Observation and astrophysics of gravitational waves: Current status and future prospects

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Based on LVK's population paper, arXiv:2111.03634

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Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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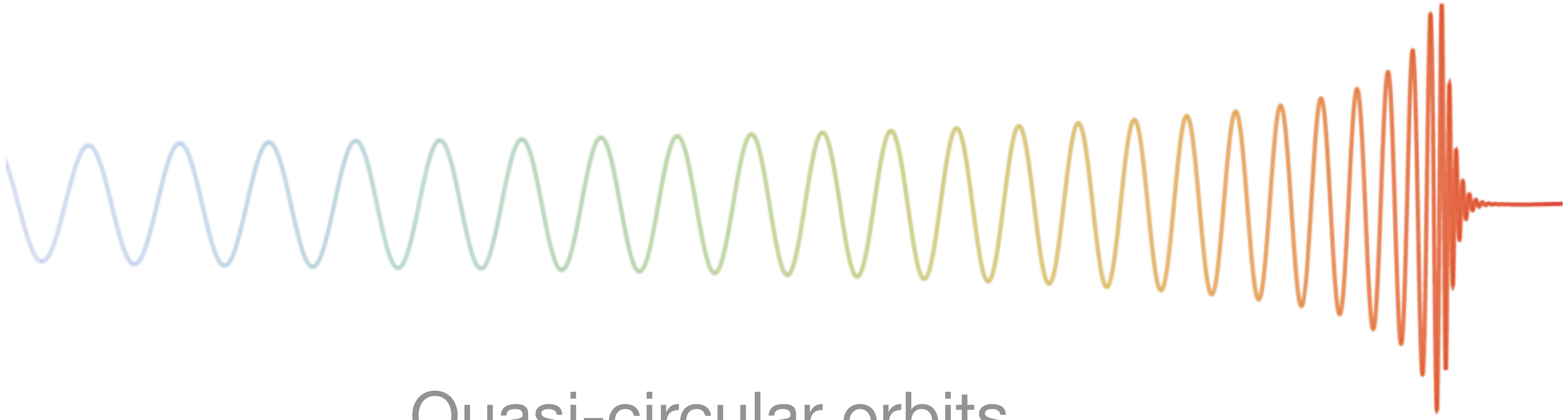
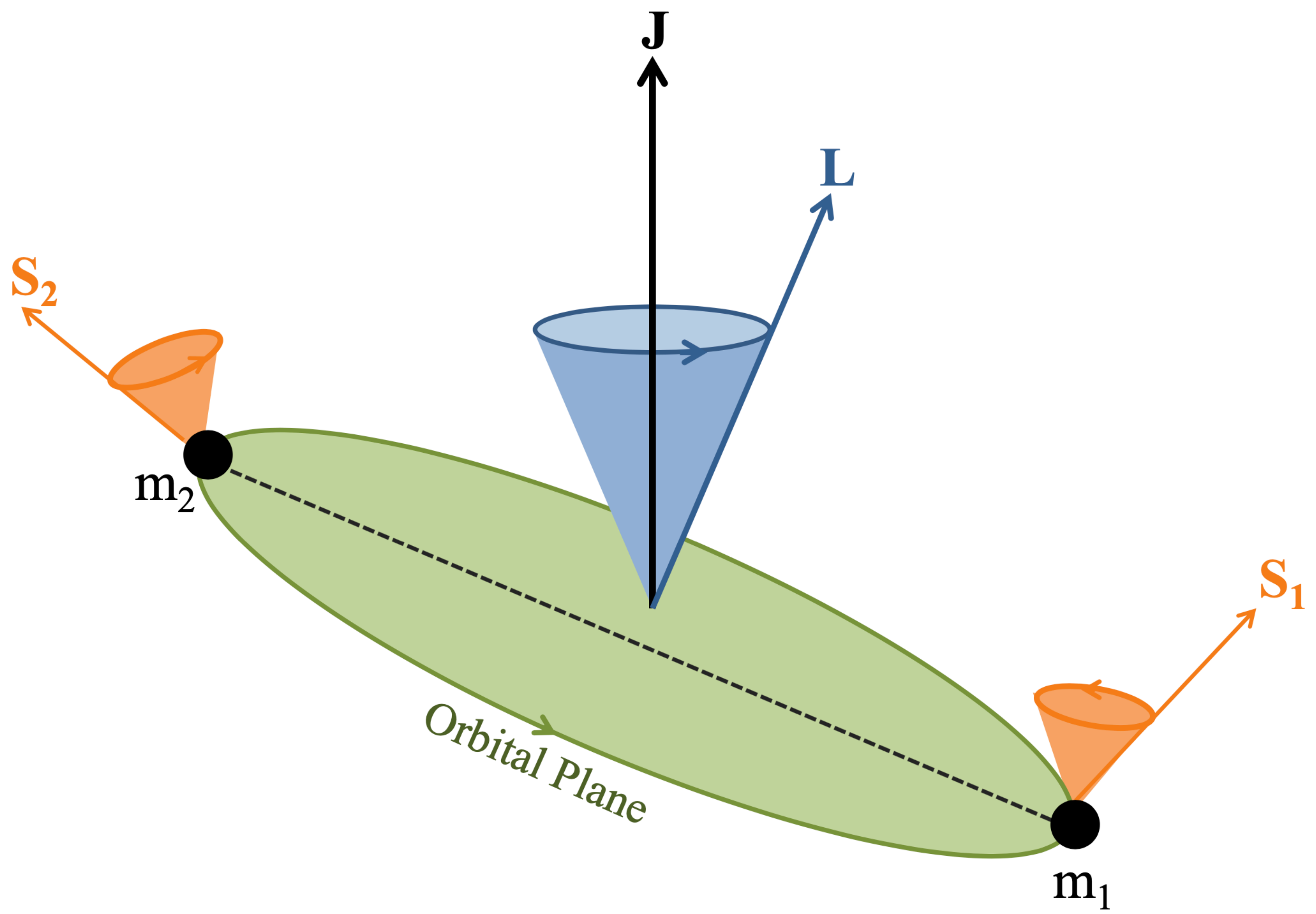
Questions:

- How these binary mergers form?
- What are the astrophysical environments in which these mergers take place?
- Is there a lower mass gap?
- Is there a higher mass gap?
- What is the rate of star formation throughout the Universe?
- New observations, new questions!

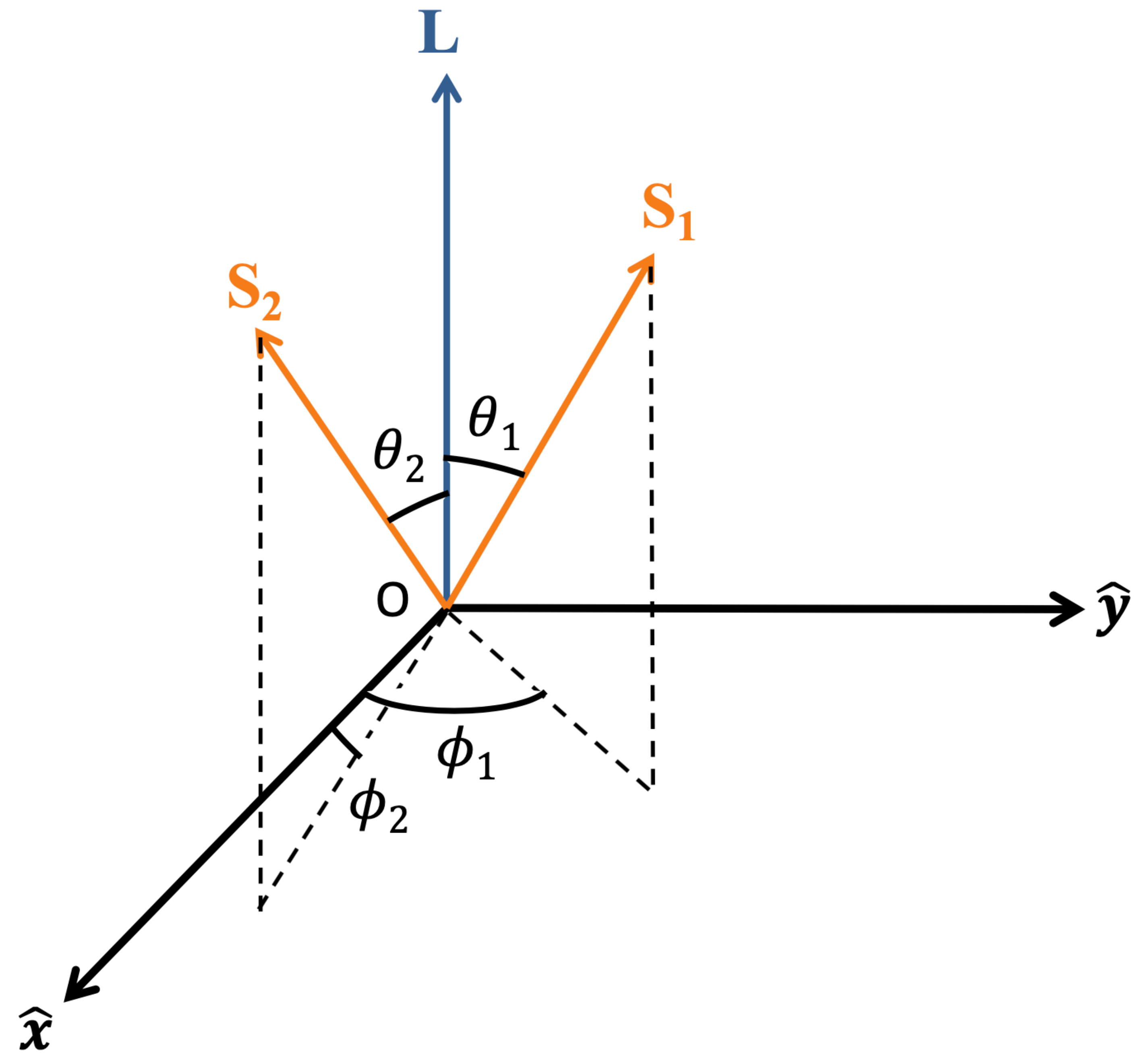


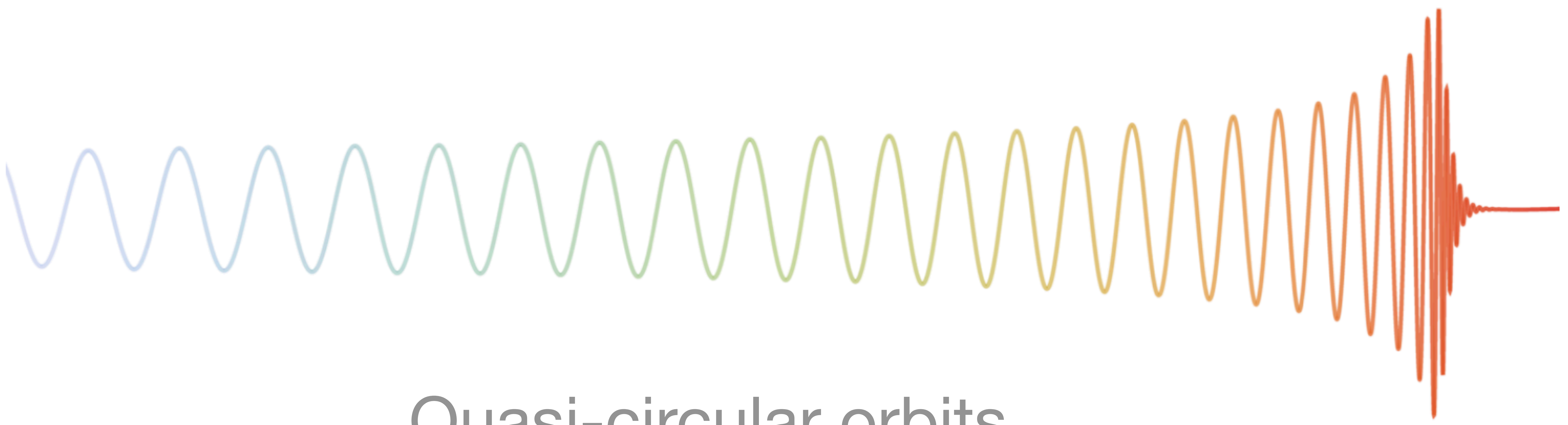
Quasi-circular orbits



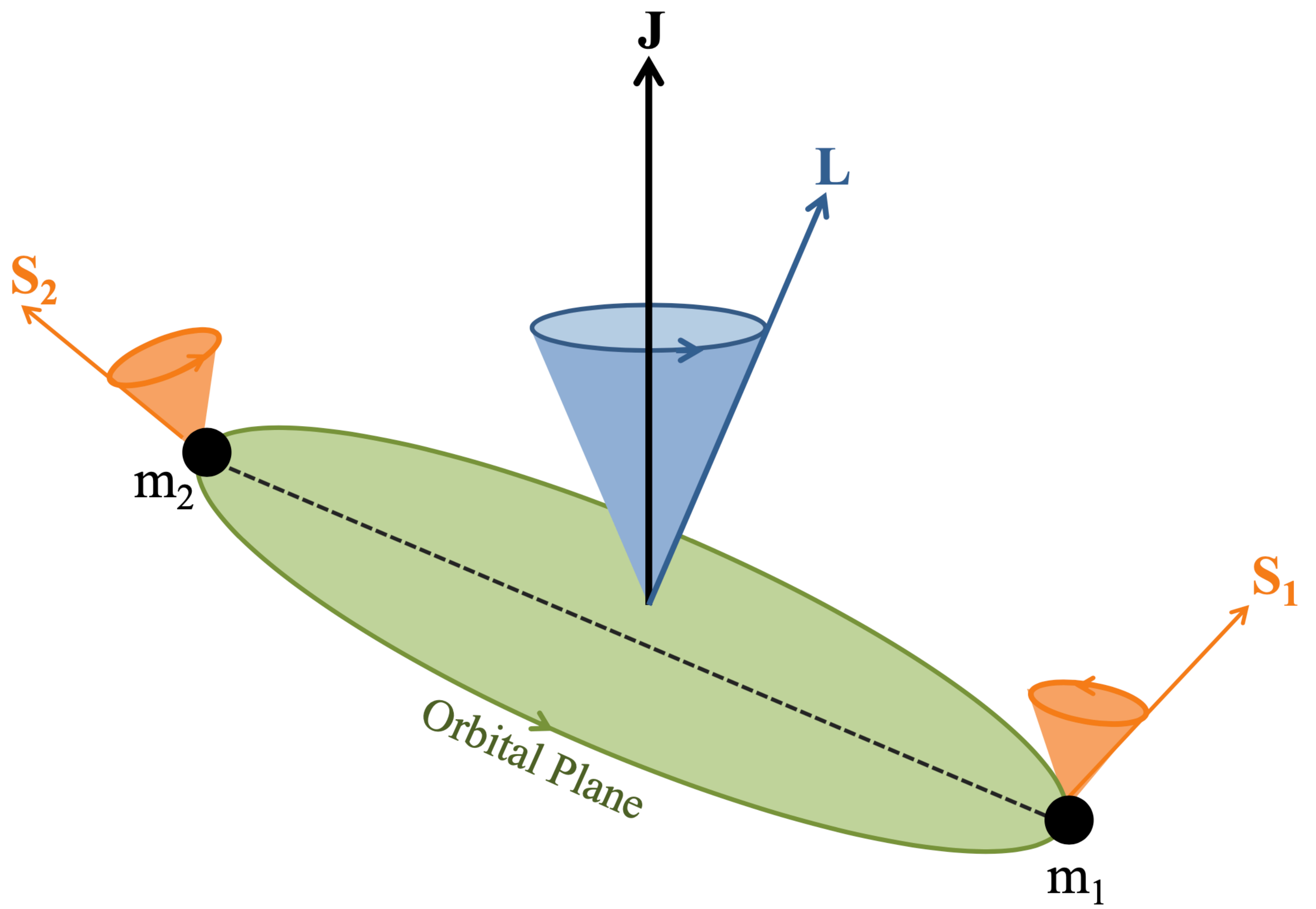
Intrinsic parameters: $m_1, m_2, \chi_1, \theta_1, \phi_1, \theta_2, \phi_2$

