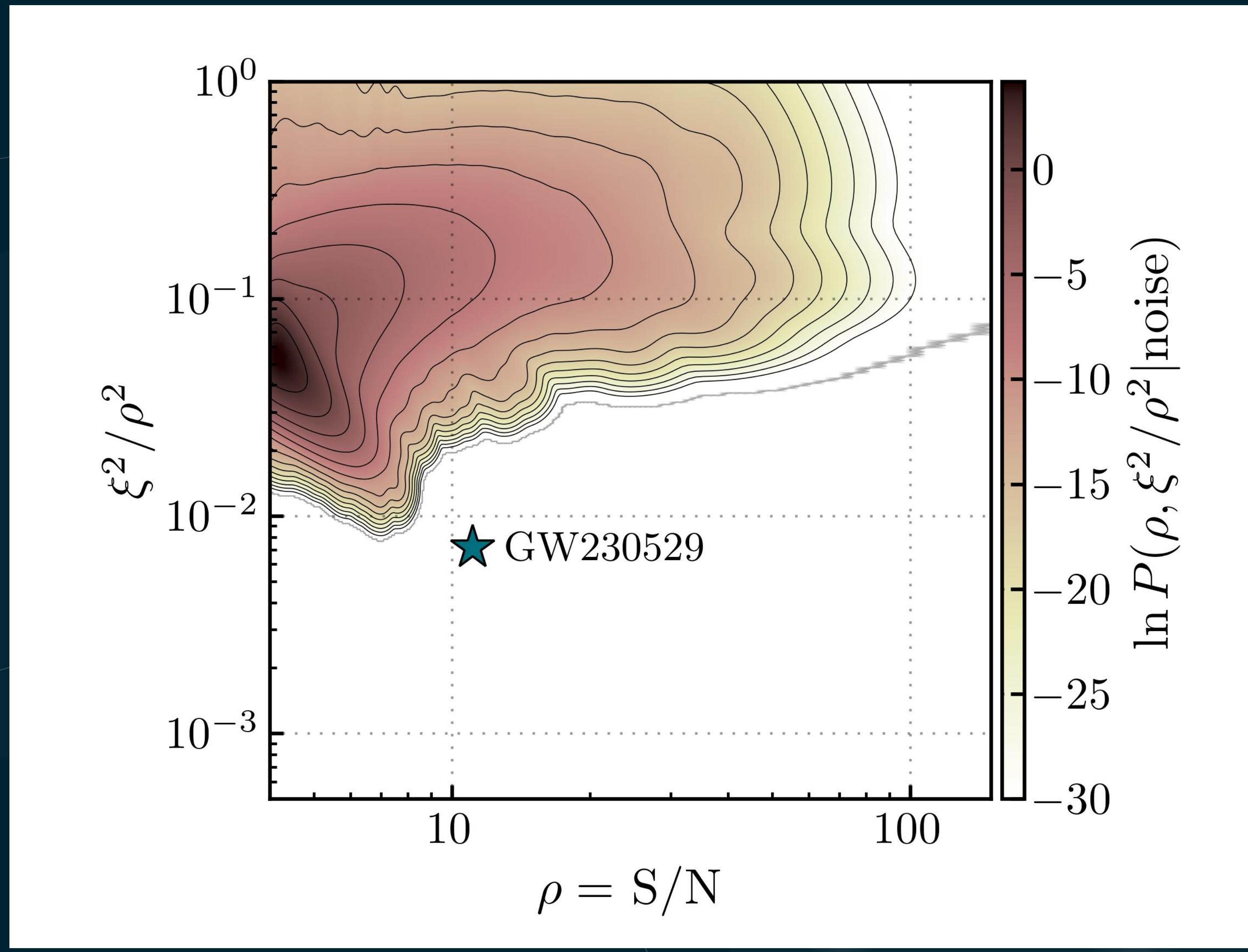
- Offline OR not operational
- Online BUT not used for analysis*
- Online AND used for analysis



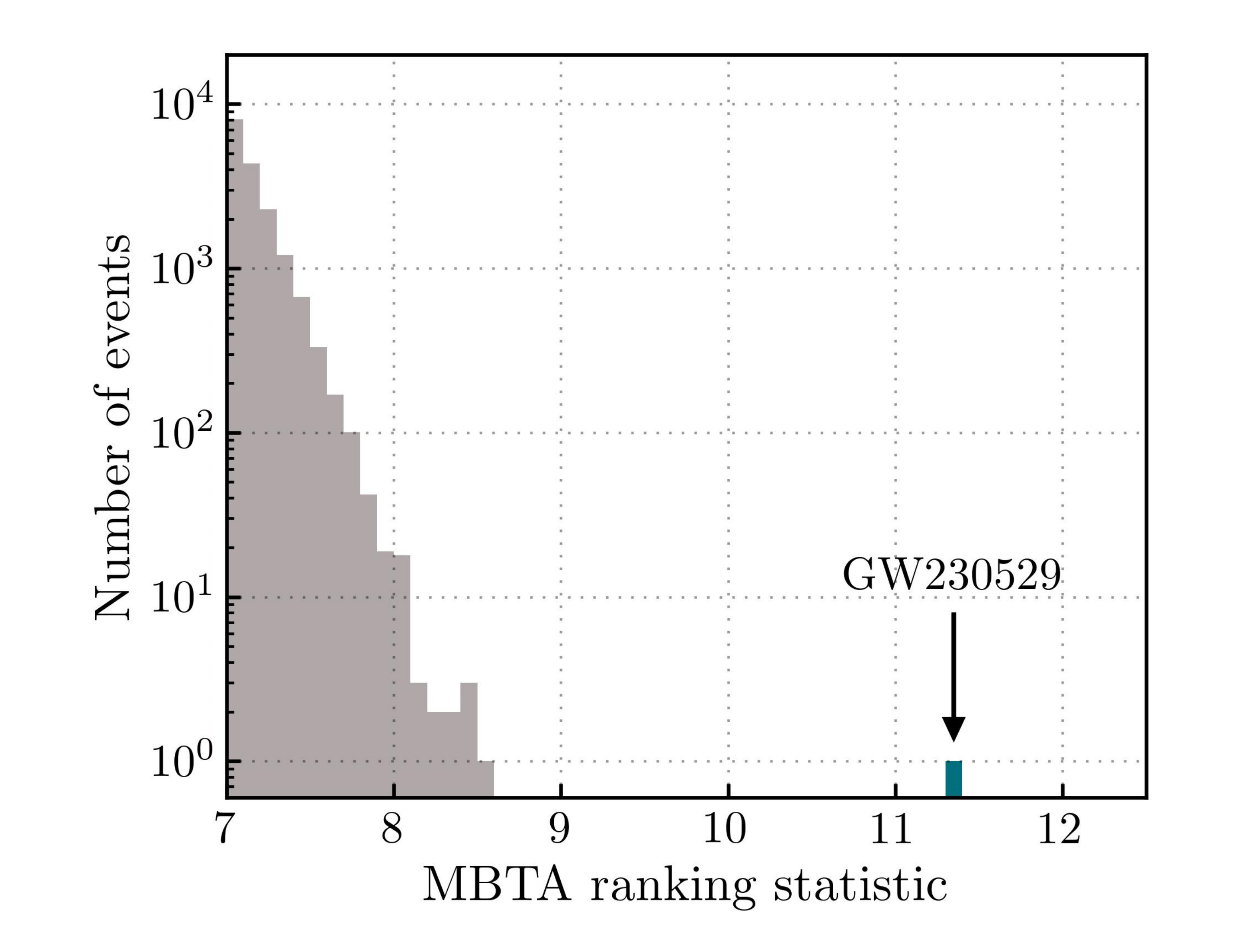
Event significance

- Observed with high significance in three search pipelines
- Note, different pipelines have different significance statistics

