



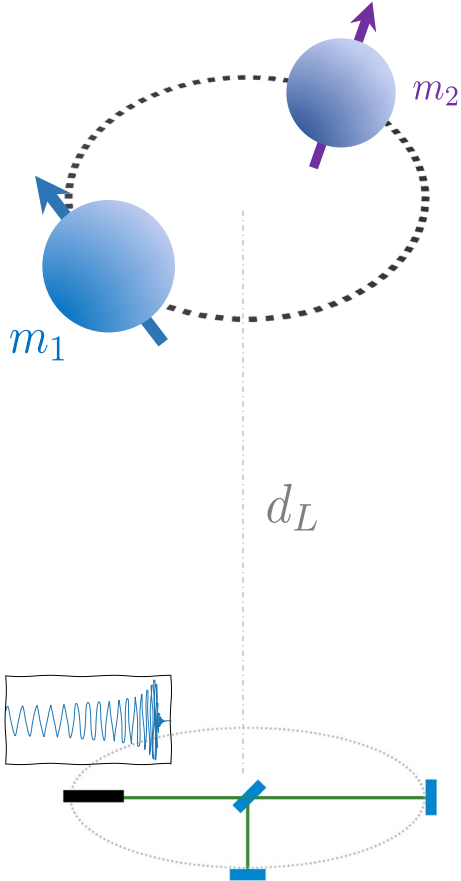
# Joint astrophysical and cosmological constraints with Gravitational Waves and Galaxy Catalogs

**Nicola Borghi**

PhD student @ University of Bologna  
*supervisors: M. Moresco, A. Cimatti*

*Project developed within the Bologna ET (BoET) Research Unit, with M. Moresco, A. Cimatti (Univ. Bologna),  
M. Mancarella (Univ. Milano Bicocca), F. Iacovelli and M. Maggiore (Univ. Geneva)*

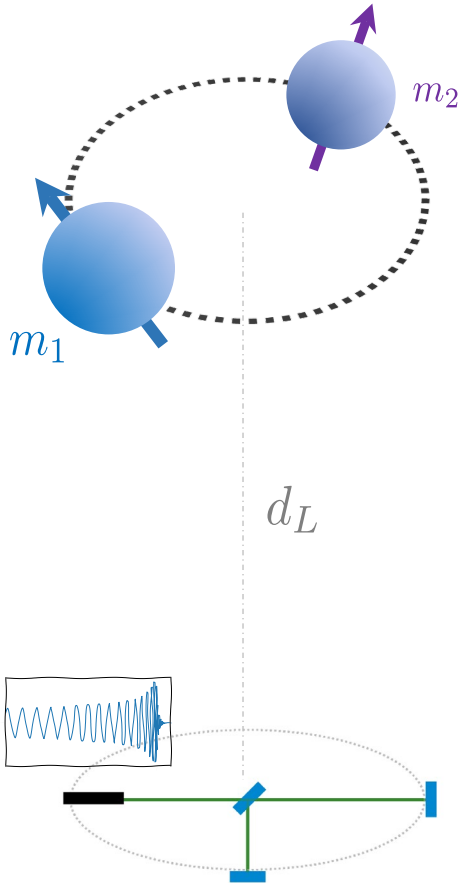
# Cosmology with Gravitational Waves - BASICS



Direct measurement of the **luminosity distance** (“*standard sirens*”)  
w/o additional calibrators (e.g., cepheids for SNeIa)  
(Schutz 1986, Holz & Hughes 2005)

$$h(t) \propto \frac{\mathcal{M}_z^{5/3} f(t)^{2/3}}{d_L} F_{+, \times}(\text{angles}) \cos(\phi(t))$$

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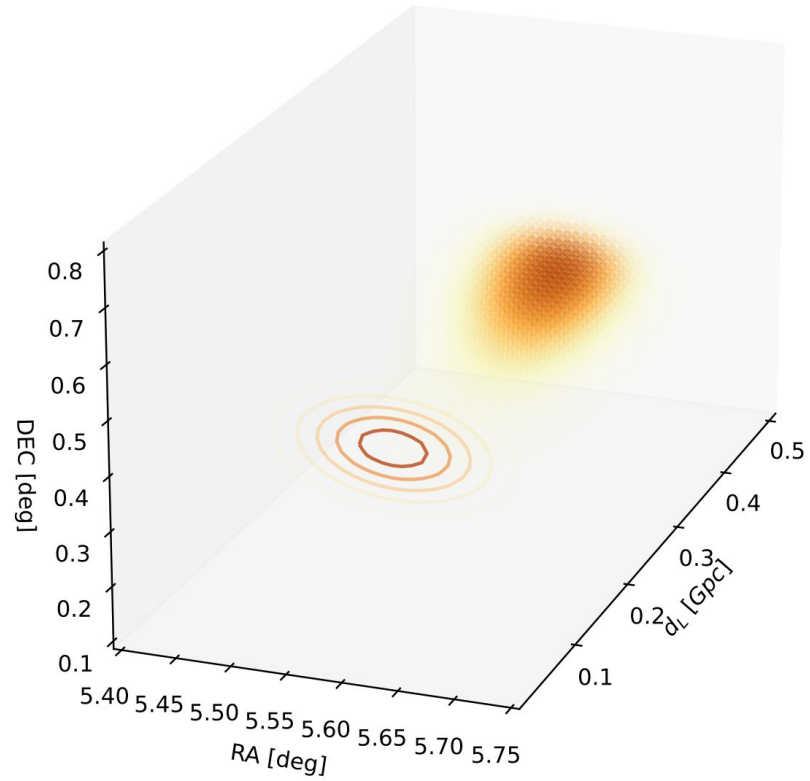
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Cosmology via the distance-redshift relation  
 ... but **no redshift** measurement with GW data alone (degen. with masses)

