Constraints on the Cosmic Expansion of the Universe and Modified Gravity

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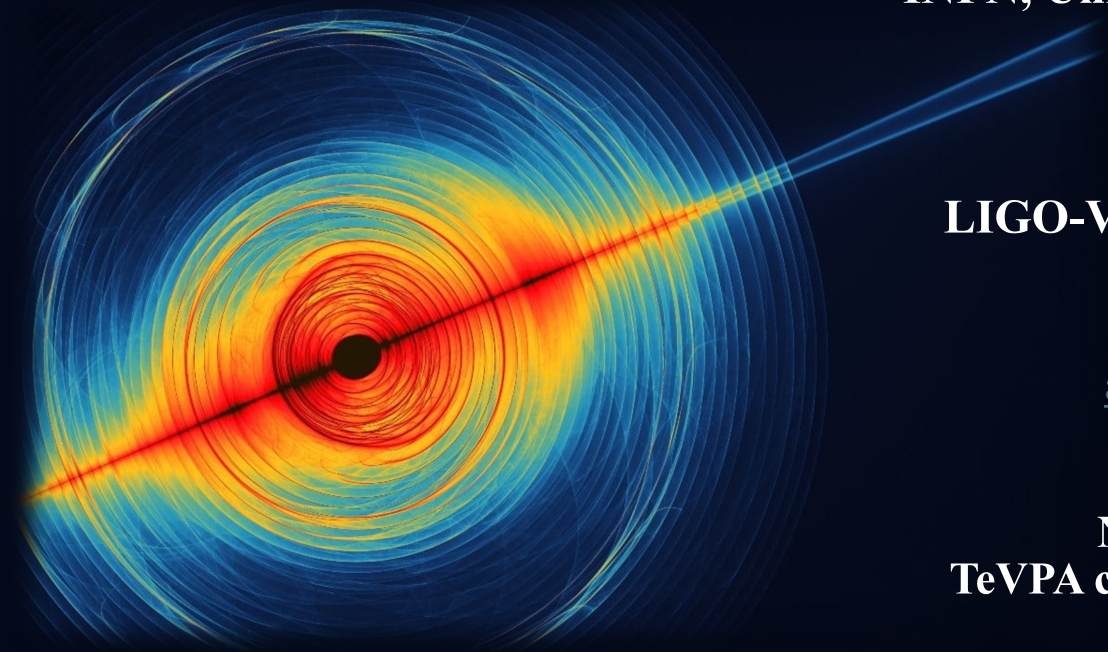

On behalf on the
LIGO-Virgo-KAGRA collaboration

arXiv:2509.04348

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01	The GWTC-4.0 catalog
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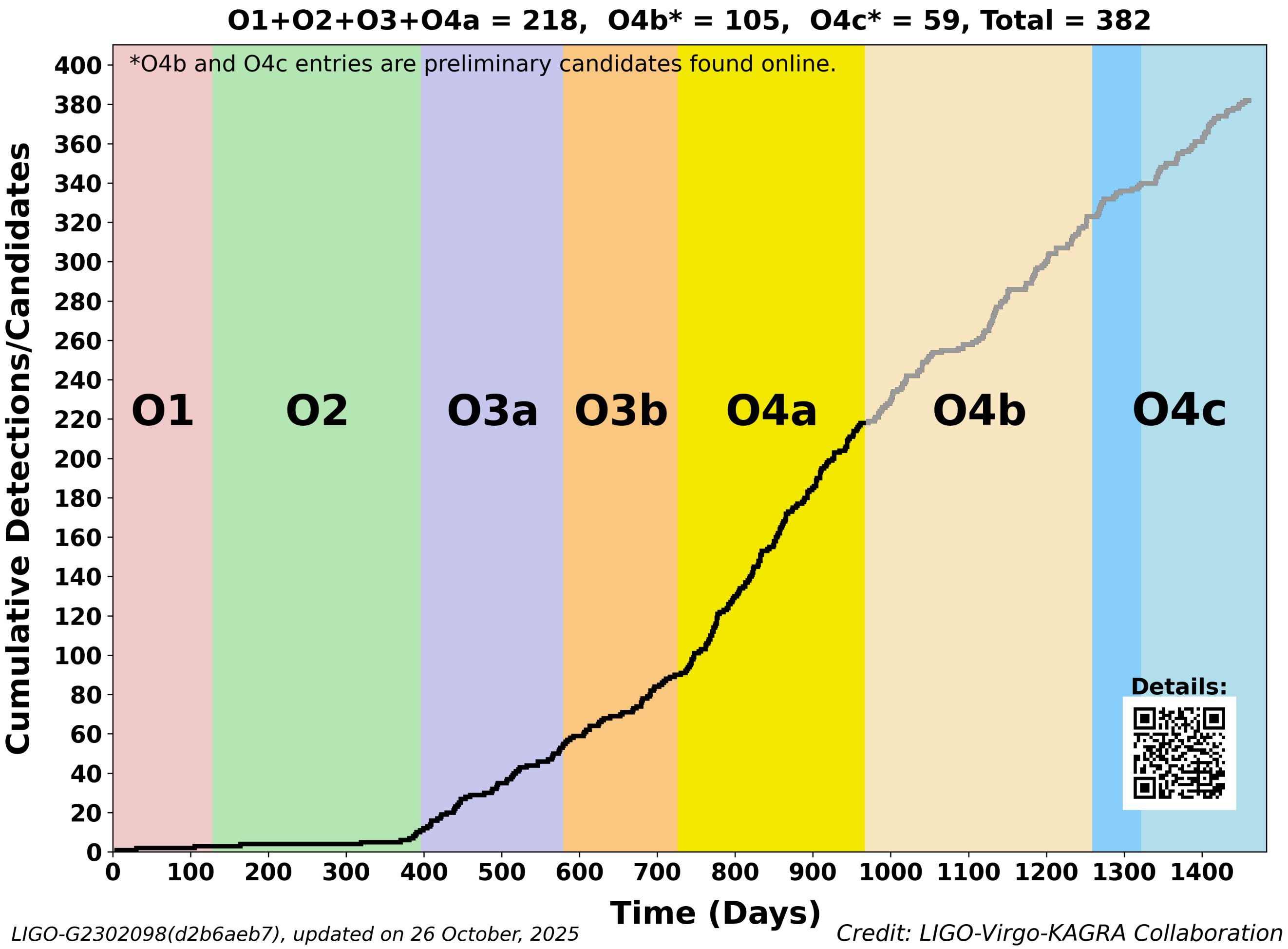
The GWTC-4.0 catalog

GWTC-4.0 combines approximately 3 yrs of data-taking, with 90 new GW events w.r.t. GWTC-3.



Some *super-events* from the O4a run

- 2 neutron-star/black-hole events
- Object in the mass gap around 3.6 $M_\odot$
- Extremely massive merger 190 - 265 $M_\odot$

arXiv:2404.04248
arXiv:2507.08219
arXiv:2508.18080
arXiv:2508.18082

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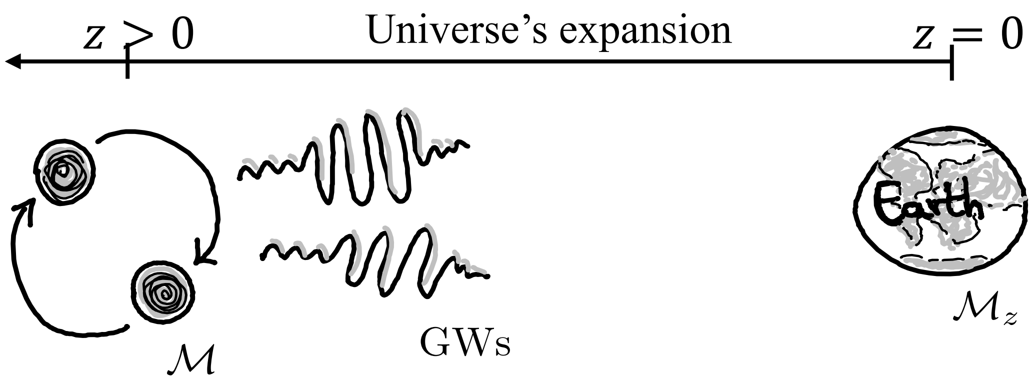
Standard sirens

GW cosmology is based on three main "*sirens*" methods.
All try to associate a *redshift* information to a *luminosity distance* of GW sources, in order to constrain *cosmology*



$$D_{\mathrm{L}}(z) = (1+z)\int_0^z c\frac{dz'}{H(z')}$$

From the GW signals, we measure both the *luminosity distance* and *redshifted* masses: $\mathcal{M}_z = \mathcal{M}(1+z)$

Assumptions on the source mass distribution can then constrain the *redshift,* hence constrain the *cosmology*!

Standard sirens

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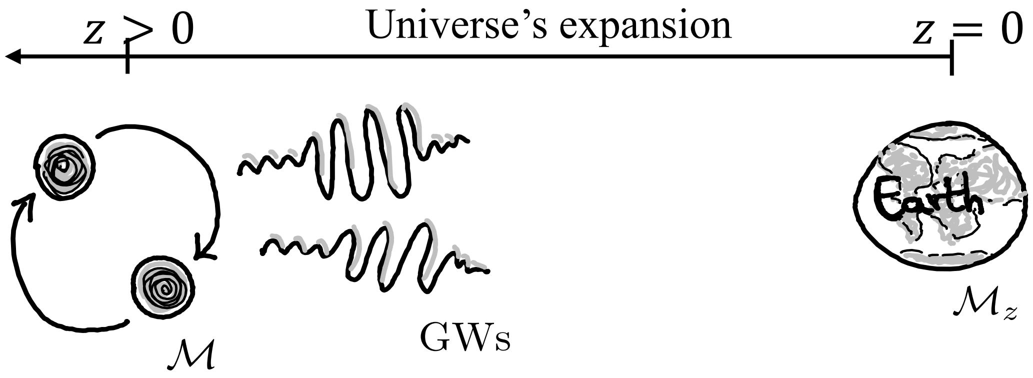

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From the GW signals, we measure both the *luminosity distance* and *redshifted* masses: $\mathcal{M}_z = \mathcal{M}(1+z)$

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$$H(z)^2 = H_0^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_{\rm DE}(1+z)^{3(1+w_0)}\right]$$

Standard sirens

The inference is done within a Bayesian framework.

