LIGO-Virgo observations of gravitational waves: The emerging picture of the BBH population

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July 29, 2021 | YITP & OzGrav workshop: Nuclear burning in massive stars

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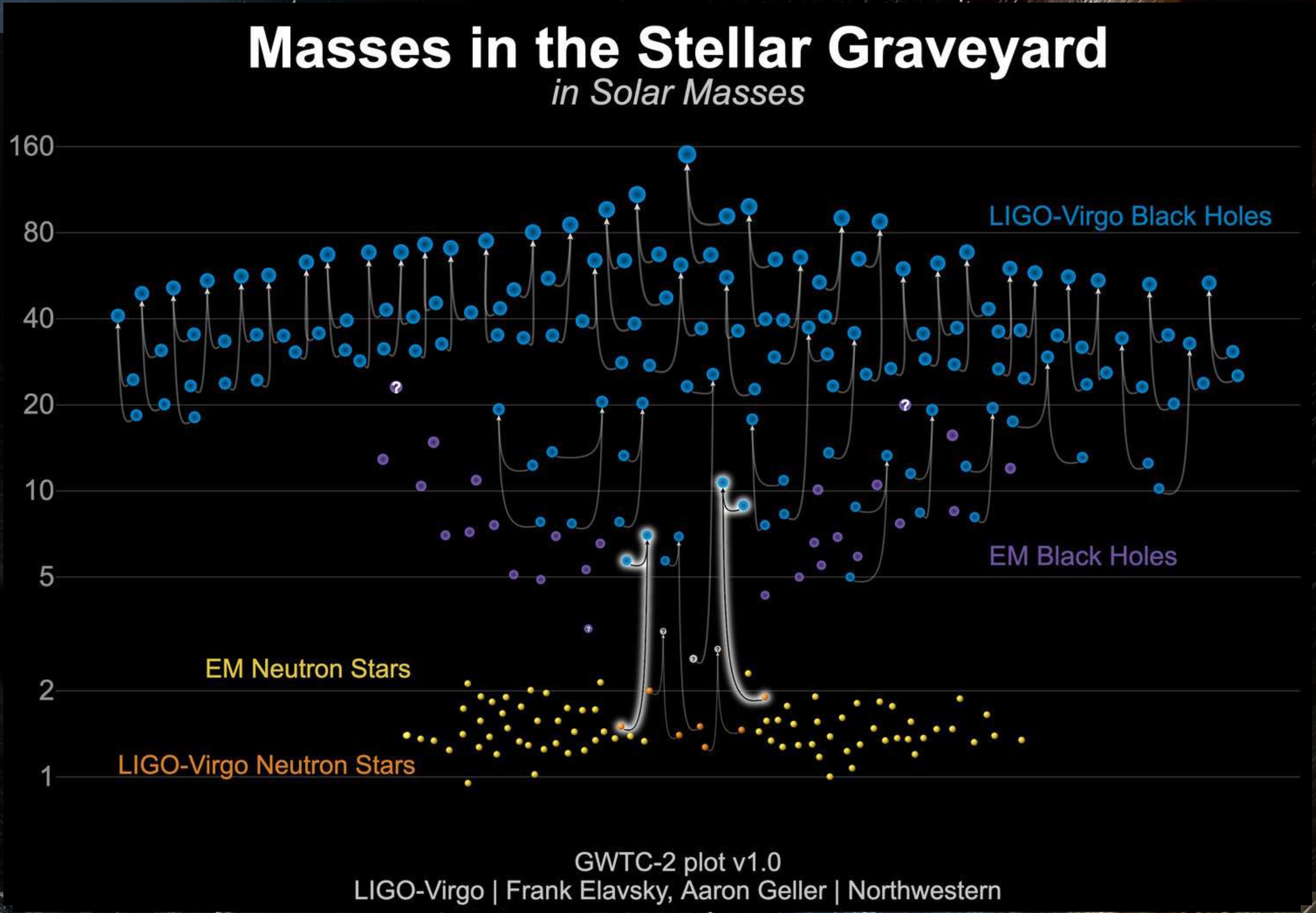

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190412

BBH with mass ratio confidently constrained away from unity

GW190425

Heaviest BNS detected; unusually massive compared to Galactic population

GW200105 + GW200115

Discovery of 2 NSBH mergers

GW190521

Most massive BBH detected with gravitational waves

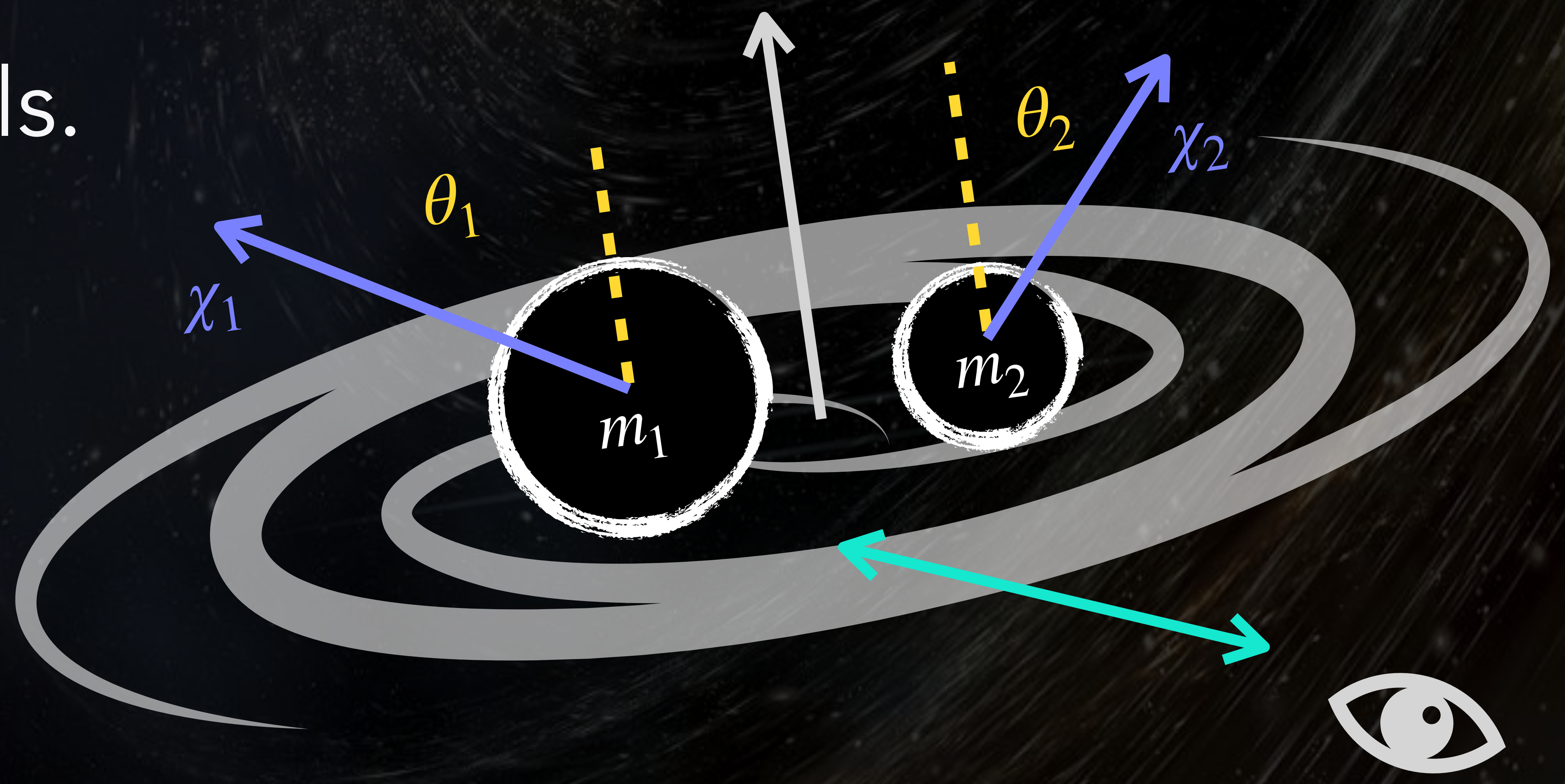
GW190814

A binary system with a BH + either the lightest BH or heaviest NS

LVC arXiv:2004.08342, Gerosa+ arXiv:2005.04243, Mandel & Fragos arXiv:2004.09288, LVC arXiv: 2001.01761, Galaudage+ arXiv:2011.01495, Safarzedah+ arXiv:2001.04502
LVC arXiv:2009.01075, LVC arXiv:2009.01190, Romero-Shaw+ arXiv:2009.04771, LVC arXiv:2006.12611, LVC arXiv:2106.15163

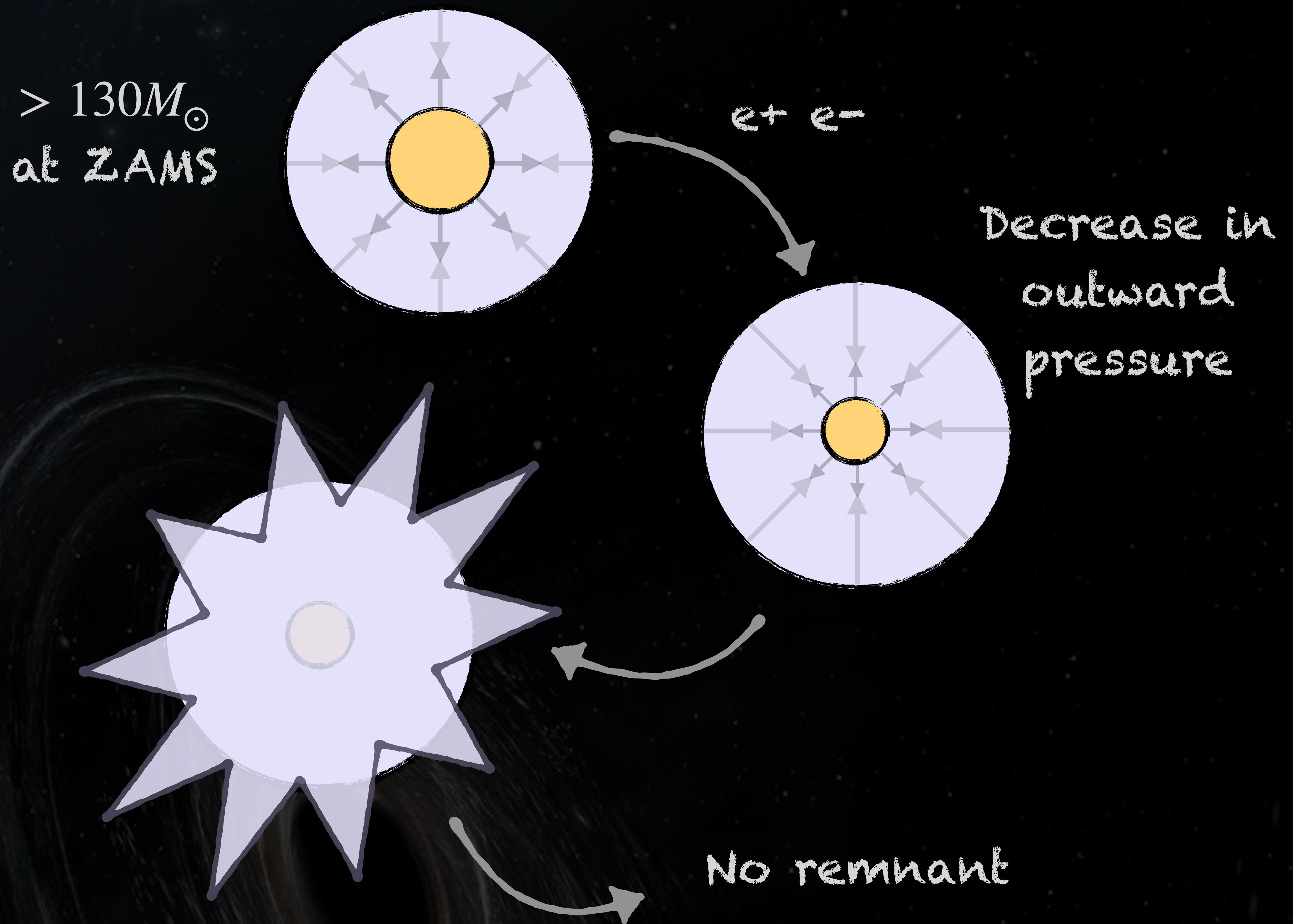
Population analysis of GWTC-2

- Second Gravitational Wave Transient Catalogue (GWTC-2) = O1 + O2 + O3a
- Total of 50 compact binaries — 47 confident detections: 44 BBH, 2 BNS and 1 compact binary that is either a BBH or NSBH
- Hierarchical inference to study the *shape* of the population
- Astrophysically motivated phenomenological models.
- Explore mass, spin & redshift models, extensions from models explored in GWTC-1 and understand features we see — arXiv:2010.14533