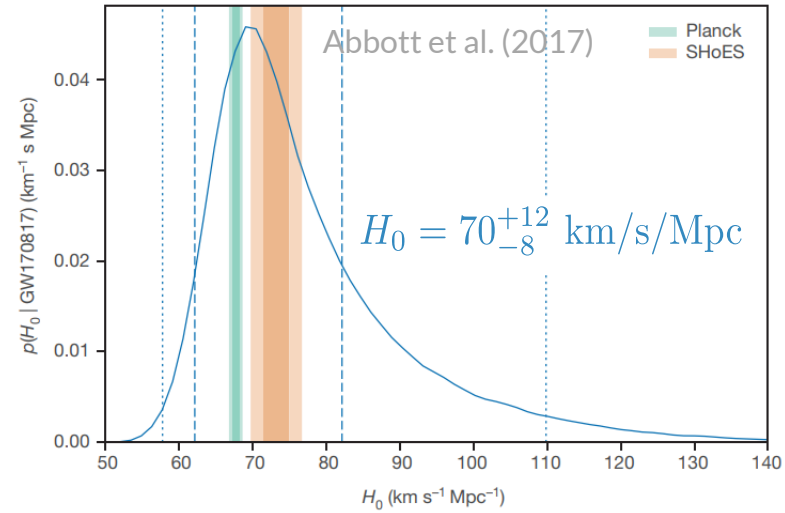
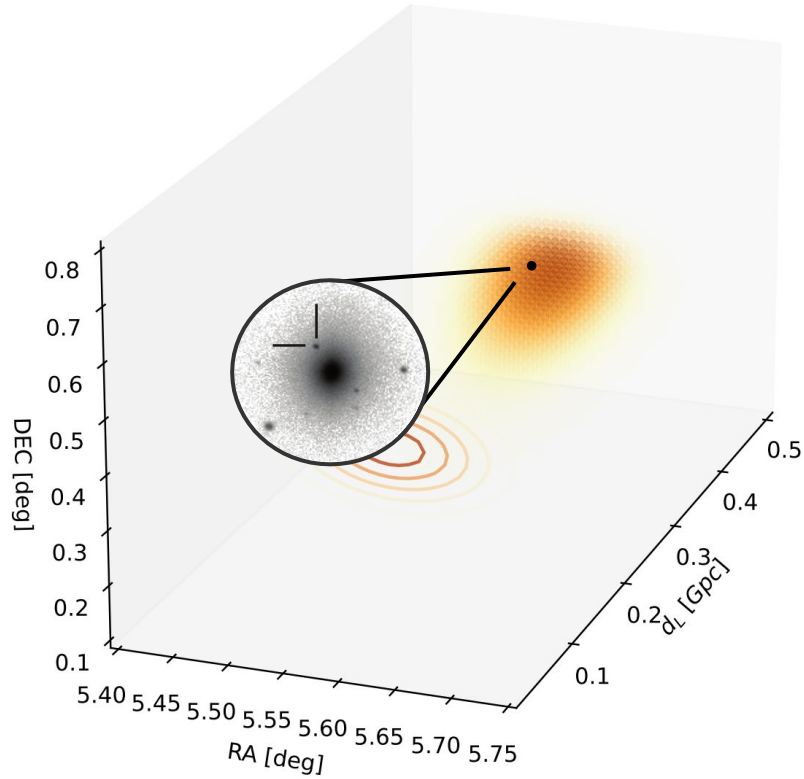
$$d_L^{\text{GW}}(z) = (1 + z) \int_0^z \frac{dz'}{H(z'; \lambda_{\text{cosmo}})} \rightarrow \{H_0, \Omega_{m0}, w_0, \dots\}$$

# Cosmology with Gravitational Waves – REDSHIFT INFORMATION

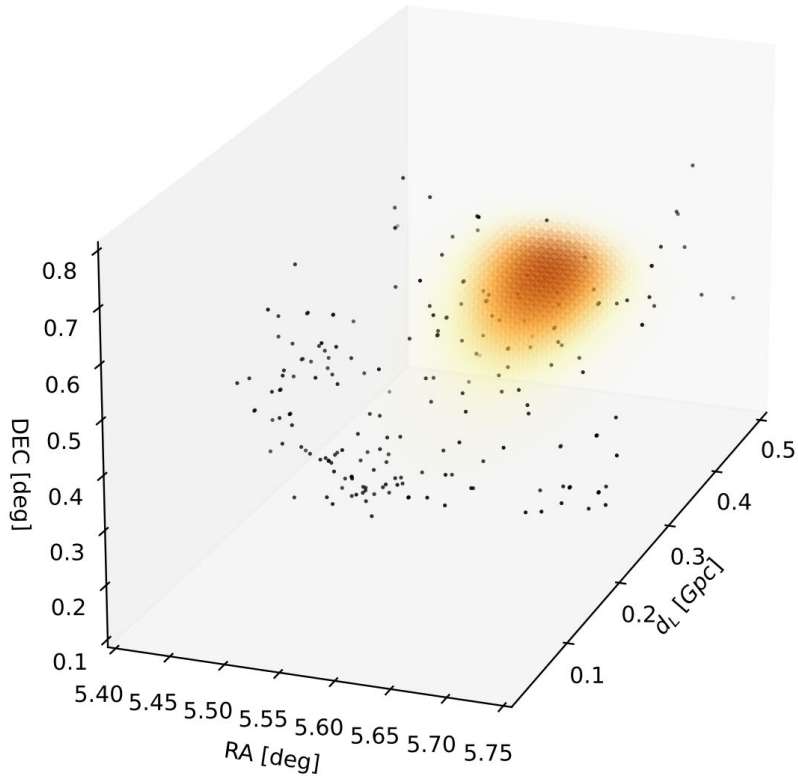


# Cosmology with Gravitational Waves – REDSHIFT INFORMATION

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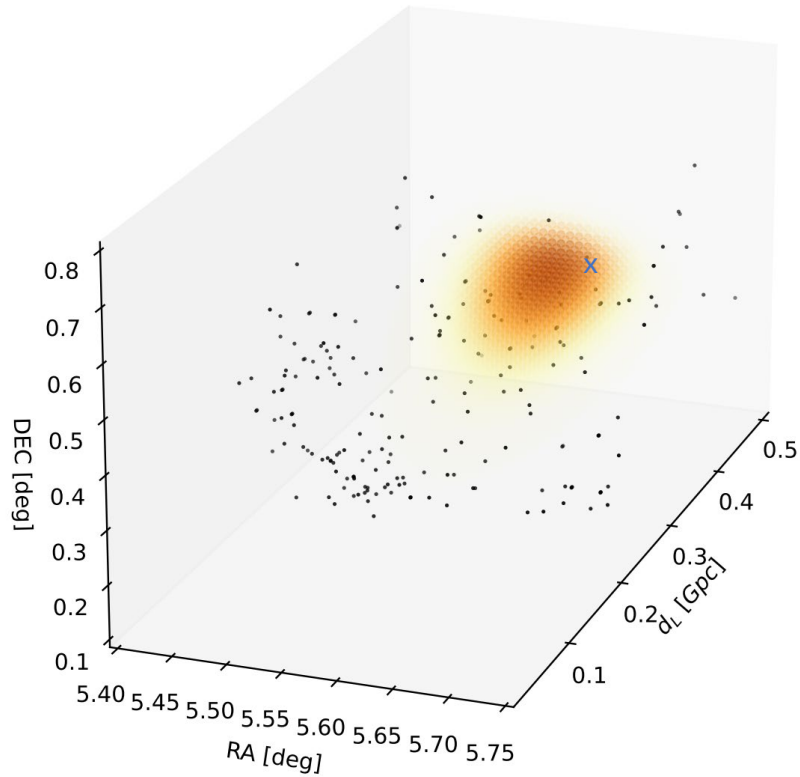