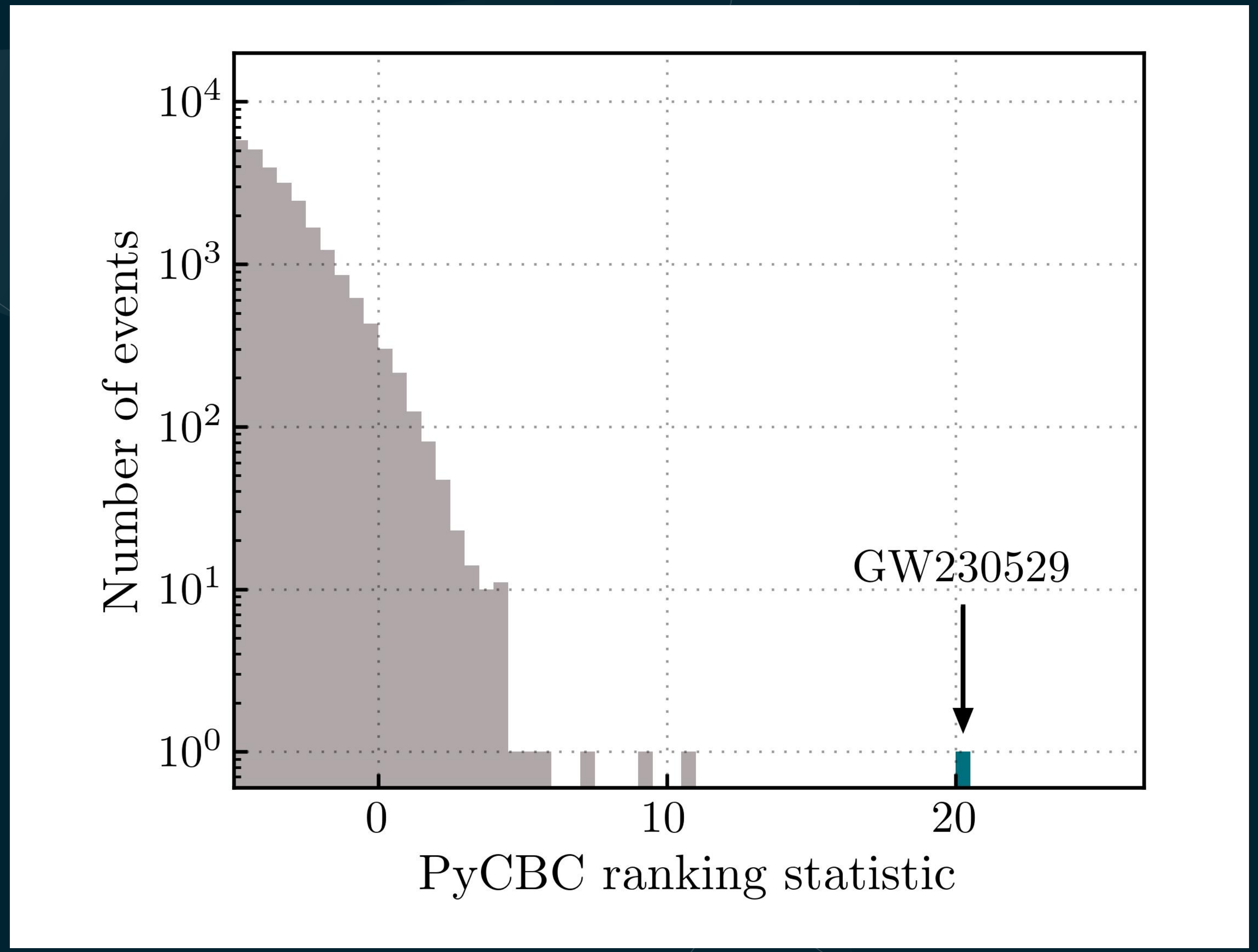
GstLAL



MBTA

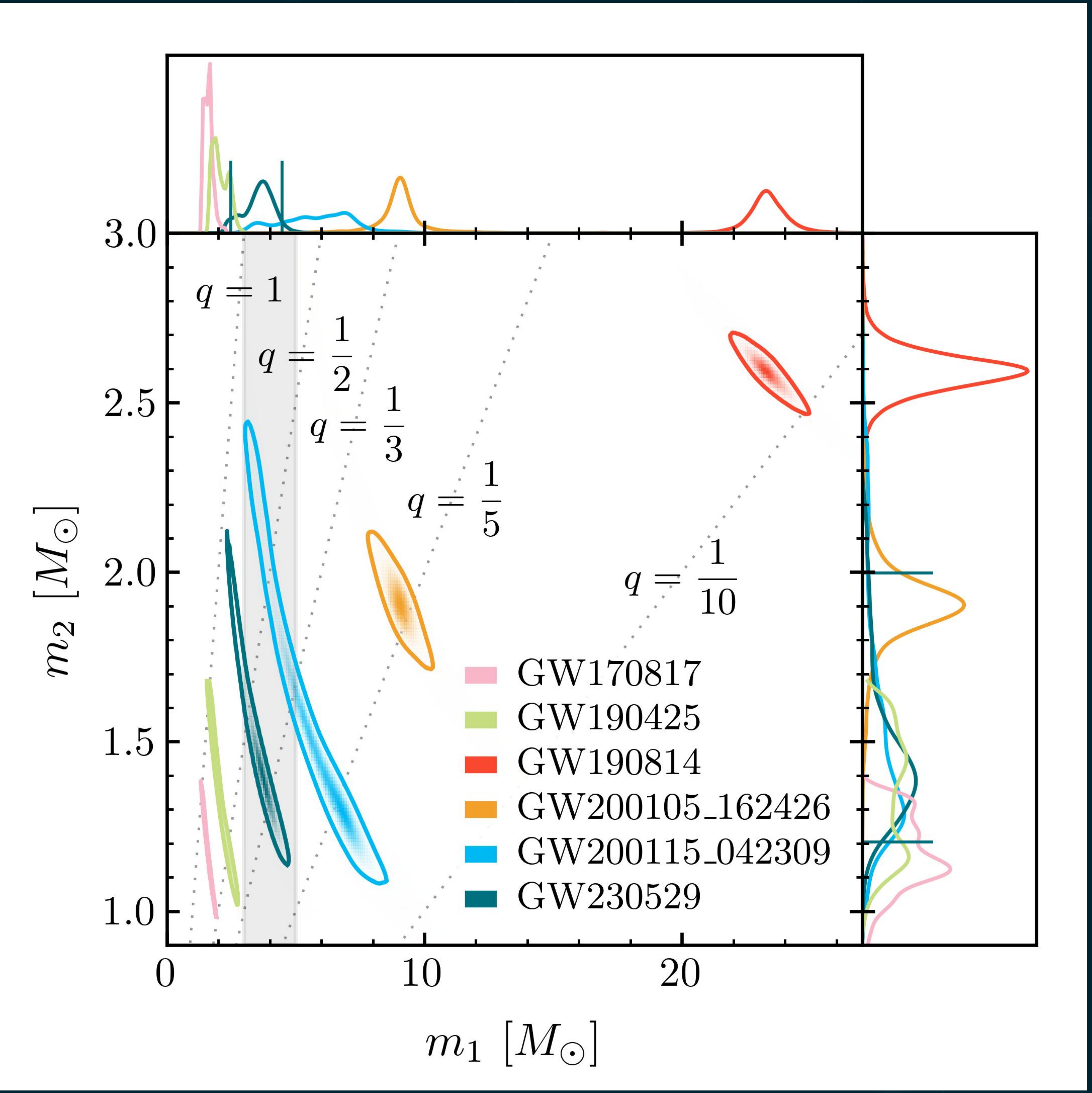


PyCBC



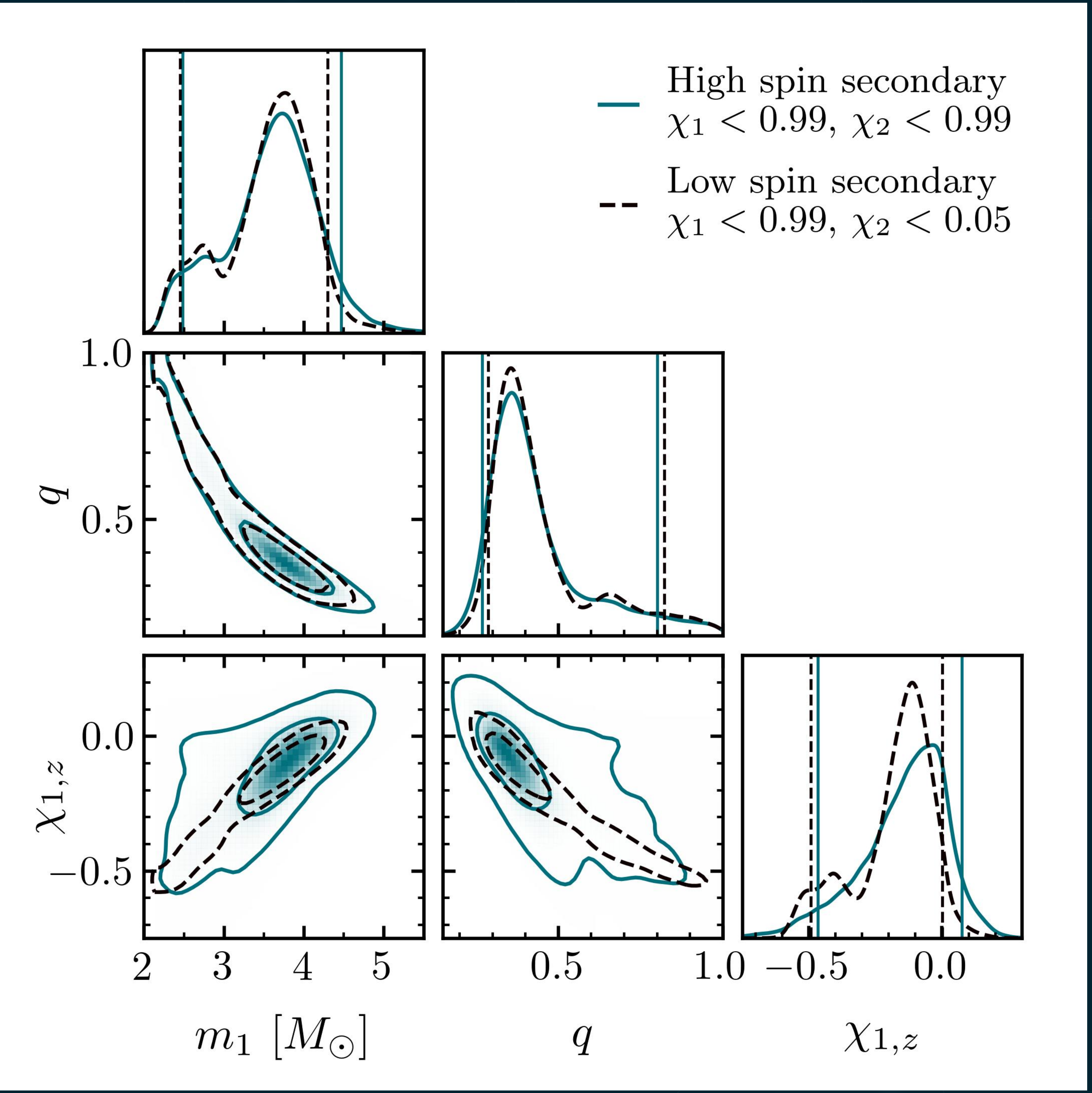
Source properties

- Primary 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



Source properties

- More massive component (primary object) 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 ($\chi_{1,z}$)