For a single GW event, we can write a likelihood:

Measured data from LVK

Parameters of the binaries $(e.g.\ \mathcal{M}_z, d_L, ...)$

$$p(\mathrm{GW\,data}|\mathbf{\Lambda}) \propto \underline{e^{-N_{\mathrm{exp}}(\mathbf{\Lambda})}} \int \overline{p(\mathrm{GW\,data}|\mathbf{\Lambda},\theta)}\,\underline{p(\theta|\mathbf{\Lambda})}\,d\theta$$

What we want to estimate $(e.g.\ H_0, \Xi_0, \mu_{\mathrm{g}}, ...)$

Selection effects (sensitivity)

Assumed population models (mass, rate, cosmo)

(This is a ‘‘*schematic*’’ derivation of the real Bayesian inference framework.)

Standard sirens

Measured data from LVK

Intrinsic parameters of the binaries $(e.g.\ \mathcal{M}_z, d_L, ...)$

$$p(\text{GW data}|\boldsymbol{\Lambda}) \propto e^{-N_{\text{exp}}(\boldsymbol{\Lambda})} \int p(\text{GW data}|\boldsymbol{\Lambda}, \theta) p(\theta|\boldsymbol{\Lambda}) d\theta$$

What we want to estimate $(e.g.\ H_0, \Xi_0, \mu_{\text{g}}, ...)$

Assumed population models (mass, rate, cosmo)

Selection effects (sensitivity)

The *"sirens"* methods

- **Bright** sirens: The redshift of the source is strongly constrained, via e.m. emission in the host galaxy.
- **Spectral** sirens: The redshift is extracted from the redshifted-mass relation using the population models.
- **Dark** sirens: **Spectral** + extra statistical redshift information from galaxy catalogs. NEW!

Standard sirens

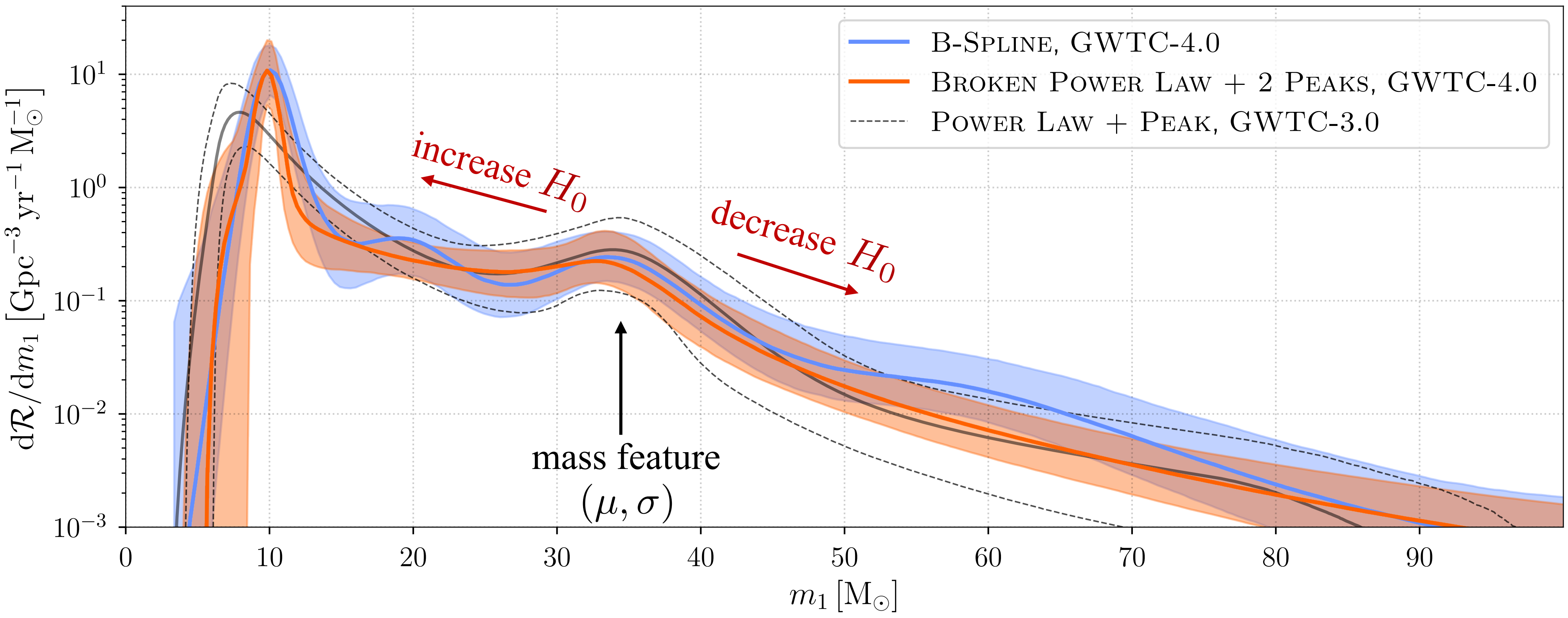
measured from GWs

extracted

$$\mathcal{M}_z = \mathcal{M}(1+z)$$

assumed form

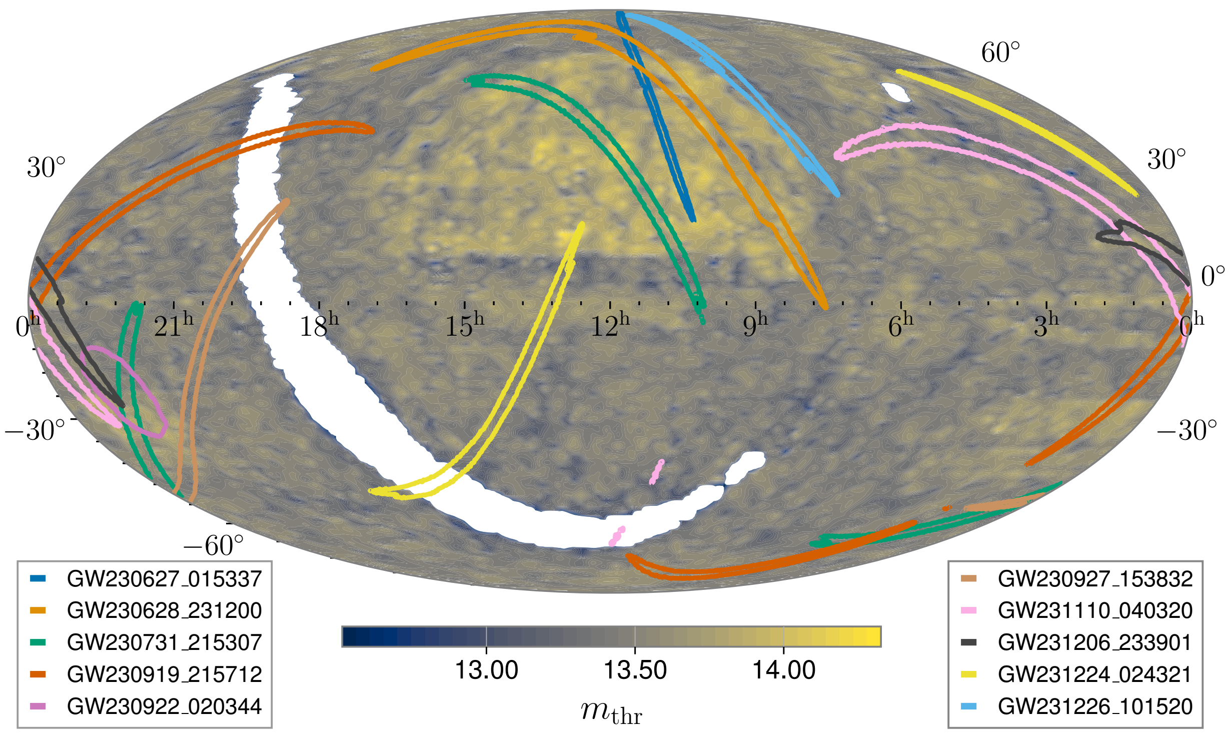
Spectral sirens, using population models.
Cosmological information is extracted thanks to *features* in the mass distribution.



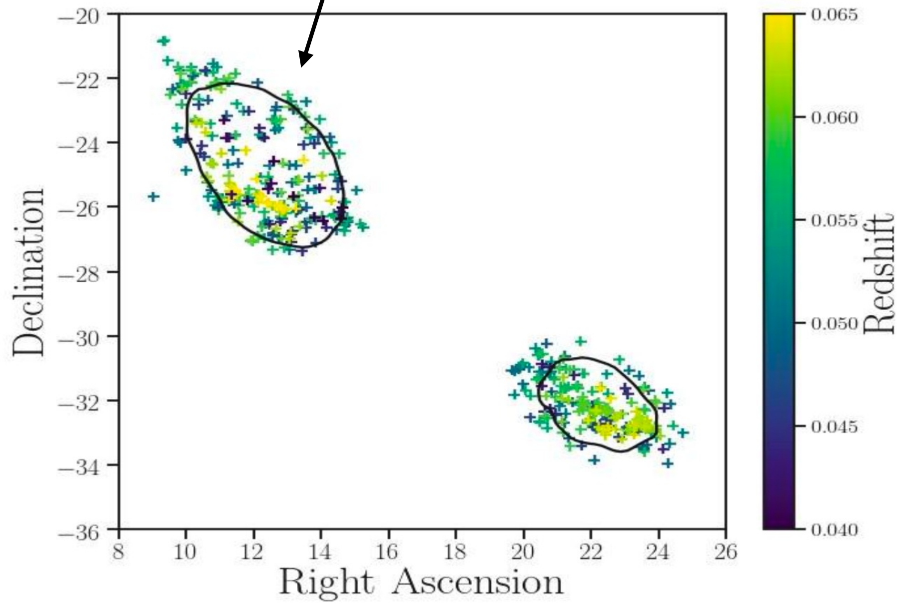
arXiv:2508.18083

Standard sirens

Dark sirens, adding galaxy catalogs.
GLADE+: Full sky, 22 millions galaxies with z-estimates, 6 surveys.



