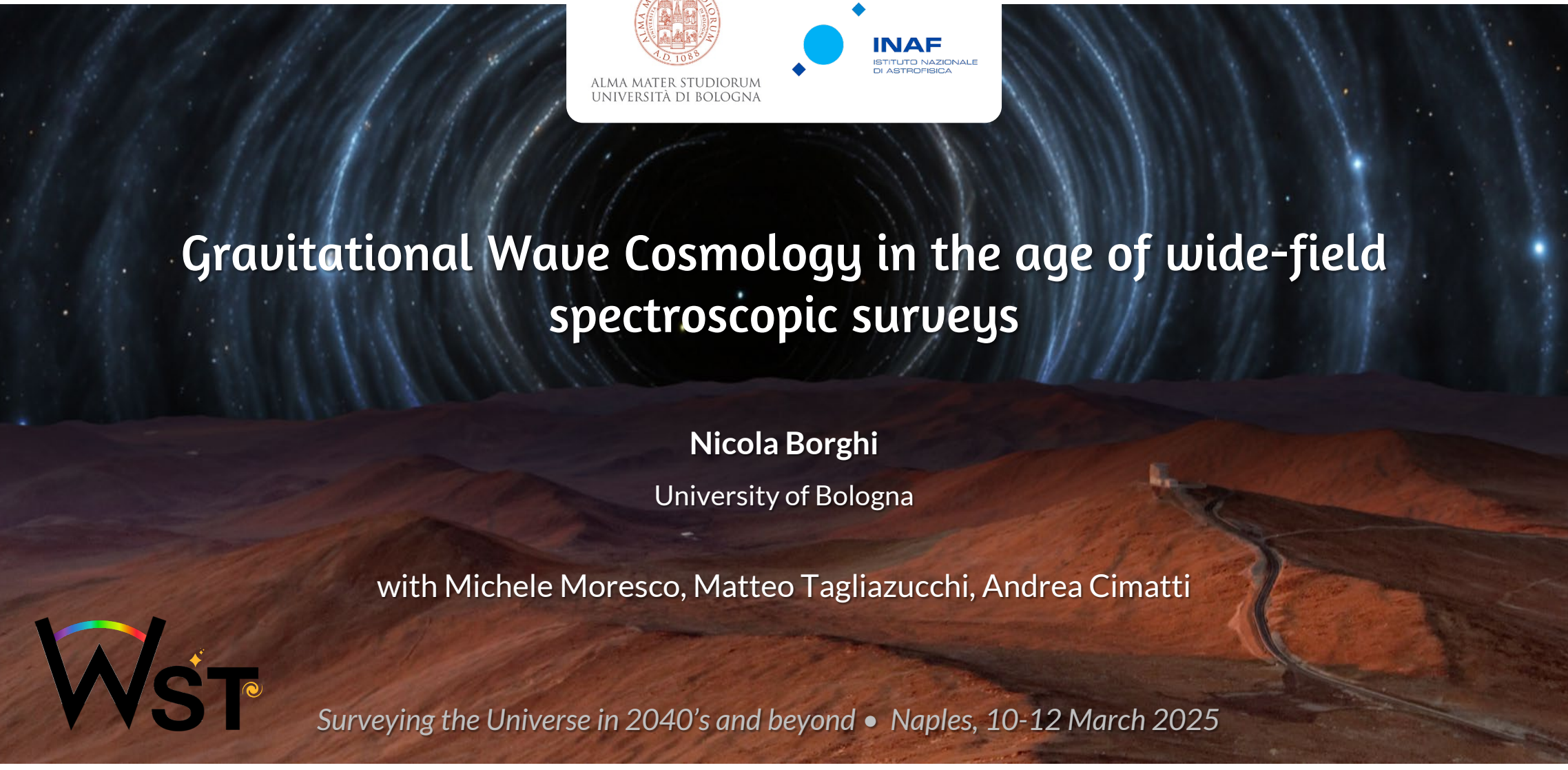


Gravitational Wave Cosmology in the age of wide-field spectroscopic surveys

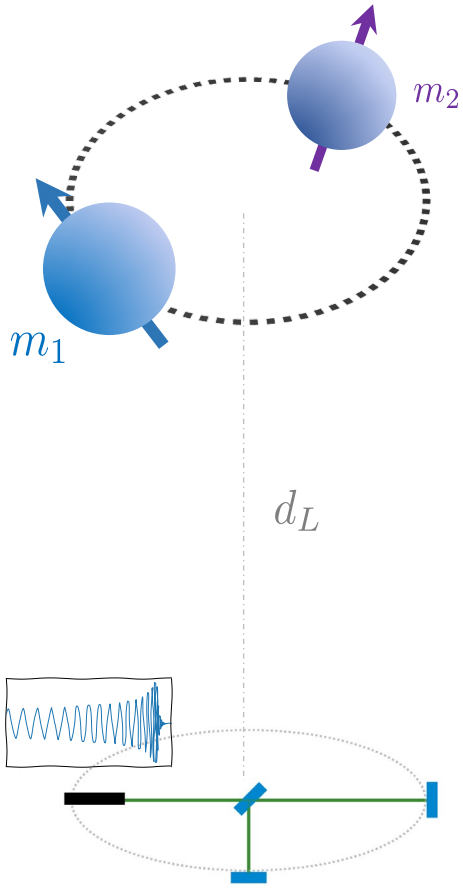
Nicola Borghi

University of Bologna

with Michele Moresco, Matteo Tagliazucchi, Andrea Cimatti

Surveying the Universe in 2040's and beyond • Naples, 10-12 March 2025

Gravitational Wave Cosmology - BASICS



Direct measurement of the luminosity distance (“*standard sirens*”)
w/o additional calibrators (Schutz 1986)

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

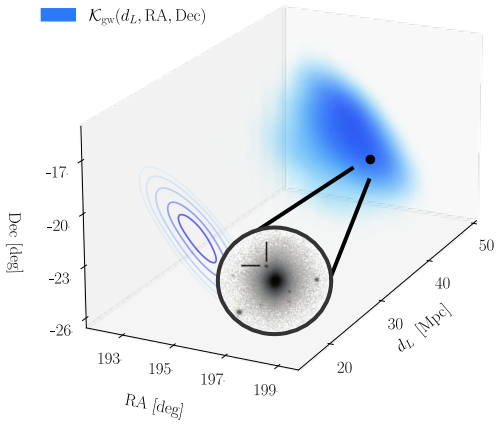
Cosmology via the distance-redshift relation
... but **no redshift measurement** with GW data alone (degen. with masses)

$$d_L^{\rm GW}(z) = (1+z)\int_0^z \frac{{\rm d}z'}{H(z';\lambda_{\rm cosmo})}$$

$$\{H_0, \Omega_{m0}, w_0, ...\}$$

Gravitational Wave Cosmology - REDSHIFT

→ **Bright sirens:** *z* from EM counterpart
(Schutz 1986, Holz & Hughes 2005, ...)



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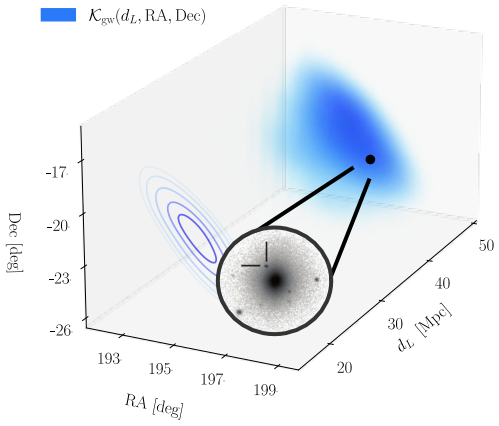

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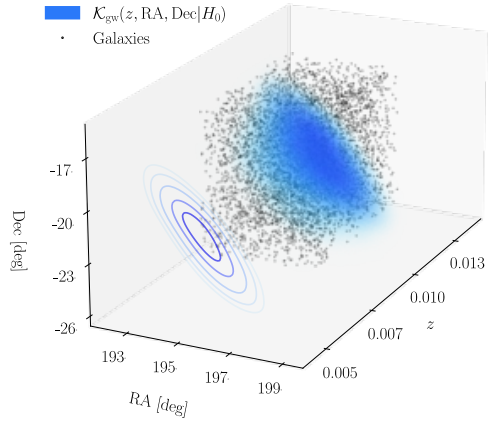

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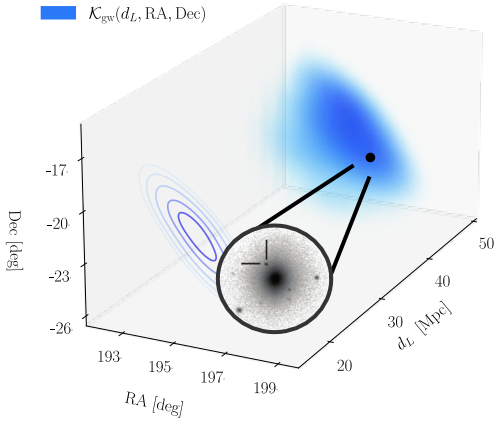

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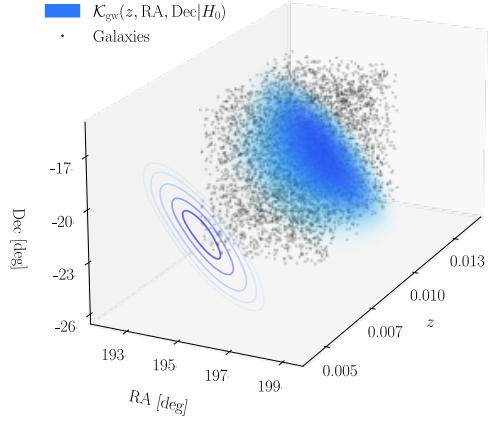
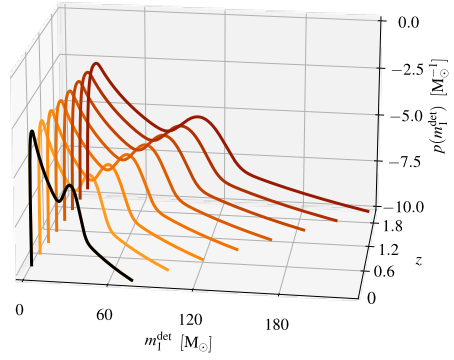


→ **Spectral sirens:** GW population modelling to break the source mass-*z* intrinsic degeneracy
(Chernoff & Finn 1993, Taylor et al. 2012, ...)