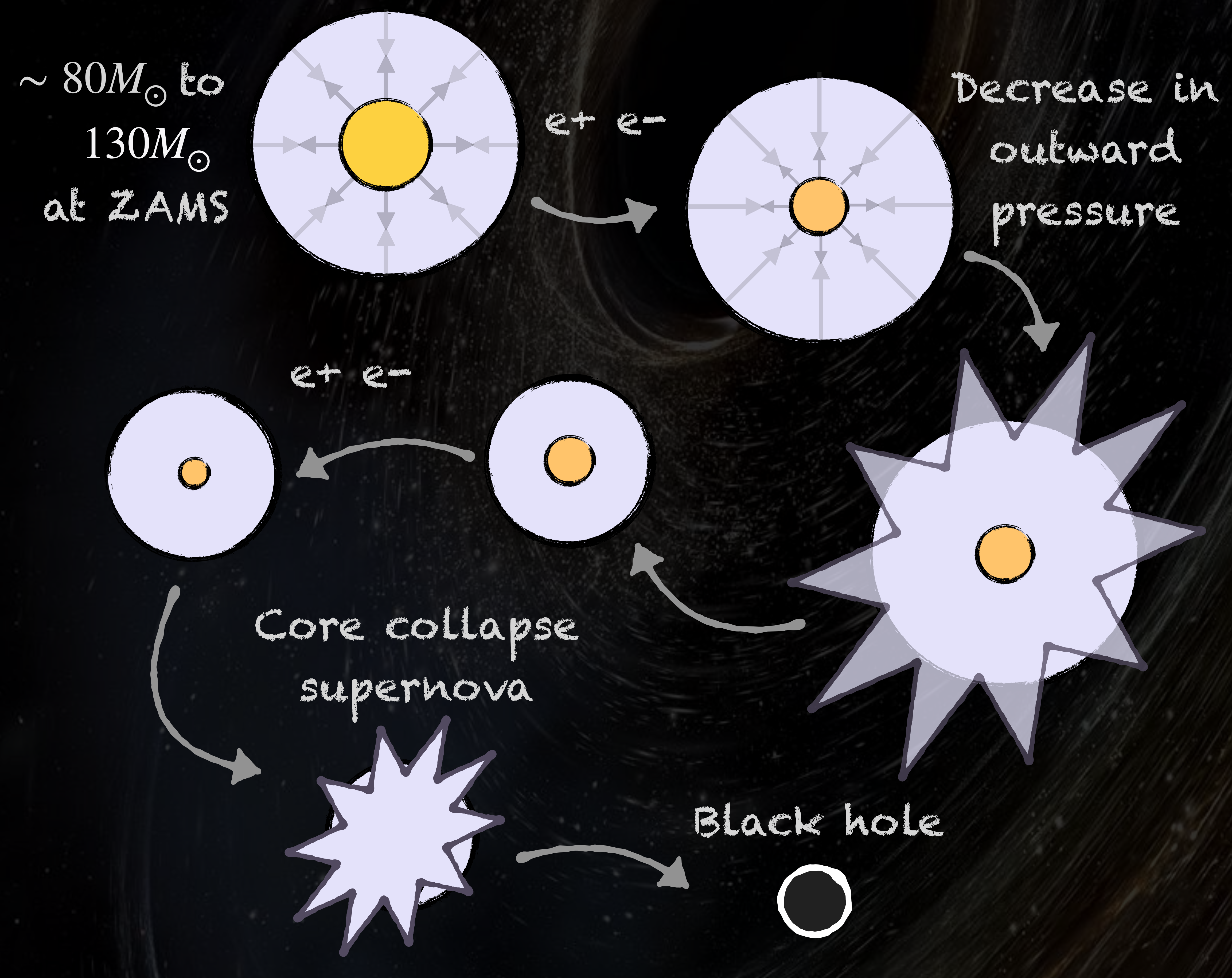


Understanding the mass distribution

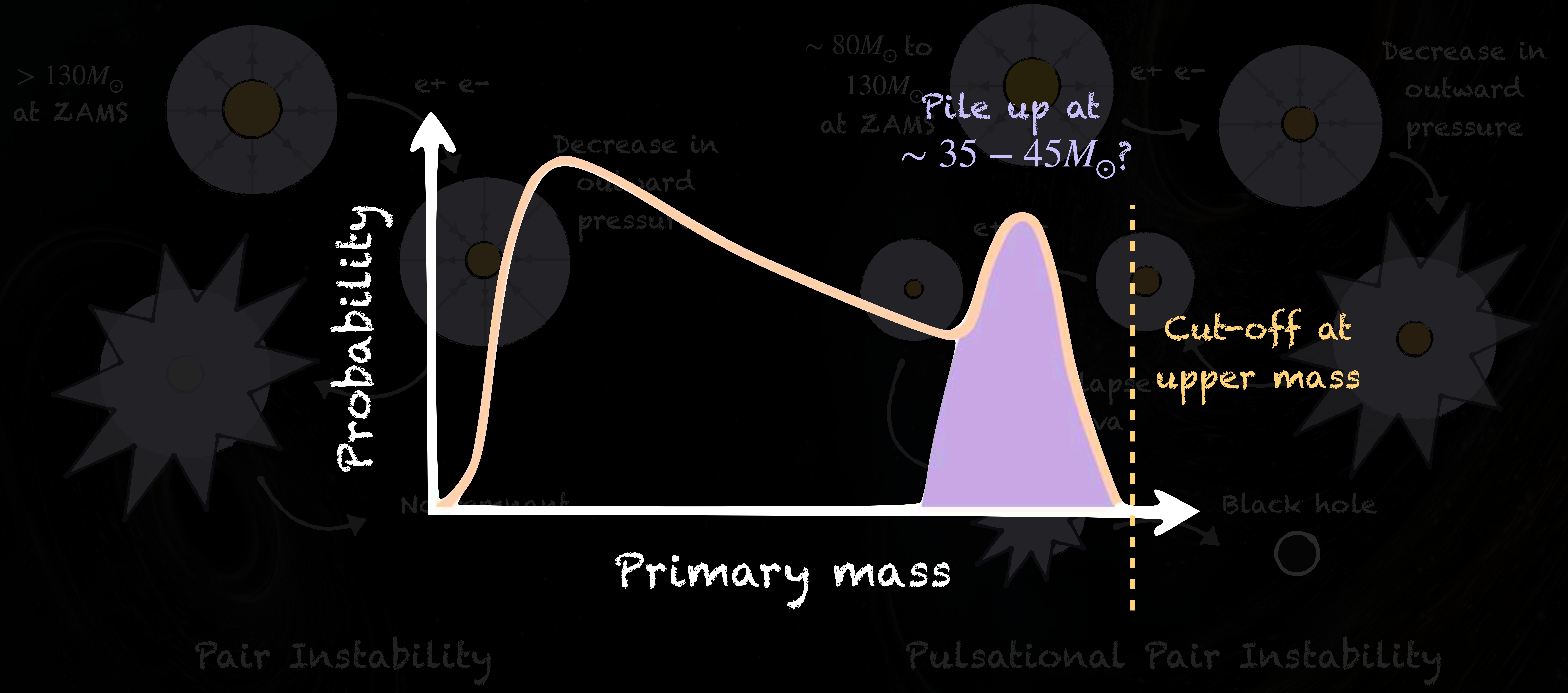
- Describe features in the population.
- Explore multiple mass models, extensions from models explored in GWTC-1

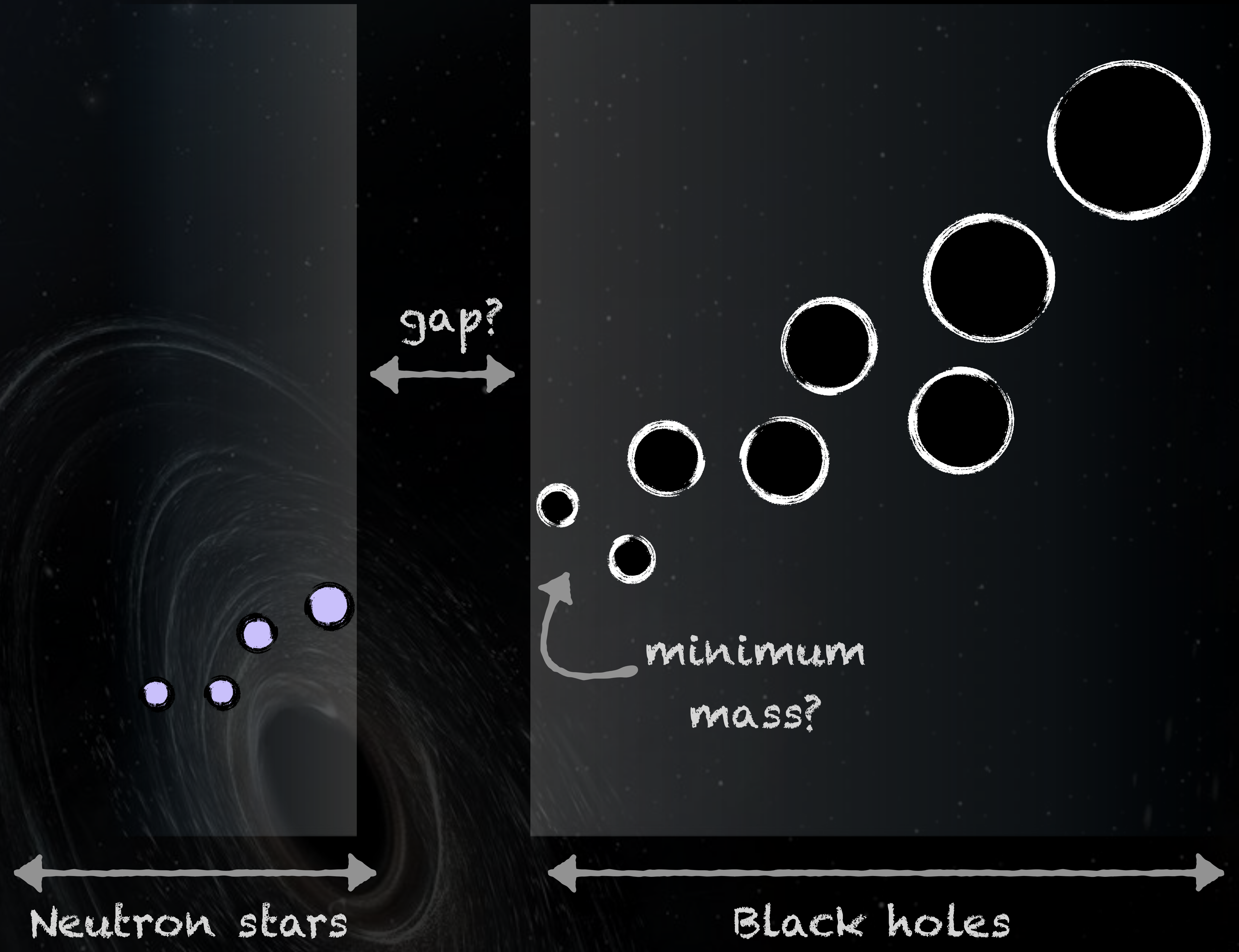


Pair Instability



Pulsational Pair Instability


Pile up at
$\sim 35 - 45 M_\odot$?
Probability
Primary mass
Cut-off at
upper mass
> $130 M_\odot$
at ZAMS
~ $80 M_\odot$ to
$130 M_\odot$
at ZAMS
Decrease in
outward
pressure
Black hole
Pair Instability
Pulsational Pair Instability

