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Prospects for measuring off-axis spins of binary black hole sources with A+/AdV+

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Introduction

LIGO/Virgo have detected gravitational waves from 50(!) coalescing compact binaries (mostly BBHs), as of GWTC-2 release (Abbott et al. 2020a).

Detections suggest a new population of BHs not seen with X-ray binaries

- Candidates in the upper and lower mass gaps test our understanding of how BBHs form.
- GW190521: heaviest component masses yet (one in the upper mass gap) with evidence for in-plane spins (Abbott et al. 2020b) — possibly a dynamical merger (Kimball et al. 2020a; Romero-Shaw et al. 2020)?

Sensitivity of GW detectors is reaching a point where we can begin to study BBH formation channels — high spin resolution is critical.

Background

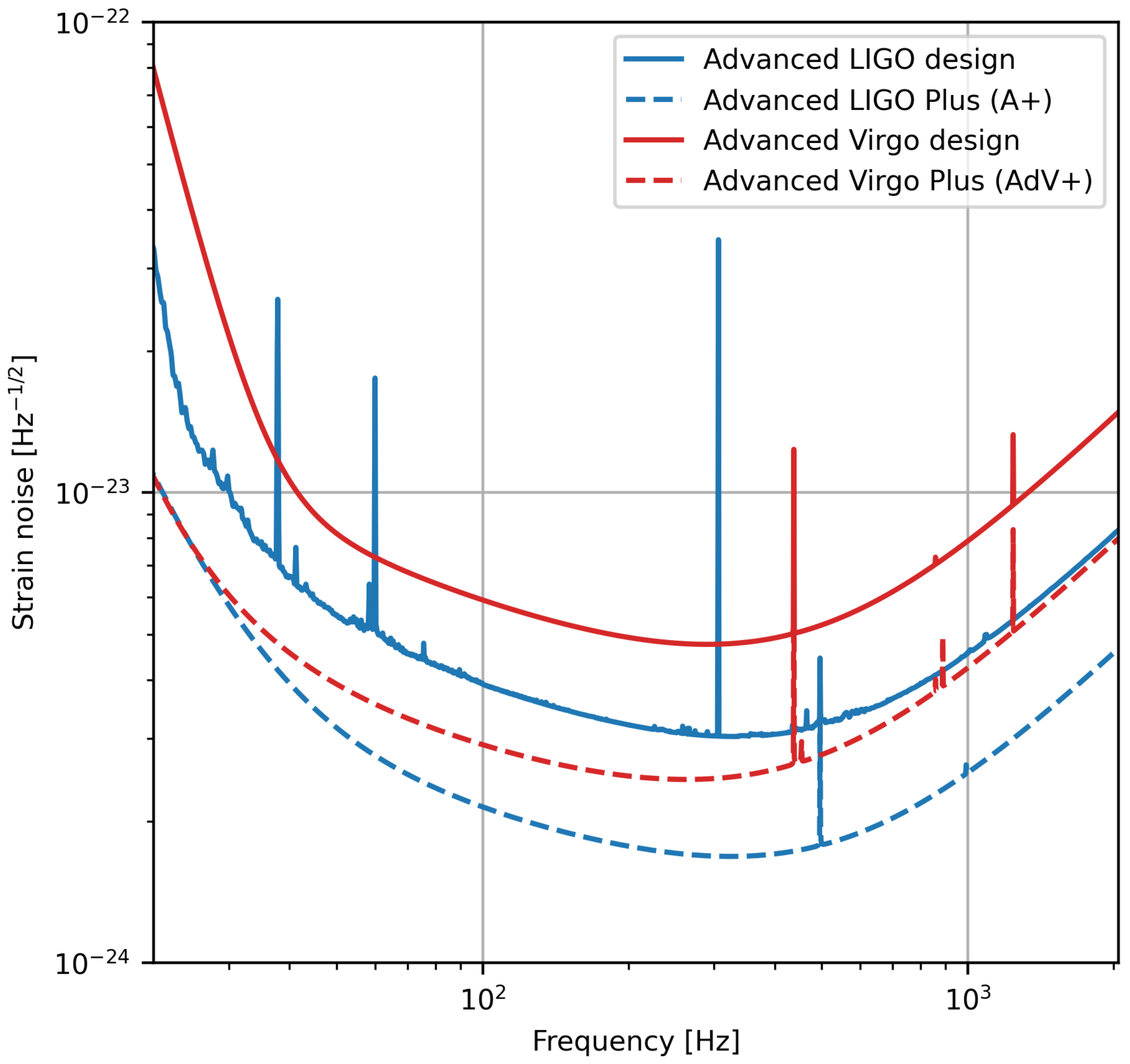
Two general categories of BBH formation channels. (Mis)alignment provides clues about formation.

Objective

Want to know how much better our constraints on BBH spins will get with the A+/AdV+ network ("Plus"), compared with "Design".

Do this by generating hundreds of simulated signals ("injections") with Gaussian detector noise coloured by either the Plus or Design PSDs, then run parameter estimation (PE) routines on these injections at the two sensitivities.

Bayesian PE done using BILBY (Ashton et al. 2019), waveform template is IMRPhenomXPHM (fully precessing + higher order modes) (Pratten et al. 2020a).



