Investigating the lives of BHs & NSs

The emerging picture from gravitational-wave astronomy

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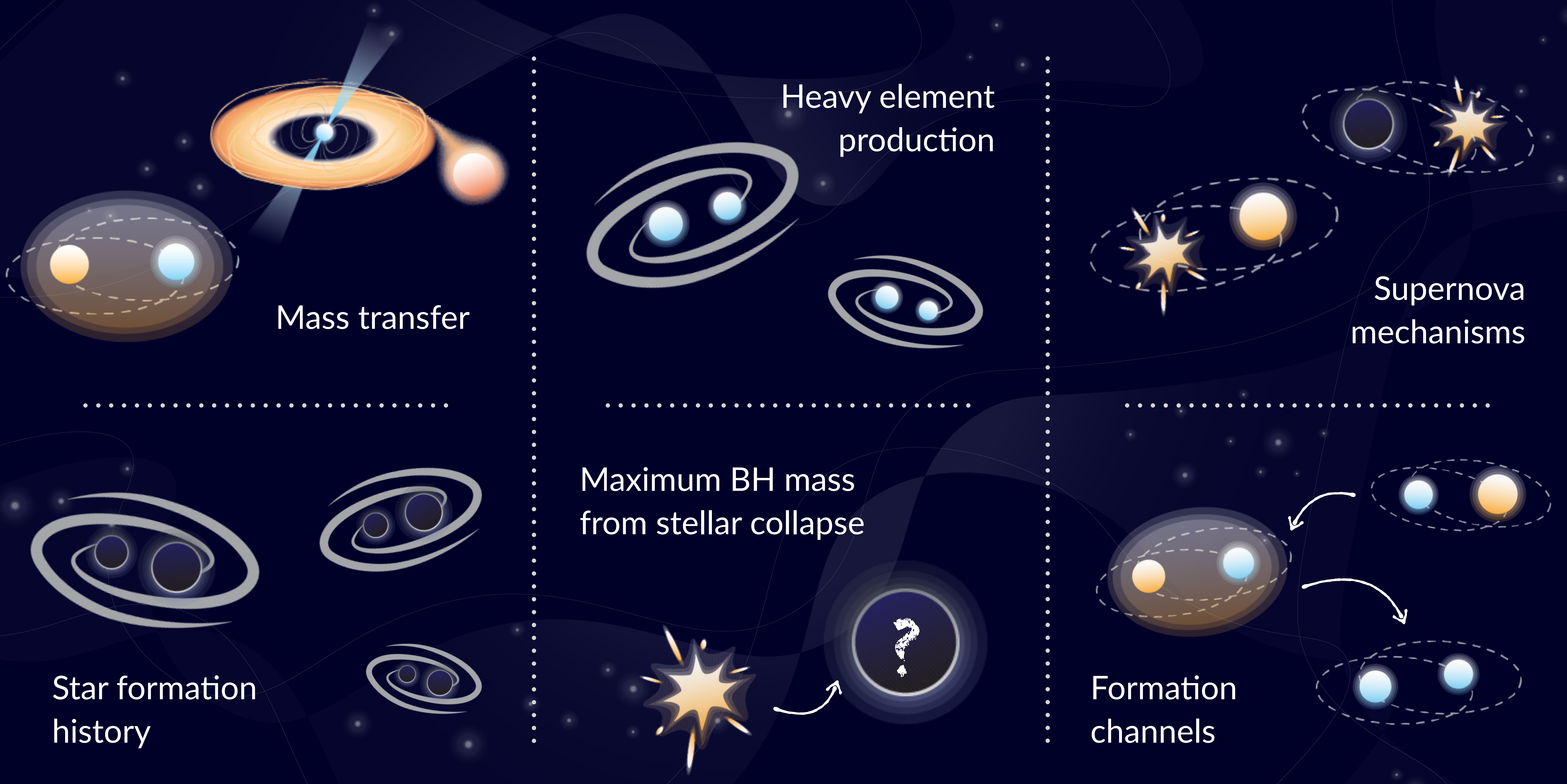
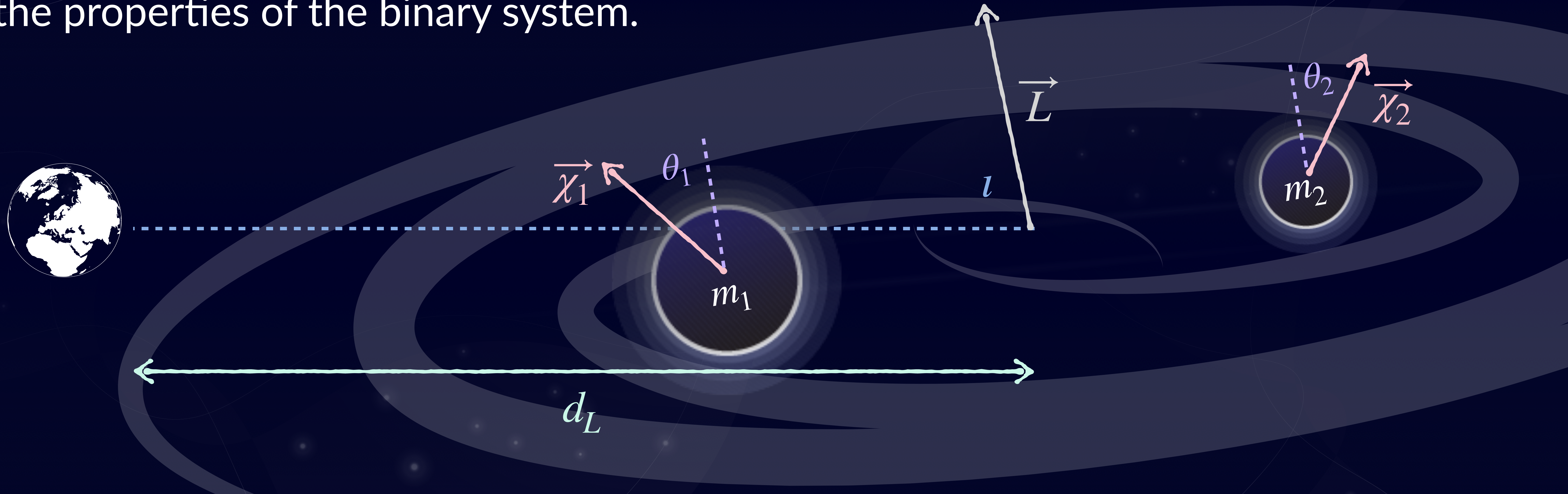

Mass transfer
Heavy element production
Supernova mechanisms
Star formation history
Maximum BH mass from stellar collapse
Formation channels

Gravitational waves

Sources so far are compact binary systems consisting of black holes (BH) and/or neutron stars (NS). The gravitational-wave (GW) signal carries information about the properties of the binary system.



The stellar graveyard so far…

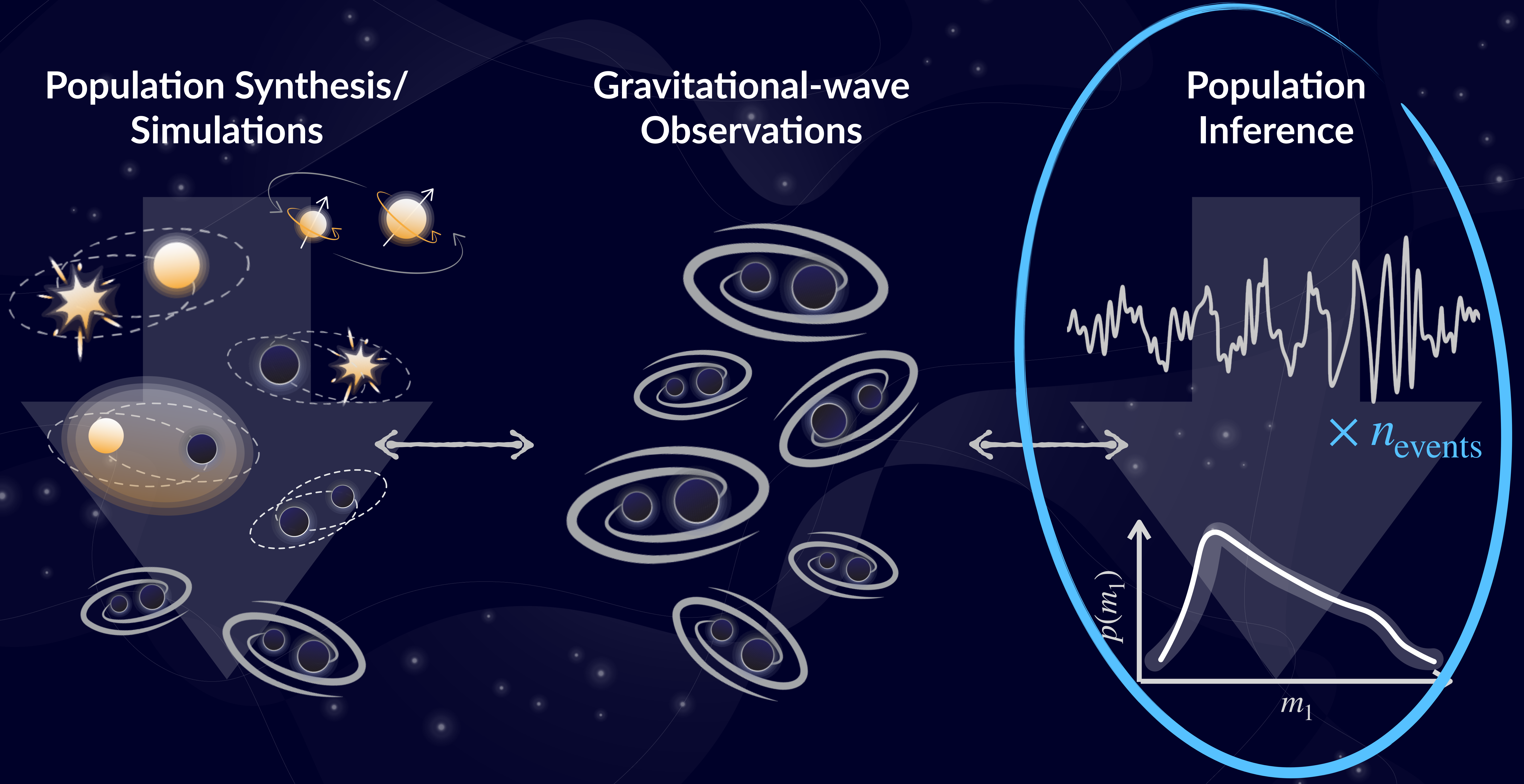
GWTC-3 =

O1 + O2 + O3a + O3b

Population Synthesis/ Simulations

Gravitational-wave Observations

Population Inference

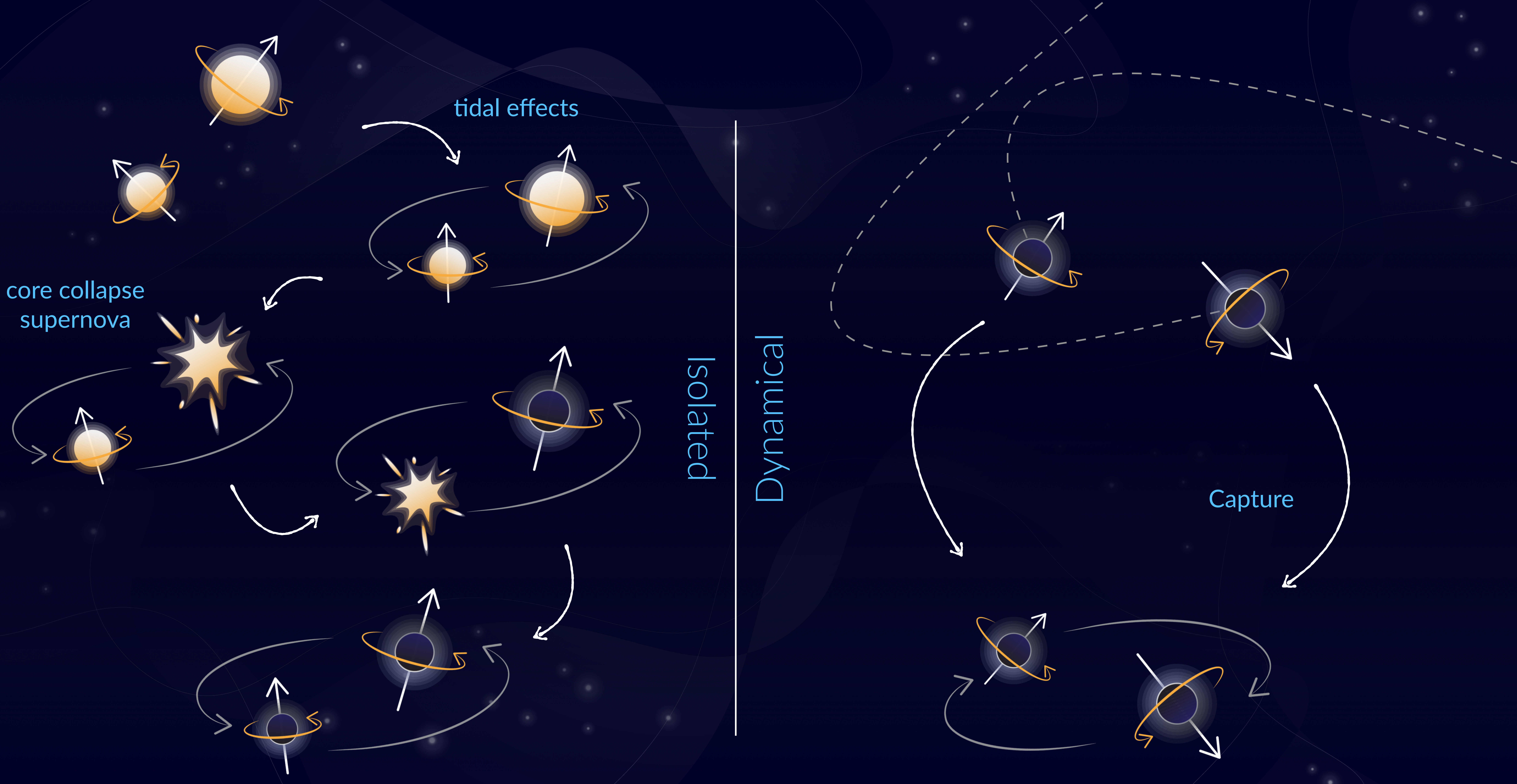


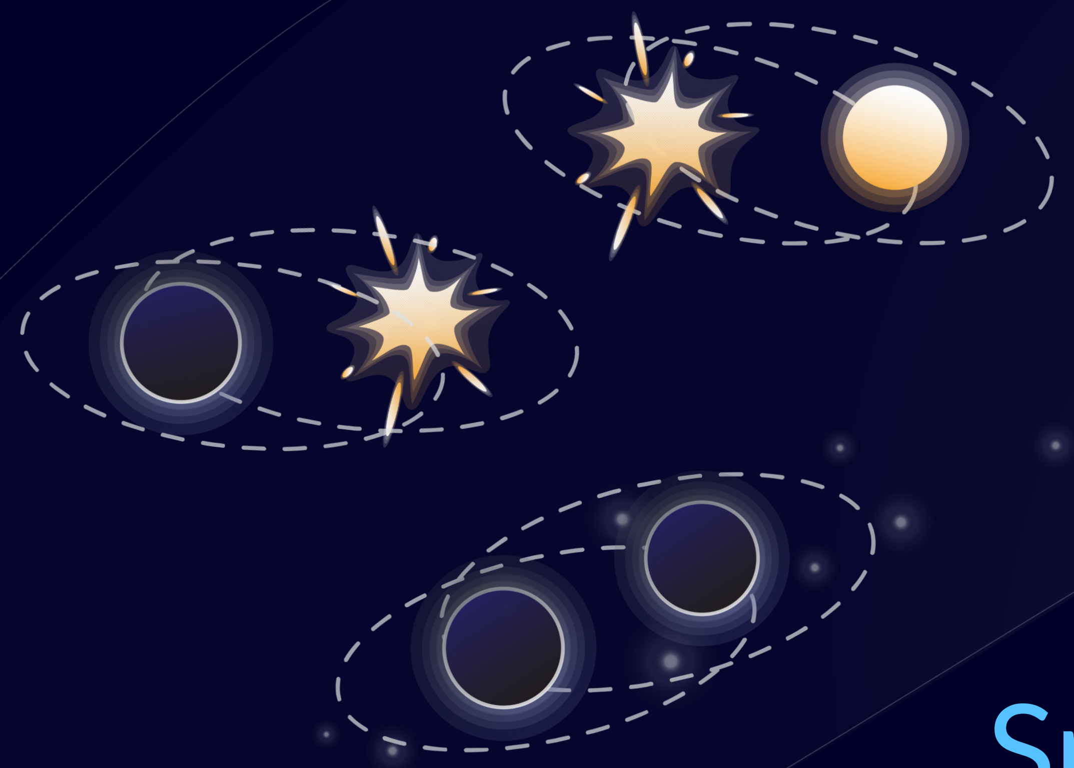
Data-driven models

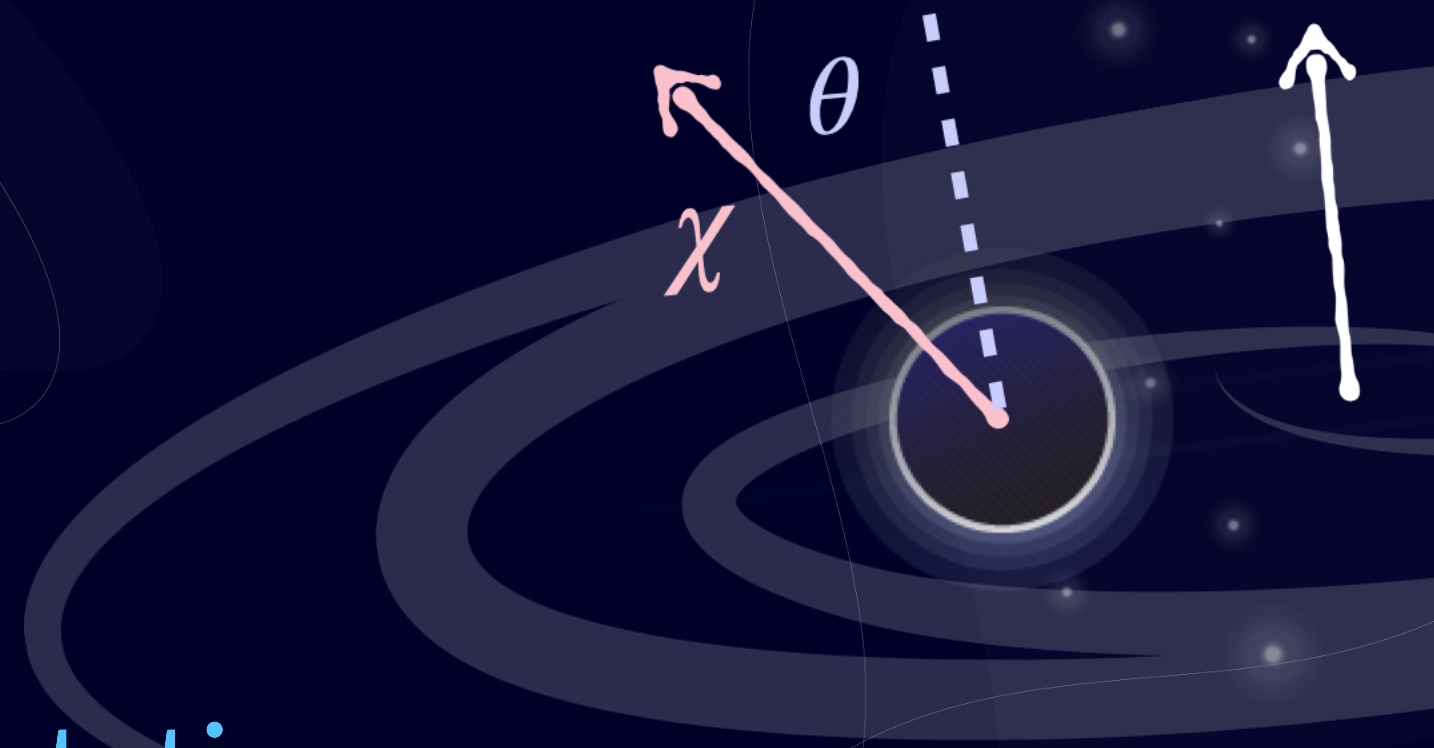
- Very flexible, designed to fit the data, with minimal assumptions.
- More challenging to do model comparison.
- Caution with overfitting, may not be able to capture sharp features.