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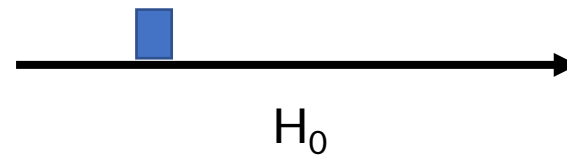
→  $H_0$

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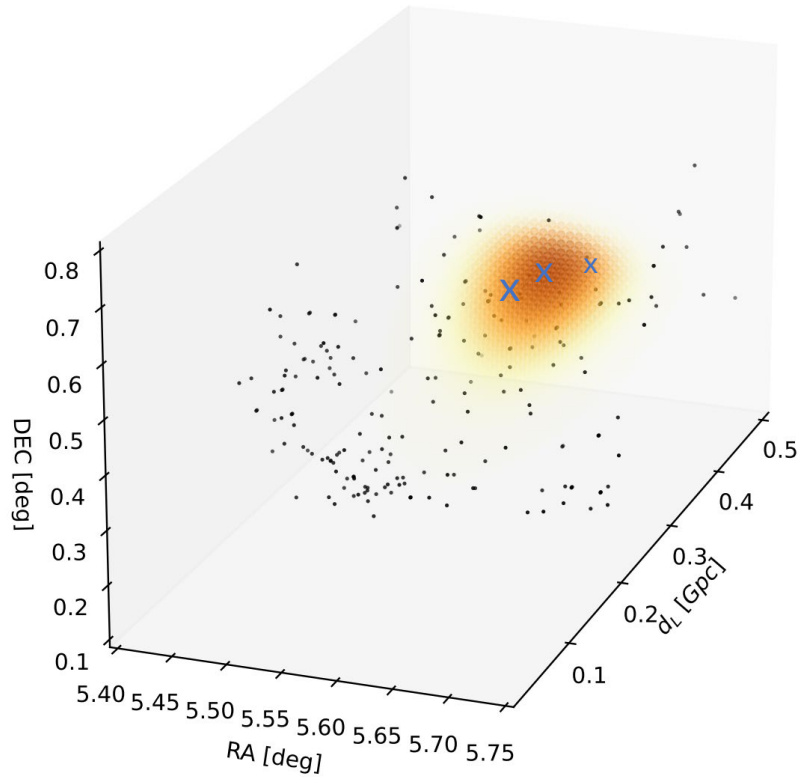


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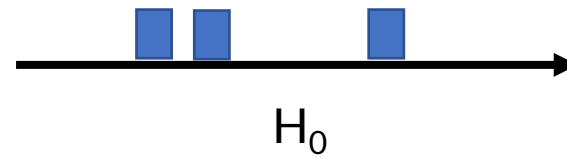


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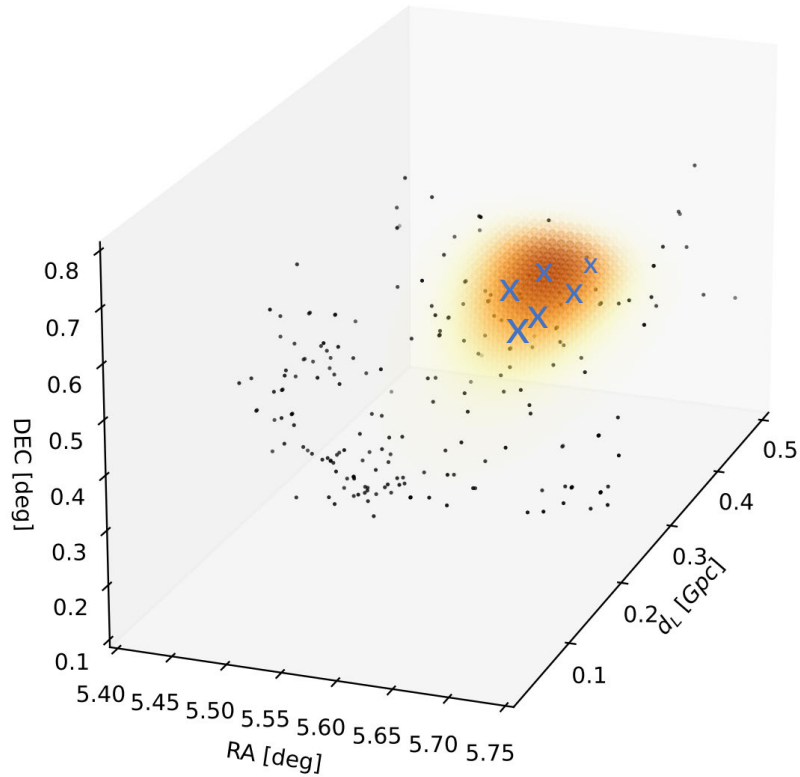
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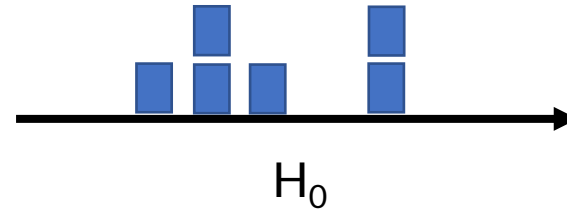


