Accurate Estimation of the Spin Distribution of Binary Black Holes Using Gravitational-Wave Data

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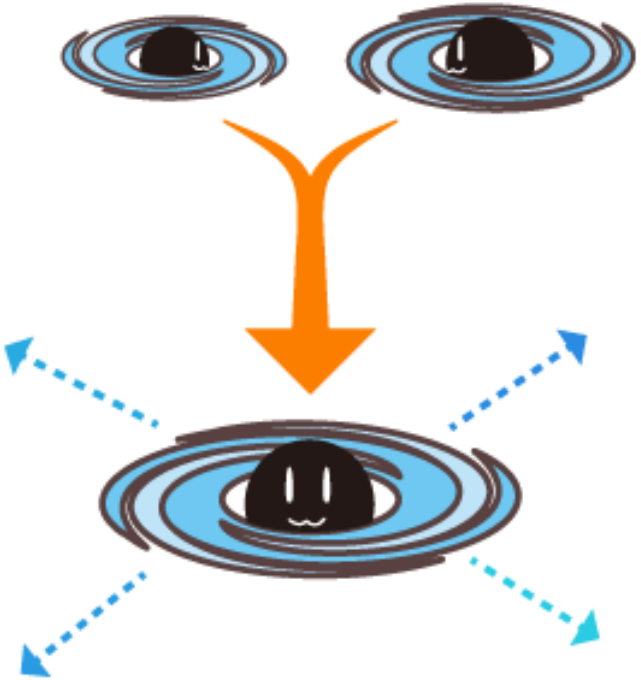
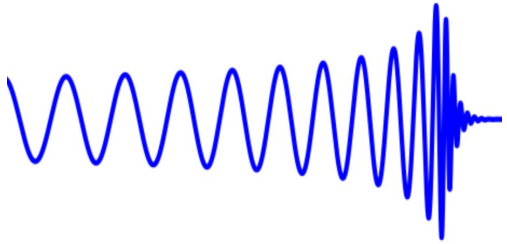
Binary Black hole(BBH)

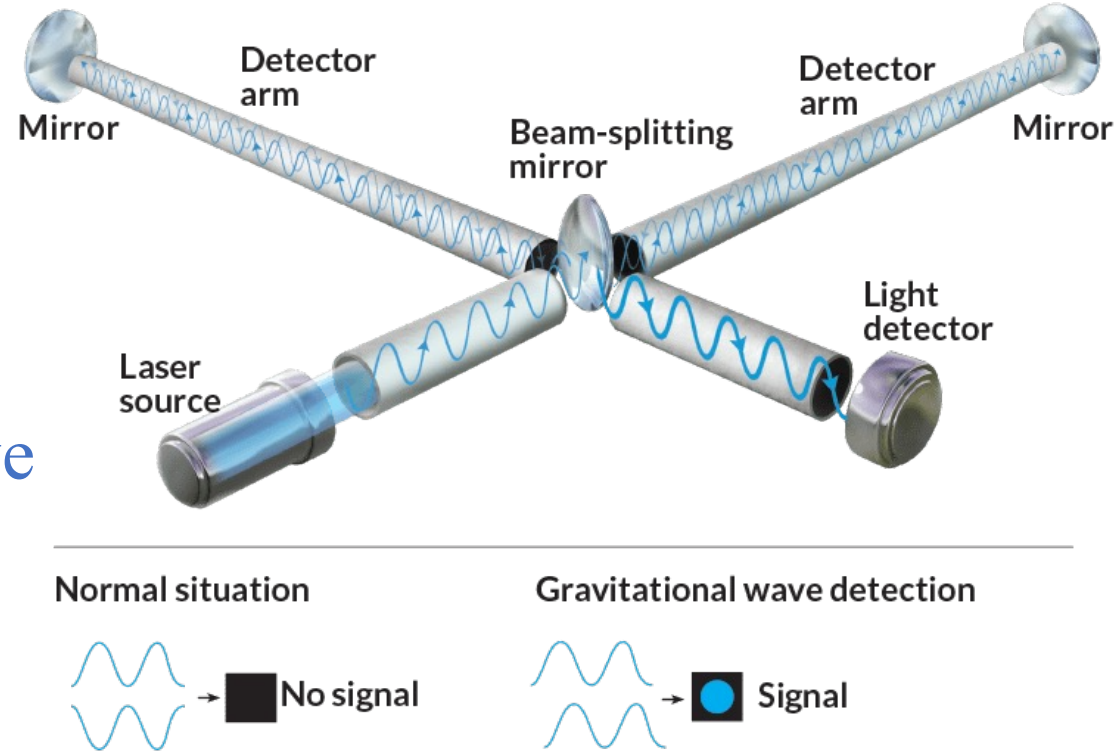


https://higgstan.com/



Gravitational wave

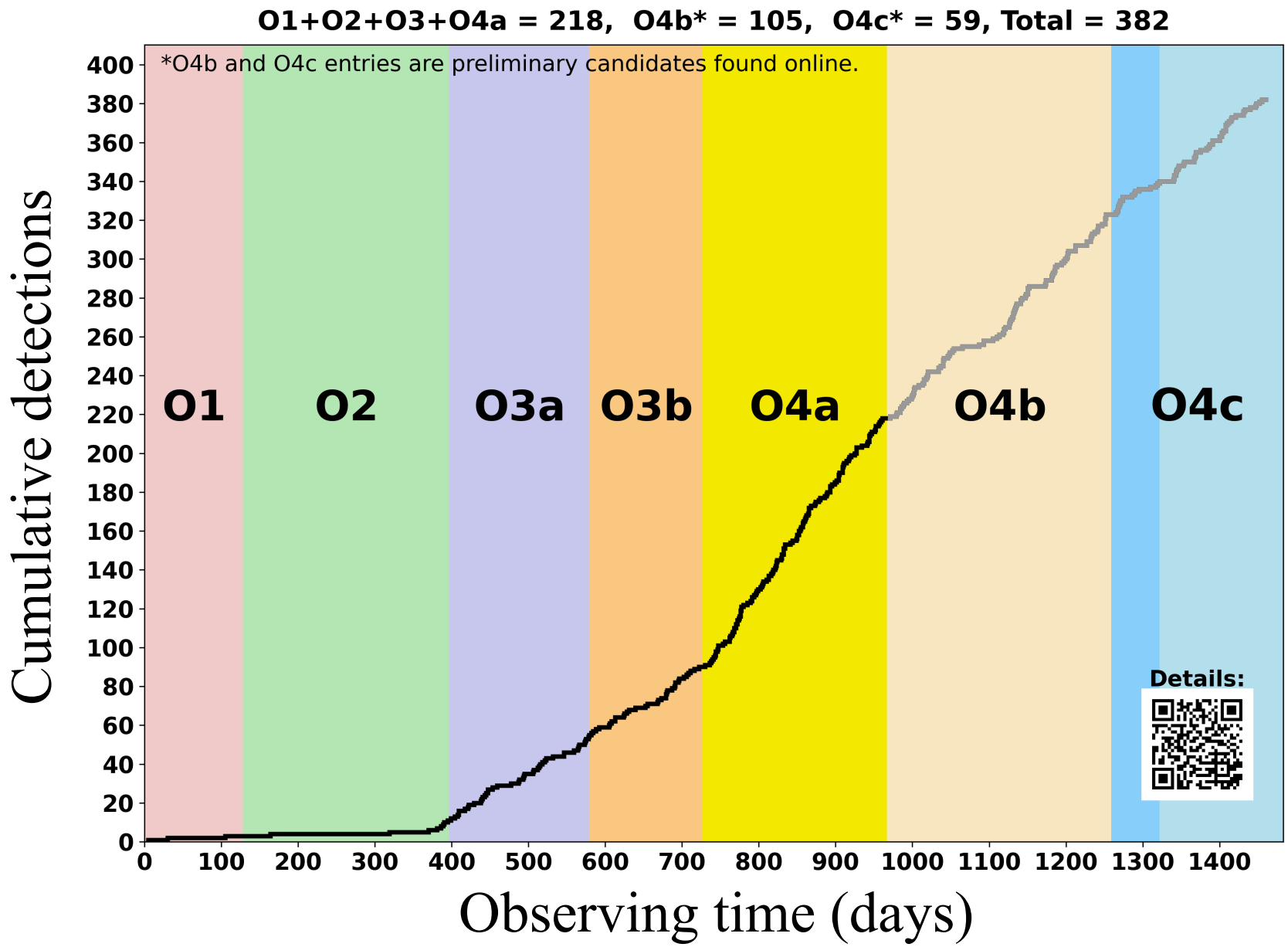
Interferometer Observatory



https://www.sciencenews.org/article/trio-wins-physics-nobel-prize-gravitational-wave-detection

