Population discussions

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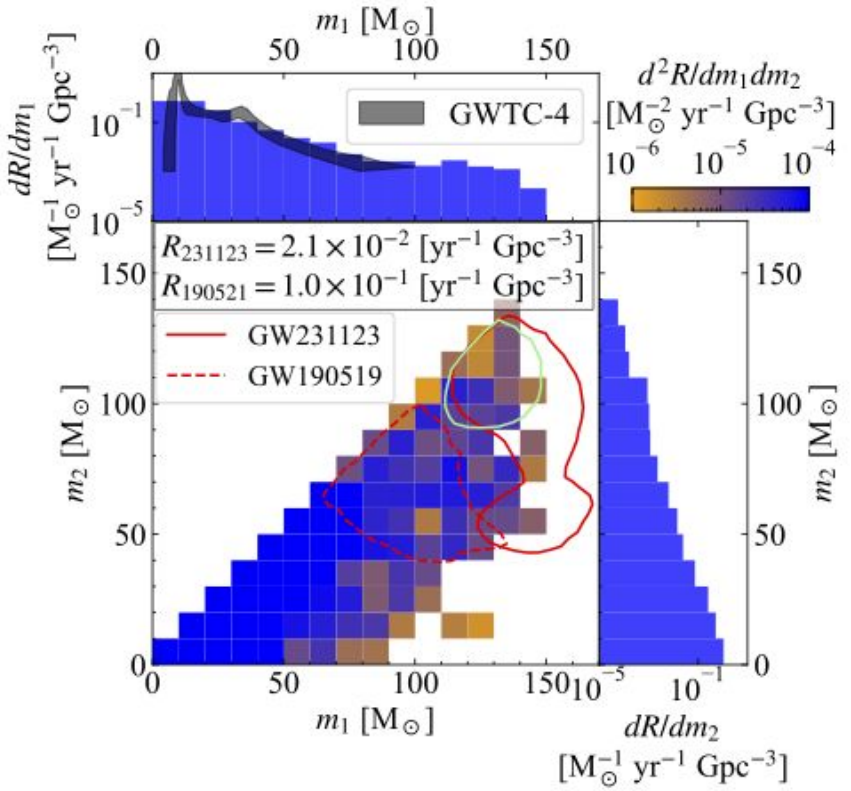
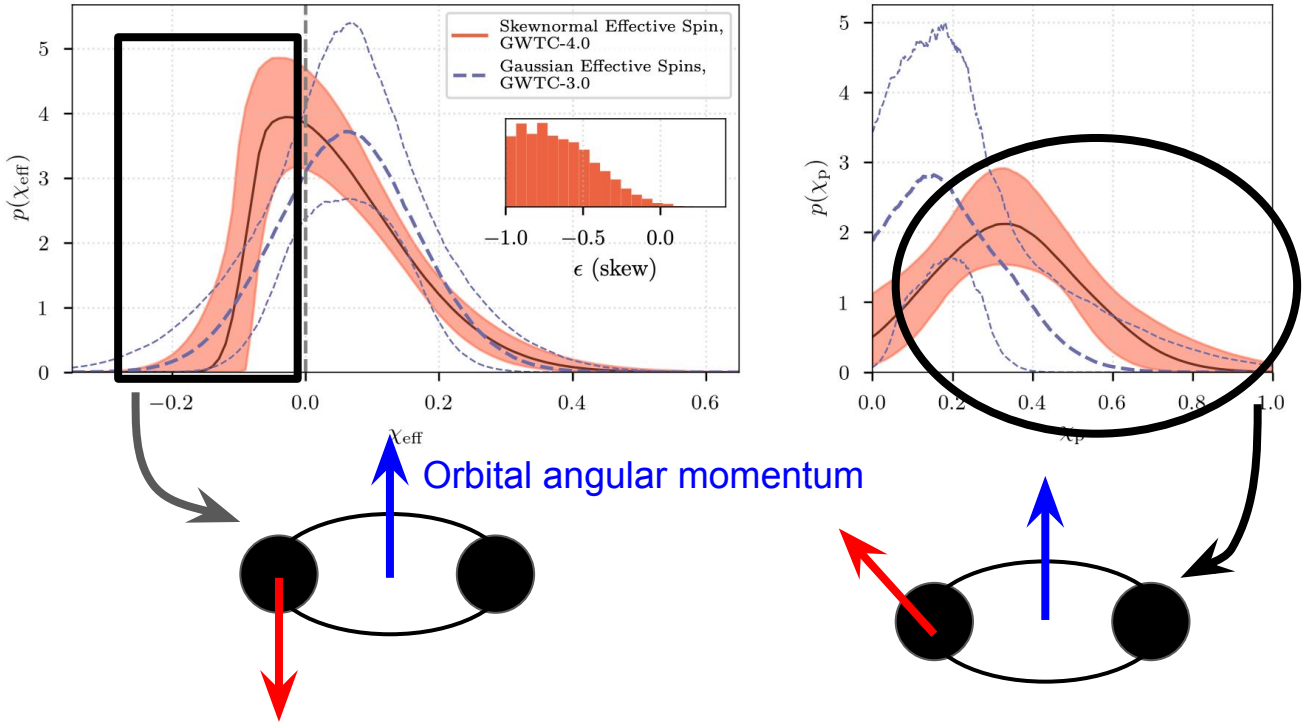
BH Mass distribution

