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NSF SPINS

Join SPINS

Results from the first part of LIGO-Virgo-KAGRA's fourth observing run

with a special

Focus on correlations

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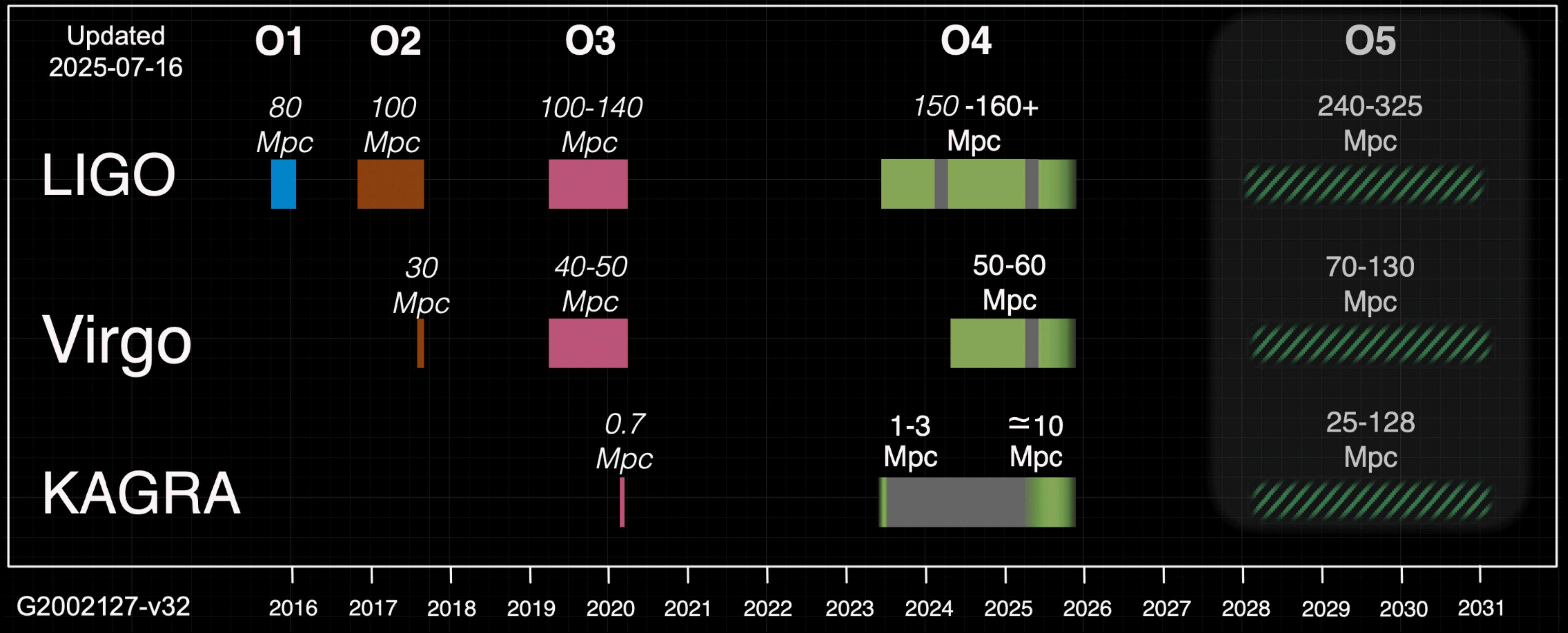
MIT KAVLI INSTITUTE

MIT

Where are we?

- Over the last 10 years, we have gone through 4 observing runs
- Detectors have steadily increased their sensitivity
- We have detected 218 binary mergers (+ ~150 candidates in O4b and O4c)
  - Mostly binary black holes
  - Two neutron star binaries
  - Six neutron star - black hole binaries

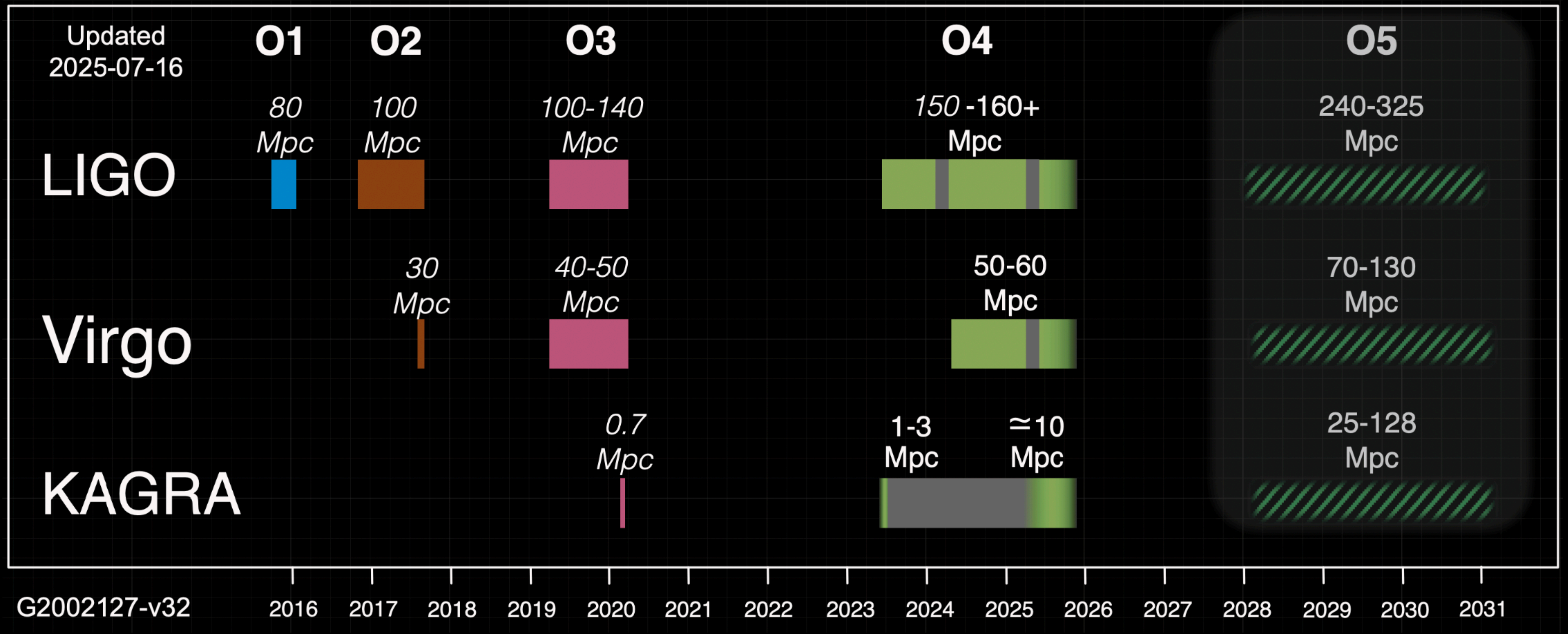


LVK https://observing.docs.ligo.org/plan/

Note: you might see different numbers quoted. That is because some papers select by false alarm ratios, others by the probability of a source to be astrophysical

Where are we?

- We have detected 218 binary mergers (+ ~150 candidates in O4b and O4c)
    - Mostly binary black holes
    - Two neutron star binaries
    - Six neutron star - black hole binaries
- Each source has unique properties that can teach us about its history, encoded in the gravitational waves we receive



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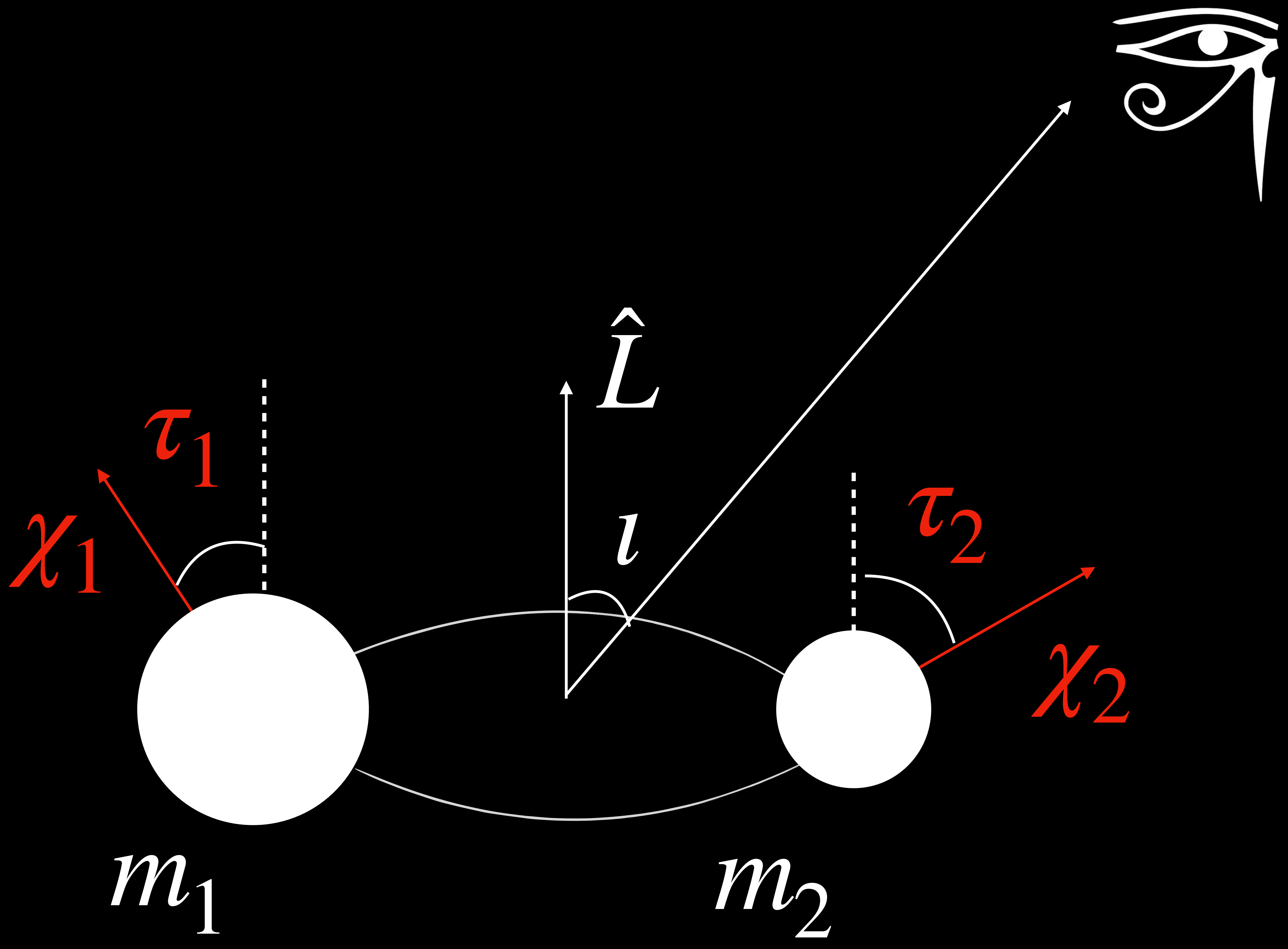
Gravitational-wave anatomy: source

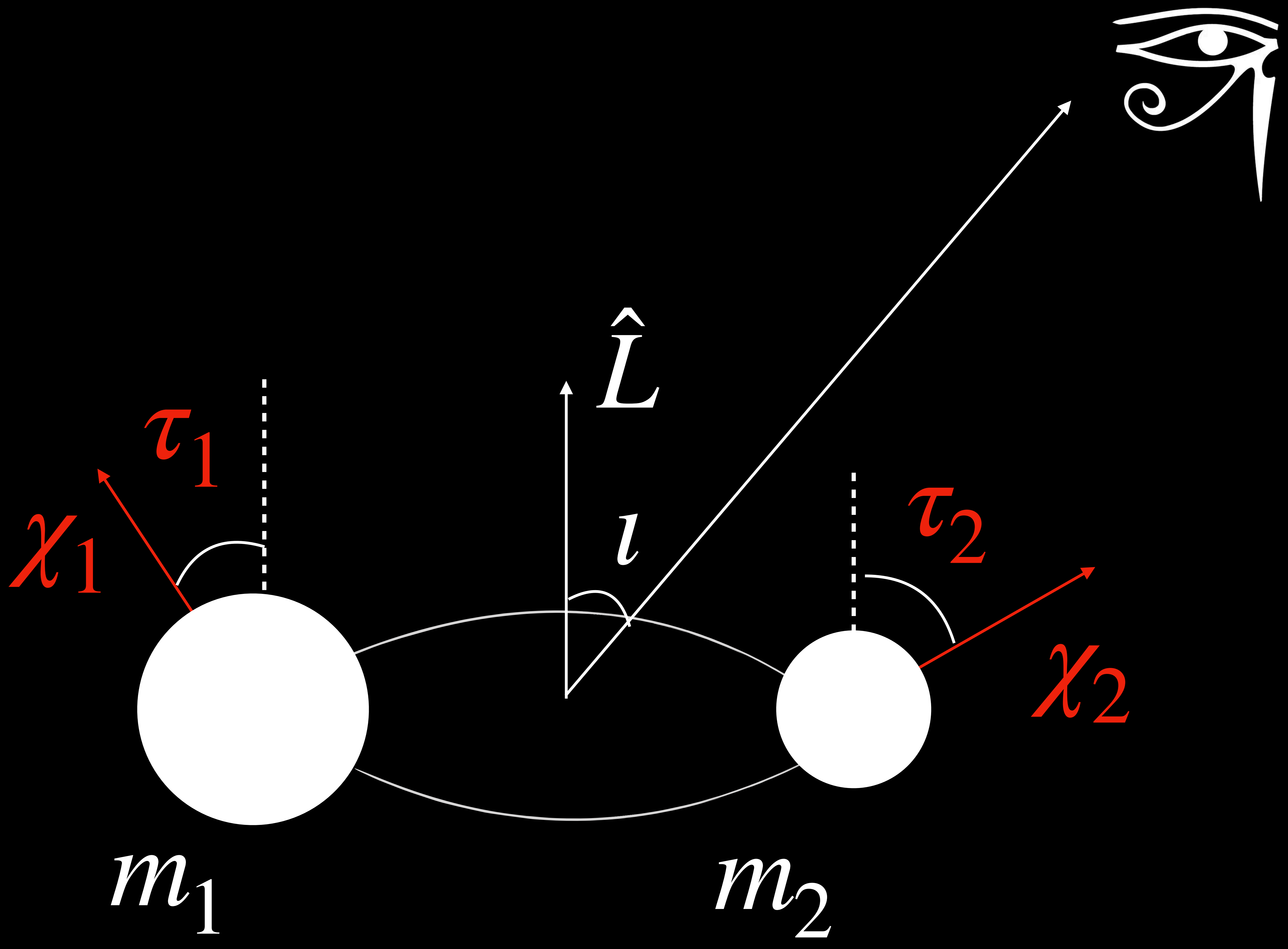


Index 1 for the most massive object

Gravitational-wave anatomy: source

Chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



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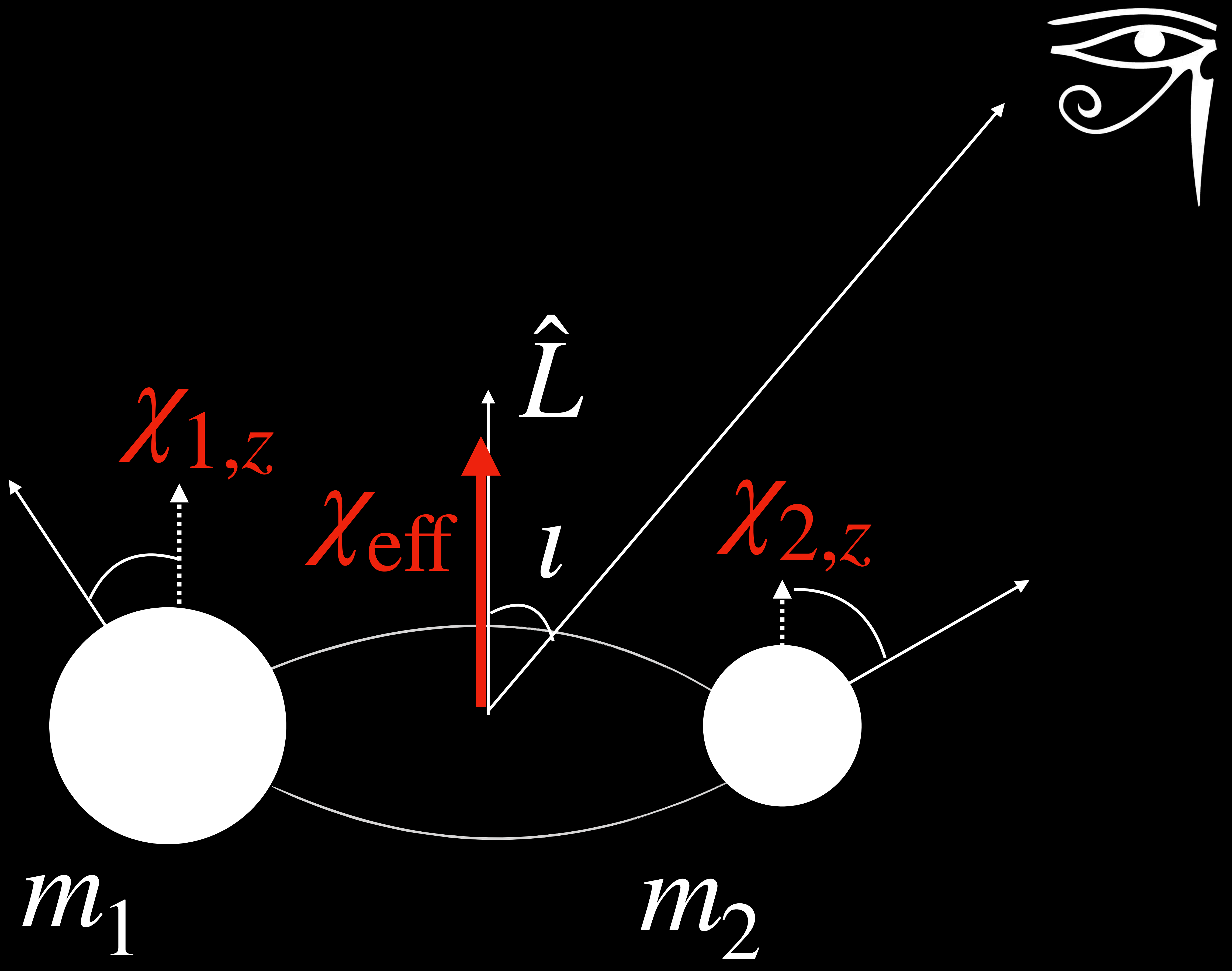
Gravitational-wave anatomy: source

Chirp mass

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

Chi effective

$$\chi_{\text{eff}} = \frac{m_1 \chi_{1,z} + m_2 \chi_{2,z}}{m_1 + m_2}$$



Index 1 for the most massive object

From single events to populations

- Now that we have hundreds of sources, we can start learning about the underlying astrophysical populations of compact binary coalescences

From single events to populations

- Now that we have hundreds of sources, we can start learning about the underlying astrophysical populations of compact binary coalescences
- Do we know what to expect?

From single events to populations

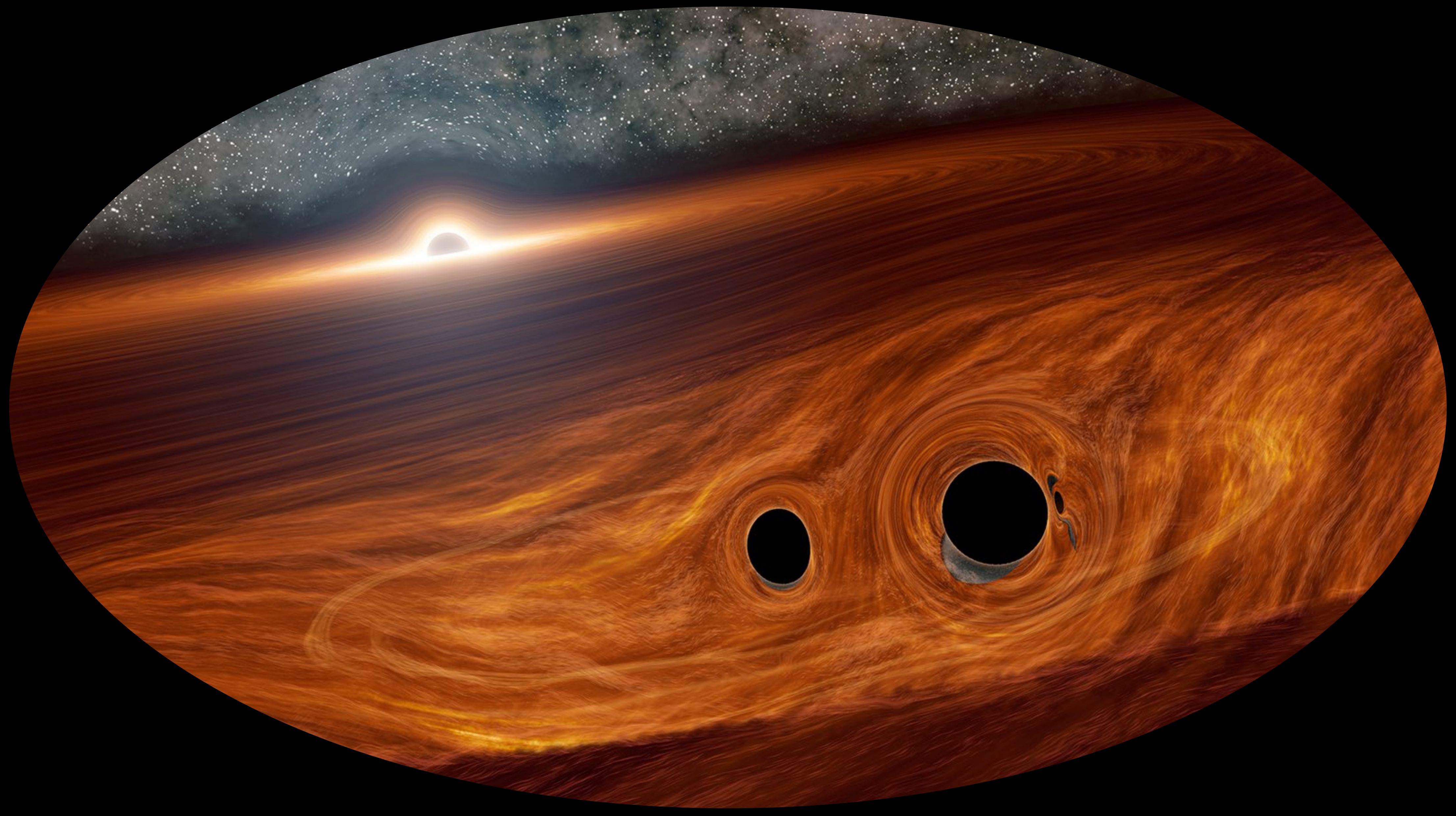
- Now that we have hundreds of sources, we can start learning about the underlying astrophysical populations of compact binary coalescences
- Do we know what to expect?
- It’s complicated…

Expectations pre-2015

- Before the discovery of gravitational waves, most of the community considered two formation scenarios
  - Common envelope evolution in field binaries (common envelope)
  - Dynamical formation in globular clusters

More recent developments

- In a field binary, all mass transfer episodes might be stable. Or the progenitor stars might not even exchange mass due to efficient mixing (chemically homogeneous evolution)
- Dynamical formation might happen not only in globular clusters but also in nuclear star clusters or the disks around supermassive black holes. Triples might contribute significantly to the rates



Credit: Caltech/R. Hurt

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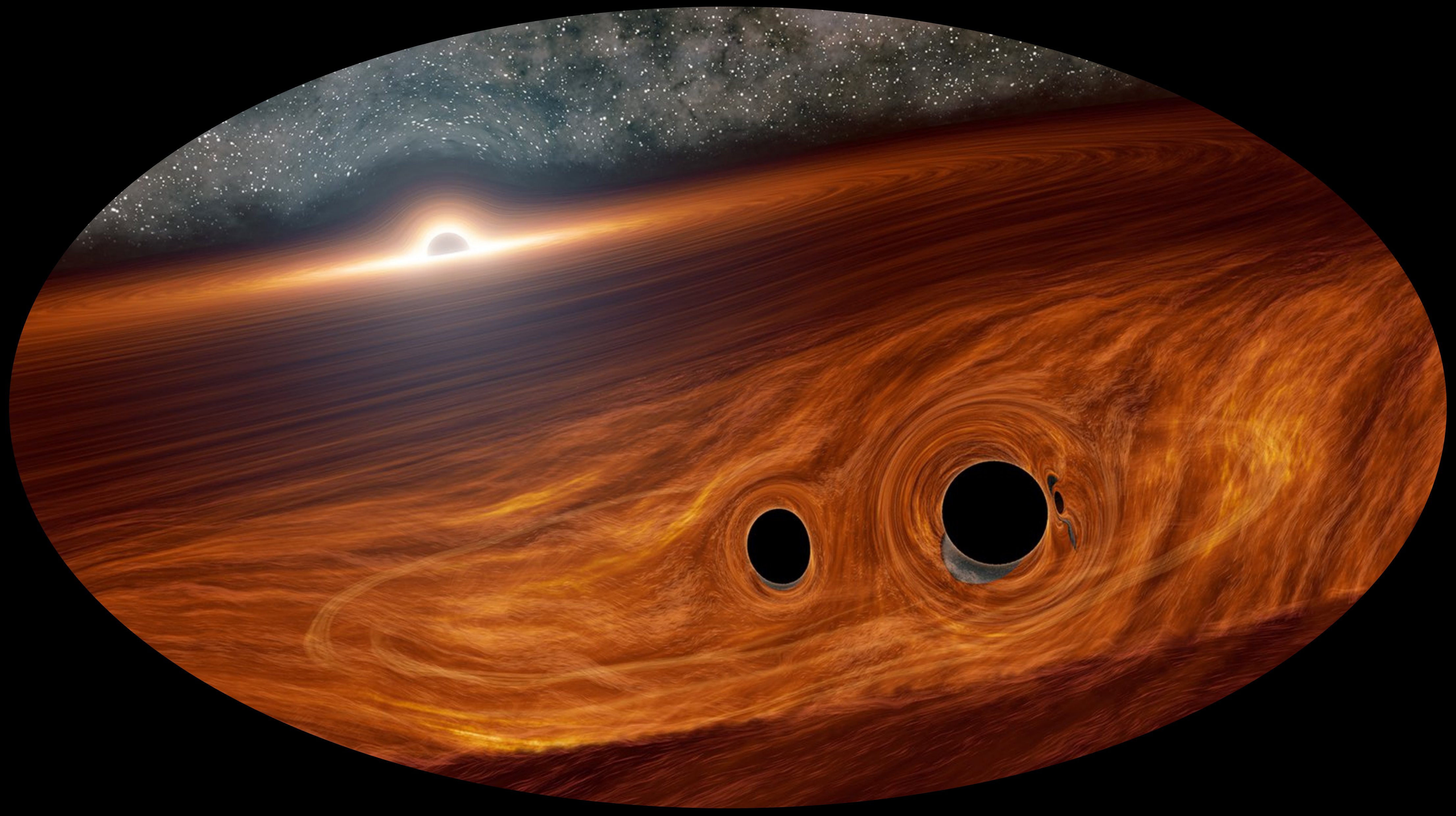
- Or Pop III stars? Primordial BHs?