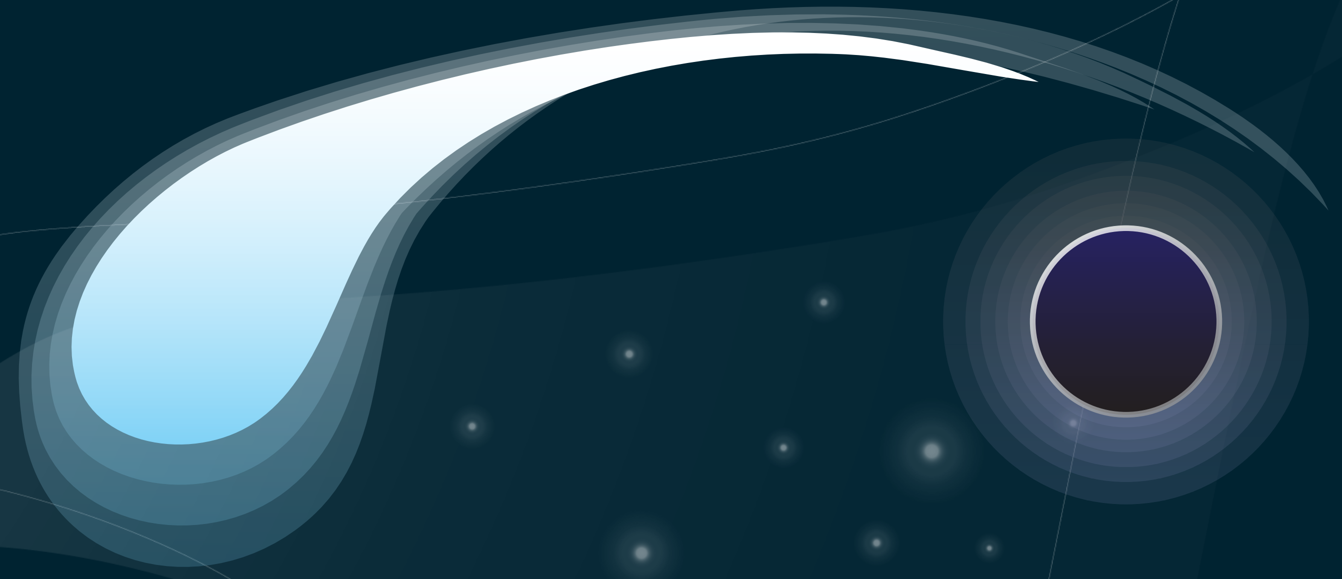



Animation credit:
I. Markin, T. Dietrich, H. Pfeiffer, A. Buonanno
-0.030 s
Universität Potsdam

Bigger black hole?

Neutron star is
ENGULFED

Smaller black hole?

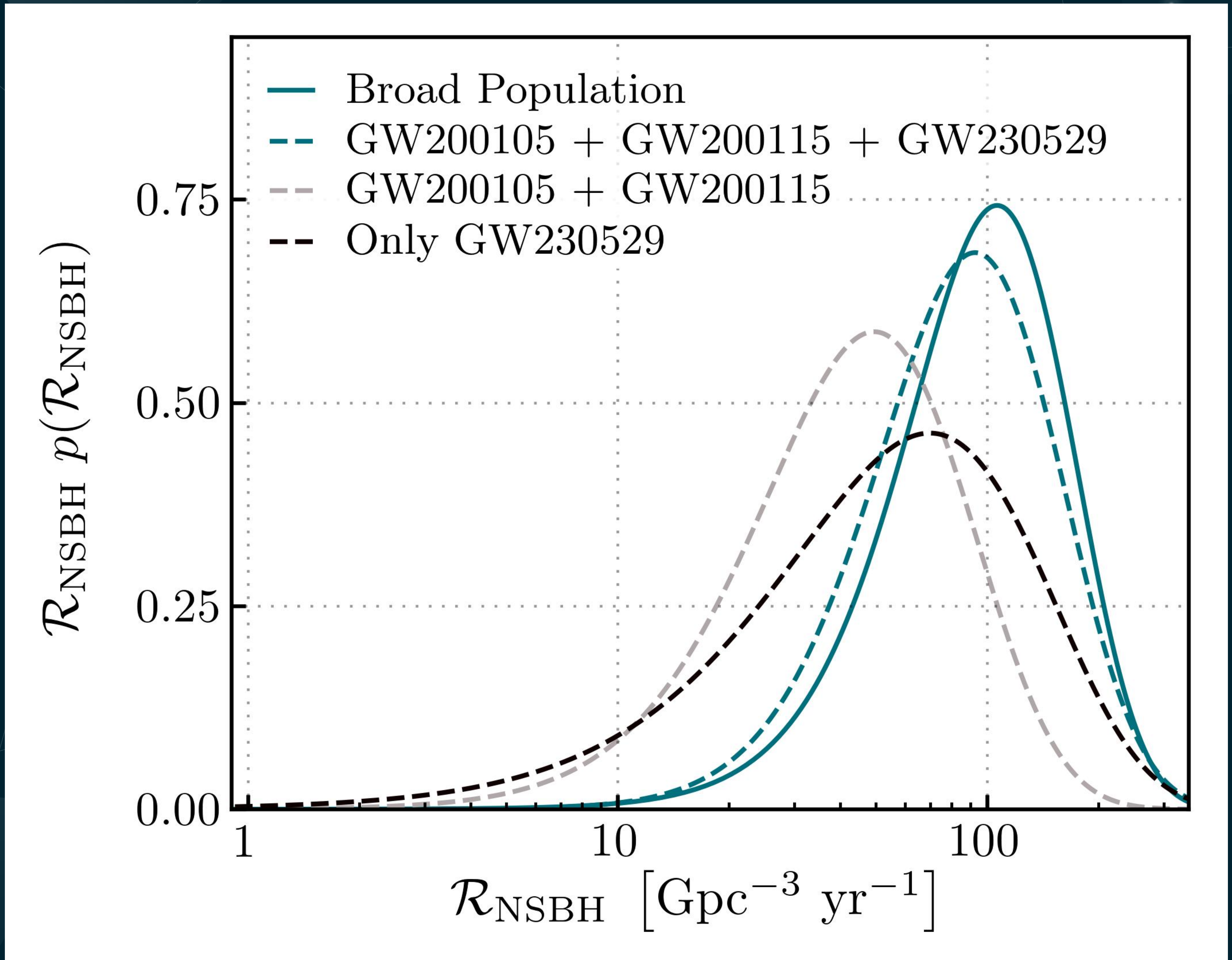


Neutron star is
RIPPED APART


Nice
Neutron Star
Black hole could
be similar in size!