(See e.g. Abbott et al. 2018)

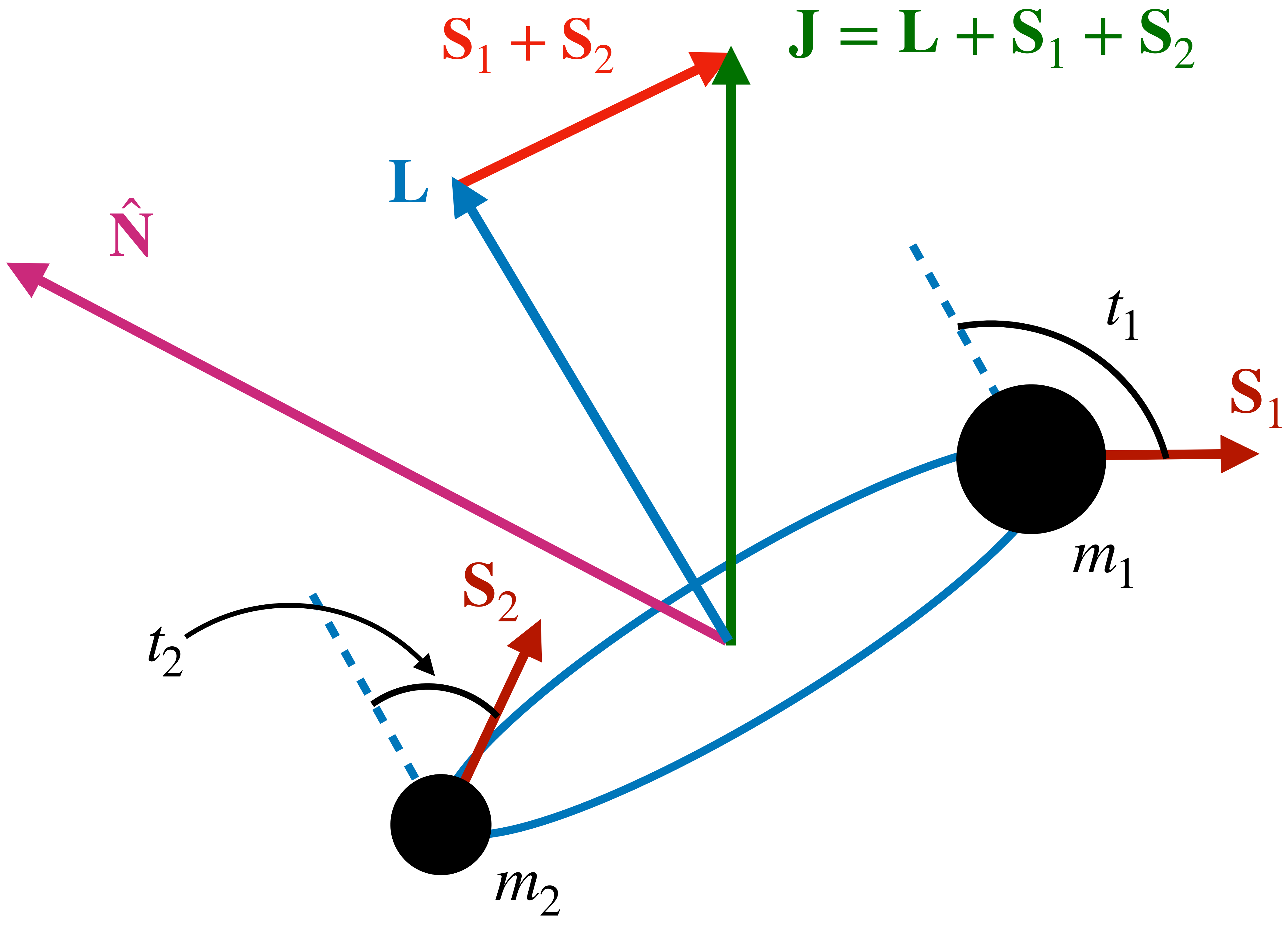
Parameterization

Spin information can be used to distinguish between isolated and dynamical binaries.

For misaligned/precessing systems, need six parameters to fully describe the spins:

- Spin magnitudes $a_i = c\,|\mathbf{S}_i|/(Gm_i^2)$
- Tilt angles $t_i = \arccos(\hat{\mathbf{L}} \cdot \hat{\mathbf{S}}_i)$
- In-plane angles $\phi_{\mathrm{JL}}, \phi_{12}$

Defined at reference frequency (20 Hz)



Effective inspiral spin χ_{eff} (Damour 2001; Racine 2008) and effective precession spin χ_{p} (Schmidt et al. 2015) are typically better constrained (Vitale et al. 2017):

$$\chi_{\mathrm{eff}} = \frac{1}{M}\left(\frac{\mathbf{S}_1}{m_1} + \frac{\mathbf{S}_2}{m_2}\right) \cdot \hat{\mathbf{L}} \qquad \chi_{\mathrm{p}} = \max\left(a_1 \sin t_1, \frac{4+3q}{q(4q+3)} a_2 \sin t_2\right), \quad q = m_1/m_2 \geq 1$$

Injection grids

We present results from three injection grids, in which we vary a pair of parameters discretely. Extrinsic parameters are randomly sampled (redshift power law for distance). 10x10=100 injections per grid.

Injected waveforms start at $f_{\text{low}} = 20$ Hz, currently re-running with $f_{\text{low}} = 15$ Hz

Mass-spin grid

Survey mass-spin parameter space

Total mass $M = 65\,M_\odot$

Mass ratio $q \in [1, 10]$

Spins $a_{1,2} \in [0, 0.9]$

Tilts $\cos t_{1,2} = 0$ (in-plane)