Credit: Caltech/R. Hurt

How do we find out?

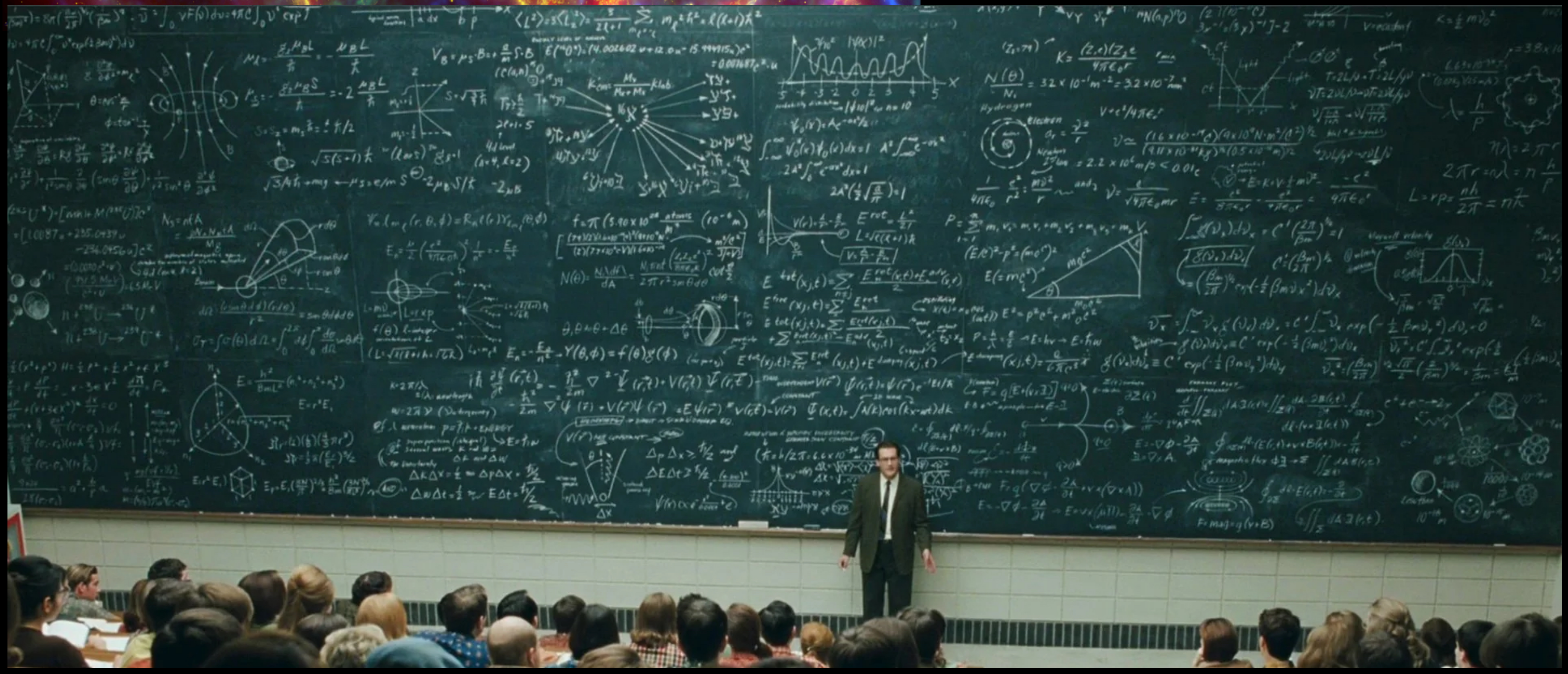
- Theoretical and numerical simulations can predict the properties that compact binary systems from different channels should have
- "Just" compare those with the properties of the population we are detecting!

POSYDON

MESA

CMC
Cluster
Monte Carlo

COMPAS

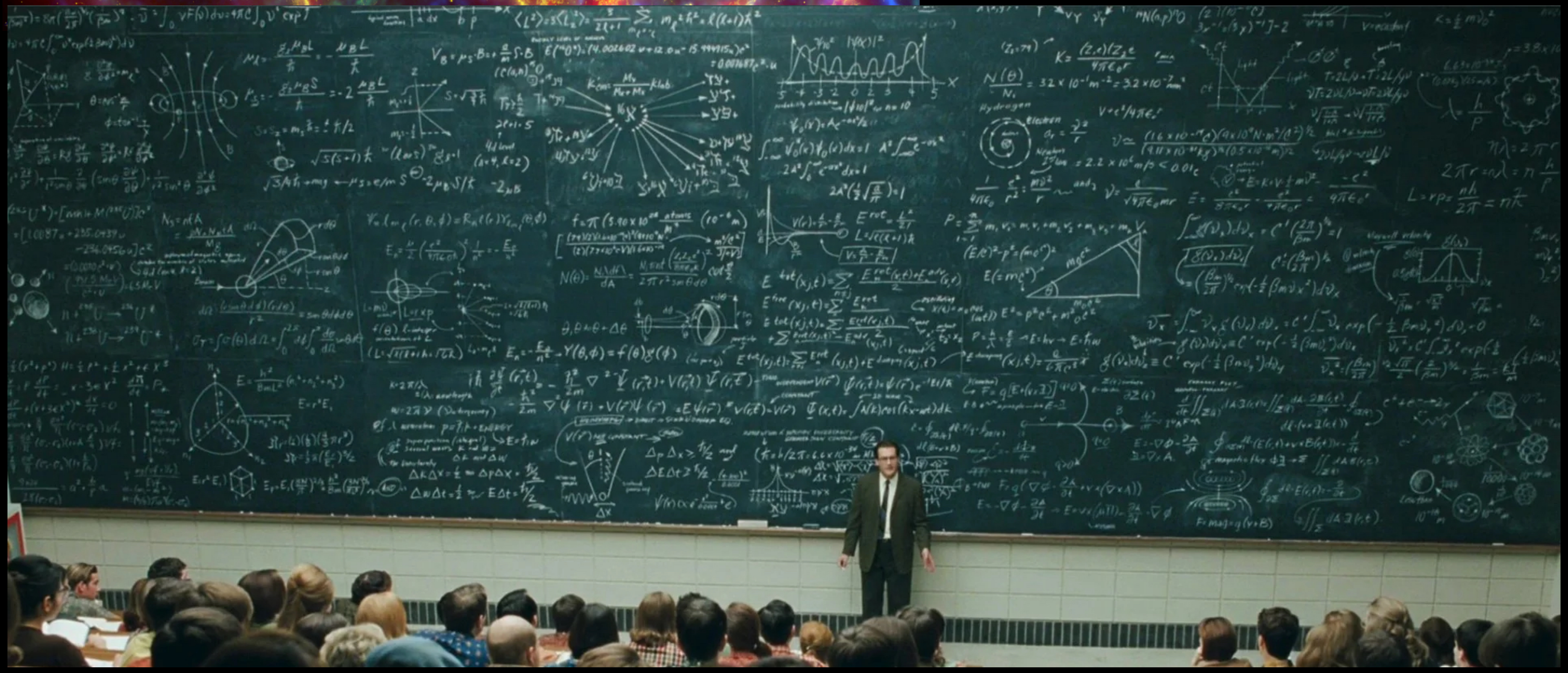


Credits: Focus Features

PopSynth: Posydon, Andrews et al. 2024; MESA, Paxton et al. 2015; COMPAS Stevenson et al. 2017; CMC, Rodriguez+ 2021

How do we find out?

- Theoretical and numerical simulations can predict the properties that compact binary systems from different channels should have
- "Just" compare those with the properties of the population we are detecting!
- The simulations are costly and don't capture all of the physics



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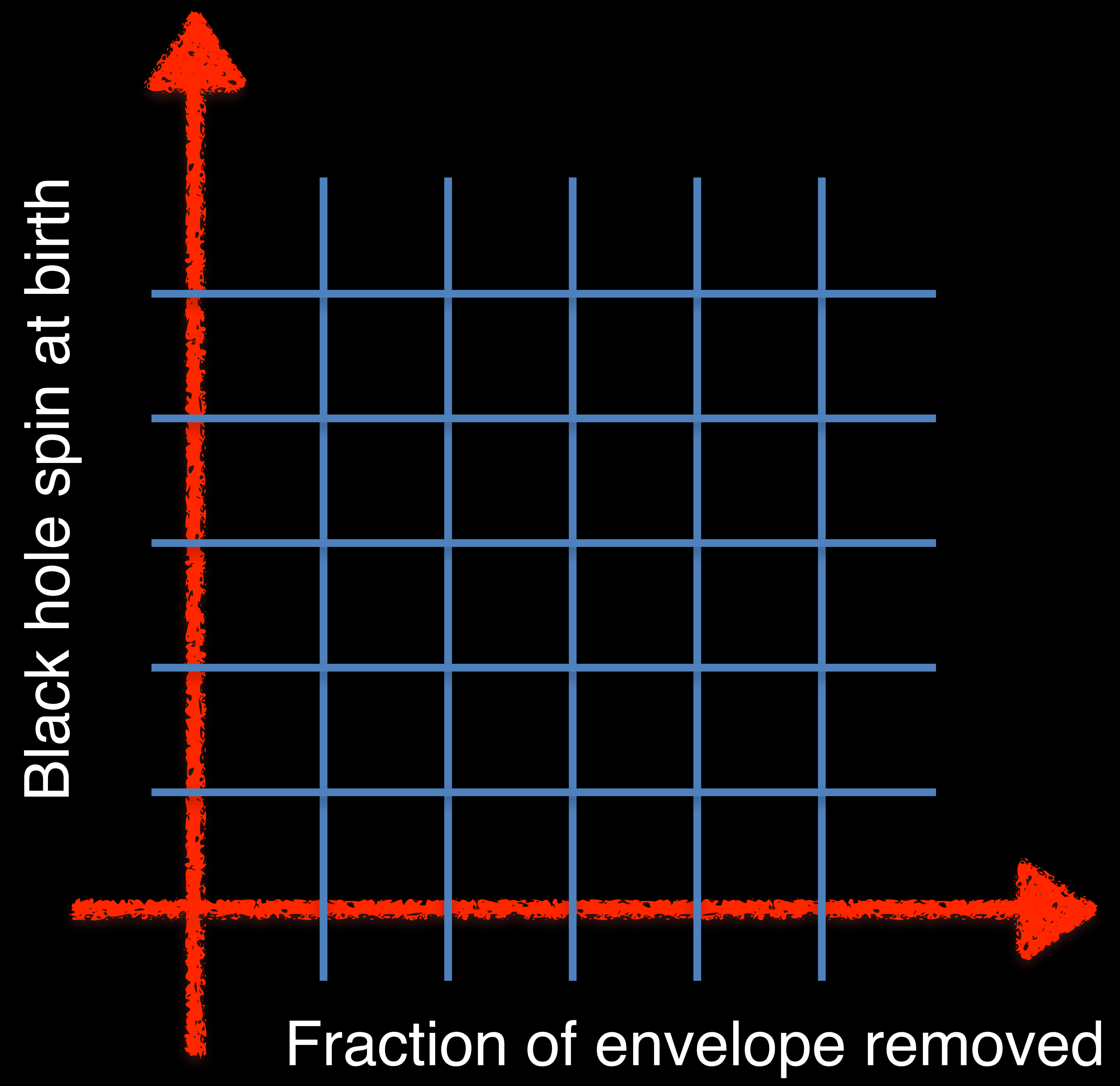
Astrophysical models!

- Direct approach (Zevin+ Apj 910 152)
  - Models for common envelope (CE), chemically homogeneous evolution (CHE), stable mass transfer (SMT), globular clusters (GC), nuclear star clusters (NSC)
  - Parametrize by fraction of common envelope that is removed and black hole spin at birth



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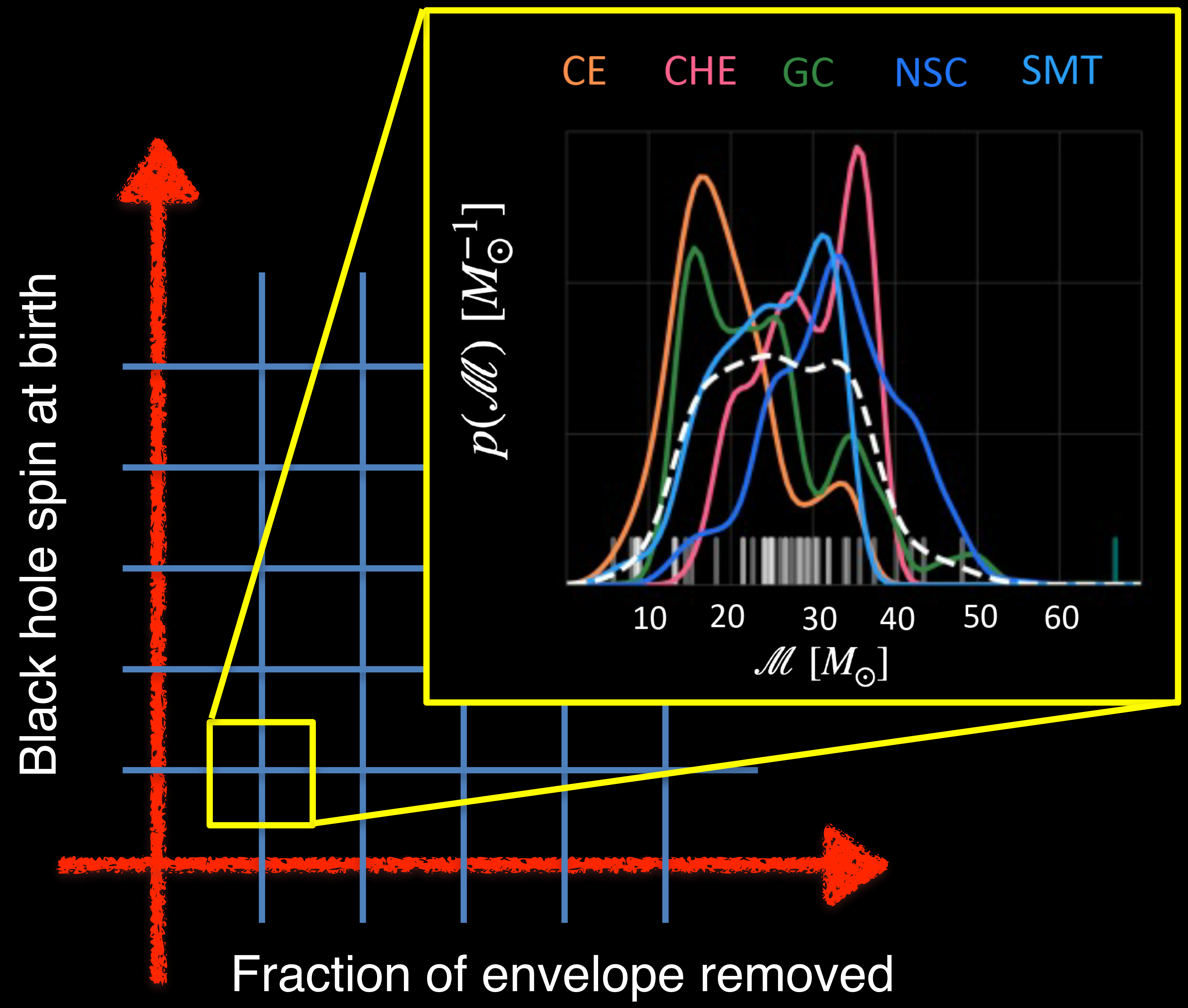

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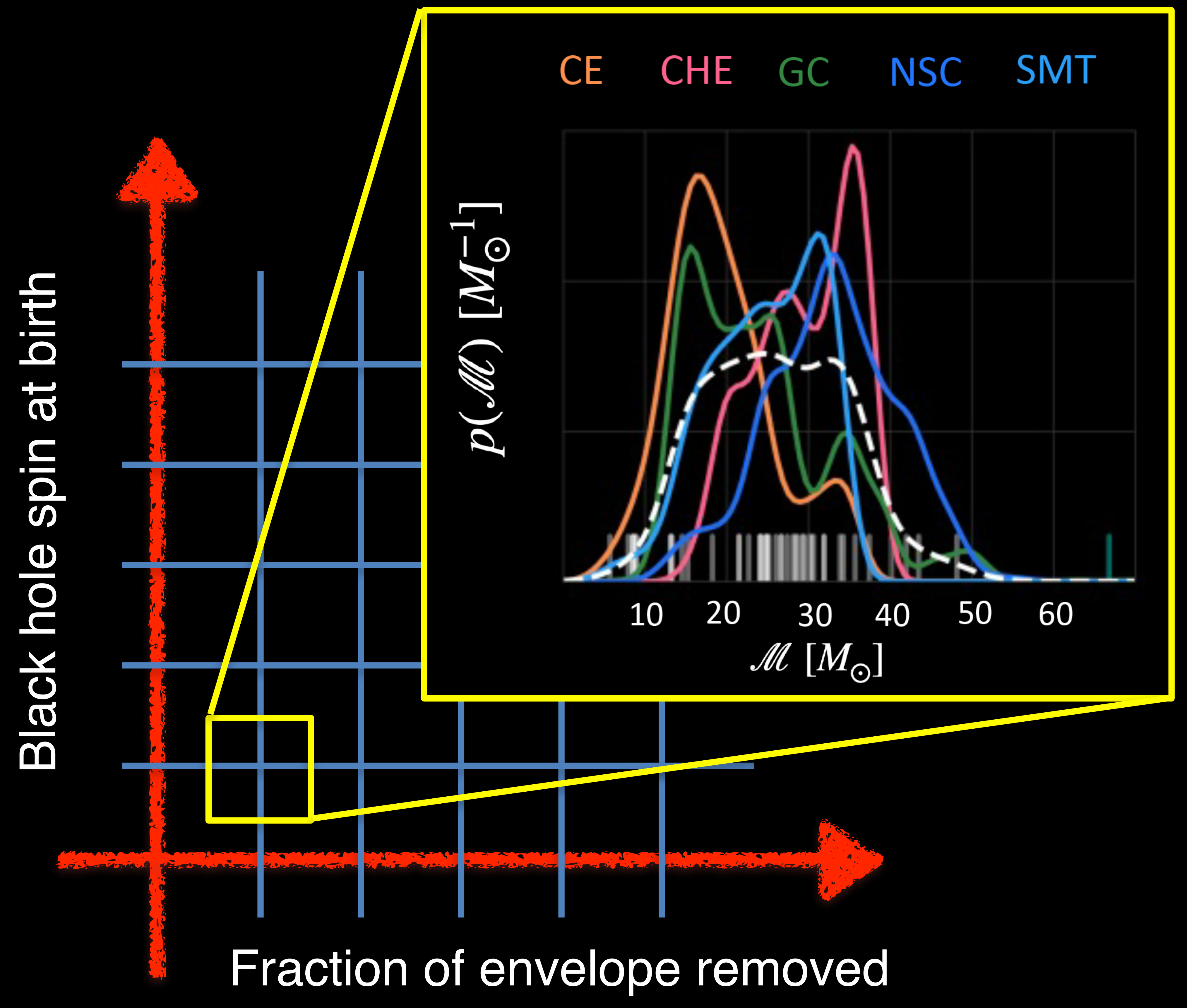
  - Parametrize by fraction of common envelope that is removed and black hole spin at birth
  - Compare with the data on a grid or using machine learning emulators (Colloms+ ApJ 988 189)