Extrinsic parameters: $D_L, \iota, \delta, \alpha, \psi, t_c, \phi_c$





Quasi-circular orbits



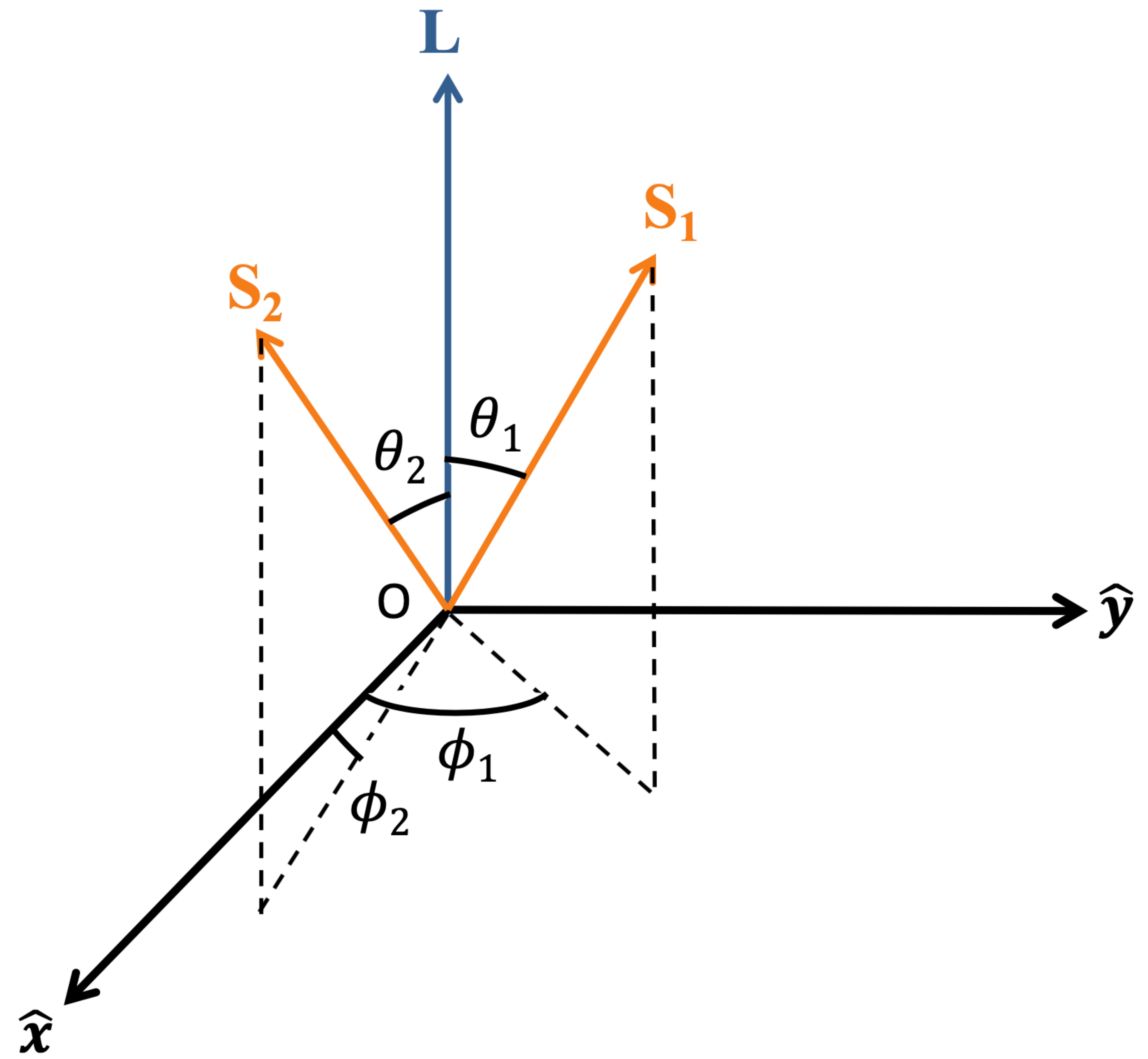
Intrinsic parameters: $m_1, m_2, \chi_1, \theta_1, \phi_1, \theta_2, \phi_2$

Chirp mass: $$\mathscr{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

mass ratio: $$q = \frac{m_2}{m_1}$$

effective inspiral spin: $$\chi_{\mathrm{eff}} = \frac{m_1\chi_1 \cos\theta_1 + m_1\chi_1 \cos\theta_2}{m_1 + m_2}$$

effective precessing spin: $$\chi_{\mathrm{p}} = \max\left[\chi_1 \sin\theta_1, \left(\frac{3+4q}{4+3q}\right) q\chi_2 \sin\theta_2\right]$$



Analysis Setup:

[More on detection and parameter estimation in Surabhi's Talk]

- GWTC-3:
  - events from O1, O2 and O3
  - 90 CBCs with $P_{\rm astro} > 0.5$
- With FAR $< 0.25\,{\rm yr}^{-1}$ in at least one detection pipeline: 2 BNSs, 2 NSBHs and 63 BBHs
  - High purity set of events whose selection biases are understood
  - Expect only 1 event to be not of astrophysical origin
- With FAR $< 1\,{\rm yr}^{-1}$: 69 BBHs
  - relative proportion of background events remains below 10%
  - Expect only 4.6 events to be not of astrophysical origin
- NS and BH are distinguished based on EOS maximum NS mass

Population Analysis Framework

- Hierarchical Bayesian approach
- Marginalize over the uncertainty in the estimate of individual event parameters

$$\mathscr{L}(\{d\}, N_{\rm det} | \Lambda, N_{\rm exp}) \propto N^{N_{\rm det}} e^{-N_{\rm exp}} \prod_{i=1}^{N_{\rm det}} \int \mathscr{L}(d_i | \theta) \pi(\theta | \Lambda) d\theta$$

$$N = \frac{N_{\rm exp}}{\xi(\Lambda)}$$

$\xi(\Lambda)$: fraction of mergers that are detectable for a population with parameter Λ

$\mathscr{L}(d_i | \theta)$: single-event likelihood described by parameter set θ

$\pi(\theta | \Lambda)$: prior governing the population distribution on event parameters θ for a given value of hyperparameters Λ

Marginalizing the likelihood after imposing the a log-uniform prior on N

$$\mathscr{L}(\{d\} | \Lambda) \propto \prod_{i=1}^{N_{\rm det}} \frac{\int \mathscr{L}(d_i | \theta) \pi(\theta | \Lambda) d\theta}{\xi(\Lambda)}$$

$\mathscr{L}(d_i | \theta)$ are computed using default prior $\pi_{\varnothing}(\theta)$, hence

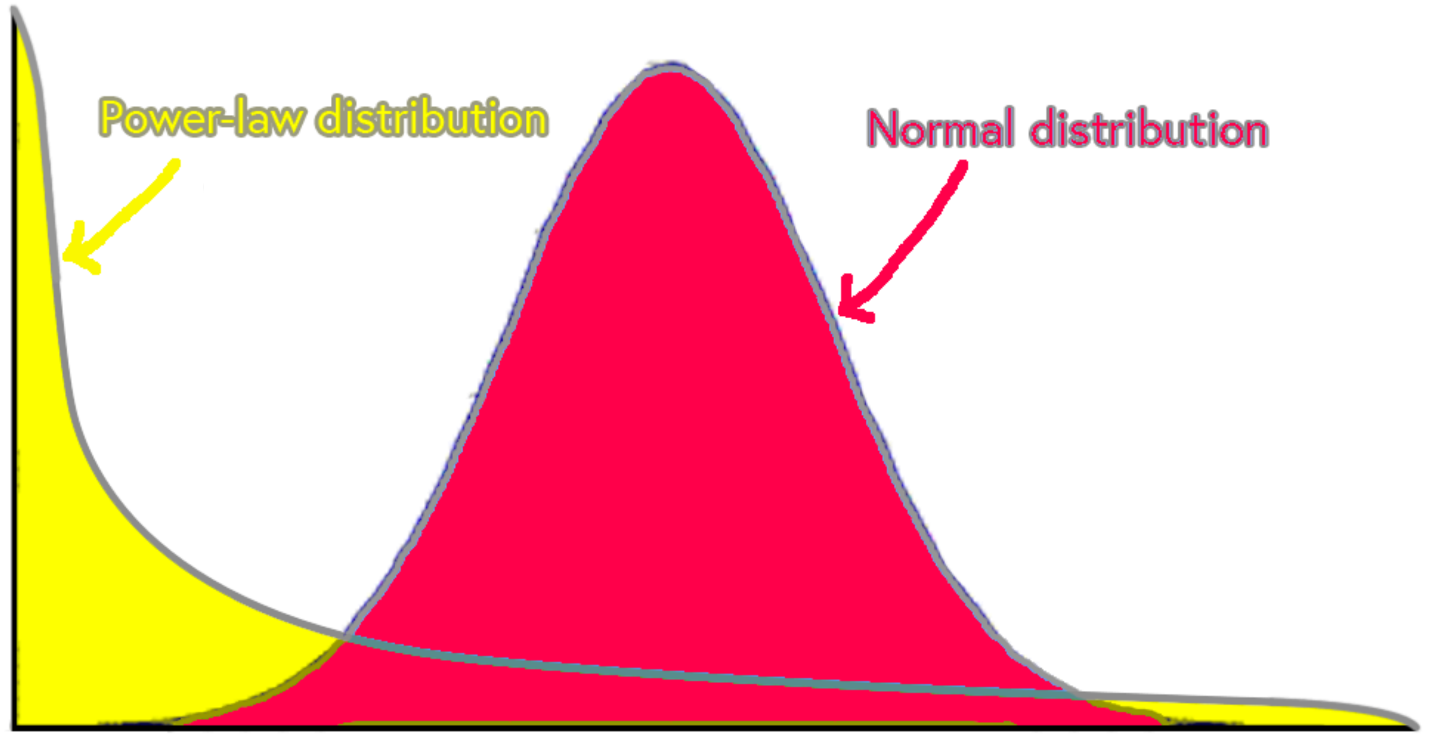
$$\mathscr{L}(\{d\} | \Lambda) \propto \prod_{i=1}^{N_{\rm det}} \frac{1}{\xi(\Lambda)} \left\langle \frac{\pi(\theta | \Lambda)}{\pi_{\varnothing}(\theta)} \right\rangle$$

Using this posterior on Λ can be computed

Population Model Assumptions

Parametric Mass Models: NS masses

- For analyses exclusively focused on the NS-containing events
  - POWER: Power Law
  - PEAK: Gaussian



- With sharp minimum and maximum mass cutoffs
- Components of BNSs are drawn independently from the common NS mass distribution
- For NSBHs, we assume a uniform BH mass distribution and random pairing with NSs

