Title: Measuring the distribution of binary black hole spins

Speakers: Javier Roulet

Series: Strong Gravity

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Abstract: With over a hundred detections to date, the discoveries of compact binary mergers by gravitational wave observatories LIGO and Virgo have allowed us to start characterizing the astrophysical population of binary black holes. This task requires measuring the fifteen parameters (masses, spins, location, orientation, etc...) that characterize each merger event. However, these high dimensional distributions are challenging to describe due to the presence of nonlinear correlations and multiple modes. In this seminar I will describe a series of coordinate changes that, by identifying parameter combinations that control specific observable signatures in the data, remove these degeneracies and multimodality, making parameter estimation amenable. Among the new coordinates is a spin azimuth that can be measured surprisingly well in several cases, hinting that some black hole spins are misaligned with the orbit. This is very interesting because the degree of spin-orbit alignment is a robust discriminator between isolated and dynamical formation channels, which predict spins preferentially aligned with the orbit or randomly oriented, respectively. At the same time, I will show that the observed proportion of events with spins aligned versus anti-aligned with the orbit disfavors the hypothesis that the spin distribution is isotropic.

Zoom link: https://pitp.zoom.us/j/91820222881?pwd=YW9vR0xwTlBCVXg4UlRBNWxuUFhCQT09

Measuring the distribution of binary black hole spins

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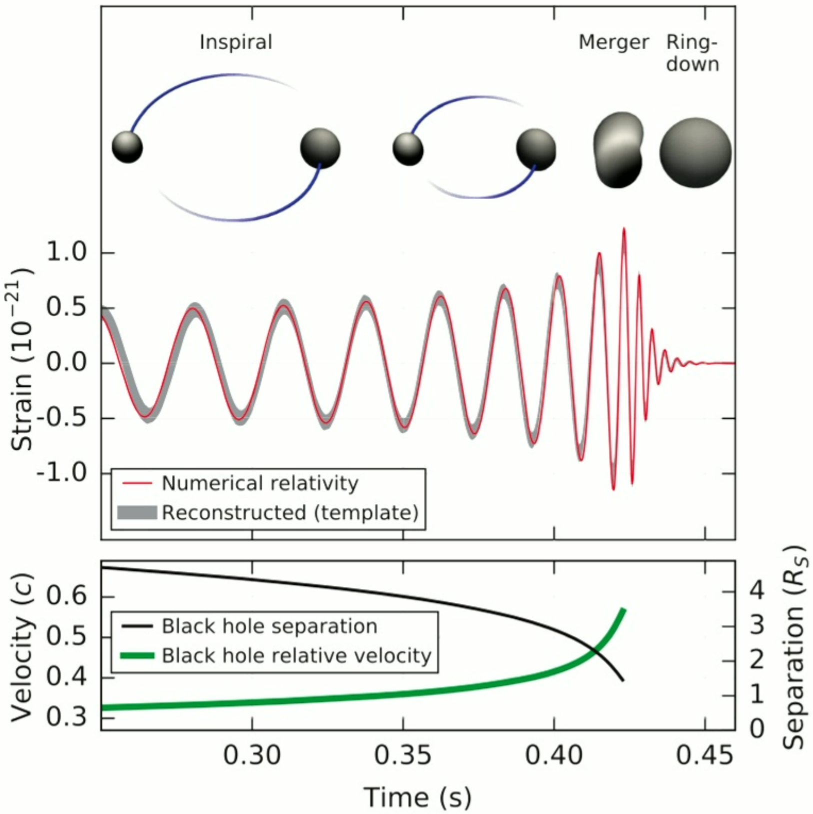
Strong Gravity Seminar
Perimeter Institute

GWs from binary mergers



GW data analysis

LIGO/Virgo acquire data, publicly released after 18 months

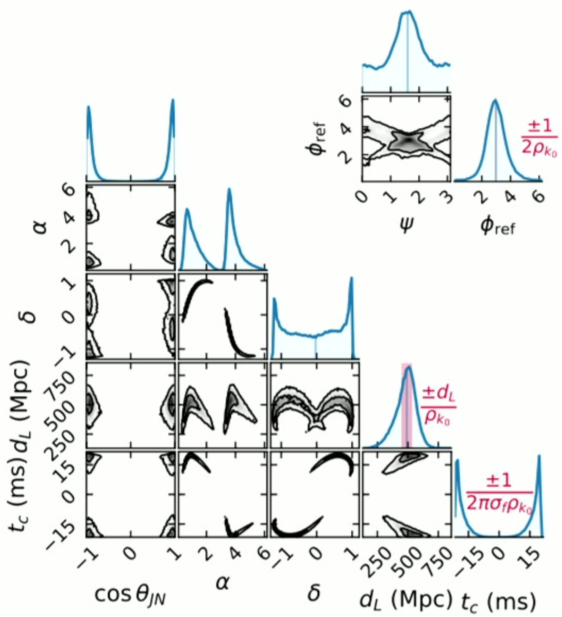
1. Search for signals
2. Estimate source parameters
3. Astrophysical population statistics

Parameter estimation

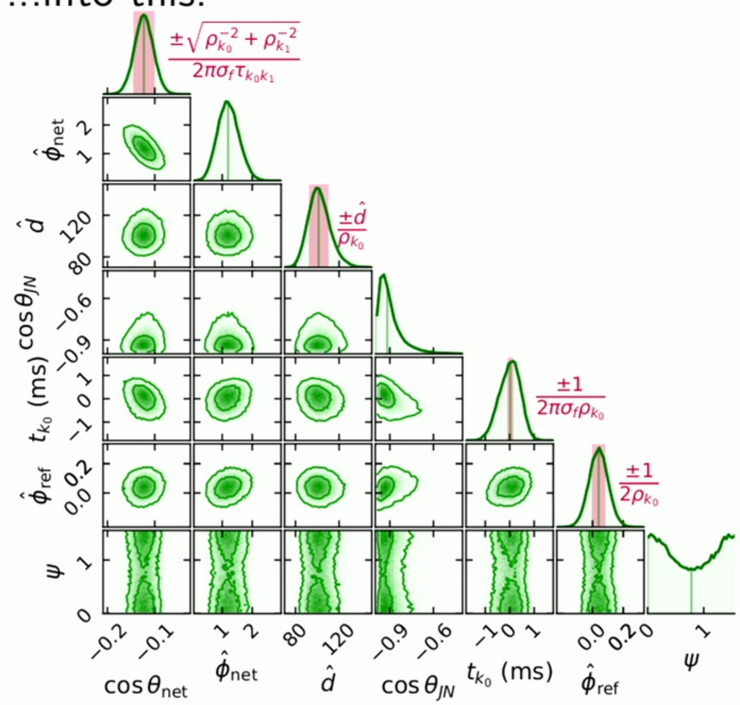
Binary mergers have 15 parameters:

