The astrophysical gravitational-wave background as a cosmological probe

Gravitational-Wave Orchestra in the Alps
Annecy, 17-19 September 2024

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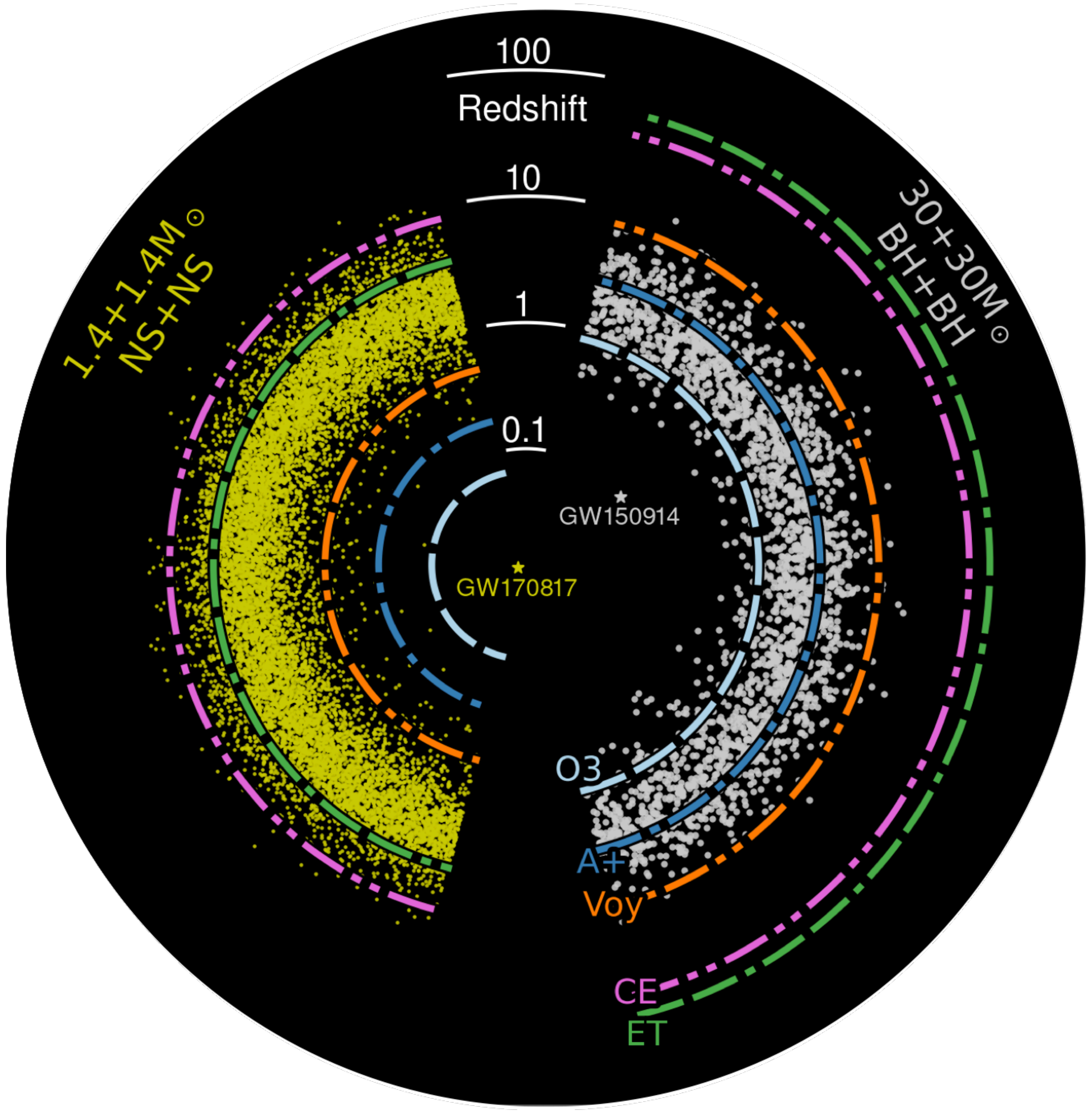
Outline

- Introduction about the astrophysical SGWB from stellar CBCs
- The SGWB as an observable to constrain both astrophysical and cosmological parameters
- Case study for BNSs
- Future applications for ET
- Based on *Capurri et al., Phys. Rev. D 109 (2024)*

SGWB from compact binary coalescences



Astrophysical horizon of current and proposed future detectors for compact binary systems
From cosmic explorer.org

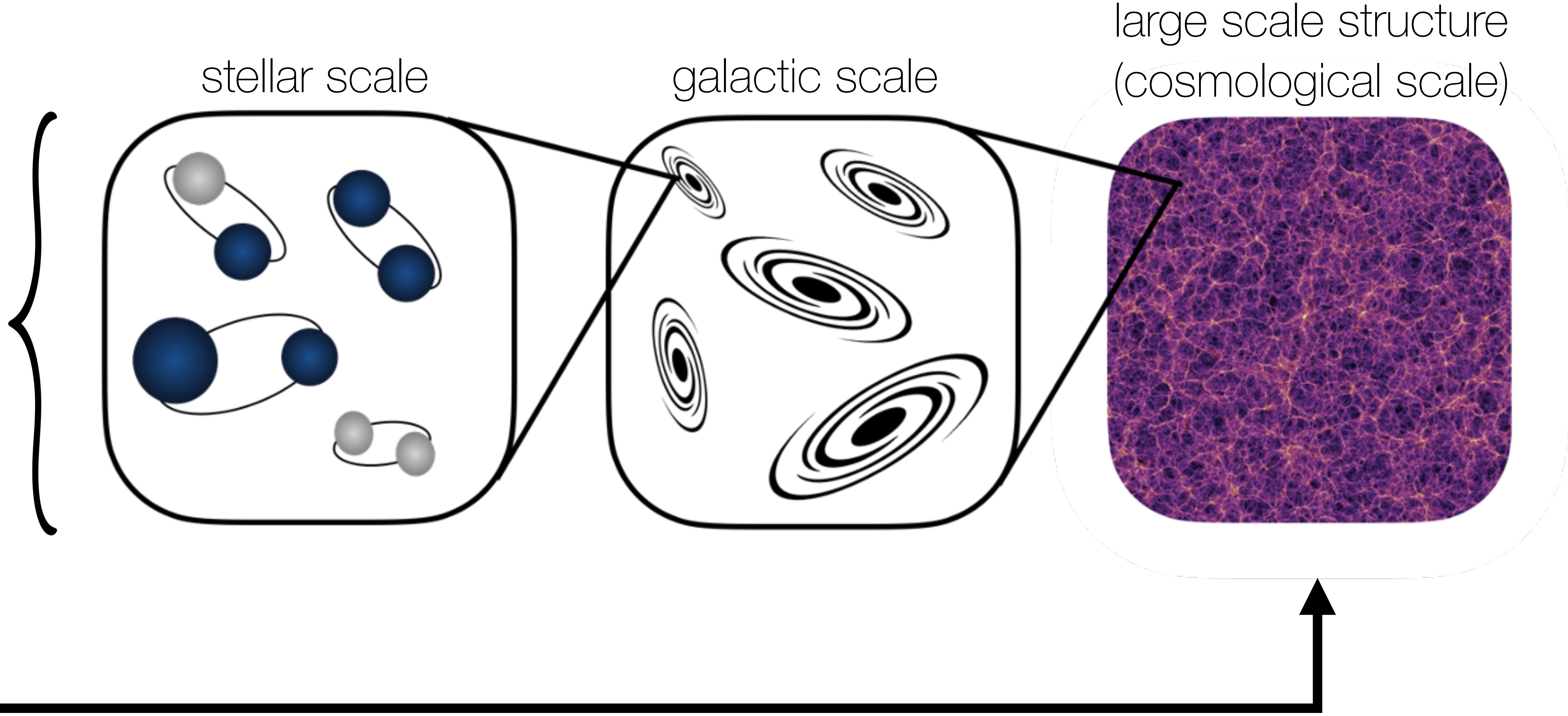
Superposition of the unresolved GW signals produced by coalescing stellar compact-object binaries

Why is it worth studying?

1) **Dominant contribution** in the 10 Hz-1 kHz band
2) **Population studies**: generated by merging binaries since the beginning of stellar activity
3) **Astrophysical probe**: many processes involved, at different time and spatial scales
4) **Cosmological probe**: sensitive to cosmological parameters, tracer of the large-scale structure

