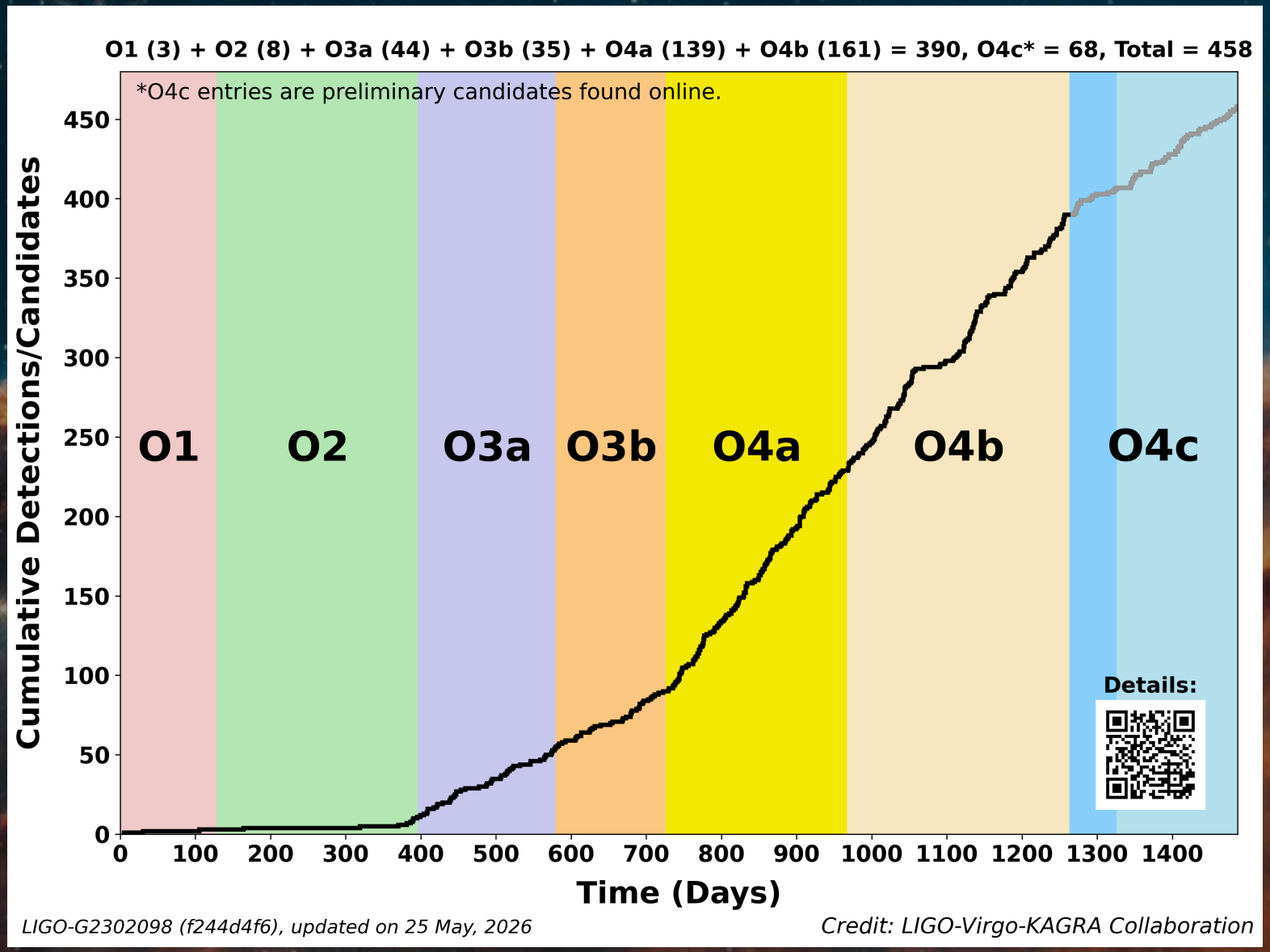
The Structure of the Binary Black Hole Spin Population Revealed by Gravitational-Wave Data

Kazuya Kobayashi[A], Masaki Iwaya[B,A], Soichiro Morisaki[A], Kenta Hotokezaka[C], Tomoya Kinugawa[D,C]

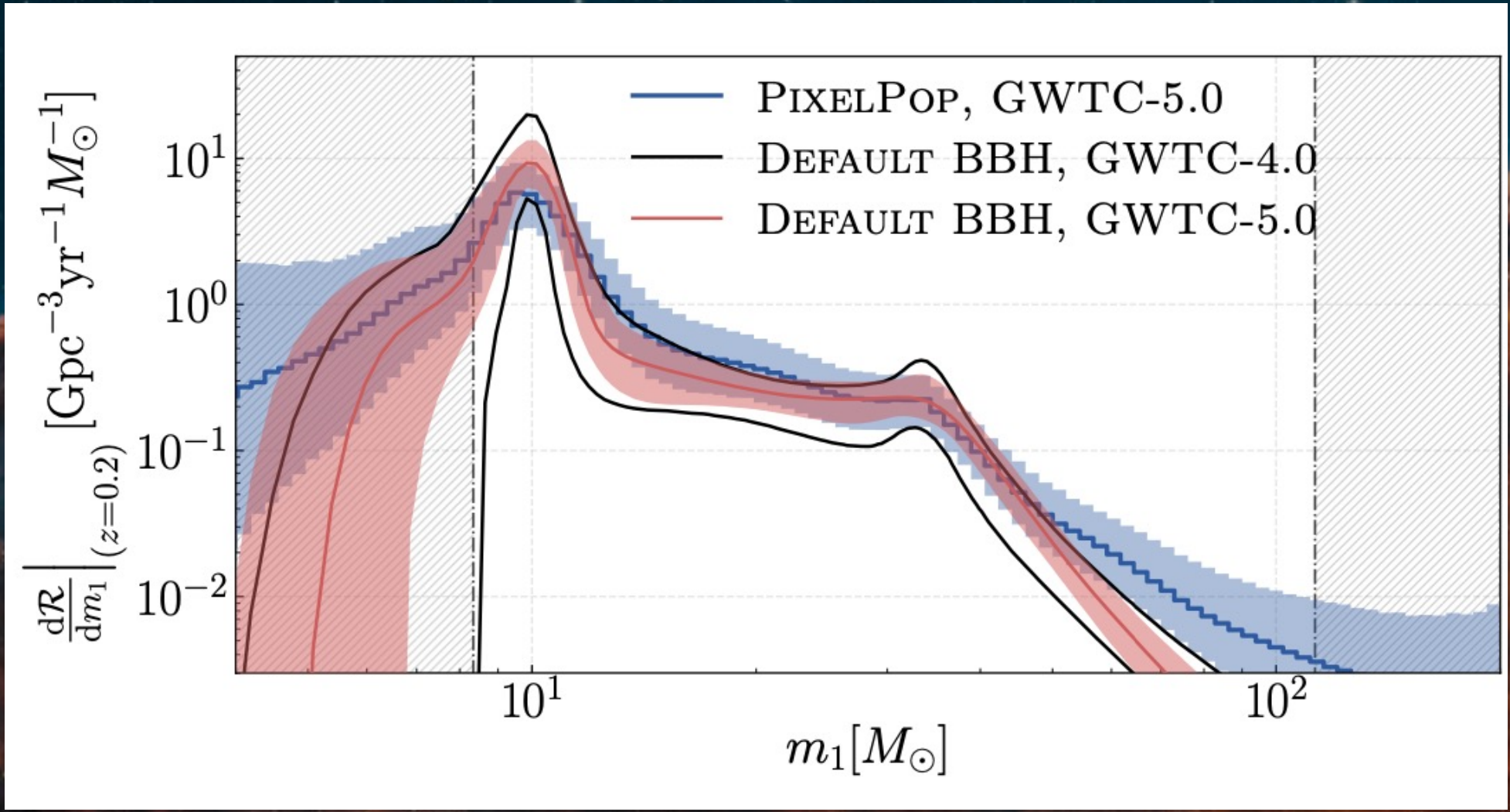
ICRR[A], GEI Cardiff University[B], RESCEU[C], Shinshu University[D]

TeV Particle Astrophysics 2026
Aug 31 2026 @Tendo



https://dcc.ligo.org/LIGO-G2302098

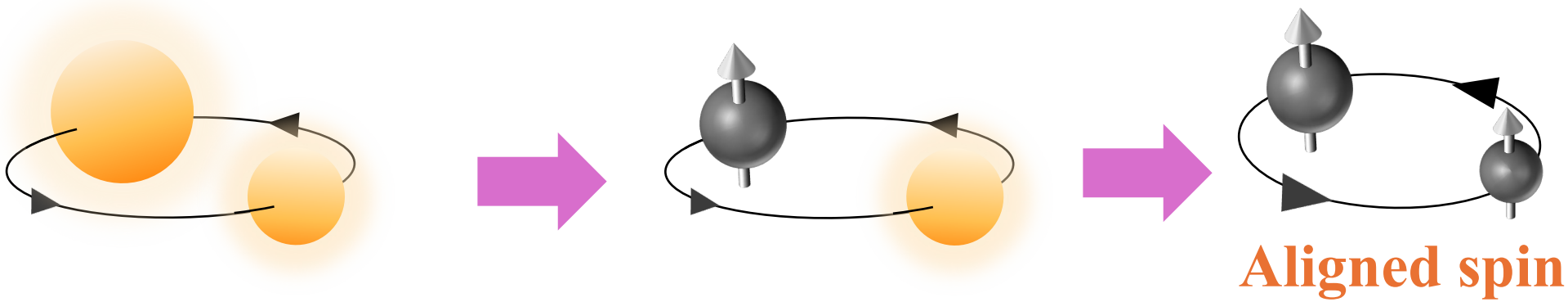
The era of population analysis



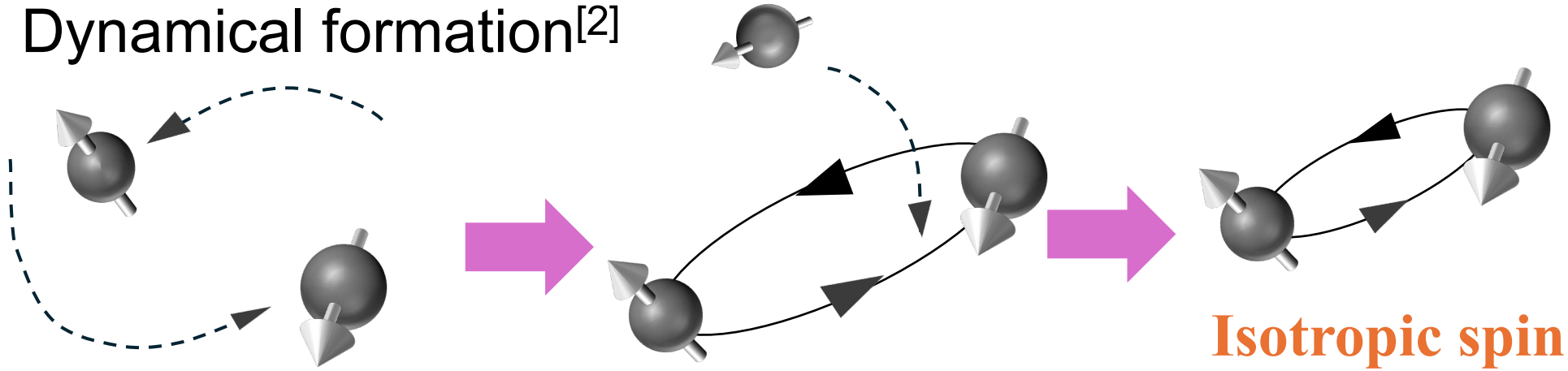
LIGO-Virgo-KAGRA Collaboration, arXiv:2605.27226 (2026).

Spin is important

- Isolated binary formation[1]

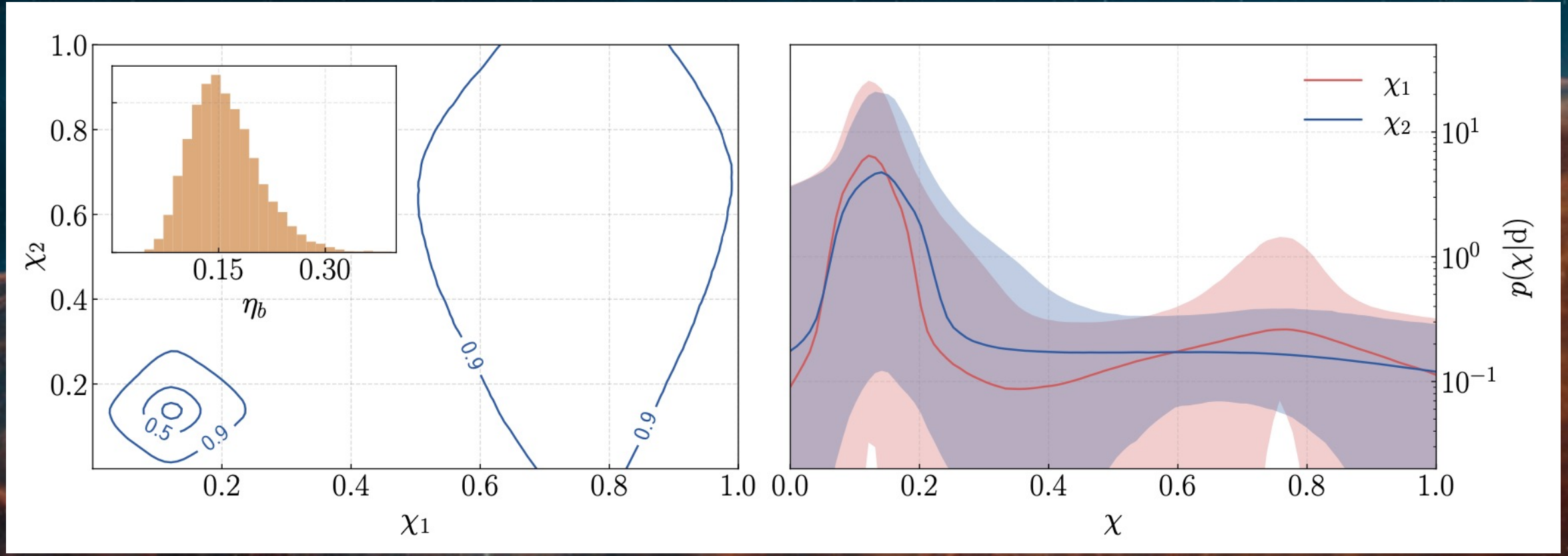


- Dynamical formation[2]



[1] D. Gerosa *et al.*, *Phys. Rev. D* **98**, 084036 (2018).
[2] F. Antonini *et al.*, *arXiv: 2406.19044 (2024).*

Evidence for spin subpopulation



LIGO-Virgo-KAGRA Collaboration, arXiv:2605.27226 (2026).

Effective spin parameters

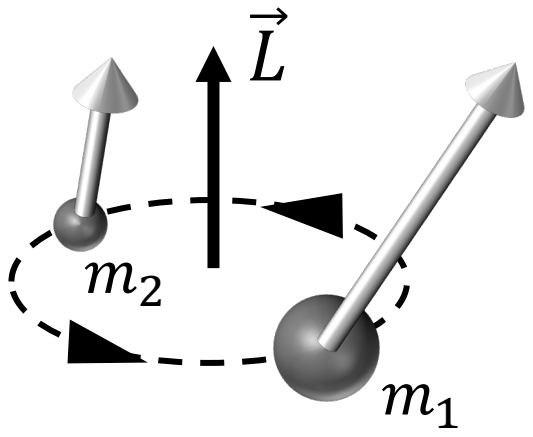
Effective spins $\chi_{\mathrm{eff}}, \chi_{\mathrm{p}}$
are accurately estimated from gravitational wave

χ_{eff} is effective spin parameters aligned with the orbital angular momentum $\vec{L}$[1].

χ_{p} is perpendicular to $\vec{L}$[2].

