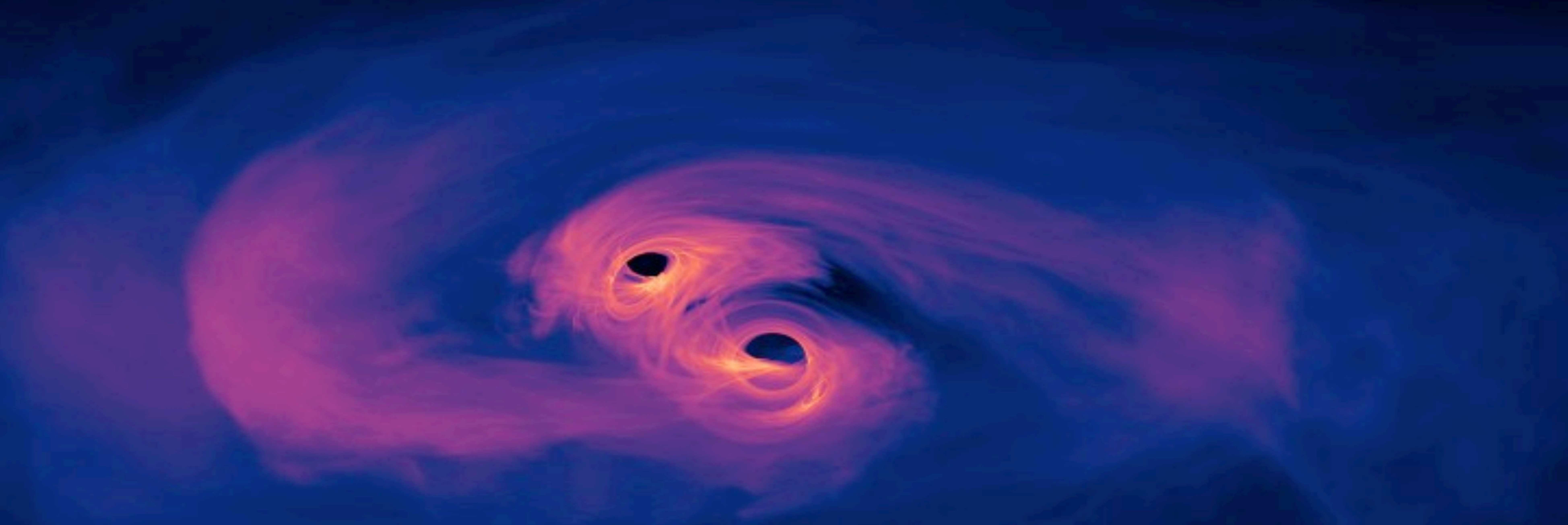
Stars or gas? Constraining the hardening processes of massive black-hole binaries with LISA



Ten years to LISA: New Challenges and Opportunities in Multimessenger/Multiband Science

Pasadena - 2nd April 2025

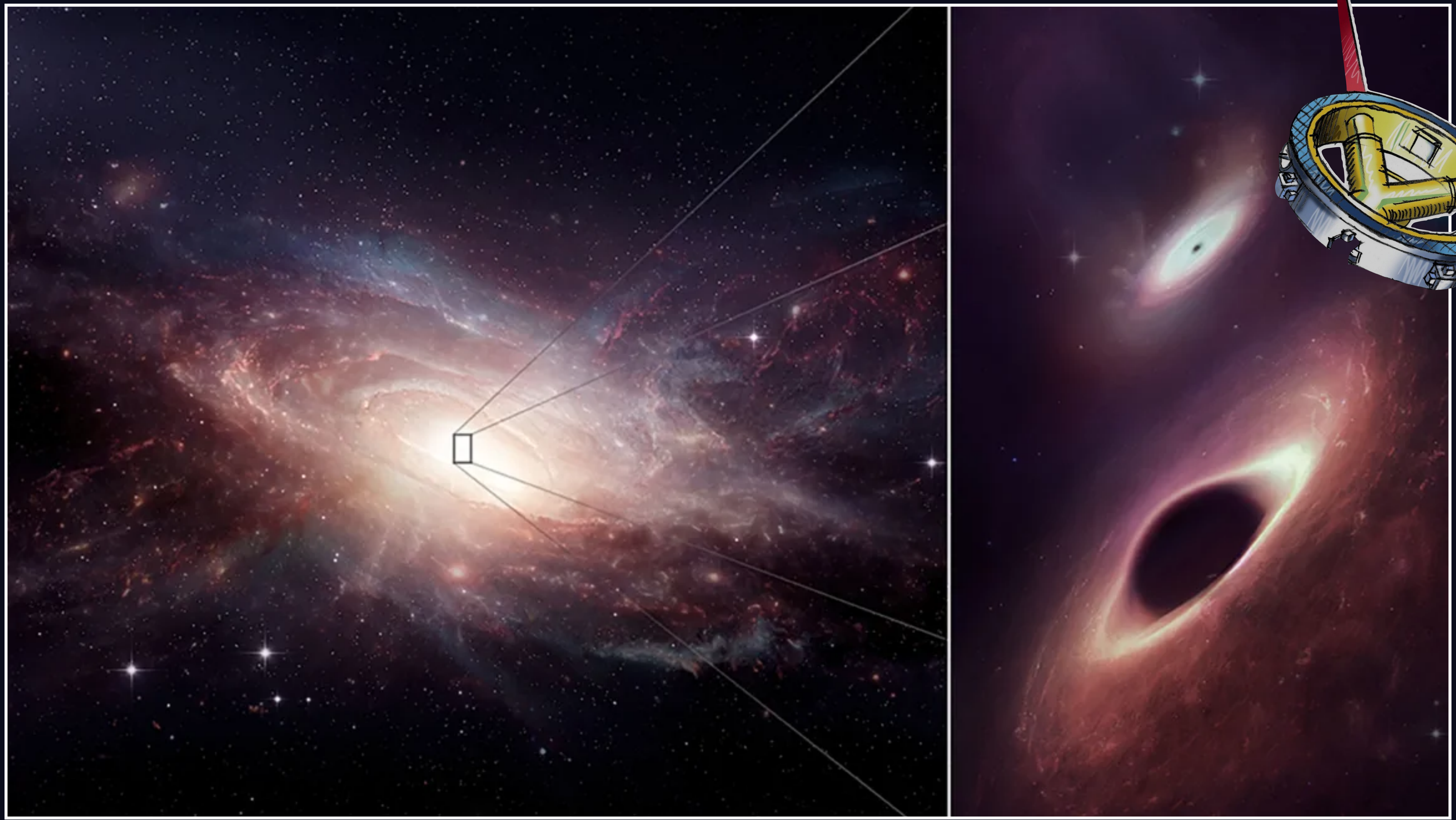
PhysRevD.111.023004

Alice Spadaro, Riccardo Buscicchio, David Izquierdo-Villalba, Davide Gerosa, Antoine Klein, Geraint Pratten

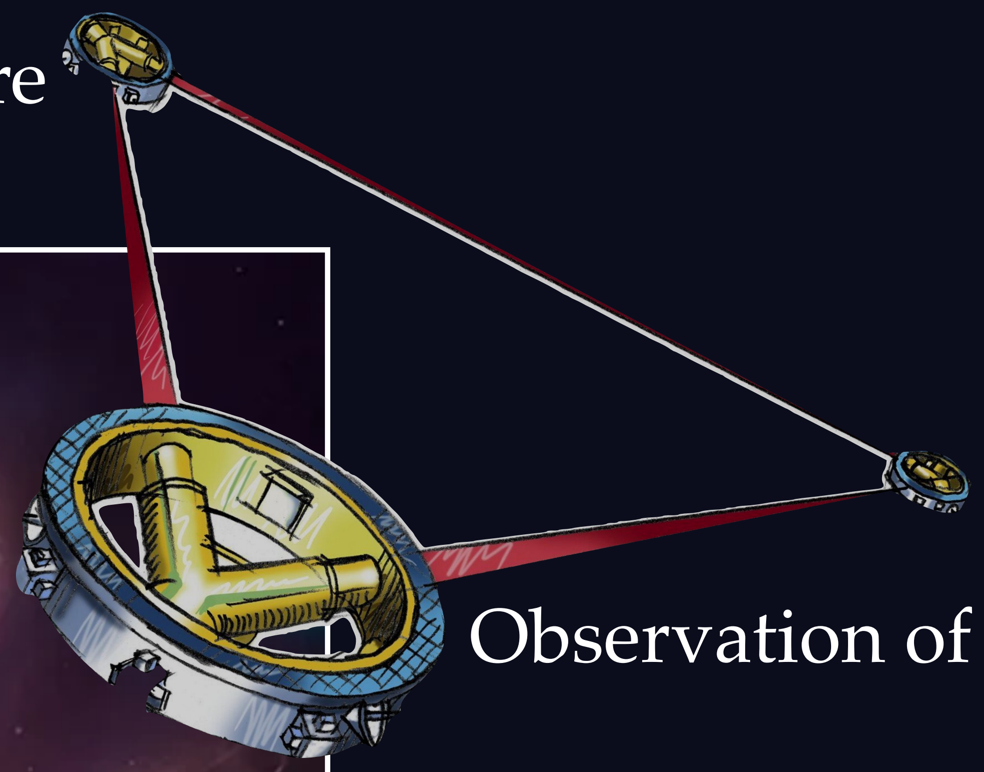
Image by NASA's Goddard Space Flight Center/Scott Noble

Massive black-hole binaries in the cosmic landscape

Galaxy mergers: building blocks for the large-scale cosmic structure



Michael Koss/ALMA (ESO/NAOJ/NRAO)/M. Weiss (NRAO/AUI/NSF)



Observation of MBHB: one of the main science objectives of LISA

How do they form?