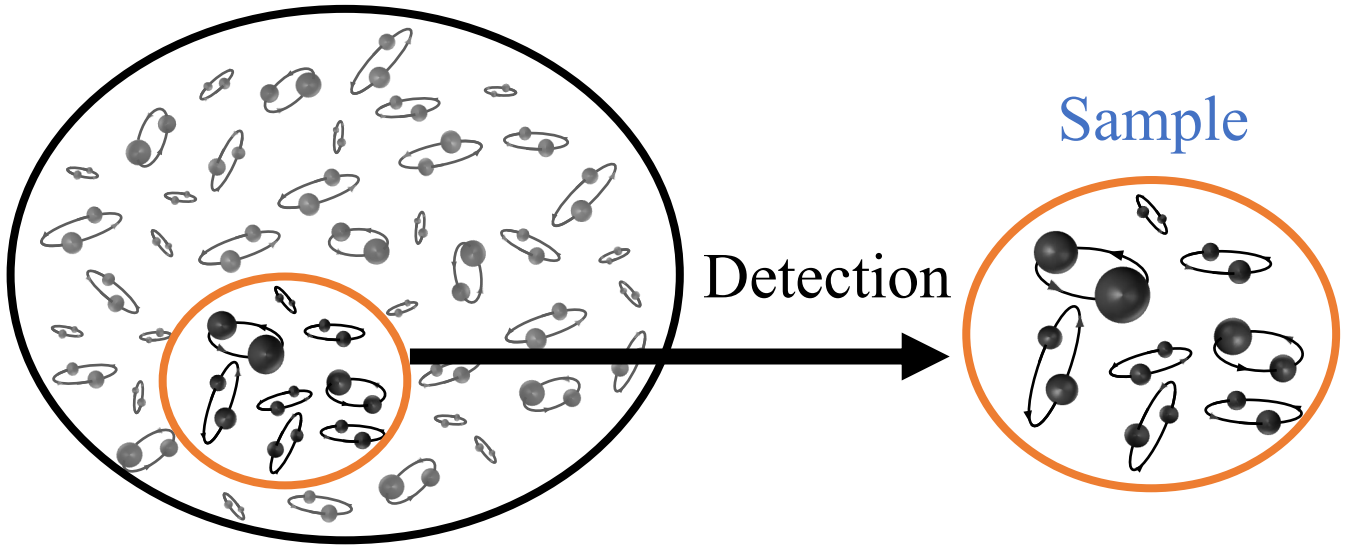
218 events!!!

were observed up to the O4a run.


O1+O2+O3+O4a = 218, O4b* = 105, O4c* = 59, Total = 382
*O4b and O4c entries are preliminary candidates found online.
Cumulative detections
Observing time (days)
O1
O2
O3a
O3b
O4a
O4b
O4c
Details:
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

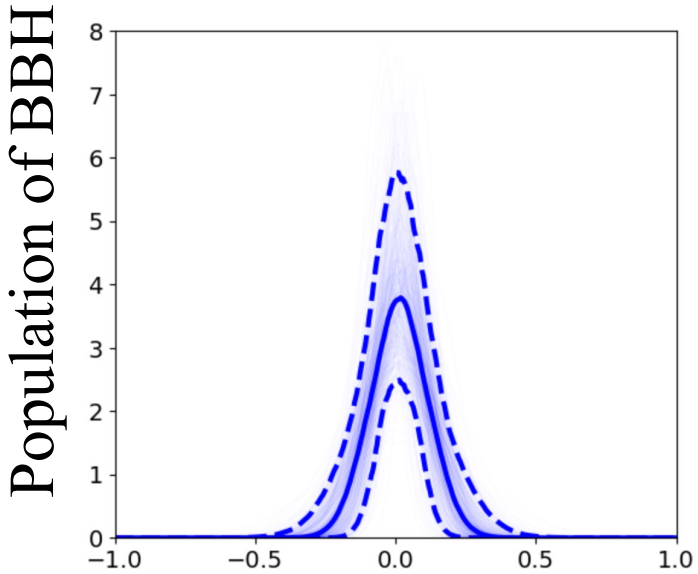
Population analysis = Statistical survey

Whole population of BBH



Detection

Sample

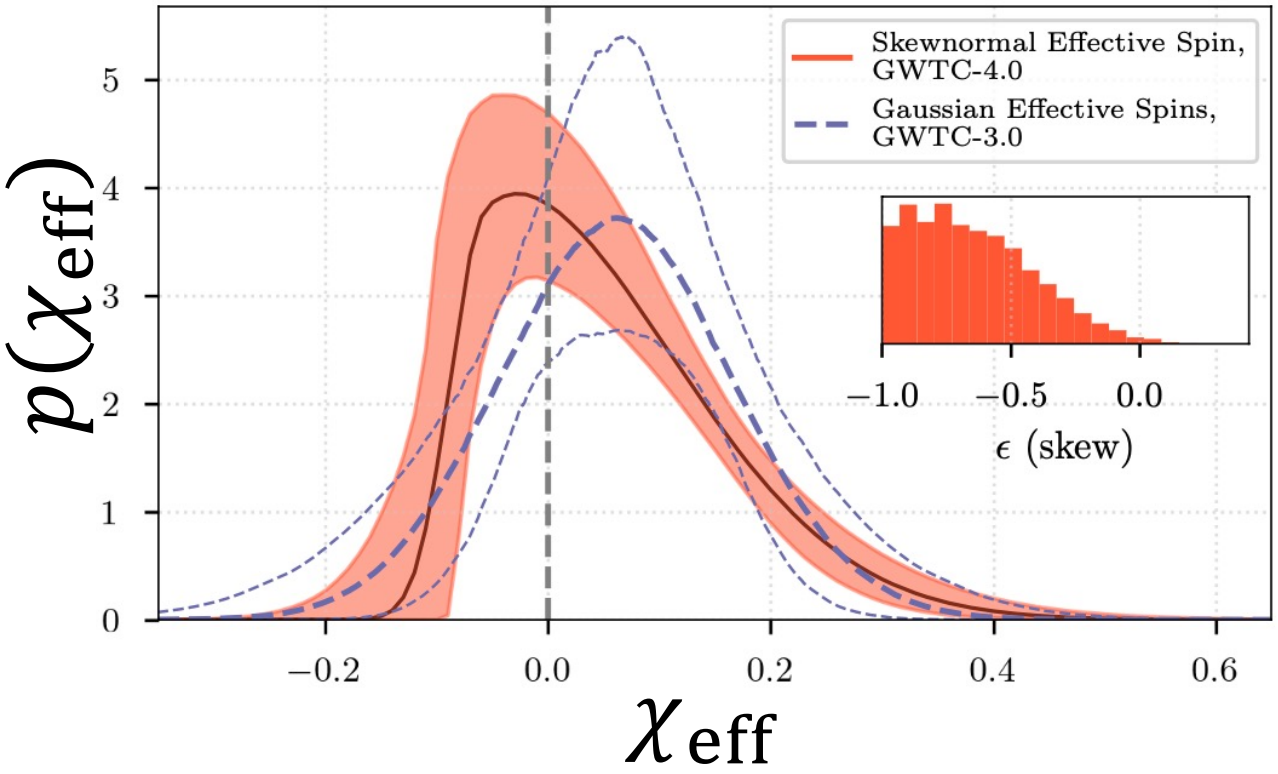


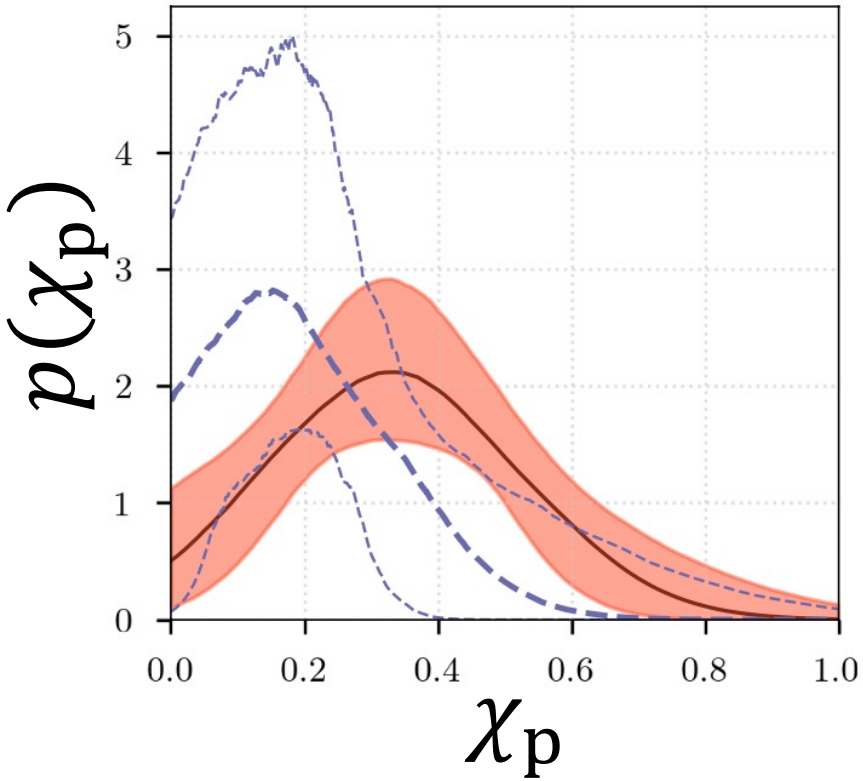
BBH parameter
such as masses, spins and etc.

