Careless whispers:

A population of sub-threshold post-merger gravitational waves constrains the hot nuclear equation of state

Fiona Panther | University of Western Australia | Forrest Research Foundation
With Paul Lasky | Monash University | OzGrav

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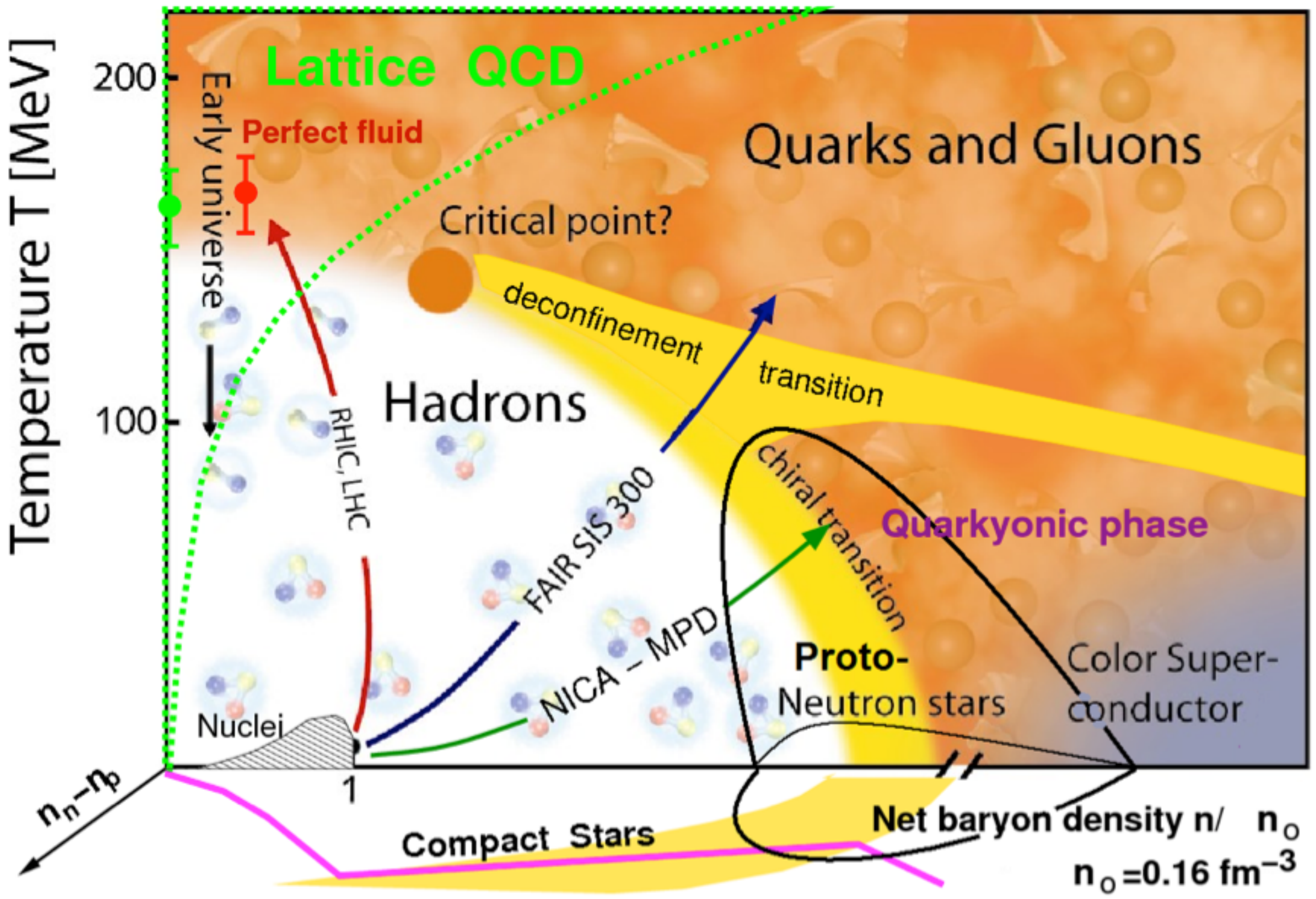
Post-merger remnants and the NS maximum mass

Hypermassive neutron stars that form from BNS mergers can help us constrain the nuclear EoS



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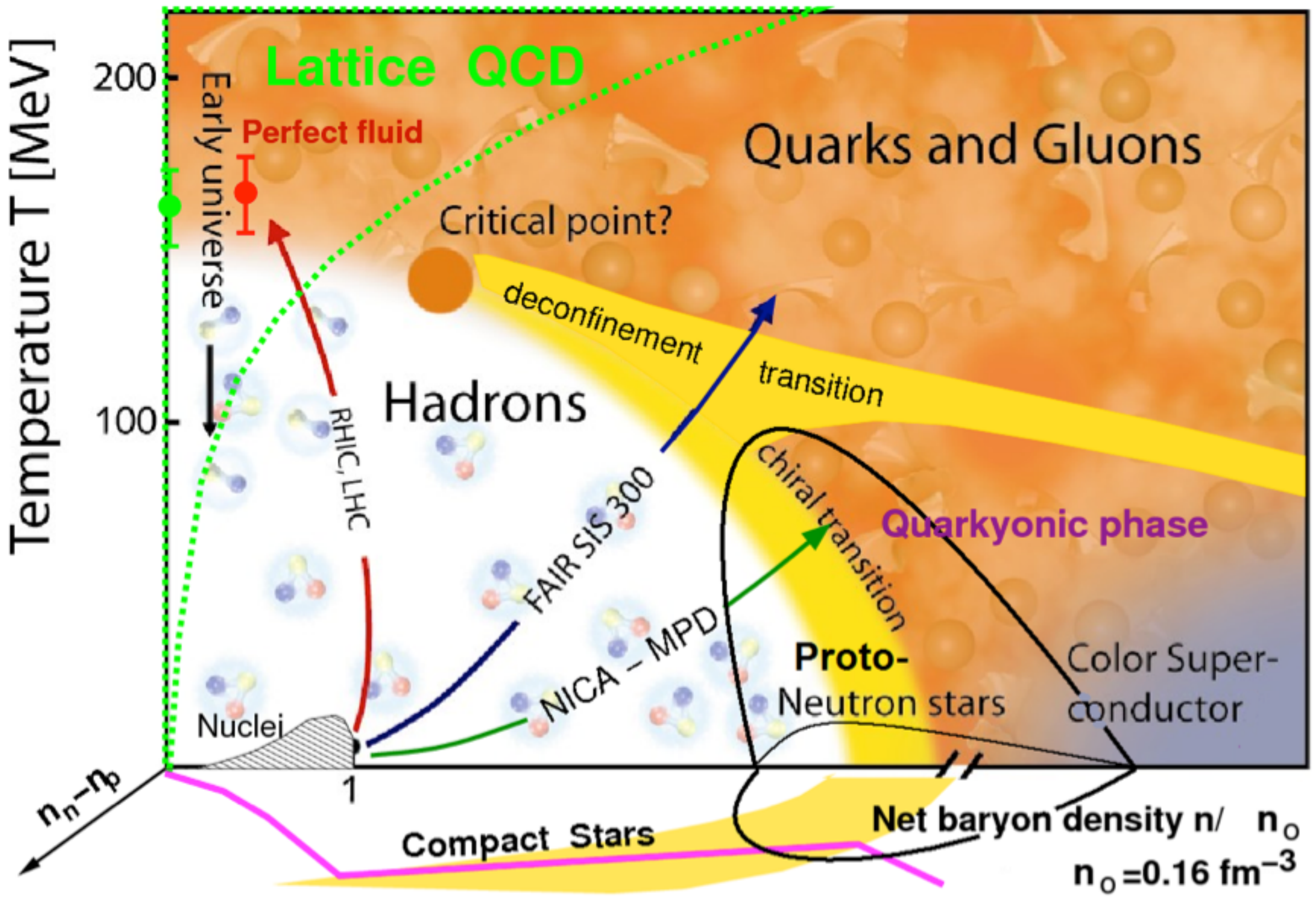

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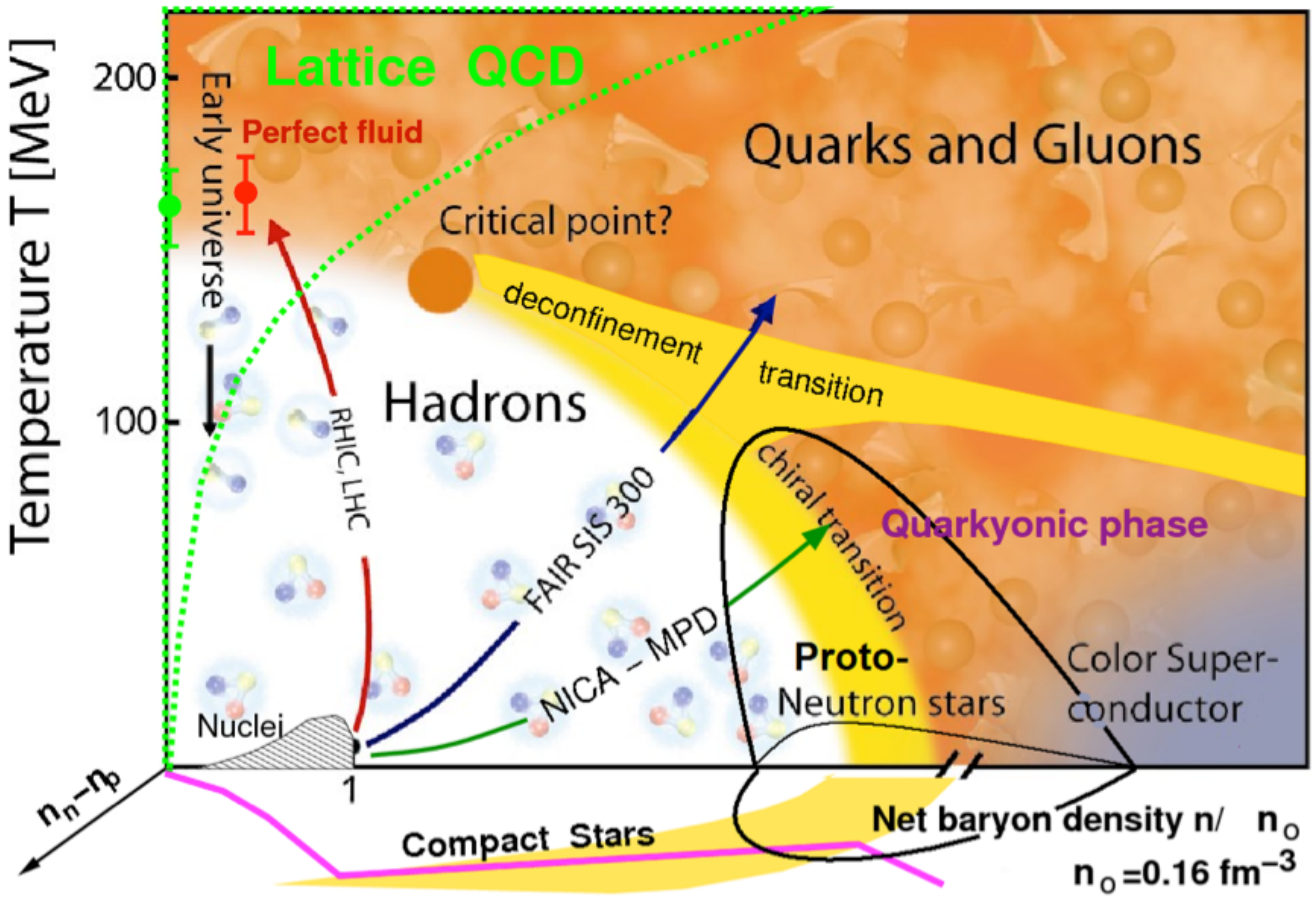

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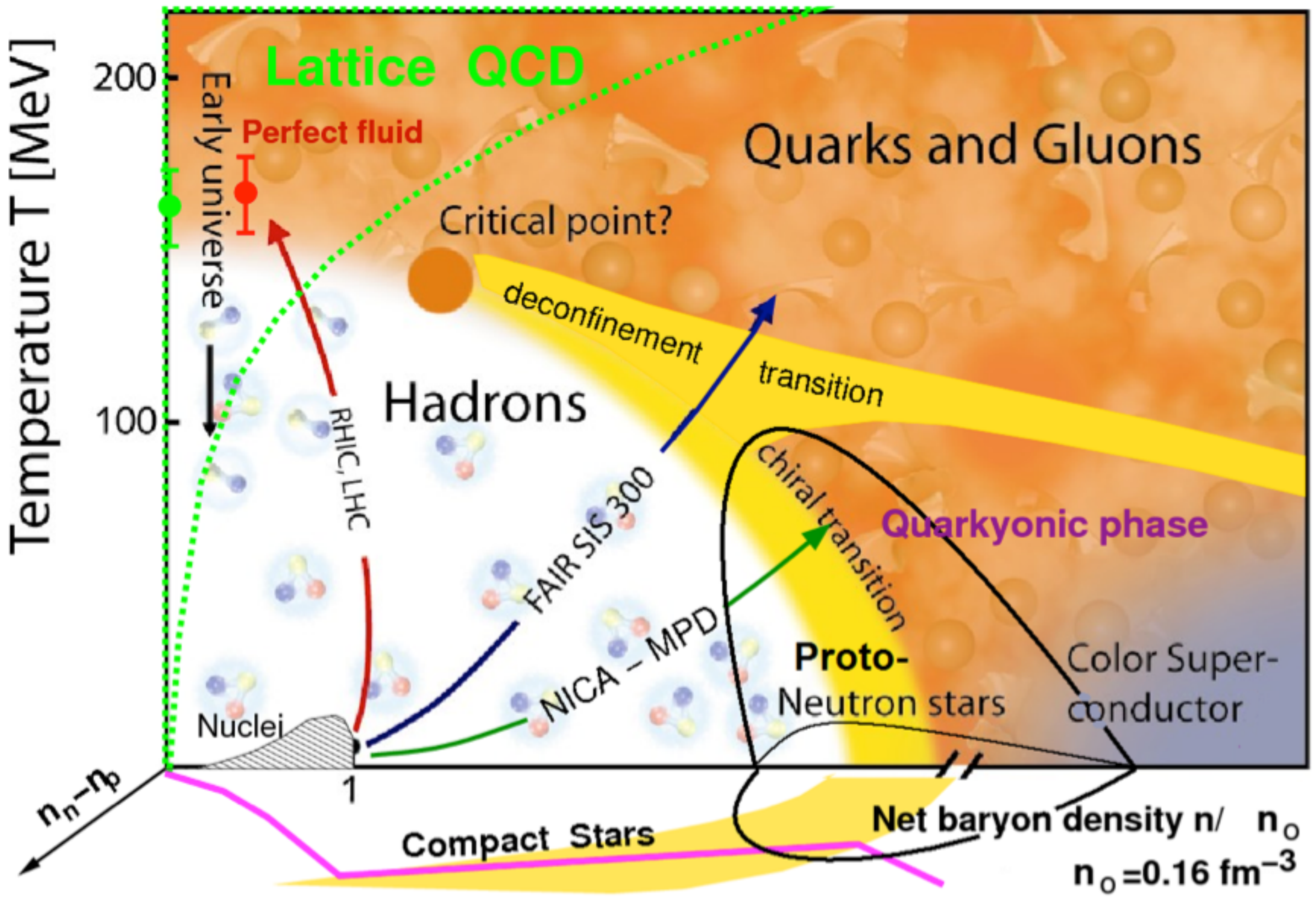
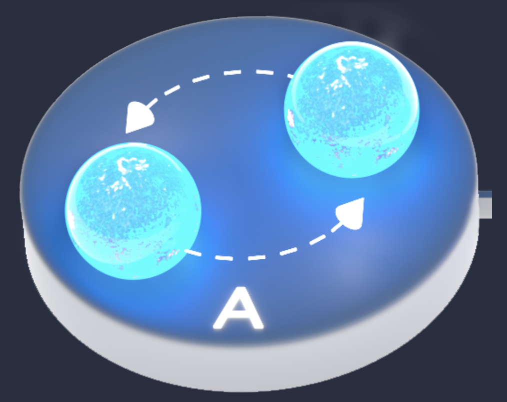
- Hypermassive NS matter described by the **hot nuclear EoS, and NS are differentially rotating** (Sarin+2021 review)
- The hot nuclear EoS can be studied in these objects



Post-merger remnants and the NS maximum mass

Measuring NS properties with GWs



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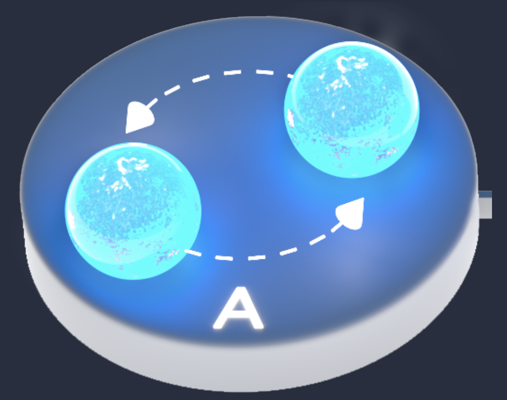

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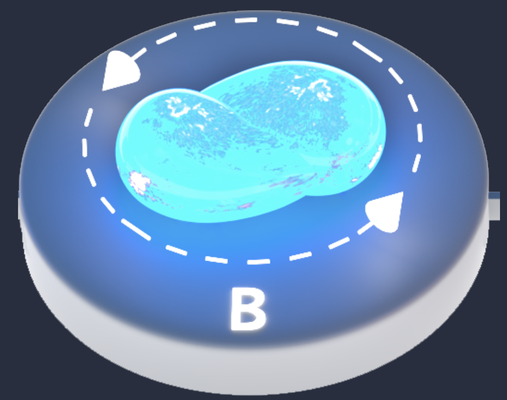

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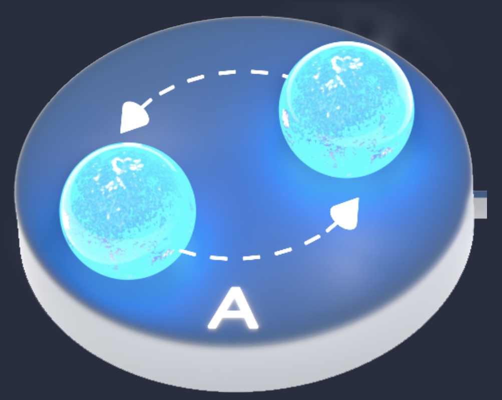

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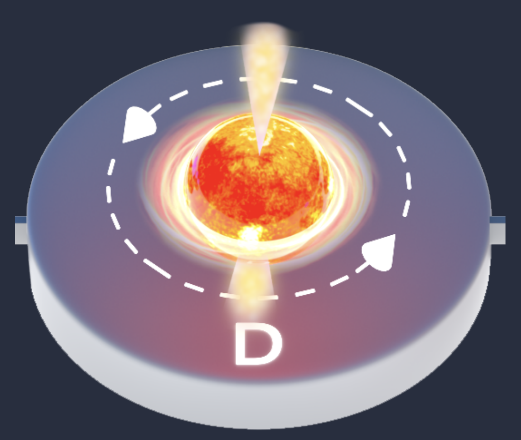

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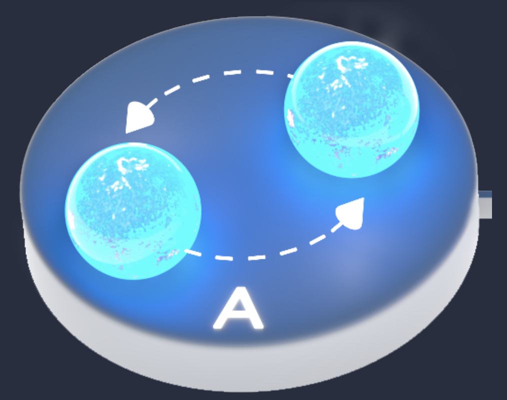