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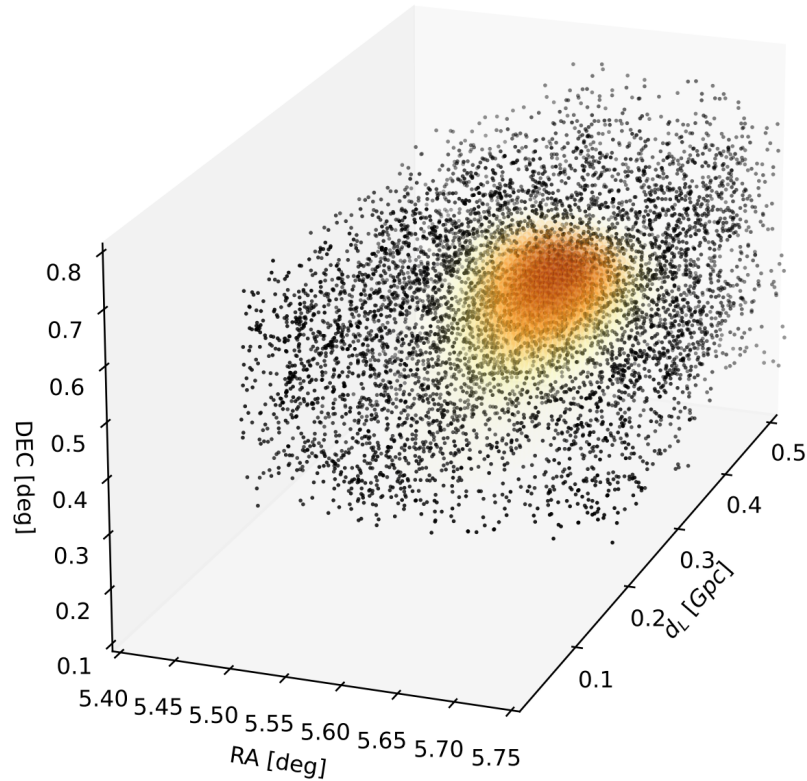


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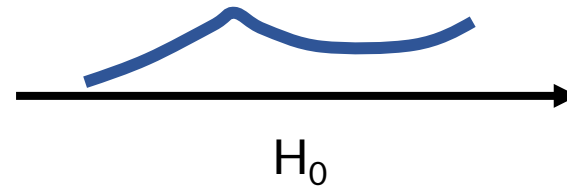


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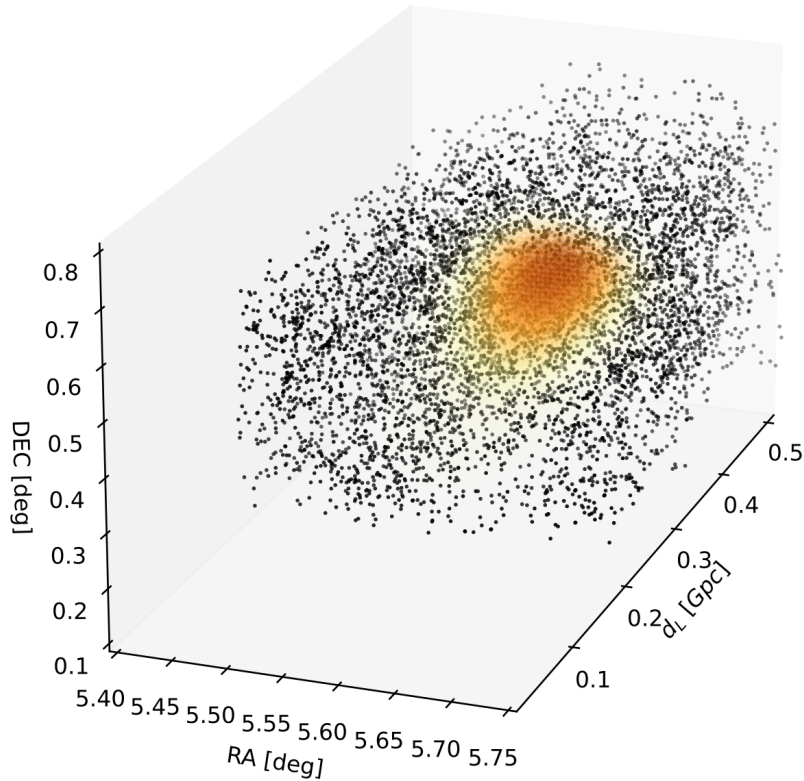


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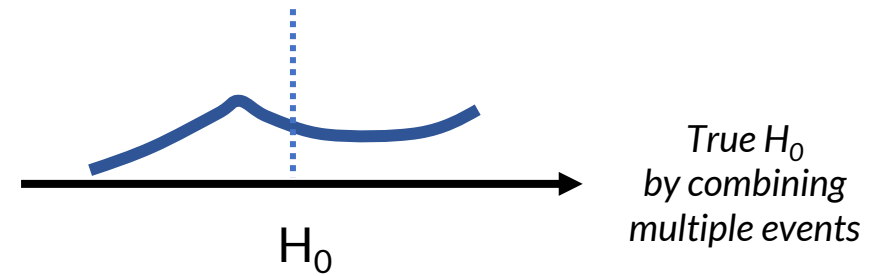


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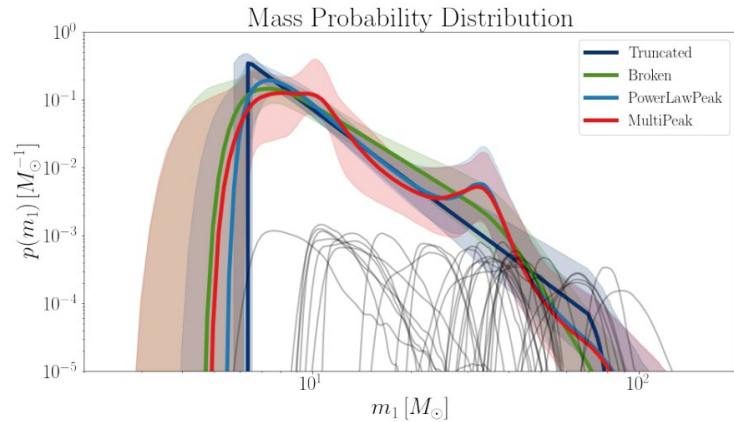


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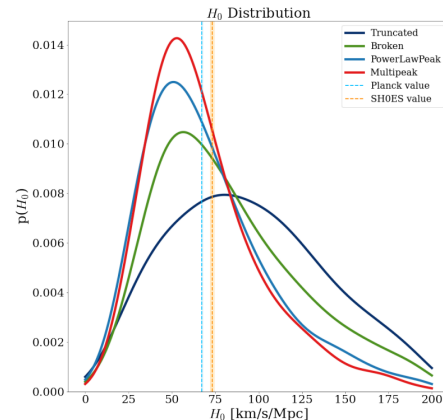