Population of spins up to O4a

χ_{eff} : Effective spin aligned with the $\vec{L}$ of binary.

χ_{p}: Effective spin perpendicular to the $\vec{L}$ of binary.



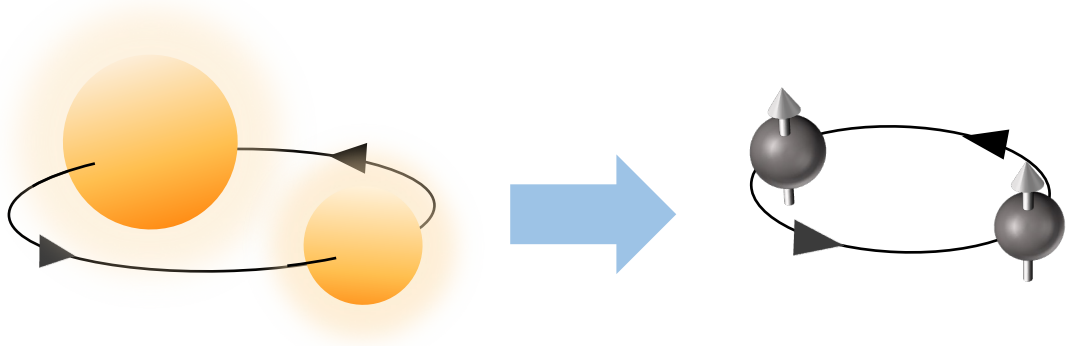


[1] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration arXiv:2508.18083(2025)

The spin population strongly depends on the formation process.

[1] K. Belczynski et al. Nature 534, 512 (2016)
[2] S. F. P. Zwart, et al. The Astrophysical Journal 576, 899 (2002)

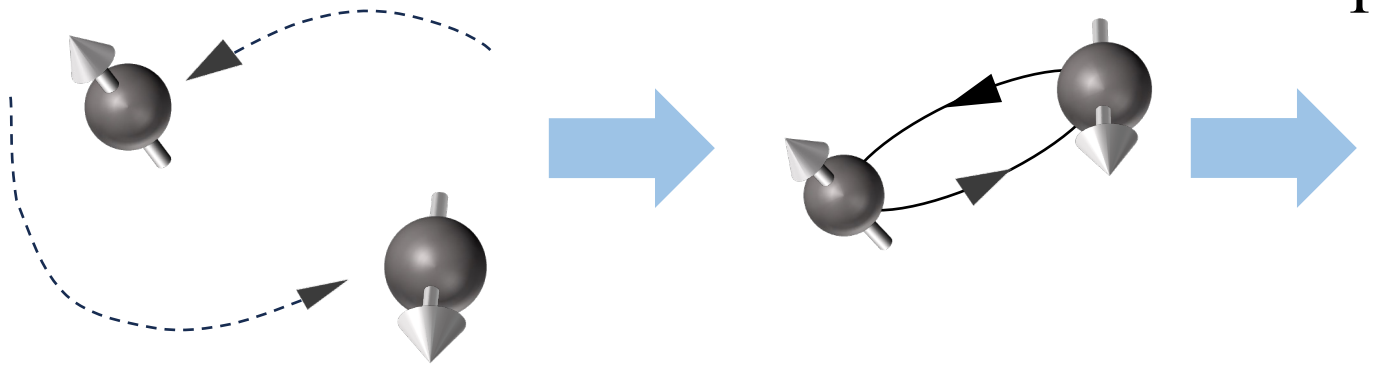
- Isolated binary formation[1]



Population:

χ_{eff} : Positive.
χ_{p}: Zero.

- Dynamical formation[2]



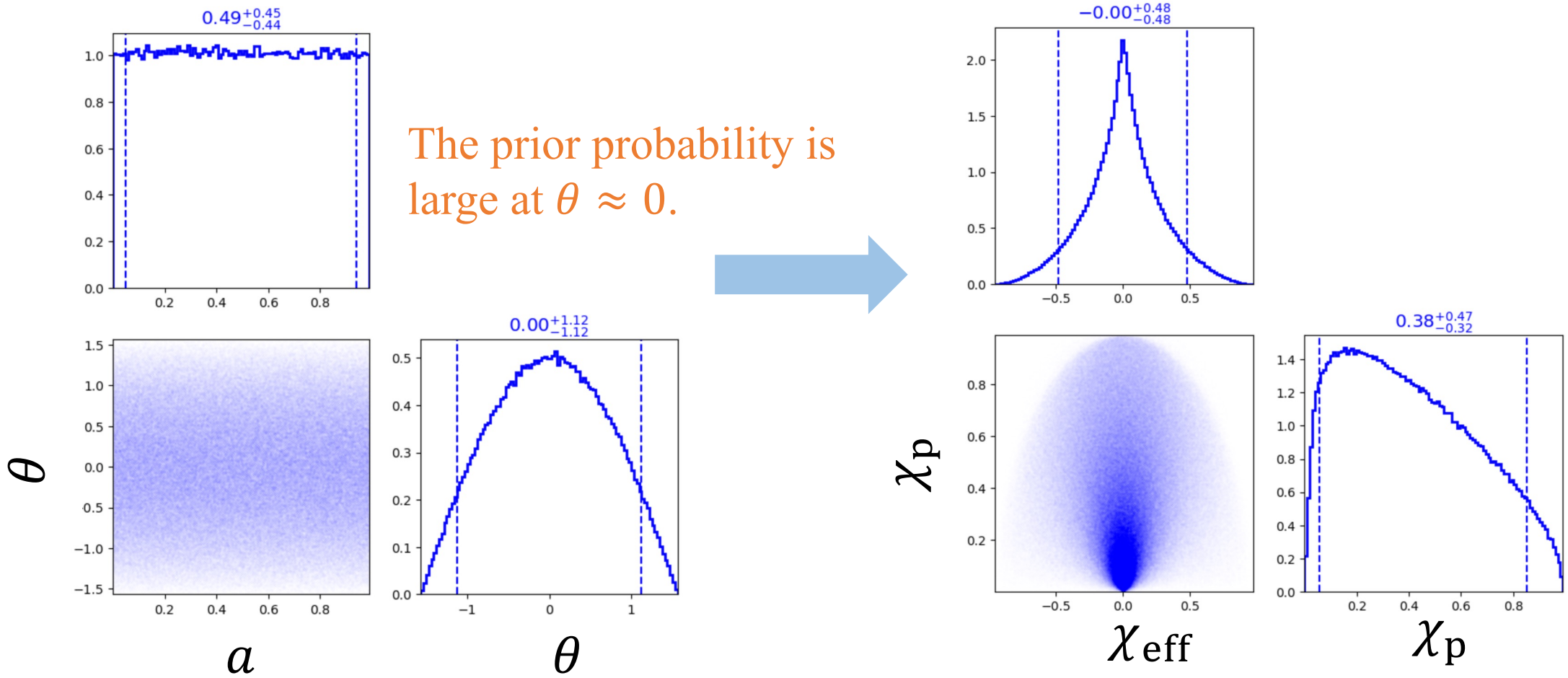
Population:

χ_{eff} : Positive or negative.
χ_{p}: Not only zero.

Issue in the previous analysis

Prior distribution of parameter estimation in previous analysis[1]

[1] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration arXiv:2508.18083(2025)



The prior probability is large at $\theta \approx 0$.

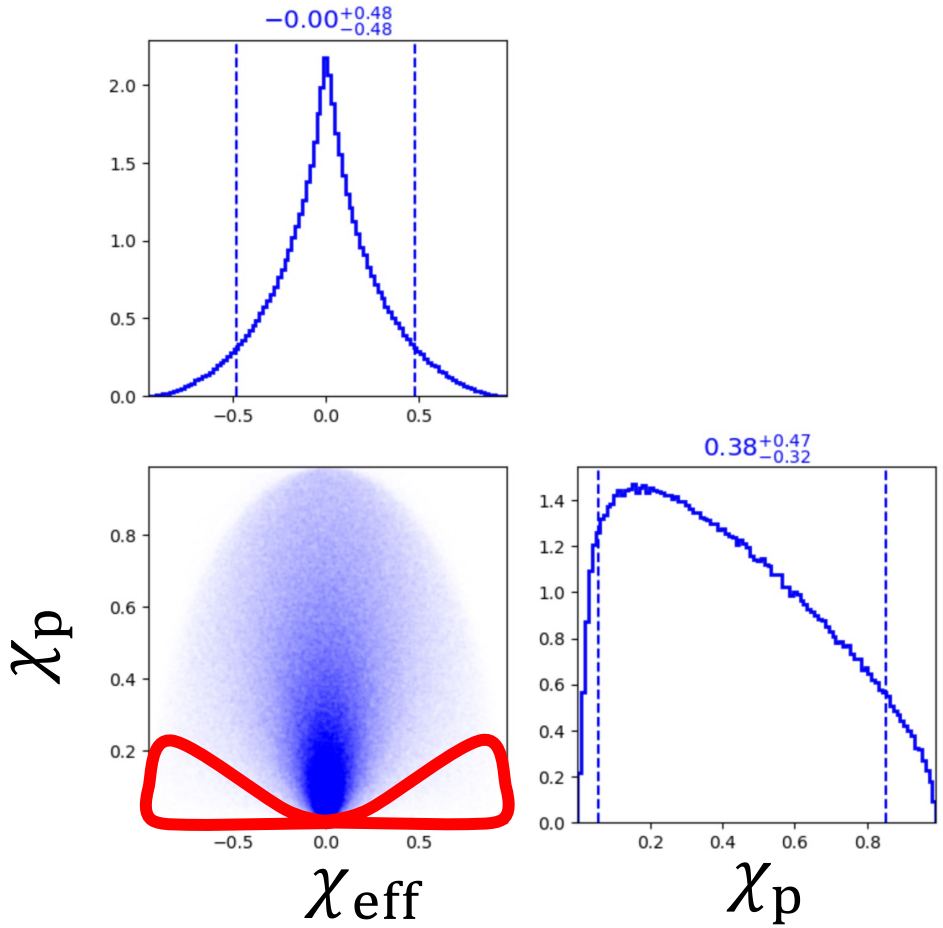
Issue in the previous analysis

[1] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration arXiv:2508.18083(2025)

The finite number of posterior samples cannot adequately cover this region.