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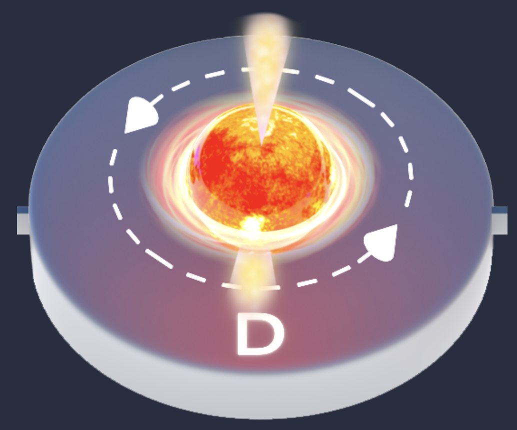

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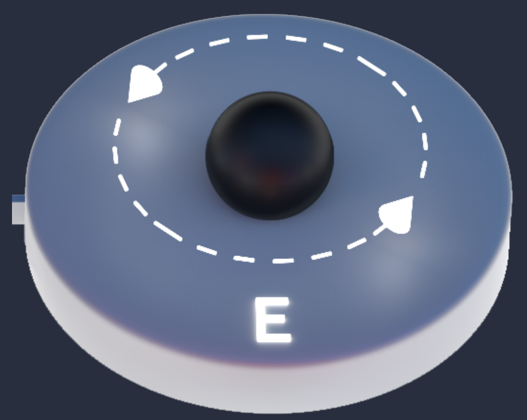

BH formation: Collapse to BH if rotational support is lost and EoS insufficiently stiff

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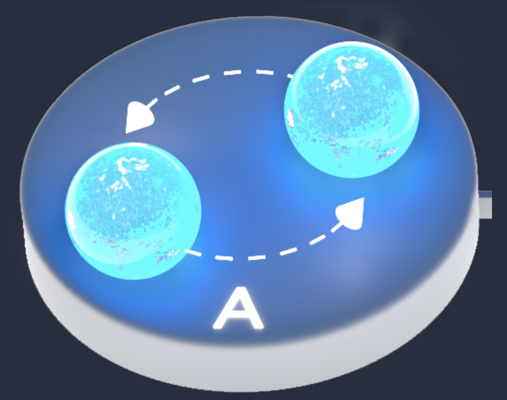

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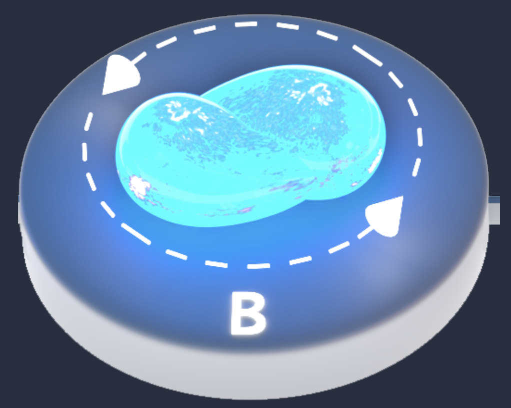

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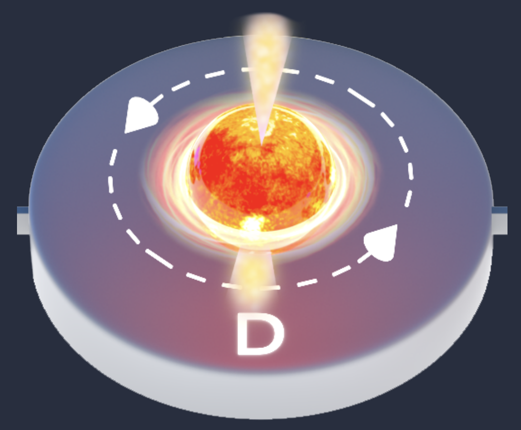

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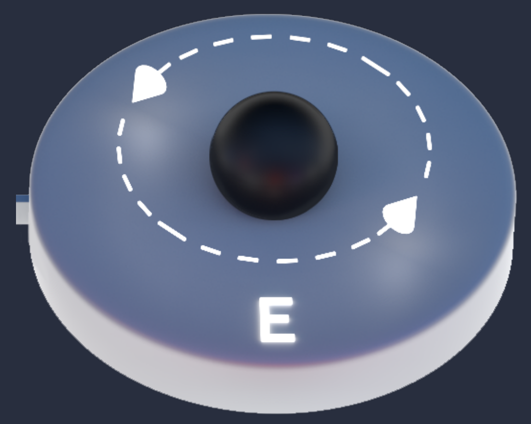

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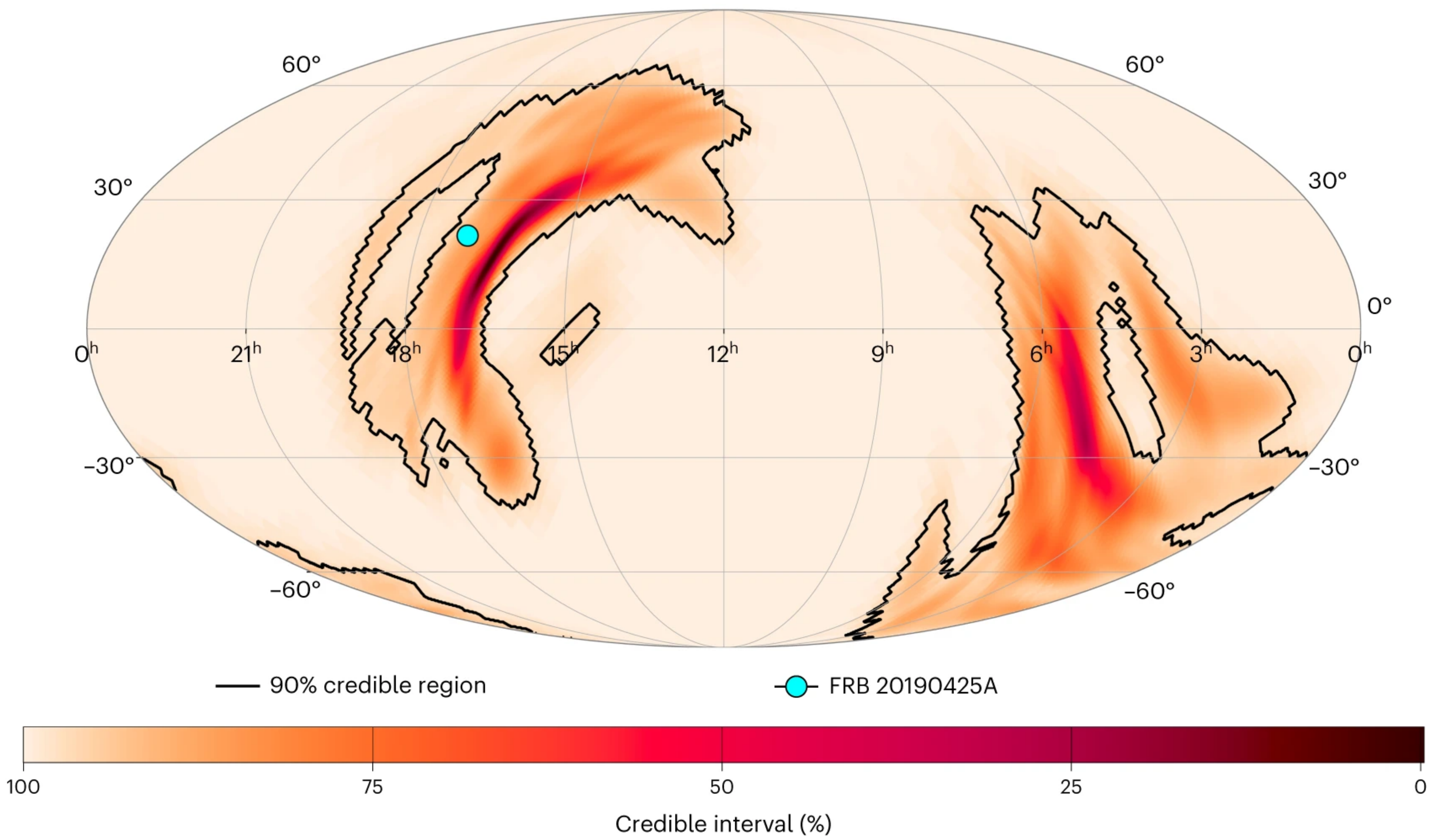
Post-merger remnants and the NS maximum mass

An FRB* 2.5 hours AFTER a BNS merger resulting from a hypermassive neutron star formed in GW190425

$> 2.63^{+0.39}_{-0.23}$ solar masses ($> 2.31^{+0.24}_{-0.08}$ solar masses)



Moroianu+2022 Nat. Astron. (MSc student, now PhD at UvA)

*I found the host galaxy of the FRB - see Panther+2022

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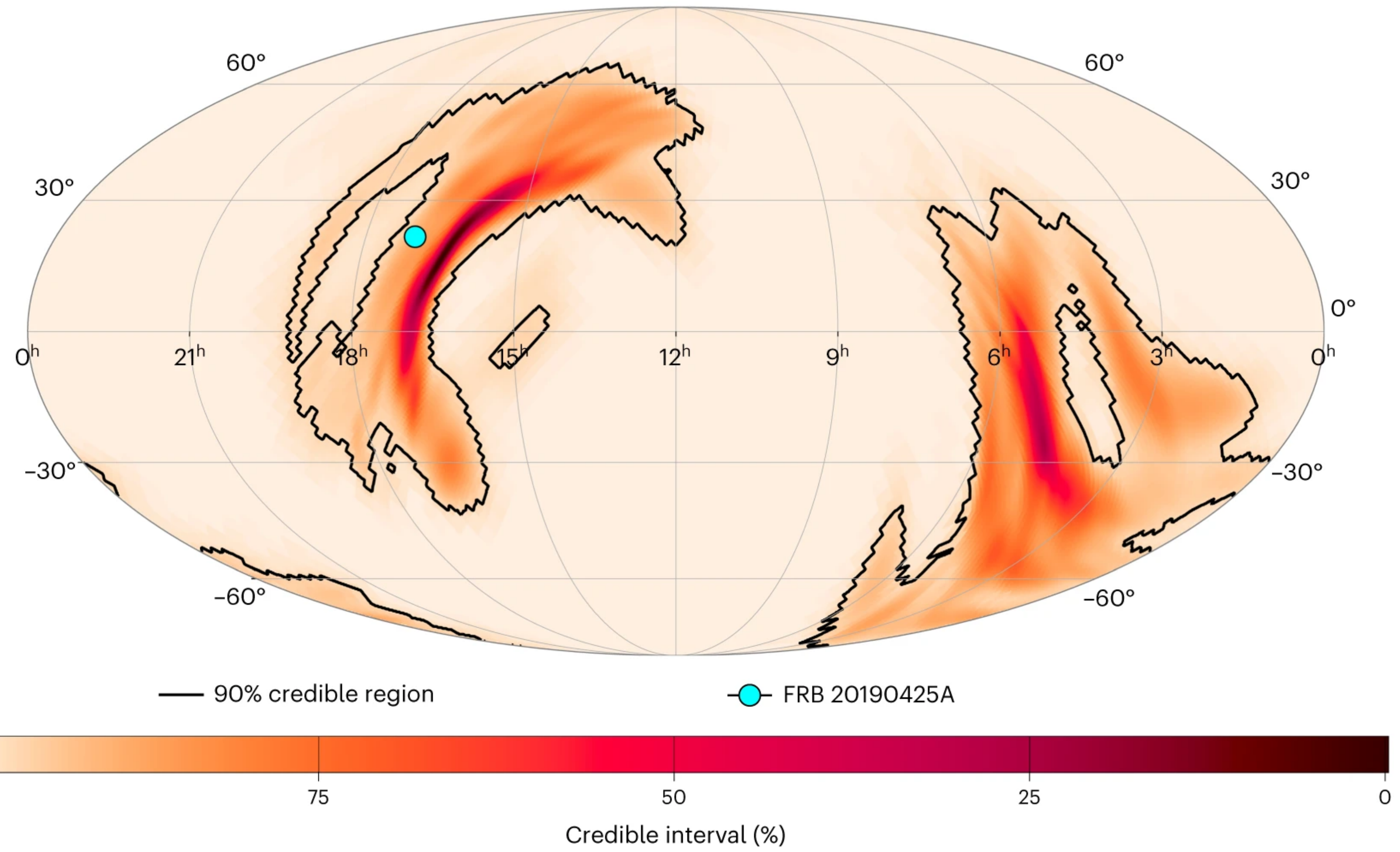

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- There is no conclusive electromagnetic signature of post-merger remnants that can allow us to measure the NS mass and probe the hot nuclear EoS

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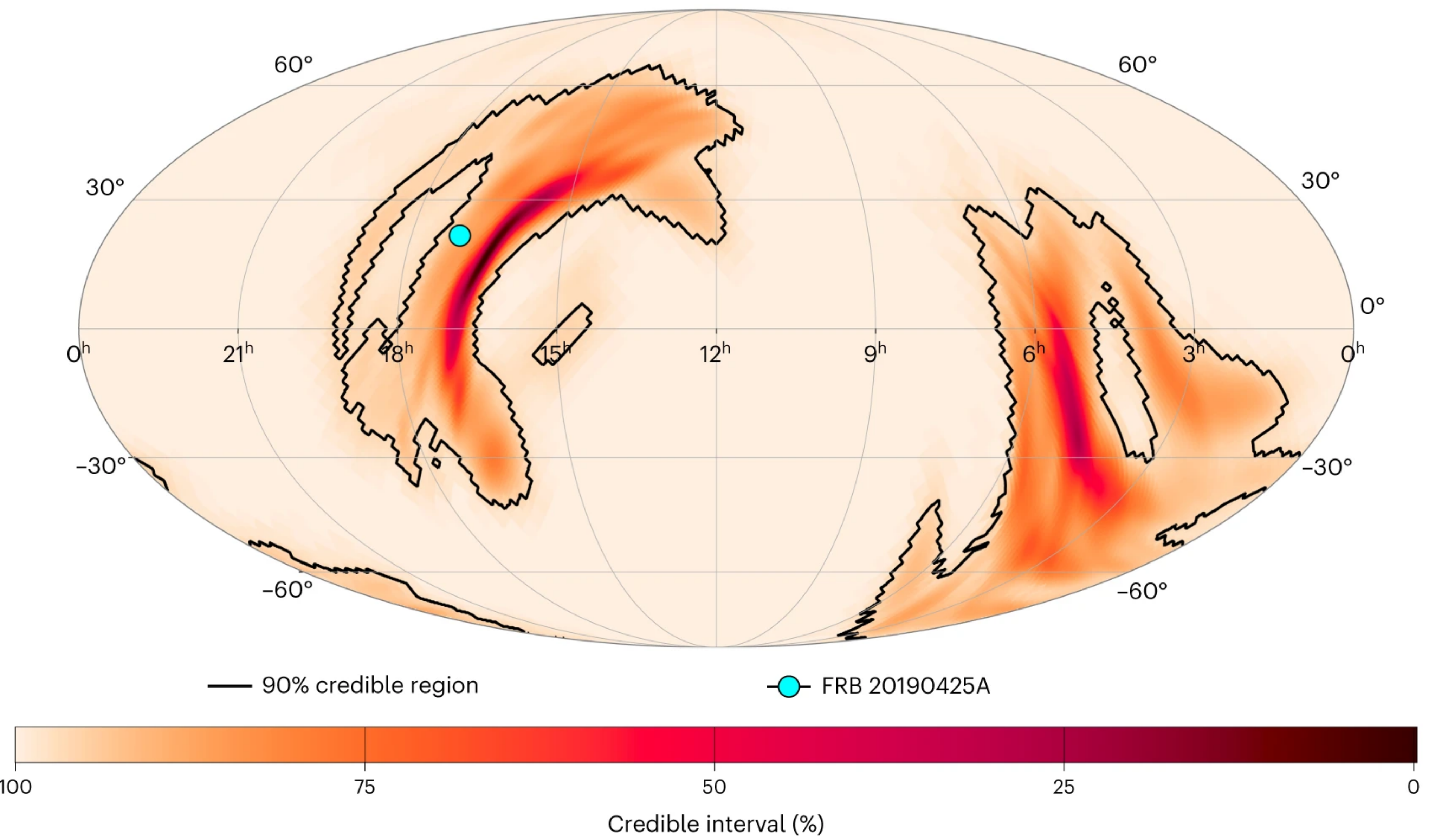

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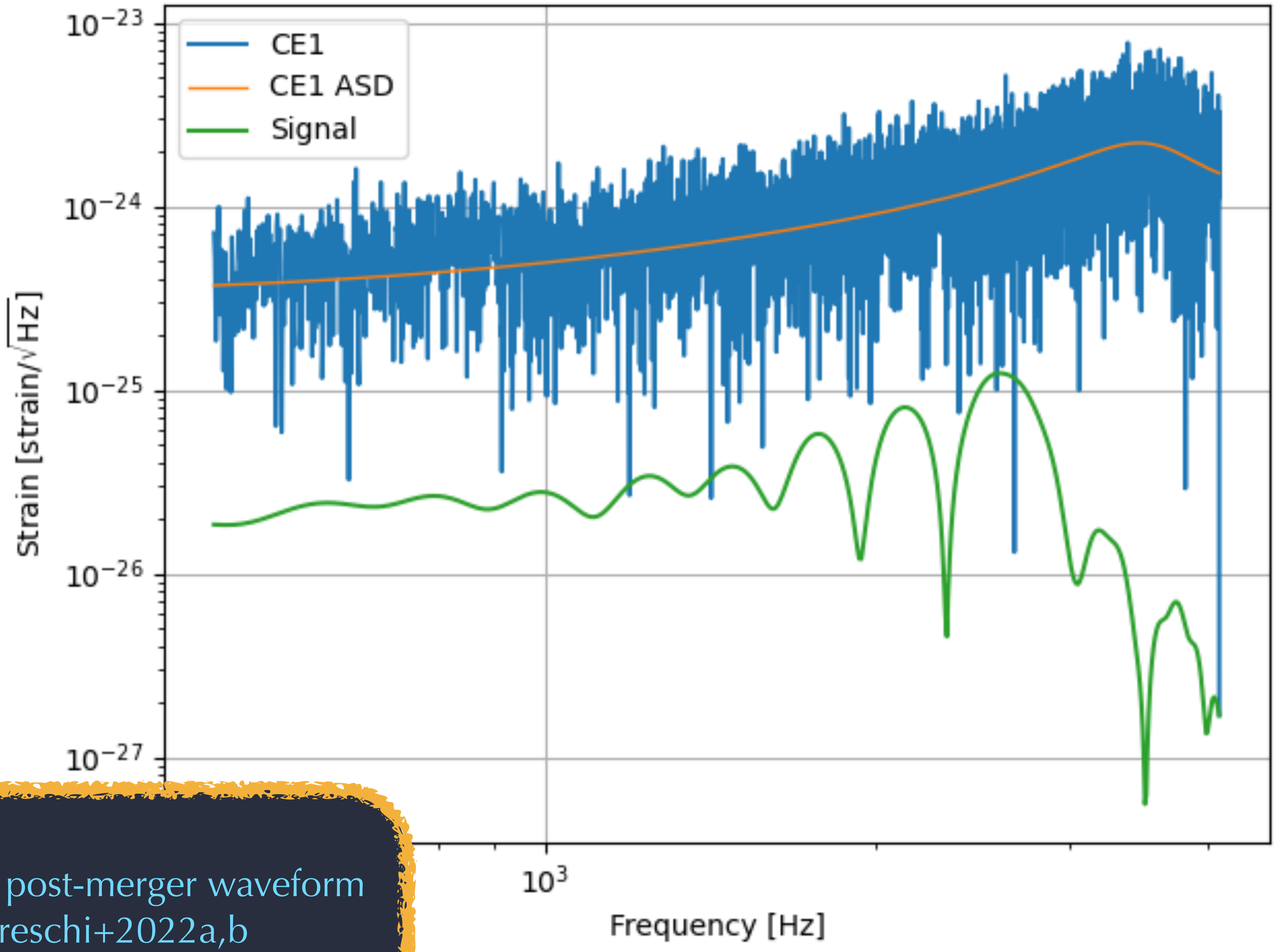
Detecting post-merger GWs