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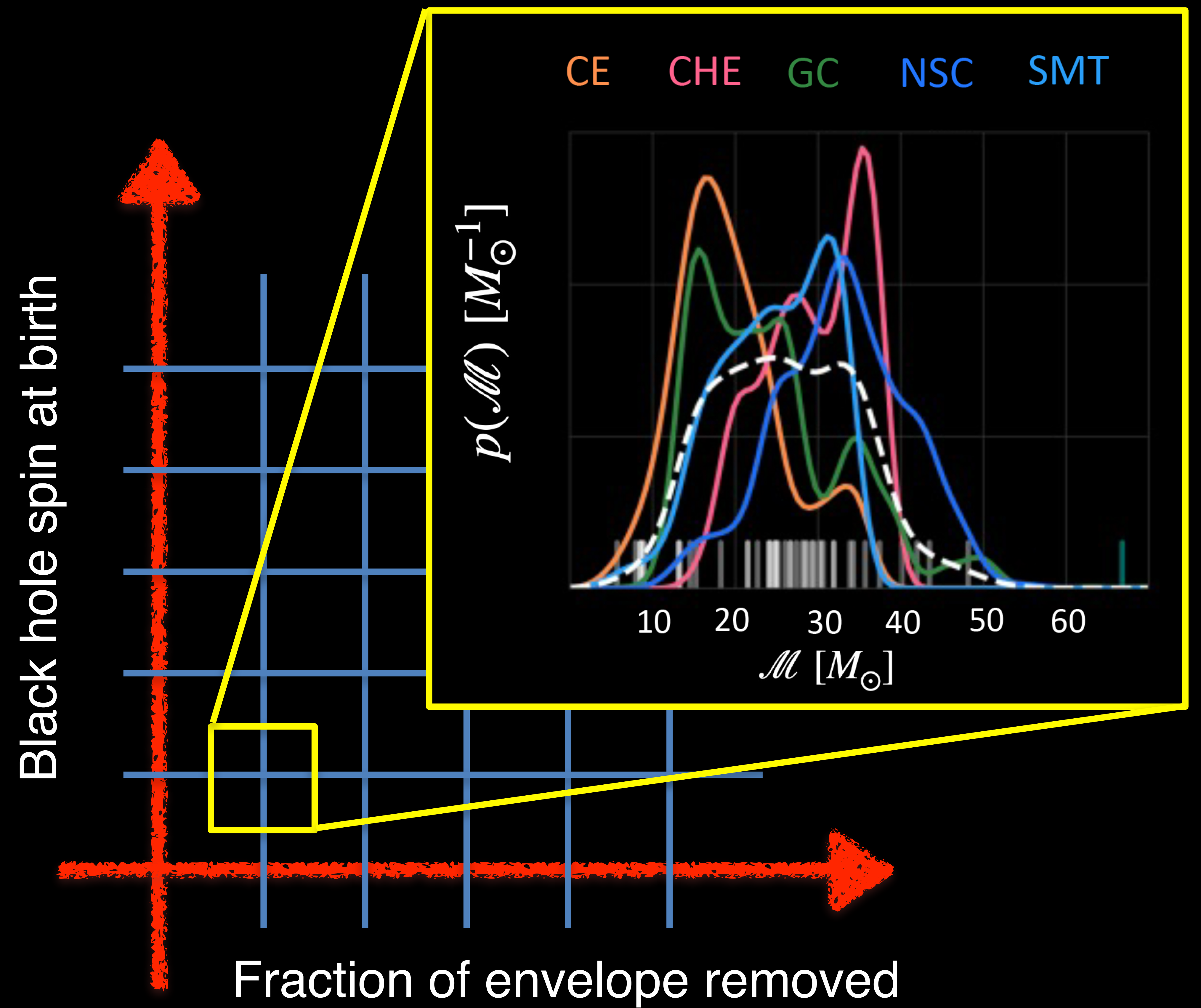
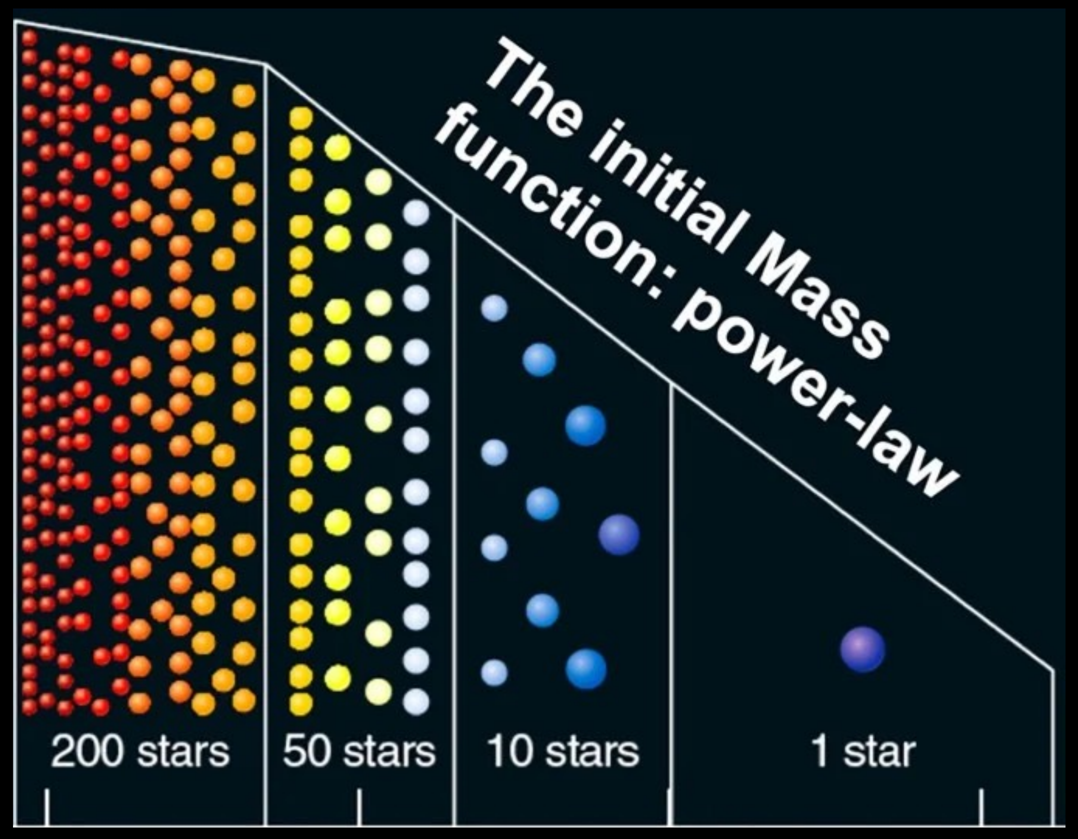
Astrophysical models!

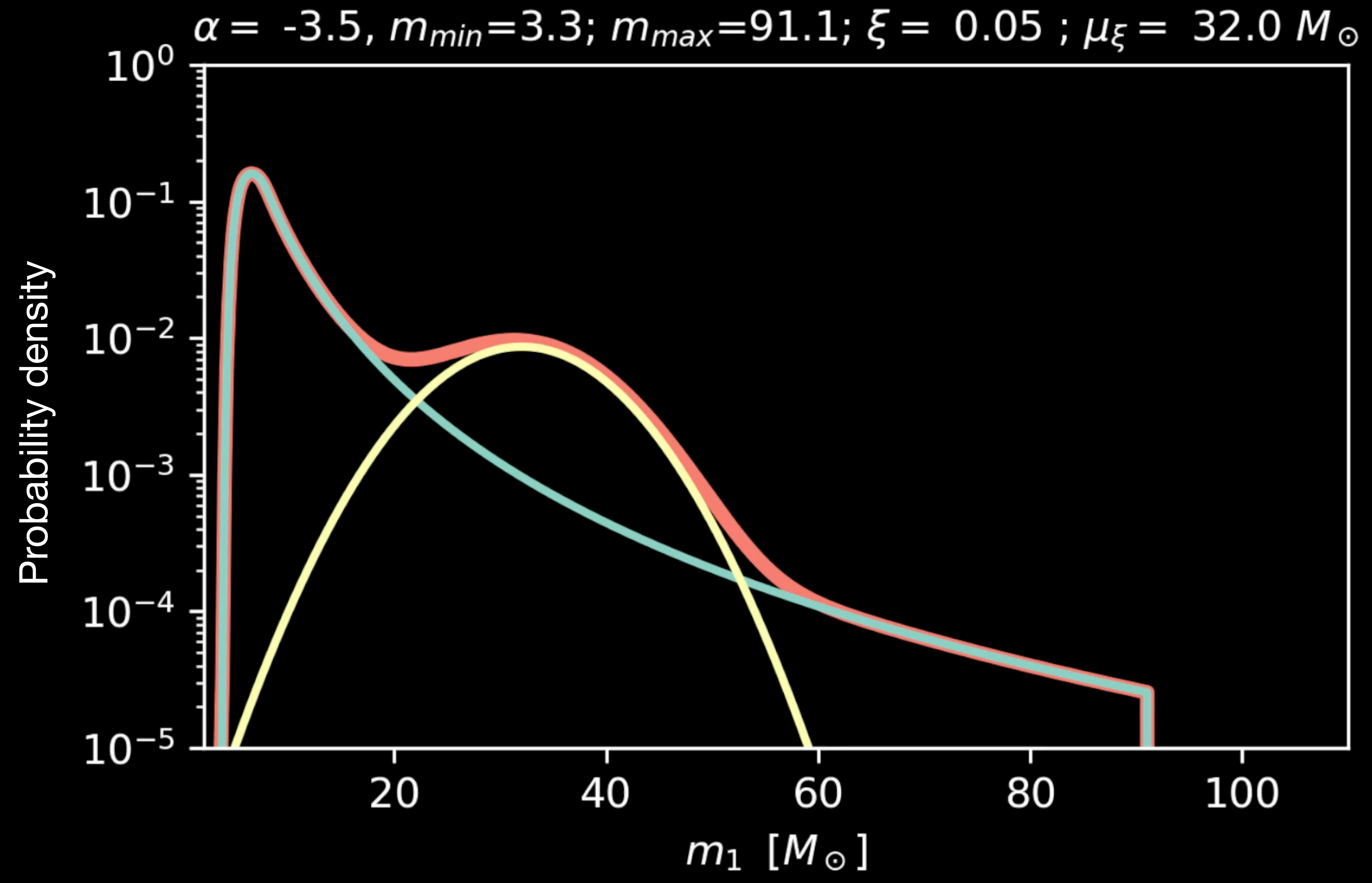
- Analysis on O3a data (2019): at least two astrophysical channels are needed
- Is this the way forward?
- In Cheng+ ApJ 955 127 we revealed limitations in this approach
  - The astrophysical models are rough approximations
  - We are not likely to have complete set of astrophysical models
  - This can introduce very large biases



Phenomenological models

- Another avenue is to use phenomenological models, inspired by astrophysical expectations
- For example, the astrophysical distribution of the black hole mass can be parametrized as a combination of a power law and a gaussian





Pulsation Pair Instability

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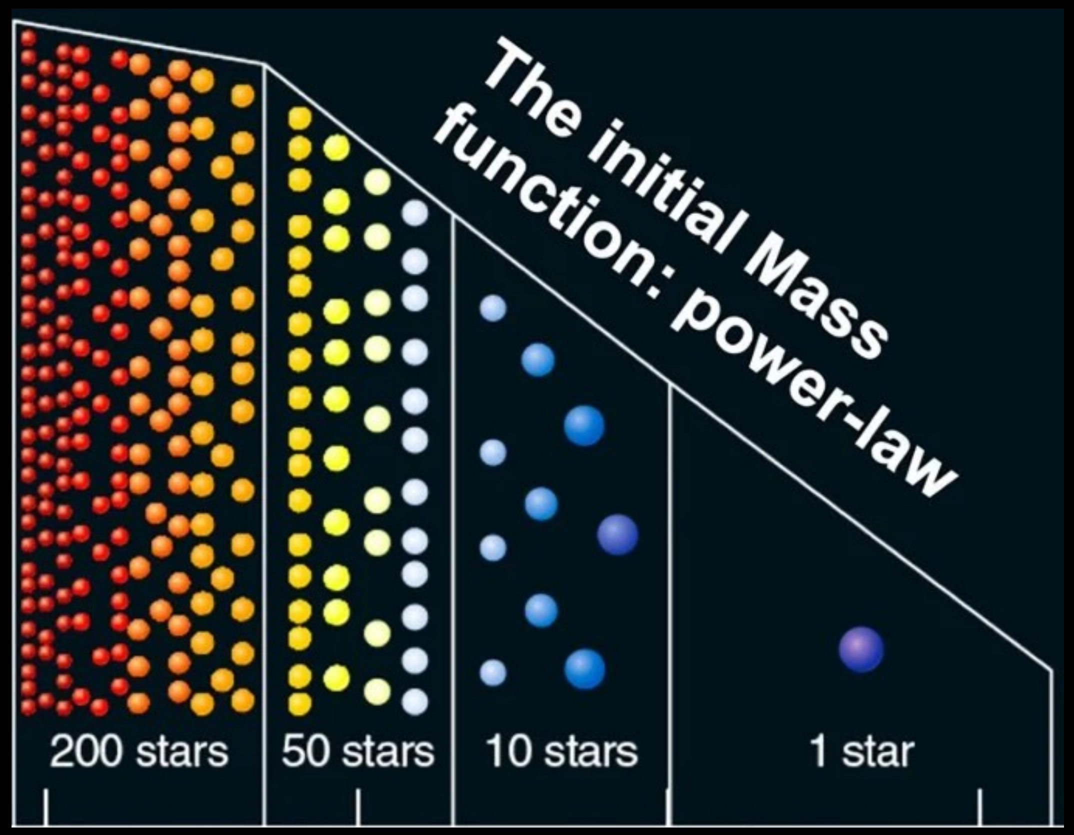
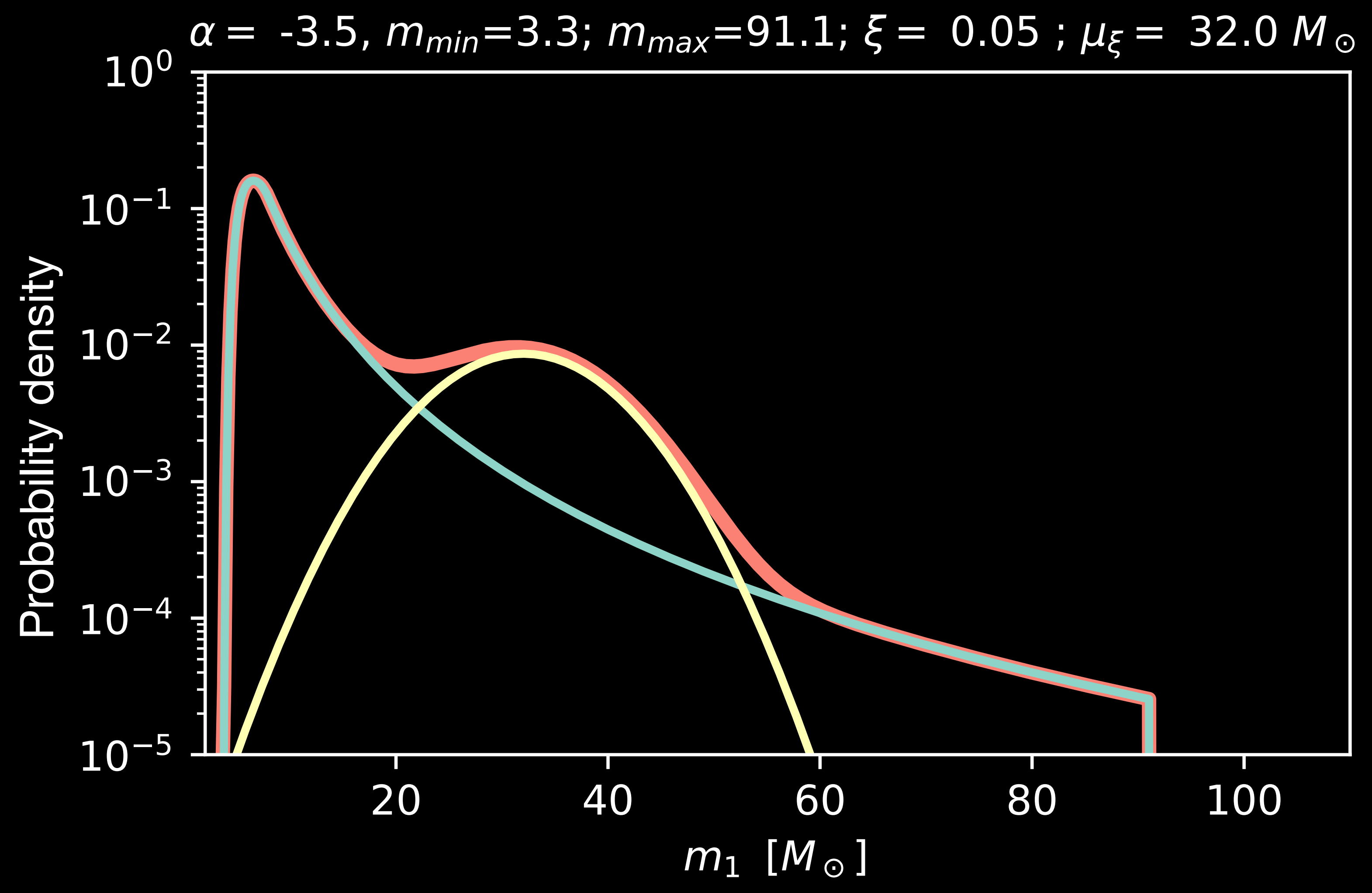
Phenomenological models

- Another avenue is to use phenomenological models, inspired by astrophysical expectations
- For example, the astrophysical distribution of the black hole mass can be parametrized as a combination of a power law and a gaussian
- Will skip all technical details, see e.g, Vitale+ 2007.05579, Mandel+ 1809.02063, LIGO/Virgo/KAGRA (LVK) catalog 2508.18083 for more details



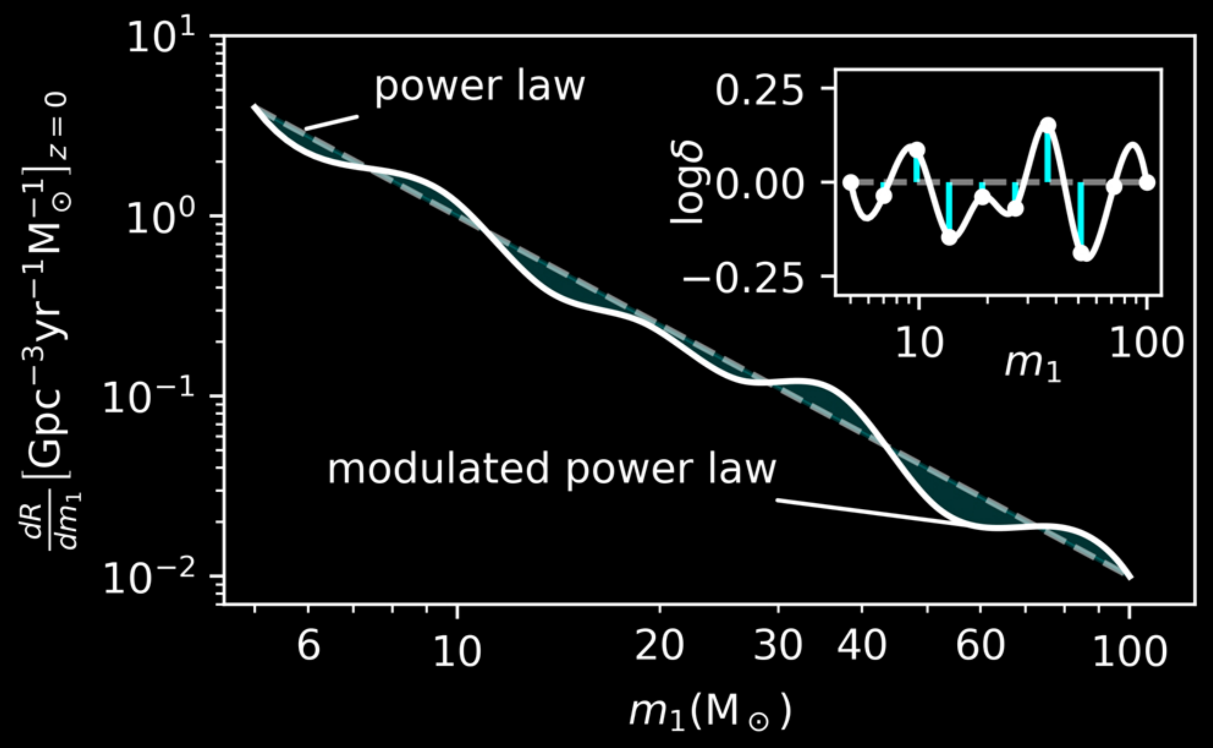


Pulsation Pair Instability

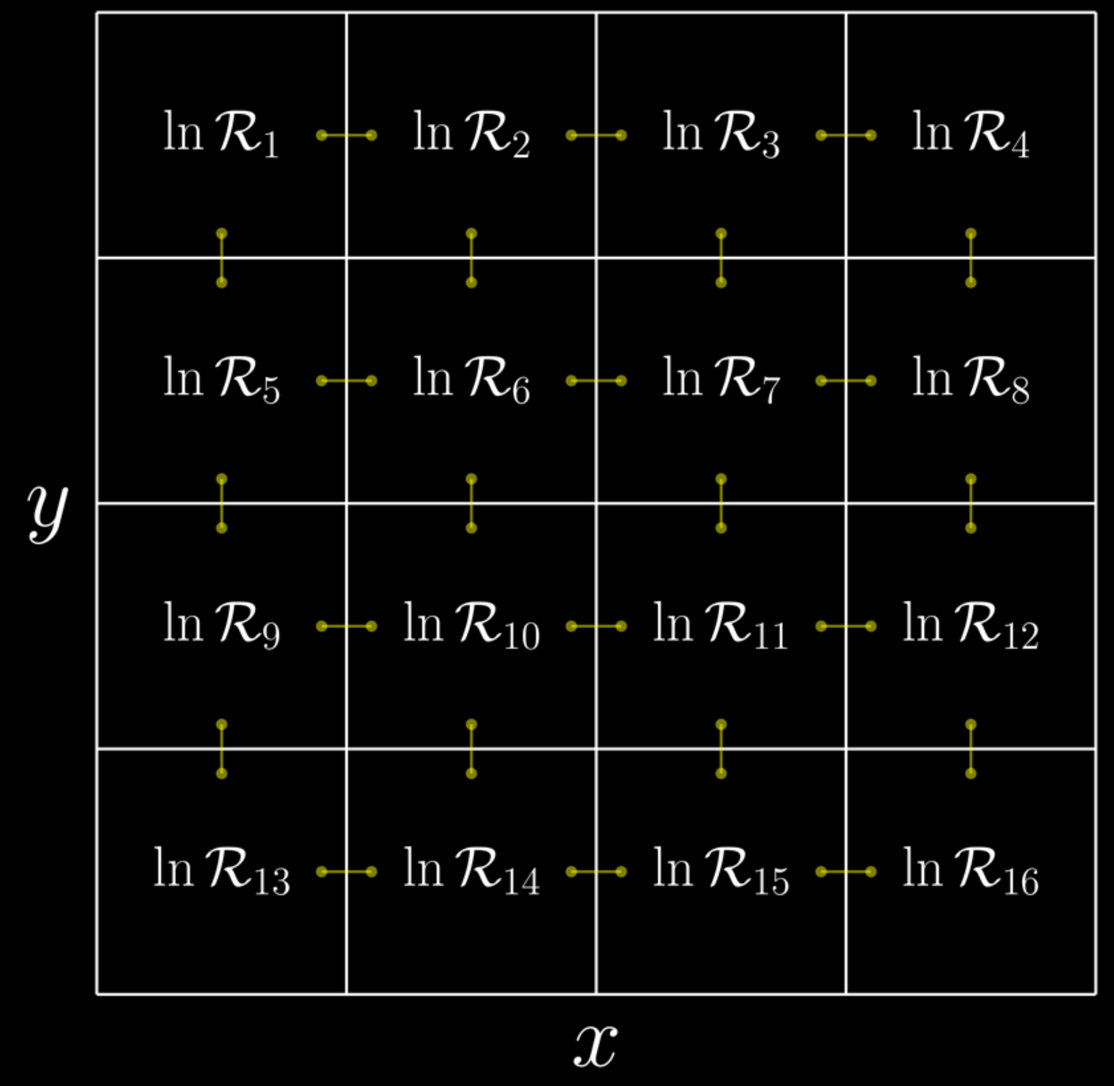
Agnostic models

- To allow for more complicated distributions we use “unmodeled” approaches
- A variety of possibility exists, e.g.
  - Splines (alone or in mixture models)
  - Autoregressive models
  - Gaussian mixture models
  - Gaussian processes
  - New ideas every day

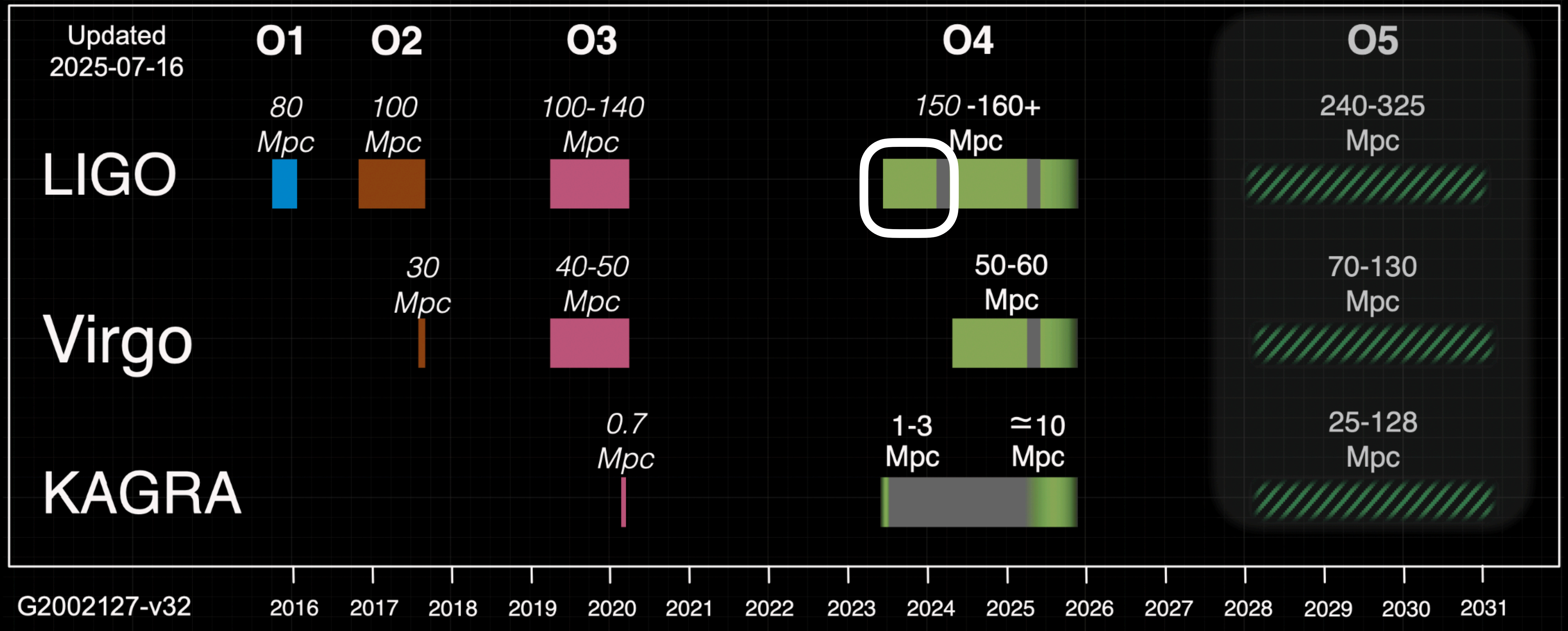
Edelman+ ApJ 946 16



Heinzel+ PRD 111, 063043



Models: B-Spines, Edelman+ (2023) Godfrey+ 2304.01288; AR, Callister+ PRX 14 2 021005; GMM, Mandel+ MNRAS 465 3254; Tiwari CQG 38 155007; GP, Ray + ApJ 957 37; Heinzel+ PRD 111, 063043