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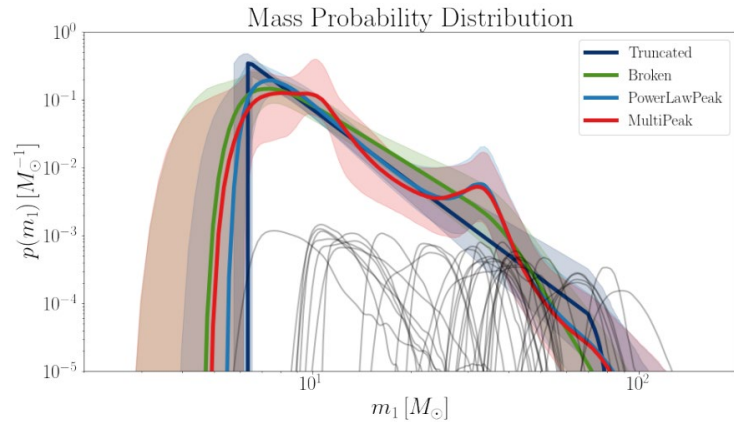
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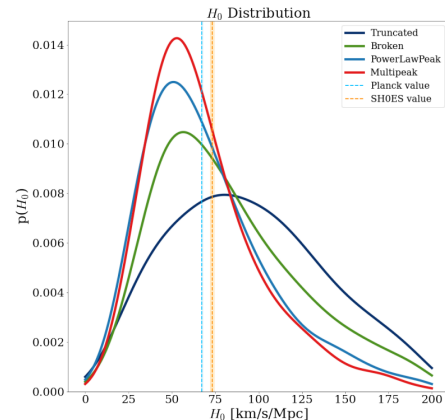
From Matteo Schulz  
Master Thesis @ UNIBO

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→ *Other methods include: GW × galaxies spatial clustering* (e.g., Mukherjee et al. 2021), *tidal distortions during merger phase* (e.g., Abbott et al. 2022), ...

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# Cosmology with Gravitational Waves – REDSHIFT INFORMATION

## AIM

New pipeline to simultaneously constrain astrophysical & cosmological parameters:

1. Study their correlations and better explore the involved **systematics**
2. Improvements in the **computational time**
3. Validation on **different regimes of  $N_{\text{GAL}}/N_{\text{GW}}$**
4. Forecasts for next gen. GW detectors and galaxy surveys

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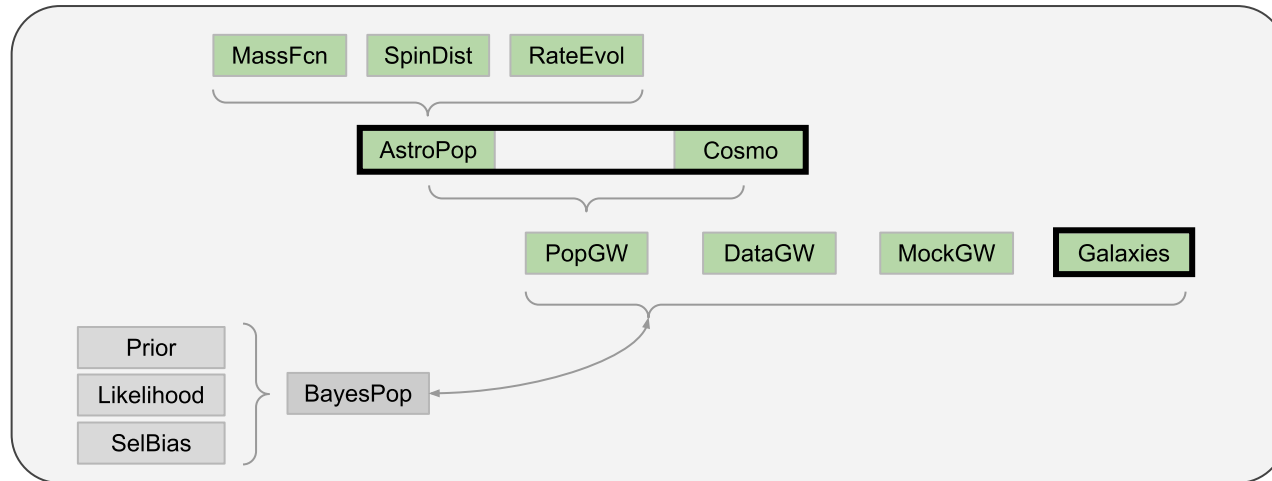
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(Borghi et al. 2023a, *in prep*)

➤ Analysis pipeline (based on hierarchical Bayesian Inference; Mandel et al. 2019, Vitale et al. 2022)

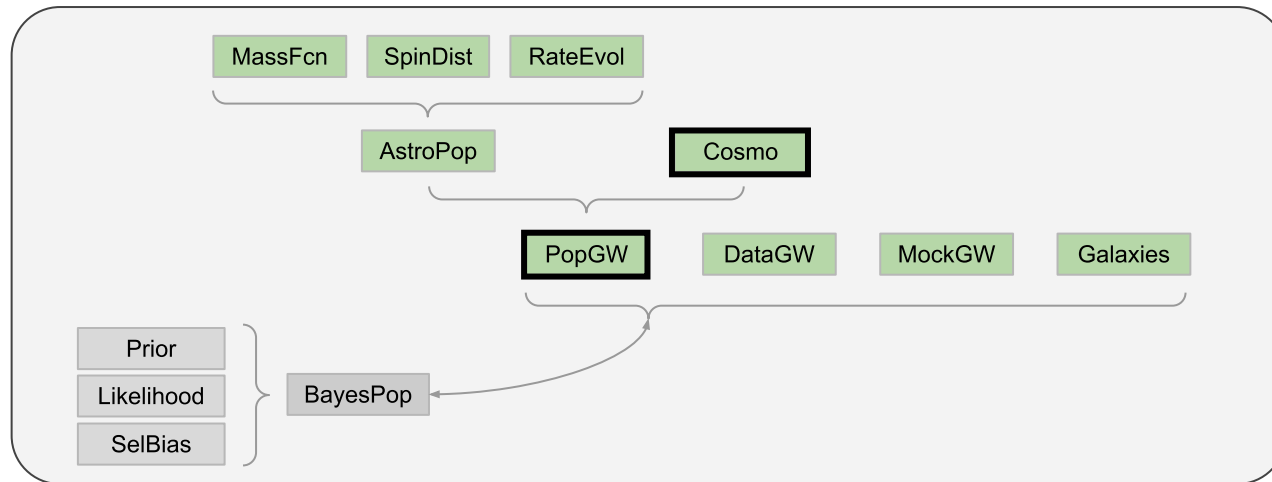


- **Joint astrophysical & cosmological parameter constraints with galaxy catalogs**