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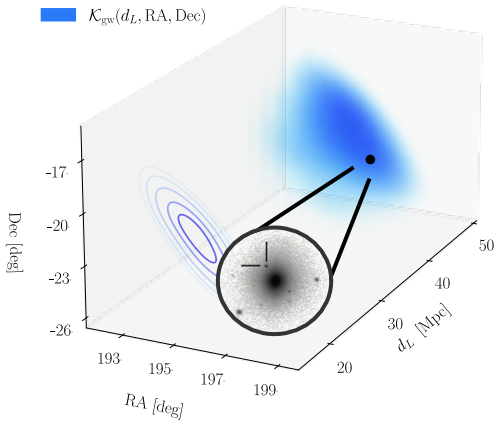
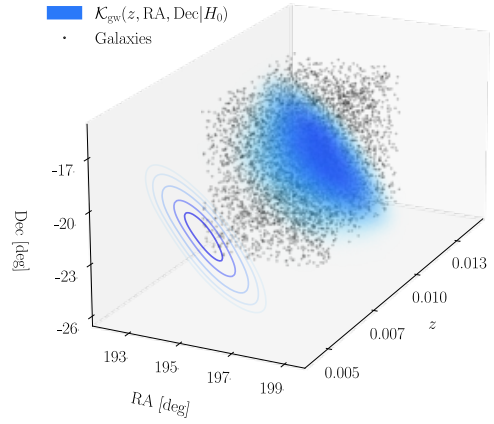
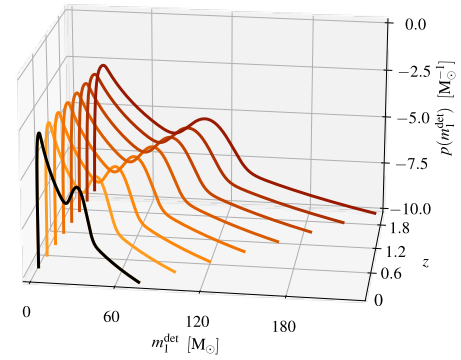






New pipeline for joint astrophysical & cosmological constraints (Borghi et al. 2024, Tagliazucchi et al. , *in prep*):

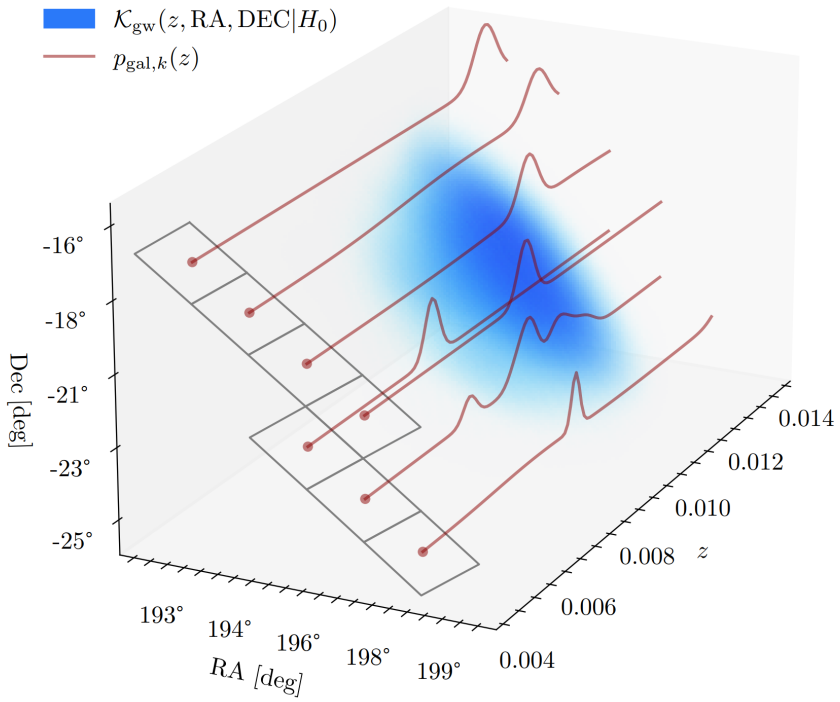
- State-of-the-art **forecasts** for future detectors and synergies with future galaxy surveys
- Study correlations with binary and galaxy properties and explore **systematics**
- **Parallelized** and capable to handle **large data sets**

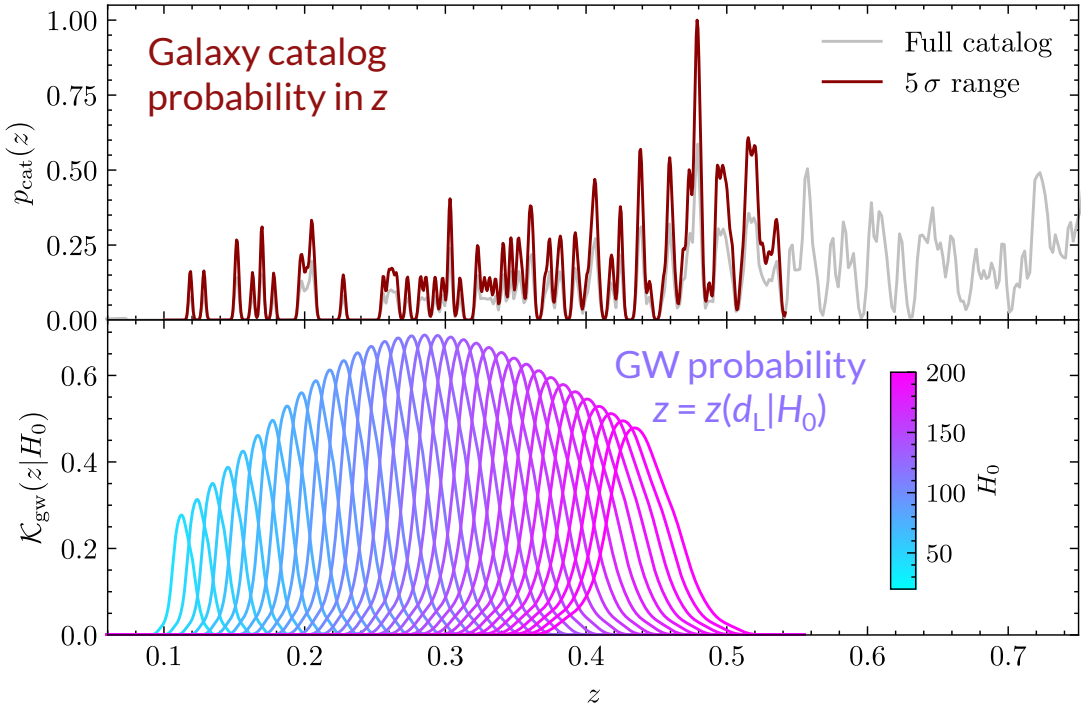
(see also *icarogw*, Mastrogiovanni et al. 2023 and *gwcosmo*, Gray et al. 2023)

CHIMERA

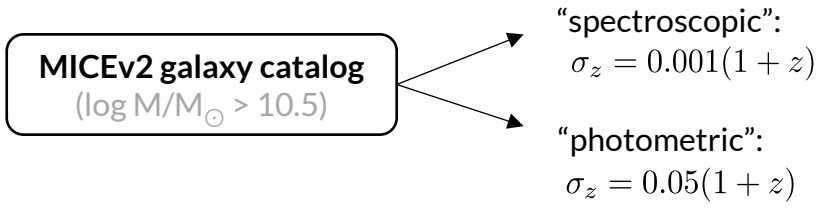
In collaboration with Michele Mancarella (Aix-Marseille Univ.), Francesco Iacovelli, and Michele Maggiore (Univ. Geneva)

Gravitational Wave Cosmology – THE CONCEPT





Mock catalog for LVK O4- and O5-like configurations (Borghi et al., 2024)



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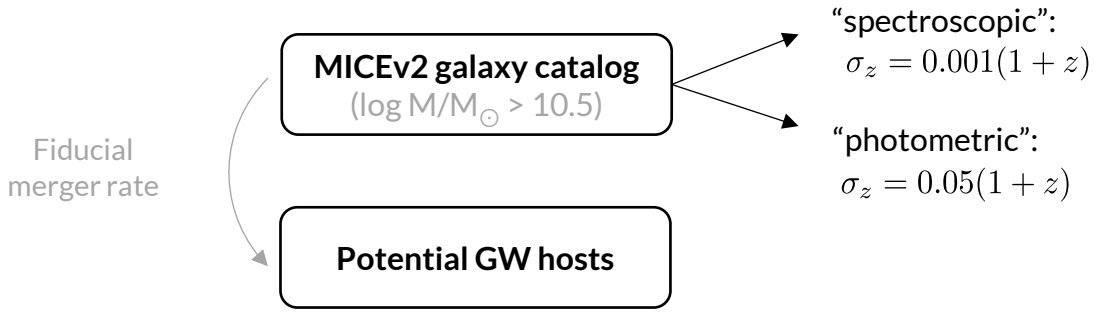

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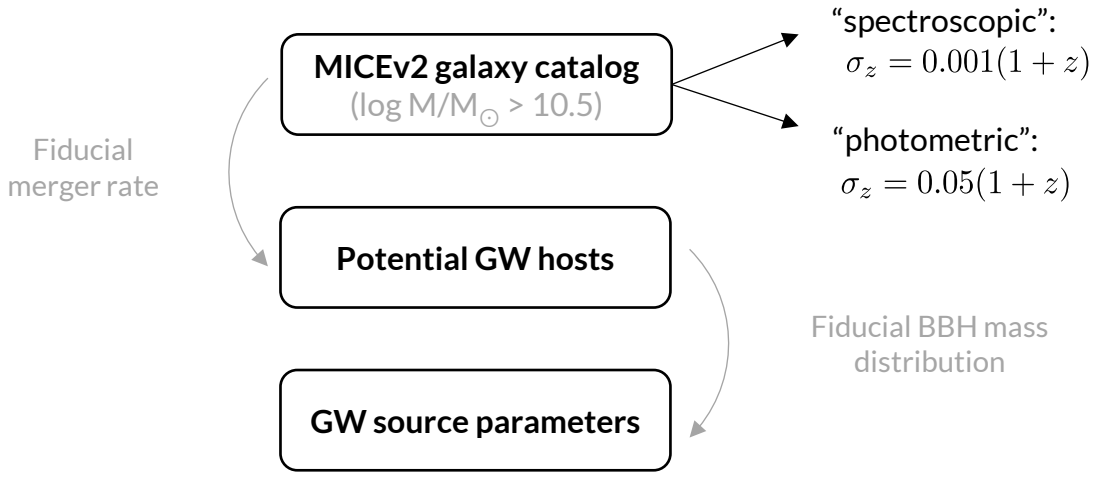