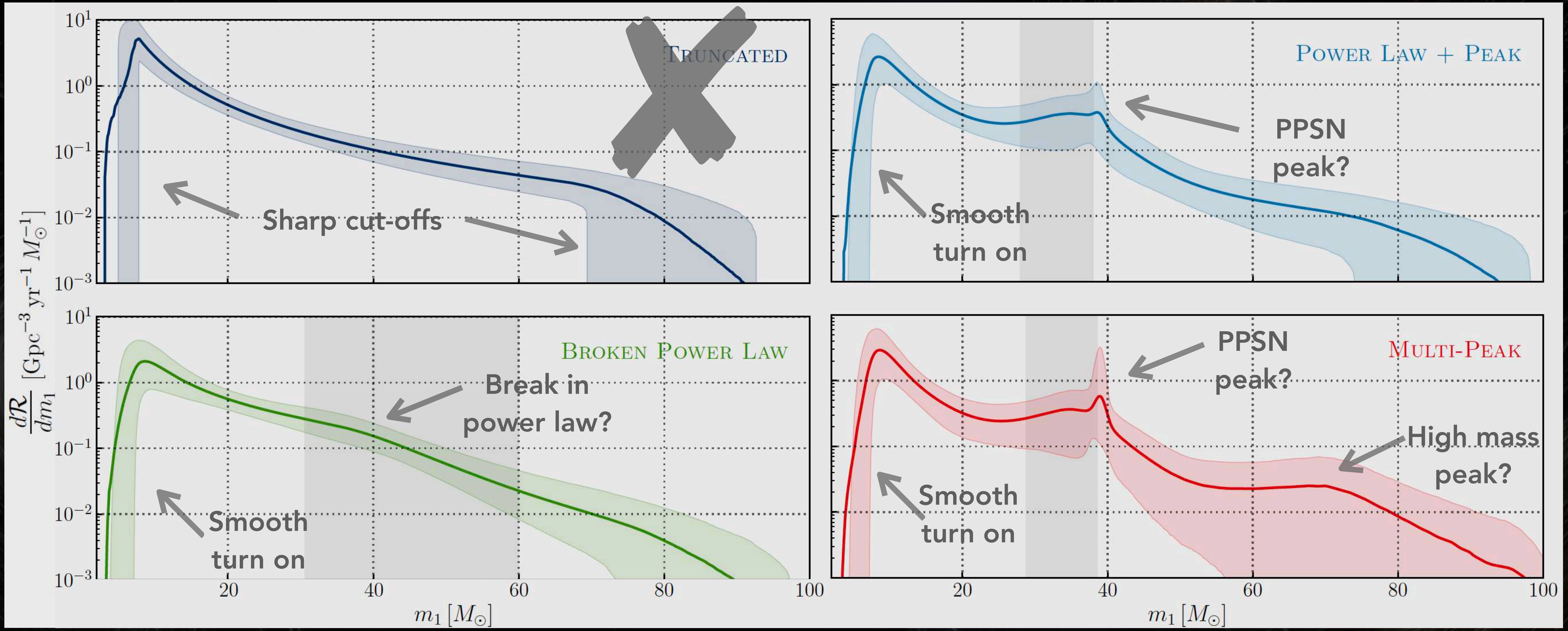


Low mass features

Hierarchical mergers

Mass models and results

- Four different mass models, building on a power law distribution

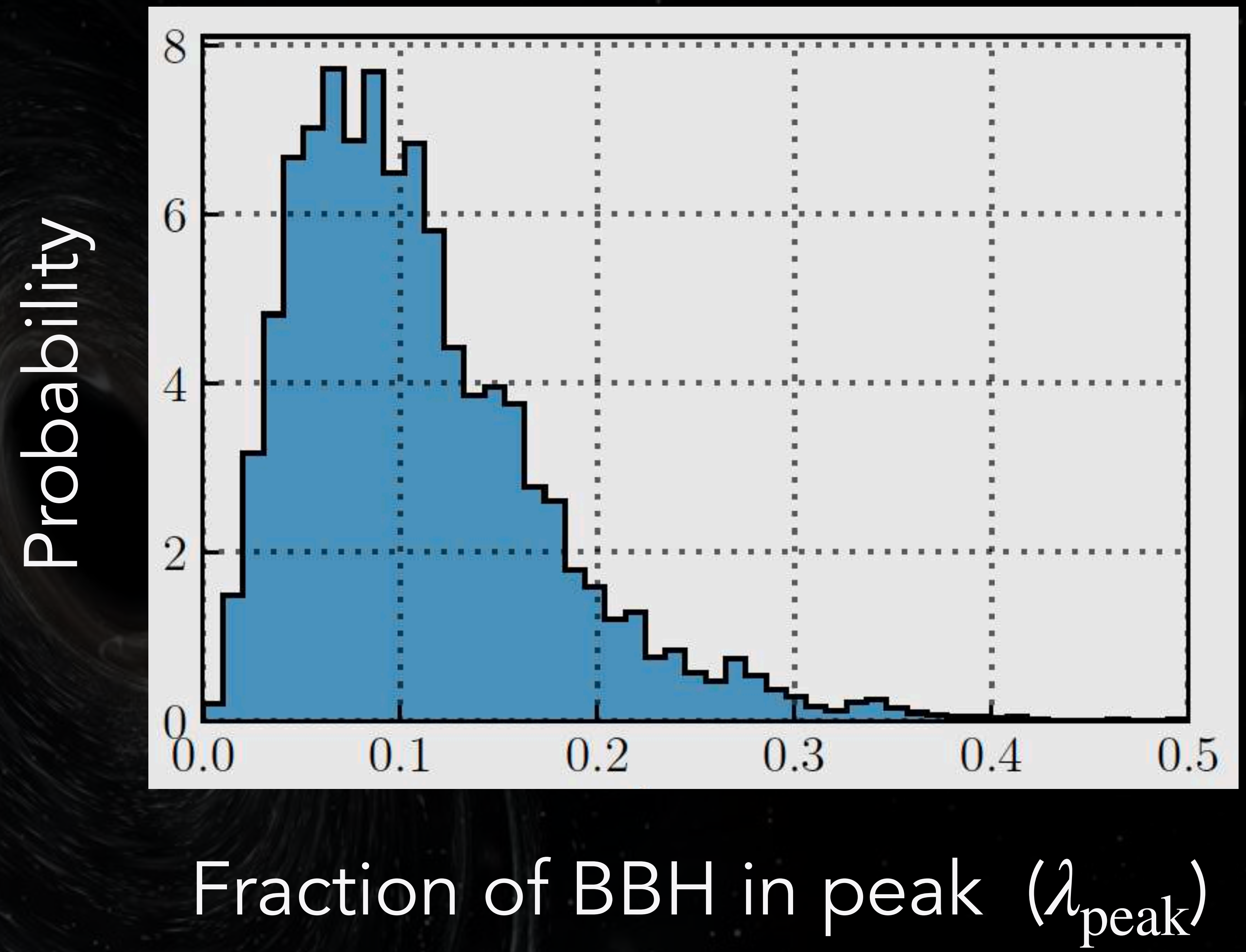


Primary mass distribution: Solid curve - mean; Shaded region - 90% credible interval

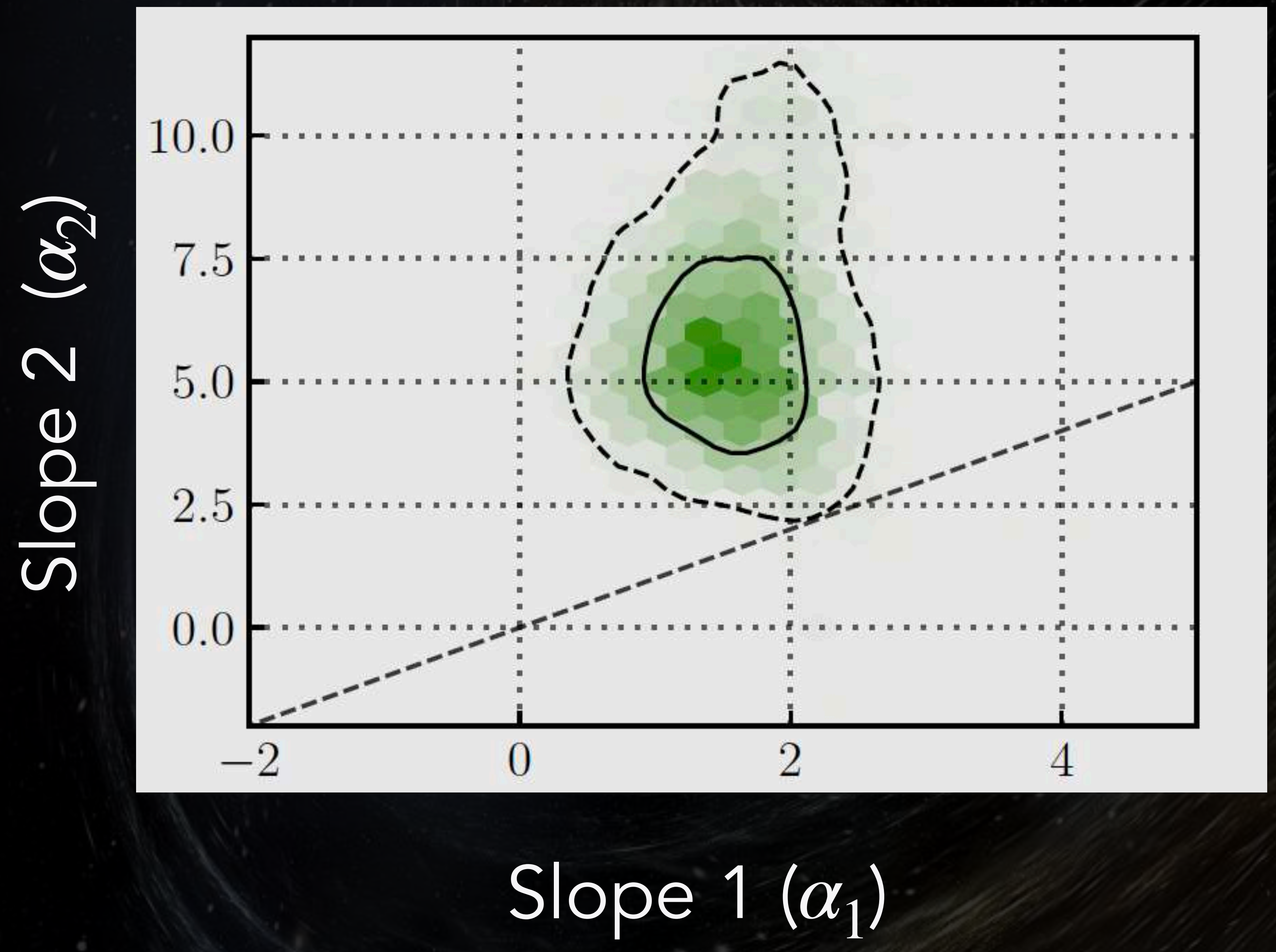
Structure in mass distribution

- Features beyond a simple power-law: slight preference for peak over break (x8)
- Multi-peak model also favoured, comparable to peak model.