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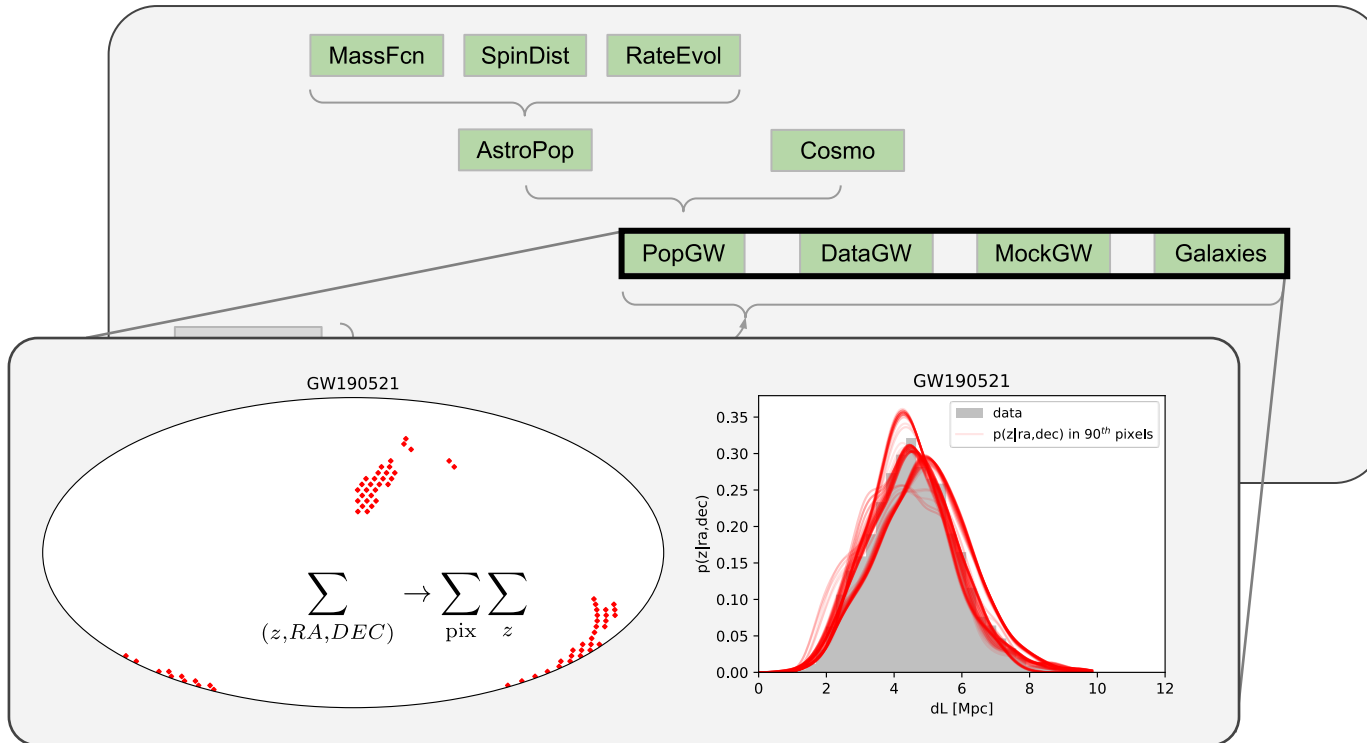
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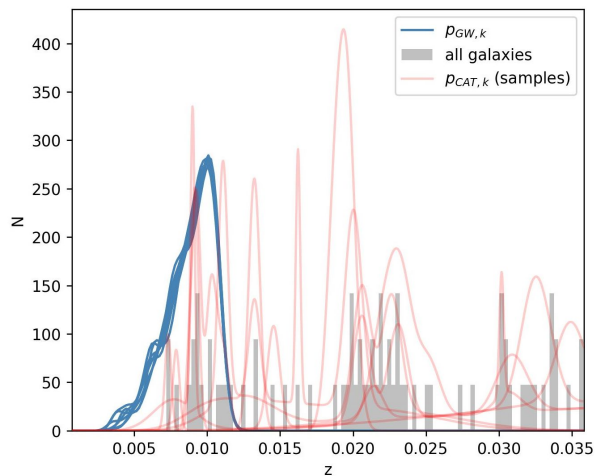
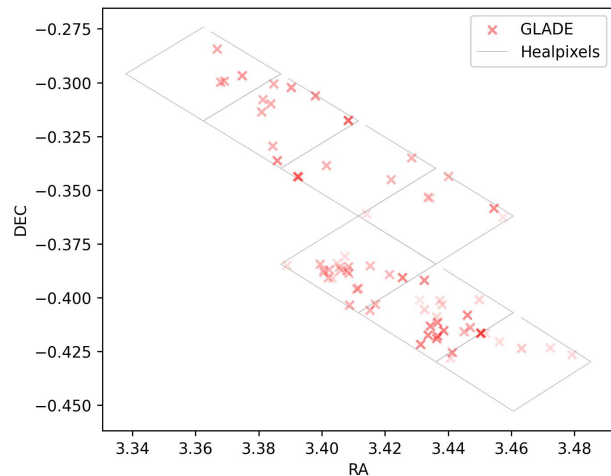


- **Joint astrophysical & cosmological parameter constraints** with galaxy catalogs
- **Performance improvements** in view of next gen. GW detectors and galaxy surveys
- **Pixelated approach** to treat galaxy catalog incompleteness (see Gray et al. 2022)
- **KDE approximation** of GW data beyond skymap approach

# Preliminary results: GW170817 as a Dark Siren

(Borghi et al. 2023a, *in prep*)

Analysis on  $H_0$  with GLADE+ galaxy catalog (Dalya+2021), mass function fixed (PowerLaw+Peak)