Merger rates of NSBH

- 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.

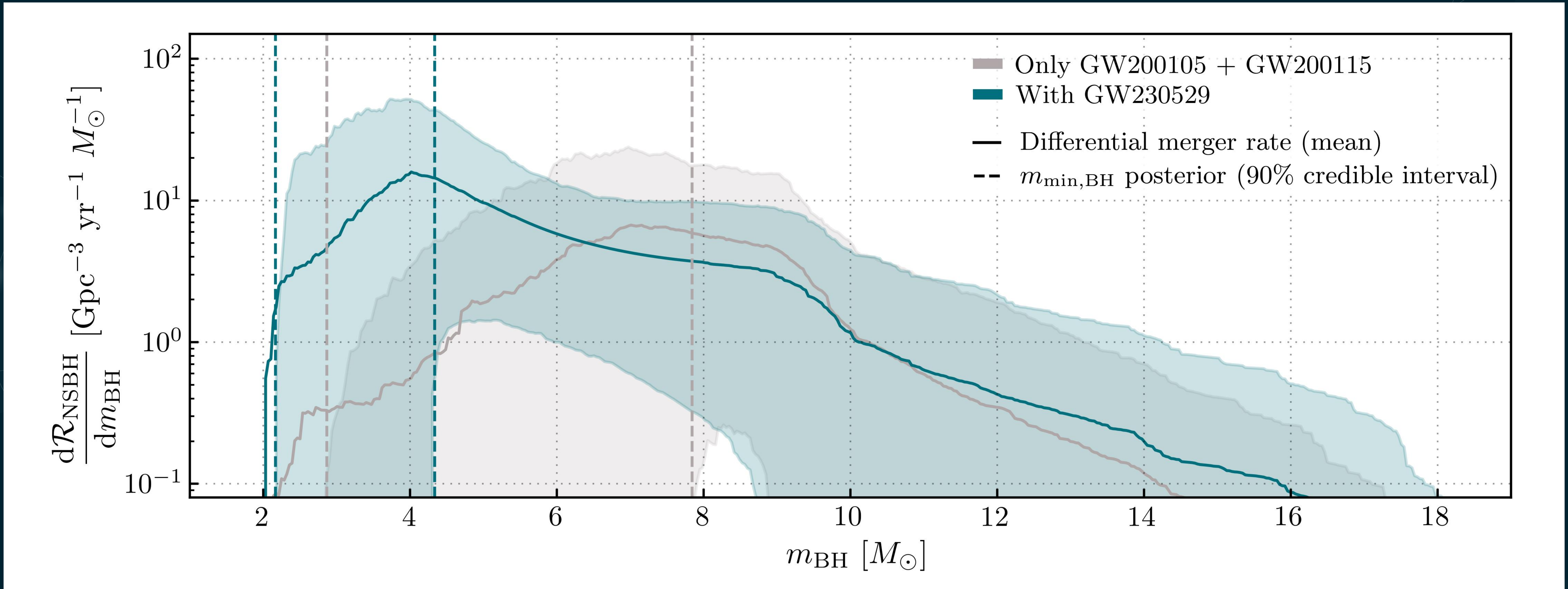


Population analyses

- Three different population models:
  - **Binned Gaussian Process:** a non-parametric, data driven model (most flexible model) to fit full compact binary population.
  - **Power law + Dip + Break:** a parametric model designed to fit full compact binary population and models dip-like feature in the mass distribution
  - **NSBH-pop:** a parametric model designed to fit NSBH population and models mass and spin distributions.

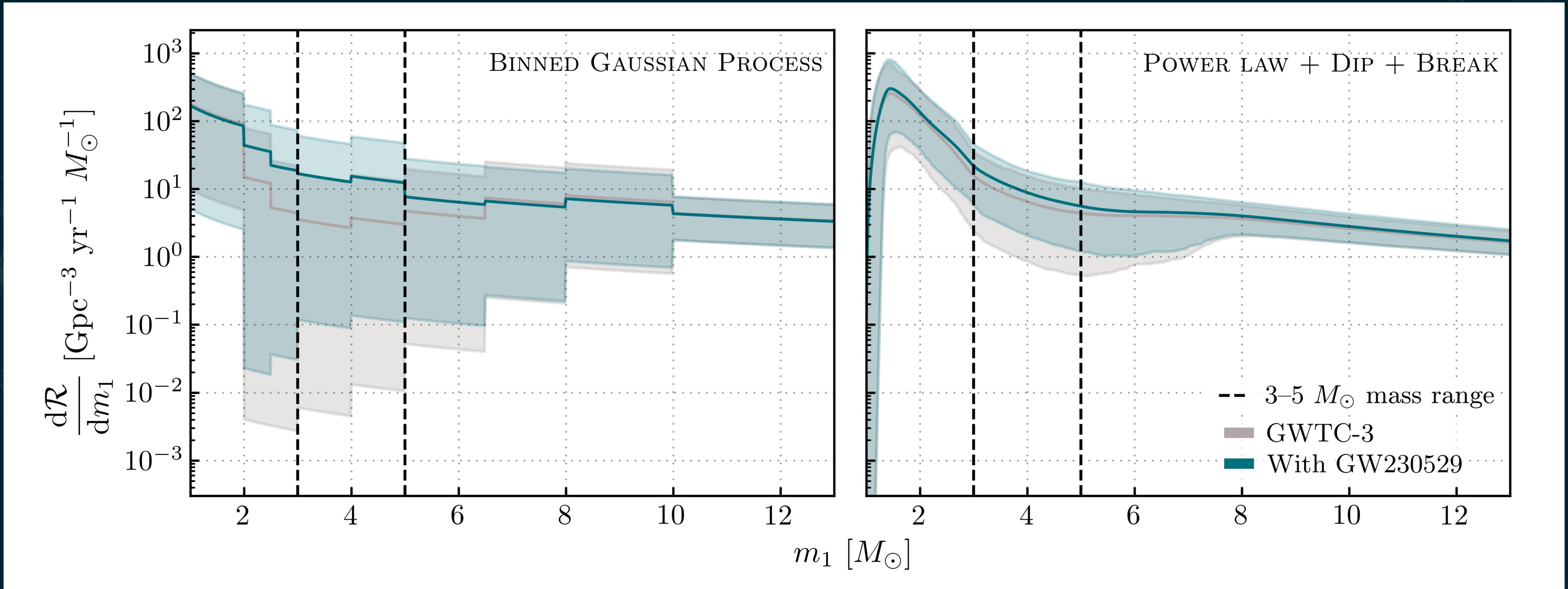
Mass distribution of NSBH population

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



Merger rate of lower mass gap objects

- Increases in inferred rate of mergers in lower mass gap

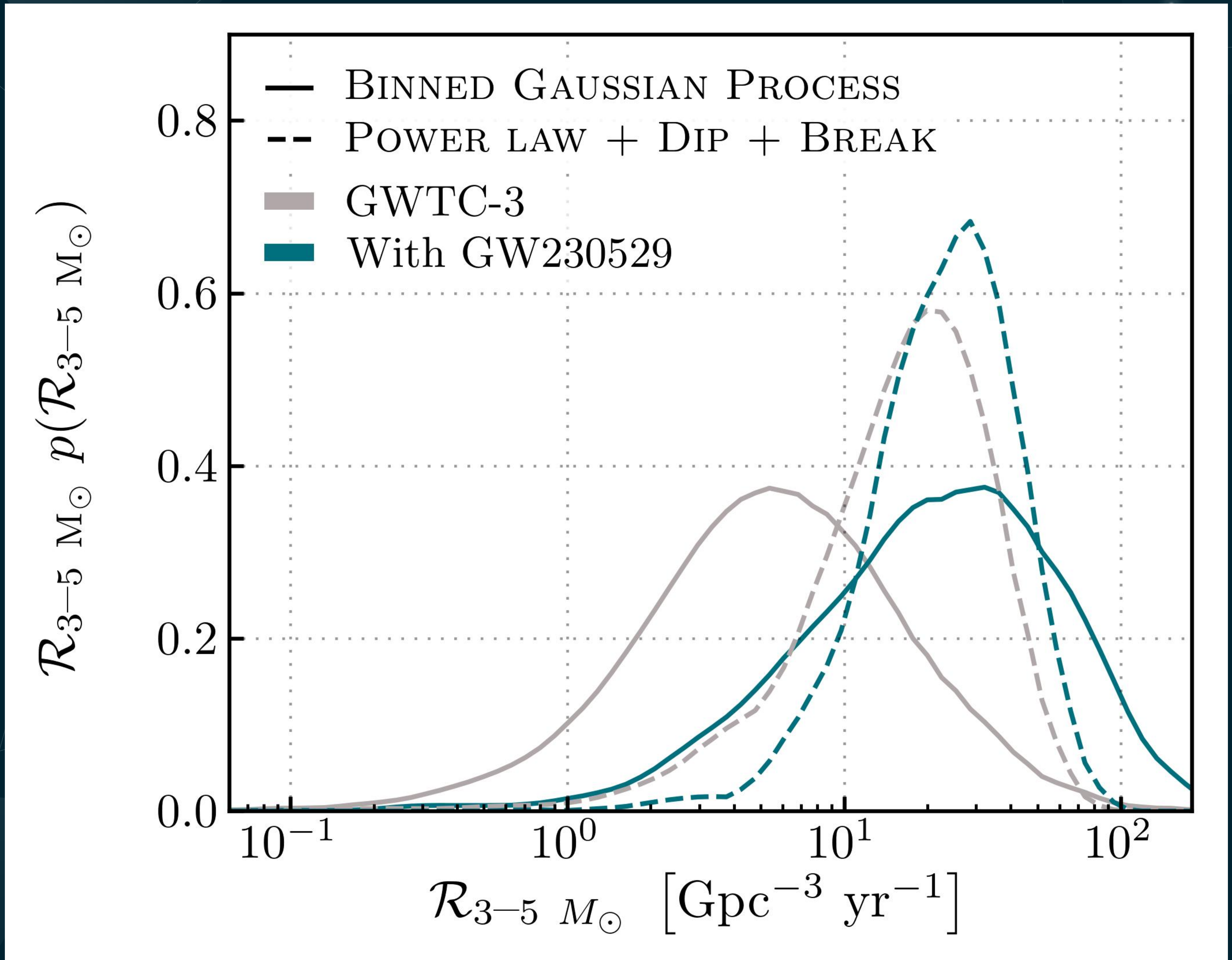
- Binned Gaussian Process:

  $$1\text{-}54\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1} \rightarrow 4\text{-}112\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

- Power law + Dip + Break:

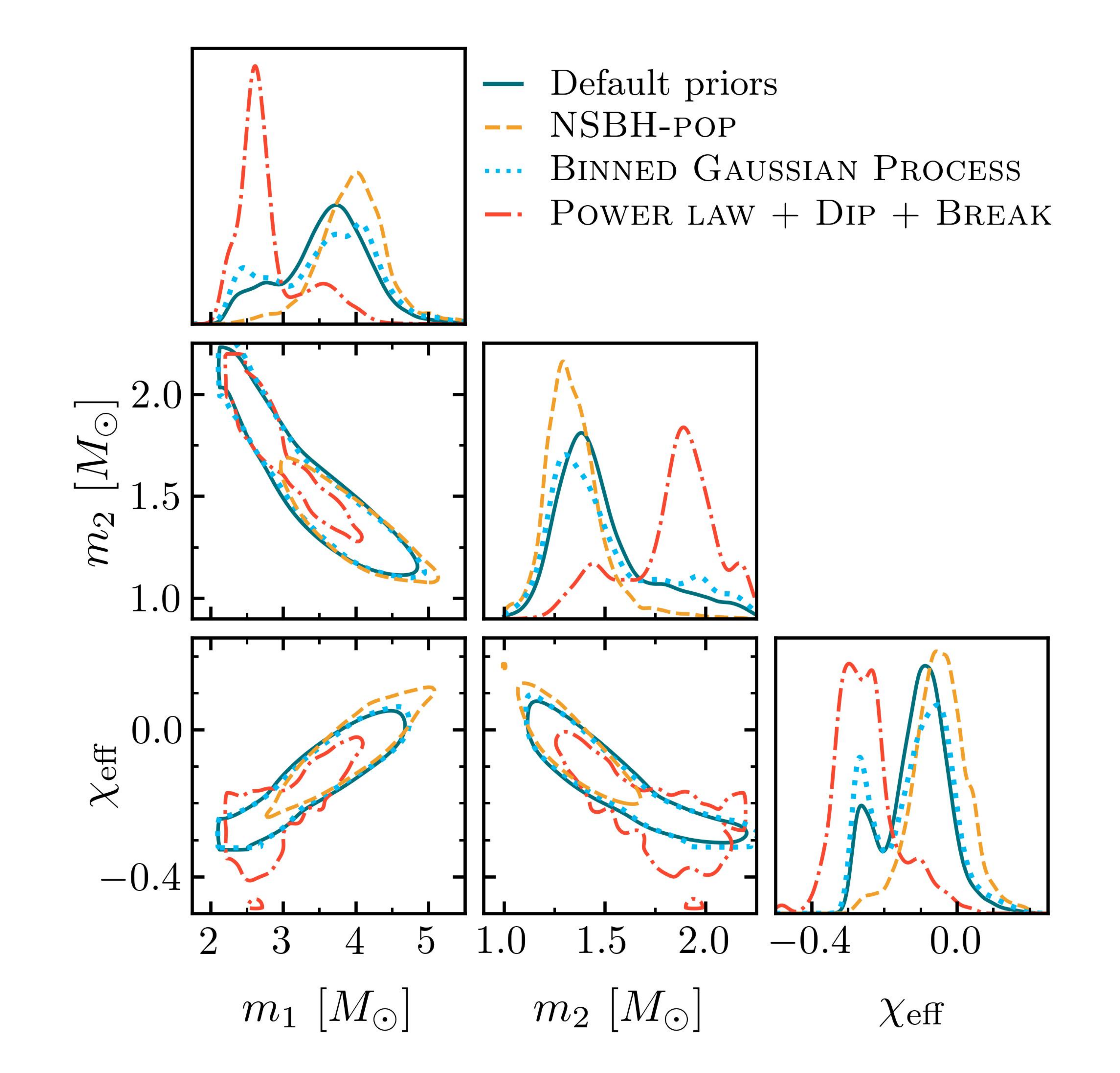
  $$3\text{-}42\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1} \rightarrow 8\text{-}52\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

- Rate of mergers in the lower mass gap inconsistent with zero



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 BNS.



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)

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)

Get to know

GW230529

Full name GW230529_181500

Discovered on 29 May 2023 at 18h15 UTC

most likely a merger between a Neutron Star & Black Hole (NSBH)

