Systematic Biases in Estimating the Properties of Black Holes Due to Inaccurate Gravitational-Wave Models

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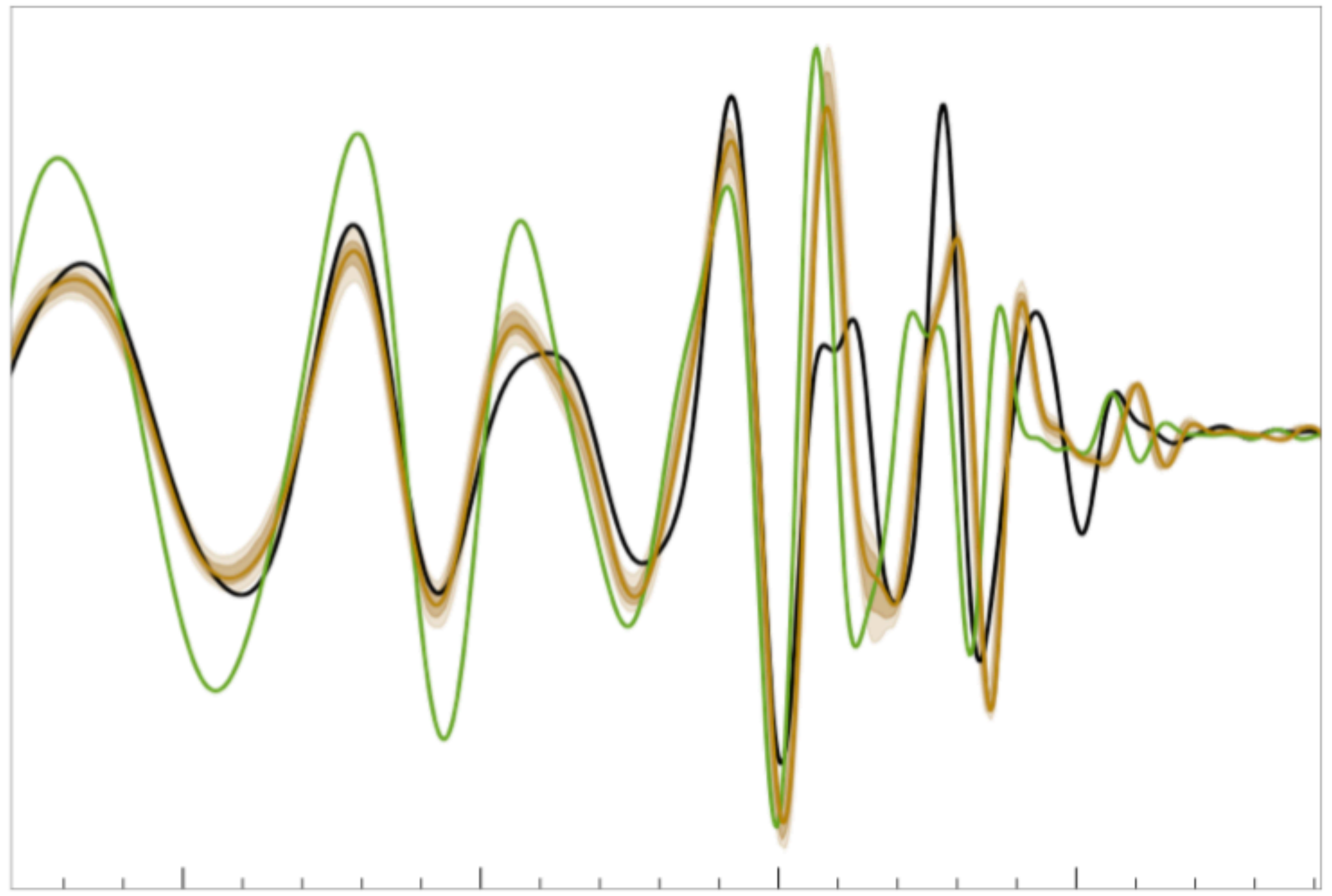

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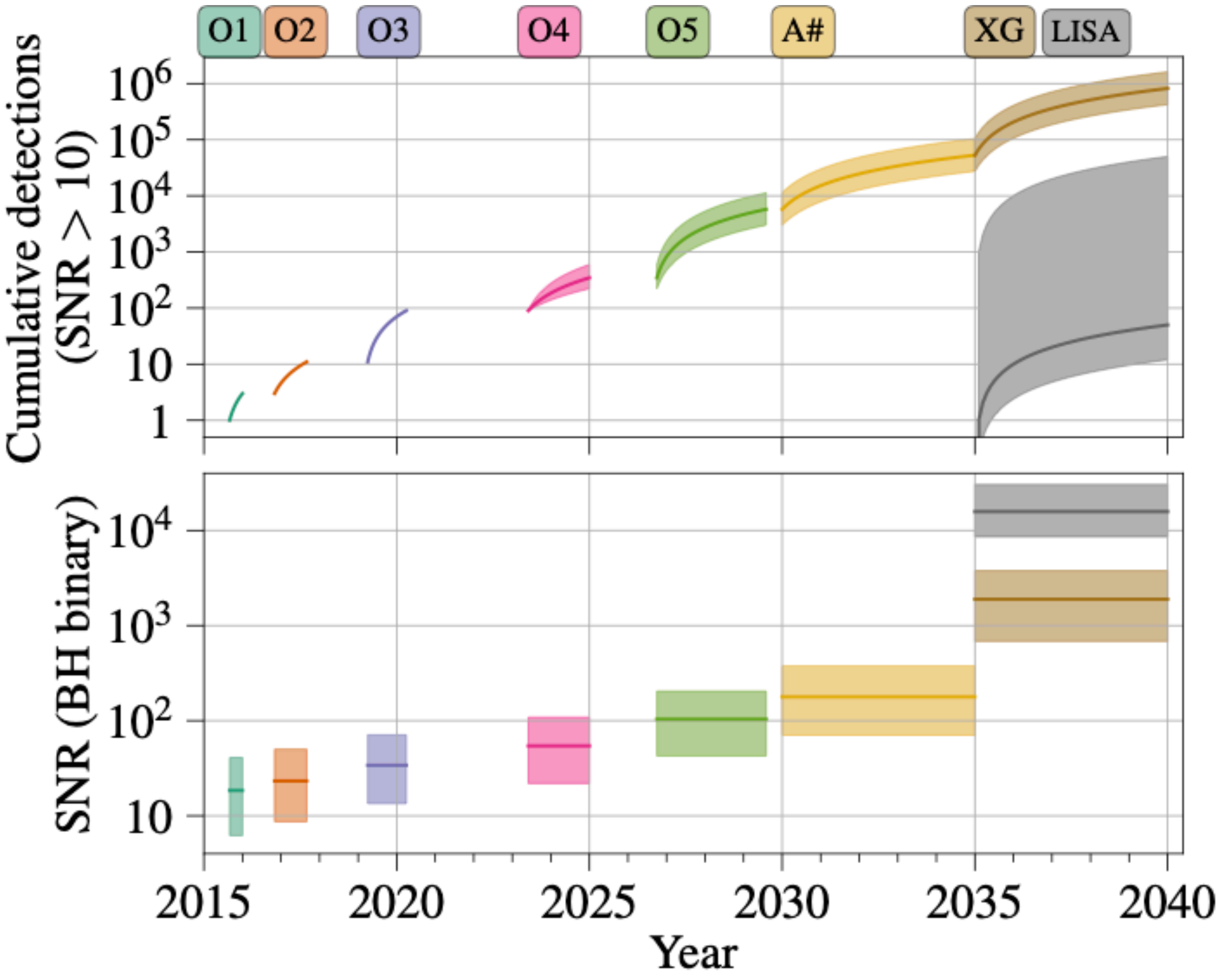
arXiv:2404.05811