Astrophysically-motivated models

- Less flexible, designed to probe predictions from astrophysical theory/observations.
- Easy astrophysical interpretations.
- May miss features that we have not thought of!


tidal effects
core collapse supernova
Isolated
Dynamical
Capture

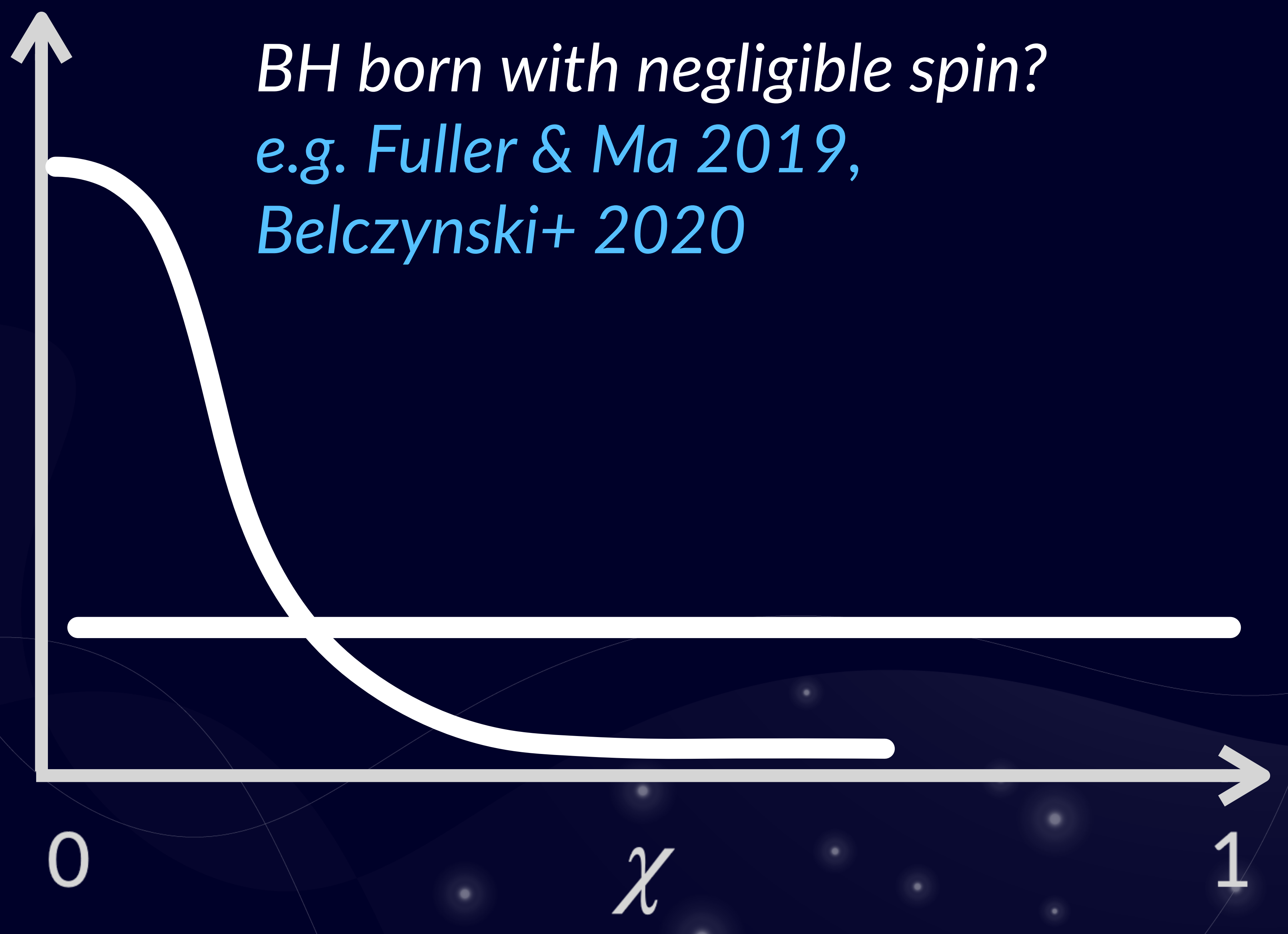




Isolated formation

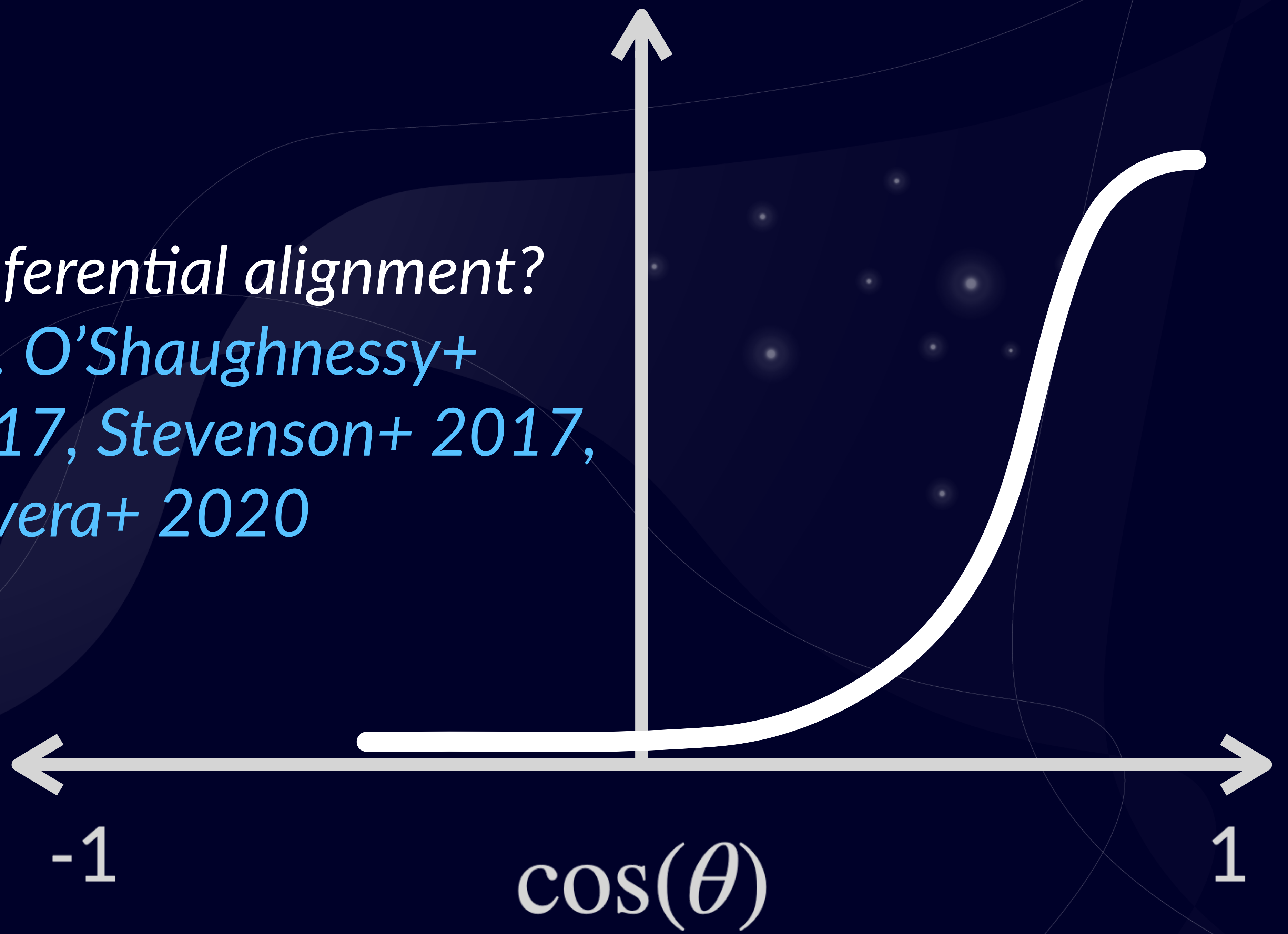
Spin magnitude

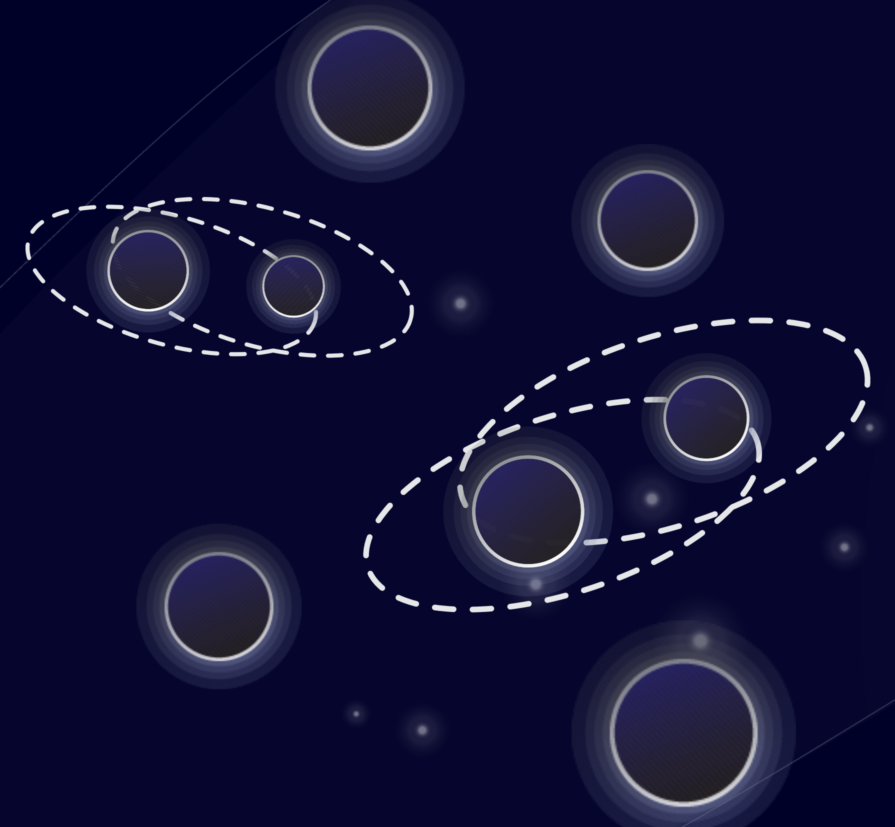
BH born with negligible spin?
e.g. Fuller & Ma 2019, Belczynski+ 2020



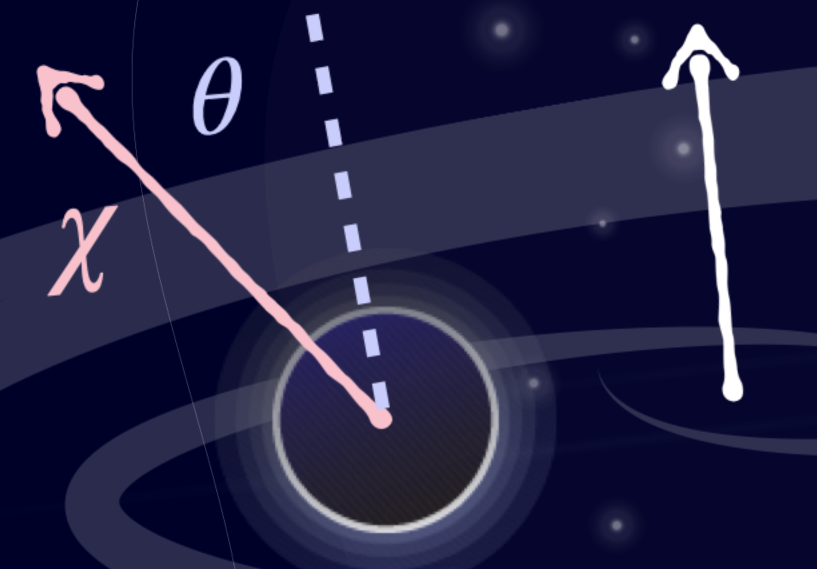
Spin orientation

Preferential alignment?
e.g. O'Shaughnessy+ 2017, Stevenson+ 2017, Bavera+ 2020





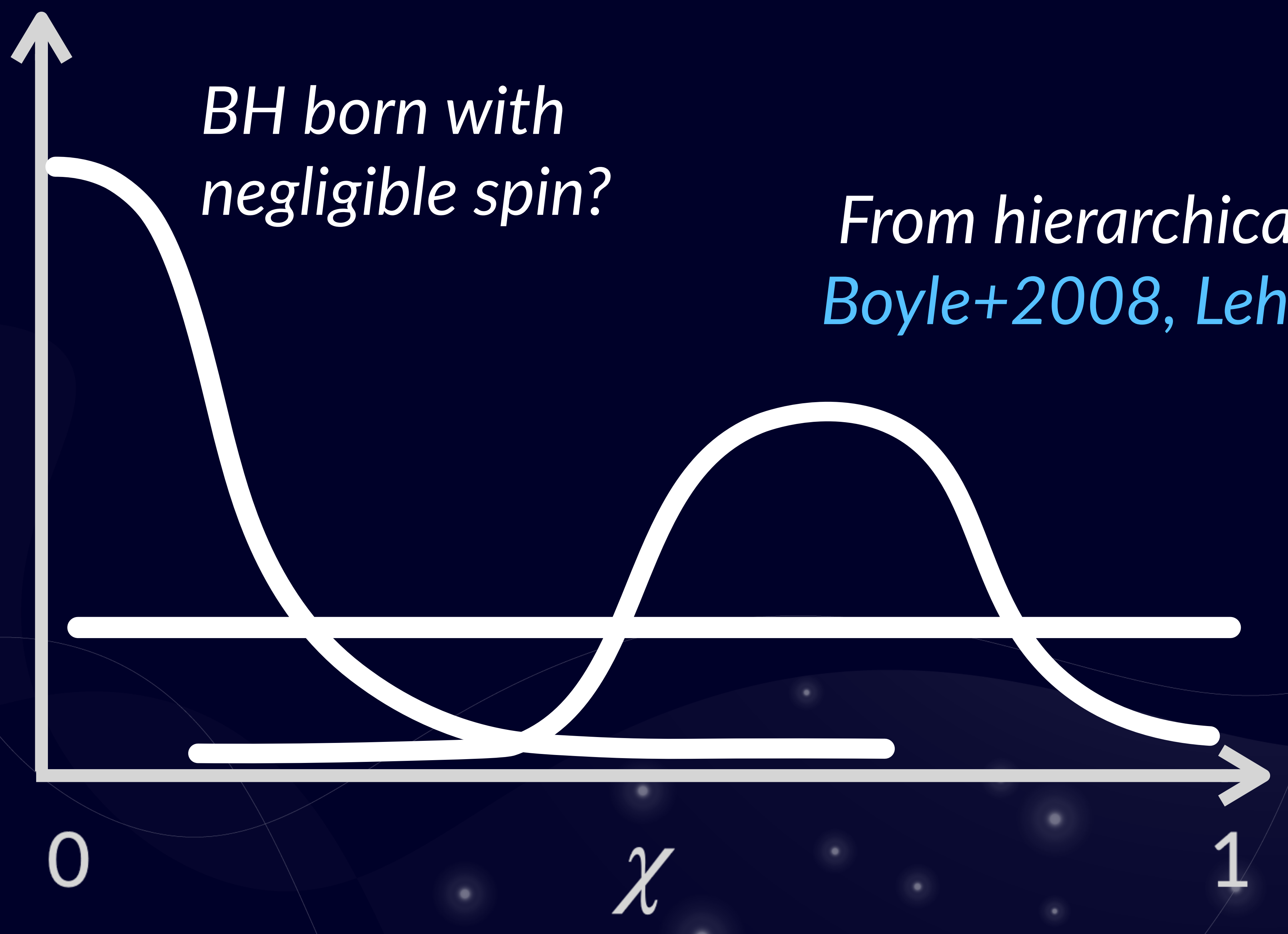
Dynamical assembly



Spin magnitude

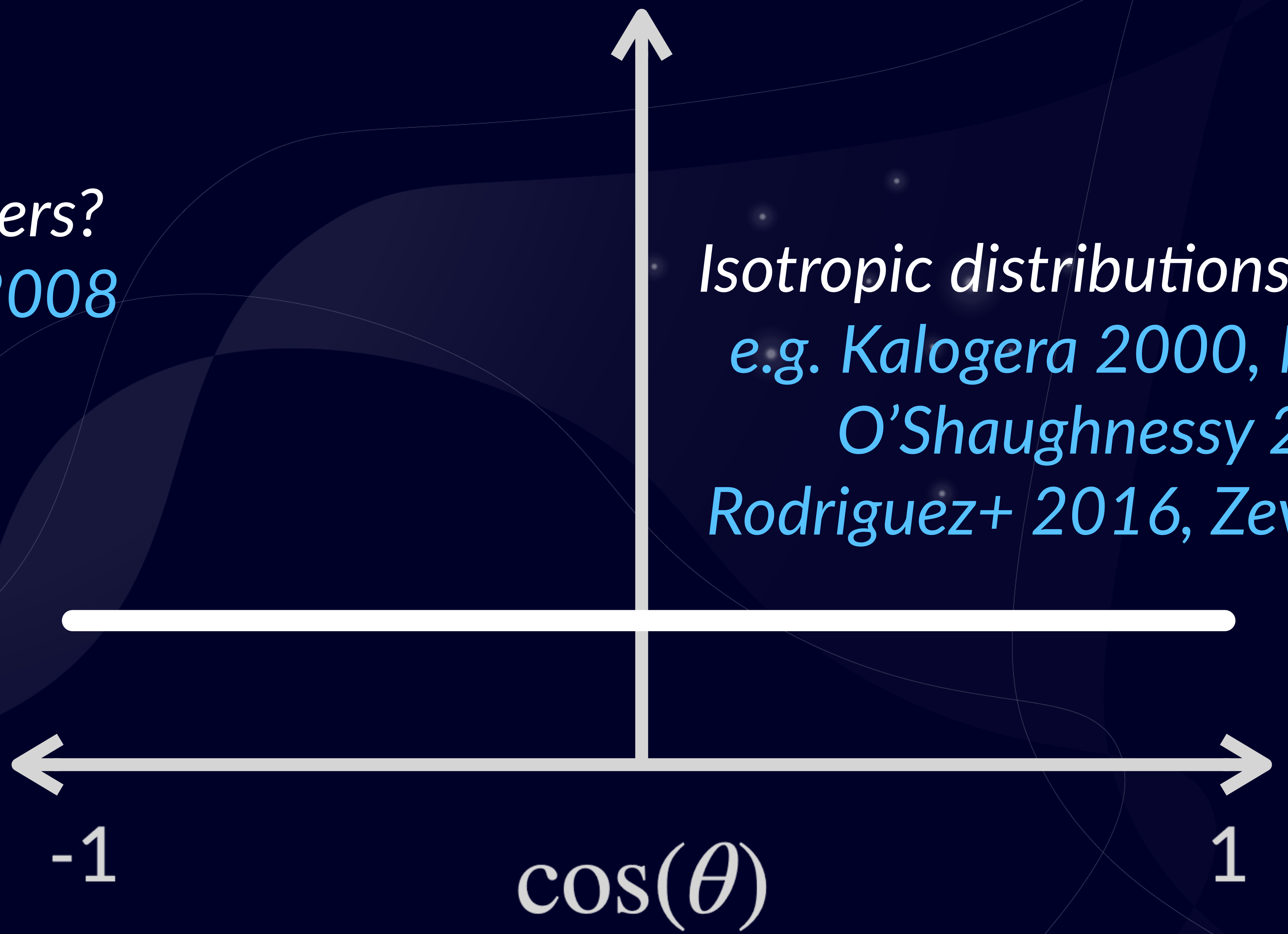
BH born with negligible spin?