POWER LAW + PEAK mass model

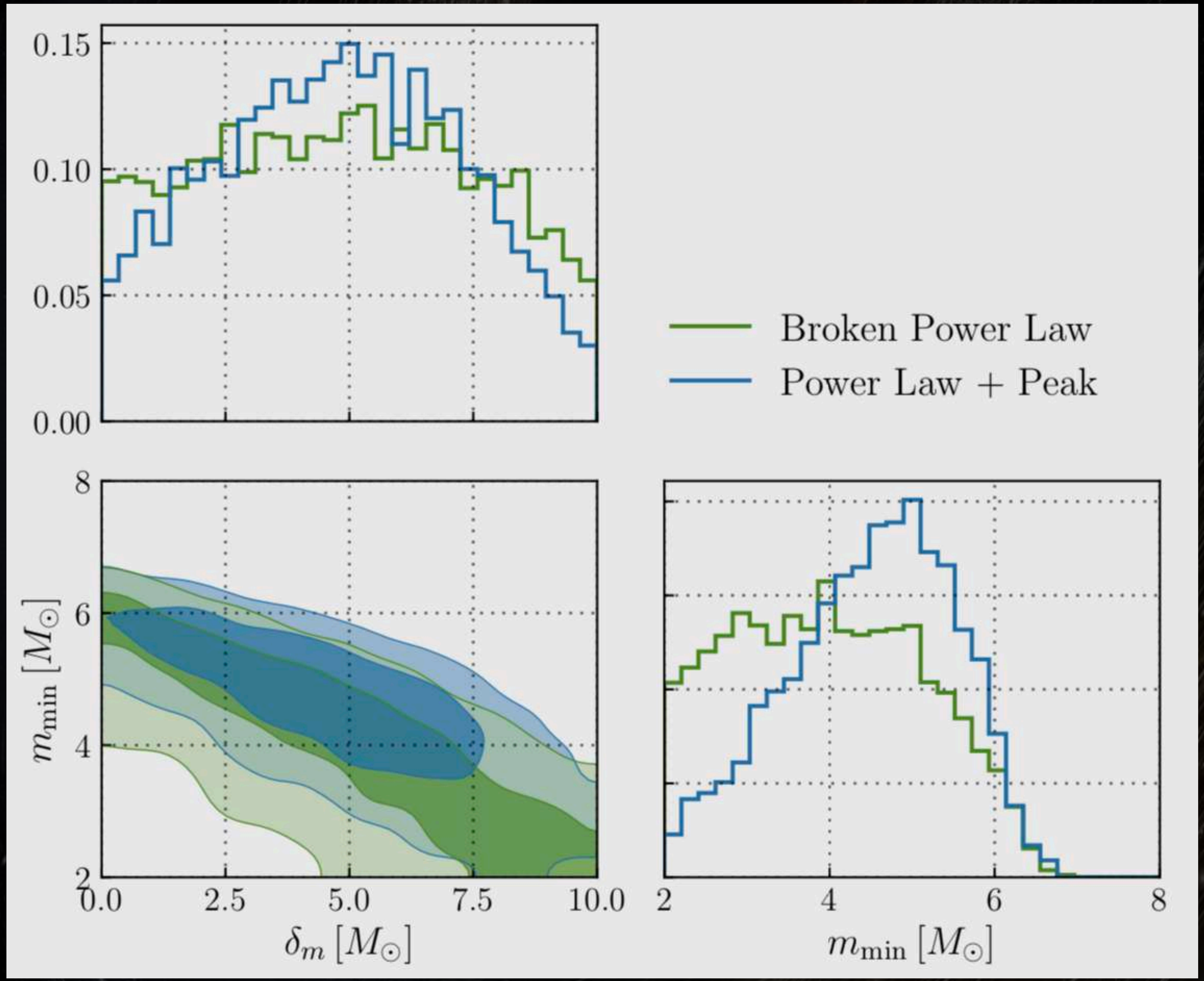


BROKEN POWER LAW mass model



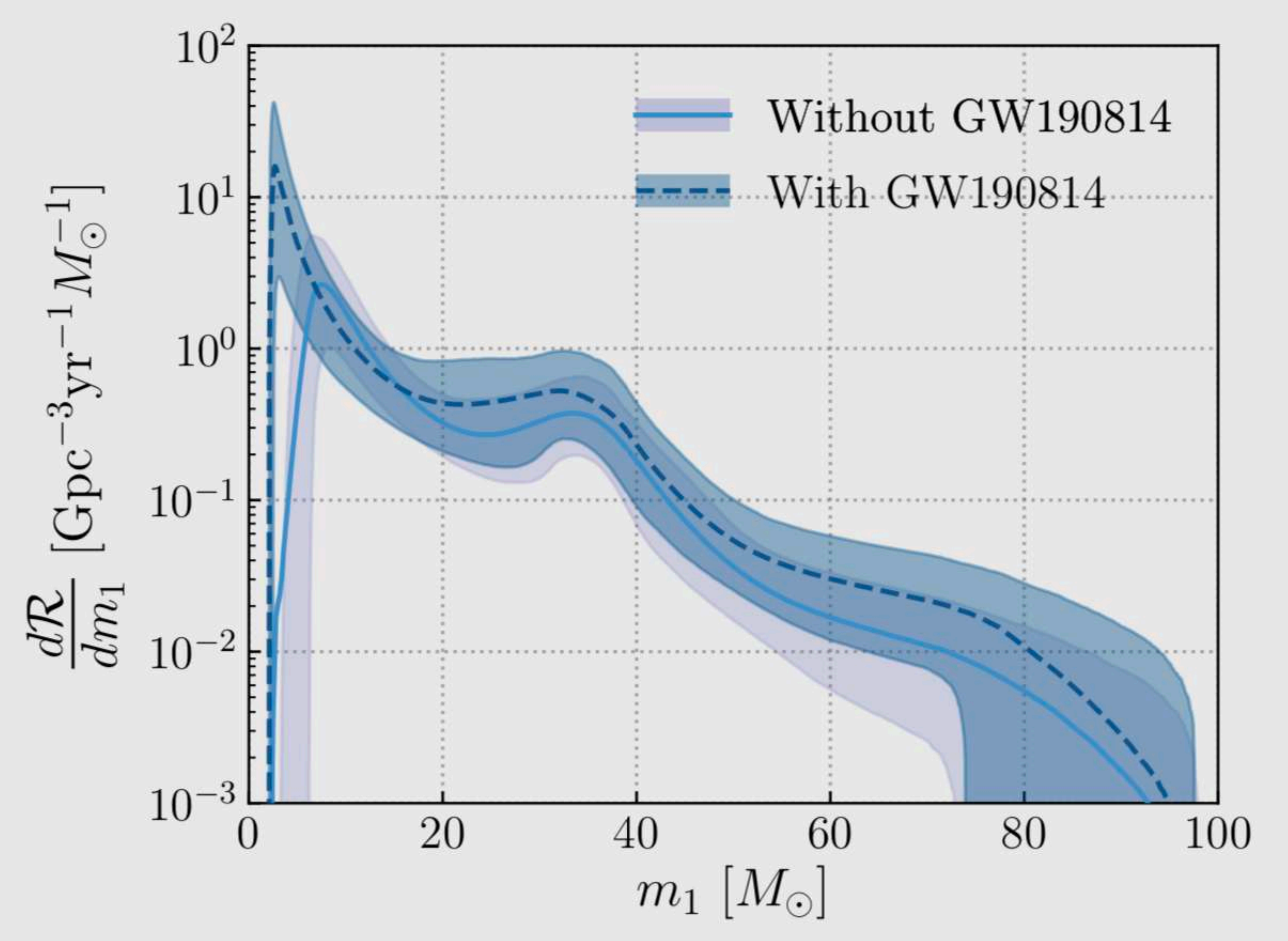
Low-mass features

- We rule out the combination of a small minimum BH mass ($\sim 2M_\odot$) and a sharp low-mass cut-off ($\delta_m \sim 0$).
- We are beginning to resolve the low-mass structure.



Understanding GW190814

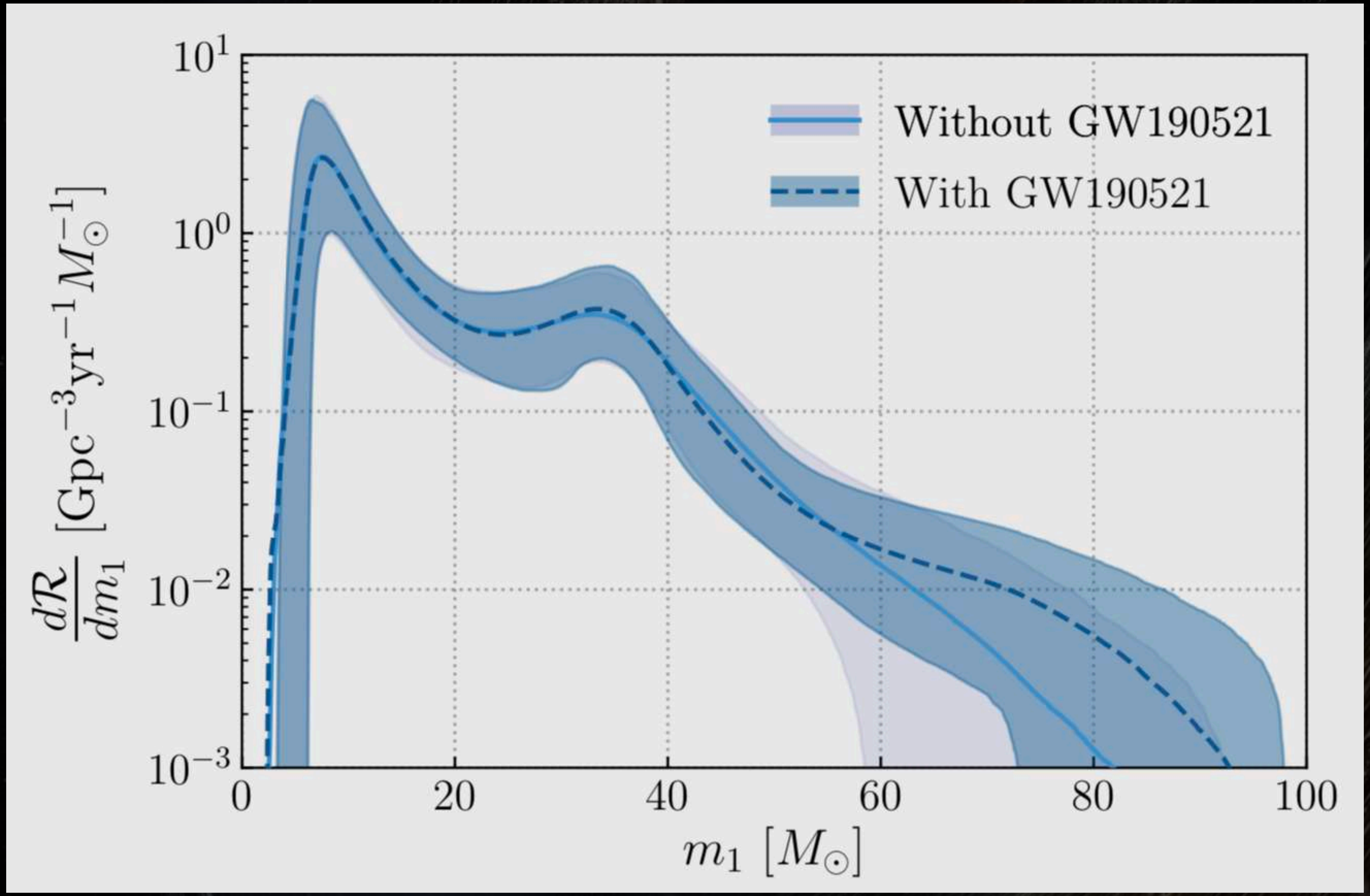
- GW190814 components are a BH + either a small BH or heavy NS.
- An outlier compared to the rest of the population.
- Difference in structure, turnover pulled from $\sim 6M_\odot$ to $\sim 2M_\odot$
- Probability of drawing an event like GW190814 is $0.02\,\%$



Primary mass distribution: Solid/dashed curves - mean; Shaded region - 90% credible interval