ET-0249A-24

Future of GW Astrophysics

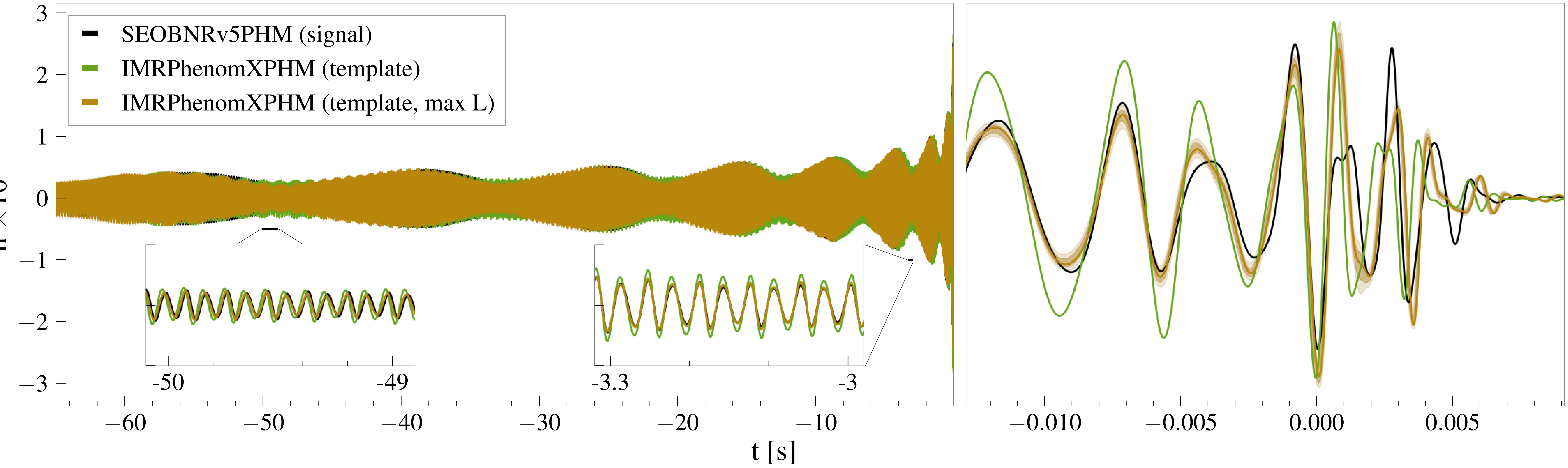
- **More sensitive detectors**
  - **More** events and **more diverse** systems
  - **Higher SNR** for loud events
  - wider detector bandwidth

- Physical completeness and accuracy of waveform models will be even more important than today



Example of challenges

- **GW190814-like**, but strongly precessing: $\chi_{\rm eff} = 0.51, \chi_p = 0.45$
- **E.g. for O5 sensitivity (SNR~75)**
  - Mismatch(signal, template) **= 0.04 (!)**
  - best-fit template gives **bias**: $\delta M/M \sim 0.03, \delta q/q \sim 0.06, \delta\chi_p/\chi_p \sim 0.13$



