The latest results from the LIGO-Virgo-KAGRA collaboration: #O4IsHere!

Shanika Galaudage (on behalf of the LIGO-Virgo-KAGRA collaboration)

Oct 15, 2024 | GdR Gravitational Waves - Marseille

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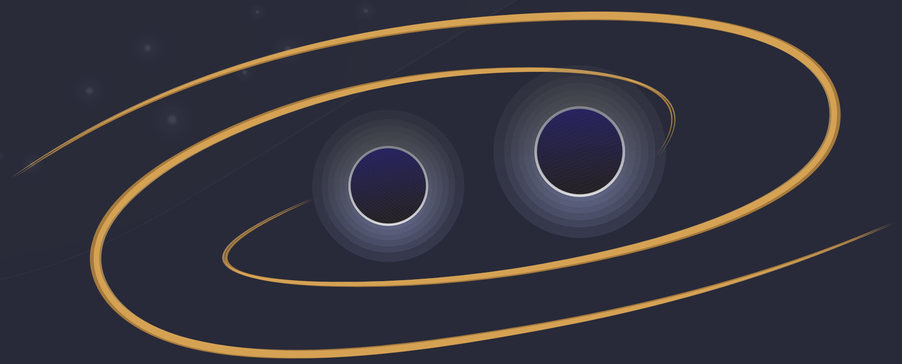
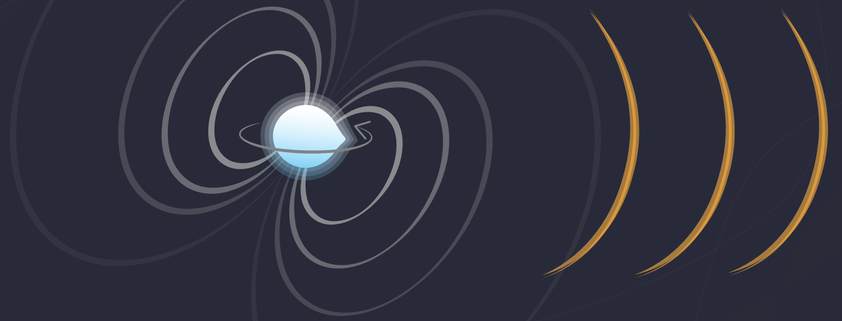
compact binary inspiral



continuous



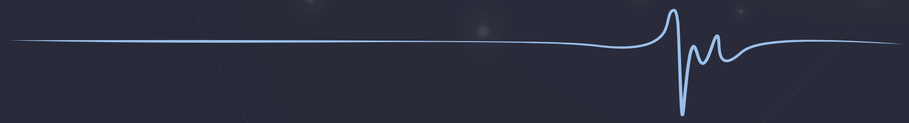
MODELLED

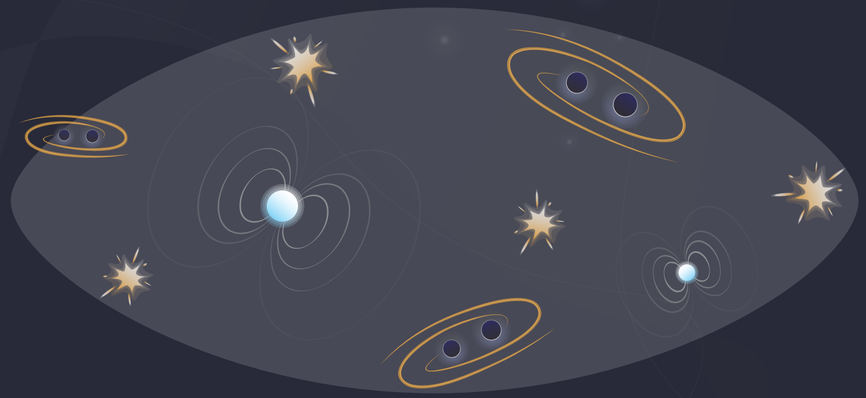
SHORT DURATION

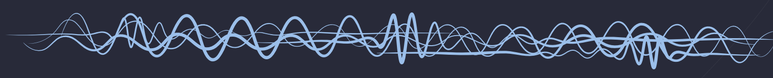
LONG DURATION

UNMODELLED

burst



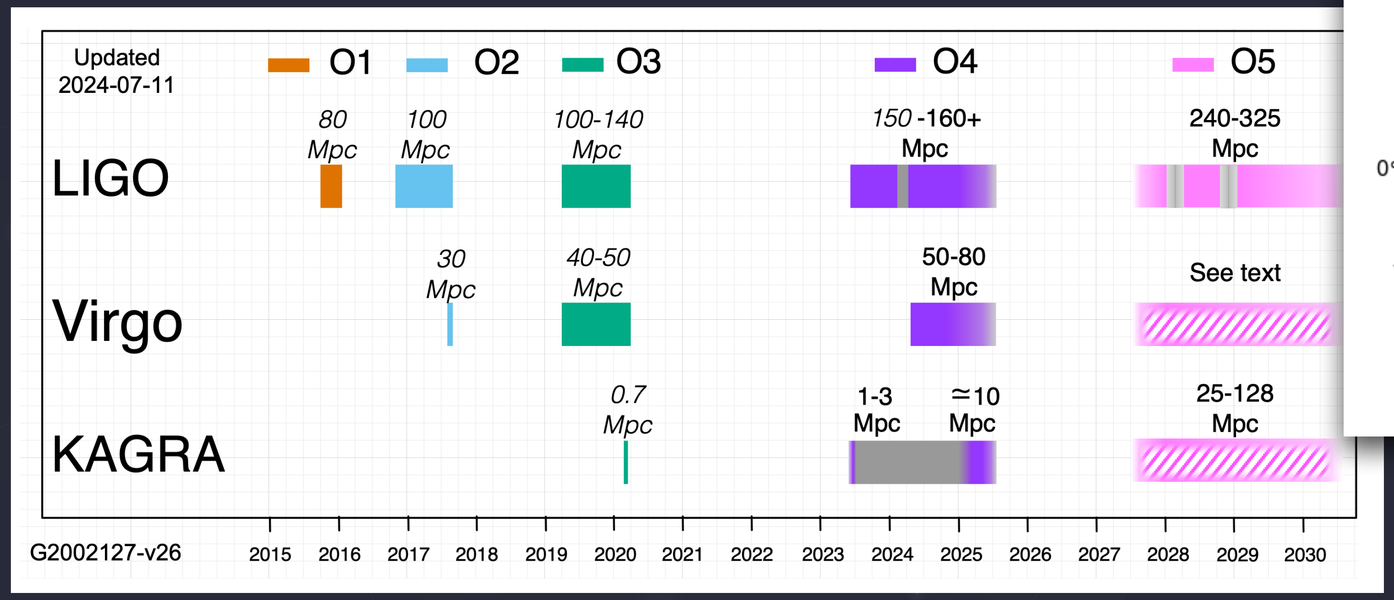


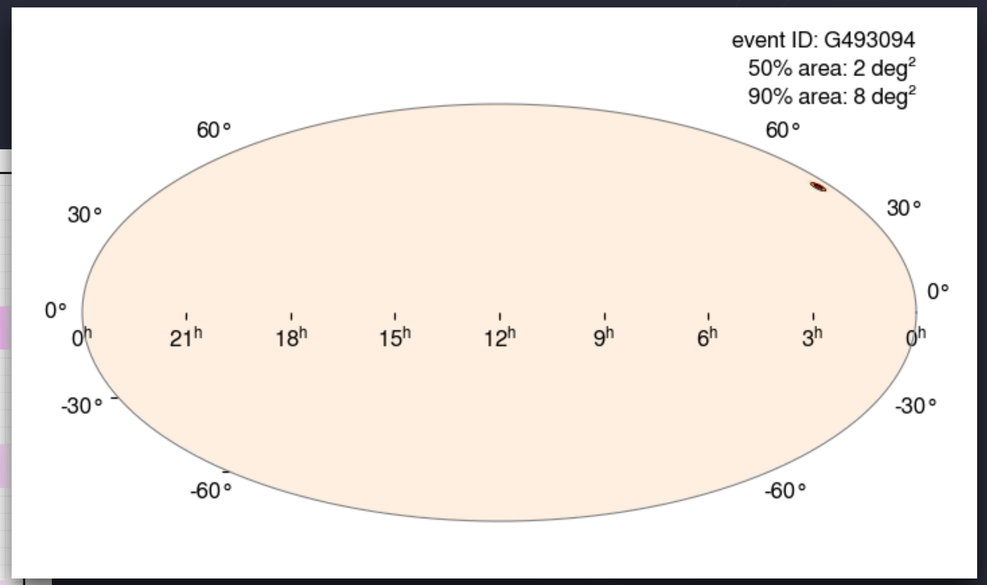


stochastic

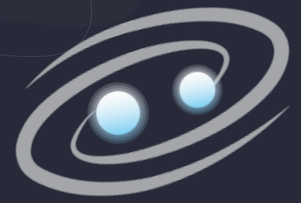
Latest observing run of LIGO-Virgo-KAGRA

- Currently in second half (O4b) with Virgo joining; O4 extended to mid-2025!
- 149 significant alerts so far in O4



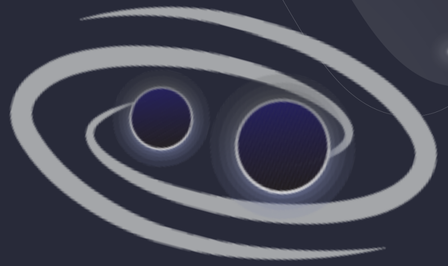


Some highlights from the past…



GW170817

LVK arXiv:1710.05832
LVK+ arXiv:1710.05833



GW190521

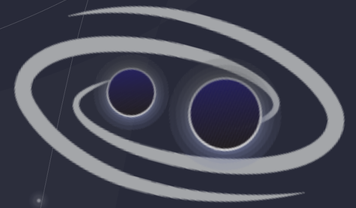
LVK arXiv:2009.01075
e.g. Romero-Shaw+ arXiv:2009.04771

GW150914

LVK arXiv:1602.03837
LVK arXiv:1602.03846

GW190814

LVK arXiv:2006.12611

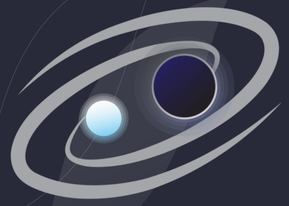


GW191109

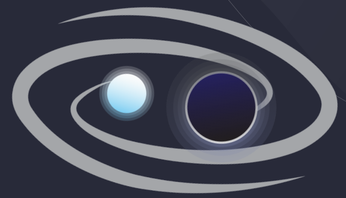
LVK arXiv:2111.03606
e.g. Zhang+ arXiv:2302.07284