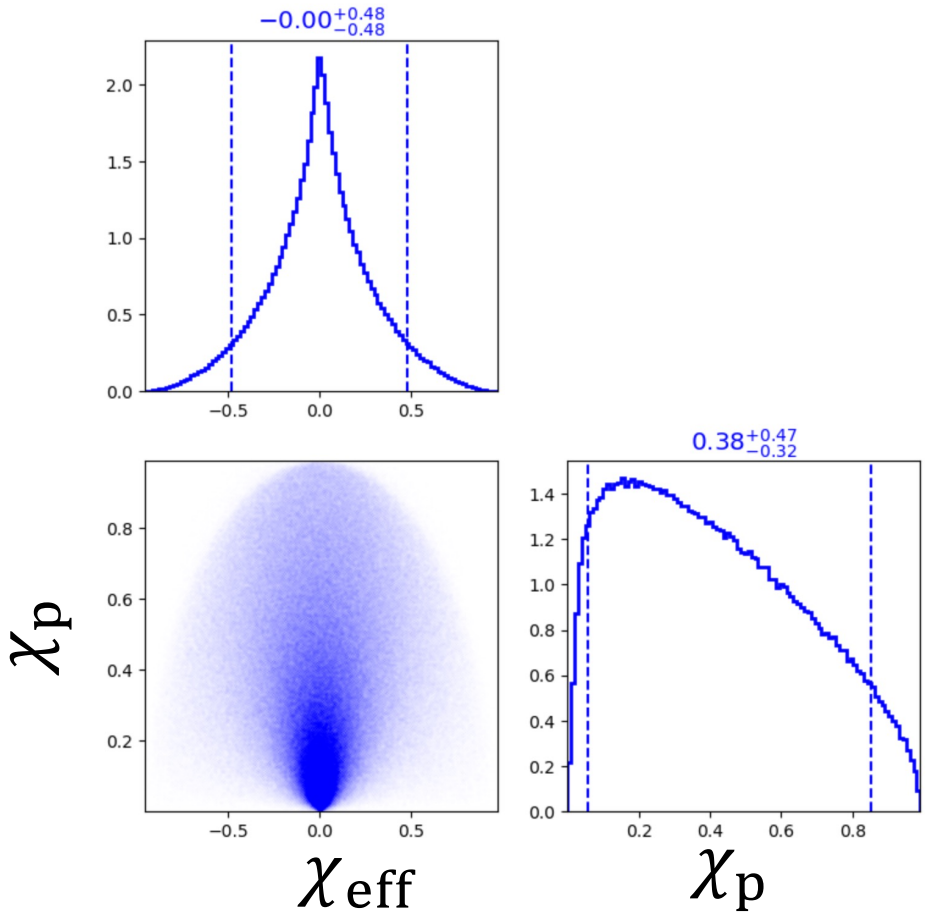
Monte Carlo integral using the posterior samples, required for population inference, may be inaccurately evaluated.

Previous method may have misestimated the population of spins.