Spin tilt (1G+2G) grid

"Typical" merger of 1G+2G BHs

Total mass $M = 100\,M_\odot$

Mass ratio $q = 2$

Spins $a_1 = 0.7, a_2 = 0.1$

Tilts $\cos t_{1,2} \in [-1, 1]$

Spin tilt (2G+2G) grid

"Typical" merger of 2G+2G BHs

Total mass $M = 100\,M_\odot$

Mass ratio $q = 1.1$

Spins $a_1 = 0.7, a_2 = 0.8$

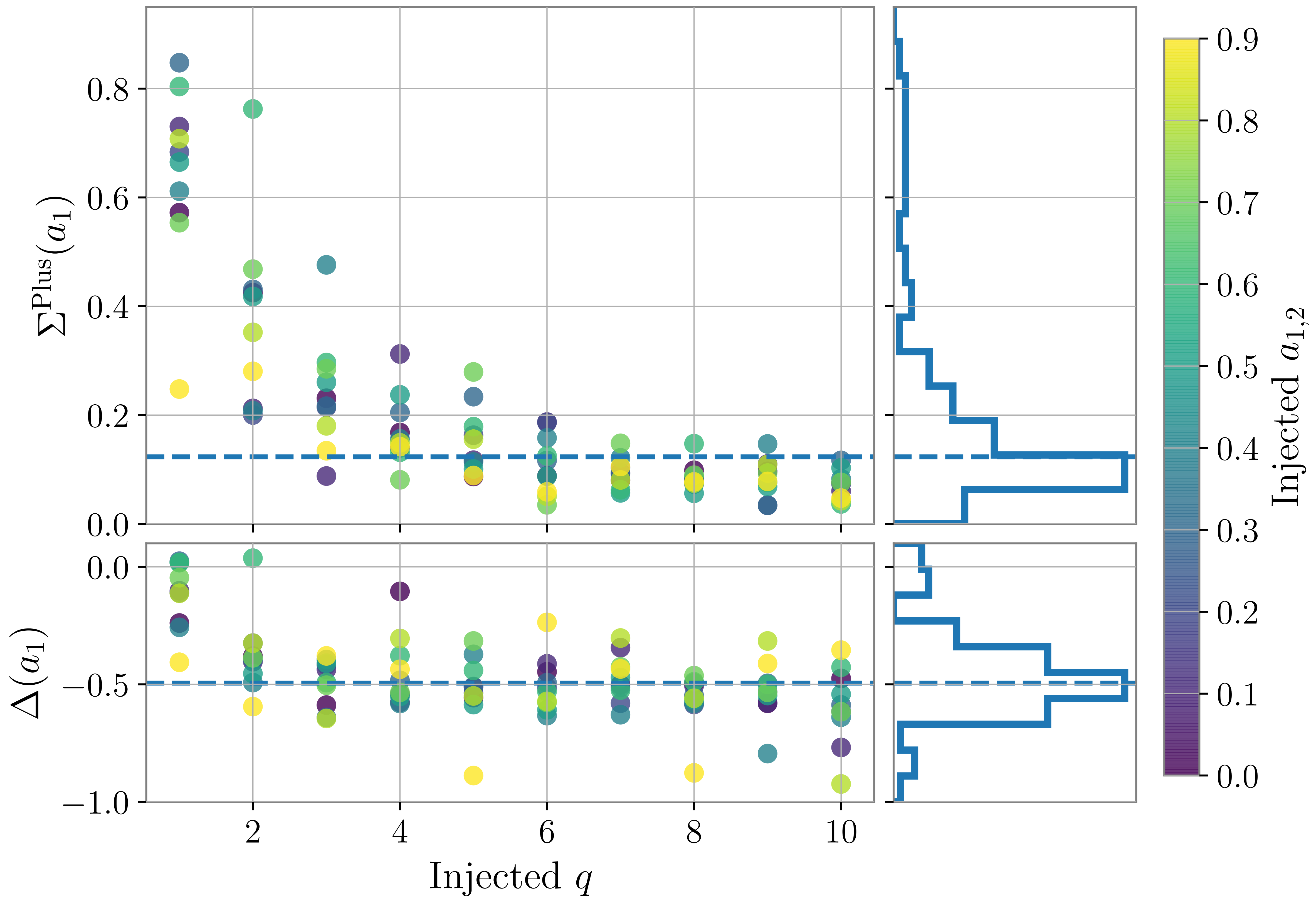
Tilts $\cos t_{1,2} \in [-1, 1]$

Results — Mass-spin