A tracer of the large-scale structure

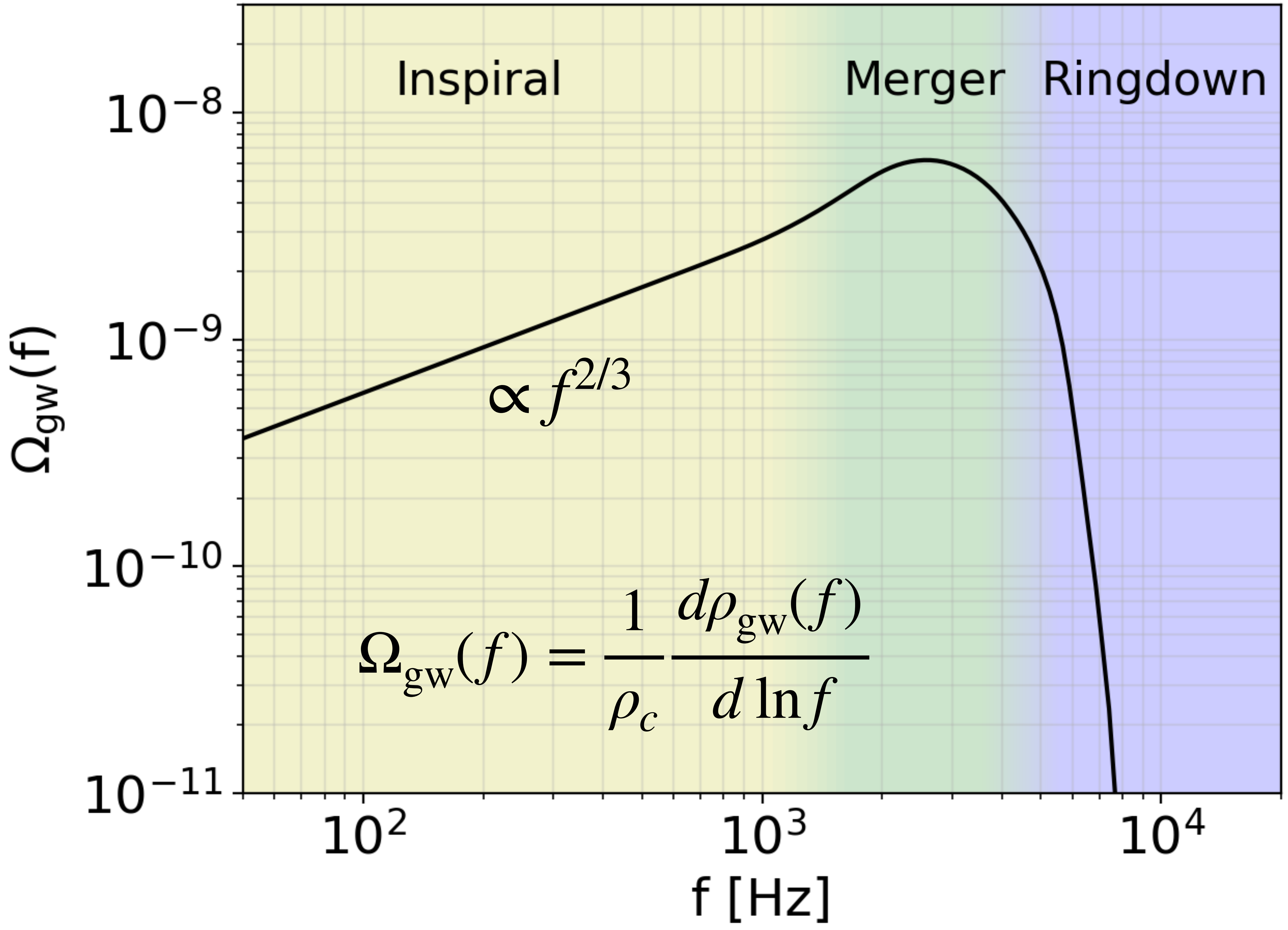
SGWB anisotropies



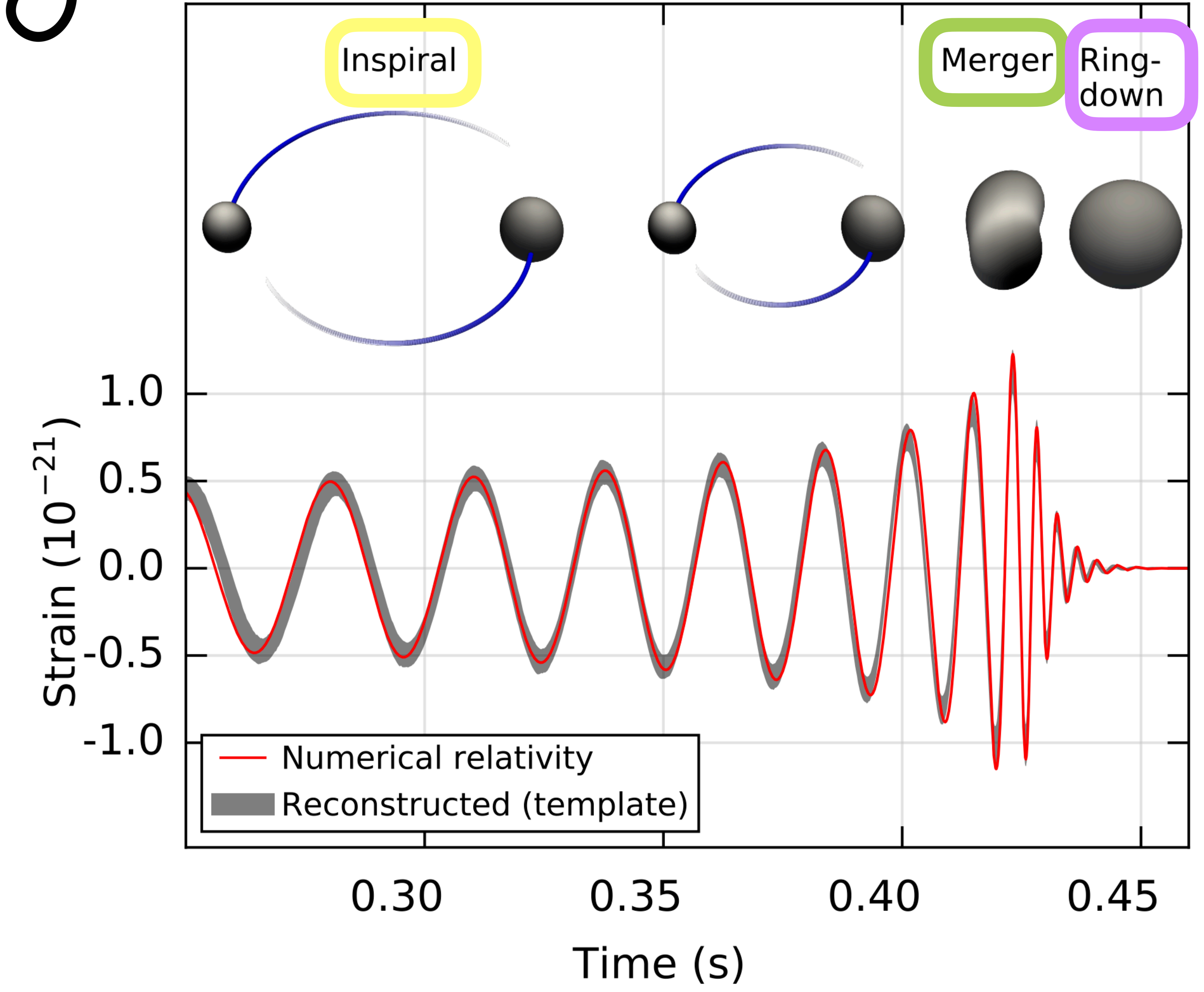
The anisotropies of the SGWB reflect those
of the underlying dark matter distribution!

The typical SGWB spectrum

Isotropic energy density parameter



Binary coalescence phases



LIGO Scientific Collaboration and Virgo Collaboration, arXiv:1602.03837

The isotropic component

Merger rates

Boco+20, arXiv:2012.02800

Santoliquido+22, arXiv:2205.05099

Waveform

Ajith+07, arXiv:0710.2335

Sky-averaged signal-to-noise ratio for a given detector

Taylor & Gair 2012, arXiv:1204.6739

$$\Omega_{\rm gw}(f) = \frac{8\pi G f}{3 H_0^3 c^2} \int dz \int d\theta\, p(\theta) \frac{\mathcal{R}(z\,|\,\theta)}{(1+z)\, h(z)} \frac{dE}{df}(f_e(z)\,|\,\theta) \int_0^{\bar{\rho}} d\rho\, P_\rho(\rho\,|\,\theta, z)$$