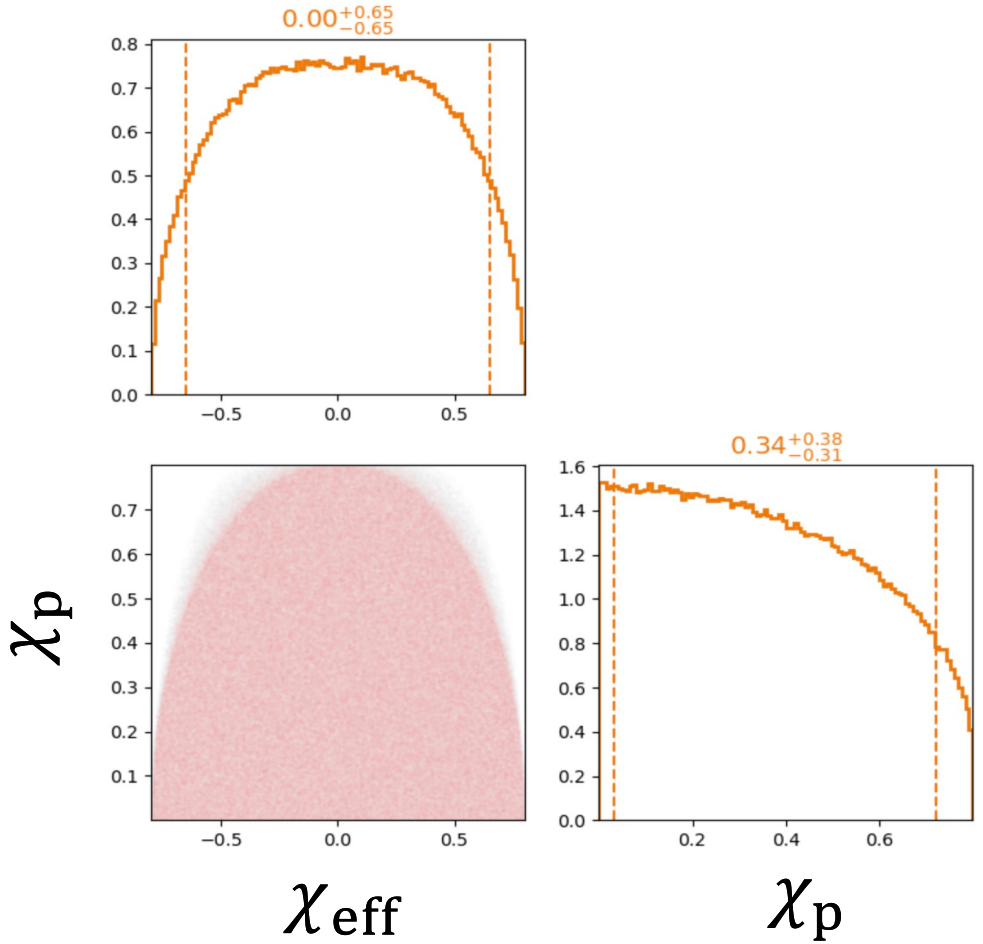


Solution: changing the prior

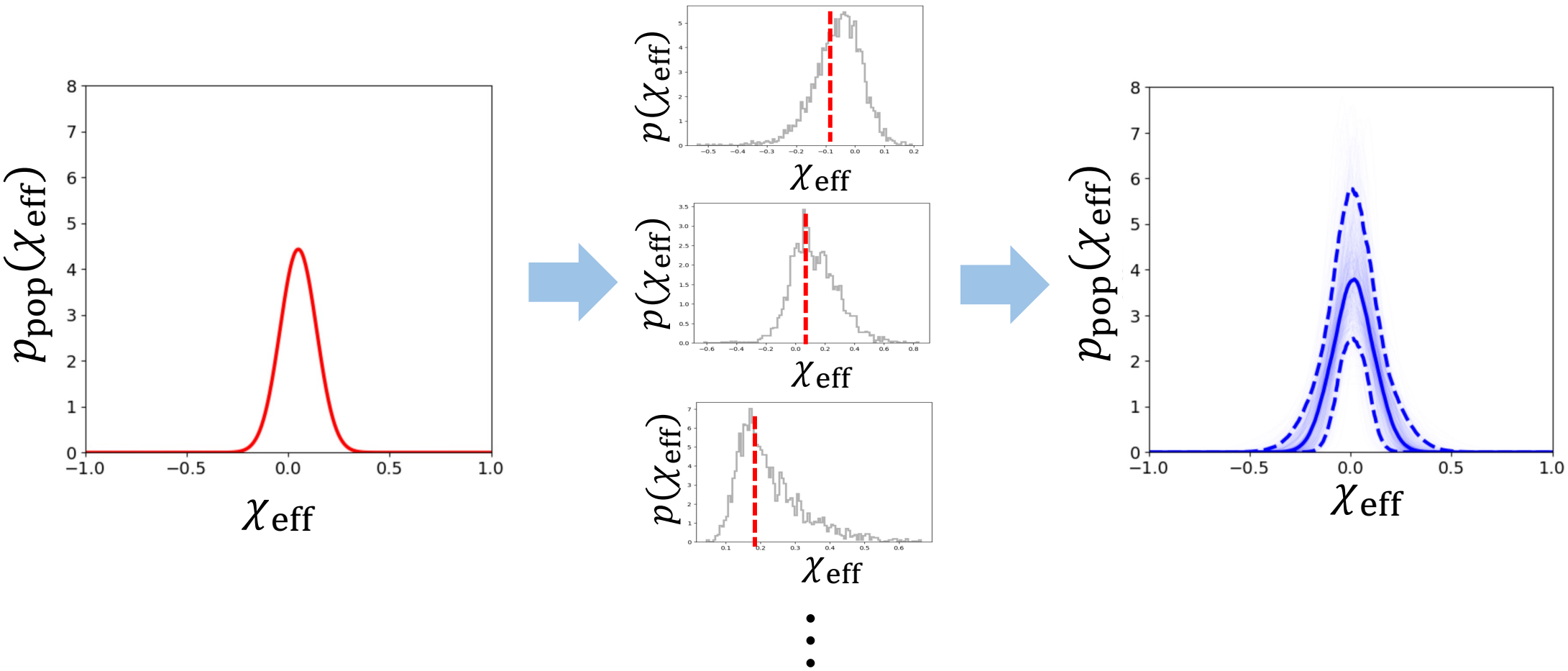
Previous prior: uniform a, isotropic θ



New prior: uniform in $\chi_{\rm eff}, \chi_{\rm p}$

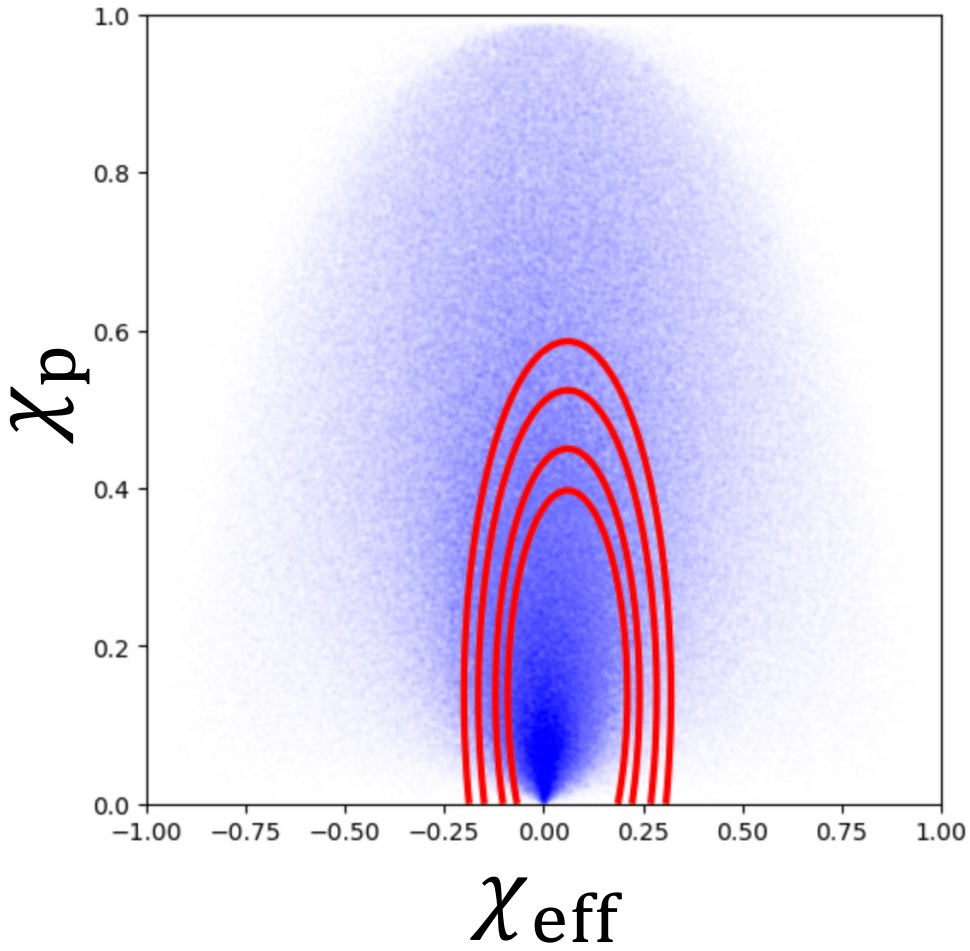


Simulation for mock population to demonstrate the effectiveness of our approach

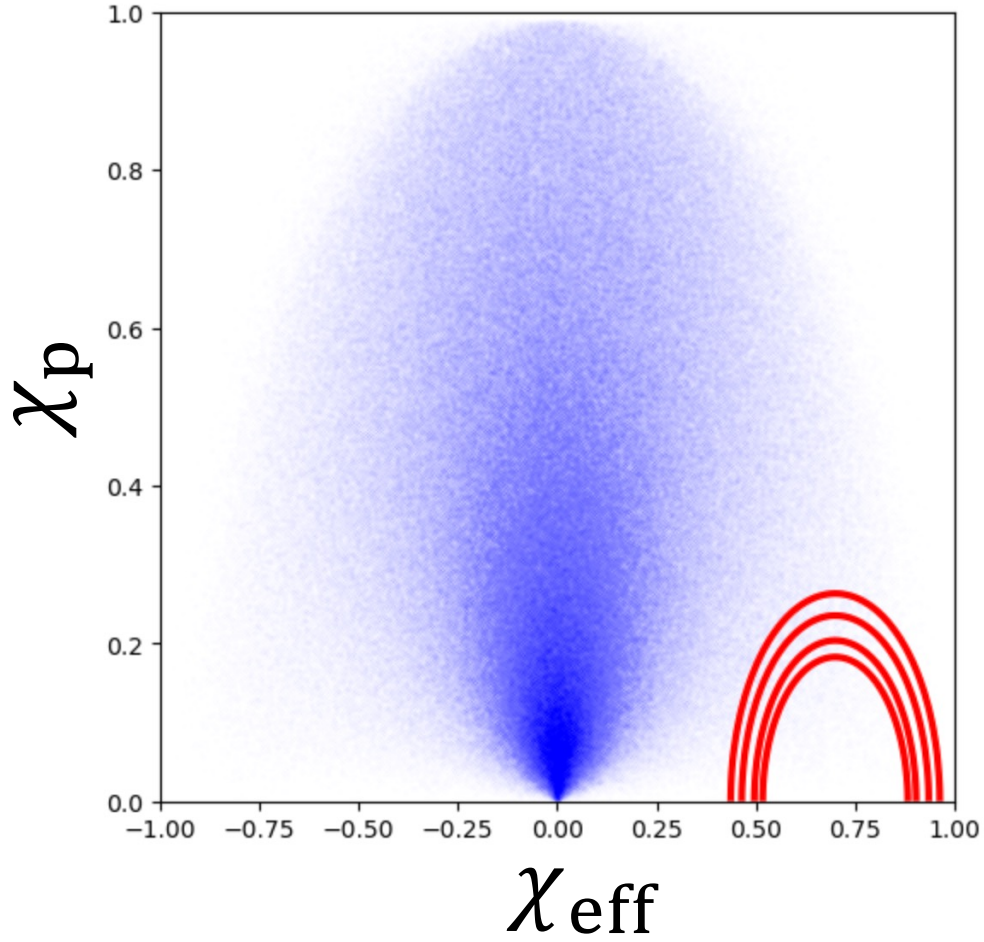


Assumed populations for spins

GWTC-3 like population