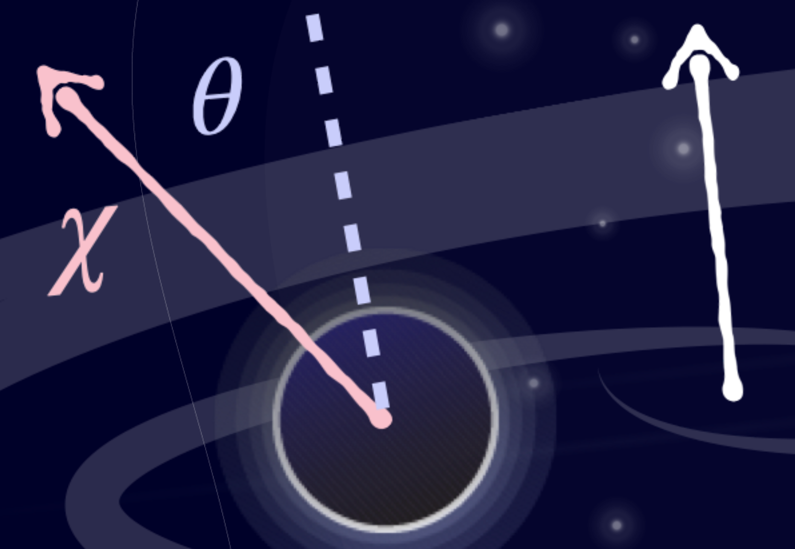
From hierarchical mergers?
Boyle+2008, Lehner+ 2008



Spin orientation

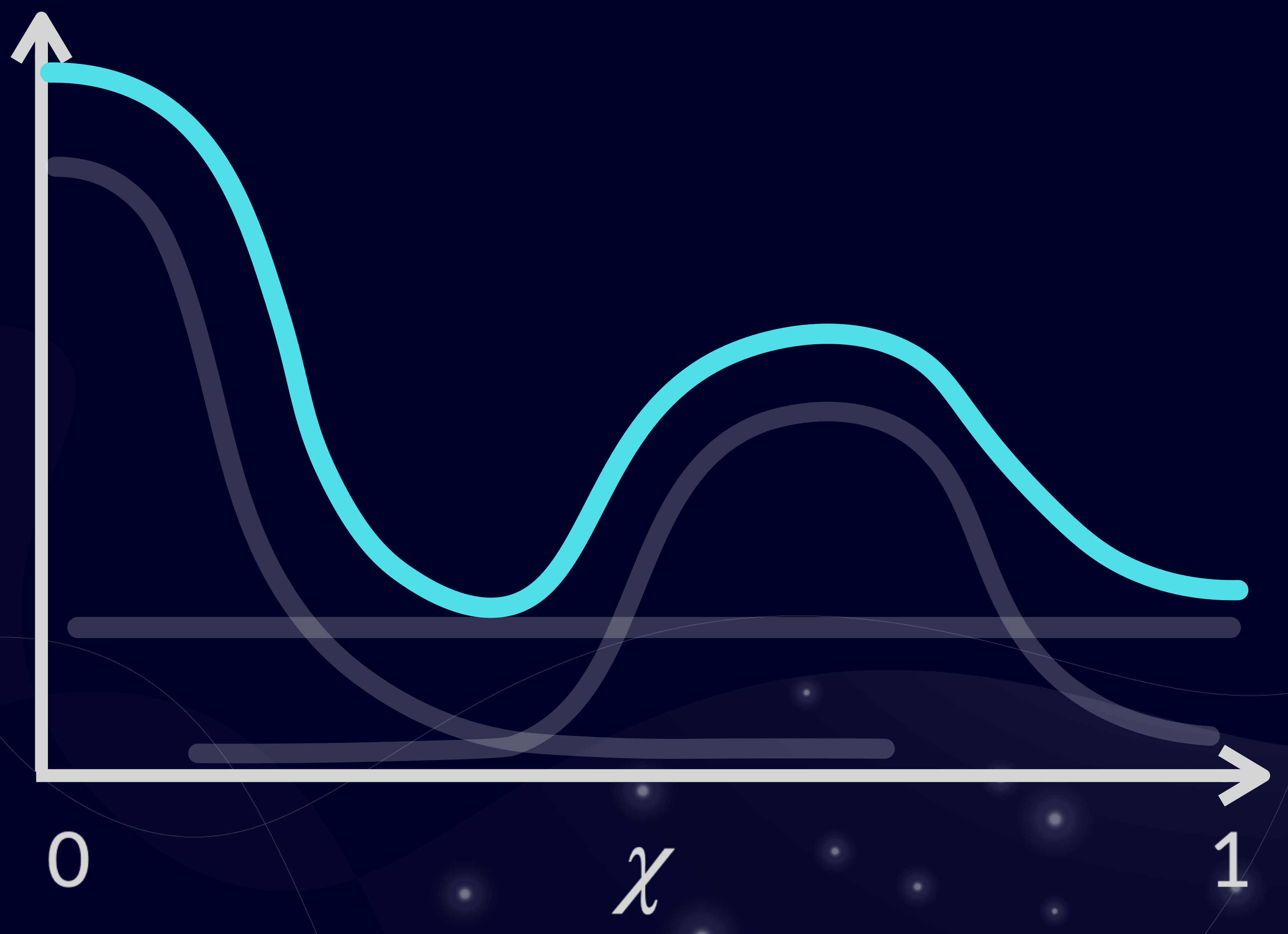
Isotropic distributions in spin tilt
e.g. Kalogera 2000, Mandel & O'Shaughnessy 2010, Rodriguez+ 2016, Zevin+ 2017



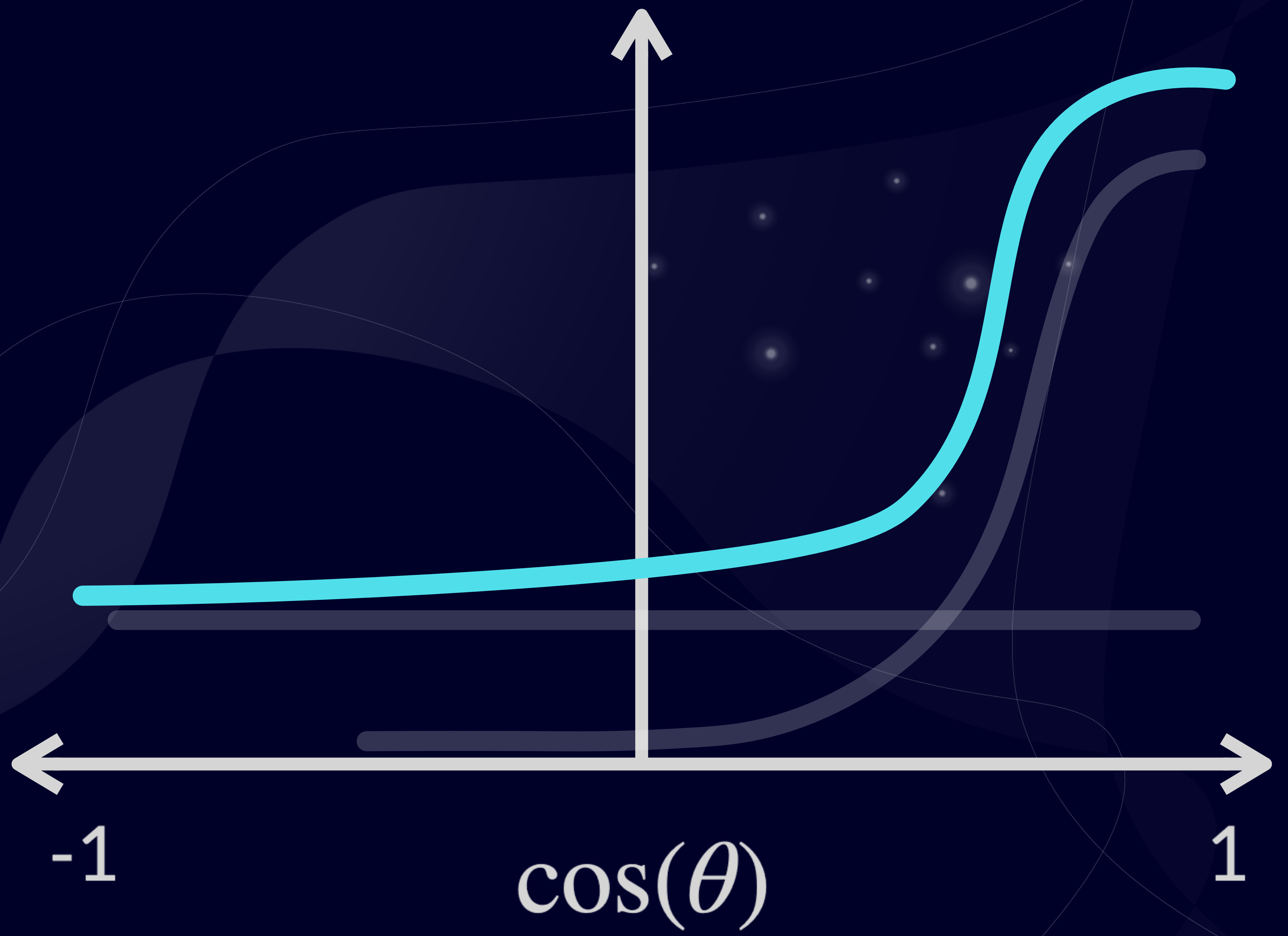


Isolated + Dynamical

Spin magnitude

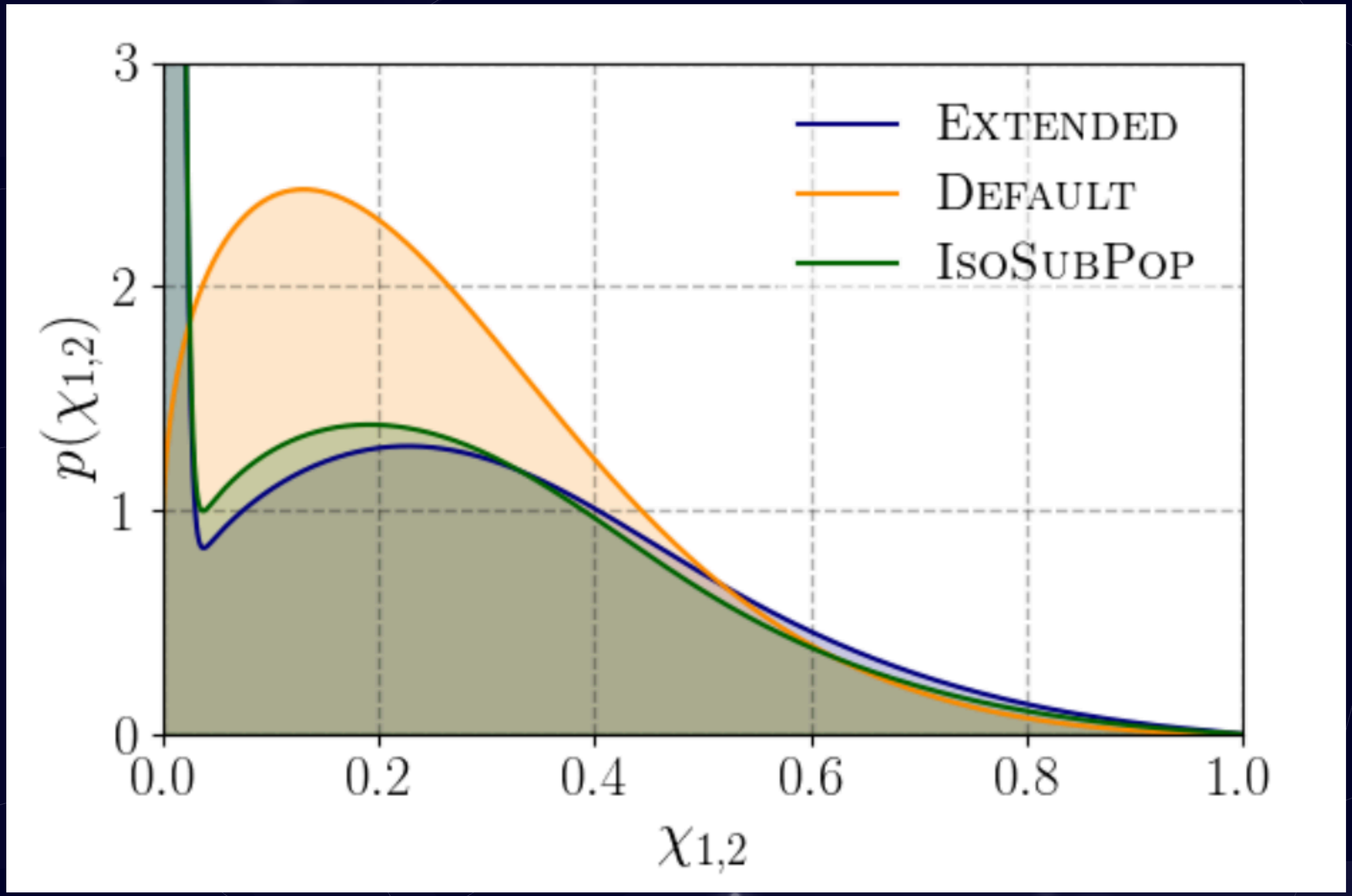


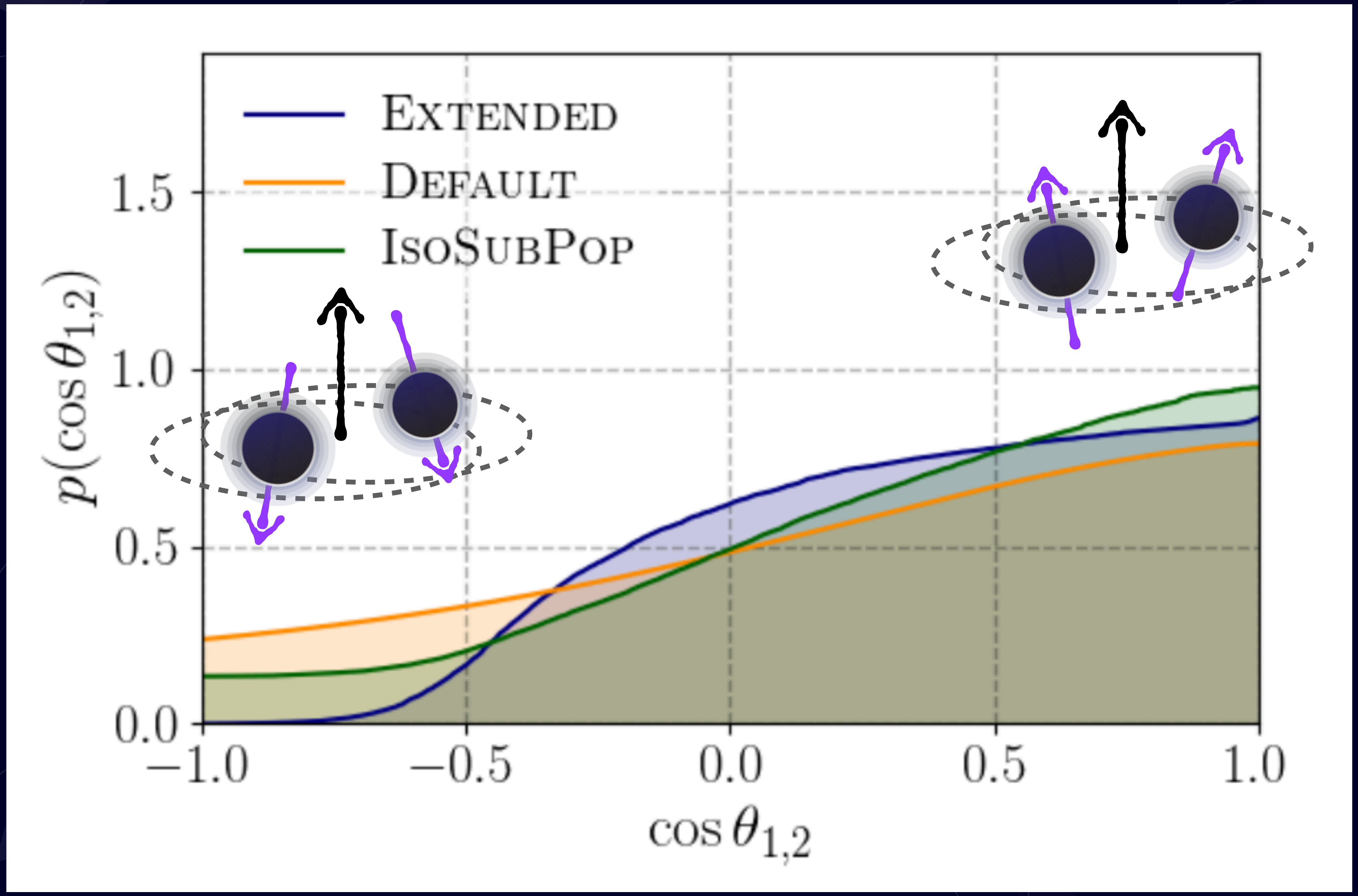
Spin orientation



Spin distributions: GWTC-3

Tong, Galaudage & Thrane arXiv:2209.02206 (GWTC-3 results; model from Galaudage+ arXiv:2109.02424)



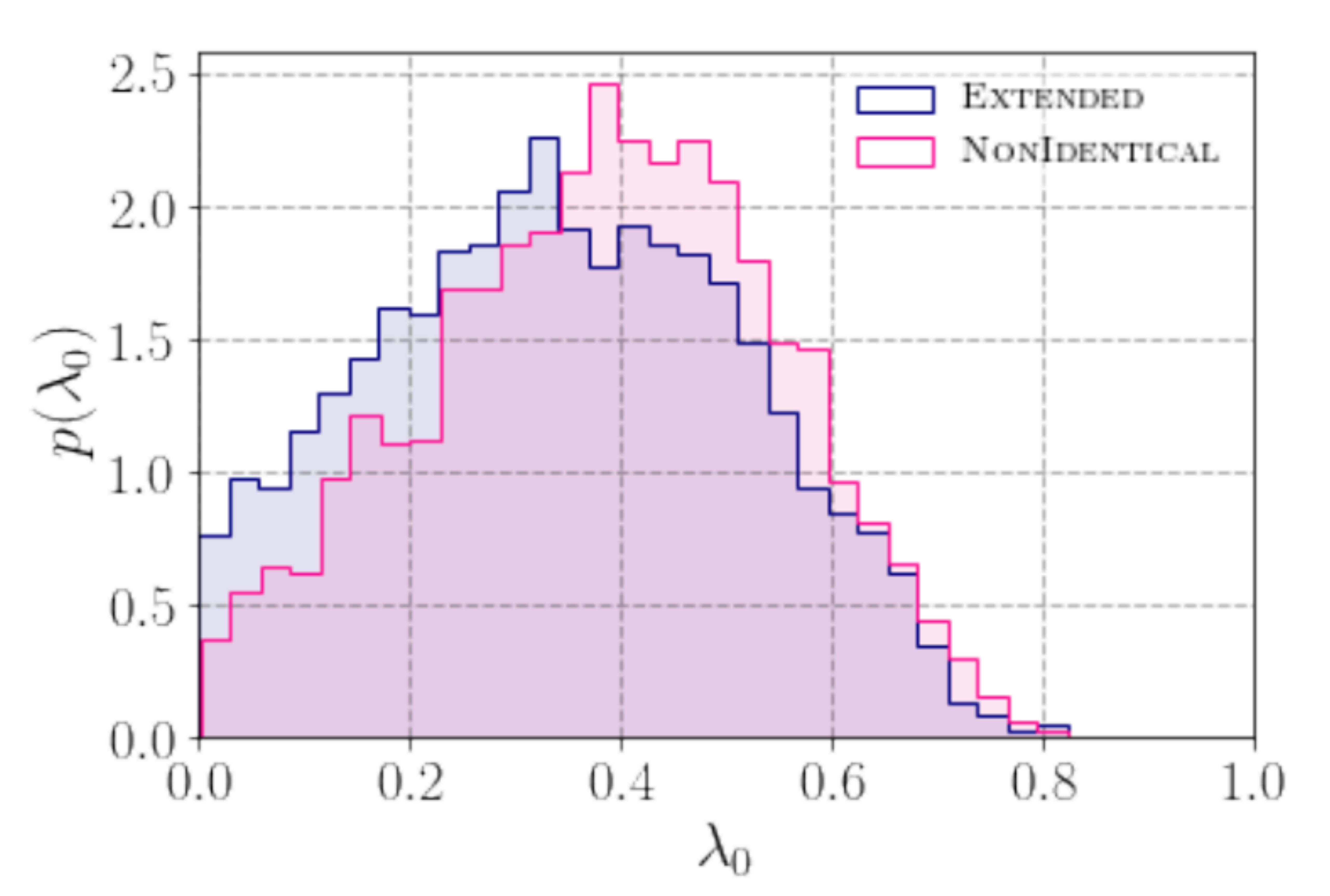


Spin magnitude distribution (left) spin orientation distribution (right)
Solid curve - mean; Shaded region - 90% credible interval

Our conclusions on spin-misalignment are model dependent!