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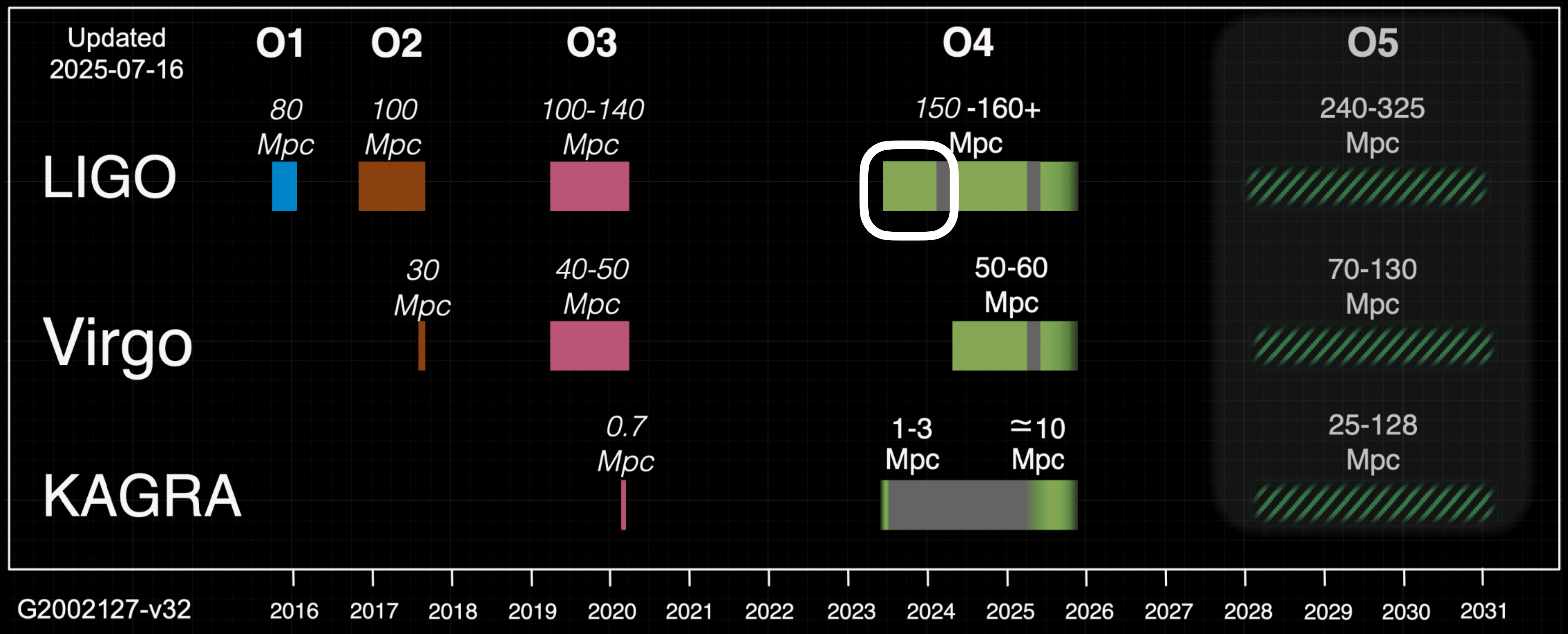
Results from GWTC-4

LVK 2508.18080, 2508.18081, 2508.18082, 2508.18083



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Results from GWTC-4

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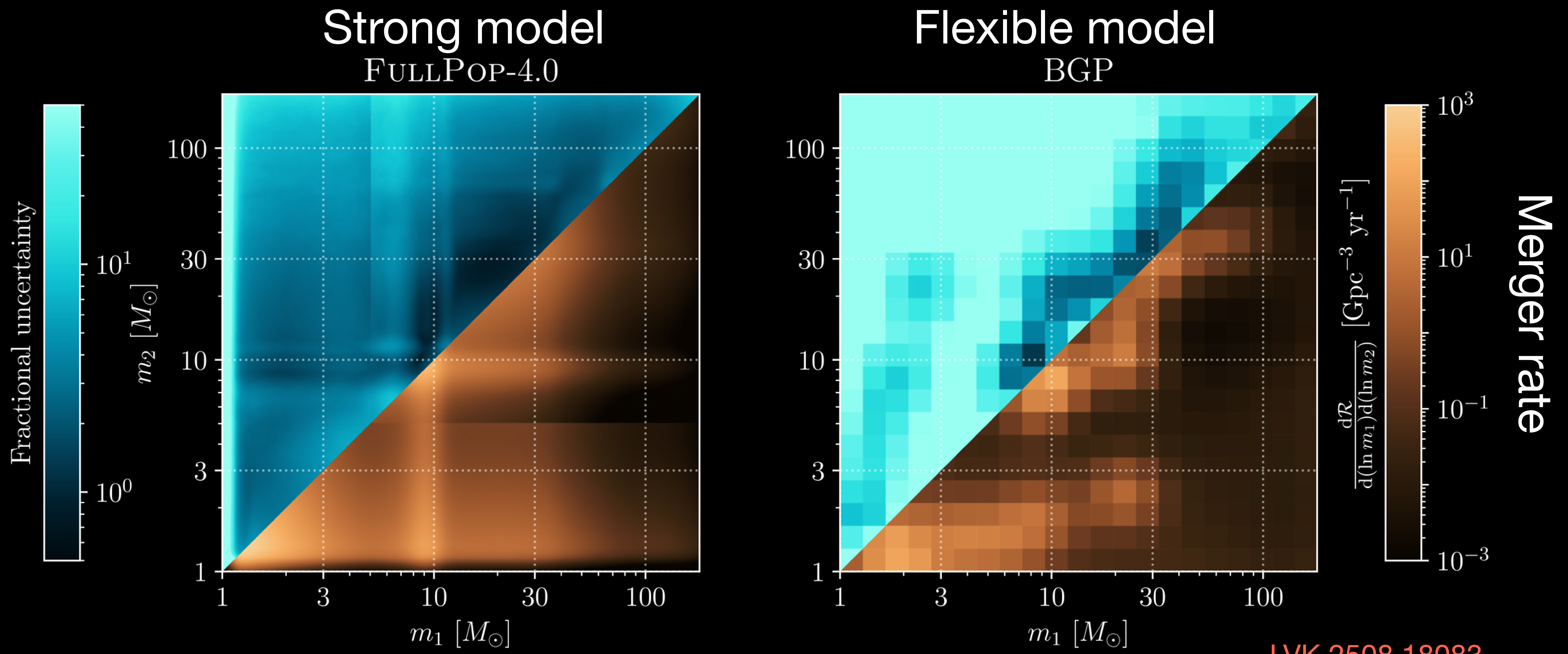
There is a ton of science in these papers, I cannot possibly cover it all.

Full spectrum mass distribution

- A strong and flexible model are run and compared on **all** types of binaries (not just binary black holes)



Models: FullPop-4.0, Fishbach et al. 2020; Farah et al. 2022; Mali & Essick 2025. BGP, Ray et al. 2023a.

LVK 2508.18083

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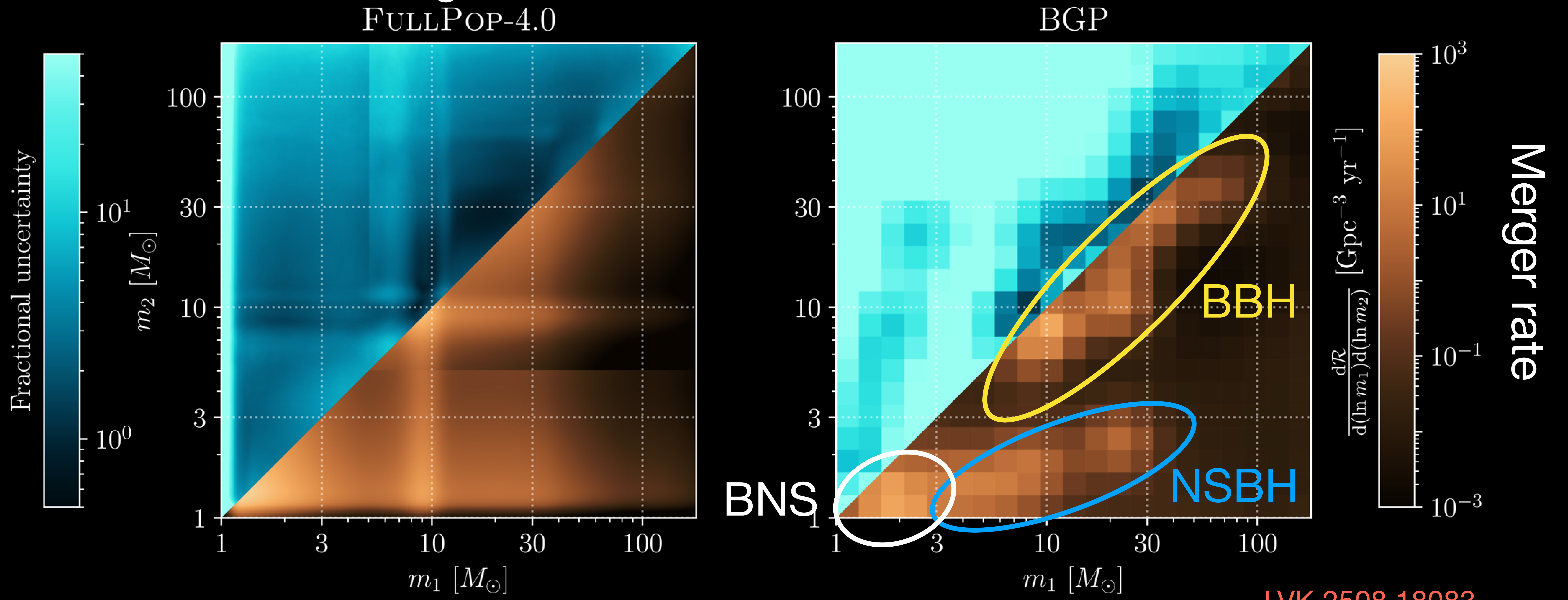
Strong model | Flexible model



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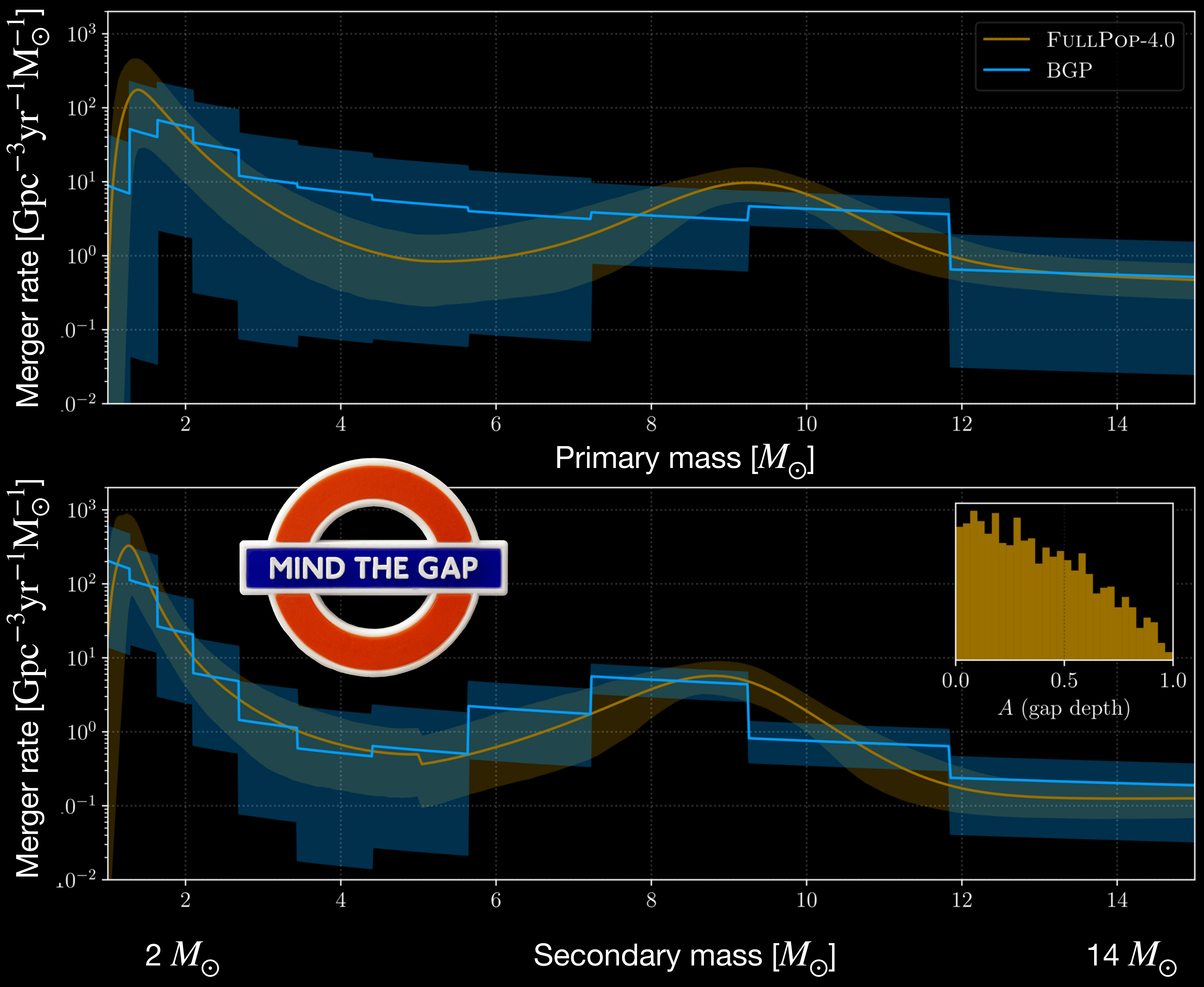
LVK 2508.18083

Full spectrum mass distribution

- The overall peak in the merger rate is below 2 $M_\odot$ (i.e., neutron stars)
- The peak for the black holes mass function is around 8-10 $M_\odot$
- Electromagnetic observations had suggested a possible gap between neutron stars and black holes
  - The LVK finds that the merger rate decreases there but doesn't go to zero
  - No evidence for an empty gap

LVK 2508.18083



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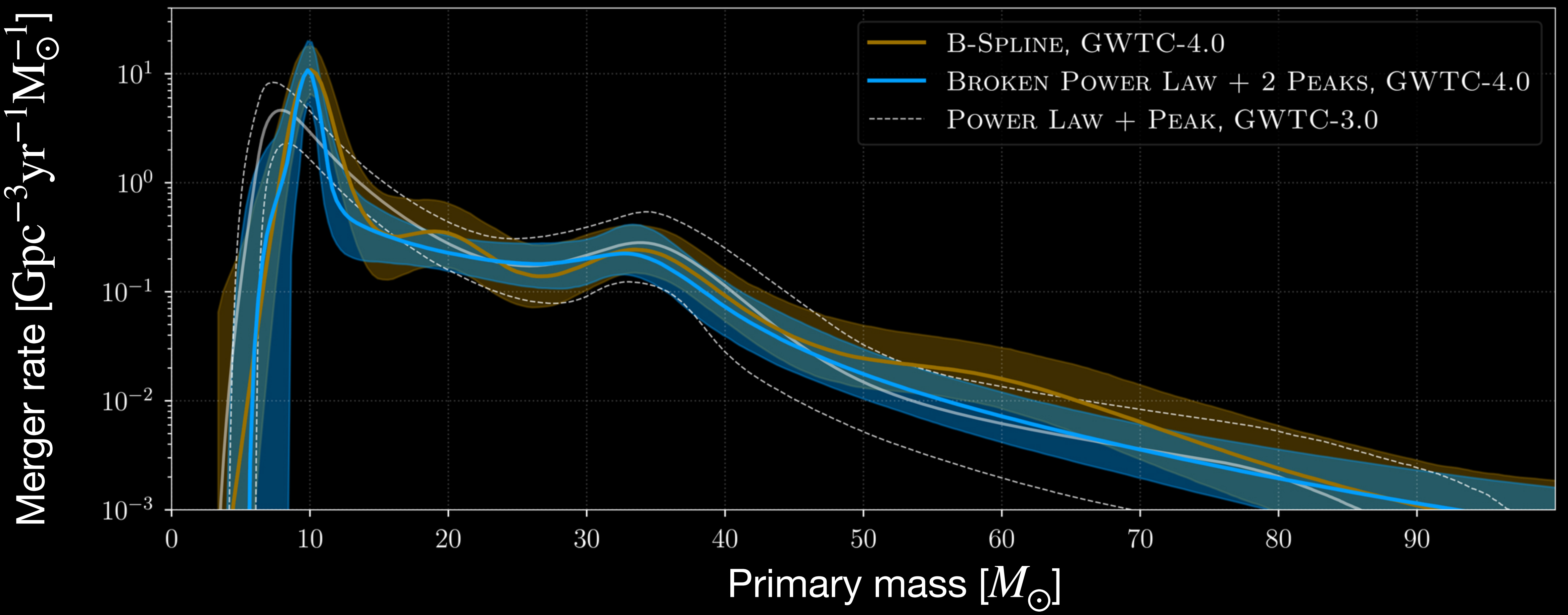
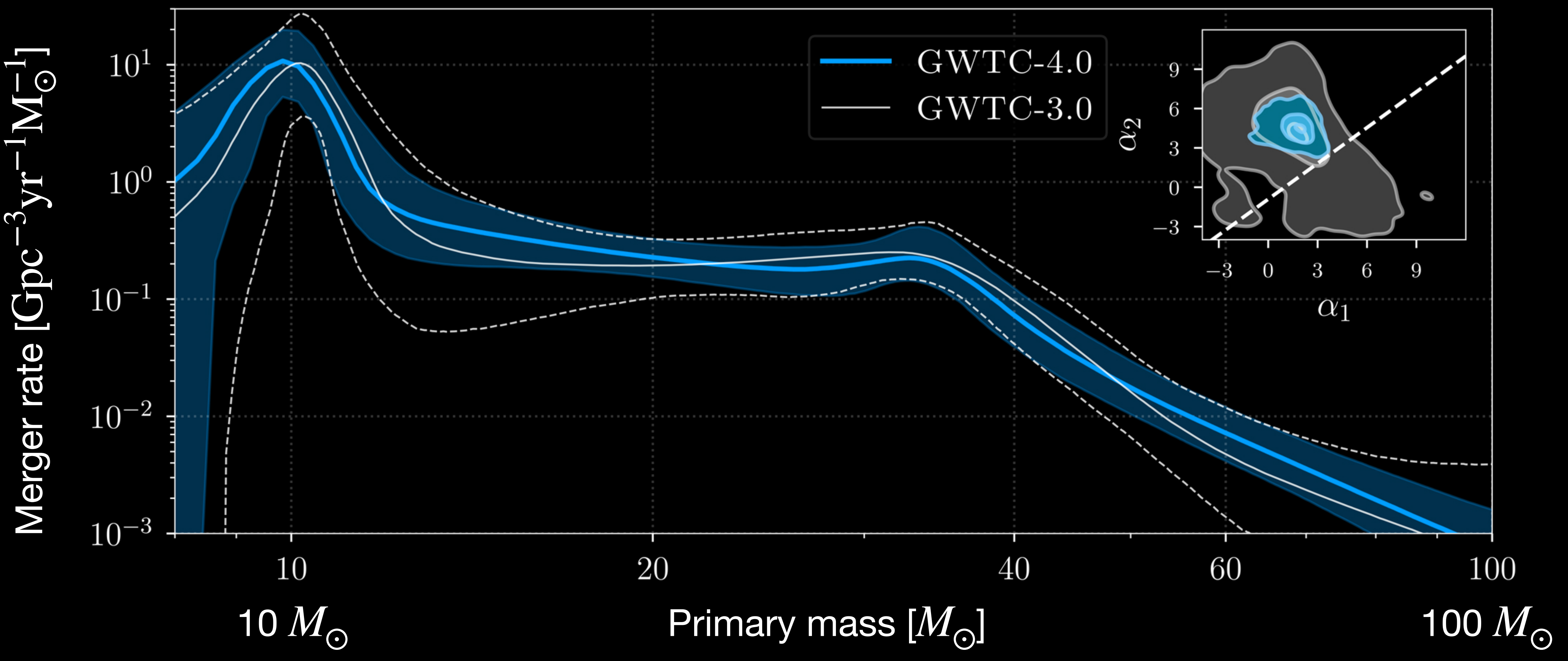
Binary black hole mass distribution

- Most of the analyses focus specifically on the binary black hole sources
- Main takeaways
  - Clear features at ~10 $M_\odot$ and ~35 $M_\odot$ (already found)
  - Hints of something at ~20 $M_\odot$?
  - Evidence that the slope of the continuum steepens after the 35 $M_\odot$ peak

LVK 2508.18083





Models: BP2P, Callister & Farr (2024); B-Spine, Edelman+ (2023)

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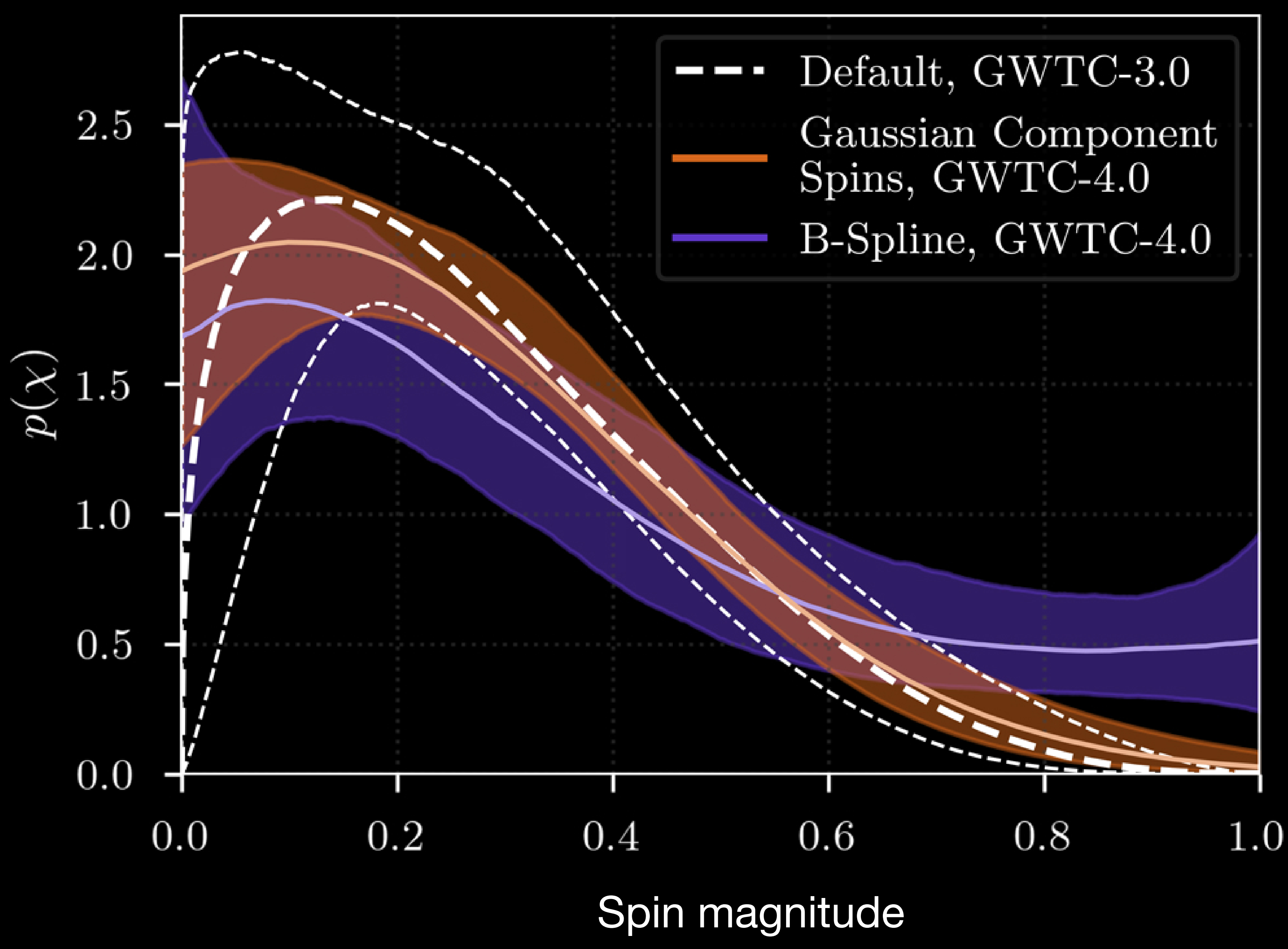
Binary black hole spins distribution