GW190425

LVK arXiv:2001.01761
e.g. **Galaudage**+ arXiv:2011.01495



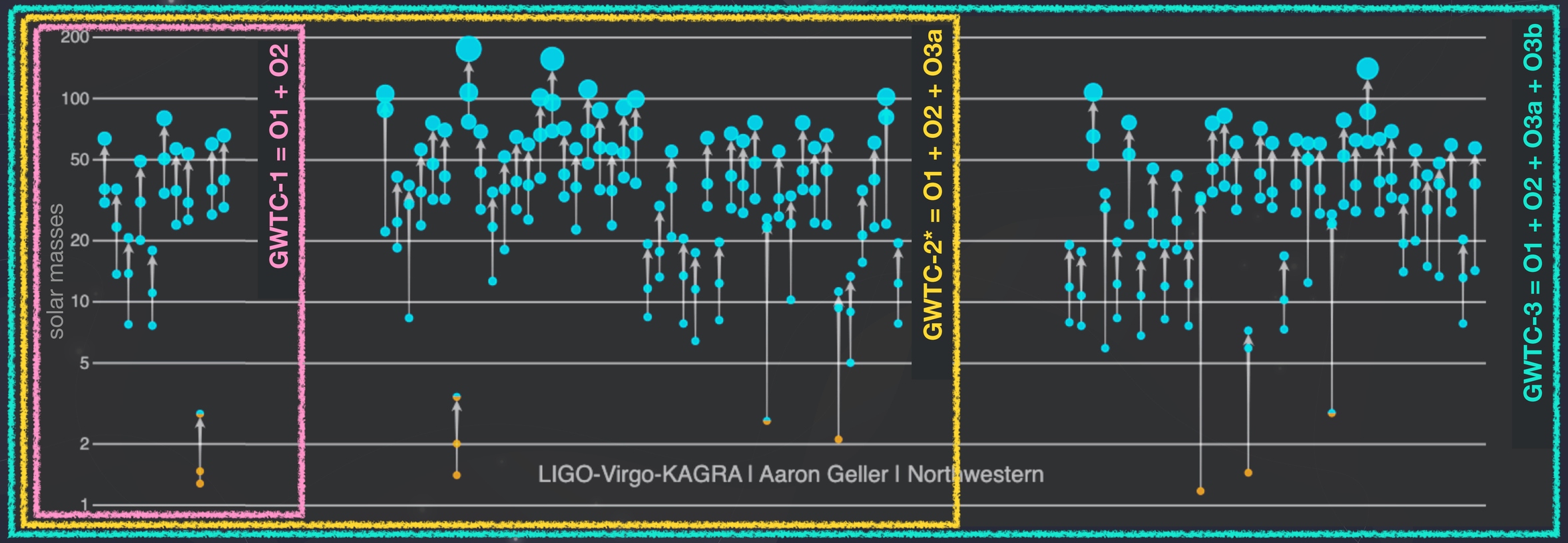
GW200105



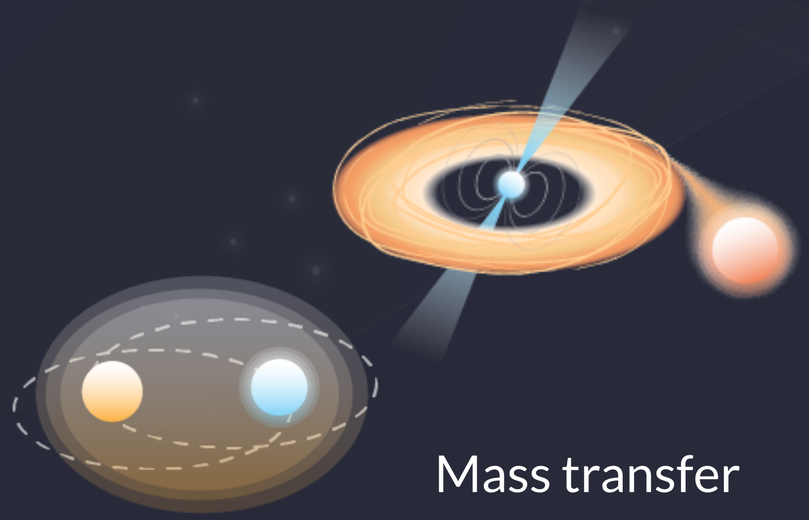
GW200115

LVK arXiv:2106.15163
e.g. Mandel & Smith arXiv:2109.14759

The growth in the GW catalogues



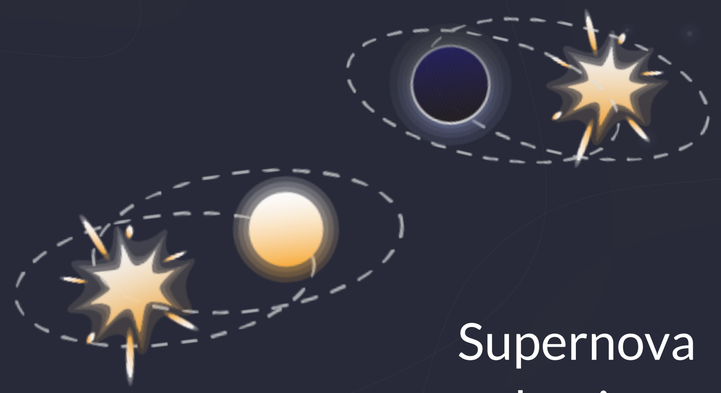
* Some events here are in GWTC-2.1 catalogue