- Isolated binary stars can form merging binary BHs whose mass distribution is consistent with that derived by GW observations.
- If we choose single and binary evolution parameters carefully…



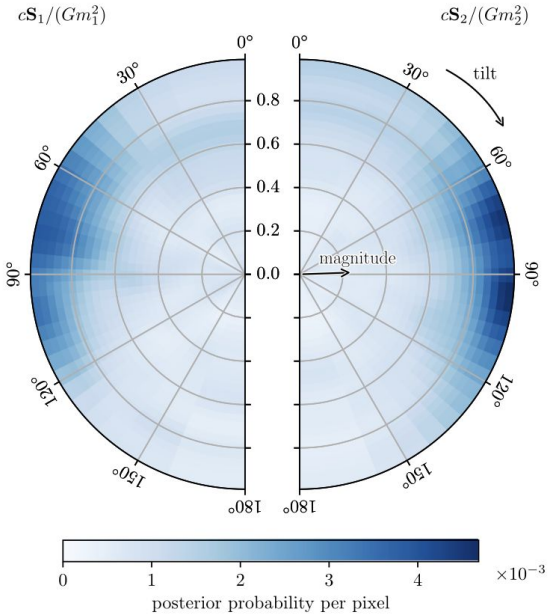
Tanikawa et al. (2025, arXiv:2508.01135)

Effective and precession spin distribution

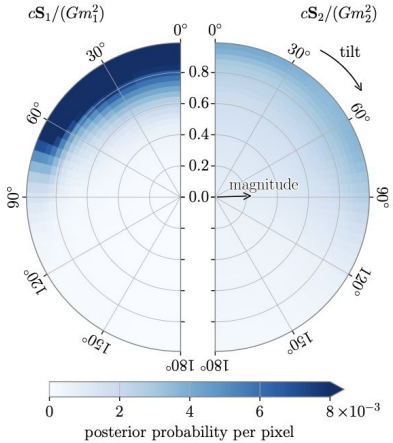


A significant fraction of BH spins are misaligned with orbital angular momenta of binary BHs.