This work

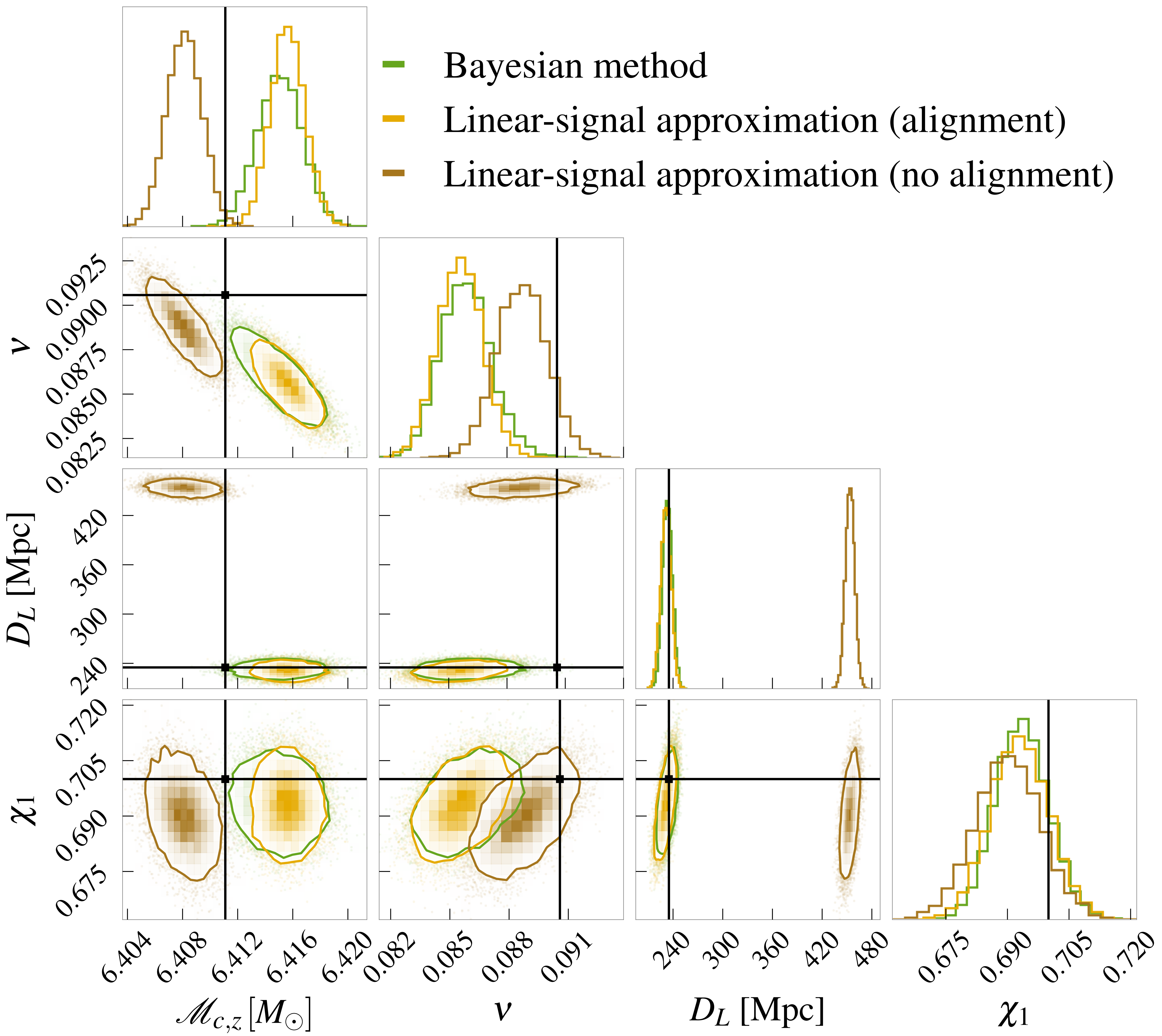
- **Estimate biases** using state-of-the-art BBH precessing HM waveforms
  - SEOBNRv5PHM $\rightarrow$ signal
  - IMRPhenomXPHM $\rightarrow$ for inference
- **Explore parameter space widely**
  - *where are problems?*
- **Study a few special cases in depth**
  - *how bad can it be?*

Linear-signal-approximation vs Bayesian

- Assumes h changes linearly in parameters θ_i
- Fisher Matrix $C^{ij} = \left(\langle \partial_{\theta_i} h, \partial_{\theta_j} h \rangle\right)^{-1}$
- **Statistical uncertainty** $\Delta\vartheta^i = \sqrt{C^{ii}} \propto \mathrm{SNR}^{-1}$
- **Parameter bias** $\delta\vartheta^i = C^{ij}\langle \partial_{\theta_j} h, \delta h \rangle \propto \mathrm{SNR}^0$

  where δh is error of waveform
- δh by difference **between waveform models**
  - **Essential to minimize** over those waveform parameters that have inconsistent definitions/conventions between models (alignment):

    $$\delta h \equiv \min_{\vec{\lambda}=\{t_c, \Psi, \Phi_{\mathrm{ref}}, \Phi_{JL}\}} h_S - h(\vec{\lambda})$$