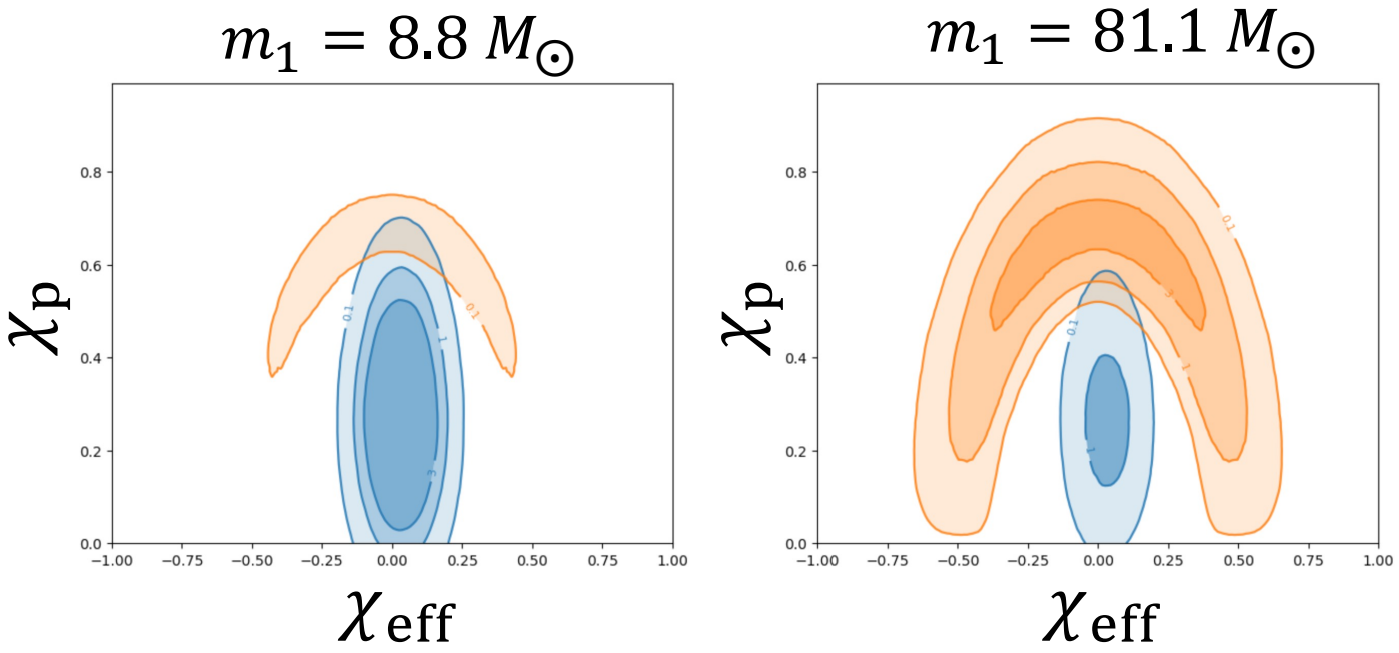
$$\chi_{\mathrm{eff}} := \frac{m_1 \chi_{1z} + m_2 \chi_{2z}}{m_1 + m_2}$$

$$\chi_{\mathrm{p}} := \max\left(\chi_{1\mathrm{p}}, \frac{3m_1 + 4m_2}{4m_1 + 3m_2}\frac{m_2}{m_1}\chi_{2\mathrm{p}}\right)$$



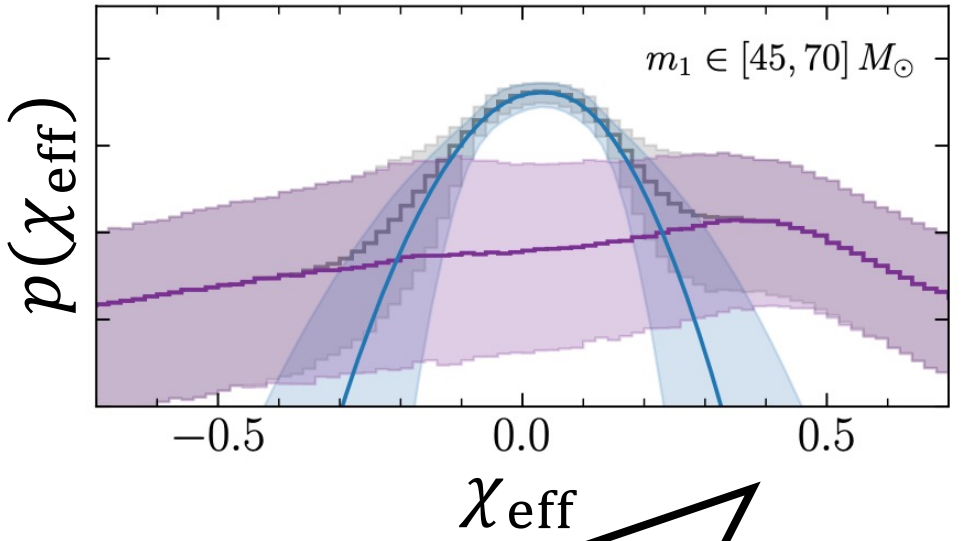
[1] T. Damour, *Phys. Rev. D* **64**, 124013 (2001).
[2] P. Schmidt *et al.*, *Phys. Rev. D* **91**, 024043 (2015).

Evidence for spin subpopulation



C. Plunkett *et al.*, *Phys. Rev. Lett.* **137**, 021404 (2026).

S. Alvarez-Lopez et al., arXiv:2606.12205(2026).



Blue: low-spin component

Orange: high-spin component

Previous study assumed high-spin population is isotopically distributed

We ask whether the high-spin BBH population is truly isotropic.

Method

We improve previous spin population inference in two ways:

(1) we use an event-level prior that is uniform in the $\chi_{\mathrm{eff}} - \chi_{\mathrm{p}}$ plane[1]
(2) we model the population in the plane using a flexible mixture model

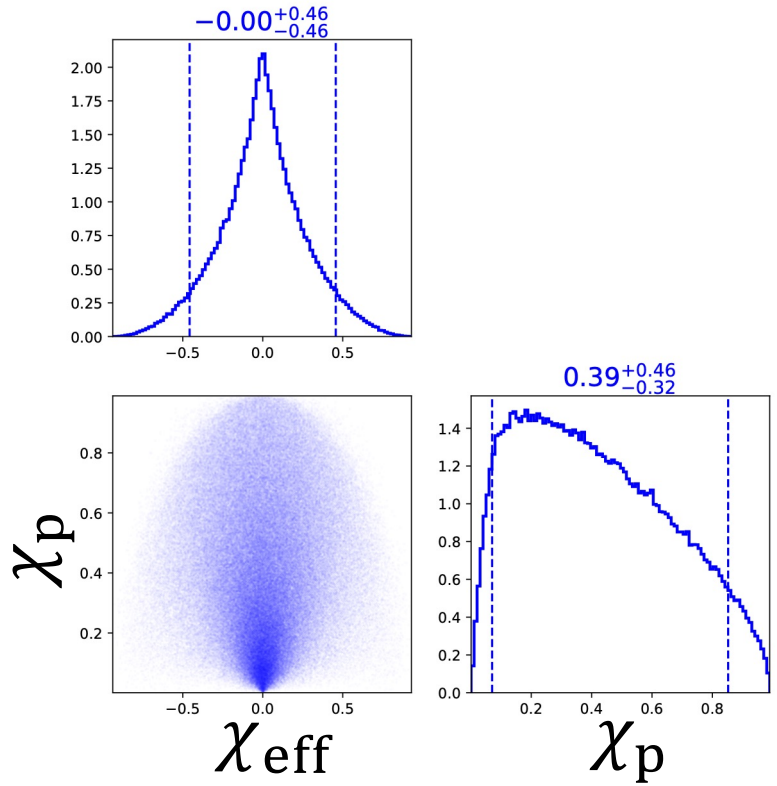
We perform hierarchical Bayesian inference for binary black hole (BBH) in GWTC-4.
To reduce computational cost, we fix the mass and redshift distributions to those inferred in previous study[2].

[1] K. Kobayashi *et al.,* arXiv: 2602.12509 (2026). [2] LIGO-Virgo-KAGRA Collaboration, arXiv:2605.27226 (2026).

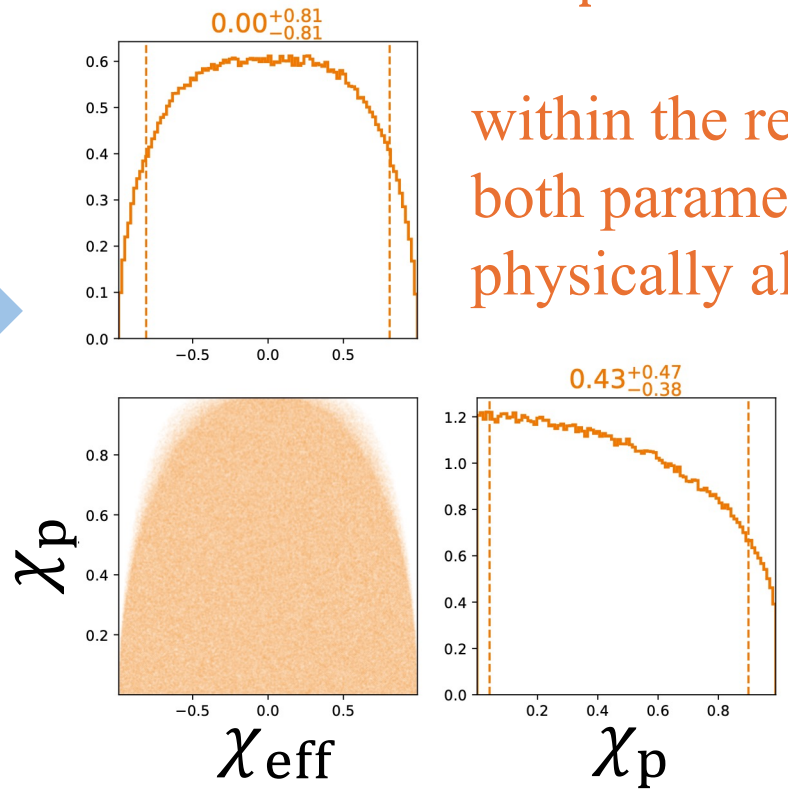
Method

(1) we use an event-level prior that is uniform in the $\chi_{\rm eff} - \chi_{\rm p}$ plane*

Isotropic spin prior



Uniform $\chi_{\rm eff} - \chi_{\rm p}$ prior

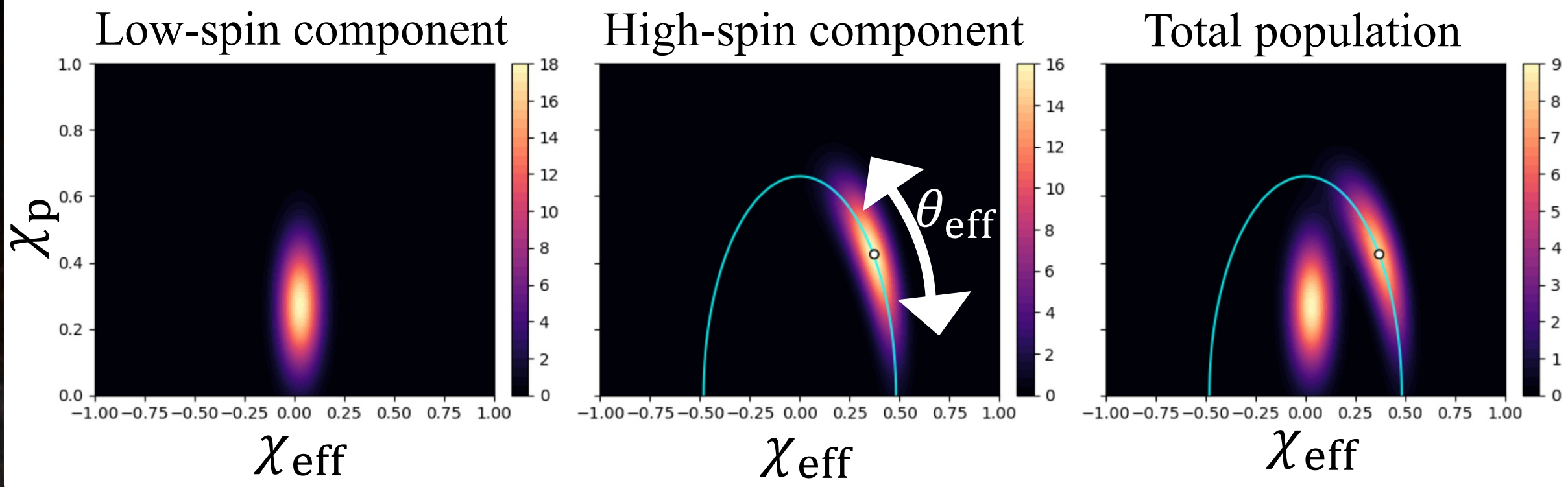


within the region where both parameters are physically allowed.

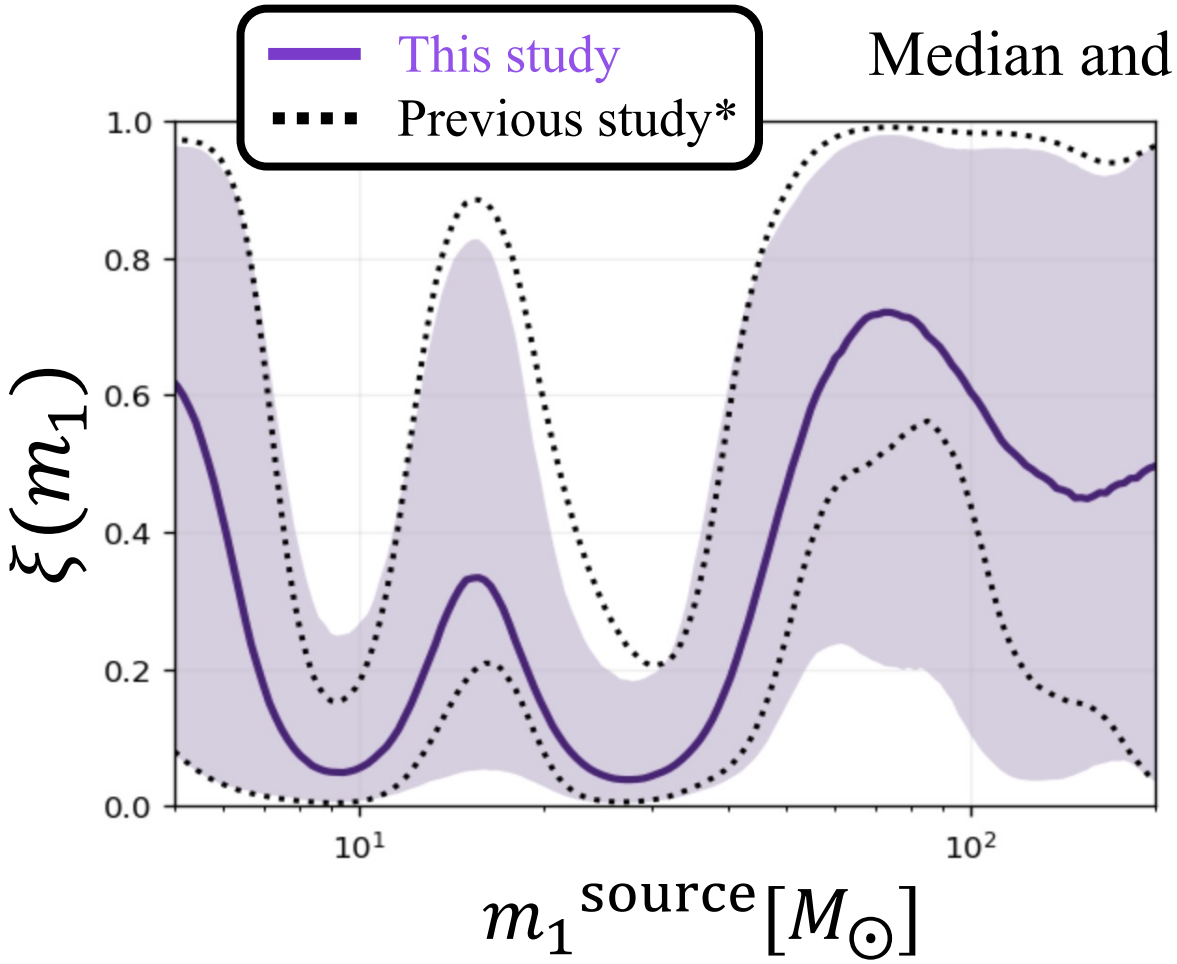
* K. Kobayashi *et al.*, arXiv: 2602.12509 (2026).