~1.4 $M_\odot$ ~3.6 $M_\odot$

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

~ 650 million light years away

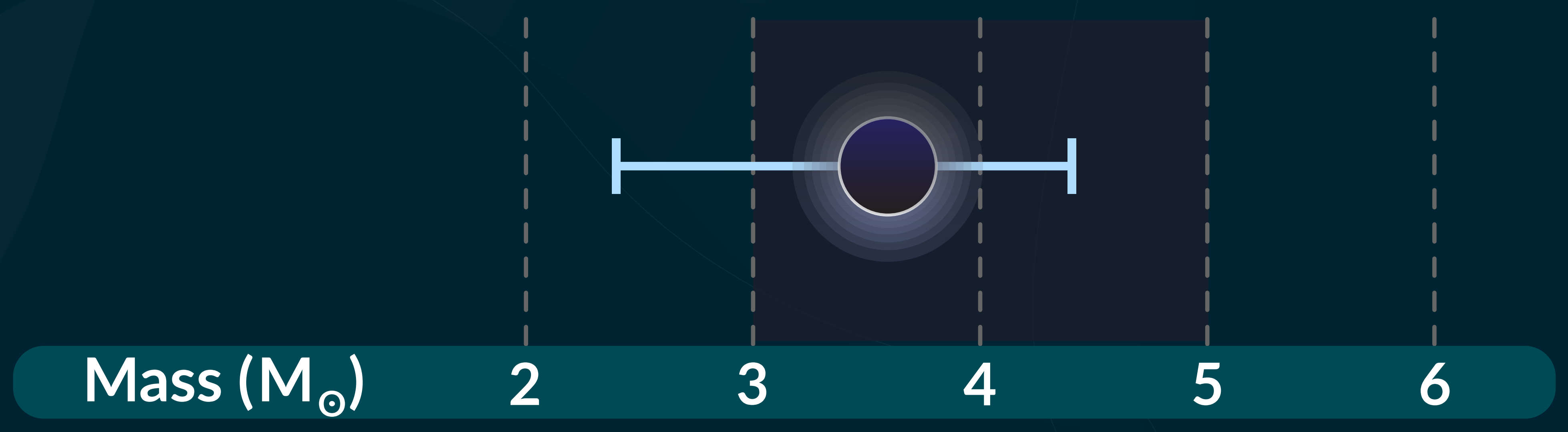
Detectors

H L V K

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

Primary object in lower mass gap

further supports that this region is not empty

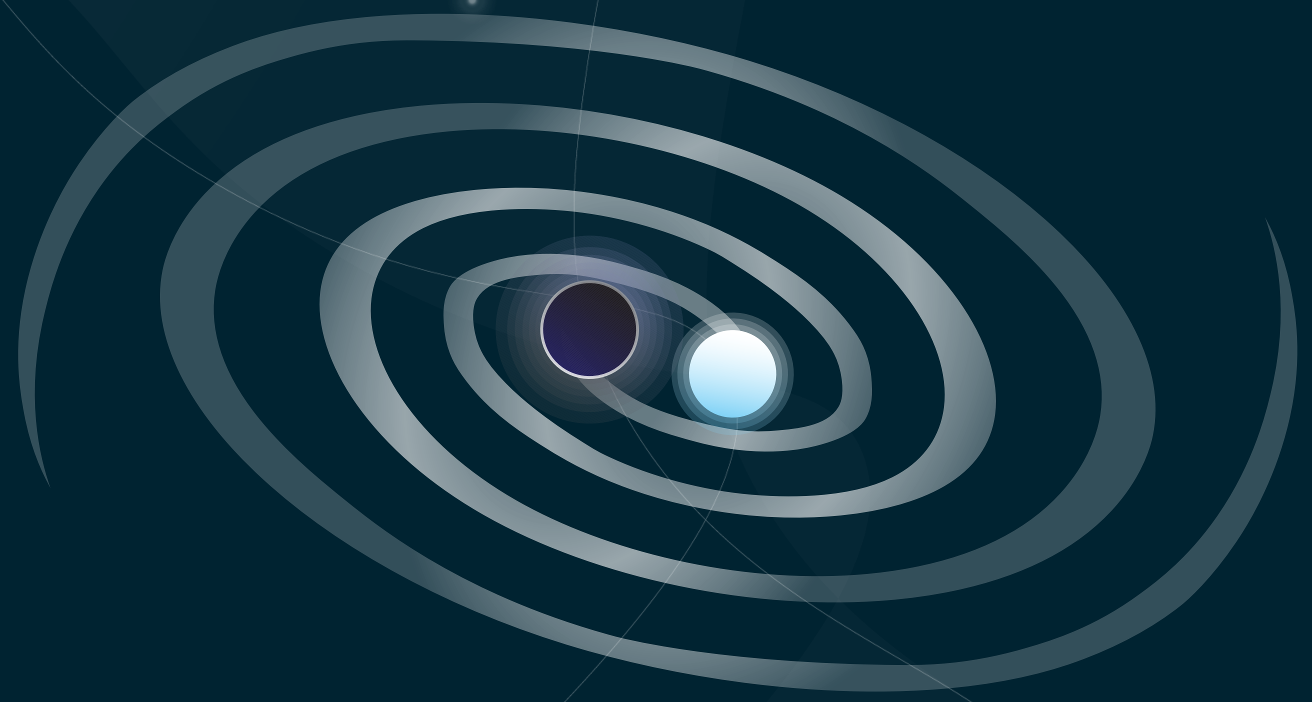


* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

Summary

- 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?
- The gap is being filled with gravitational wave events too! GW230529's primary component is well within this gap.

- #O4IsHere with 83 events as of this morning! Follow along on gracedb: https://gracedb.ligo.org/superevents/public/O4/



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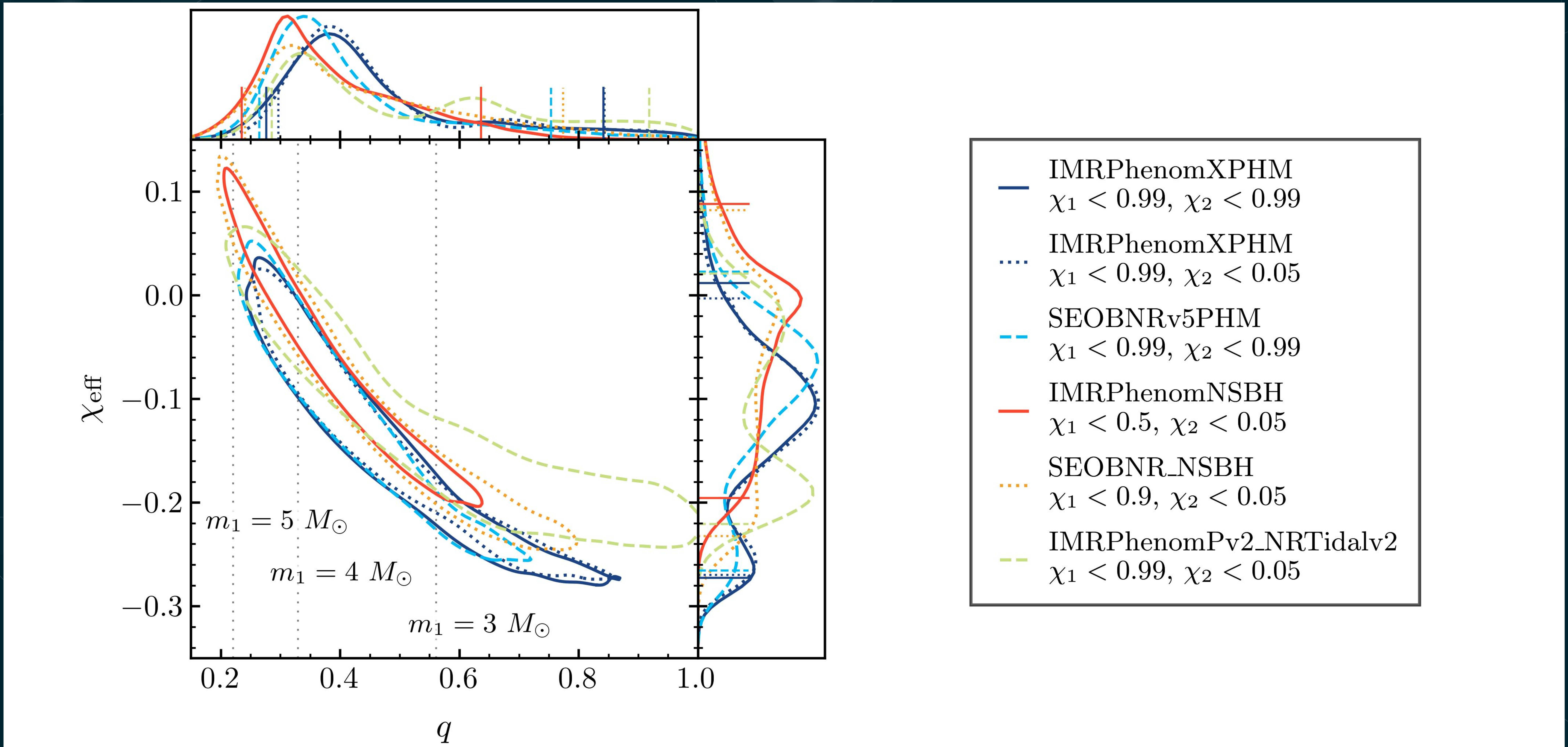
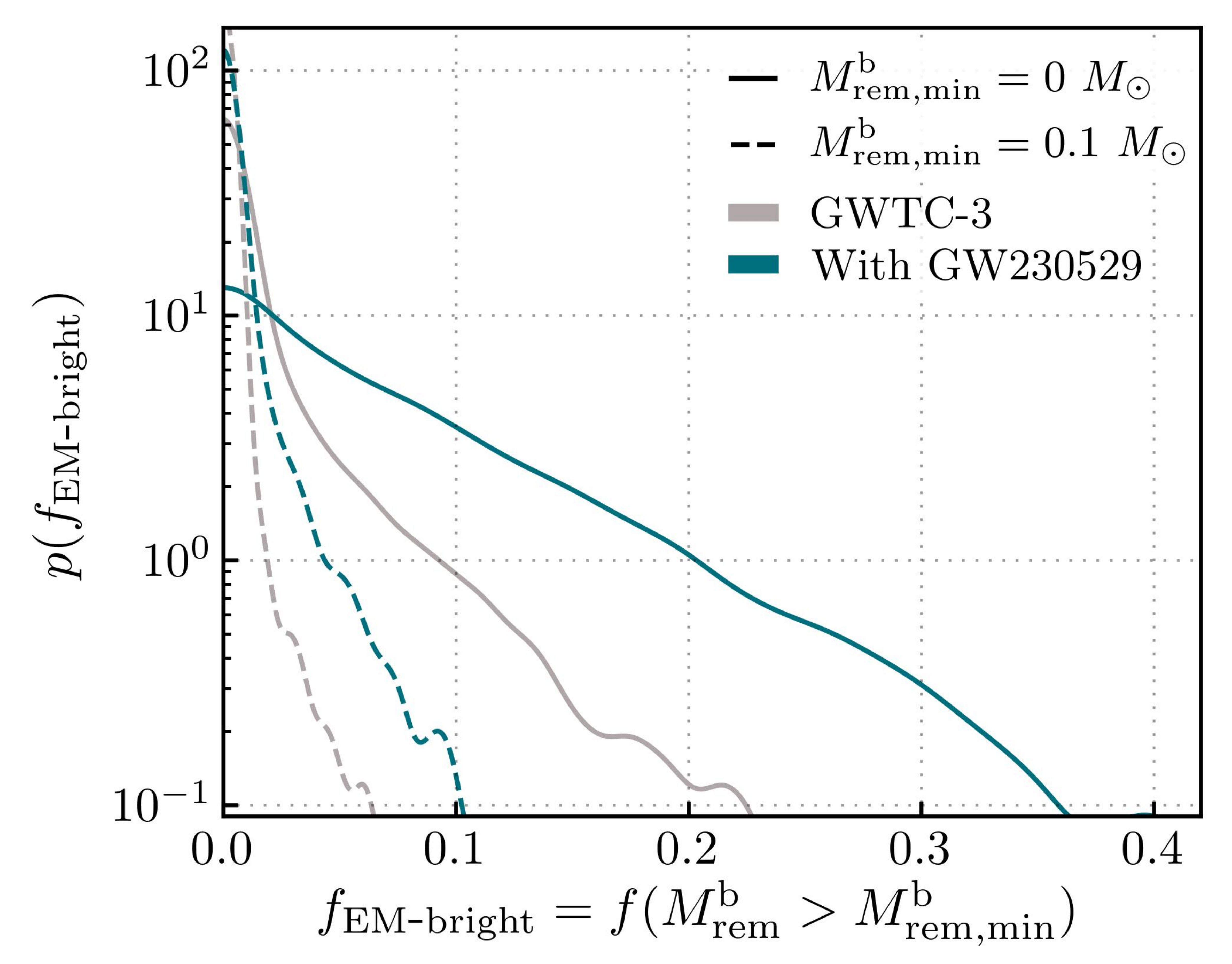
Waveform systematics