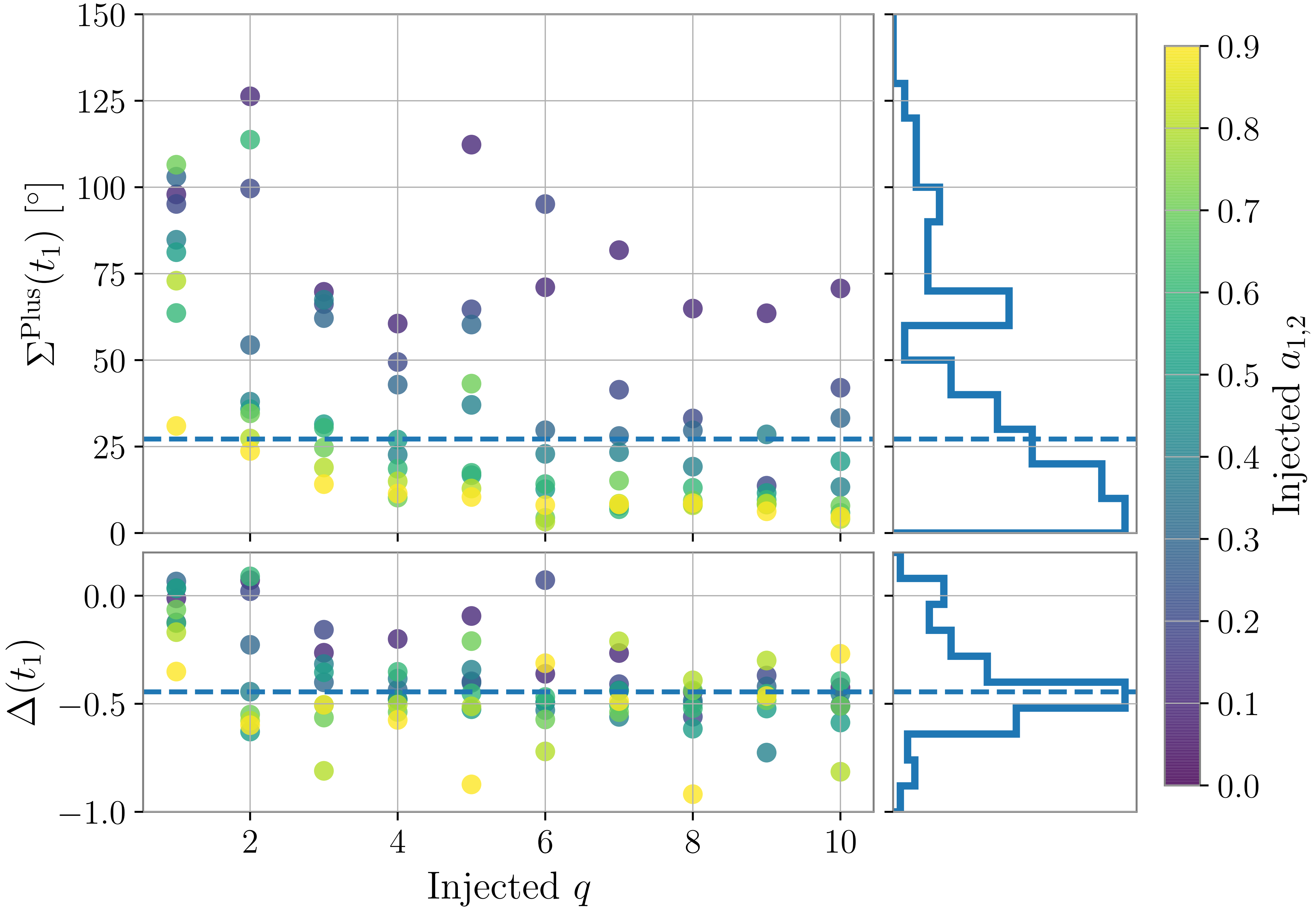
$\Sigma(\theta)$:= width of the 90% credible intervals on parameter θ, as derived from its posterior

$\Delta(\theta)$:= relative change in $\Sigma(\theta)$ between Design and Plus sensitivity

$$a_1 = \frac{c\,|\mathbf{S}_1|}{Gm_1^2}$$



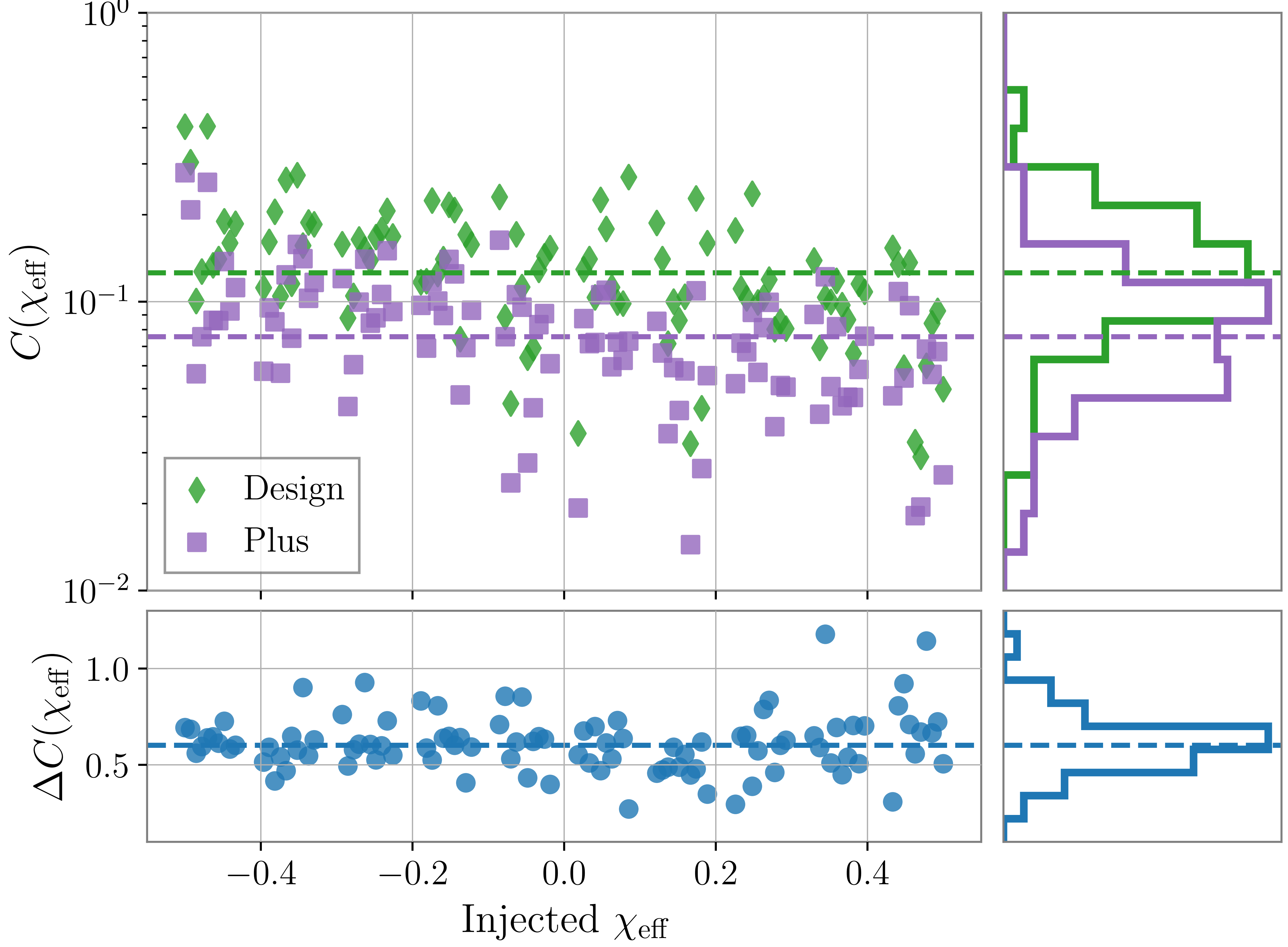
$$t_1 = \arccos(\hat{\mathbf{L}} \cdot \hat{\mathbf{S}}_1)$$