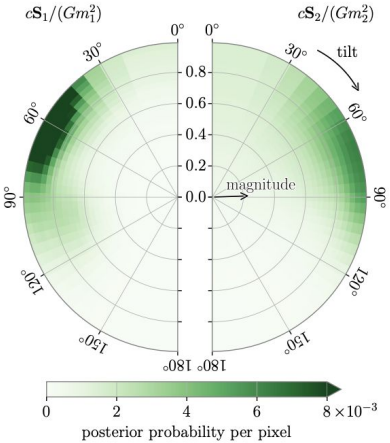
Pair instability mass gap events



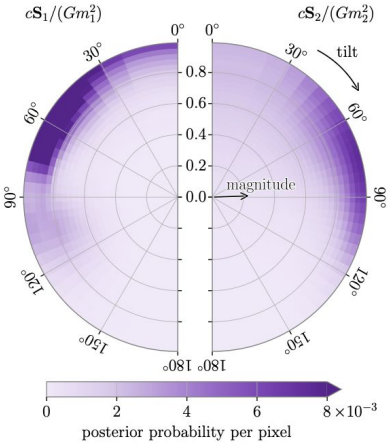
GW190521



LIGO-Hanford



LIGO-Livingston



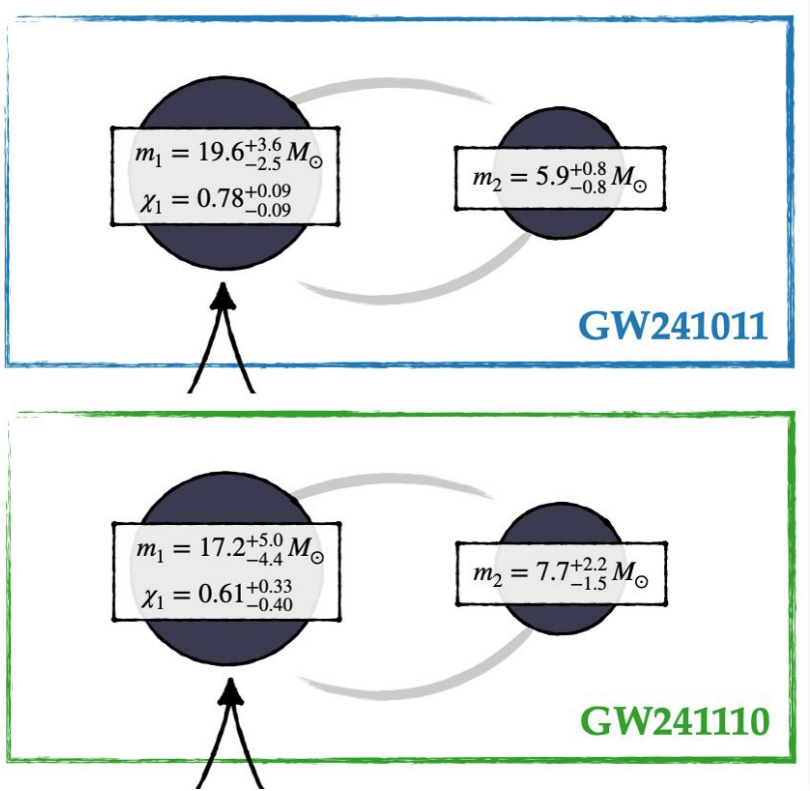
Hanford+Livingston

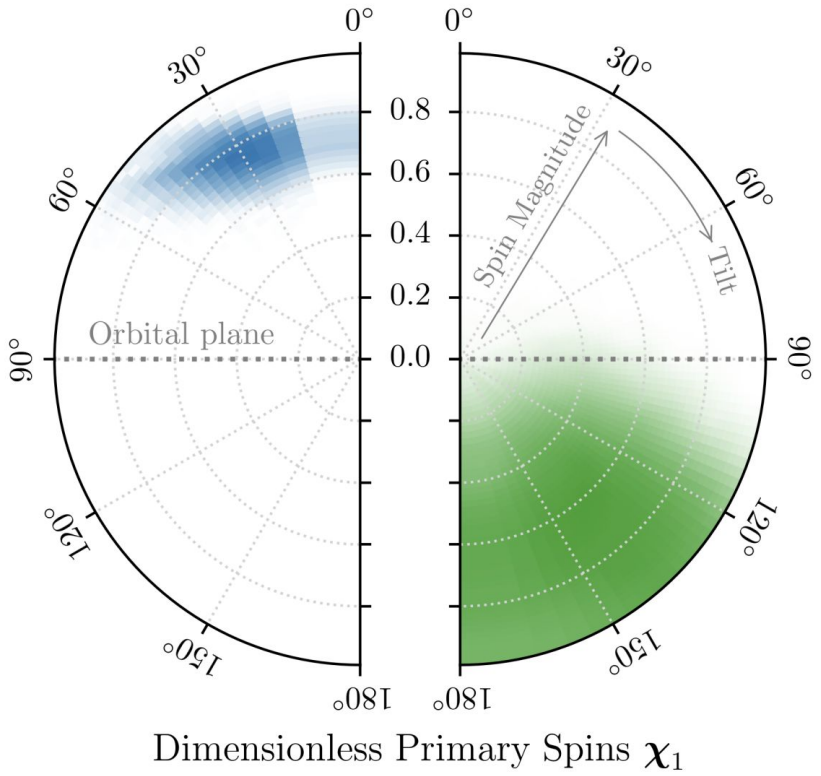
GW231123

BH spins of individual events may be tilted from the orbital angular momenta.

GW241011 and GW241110: Possible Hierarchical Mergers

Credit: LIGO-Virgo-KAGRA, ApJL **993** L21 (2025).





Isolated binary scenario in crisis?

- No mechanism to tilt BH spins from the orbital angular momentum of binary BHs without large BH natal kicks.
  - BH spins should be aligned with the orbital angular momentum.
- Isn’t isolated binary scenario dominant for forming merging binary BHs?

Spin distribution can depend on mass

- There may be subpopulations of spinning black holes from hierarchical mergers.
- Tong et al. (2025) fits observed χ_{eff} with mixture of Gaussian (low-spin, 1G+1G) and uniform (high-spin, 1G+2G) distributions.
- See also Y.-J Li et al. (2024), F. Antonini et al. (2025), G. Pierra et al. (2024), J. Sadiq et al. (2025).

Credit: Tong et al., arXiv: 2511.05316.