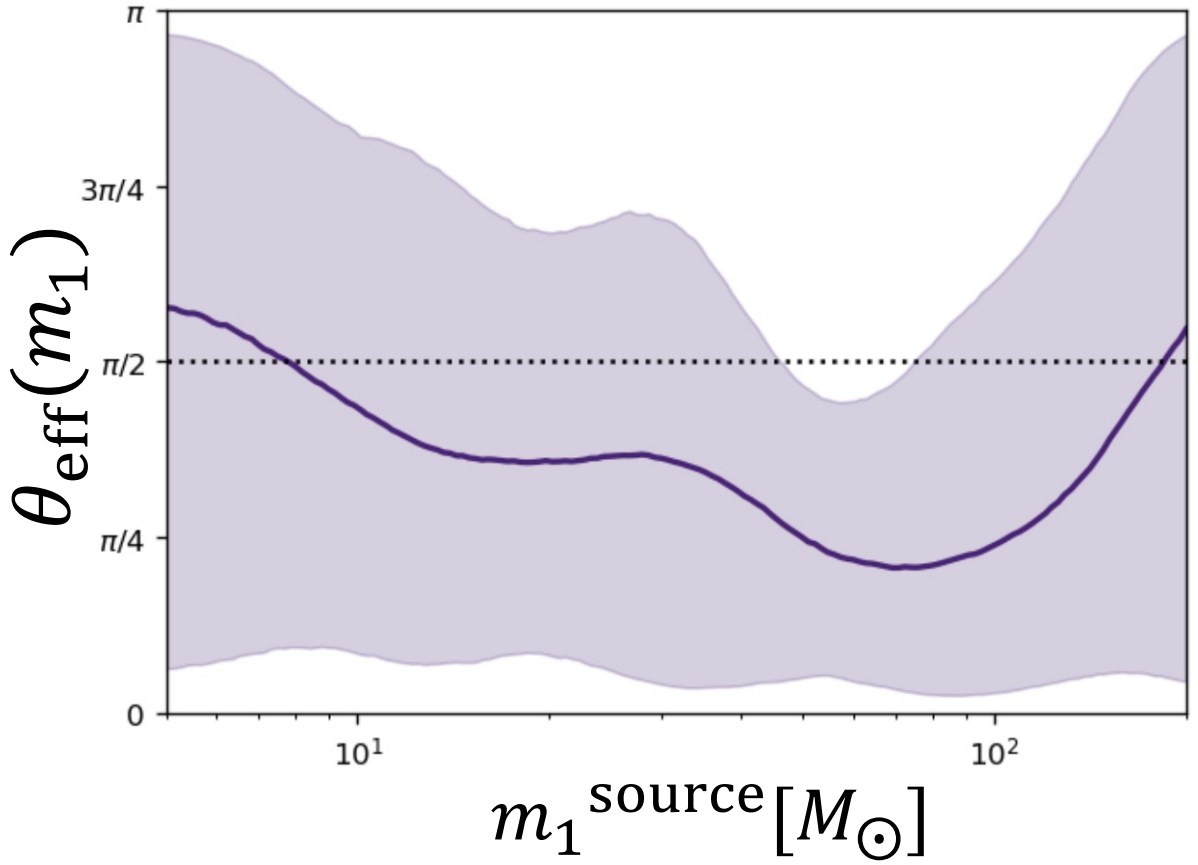
Method

(2) we model the population in the plane using a flexible mixture model



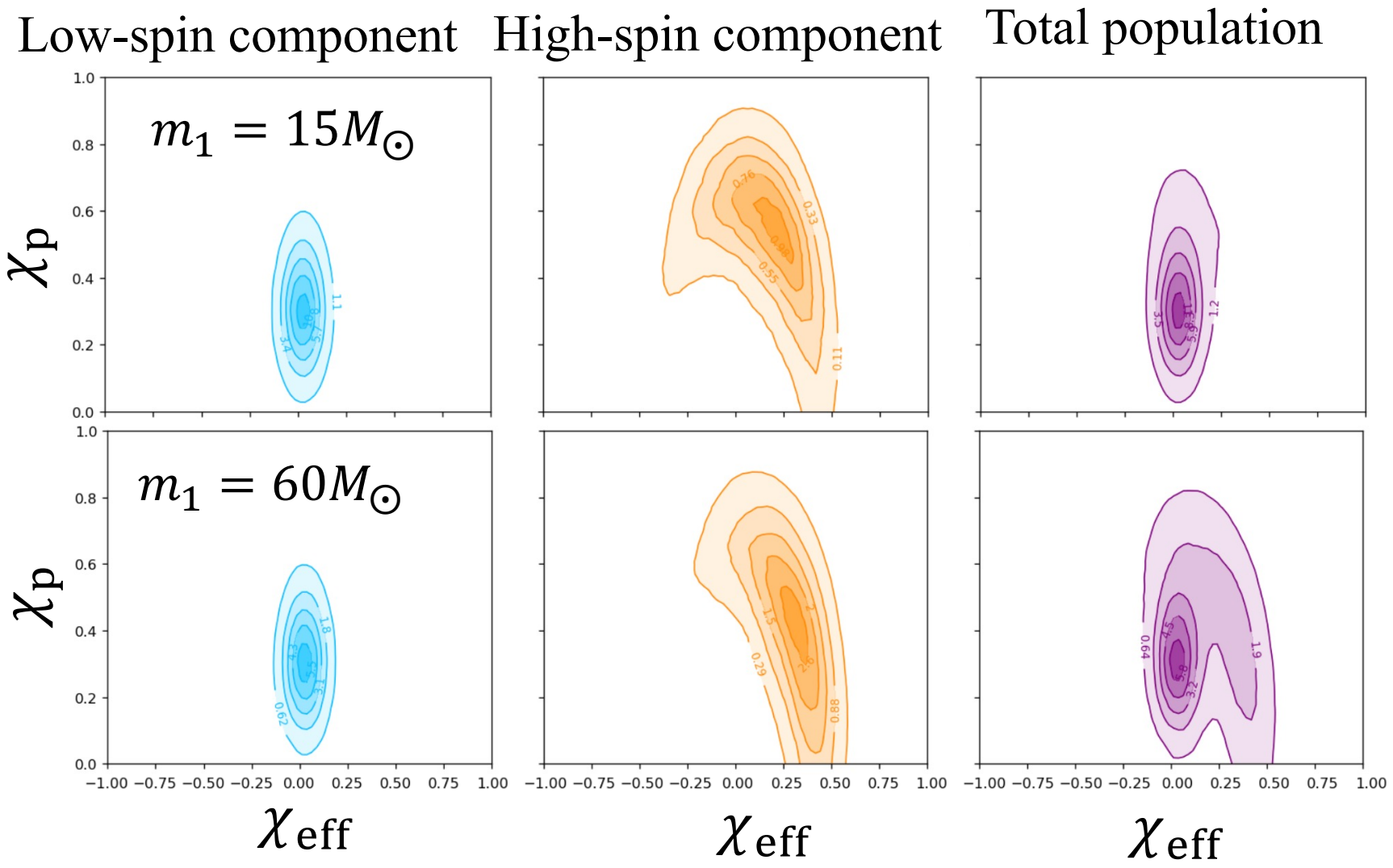
Result



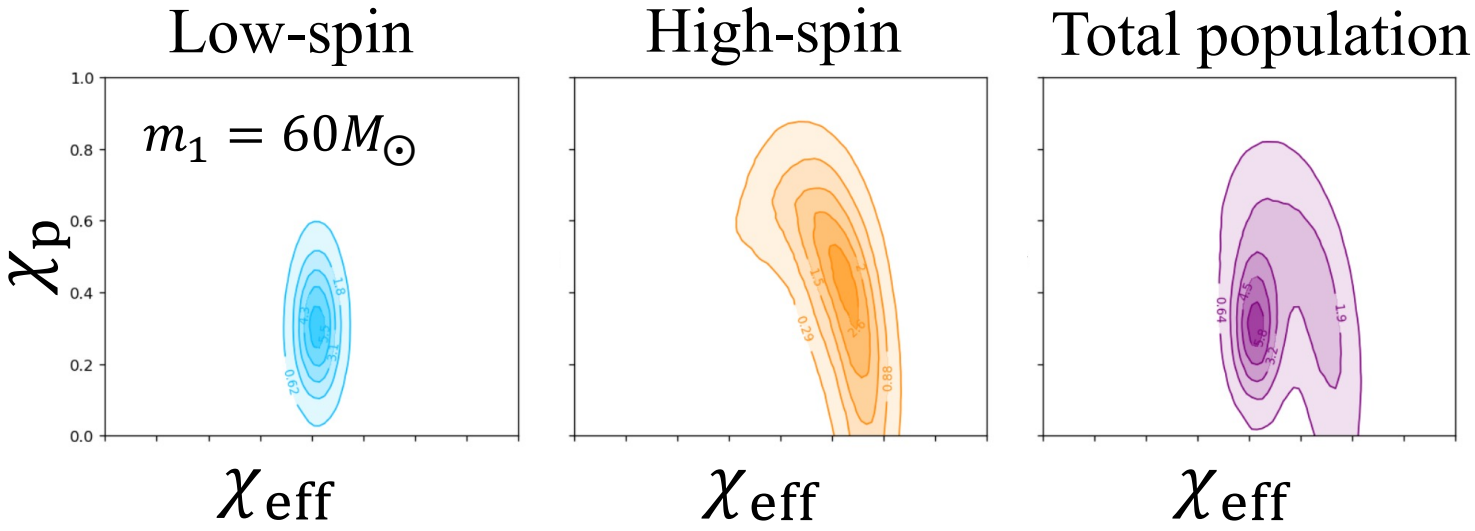


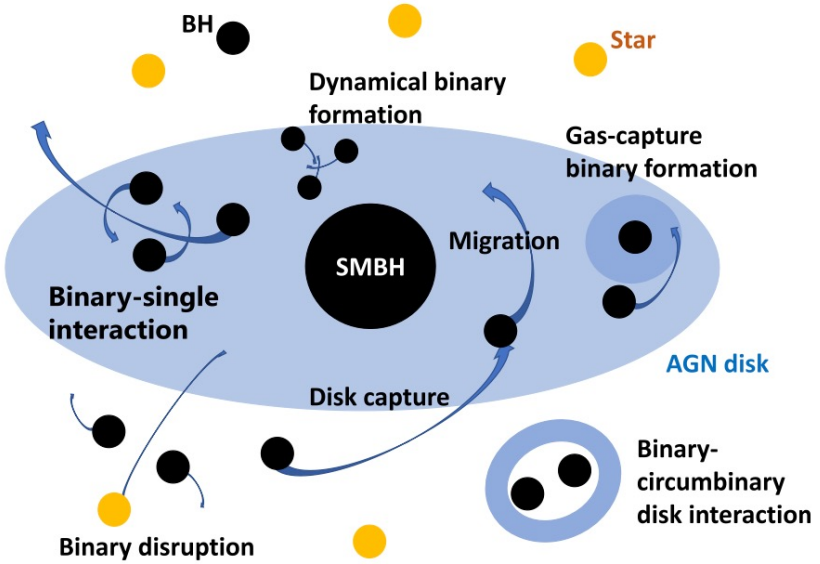
*C. Plunkett *et al.*, *Phys. Rev. Lett.* **137**, 021404 (2026).

Result


Low-spin component
High-spin component
Total population
$m_1 = 15M_\odot$
$m_1 = 60M_\odot$
χ_p
χ_{eff}
1.0
0.8
0.6
0.4
0.2
0.0
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00

Discussion





H. Tagawa *et al., ApJ.* **898,** 25(2020).

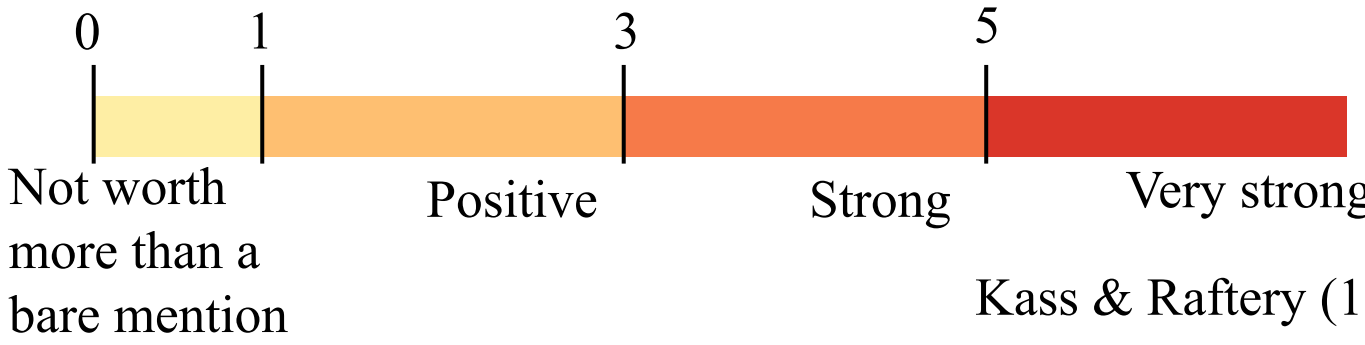
This suggests a high-spin population with some preference for aligned spins rather than isotropic orientations around $m_1 = 60M_\odot$. Hierarchical mergers have difficulty explaining the positively skewed $\chi_{\rm eff}$ distribution.

A similar discussion can be found in [1], where tidal spin-up[2], chemically homogeneous evolution[3], and AGN-disk scenarios[4] are suggested.

[1] S. Alvarez-Lopez et al., arXiv:2606.12205(2026). [2] S. S. Bavera et al. A&A 635, A97 (2020).
[3] I. Mandel et al., MNRAS 458, 2634–2647 (2016). [4] Yin-Jie Li et al., Phys. Rev. Lett. 137, 021407 (2026).

Discussion

ln Bayes factor:



Kass & Raftery (1995), JASA 90, 773

This work's model / 2D Gaussian model in $\chi_{\mathrm{eff}} - \chi_{\mathrm{p}}$ plane: **ln BF = 4.5**

A mass-dependent mixture of low- and high-spin populations is strongly favored over a simple mass-independent Gaussian spin model.

This work's model / Plunkett's isotropic high-spin model : **ln BF = -0.94**

Our model is not significantly favored from a Bayesian perspective.
Thus, GWTC-4 data do not require a non-isotropic high-spin population, and the isotropic model still provides an adequate description of the data.

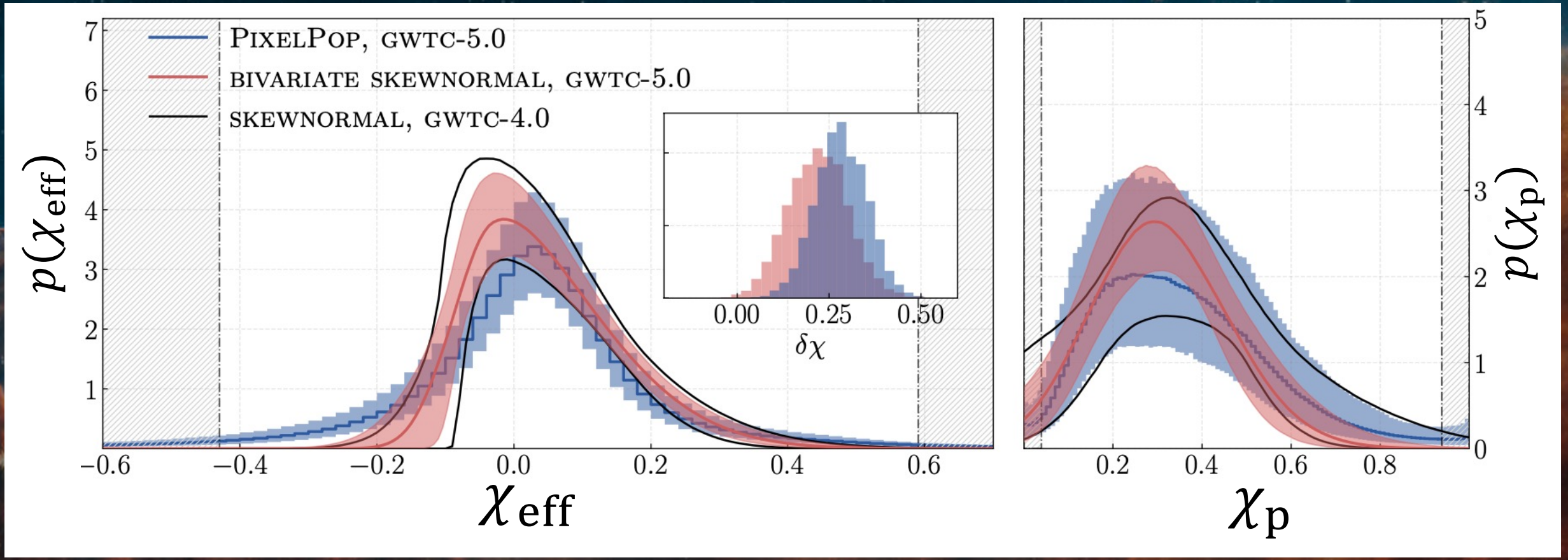
Summary

- We infer the BBH spin population with a revised prior and a flexible $\chi_{\mathrm{eff}} - \chi_{\mathrm{p}}$ model.
- High-spin BBHs may prefer aligned spins at high masses.
- GWTC-4 data do not yet rule out isotropic high-spin orientations.