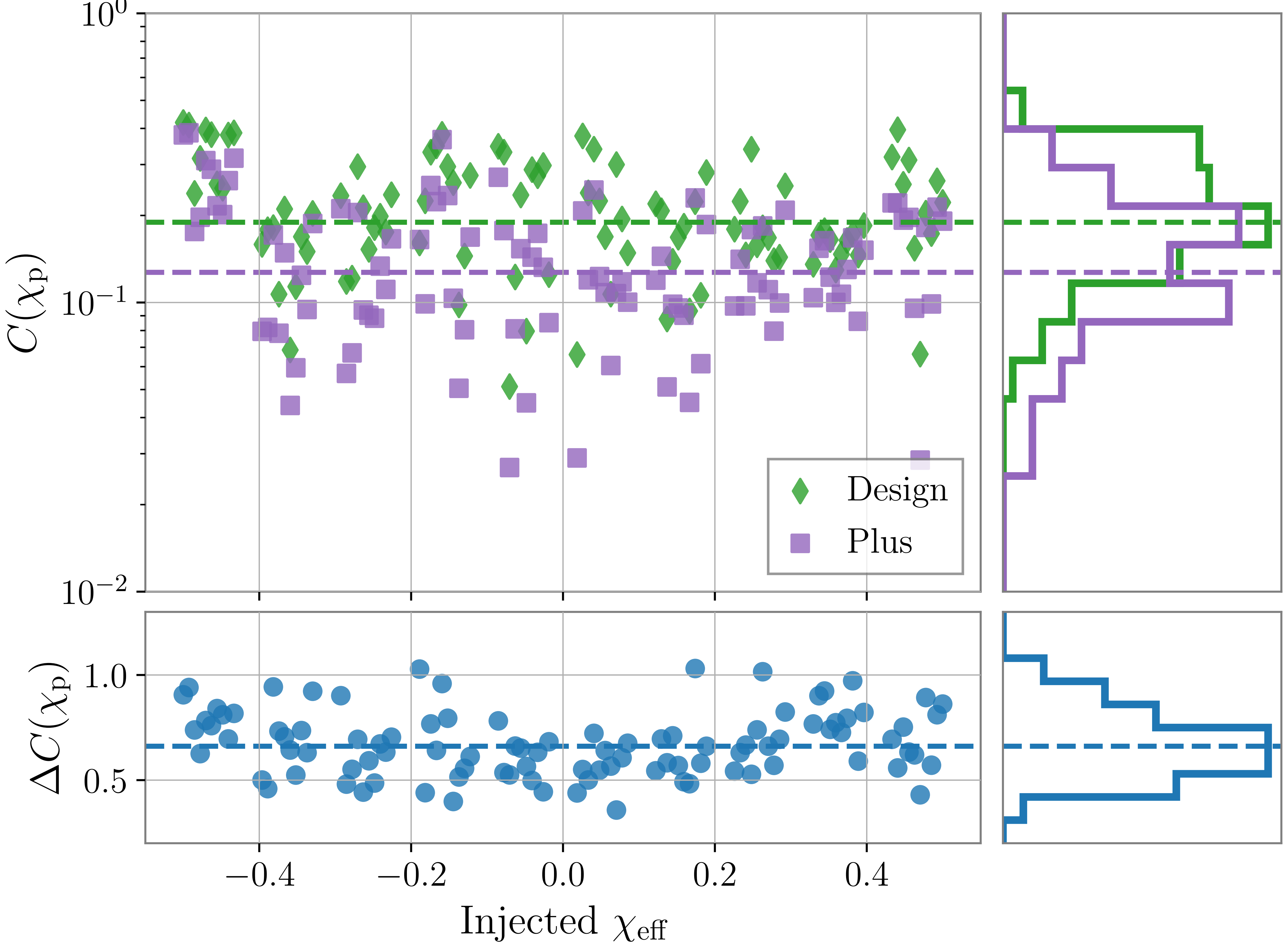
Results — Spin tilt 1G+2G

Vertical axis: $C(\theta) := \left[\left[\int_{\theta_{\min}}^{\theta_{\max}} d\theta \, P(\theta \,|\, \mathbf{d}, H)(\theta - \theta_0)^2 \right] \right]^{1/2} \sim \sqrt{\mathrm{Stdev}^2 + \mathrm{Bias}^2}$, $\quad \Delta C(\theta) := \dfrac{C^{\mathrm{Plus}}(\theta)}{C^{\mathrm{Design}}(\theta)}$

$\chi_{\mathrm{eff}} = \dfrac{1}{M}\left(\dfrac{\mathbf{S}_1}{m_1} + \dfrac{\mathbf{S}_2}{m_2}\right) \cdot \hat{\mathbf{L}}$