Multimessenger prospects

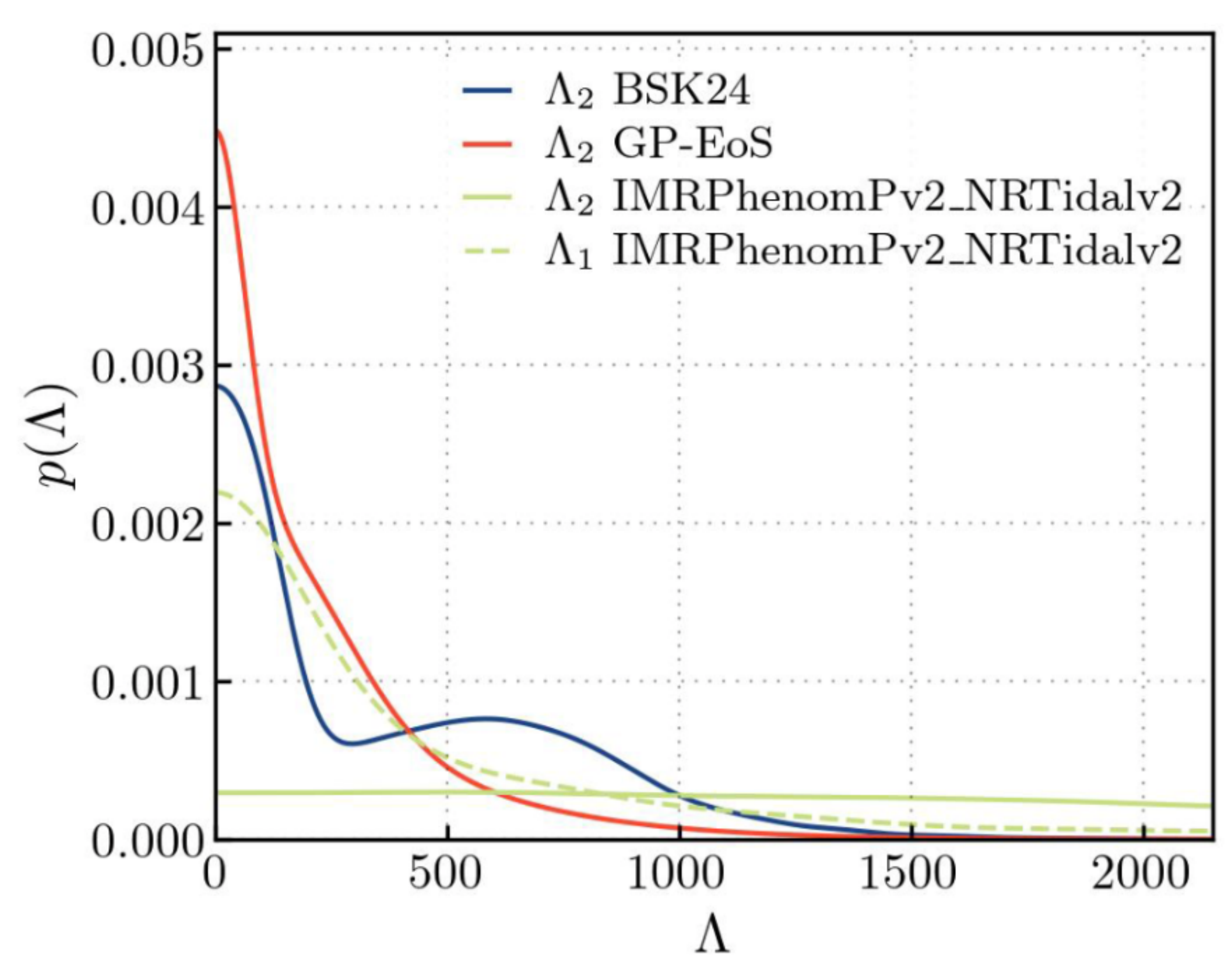
- Increases upper limits on fraction of EM-bright NSBH mergers from $\leq 6\,\%$ to $\leq 18\,\%$
- At most $1.1\ M_\odot\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ contributes to heavy element production, and rate of gamma-ray bursts with NSBH progenitors is at most $23\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$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