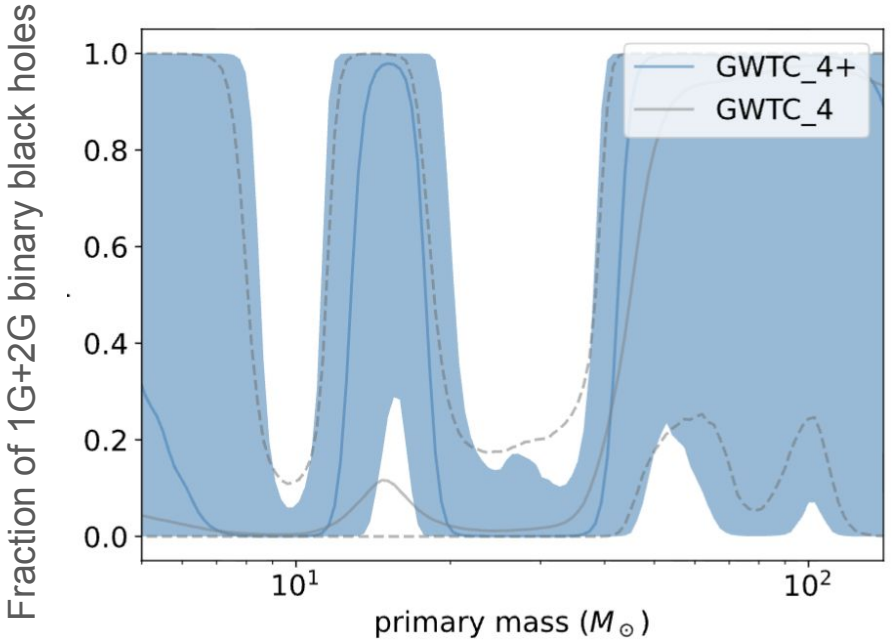
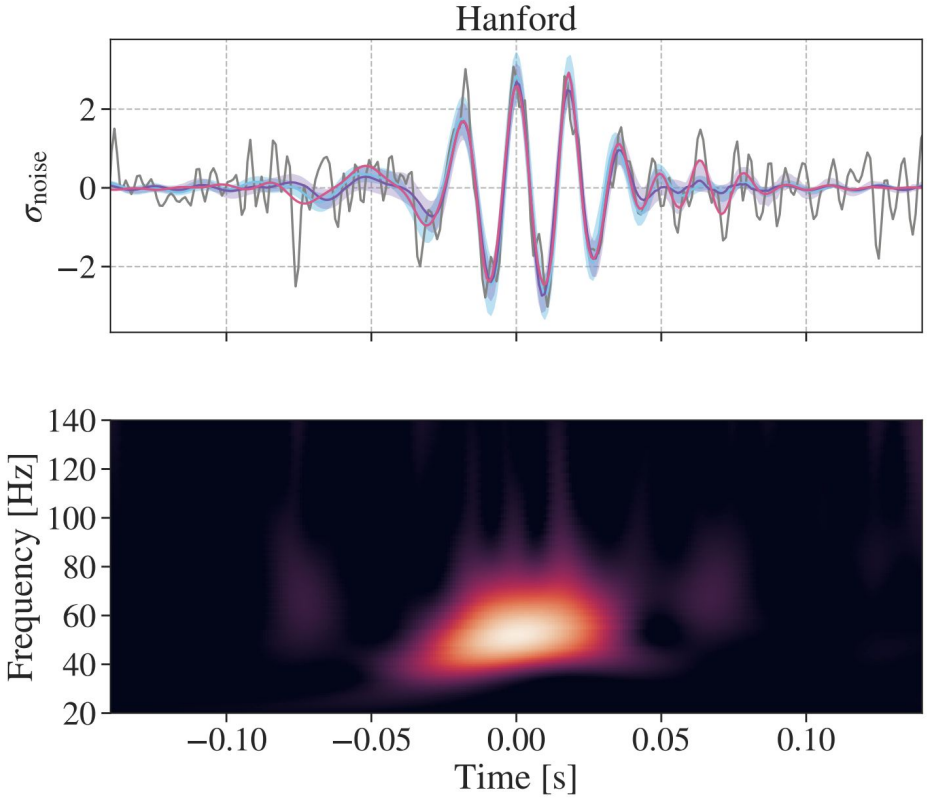
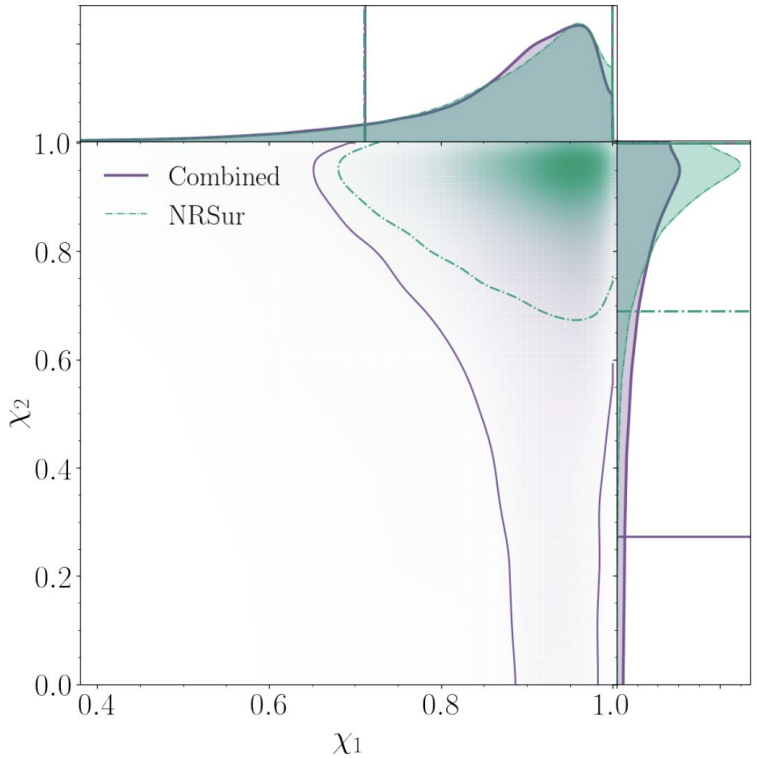