$\chi_{\mathrm{p}} = \max\left(a_1 \sin t_1, \dfrac{4+3q}{q(4q+3)} a_2 \sin t_2\right)$



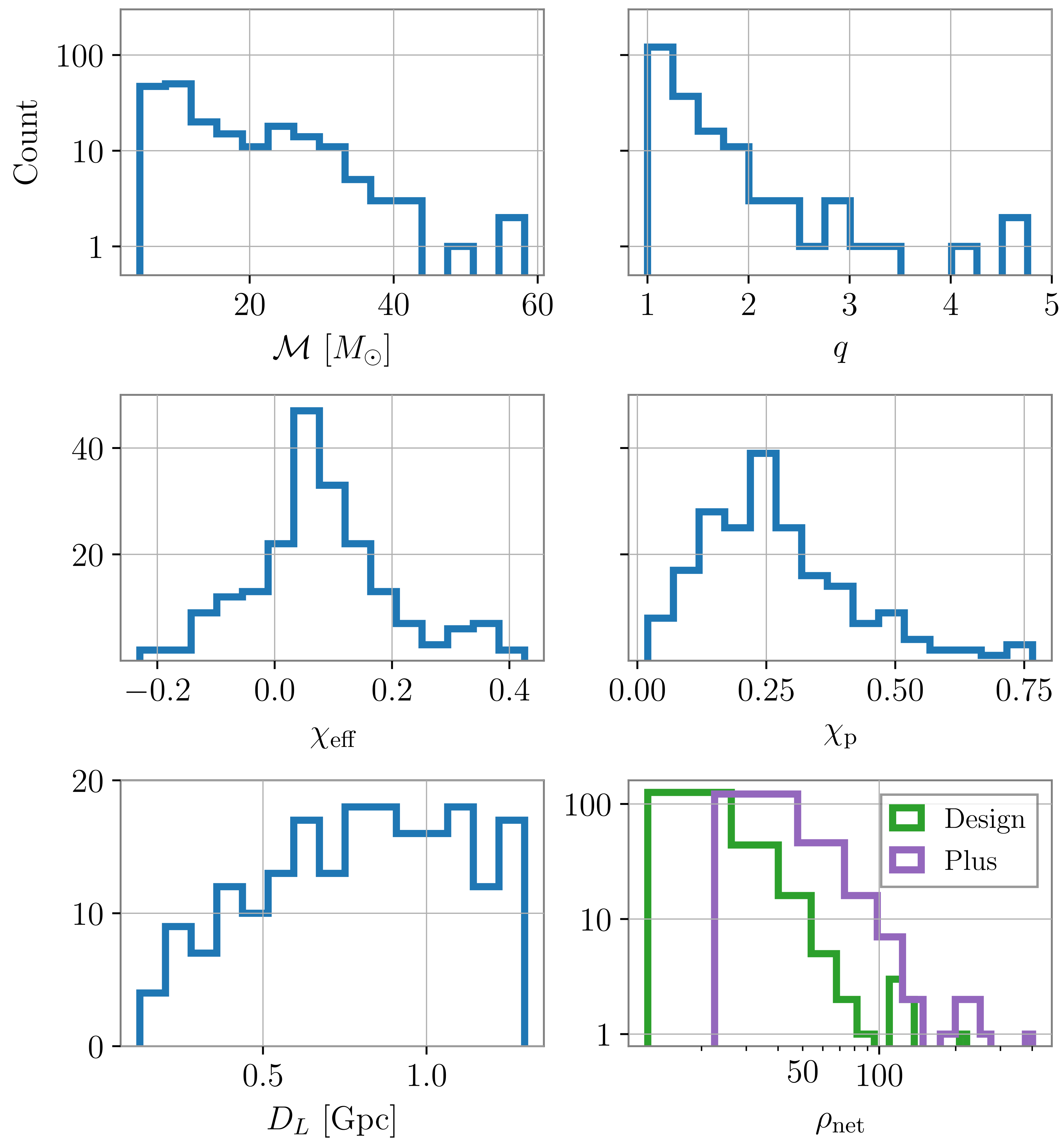
Population study

Fourth injection set: sample masses and spins from population models

"Power law + peak": primary masses drawn from power law w/ Gaussian peak to model PPSN graveyard, secondary masses drawn assuming power law in mass ratio

"Default spin": sample spin magnitudes from beta distributions, sample tilt angles from an aligned + isotropic mixture model