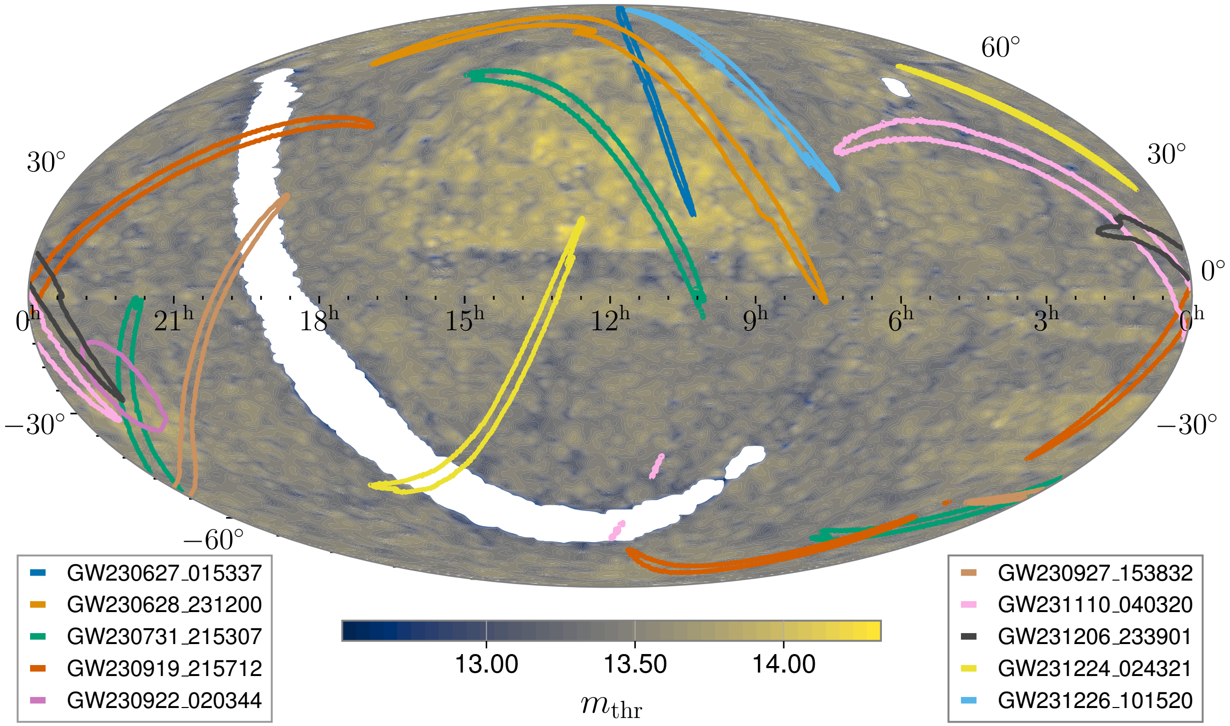
statistically associated redshift of host galaxies



Dalya et al (2018)
Dalya et al (2022)
arXiv:2509.04348

Standard sirens

Dark sirens, adding galaxy catalogs.
GLADE+: Full sky, 22 millions galaxies with z-estimates, 6 surveys.



Main O4a limitations with GLADE+

- Limited to K-band here (~1M galaxies)
- Low completeness above z ~ 1
- Virgo was off → poor sky localizations

Dalya et al (2018)
Dalya et al (2022)
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Cosmology results

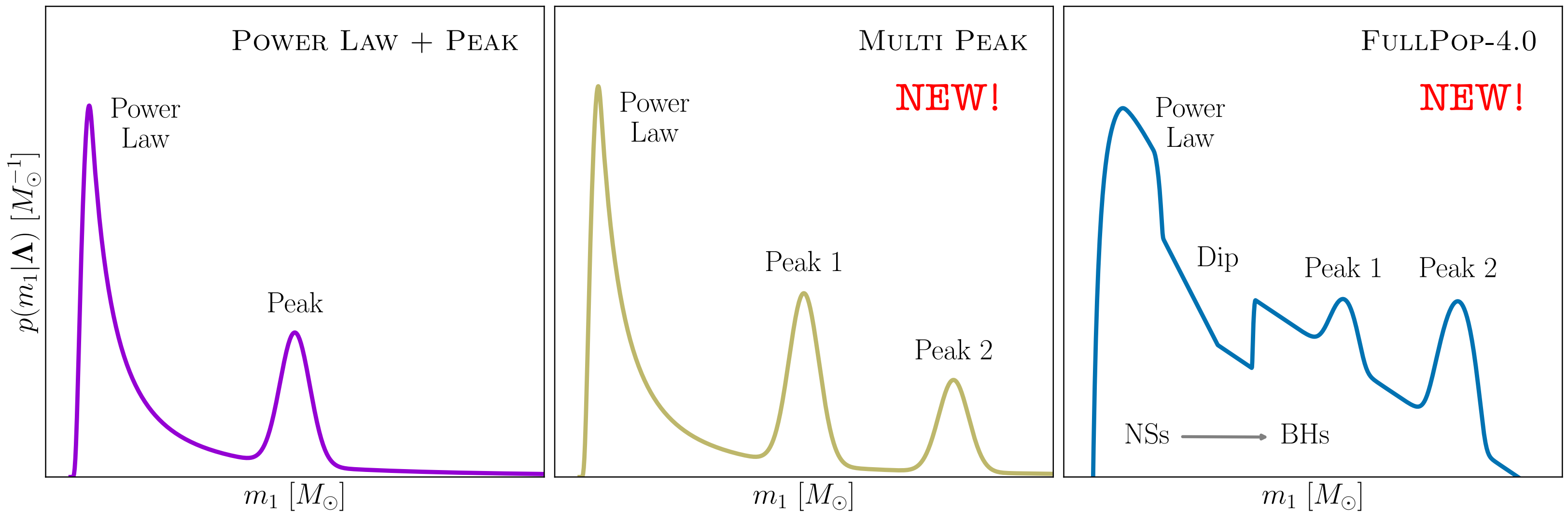
We analyze **141 dark** sirens from GWTC-4.0 + **bright** siren GW170817.

- The events are selected using a cut on the False Alarm Rate (FAR) < 0.25 yr^{-1}.
- Two independent codes are used, we present joint results: NEW!

icaroGW 2.0 — Mastrogiovanni et al (2024)

GWcosmo 3.0 — Gray et al (2023)

- Explore three mass distributions



BHs only | BHs only | NSs + BHs

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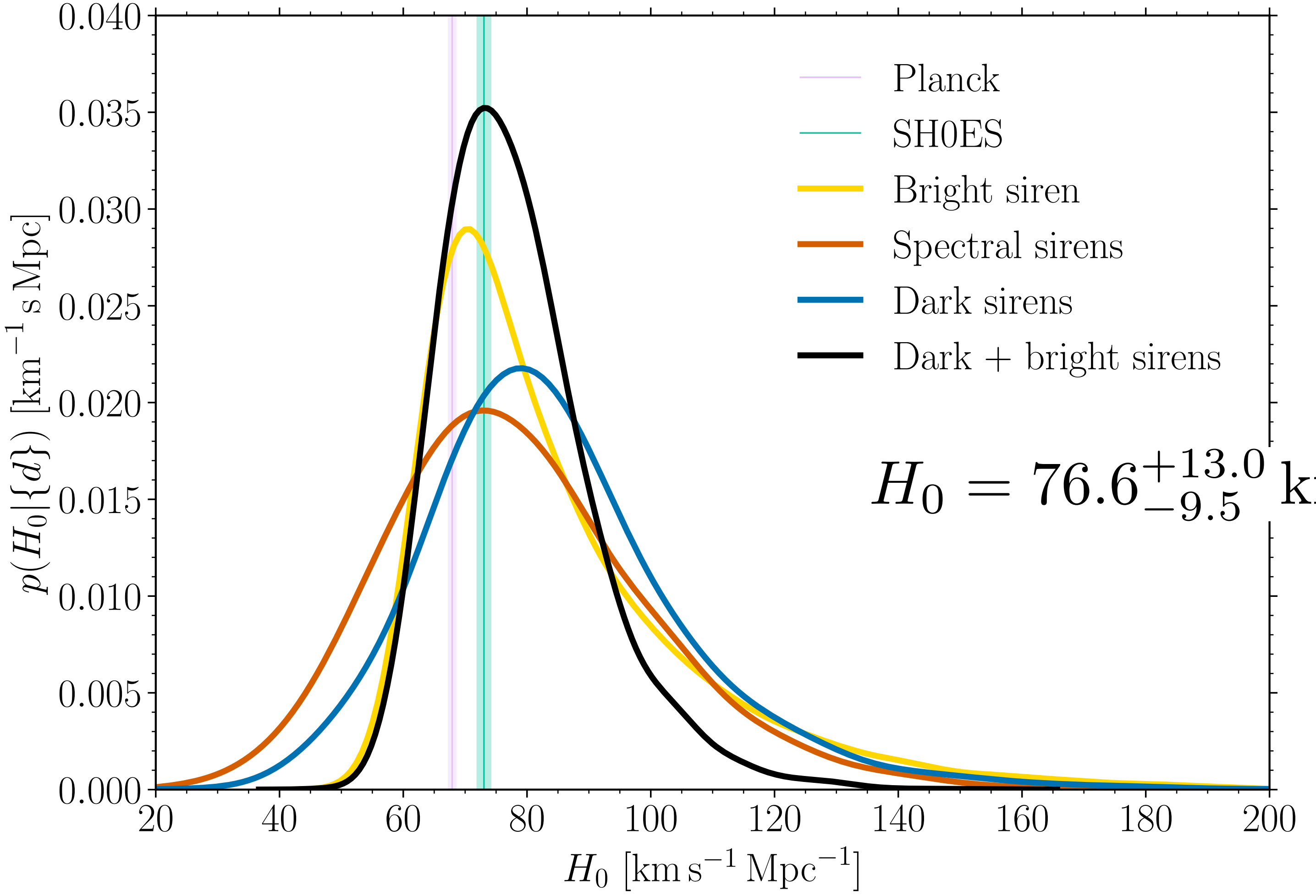
Cosmology results

Jointly inferred population and cosmology with 142 CBCs from GWTC-4.0.