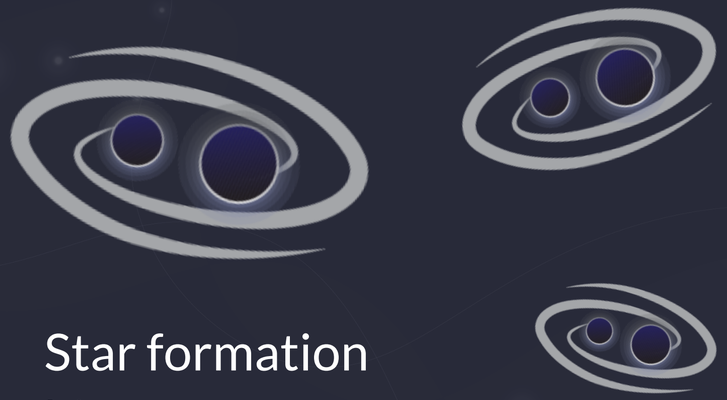


Mass transfer

Heavy element production

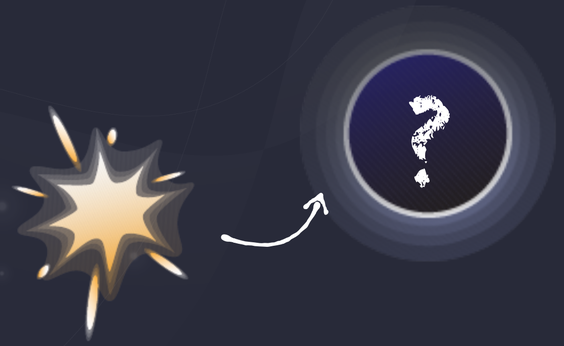
Supernova mechanisms

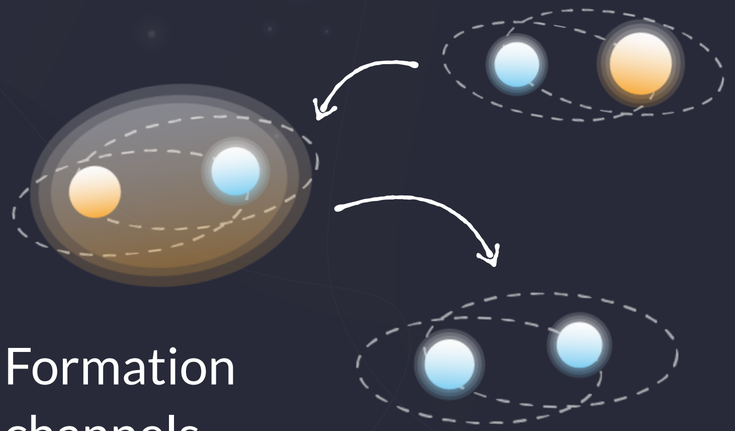




Star formation history

Maximum BH mass from stellar collapse

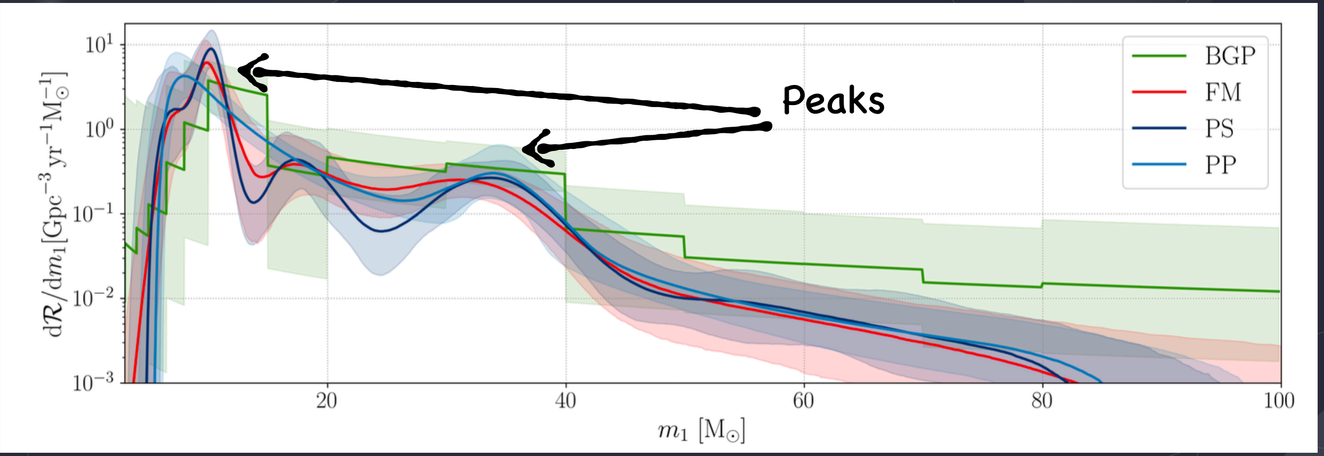


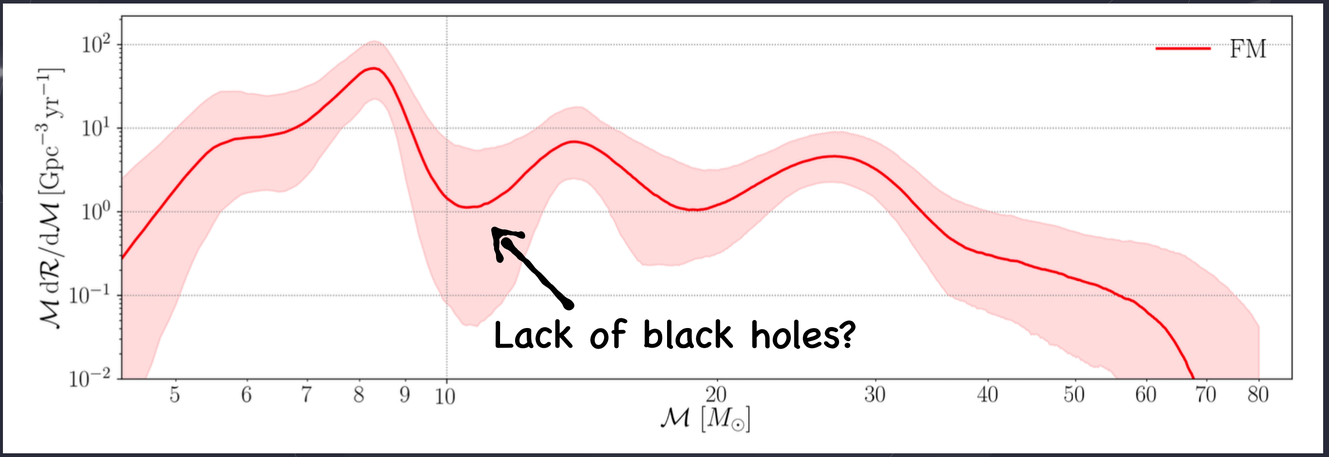


Formation channels

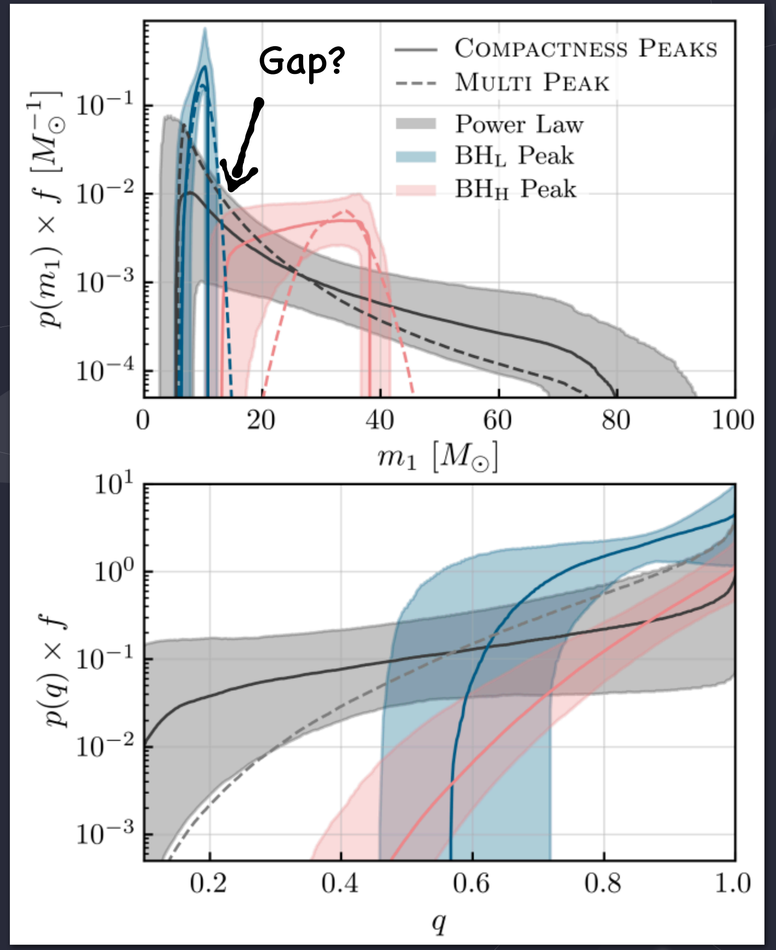
Proding features in the mass distribution

LVK+ arXiv:2111.03634

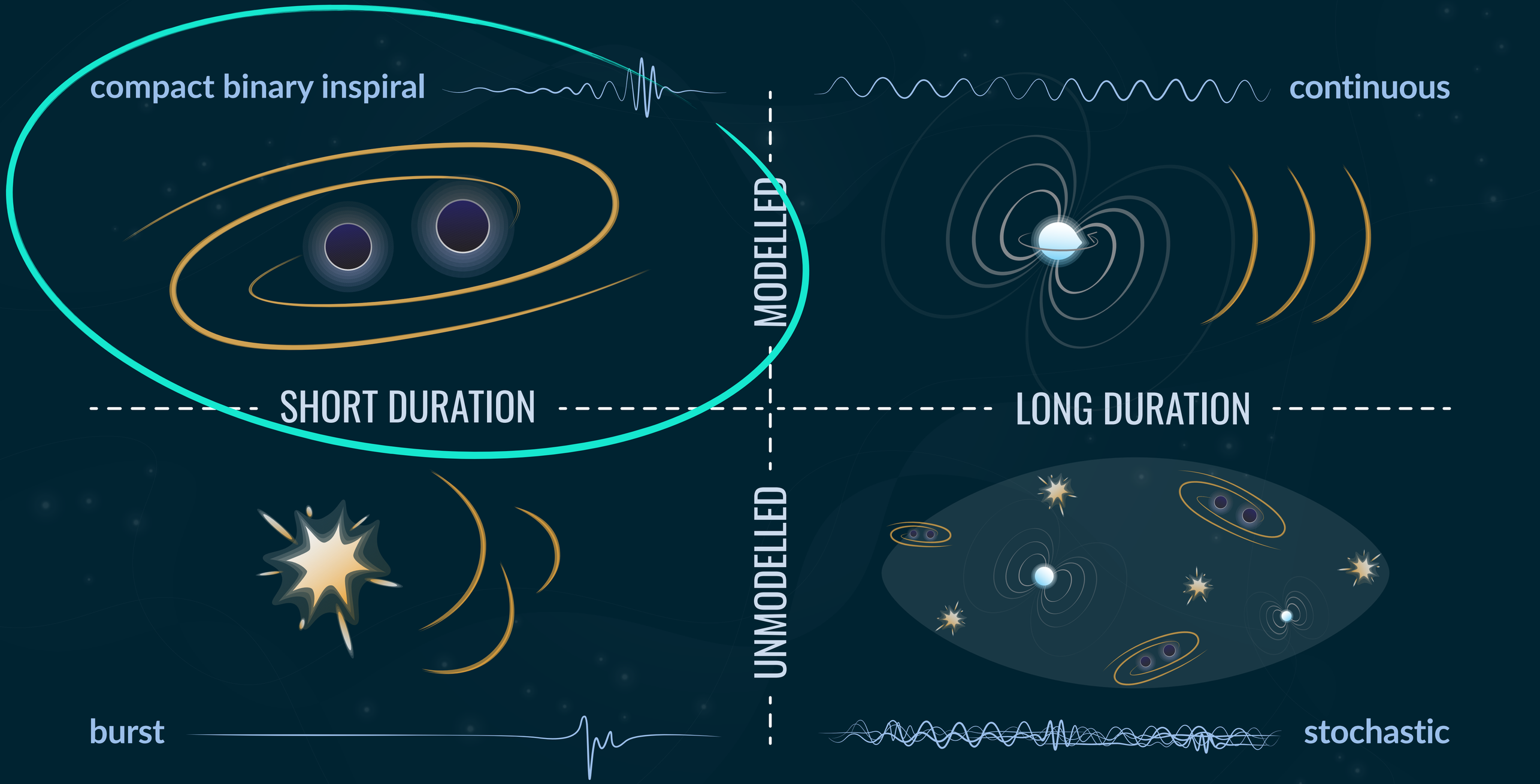




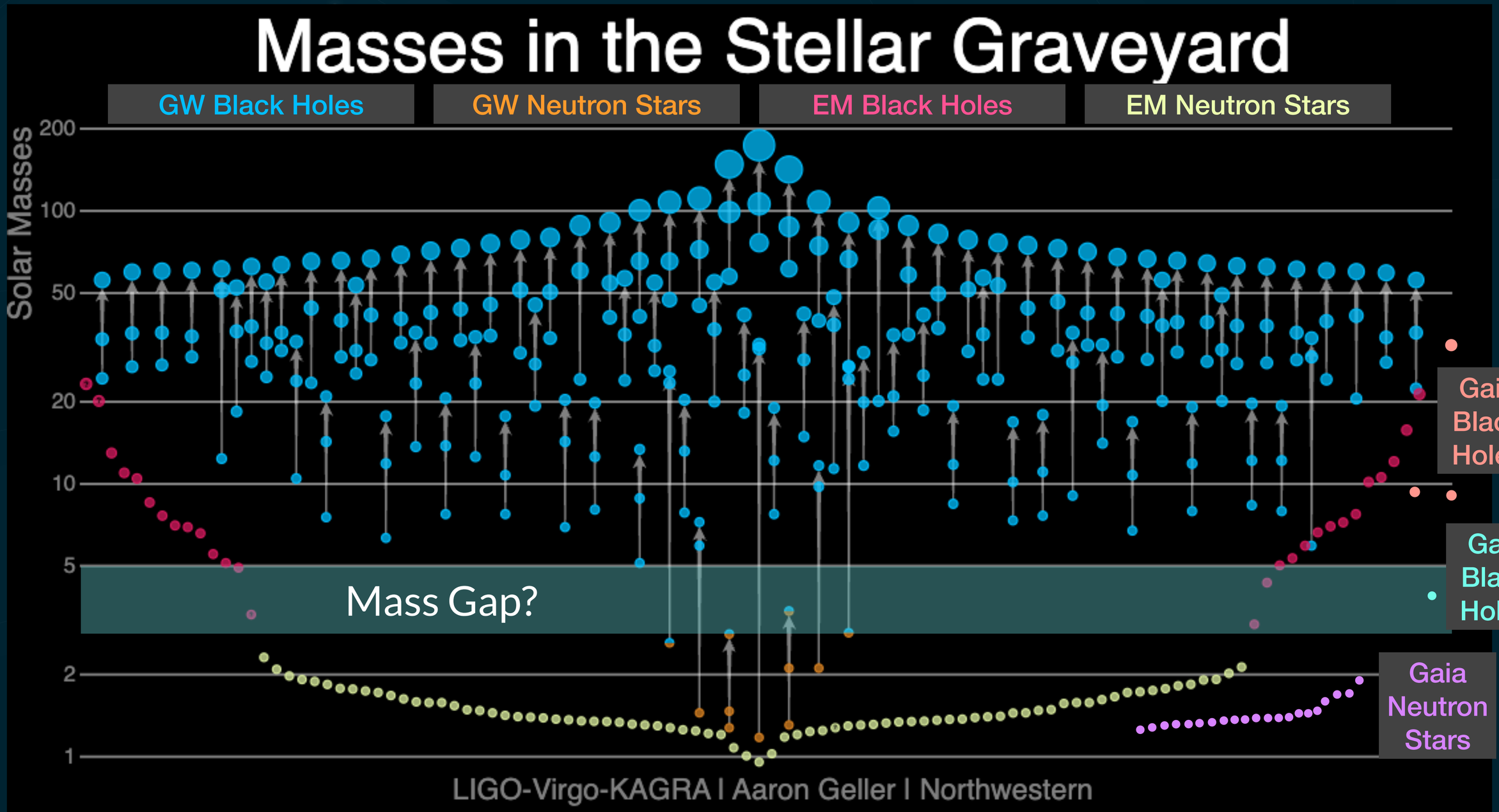
Galaudage & Lamberts arXiv:2407.17561



also see work by Adamcewicz+ 2406.11111


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

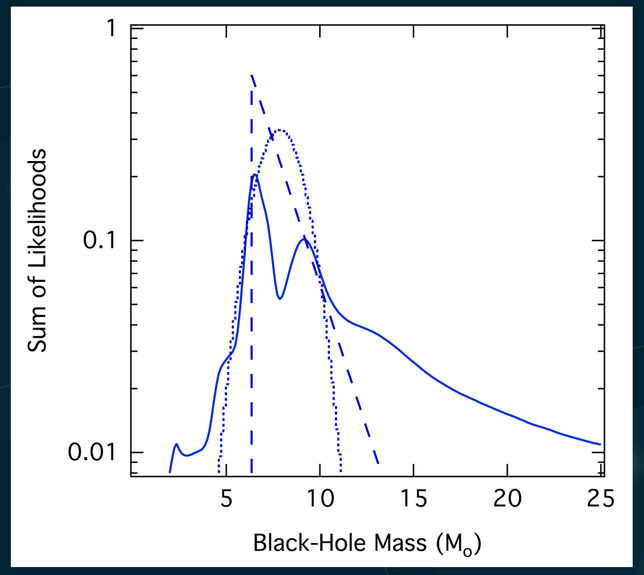
Masses in the Stellar Graveyard



Is there a gap between masses of NS and BH?