Astrophysical parameters

$\theta = \{\mathcal{M}_c, q, \chi, \ldots\}$

Removing (or not) resolved events

Total vs residual SGWB

Phinney, 2001, arXiv:astro-ph/010

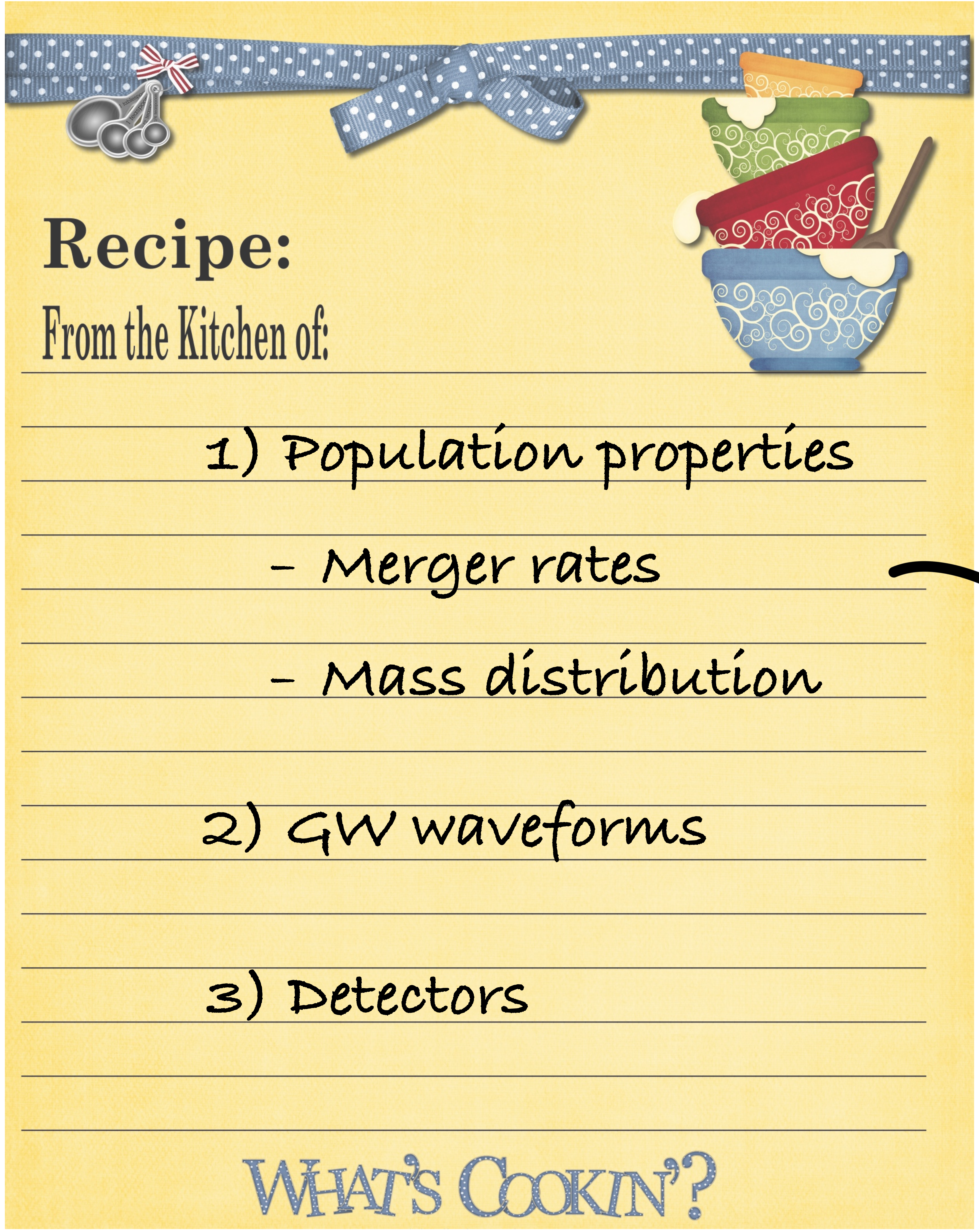
Regimbau 2011, arXiv:1101.2762

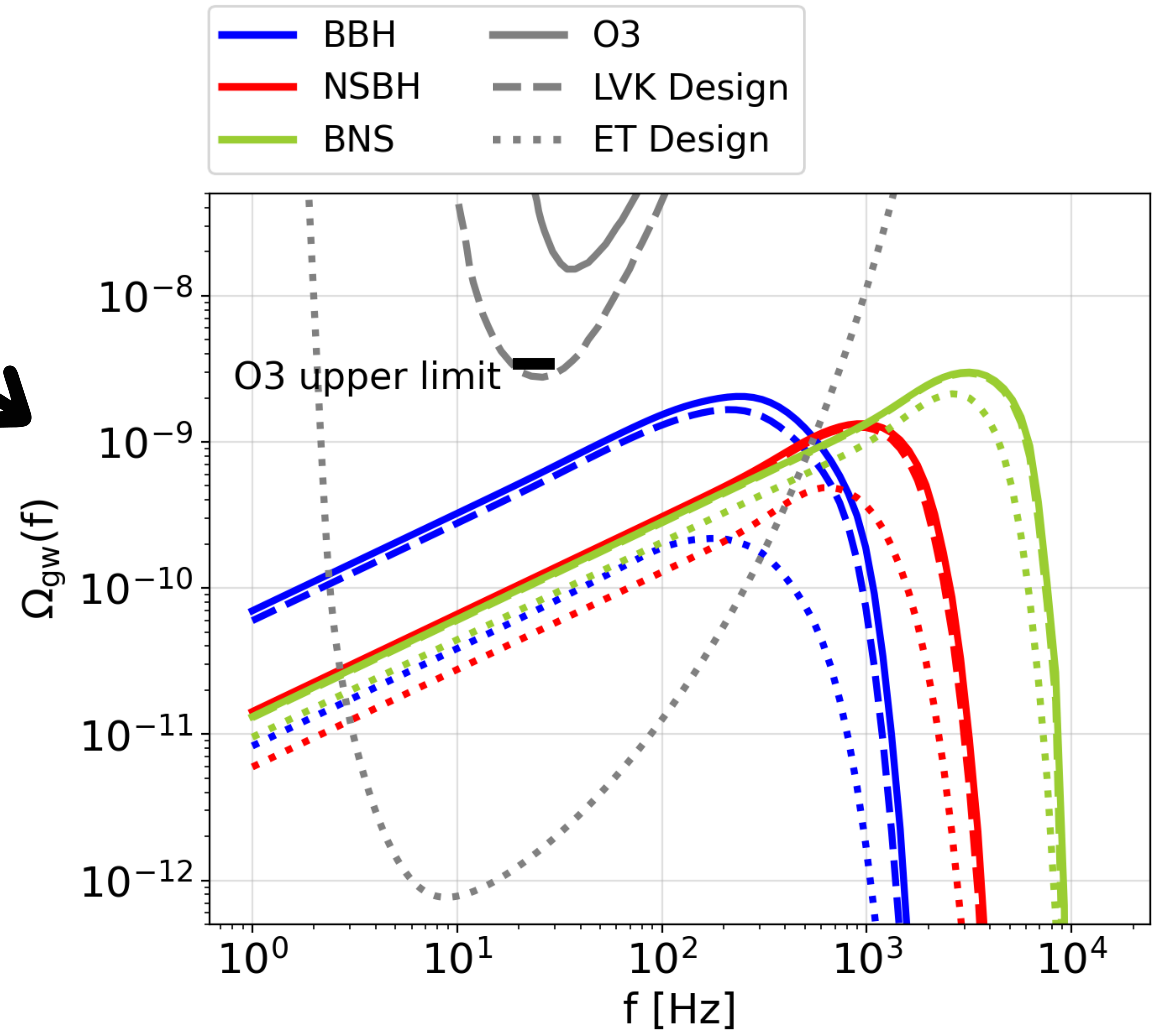
LVK Collab., 2021, arXiv:2101.12130

Bavera+21, arXiv:2109.05

Périgois+22, arXiv:2112.0119

Theoretical predictions for the SGWB





Capurri+21, arXiv:2103.12037

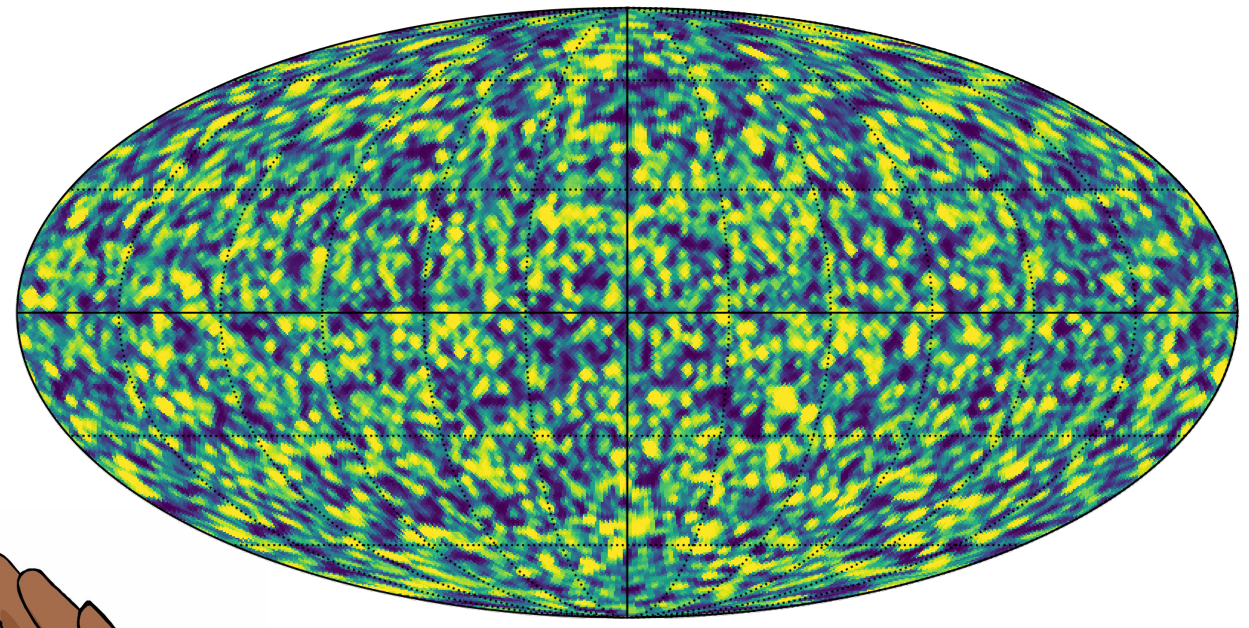
Can we reverse-engineer the recipe?

Recipe:

From the Kitchen of:

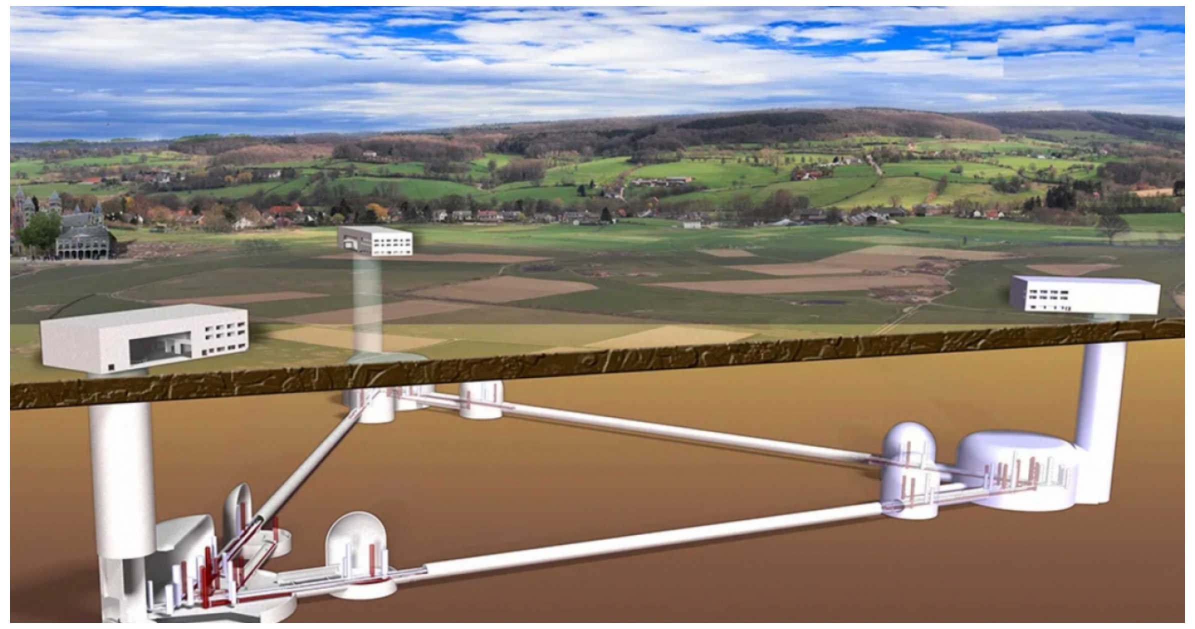
1) Merger rates
2) Mass distribution
3) Binary population properties
   - Star formation rate density
   - Metallicity evolution
   - Common envelope
   - Natal kicks
4) Cosmological parameters

WHAT'S COOKIN'?

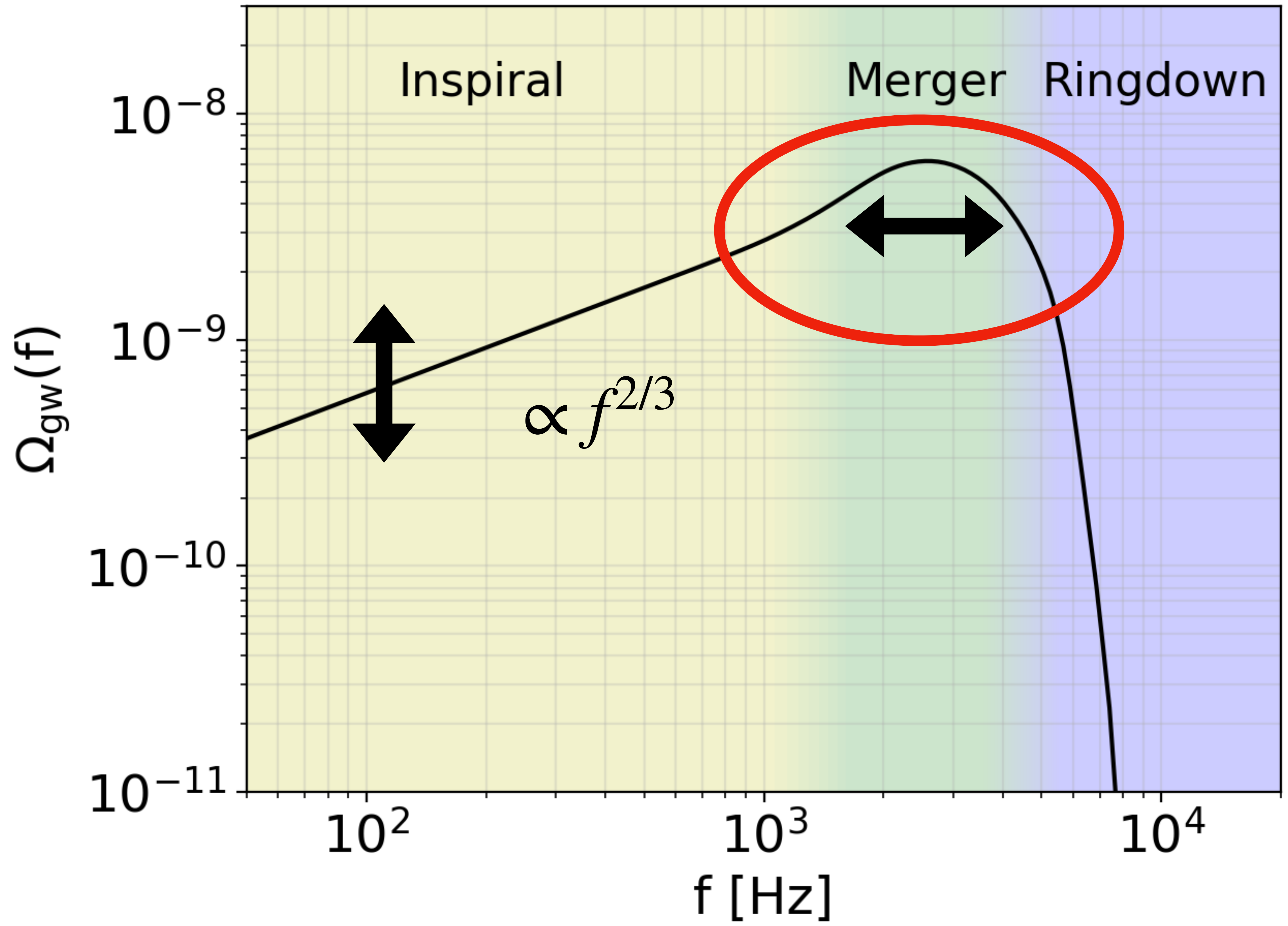


SGWB measurements (**isotropic component**)