Thank you for your attention!!

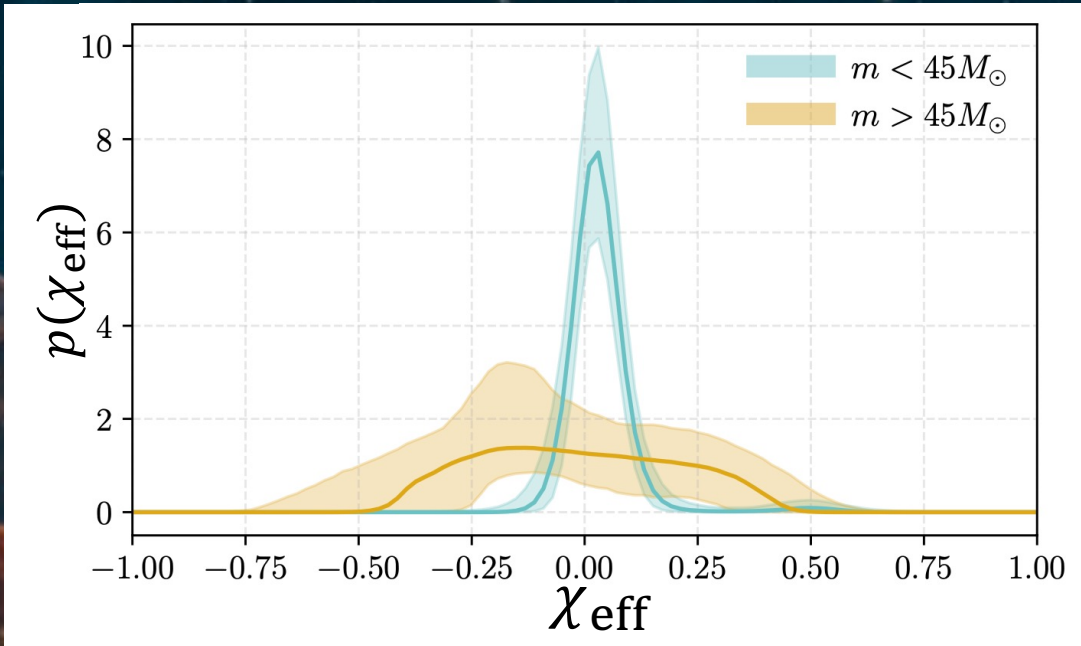
Extra

Spin population

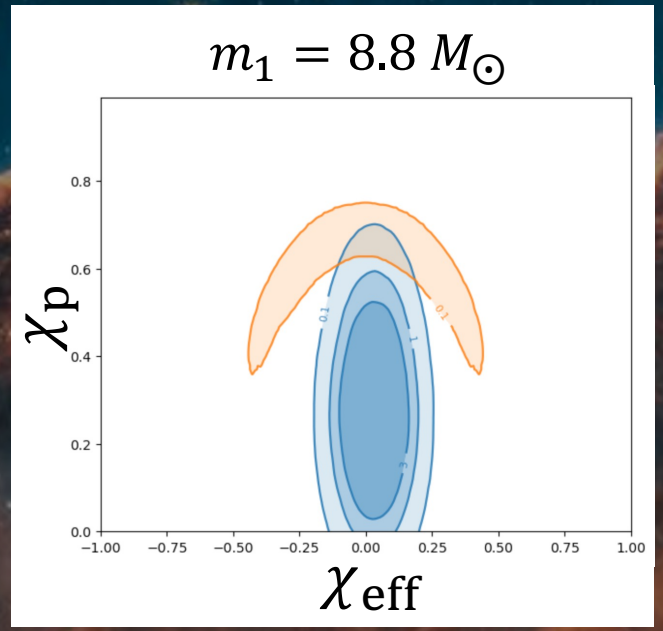


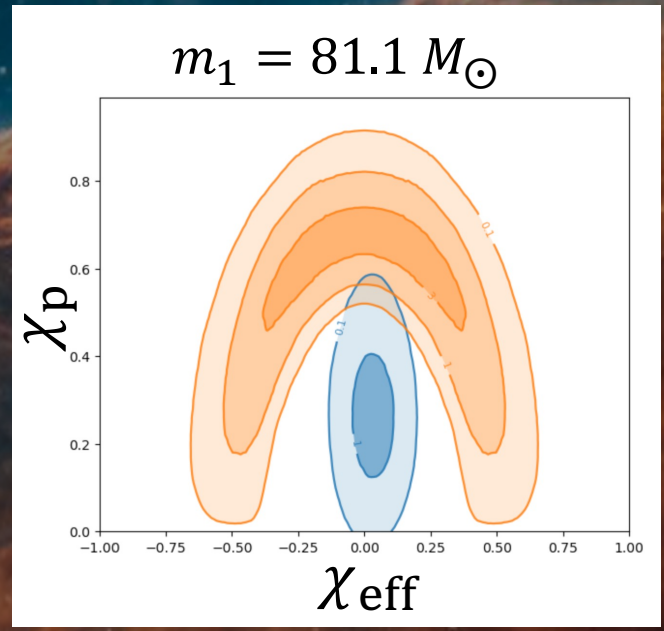
LIGO-Virgo-KAGRA Collaboration, arXiv:2605.27226 (2026).

Evidence of Correlation & Subpopulation



E. Flanagan *et al.*, arXiv:2606.14472 (2026).





C. Plunkett *et al.*, *Phys. Rev. Lett.* **137**, 021404 (2026).

Total Spin Population Density

The spin population is a two-component mixture:

$$p_{\rm spin}(\chi_{\rm eff}, \chi_p \mid m_1, \Lambda) = [1 - \xi(m_1 \mid \Lambda)]\, p_{\rm L}\,(\chi_{\rm eff}, \chi_p \mid \Lambda) + \xi(m_1 \mid \Lambda)\, p_{\rm H}\,(\chi_{\rm eff}, \chi_p \mid \Lambda)$$

Inputs:

- $\chi_{\rm eff}$, χ_p: spin coordinates
- m_1: primary mass
- Λ: population hyperparameters
- $\xi(m_1 \mid \Lambda)$: mass-dependent branching fraction

Total Spin Population Density

The spin population is a two-component mixture:

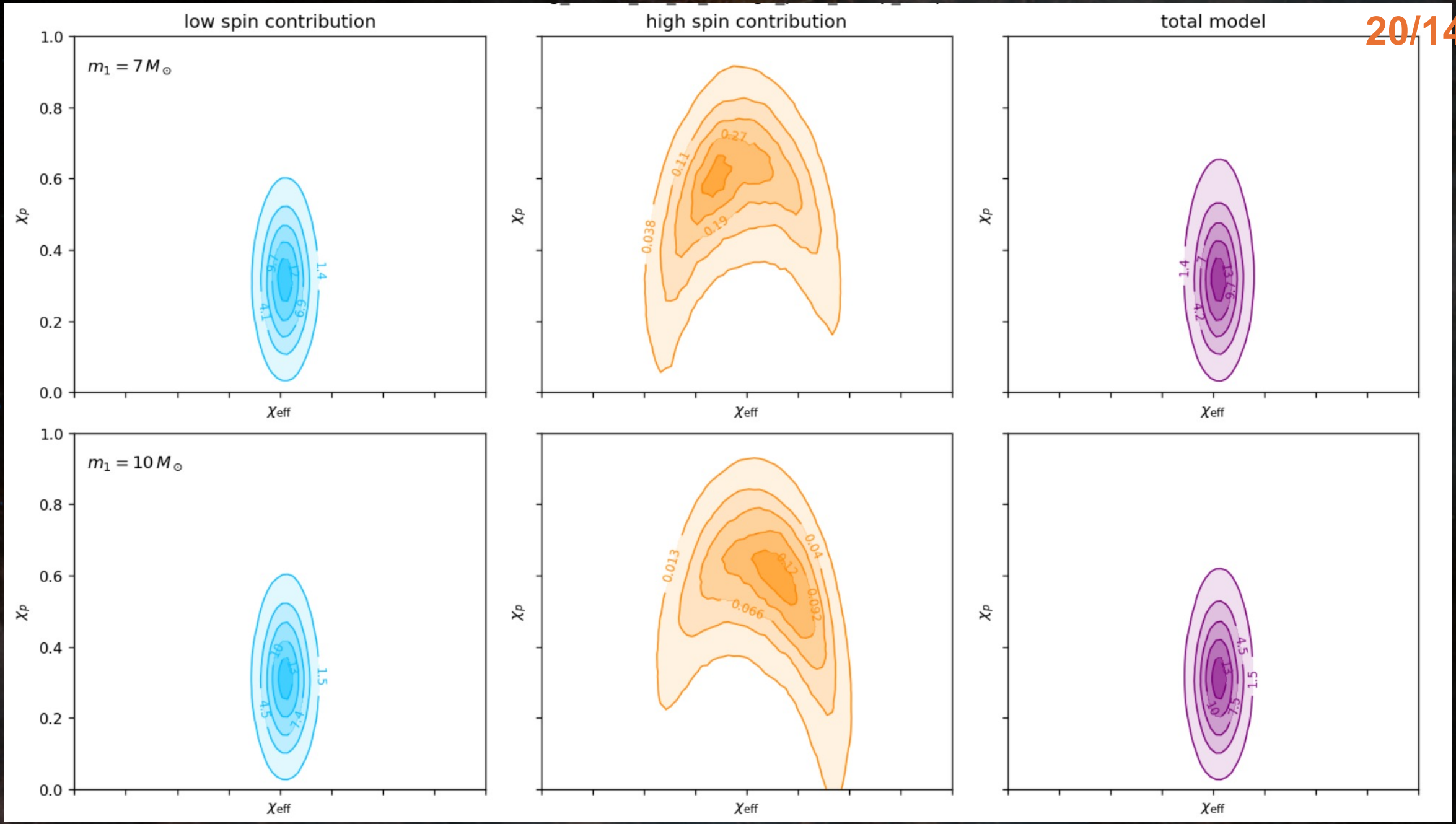
$$p_{\rm spin}(\chi_{\rm eff}, \chi_p \mid m_1, \Lambda) = [1 - \xi(m_1 \mid \Lambda)]\, p_{\rm L}\,(\chi_{\rm eff}, \chi_p \mid \Lambda) + \xi(m_1 \mid \Lambda)\, p_{\rm H}\,(\chi_{\rm eff}, \chi_p \mid \Lambda)$$

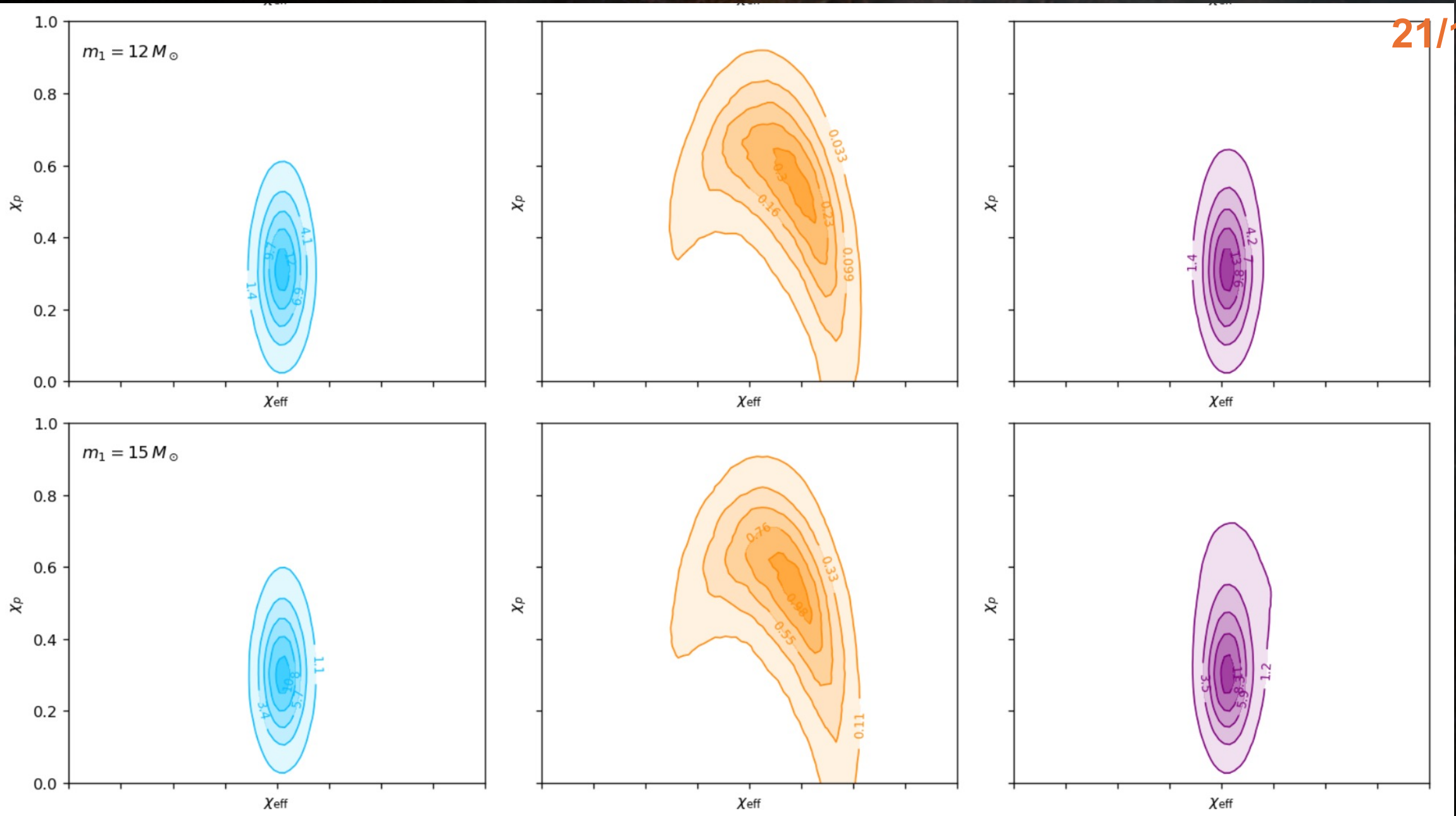
$$p_{\rm L}(\chi_{\rm eff}, \chi_{\rm p}|\Lambda) \propto {\rm TNormal}(\chi_{\rm eff}|\mu_{\rm eff}, \sigma_{\rm eff}){\rm TNormal}(\chi_{\rm p}|\mu_{\rm p}, \sigma_{\rm p})$$