Parametric Mass Models: BH masses

- Fiducial Power Law + Peak (PP) model + redshift evolution

$$p(m_1, q, z) \propto q^{\beta} p(m_1)(1+z)^{\kappa-1}$$

- Merger rate normalization is chosen such that

$$\mathcal{R}(z) = \frac{dN}{dV_c dt}(z) = \mathcal{R}_0(1+z)^{\kappa}$$

- The corresponding redshift distribution

$$p(z|\kappa) \propto \frac{1}{1+z}\frac{dV_c}{dz}(1+z)^{\kappa}$$

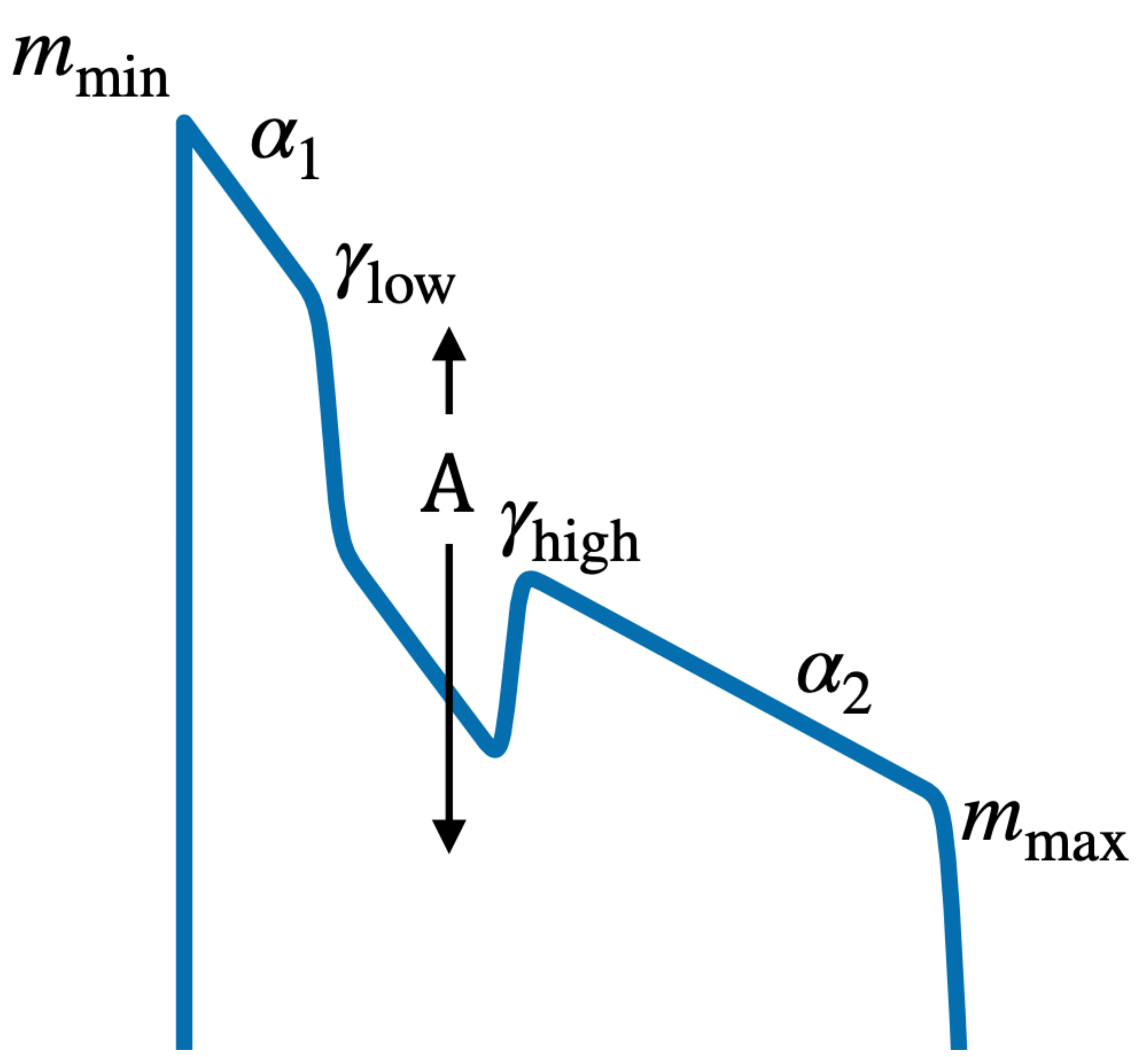
Parametric Mass Models: BH masses

- Power Law + Dip + Break model (PDB)
- To fit the distribution of BH and NS masses, we use a parameterized model, consisting of a broken power law with a notch filter

notch filter with depth A applied between $M^{\text{gap}}_{\text{low}}$ and $M^{\text{gap}}_{\text{high}}$

$$p(m\,|\,\lambda) = n(m\,|\,M^{\text{gap}}_{\text{low}}, M^{\text{gap}}_{\text{high}}, A) \times l(m\,|\,m_{\text{max}}, \eta)$$
$$\times \begin{cases} m^{\alpha_1} \text{ if } m < M^{\text{gap}}_{\text{high}} \\ m^{\alpha_2} \text{ if } m > M^{\text{gap}}_{\text{high}} \\ 0 \text{ if } m > m_{\text{max}} \text{ or } m < m_{\text{min}} \end{cases}$$

low pass filter with powerlaw η applied at mass m_{max}



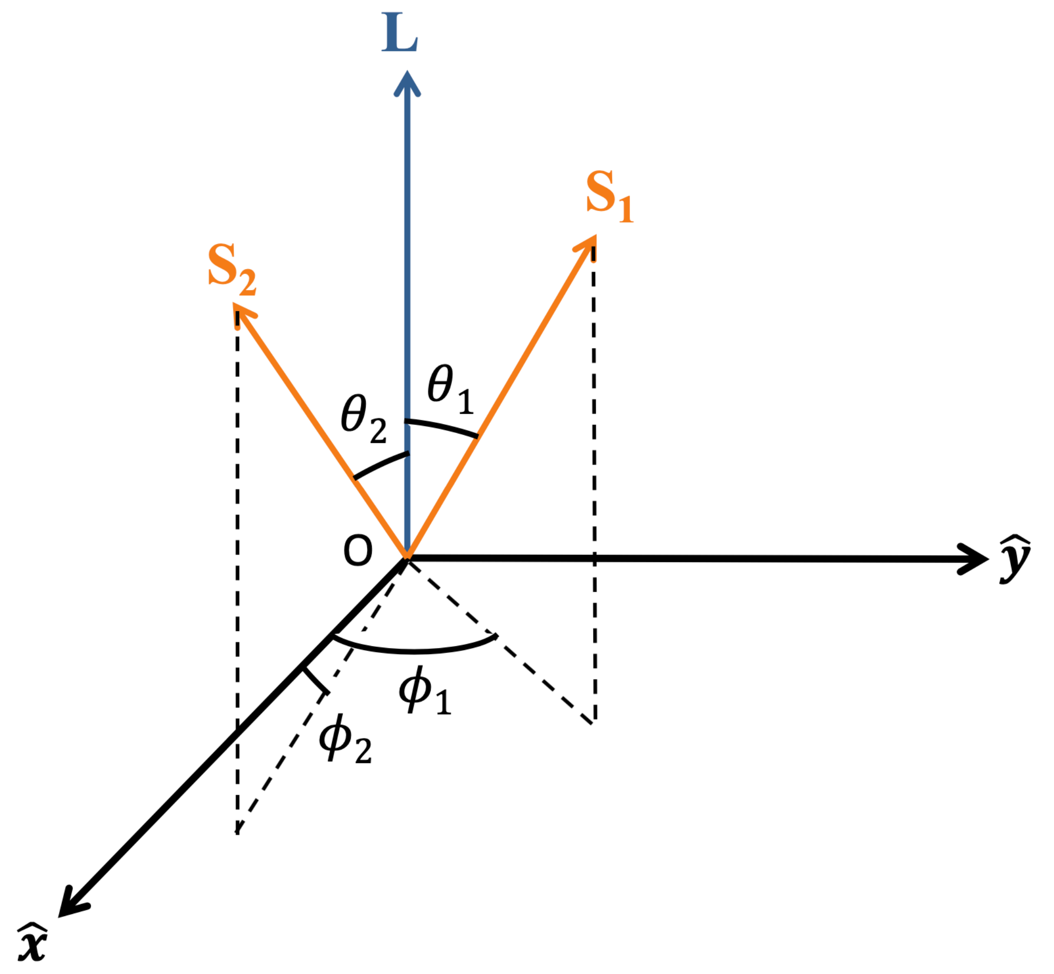
- Two pairing probability:
  - Random: $p(m_1, m_2\,|\,\Lambda) \propto\ p(m = m_1\,|\,\Lambda)\,p(m = m_2\,|\,\Lambda)\,\Theta(m_2 < m_1)$
  - power-law-in-mass-ratio: $p(m_1, m_2\,|\,\Lambda) \propto\ p(m = m_1\,|\,\Lambda)\,p(m = m_2\,|\,\Lambda)\,q^{\beta}\,\Theta(m_2 < m_1)$

BH Spin Models

- **Default spin model**
  - Spin magnitude drawn from Beta distribution $p(\chi_i \,|\, \alpha_\chi, \beta_\chi) \propto \chi_i^{\alpha-1} \left(1-\chi_i\right)^{\beta-1}$
  - Spin tilts are mixture of isotropic and aligned

$$p(\cos\theta_i \,|\, \zeta, \sigma_t) = \frac{1}{2}\left(1-\zeta\right) + \zeta\, \mathcal{N}_{[-1,1]}(\cos\theta_i; 1, \sigma_t)$$

4 model parameters



- **Gaussian spin model**
  - Bivariate Gaussian in $\chi_{\rm eff}$ and χ_p

$$p(\chi_{\rm eff}, \chi_{\rm p} \,|\, \mu_{\rm eff}, \sigma_{\rm eff}, \mu_{\rm p}, \sigma_{\rm p}, r) \propto \mathcal{N}(\chi_{\rm eff}, \chi_{\rm p} \,|\, \mu, \boldsymbol{\Sigma})$$

$$\mu = (\mu_{\rm eff}, \mu_{\rm p}) \text{ and } \boldsymbol{\Sigma} = \begin{pmatrix} \sigma_{\rm eff}^2 & r\sigma_{\rm eff}\sigma_{\rm p} \\ r\sigma_{\rm eff}\sigma_{\rm p} & \sigma_{\rm p}^2 \end{pmatrix}$$

5 model parameters

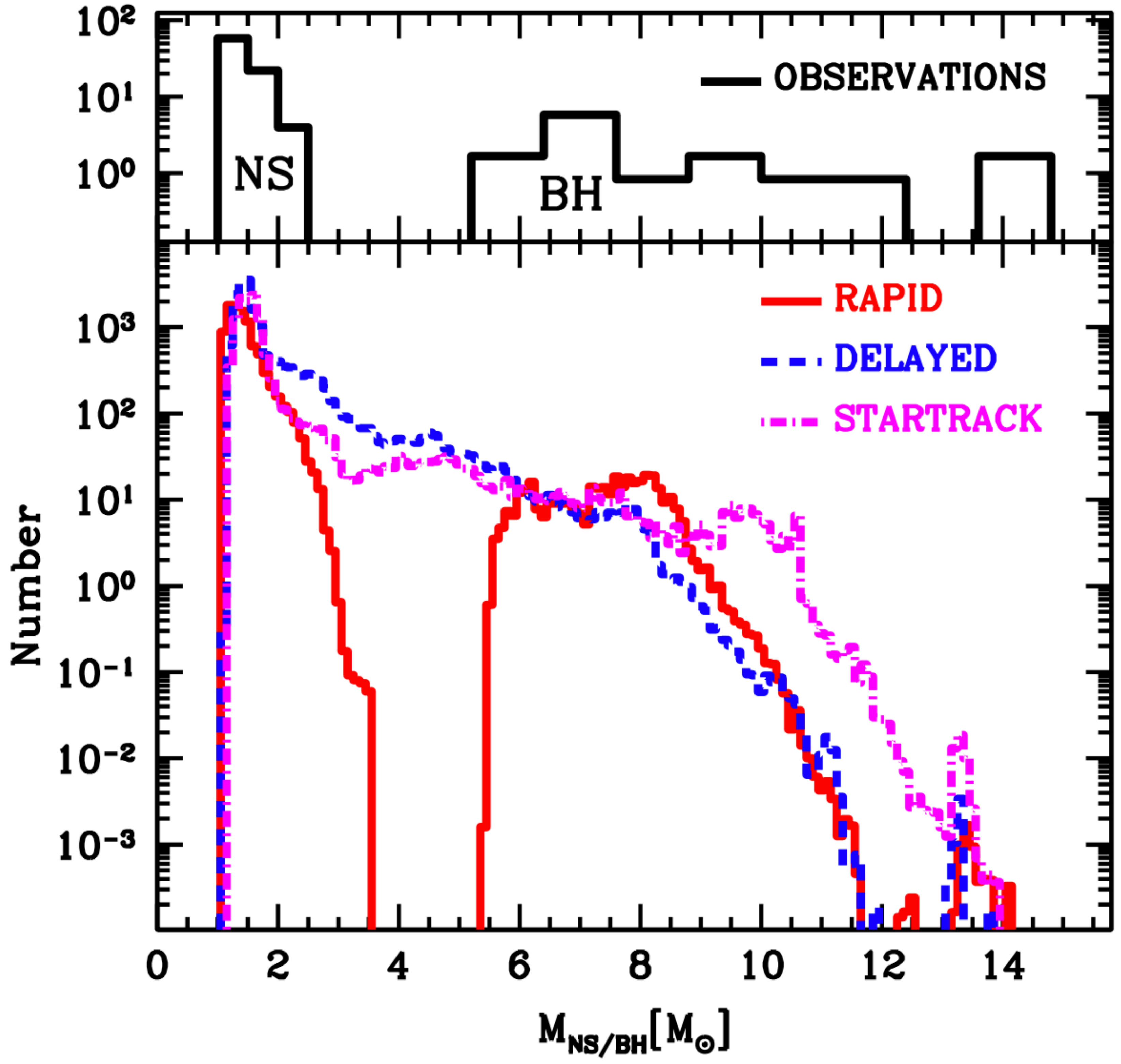
Merger Rates

	BNS $m_1 \in [1, 2.5] M_\odot$ $m_2 \in [1, 2.5] M_\odot$	NSBH $m_1 \in [2.5, 50] M_\odot$ $m_2 \in [1, 2.5] M_\odot$	BBH $m_1 \in [2.5, 100] M_\odot$ $m_2 \in [2.5, 100] M_\odot$	NS-Gap $m_1 \in [2.5, 5] M_\odot$ $m_2 \in [1, 2.5] M_\odot$	BBH-gap $m_1 \in [2.5, 100] M_\odot$ $m_2 \in [2.5, 5] M_\odot$	Full $m_1 \in [1, 100] M_\odot$ $m_2 \in [1, 100] M_\odot$
PDB (pair)	960^{+1740}_{-700}	59^{+81}_{-38}	$25^{+10}_{-7.0}$	41^{+69}_{-30}	$9.3^{+18.7}_{-7.6}$	1100^{+1700}_{-750}
PDB (ind)	250^{+640}_{-196}	170^{+150}_{-89}	$22^{+9.0}_{-6.0}$	29^{+55}_{-23}	$10^{+15}_{-8.0}$	470^{+830}_{-300}
MS	470^{+1430}_{-413}	57^{+123}_{-42}	42^{+88}_{-20}	$3.7^{+20.3}_{-3.4}$	$0.17^{+55.83}_{-0.16}$	650^{+1550}_{-460}
BGP	99^{+260}_{-86}	32^{+62}_{-25}	33^{+16}_{-10}	$2.1^{+33.0}_{-2.1}$	$5.1^{+12.0}_{-4.0}$	180^{+260}_{-110}
MERGED	13 – 1900	7.4 – 320	16 – 130	0.029 – 84	0.0095 – 56	71 – 2200