Ground-based interferometers



The SGWB peak as an observable to constrain astrophysical and cosmological parameters



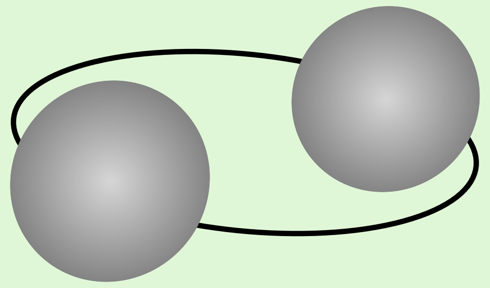
1. Focus on the **peak** of the energy density
2. Identify a proper set of **astrophysical and cosmological parameters**
3. **Simulate signal** with different input parameters
4. **MCMC** to reconstruct the injected parameters
5. We work with the SGWB from **BNSs**

Astrophysical and cosmological parameters

$$\Omega_{\rm gw}(f) = \frac{8\pi G f}{3 H_0^3 c^2} \int dz \int d\theta_{\rm a}\, p(\theta_{\rm a}) \frac{\mathcal{R}(z\,|\,\theta_{\rm a})}{(1+z)\, h(z\,|\,\theta_{\rm c})} \frac{dE_{\rm gw}}{df}(f, z\,|\,\theta_{\rm a})$$

Astrophysical parameters θ_a

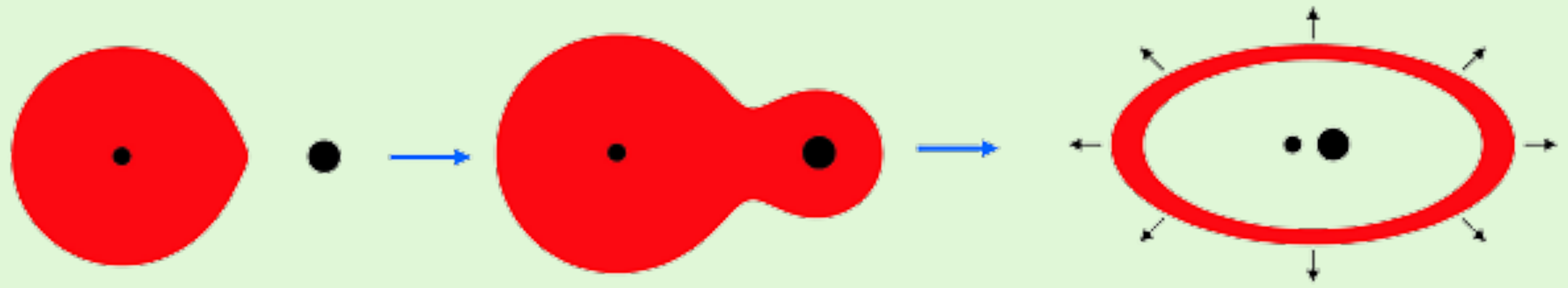
1) Peak of the BNS chirp mass distribution $\mathcal{M}_c$



$\sim 1.3\,{\rm M}_\odot$ Farrow+19, arXiv:1902.03300; Landry+21, arXiv:2107.04559

$\sim 1.3\,{\rm M}_\odot$

2) Common envelope efficiency α

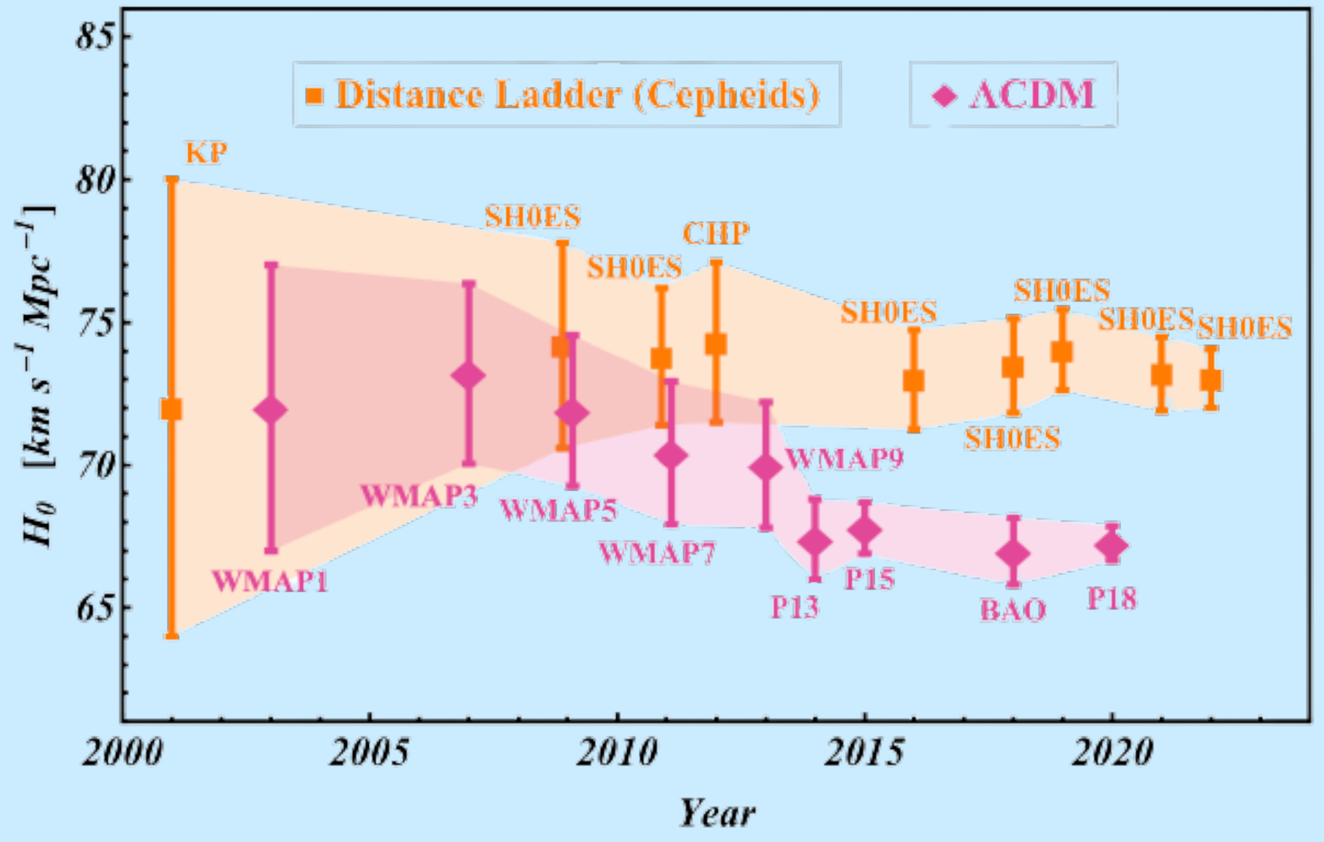


Fragos+19, arXiv:1907.12573; Giacobbo+18, arXiv:1805.11100; Santoliquido+21, arXiv:2009.03911

Cosmological parameters θ_a

1) Hubble parameter H_0

Hubble Tension:
Planck Collaboration 2020, arXiv:1807.06209;
Riess+22, arXiv:2112.04510