- The LVK find that the **component** spins in black holes are usually small
- Assuming the same underlying distribution for the two spins, the population has a peak at $\lesssim 0.2$
- Seems to support theory and numerical work (e.g. Fuller & Ma ApJL 881 L1)

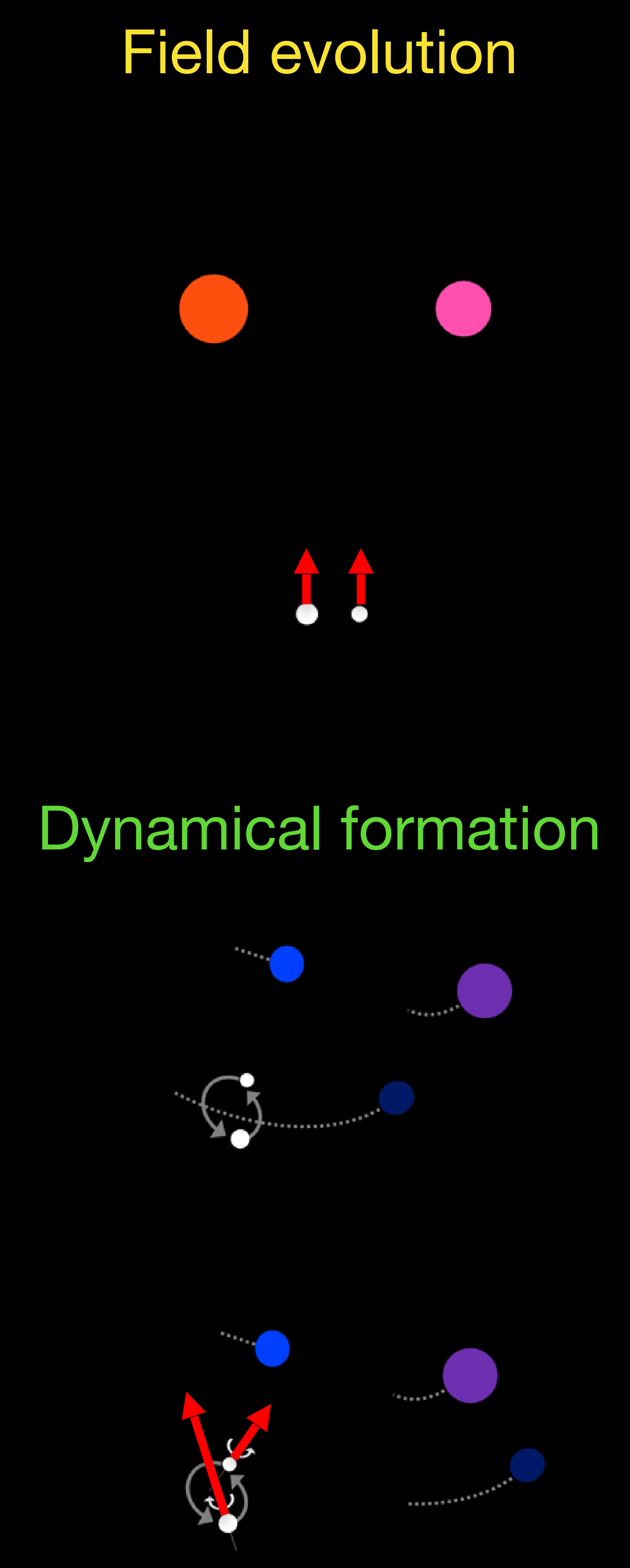
LVK 2508.18083



Models: Wysocki et al. 2019; Edelman+ 2023; LVK 2508.18083

Spin tilts and formation channels

- The *orientation* of the black hole spins can yield precious information about their formation channels - Vitale+ CQG 34, 03LT01; Rodriguez+ ApJL 832 L2; Farr+ Nature 548 426; Talbot & Thrane PRD 96 023012
- Field evolution is expected to yield spins which are (roughly) aligned to one another and to the angular momentum
- Dynamical formation in clusters should yield isotropic spin orientation



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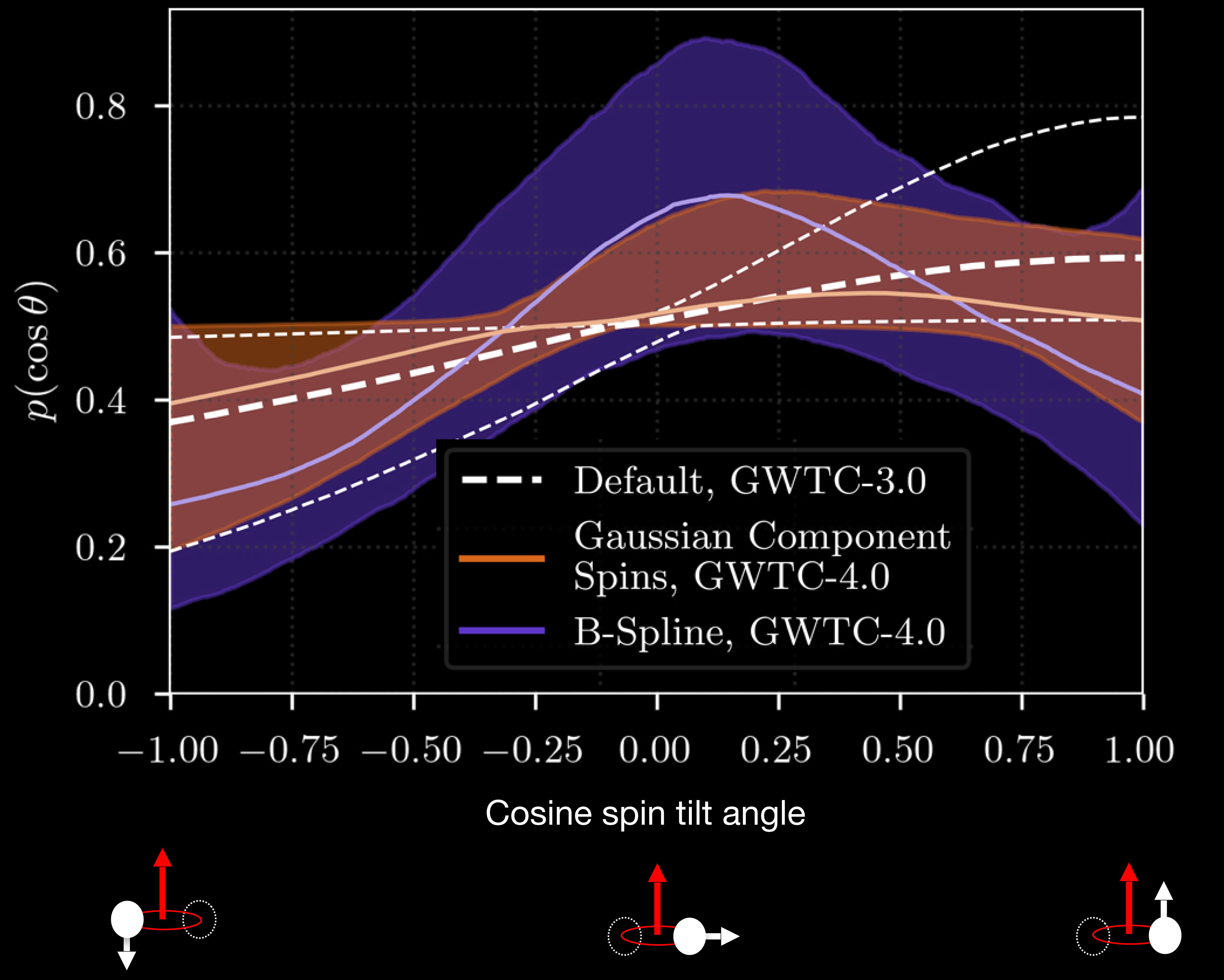
Binary black hole spin tilts distribution

- Model the distribution of spin orientations as a sum of an isotropic component and a Gaussian with mean and scale measured from the data (Vitale+ A&A 668 L2)
- Or as a flexible spline model (Edelman+ ApJ 946 16)
- No obvious sign of a peak at +1, expected for aligned spins
  - Possible peak away from +1?
  - Triples? (Stegman+ 2512.15873)

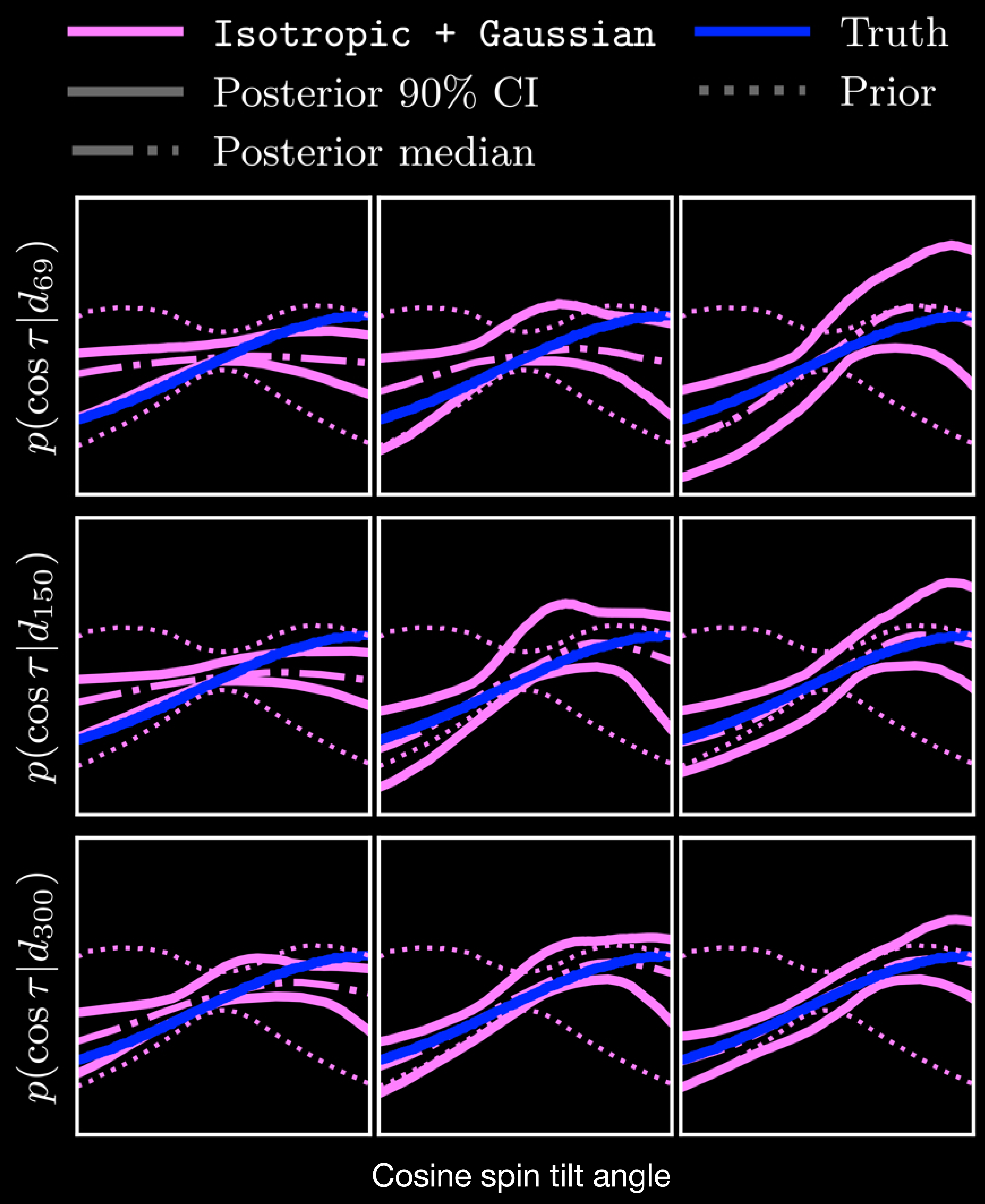
LVK 2508.18083



Models: Vitale+ 2015, 2022; Talbot & Thrane 2017; Edelman+ 2023

Binary black hole spin tilts distribution

- In Vitale & Mould 2505.14875 we caution that spurious peaks are possible
  - Even if the true population has a peak at +1
  - With catalog sizes comparable to GWTC-4 or larger



LVK 2508.18083

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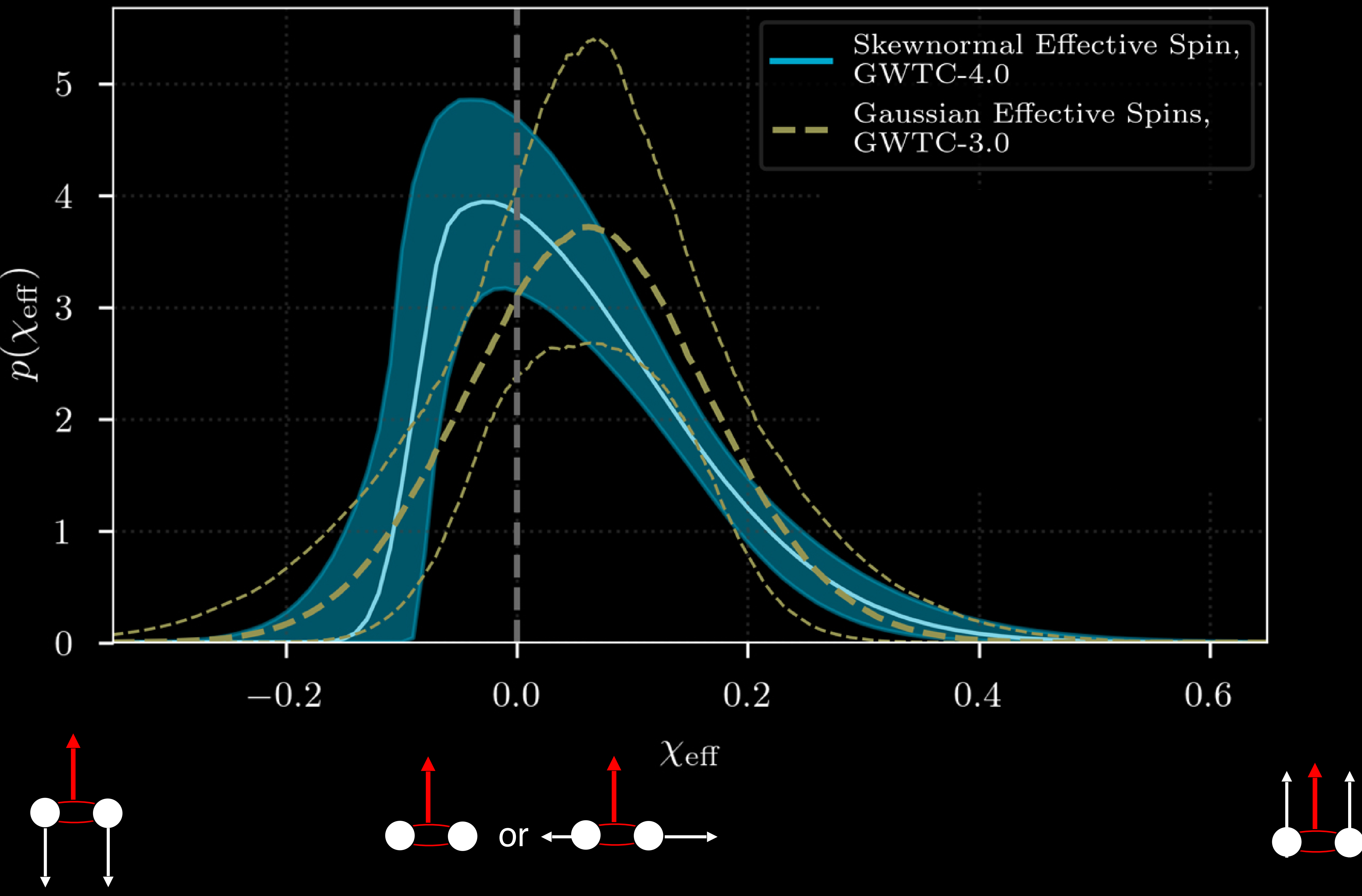
Binary black hole χ_{eff} distribution

- The effective spin χ_{eff} is measured to be peaking at ~0 and skewed to the right at 99.3% credibility
  - Suggestive of at subpopulation of sources evolved in isolation
  - No more than 84% of the sources can come from dynamical channels (imply isotropy, χ_{eff} symmetric around zero)

LVK 2508.18083

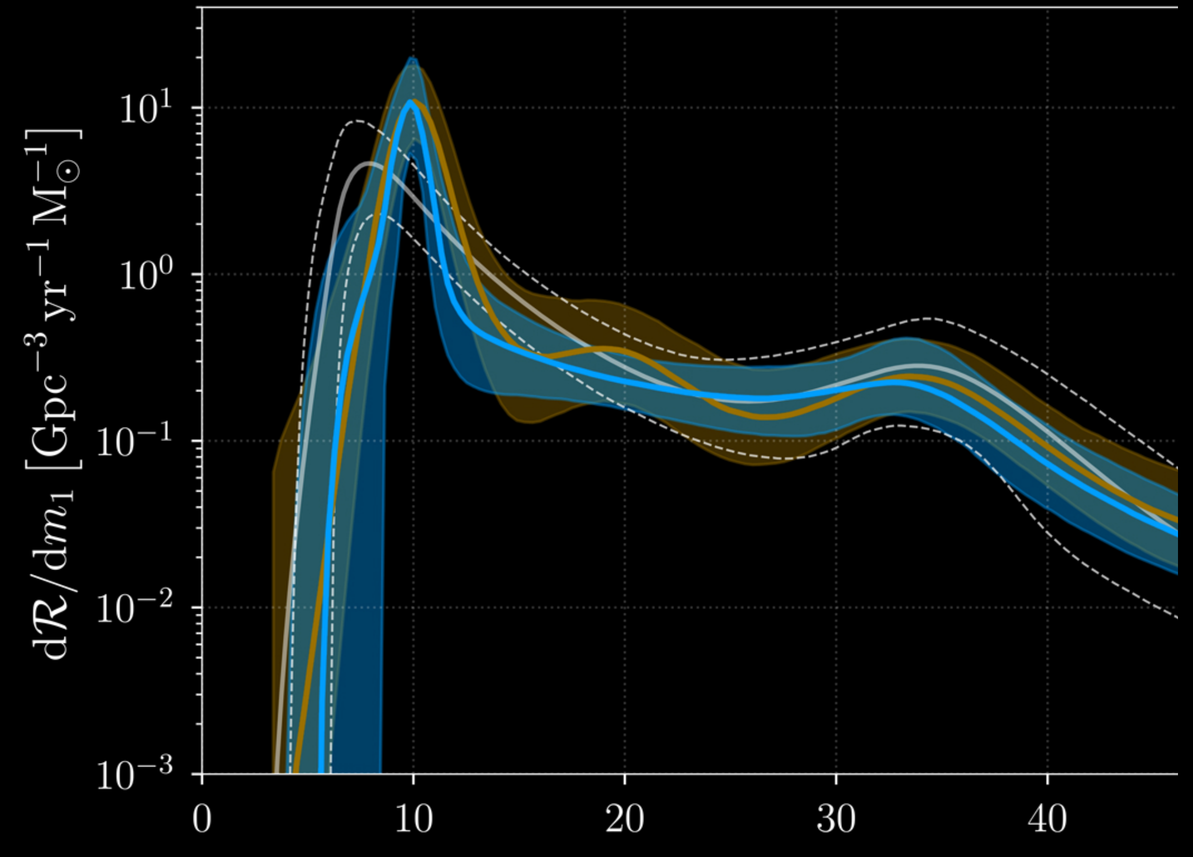


Models: Miller et al. 2020; Roulet & Zaldarriaga 2019; Banagiri+ 2025

Astrophysical correlations

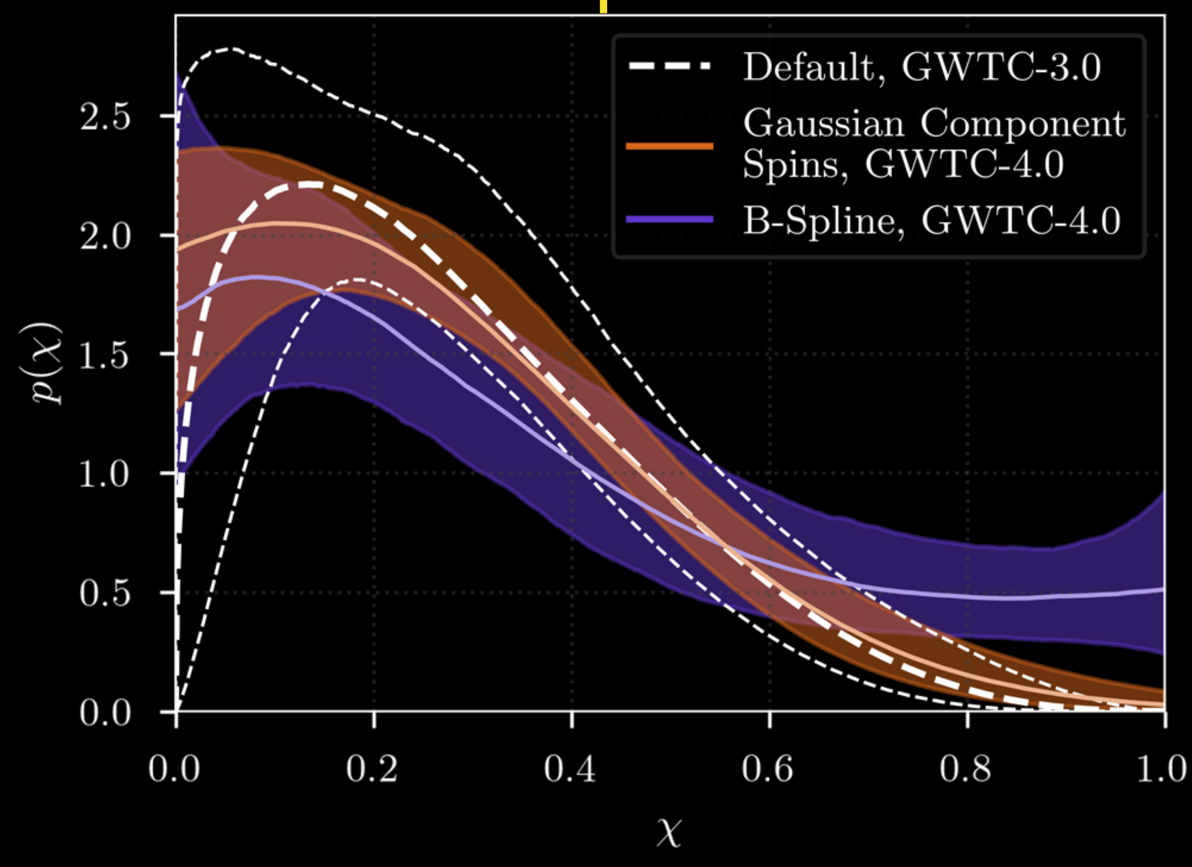
- Many of the models described so far assume independence among parameters
- There are good reasons to believe astrophysical processes *will* correlated source parameters
- Correlations can be probed with larger datasets

Mass distribution



Statistically independent??