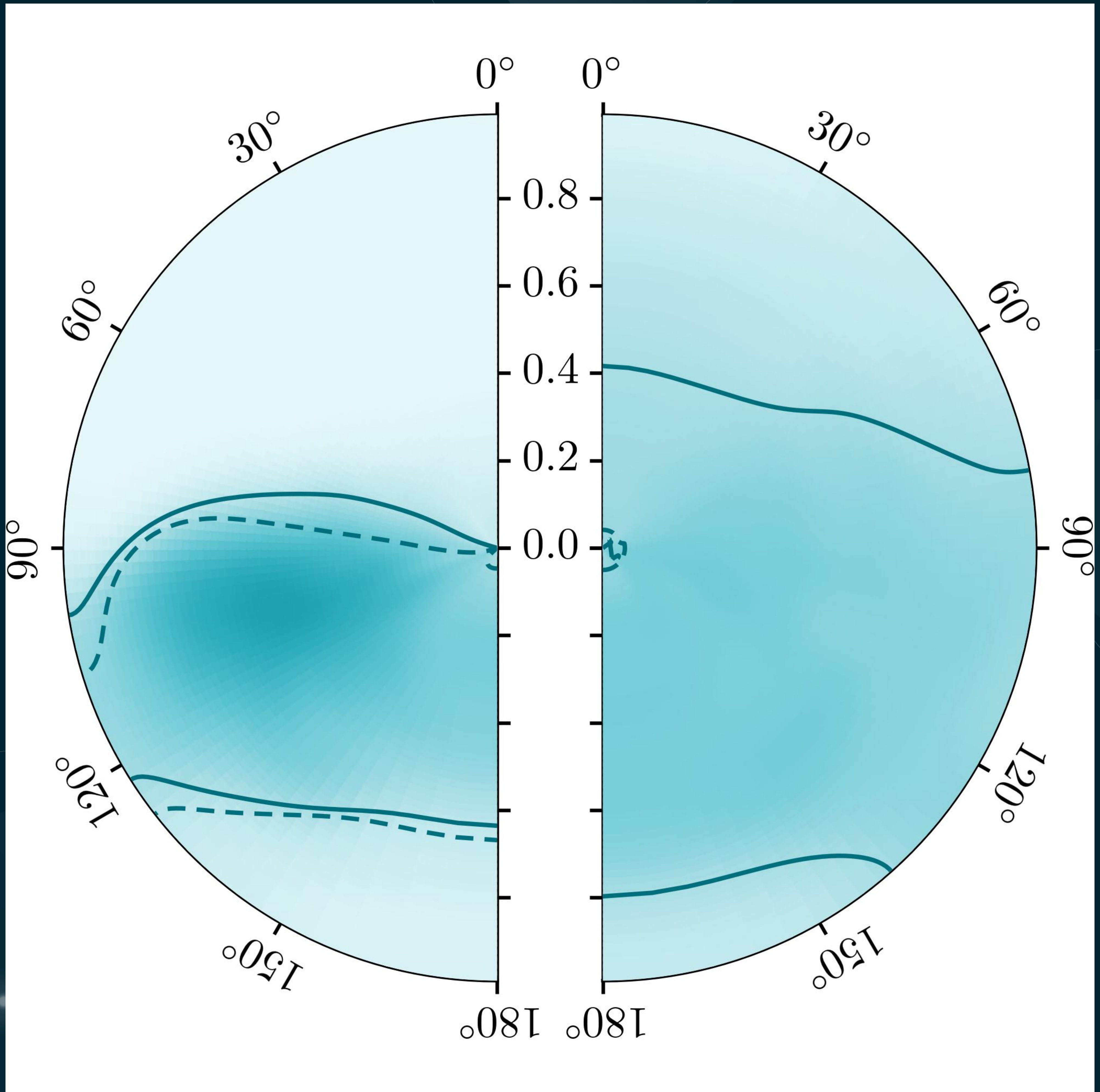
Waveform details

Waveform Model	Precession	Higher Multipoles	Tides	Disruption	Spin Prior
IMRPhenomNSBH	–	–	✓	✓	$\chi_1 < 0.50, \chi_2 < 0.05$
IMRPhenomPv2_NRTidalv2	✓	–	✓	–	$\chi_1 < 0.99, \chi_2 < 0.05$
IMRPhenomXPHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
SEOBNRv5PHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
SEOBNRv4_ROM_NRTidalv2_NSBH	–	–	✓	✓	$\chi_1 < 0.90, \chi_2 < 0.05$
IMRPhenomXPHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.05$
IMRPhenomXP	✓	–	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
IMRPhenomXHM	–	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
IMRPhenomXAS	–	–	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
IMRPhenomXAS	–	–	–	–	$\chi_1 < 0.50, \chi_2 < 0.05$
IMRPhenomPv2_NRTidalv2	✓	–	✓	–	$\chi_1 < 0.05, \chi_2 < 0.05$
IMRPhenomXPHM	✓	✓	–	–	$\chi_1 < 0.05, \chi_2 < 0.05$
SEOBNRv5PHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.05$

Tidal deformability

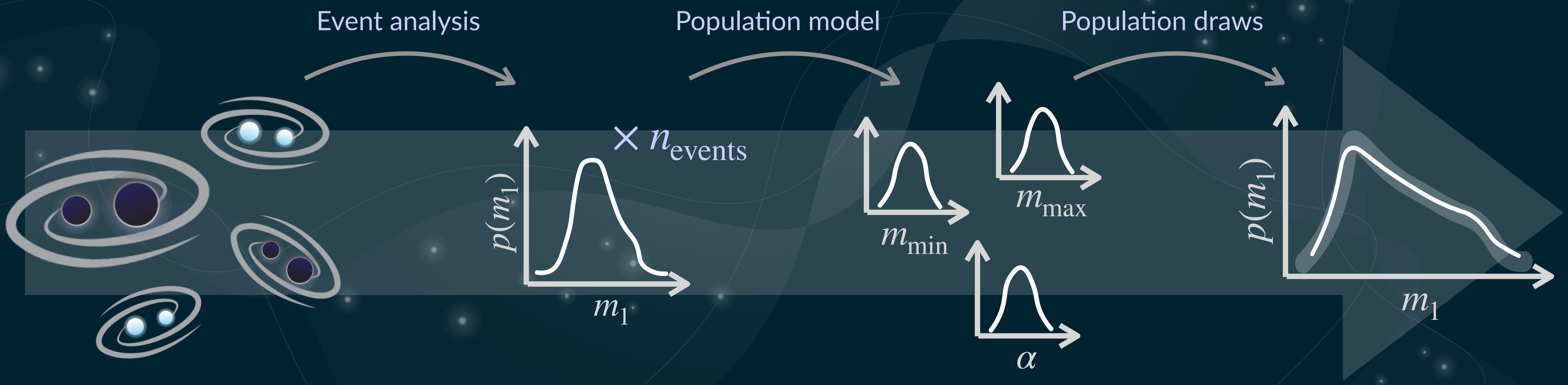


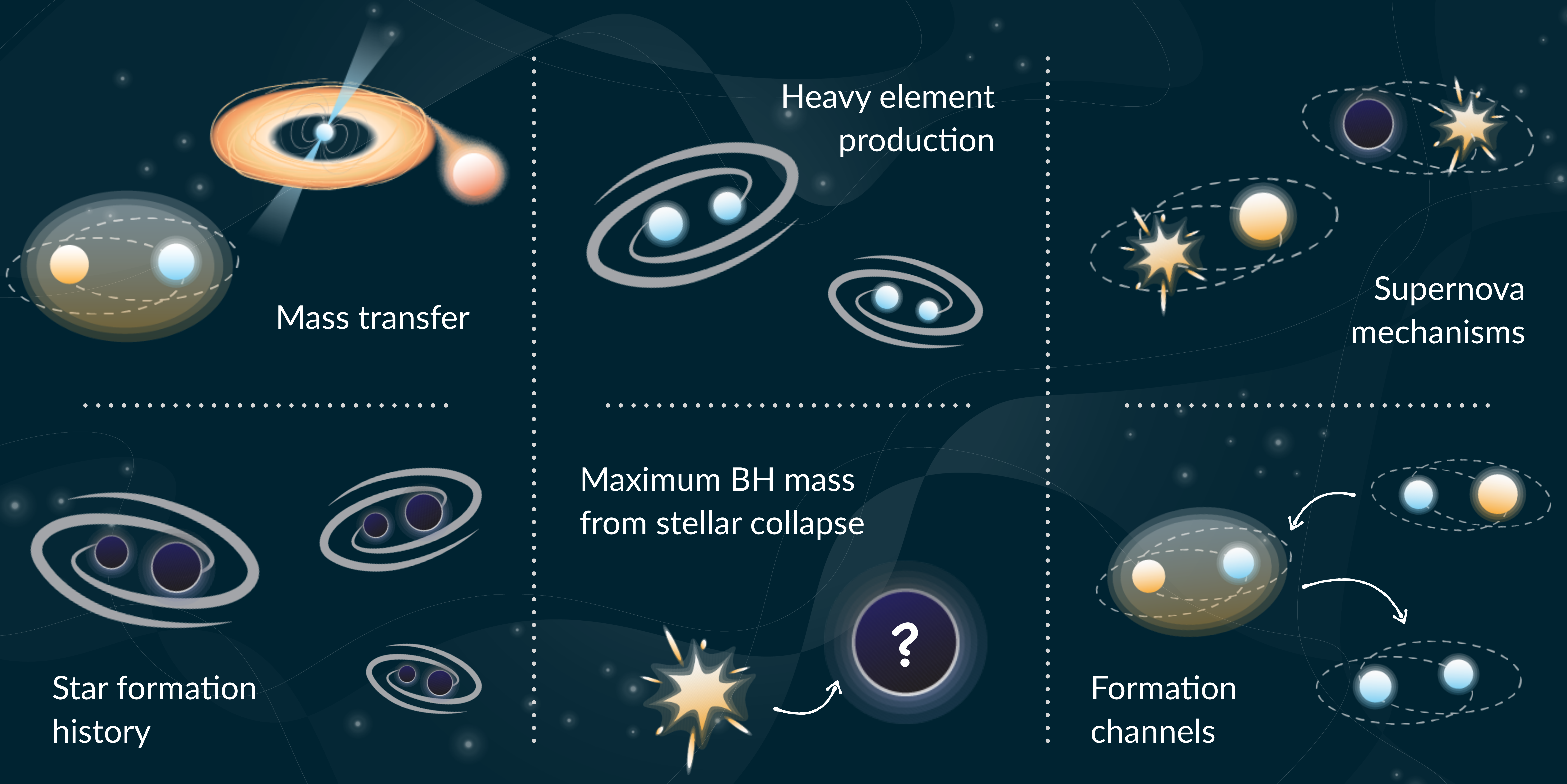
Component spins



Population inference

- Parameter estimation programs (e.g. BILBY), employing Bayesian inference to extract source properties (e.g. mass, spin) from gravitational-wave signals.
- Hierarchical Bayesian inference to study the *shape* of the population. Define model where parameters you sample are describing the shape (e.g. slope, min and max values)




Mass transfer
Heavy element production
Supernova mechanisms
Star formation history
Maximum BH mass from stellar collapse
?
Formation channels