Making a detection* of PMGWs is a significant challenge:



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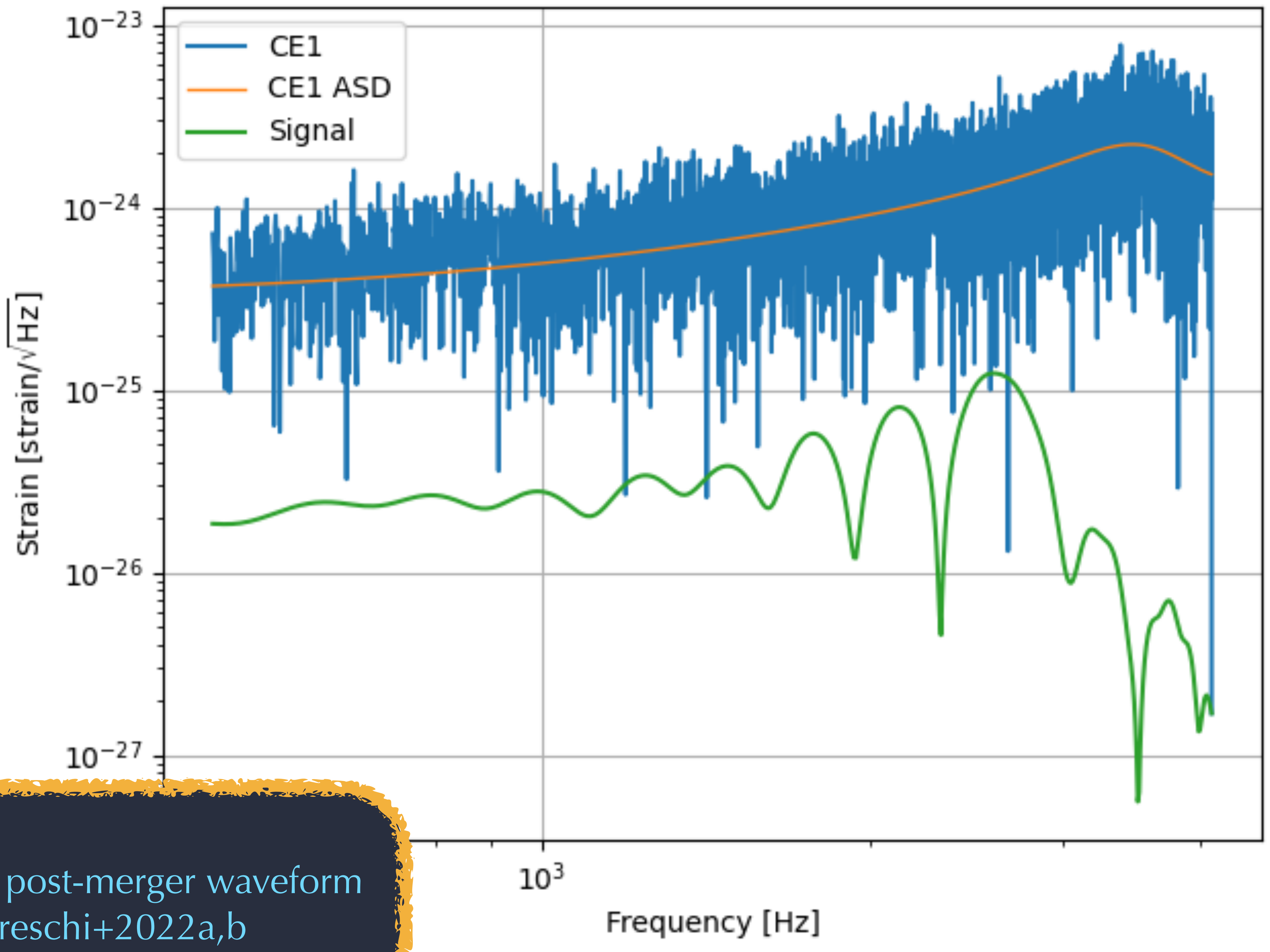

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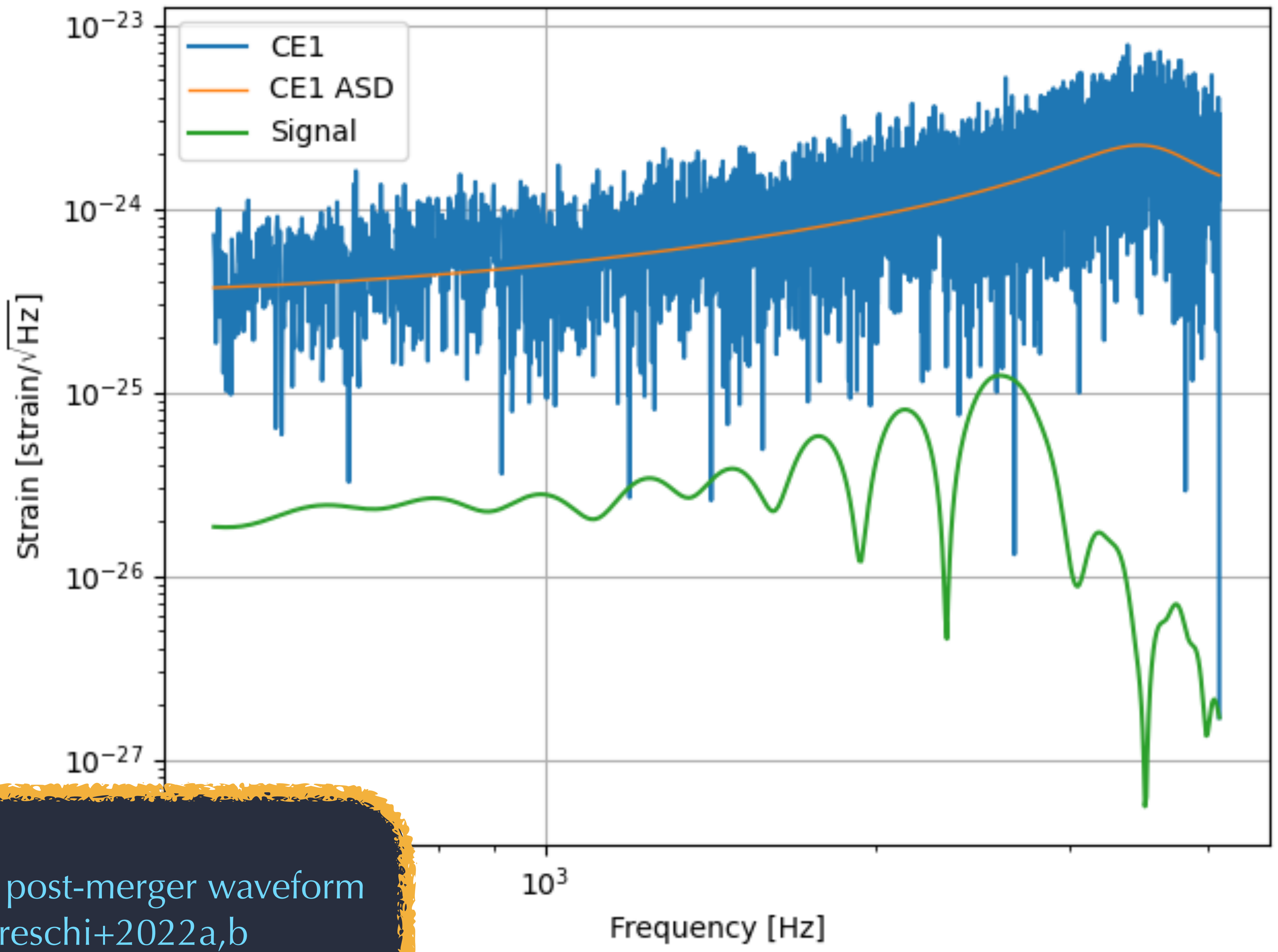

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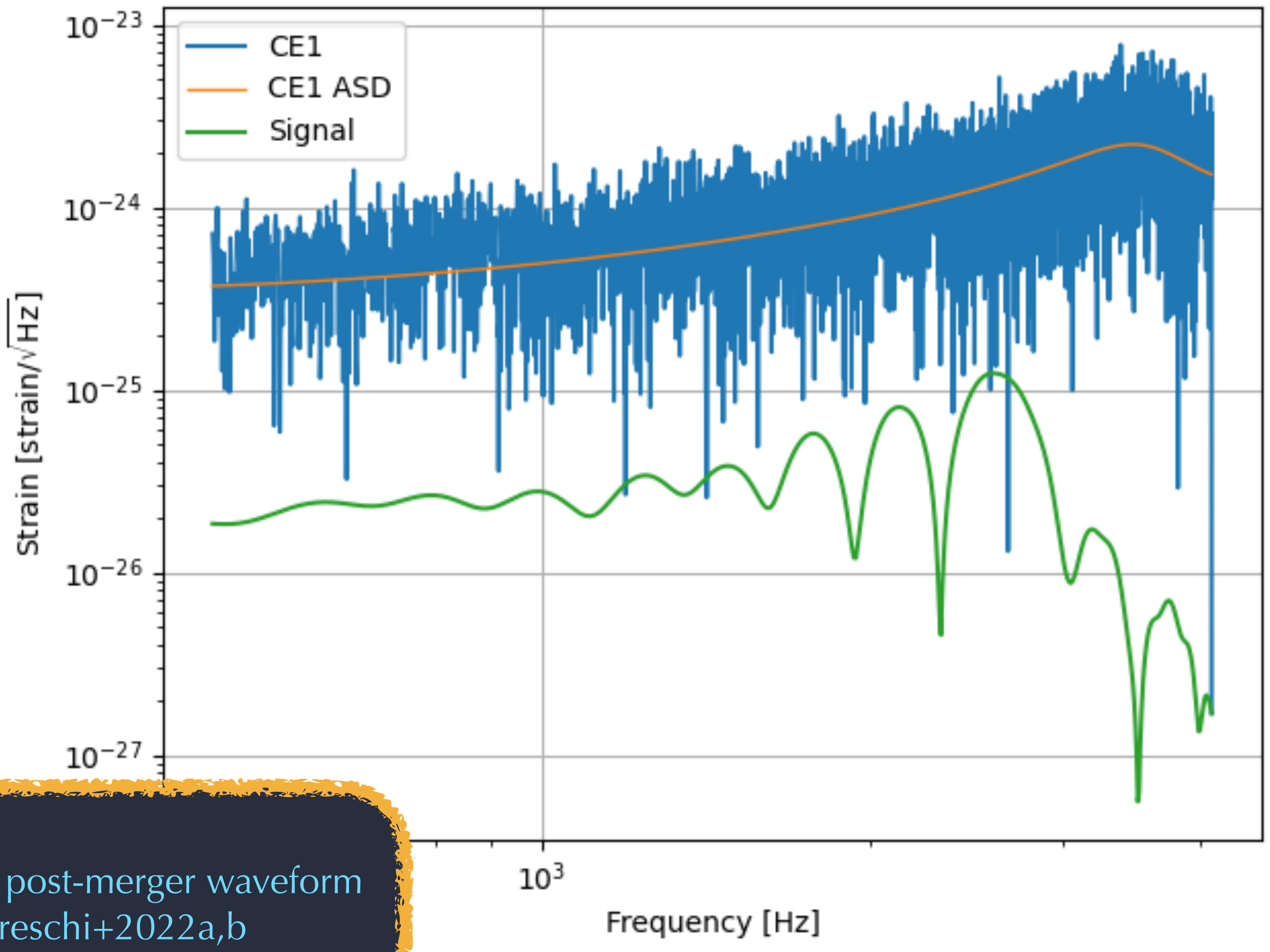

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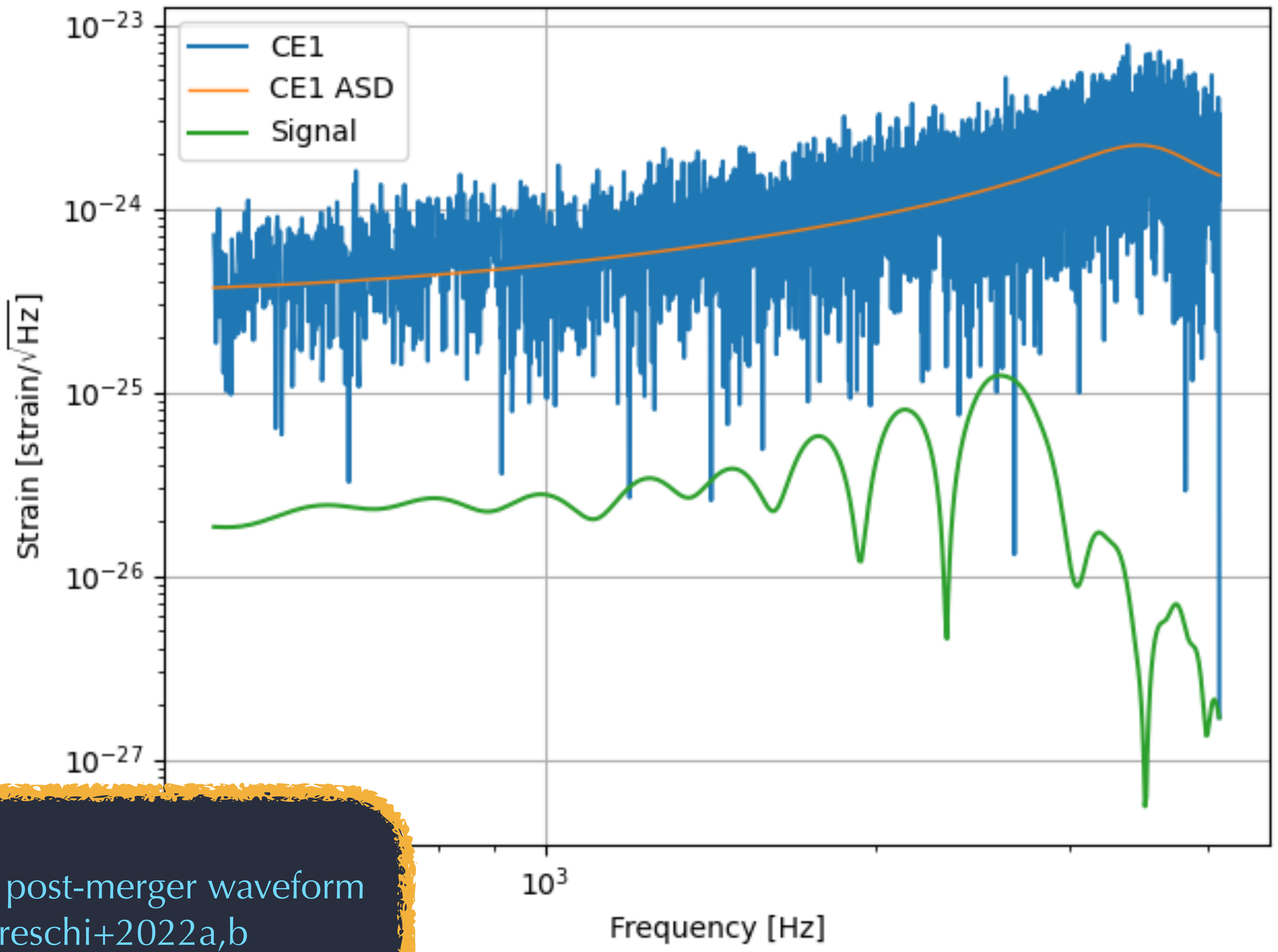
- Lots of model uncertainty!!



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A solution for faint sources: stacking

- Stacking data common in astronomy when we have a faint source and need to boost our SNR.
- How can we combine many observations of PMGWs? We cannot naively stack them in the data space.
- Stack observations of heterogeneous sources in the **model space** by creating a 'stacked signal likelihood' instead!

Stacking in the data space with optical images

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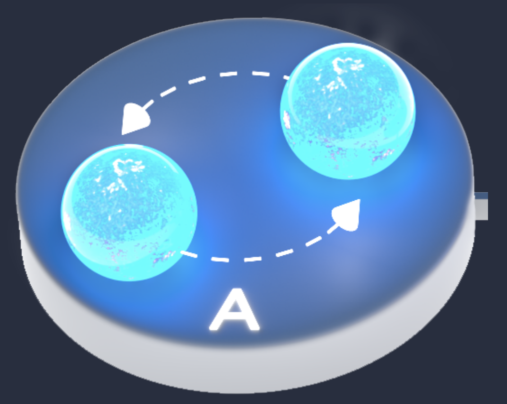
Stacking in the data space with optical images

Stacking increases the **contrast** of the image: noise level grows at a slower rate to the signal level, so by combining many exposures to lengthen the observing time we can maximise the ratio of the signal to the noise.