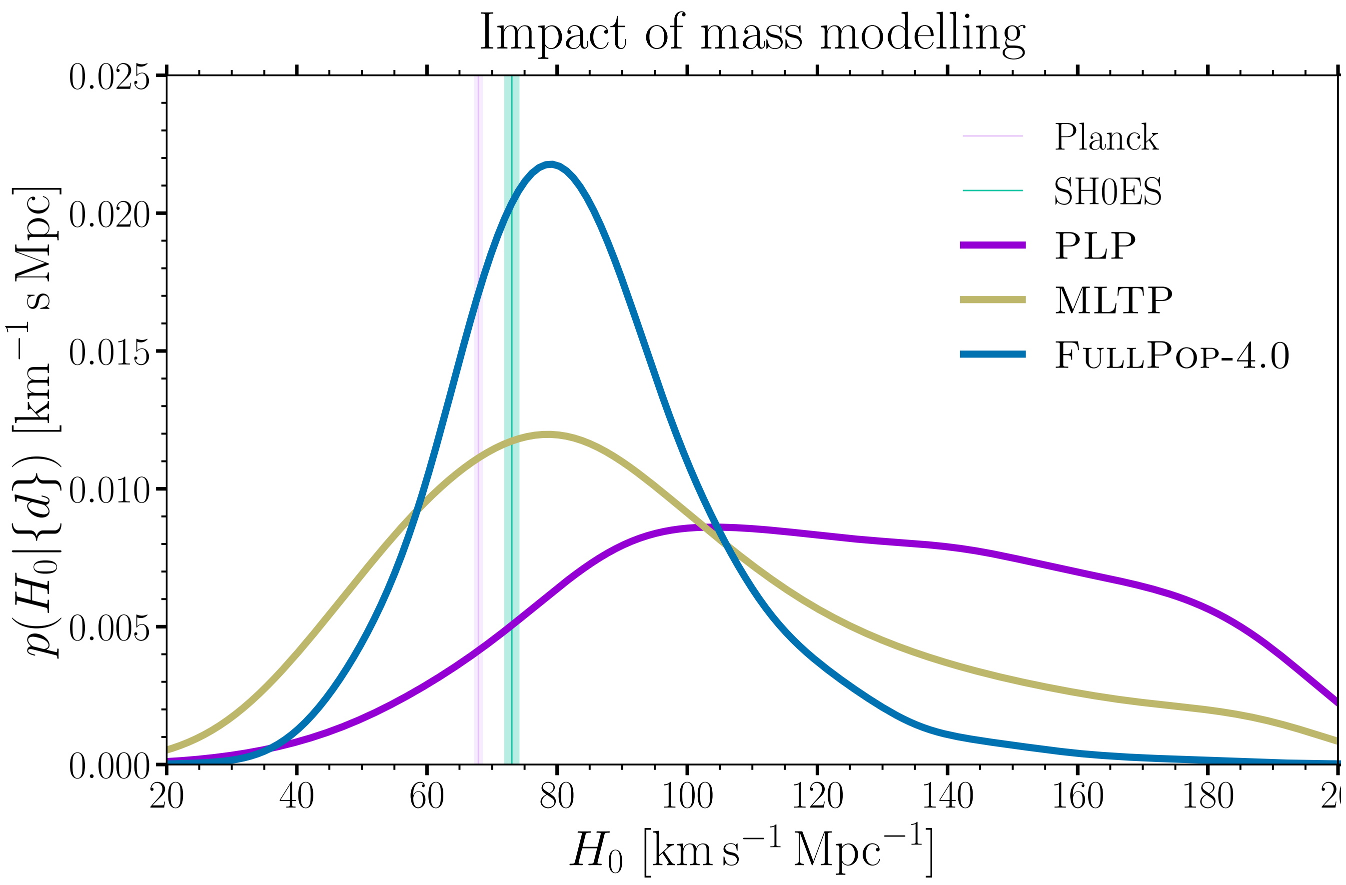


$$H_0 = 76.6^{+13.0}_{-9.5}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(68% symmetric credible interval)

arXiv.2509.04348

Cosmology results



Significant impact from
the mass model.

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Modified Gravity results

Beside changing the population models, we can also test different cosmological models.
For example **modified gravity**, which predicts a modification of the GW propagation (friction).

Modification of the GW propagation $\longrightarrow$ modification of the estimated distance of the GW source $\longrightarrow$ $\dfrac{D_{\mathrm{L}}^{\mathrm{GW}}}{D_{\mathrm{L}}^{\mathrm{EM}}} \neq 1$

Phenomenological model

$$D_{\mathrm{L}}^{\mathrm{GW}} = D_{\mathrm{L}}^{\mathrm{EM}} \left(\Xi_0 + \frac{1 - \Xi_0}{(1+z)^n} \right)$$

Horndeski gravity

$$D_{\mathrm{L}}^{\mathrm{GW}} = D_{\mathrm{L}}^{\mathrm{EM}} \exp\left(\frac{1}{2} \int_0^z \frac{\mathrm{d}z'}{1+z'} \frac{\Omega_\Lambda(z')}{\Omega_{\Lambda,0}} c_{\mathrm{M}} \right)$$

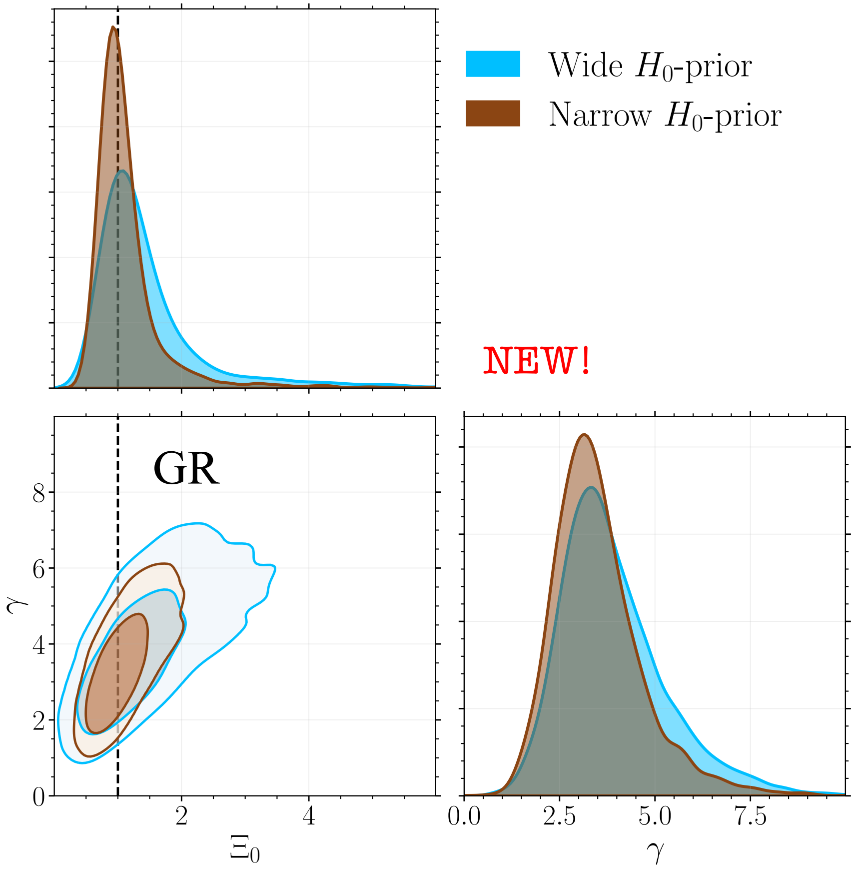
Belgacem et al (2019)
Horndeski et al (1974)