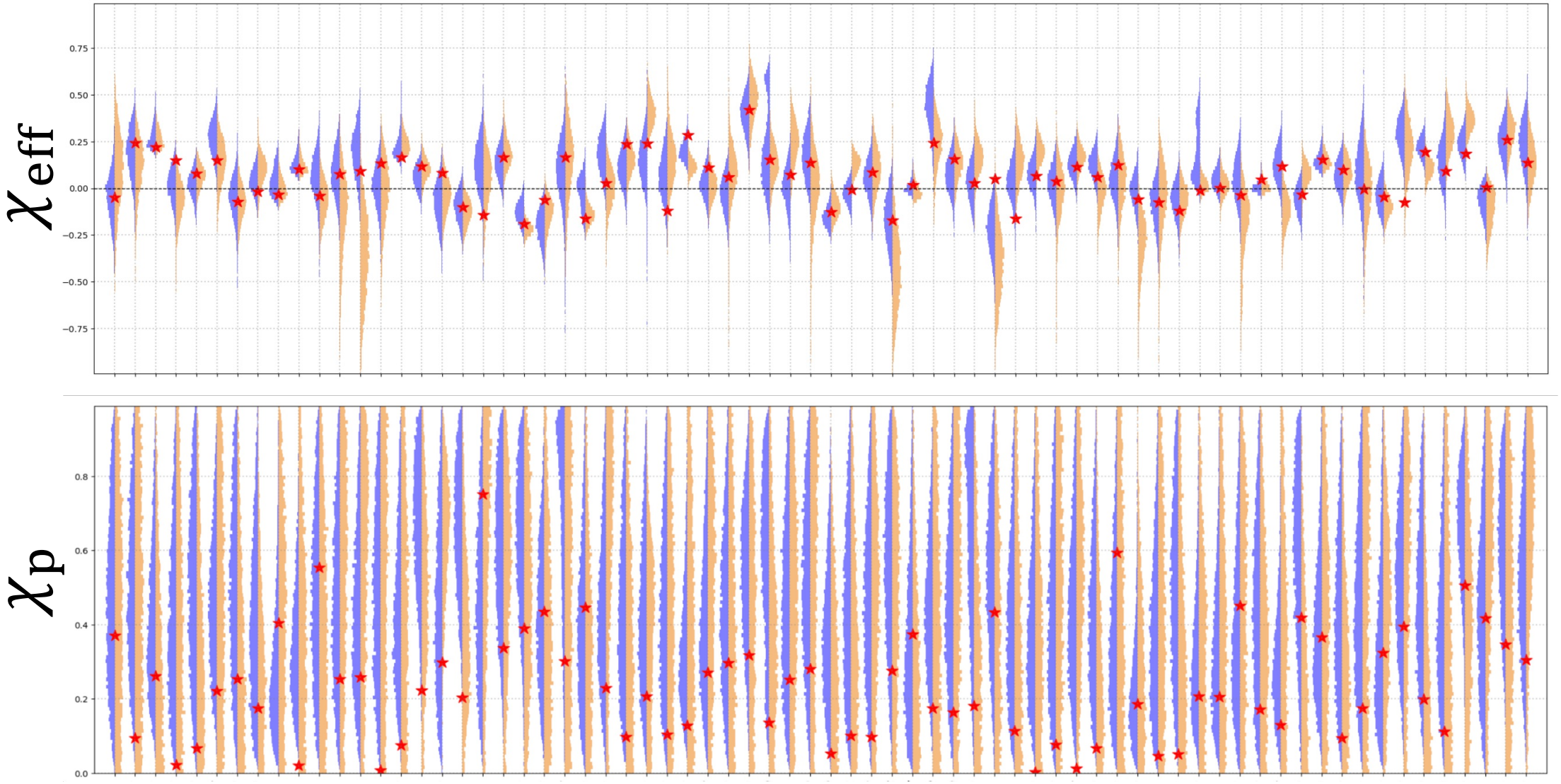


Large χ_{eff} population



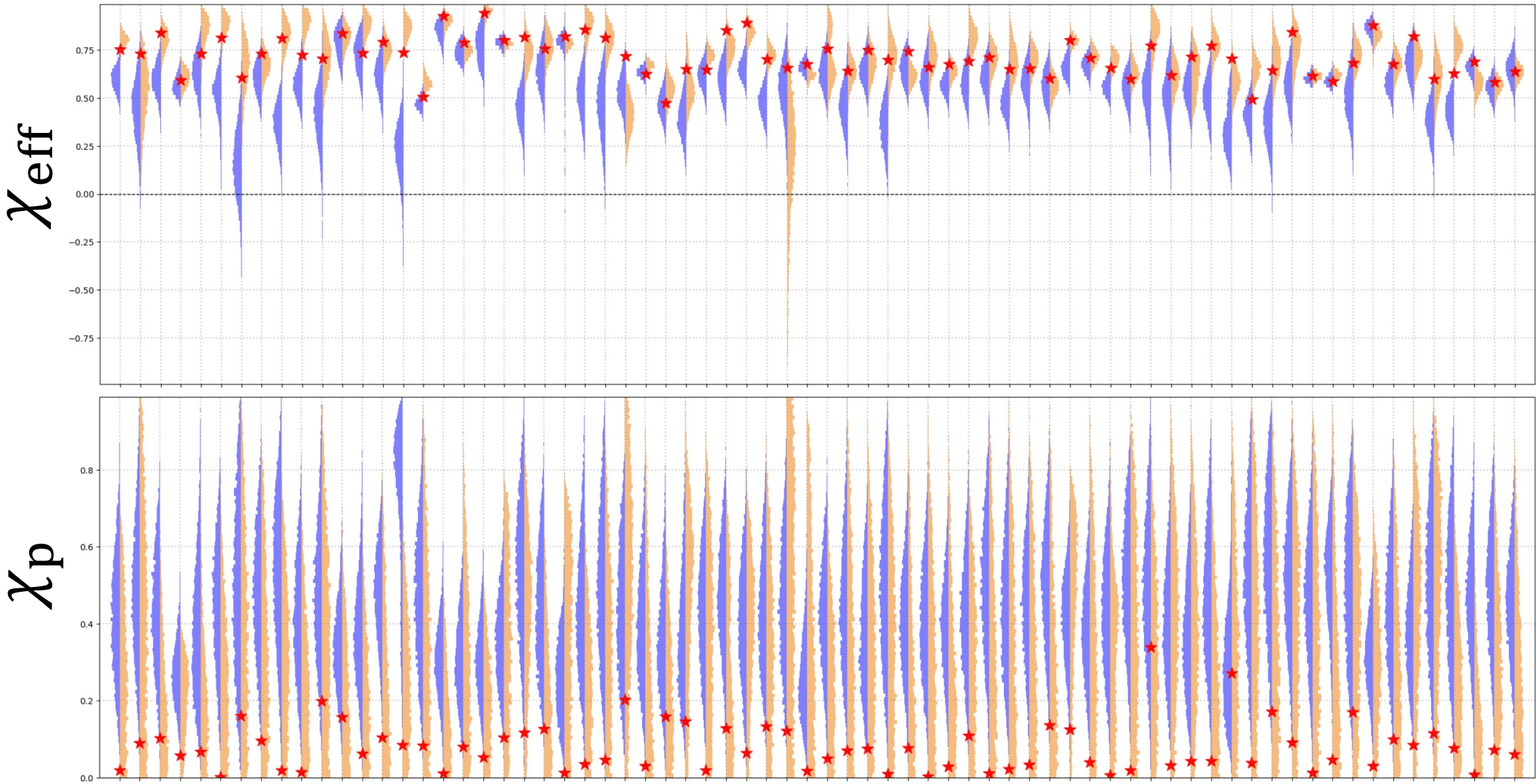
Individual results of GWTC-3 like population

Red: injection value, Blue: isotropic, Orange: $\chi_{\rm eff}$, $\chi_{\rm p}$ uniform



Individual results of large $\chi_{\rm eff}$ population

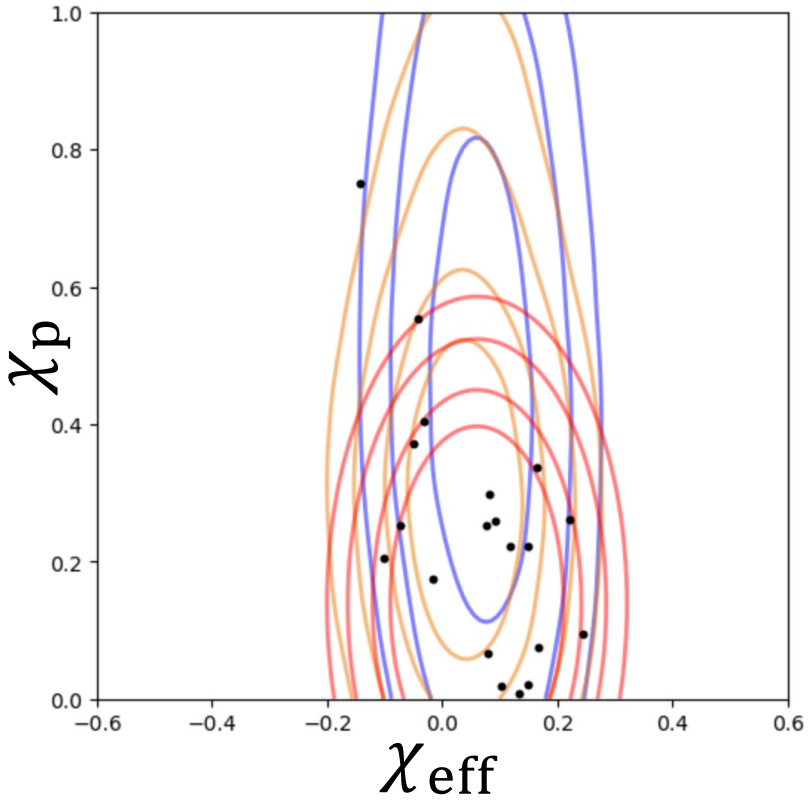
Red: injection value, Blue: isotropic, Orange: $\chi_{\rm eff}$, $\chi_{\rm p}$ uniform