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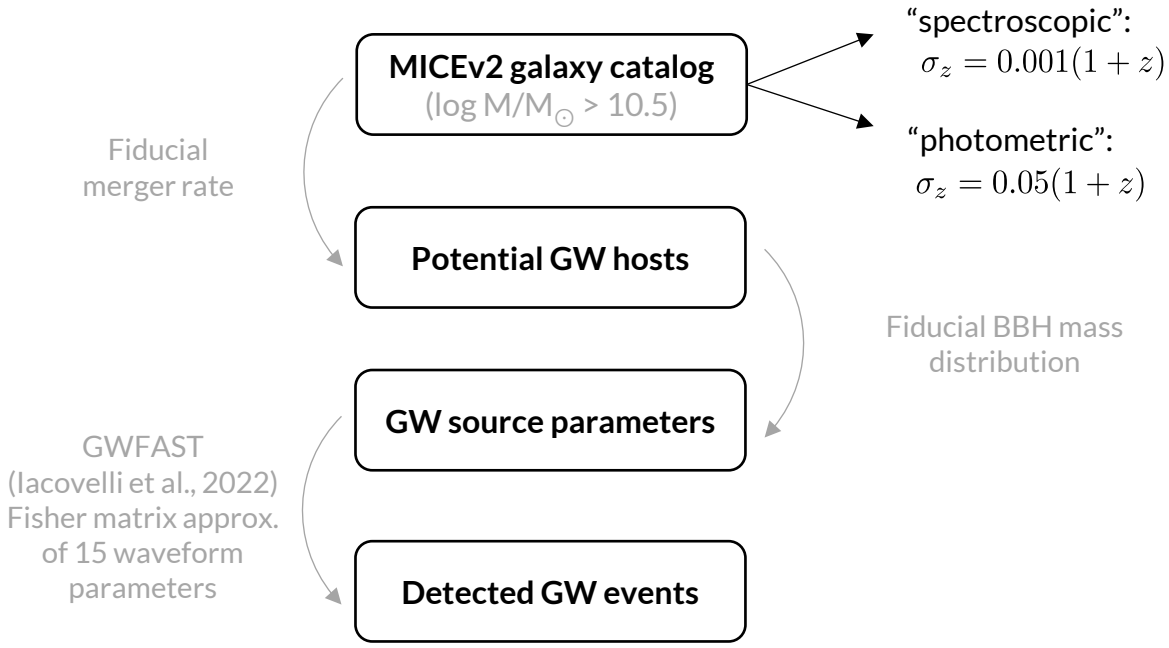

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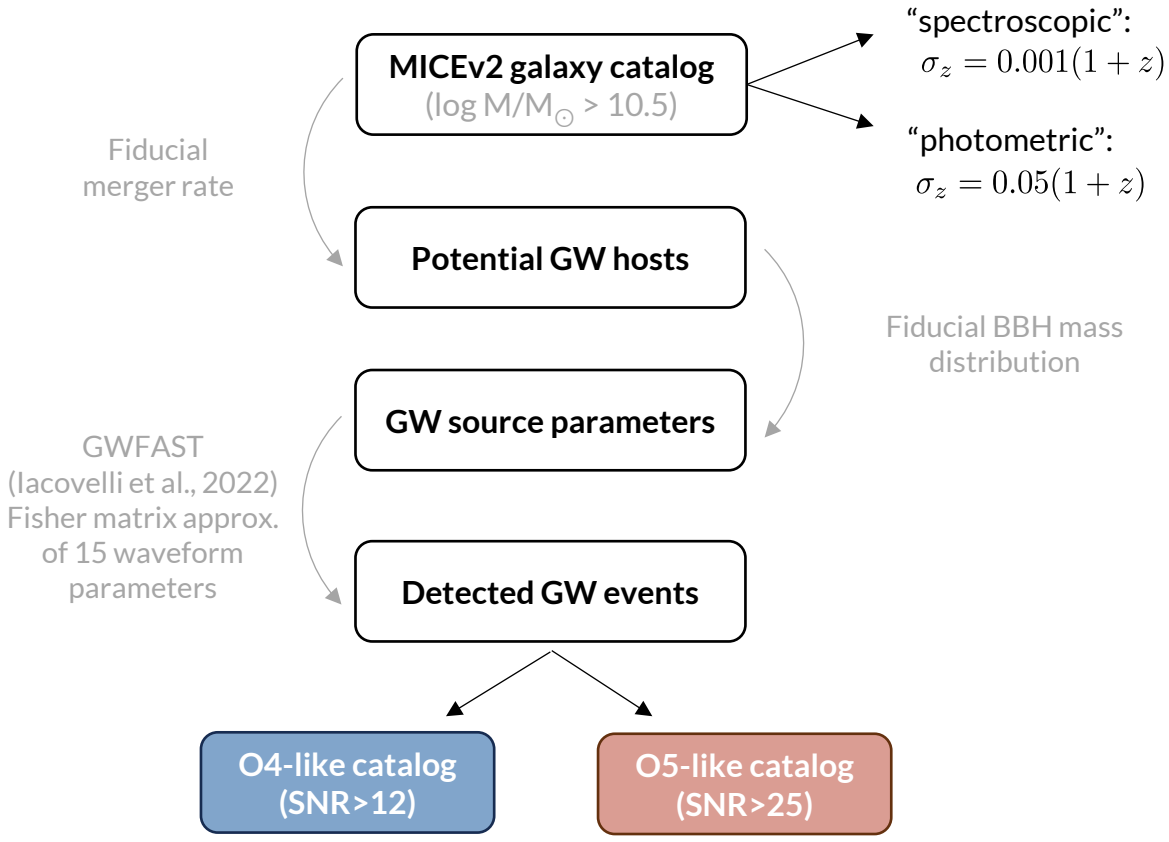

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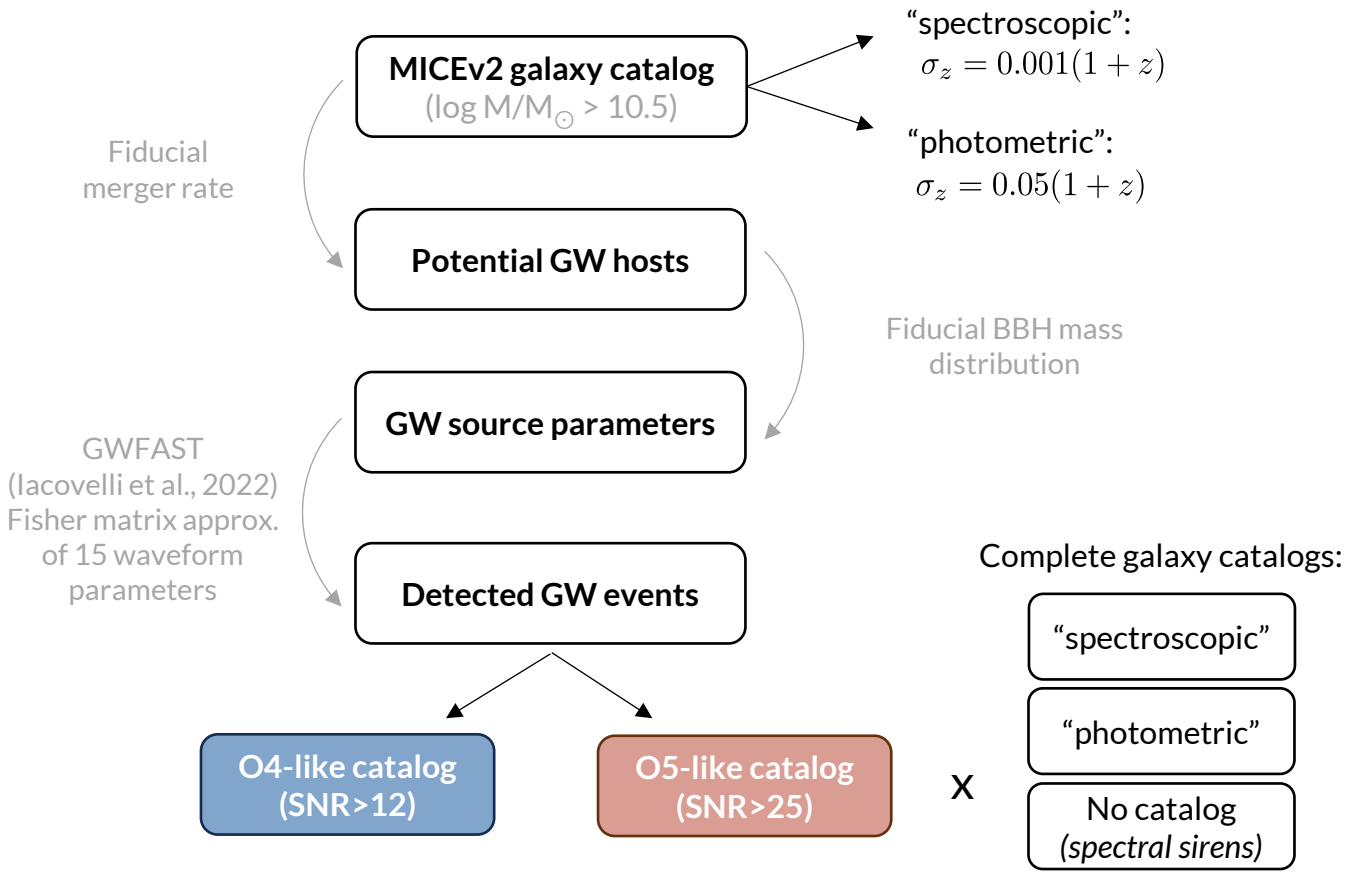

6 total configurations, ~ 10'000 CPU hours (run at Open Physics Hub cluster @ DiFA, Univ. Bologna)

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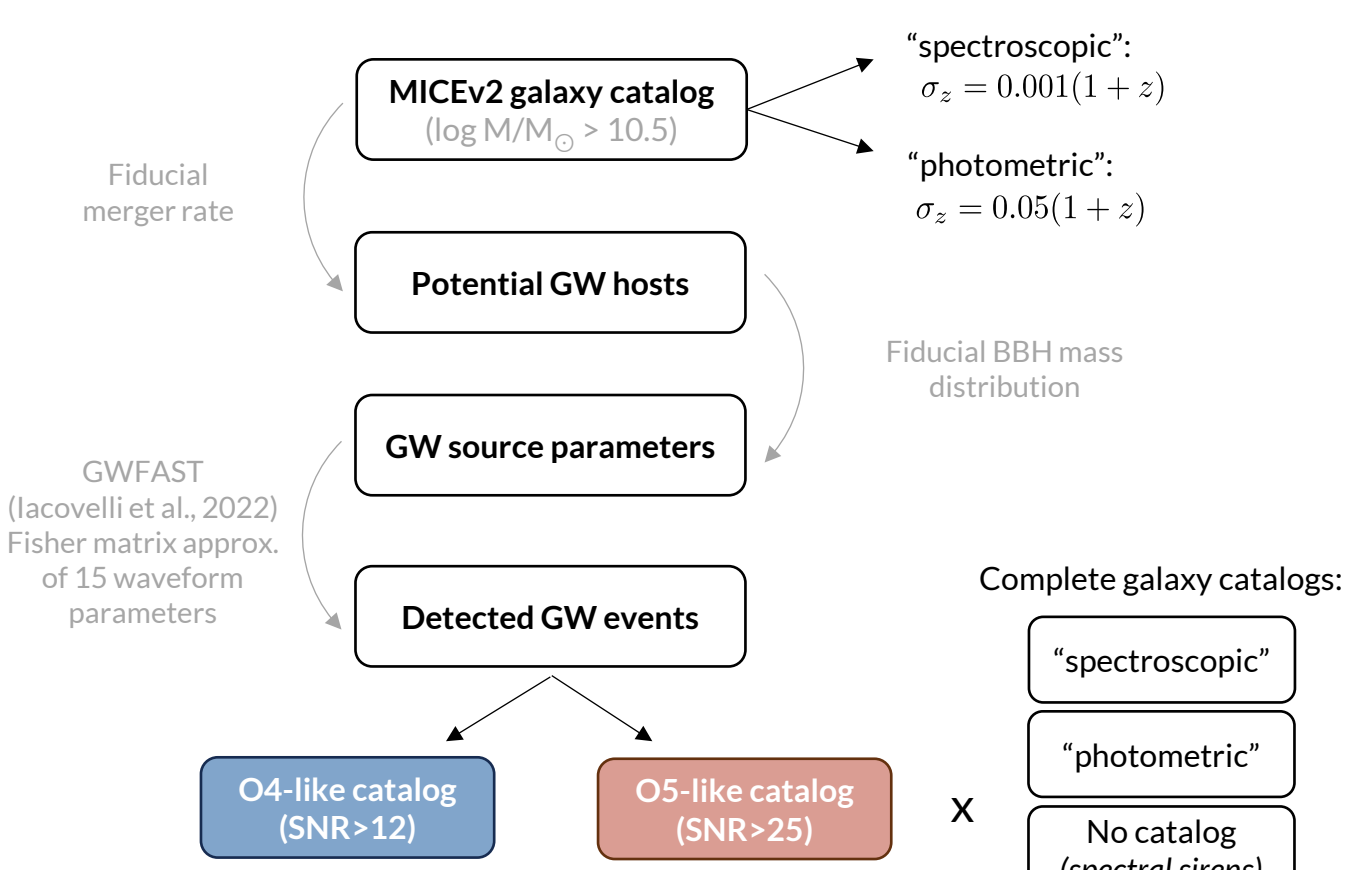