Figure: Fraction of 1G+2G binary black holes inferred from LIGO-Virgo-KAGRA events

Waveform systematics

Credit: LIGO-Virgo-KAGRA, ApJL **993** L25 (2025).





Numerical issues

Likelihood depends on **single-event likelihood** and **selection function**, which are computed as Monte-Carlo sums:

$$\hat{\mathcal{L}}(d_i|\mathbf{\Lambda}) \propto \frac{1}{N_{\mathrm{PE}}} \sum_{j=1}^{N_{\mathrm{PE}}} \frac{\pi(\boldsymbol{\theta}_{ij}|\mathbf{\Lambda})}{p(\boldsymbol{\theta}_{ij})},$$

Sum over posterior samples from single-event analysis

prior in single-event analysis

$$\hat{\xi}(\mathbf{\Lambda}) \propto \frac{1}{N_{\mathrm{draw}}} \sum_{j=1}^{N_{\mathrm{found}}} \frac{\pi(\boldsymbol{\theta}_j|\mathbf{\Lambda})}{\pi(\boldsymbol{\theta}_j|\mathbf{\Lambda}_{\mathrm{draw}})},$$

Sum over simulated signals for sensitivity evaluation

Credit: LIGO-Virgo-KAGRA, arXiv: 2508.18083.