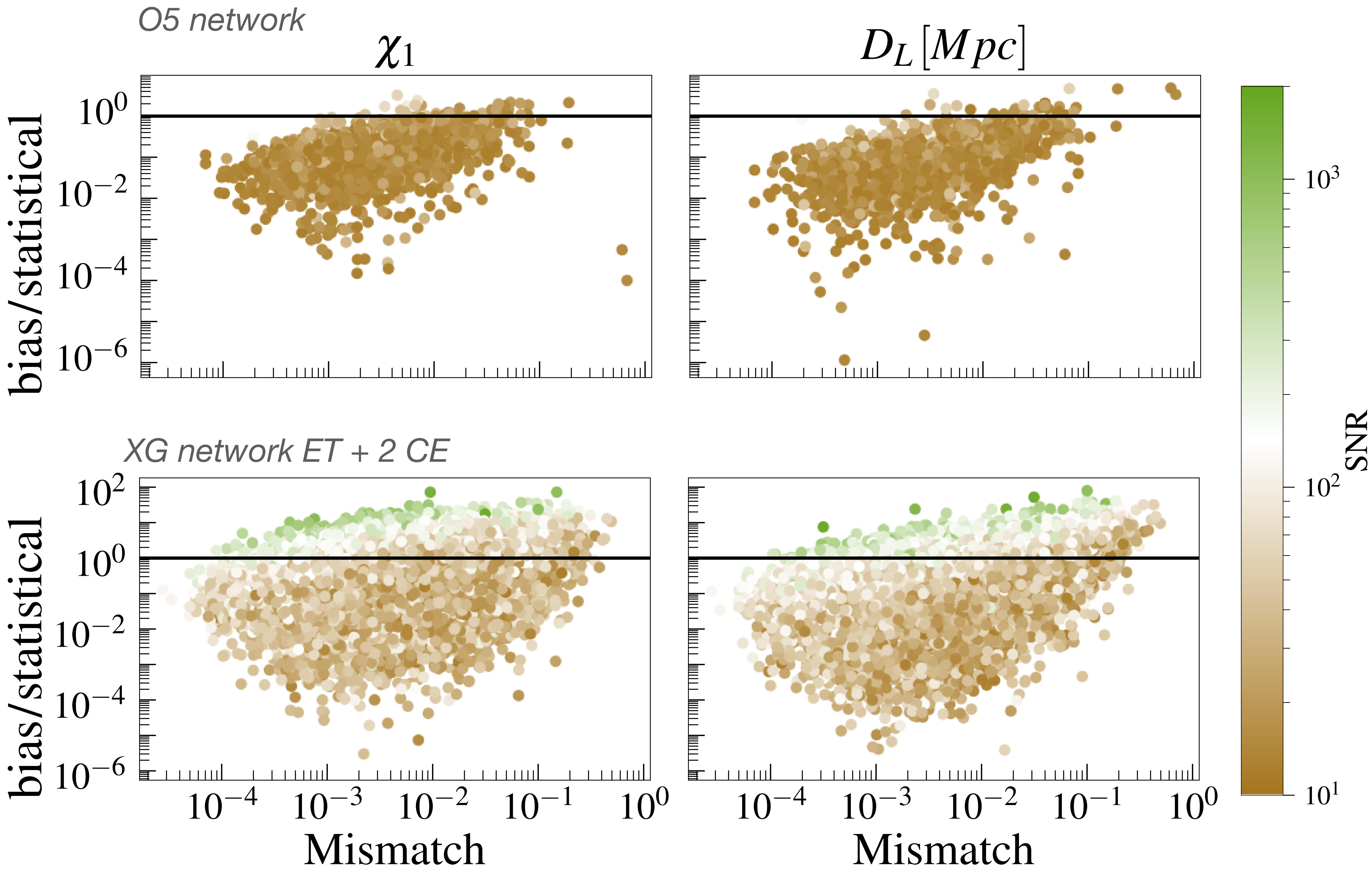


 H. Pfeiffer   Finn & Chernoff 93, Flanagan & Hughes 98, Cutler & Vallisneri 07   O5 network, GW170814-like, precessing, SNR 75

Results: LVK-like population

- Masses: LVK GWTC-3
- Spins: uniform and isotropic
- $z \in [0,3]$

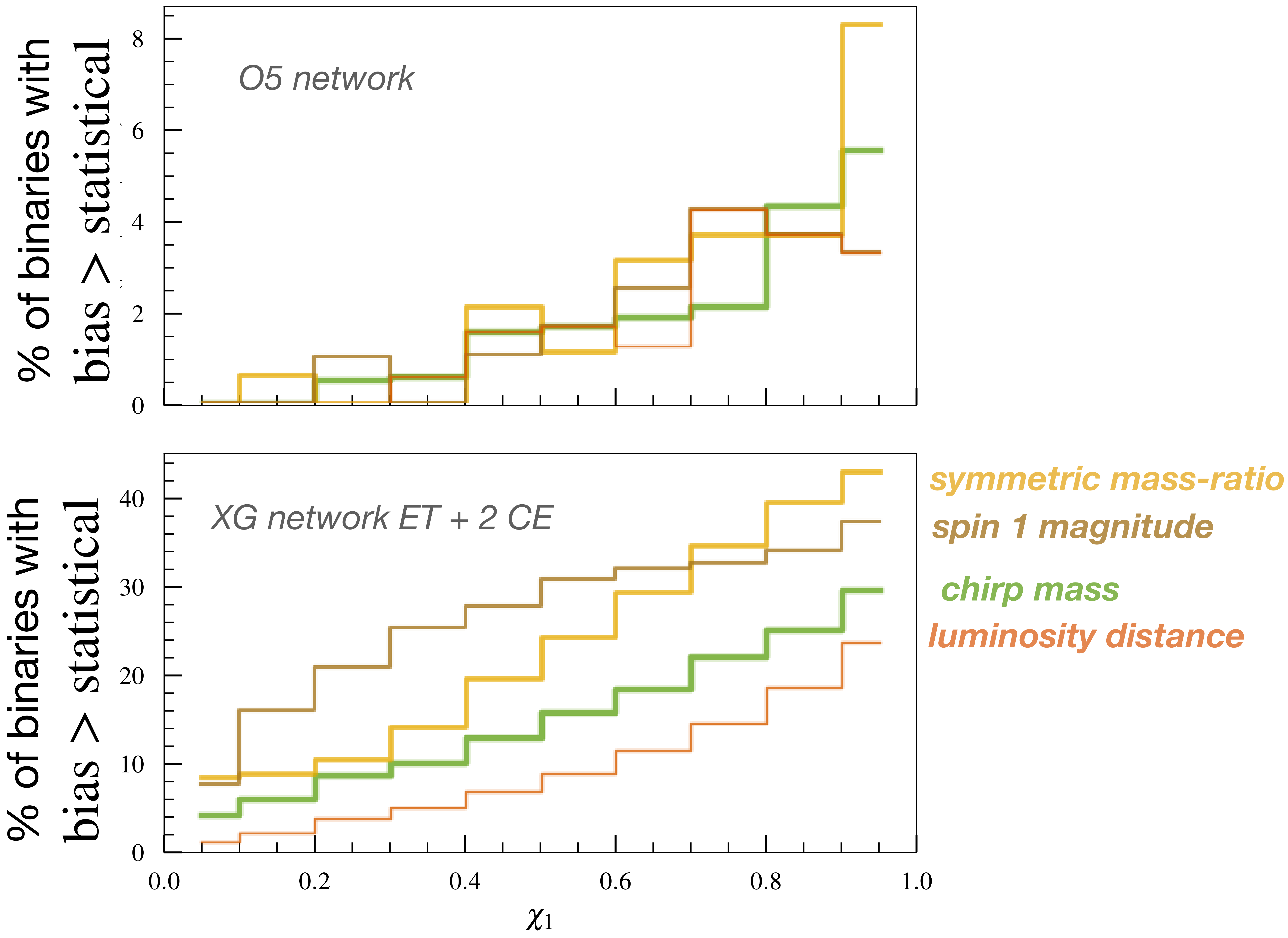
- **Even in O5 some signals biased**
- **XG network, 10-25% of signals biased**



Exemplary results (more in arXiv:2404.05811)