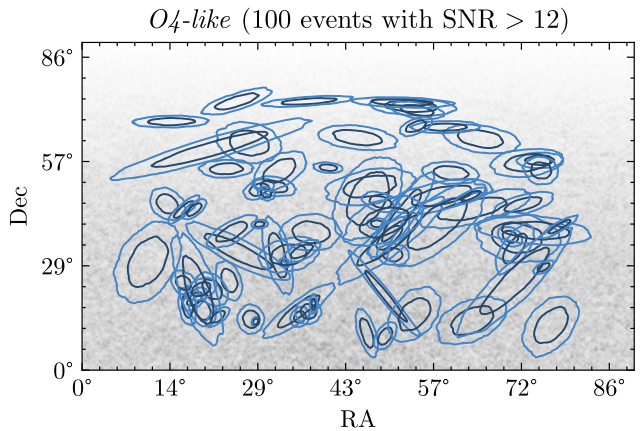

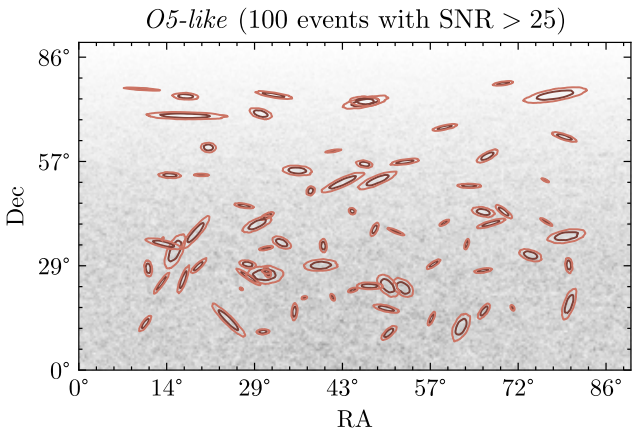

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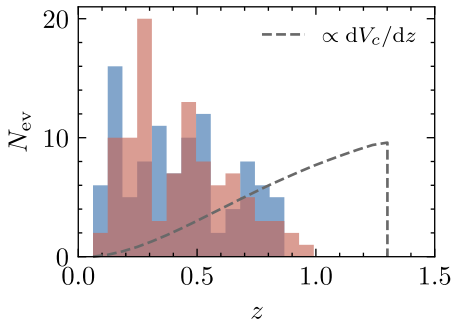
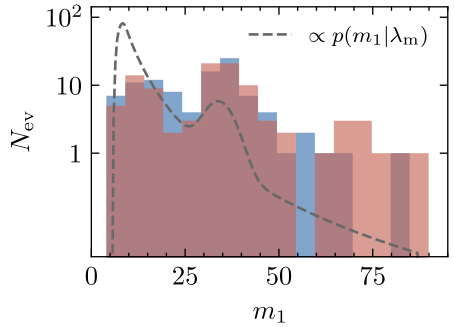
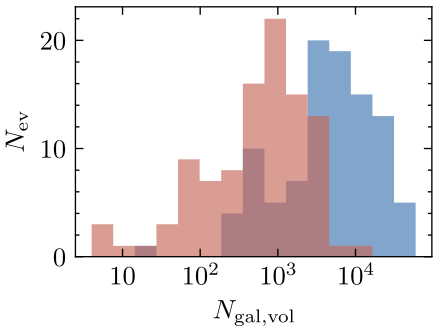






O4-like catalog (SNR>12)

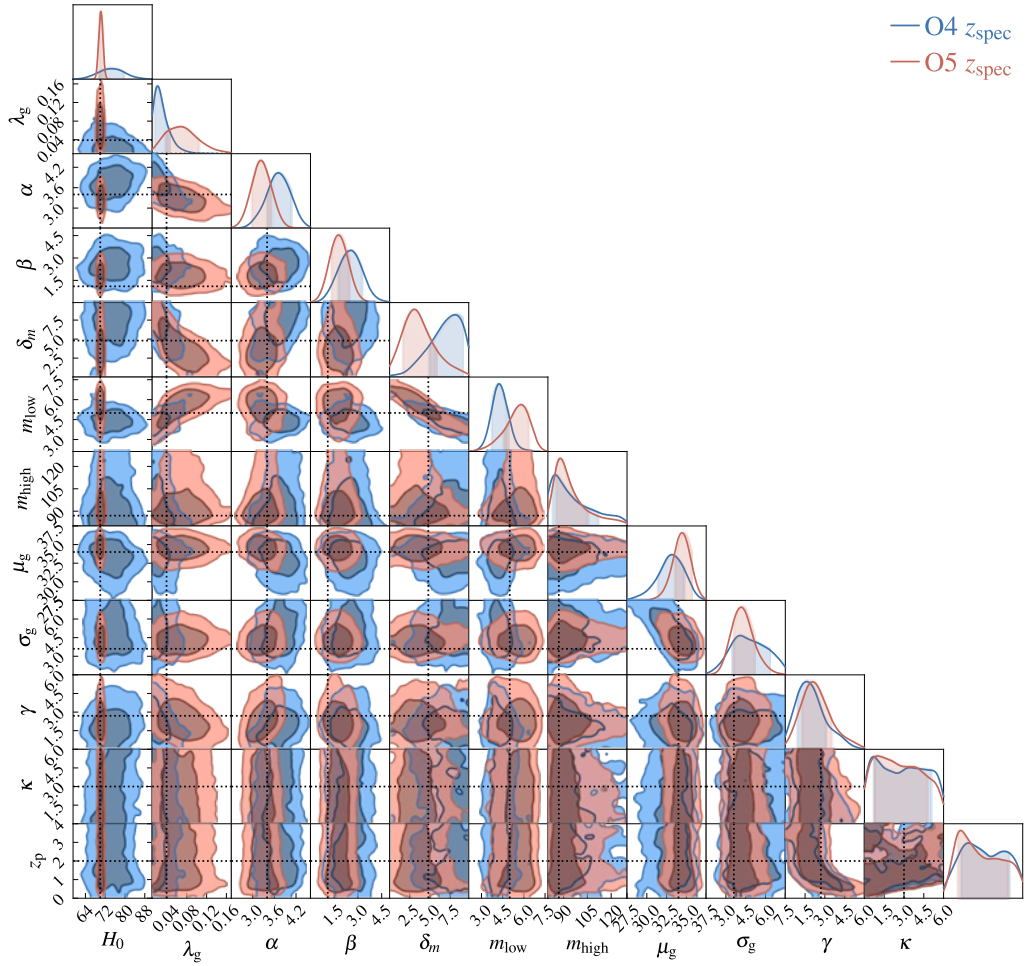
- $z \lesssim 0.9$
- sky loc. areas 10-100 deg^2
- $\gtrsim$ 500 potential hosts for 90% events
- "golden" events with 2 deg^2 localization

O5-like catalog (SNR>25)

- $z \lesssim 1$ (but higher SNR cut!)
- sky loc. areas 1-10 deg^2
- $\gtrsim$ 50 potential hosts for 90% events
- "golden" events with ~0.5 deg^2 localization

(best 100 BBH events in 1 year of observation)

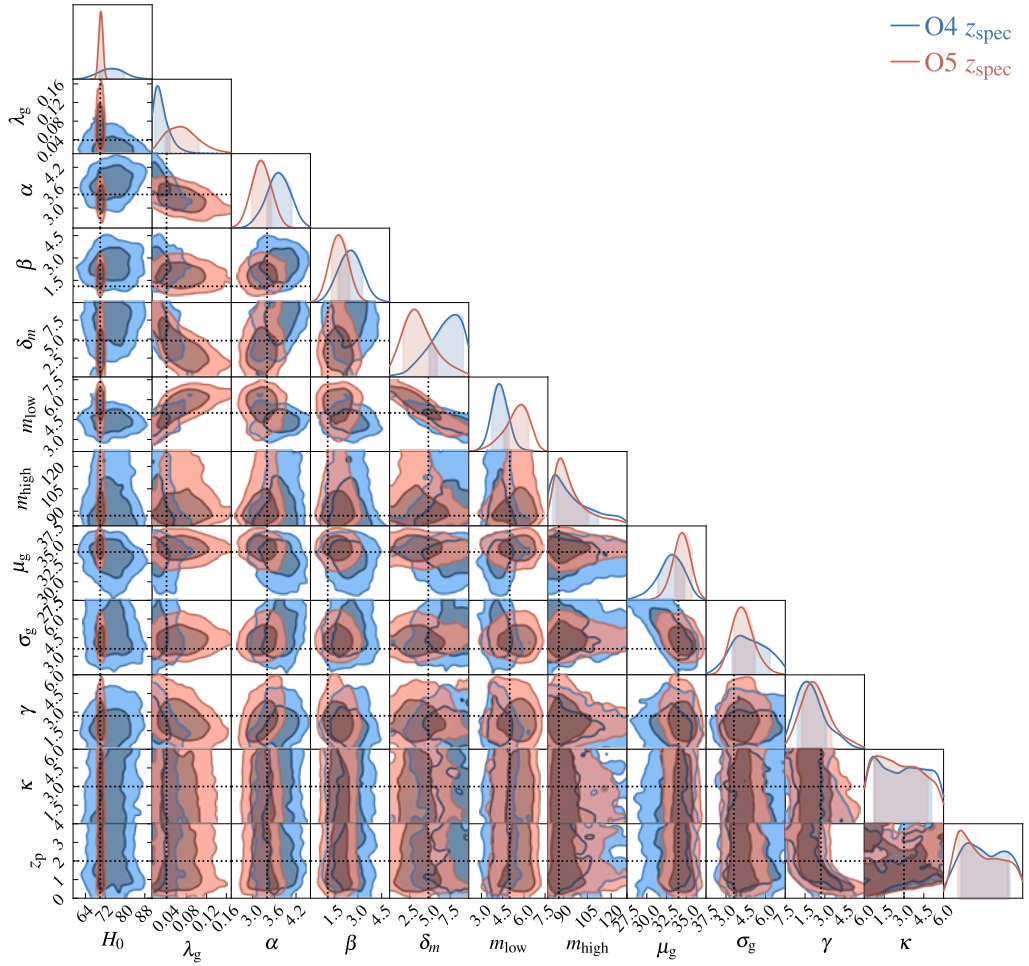
Joint forecasts for LVK O4- and O5-like configurations



- Fiducial values for all **12 hyperparameters** are recovered within the 68% credible levels in all configurations.