Spin distribution



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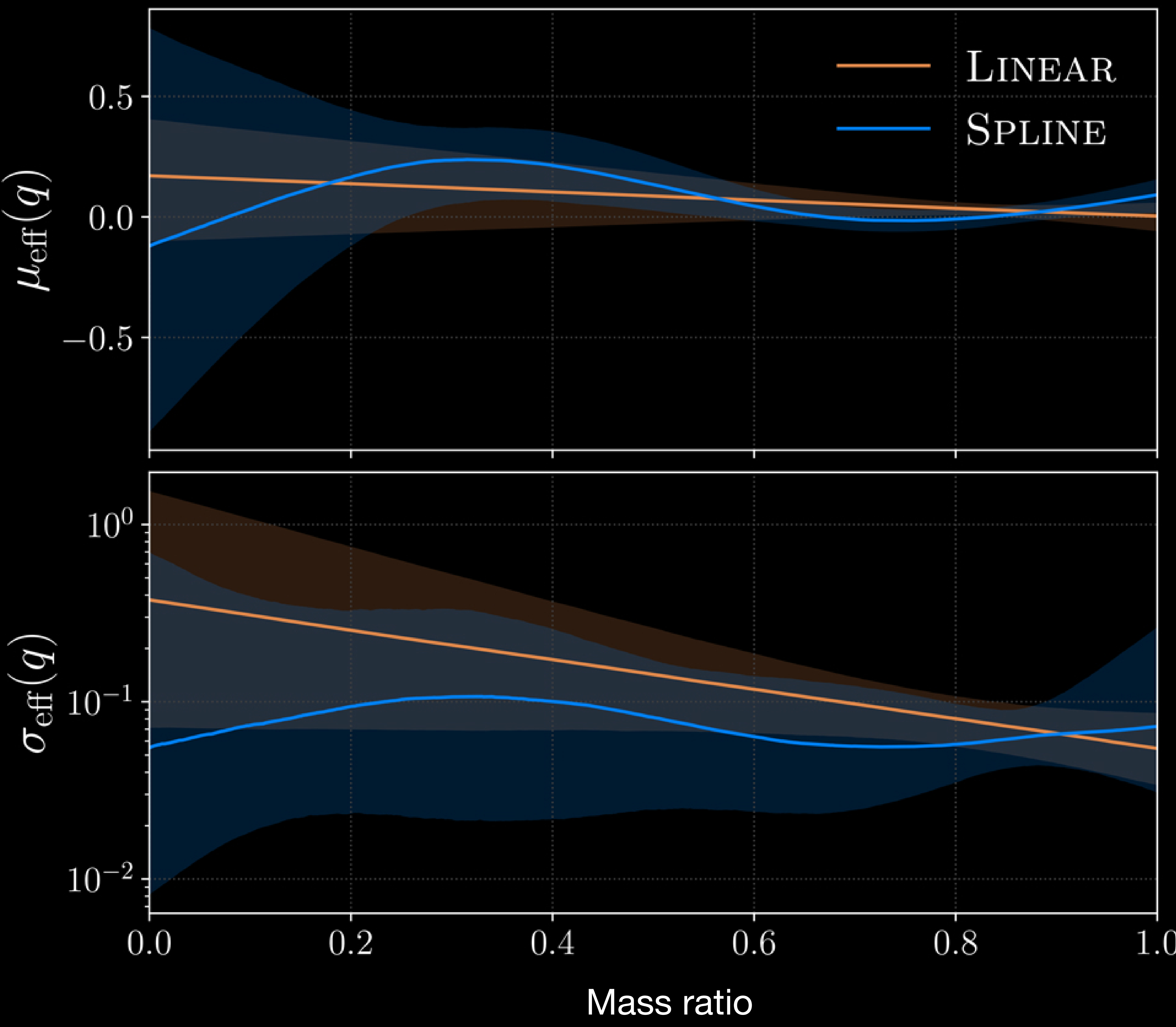
Mass ratio/$\chi_{\rm eff}$ correlation

- First reported by Callister+ ApJL 922 L5 in GWTC-2 data with a linear correlation
    - Corroborated by Adamcewicz & Thrane MNRAS 517 3928 with copulas
    - And by Heinzel+ PRD 109 103006 with splines
- In GWTC-4, it is unclear if is the mean or the width of $\chi_{\rm eff}$ that evolve with the mass ratio

LVK 2508.18083



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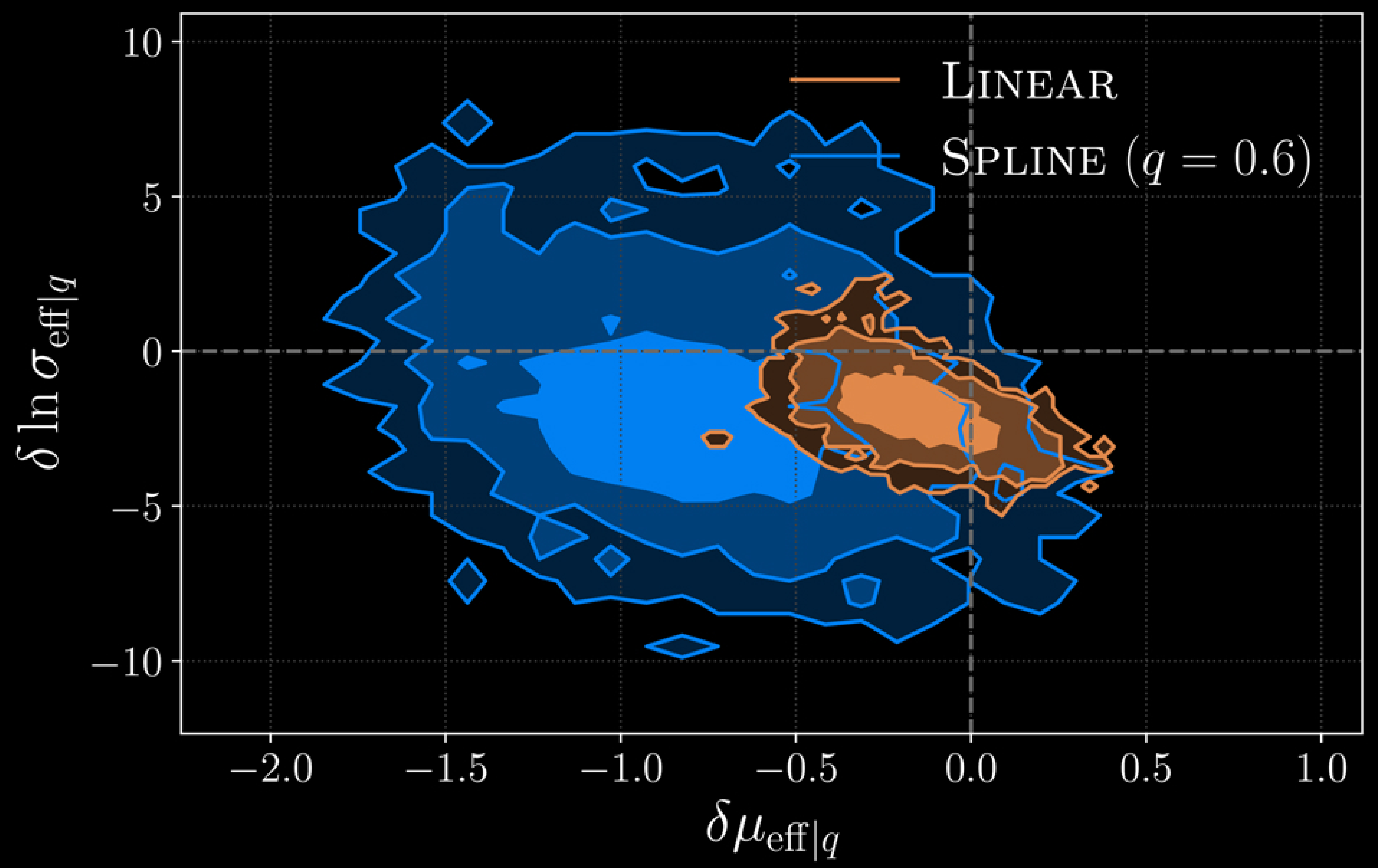
Mass ratio/$\chi_{\rm eff}$ correlation

- In GWTC-4, it is unclear if is the mean or the width of $\chi_{\rm eff}$ that evolve with the mass ratio
- But configurations where neither evolve are disfavored at 99% credibility for the linear model (92% with a copula model)

LVK 2508.18083



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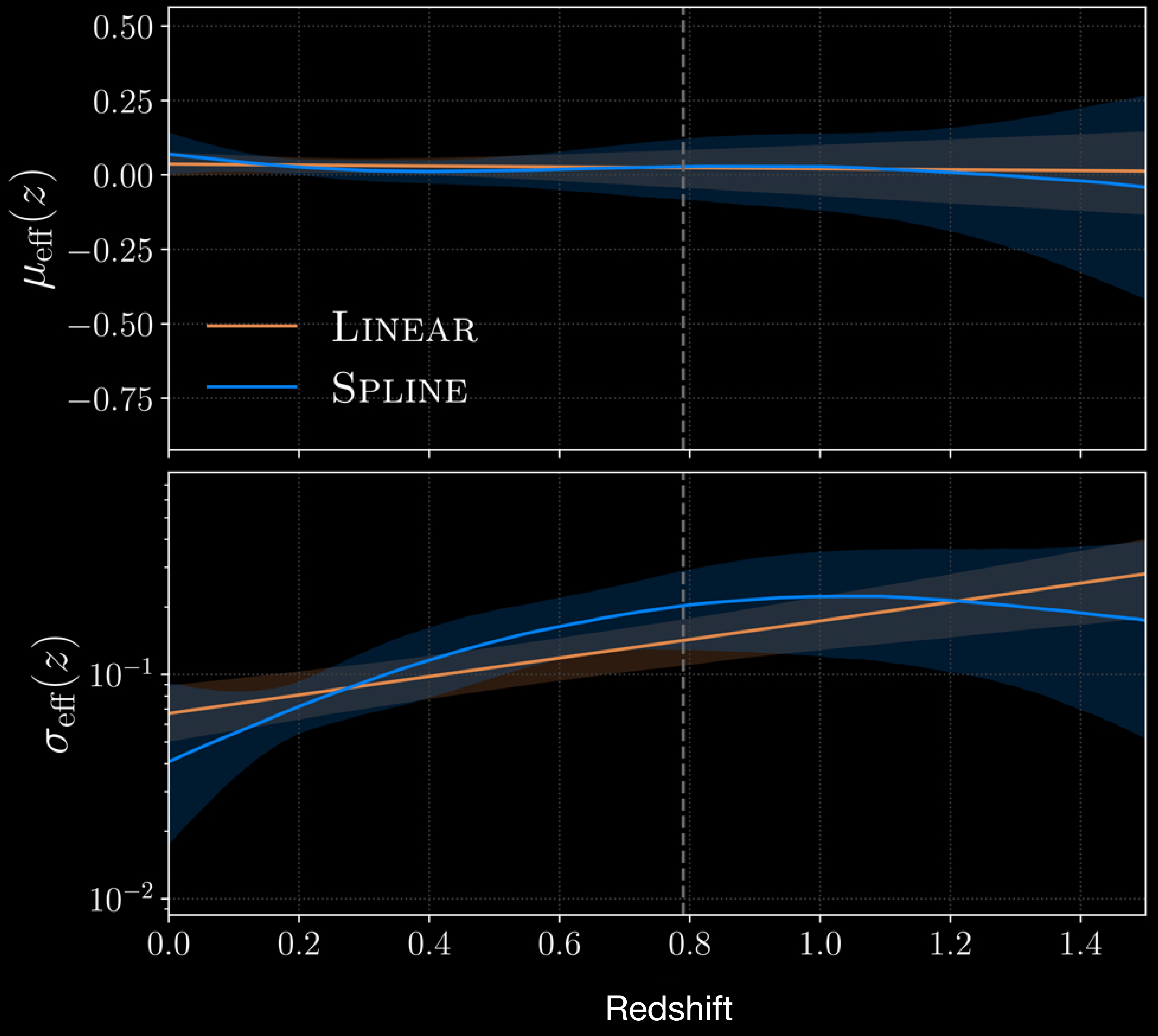
Redshift/χ_{eff} correlation

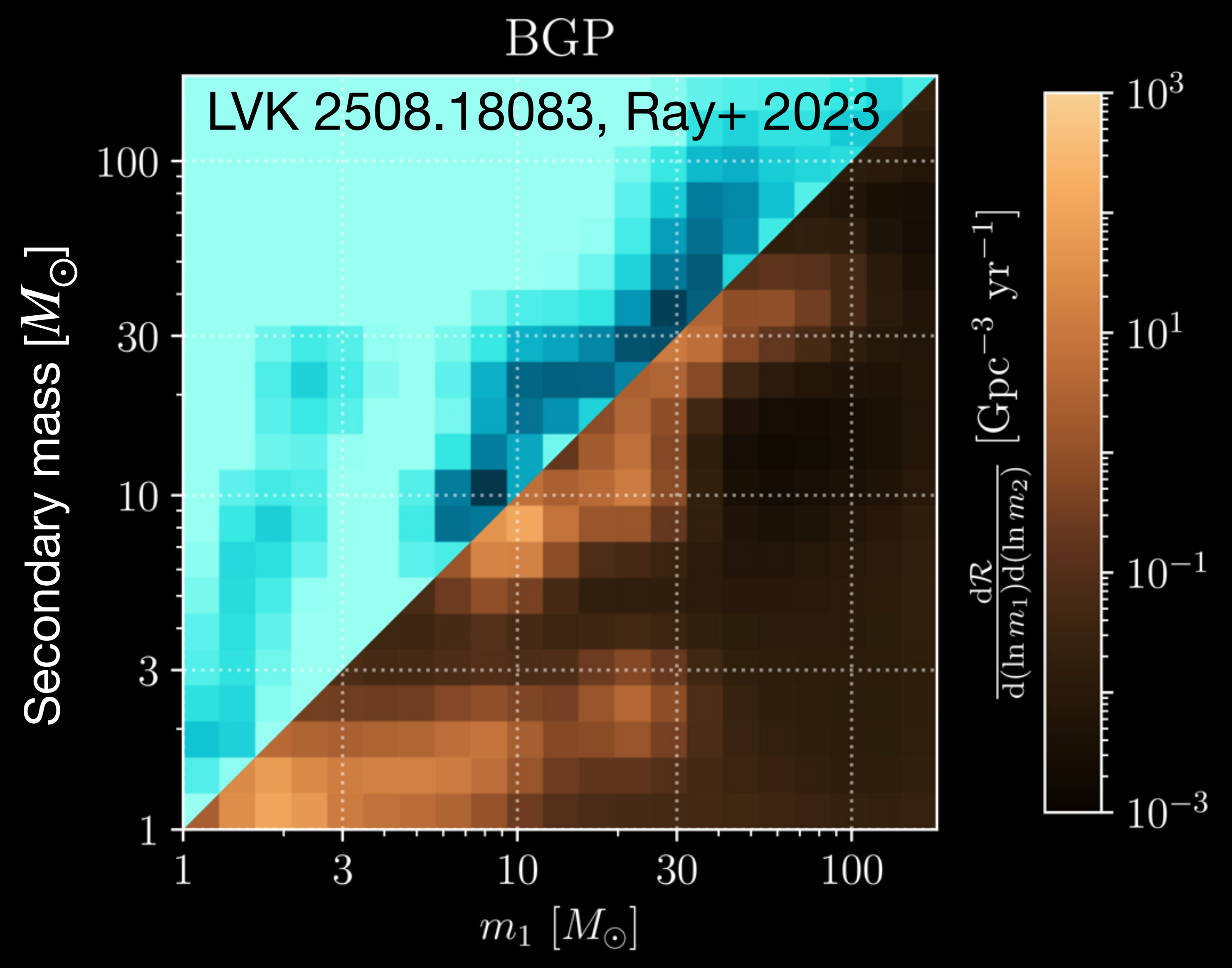
- In Biscoveanu+ ApjL 932 L19 we reported evidence that the distribution of χ_{eff} broadens with redshift in GWTC-3 data
  - …while the position does not evolve
  - Maybe due to metallicity evolution with redshift - Bavera+ A&A 665 A59
- This finding is confirmed in GWTC-4 with both linear and agnostic approaches

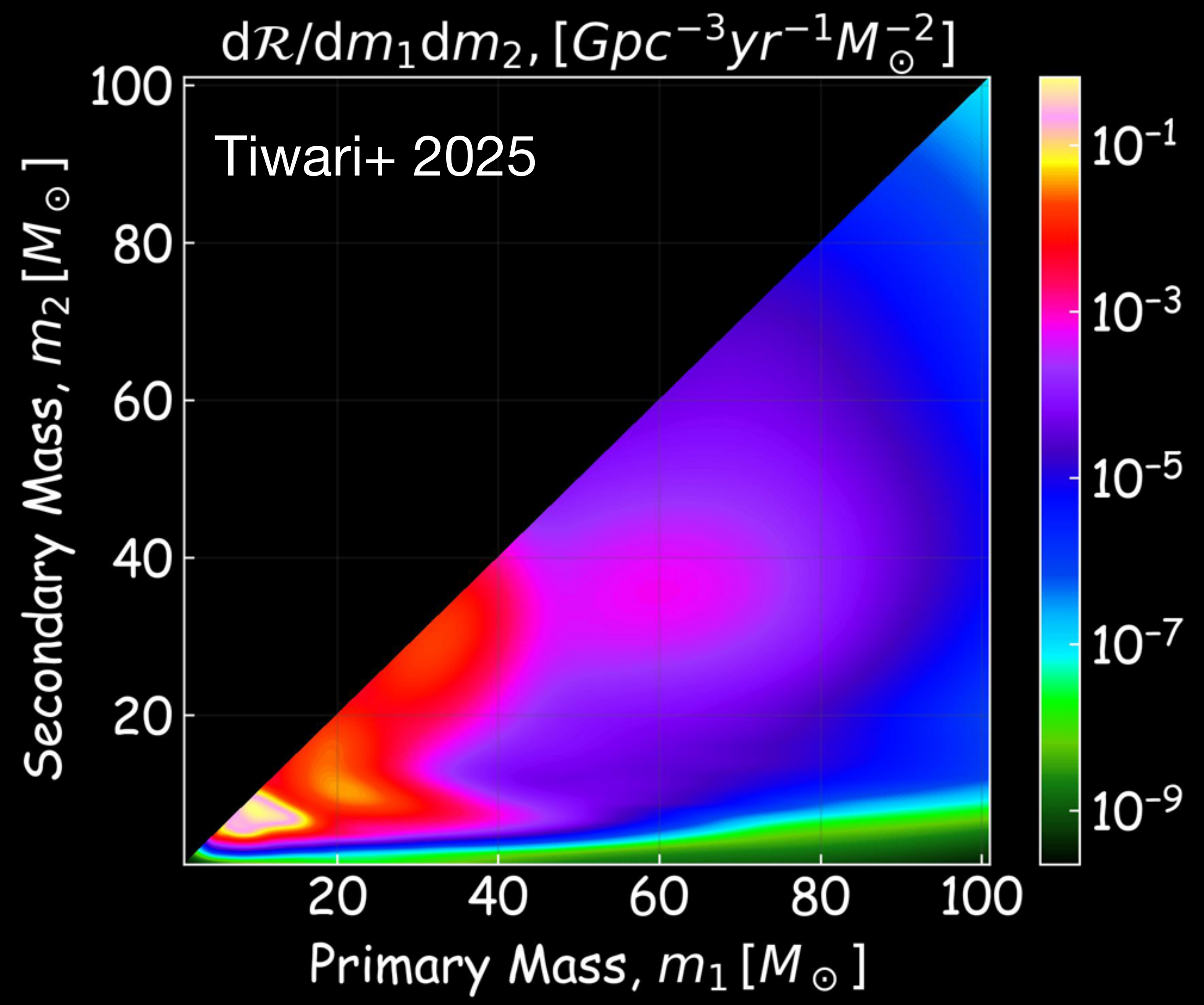
LVK 2508.18083



Toward generic correlations

- As the dataset increases in size, more generic models are needed
- Several have been proposed in the last few years
  - VAMANA (Mixture Model) - Tiwari+ 2020*
  - Binned Gaussian processes -Ray+ 2023
- Incorporated by LVK in the GWTC-4 paper

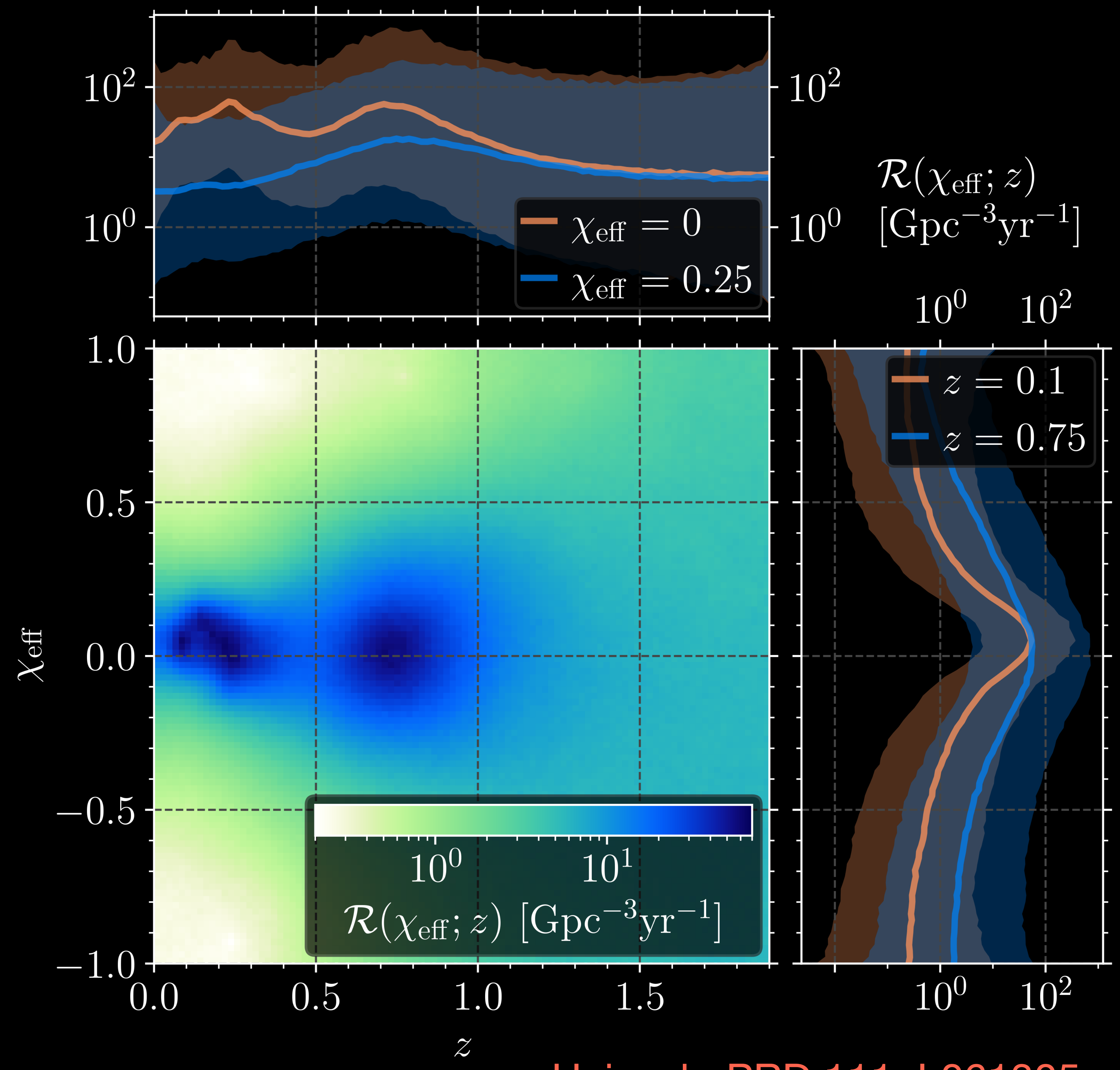




* Really a mixture of strong-ish pieces

What comes next - PixelPop

- At MIT, we have been developing a high-resolution high-dimensional agnostic approach to population inference, based on gaussian processes
- PixelPop - Heinzel+, PRD 111, 063043 and PRD 111, L061305