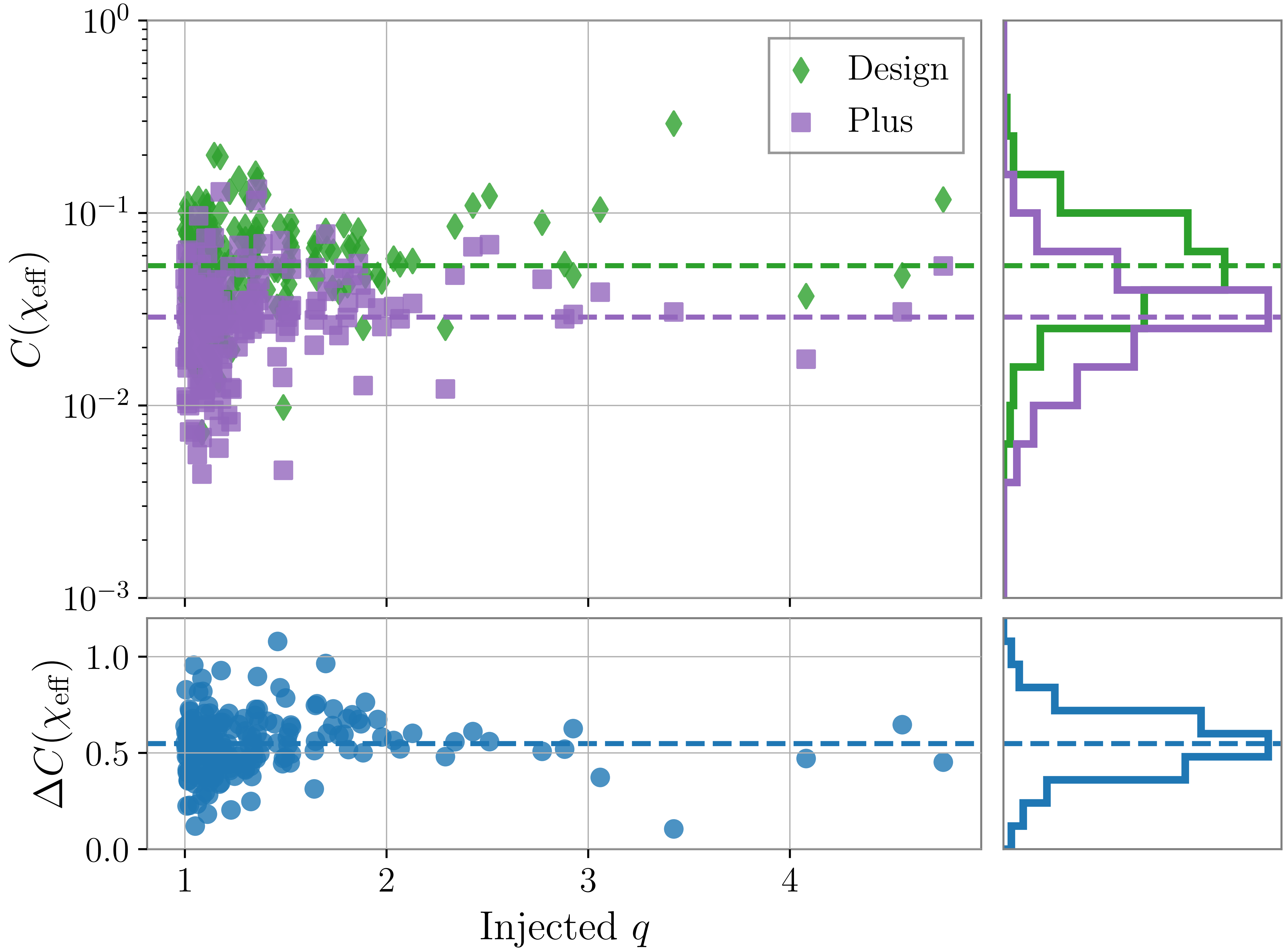
(See Abbott et al. 2020c)