- Only ~ 10 independent combinations typically constrained $\Rightarrow$ **degeneracy**
- Approximate symmetries $\Rightarrow$ **multimodality**

Next: how to turn this



...into this:



Amplitude, phase and time

$$\ln \mathcal{L}(\theta) = \sum_{k \in \text{det}} \langle d_k \mid h_k \rangle_k - \frac{1}{2} \langle h_k \mid h_k \rangle_k$$

The leading effect of extrinsic parameters is to change the amplitude, phase and time of the waveform:

$$h_k \approx a_k e^{i\varphi_k} e^{-i2\pi(f-\bar{f}_k)t_k} h_0(f; \theta_{\text{int}})$$

$$\begin{cases} a_k = \dfrac{\mathcal{M}^{5/6}}{d_L} |R_k(\iota, \alpha, \delta, \psi)| \\ \varphi_k = \arg R_k(\iota, \alpha, \delta, \psi) + 2\phi_c - 2\pi \bar{f}_k t_k \\ t_k = t_c - \hat{\boldsymbol{n}}(\alpha, \delta) \cdot \boldsymbol{r}_k / c \end{cases}$$

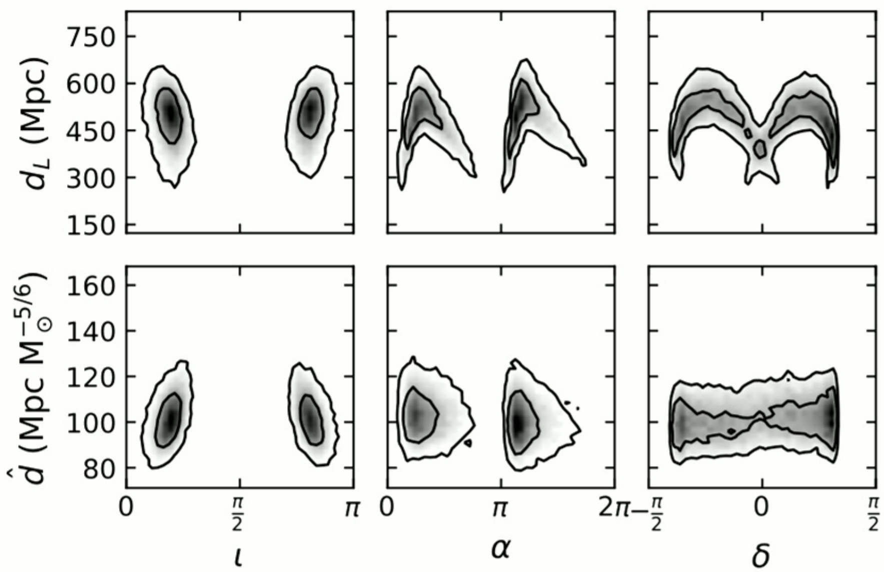
$$R_k = \frac{1 + \cos^2 \iota}{2} F_k^+(\alpha, \delta, \psi) - i \cos \iota F_k^\times(\alpha, \delta, \psi)$$

$$\bar{f}_k = \frac{\int \mathrm{d}f |h_0|^2 f / S_k(f)}{\int \mathrm{d}f |h_0|^2 / S_k(f)}$$

Amplitude at reference detector

Sort detectors by SNR, $\rho_{k_0} > \rho_{k_1} > \dots$
Trade distance for amplitude at loudest detector:

$$d_L \to \hat{d} \equiv \frac{d_L}{\mathcal{M}^{5/6}|R_{k_0}(\iota, \alpha, \delta, \psi)|} = \frac{1}{a_{k_0}}$$

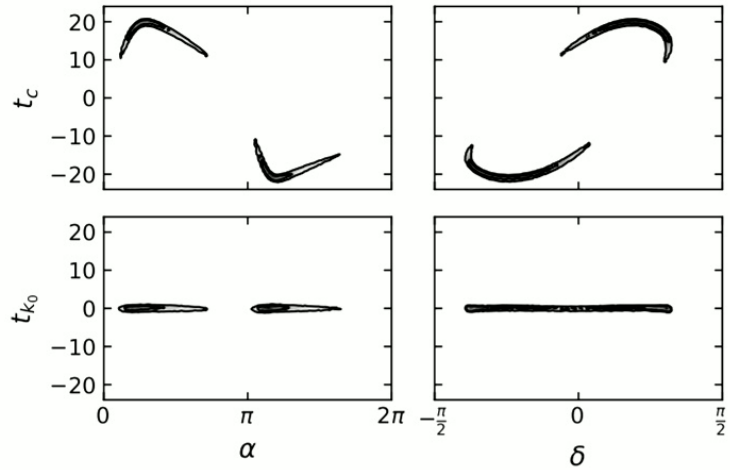


Brady & Fairhurst (2008)

Arrival time at reference detector

Specify arrival time at reference detector

$$t_c \rightarrow t_{k_0}(t_c, \alpha, \delta)$$



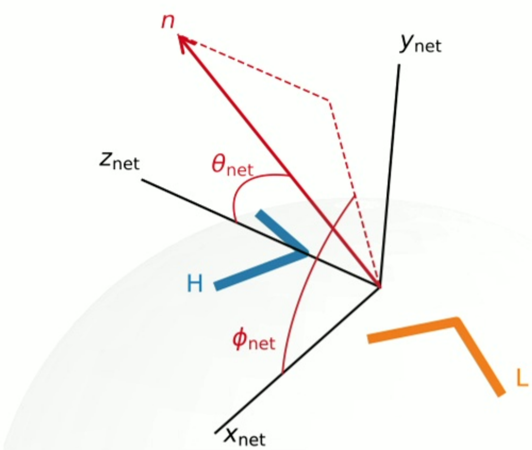
Romero-Shaw *et al.* (2020)