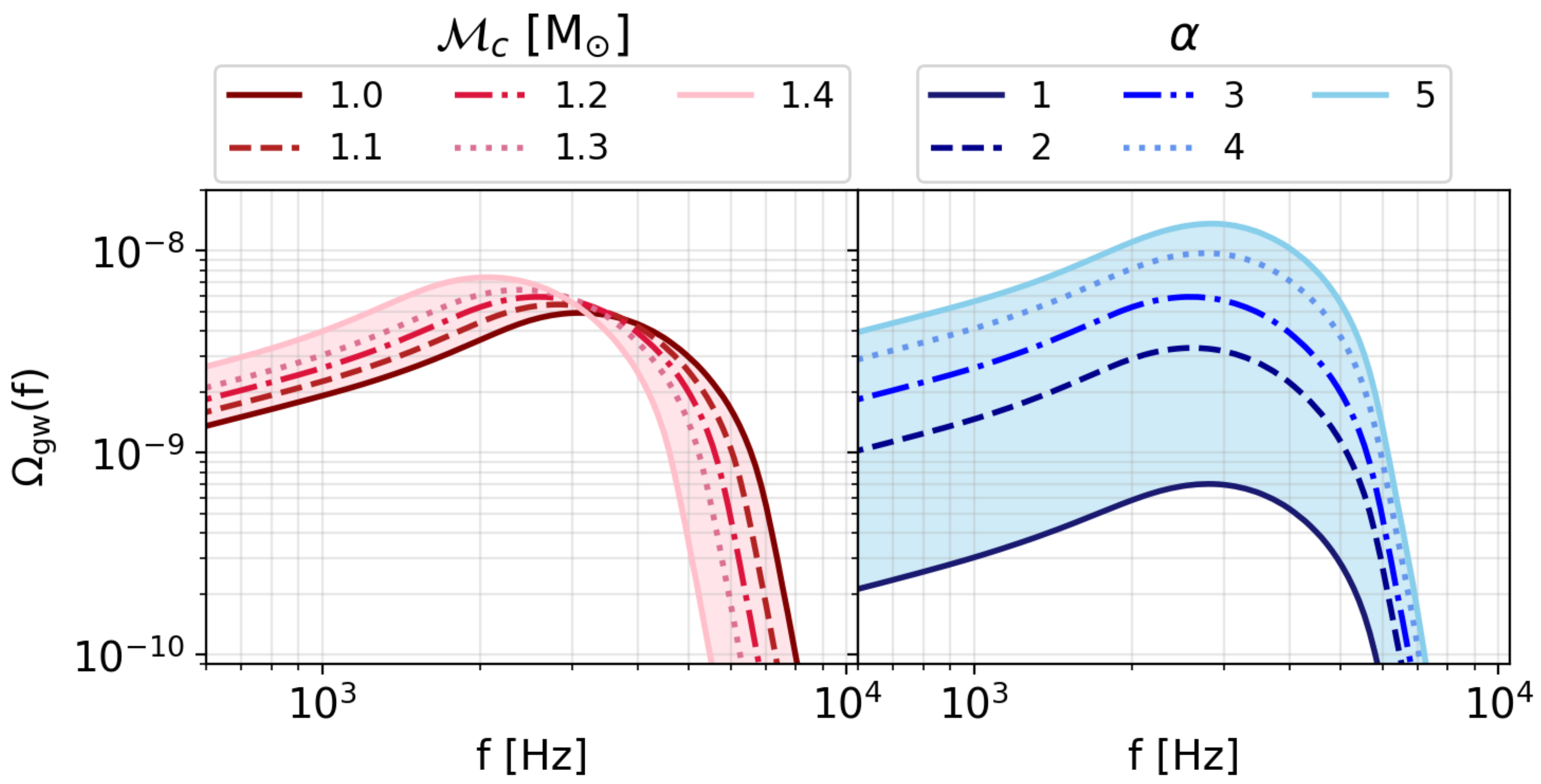


2) Matter density parameter Ω_M

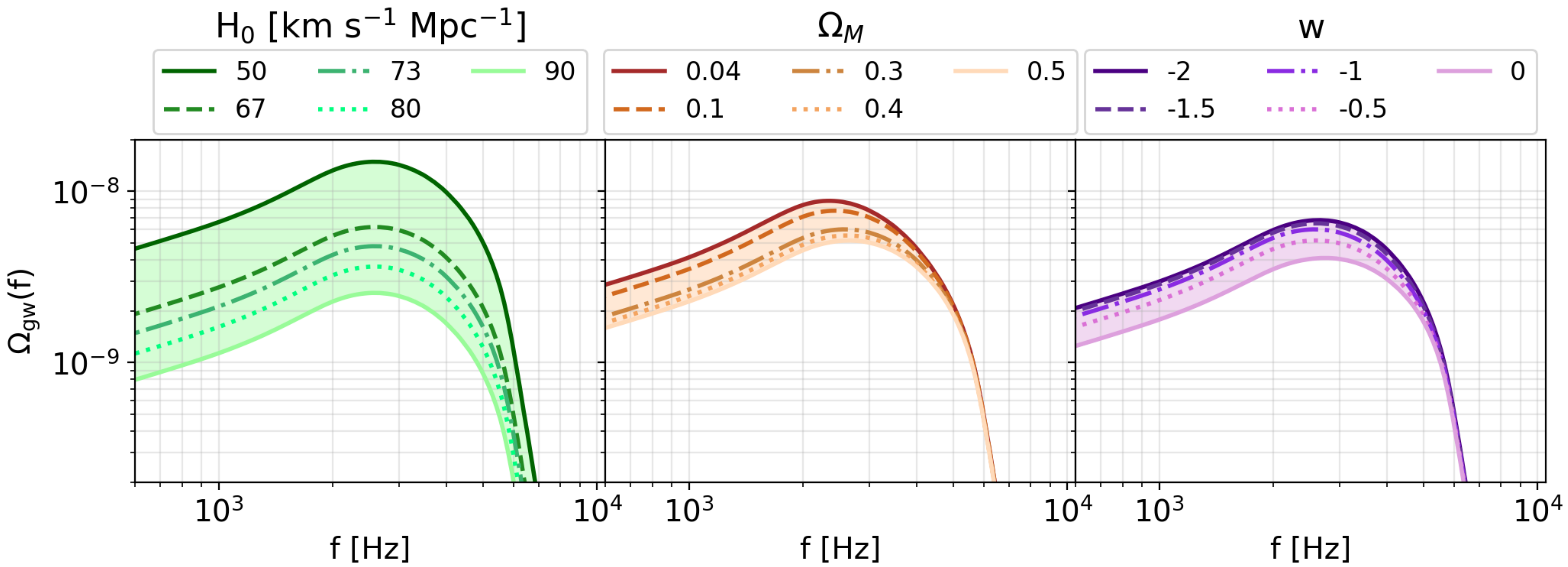
3) Dark energy effective EoS w

Effect of varying parameters

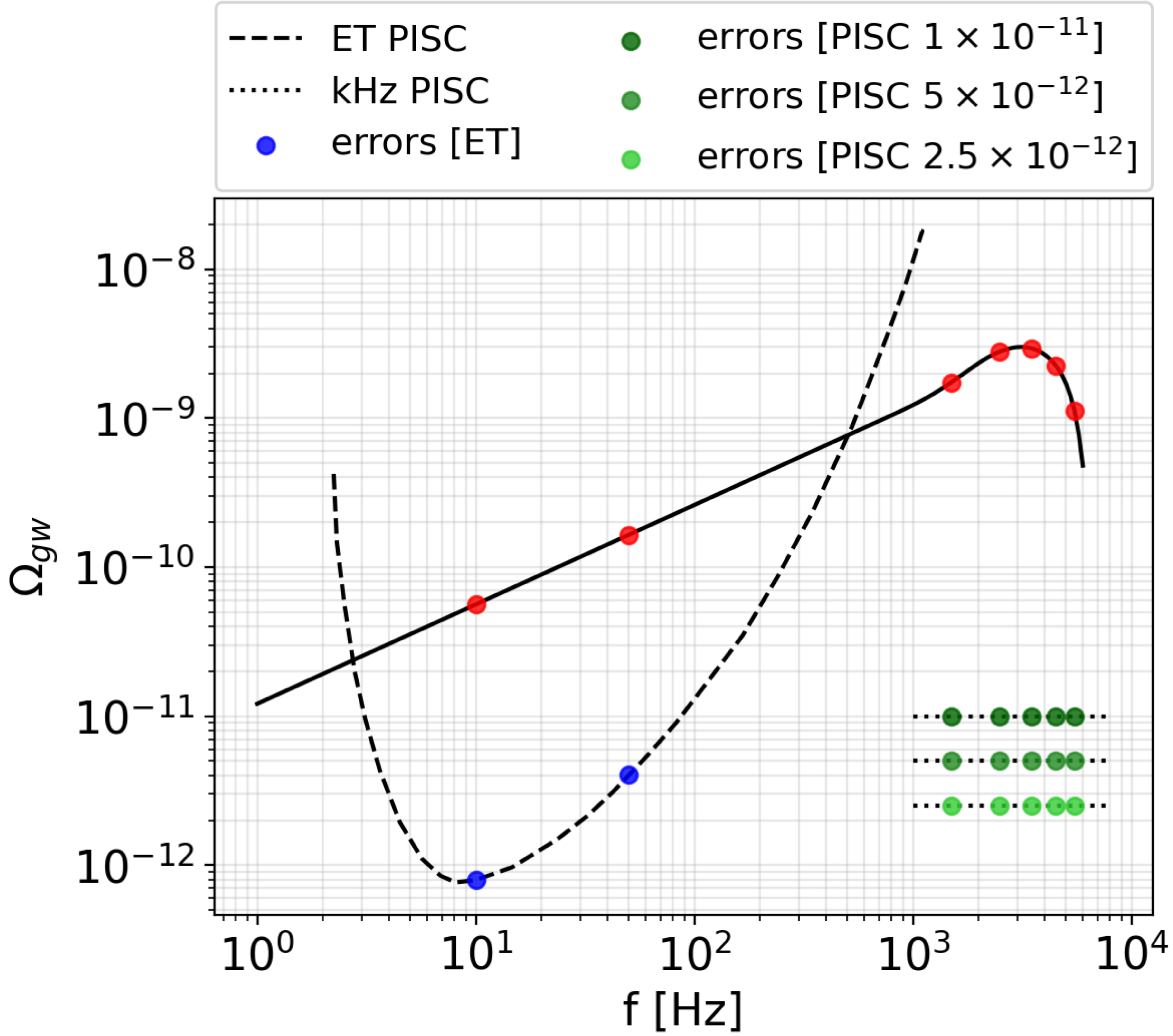
Astrophysical parameters
$\theta_a = \{\mathcal{M}_c, \alpha\}$



Cosmological parameters
$\theta_c = \{H_0, \Omega_M, w\}$



Mock data points construction

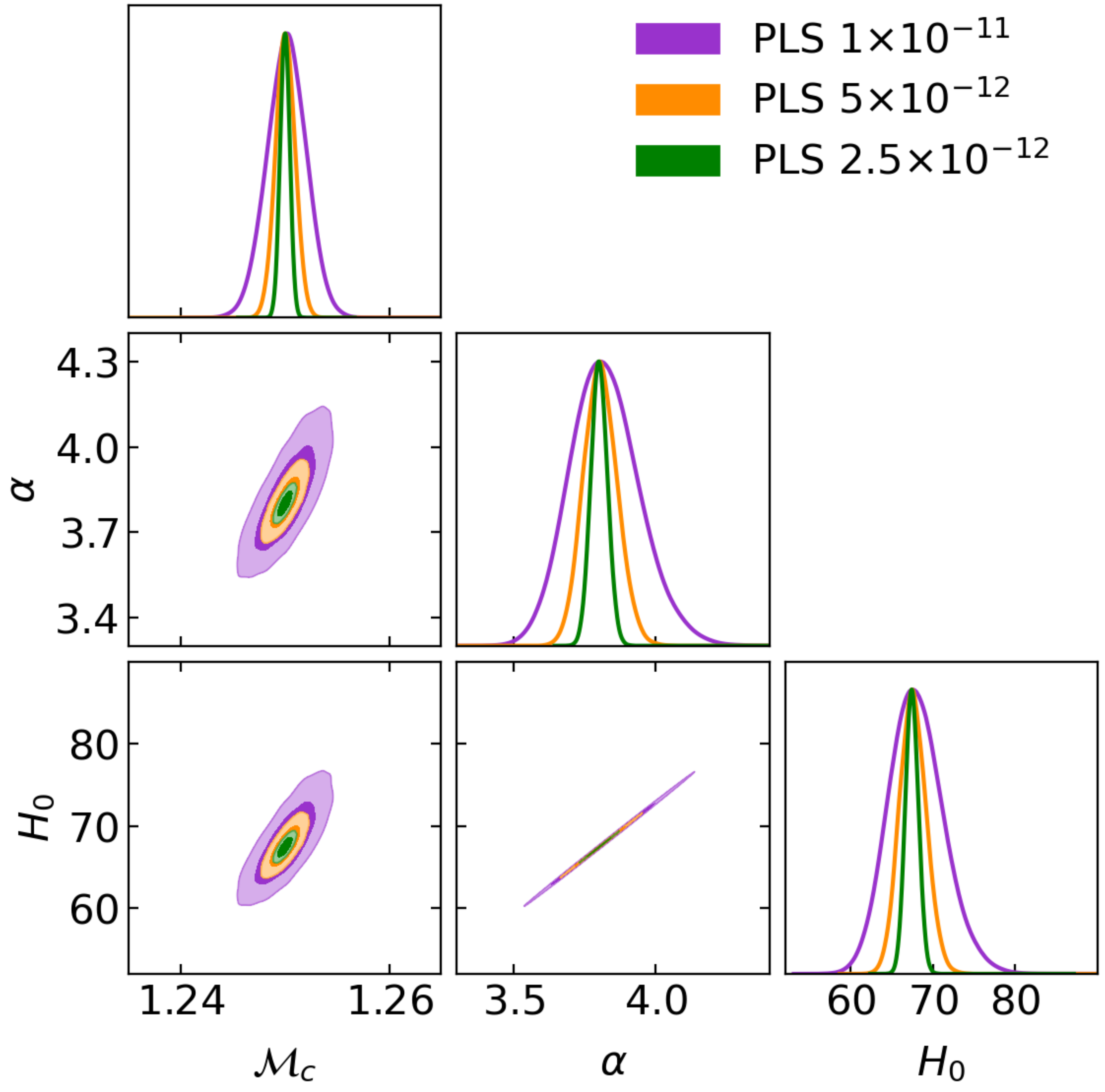


Parameter	Fiducial value(s)	Prior interval	Units
$\mathcal{M}_c$	1.25	[1,1.5]	$M_\odot$
α	3.8	[1,5]	/
H_0	67.4 73	[50,90]	km s^{-1}Mpc^{-1}
Ω_M	0.315	[0.04, 0.5]	/
w	-1.5	[-2,0]	/