Spin dependence of biases

- **Large primary spin causes stronger biases**



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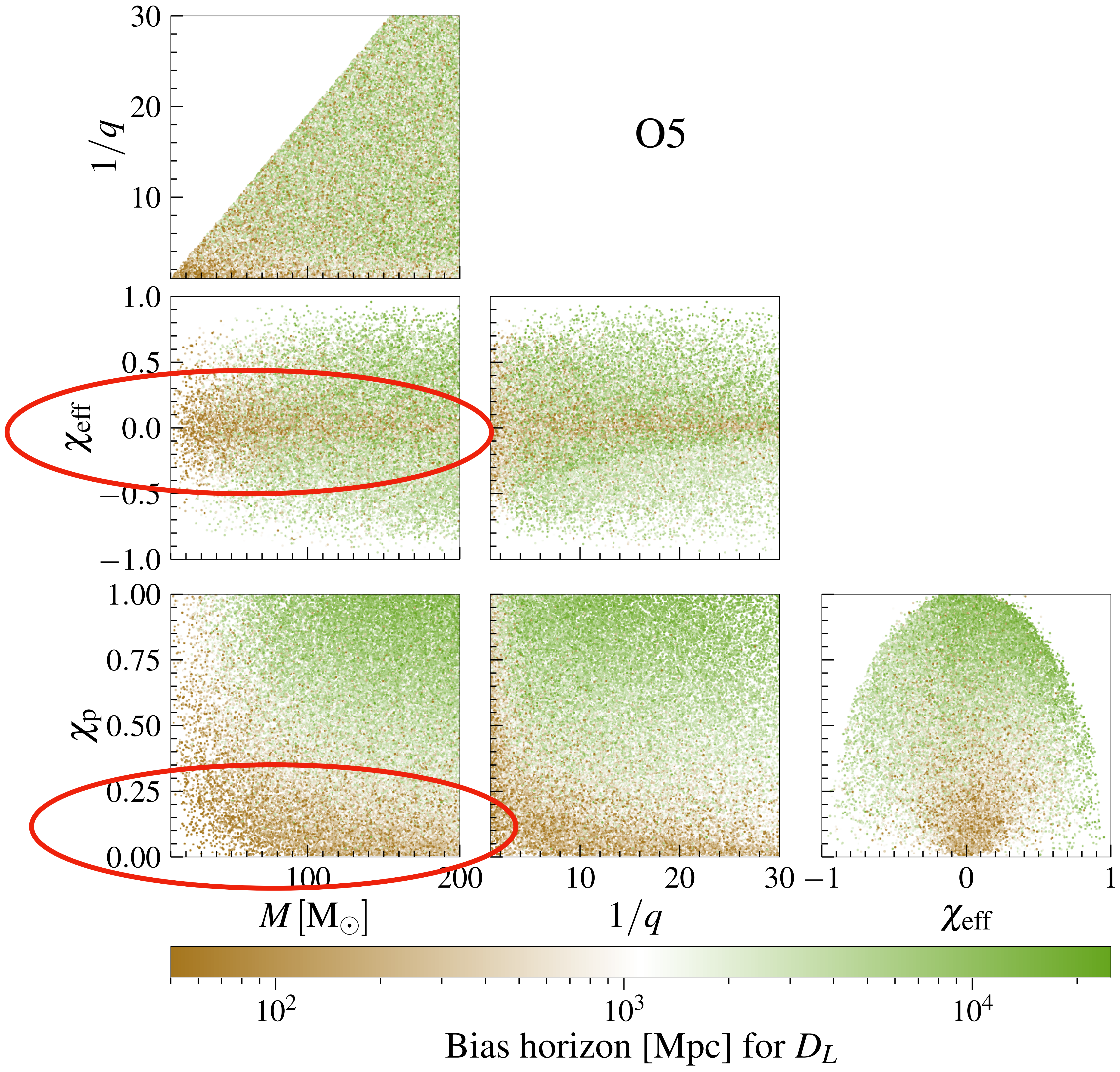
More comprehensive scan of parameter space

- $q \geq 1/30$
- Distance up to which
  bias > statistical error
- Example how to read this plot:
  for small spins (highlighted in red)
  - biased only for very close sources
    - i.e. only at high SNR
    - i.e. waveform models quite good