A mixture model formalism to 'stack' GWs

Develop a mixture model formalism based on Smith & Thrane 2018 (An Optimal Search for a GW background) to search for PMGWs



*We use the usual GW (Whittle) likelihood for a signal h in Gaussian noise $\ln \mathcal{L}(d\,|\,\theta) \propto \langle d - h(\theta),\; s - h(\theta)\rangle$

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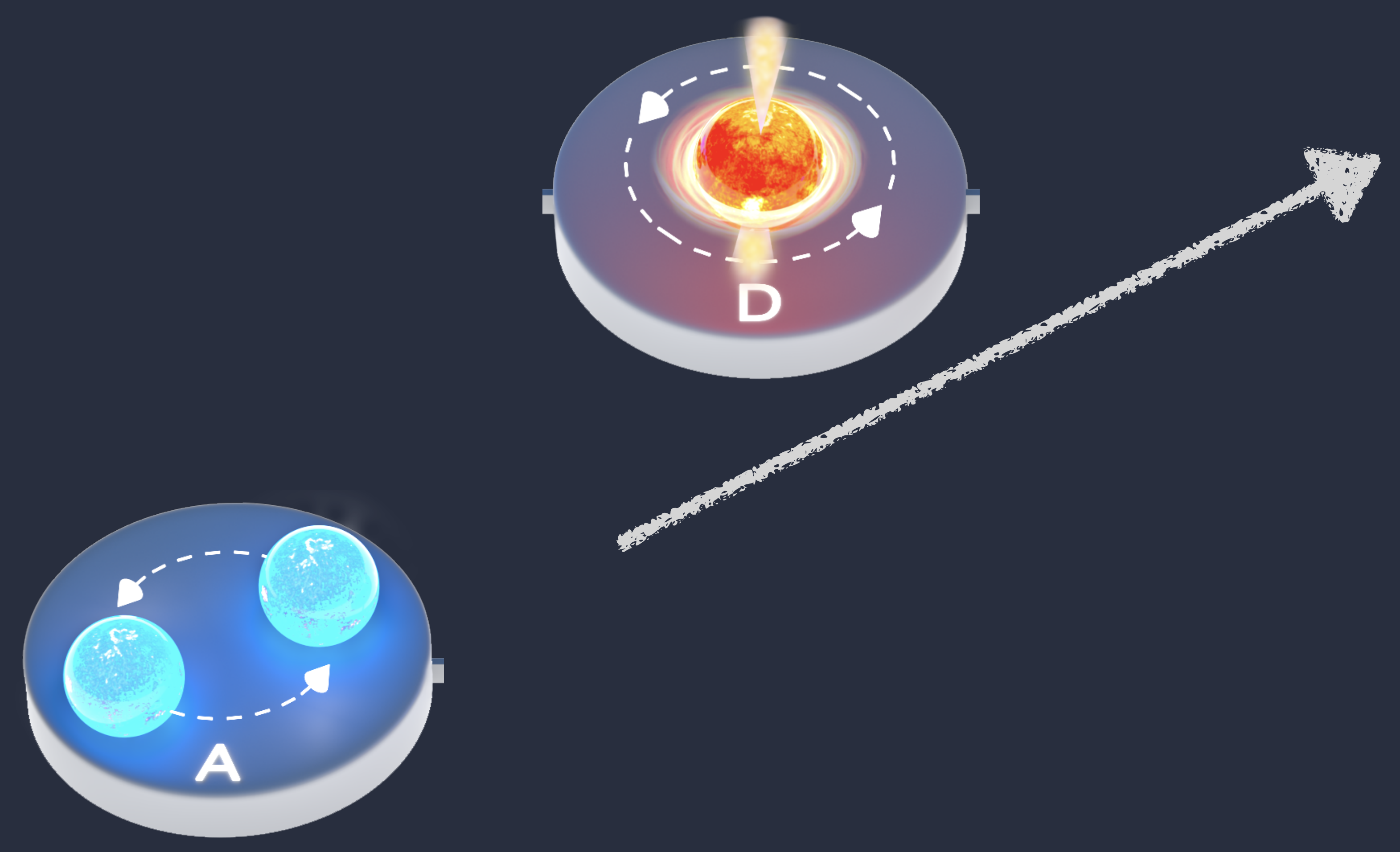

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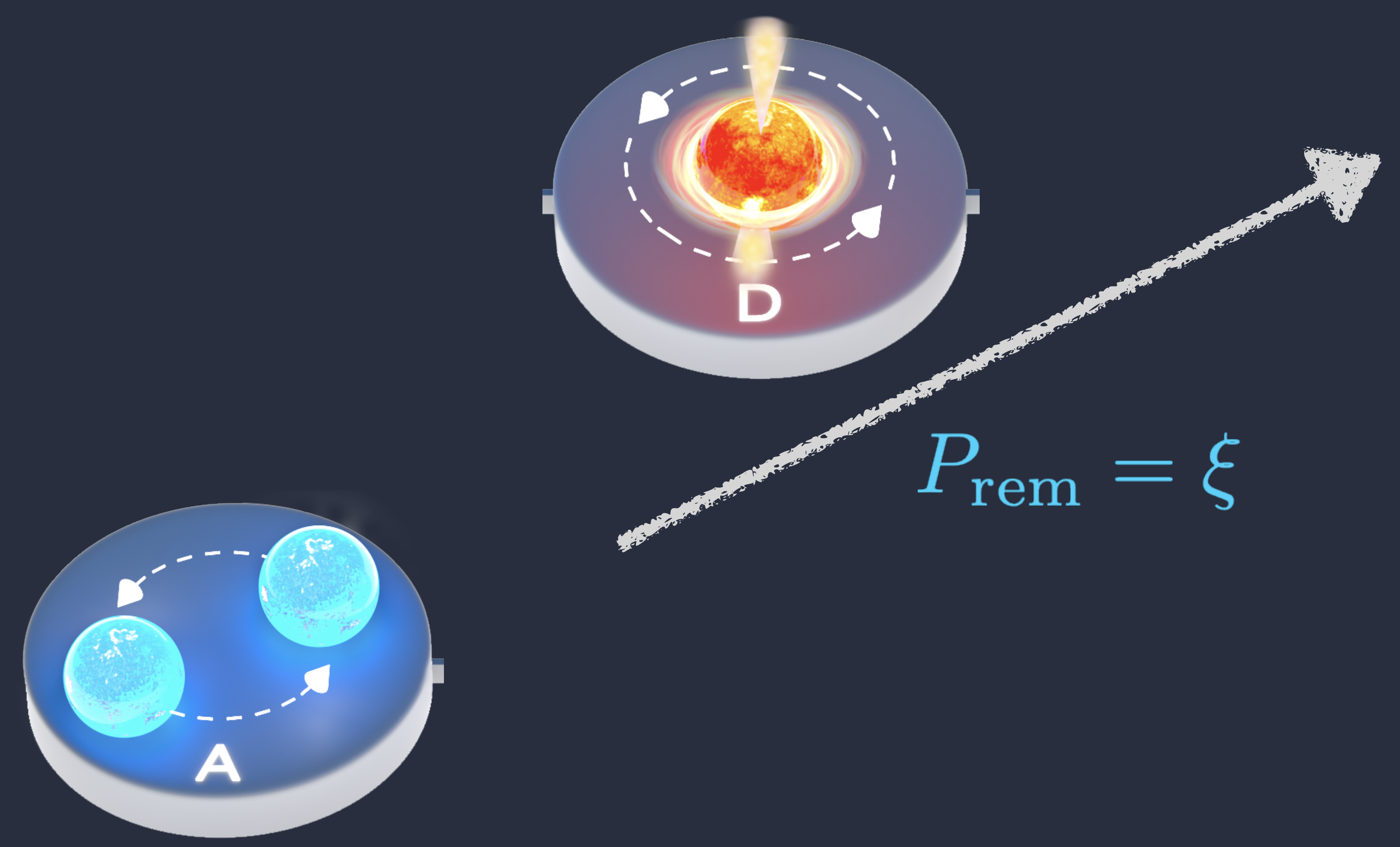

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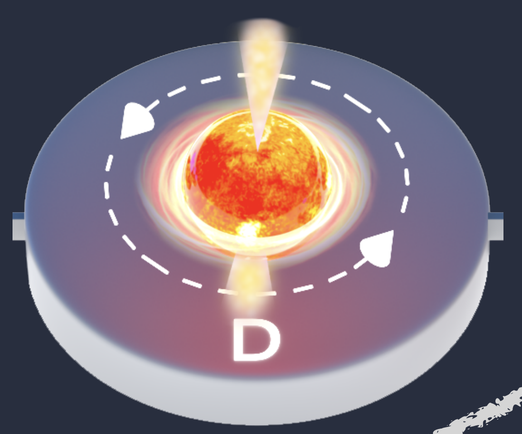

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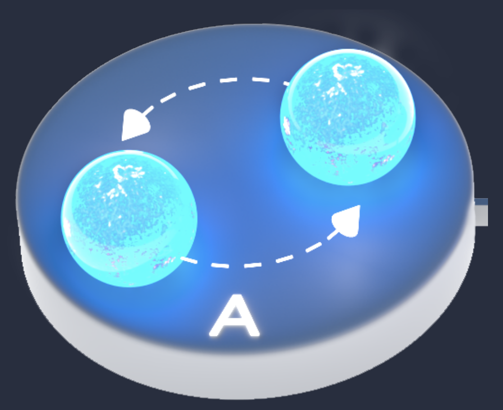

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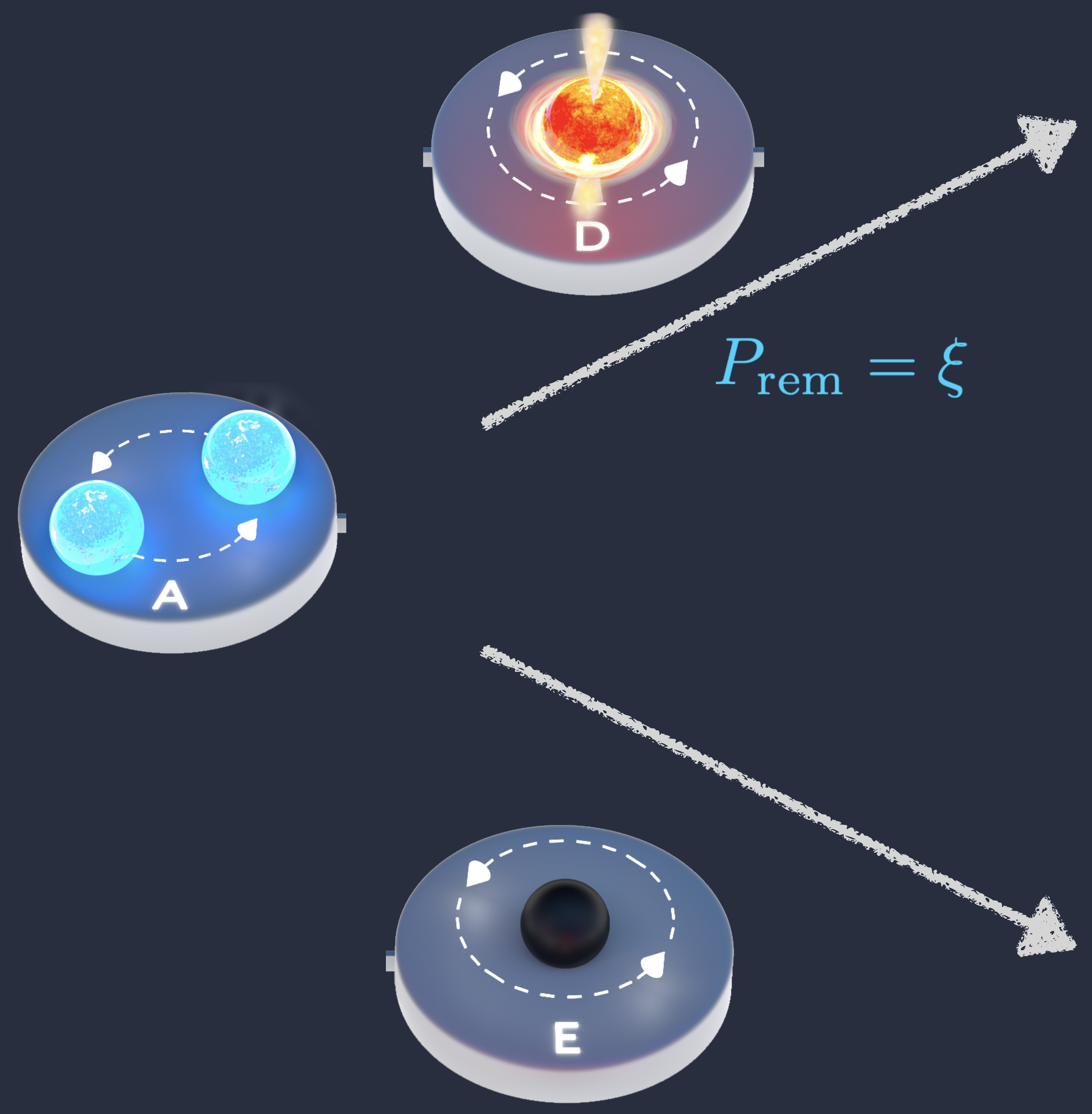

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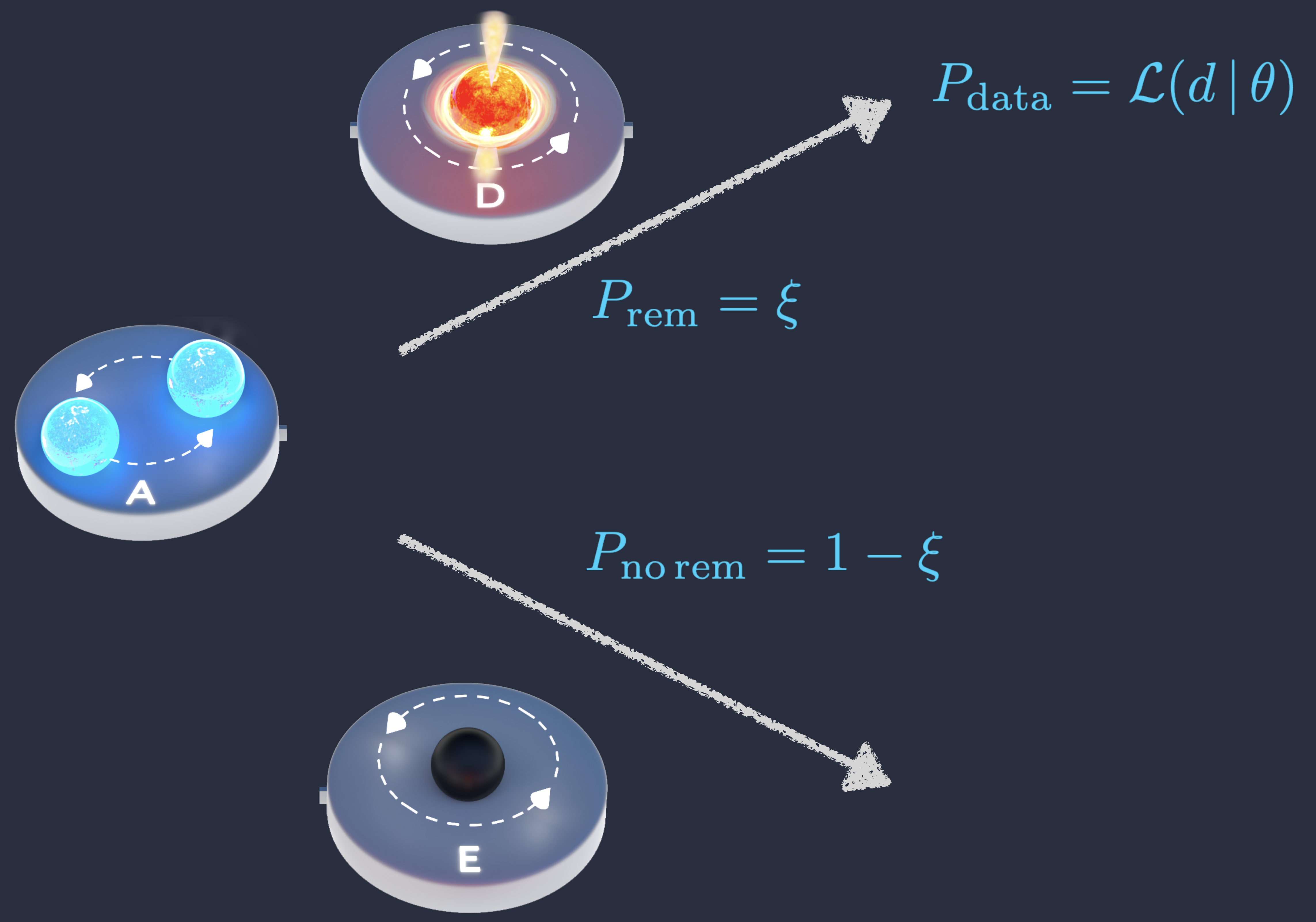

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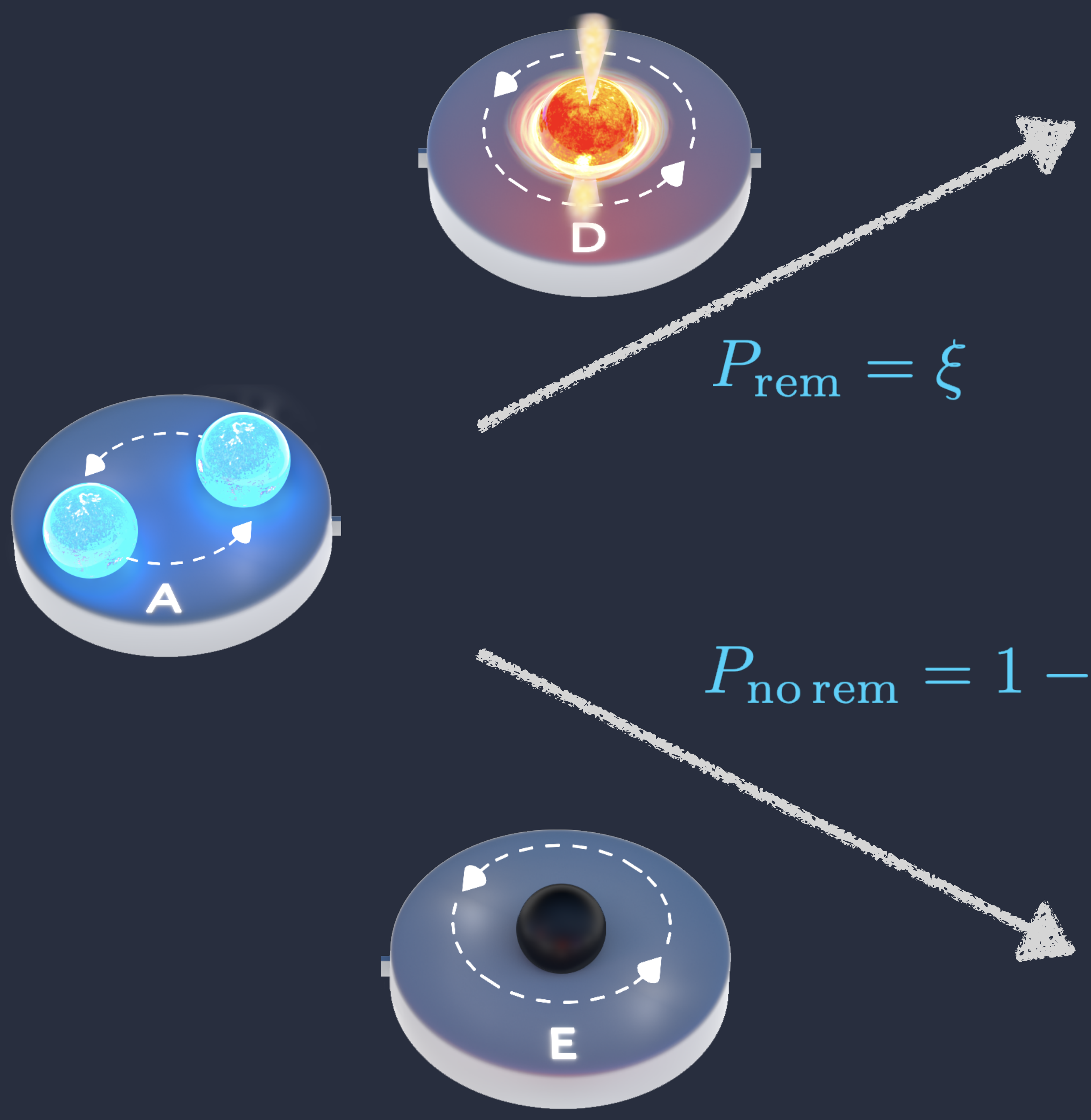