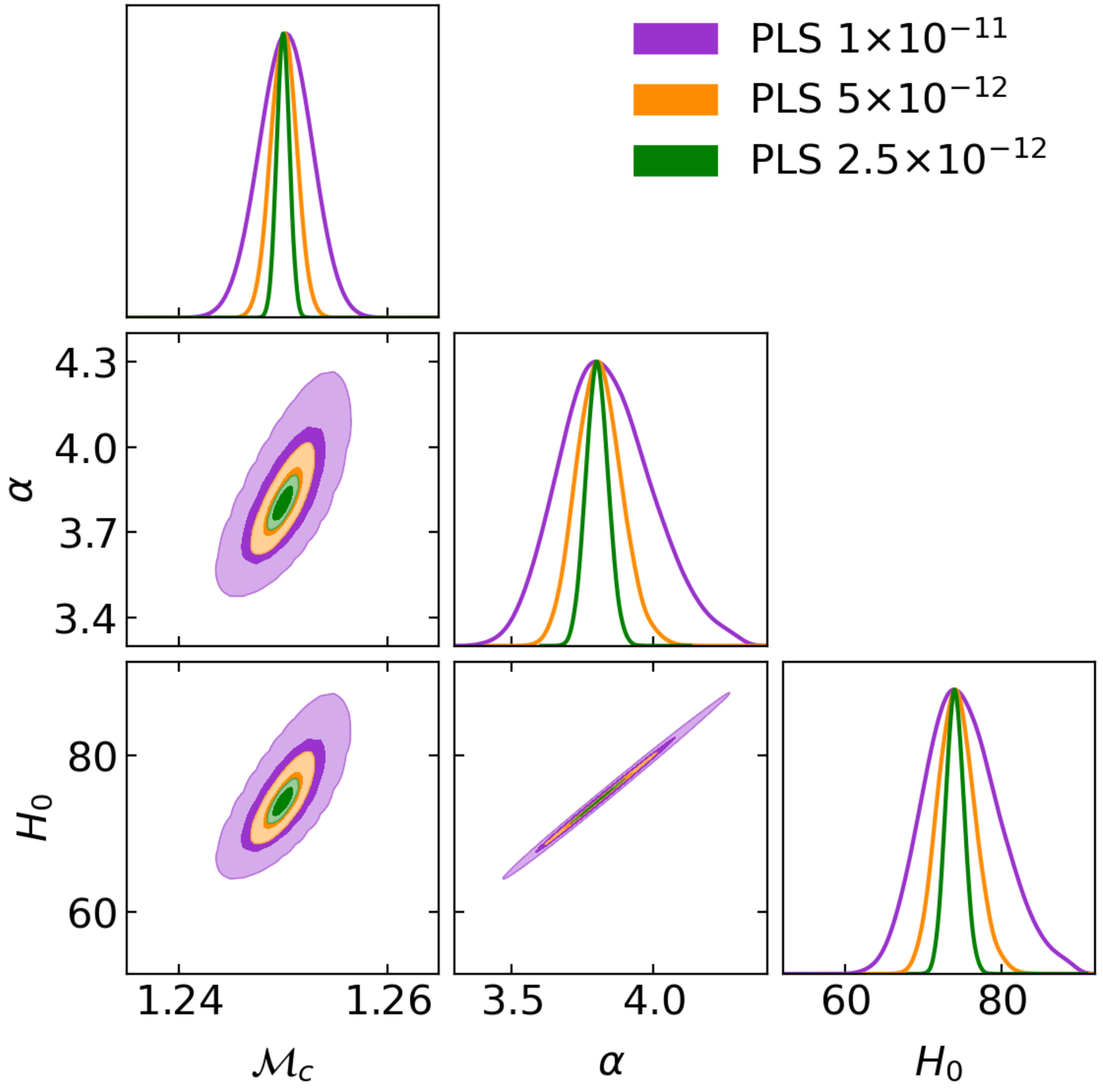
- Chose fiducial input parameters
- Generate mock data points with errors
- Gaussian likelihood