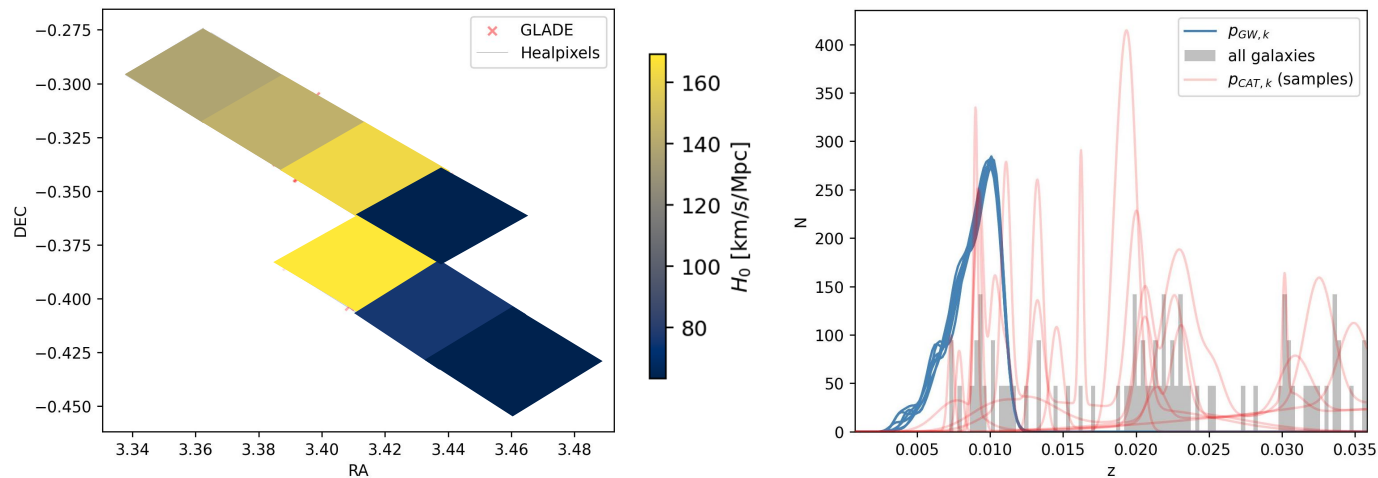


- HEALPix pixelization with  $n_{\text{side}}=32$  (1 pix  $\sim$  3 sq. deg.)
- Luminosity cut  $L_K > 0.005 L_K^*$
- 74 galaxies ( $0.001 < z < 0.036$ )

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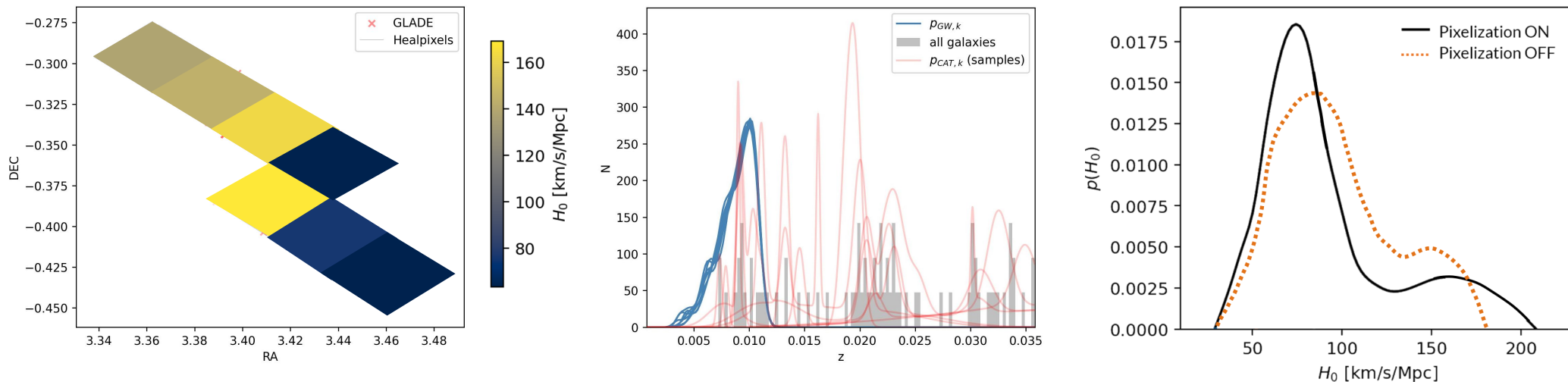


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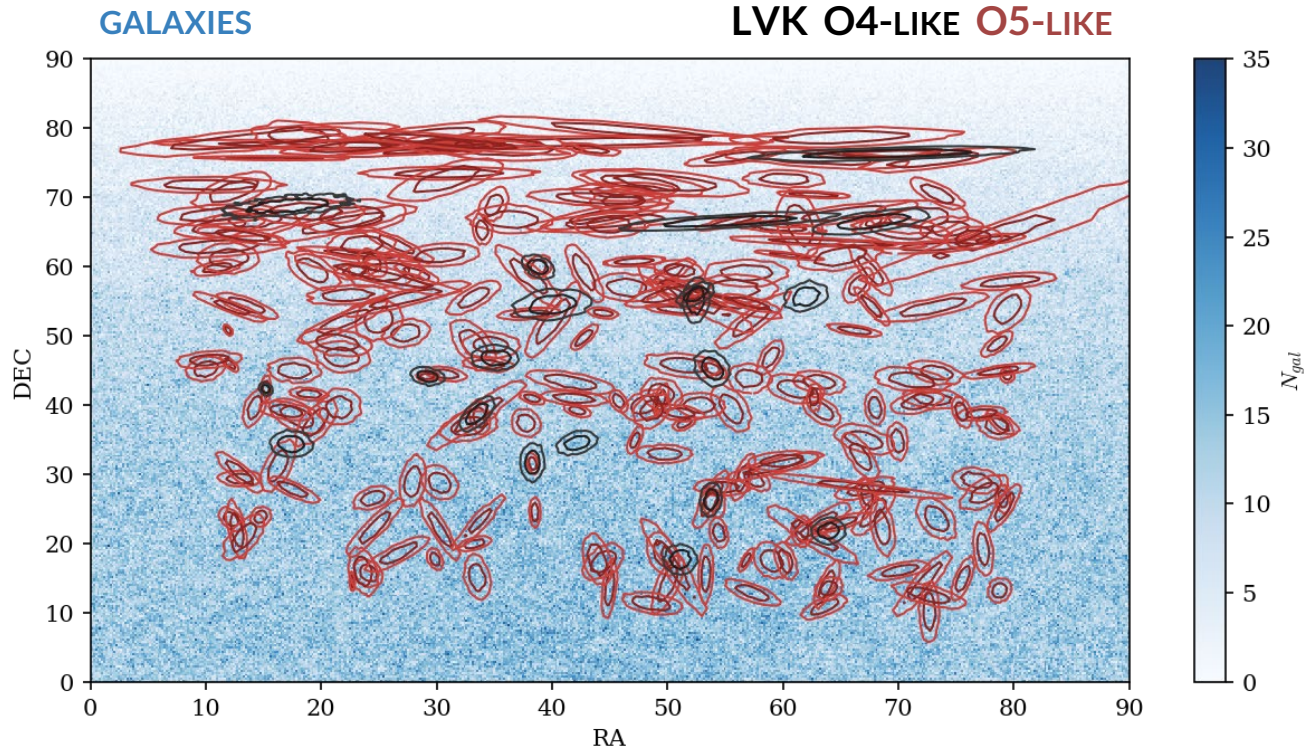