O5 network



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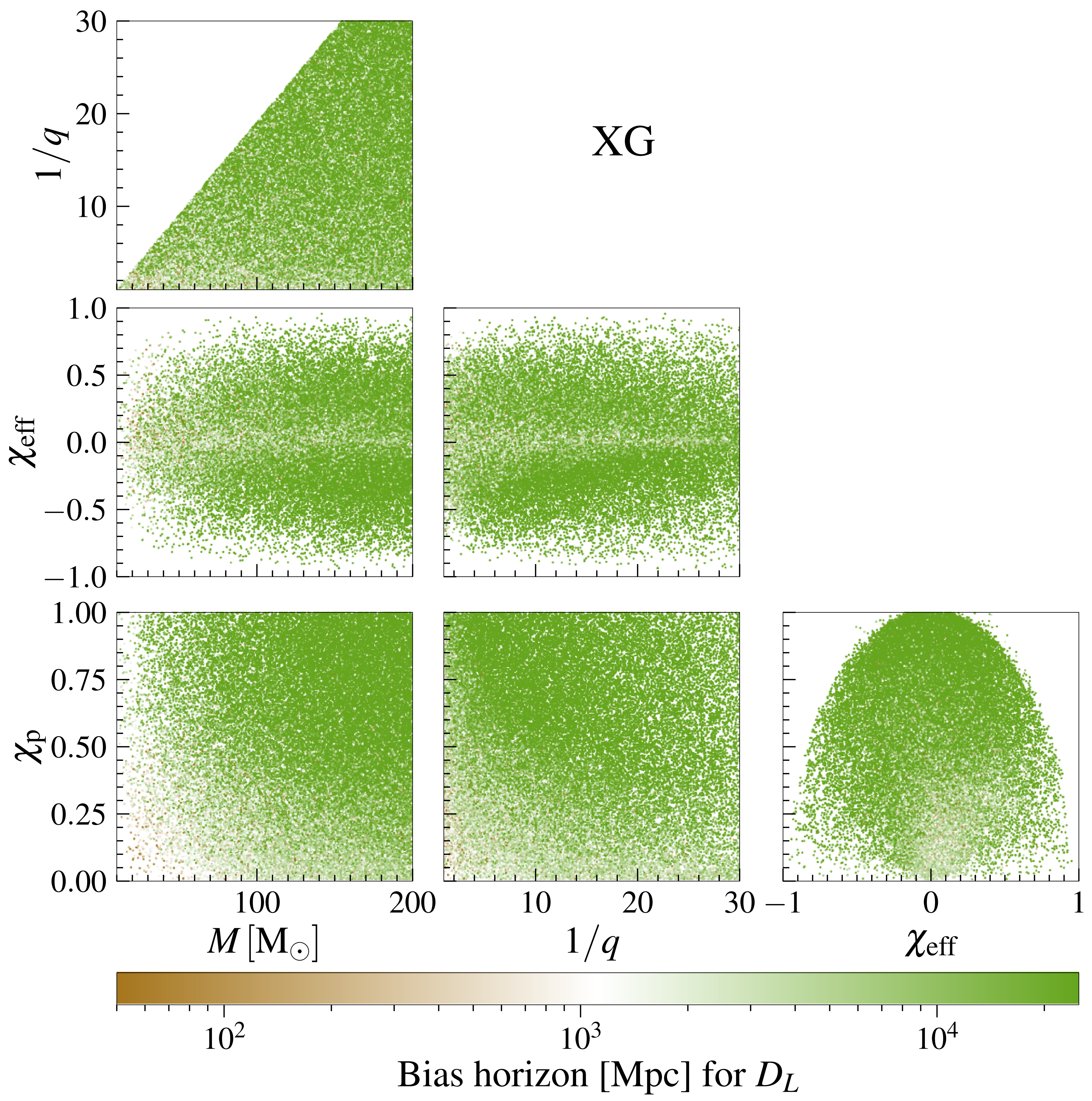
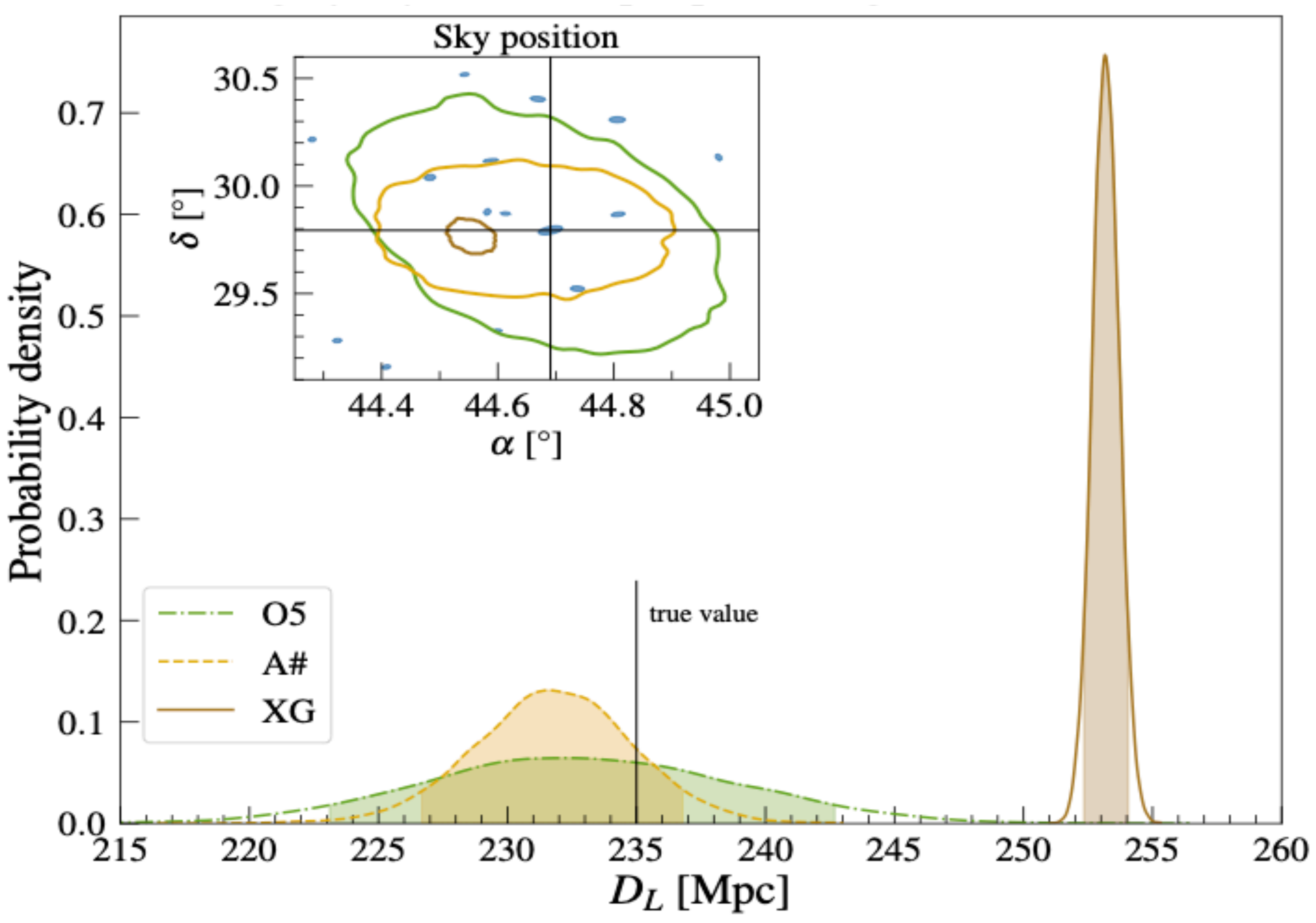
- **For XG network, biases pervasive out to distances of many Gpc.**