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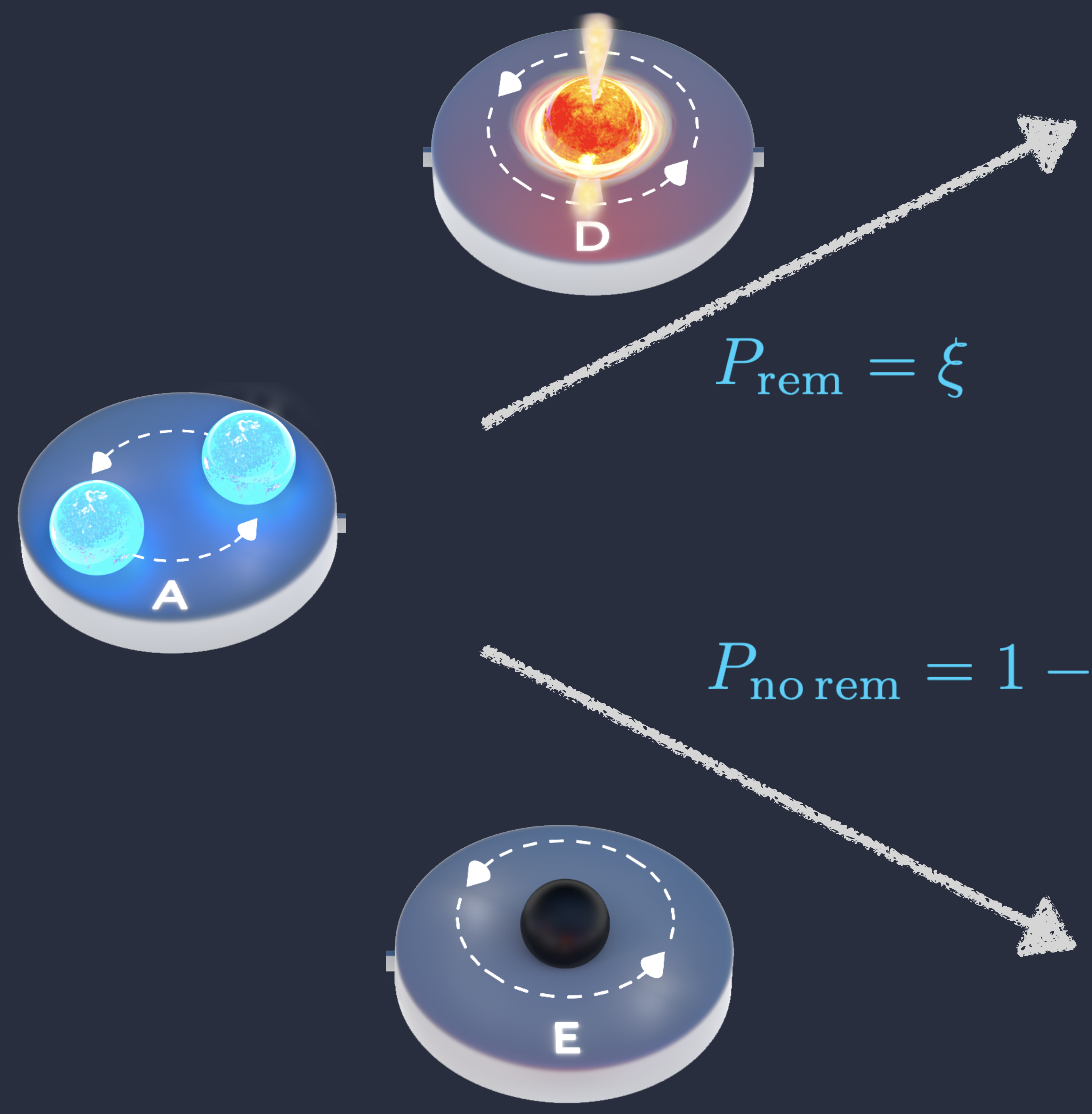

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The total likelihood in this scenario is

$$\mathcal{L}(d\,|\,\theta,\,\xi) = \xi\mathcal{L}(d\,|\,\theta) + (1-\xi)\mathcal{L}(d\,|\,\emptyset)$$

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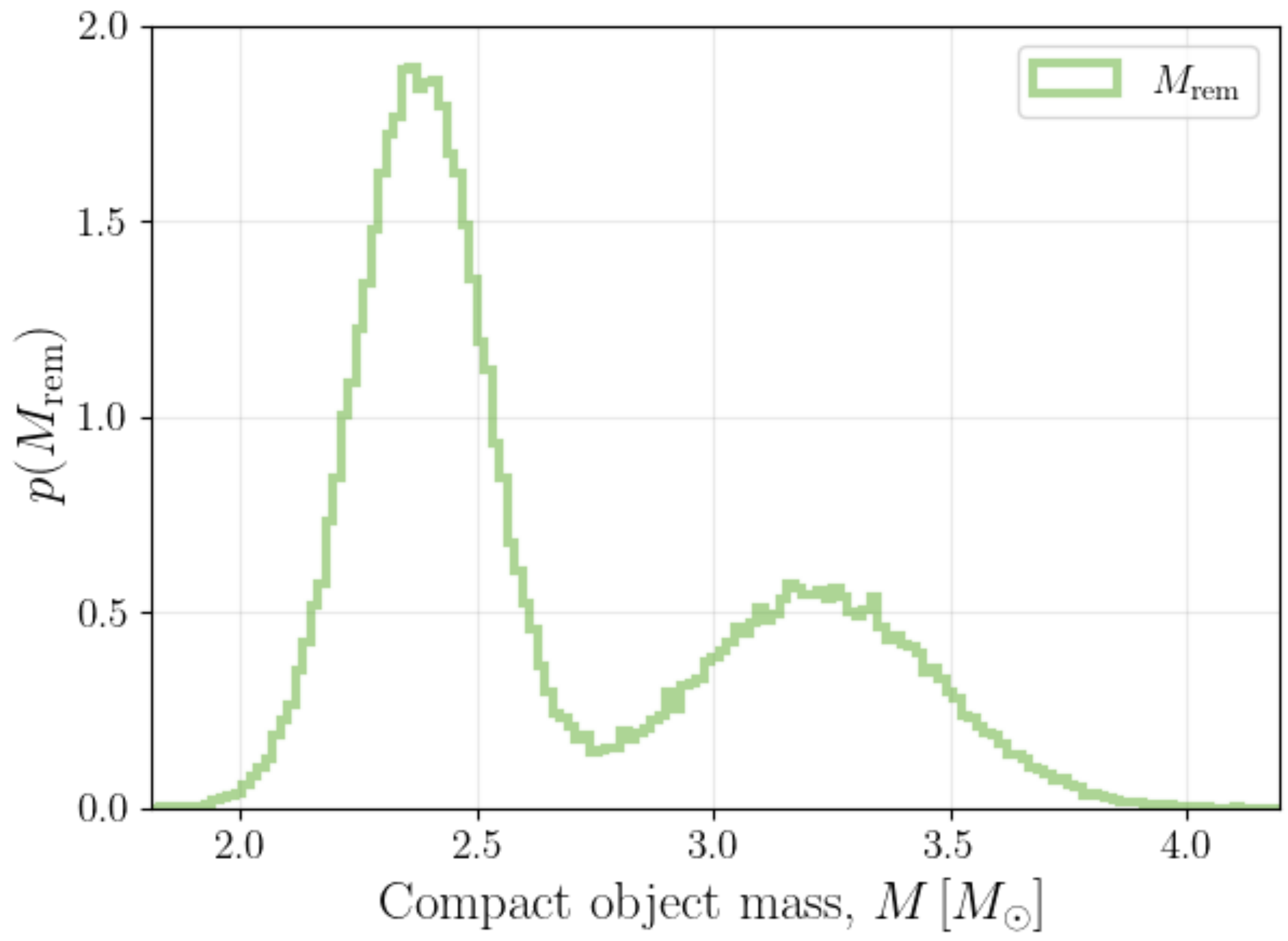
What's in the mixing fraction?

Physics determines the fraction of BNS mergers that leave behind a remnant



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Remnant mass: The remnant mass is the sum of the **rest masses** of the individual neutron stars, minus the mass lost ($0.1M_{Sun}$). The rest mass is conserved in the merger

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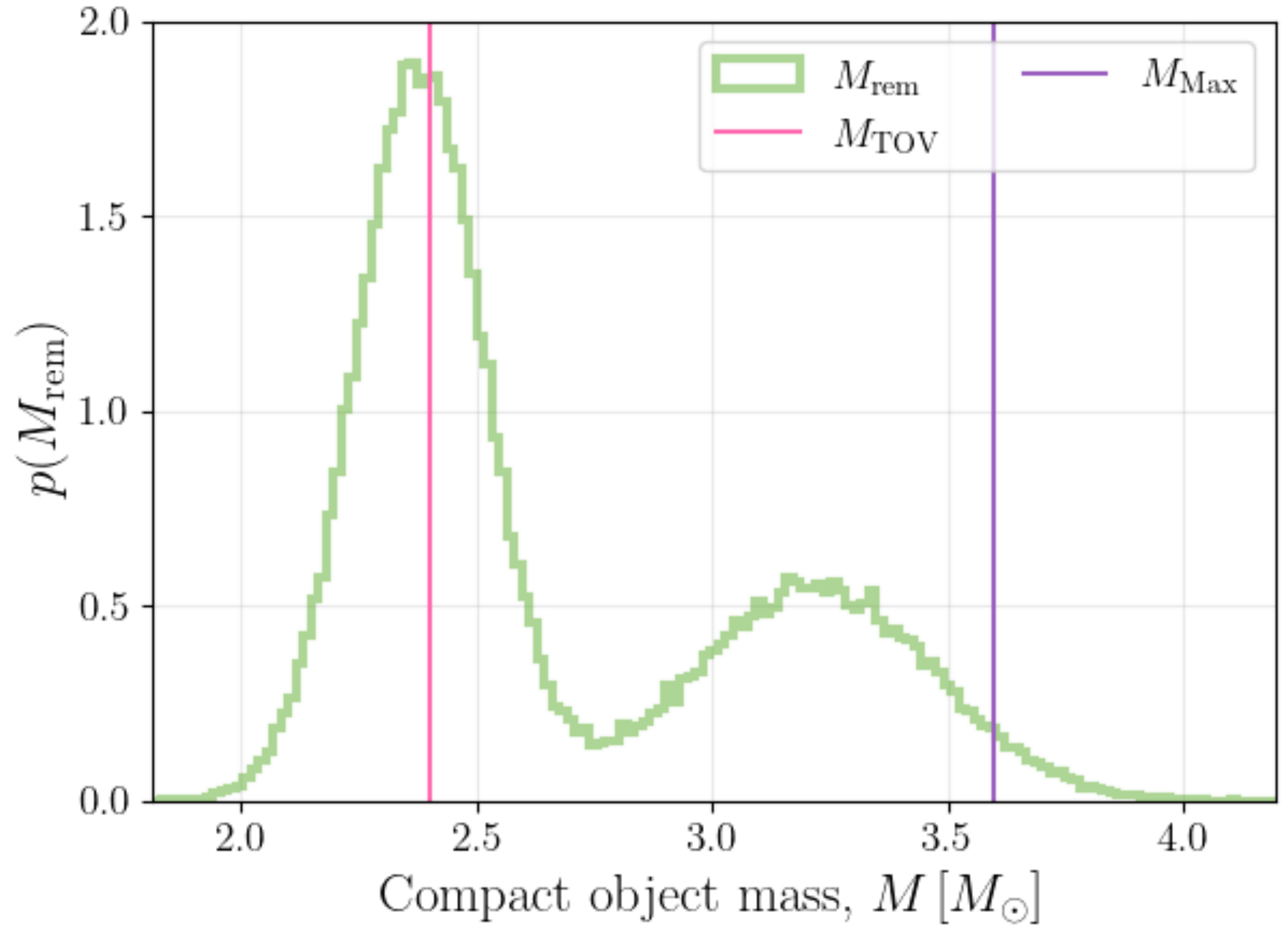

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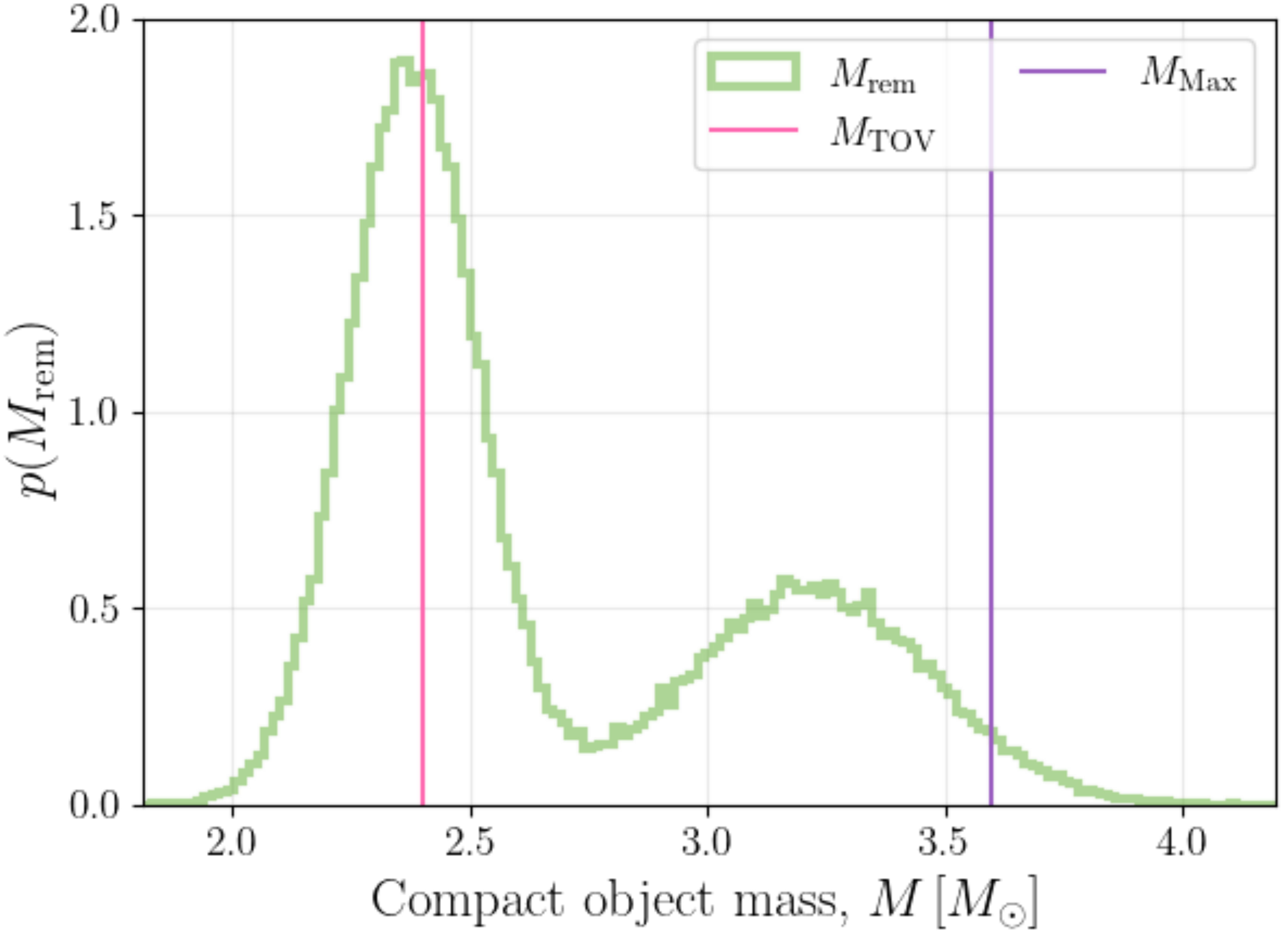

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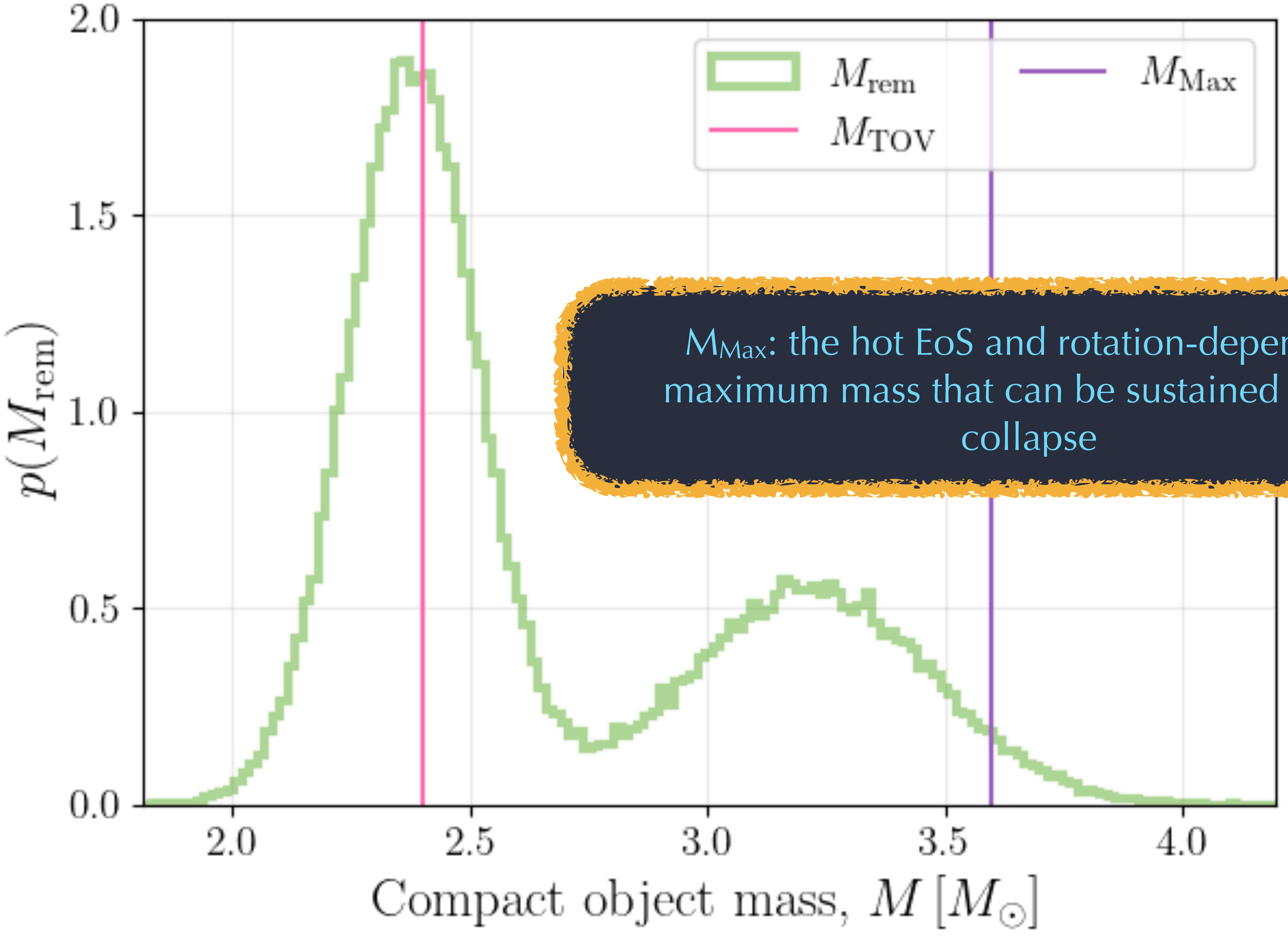

M_{Max}: the hot EoS and rotation-dependent maximum mass that can be sustained before collapse

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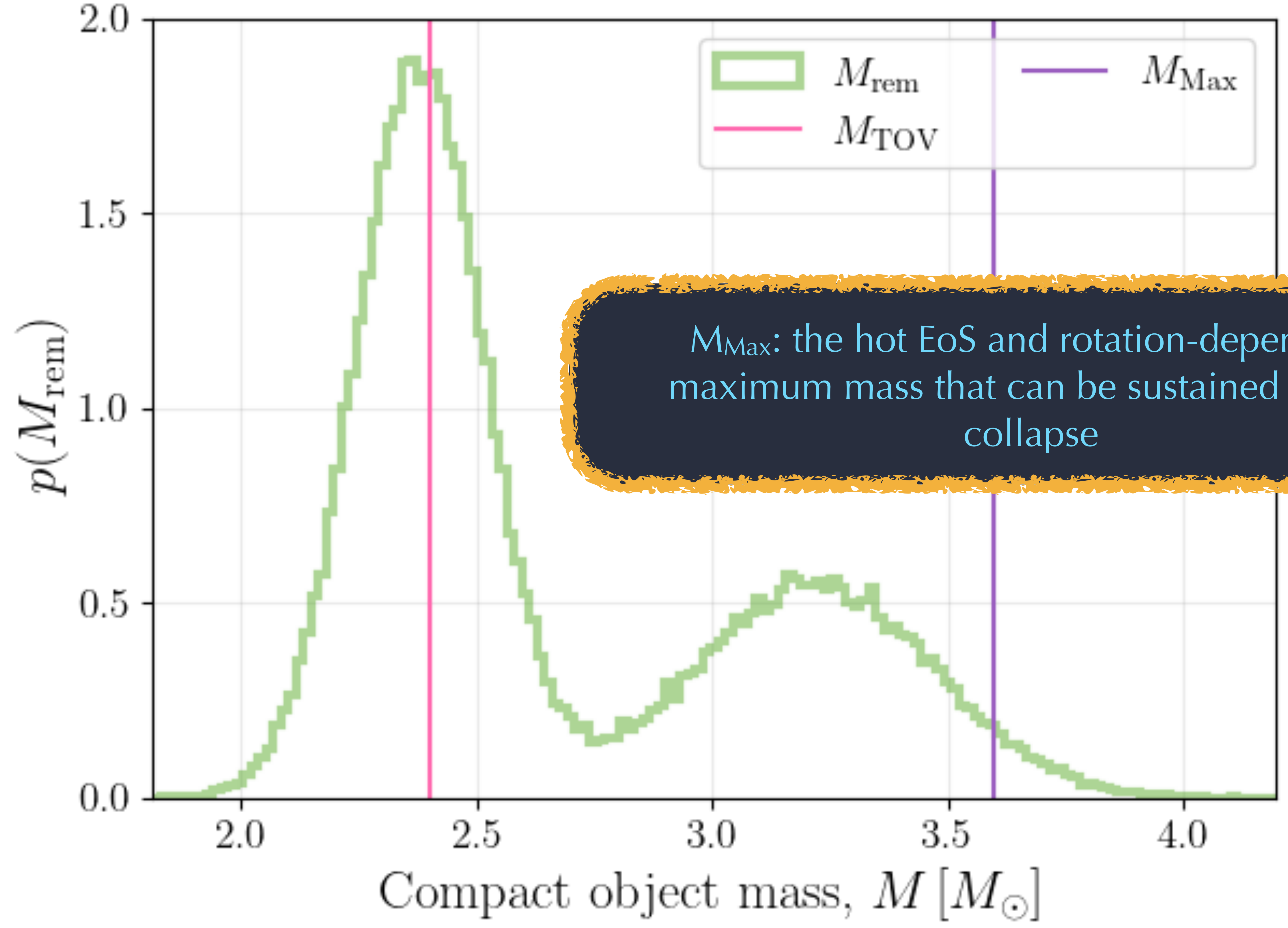