Arrival time at second detector

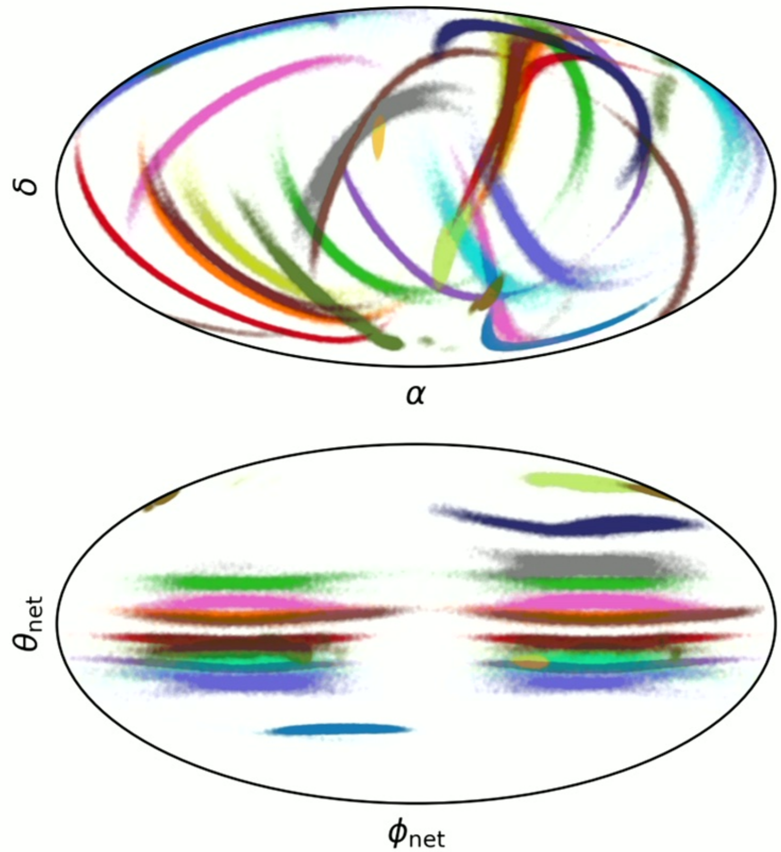
Parametrize sky location using "network" angles, where the z axis contains detectors k_0 and k_1:

$$\alpha, \delta \to \theta_{\text{net}}, \phi_{\text{net}}$$

$$\cos\theta_{\text{net}} \equiv \hat{\boldsymbol{n}}(\alpha, \delta) \cdot \hat{\boldsymbol{z}} = \frac{\Delta t_{01}}{\Delta t_{\text{max}}}$$



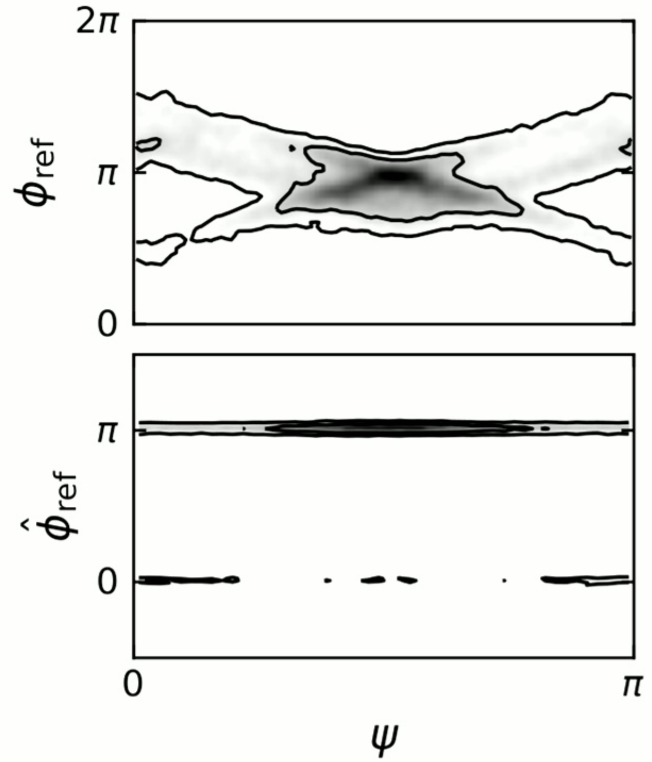
Romero-Shaw *et al.* (2020)



Phase at reference detector

Trade orbital phase for phase at reference detector:

$$\phi_{\rm ref} \to \hat{\phi}_{\rm ref} \equiv \phi_{\rm ref} + \frac{\arg R_{k_0}(\iota, \hat{\boldsymbol{n}}, \psi) - 2\pi \overline{f}^{\rm ML}_{k_0} t_{k_0} - \varphi^{\rm ML}_{k_0}}{2} = \frac{\varphi_{k_0} - \varphi^{\rm ML}_{k_0}}{2}$$



Symmetries

The likelihood constrains mostly $\hat{d}, \hat{\phi}_{\rm ref}, t_{k_0}, \cos\theta_{\rm net}$

$$\mathcal{L} \approx \mathcal{L}(\theta_{\rm int}, \hat{d}, \hat{\phi}_{\rm ref}, t_{k_0}, \cos\theta_{\rm net}, \cancel{\phi_{\rm net}, \iota, \psi})$$

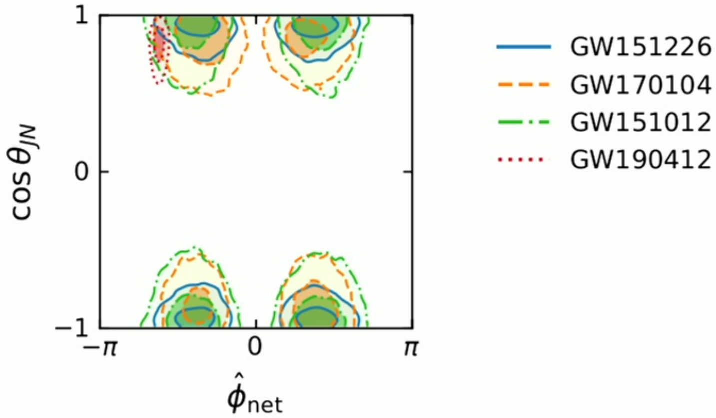
Often, $\phi_{\rm net}, \iota, \psi$ are informed by the prior

$$\pi(\hat{d}) \propto \hat{d}^2 \mathcal{M}^{5/2} |R_{k_0}(t_{k_0}, \cos\theta_{\rm net}, \phi_{\rm net}, \iota, \psi)|^3$$