Modified Gravity results

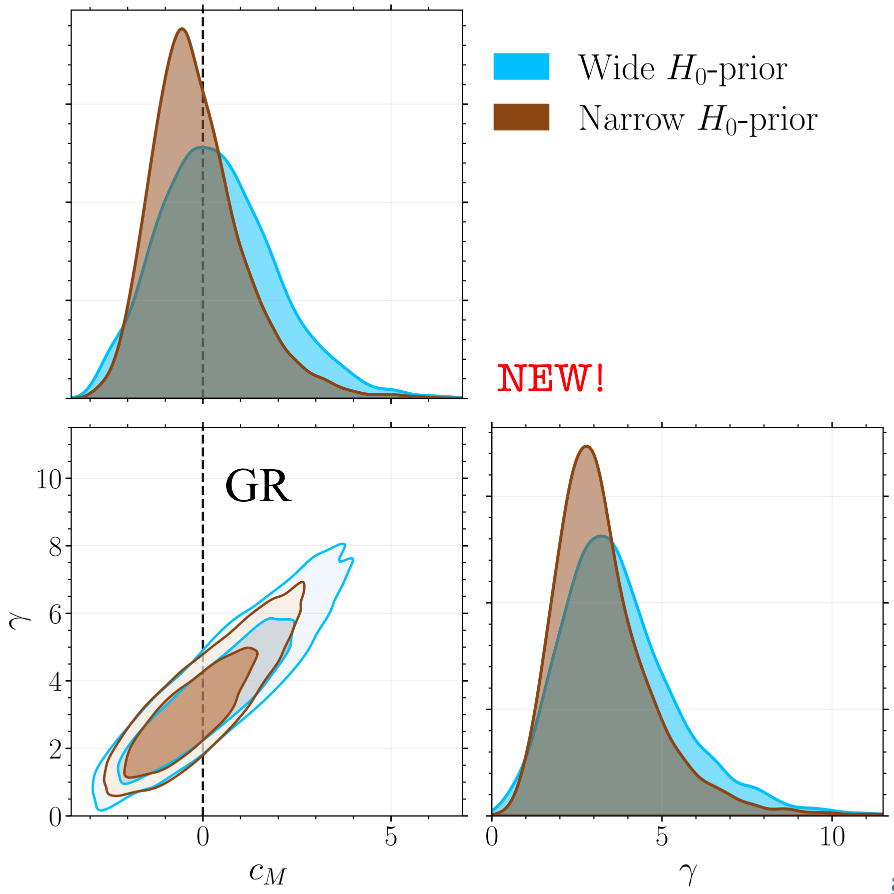
merger rate model

$$\mathcal{R}(z|\gamma, \kappa, z_{\mathrm{p}}) \sim (1+z)^{\gamma}$$

Phenomenological model



Horndeski gravity



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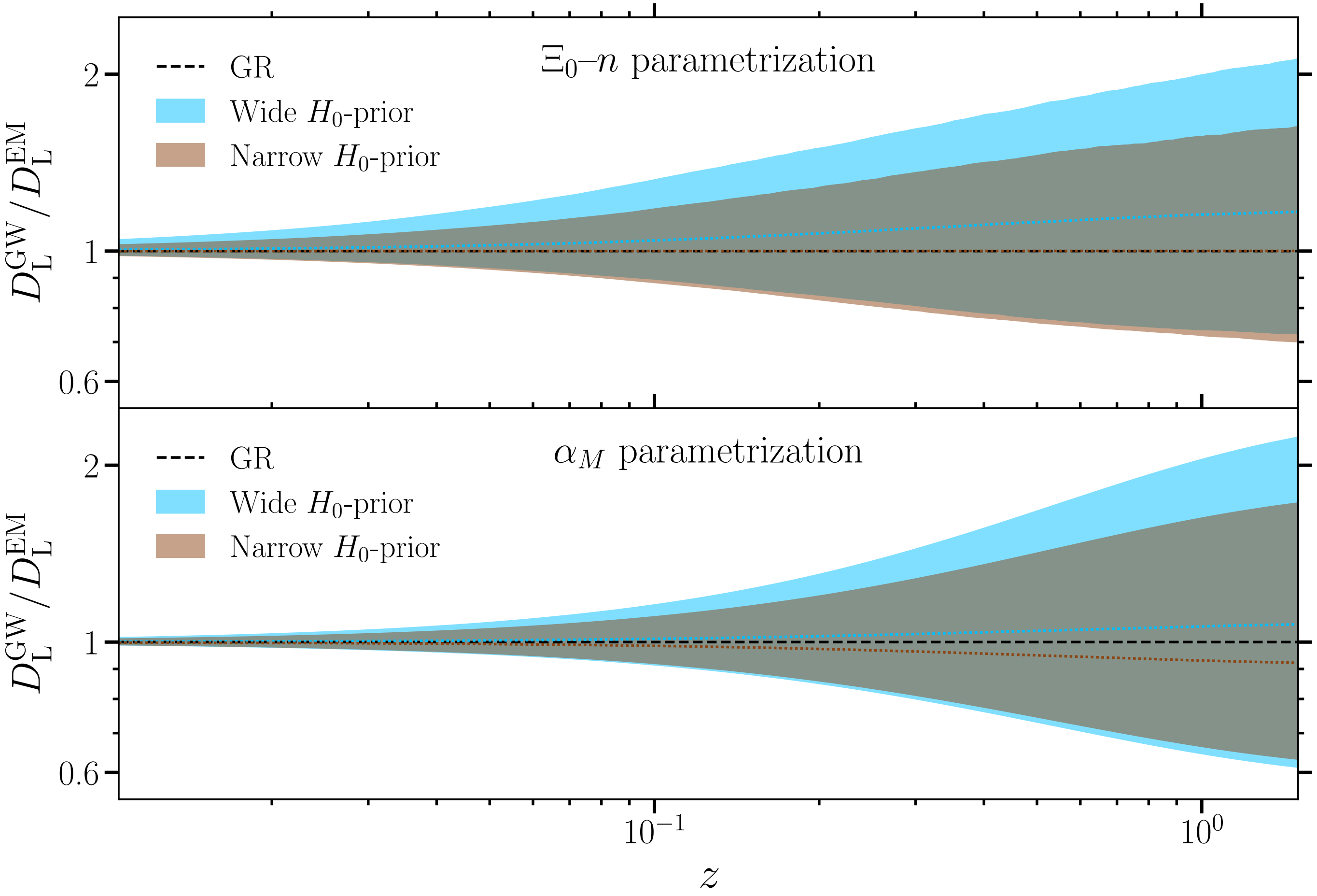
Strong correlation with γ as the GW detectability can be strongly impacted by either $D_{\mathrm{L}}^{\mathrm{GW}}$ or the merger rate.

Modified Gravity results

We can also reconstruct the distance ratio (90% credible interval), with both narrow and wide H_0 priors.



General Relativity seems to work well so far!

$$\Xi_0 = 1.2^{+0.4}_{-0.2}$$

$$c_M = 0.3^{+1.4}_{-1.0}$$

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Conclusions

- Dark sirens are now at the center of GW cosmology.

- Best H_0 constraint with GWTC-4.0 is

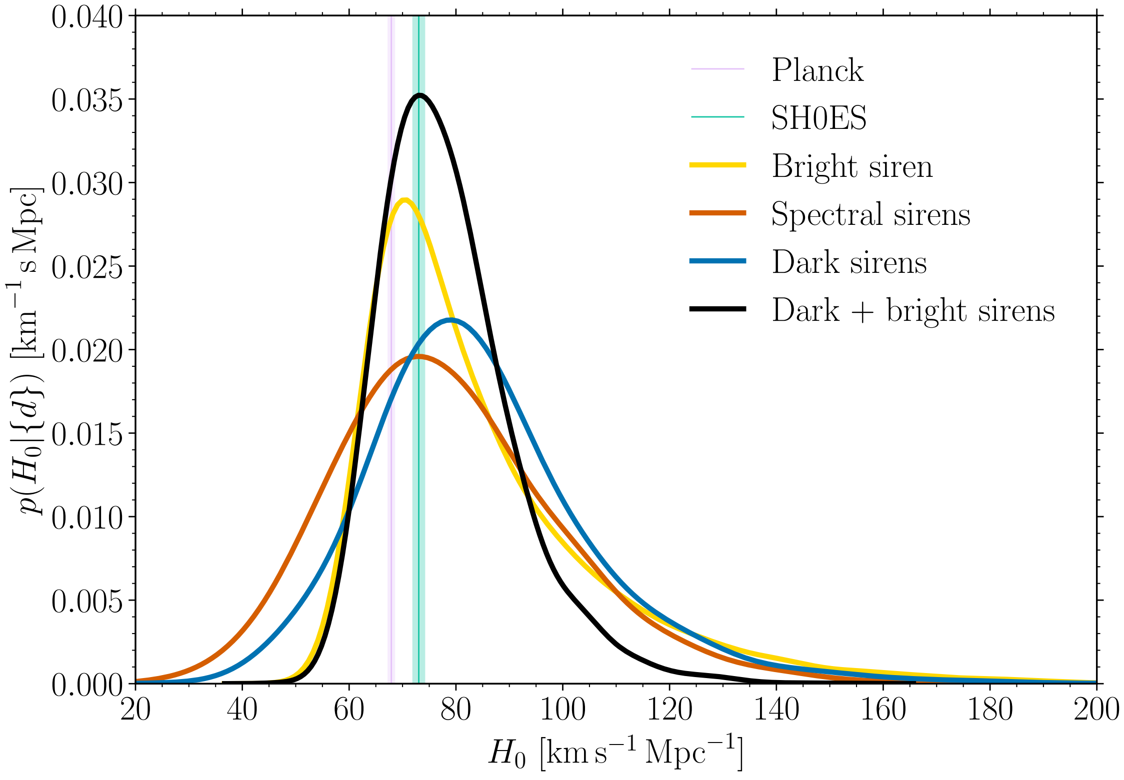
$$H_0 = 76.6^{+13.0}_{-9.5}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Not competitive for the "Hubble Tension"

- But, we highlight a 60% improvement w.r.t to GWTC-3 (better method, model, events)

- No sign of modified gravity so far.

Coolest plot imo



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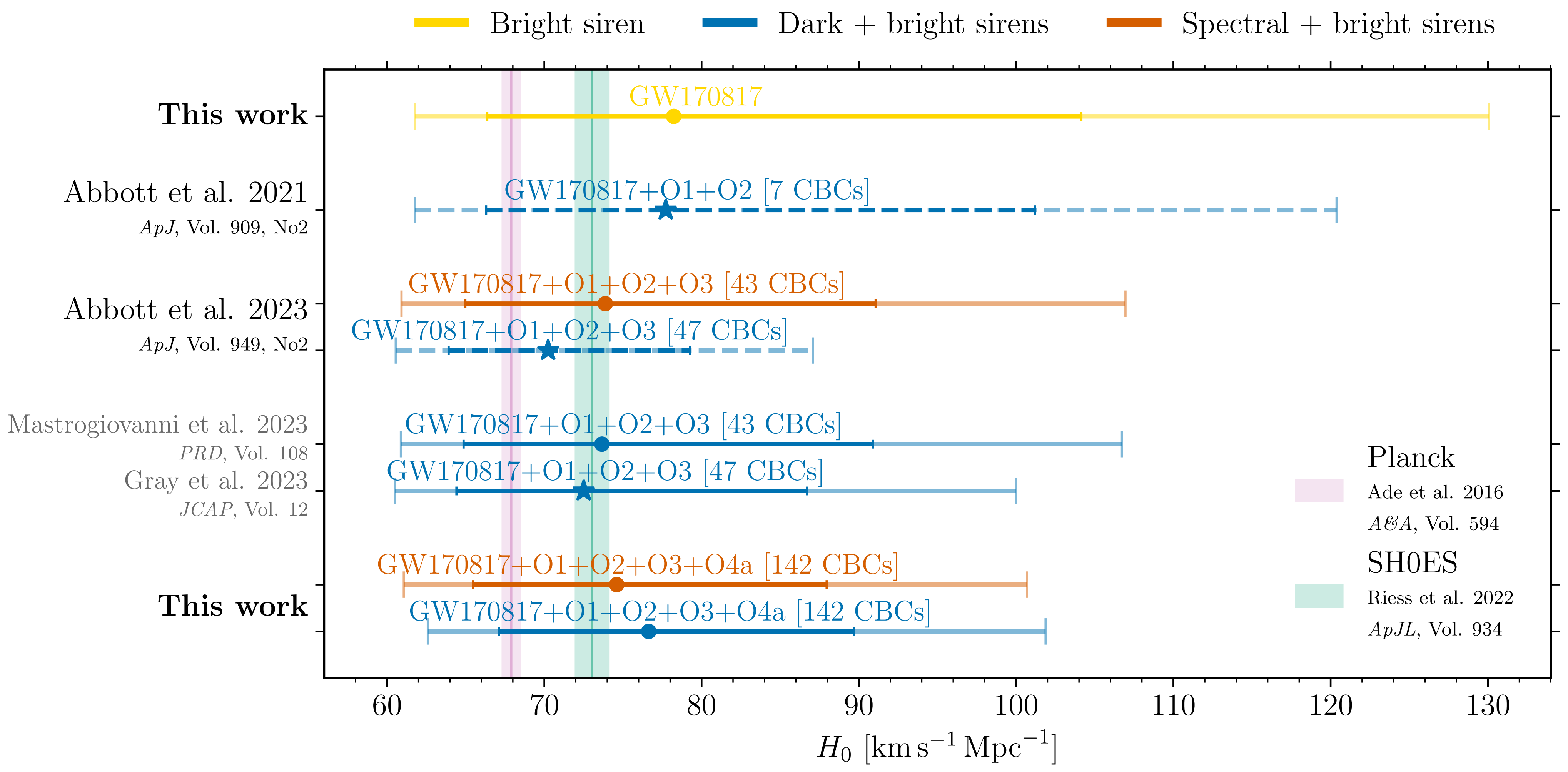
Back up
SLIDES