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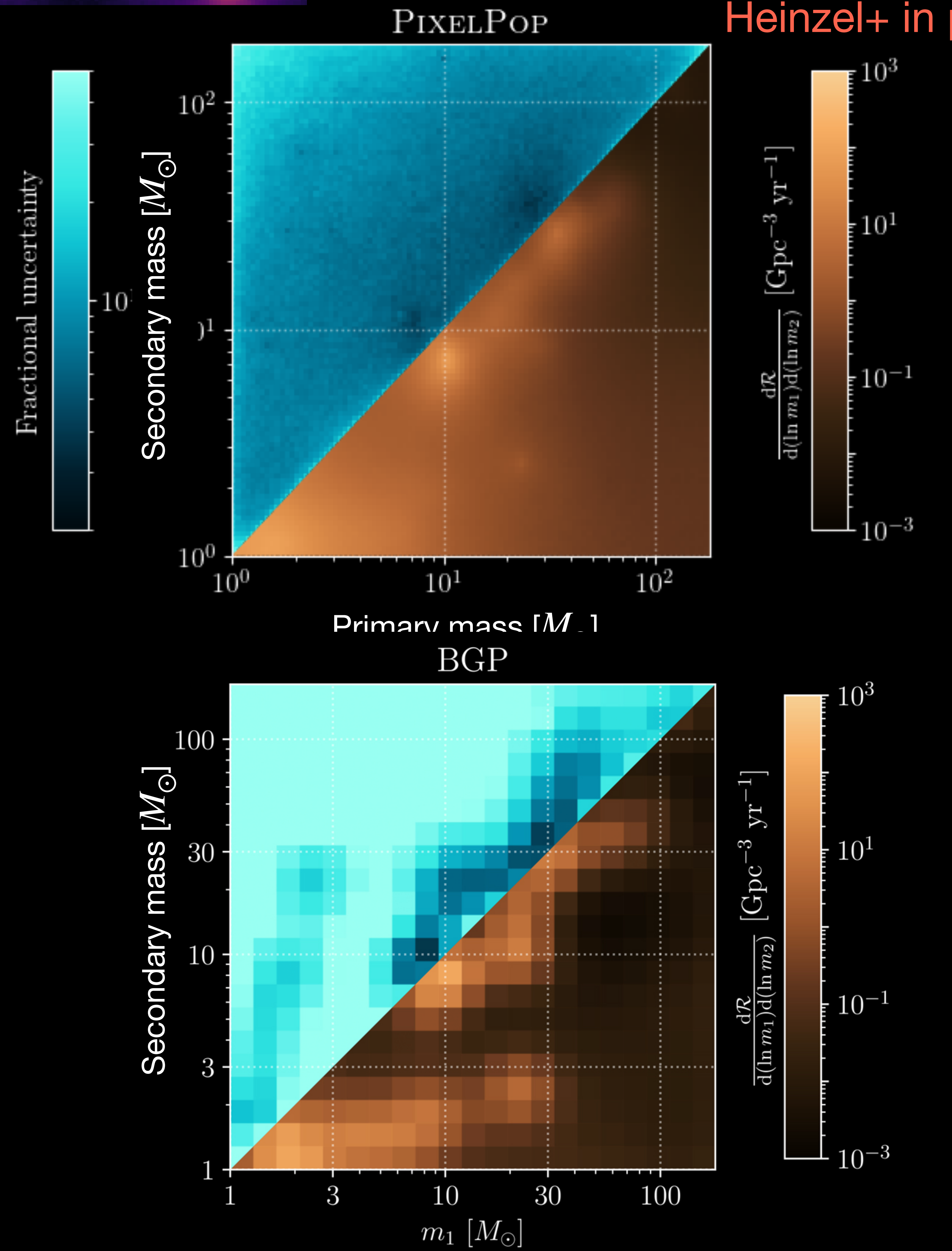
  - Can already run with 3 correlated parameters
  - Nothing assumed but smoothness

Heinzel+ in prep



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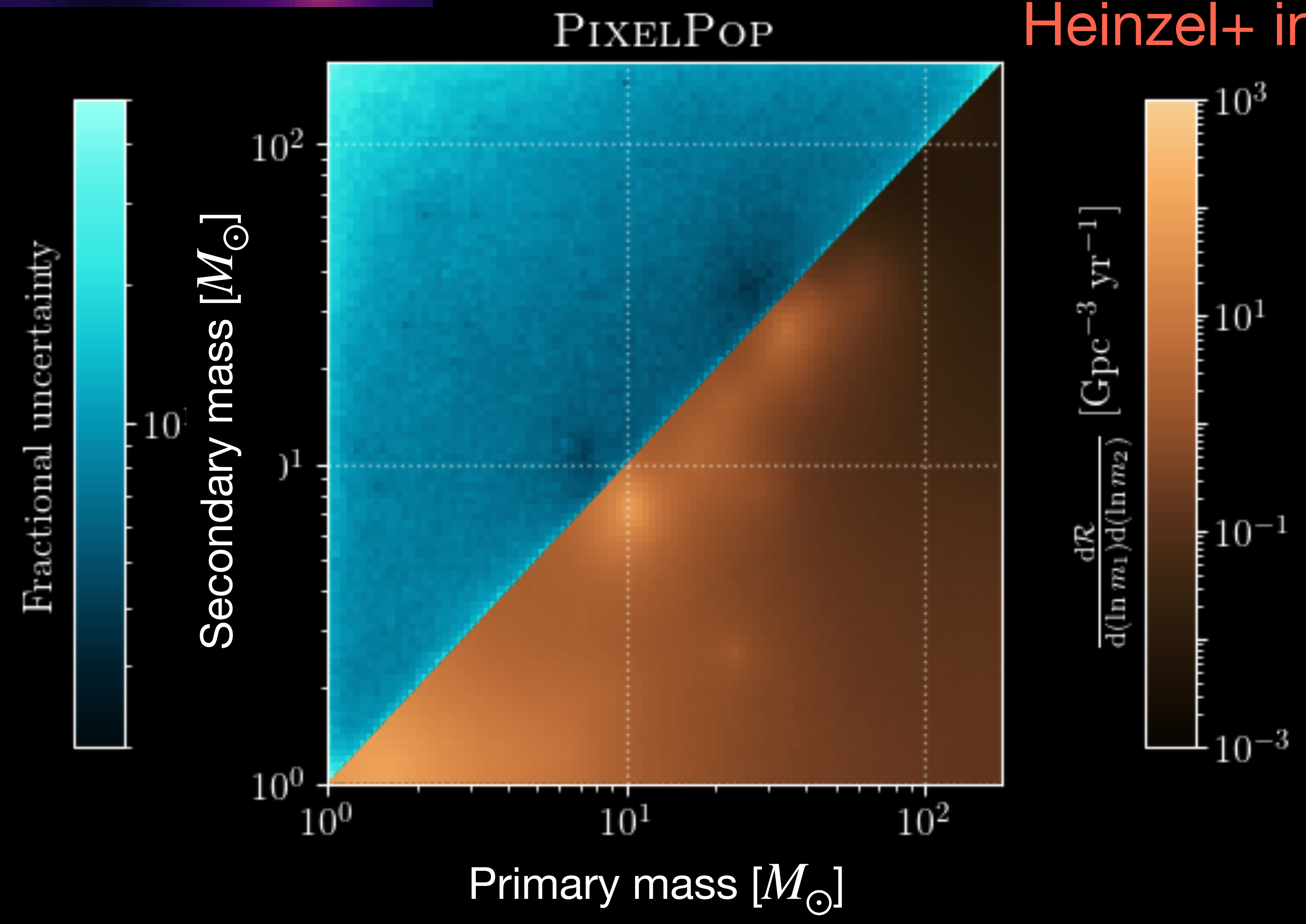
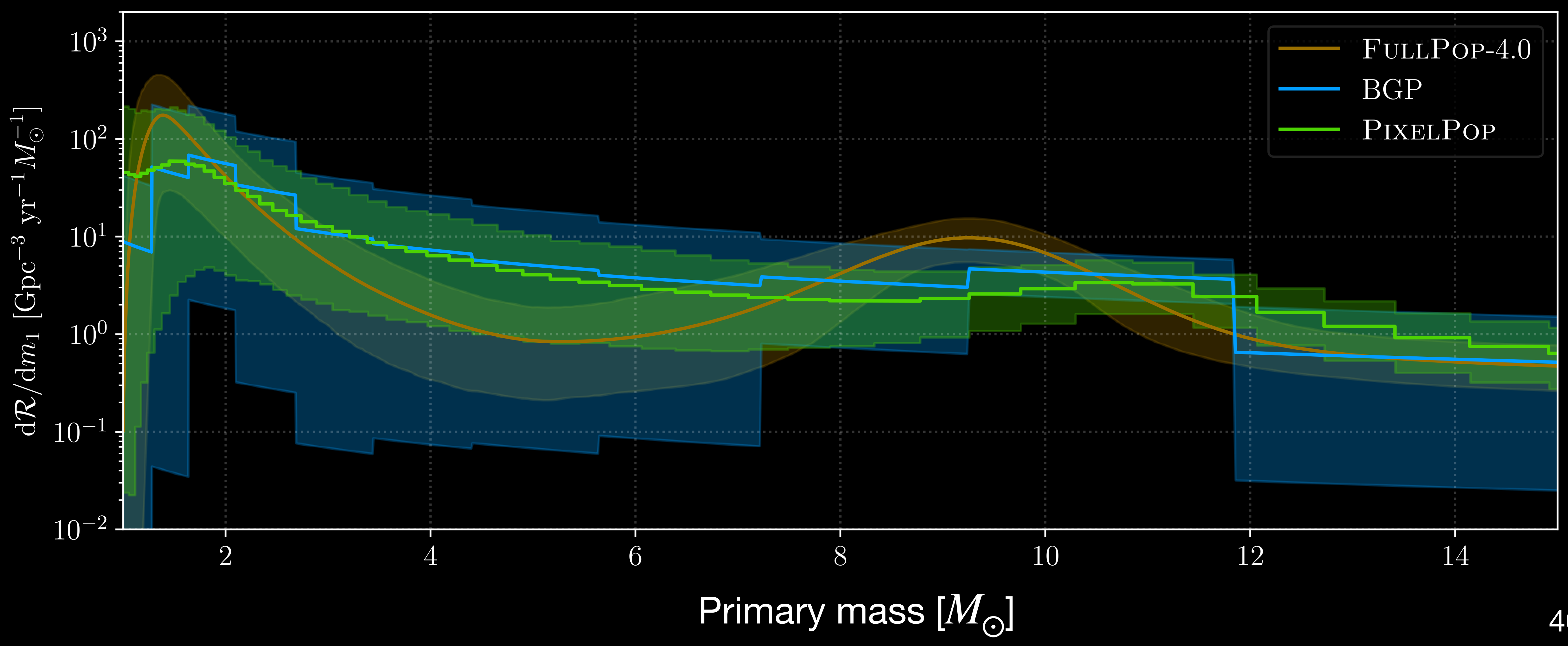
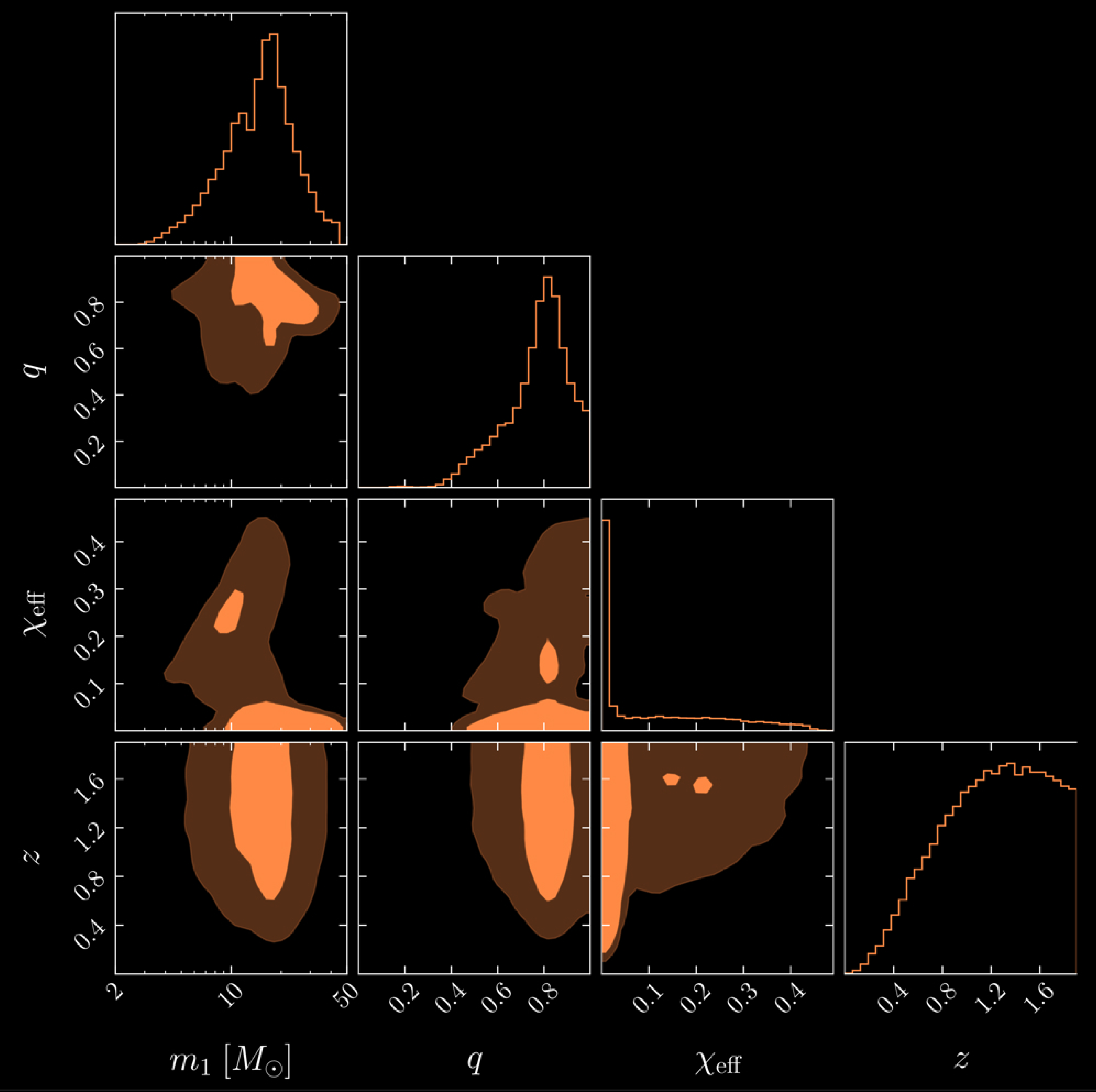




PixelPop's view of non-trivial correlations

- In Alvarez-Lopez+ 2506.20731 we have applied PixelPop to a common envelope population as predicted by pop synth
- Simulated a universe with 400 BBHs from common envelope
  - Highly non-trivial high-D correlations



Zevin+ Apj 910 152; Alvarez-Lopez+ 2506.20731

LIGO

PixelPop's view of non-trivial correlations

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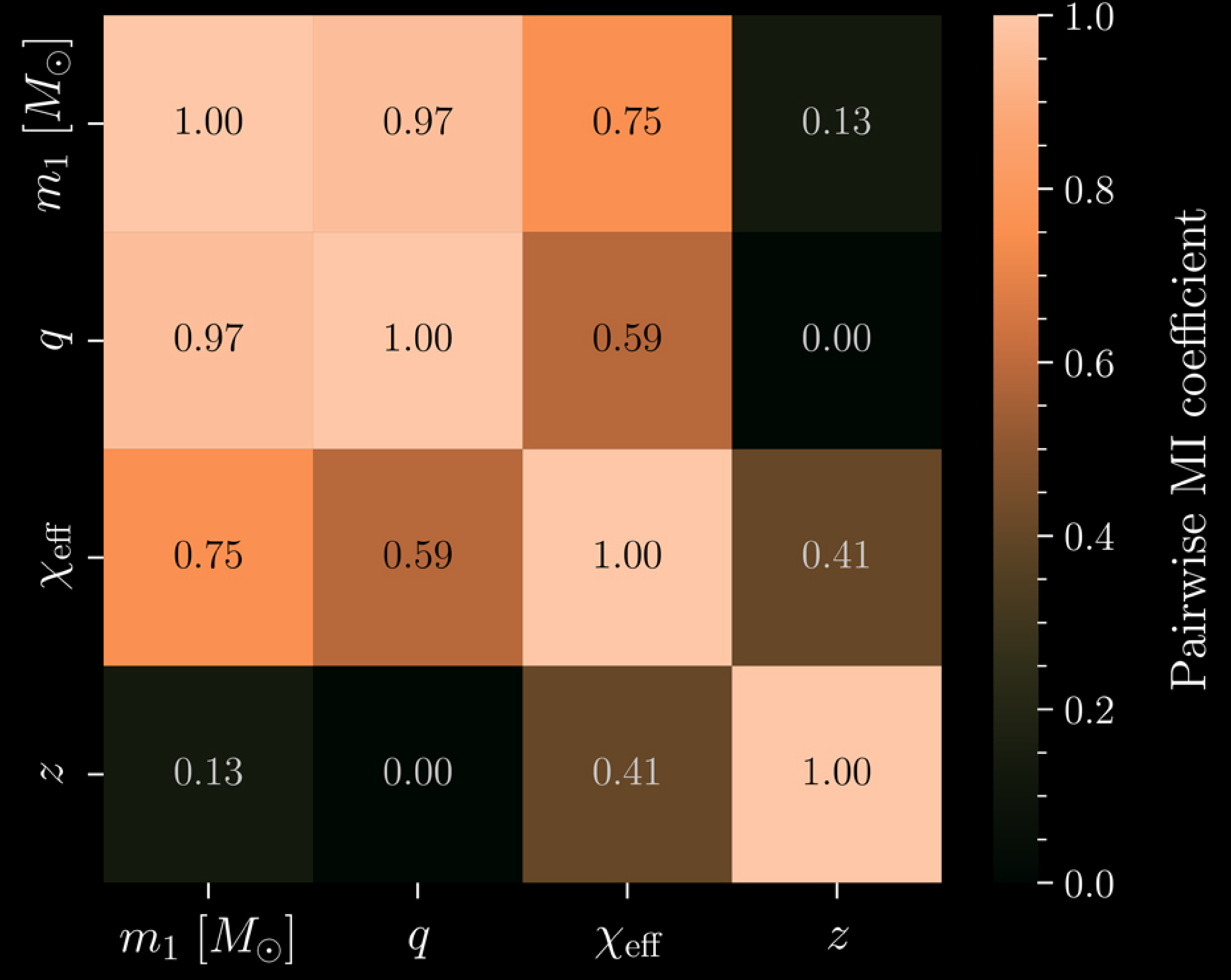
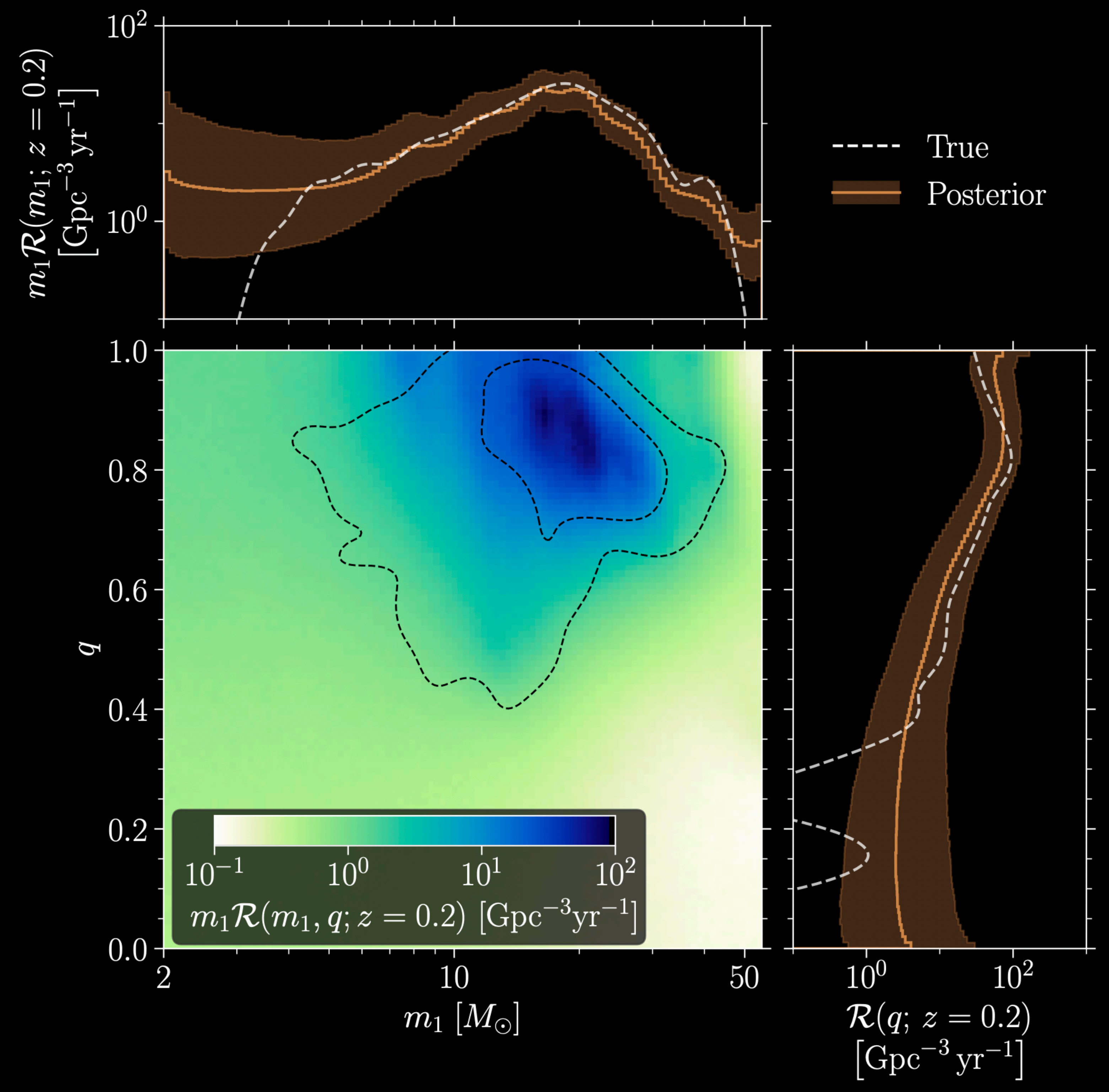


Zevin+ Apj 910 152; Alvarez-Lopez+ 2506.20731

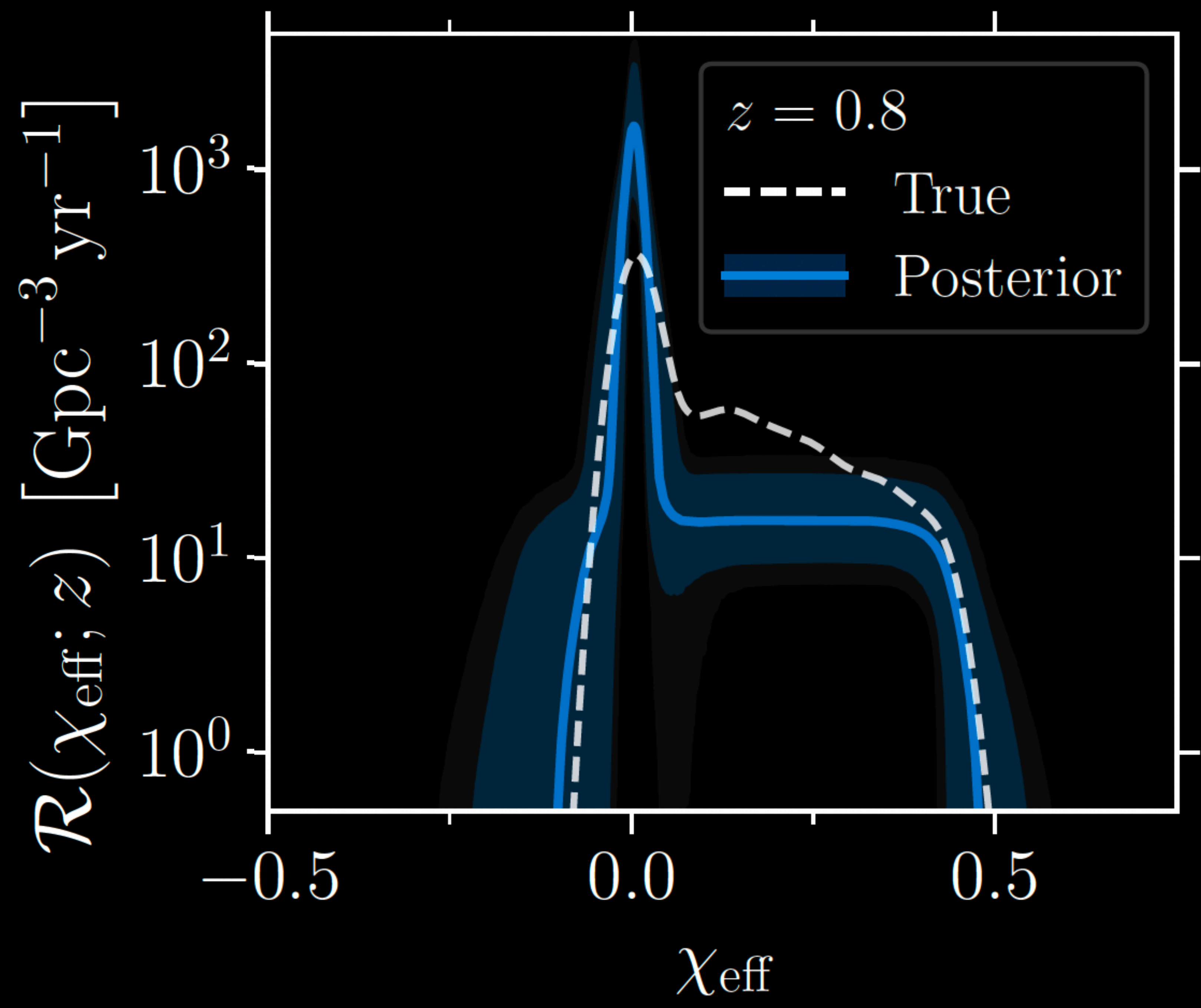
PixelPop's view of non-trivial correlations