$|R_{k_0}|$ has two approximate discrete symmetries in $\phi_{\rm net}, \iota$ that can cause 4-modality:

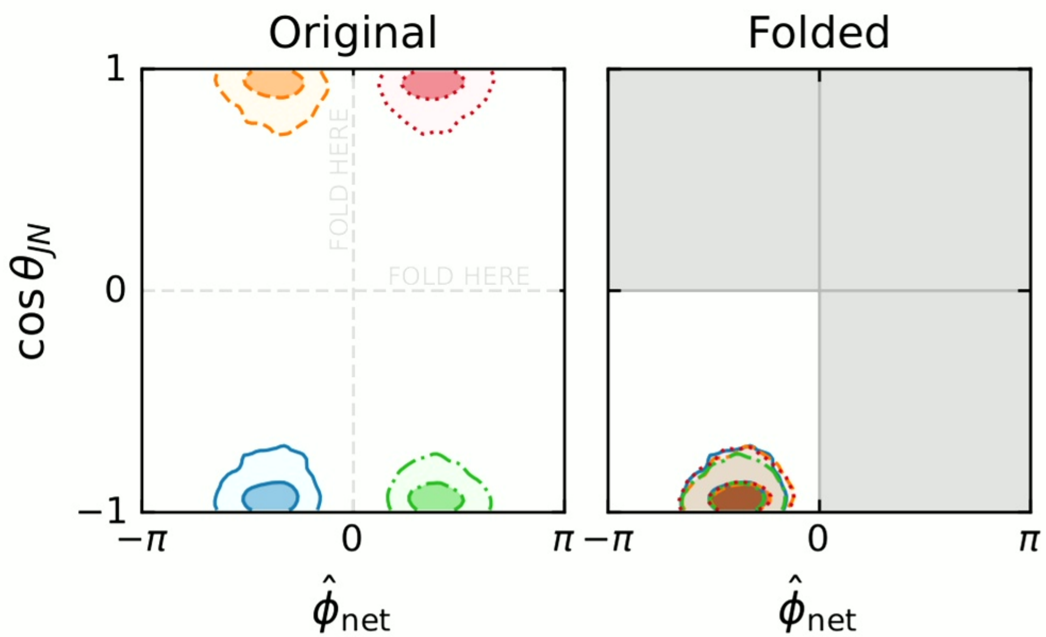
1. $\hat{\phi}_{\rm net} \to -\hat{\phi}_{\rm net}$
2. $\cos\iota \to -\cos\iota$

with $\hat{\phi}_{\rm net} = \phi_{\rm net} + \pi\Theta(\cos\iota)$



Removing multimodality

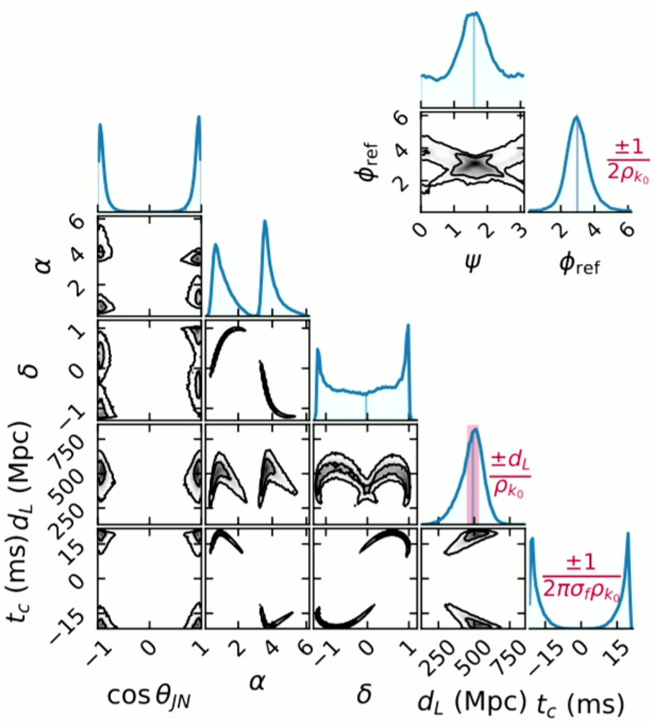
When multimodality arises from known approximate symmetries, we can "fold" the distribution (sum its appropriately reflected modes) to make it unimodal.



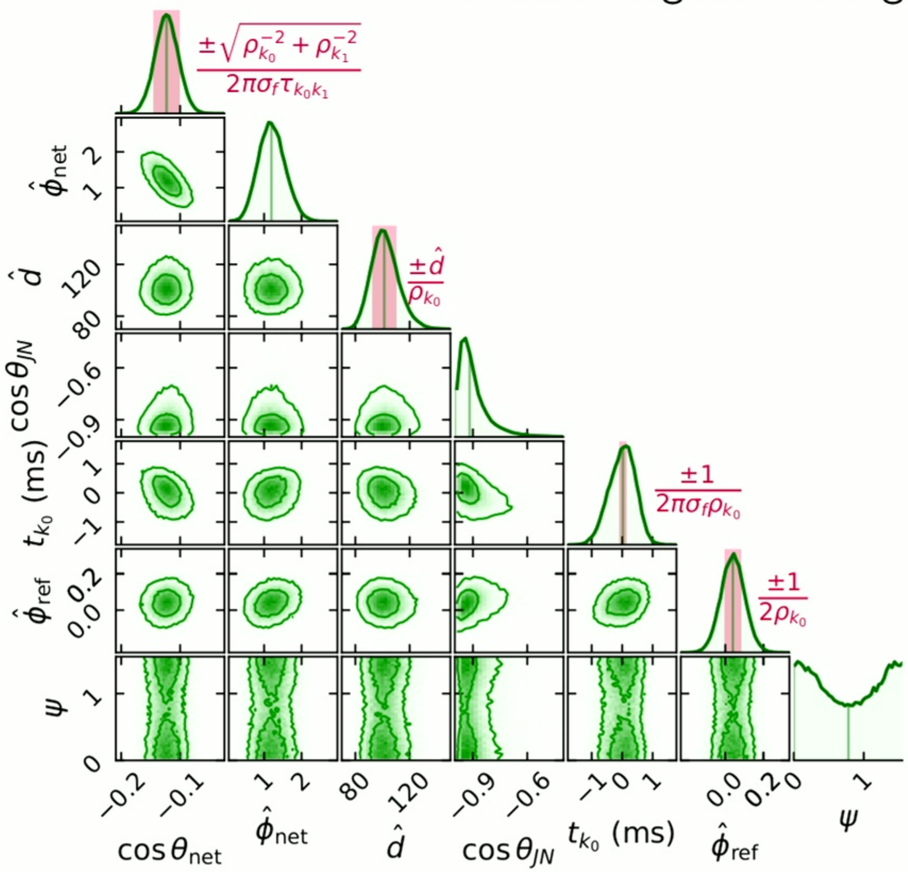
We sample the folded distribution and reconstruct the original in postprocessing.