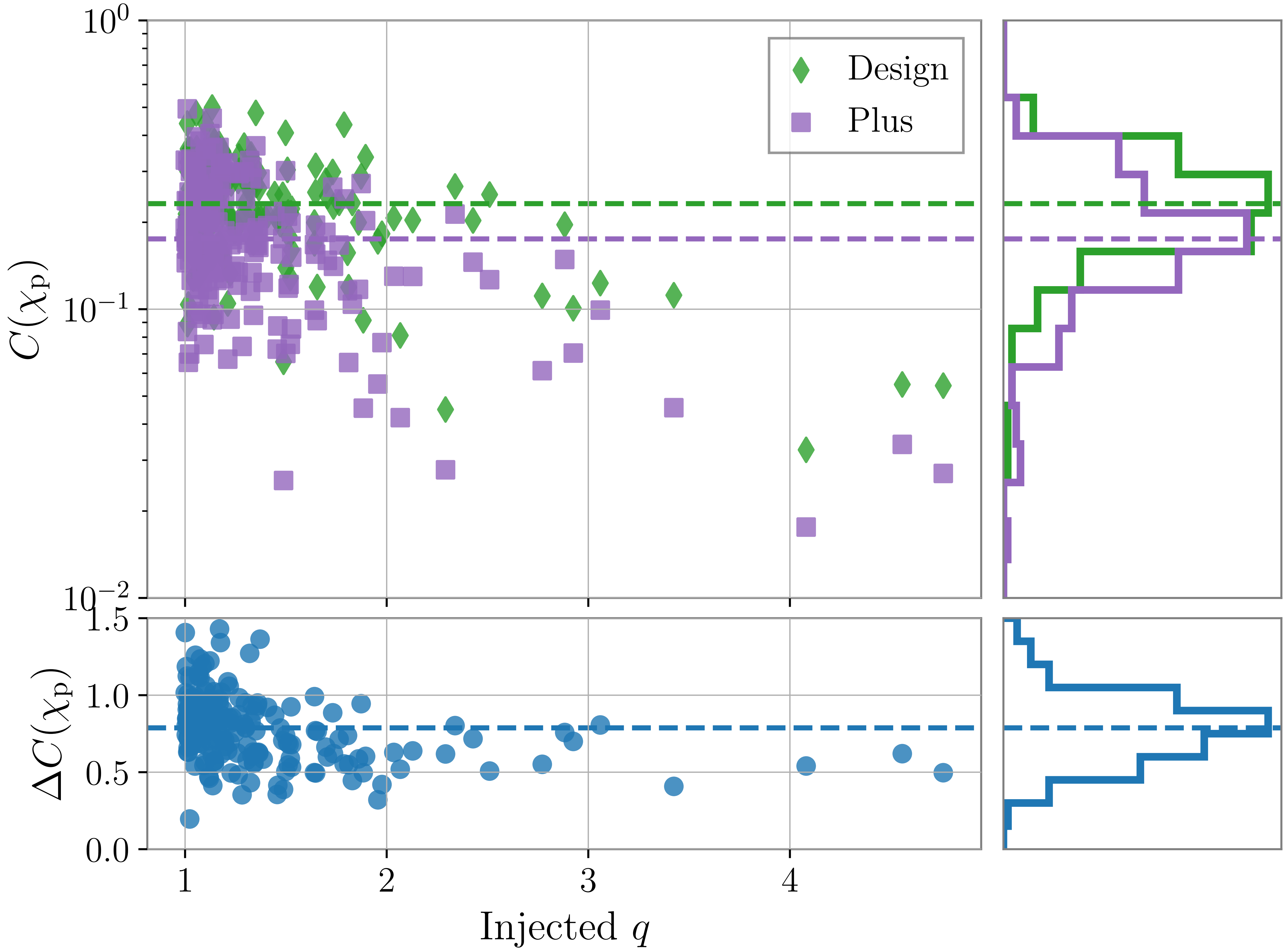


Results — Population study

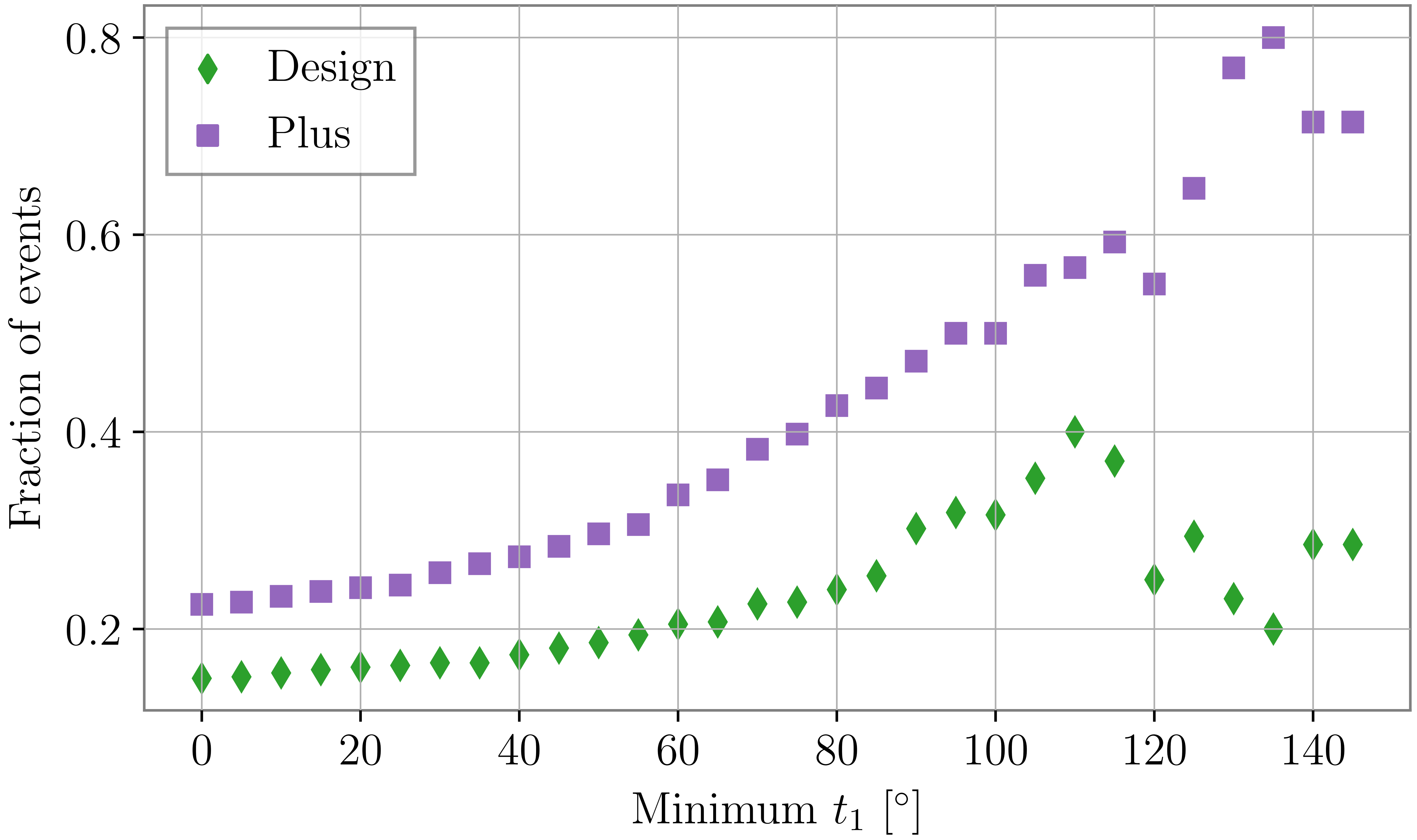
$$\chi_{\rm eff} = \frac{1}{M}\left(\frac{\mathbf{S}_1}{m_1} + \frac{\mathbf{S}_2}{m_2}\right)\cdot\hat{\mathbf{L}}$$

$$\chi_{\rm p} = \max\left(a_1 \sin t_1, \frac{4+3q}{q(4q+3)} a_2 \sin t_2\right)$$





Results — Population study



When can we identify aligned/misaligned spins?

Out of events with a given minimum primary tilt (horizontal axis), find fraction with 5th posterior percentile $> 45^{\circ}$

Summary

Key points

- Plus sensitivity yields largest improvements over Design for high mass ratio, high spin binaries
- 40% smaller cost in precession measurement between Design and Plus sensitivity over all tilt angles
- More consistent measurement of misaligned spins with Plus compared to Design
- Followup on related work, e.g. Pratten et al. 2020b, Vitale et al. 2017, Kimball et al. 2020b, Green et al. 2020, Stevenson et al. 2017

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