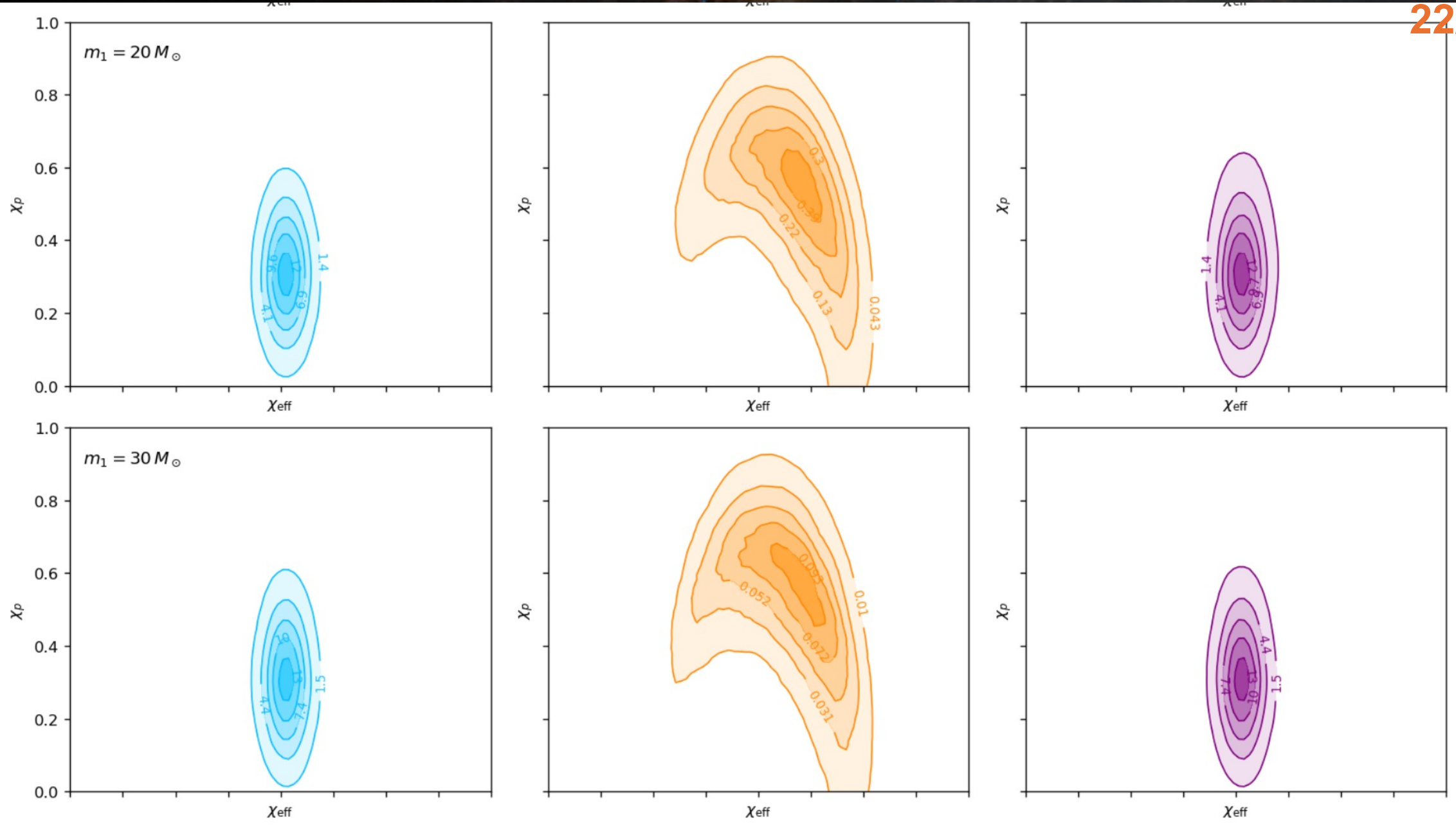
$$p_{\rm H}(\chi_{\rm eff}, \chi_{\rm p}|\Lambda) \propto \exp\left[-\frac{1}{2}\left\{\left(\frac{r - r_c}{\sigma_r}\right)^2 + \left(\frac{\theta - \theta_{\rm eff}(m_1)}{\sigma_\theta}\right)^2\right\}\right]$$

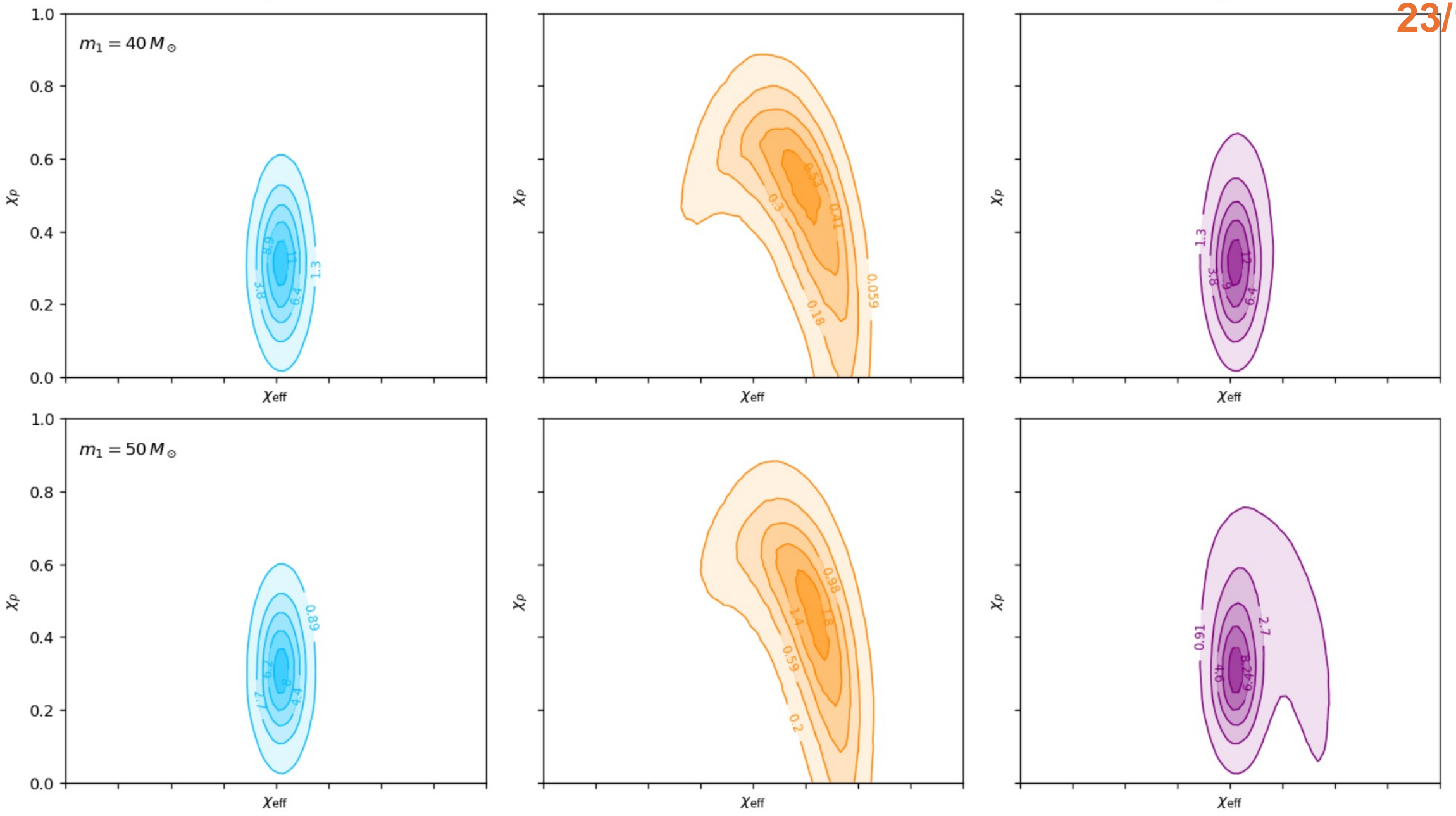
$$\theta_{\rm eff}(m_1) = \pi\ {\rm sigmoid}[S_\theta(\log m_1)]$$

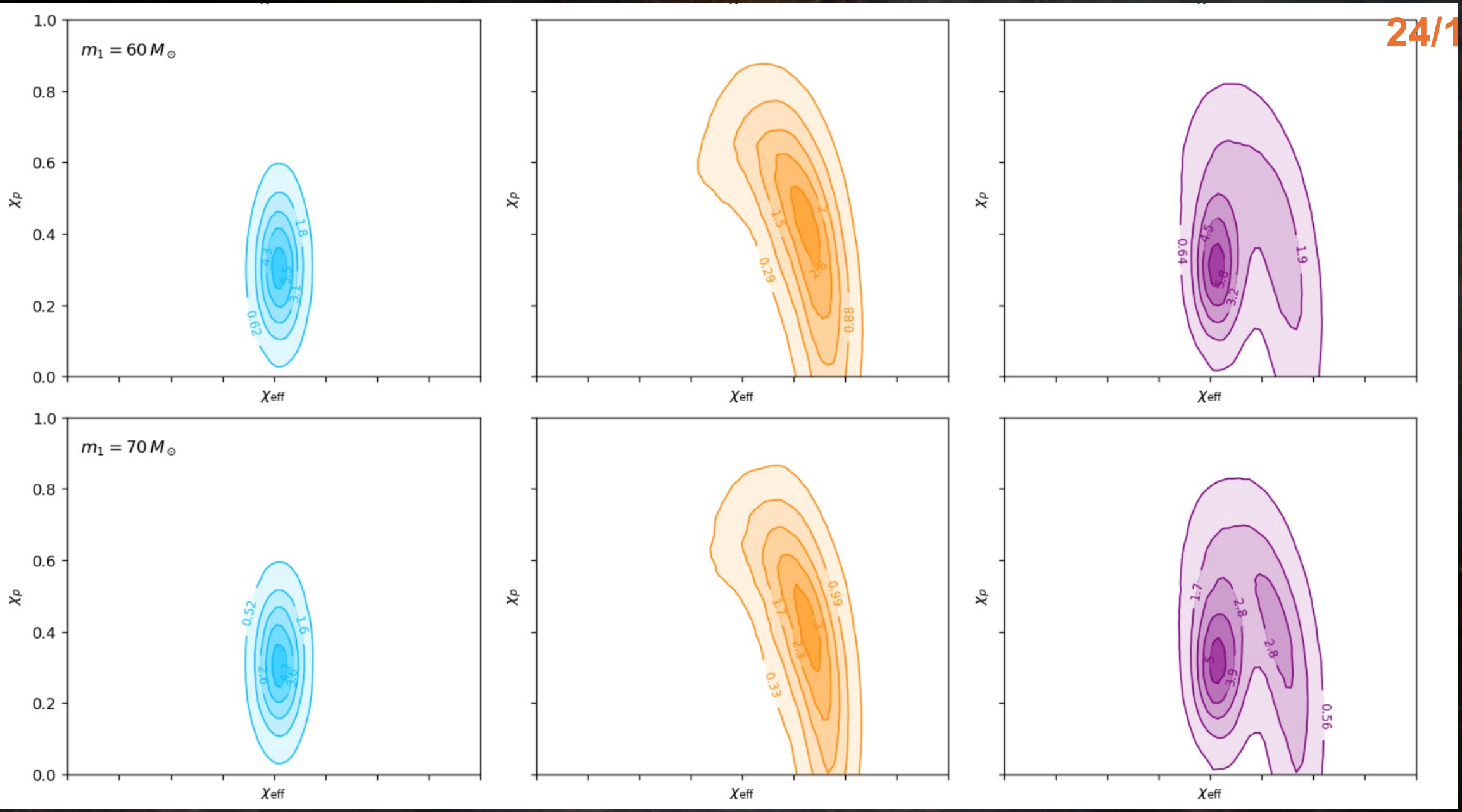
$$\xi(m_1) = {\rm sigmoid}[S_f(\log m_1)]$$

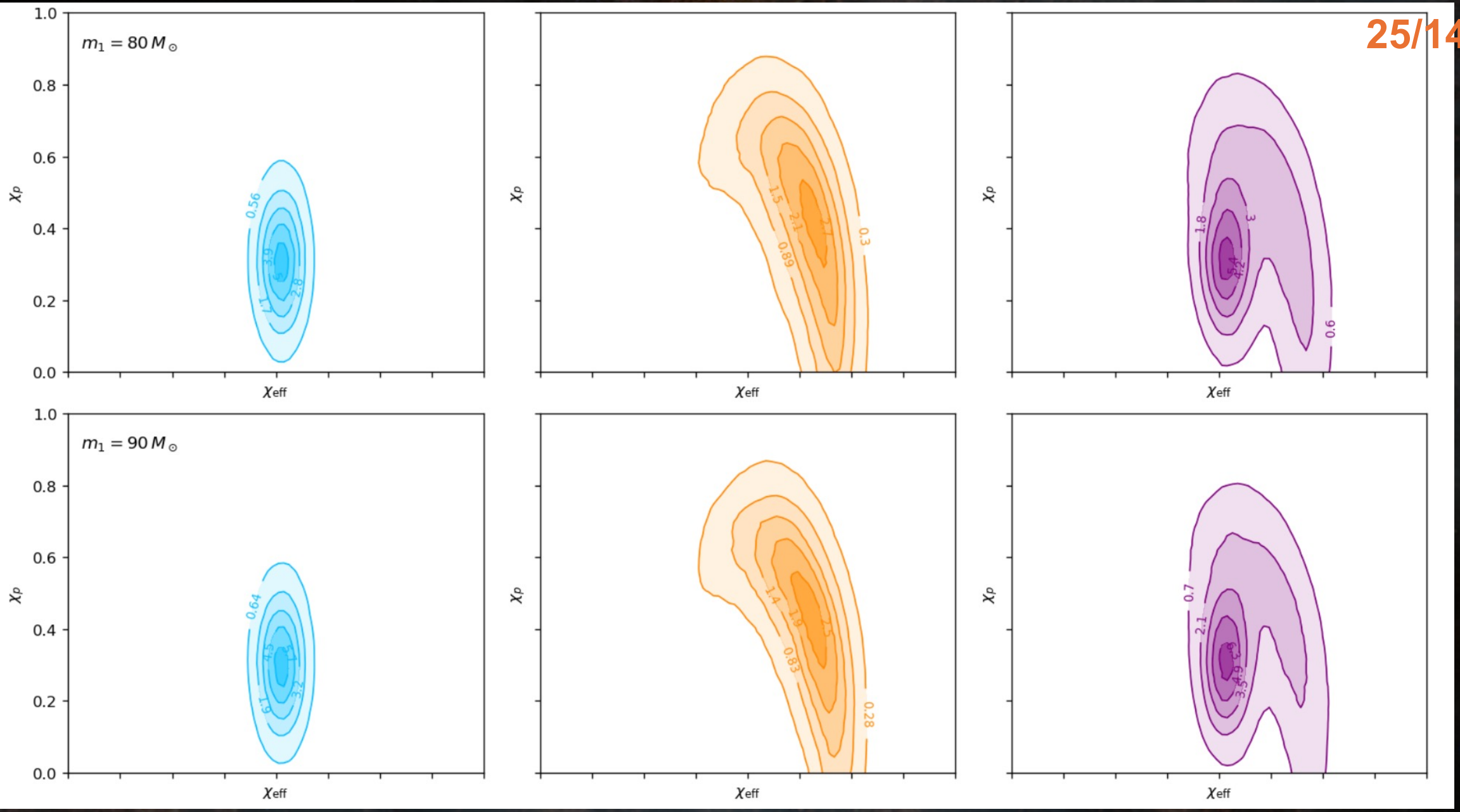

low spin contribution
high spin contribution
total model
$m_1 = 7\,M_\odot$
$m_1 = 10\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
0.27
0.11
0.19
0.038
0.04
0.092
0.066
0.013
0.12

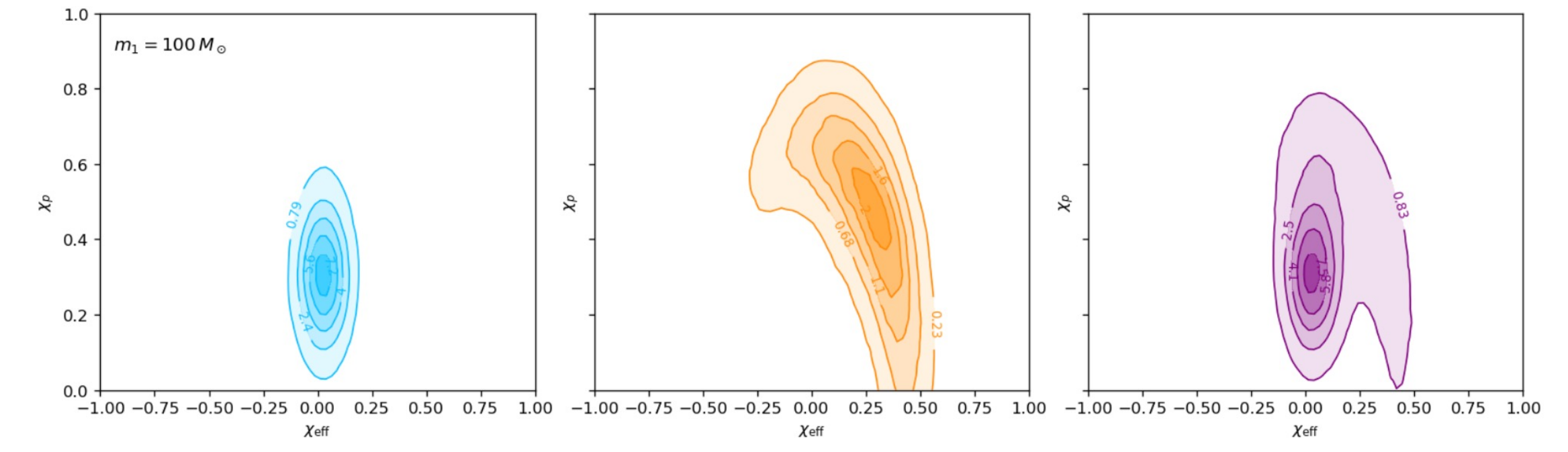

$m_1 = 12\,M_\odot$
$m_1 = 15\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
4.1
2.6
1.4
6.9
0.033
0.3
0.16
0.23
0.099
4.2
1.4
9.8
1.1
3.4
0.76
0.33
0.98
0.55
0.11
1.2
5.5
5.9