Results

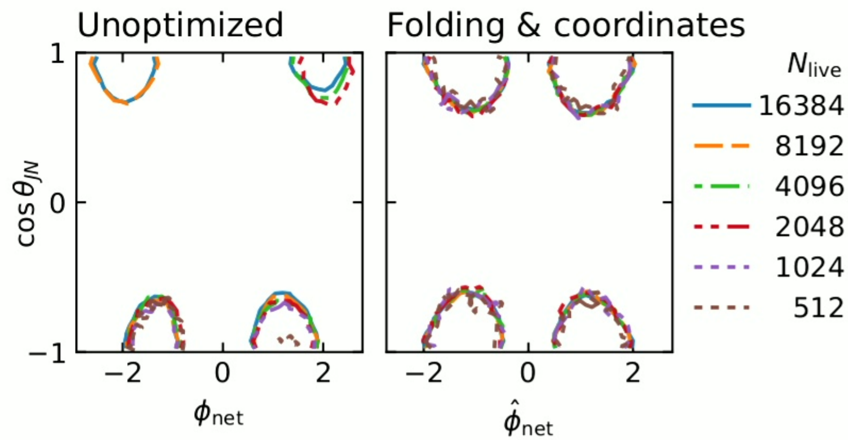
Before

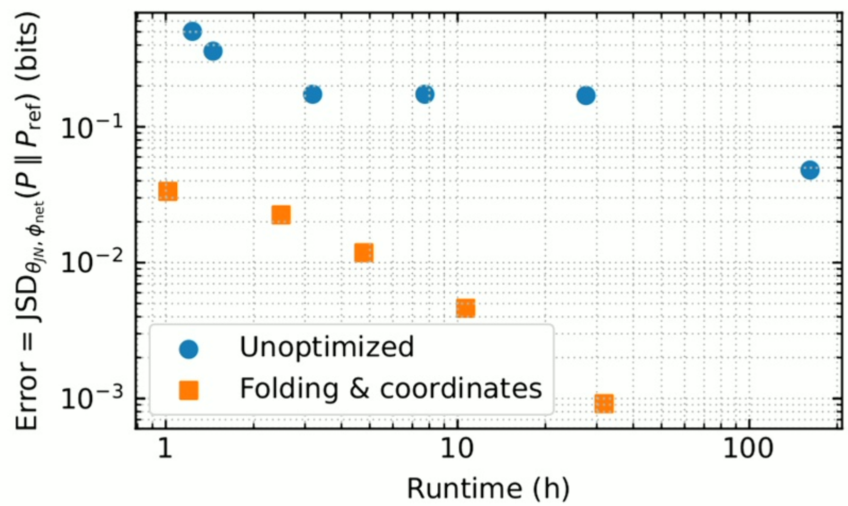


After transforming and folding



Performance





github.com/jroulet/cogwheel

Spins

- Describe aligned spins using χ_{eff}.

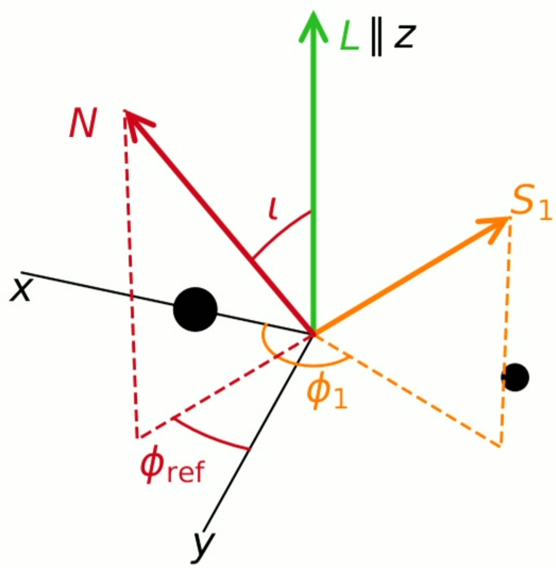
$$\chi_{\text{eff}} = \frac{m_1 \boldsymbol{\chi}_1 + m_2 \boldsymbol{\chi}_2}{m_1 + m_2} \cdot \hat{\boldsymbol{L}}$$

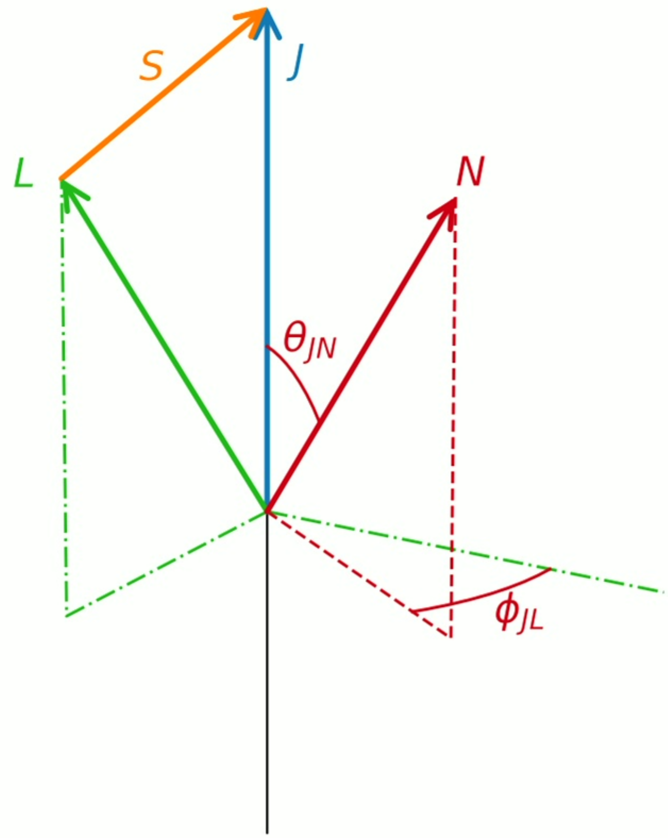
- Precession changes the spin orientations. Specify them at a reference frequency inside the detector sensitive band, e.g. $f_{\text{ref}} = \overline{f}$.