λ_i	Description	Fiducial	Prior
	Cosmology (flat ΛCDM)		
H_0	Hubble constant [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	70.0	$\mathcal{U}(10.0, 200.0)$
$\Omega_{\rm m,0}$	Matter energy density	0.25	Fixed
	Rate evolution (Madau-like)		
γ	Slope at $z < z_p$	2.7	$\mathcal{U}(0.0, 12.0)$
κ	Slope at $z > z_p$	3	$\mathcal{U}(0.0, 6.0)$
z_p	Peak redshift	2	$\mathcal{U}(0.0, 4.0)$
	Mass distribution (PowerLaw+Peak)		
α	(Primary) slope of the power law	3.4	$\mathcal{U}(1.5, 12.0)$
β	(Secondary) slope of the power law	1.1	$\mathcal{U}(-4.0, 12.0)$
δ_m	(Primary) smoothing parameter	4.8	$\mathcal{U}(0.01, 10.0)$
$m_{\rm low}$	Lower value [$\mathrm{M_\odot}$]	5.1	$\mathcal{U}(2.0, 50.0)$
$m_{\rm high}$	Upper value [$\mathrm{M_\odot}$]	87.0	$\mathcal{U}(50.0, 200.0)$
$\mu_{\rm g}$	(Primary): mean of the Gaussian peak [$\mathrm{M_\odot}$]	34.0	$\mathcal{U}(2.0, 50.0)$
$\sigma_{\rm g}$	(Primary): standard deviation of the Gaussian peak	3.6	$\mathcal{U}(0.4, 10.0)$
$\lambda_{\rm g}$	(Primary): fraction of the Gaussian peak	0.039	$\mathcal{U}(0.01, 0.99)$

Joint forecasts for LVK O4- and O5-like configurations



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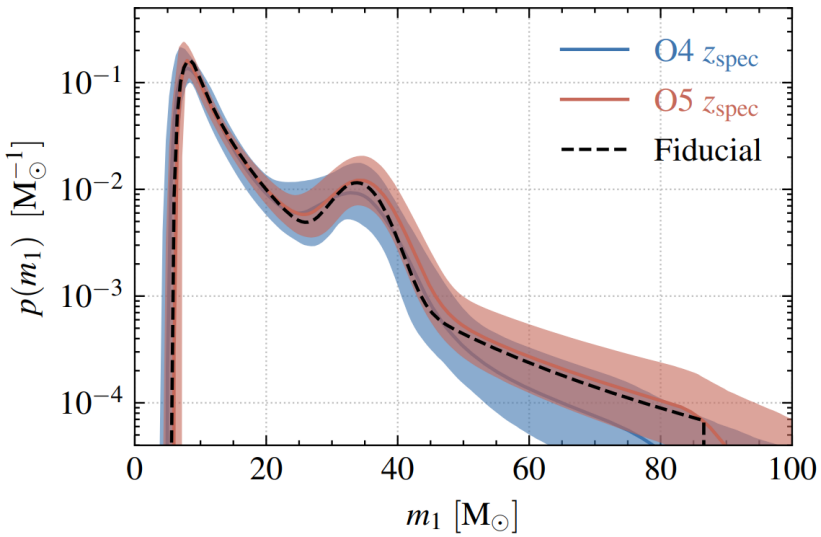


Joint forecasts for LVK O4- and O5-like configurations

Spectral-only analysis

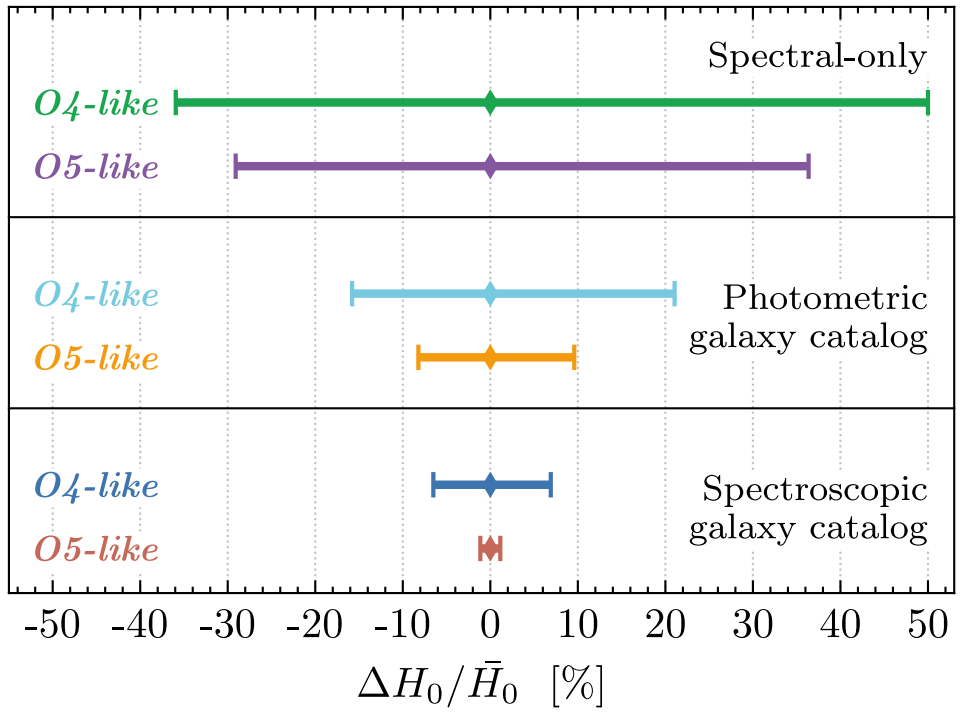
- Constraints on H_0 from the BBH mass distribution
  ~40% O4-like
  ~30% O5-like

Spectroscopic vs. photometric galaxy catalog

- Constraints on H_0 are notably weaker
  ~ 3x for O4-like
  ~ 9x for O5-like

Spectroscopic galaxy catalog

- Constraints on H_0 in about ~1 yr of observations
  7% with O4-like
  1% with O5-like



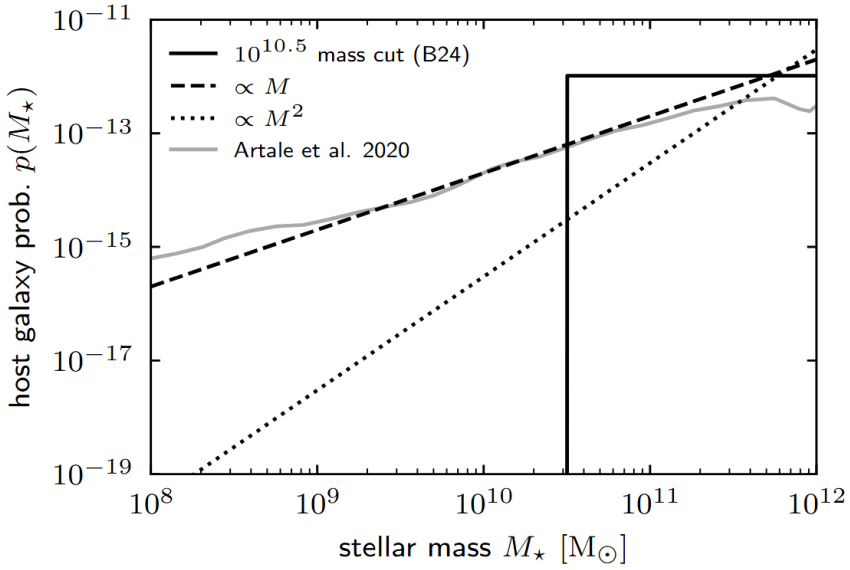
Current constraints: 46% with 42 BBHs from GWTC-3 (Mastrogiovanni+23, Gray+23)

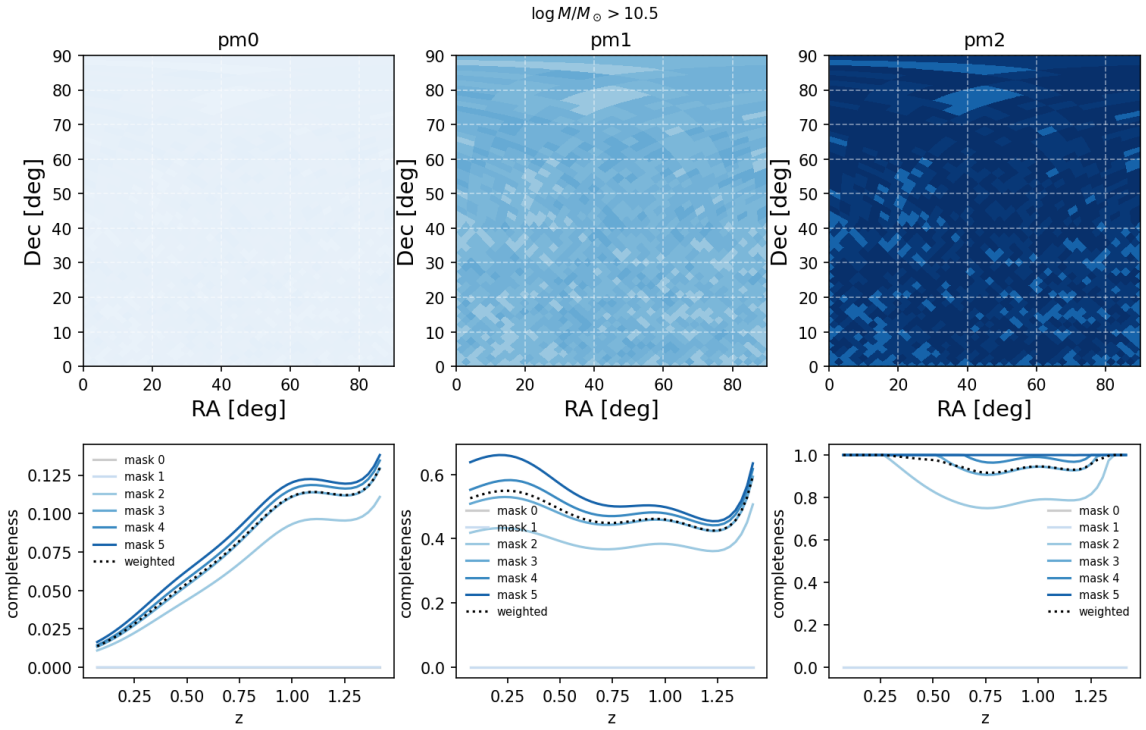
Going beyond: galaxy catalog incompleteness and weighting