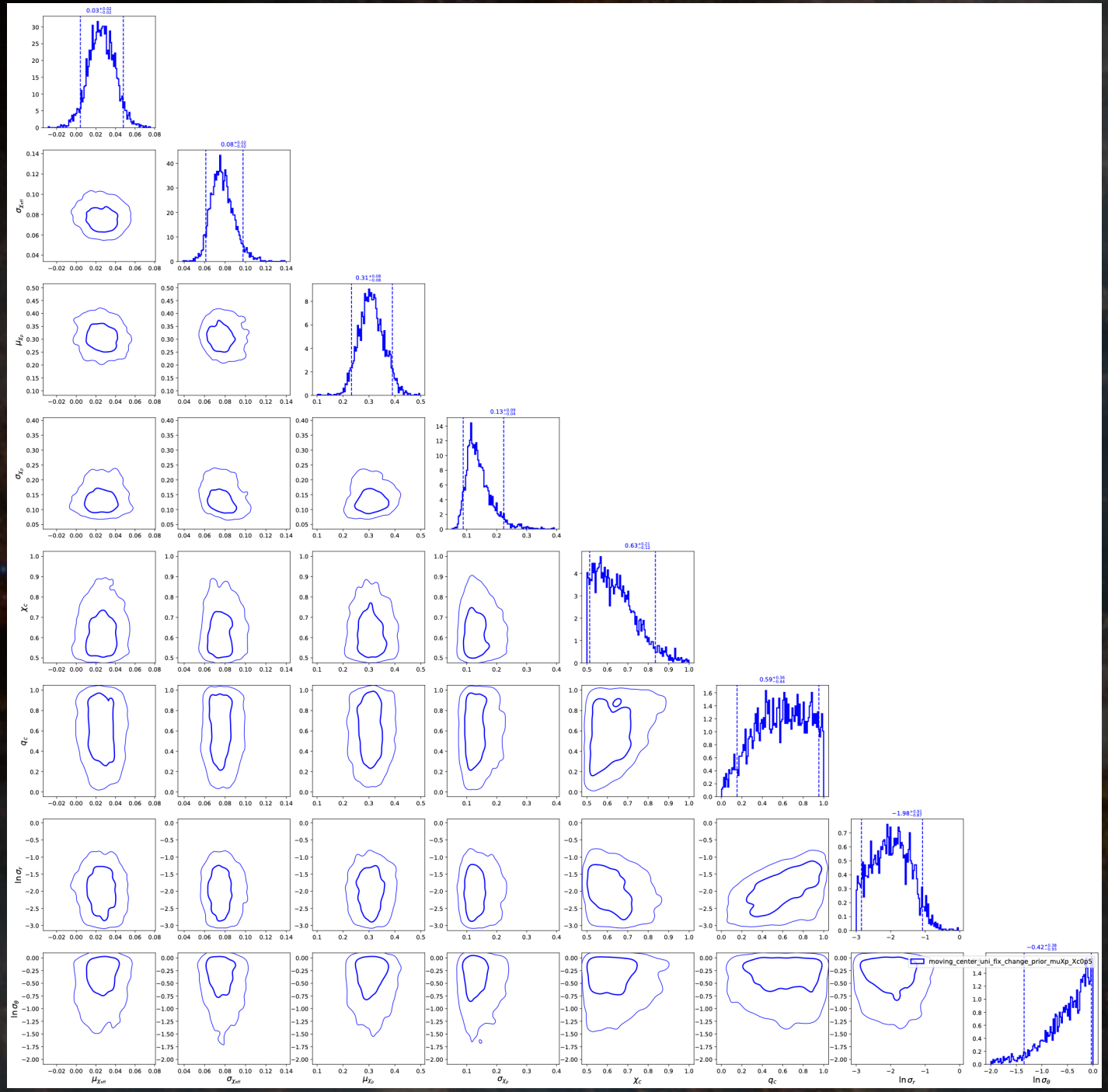

$m_1 = 20\,M_\odot$
$m_1 = 30\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
1.4
0.9
1.2
0.9
1.1
4.1
0.3
0.22
0.13
0.043
1.4
4.1
0.9
1.2
0.9
1.1
1.5
4.4
7.4
0.052
0.072
0.031
0.01
4.4
7.4
1.5


$m_1 = 40\,M_\odot$
$m_1 = 50\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
0.89
1.3
3.18
6.4
0.53
0.3
0.41
0.059
0.18
0.98
1.4
1.8
0.59
0.2
2.7
0.91

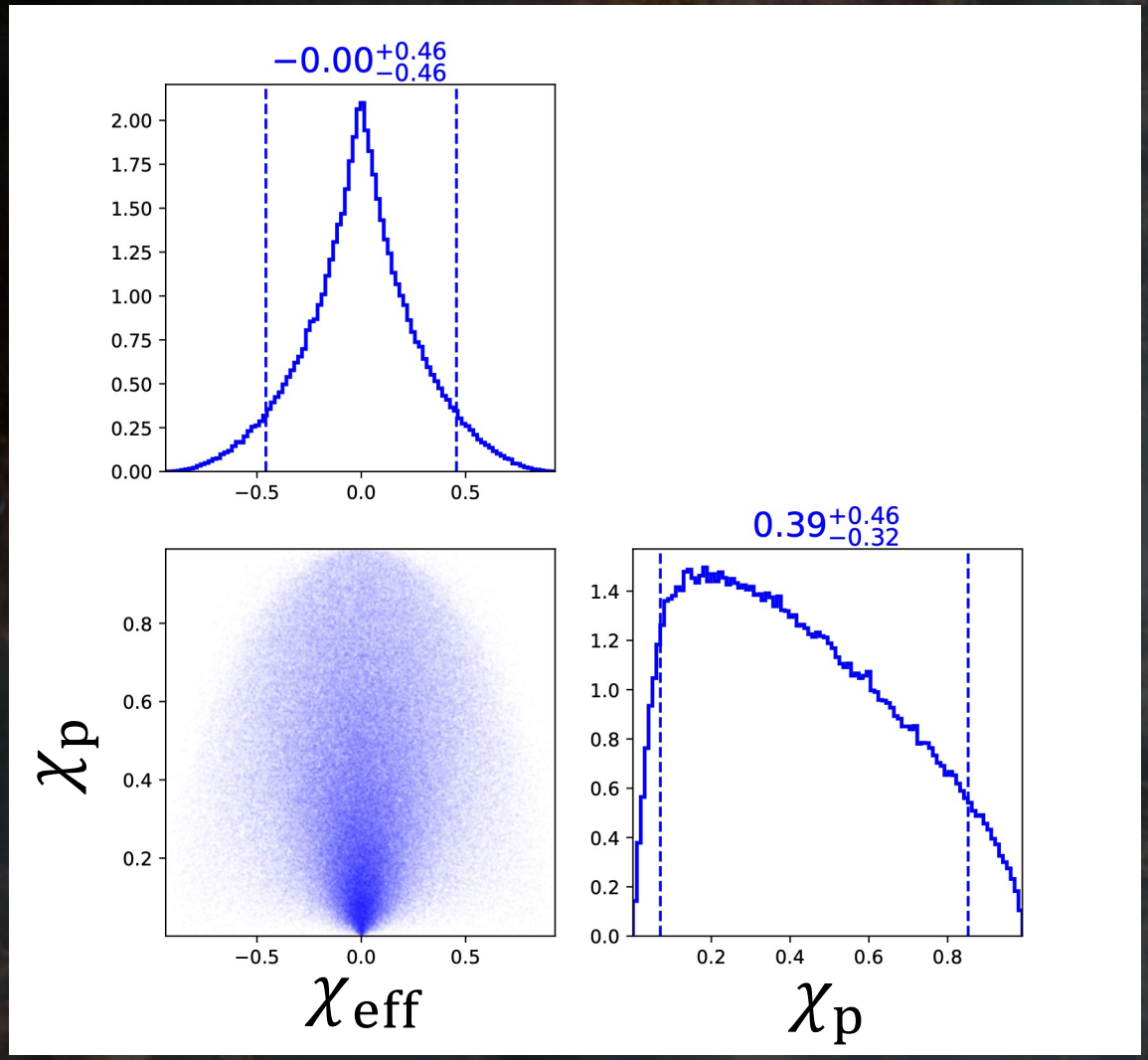

$m_1 = 60\,M_\odot$
$m_1 = 70\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
1.8
4.3
5.3
3.3
0.62
1.5
2
0.29
2.6
0.88
0.64
4.5
5.8
3.2
1.9
0.52
1.6
2.6
3.6
0.99
1.7
2.3
1
0.33
1.7
2.8
5
3.9
2.8
0.56


$m_1 = 80\,M_\odot$
$m_1 = 90\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
0.56
3.9
2.8
1.7
1.5
2.1
0.89
0.3
1.8
3
4.2
5.4
0.6
0.64
4.5
3.2
1.9
1.4
1.9
0.83
0.28
0.7
2.1
3.5
4.9

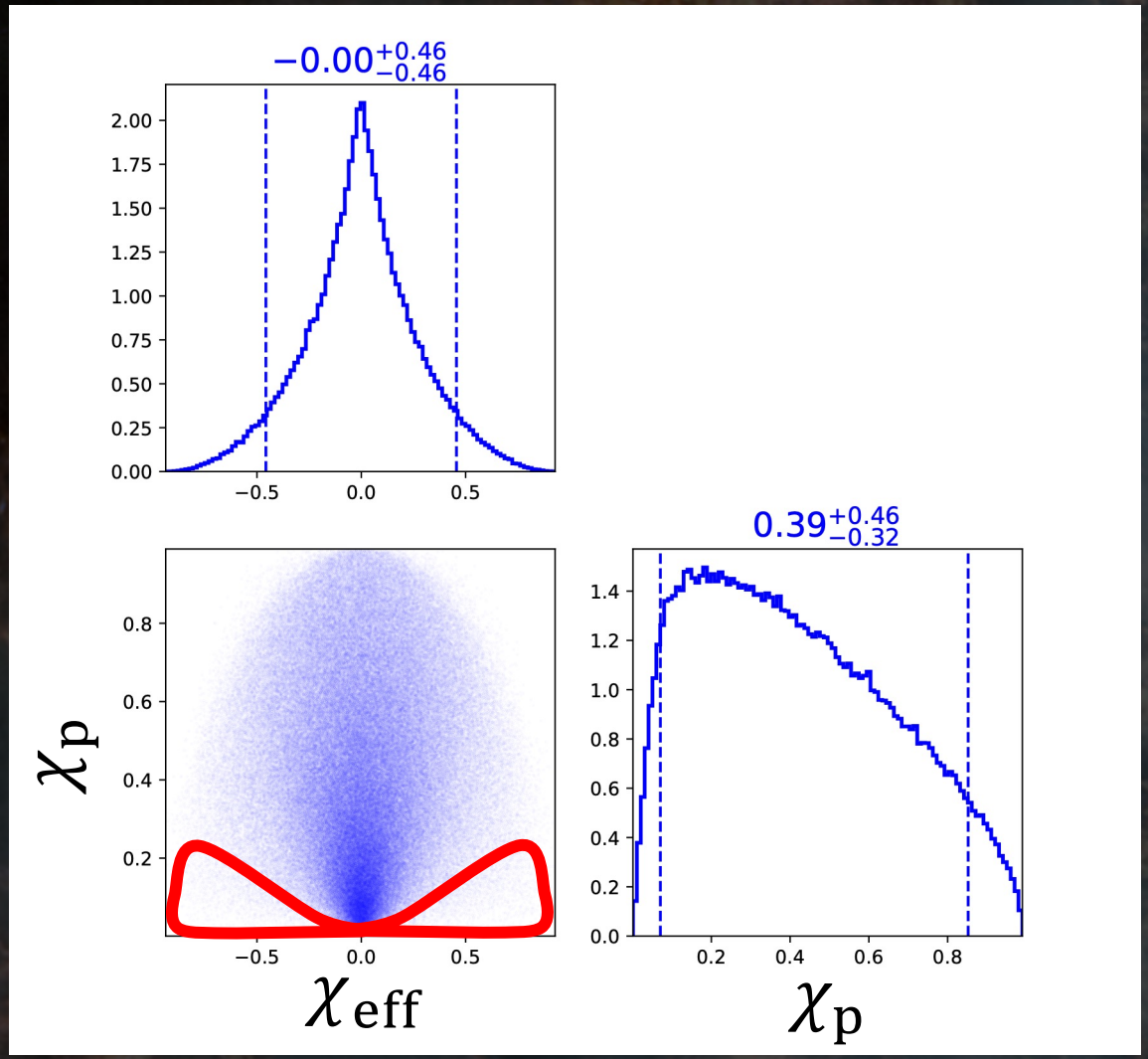

$m_1 = 100\,M_\odot$
χ_p
$\chi_{\rm eff}$
1.0
0.8
0.6
0.4
0.2
0.0
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
0.79
0.68
0.23
0.83
2.5
1.6
1.1
4.1
5.8
7


$\mu_{\chi_{eff}}$
$\sigma_{\chi_{eff}}$
μ_{χ_p}
σ_{χ_p}
χ_c
q_c
$\ln \sigma_r$
$\ln \sigma_\theta$
moving_center_uni_fix_change_prior_muXp_Xc0p5

Problem in spin population analysis

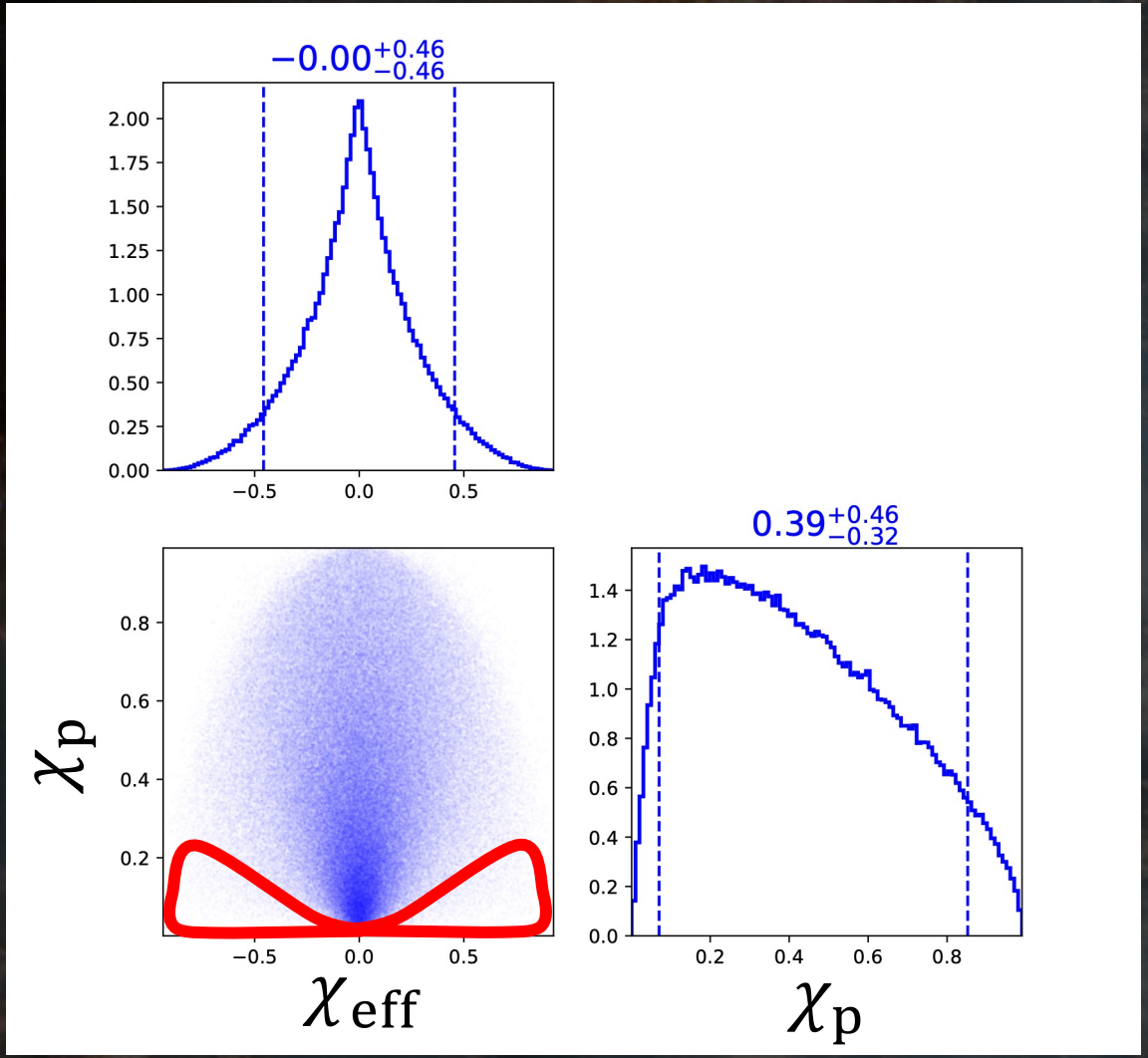


Problem in spin population analysis



The prior excludes the region near $\chi_{\rm eff} \approx 1$ and $\chi_{\rm p} \approx 0$.