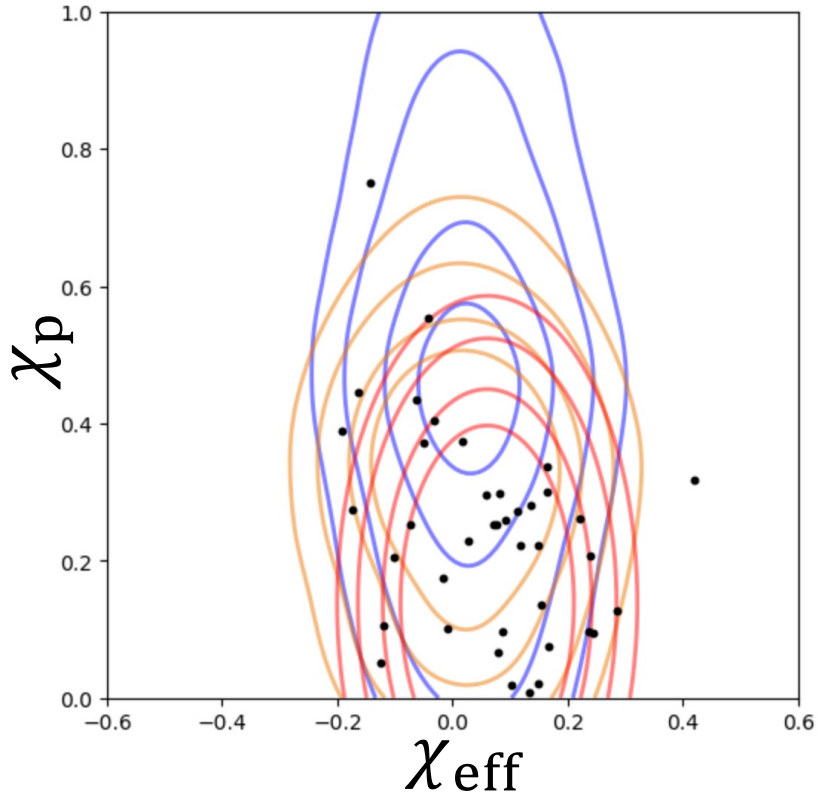
Reconstructed populations for GWTC-3 like one

The blue (isotropic case) and orange ($\chi_{\mathrm{eff}}, \chi_{\mathrm{p}}$ uniform case) contours should match the assumed population(red). The black points are the injection values from assumed population.

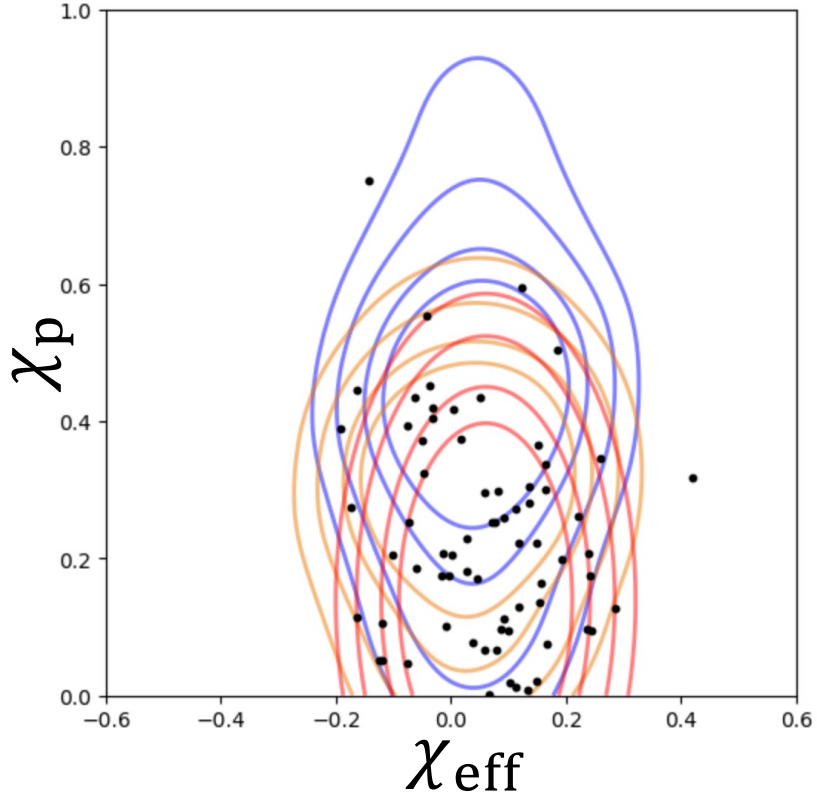
$N = 20$



$N = 40$



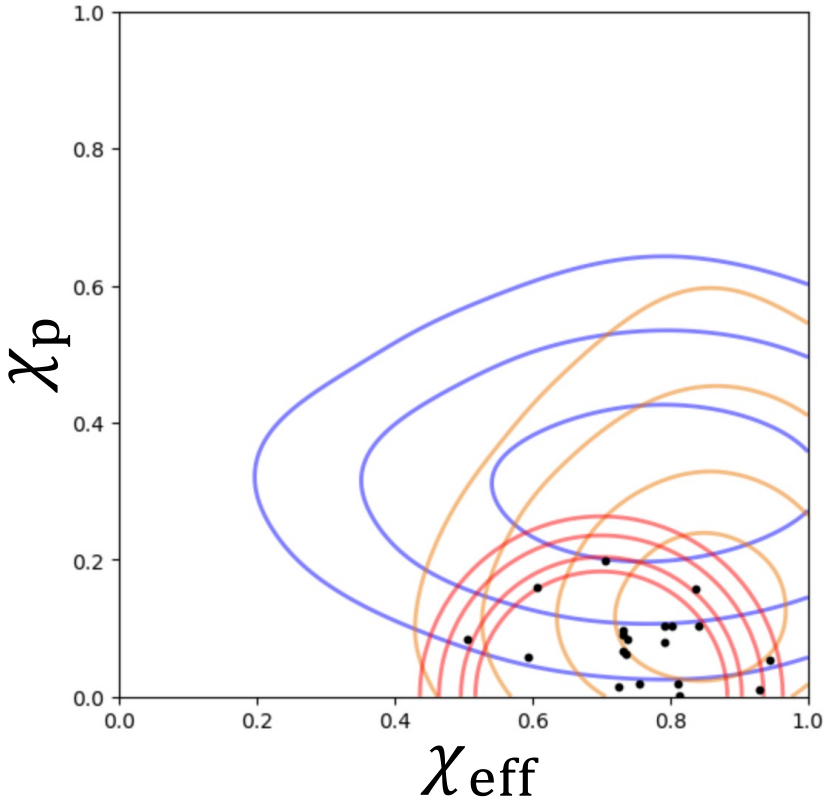
$N = 70$



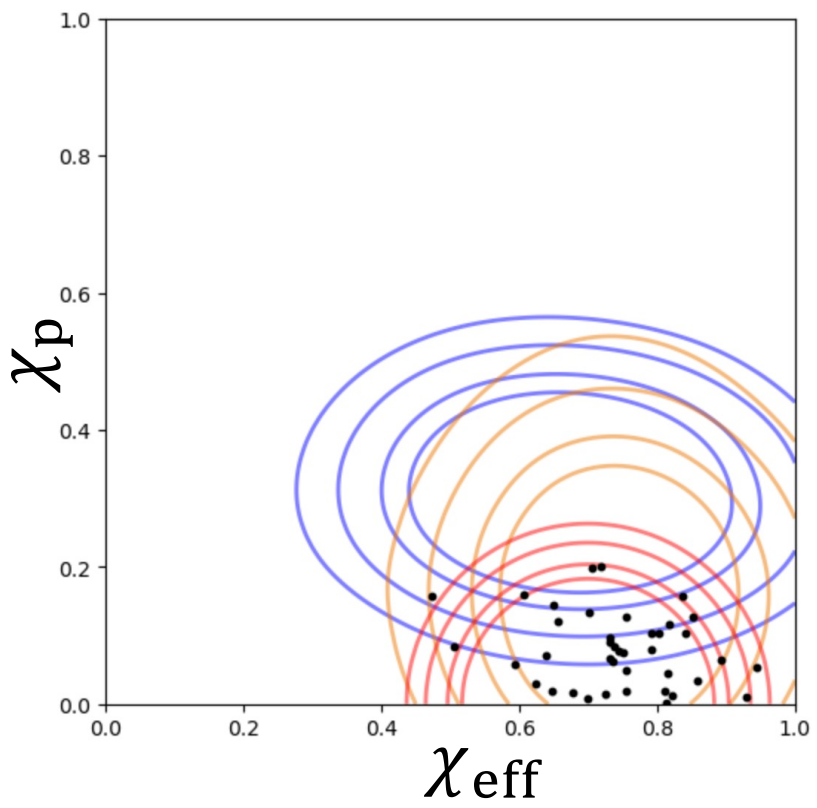
Reconstructed populations for Large χ_{eff} one

The blue (isotropic case) and orange ($\chi_{\mathrm{eff}}, \chi_{\mathrm{p}}$ uniform case) contours should match the assumed population(red). The black points are the injection values from assumed population.