Bayesian inference on $\{\mathscr{M}_c, \alpha, H_0\}$

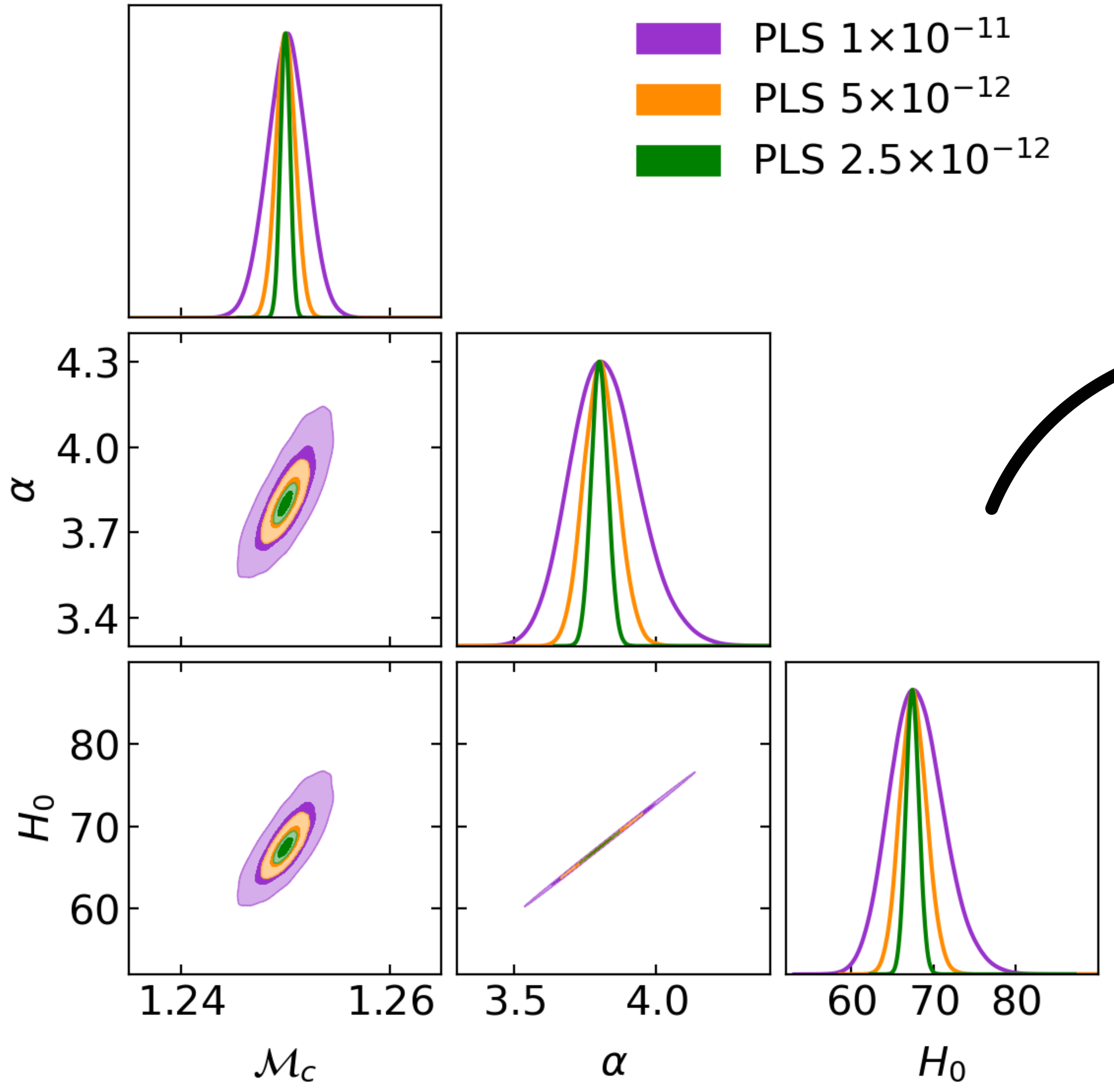
Input: H_0 = 67.4 km s^{-1} Mpc^{-1}

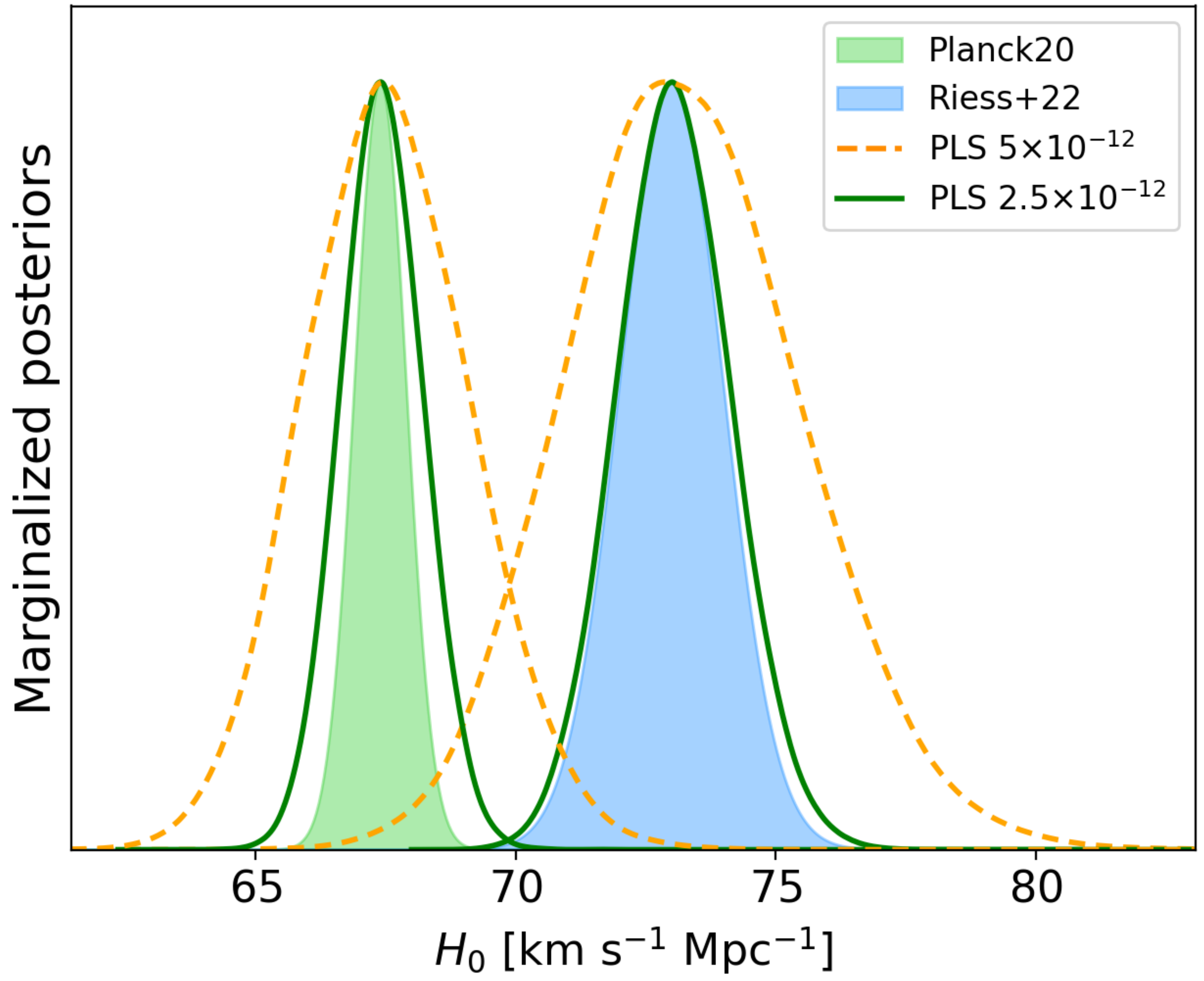


Input: H_0 = 73 km s^{-1} Mpc^{-1}



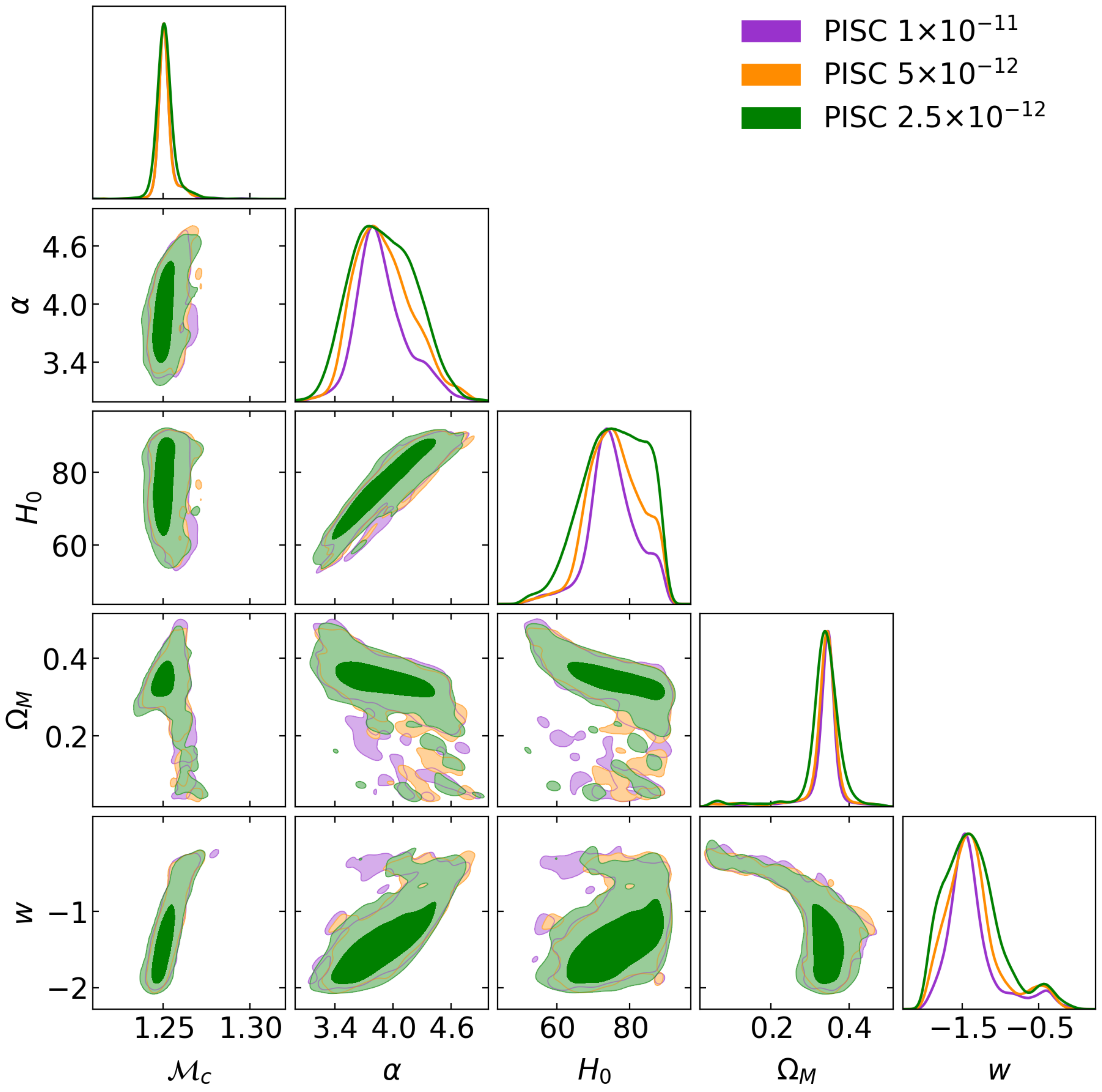
Bayesian inference on $\{\mathscr{M}_c\,, \alpha\,, H_0\}$





We find the required kHz sensitivity to distinguish the two H0 values measured by Planck and Cepheid-SNe