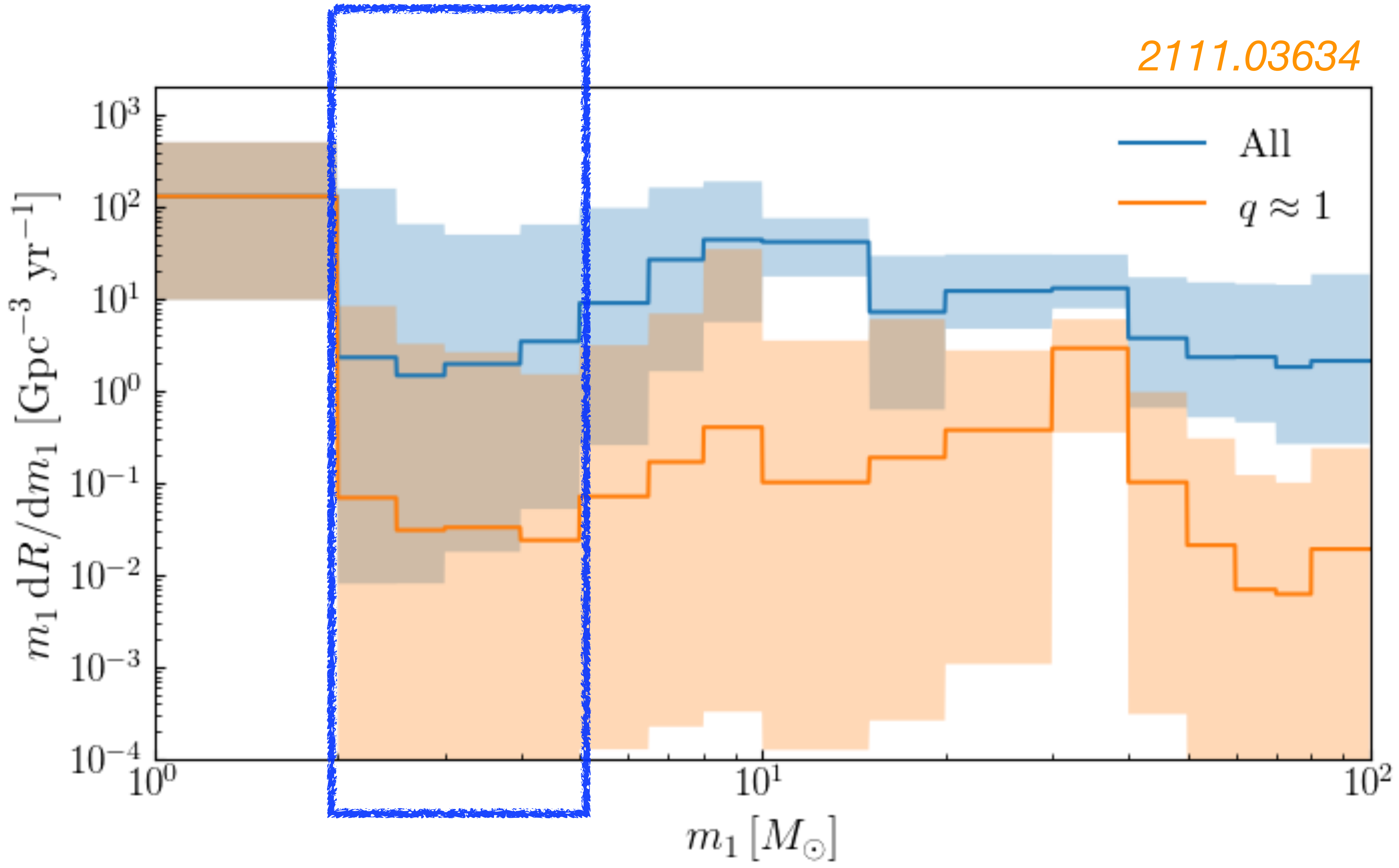
- Self consistent measure of merger rate of all detected CBCs
- Subdivided into astrophysically interesting mass ranges
- Constant co-moving volume merger rate density
- BBH merger rates are consistent with previously published estimates
- For BNS/NSBH, the inferred rate depends on the presumed mass distribution
- Different approaches arrive at different binary mass distributions between $1\,M_\odot$ and $2.5\,M_\odot$
- Highlights the importance of modeling systematics when drawing inferences about populations with few confident members

Lower mass gap

- NSs are expected to have a maximum mass of ~3 $M_\odot$
- Heaviest NS observed to date has mass 2.01±0.04 $M_\odot$
- PSR J0740+6620 'may' host a ~2.07-2.08 $M_\odot$ NS
- X-ray observations found a dearth of objects in the 3 - 5 $M_\odot$ range
- Population synthesis models with rapid supernova instabilities can not produce BHs of mass < 5 $M_\odot$
- Thus, we don't expect to observe binaries with component masses in ~3-5$M_\odot$in GWs
  - provided they are formed in a way similar to the binaries observed with EM radiation



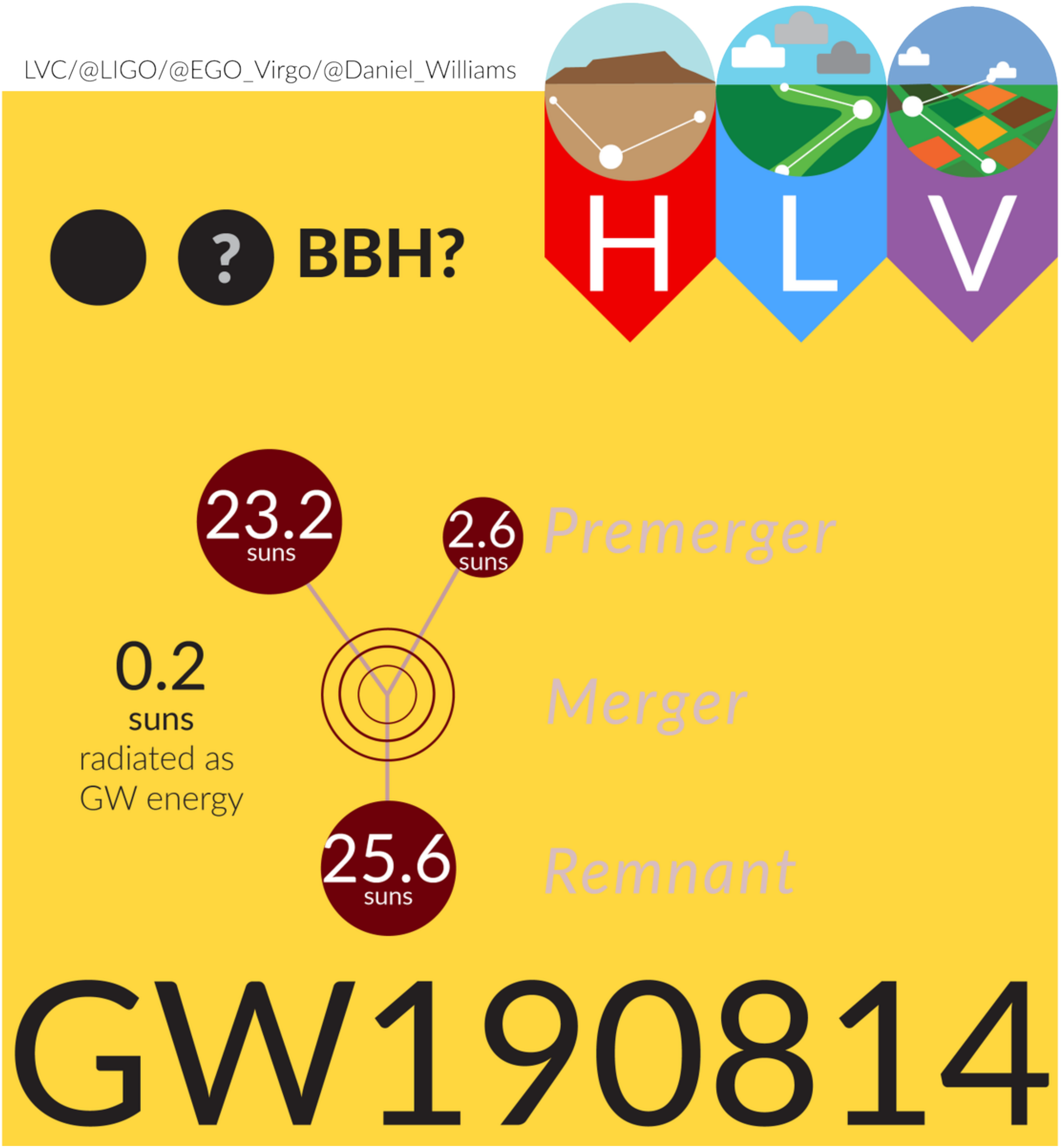
Belczynski et al, 2012



- A reduction in the rate above NS masses
- Unable to confidently infer absence or presence of a subsequent rise in merger rates from lower mass gap masses
- Neither find evidence for nor rule out the existence of a two-sided lower mass gap
- Rates in mass gap are 1 or 2 order of magnitude different; GW data suggest two distinct populations of compact objects
- If a lower mass gap does exists, it may not be totally empty

Possible ways to populate this gap

- Remnants of binary neutron stars (Gupta et al, 2020)
- Hierarchical merger of stellar few-body systems (Safarzadeh et al, 2020, Lu et al, 2020)
- BHs of primordial origin (García-Bellido, 2019)
- Still a mystery that what the secondary of GW190814 is?
- Primary of GW190425 ($m_1 \in [1.61, 2.52] M_{\odot}$) could be a low-mass gap BH



Masses

NS masses in binaries

- Classification criteria: probability that at least one of the component masses is less than the maximum NS mass > 50%

- $M_{\rm max,TOV} = 2.21^{+0.31}_{-0.21} M_\odot$ from 2106.05313 based on pulsar timing, GW and X-ray observations of NSs

Name	$\mathrm{FAR_{min}}$ (yr^{-1})	$P(m < M_{\rm max,TOV})$	$P(m < M_{\rm low}^{\rm gap})$	Classification
GW170817	$< 1 \times 10^{-5}$	0.99	0.98	BNS
GW190425	3.38×10^{-02}	0.68	0.73	BNS
~~GW190814~~	~~$< 1 \times 10^{-5}$~~	~~0.06~~	~~0.19~~	~~BBH~~
GW200105	2.04×10^{-01}	0.94	0.74	NSBH
GW200115	$< 1 \times 10^{-5}$	0.95	0.97	NSBH
GW190426	9.12×10^{-01}	0.82	–	NSBH
GW190917	6.56×10^{-01}	0.56	–	NSBH

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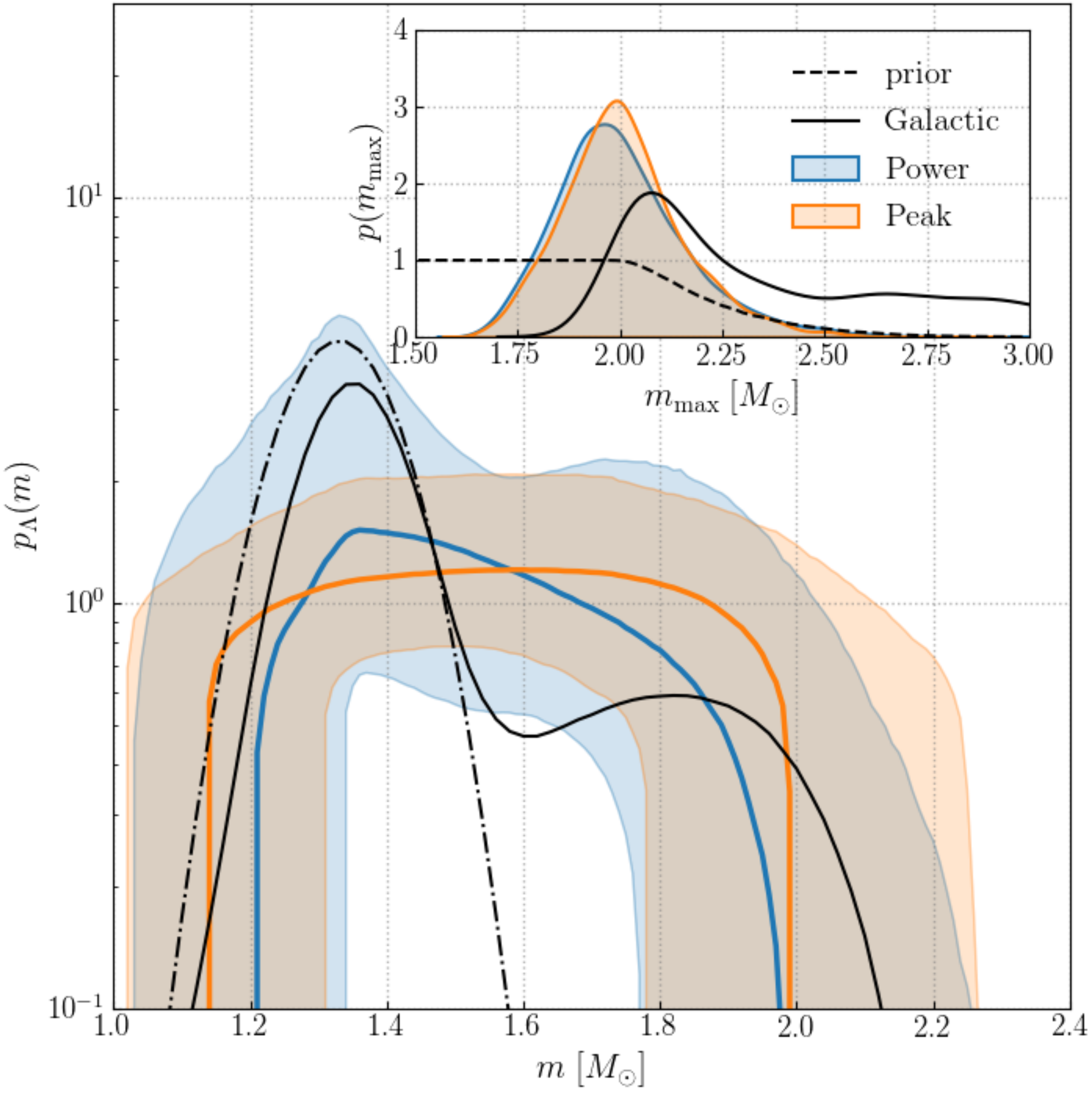

Power: $\alpha = -2.0^{+5.1}_{-7.0}$

Peak: $\sigma = 1.1^{+0.8}_{-0.8} M_\odot$ and $\mu = 1.5^{+0.4}_{-0.4} M_\odot$

- GW observations to date do not support a NS mass distribution with a pronounced single peak
- In contrasts with the Galactic BNS subpopulation whose mass distribution is sharply peaked around $1.35 M_\odot$
- Mass distribution of NSs observed in GWs is broader and has greater support for high-mass NSs
- Galactic NS population distribution has a double-peaked shape