Understanding GW190521

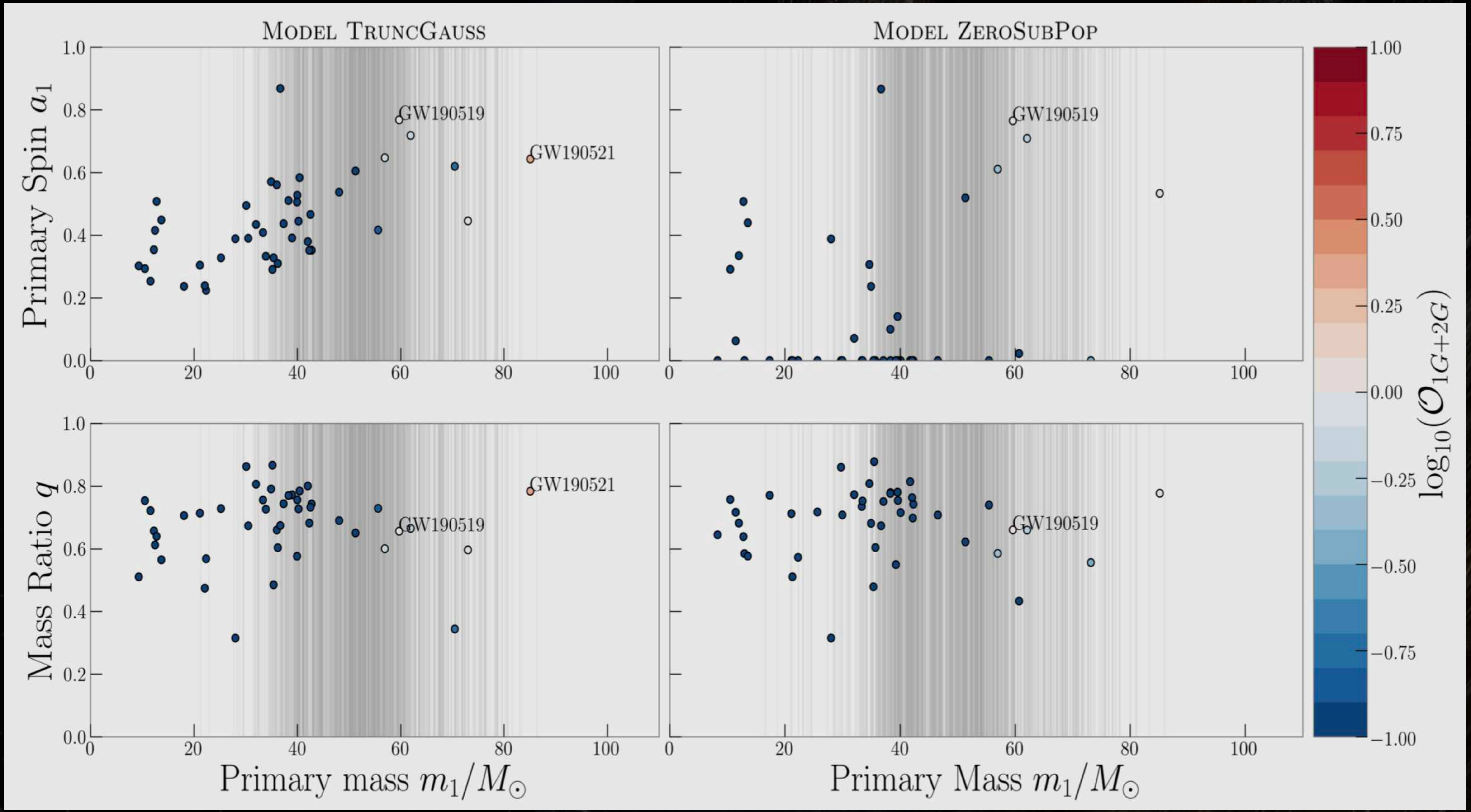
- GW190521 not an outlier with respect to the population.
- Masses beyond $45M_{\odot}$, no sharp cut-off, instead we see a tail.
- GW190521 most massive event to date, possibly a hierarchical merger.



Primary mass distribution: Solid/dashed curves - mean;
Shaded region - 90% credible interval

Hierarchical mergers

- No clear evidence for hierarchical mergers in LVC population study.
- Kimball+ find preference for models with hierarchical mergers.
- GW190521 is favoured to contain two 2g BH
- Dependent on cluster escape velocity



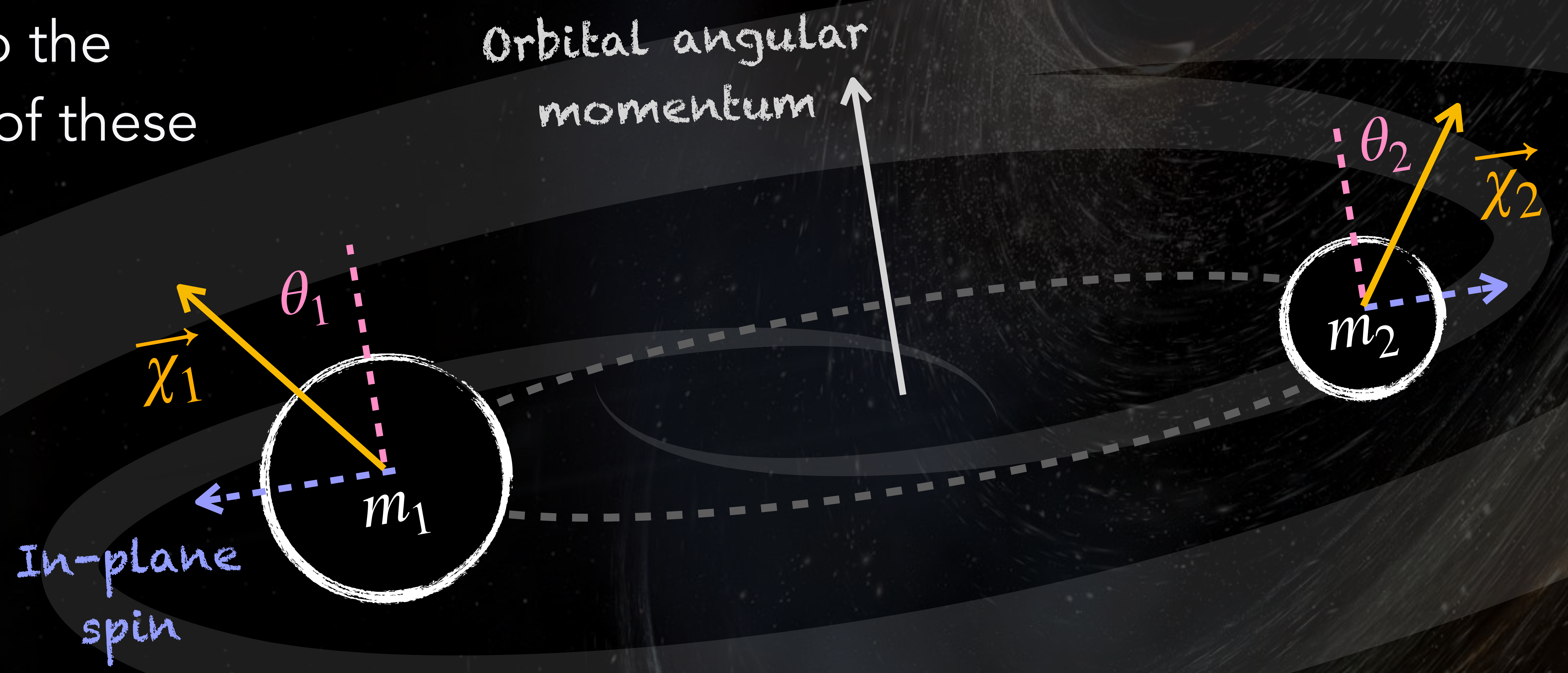
Kimball+ arXiv:2011.05332

Understanding the spin distribution

Spins and orientations of black holes can give us clues to the formation and evolution of these compact binaries.