Inference on $\{\mathcal{M}_c, \alpha, H_0, \Omega_M, w\}$ and summary

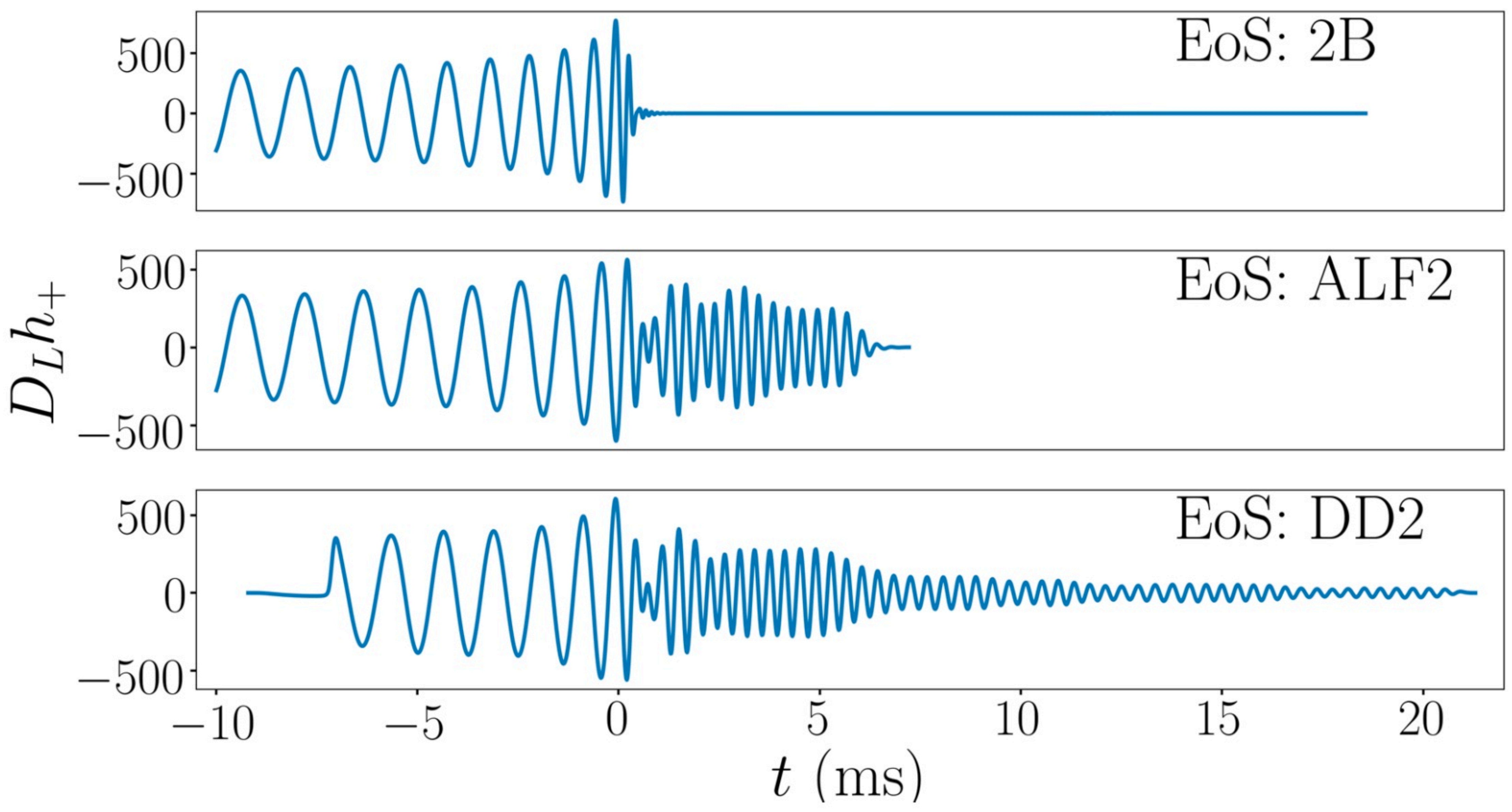


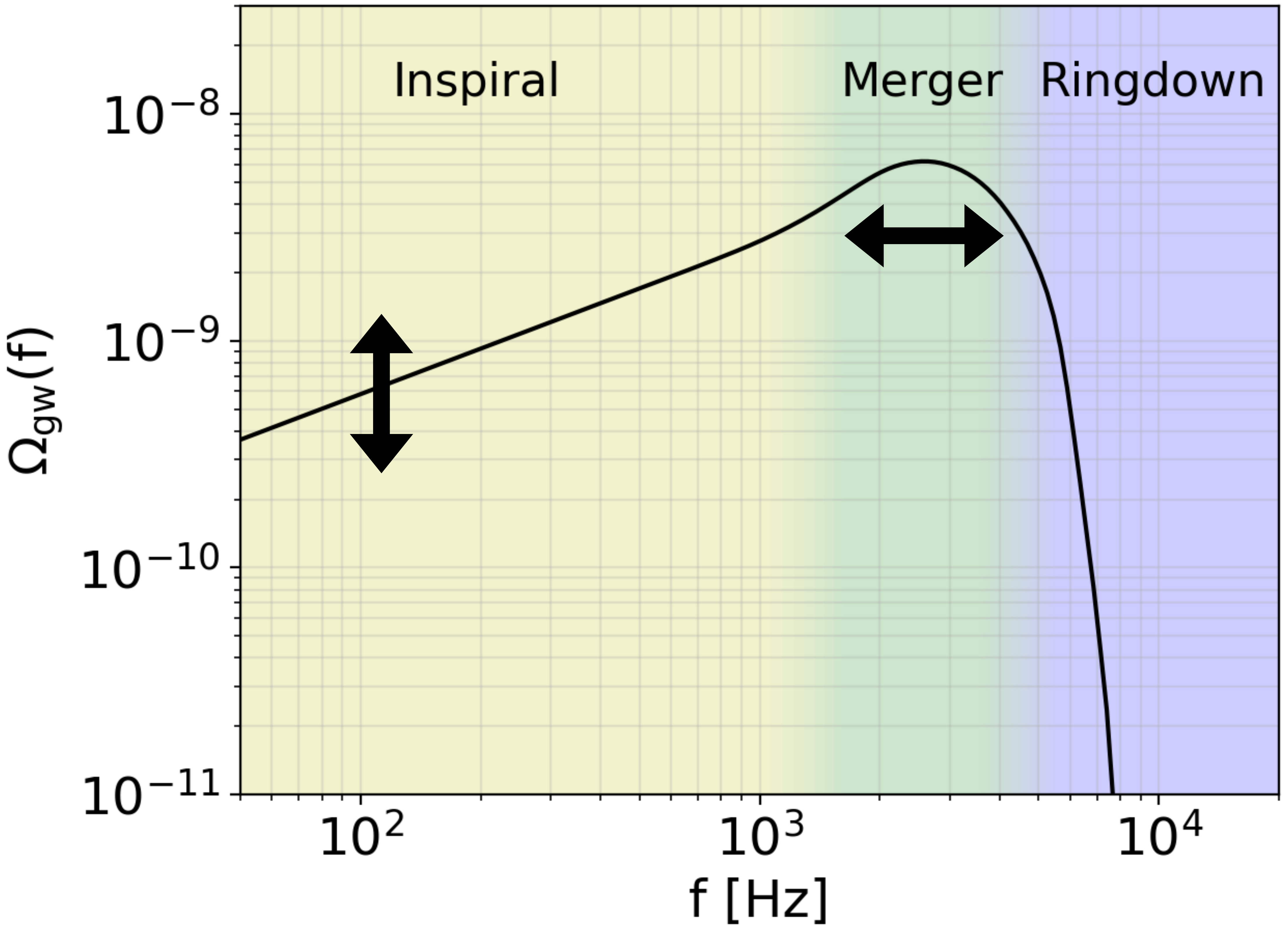
Summary:

- Science case: SGWB by BNSs as an observational tool in the kHz frequency range
- Its peak contains a significant amount of physical information
- Constraints on astrophysical and cosmological processes involved in the production of the SGWB

Future prospects: different NS equations of state

Toubiana+21, arXiv:2011.12122





Future prospects for ET: SGWB from BBHs

1) SGWB peak within ET sensitivity band.

2) Many astrophysical parameters:

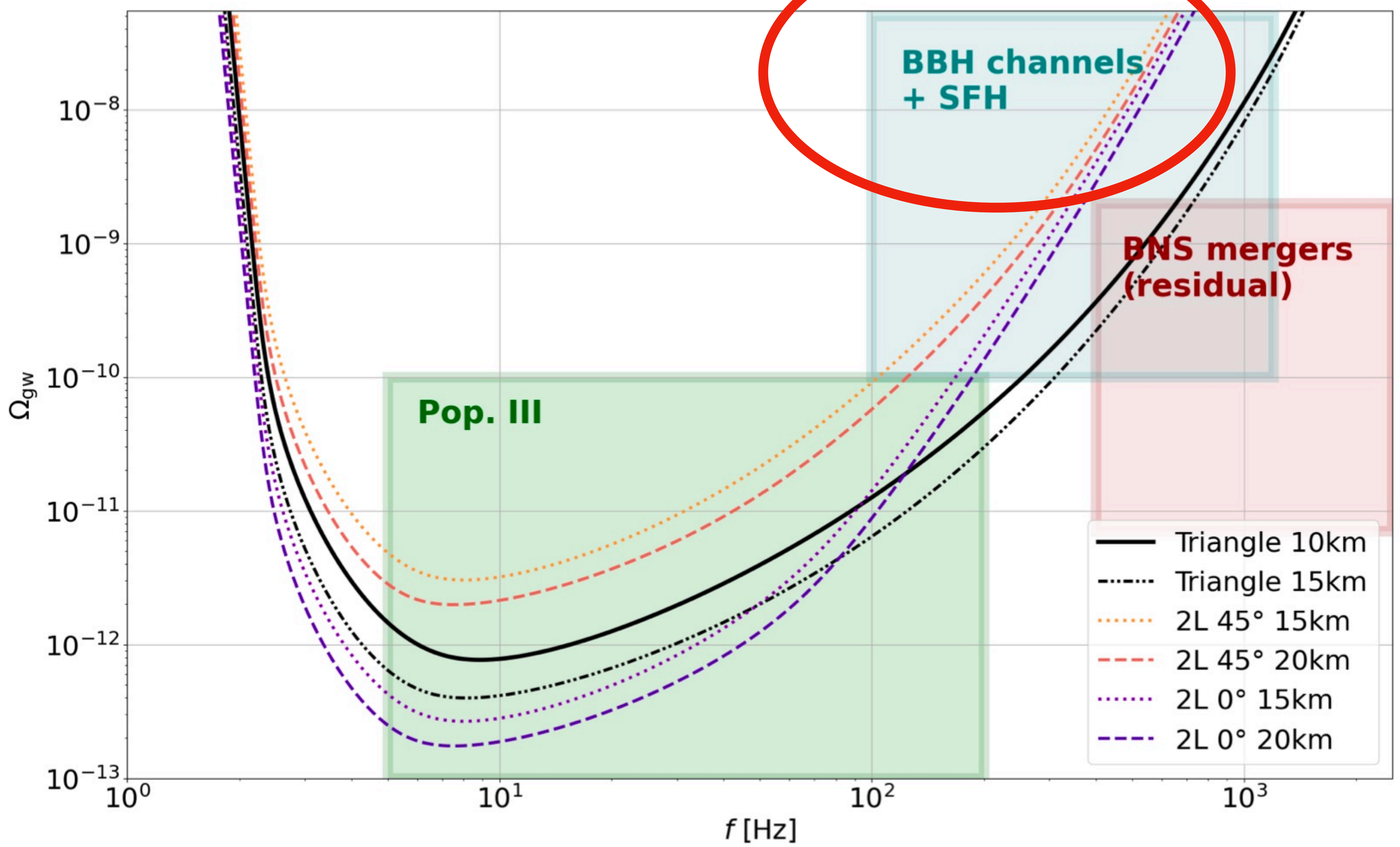
- Strong dependence on metallicity
- Various formation channels
- Complicated mass distribution

3) Careful subtraction/separation from resolved events

4) Issue of correlated noise (for ET triangular configuration)

Stochastic searches with ET
(sensitivity of different designs)

Branchesi+23, arXiv:2303.15923



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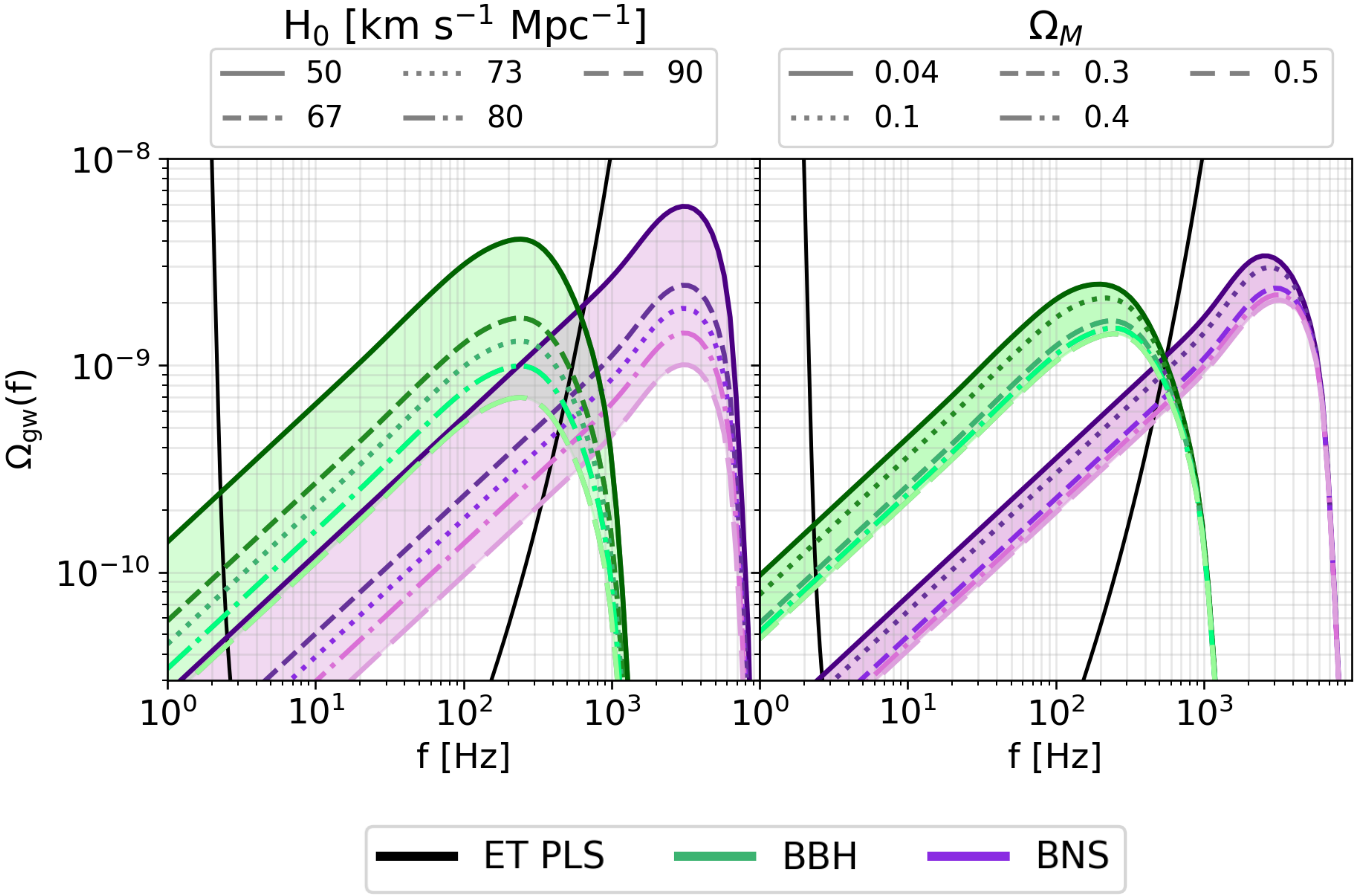

Thank you so much for your attention!

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