Borghi et al., *in prep*

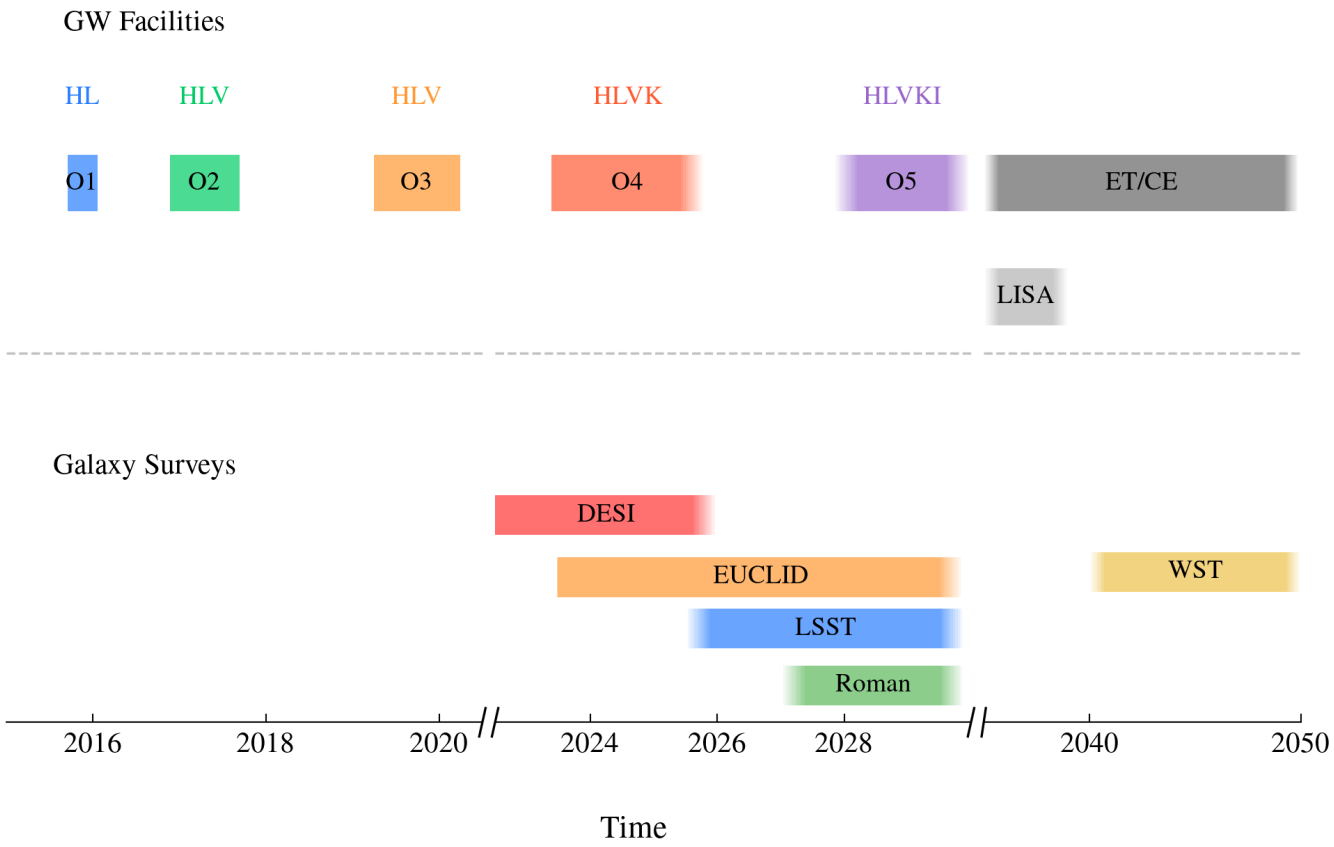
Incompleteness → Wider H_0 posterior

Weighting → Narrower H_0 posterior (if *w* toward more complete sources)
but potential biases when mismodelling weights (Perna et al. 2024)





What about the future?



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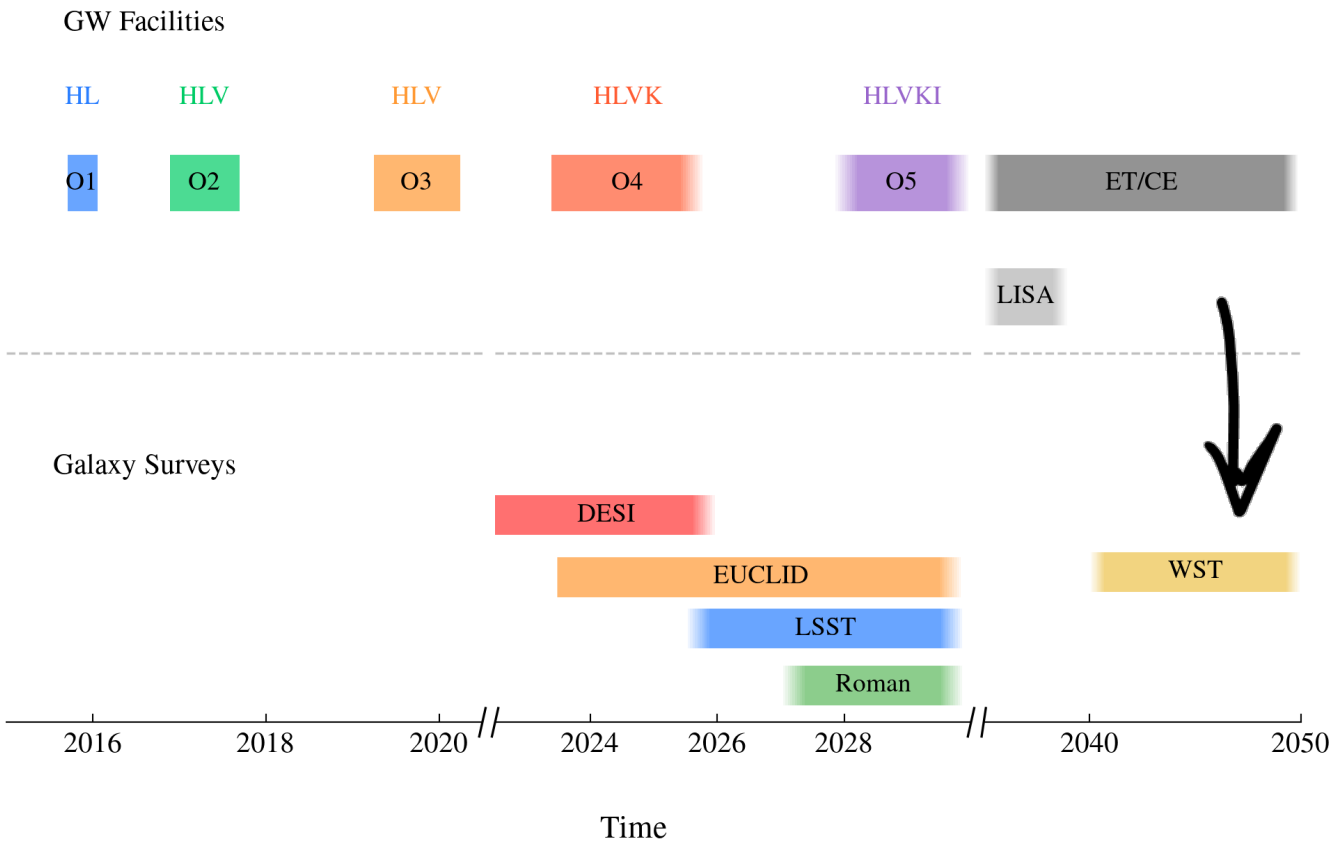

- Time domain
- Cosmology (bright, dark sirens)
- Host galaxy properties

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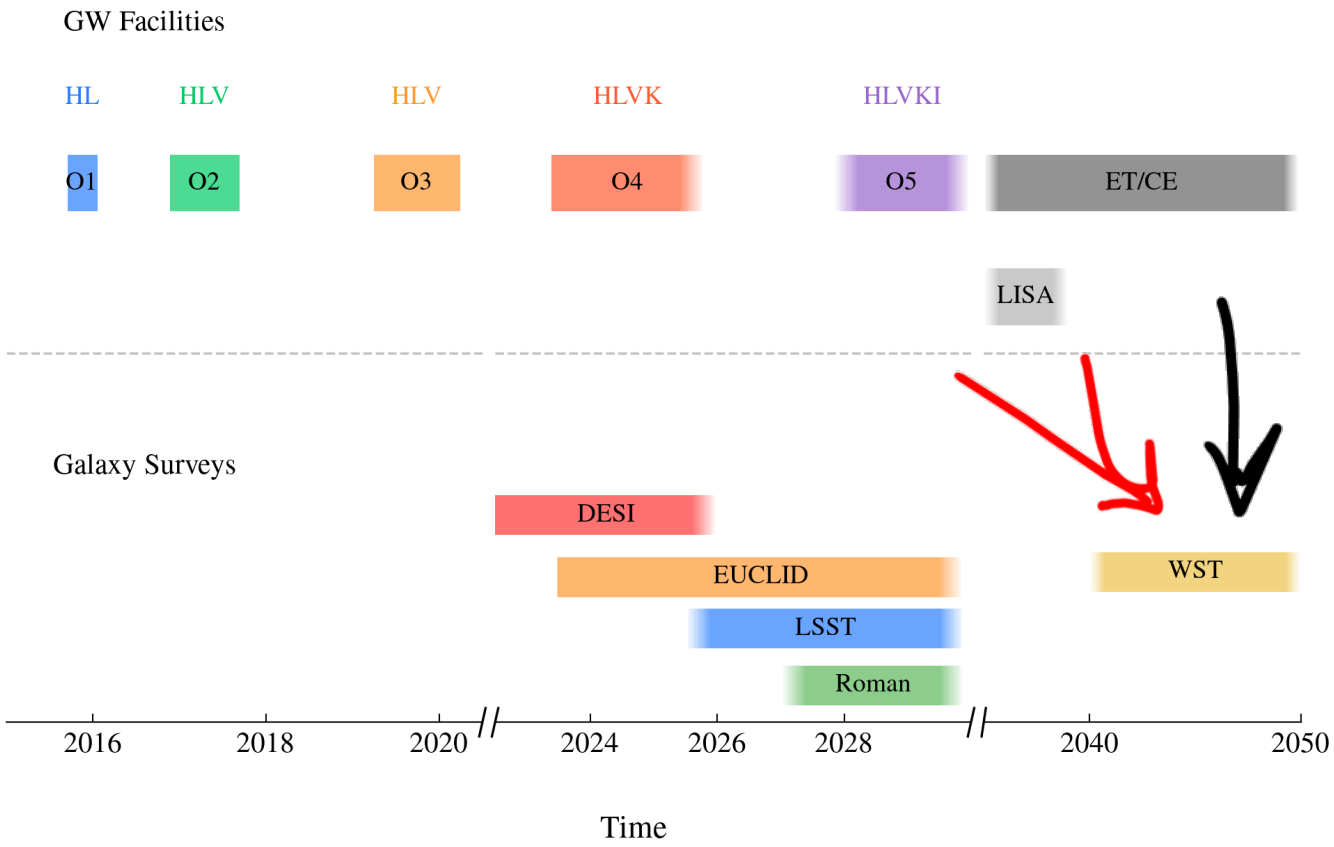


- Time domain
- Cosmology (bright, dark sirens)
- Host galaxy properties

- Cosmology (dark sirens)
- Host galaxy properties (stat.)