GW cosmology so far



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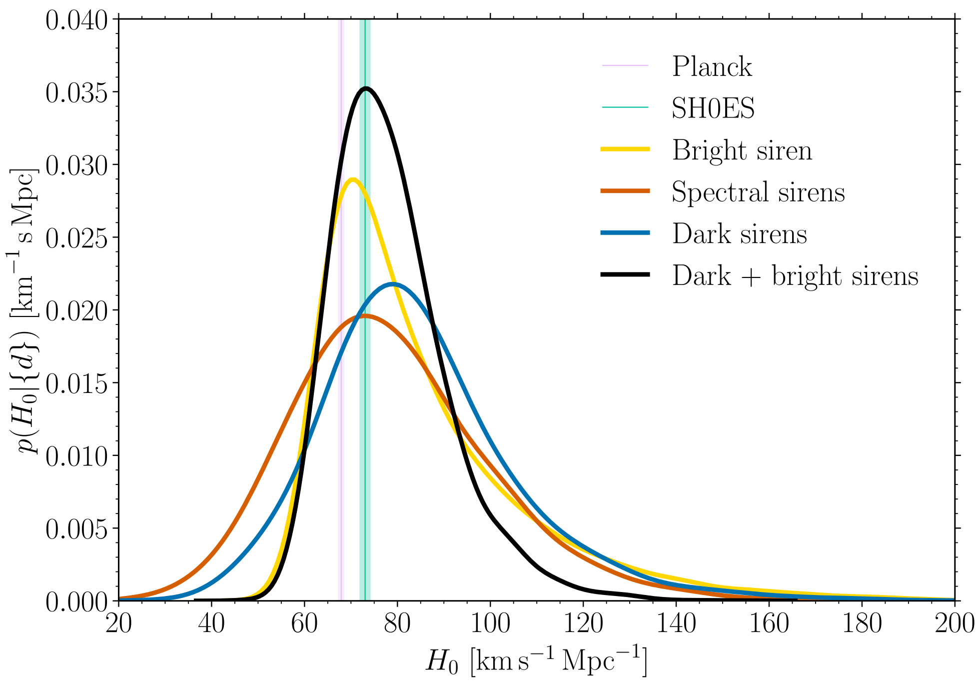
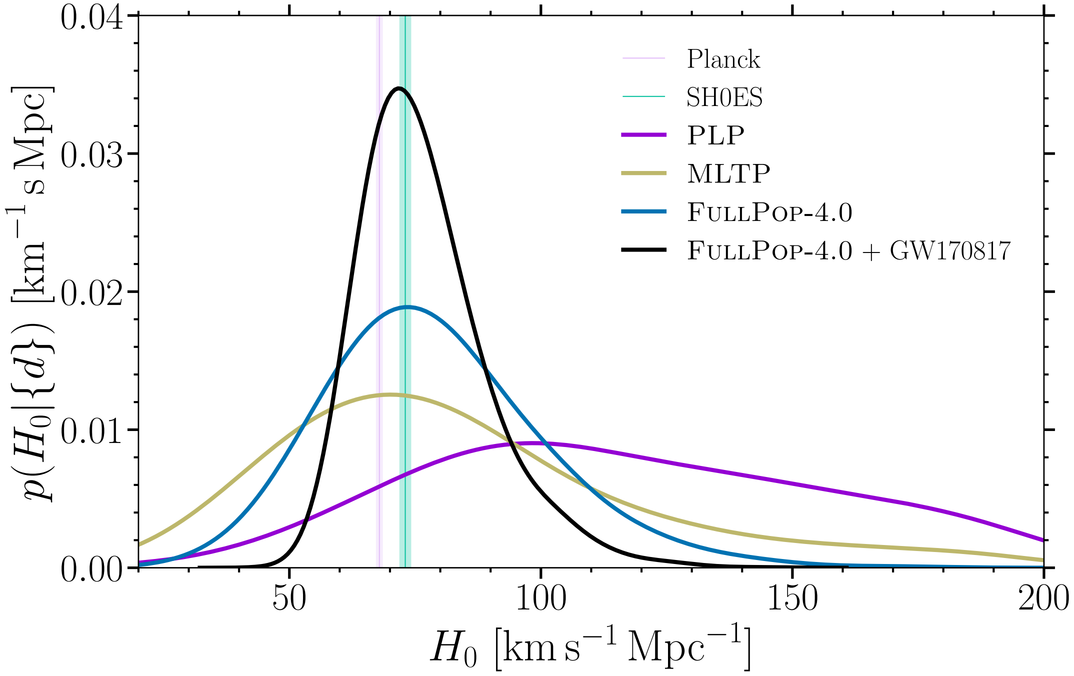
Flat-LCDM





ΛCDM – Dark sirens			
Population model	GW candidates	H_0 (Dark sirens) [km s^{-1} Mpc^{-1}]	H_0 (Dark + bright sirens) [km s^{-1} Mpc^{-1}]
Power Law + Peak	137 (138)	$124.8^{+45.2}_{-39.4}$ $(124.8^{+63.2}_{-60.1})$	$85.9^{+24.4}_{-15.9}$ $(85.9^{+48.8}_{-22.1})$
Multi Peak	137 (138)	$87.3^{+48.0}_{-28.2}$ $(87.3^{+85.6}_{-42.7})$	$77.0^{+17.6}_{-10.9}$ $(77.0^{+35.3}_{-15.7})$
FullPop-4.0	141 (142)	$81.6^{+21.5}_{-15.9}$ $(81.6^{+42.0}_{-26.8})$	$76.6^{+13.0}_{-9.5}$ $(76.6^{+25.2}_{-14.0})$

ΛCDM – Spectral sirens			
Population model	**GW sources**	H_0 (Spectral sirens) [km s^{-1} Mpc^{-1}]	H_0 (Spectral + bright sirens) [km s^{-1} Mpc^{-1}]
Power Law + Peak	137 (138)	$112.7^{+51.0}_{-35.9}$ $(112.7^{+74.0}_{-55.1})$	$74.8^{+15.5}_{-9.9}$ $(74.8^{+31.6}_{-14.4})$
Multi Peak	137 (138)	$77.1^{+40.8}_{-26.3}$ $(77.1^{+83.5}_{-39.1})$	$74.8^{+15.5}_{-9.9}$ $(74.8^{+31.6}_{-14.4})$
FullPop-4.0	141 (142)	$76.4^{+23.0}_{-18.1}$ $(76.4^{+41.2}_{-28.6})$	$74.6^{+13.4}_{-9.1}$ $(74.6^{+26.1}_{-13.5})$

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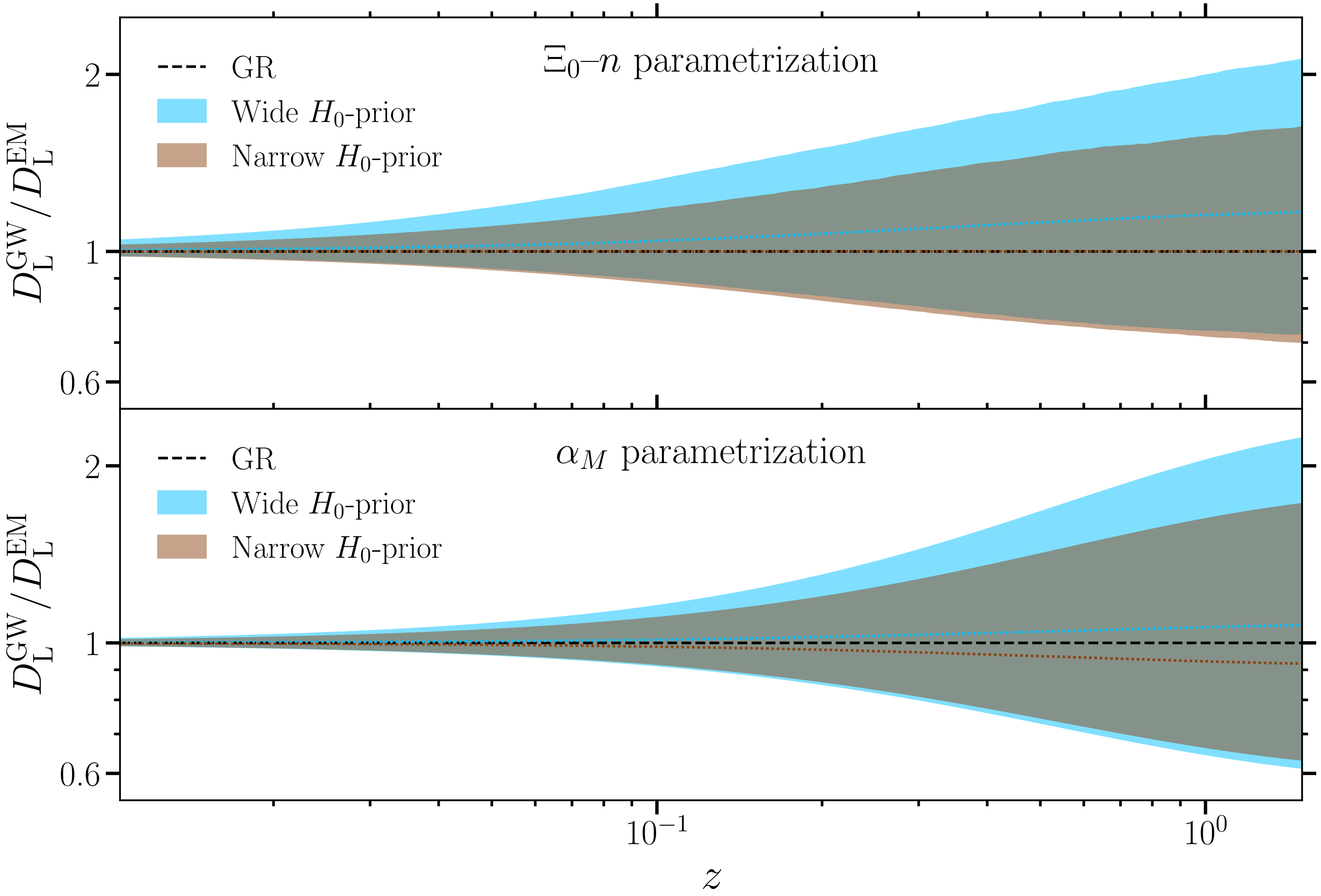
Modified gravity