Problem in spin population analysis

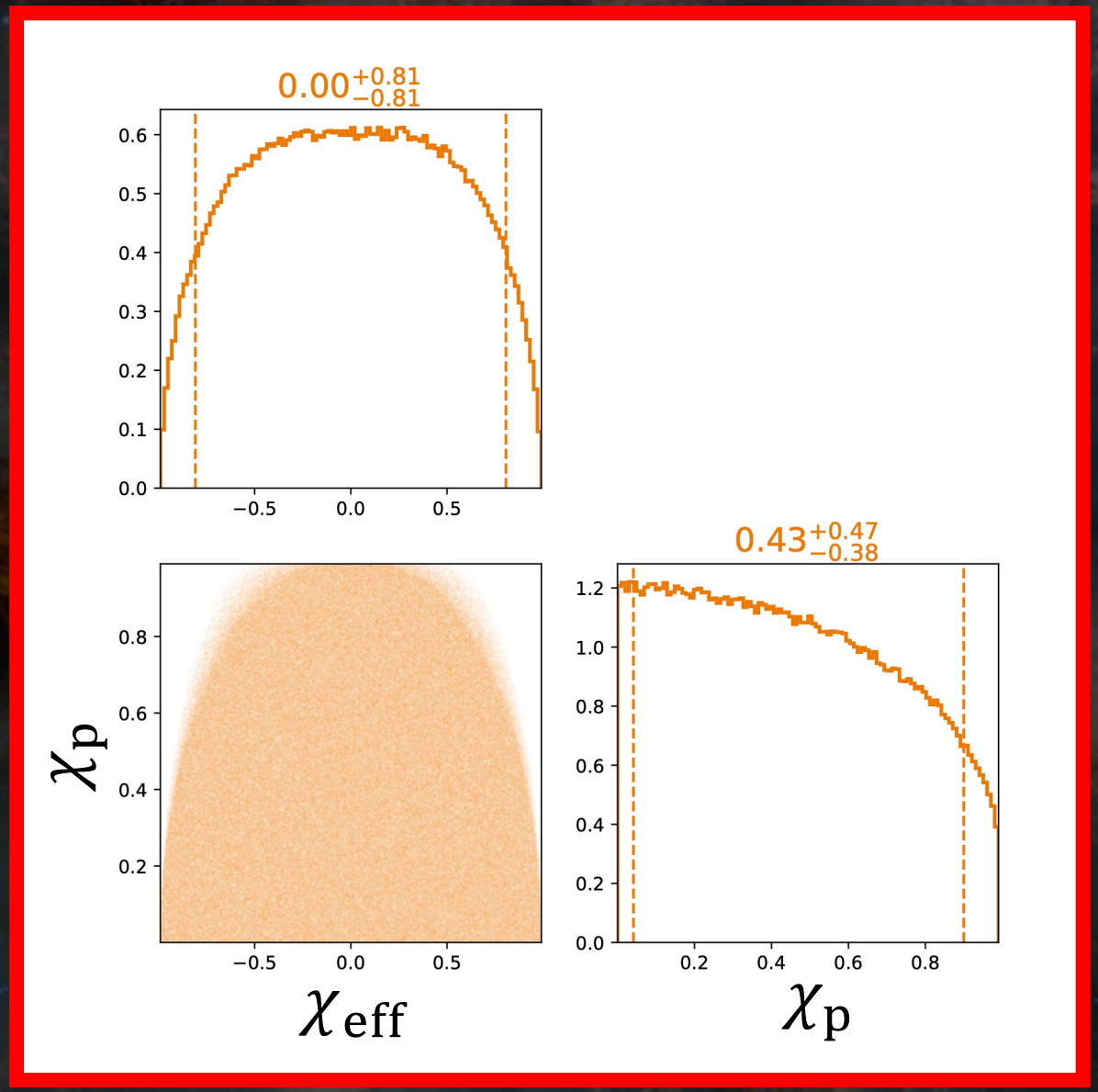


The prior excludes the region near $\chi_{\rm eff} \approx 1$ and $\chi_{\rm p} \approx 0$.

Biased parameter estimation.

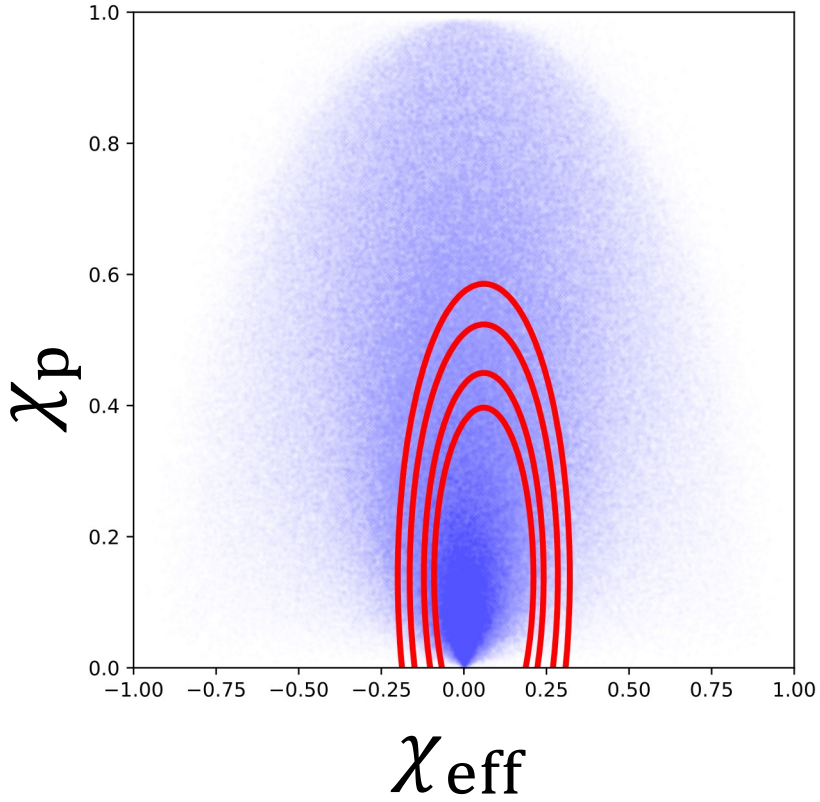
Biased population inference.