- We showed how a simple 2-D correlation is insufficient
  - Model m_1/q with PixelPop, but use strong models for z and $\chi_{\rm eff}$

Mass ratio



Primary mass [$M_\odot$]



Alvarez-Lopez+ 2506.20731

PixelPop's view of non-trivial correlations

- We also showed how a simple ~~2-D~~ 3-D correlation is insufficient
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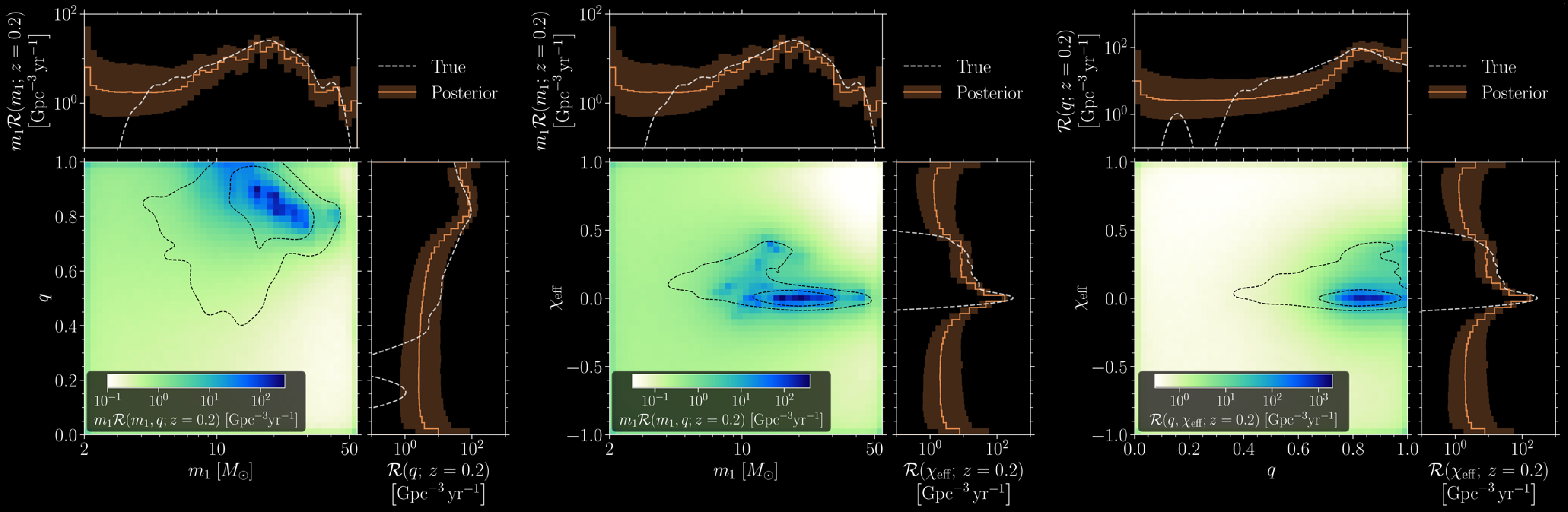

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PixelPop's view of non-trivial correlations

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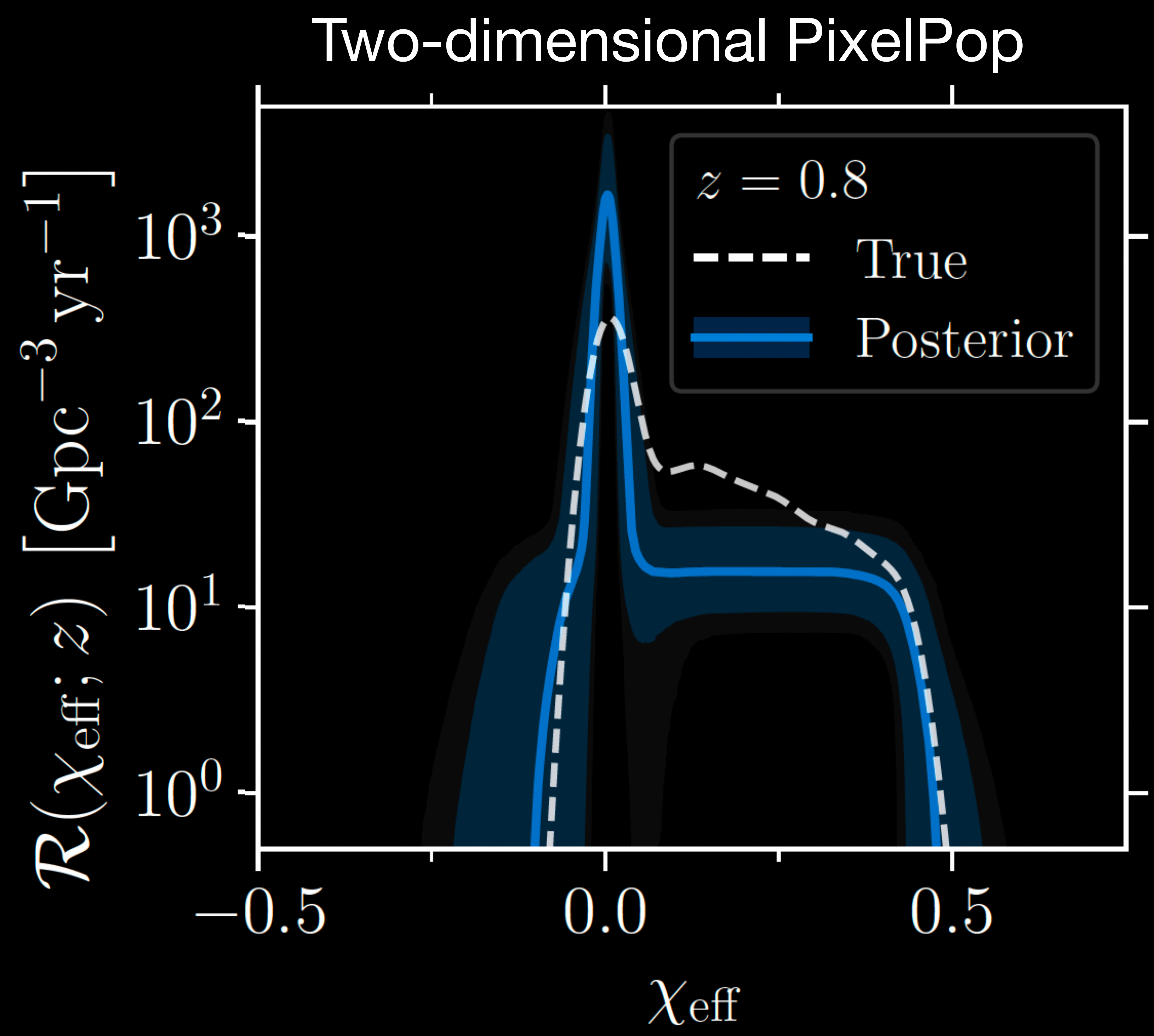
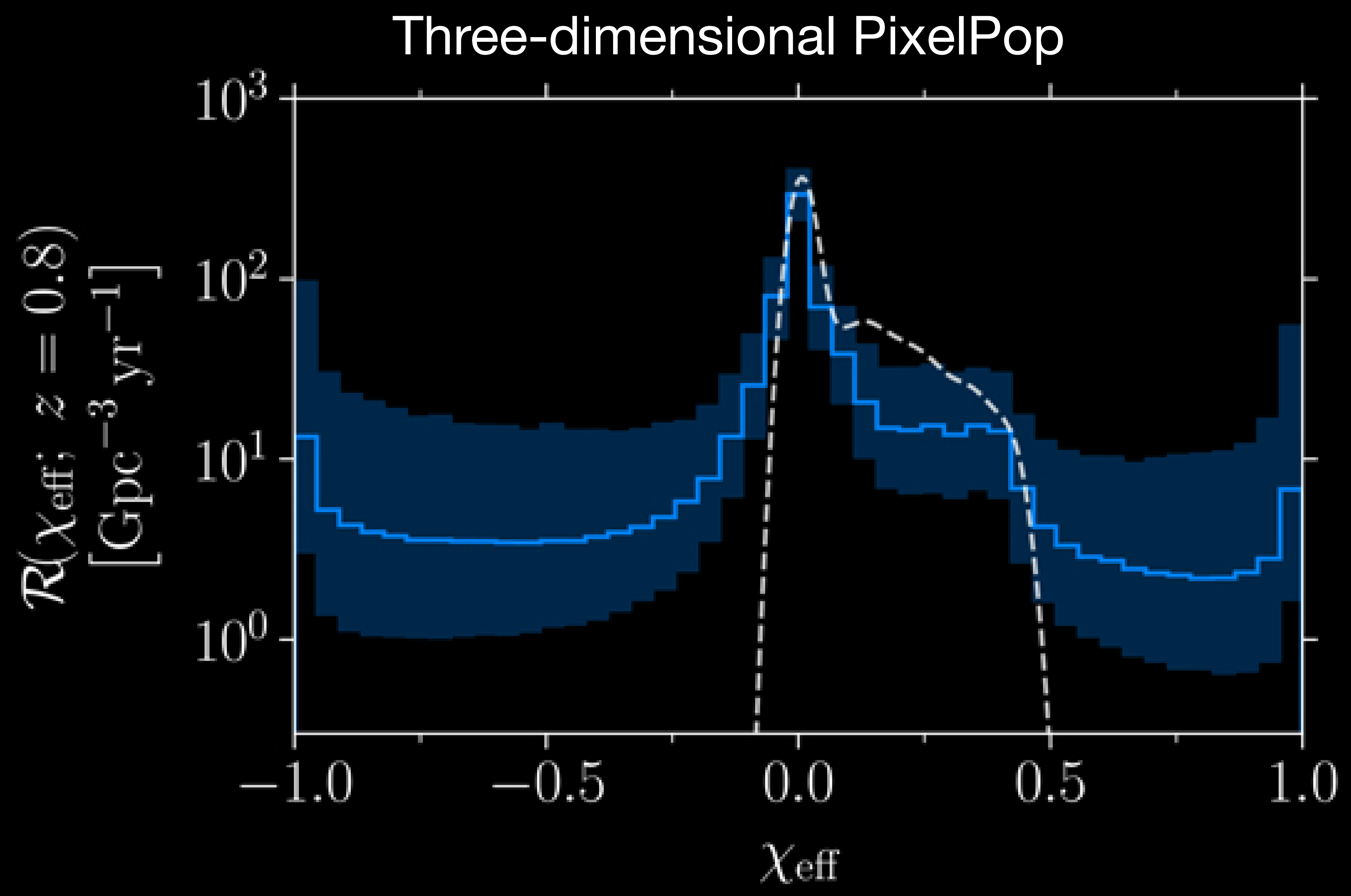




LIGO

NSF SPINS

PixelPop's view of non-trivial correlations

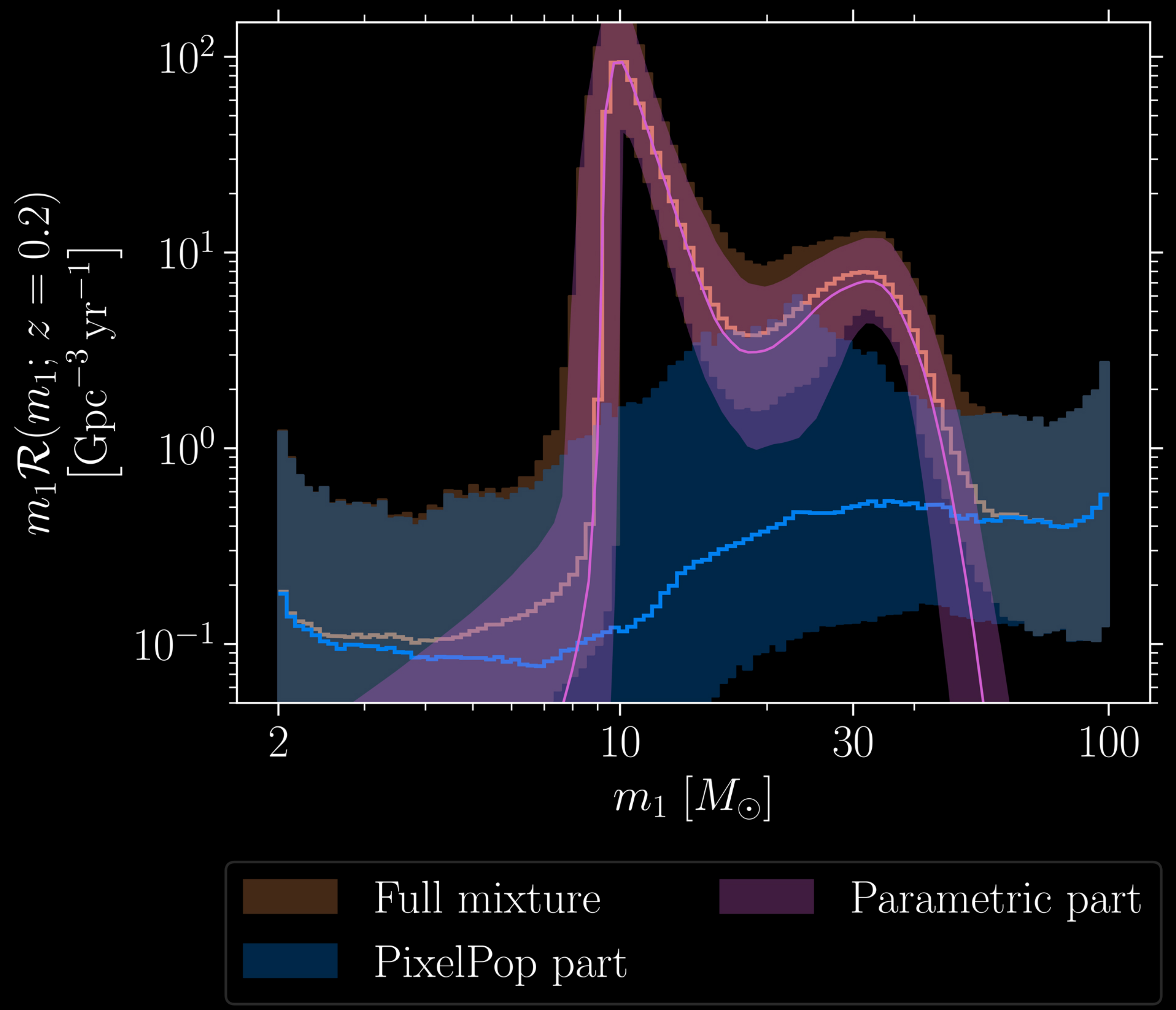
- We also showed how a 4-D correlated model is needed
  - Model $m_1/q/\chi_{\rm eff}$ with PixelPop, but use strong correlated models for $p(z\,|\,\chi_{\rm eff})$ ("Hybrid PixelPop" - ask me about clairvoyance)

PixelPop's next steps

- Working on an a version with actual 4-D generic correlations (Jack Heinzel)
  - The main issue is the estimation of the detectors' sensitivity
- Working on mixture models of PixelPop with strong models (Sofia Alvarez-Lopez)
  - Best of both worlds?
  - Strong model can do its thing while PixelPop hooks on glitches/outliers/oddballs and captures residual correlations
- Woking on interpretability and tails

PixelPop's next steps

- Strong model can do its thing while PixelPop hooks on glitches/outliers/oddballs and captures residual correlations
- For example, run on GWTC-3 w/o excluding GW190814 ($m_2 = 2.6 M_\odot$)



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PixelPop's next steps

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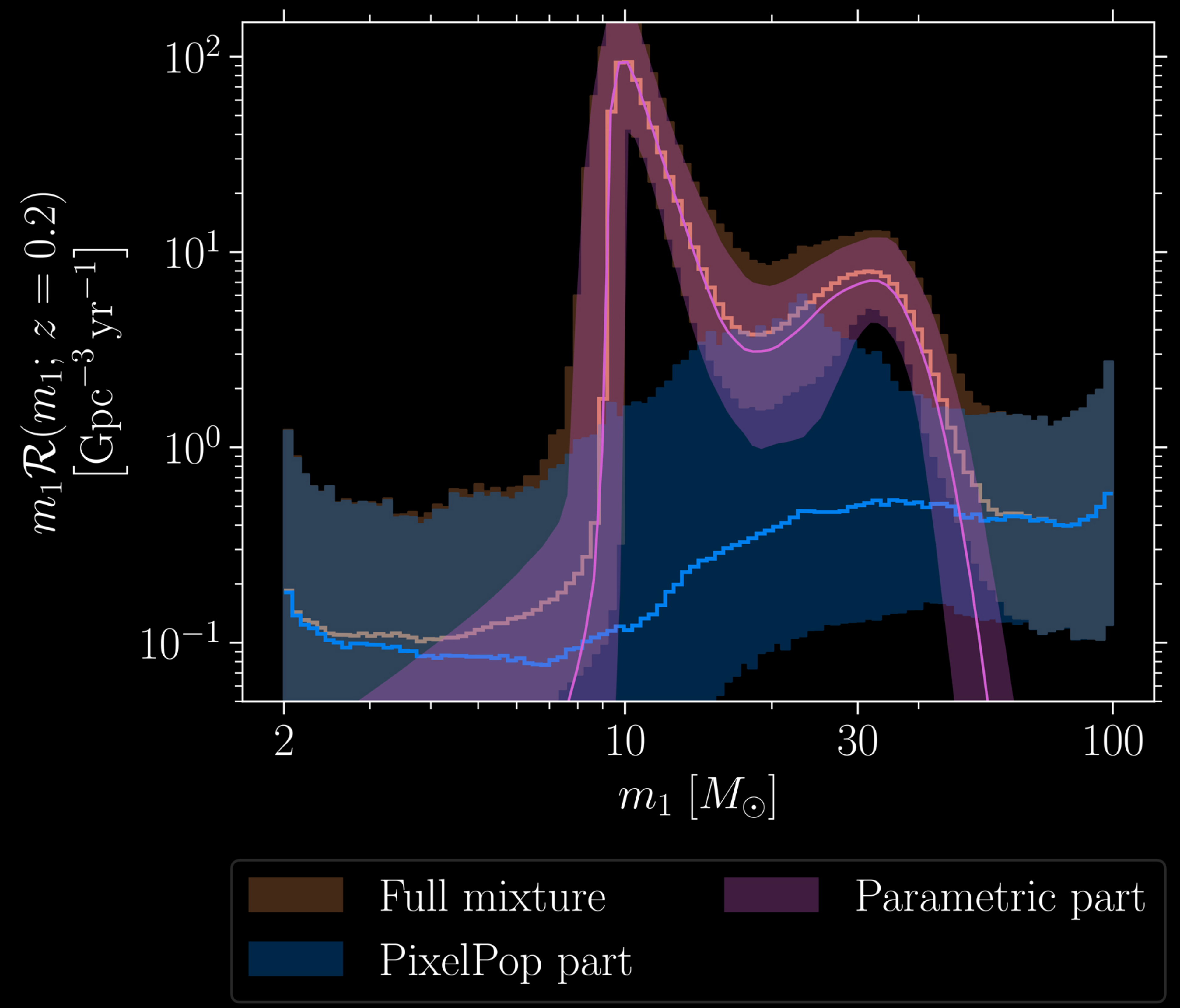

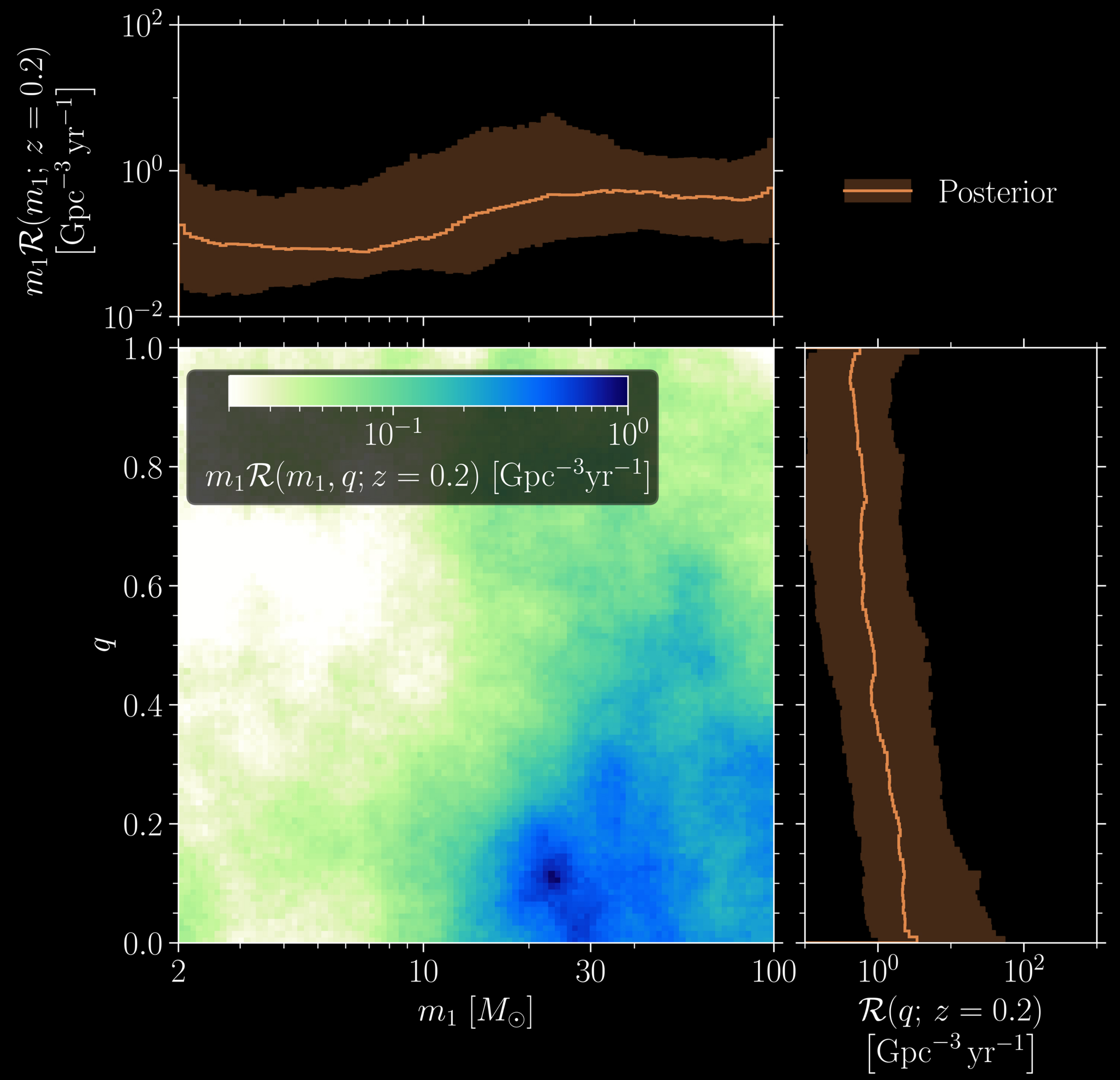

Conclusions

- GTWC-4 has doubled the number of known sources and revealed
  - Excesses of $10\,M_\odot$ and $35\,M_\odot$ black holes
  - Existence of black holes with masses below $5\,M_\odot$ (i.e., no mass gap) and above $100\,M_\odot$
  - Dearth of large spins, and preference for positively aligned spins
  - Larger spins at larger redshifts; mass ratio pairing evolving with mass; correlation between $\chi_{\rm eff}$ and mass ratio
    - Are we seeing hints of multiple populations?
- Will probably double again the size of the catalog by the end of O4c!
- We urgently need agnostic methods to measure correlations in the data