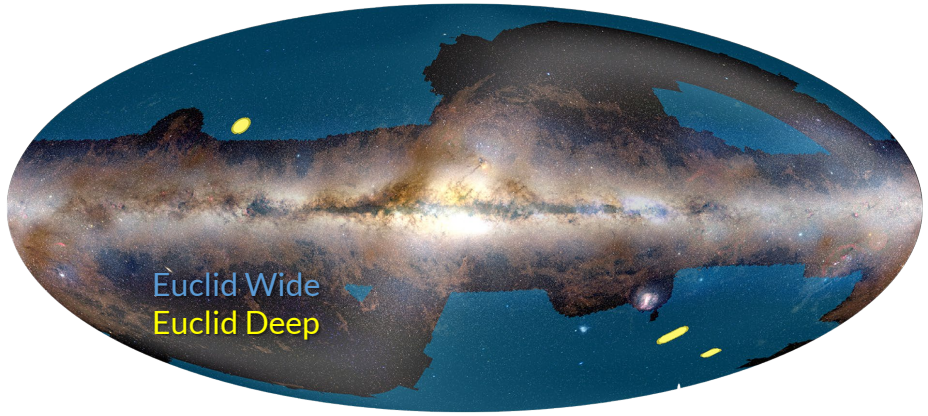
What about the future?

LVK O5 x WST

- **Remapping GW localization volumes with deeper and spectroscopic observations**

Improvements in dark siren measurements

+ Extension to other LCDM params.: Ω_m, w_0
    - Work ongoing in Euclid GW SWG



ESA/Euclid/Euclid Consortium/NASA/Planck Collaboration/A. Mellinger

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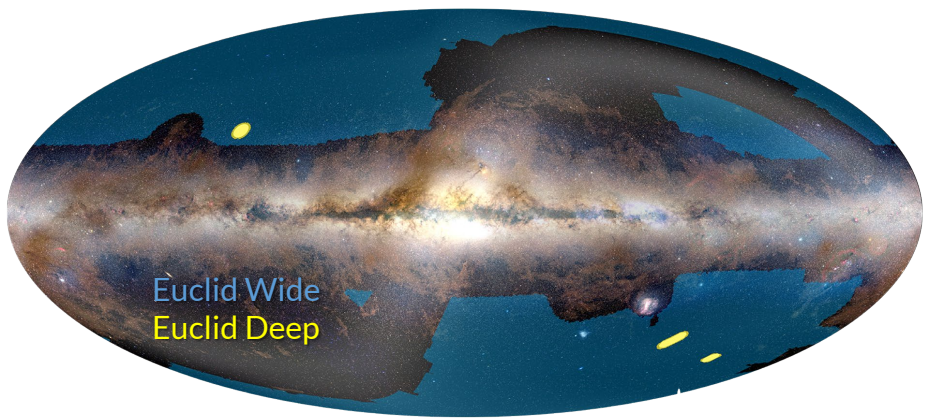
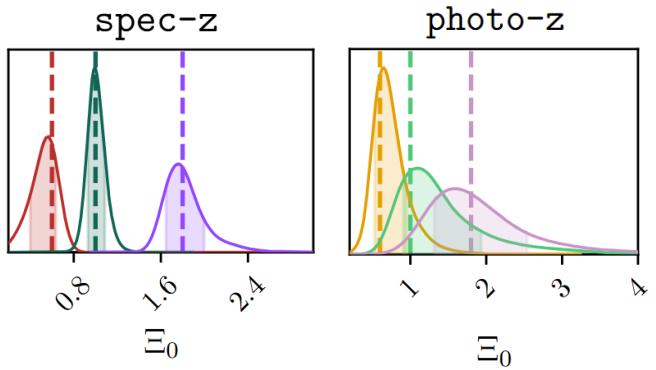


ESA/Euclid/Euclid Consortium/NASA/Planck Collaboration/A. Mellinger

Constraints to modified GW propagation

Modifications in the tensor perturbation sector; can be parameterized as (Belgacem et al. 2018)

$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$



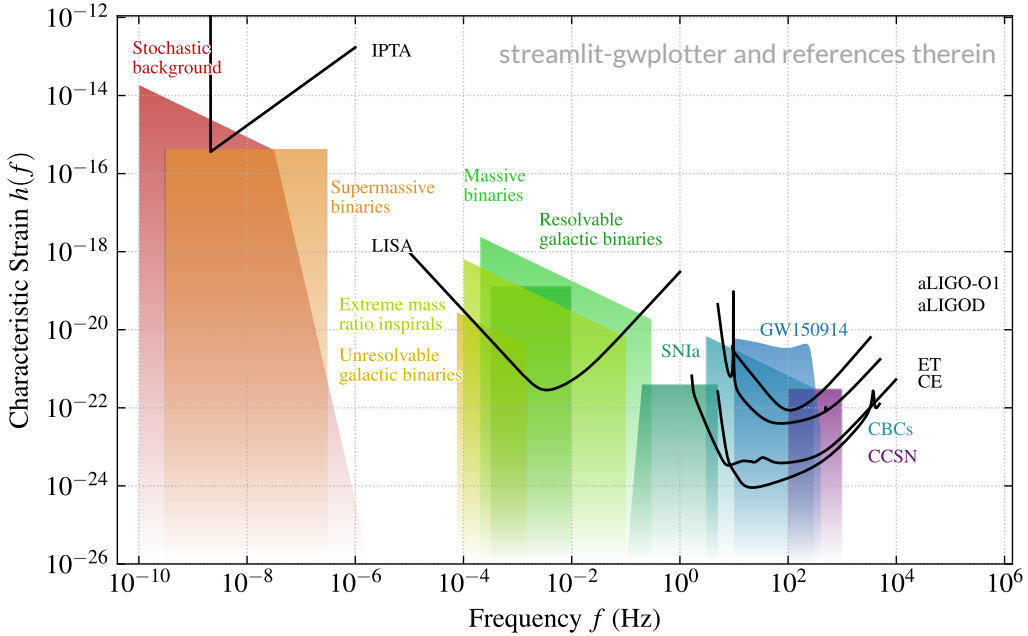
Tagliazucchi, et al. *in prep*

What about the future?

LISA x WST

- **Remapping best localized extreme mass ratio inspirals and massive BBH mergers**

  MBHB mergers (m_1~$10^{5\text{-}6}\,M_\odot$) and EMRIs can be used as standard sirens (see LISA Redbook, 2024)



EMRIs (e.g., Laghi et al 2021)

- Full population up to $z \sim 4$
- Standard sirens (<2 deg^2, $d d_L/d_L$<0.1):
  - $0.1 < z < 1$
  - 1-100/yr
  - dH_0/H_0 ~ 1-10%

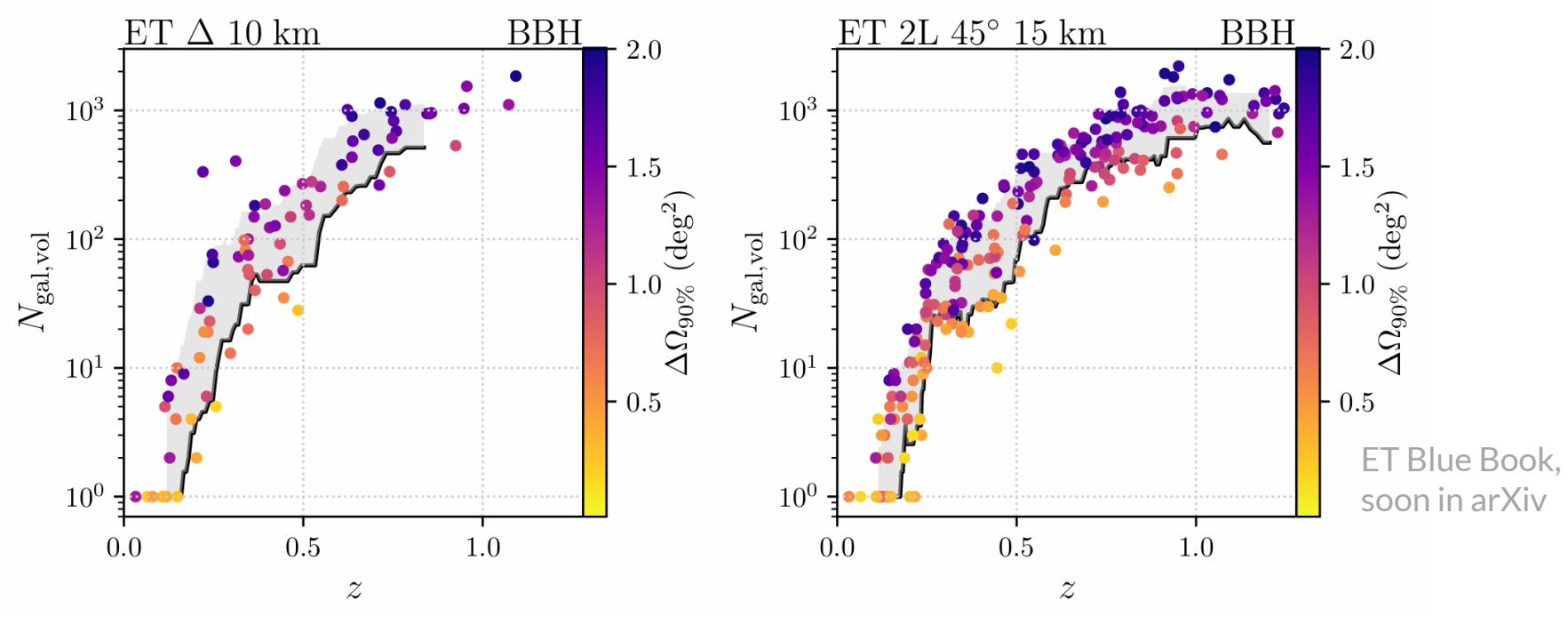
MBHBs (e.g., Tamanini+2016, Mangiagli+2021)

- Full population up to $z \sim 10$
- Up to ~5 bright sirens / yr

What about the future?