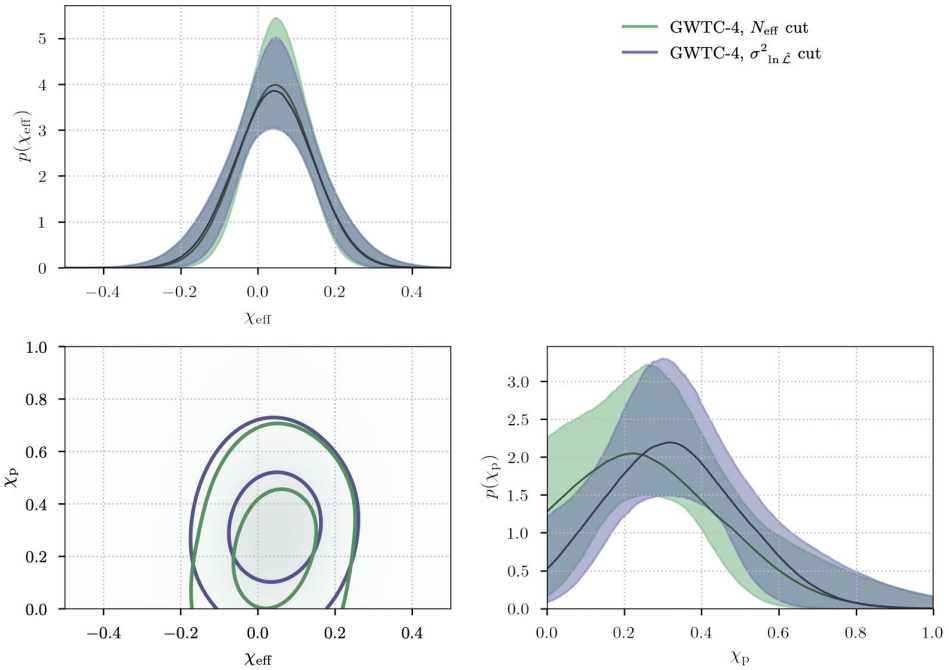
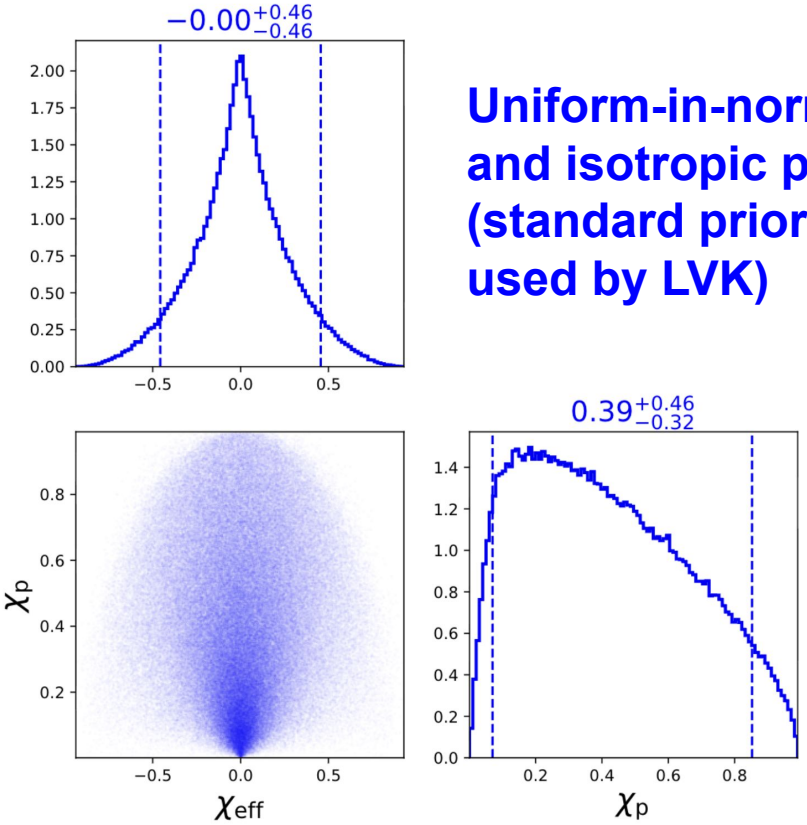