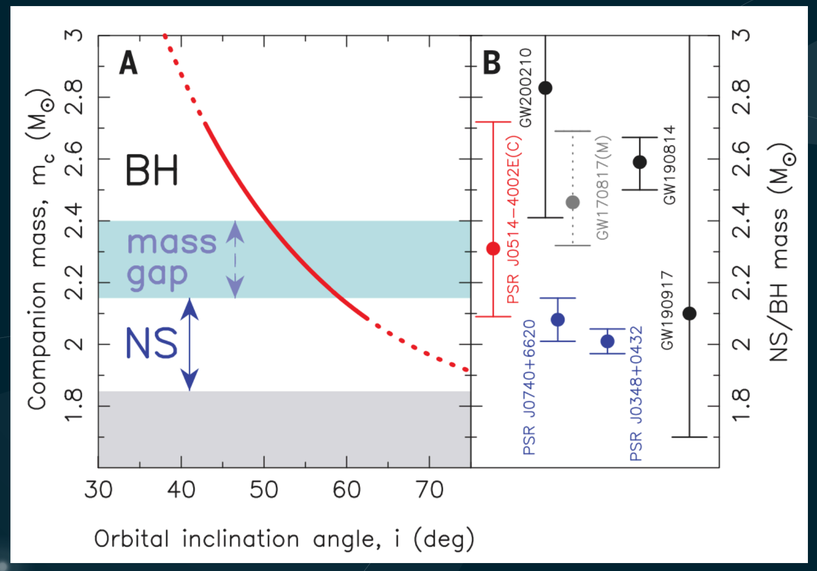
- Dearth of compact objects observed in the Milky Way between $\sim$ 3-5 $M_\odot$ (from observations of X-ray binaries)

X-ray Binaries



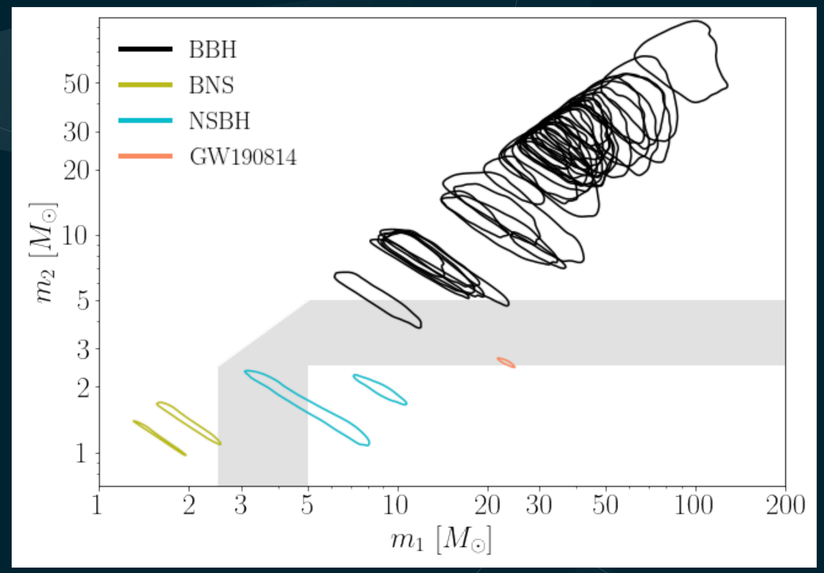
Özel+2010 arXiv:1006.2834

Detached Galactic Binaries



Barr+2024 arXiv:2401.09872

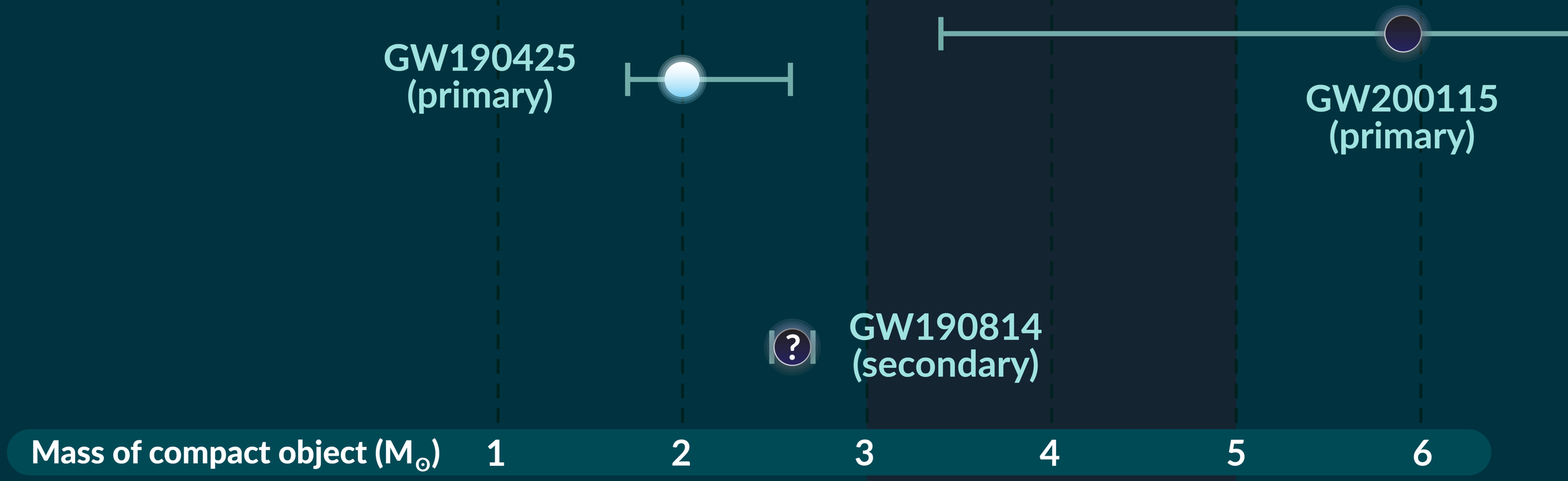
Gravitational Waves



Farah+2021 arXiv:2101.02212

FILLING THE MASS ⟷ GAP

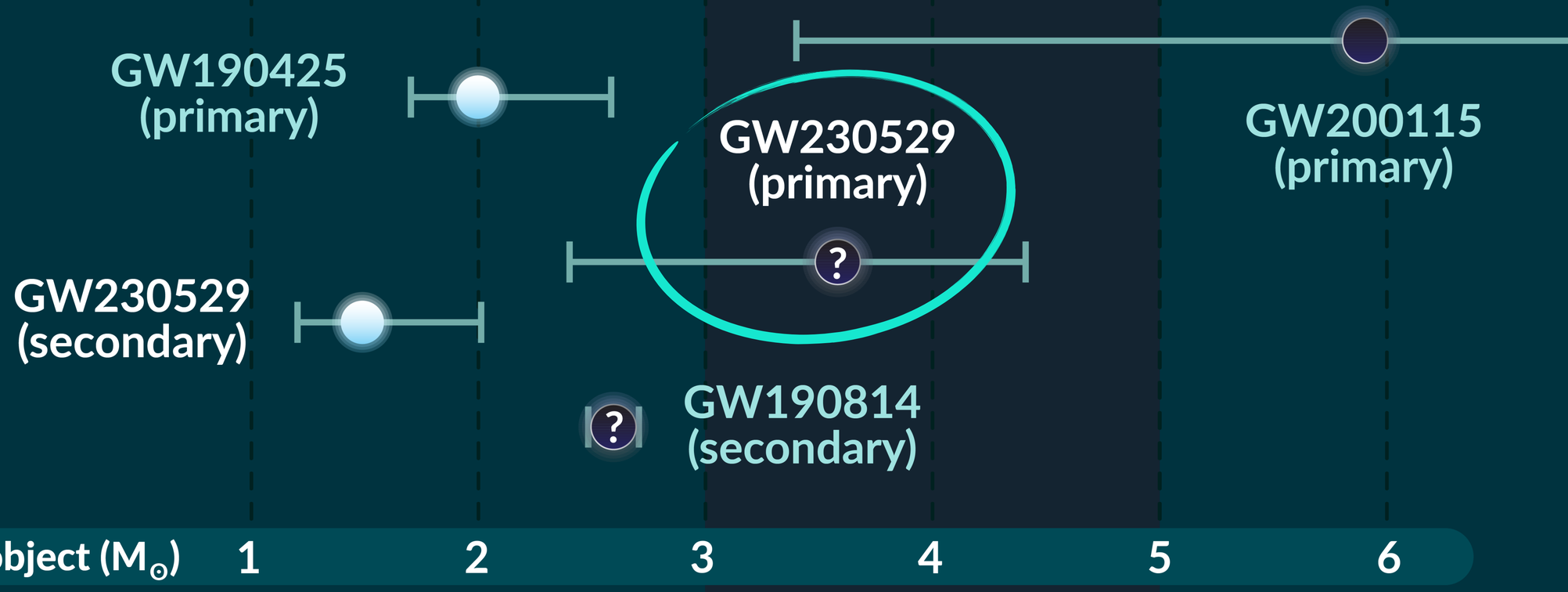
with observations of compact binaries from gravitational waves