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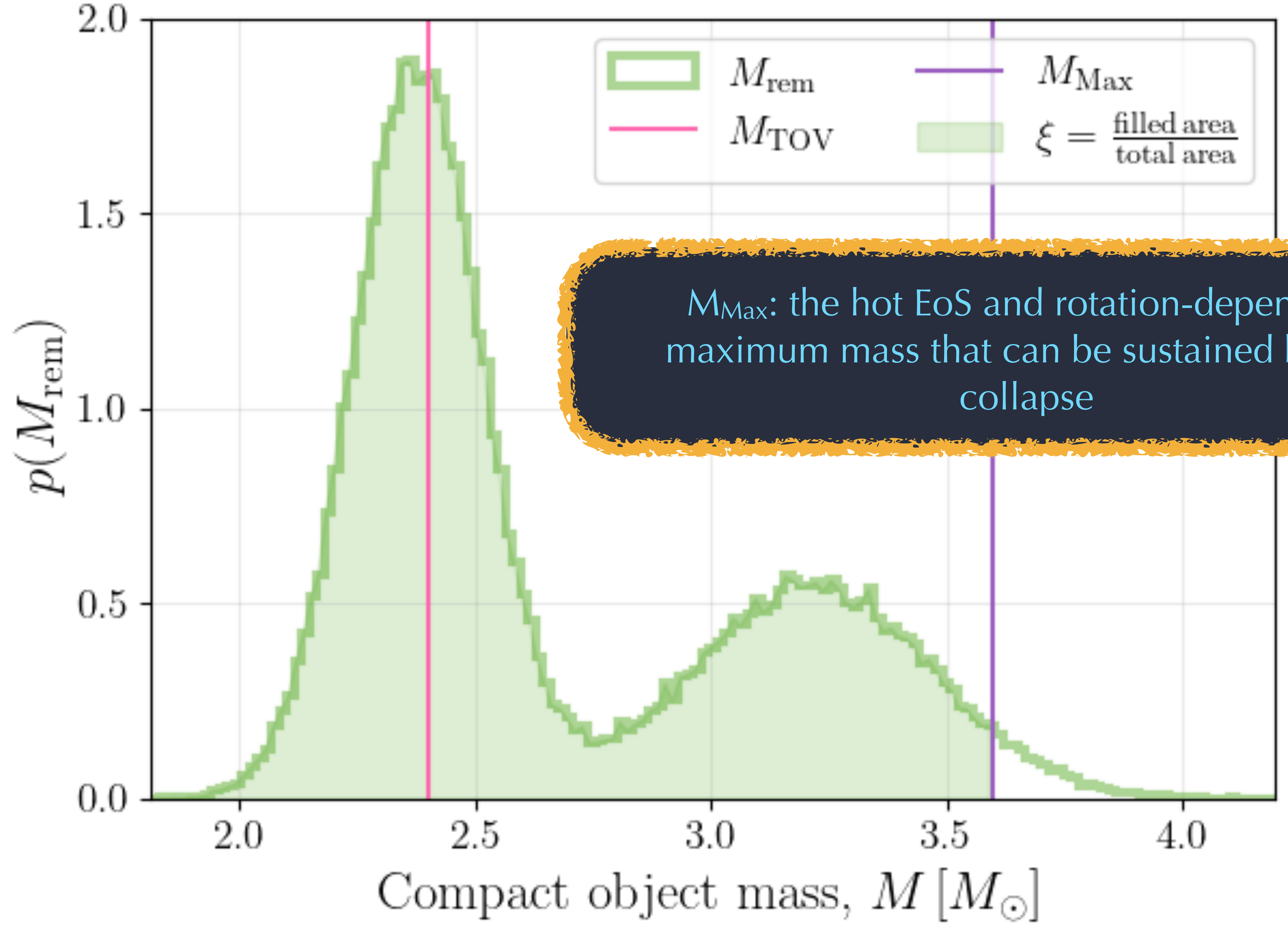

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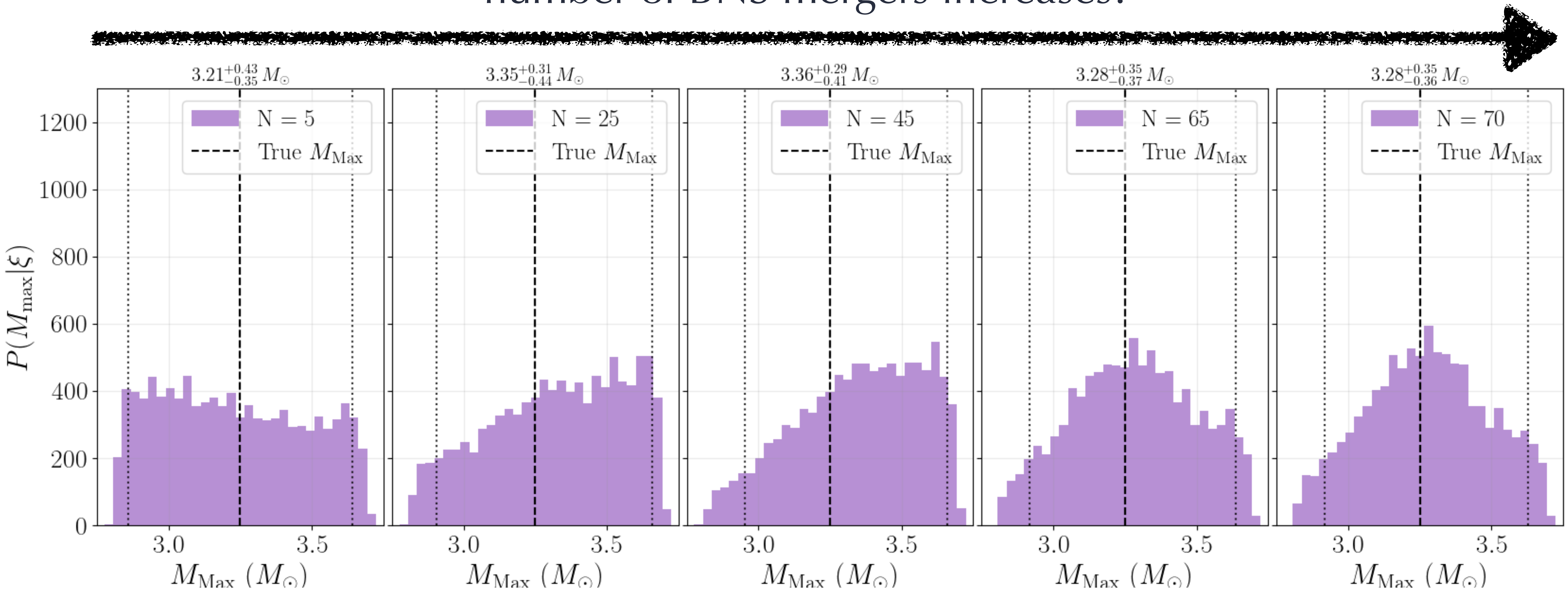
Measuring M_{max}

How accurately and precisely can we measure Mmax as the number of BNS mergers increases?



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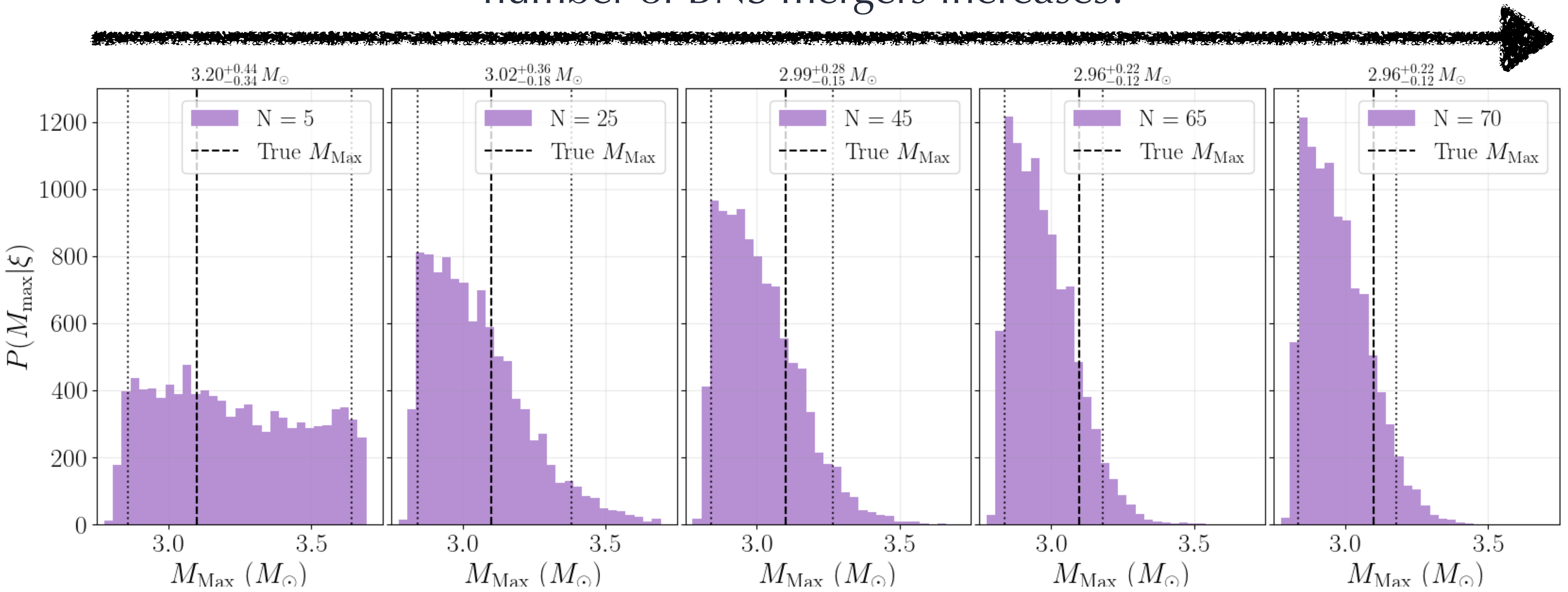

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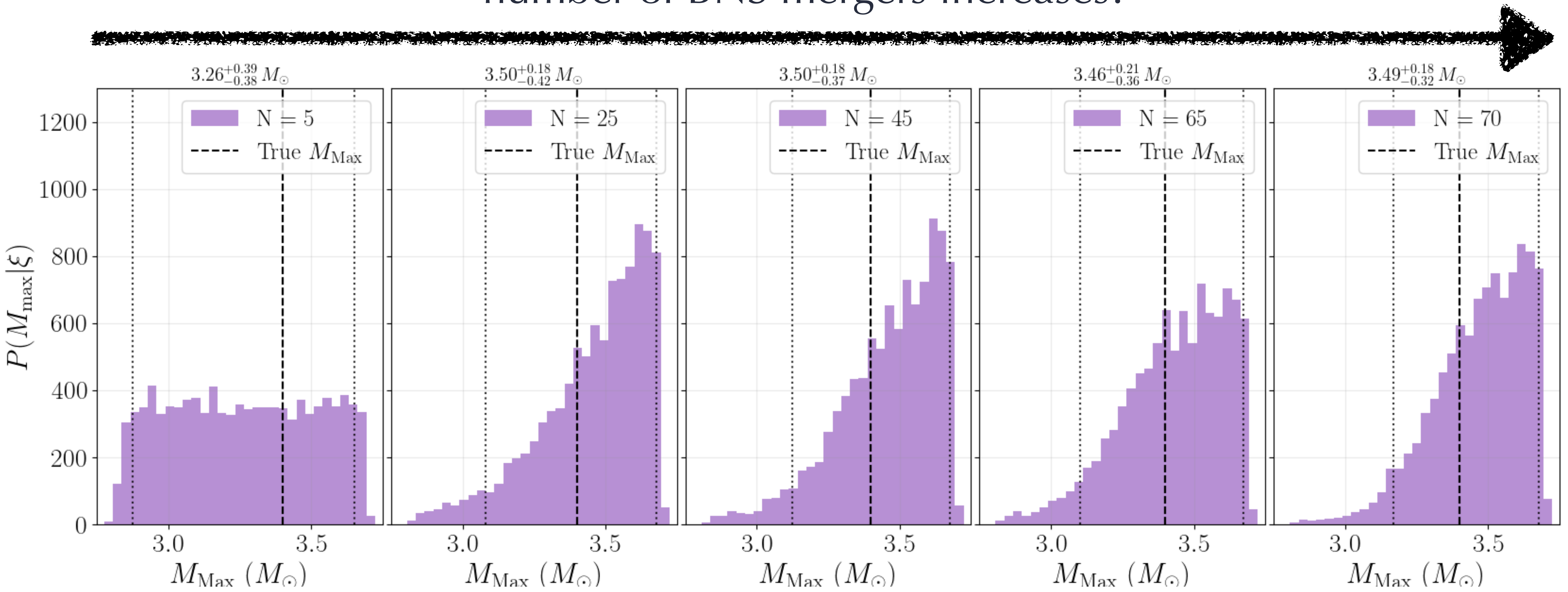

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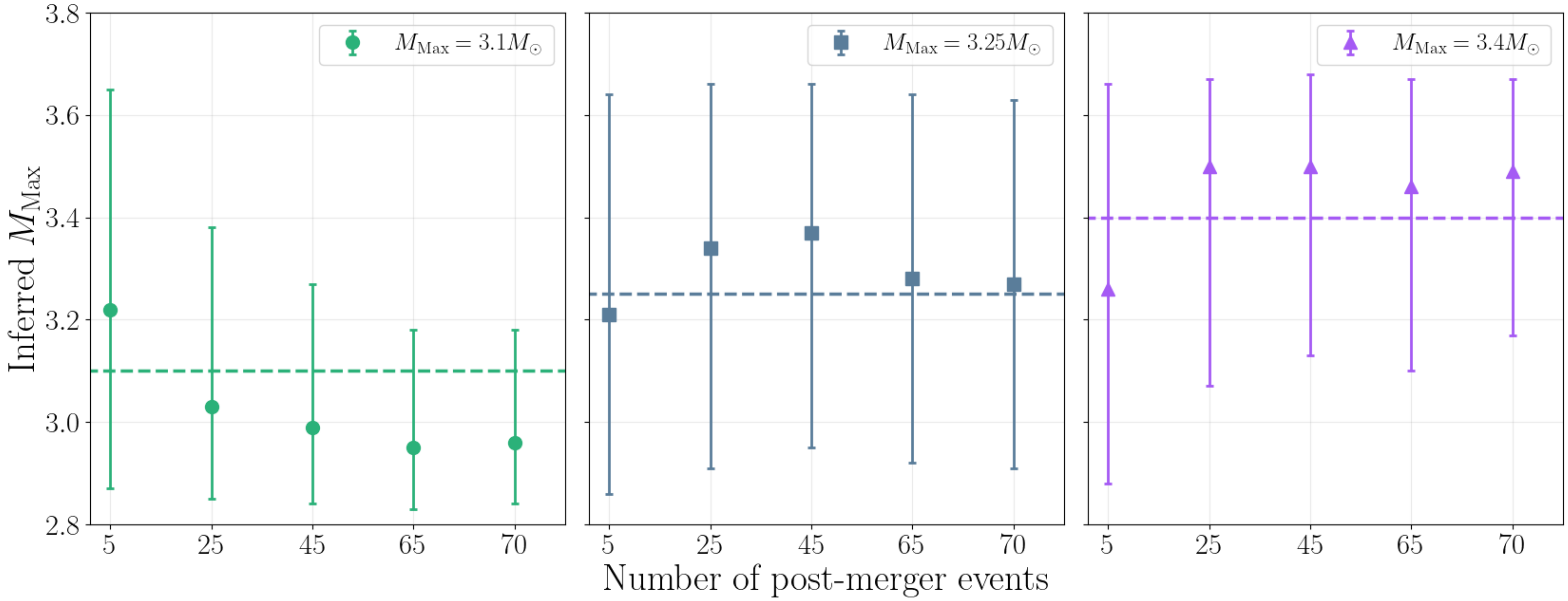

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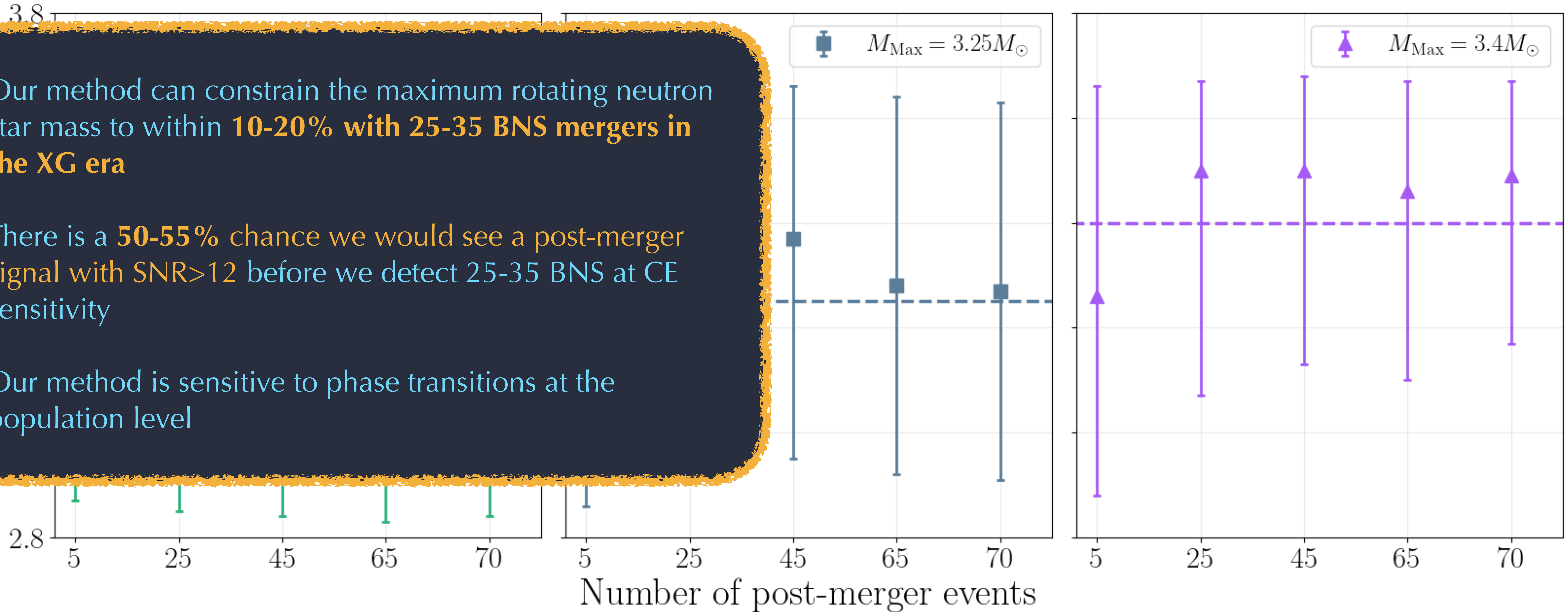