Our novel prior

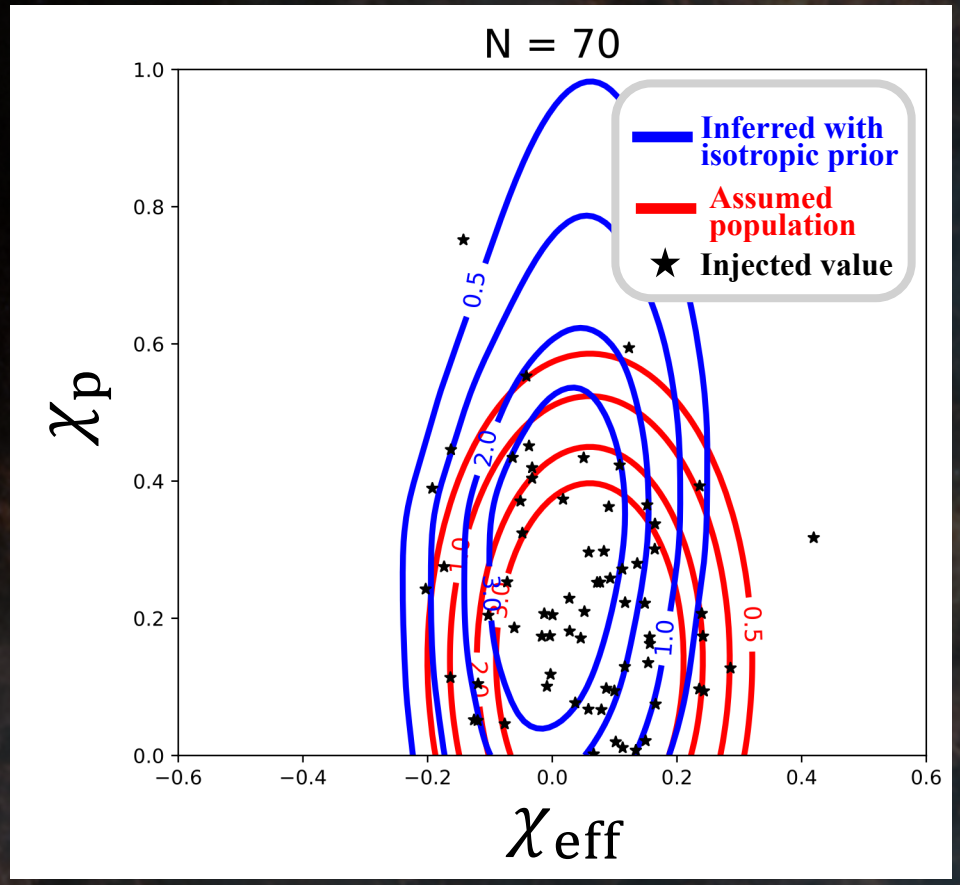


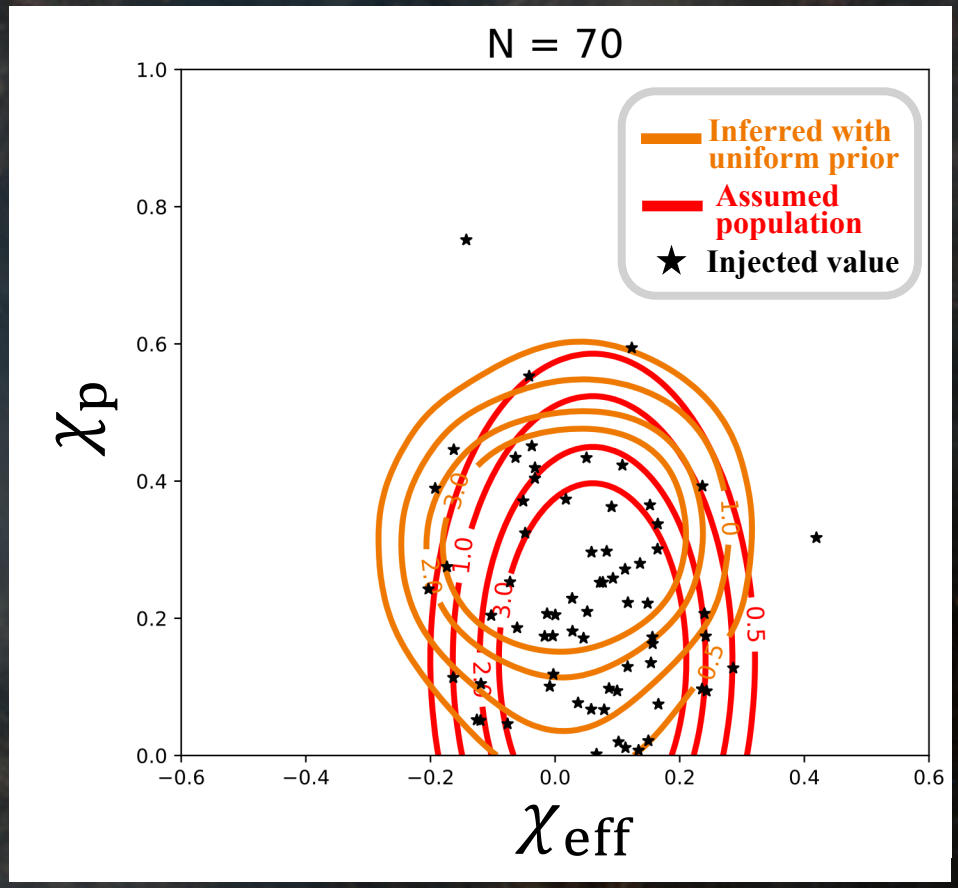
Performance test ~standard case~

Red: Assumed population like GWTC-3 result



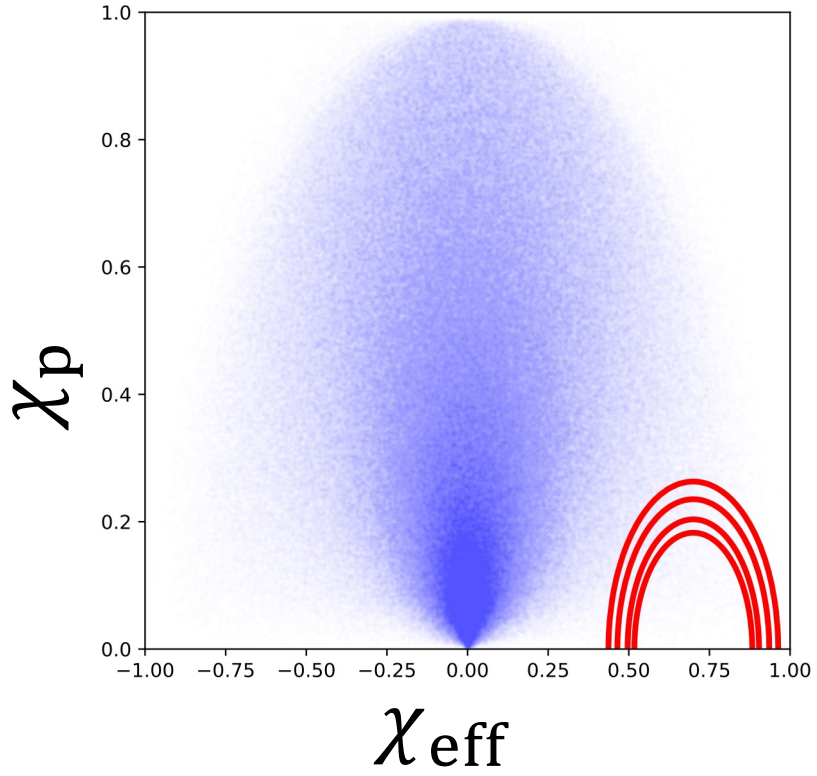
Performance test ~standard case~



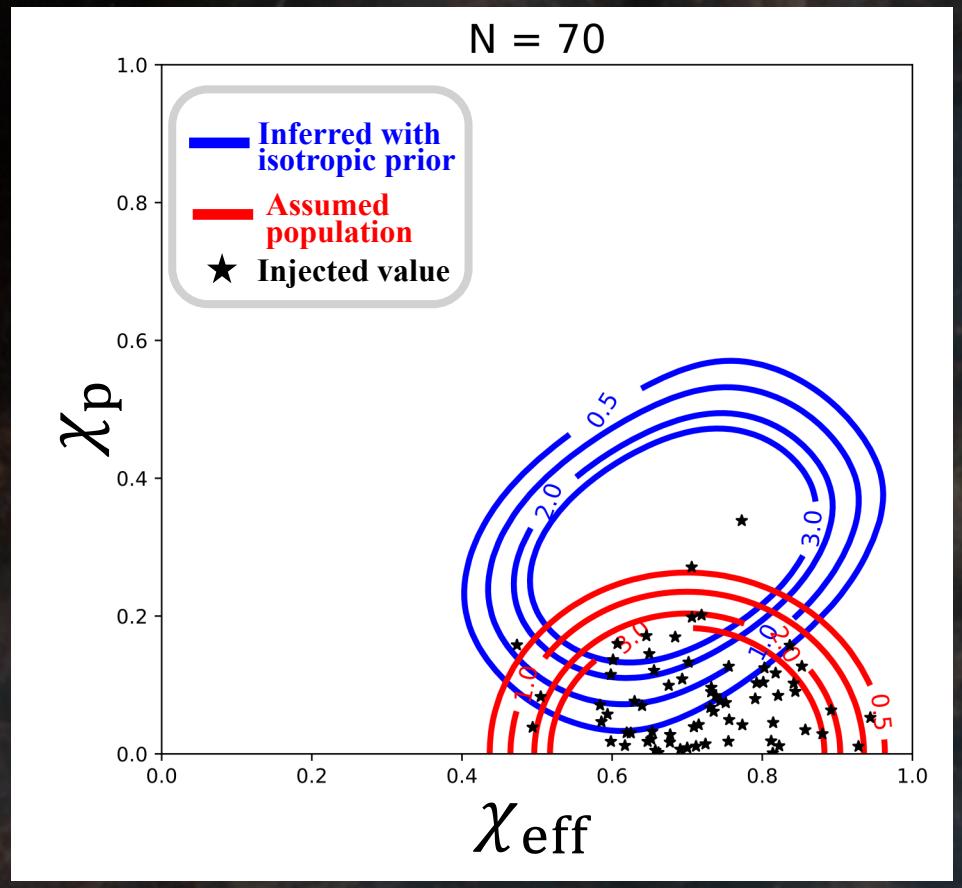


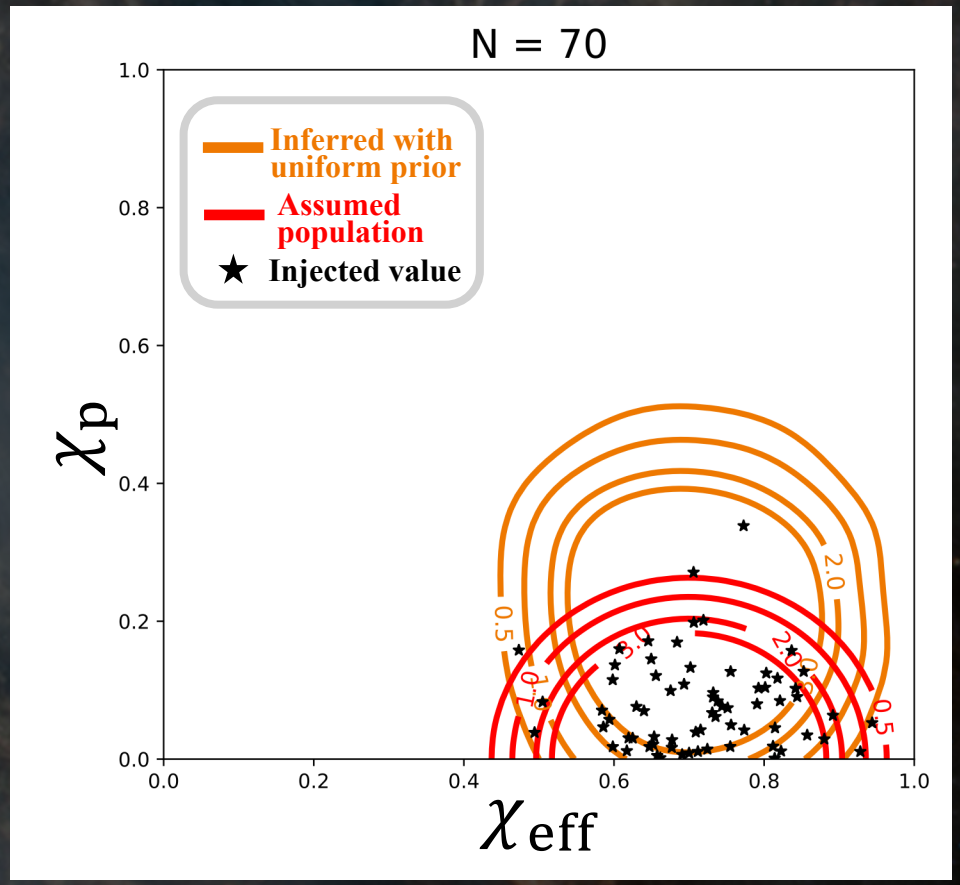
Performance test ~extreme case~

Red: Assumed population with large $\chi_{\rm eff}$

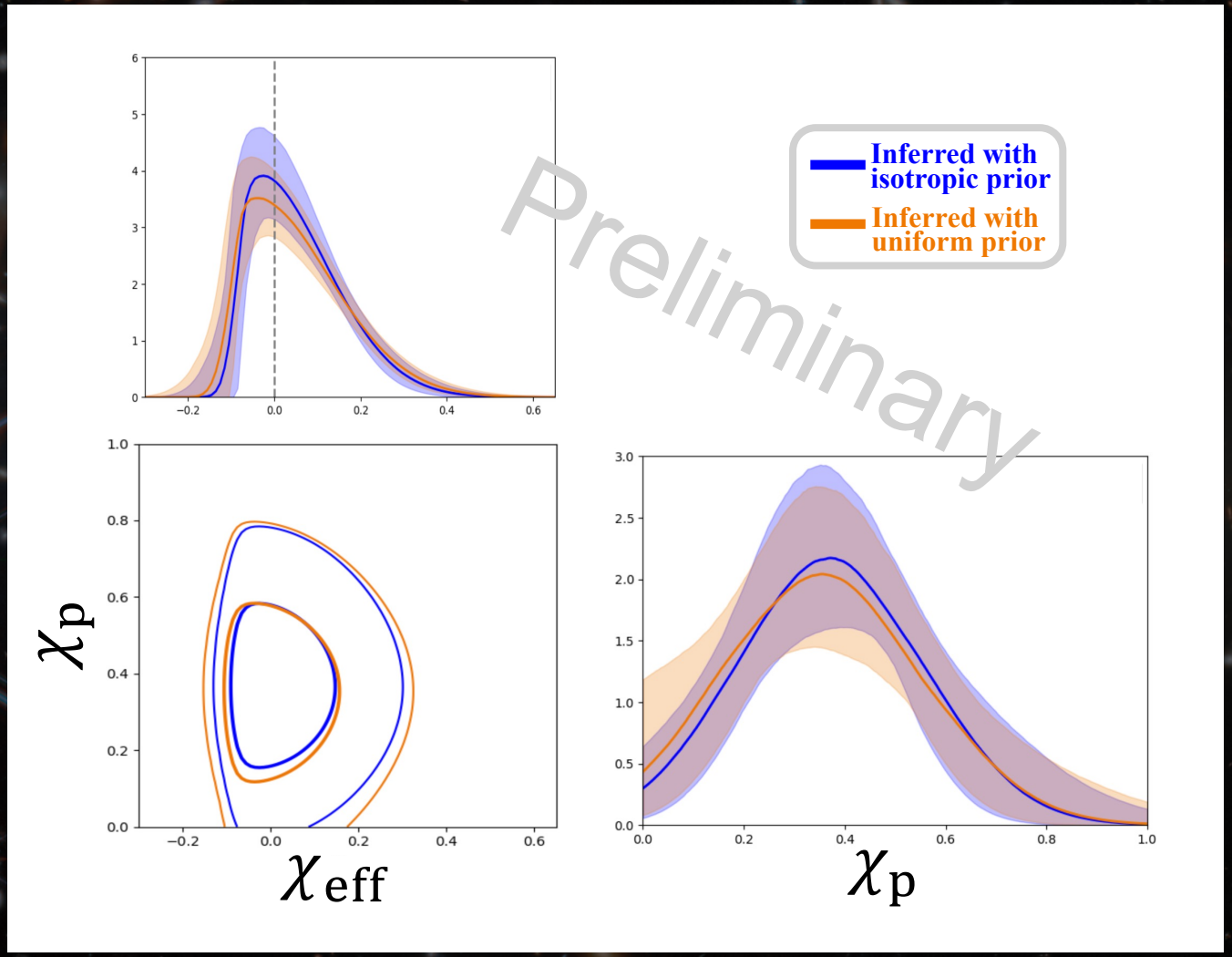


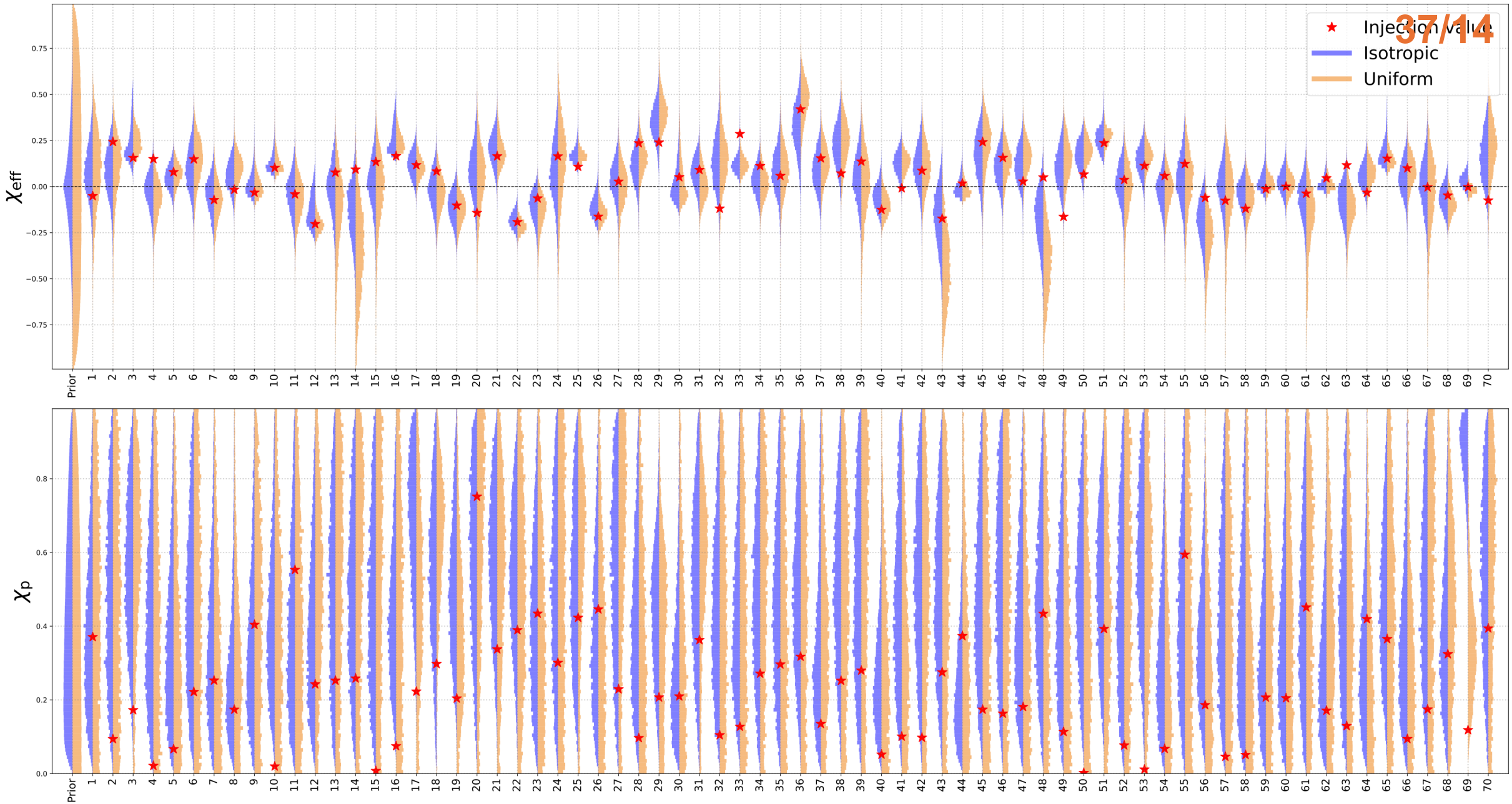
Performance test ~extreme case~

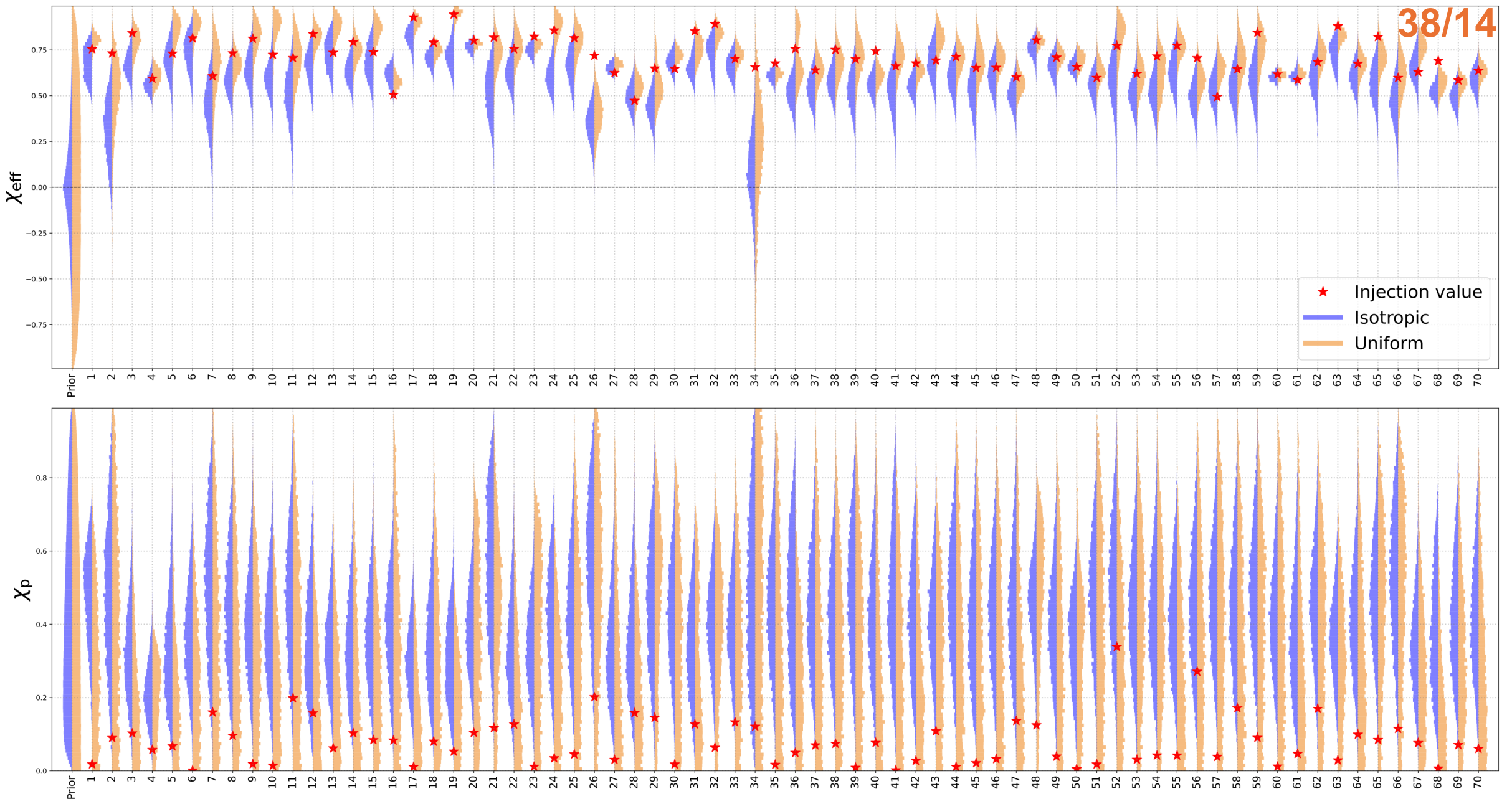




Application for real data (~GWTC4)




37/14
Injection value
Isotropic
Uniform
$\chi_{\rm eff}$
$\chi_{\rm p}$
Prior
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70


38/14
$\chi_{\rm eff}$
$\chi_{\rm p}$
Injection value
Isotropic
Uniform
Prior