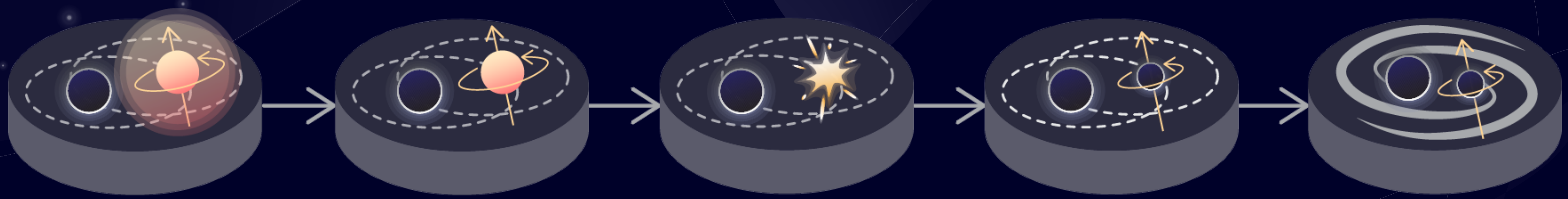
Are there non-spinning black holes?

- Around 40% of binary black holes could be non-spinning.
- Support at zero; no clear evidence for non-spinning subpopulation.
- Around 20% definitely spinning.

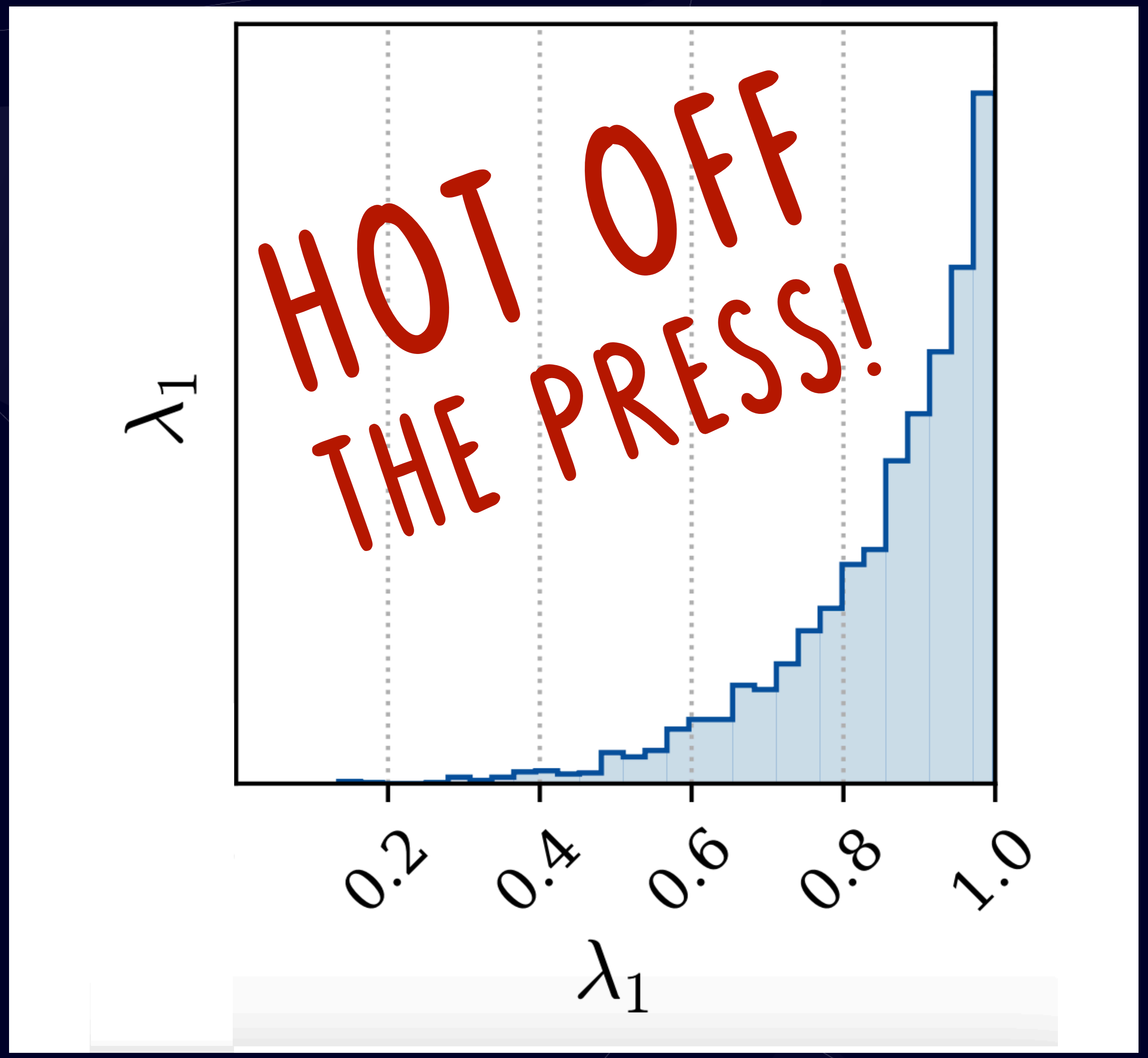


Tong, Galaudage & Thrane arXiv:2209.02206

What if only *one* black hole is spinning?



- We consider the case where only one BH spins from tidal spin up of **second born** BH (e.g. Ma & Fuller 2023; Hu et al. 2022; Qin et al. 2018)
- At least 28% of the BBH contain a primary with significant spin, possibly indicative of mass-ratio reversal. No evidence of secondary spin.



Adamcewicz, Galaudage, Lasky & Thrane arXiv:2311.05182

What do we *actually* know about spin?

- **Possible** non-spinning subpopulation (see also Callister+ 2022, Mould+ 2022)
- BHs **are not** maximally spinning.
- **Possible** that all BBH form via isolated channel (if you only consider spin!)

We need to consider **correlations**, measure **eccentricity** and perform **detailed population synthesis studies** to narrow down formation scenarios.

Stellar graveyard: The BNS

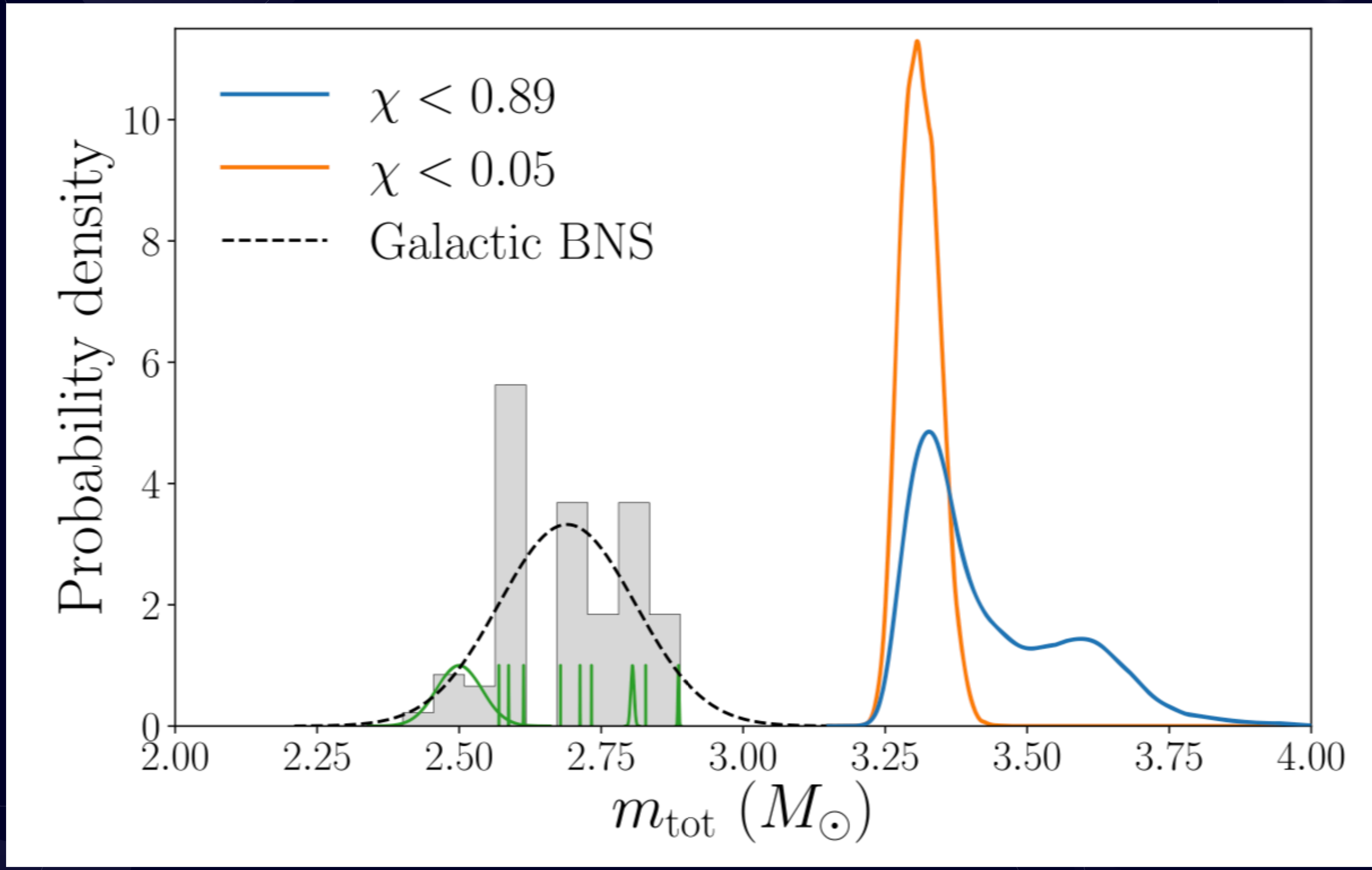
GWTC-3 =

O1 + O2 + O3a + O3b

Understanding the BNS population

- GW190425, most massive BNS
- Why are there no heavy BNS in the Galactic population?
- GW190425; found to be an outlier in LVK analysis.
- Total mass $\sim 3.4 M_{\odot}$, 5σ away from Galactic population.

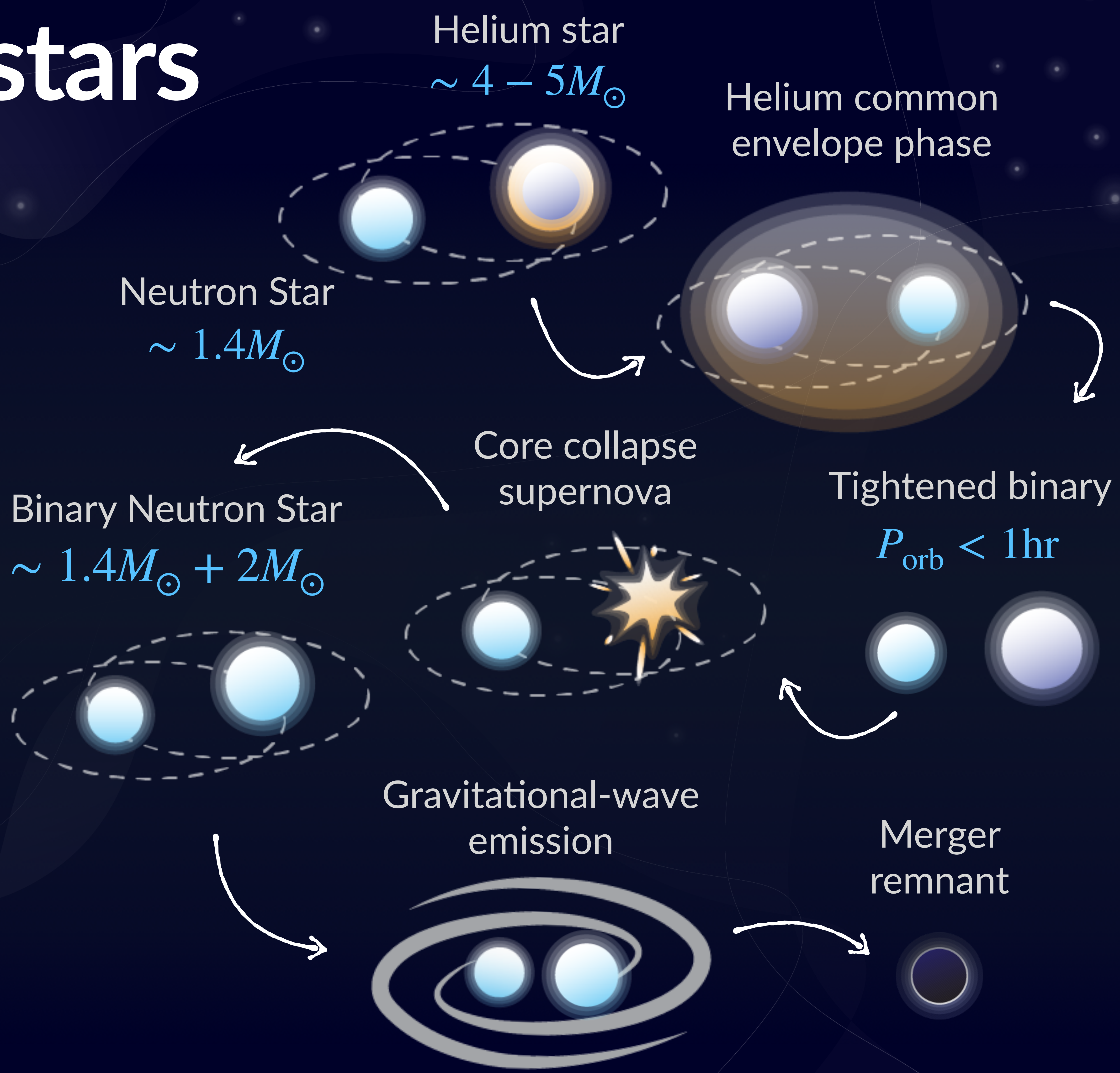
What connects the GW and radio-visible populations? The birth population!



LVK collaboration arXiv:2001.01761

Forming binary neutron stars

- Standard formation scenario BNS: first-born **recycled** neutron star sped up from accretion and second-born **slow** neutron star.
- Possible explanations for heavy BNS not observed in radio:
  - Fast-merging via unstable case BB mass transfer; (Romero-Shaw+ 2020)
  - Invisible due to buried magnetic field (Safarzedah+ 2020)



Population of DNS at birth

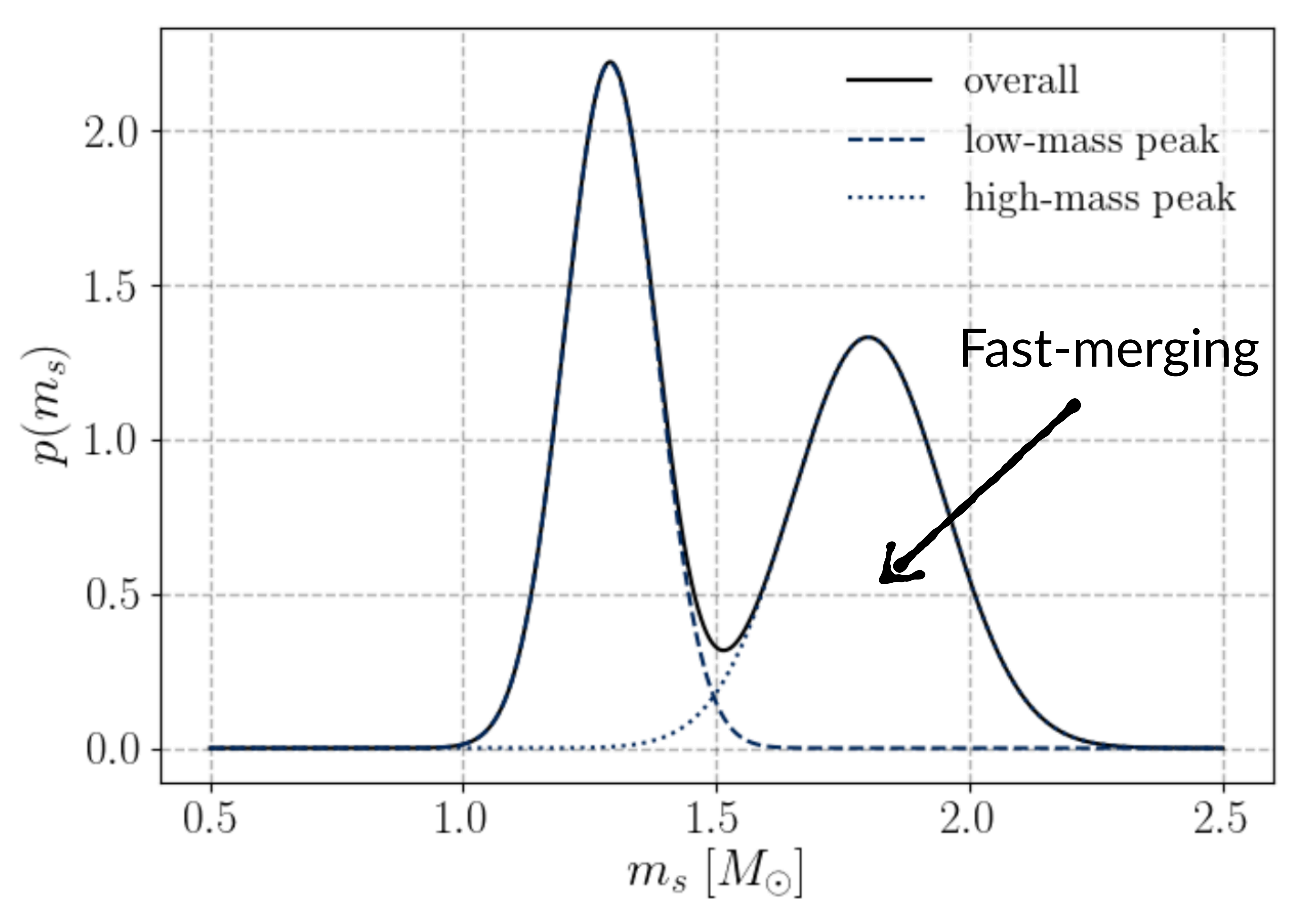
Mass distribution:

- Double Gaussian for **recycled** NS distribution (Farrow+ 2019)
- For **slow,** we consider a double Gaussian where high-mass peak is motivated by fast-merging DNS.