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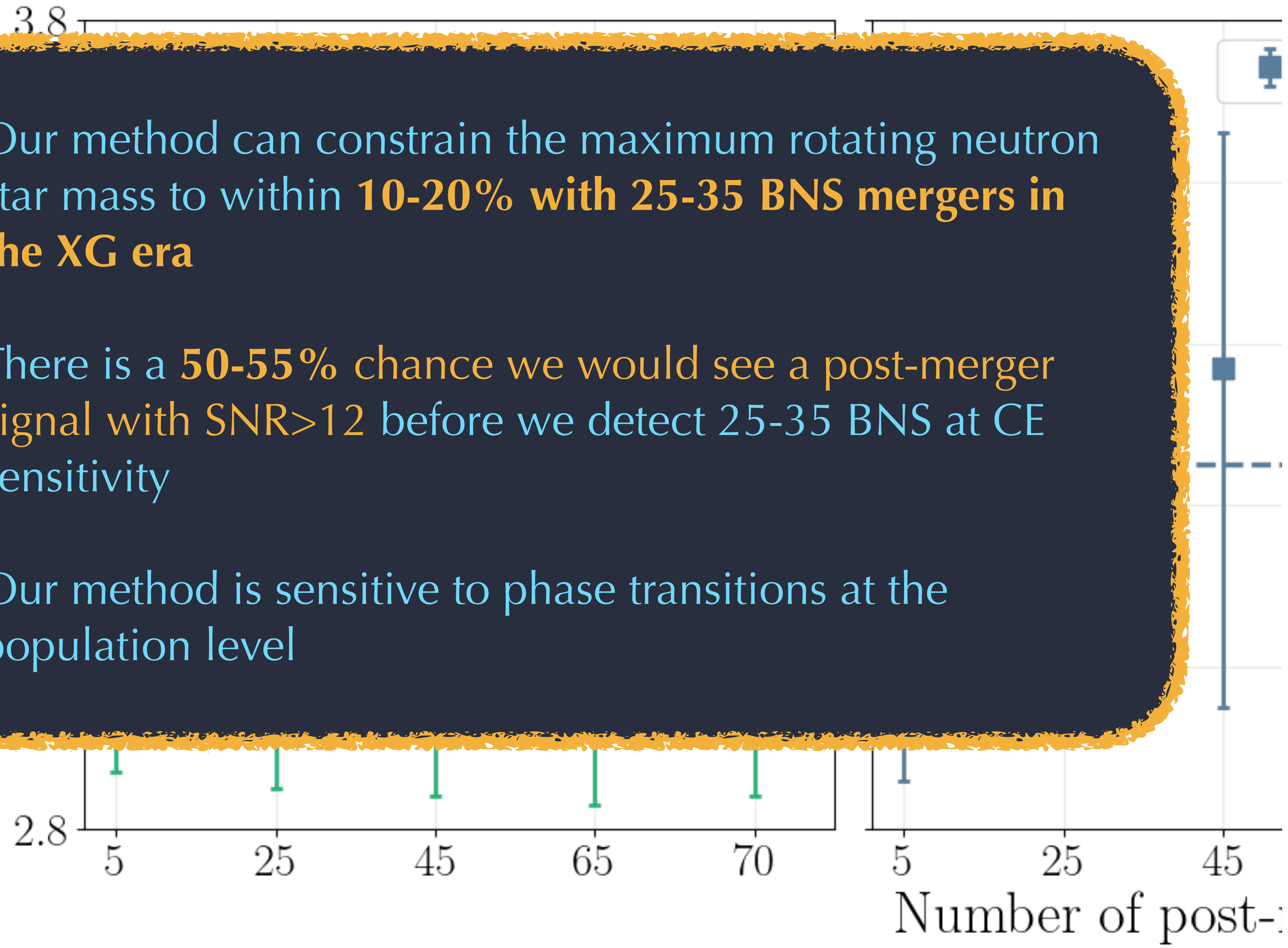

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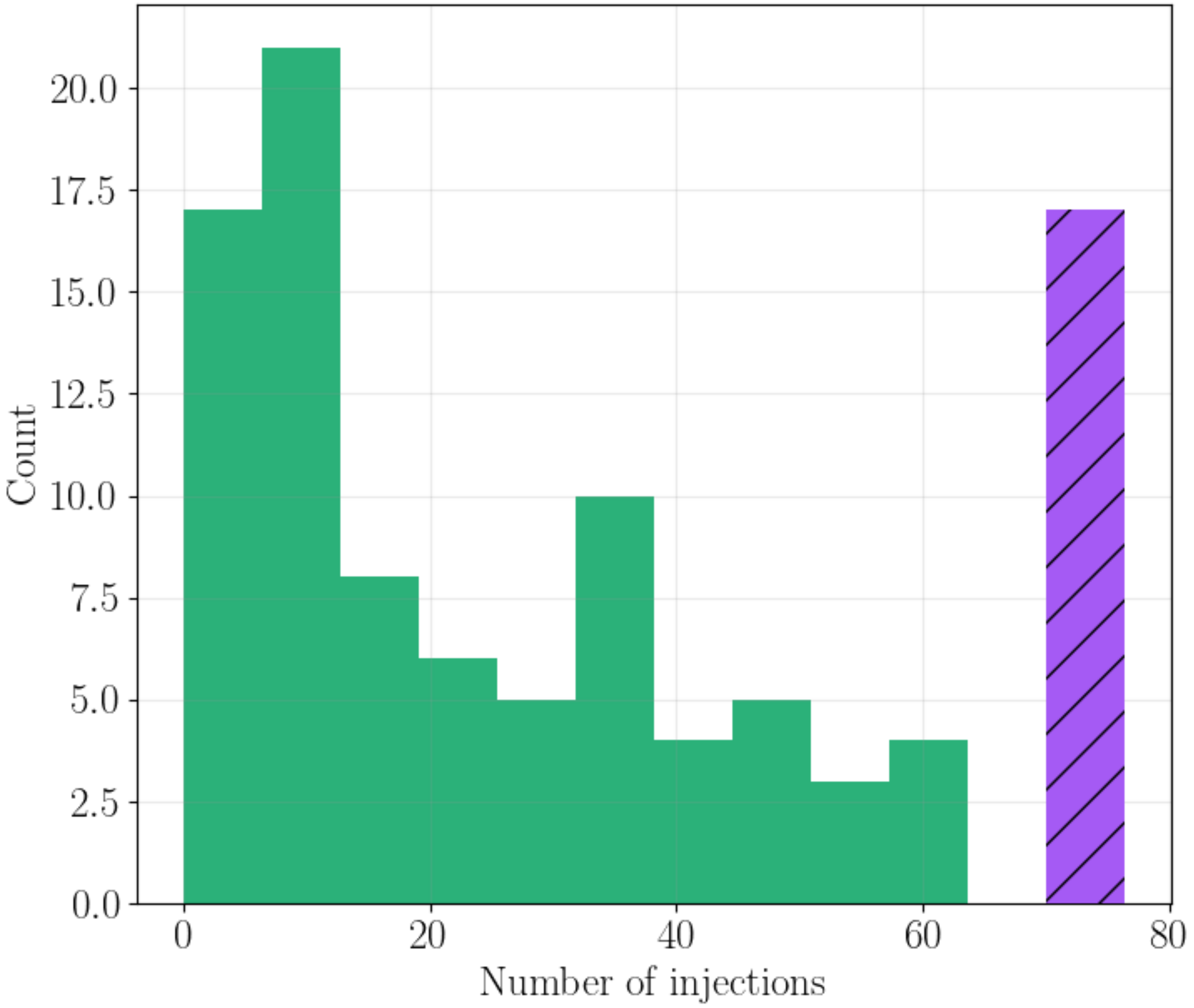

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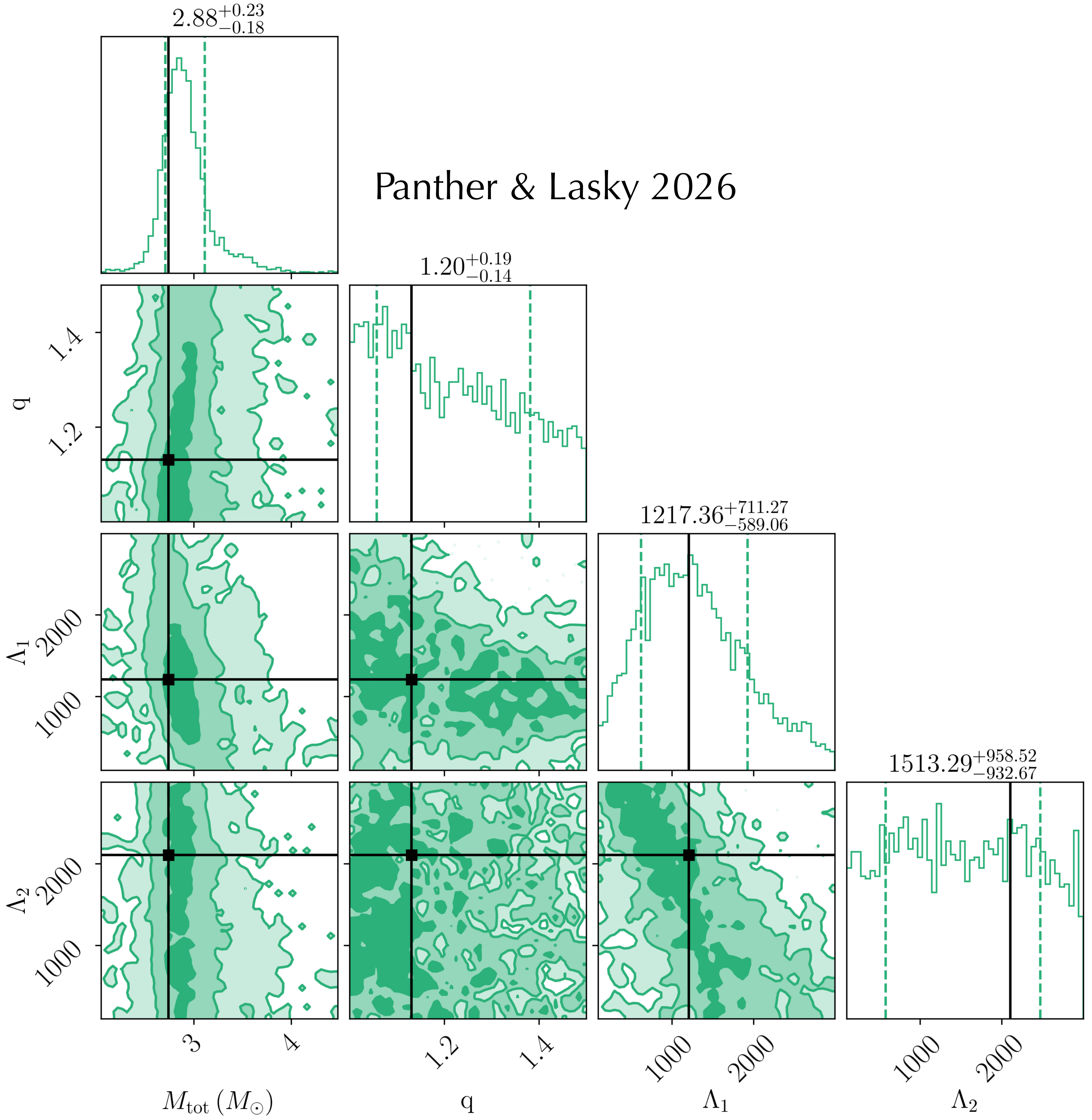
- Formalism is robust to model misspecification unlike single-event inference
- A population of ~25-35 nearby BNS mergers allow us constrain the threshold mass for gravitational collapse of post-merger neutron stars
- Inconsistencies in MTOV measured between post- and pre-merger can provide evidence for phase transitions between hadronic matter and QGP in extreme spacetime environments

Individual PMNS parameter estimation

PE for individual events does not yield strong evidence for a signal being present, nor are the posteriors particularly informative



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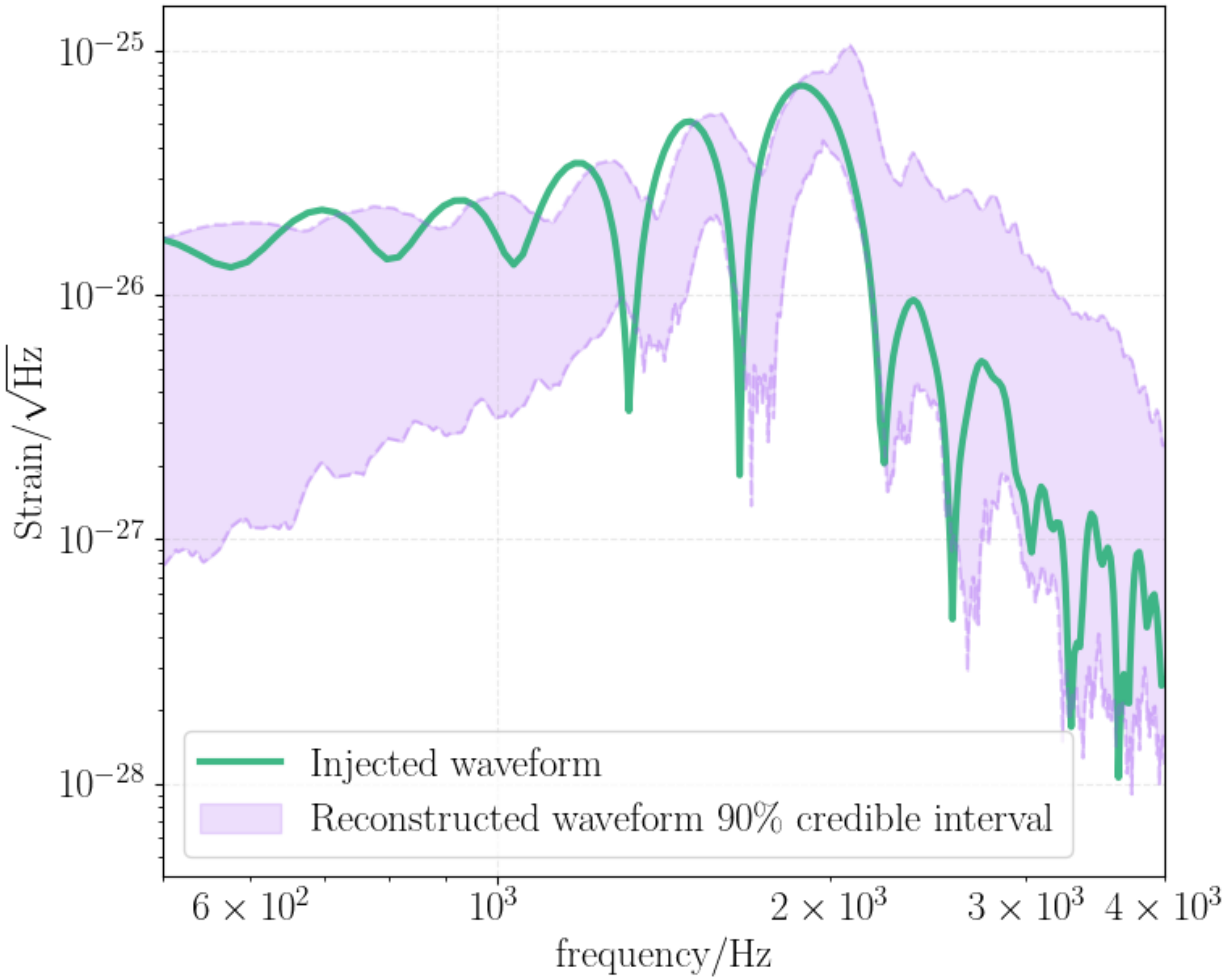
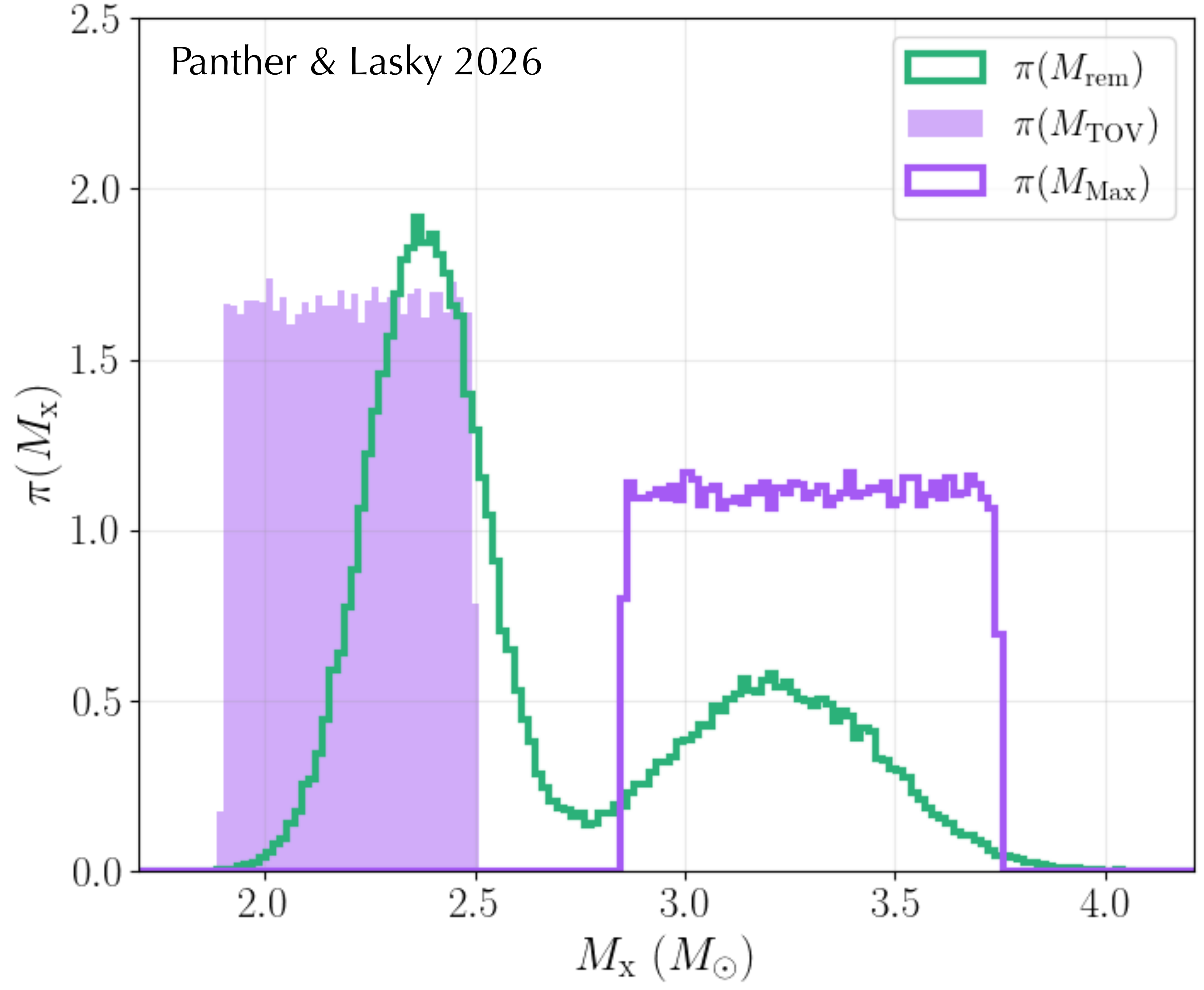