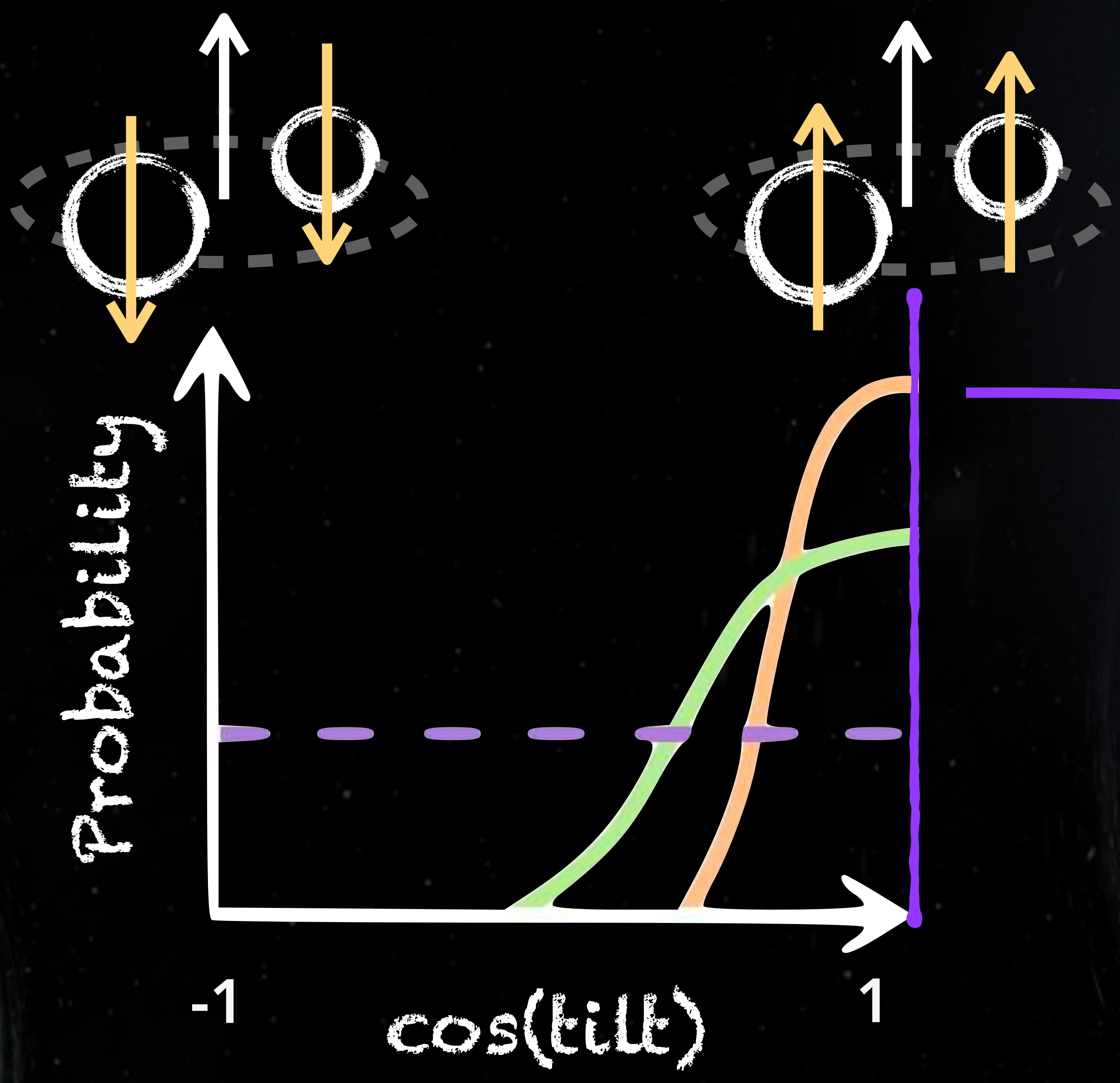
χ - spin magnitude

θ - spin tilt

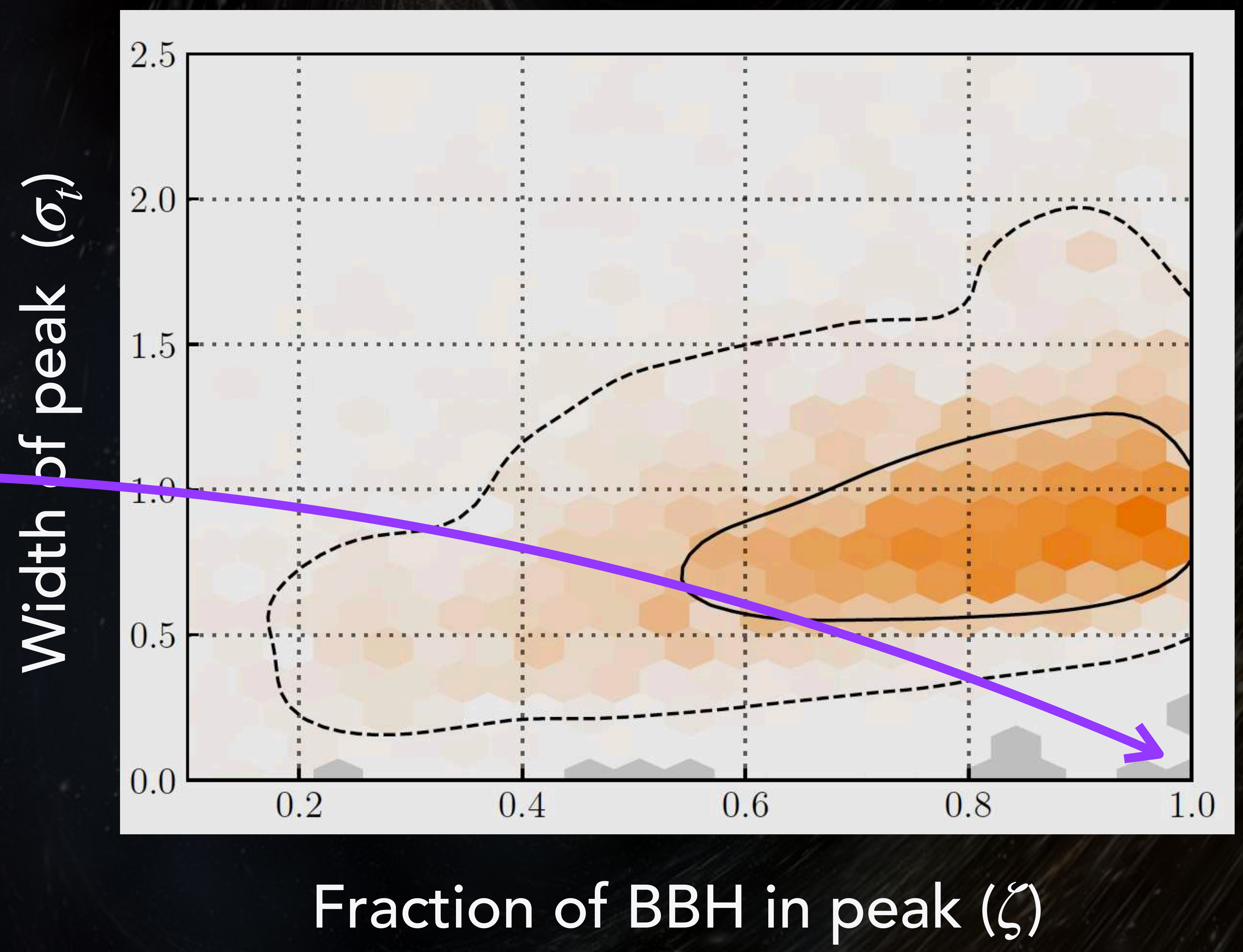


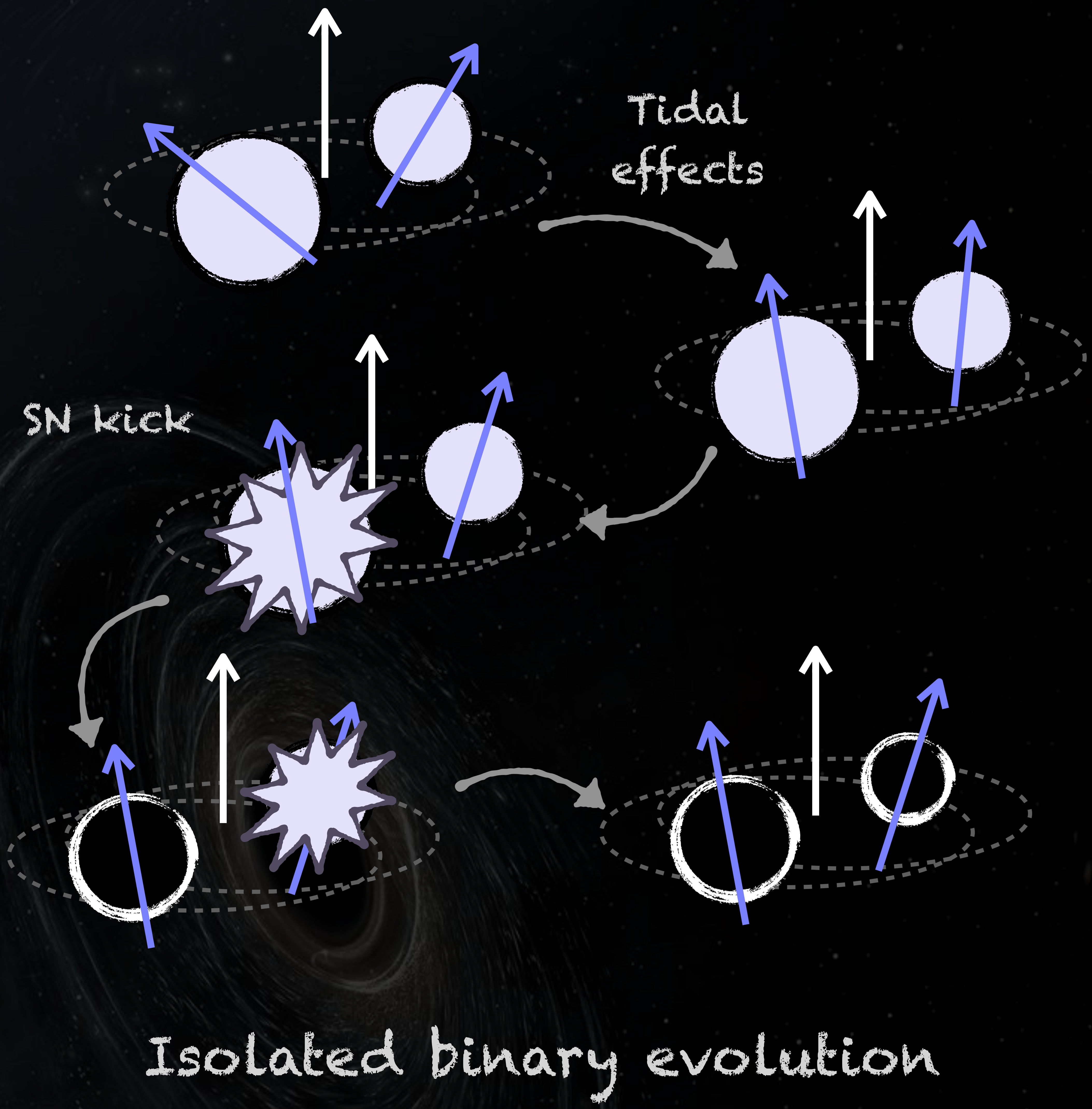
Spin induced precession

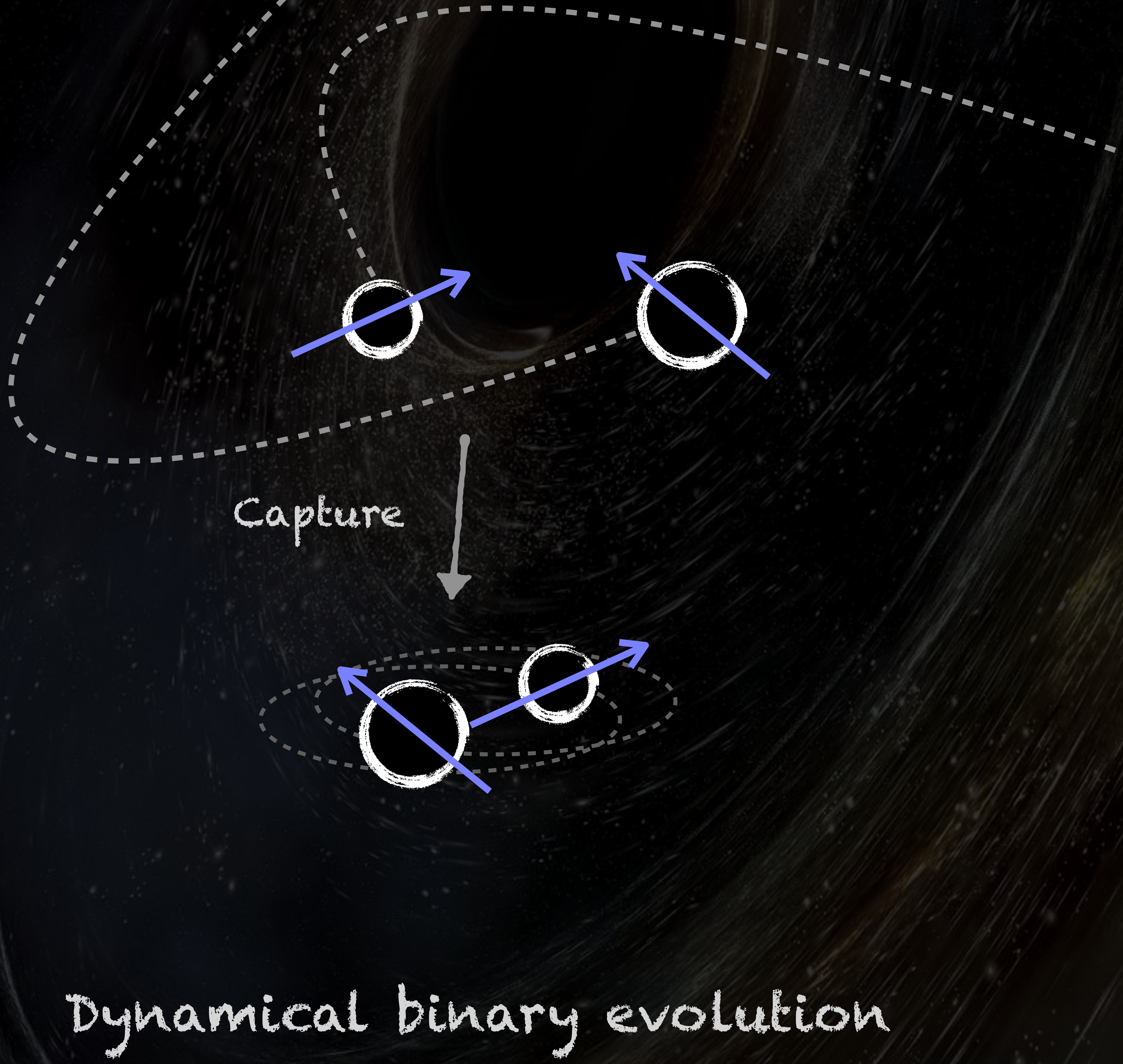
- If spins are not perfectly aligned with orbital angular momentum, there is in-plane = spin induced precession.
- We rule out a population with perfectly aligned spins $\zeta = 1,\ \sigma_t = 0$