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

FILLING THE MASS ⟷ GAP

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

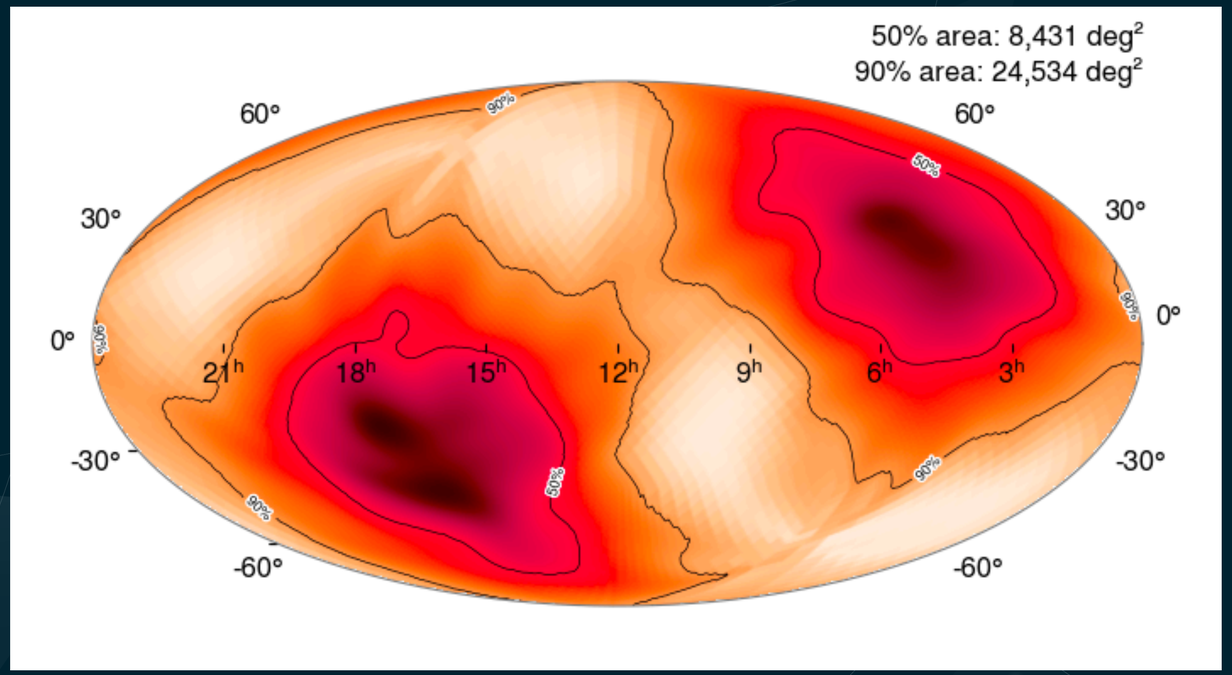
Discovery of GW230529

- 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

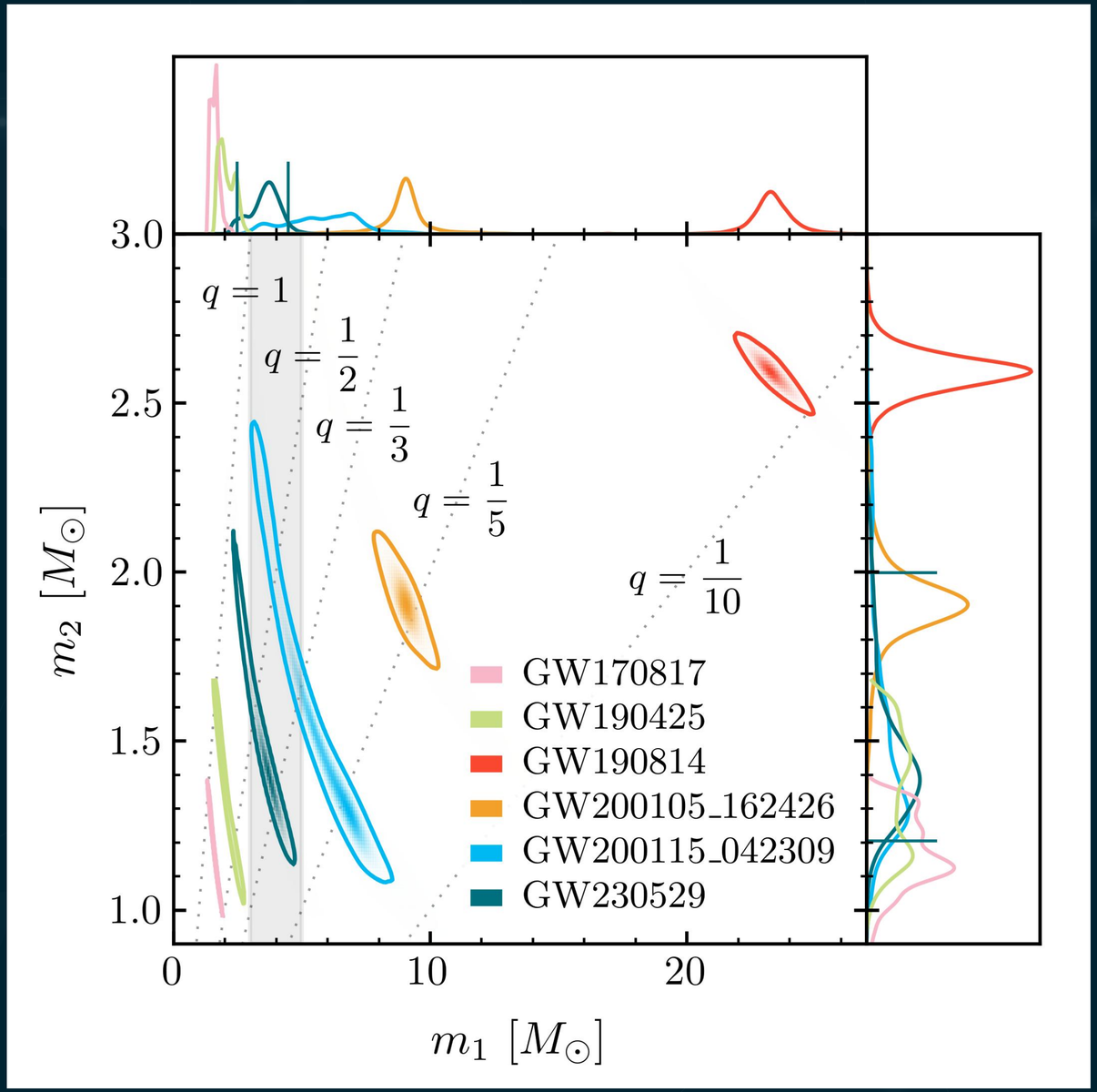
H L V K

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



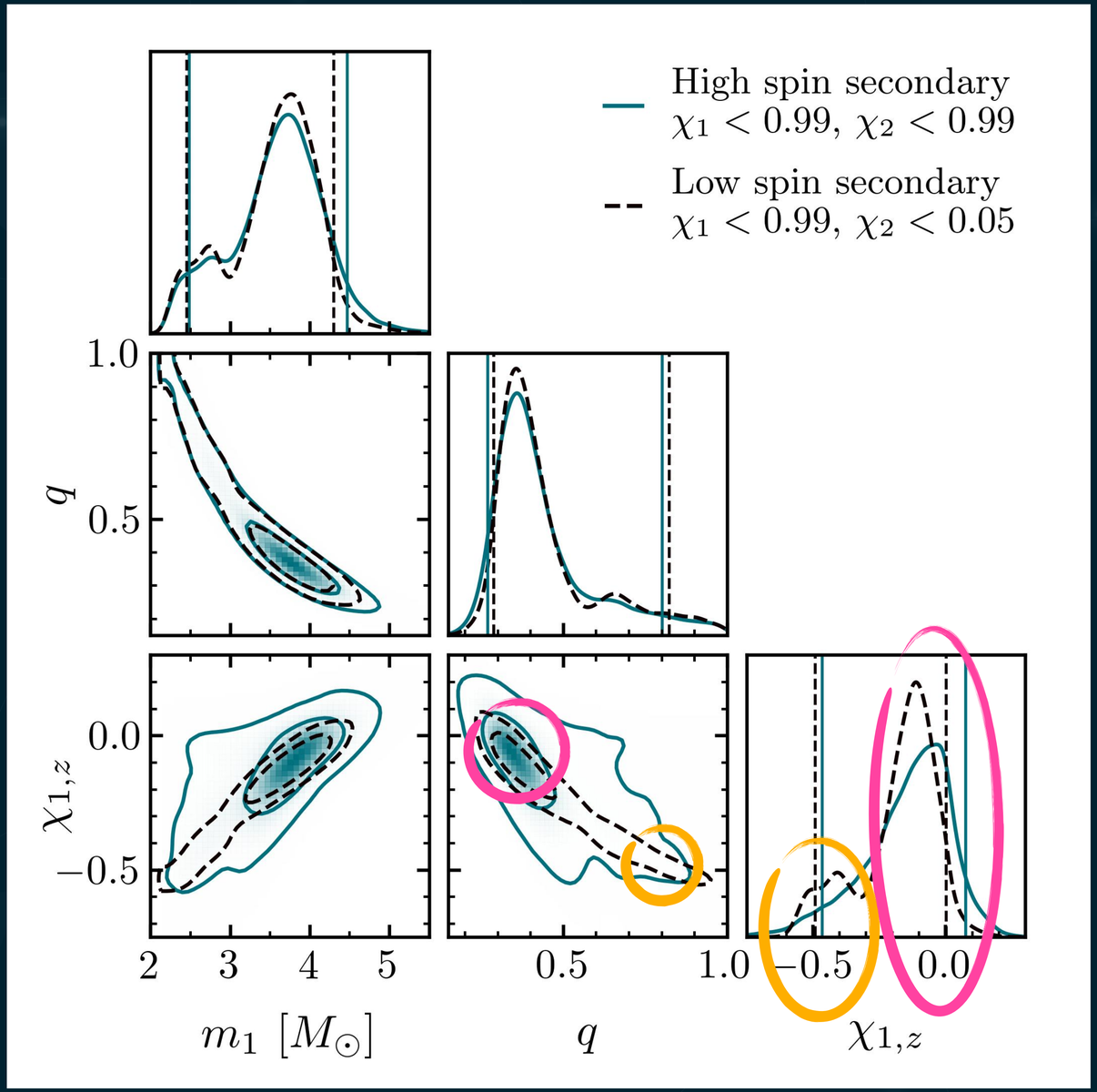
Source properties

- 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



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 ($\chi_{1,z}$)