$m_{min} = 1.2^{+0.1}_{-0.2} M_\odot$ $m_{max} = 2.0^{+0.3}_{-0.2} M_\odot$

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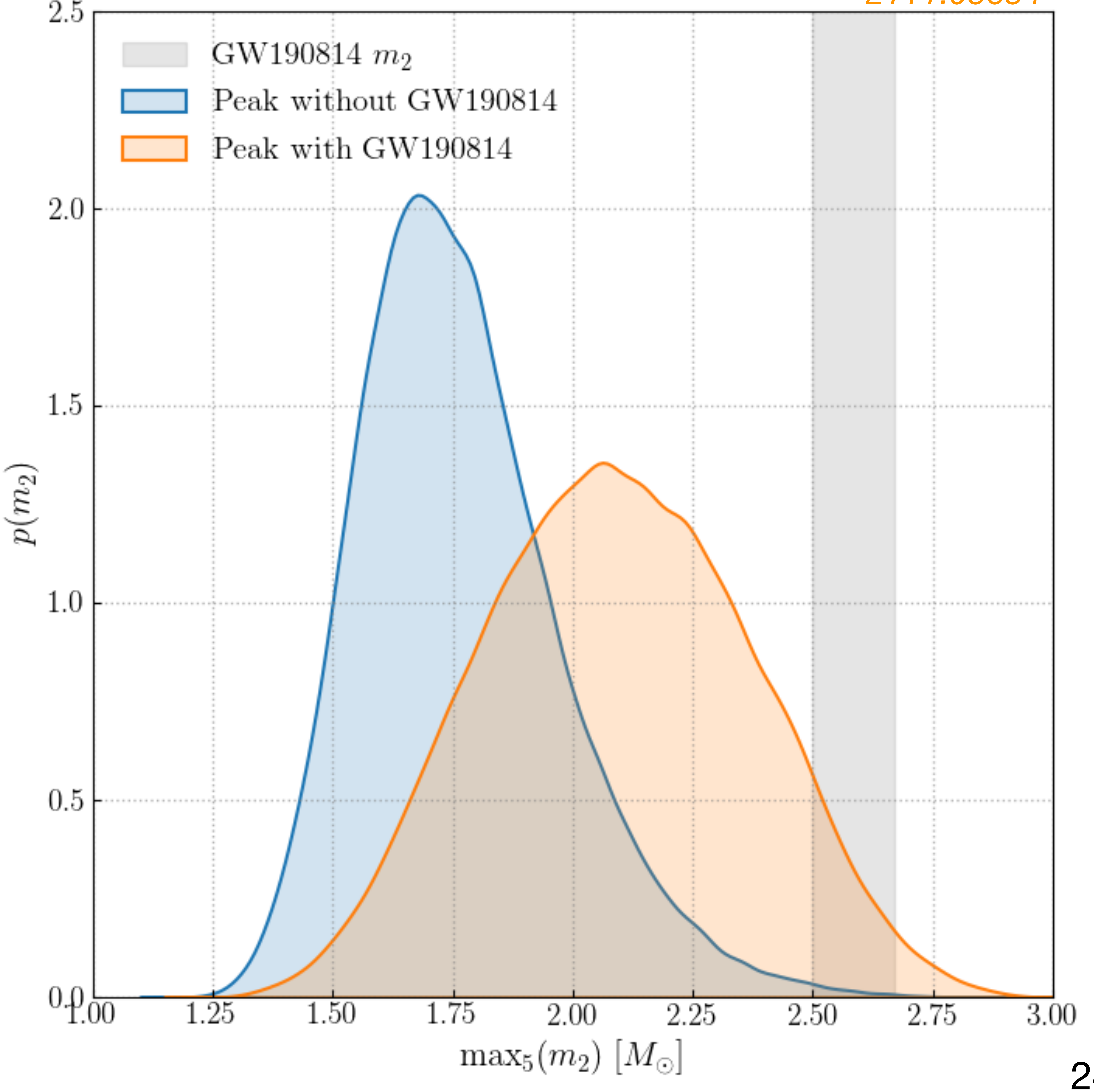


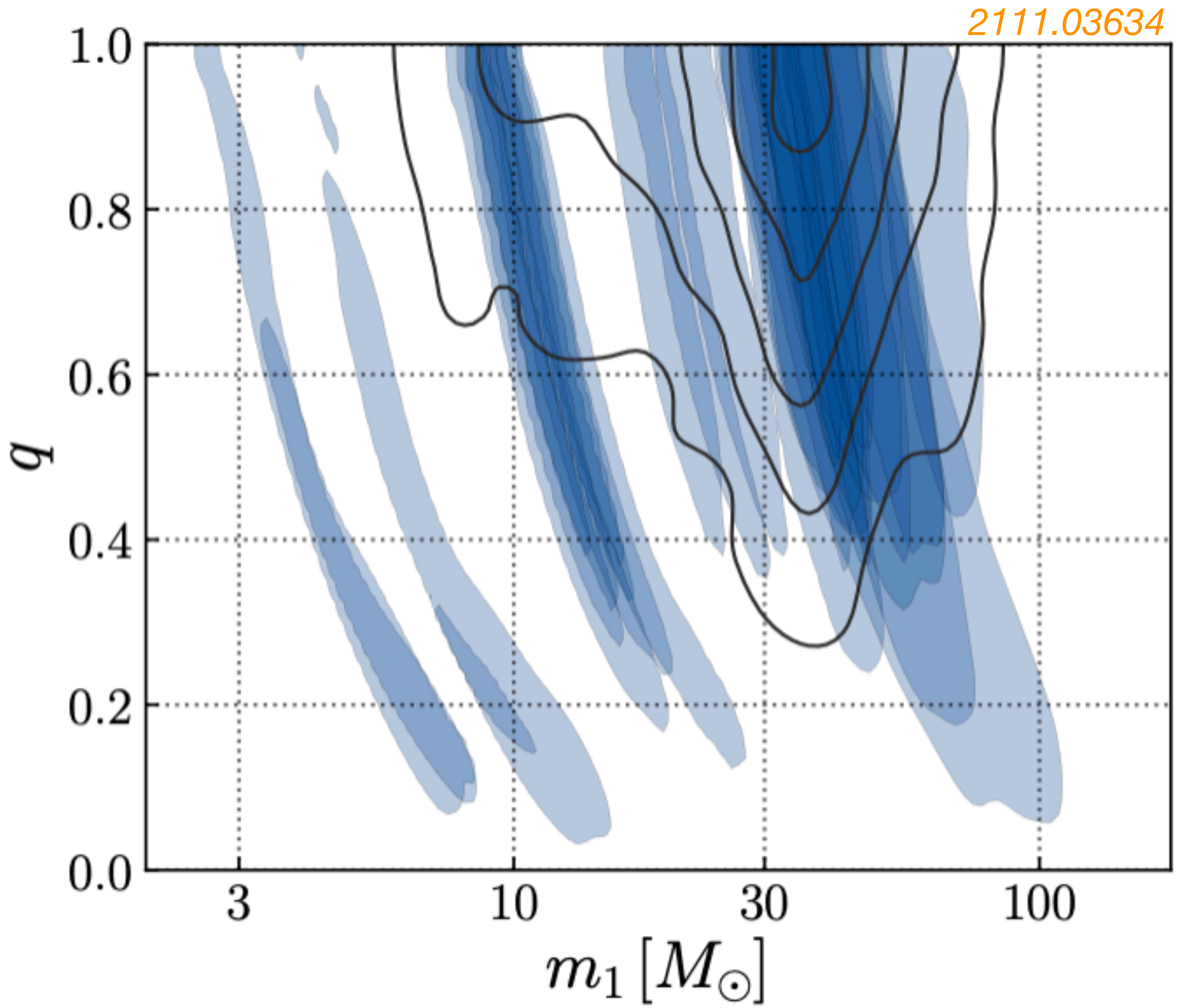
GW190814 is an outlier from the secondary masses in BNS and NSBH systems

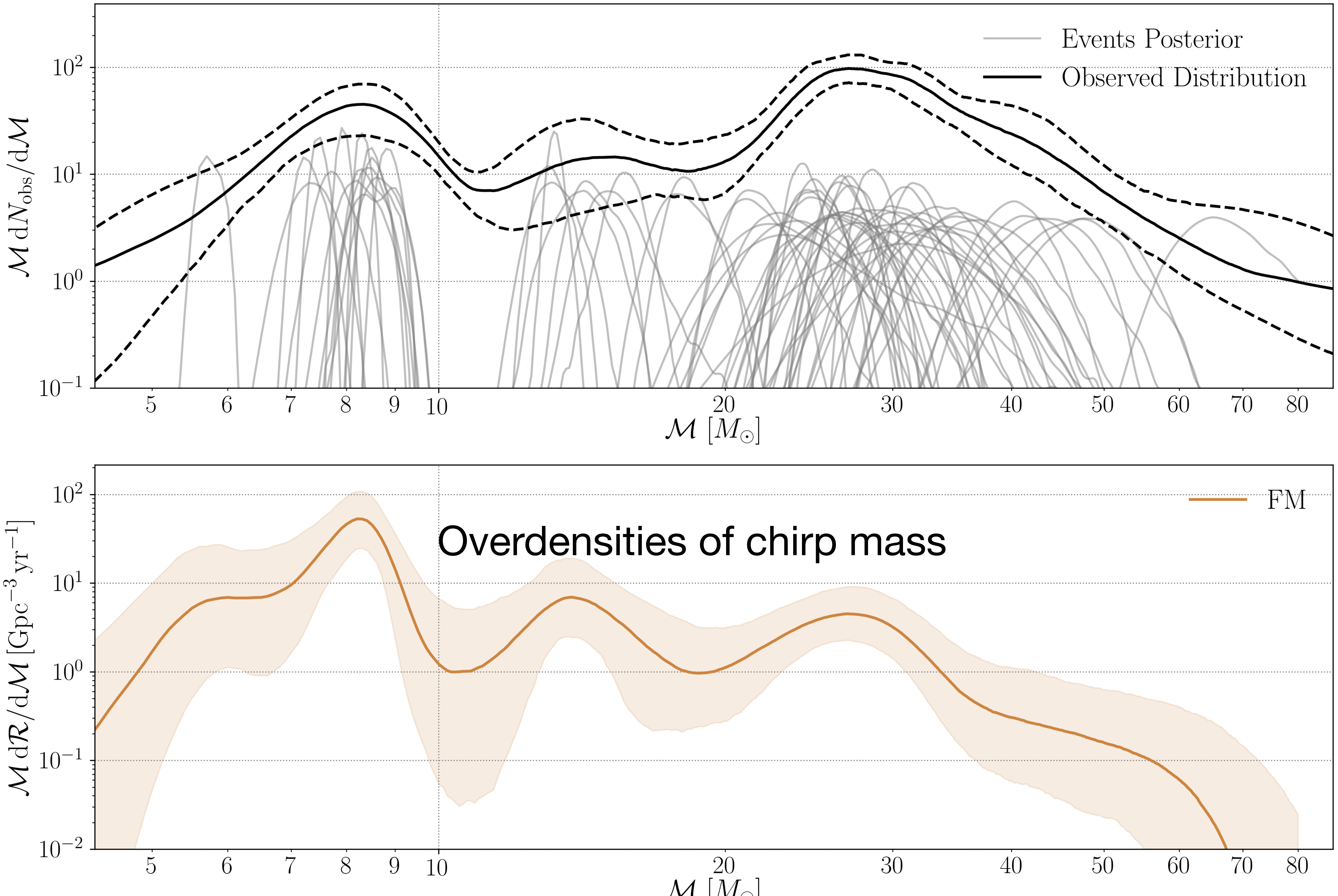
$\max_5(m_2)$: the largest observed secondary mass after 2 BNS observations and 3 NSBH observations

BH masses in binaries

FAR threshold of $1\ \mathrm{yr}^{-1}$ and redshift dependance

BH mass distribution is consistent with GWTC-2




Events Posterior
Observed Distribution
$\mathcal{M}\, dN_{obs}/d\mathcal{M}$
10^{-1}
10^{0}
10^{1}
10^{2}
5
6
7
8
9
10
20
30
40
50
60
70
80
$\mathcal{M}\ [M_\odot]$
FM
Overdensities of chirp mass
$\mathcal{M}\, d\mathcal{R}/d\mathcal{M}\, [\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}]$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
5
6
7
8
9
10
20
30
40
50
60
70
80
$\mathcal{M}\ [M_\odot]$