Formation rate densities:

- Milky Way: Uniform over cosmic time.
- Extra-galactic: Madau-Dickinson

Galaudage+ arXiv:2011.01495



The radio and GW BNS are from two different environments.

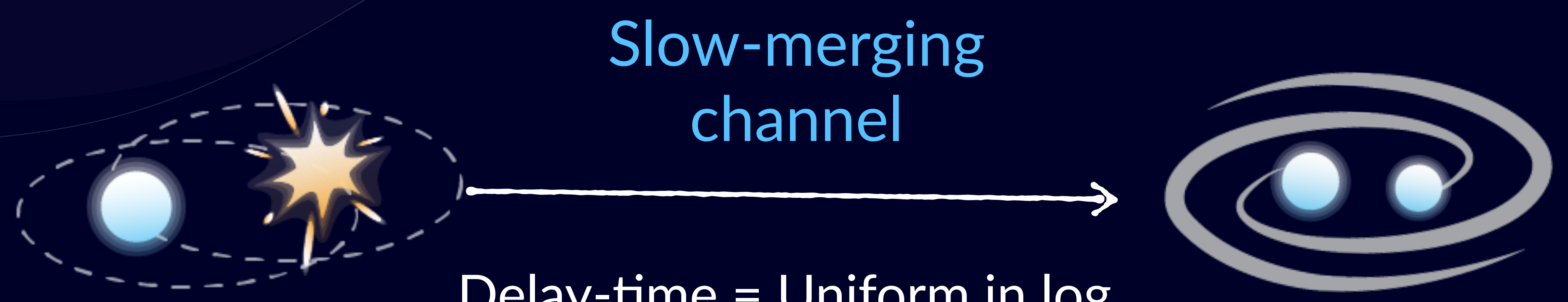
Population at death (GWs)

- Using the BNS formation rate density and delay-time distribution we can calculate the merger rate density.

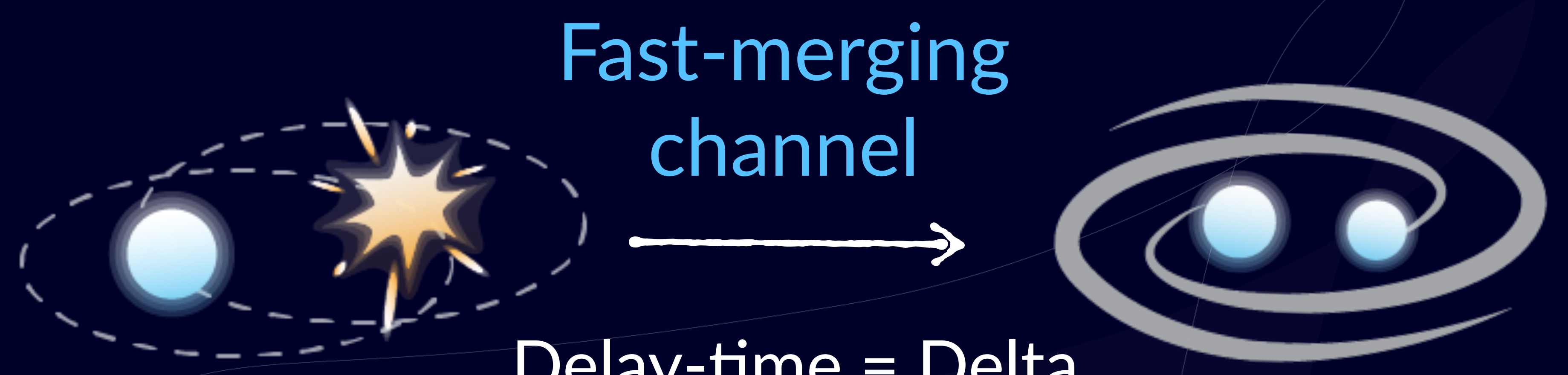
$$R_m(t) = \int_0^t dt_b R_b\left(t_b\right) \pi\left(t - t_b\right)$$

Delay time distributions

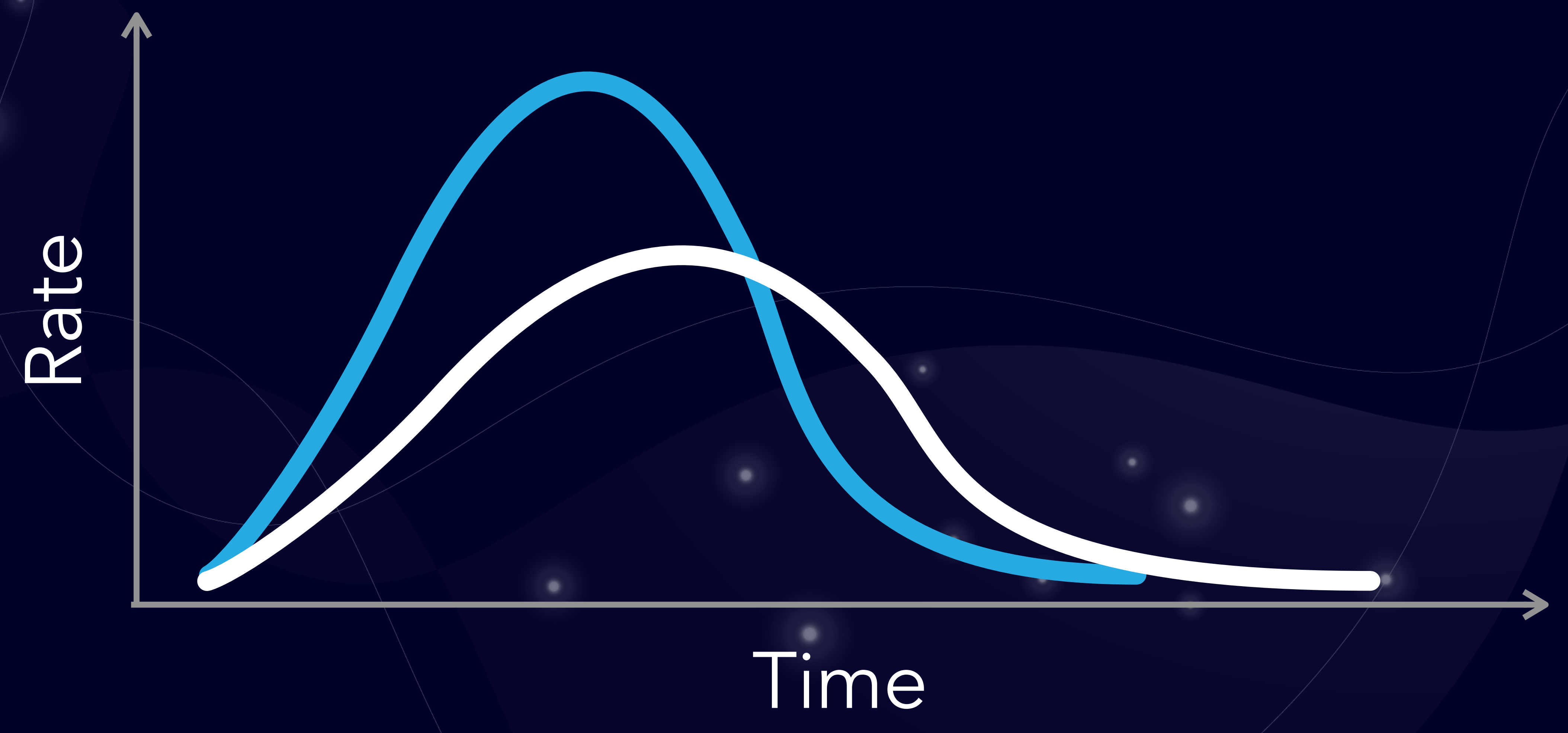
Time taken from formation to merger differs for the two channels.

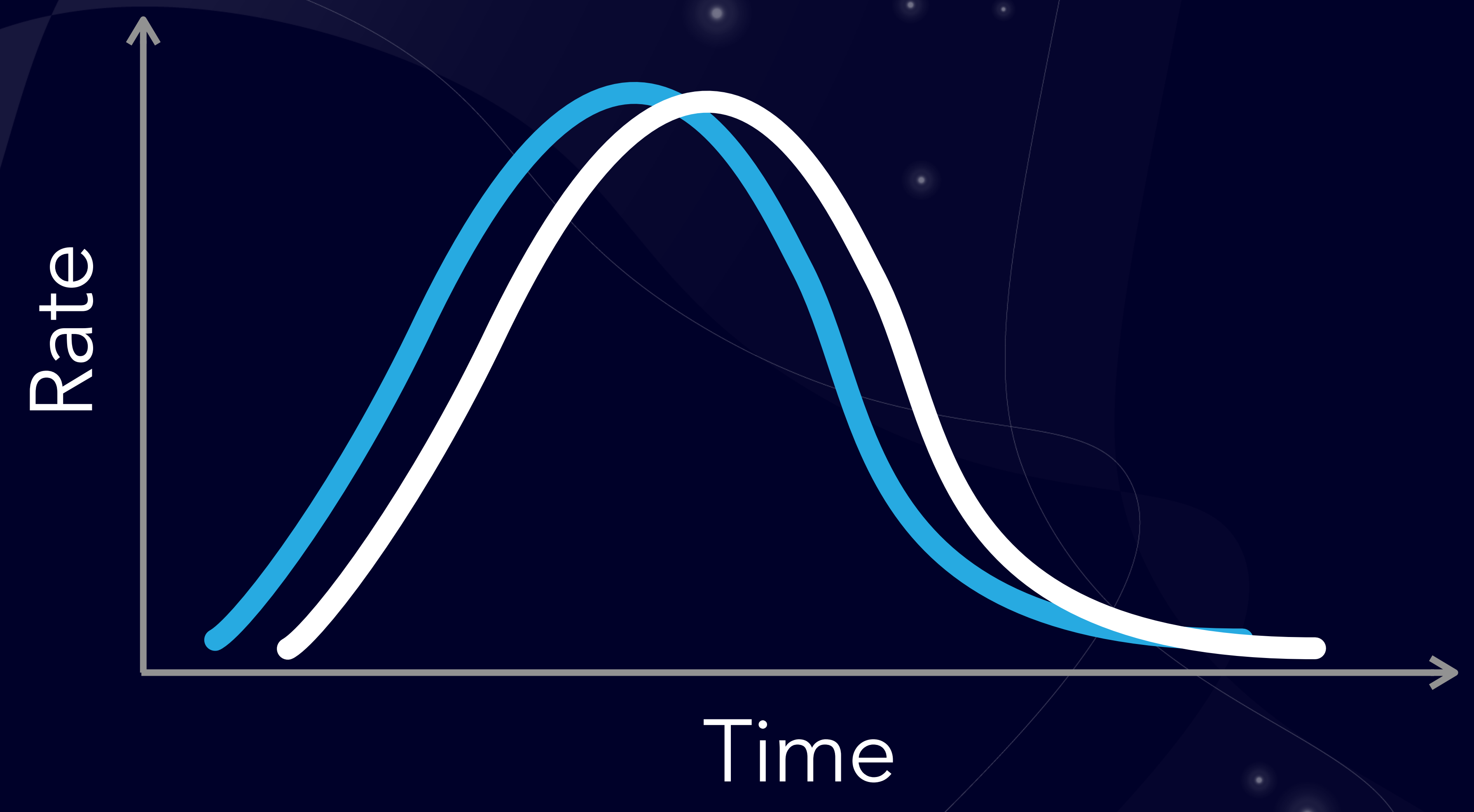


Delay-time = Uniform in log, 30 Myr to age of Milky Way



Delay-time = Delta function at 10 Myr





Population at mid-life (radio)

- Radio population is determined from the birth and merger rate densities. The fraction of binaries visible due to beaming is about 10%.

$$N_r(t) = \int_0^t dt' \left(R_b(t') - R_m(t')\right) \epsilon(t')$$

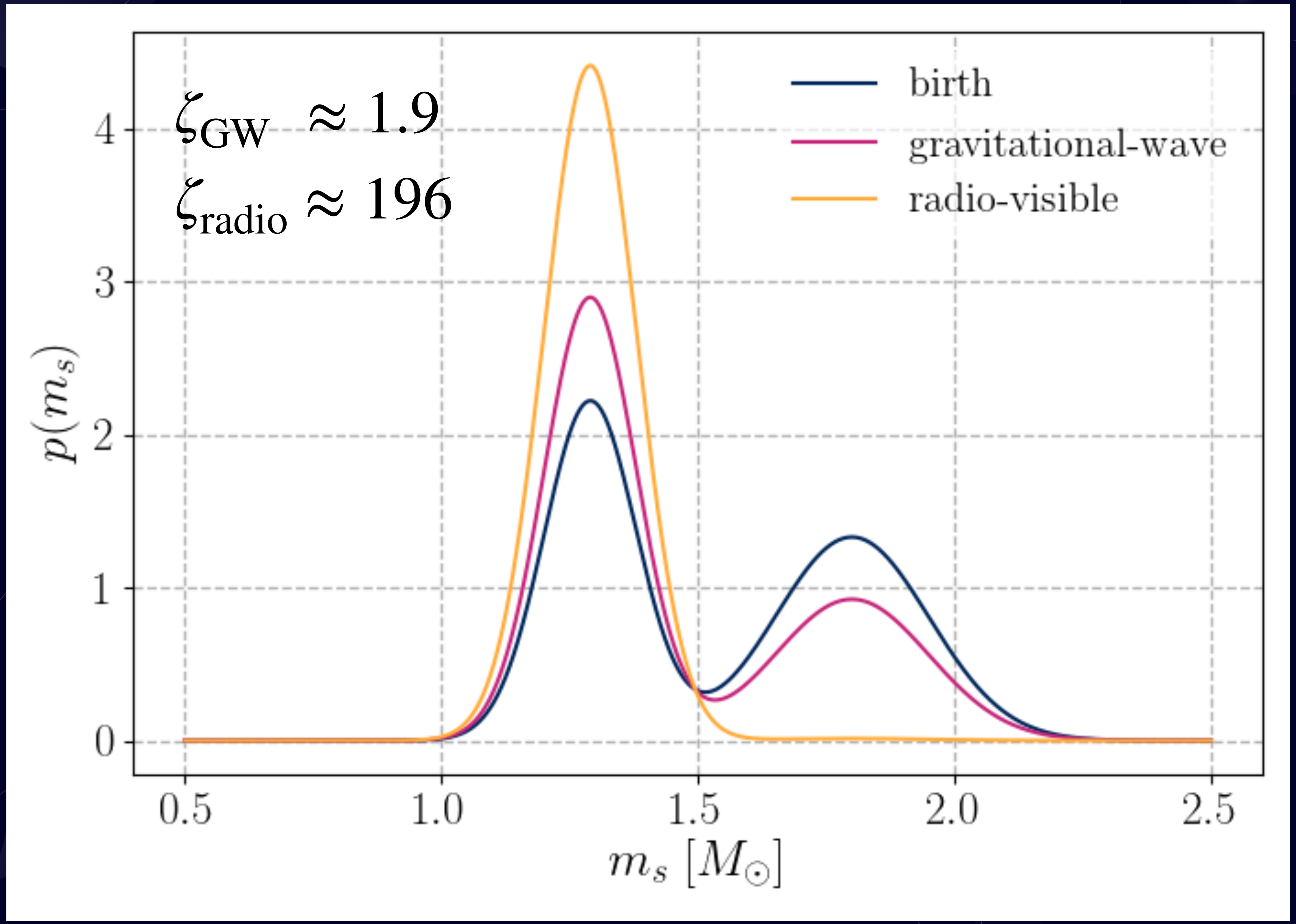
Population at mid-life and death

- We can calculate the **merger rate density** and the **number of radio binaries** for our two channels: fast/slow-merging BNS
- Calculate ratio between the two channels

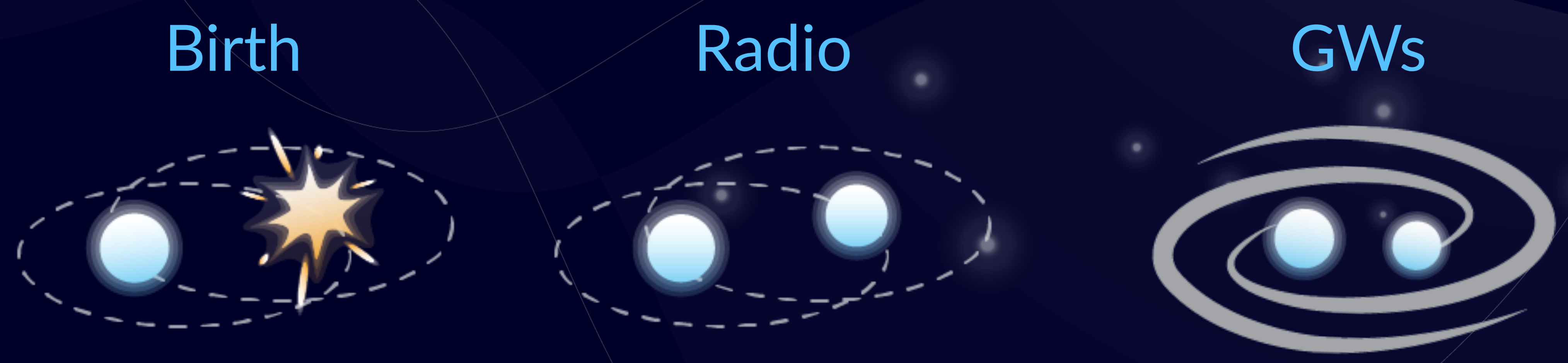
$$\zeta_{\mathrm{GW}} = R_m(\mathrm{slow})/R_m(\mathrm{fast})$$

$$\zeta_{\mathrm{radio}} = N_r(\mathrm{slow})/N_r(\mathrm{fast})$$

- The ζ parameter shows how the BNS distribution evolves.