How do they grow?

How do they merge?

This work: **Do they evolve in either gaseous or stellar environment?**

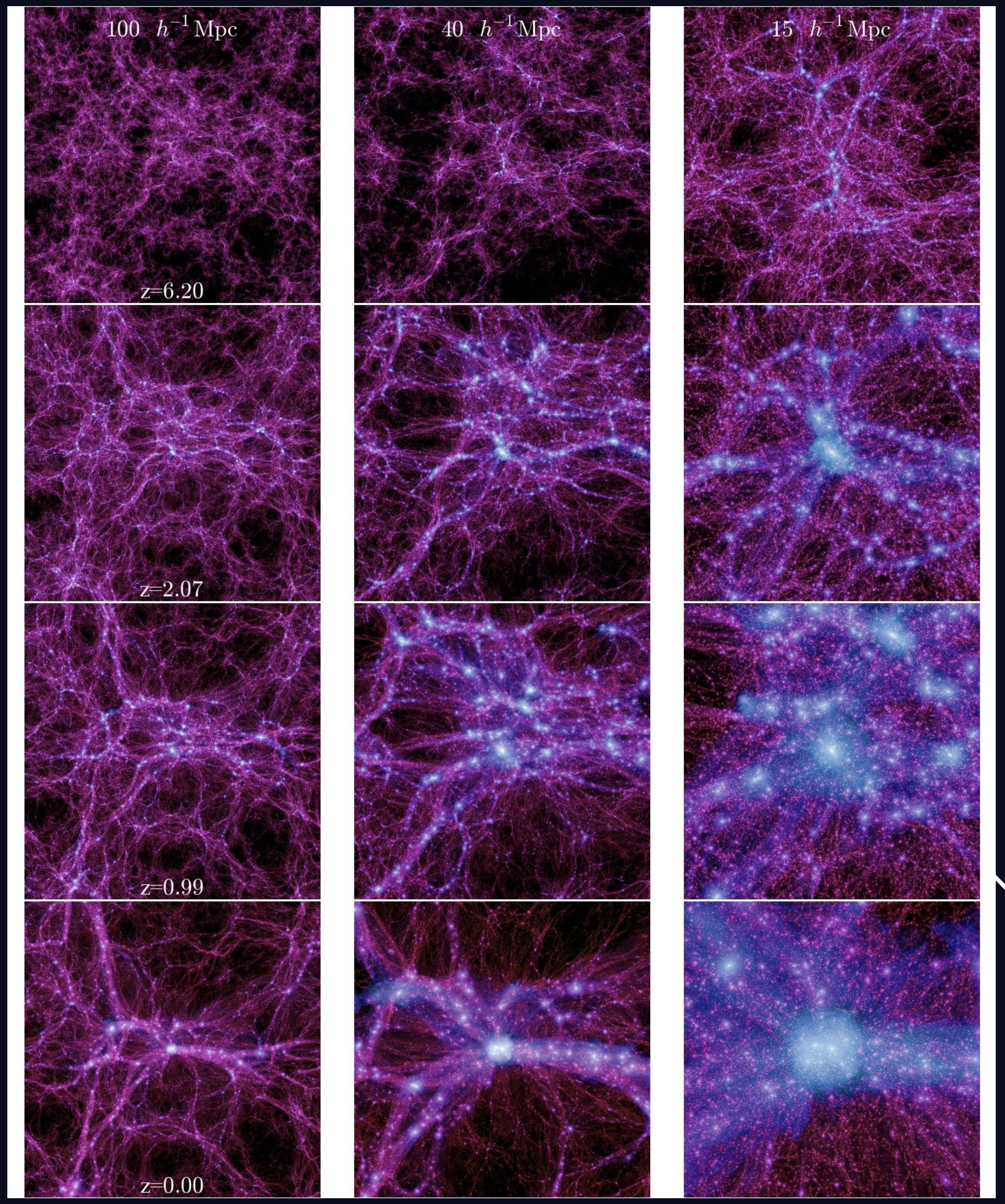
Astrophysical population of massive black-hole binaries

- N-body simulation of dark matter evolution (ΛCDM cosmology) ⟶ halo merger trees
- Semi-analytical model to follow the cosmological evolution of galaxies, MBHs, and MBHBs

L-Galaxies

See David Izquierdo-Villalba's talk!
(Today - 1:30pm)

Millennium II simulation



Millennium-II simulation [Nature, 435, 629]