XG network

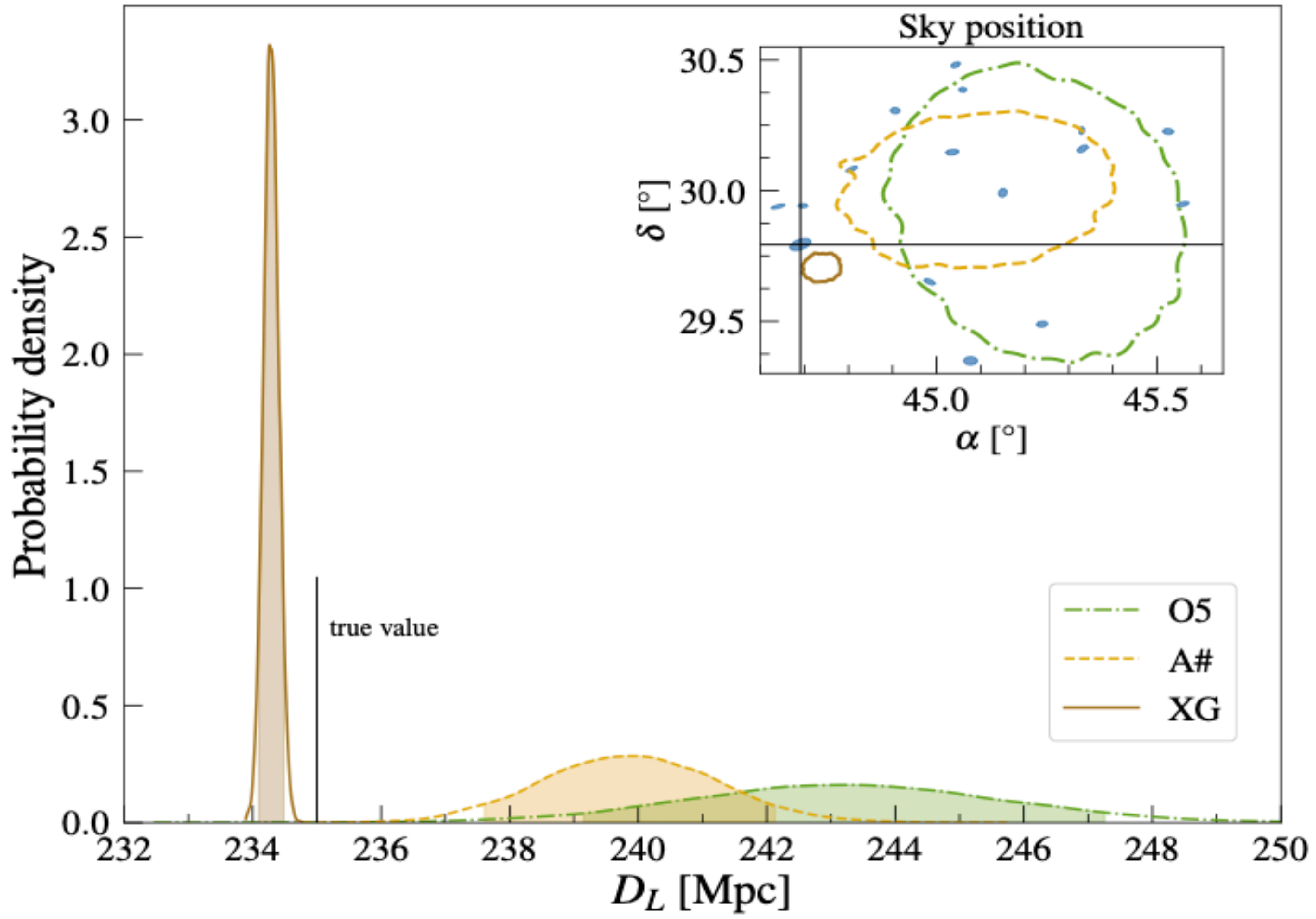


Concrete examples w/ full Bayesian PE

- $m_1 = 23.2M_\odot, m_2 = 2.6M_\odot$
- $\chi_{eff} = 0.51, \chi_p = 0.45$
- $SNR_{O5} = 75, SNR_{XG} = 1040$



- $m_1 = 61.8M_\odot, m_2 = 9.5M_\odot$
- $\chi_{eff} = -0.43, \chi_p = 0.77$
- $SNR_{O5} = 119, SNR_{XG} = 2490$



D_L biased
sky position biased > galaxy size
[Hubble constant, EM counterparts]