Modified gravity – Dark sirens	
Parametrization Ξ_0–n	Ξ_0
Wide H_0-prior	$1.2^{+0.8}_{-0.4}$ $(1.2^{+2.4}_{-0.5})$
Narrow H_0-prior	$1.0^{+0.4}_{-0.2}$ $(1.0^{+1.1}_{-0.4})$
Parametrization α_M	c_M
Wide H_0-prior	$0.3^{+1.6}_{-1.4}$ $(0.3^{+2.9}_{-2.2})$
Narrow H_0-prior	$-0.3^{+1.4}_{-1.0}$ $(-0.3^{+2.5}_{-1.5})$

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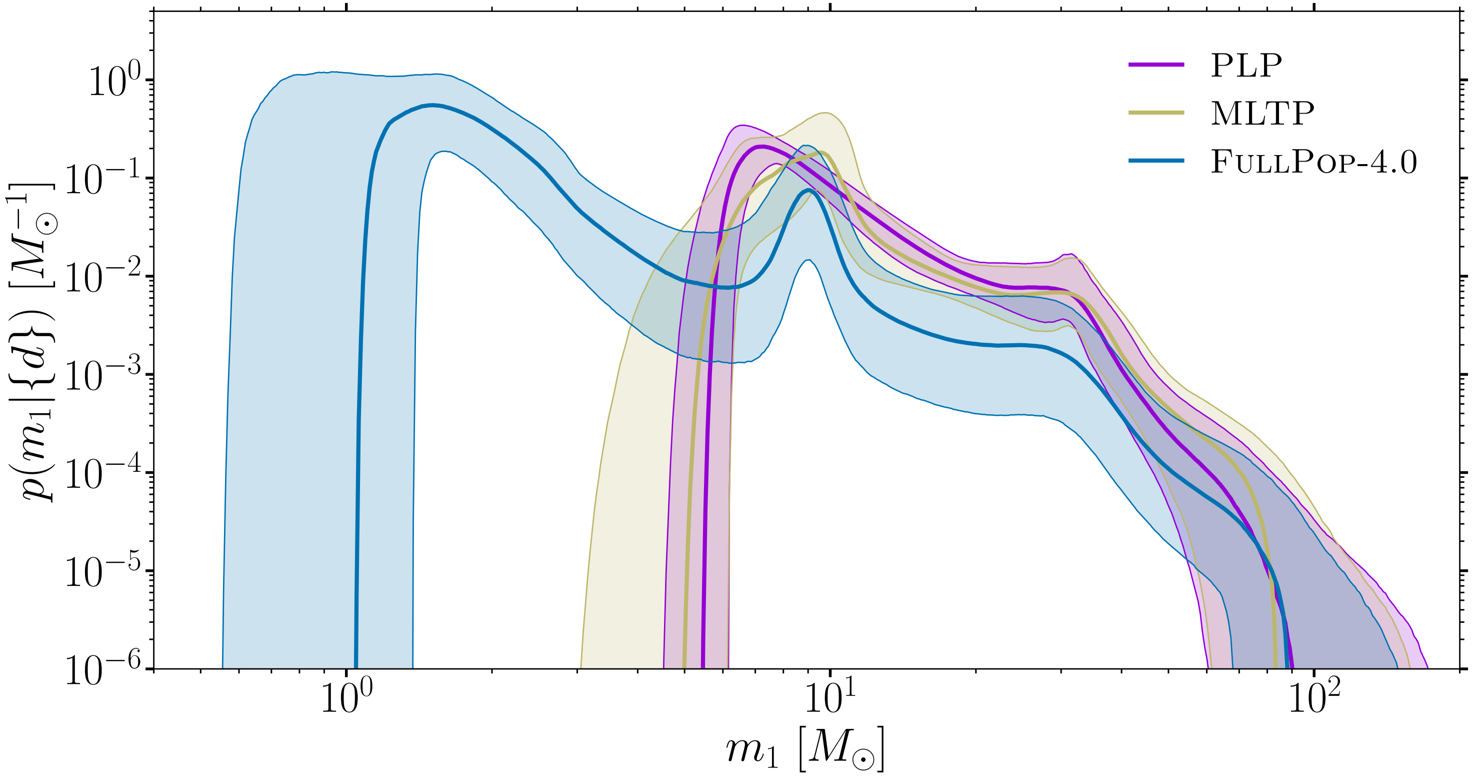
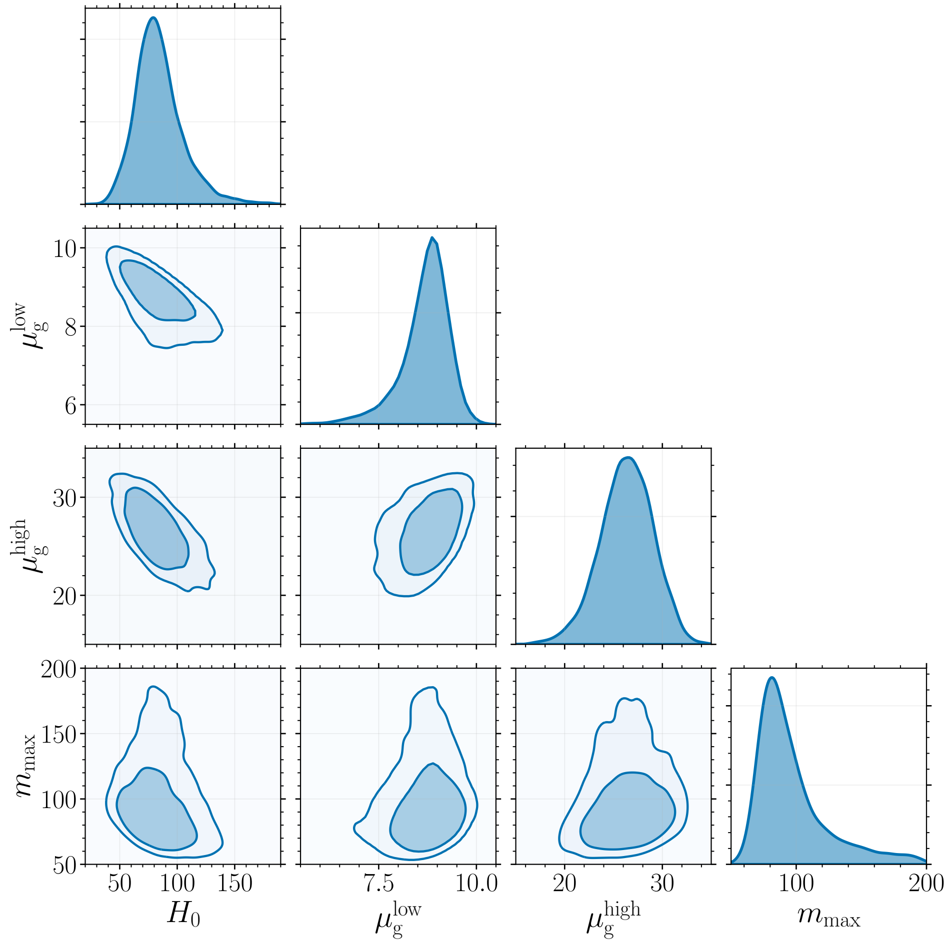
Measurement of the mass spectrum