A mixture model formalism

We can obtain a posterior distribution on the mixing fraction - and hence M_{Max} - by using Bayes theorem



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$$\mathcal{L}(d\,|\,\xi, \theta_i) = \xi \mathcal{L}(d\,|\,\theta) + (1 - \xi)\, \mathcal{L}(d\,|\,0)$$

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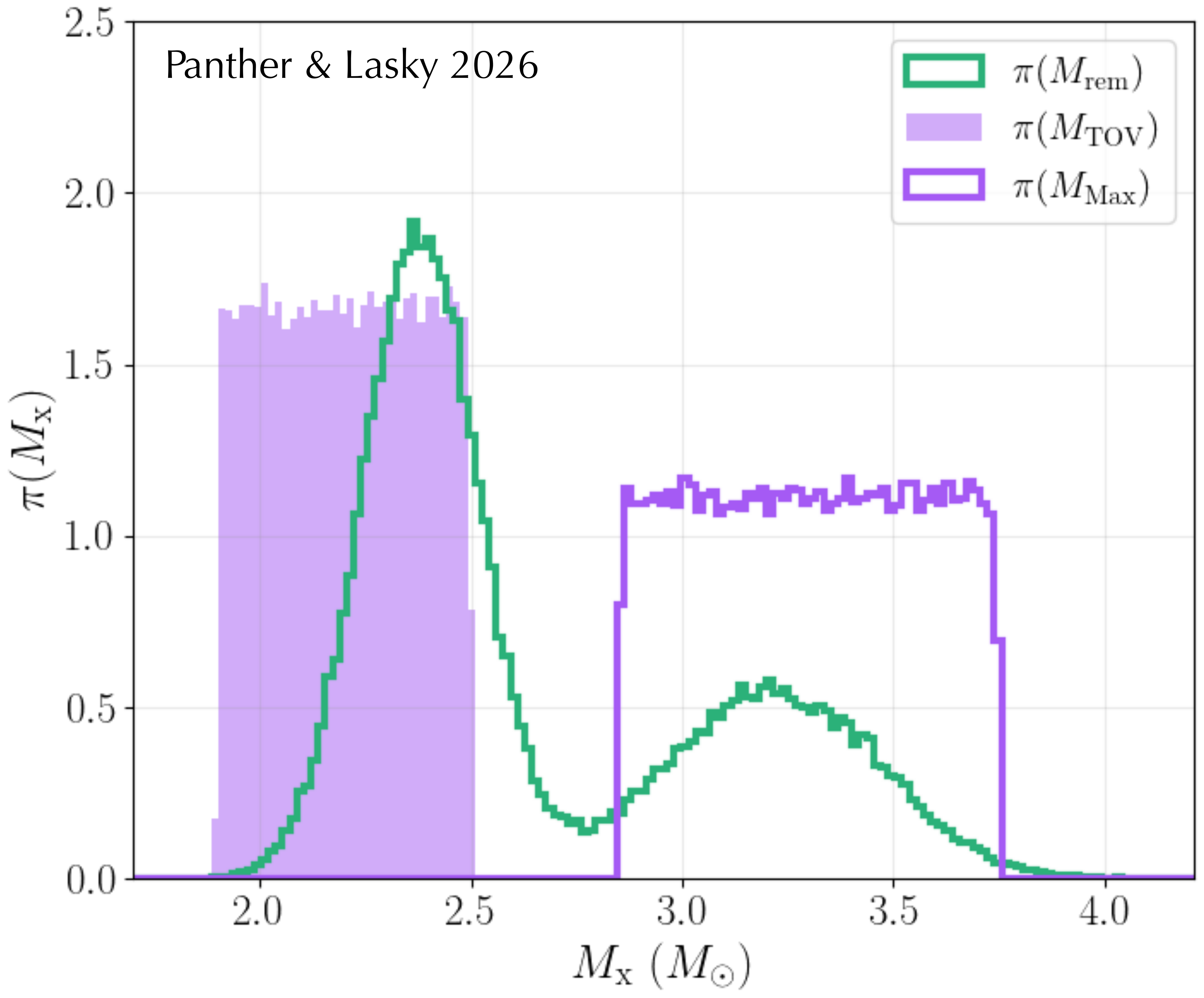

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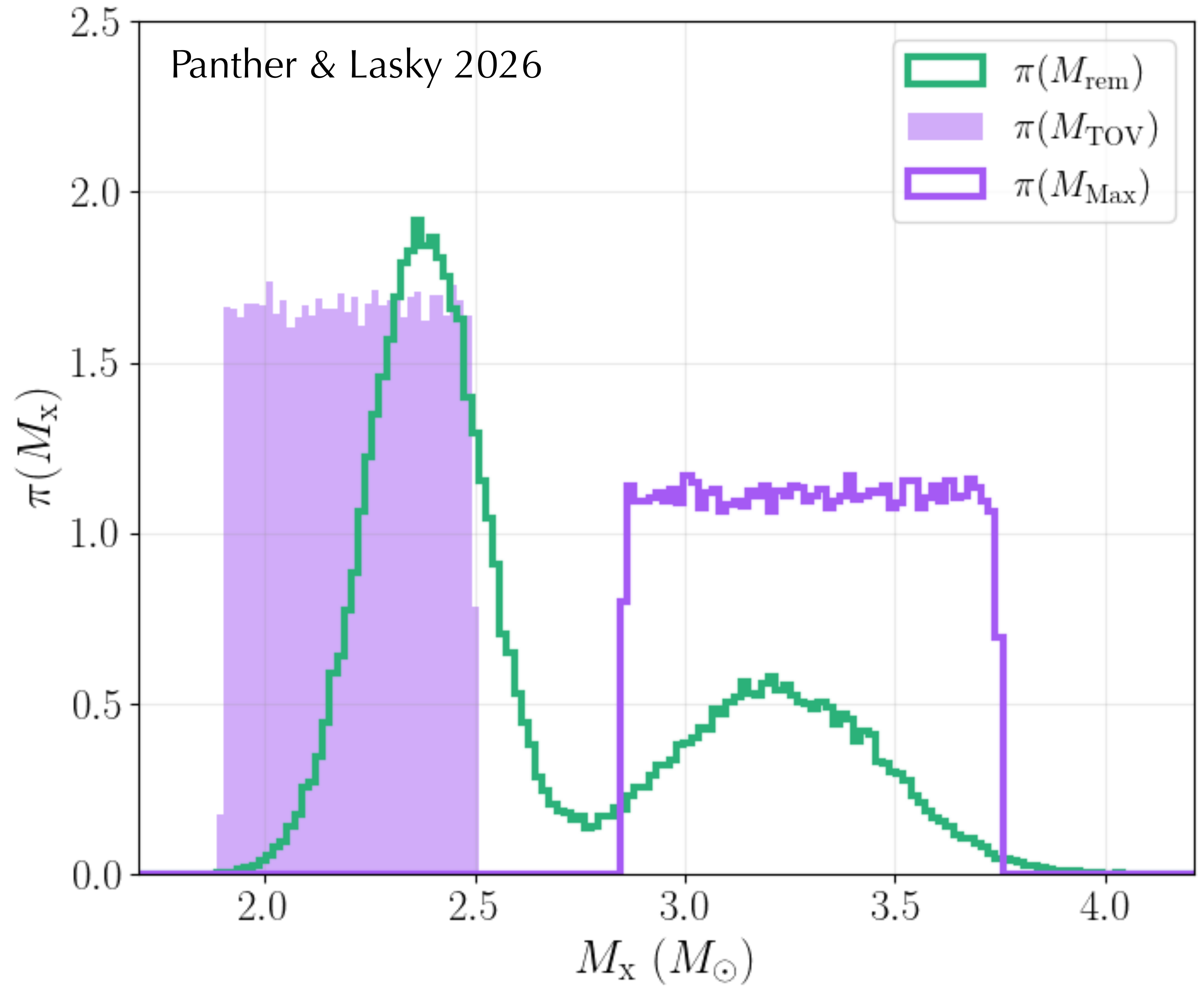

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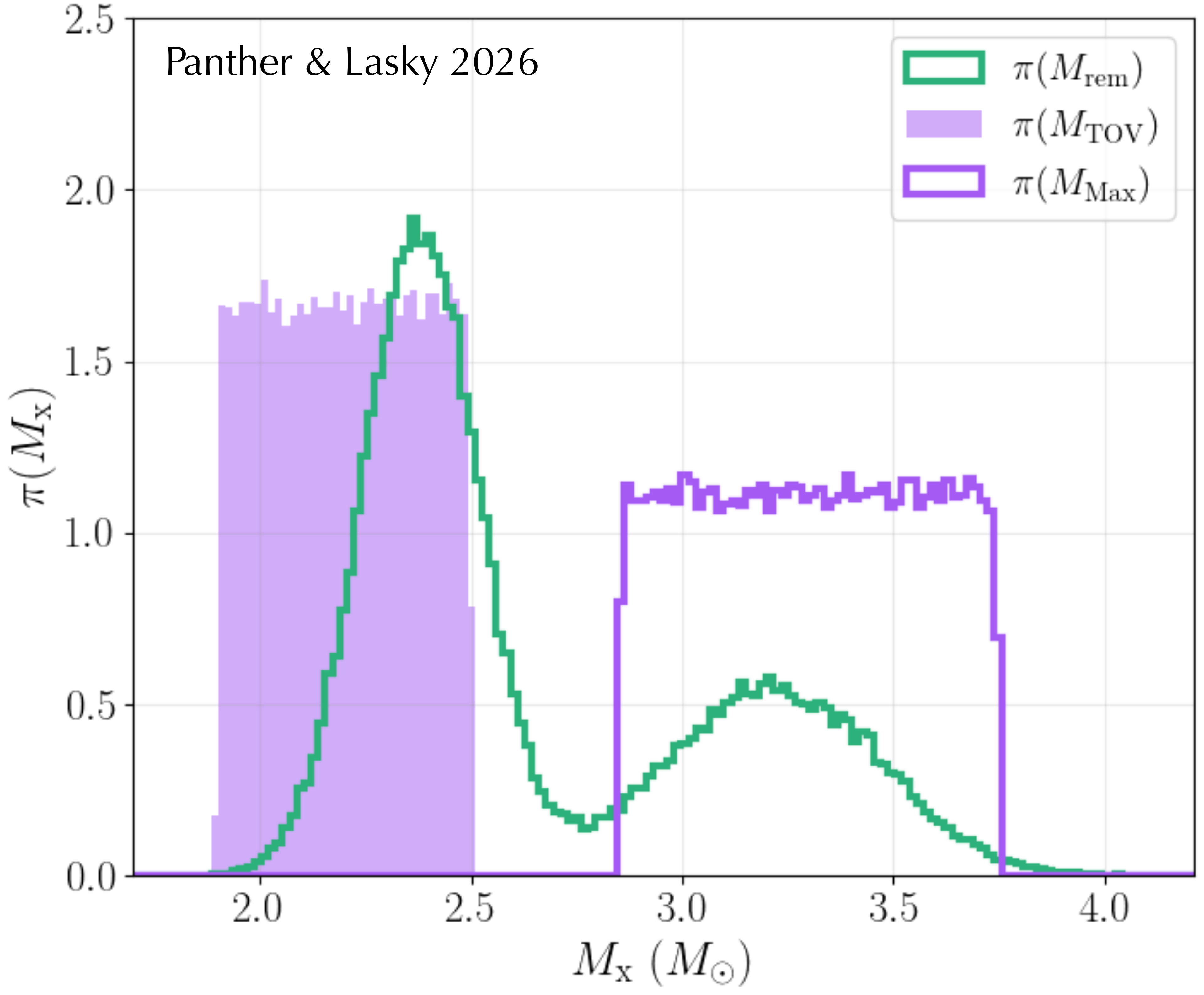

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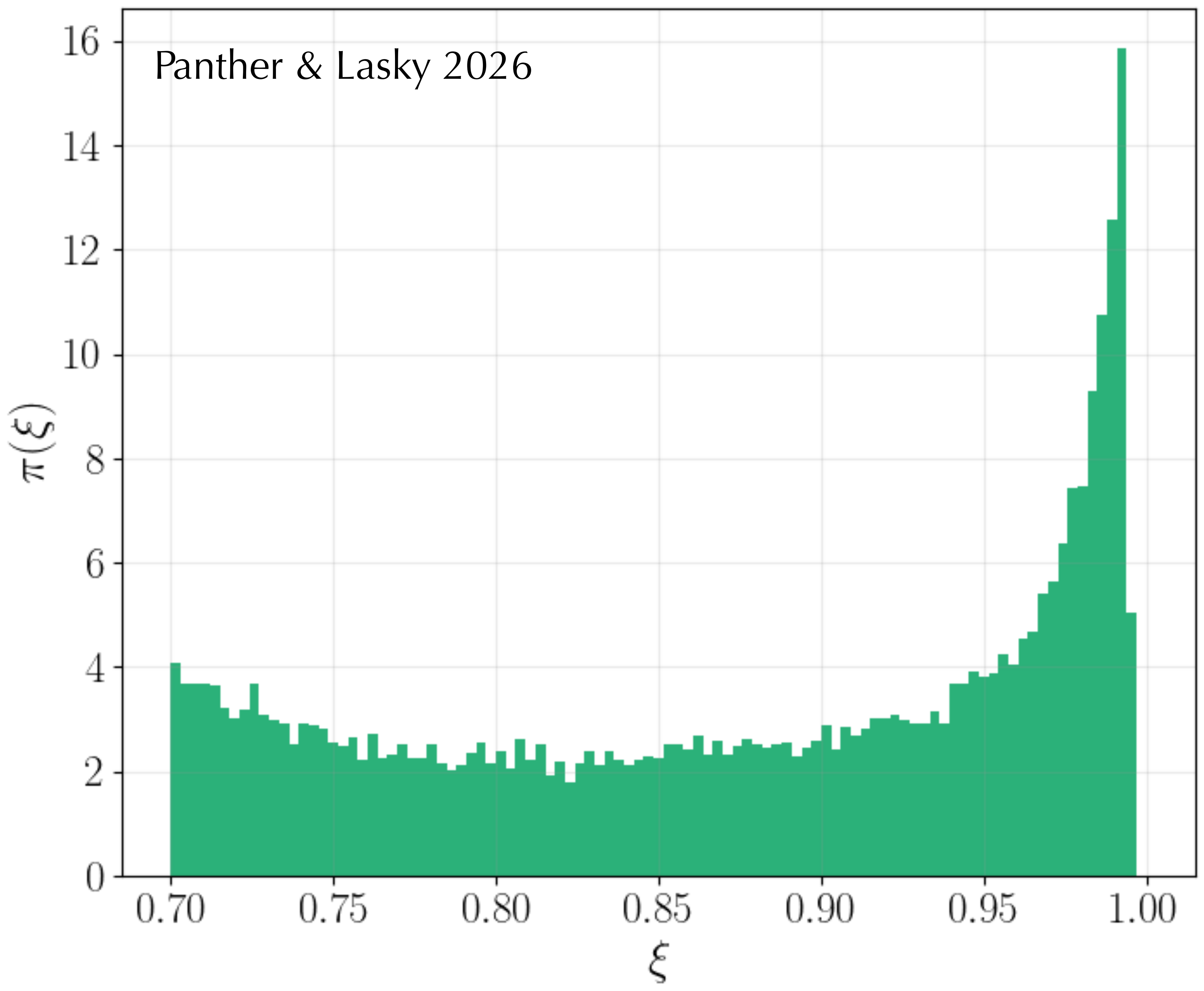

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Simulated data

We simulate a sample of 70 post-merger remnants for our 'injection set' and add them to coloured Gaussian noise

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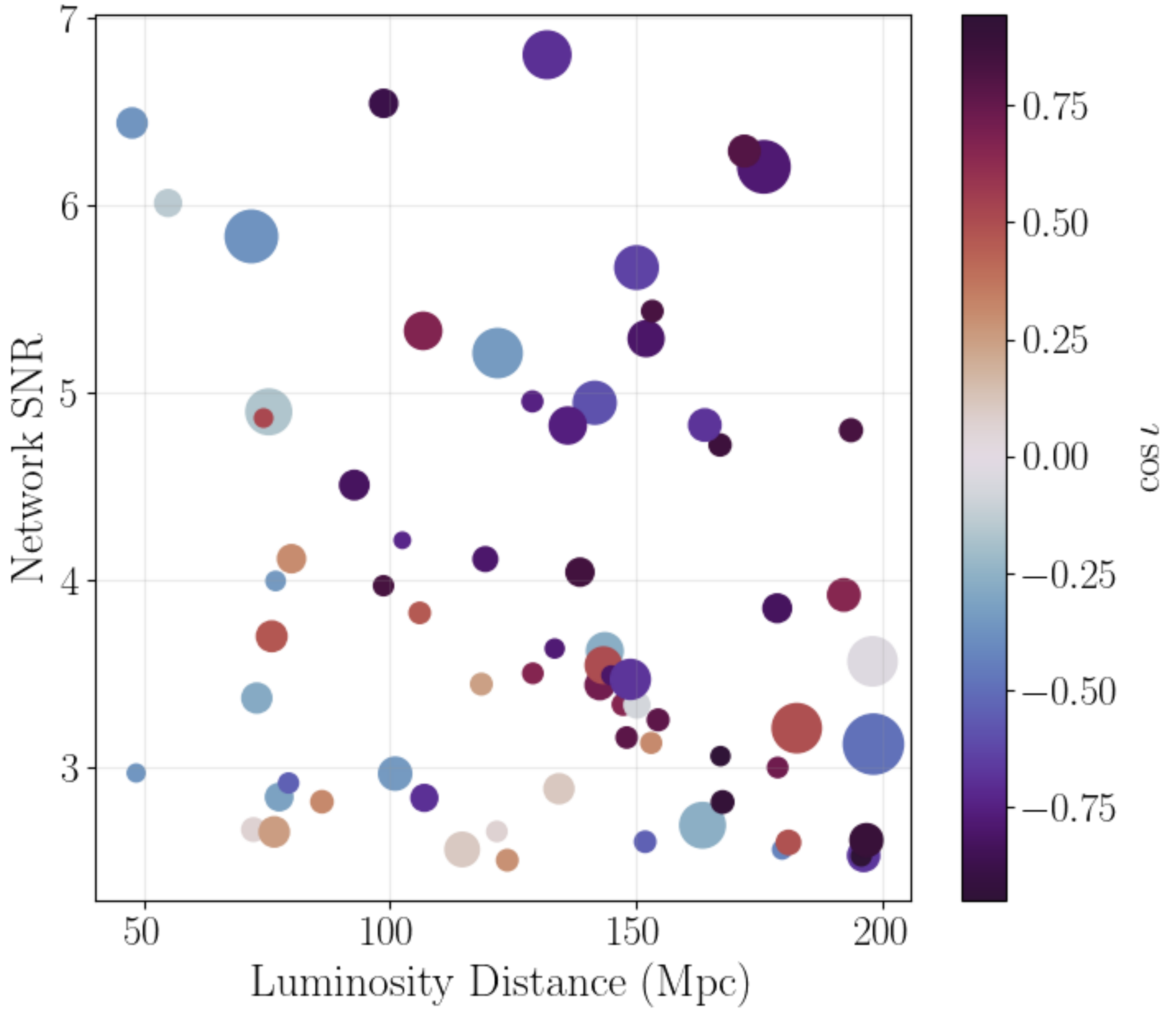

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