L-Galaxies code

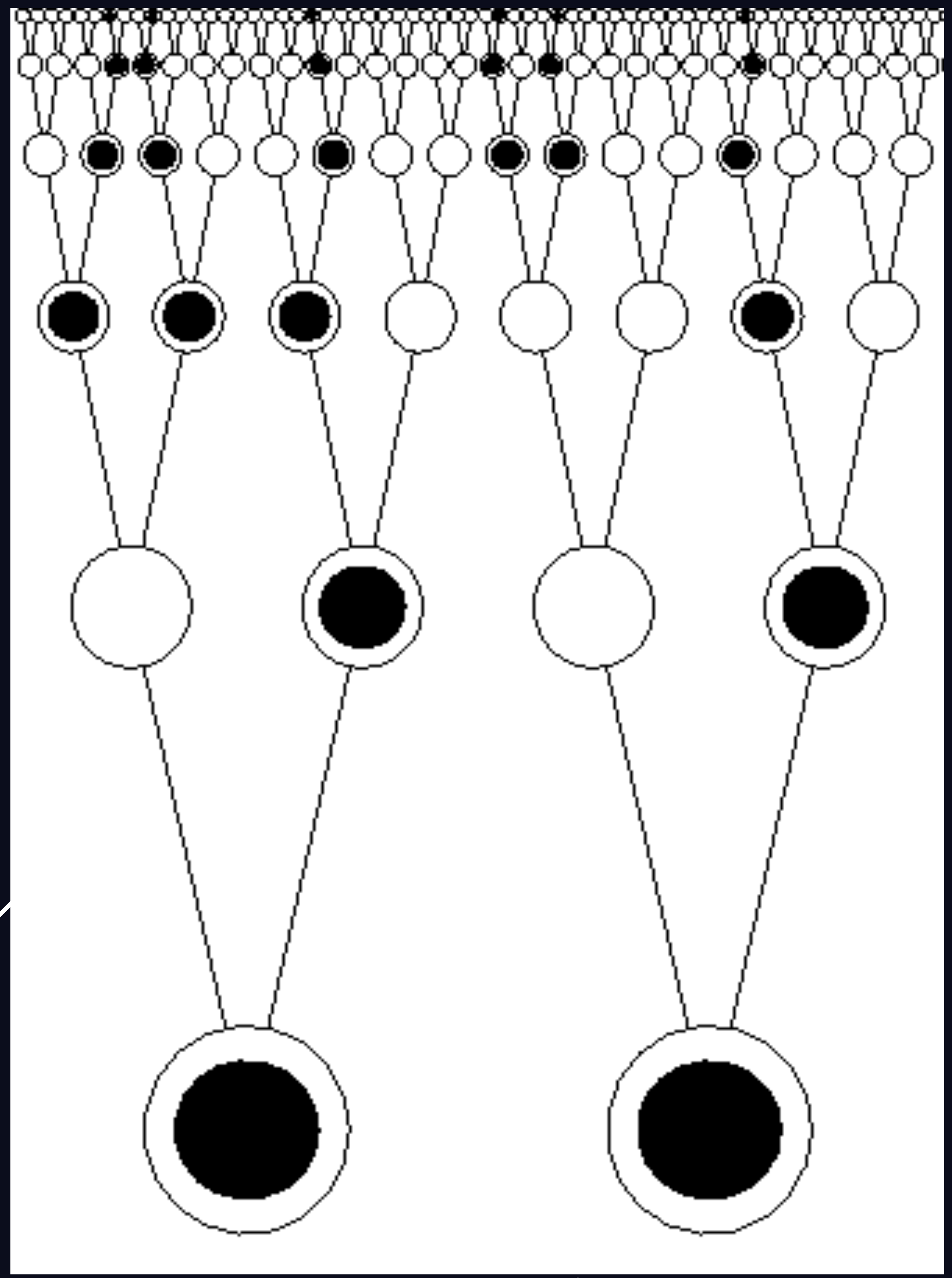


Figure adapted from Schnittman at al. 2007

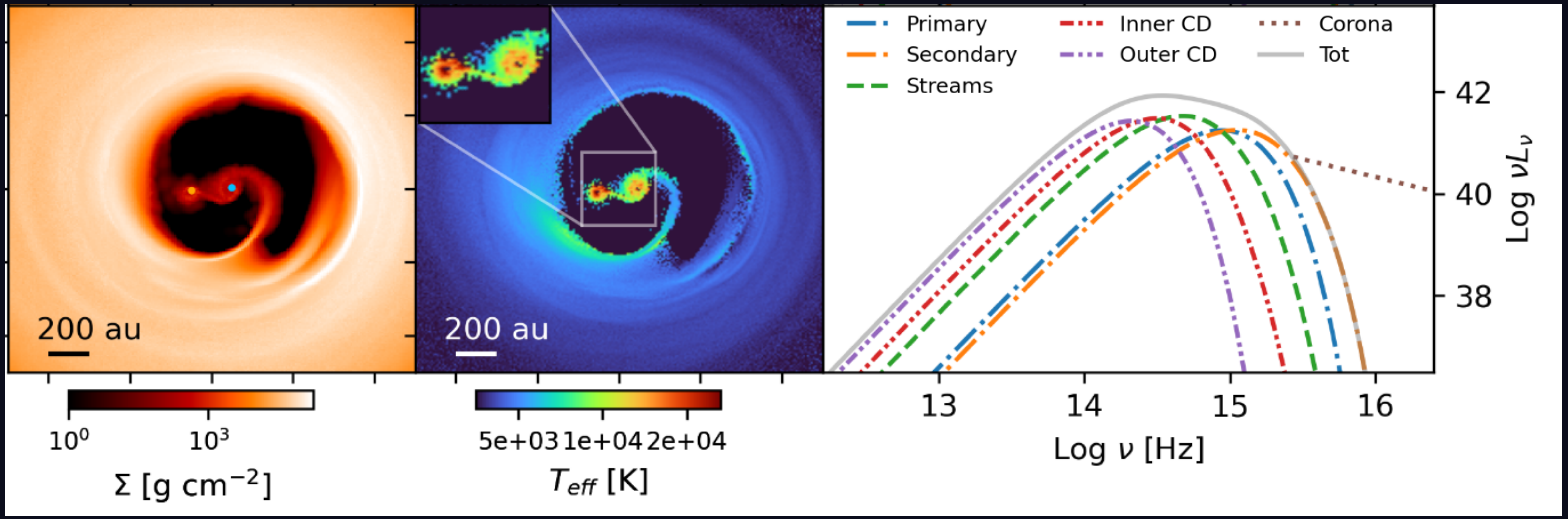
MBHB merger population ✓

Astrophysical environment

- N-body simulation of dark matter evolution (ΛCDM cosmology) ⟶ halo merger trees
- Semi-analytical model to follow the cosmological evolution of galaxies, MBHs, and MBHBs

BH-BH evolution:

- Pairing (~Kpc)
- Hardening (~pc)



F. Cocchiararo, et al. A&A 691, A250 (2024)

- stellar $\frac{da}{dt} \propto \rho_{star}$

- gas $\frac{da}{dt} \propto \dot{M}_{bin}$

$$f_{gas} = \frac{M_{reservoir}}{M_{bin} + M_{reservoir}} \lessgtr 0.5$$

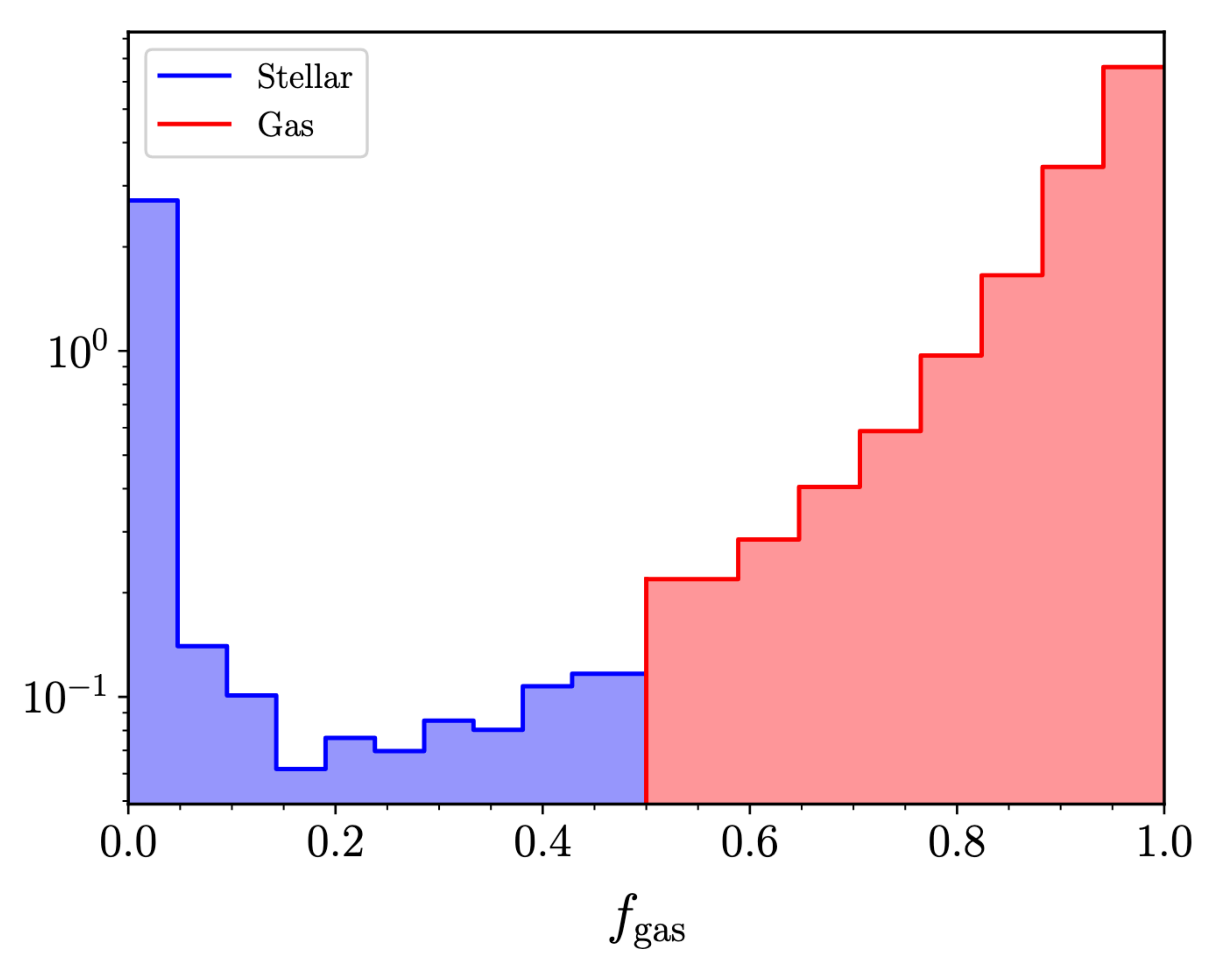
stellar hardening

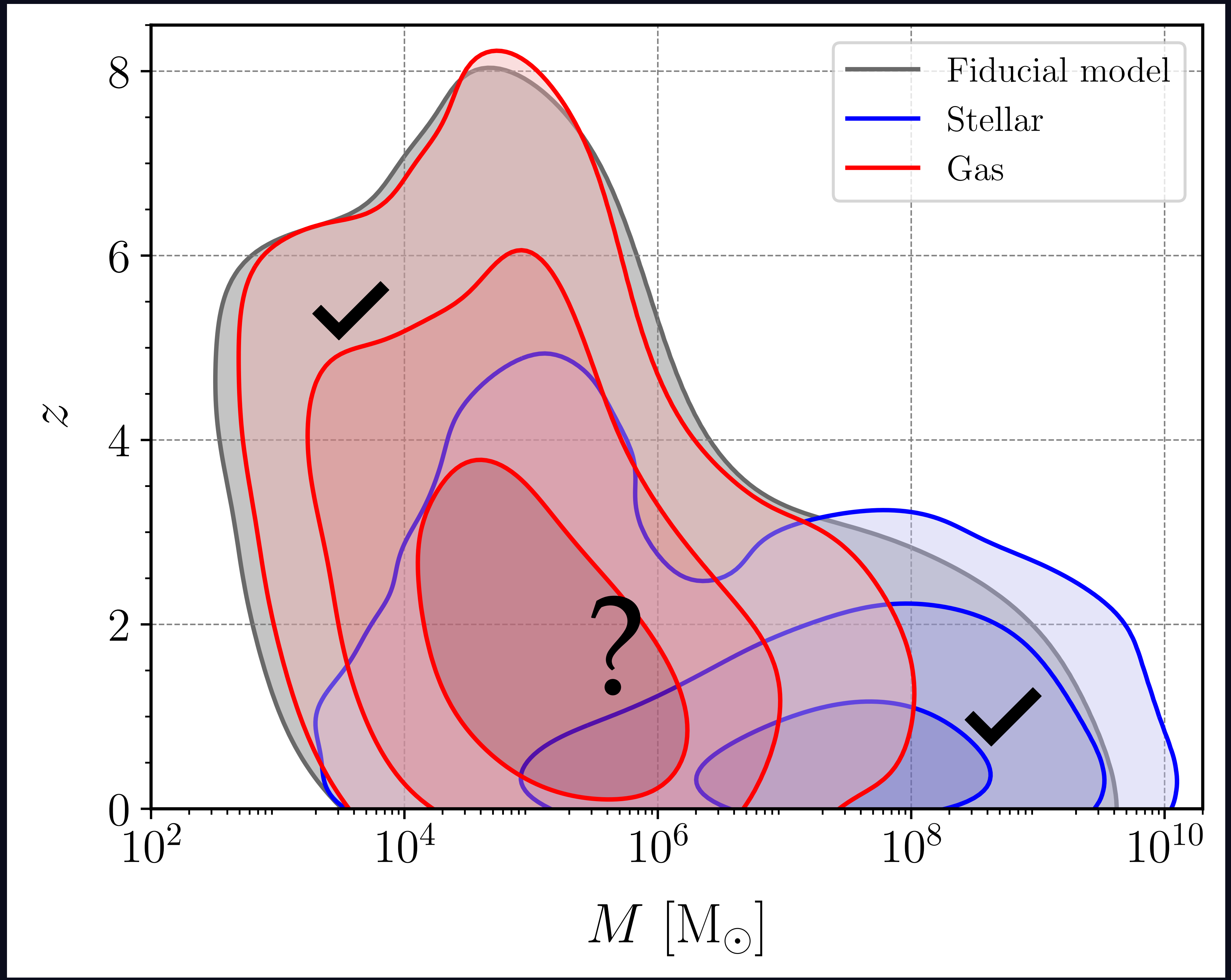
gas hardening ⟶ electromagnetic emission