Power Law + Peak

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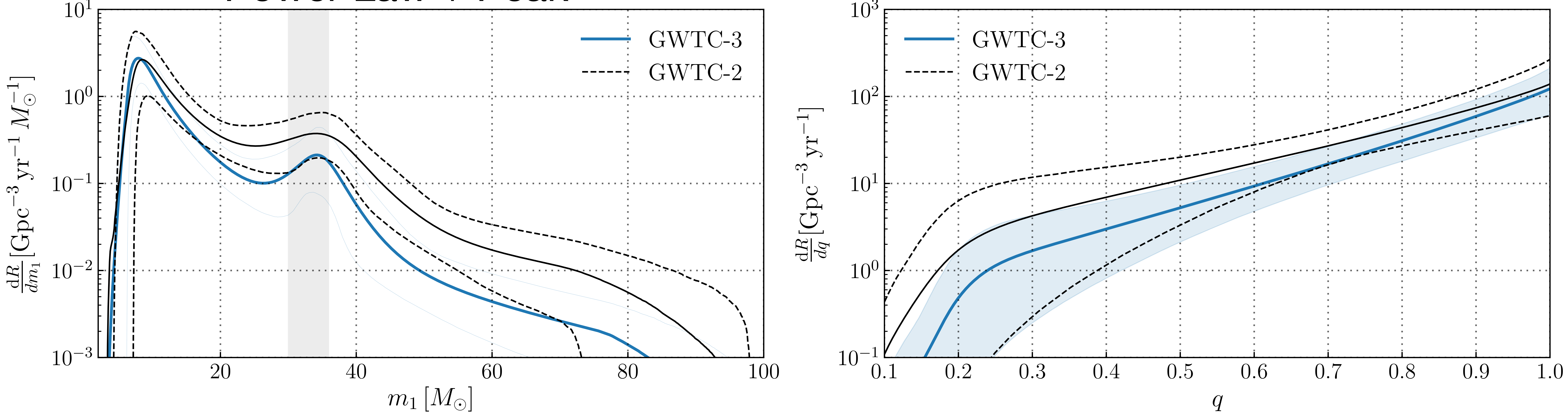
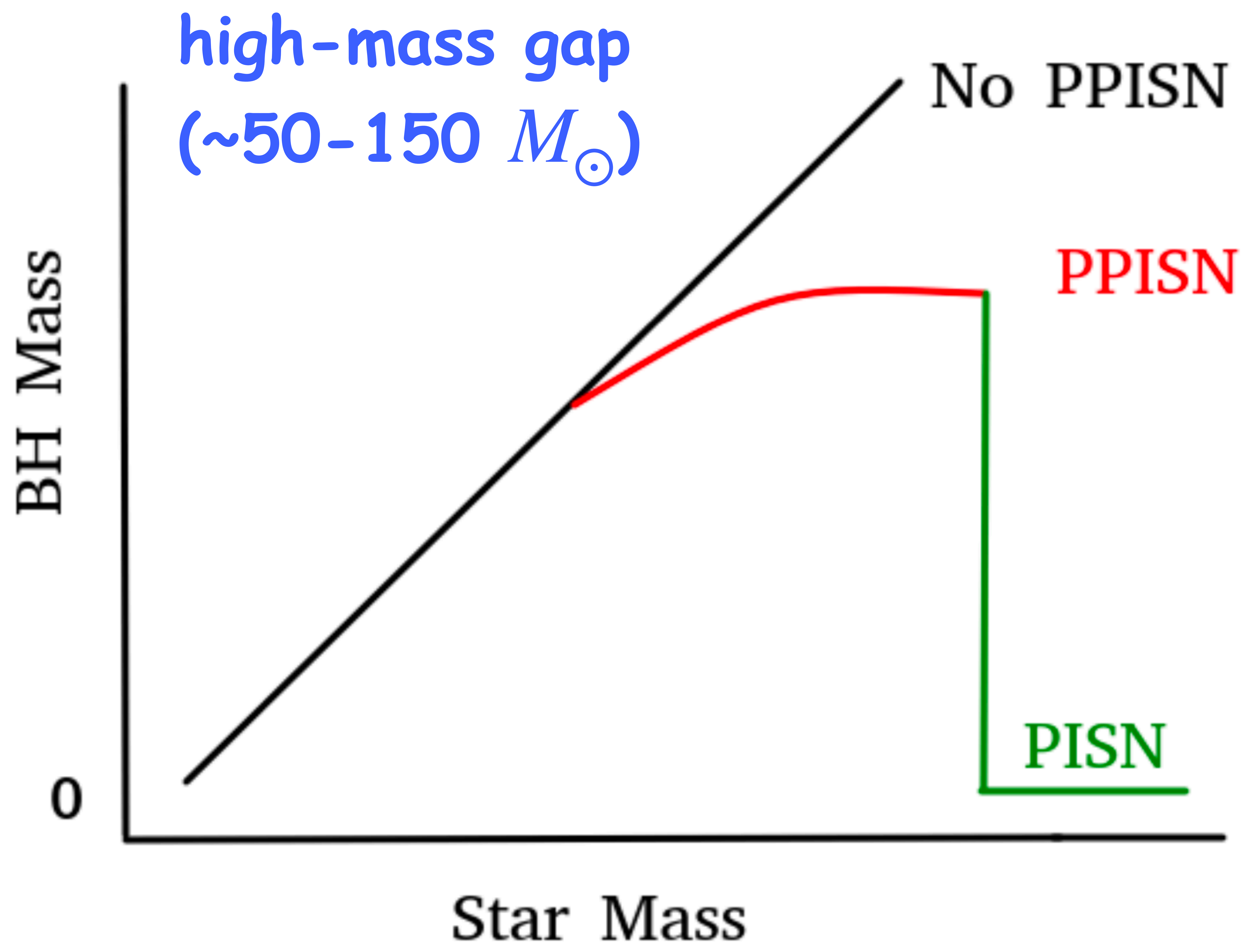


- The inferred mass spectrum decays more rapidly
- Expected because new observations in GWTC-3 contain a greater fraction of lower mass systems
- The inferred mass ratio distribution is less peaked towards equal mass binaries compared to GWTC-2
- Inconclusive evidence for an upper mass gap (~50-150 $M_\odot$)

High-mass gap: what theory says?



Pulsational pair instability supernovae (PPISN)

Pair instability supernovae (PISN)

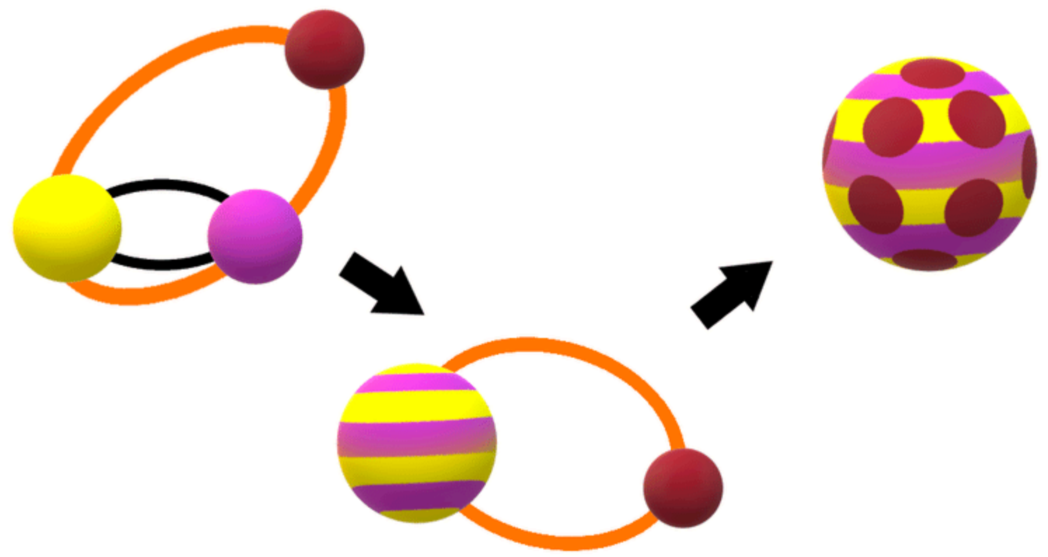
Inconclusive evidence for upper mass gap

- A gap is defined as a rapid decline and a rapid rise in merger rate at significantly higher mass
- No evidence is found for such a gap
- The PPISN mass gap could start at higher mass than theory expects
- Or the high-mass binaries in GWTC-3 could be formed in a way that avoids PPISN

Possible ways to populate this gap

[More in Vishal and Parthapratim's Talks]

- Hierarchical BBH mergers
- Stellar mergers
- BH remnants of population III stars
- Stellar triples in the field of the galaxy
- Growth via accretion in an Active Galactic Nuclei (AGN)



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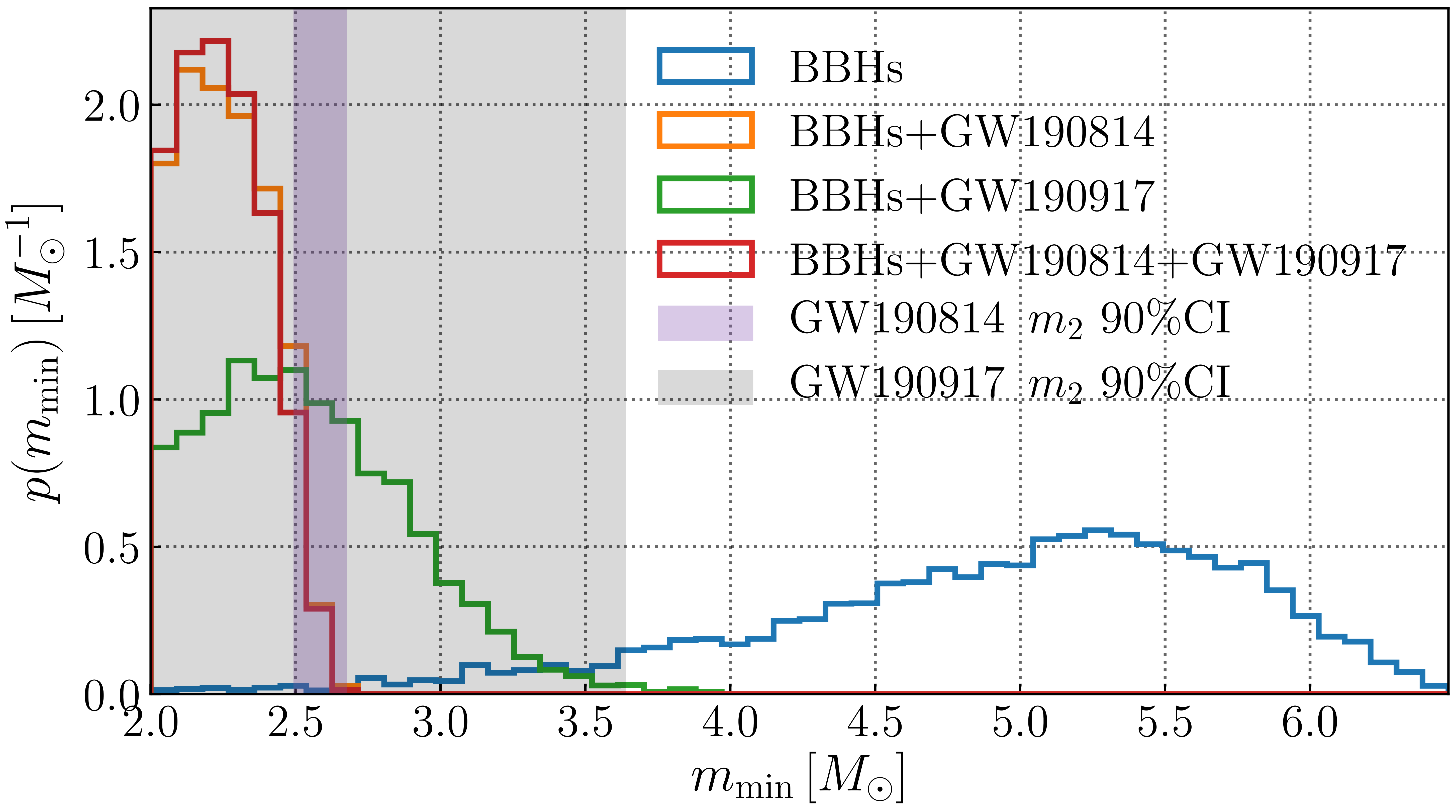