Dark sirens analysis with luminosity weights





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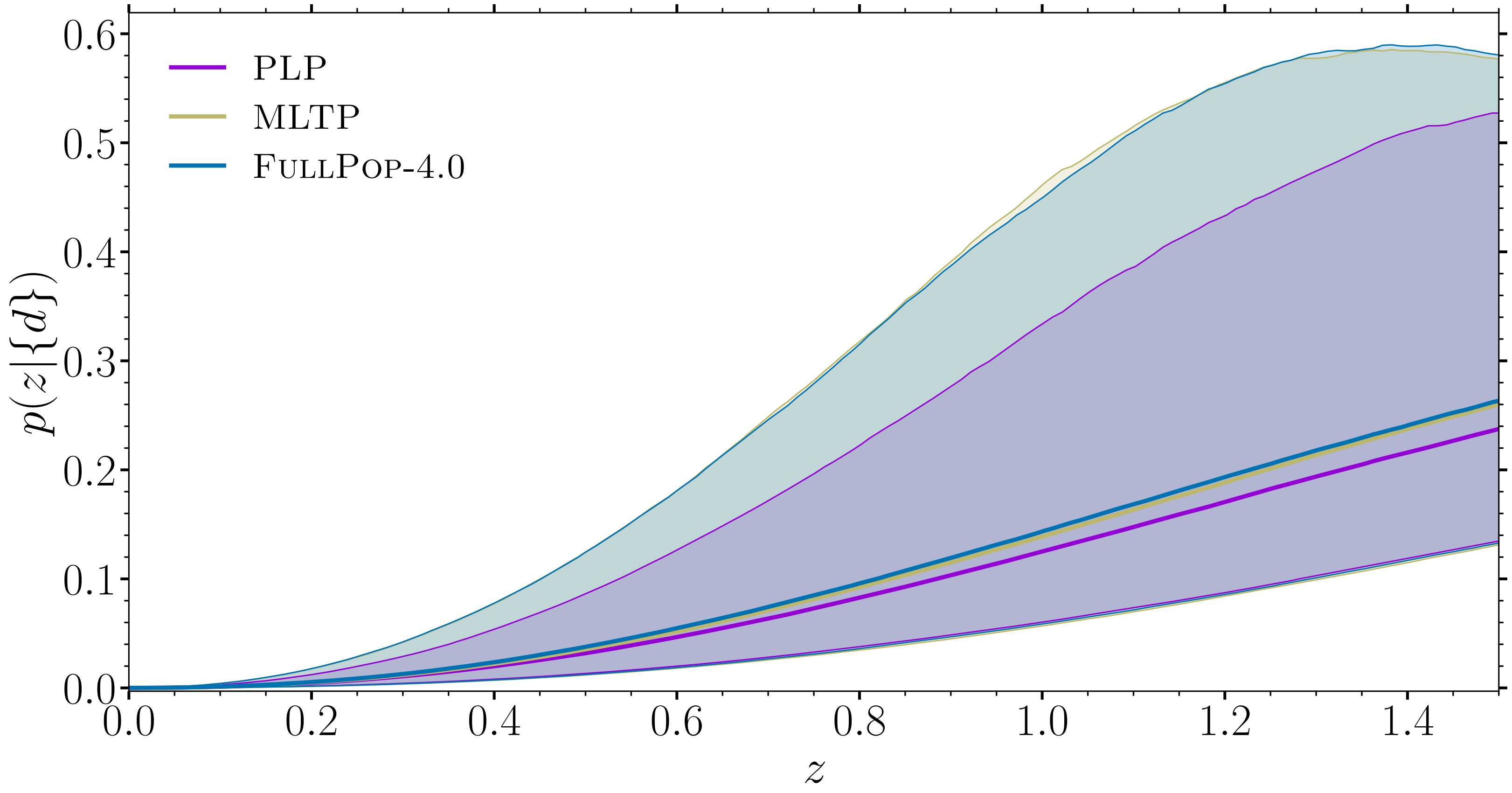
Measurement of the merger rate



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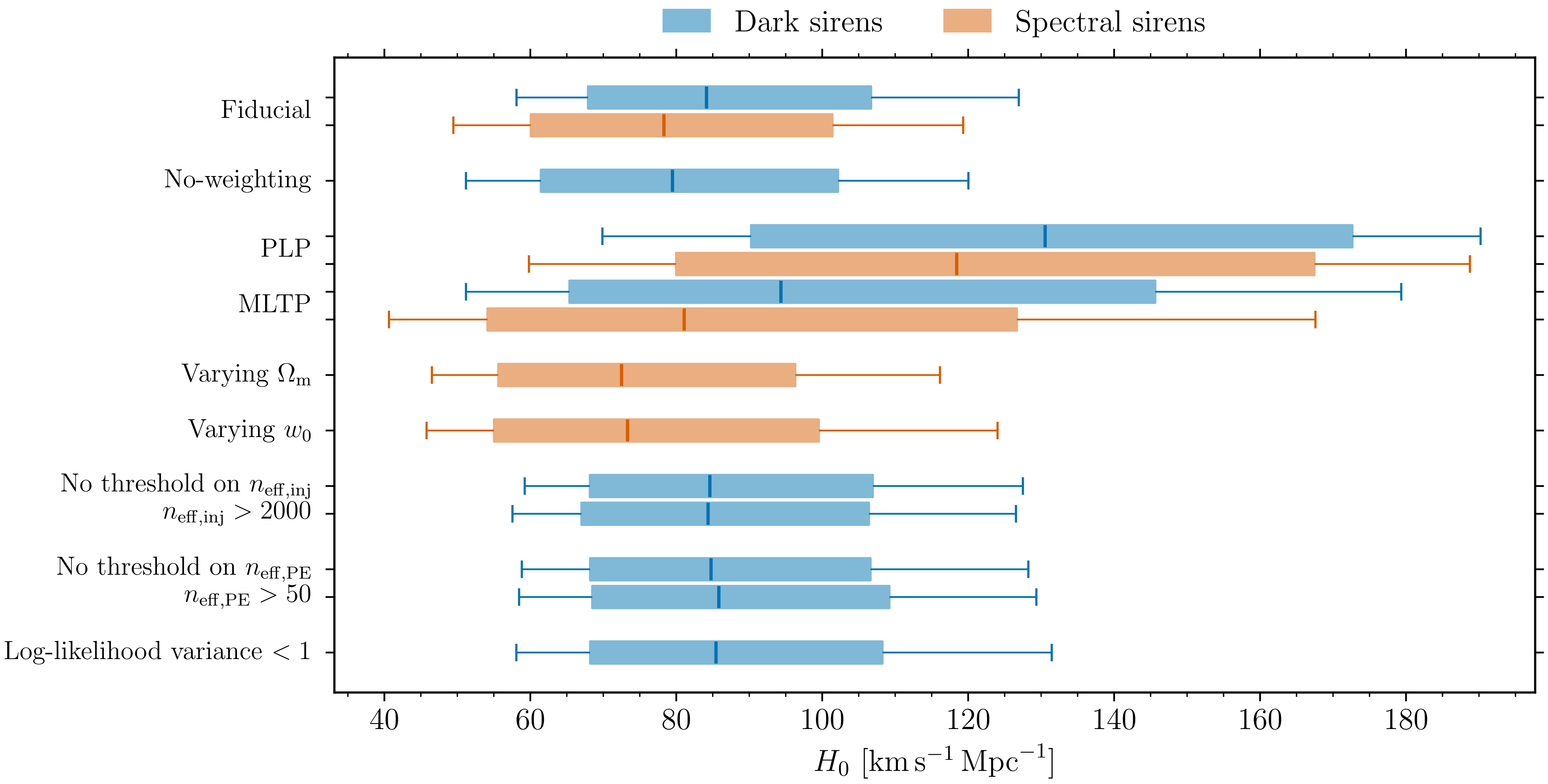
Systematics and stability checks



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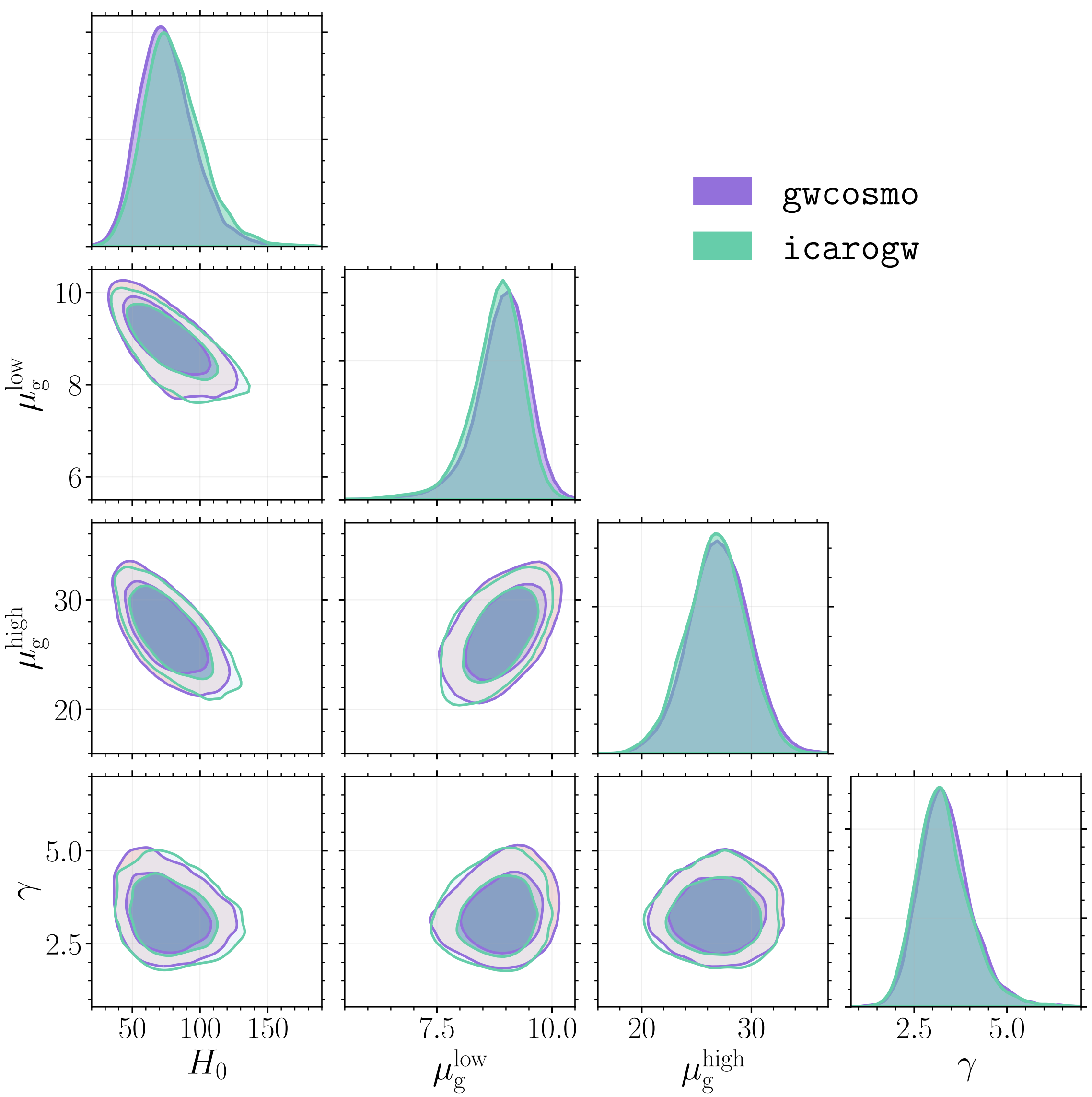
Pipelines compatibility



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