DEFAULT spin model

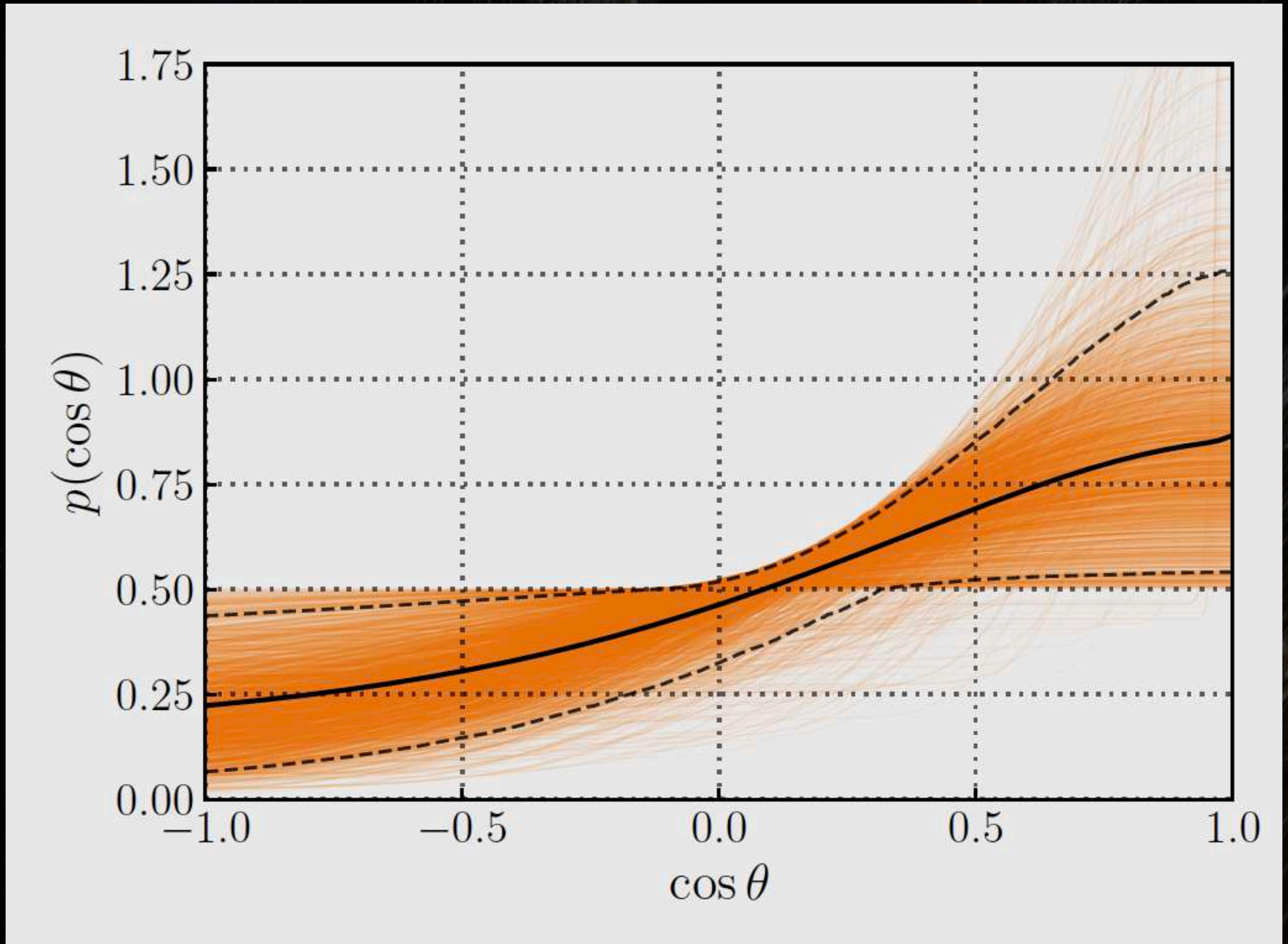



Tidal
effects
SN kick
Isolated binary evolution


Capture
Dynamical binary evolution

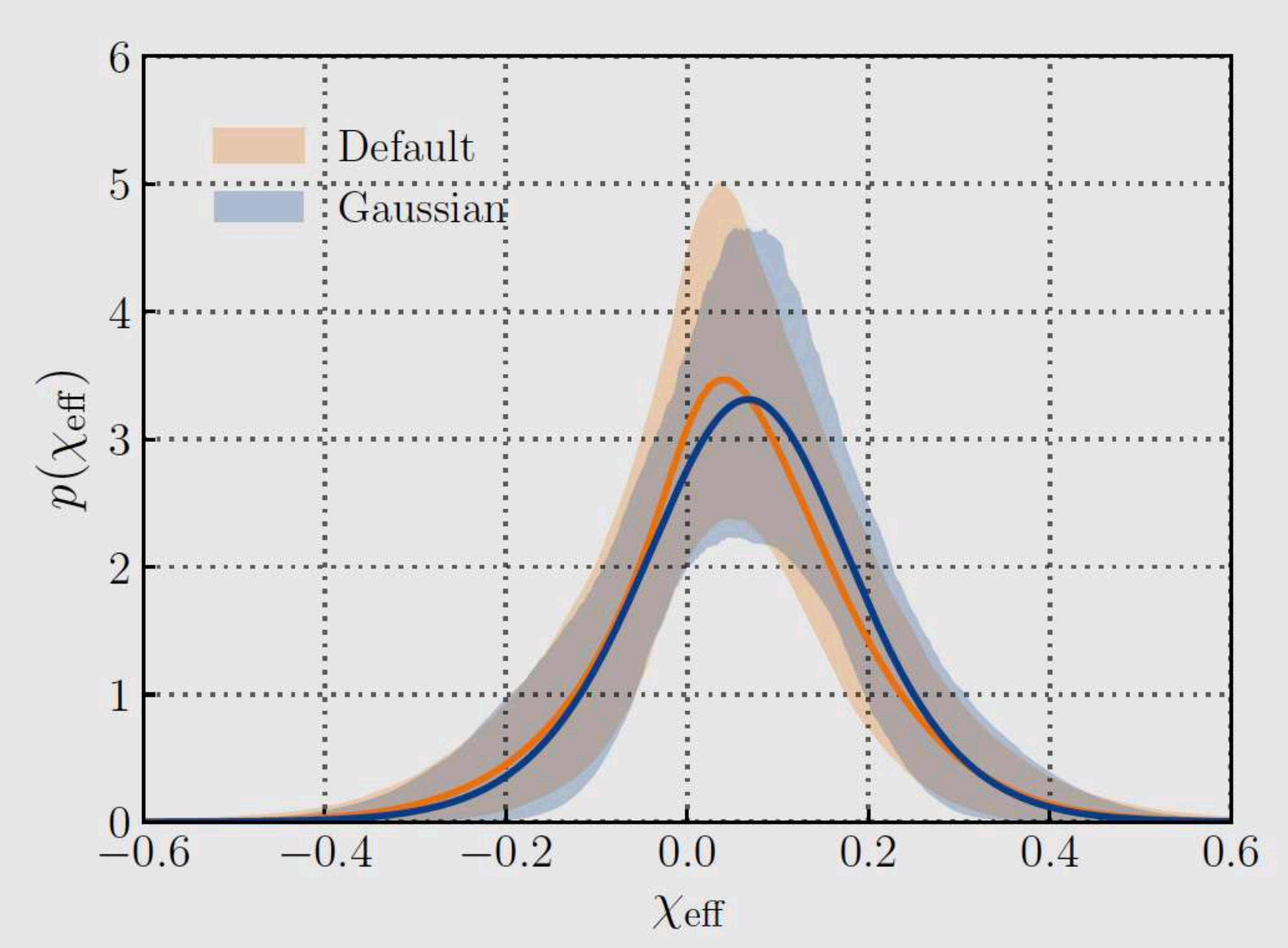
Spin alignment results

- Perfectly aligned spins: $\cos(\theta) = 1$
- Population shows a preference for spins of the components of the binary having spins aligned with the orbital angular momentum.



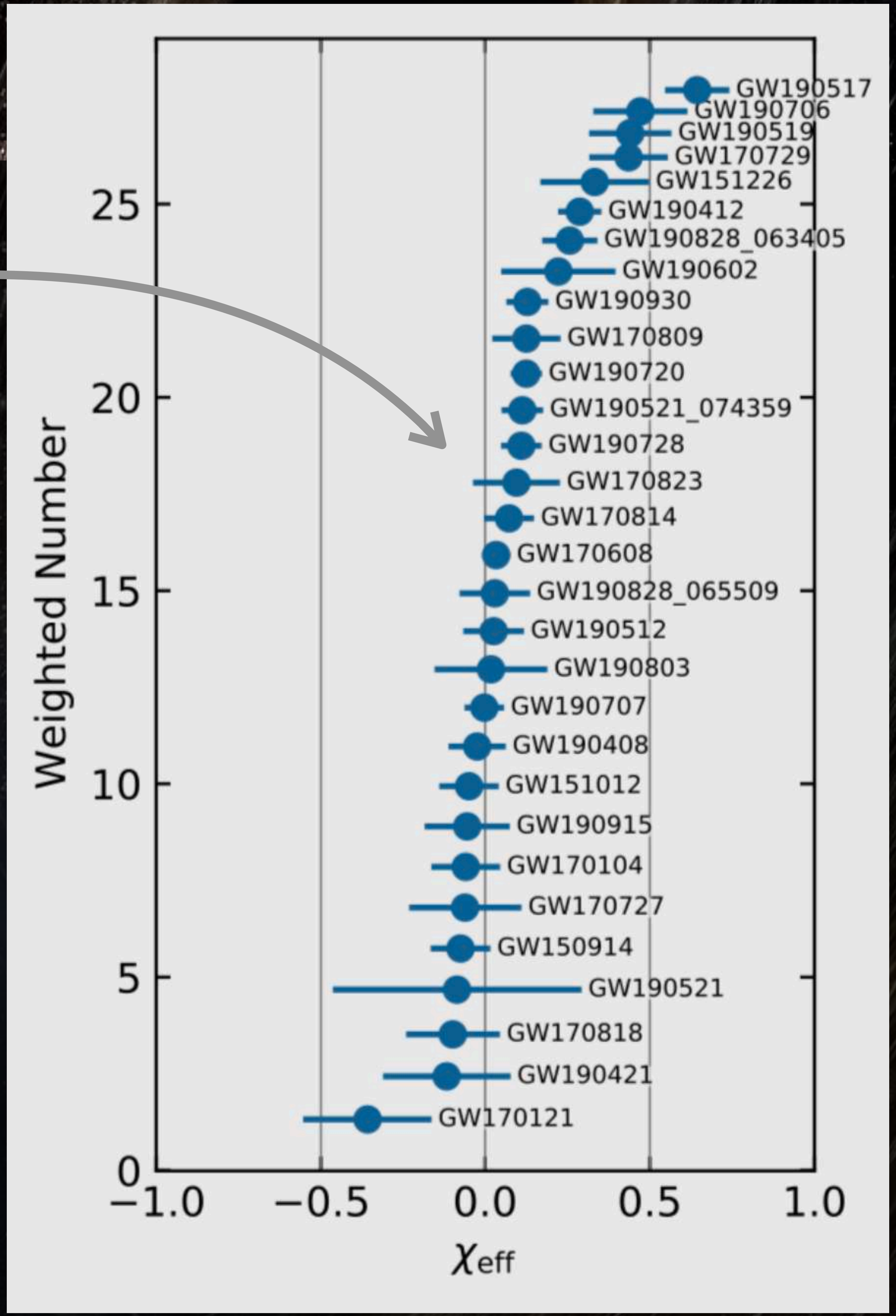
Misaligned spins

- Negative χ_{eff} = misaligned spins
- 12-44% of the black hole population are tilted >90 degrees with respect to the orbital angular momentum of the binary.
- Support for dynamical binary evolution.
- In contention with results from Roulet+ arXiv:2105.10580



Misaligned spins

- Population can be explained with just $\chi_{\text{eff}} \geq 0$
- Models consider a subpopulation with negligible spin.
- Ongoing project looking into the contention between results and exploring these models.
- Stay tuned for results! :)



Roulet+ arXiv:2105.10580

Summary

- Features in mass distributions beyond a power law with sharp cut-offs.
- Evidence for spin induced precession; preference for aligned spins, support for anti-aligned spins —> support for both isolated + dynamical formation
- Spin results are being investigated further, stay tuned for results! :)
- Evidence for hierarchical mergers, GW190521 likely contains second generation BH
- For more details, see paper at arXiv:2010.14533
- **More events from** O3b results!