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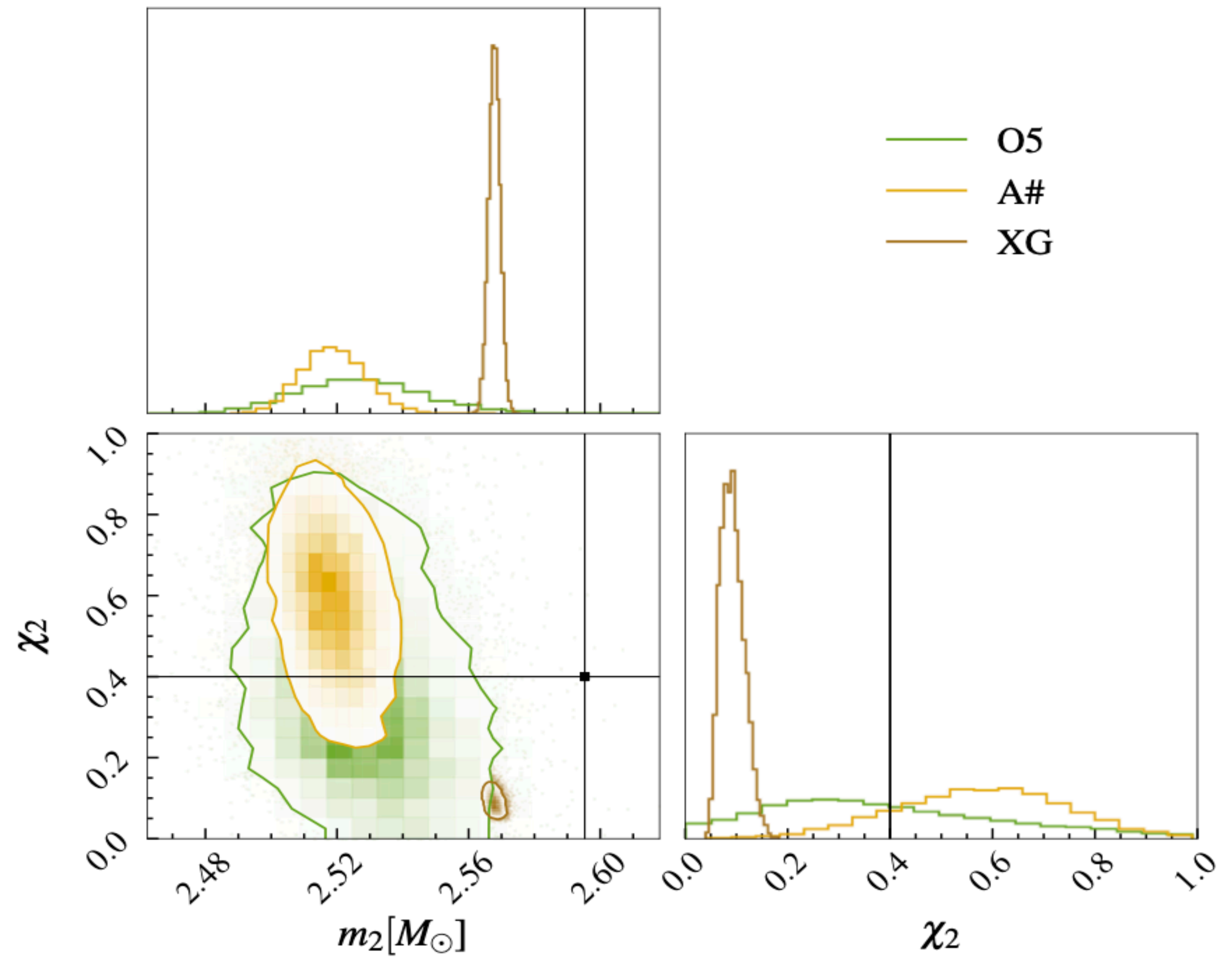
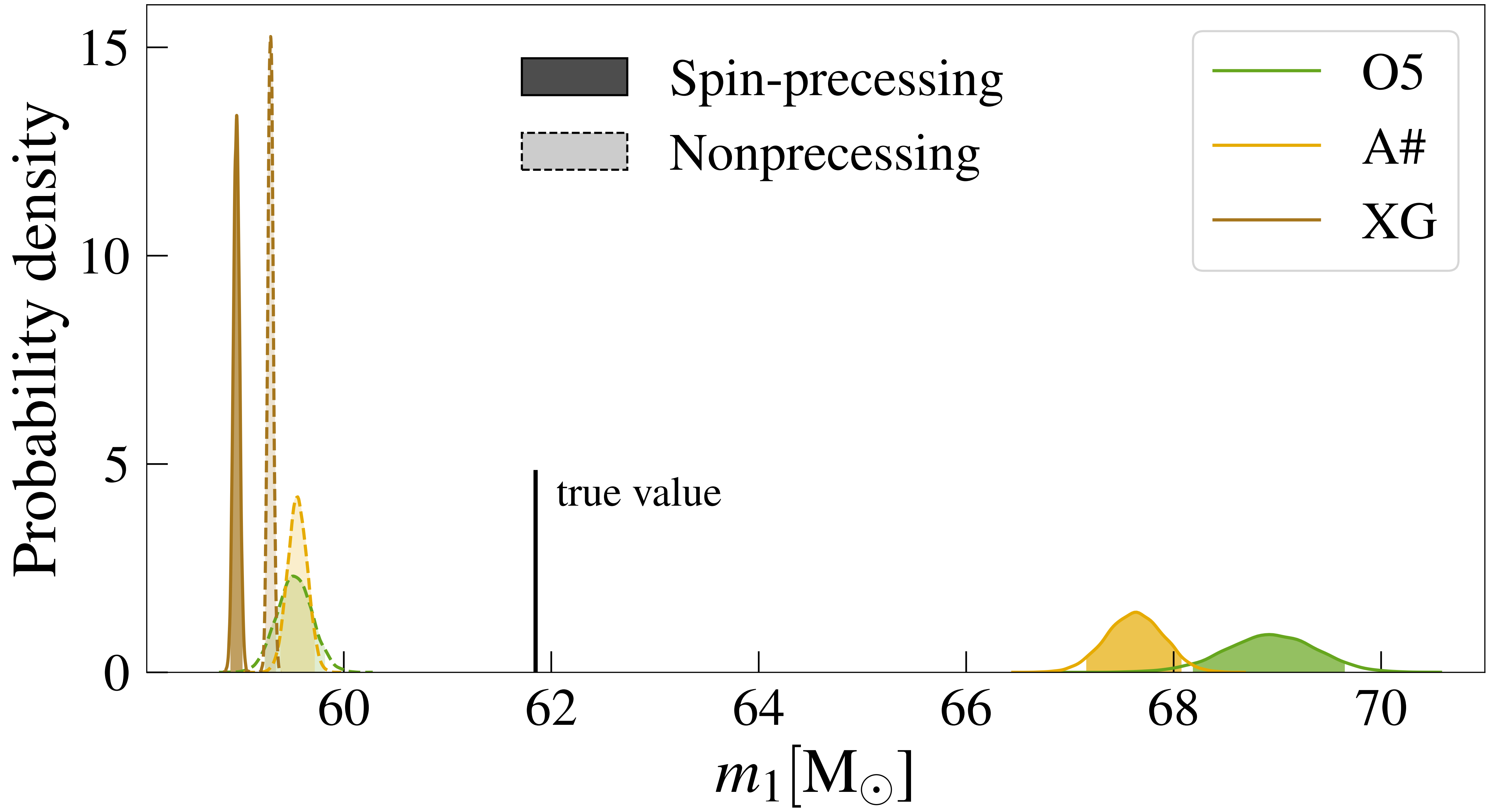


m_2 **biased** ***[NS max mass]***

- $m_1 = 61.8 M_\odot, m_2 = 9.5 M_\odot$
- $\chi_{eff} = -0.43, \chi_p = 0.77$ and $\chi_{eff} = 0.89, \chi_p = 0$
- $SNR_{O5} = 119, SNR_{XG} = 2490$



m_1 ***biased by several*** $M_\odot$
[edge of mass-gap]

Summary

- Today's state-of-the-art BBH waveform models would lead to **widespread parameter estimation biases in XG detectors**.
- Such biases **can affect scientific conclusions**:
  - Position of mass gaps → supernova physics, NS max mass
  - Distance, sky position → Hubble constant
  - Mass & spin distribution of BBH → formation scenarios
  - Tests of GR
- Biases most pronounced for large spins and/or large mass-ratios
- **Improved waveform models required** for full science exploitation of XG detectors.