- GW phase (~mpc)

Galactic environment ✔

Our fiducial model





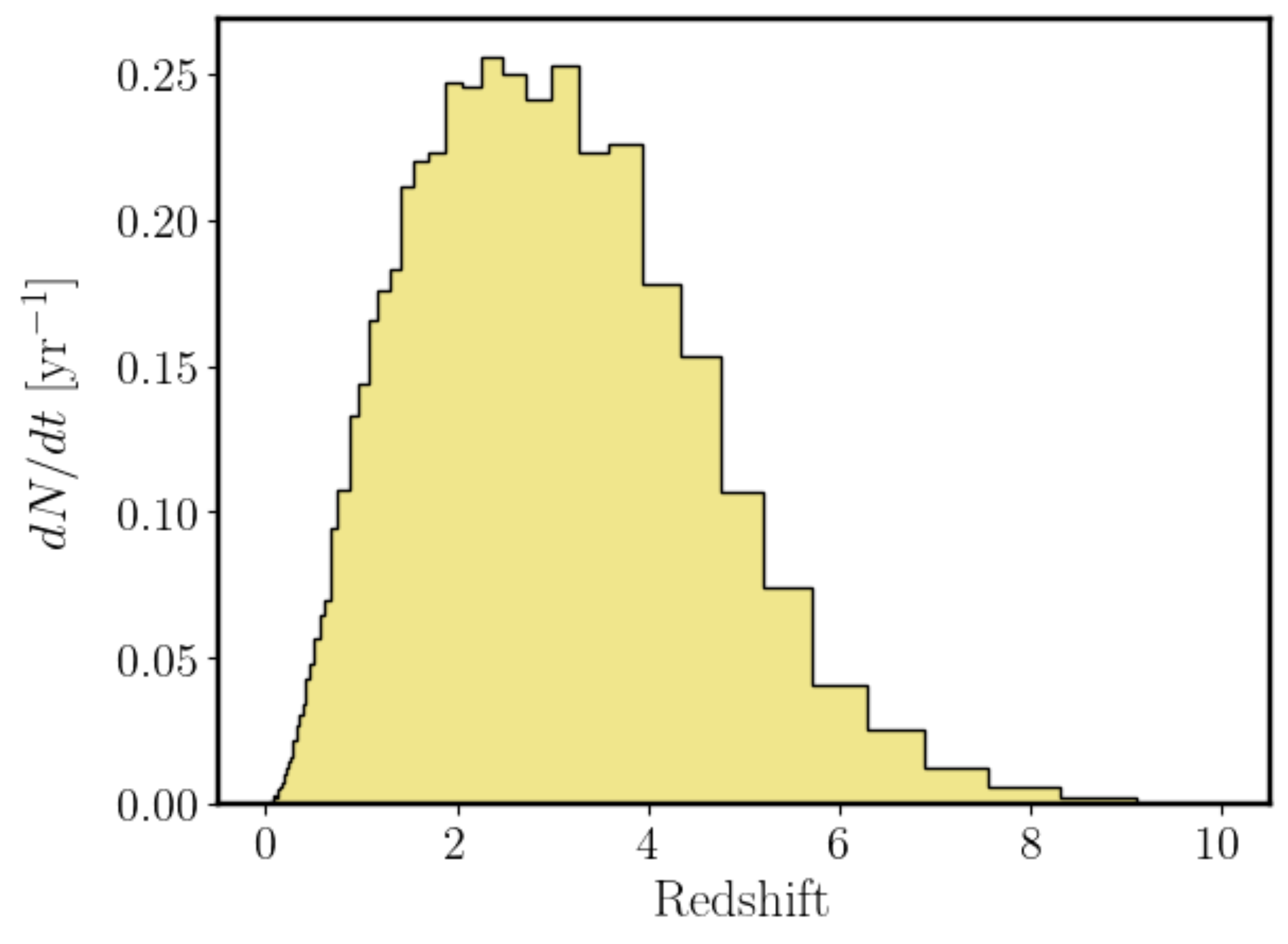
- Clear picture: high-mass and low-redshift: stellar hardening
  low-mass and high-redshift: gas hardening
- Not so clear: intermediate ranges

→ Do they evolve in either gaseous or stellar environment?

Building mock LISA catalogs

Our recipe:

- Predicted merger rate by L-Galaxies: $\frac{dN}{dt_{obs}} = \frac{dN}{dz} 4\pi \left[\frac{d_L}{(1+z)}\right]^2 \frac{dz}{dV_c}$

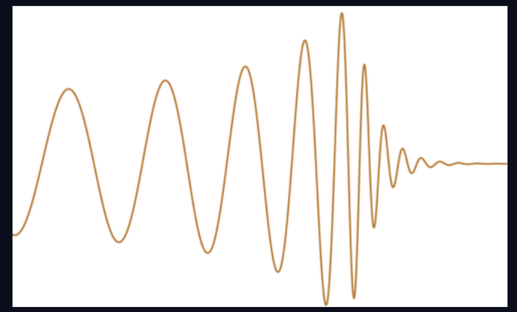


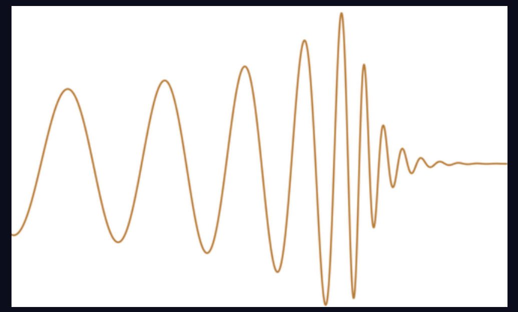
- Source samples: $P_\lambda(N_{cat}) = \frac{\lambda^{N_{cat}} e^{-\lambda}}{N_{cat}!}$ where $\lambda = T_{obs} \int \frac{dN}{dt_{obs}} dz$

Each source characterized by $m_1, m_2, \chi_1, \chi_2, z$

- Extrinsic parameters:

Merger time t_m





$T_{LISA} = 4yrs$

$T_{obs} = 5yrs$

λ ~U $(0, 2\pi)$ $cos\iota$ ~U(-1, 1) t_m ~U$(0, T_{obs})$

ϕ_0 ~U$(0, 2\pi)$ $sin\beta$ ~U(-1, 1) ψ ~U$(-\pi/2, \pi/2)$

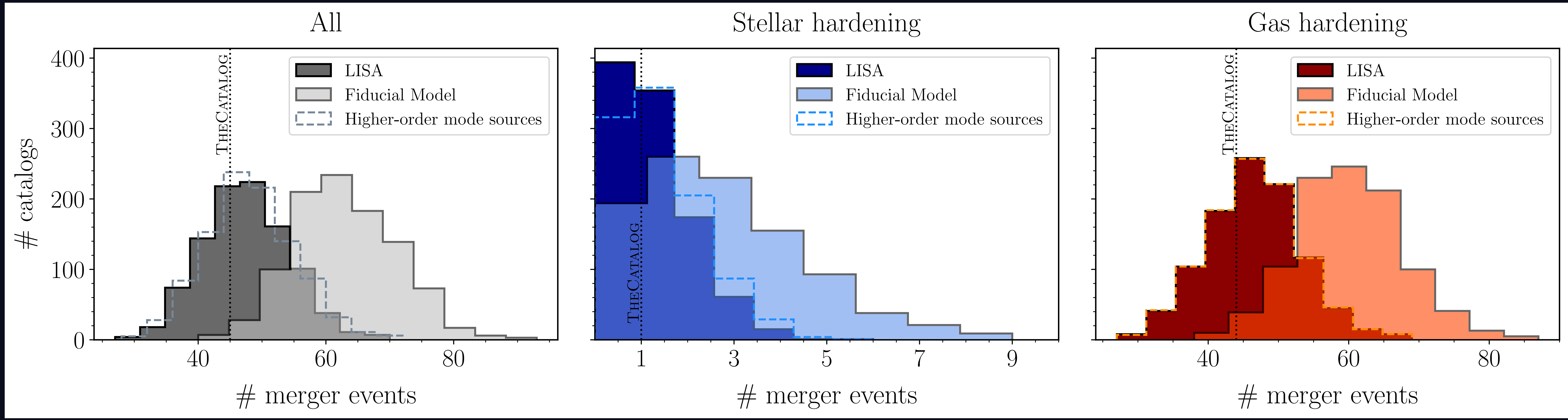
Building mock LISA catalogs

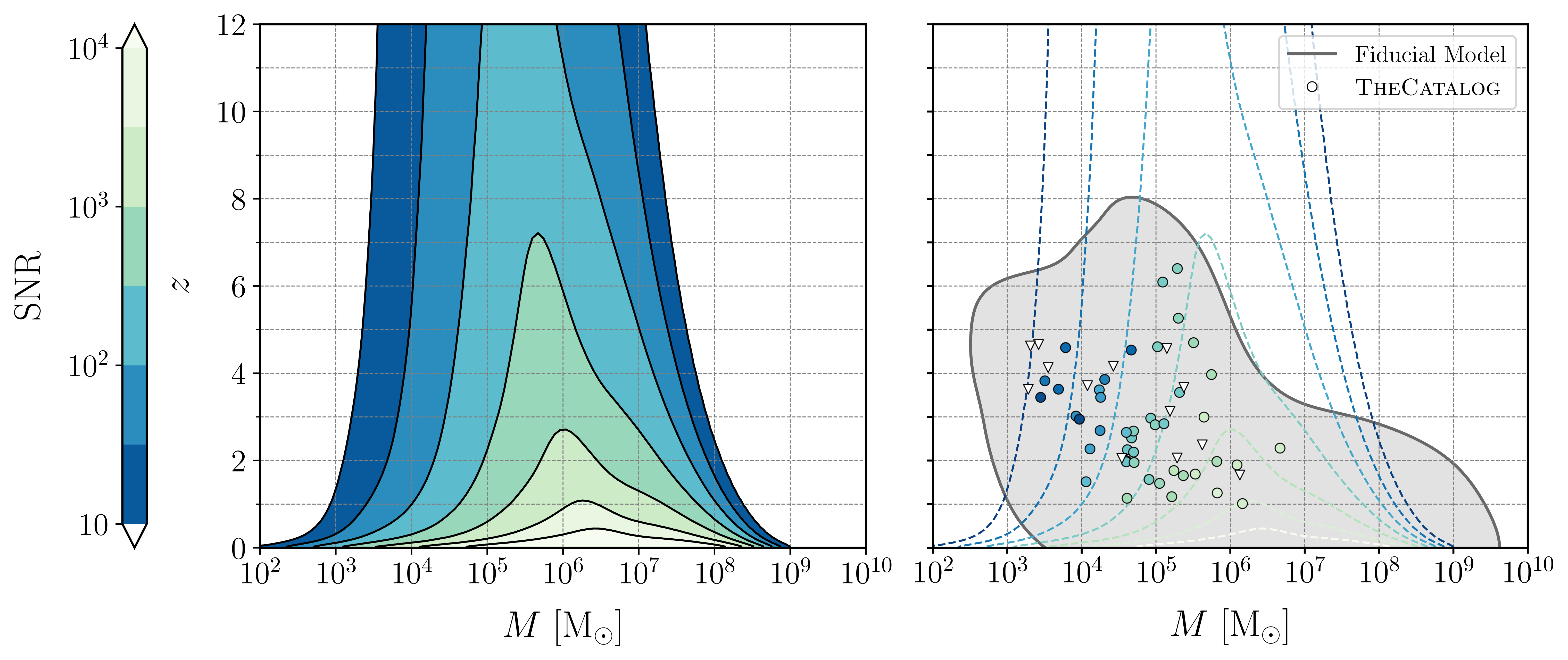
- Detectability:

-SNR computation (with TDIs): SNR > 10

-Dominant mode in LISA band: $5\,f_{isco} > 10^{-4}$

-IMRPhenomXHM approximant: $q > 10^{-2}$





Inference on astrophysical (sub)populations

GW events

→ ✗ Gas/stellar hardening

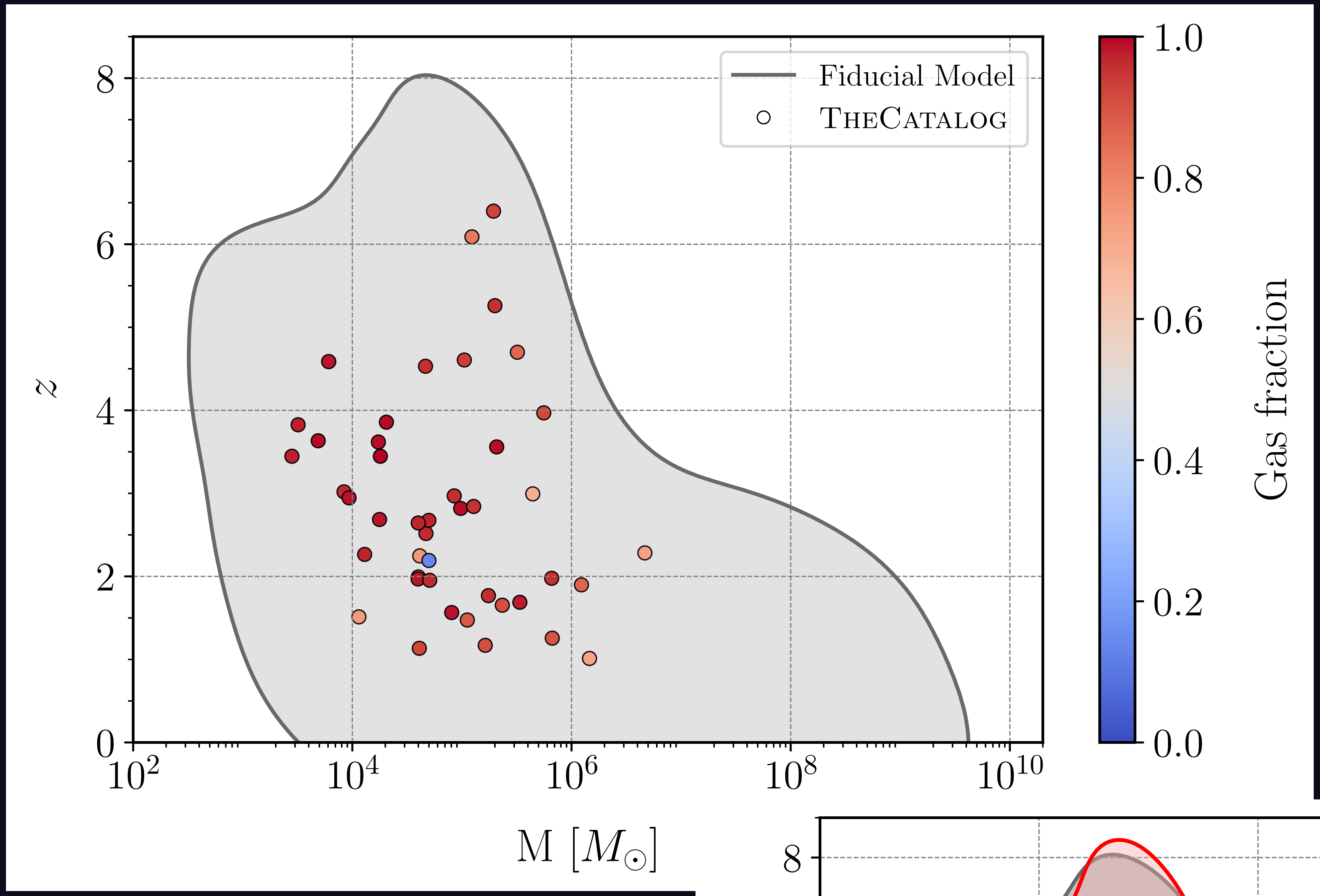
→ Posterior samples on source parameters