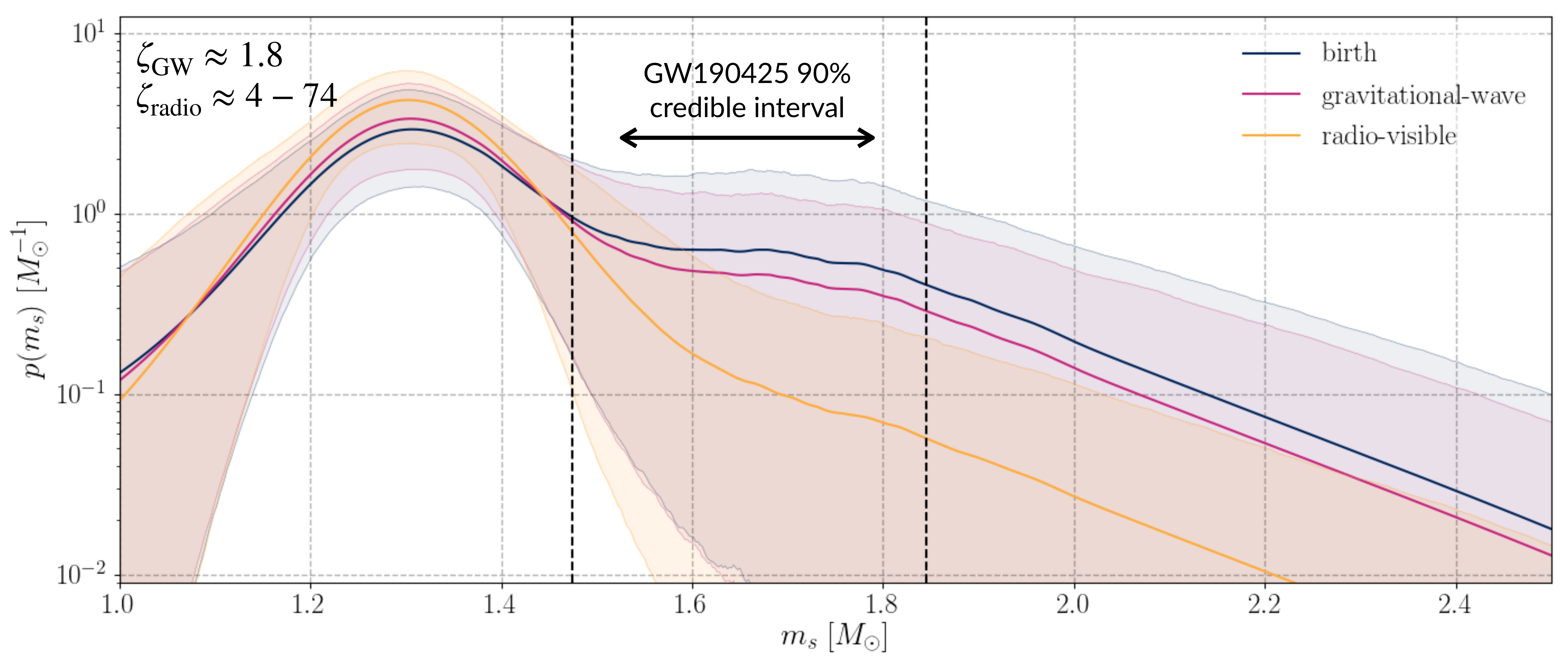


Galaudage+ arXiv:2011.01495



Population of binary neutron stars

Galaudage+ arXiv:2011.01495



Slow neutron mass distribution: Solid curve - mean; Shaded region - 90% credible interval

Birth population of DNS and GW190425

- Mild evidence to support the fast-merging channel hypothesis; GW190425 is not a clear outlier from the Galactic population; consist with findings in population synthesis studies (Kruckow 2020, Mandel+ 2021)

- If we assume this hypothesis is correct:
  - 8-79% of BNS born are fast-merging
  - Typical fast-merging delay-time is 5-401 Myr

- Implications & areas to explore: r-process enrichment in globular clusters/ultra-faint dwarf galaxies and short gamma-ray burst host galaxy offset observations.

Summary

- So far we have 90+ BBH; already uncovering some general trends: black hole spins of merging systems not maximal; no clear evidence for extreme anti-alignment; possible non-spinning subpopulation.
- Heavy BNS may be explained via fast-merging hypothesis. Also important to consider recycled/slow parameterisations vs primary/secondary (need more events to confirm — let's hope for more BNS in O4!)
- #O4IsHere with 63 events as of this morning! Follow along on gracedb: https://gracedb.ligo.org/superevents/public/O4/

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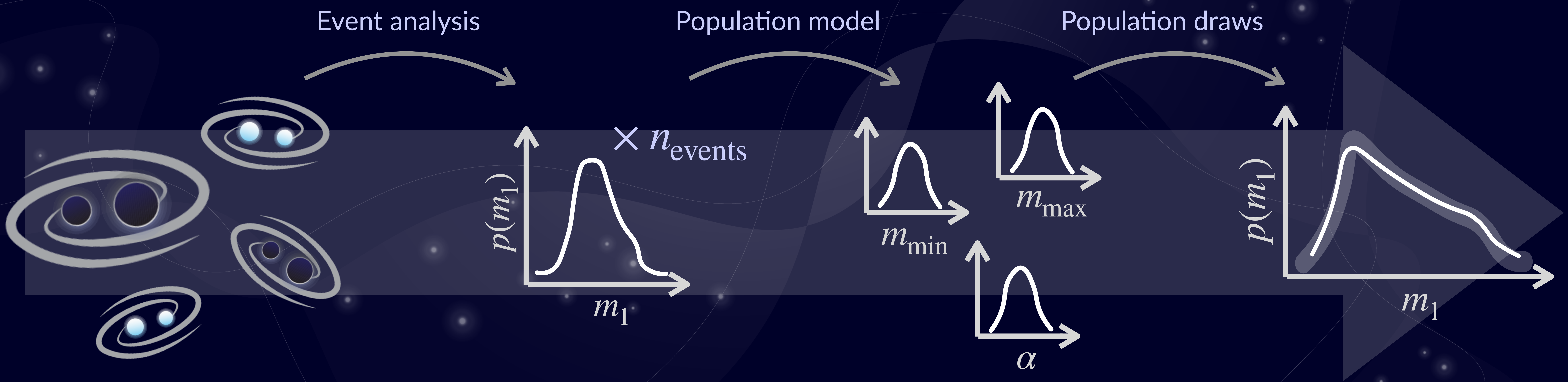
Population inference

- 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)

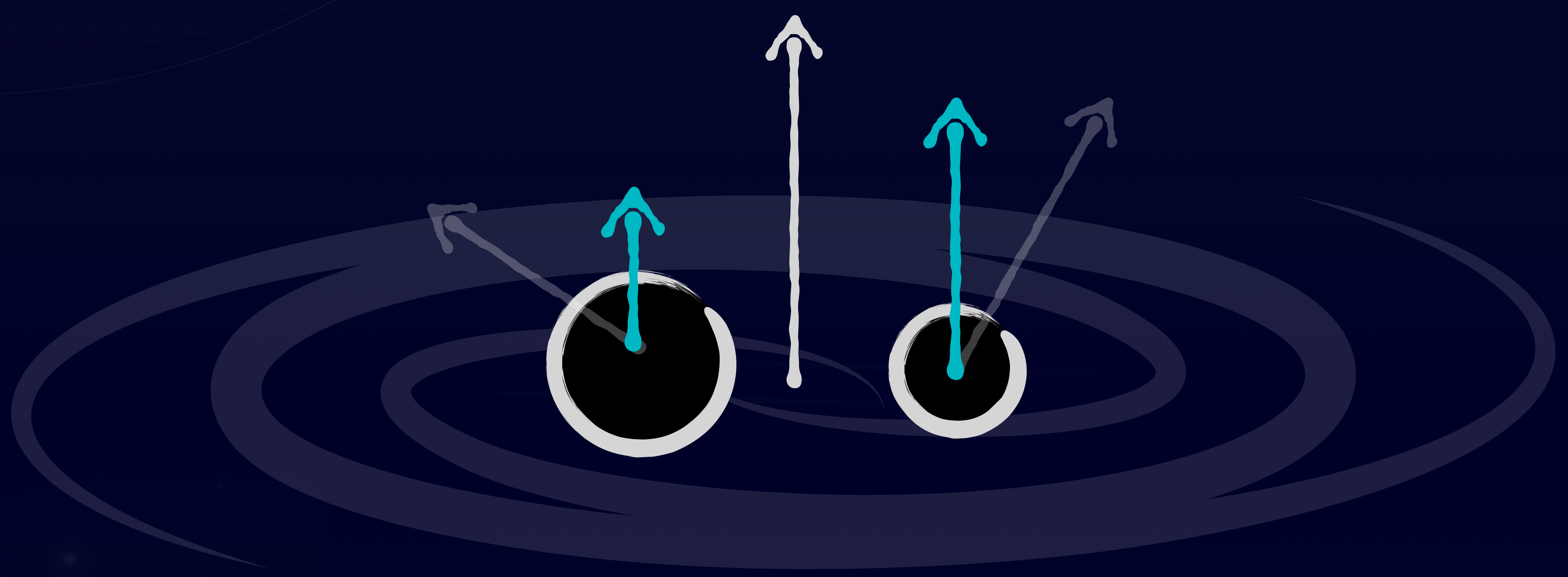


Spin parameters: physical quantities

Compact objects in a binary are sorted by mass; see Biscoveanu+ 2021 (arXiv:2007.09156) for work sorting by spin.

Spin parameters: effective spins

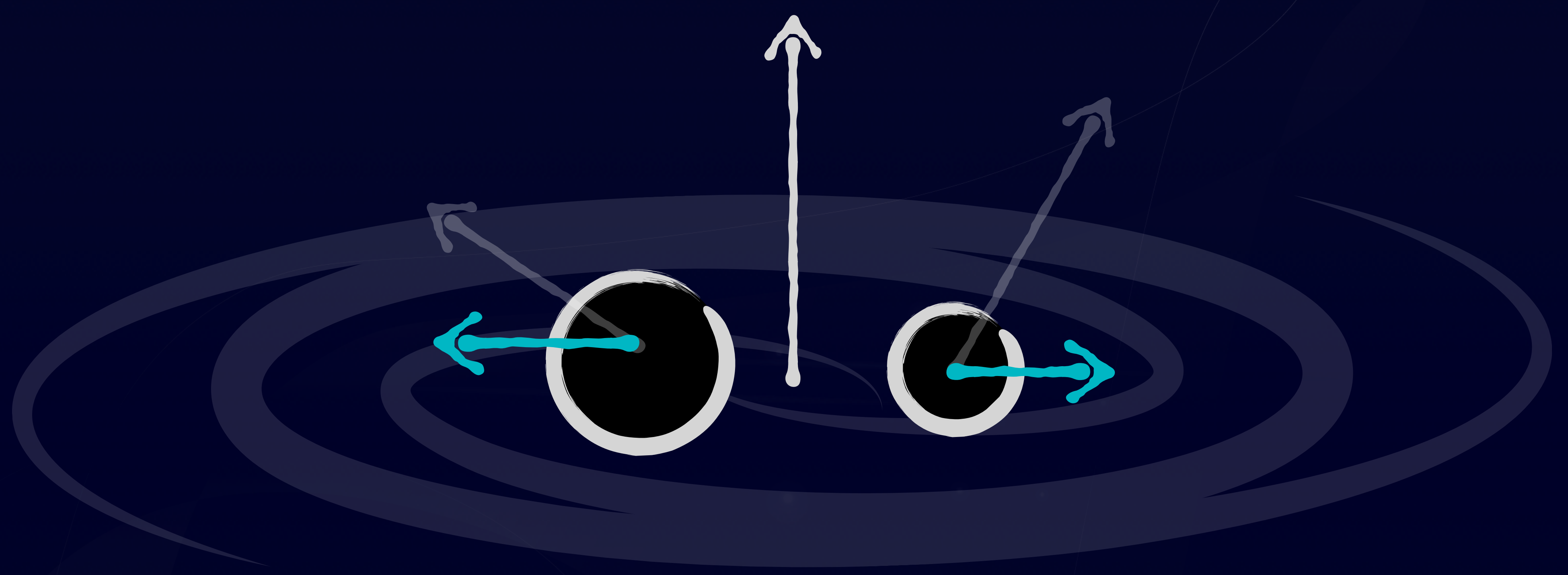
Effective inspiral spin parameter ($\chi_{\rm eff}$)



$$\chi_{\rm eff} = \frac{\chi_1 \cos(\theta_1) + q\chi_2 \cos(\theta_2)}{1+q}$$

Mass weighted spin projected along orbital angular momentum vector; conserved over evolution

Effective precession spin parameter (χ_p)

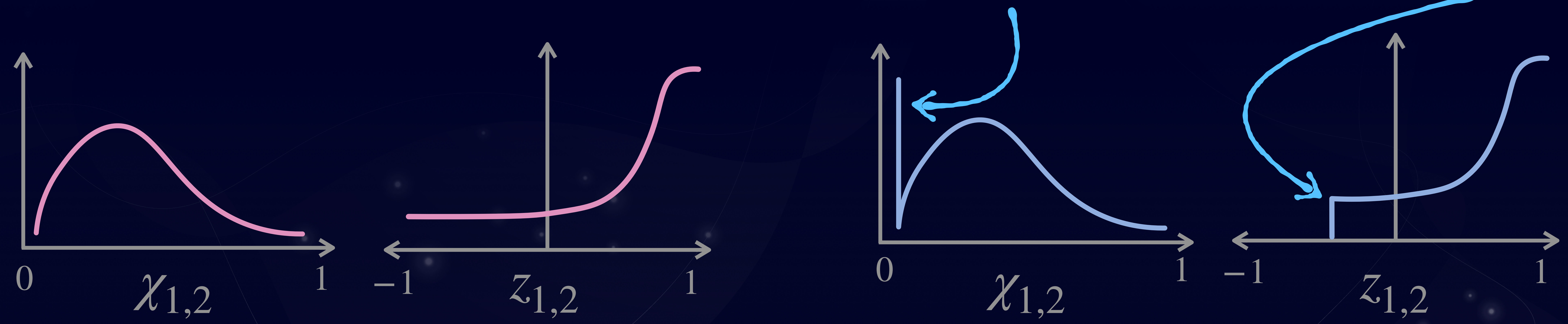


$$\chi_p = \max\left[\chi_1 \sin(\theta_1),\ \frac{4q+3}{3q+4} q\chi_2 \sin(\theta_2)\right]$$

Mass weighted spin projected in the plane of the binaries orbit; measure of orbital precession

Accounting for negligible spin

- Theoretical studies of angular momentum transport show that BHs are born rotating slowly (Fuller & Ma 2019, Belczynski+ 2020).
- Update models to account for a subpopulation of BHs motivated by the expectation of BBH with $\chi \sim 0$ (Galaudage+ 2021)
- New parameters: Fraction of BBH with $\chi \sim 0$ is λ_0 ; minimum spin tilt is z_{min}



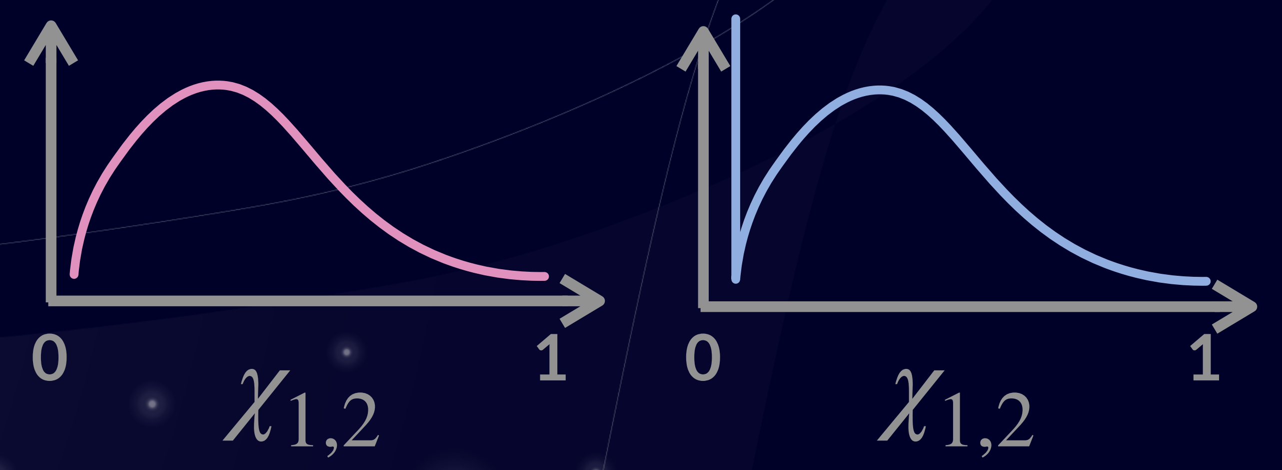
Population spin models: Default VS Extended

Spin magnitude model

$\mu = 0;\ \sigma = 0$

$$\pi(\chi_{1,2} \mid \alpha_\chi, \beta_\chi) = \mathrm{Beta}(\chi_{1,2} \mid \alpha_\chi, \beta_\chi)$$

$$\pi(\chi_{1,2} \mid \alpha_\chi, \beta_\chi, \lambda_0) = (1-\lambda_0)\mathrm{Beta}(\chi_{1,2} \mid \alpha_\chi, \beta_\chi) + \lambda_0 G_\mathrm{t}(\chi_{1,2})$$

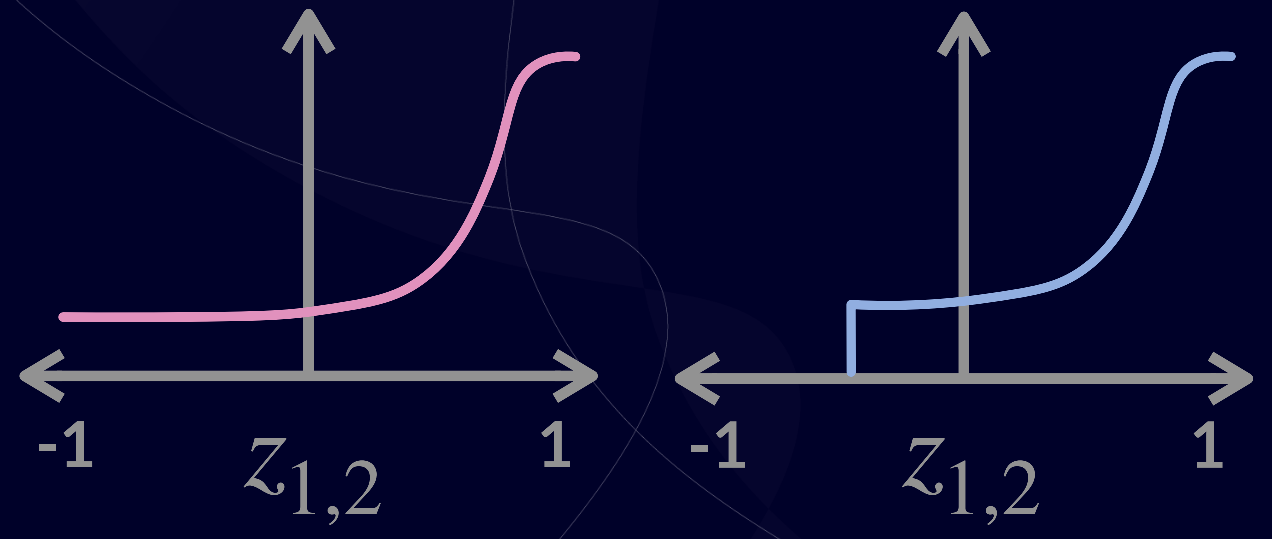


Spin orientation model

$z \equiv \cos(\theta)$

$$\pi(z_{1,2} \mid \zeta, \sigma_t) \propto \zeta G_t(z_{1,2} \mid \sigma_t) + (1-\zeta)\mathfrak{I}(z_{1,2})$$