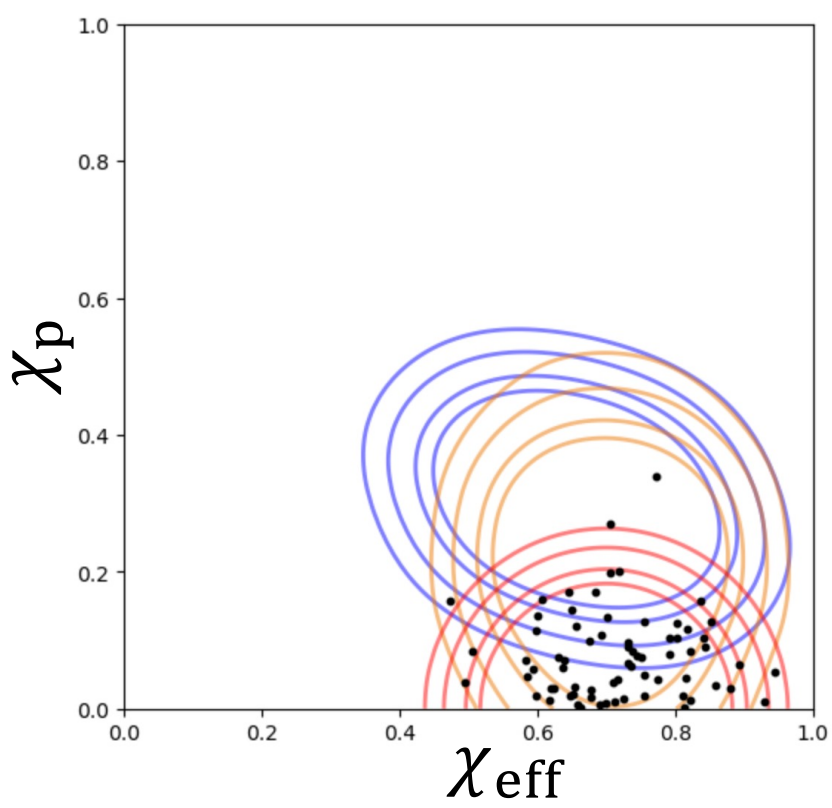
$N = 20$



$N = 40$

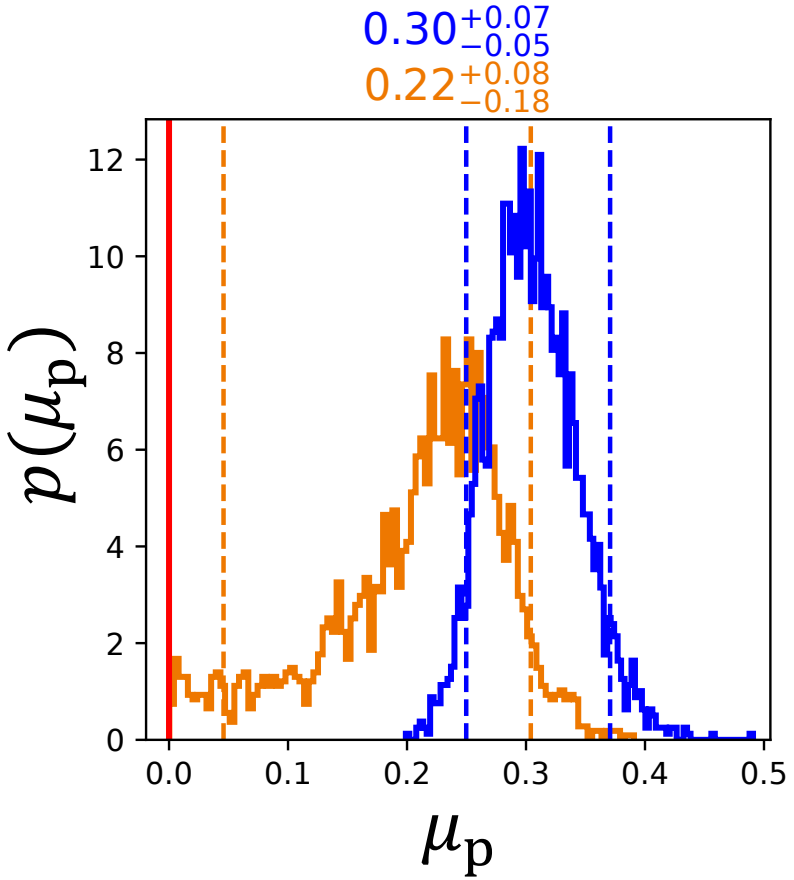


$N = 70$



Results of Large χ_{eff} population reconstruction

$N = 70$



Red: value of assumed population

Blue: isotropic

Orange: $\chi_{\mathrm{eff}}, \chi_{\mathrm{p}}$ uniform

The μ_{p} is mean of the Gaussian population model for χ_{p}.

The left panel shows the posterior for μ_{p}.

The $\chi_{\mathrm{eff}}, \chi_{\mathrm{p}}$ uniform case does not rule out the injected values, **making this approach more effective!**

Analysis for real data

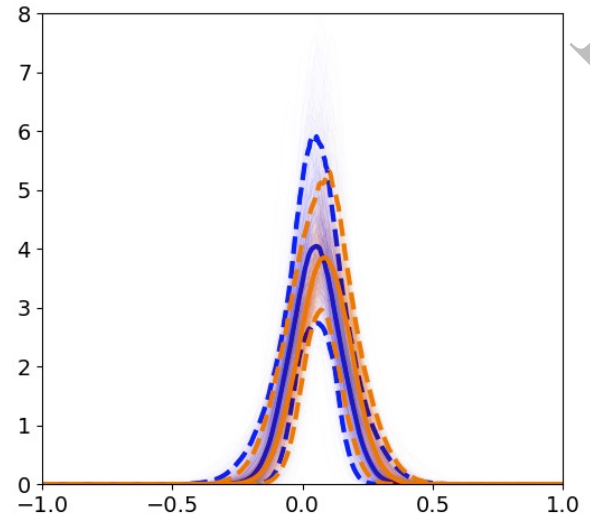
- Event selection[1]:
  - Up to O3(our analysis for O4a data is on going)
  - False alarm rate < 1/year

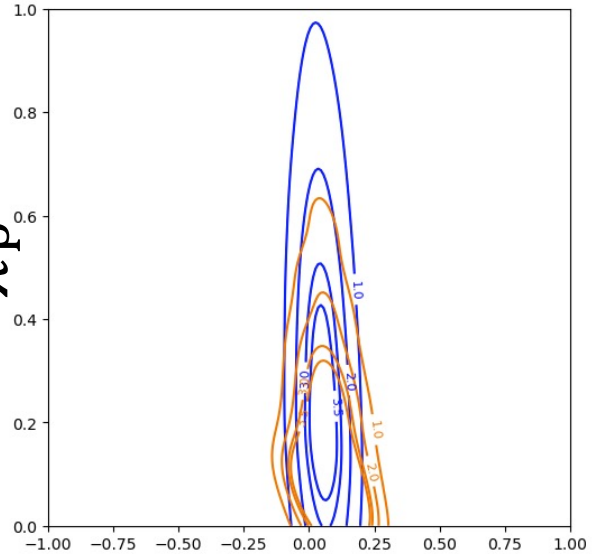
➡ **69 events**

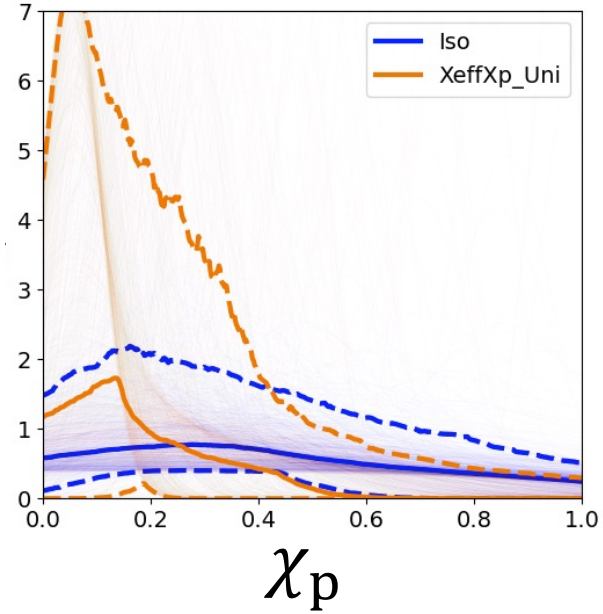
- Waveform model: IMRPhenomXPHM[2]
- Bayesian parameter estimation: Bilby[3]
- Population inference: emcee[4]

[1] R. Abbott et al. arXiv:2111.03634 (2022)
[2] Geraint P, et al. arXiv:2004.06503 (2021)
[3] Gregory Ashton et al. arXiv:1811.02042(2019)
[4] D. Foreman-Mackey et al. arXiv:1202.3665 (2013)

Results of population analysis (preliminary)







Blue: isotropic

Orange: $\chi_{\mathrm{eff}}, \chi_{\mathrm{p}}$ uniform

The distribution of χ_{eff} does not change much, but for χ_{p}, specifically, the population around $\chi_{\mathrm{p}} = 0$ increases.

BBH formation may depend more on isolated binary formation than previously thought.

Conclusion and future work

- Analyses that use priors from previous studies may introduce the bias in estimating the population of the effective spins.
- By using the prior we developed, **our analysis can reduce that bias and provide a more accurate estimate.**
- BBH formation may rely more on isolated binaries than previously thought.
- As future work, we plan to apply our method to analysis for O4a data.
- Our method will be useful when considering **subpopulations** in the region where the spins are large.

Thank you for your attention!