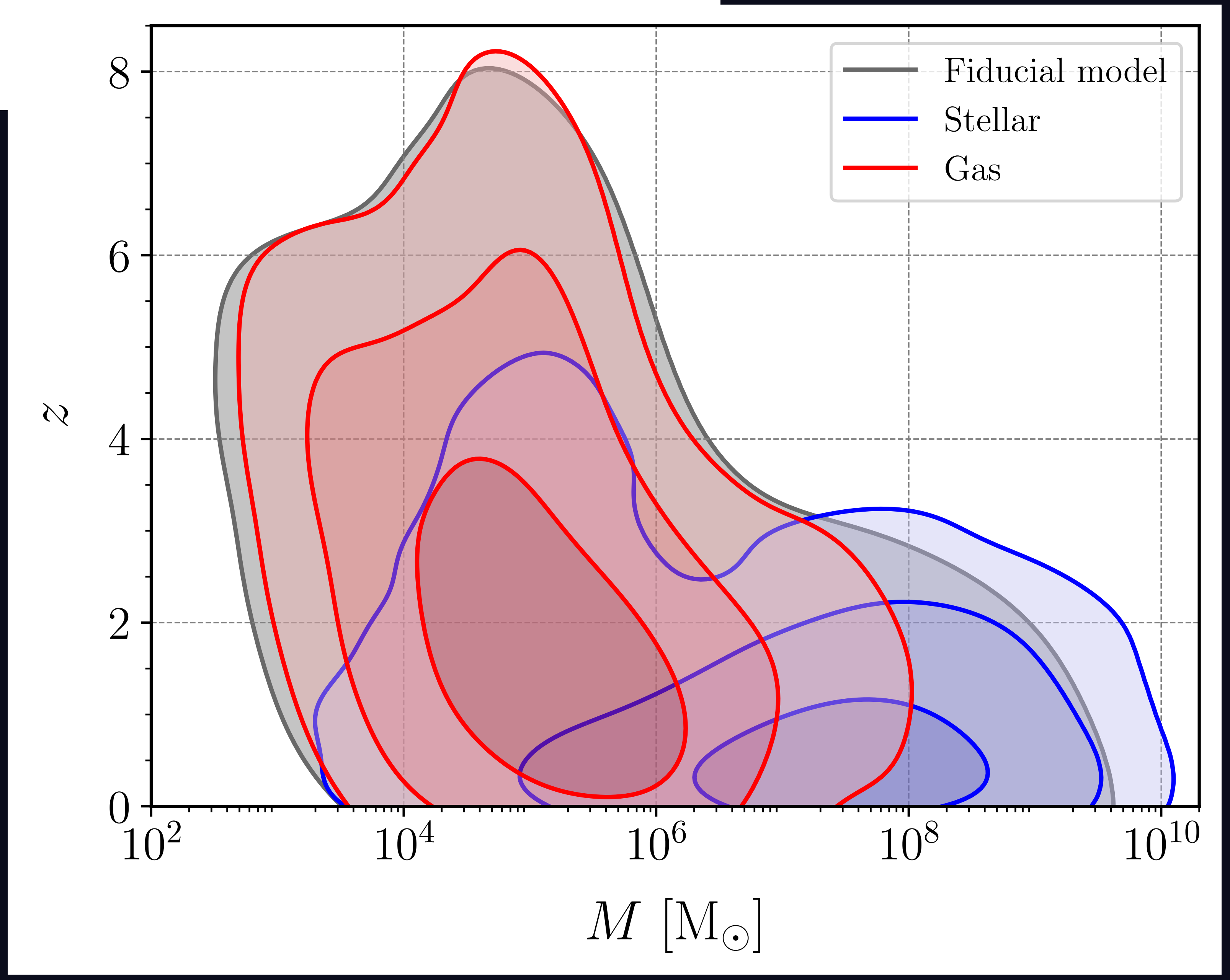
+

Probability density estimate of the astrophysical sub-populations

↓

Gas/stellar hardening





The 'one to many' formalism

U = uninformative model

G = gas hardening

S = stellar hardening

- Posterior

$$p(\theta|d,G) = p(\theta|d,U)\frac{p(\theta|G)Z(d|U)}{p(\theta|U)Z(d|G)}$$

LISA posterior

- Bayes factors

$$B_{G/U} = \frac{Z(d|G)}{Z(d|U)} = \int p(\theta|d,U)\frac{p(\theta|G)}{p(\theta|U)}d\theta$$

$$B_{G/S} = \frac{Z(d|G)}{Z(d|S)} = \frac{\int p(\theta|d,U)p(\theta|G)d\theta}{\int p(\theta|d,U)p(\theta|S)d\theta}$$

KDE

Astrophysical information

KDE

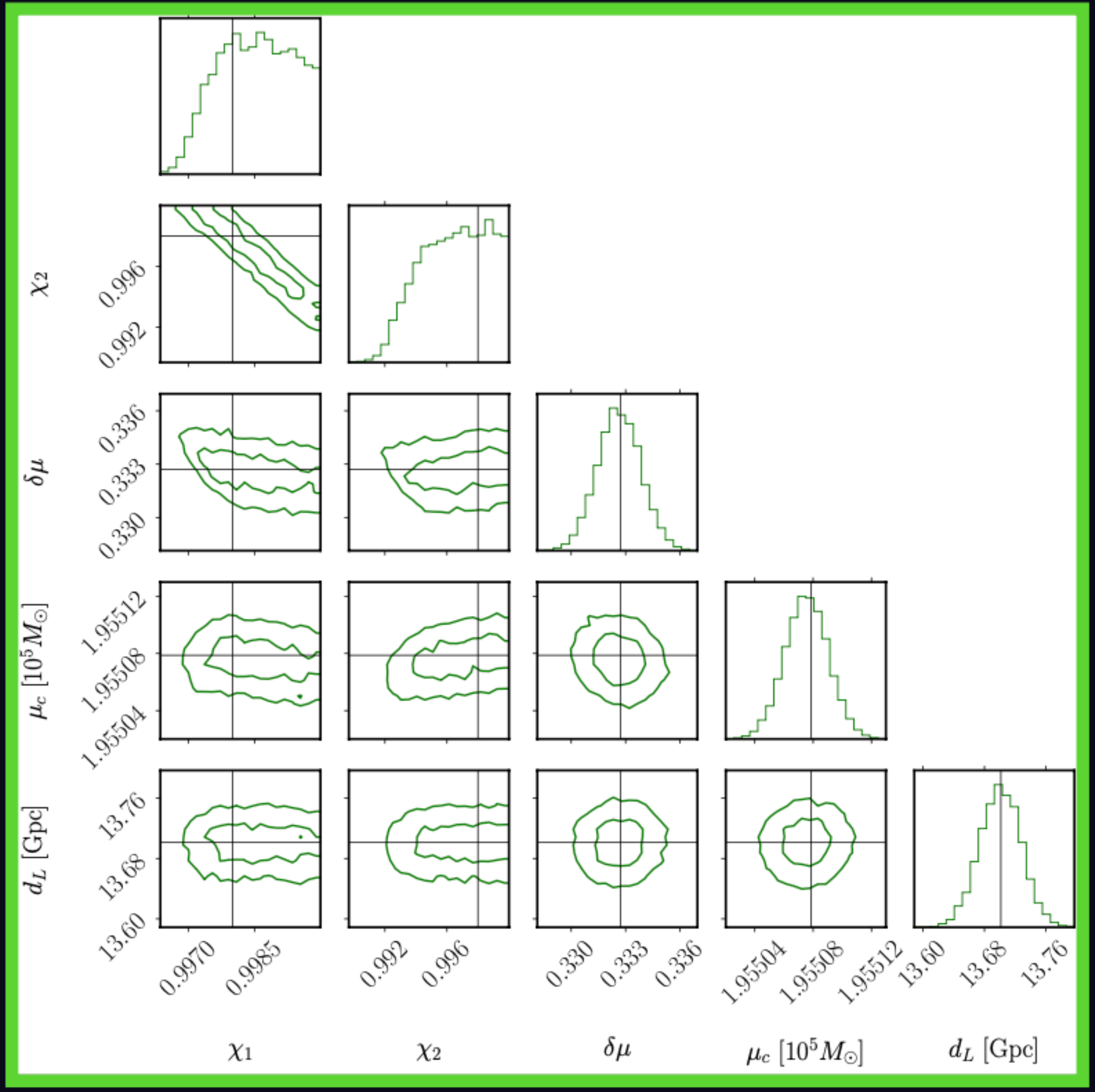
$\theta = \mu_c, \delta\mu, \chi_1, \chi_2, d_L$