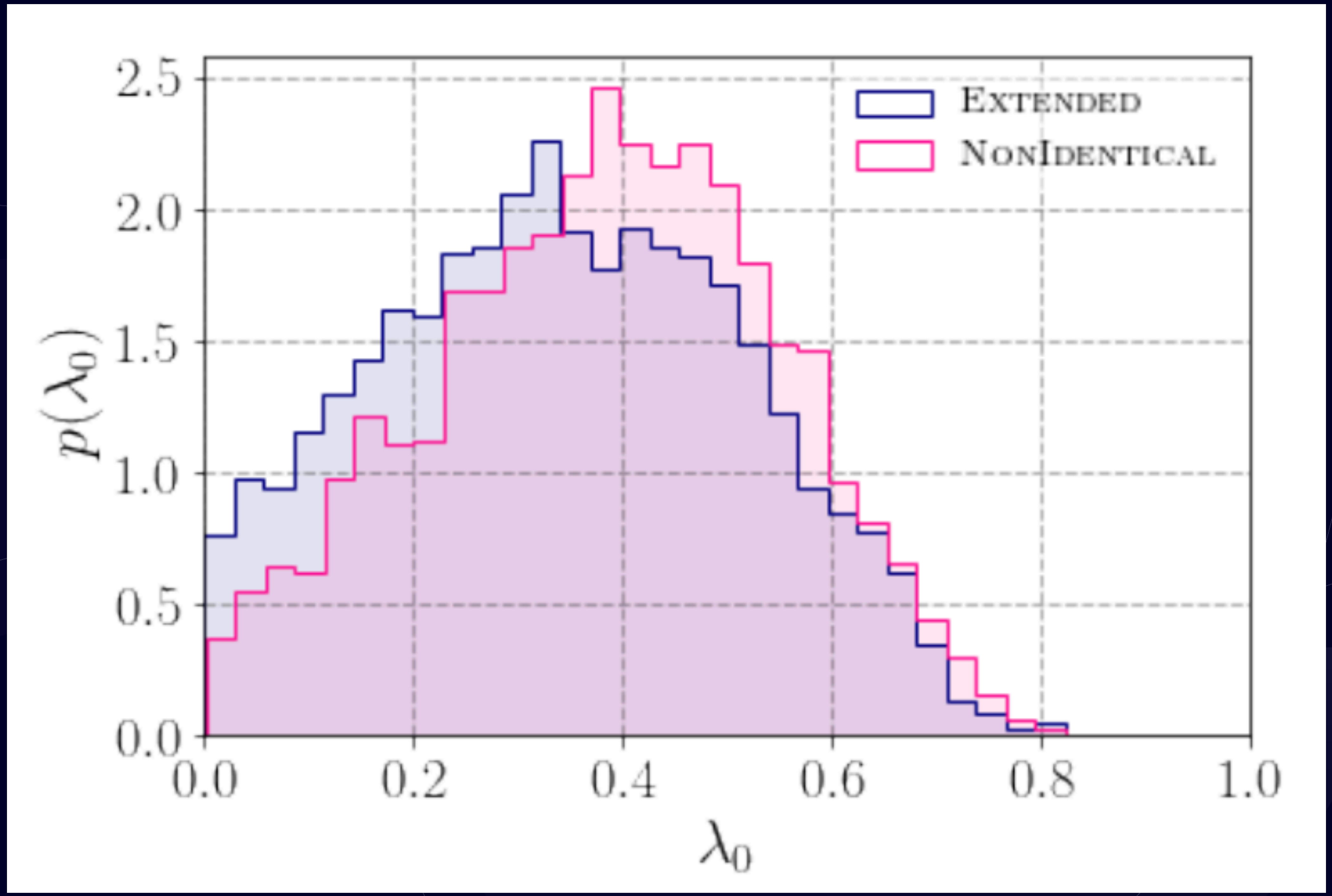
$$\pi(z_{1,2} \mid \zeta, \sigma_t, z_\mathrm{min}) \propto (\zeta G_t(z_{1,2} \mid \sigma_t) + (1-\zeta)\mathfrak{I}(z_{1,2}))\Theta(z_{1,2} - z_\mathrm{min})$$

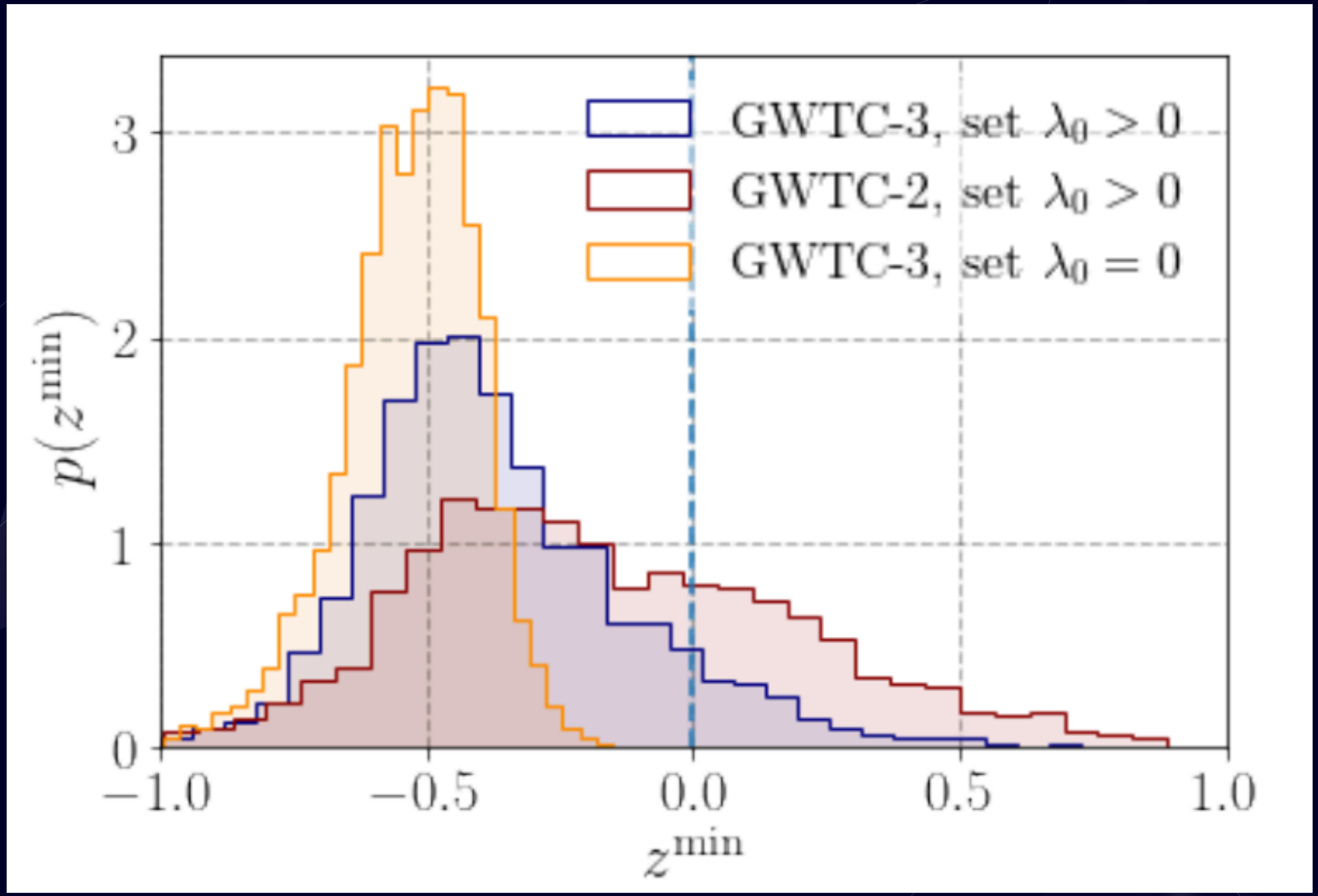


Updates following GWTC-3

- Support at $\lambda_0 = 0$; no clear evidence for non-spinning subpopulation.
- Spin mislignment of $> 90°$ varies with model.

Tong+ arXiv:2209.02206





Heavy DNS: Future work

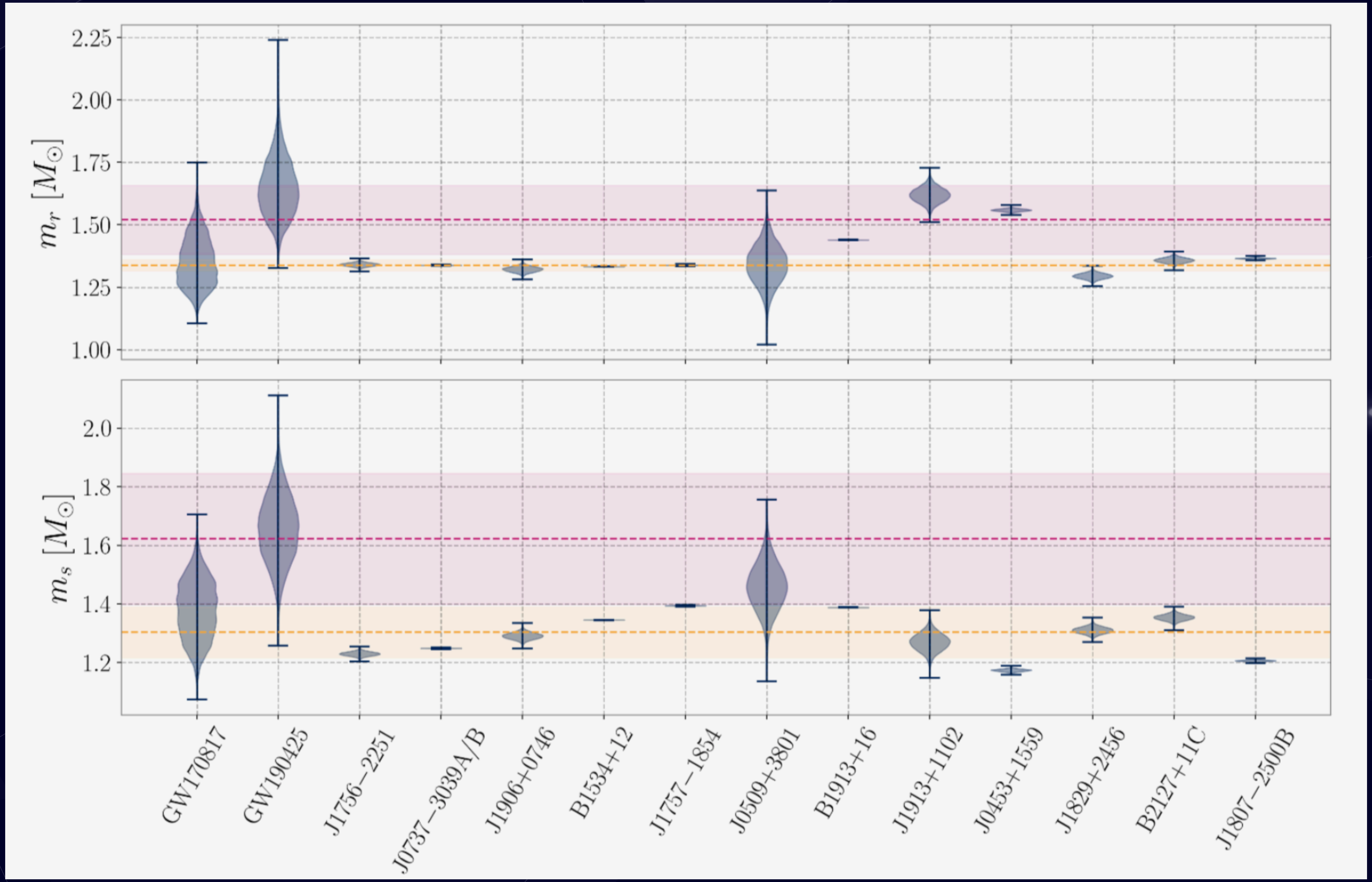
- Used a Delta-function for the fast merging channel delay-time distribution, not very realistic. Use more realistic models for fast-merging channel delay-time distribution.

- Did not account for possibility that the magnetic field might decay with time (Bransgrove et al. 2018). Model this effect into the radio-visible calculation.

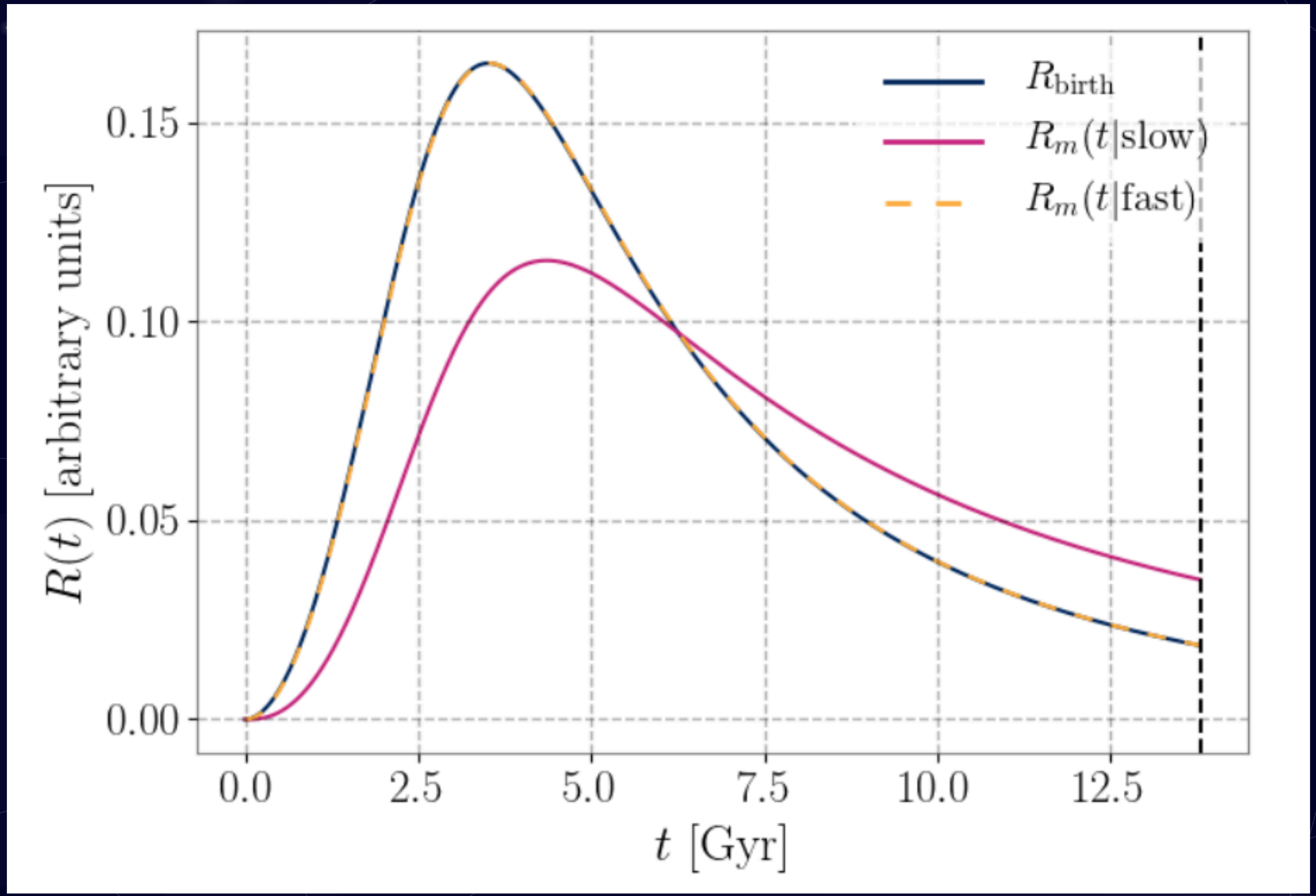
- Assumed that all DNS systems are equally detectable in the radio. Account the difficulty detecting ultra-relativistic DNS with radio (Pol et al. 2020).

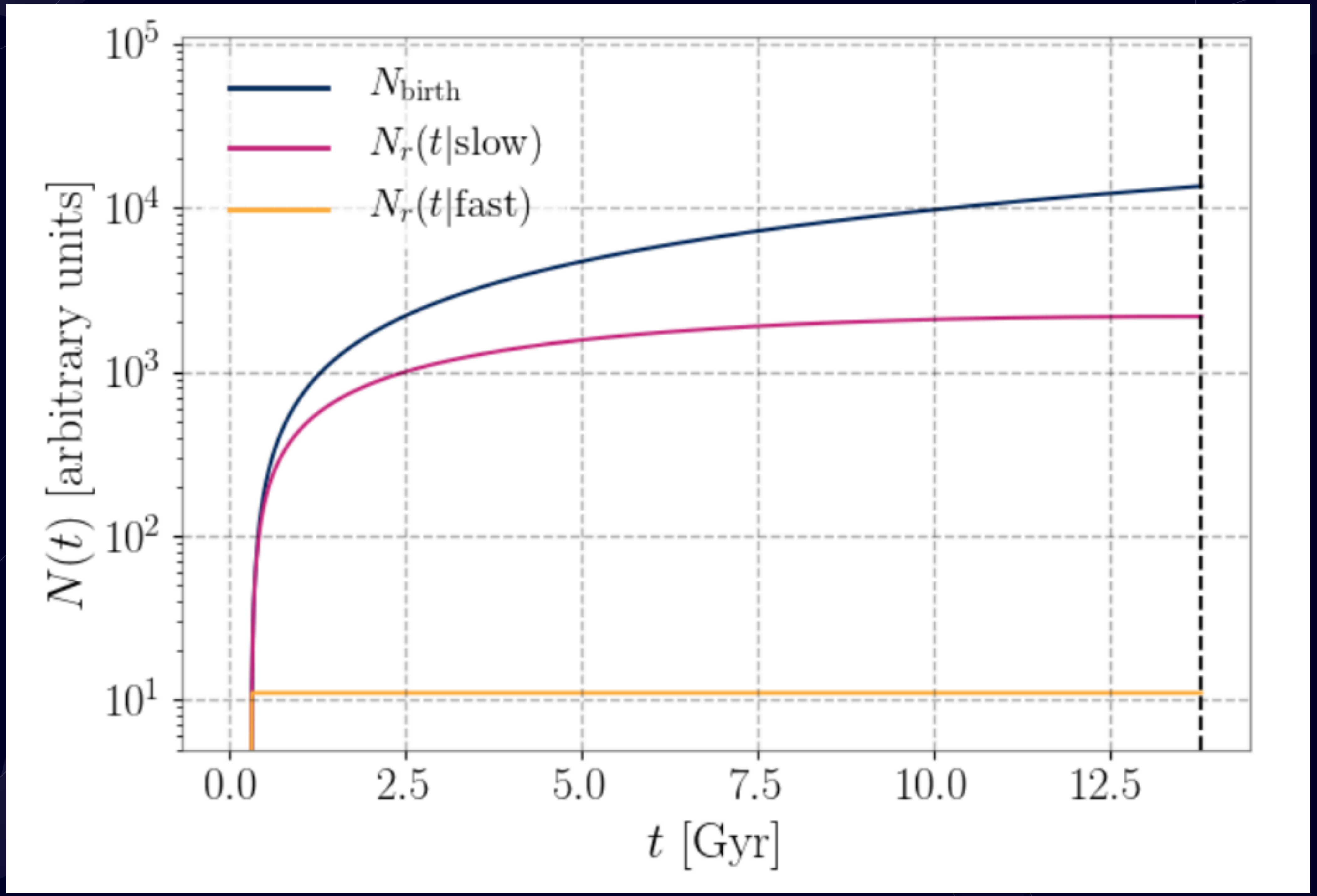
- Used a zero-redshift approximation. Make radio and gravitational-wave transfer functions redshift-dependent.