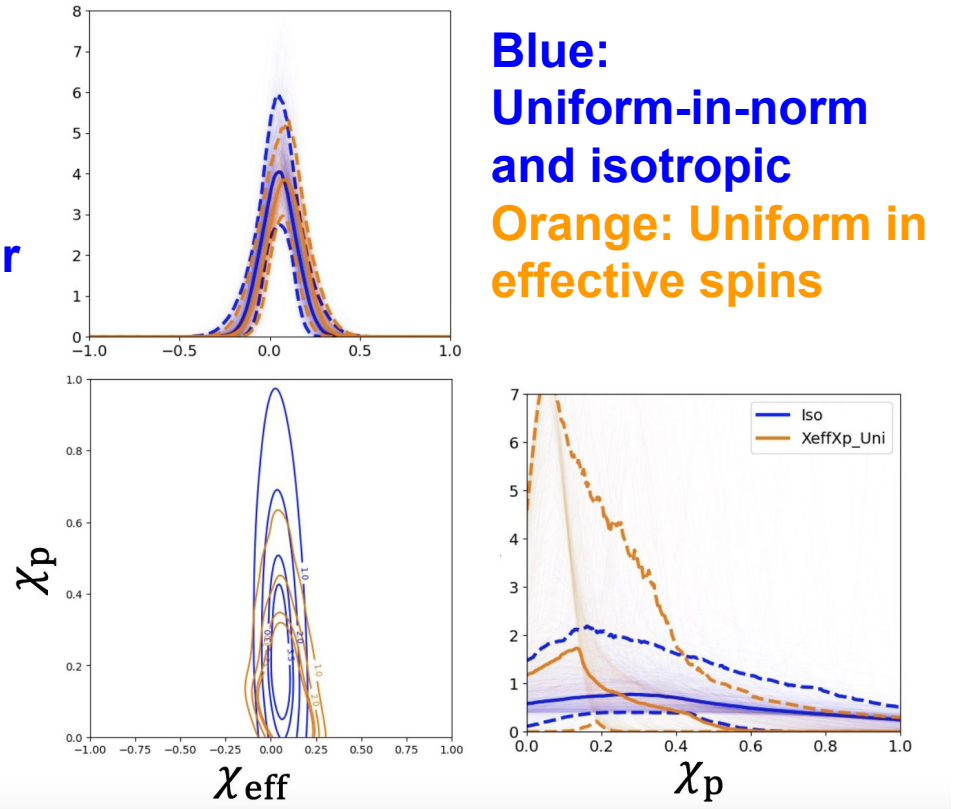
Figure: Recovered spin distributions obtained with different convergence criteria