+ selection effects $$D_{G/S} = \frac{p(det|G)}{p(det|S)}B_{G/S}$$

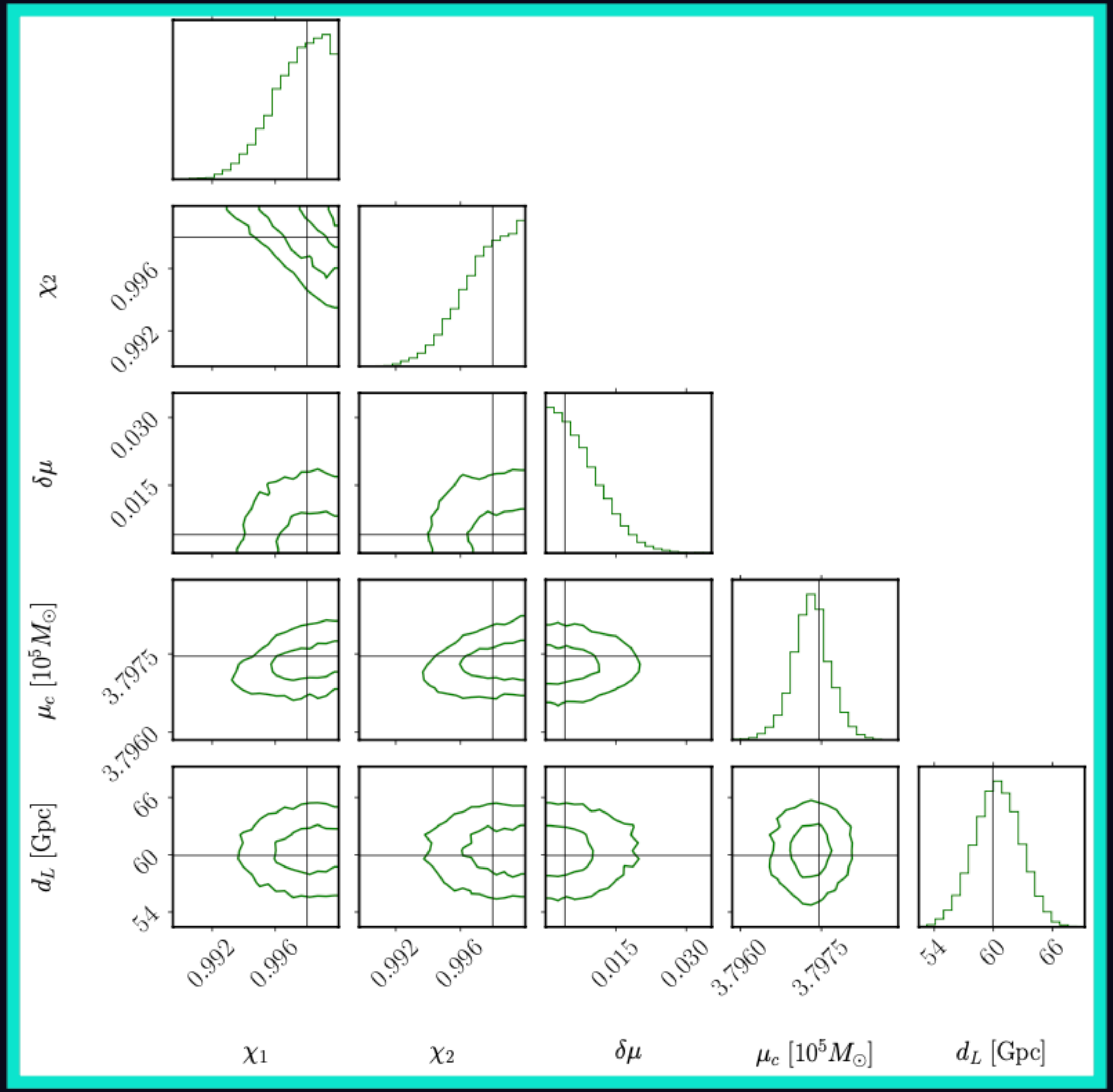
M. Mould et al., 2023, MNRAS 525, 3986

Single-event parameter estimation

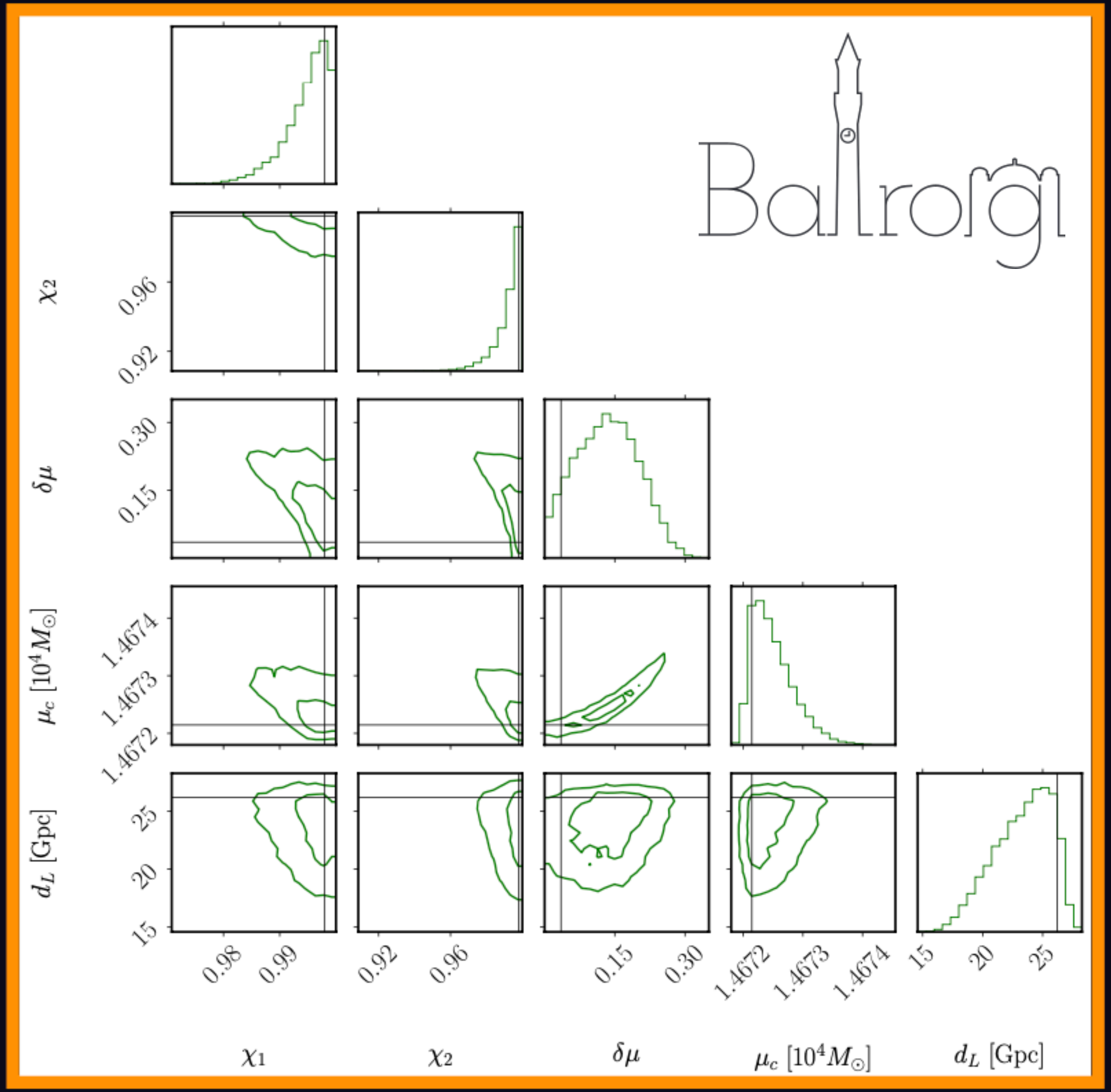
SNR~1300



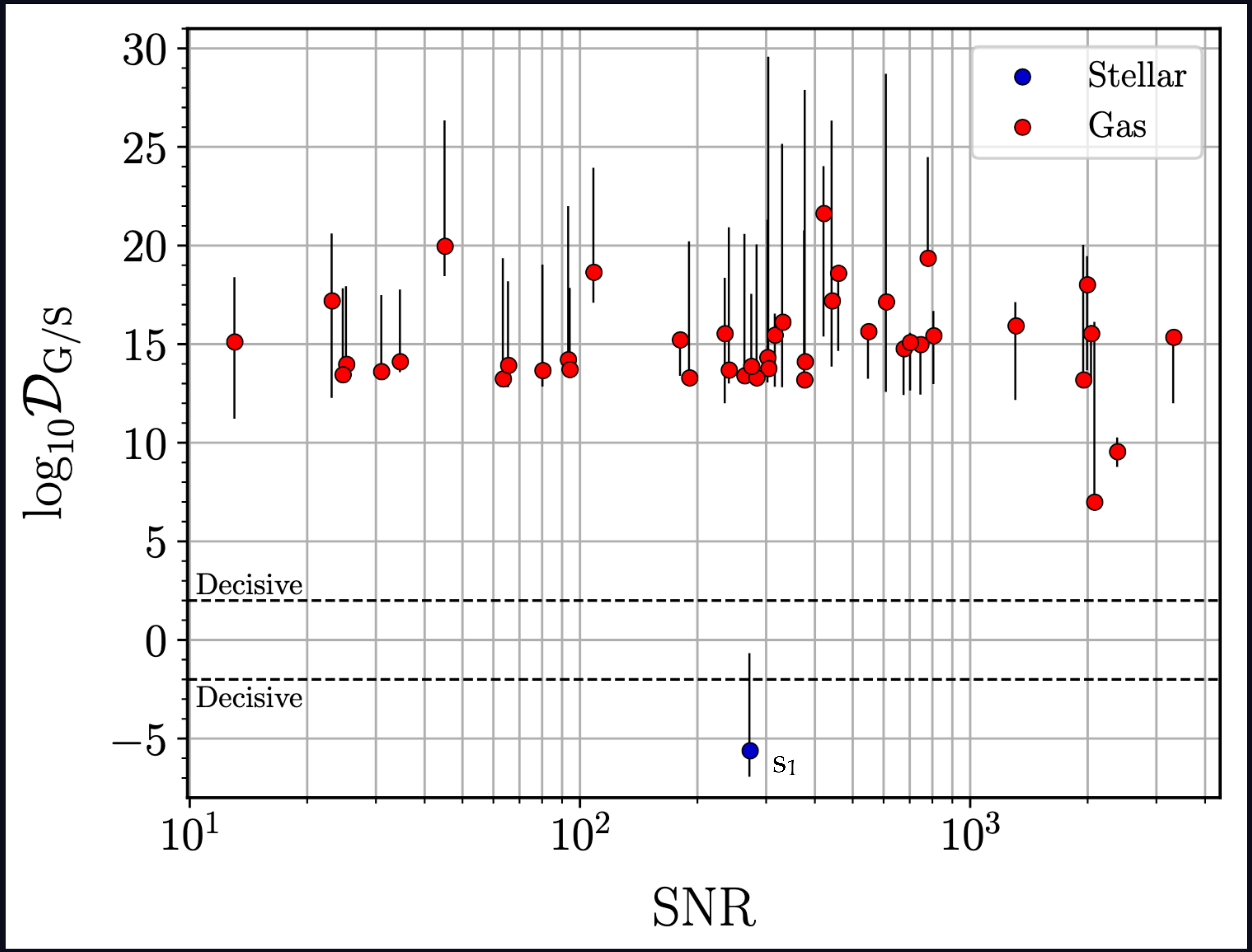
SNR~300

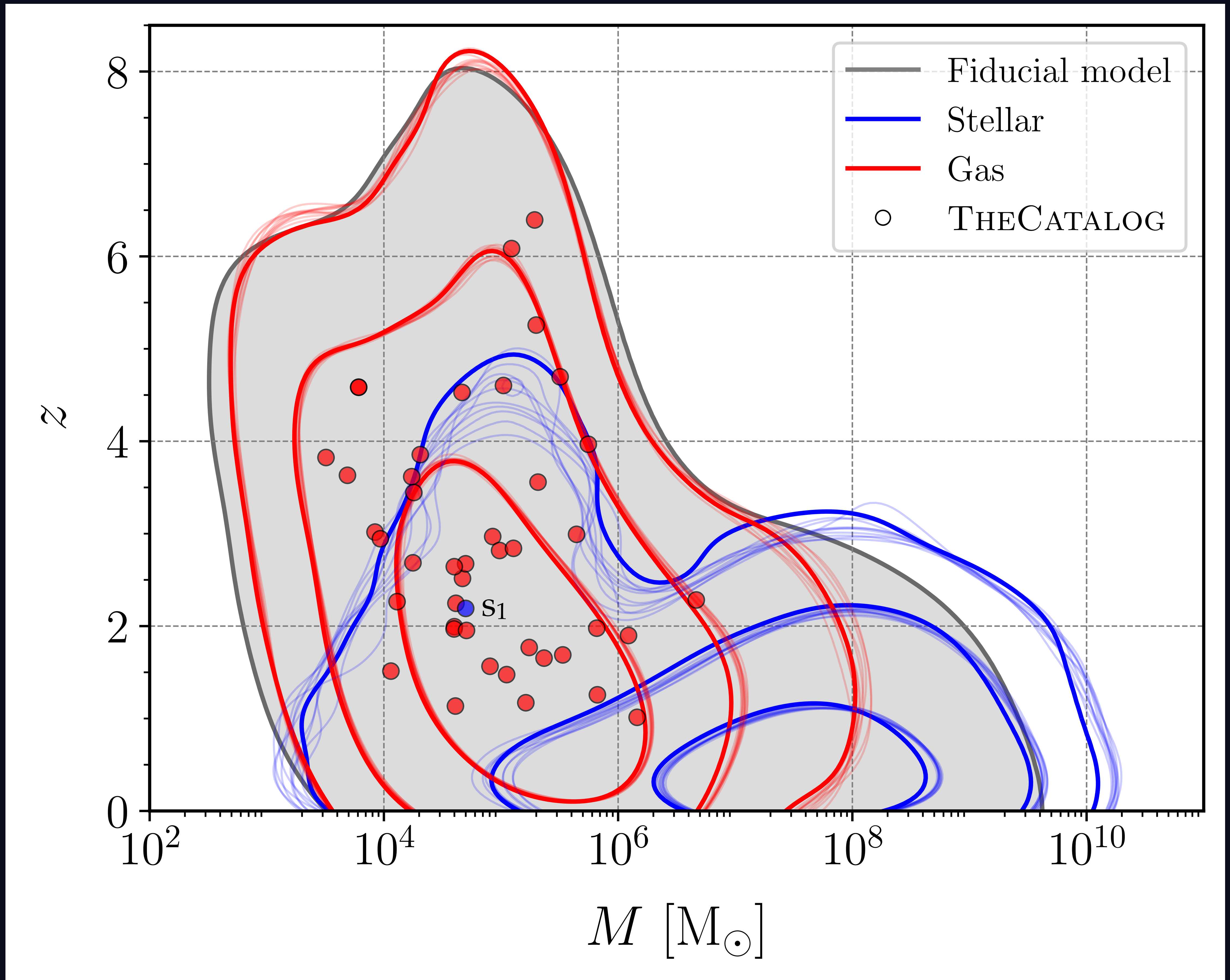


SNR~65



Astrophysical model selection



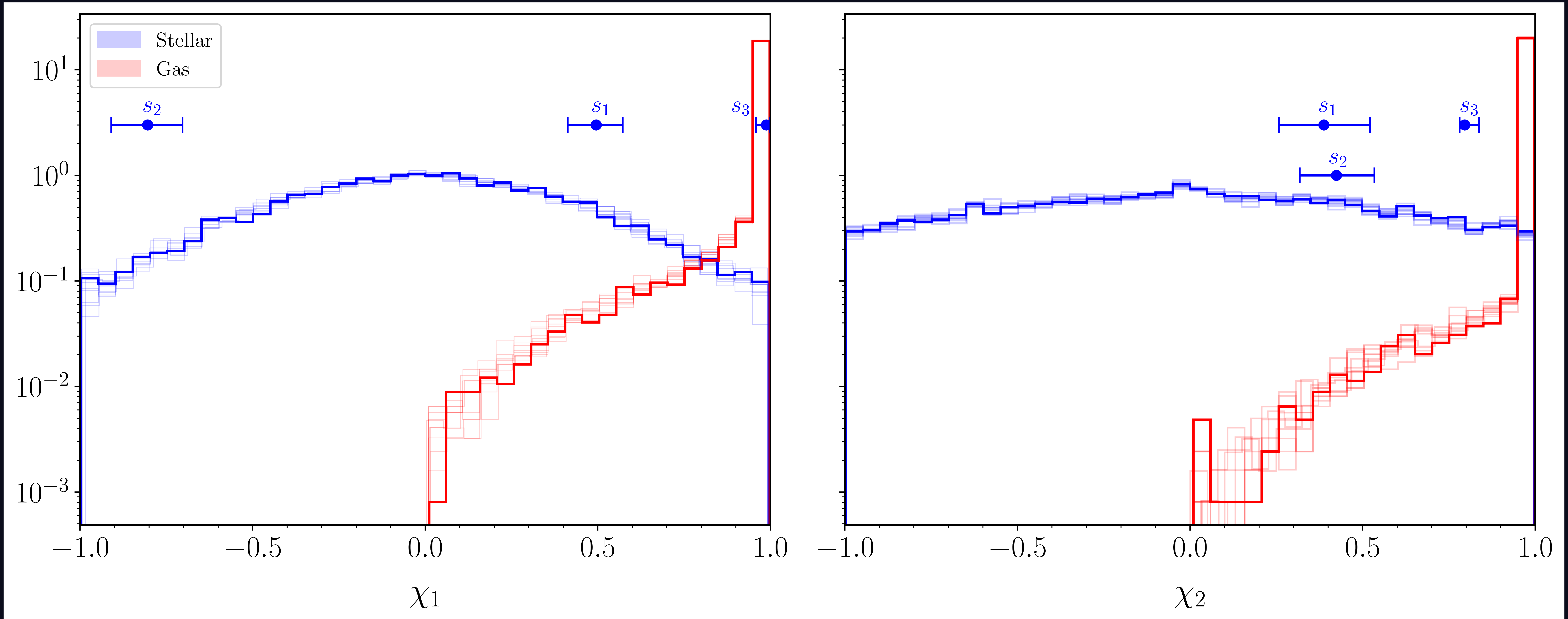


Can we constrain the astrophysical environment with LISA observations?

Yes…within context of the adopted astrophysical models

Which features help us to distinguish stars from gas?

Importance of the BH spins



Gas-rich environments: spin alignment → Actually, more complex picture due to internal properties of the disk

Gas-poor environments: isotropic spin orientations

→ We need more accurate astrophysical models!

Thanks for the attention!