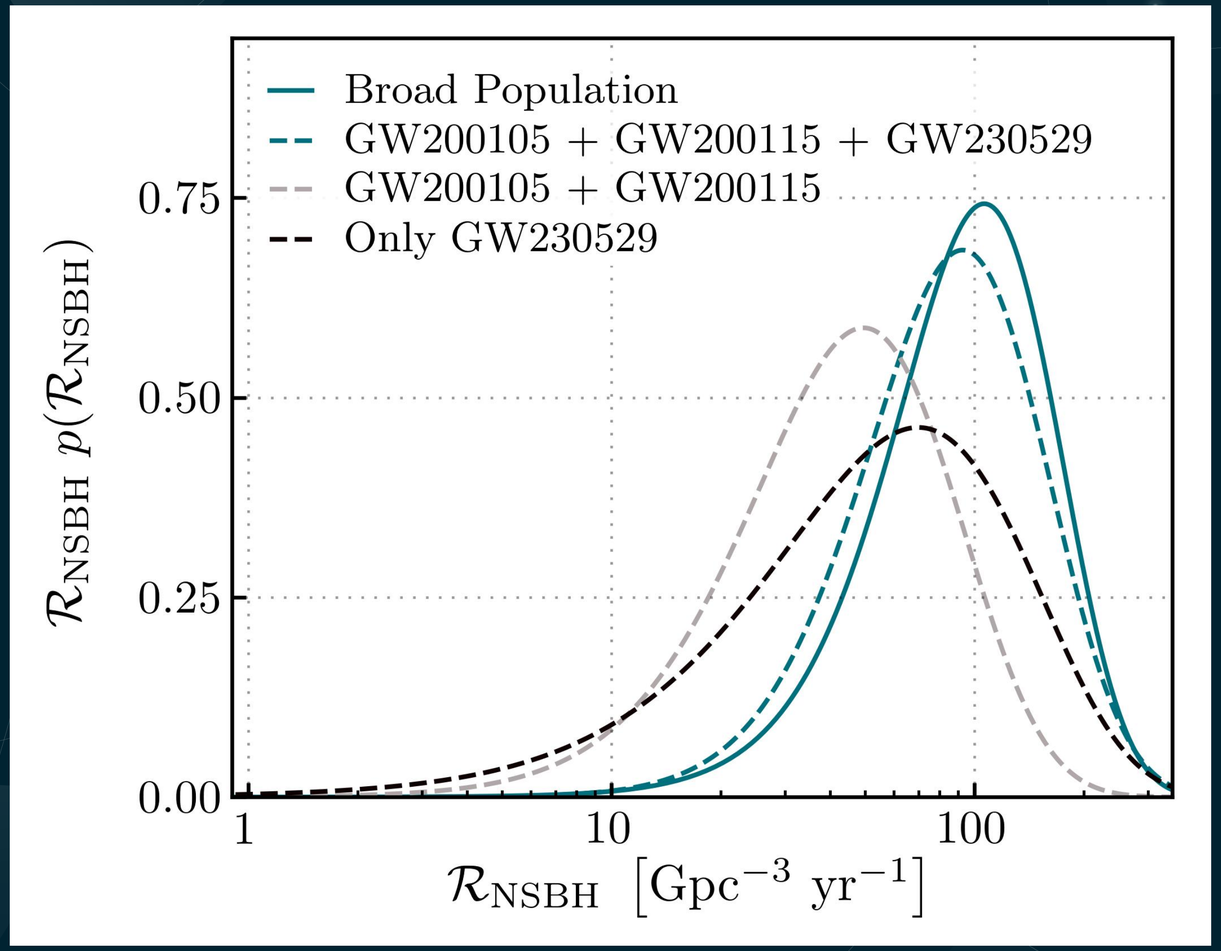


Animation credit:
I. Markin, T. Dietrich, H. Pfeiffer, A. Buonanno

https://www.youtube.com/watch?v=3PKsBwH_bJE

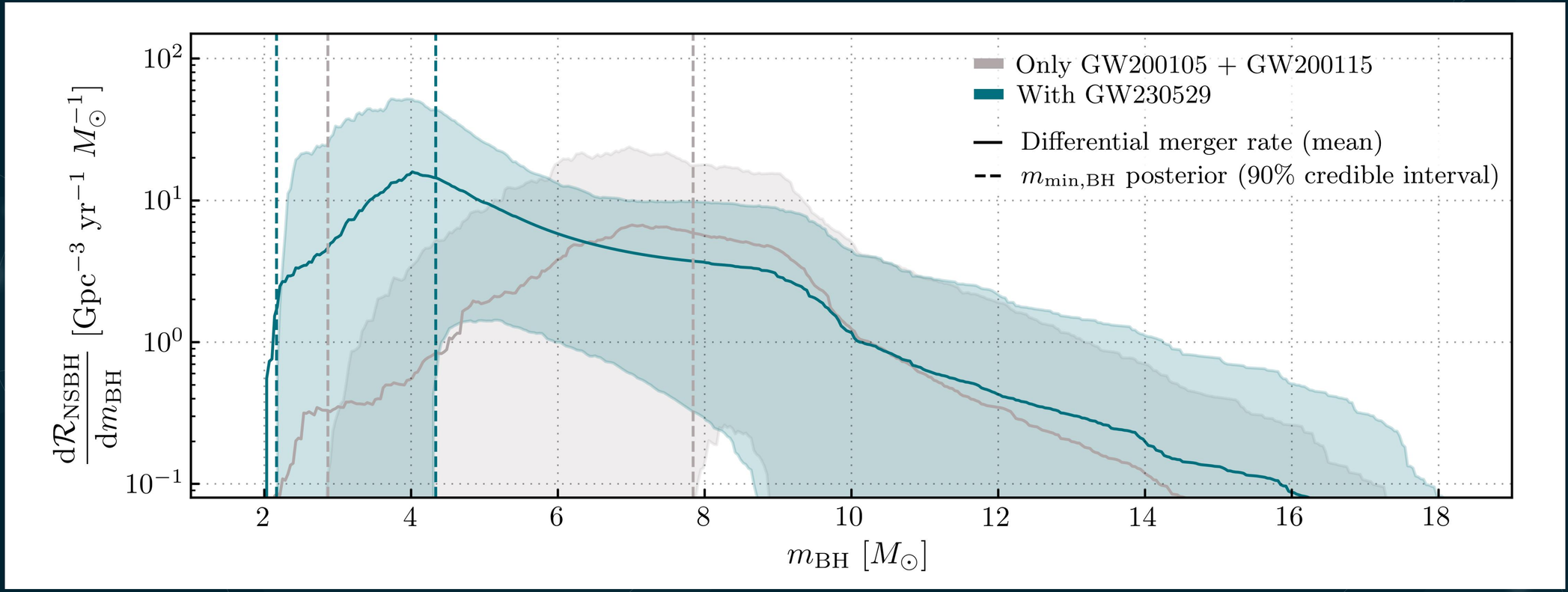
What is the NSBH merger rate?

- 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.