Numerical issues



Uniform-in-norm and isotropic prior (standard prior used by LVK)

Credit: Kazuya Kobayashi (ICRR/UTokyo)



Blue: Uniform-in-norm and isotropic
Orange: Uniform in effective spins

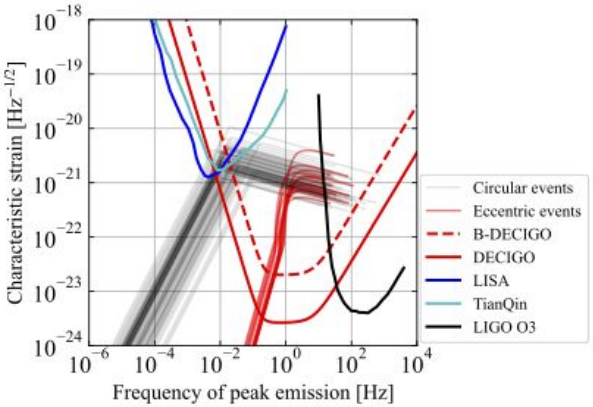
Figure: Spin distributions recovered with O1–O3 BBH events and different priors

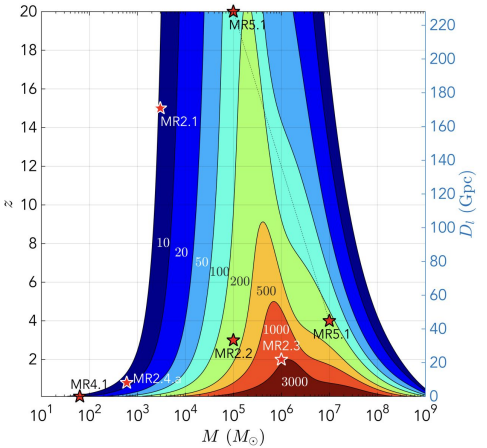
What scenarios do you like?

- Binary stars?
- Star clusters?
- AGN disks?
- Primordial BHs?
- ~~Multiple origins?~~

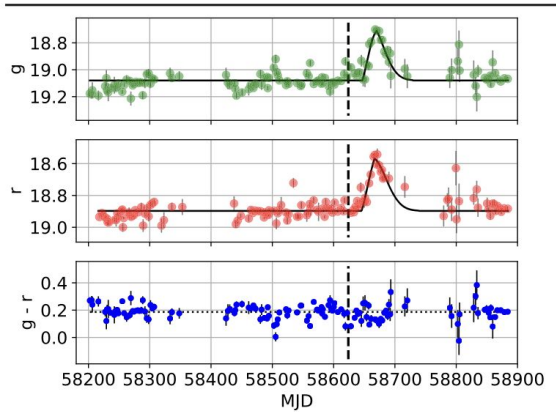
Any ideas?

- Eccentricity
- Future observatories such as LISA
- Multi-messenger observations





LISA's observable range (P. Amaro-Seoane et al. (2017))



Graham et al. (2020)