GW190814 and GW190917 are outliers from the secondary masses in BBH systems

m_{min}: minimum recovered BH mass

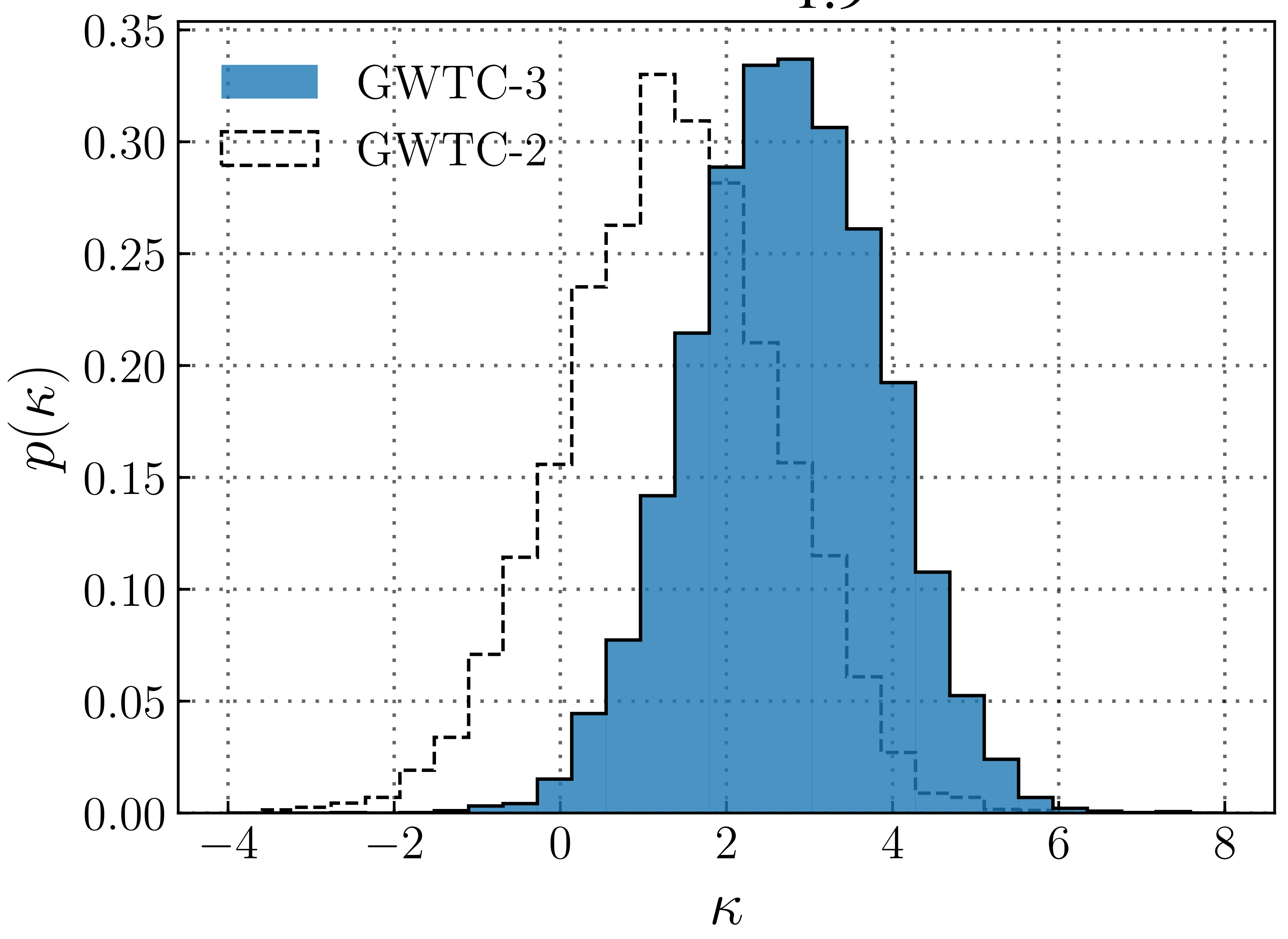
Evolution of rates with redshift

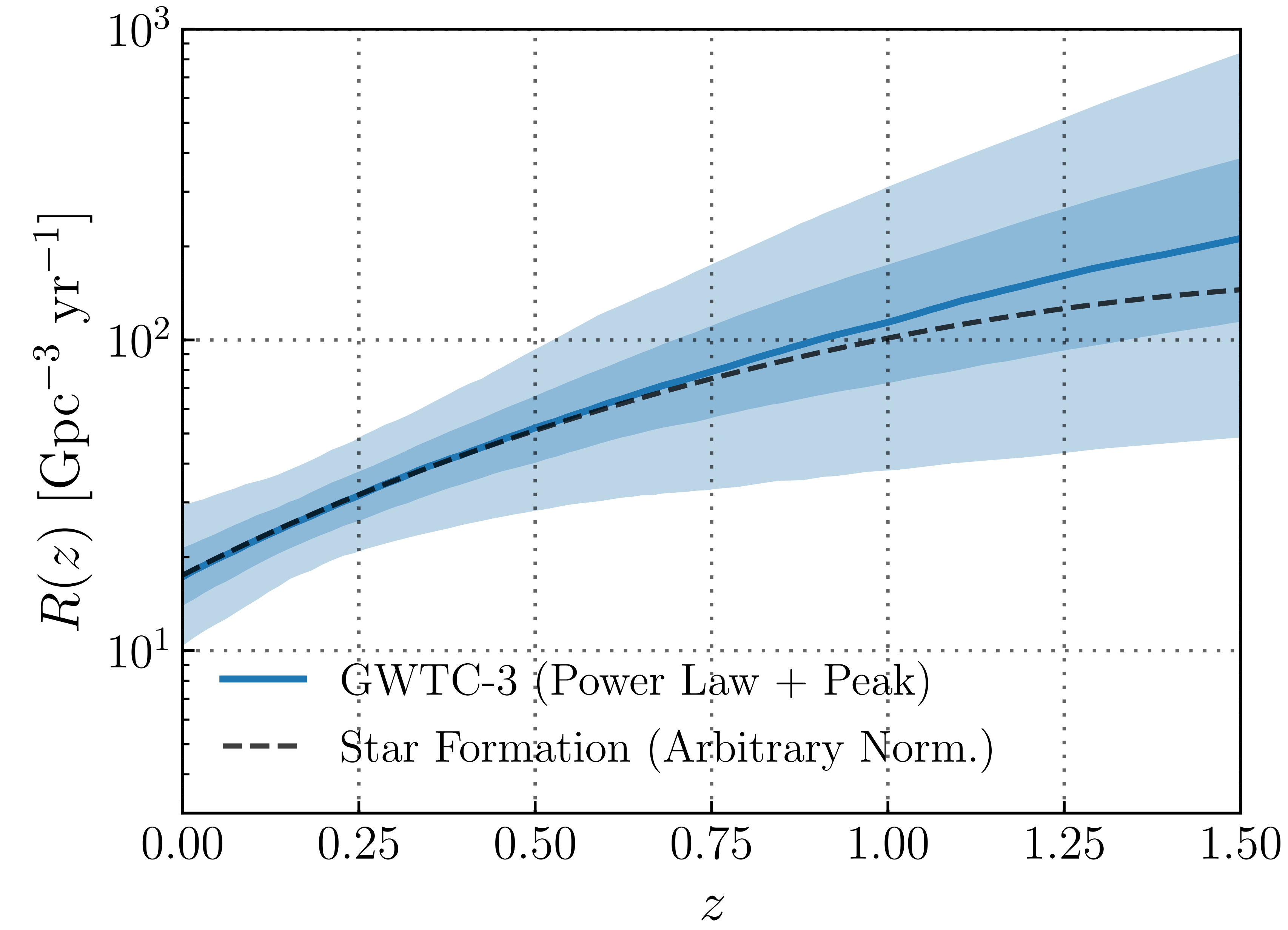
$$\mathscr{R}(z) = \frac{dN}{dV_c dt}(z) = \mathscr{R}_0(1+z)^\kappa$$

- Initially there was a preference for a rate that increased with redshift but still consistent with a non-evolving merger rate