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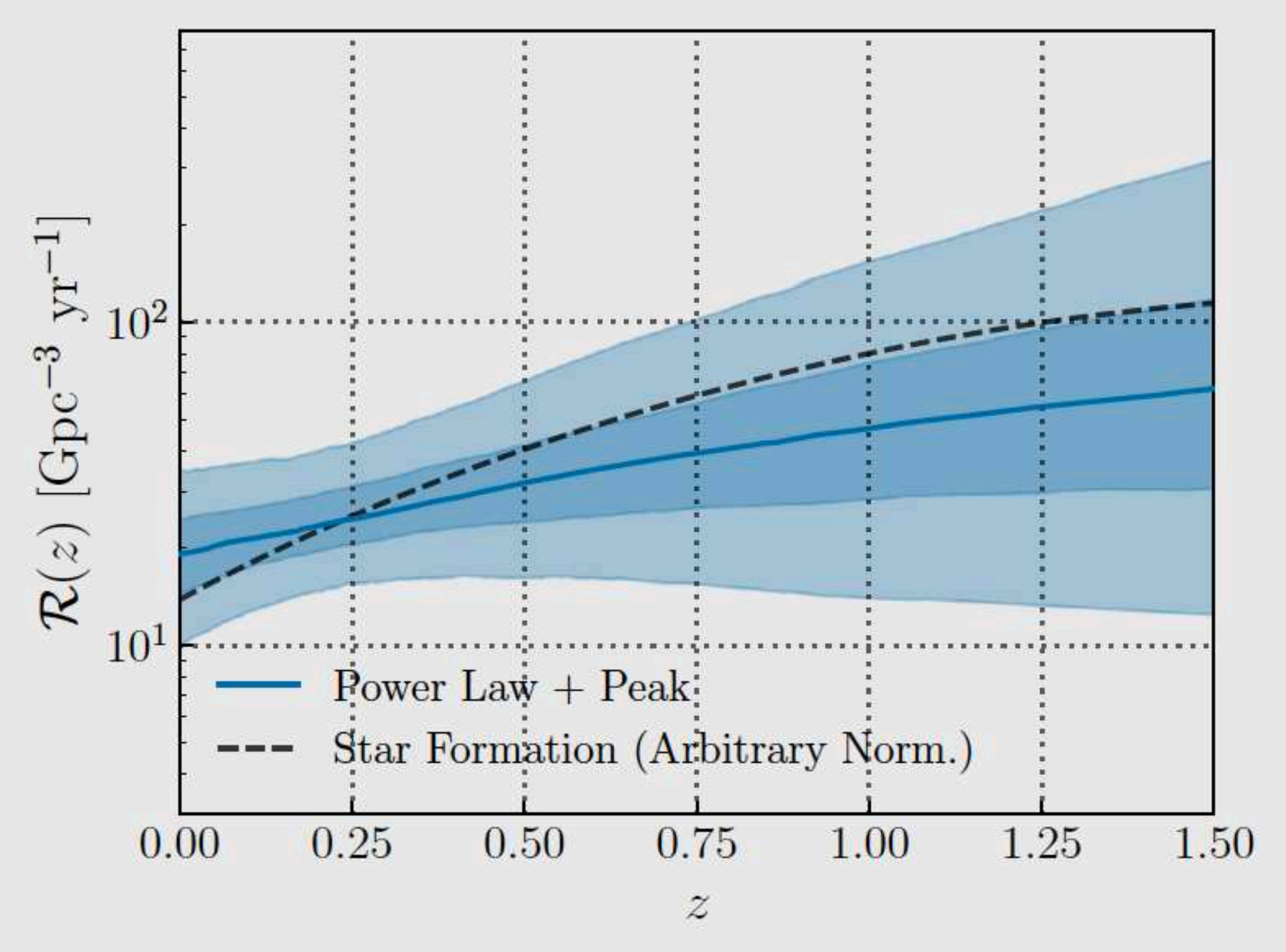
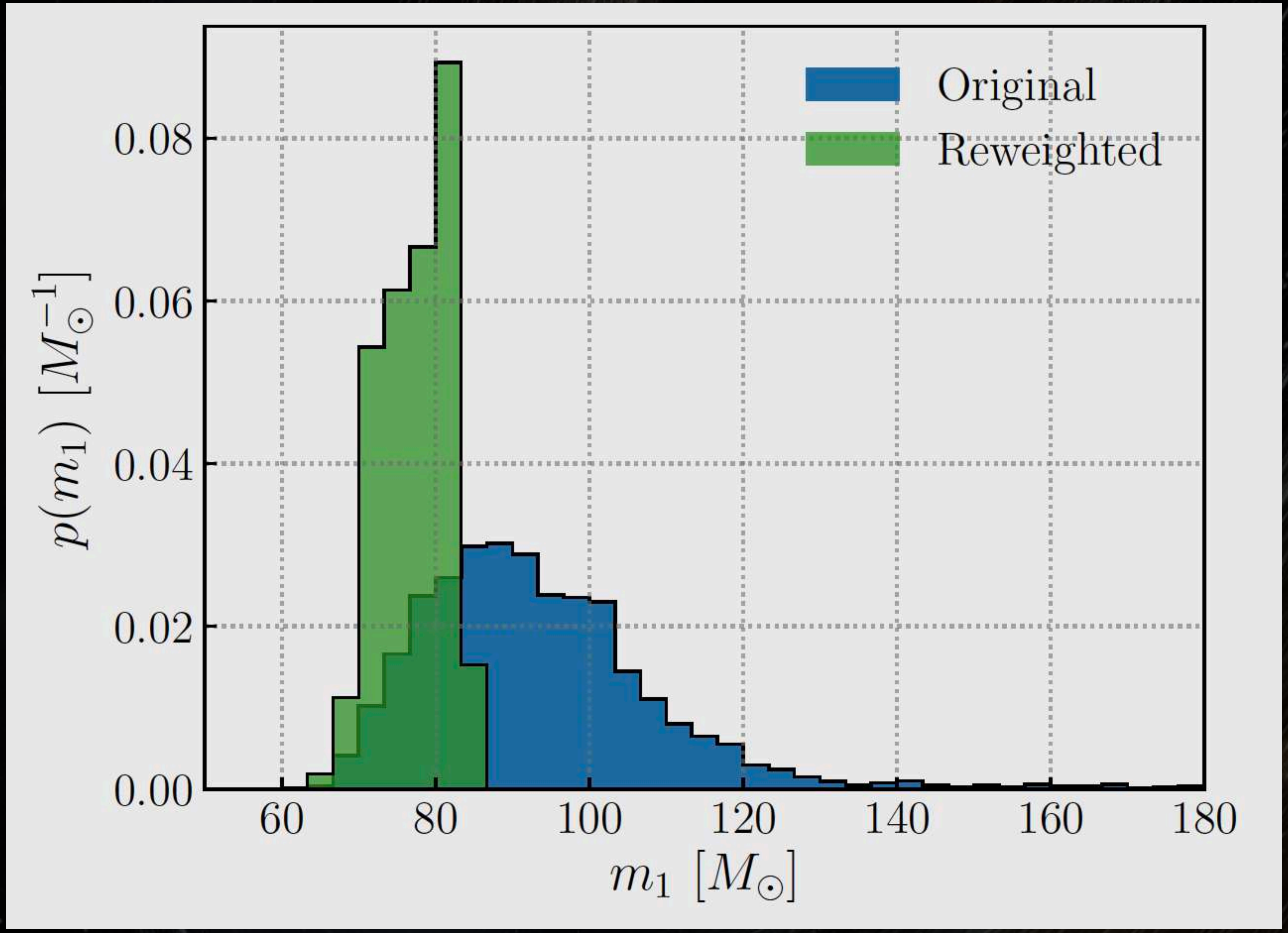
Merger rate updates

- Updated rates for BBH and BNS
- $R_{\rm BBH} = 23.9^{+14.9}_{-8.6}\ \mathrm{Gpc^{-3}yr^{-1}}$
- $R_{\rm BNS} = 320^{+490}_{-240}\ \mathrm{Gpc^{-3}yr^{-1}}$
- BBH merger rate density increases with redshift, but slower than the star formation rate density.



Population priors

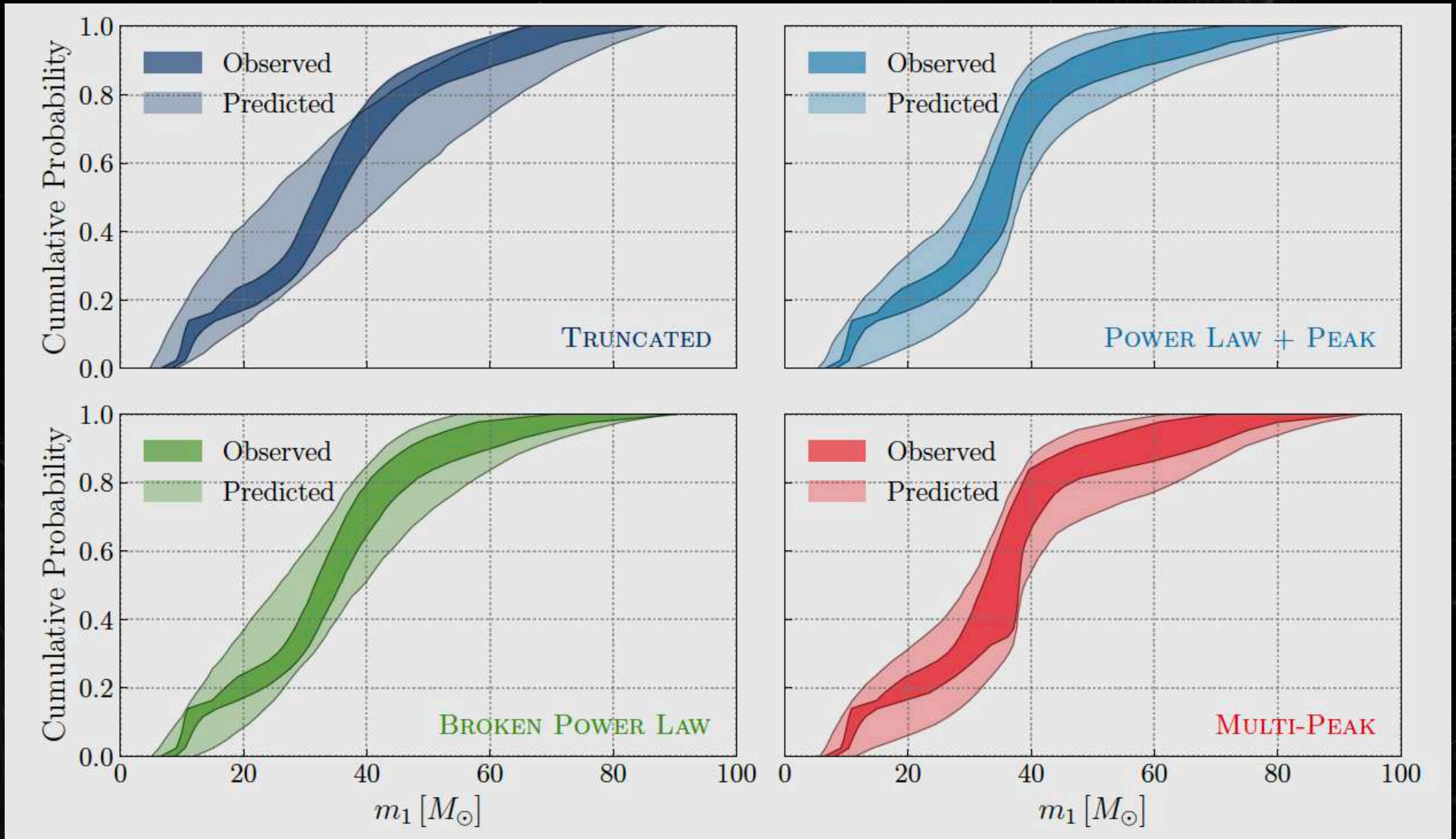
- With a growing population we can better understand the true mass distribution.
- Currently we use uniform priors for mass, but we can use the population mass distribution as the prior distribution instead!
- GW190521, largest binary black hole from O3a. Posterior support to lower masses ($m_1 < 83M_\odot$ at 90% credibility)



Understanding GW190412

- Excluding GW190814, GW190412 is the other event that has mass ratios confidently away from $q = 1$ with $q < 0.55$ at 99% credibility.
- 50% overlap in distribution with and without GW190412, likely low mass ratio tail instead of a subpopulation.

Mass model checks



Shaded regions - 90% credible interval

Spin mis-alignment checks

- Check involved truncating the $\chi_{\rm eff}$ distribution from $(\chi_{\rm eff}^{\rm min}, 1)$.
- Found $\chi_{\rm eff}^{\rm min} < 0$ at 99% credibility.