Event posteriors



Birth, radio and GW distributions

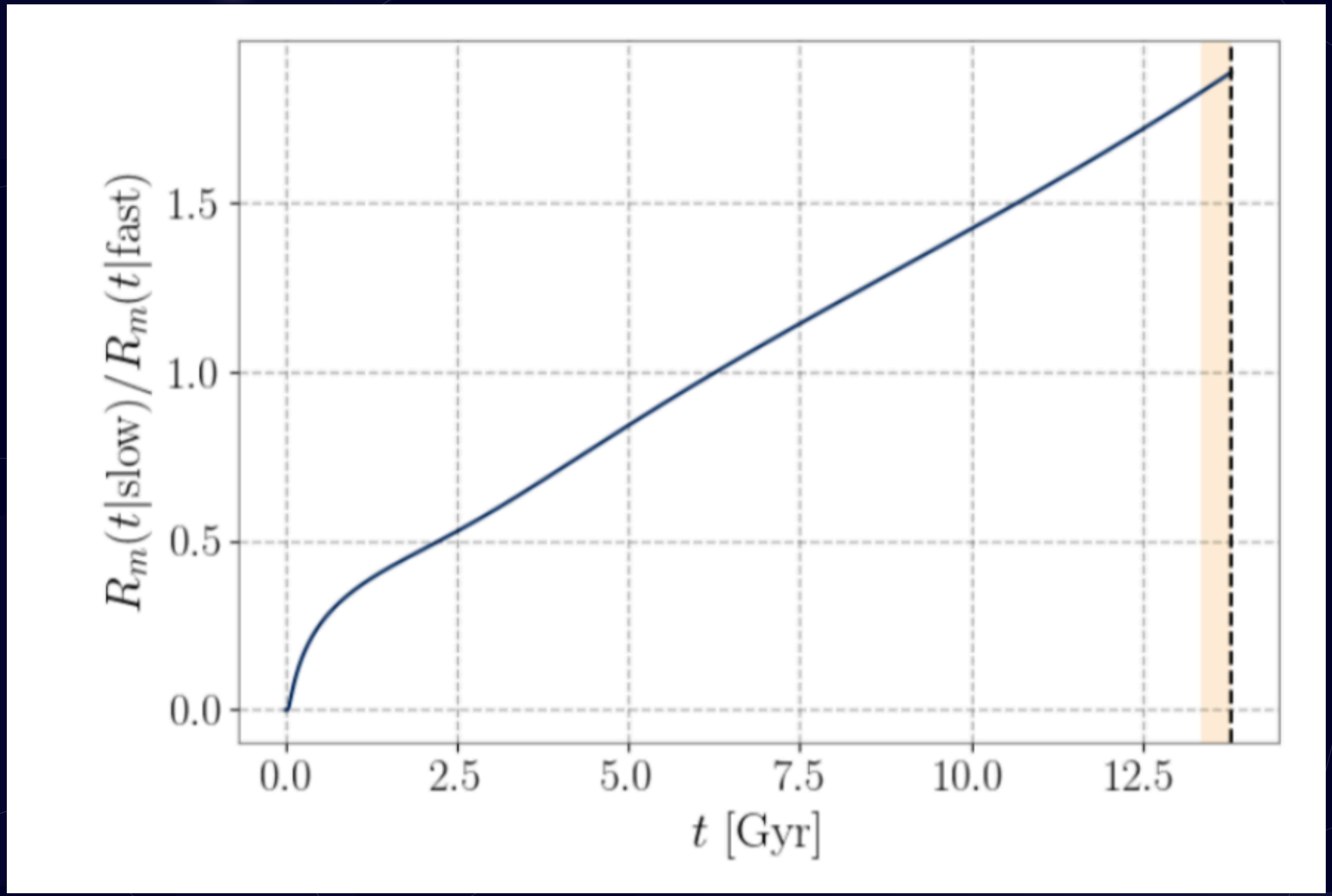


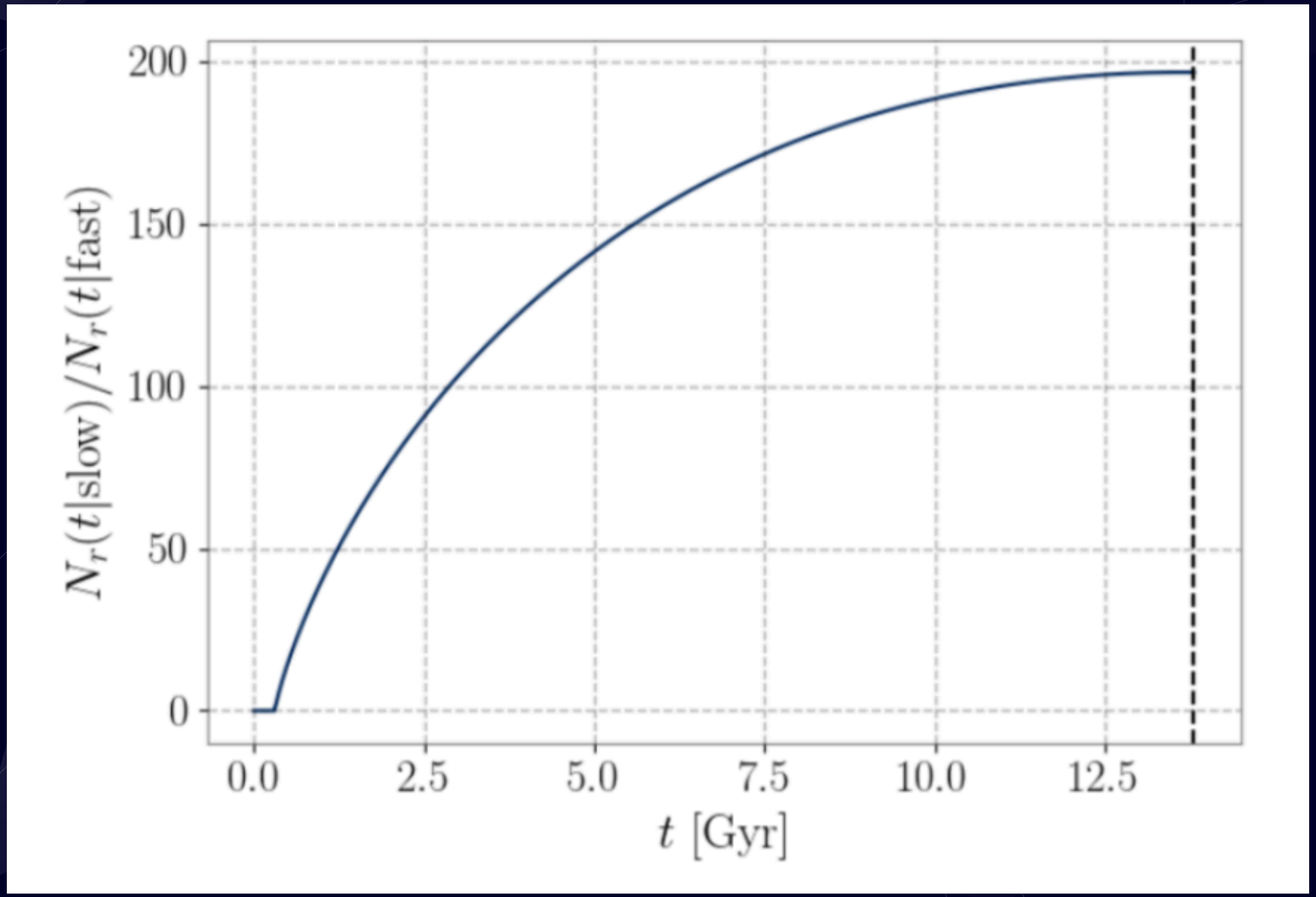


$$R_m(t) = \int_0^t dt_b R_b\left(t_b\right) \pi\left(t - t_b\right)$$

$$N_r(t) = \int_0^t dt' \left(R_b(t') - R_m(t')\right) \epsilon(t')$$

Ratios: mergers & number of radio-visible DNS





$\zeta_{\mathrm{GW}} = R_m(\mathrm{slow})/R_m(\mathrm{fast})$

$\zeta_{\mathrm{radio}} = N_r(\mathrm{slow})/N_r(\mathrm{fast})$

Population synthesis study

- Simple population synthesis analysis in order to estimate the typical supernova kick velocities required in order to disrupt a non-negligible fraction of slow-merging binaries without disrupting the fast-merging binaries created by unstable case-BB mass transfer.

$$m_{\mathrm{core}} = 2.65 m_s - 0.95$$

(Mandel & Müller 2020)

$$v_{\mathrm{kick}} = k m_{\mathrm{core}}$$

$$f_{\mathrm{radio}} = \frac{N\left(v_{\mathrm{kick}} < v_{\mathrm{max}} \,\&\, P_b > 1.5\mathrm{hr} \,\&\, m_{\mathrm{tot}} > m_{\mathrm{tot}}^{\mathrm{GW190425}}\right)}{N\left(v_{\mathrm{kick}} < v_{\mathrm{max}} \,\&\, P_b > 1.5\mathrm{hr}\right)}$$

$$f_{\mathrm{GW}} = \frac{N\left(v_{\mathrm{kick}} < v_{\mathrm{max}} \,\&\, m_{\mathrm{tot}} > m_{\mathrm{tot}}^{\mathrm{GW190425}}\right)}{N\left(v_{\mathrm{kick}} < v_{\mathrm{max}}\right)}$$

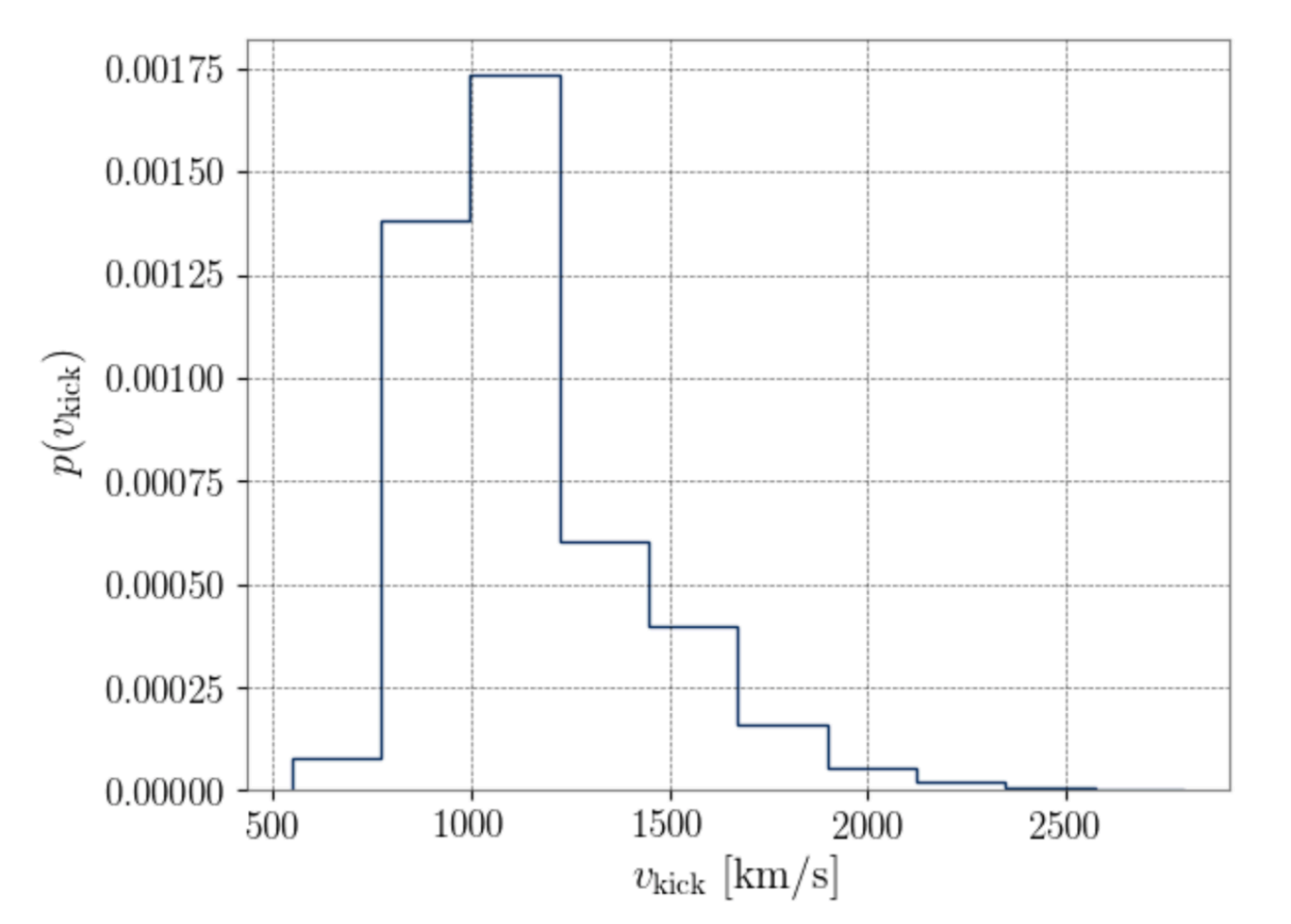
Population synthesis study: Results

- Difference in fractions only apparent when k = 400 km/s/Msun; need fairly large kicks to explain fast-merging channel. Kicks ~1000 km/s

- Difference in fractions only apparent when k = 400 km/s/Msun; need fairly large kicks to explain fast-merging channel. Kicks ~1000 km/s

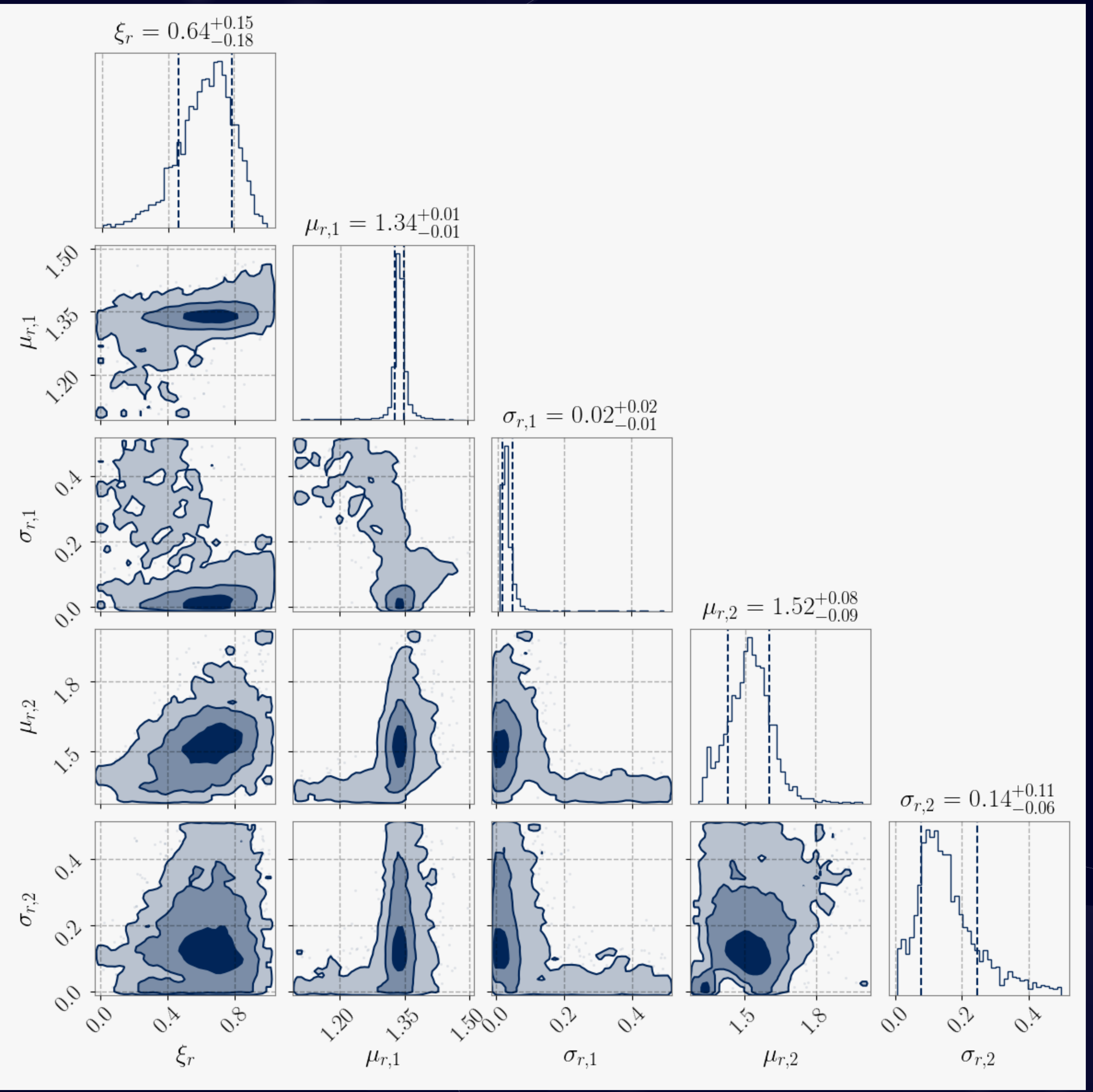
k (km $s^{-1} M_{\odot}^{-1}$)	f_{radio}	f_{GW}
100	0.084	0.083
200	0.084	0.083
300	0.082	0.083
400	0.059	0.083
500	0.042	0.083
600	0.02	0.081
700	0.004	0.06
800	0	0.034

Fraction of heavy binaries surviving the slow and fast merging channels.

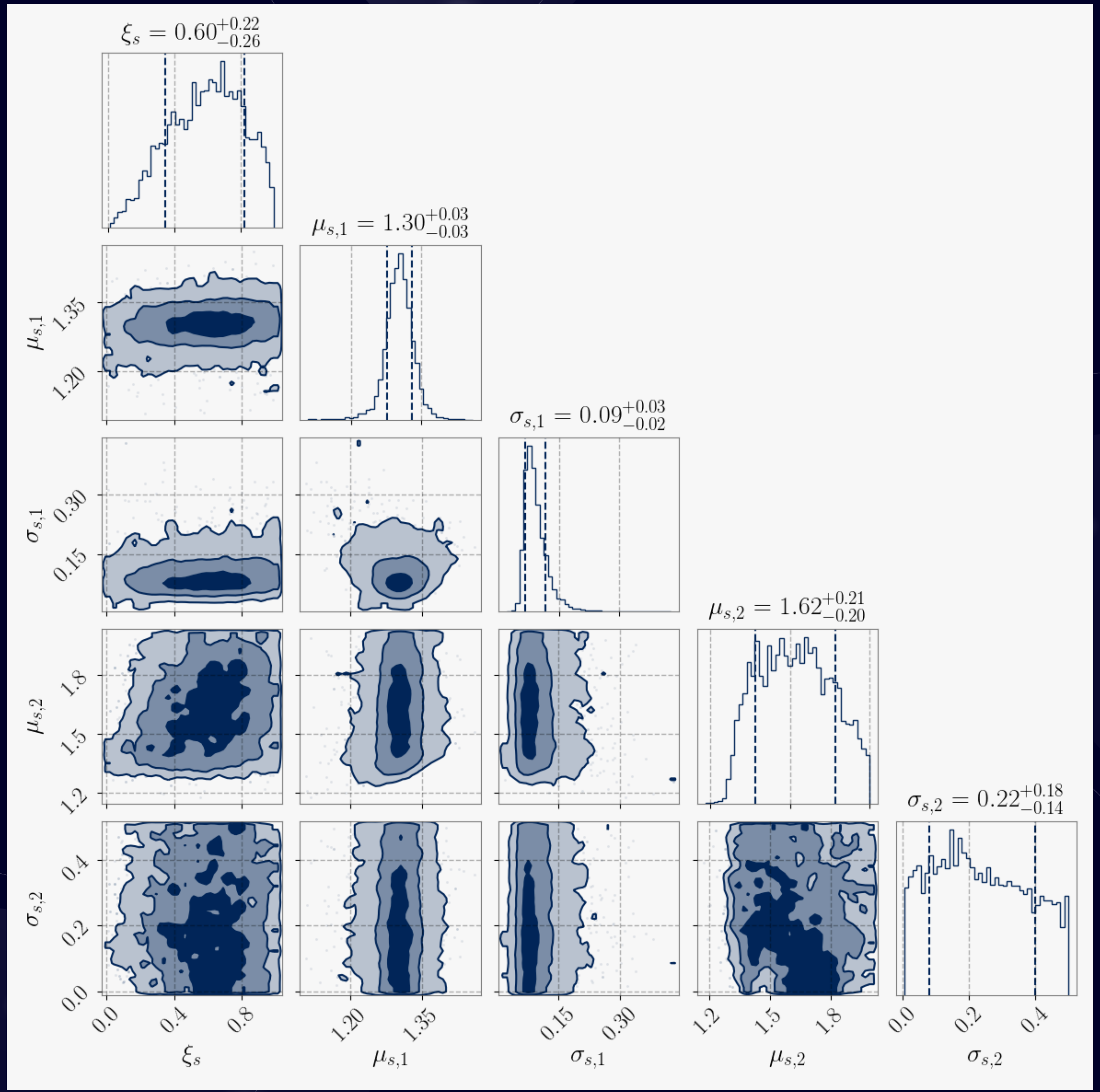


Kick velocity distribution for k = 400 km/s/Msun

Hyper-parameter posteriors



Recycled mass distribution



Slow mass distribution