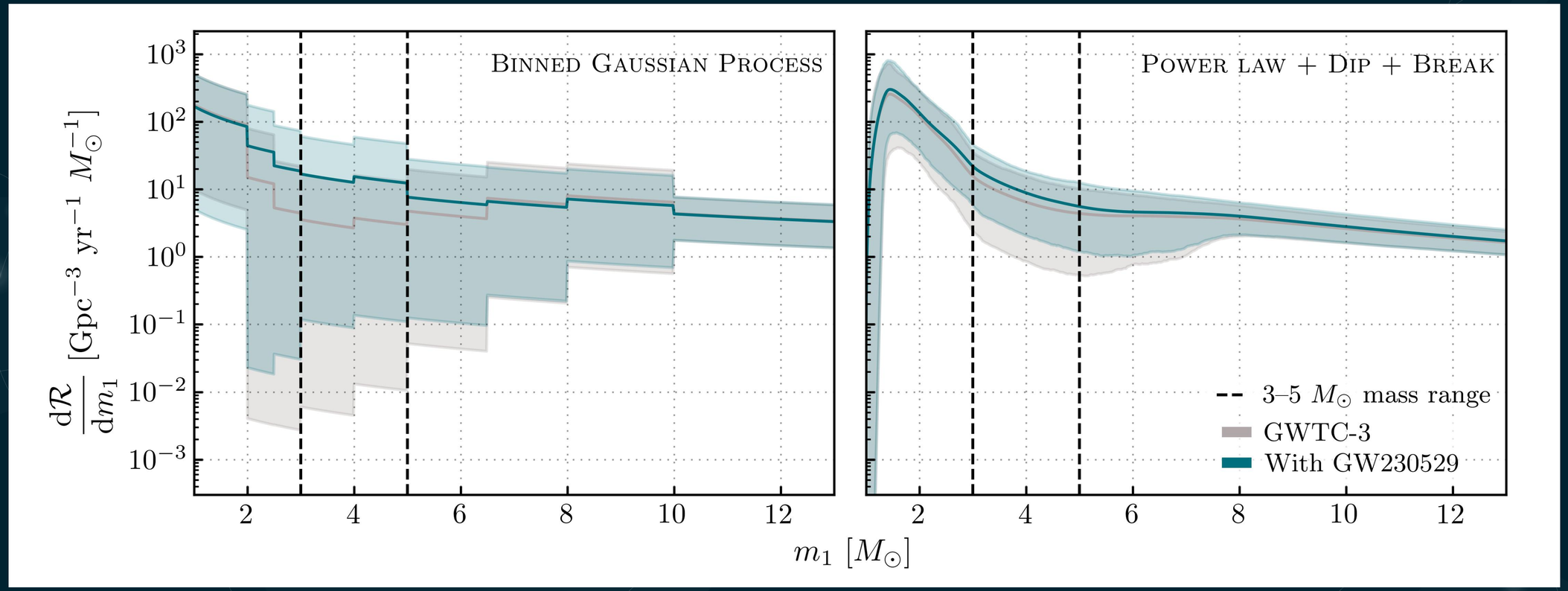
Mass distribution of NSBH population

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



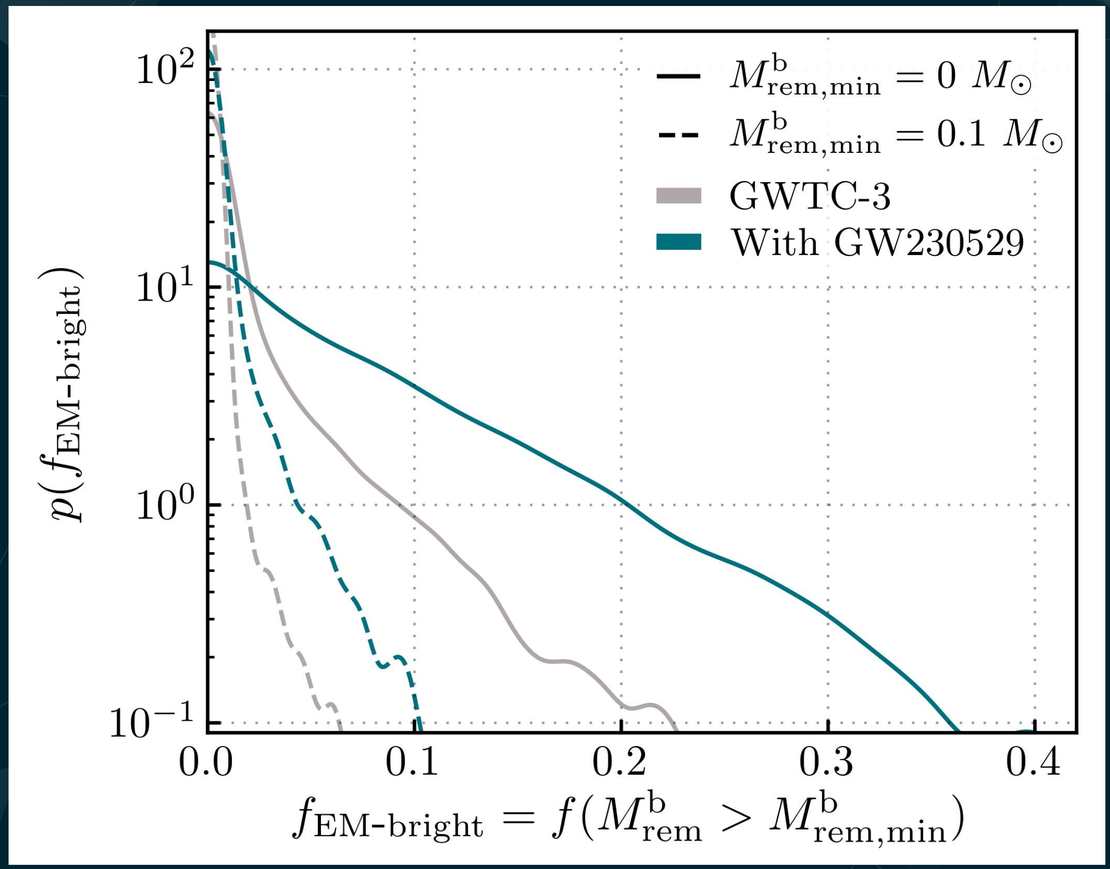
Mass distribution of CBC population

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



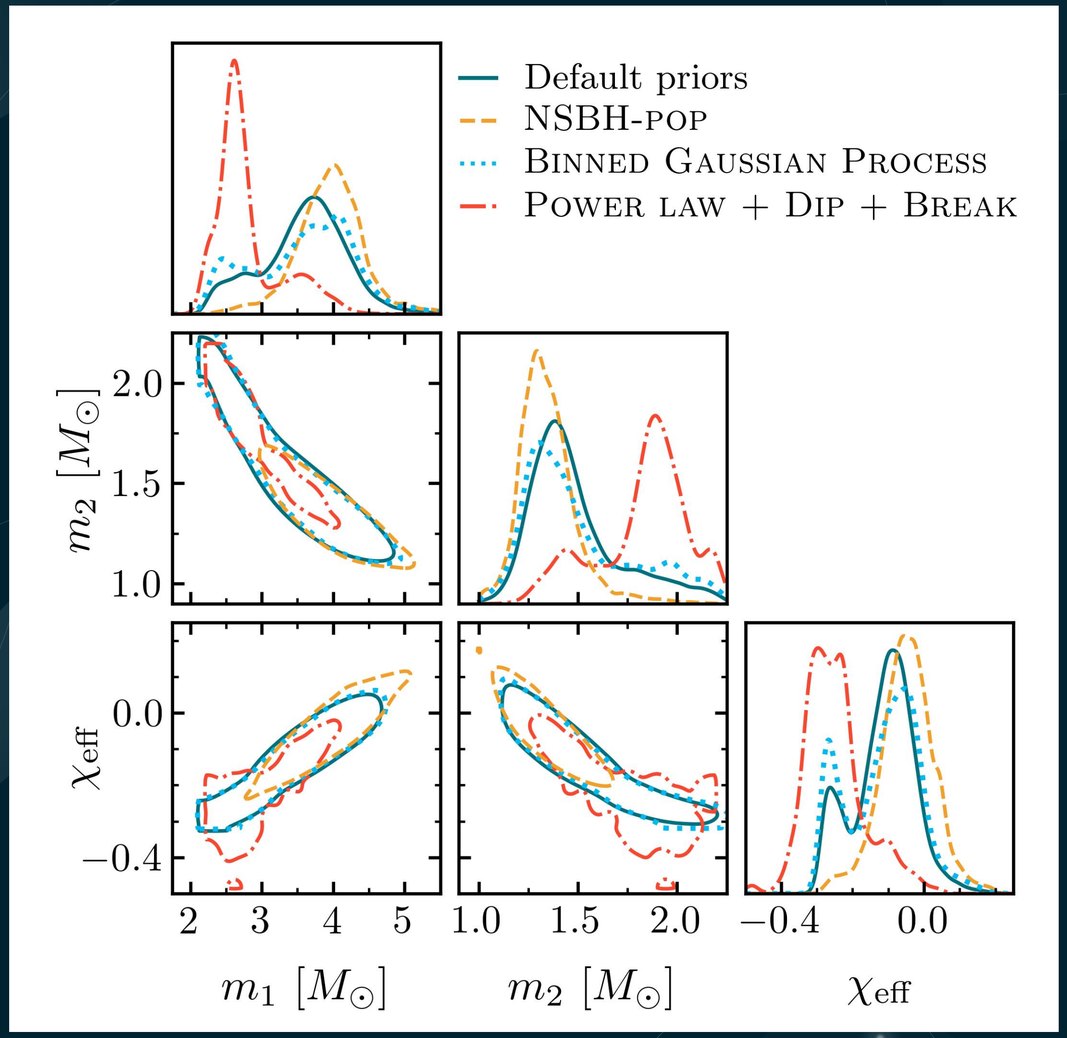
Multimessenger prospects

- 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.



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.

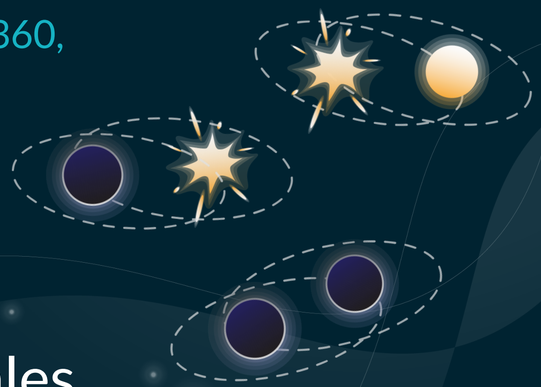


How did GW230529 form?

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!

@astronerdika shanika.galaudage@oca.eu

- #O4IsHere with 149 events as of this morning! Follow along on gracedb: https://gracedb.ligo.org/superevents/public/O4/
- GW230529, most symmetric NSBH so far, with mass gap object.
- Stay tuned for more results from O4 (maybe in the near future)!

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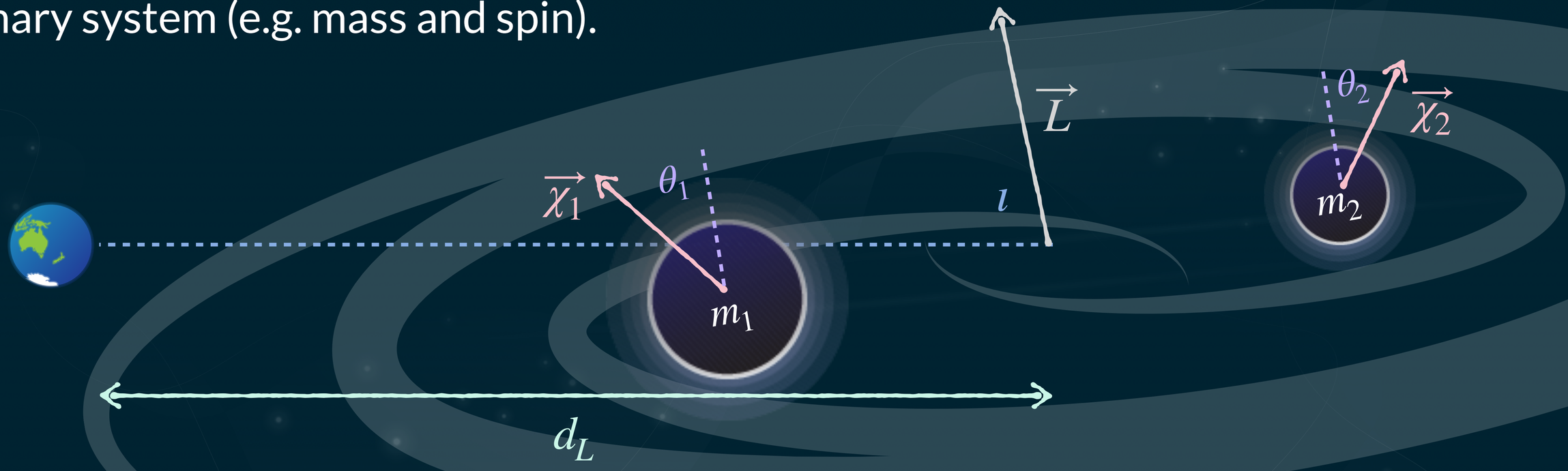
Compact binary mergers

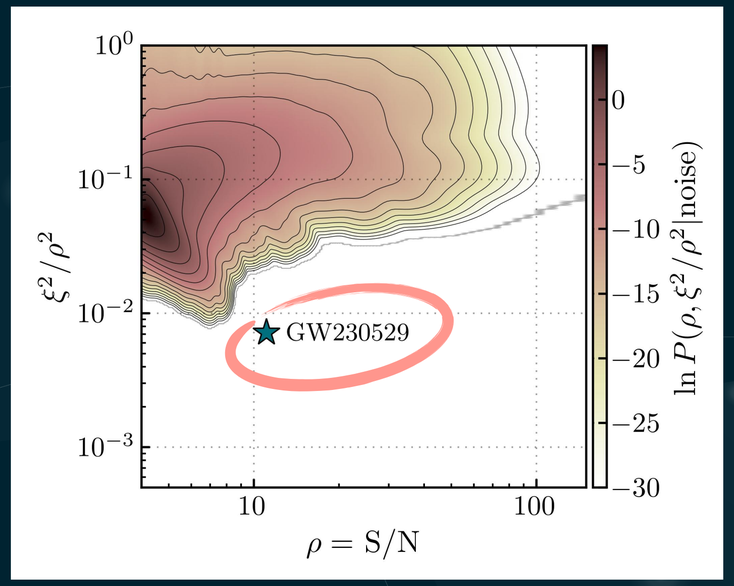
LIGO-Virgo-KAGRA (LVK) observes mergers of binary black holes (BBH) binary neutron stars (BNS) and neutron star-black hole (NSBH) systems. The gravitational-wave (GW) signal carries information about the properties of the binary system (e.g. mass and spin).