Farr *et al.* (2014), Varma *et al.* (2021)

Spin azimuth

Two choices:





Spin azimuth

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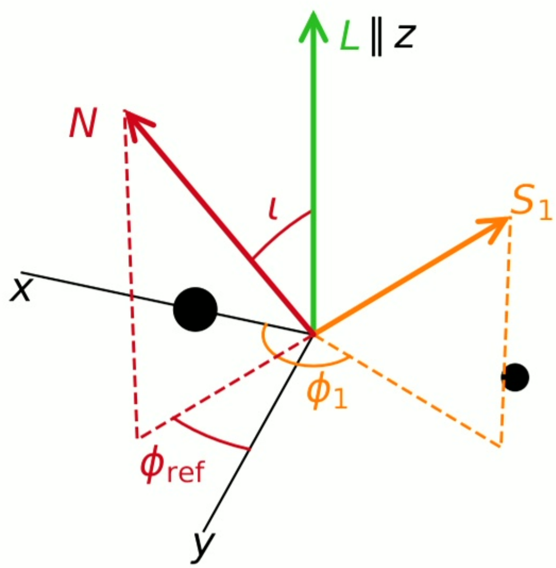
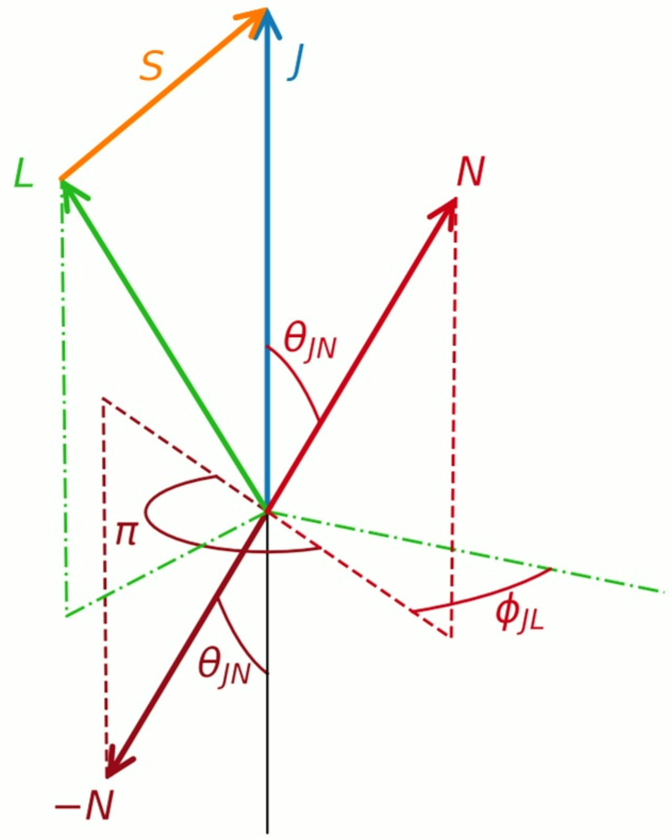
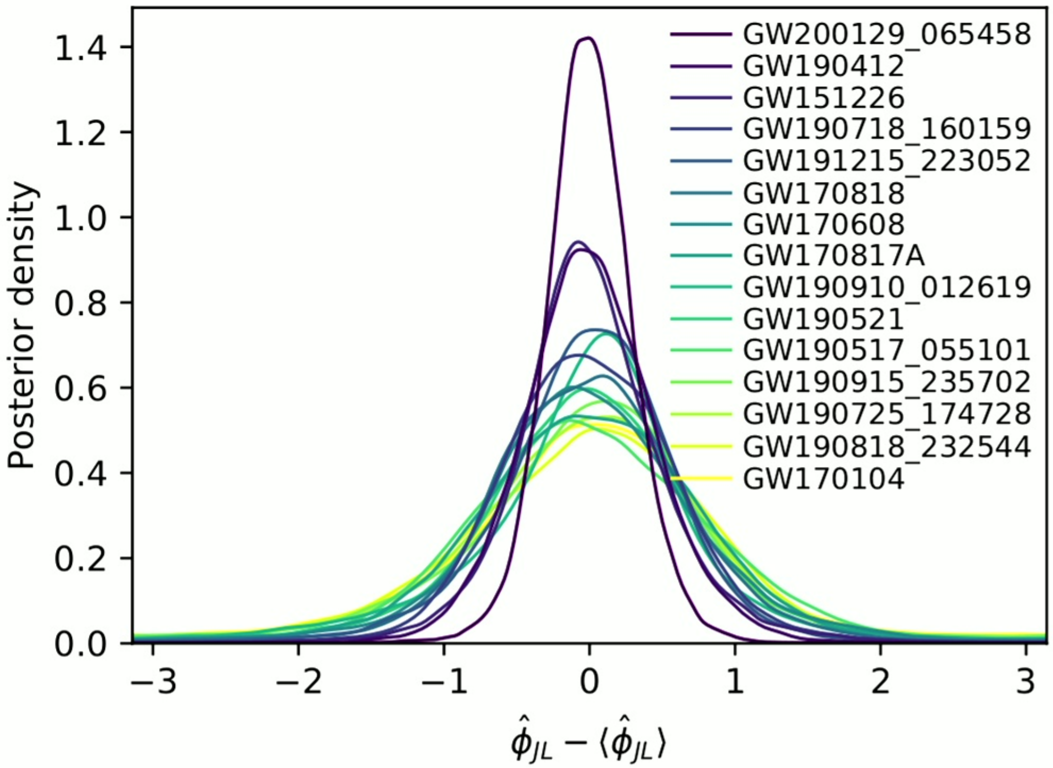




$$\hat{\phi}_{JL} = \phi_{JL} + \pi\Theta(\cos\theta_{JN})$$

Spin azimuth

The spin azimuth $\hat{\phi}_{JL}$ is well measured in several events.