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# Simulated measurements: forecasts for O<sub>4</sub> & O<sub>5</sub>

(Borghi et al. 2023a, *in prep*)

- Mock galaxy catalog (MICEv2, Crocce+2015) x simulated BBH events (using **GWFast**; Iacovelli+2022)

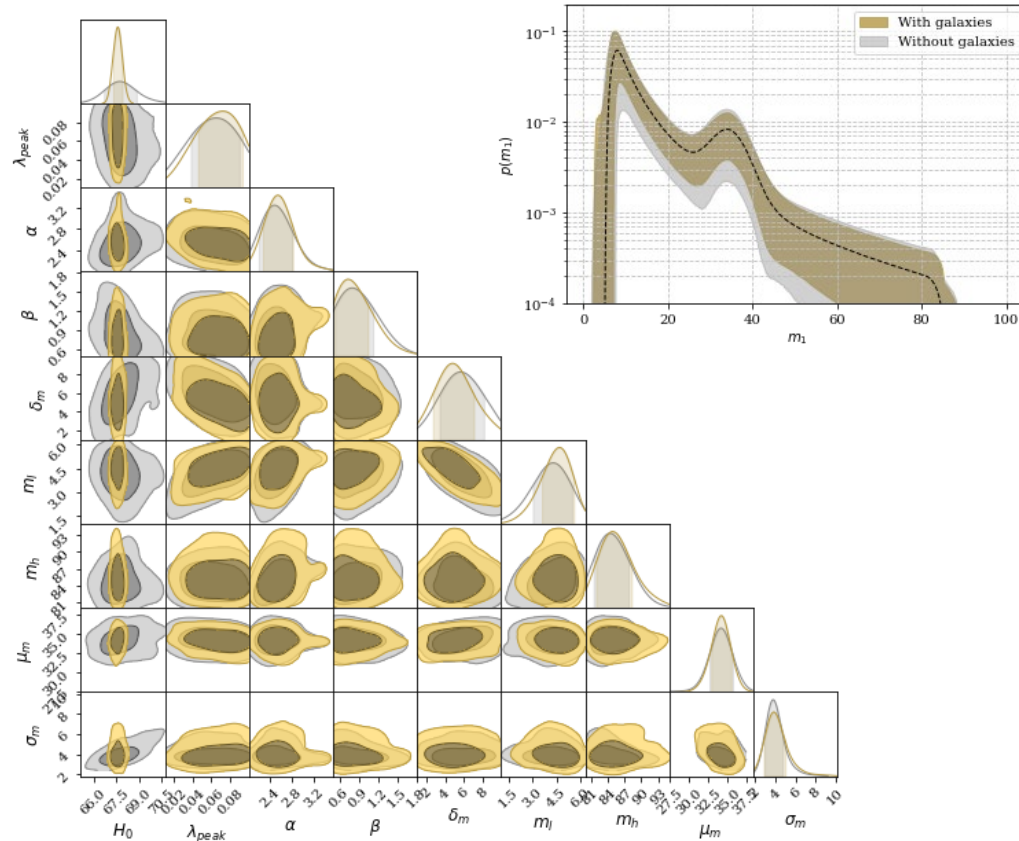


- Analysis of well-localized events ( $\Delta\Omega_{90\%} < 10 \text{ deg}^2$ ):
  - ~ 15 events in LVK-O4
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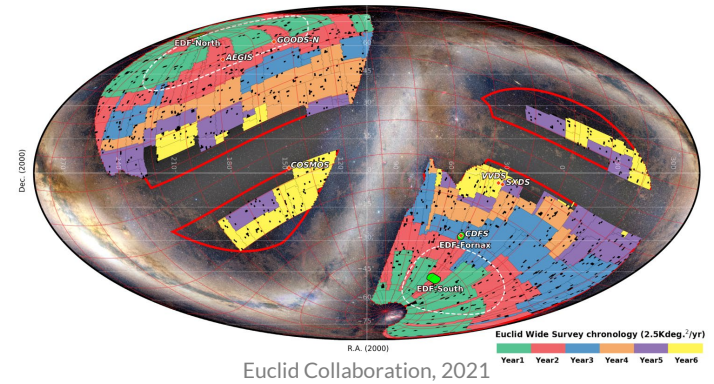
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- Preliminary results on a validation set to test the code efficiency and accuracy
- Ongoing: GW posterior data from full parameter estimation

## SUMMARY & FUTURE WORK

- Extended pipeline for joint astro & cosmo analysis with galaxy catalogs:
  - Forecasts for **O4 and O5 x DES-like survey** with  $\Omega < 10$  sq. deg. GW events. (Borghi et al. 2023a, *in prep*)

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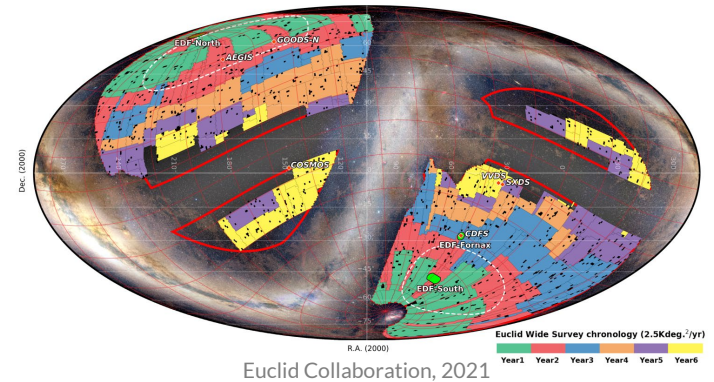
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- Several follow-ups ongoing in the GW group at Unibo:
  1. *Performance improvements* (Julia + HPC, ML techniques)
  2. *Galaxy catalogs*: detailed study of the impact of redshift uncertainties & incompleteness  
+ additional information from specific galaxy properties