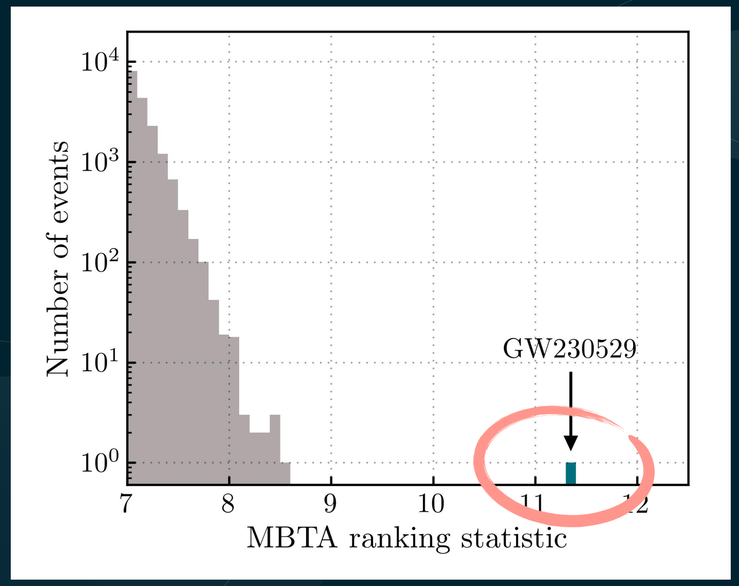
Event significance

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

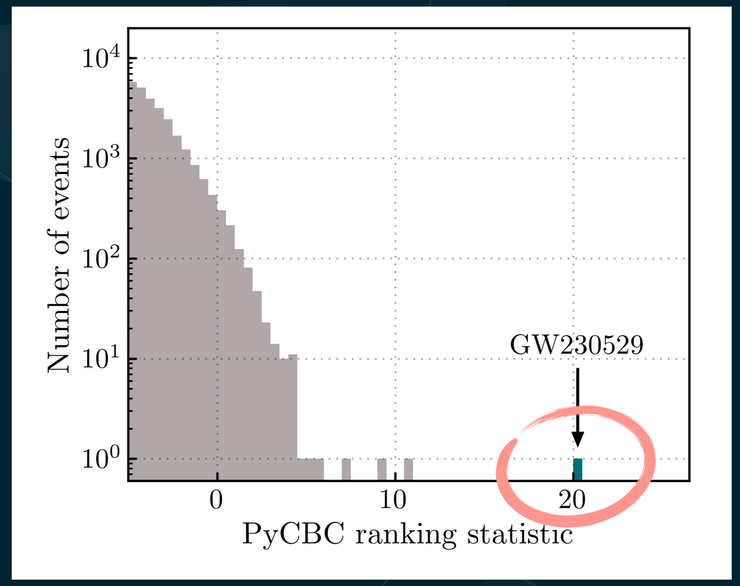
GstLAL



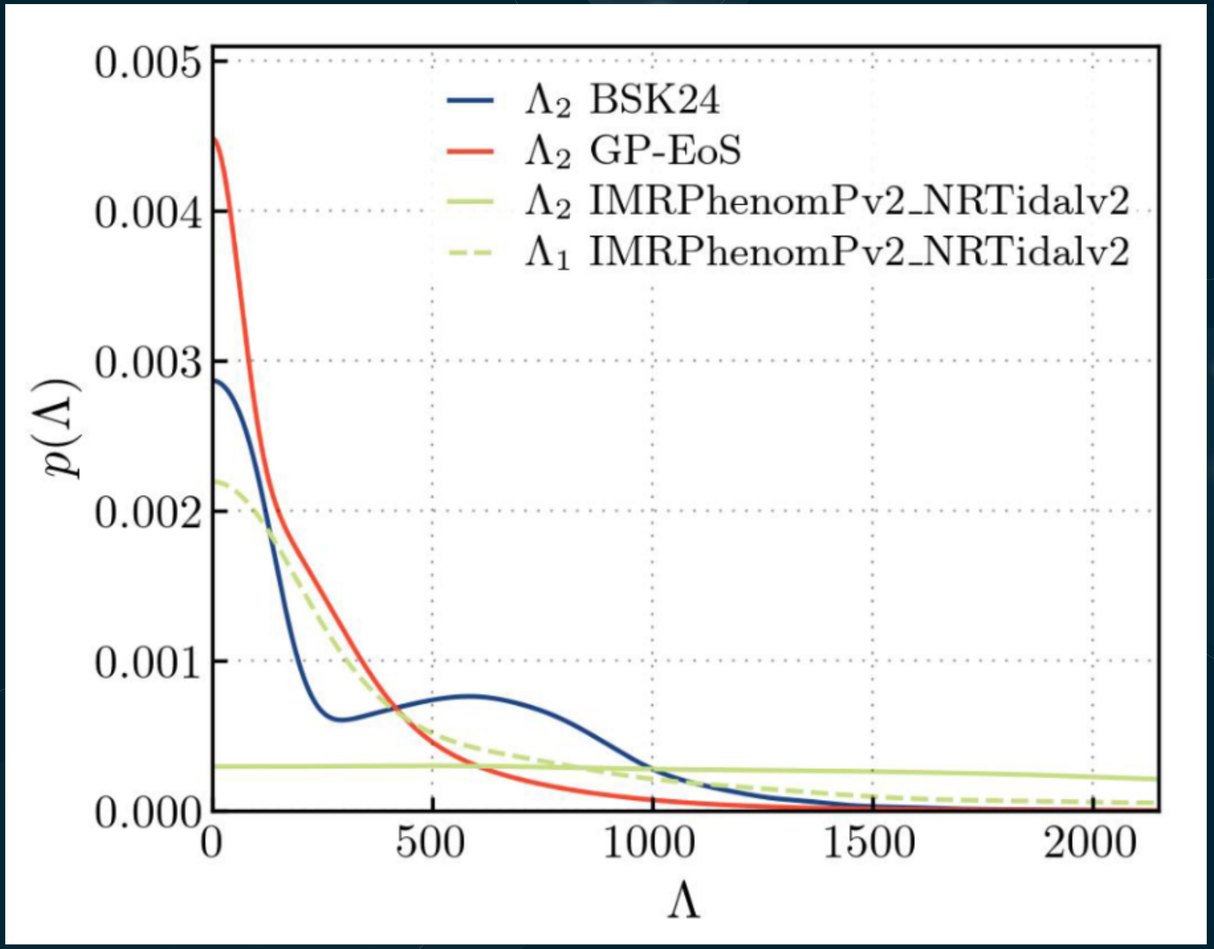
MBTA



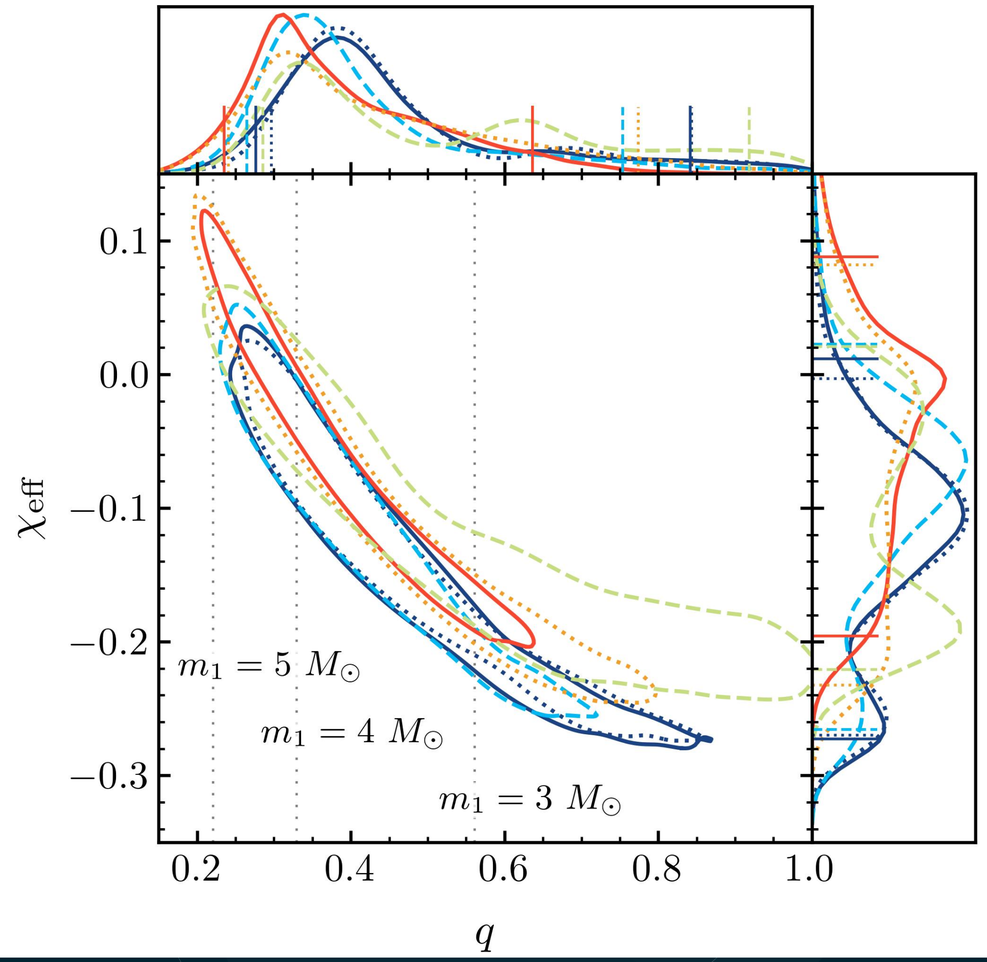
PyCBC



Tidal deformability



Waveform systematics



IMRPhenomXPHM
$\chi_1 < 0.99,\ \chi_2 < 0.99$

IMRPhenomXPHM
$\chi_1 < 0.99,\ \chi_2 < 0.05$

SEOBNRv5PHM
$\chi_1 < 0.99,\ \chi_2 < 0.99$

IMRPhenomNSBH
$\chi_1 < 0.5,\ \chi_2 < 0.05$

SEOBNR_NSBH
$\chi_1 < 0.9,\ \chi_2 < 0.05$

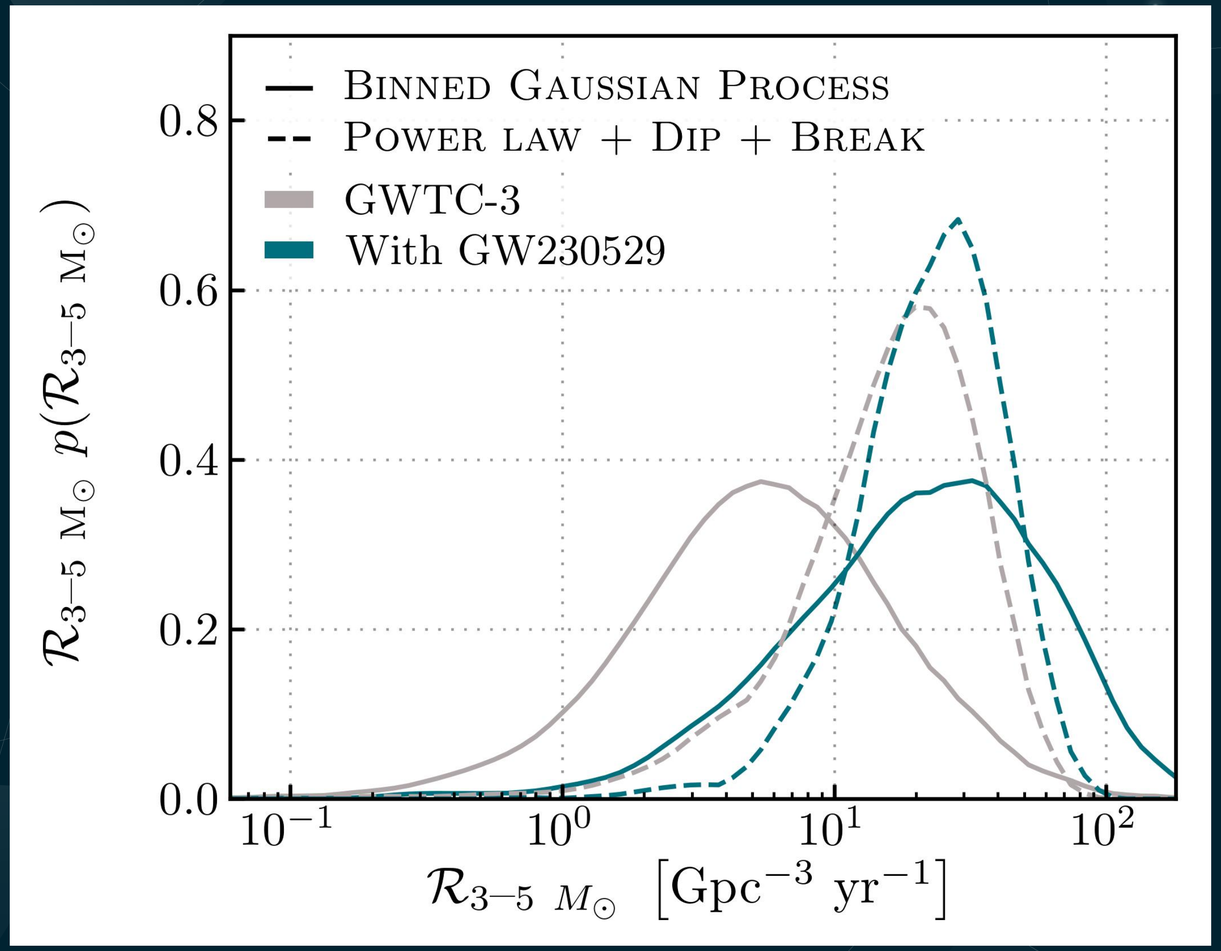
IMRPhenomPv2_NRTidalv2
$\chi_1 < 0.99,\ \chi_2 < 0.05$

Merger rate of lower mass gap objects

- Increases in inferred rate of mergers in lower mass gap
- Binned Gaussian Process:

  $1\text{-}54\,\mathrm{Gpc^{-3}\,yr^{-1}} \rightarrow 4\text{-}112\,\mathrm{Gpc^{-3}\,yr^{-1}}$
- Power law + Dip + Break:

  $3\text{-}42\,\mathrm{Gpc^{-3}\,yr^{-1}} \rightarrow 8\text{-}52\,\mathrm{Gpc^{-3}\,yr^{-1}}$
- Rate of mergers in the lower mass gap inconsistent with zero



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	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.05$

Component spins