Effective spin distribution

$$\chi_{\text{eff}} = \frac{m_1 \chi_1 + m_2 \chi_2}{m_1 + m_2} \cdot \hat{L}$$

- Symmetric distribution for dynamical formation channels
- Predominantly positive for isolated formation channels

Effective spin distribution

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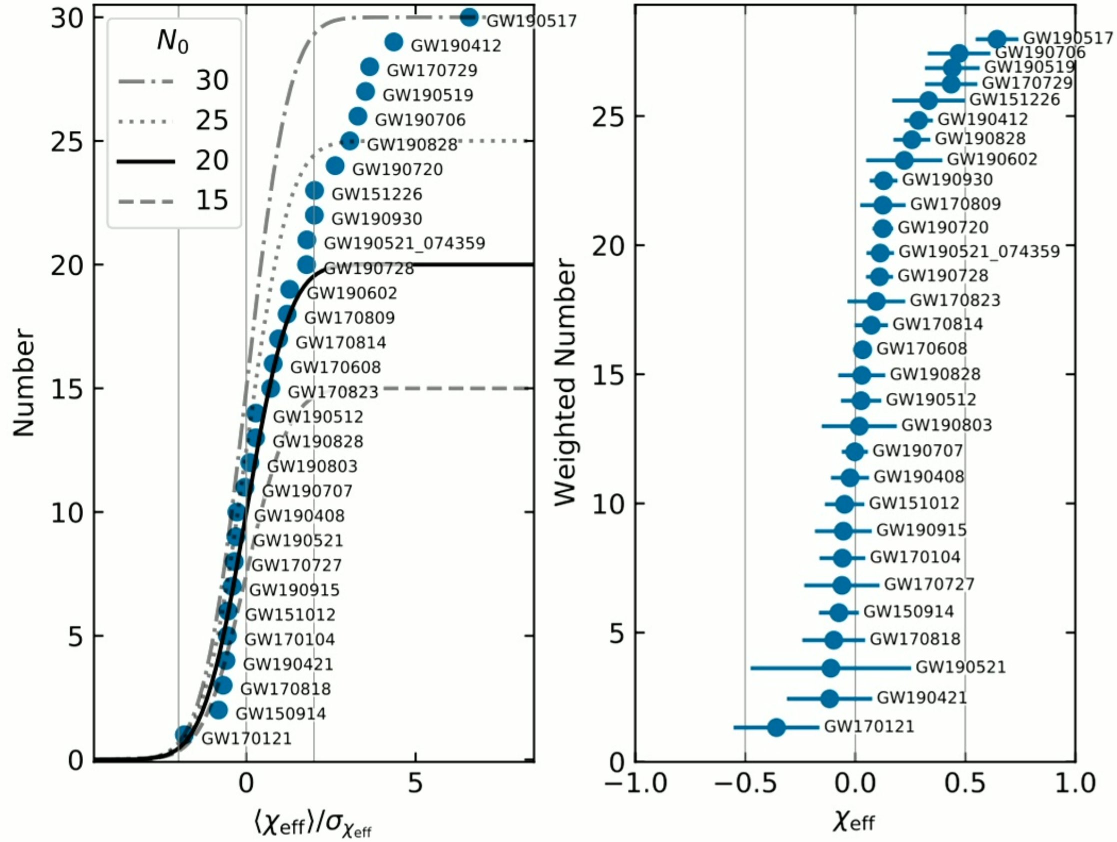
- Predominantly positive for isolated formation channels

Empirical effective spins distribution

"Gold" sample (events found by 2+ pipelines in data with no artifacts)



$$w = \frac{V(\chi_{\rm eff} = 0)}{V(\chi_{\rm eff})}$$

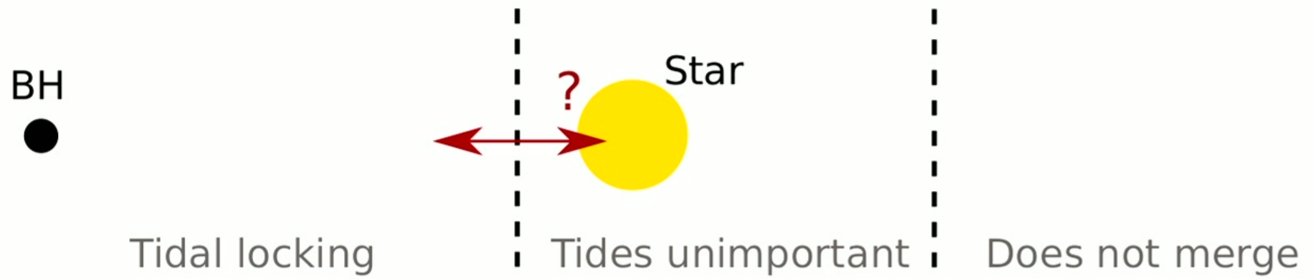
Tidally-locked progenitors?

Within the isolated-binary scenario, it is expected* that the progenitor of the secondary BH is tidally locked in a fraction of the cases, leading to a high aligned spin χ_2.

*Zaldarriaga *et al.* 2017; Hotokezaka & Piran 2017; Qin *et al.* 2018; Bavera *et al.* 2019

After common envelope:

$$d(\text{lock in star life}) \sim d(\text{merge in } t_H)$$



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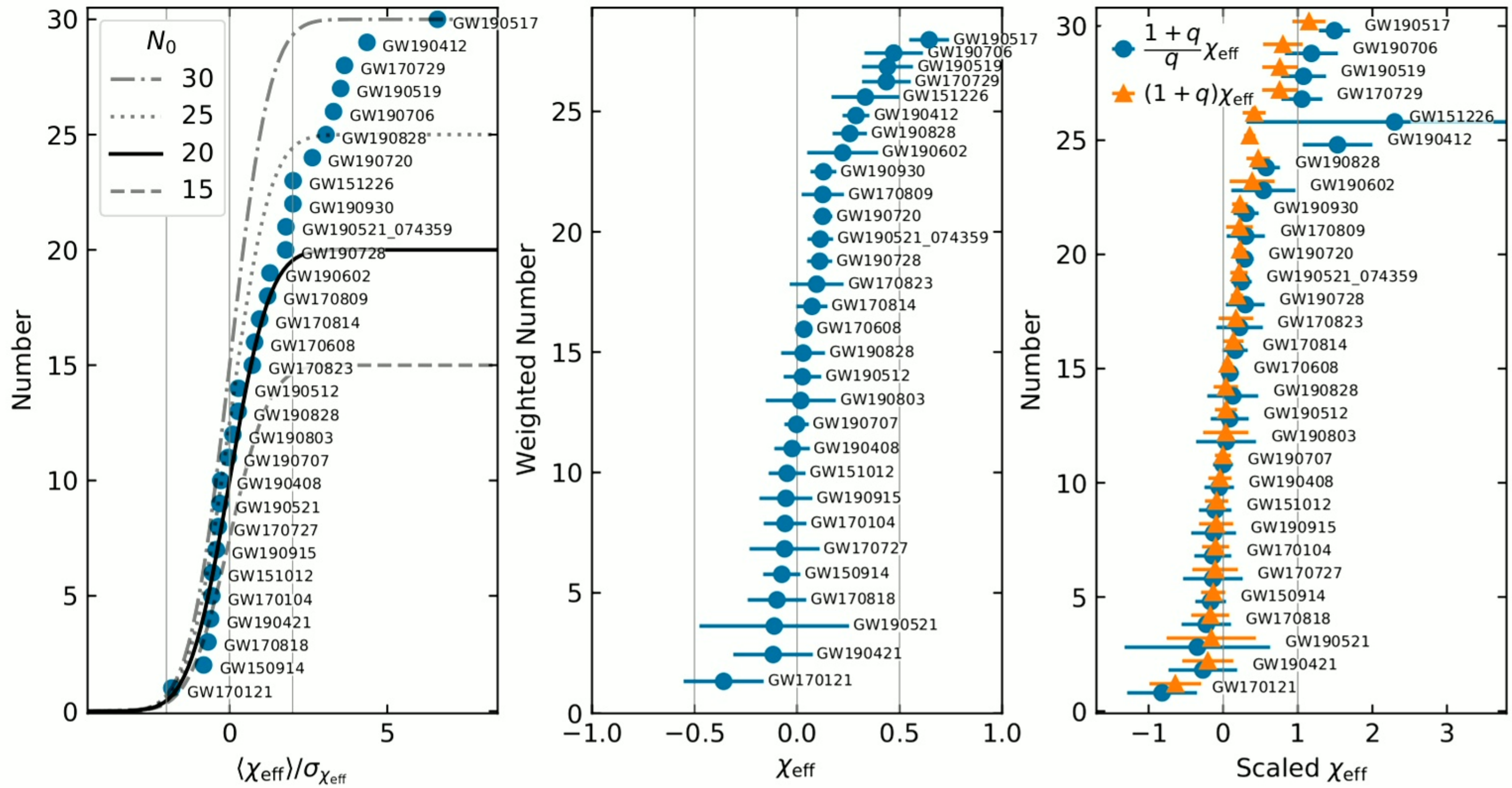
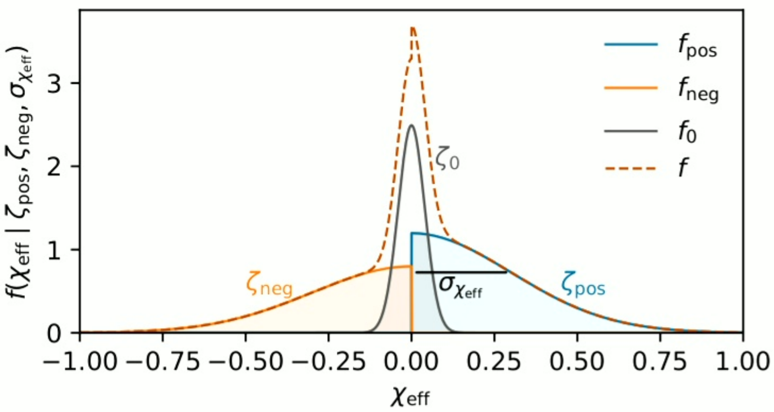
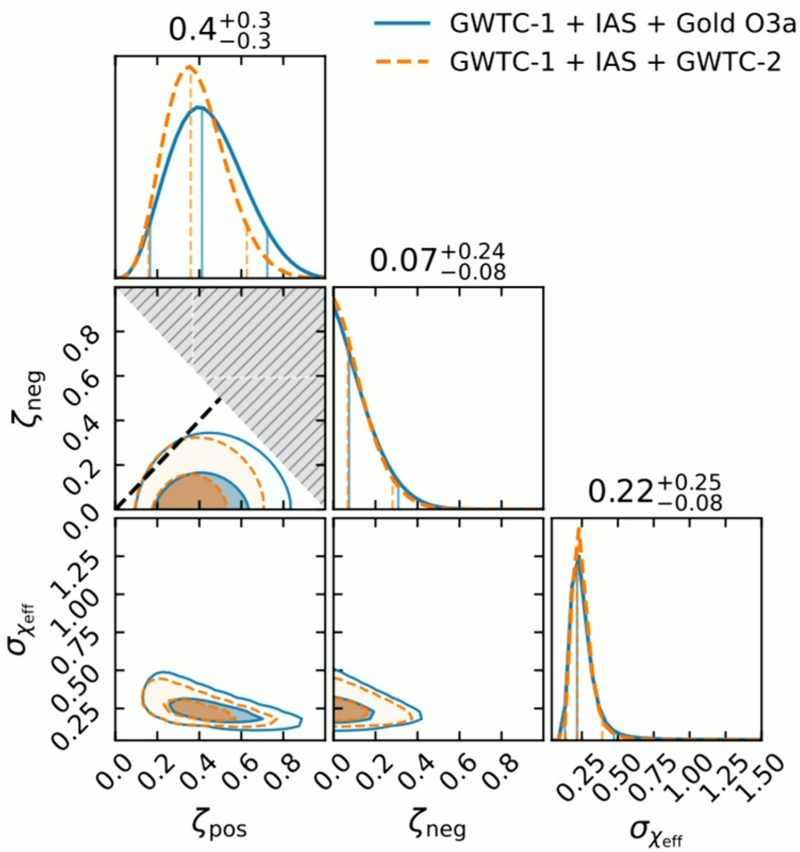


Results (O1 + O2 + O3a)





- More positive effective spins than negative
- Consistent with no negative spins

Conclusions

- Our coordinates are ideal for parameter estimation:
  - Remove degeneracies
  - Remove multimodality by a factor up to 8
  - Simple Jacobian
  - Invertible analytically
- Parameter estimation code: `github.com/jroulet/cogwheel`
- There is an excess of aligned ($\chi_{\text{eff}} > 0$) events over anti-aligned ($\chi_{\text{eff}} < 0$).
- We find no evidence for anti-aligned spins in the population.