- But with GWTC-3 we are confident that BBH rate is evolving with redshift

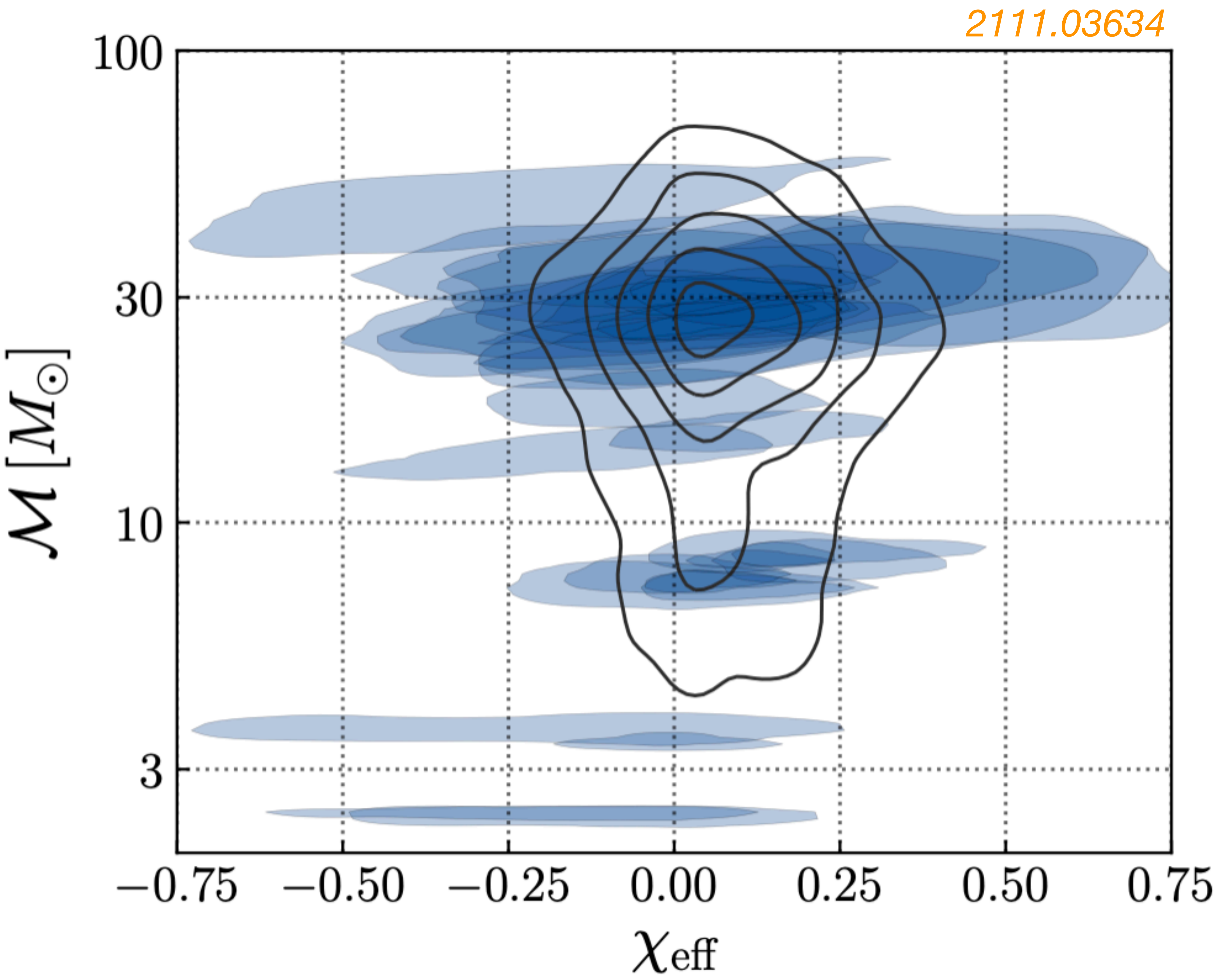
$\kappa = 2.7^{+1.8}_{-1.9}$ 2111.03634

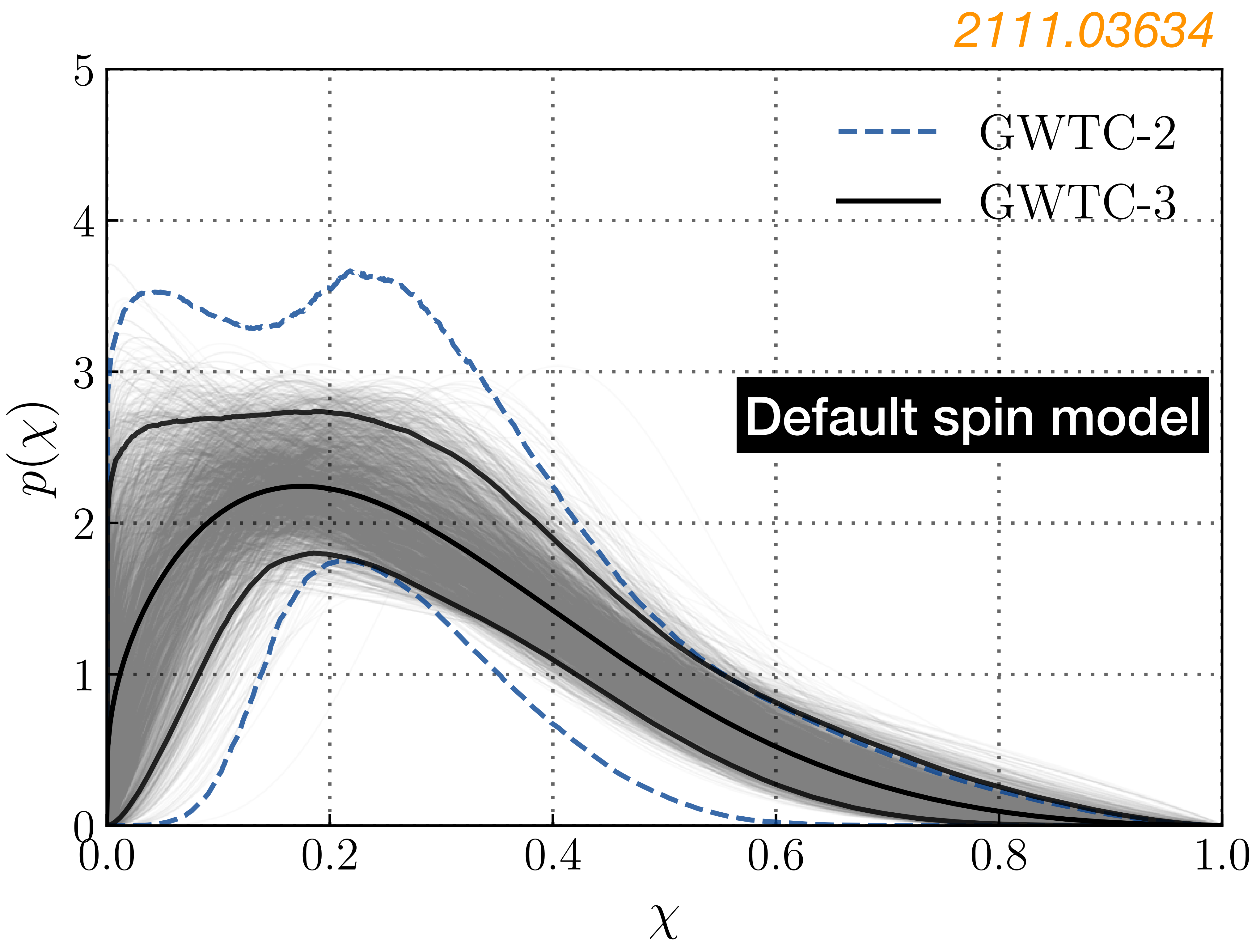


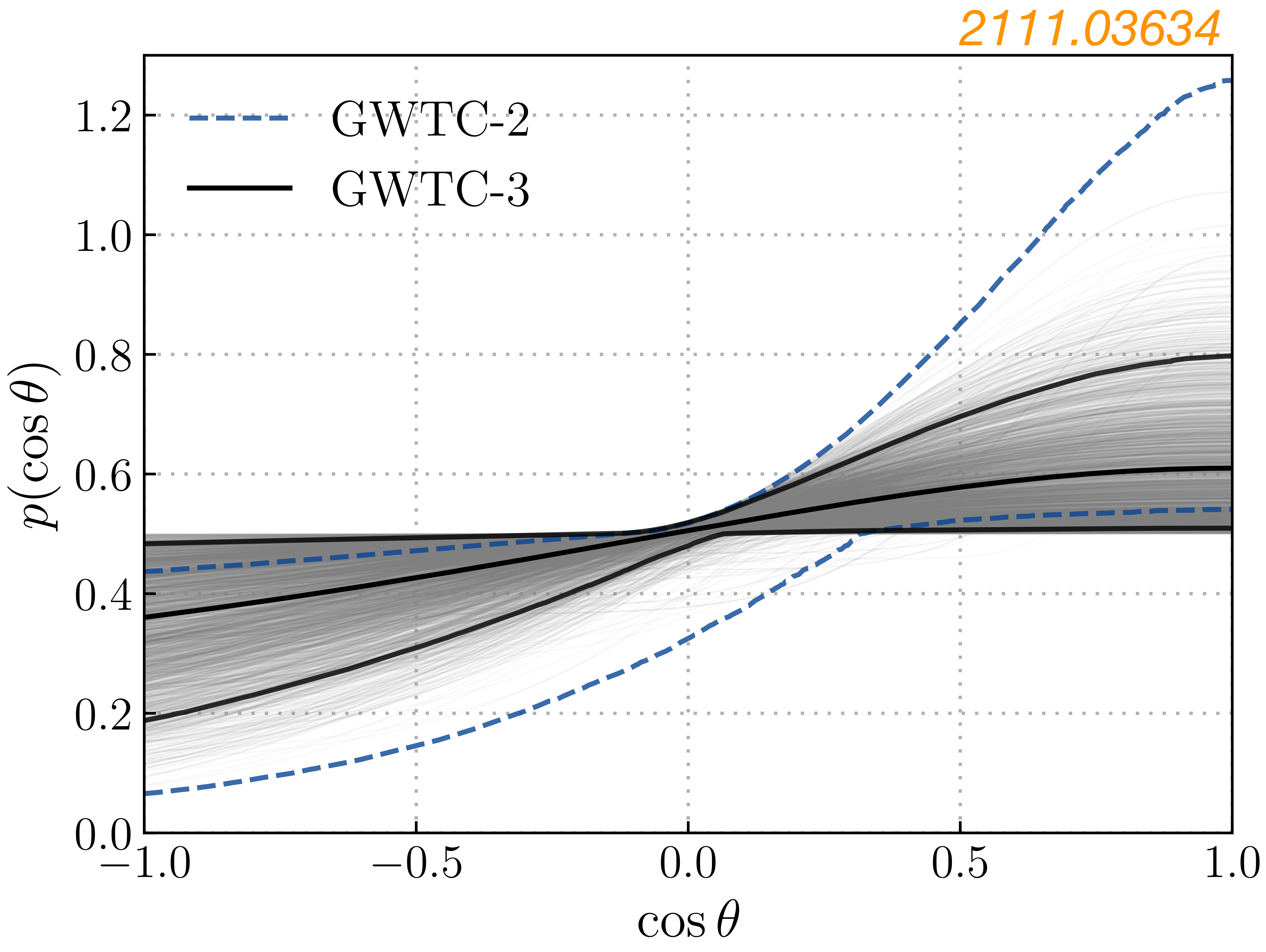


Spin distribution in BBHs

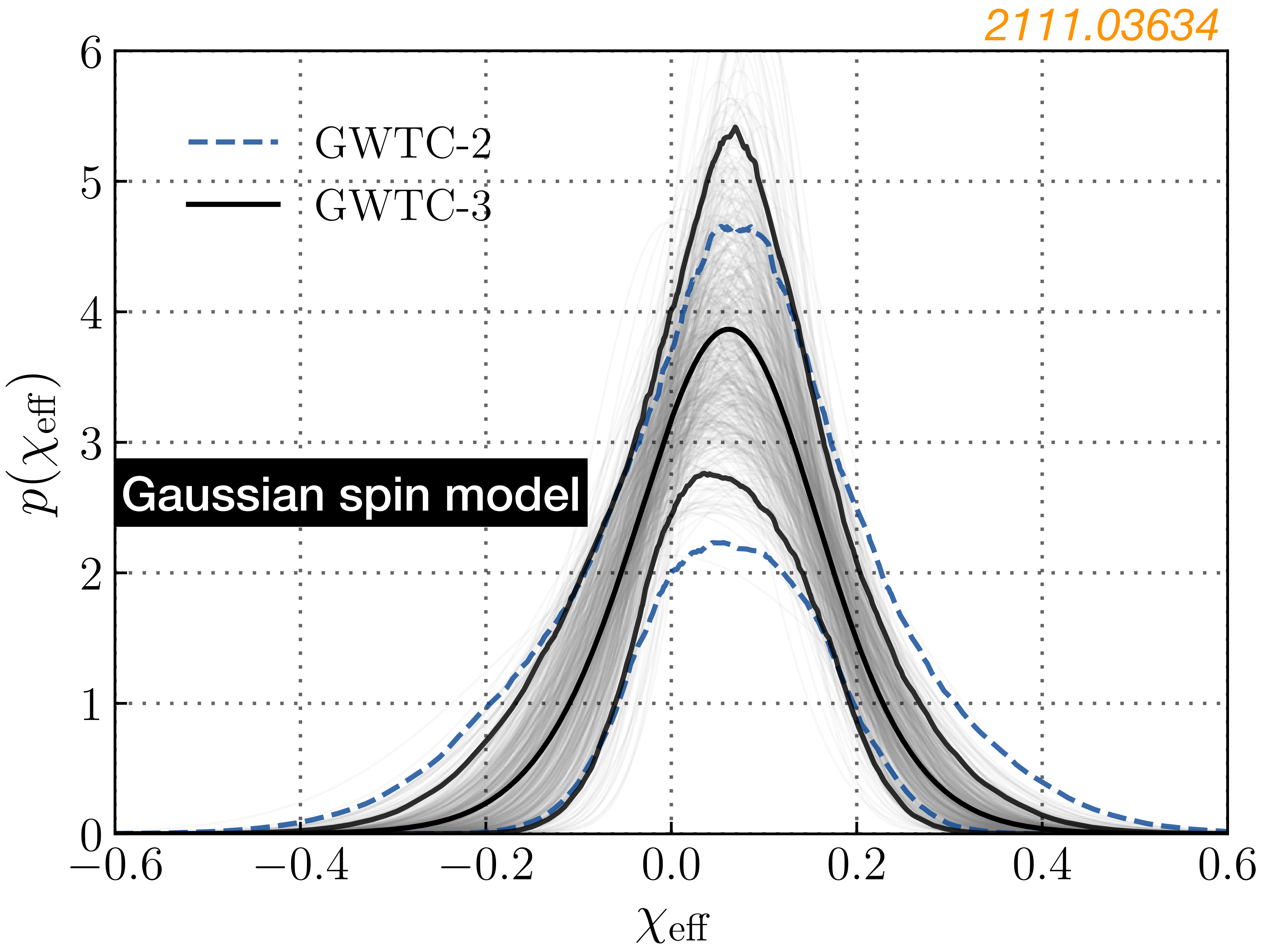
BBH spin distribution is consistent with GWTC-2

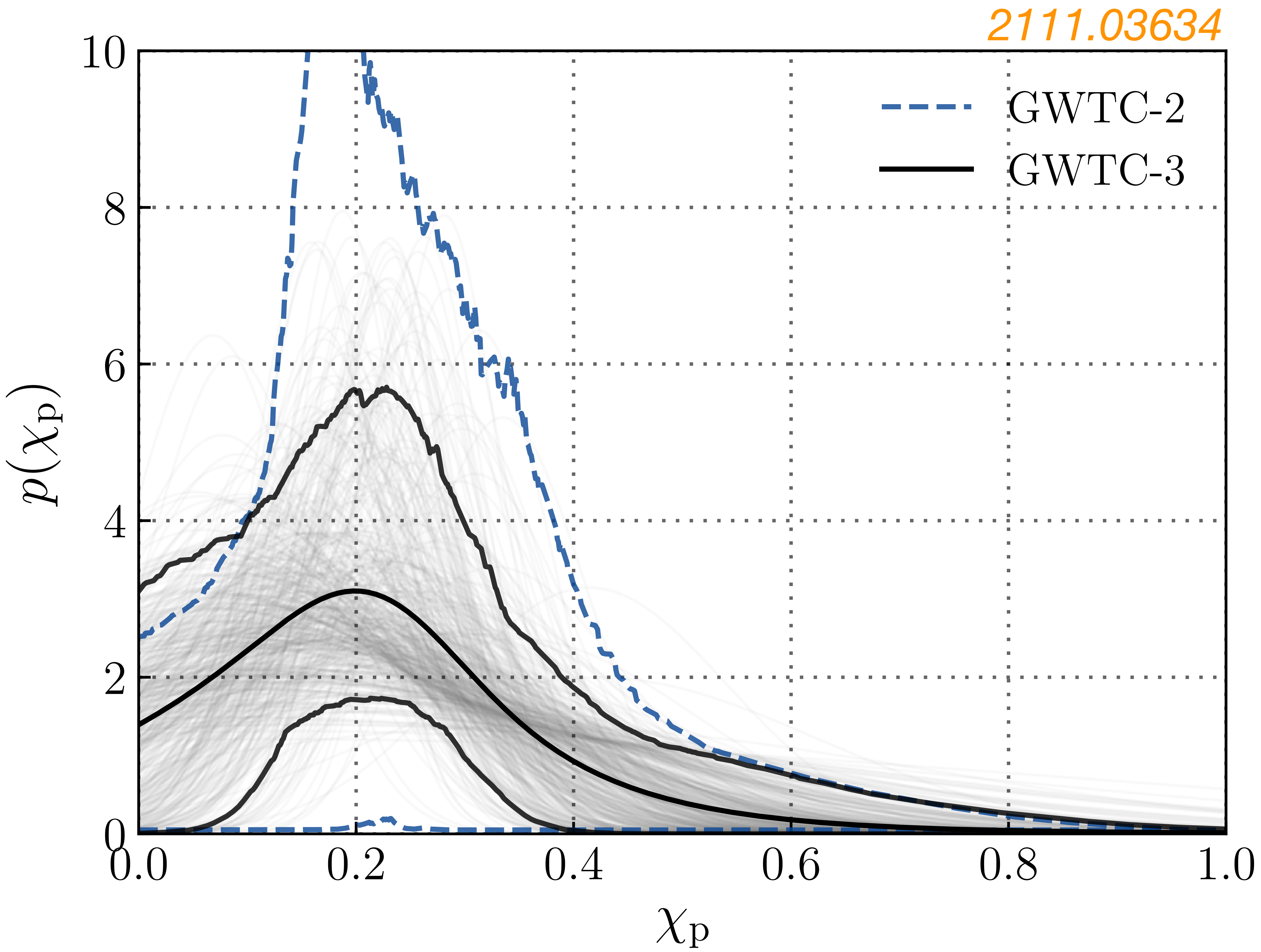






Again excluded the case of perfect spin–orbit alignment and now data strongly favor a broad or isotropic distribution of spin tilts





- As with GWTC-2 we again infer a $\chi_{\rm eff}$ distribution compatible with small but non-vanishing spins, with a mean centered at $0.06^{+0.04}_{-0.05}$

- χ_p measurements can be explained either by a broad distribution centered at $\chi_p = 0$, or a narrow distribution centered at $\chi_p \approx 0.2$

Evidence of extreme spin-orbit misalignment

- Spin tilts $> 90^{\circ}$ unlikely for BBH formation from isolated stellar progenitors (Kalogera, 2000)
- $\chi_{\text{eff}} < 0$ would serve as a strong indicator of dynamical interaction during BBH evolution
- Extended the Gaussian model to truncate χ_{eff} on the range $\chi_{\text{eff,min}} \leq \chi_{\text{eff}} \leq 1$(rather than $-1 \leq \chi_{\text{eff}} \leq 1$) and hierarchically measured $\chi_{\text{eff,min}}$
- $\chi_{\text{eff,min}} < 0$ at 99.8% credibility
- There were objection that unless BBH spin models are expanded to allow the existence of a secondary subpopulation with vanishingly small spins and spins allowed to correlate with other BBH parameters like the mass ratio
- Repeat the inference of $\chi_{\text{eff,min}}$ but under an expanded model that allows for a narrow subpopulation of BBHs with extremely small χ_{eff}
- Data still prefer a negative $\chi_{\text{eff,min}}$ but with lower significance, $\chi_{\text{eff,min}} < 0$ at 88.4% credibility

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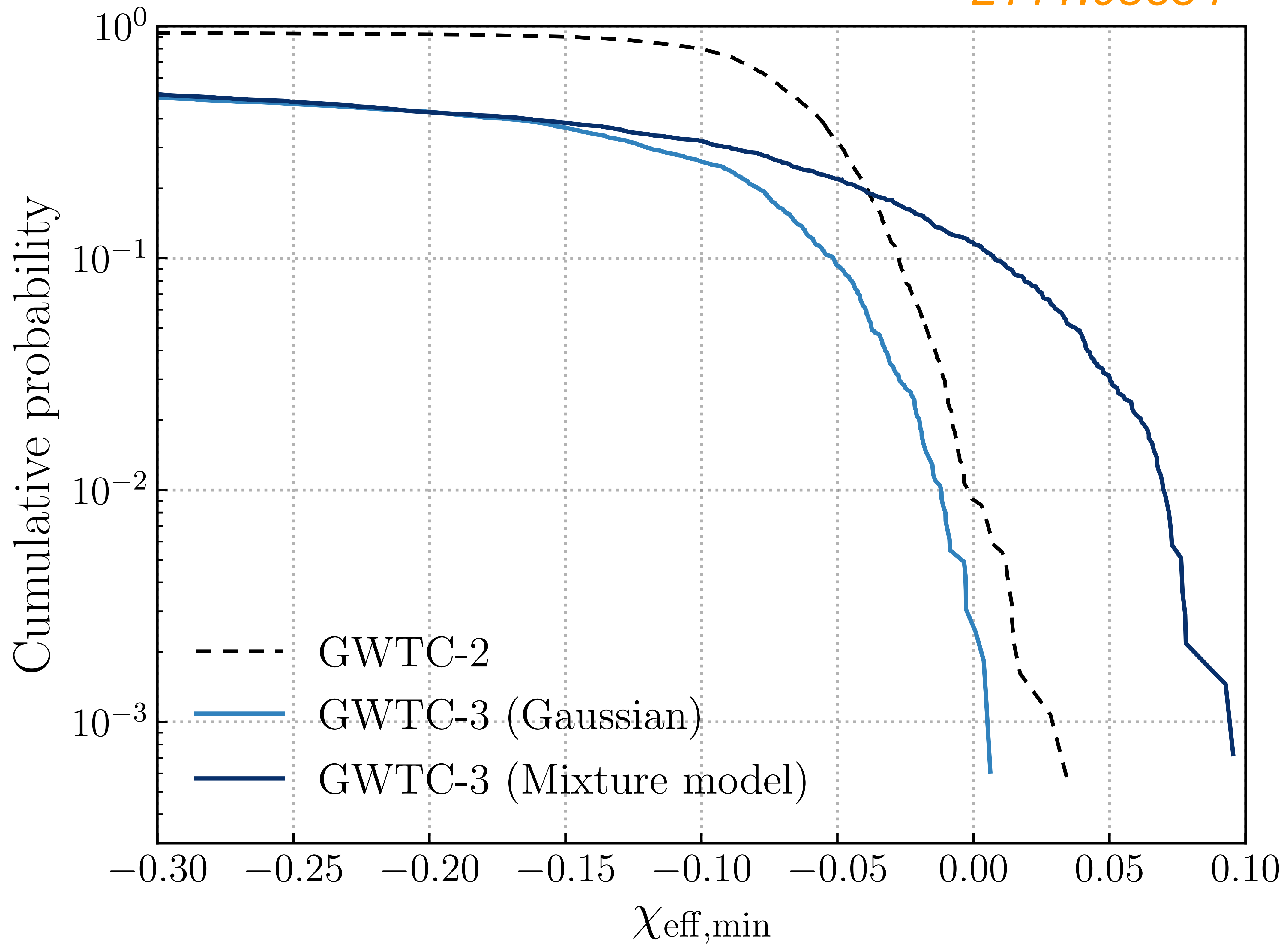

Summary

- Mass and spin distributions are consistent with GWTC-2
- More BBHs with preferentially negatively aligned spins but it could be by chance as well
- The BBH merger rate density increases with redshift
- A relative dearth of observations with component masses between 3 and 5 $M_\odot$
- No strong evidence for lower and higher mass gaps
- The inferred NS mass distribution, albeit based on a limited sample of observations, does not exhibit a peak at $1.35\,M_\odot$
- GW190814 is an outlier for the secondary mass of BNS/NSBH and BBH population

1906.04197
O3
Design
A+
A++
Voyager
CE
BBH
BNS
NSBH
We are here!
Size of catalog
10^7
10^6
10^5
10^4
10^3
10^2
10
1
2020
2025
2030
2035
2040

- LIGO-Virgo-KAGRA
    - Stellar mass NS/BH merger up to redshift $z \sim 1$
- 2G: Voyager (Livingston, Hanford, Pisa, Hingoli, Kamioka)
    - 4-5 times better sensitivity, detections up tp redshift $z \sim 10$
- 3G: Einstein Telescope, Cosmic Explorer
    - 20 times better sensitivity, detections up tp redshift $z \sim 30$
- Other: LISA, TianQin, DECIGO, Pulsar Timing array
    - Explore lower frequency regime and new sources

Loud Future for GW science

Thank You!