ET x WST

- **Dark sirens with best localized events (up to z~1), H(z)?, correlation with host properties**



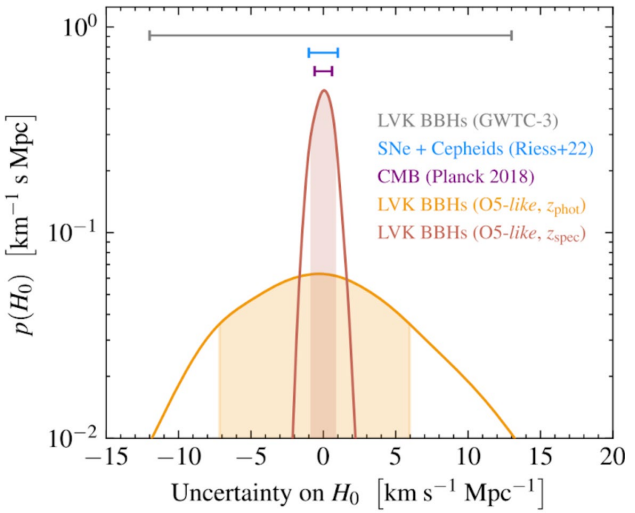
ET Blue Book, soon in arXiv

- *O*(100) events with localization area < 10 deg^2 up to z~0.7
- *Few tens* of events with < 100 galaxies in localization volume

Gravitational Wave Cosmology in the age of wide-field spectroscopic surveys - SUMMARY

GWs provide a direct measurement of H_0 and can probe H(z) via $d_L(z)$

- In Borghi et al. (2024), we present a novel pipeline (CHIMERA): **joint cosmological and astrophysical population constraints** with the **100 best BBH** for the LVK O4- and O5-like scenarios:
  - H_0 + spectroscopic galaxy catalog, **~1% with O5-like** in about one year
  - H_0 + photometric galaxy catalog, **~9x weaker** constraints
  - O4-like with spectroscopic catalog > O5-like with photometric



- Future wide field spectroscopic surveys may for transform GW cosmology:
  - **Time domain + bright sirens** with concurrent GW facilities
  - **Dark sirens** (H(z), modified GW propagation) also with previous GW catalogs

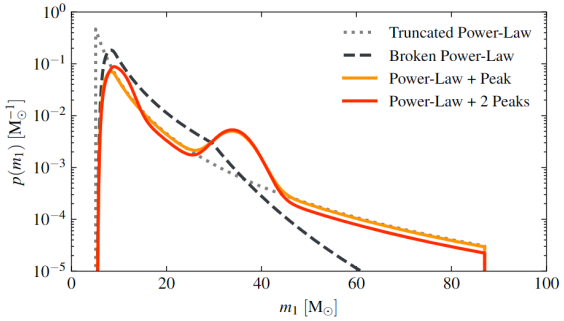
If you are interested join us at WST Cosmology **WP6 - Alternative probes** (Leads: Dinko Milaković, Nicola Borghi)

CHIMERA

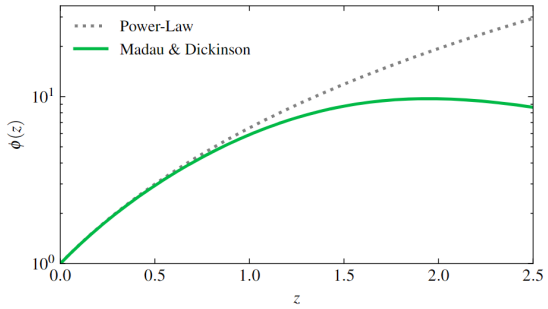
GitHub CHIMERA | arXiv 2106.14894 | docs passing | license MIT | latest-release v1.0.0

https://chimera-gw.readthedocs.io/latest/

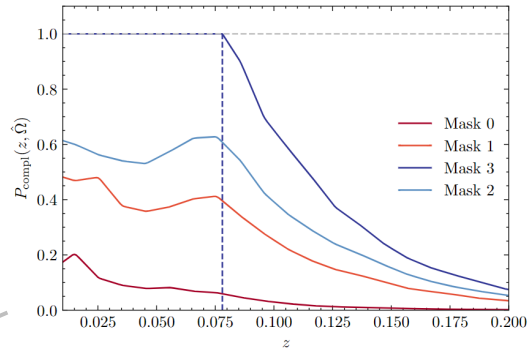
GW properties: mass distribution model

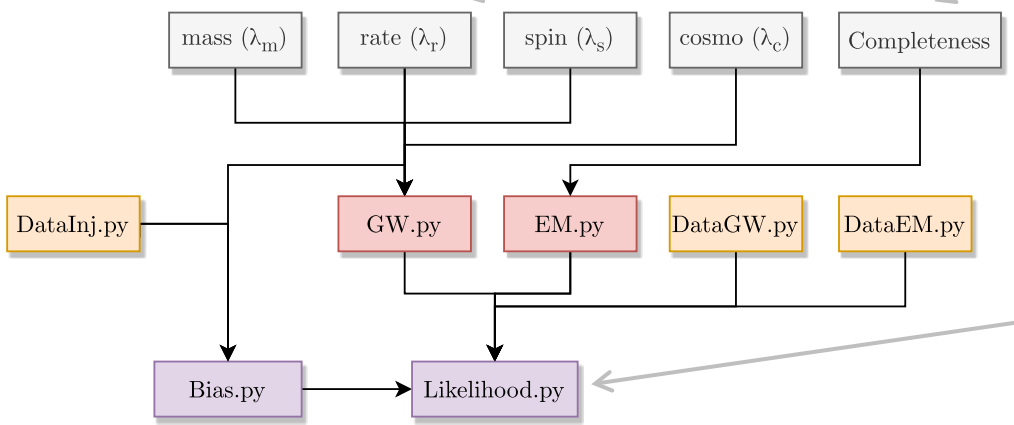


GW properties: Rate evolution model

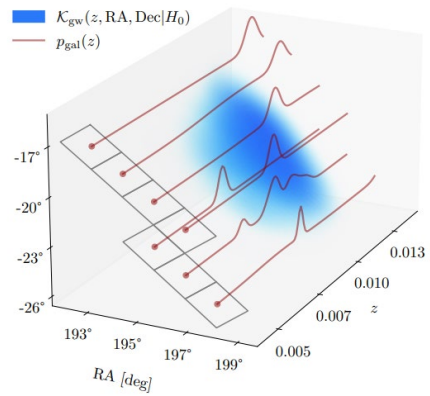


Galaxy catalog properties: Redshift uncertainty, completeness

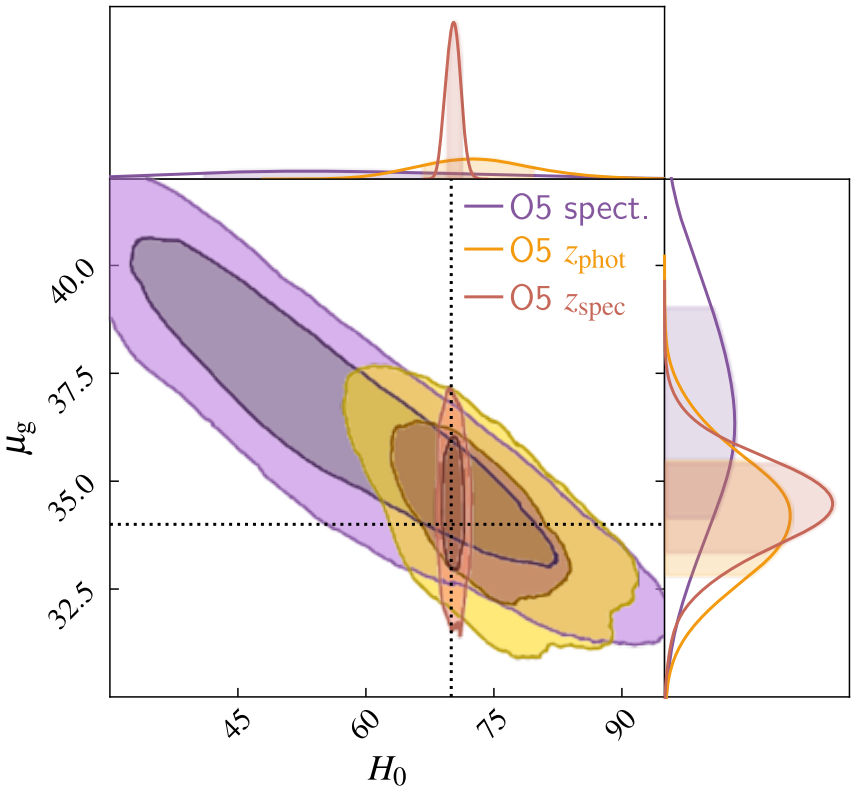


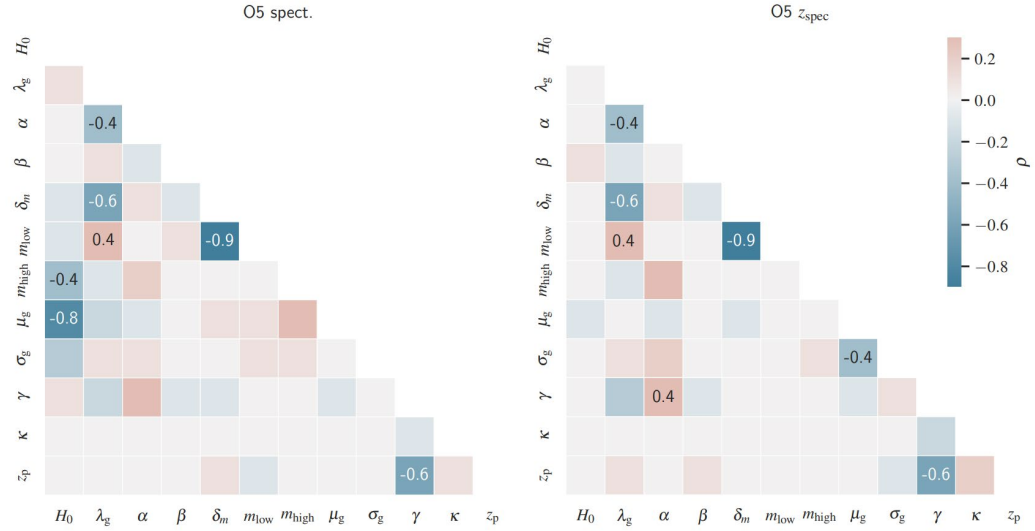


Data processing: GW KDE, pixelization, selection effects



Cosmological and astrophysical hyperparameters correlations





- Well known degeneracy in the spectral siren case between H_0 and the peak of the mass function (see e.g., Abbott et al 2023 Cosmology paper)
- The degeneracy is broken with 100 BBHs in the case of a spectroscopic galaxy catalog