Cosmological contraints obtained with the fourth gravitational wave transients catalog (GWTC-4.0) of the LVK collaboration

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For the LIGO-Virgo-KAGRA collaboration
GDR, Paris, October 2025

Credit: Deborah Ferguson (UT Austin), Bhavesh Khamesra (Georgia Tech), and Karan Jani (Vanderbilt University).

1. The data: GWTC-4.0
2. Analysis method
3. Cosmological constraints with GWTC-4.0

LVK publications:
https://pnp.ligo.org/ppcomm/Papers.html

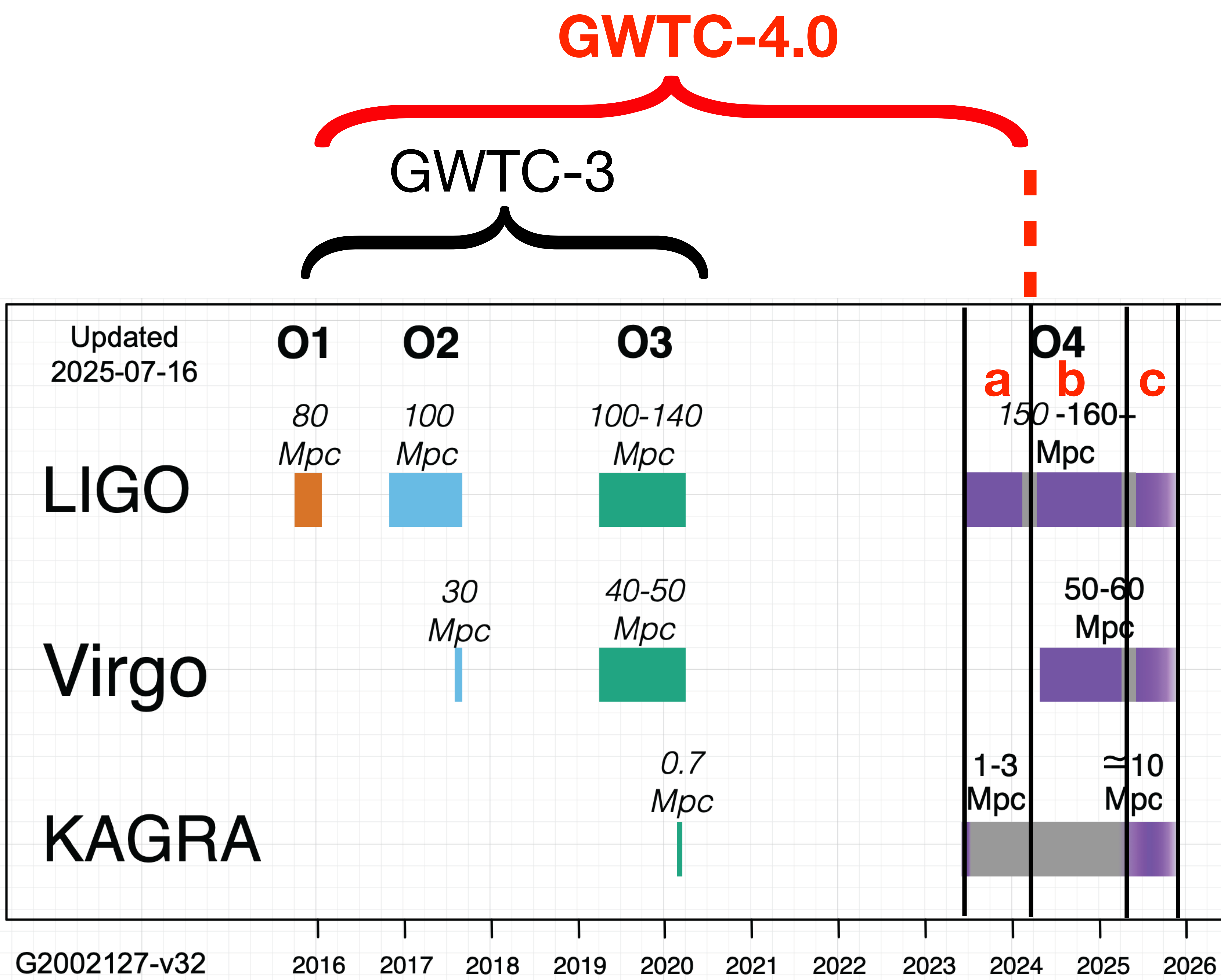
1. The data: GWTC-4.0

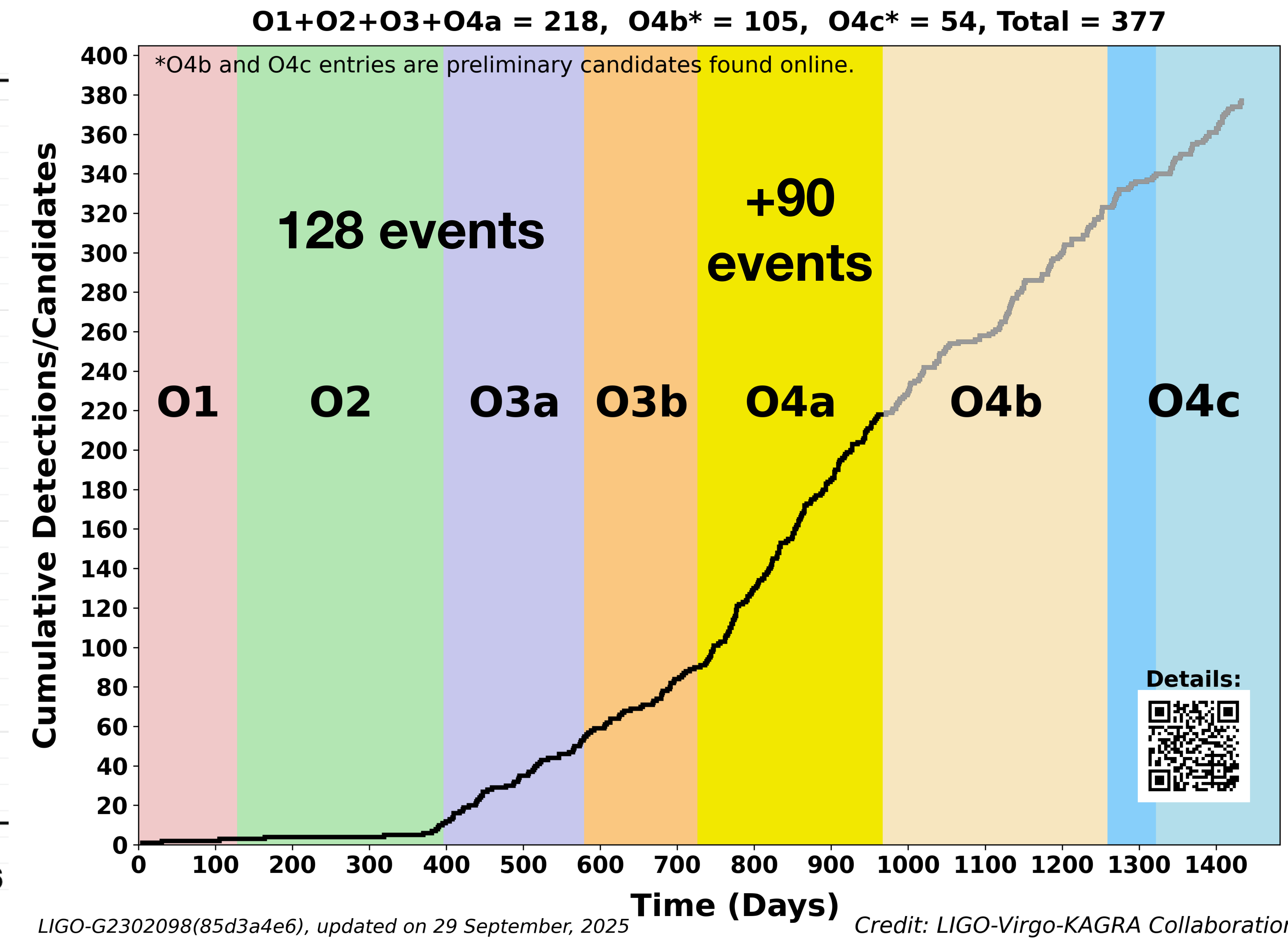
arXiv:2508.18080 (intro to GWTC-4.0)
arXiv:2508.18082 (GWTC-4.0 catalog paper)
arXiv:2508.18083 (astrophysical population)

The data: GWTC-4.0

Sept 2015-January 2024

O4a: May 24th, 2023 - January 16th, 2024





Total of 218 candidates in GWTC-4.0

Cosmology with GWs

From the GW signal alone, we can estimate the distance to the source:

$$d_L \propto \ < h_{\rm GW} >^{-1} \ \tau_{\rm coal}^{-1} \ f_{\rm GW}^{-2}$$

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From the GW signal alone, we can estimate the distance to the source:

$$d_L \propto \ < h_{\mathrm{GW}} >^{-1} \ \tau_{\mathrm{coal}}^{-1} \ f_{\mathrm{GW}}^{-2}$$

In the Big-Bang model, d_L is related to cosmology.
In particular, assuming the flat ΛCDM model:

$$d_L = \frac{(1+z)\,c}{H_0} \int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} \overset{z \ll 1}{\approx} \frac{c\,z}{H_0}$$

We measure d_L: any information on z provides constraints on H_0

$$H_0 = c\,\frac{z}{d_L}$$

redshift of the host galaxy

given by the GW signal

2. Analysis method

Hierarchical bayesian inference

$$p(m_{1,s}, m_{2,s})\, p(\vec{s}_1, \vec{s}_2)\, R(z)...$$

second inference to estimate
the hyper-parameters **Λ** describing the full population

Λ: H_0, parameters describing the mass spectra...

15-20 parameters, jointly inferred

$$\theta_i = \begin{pmatrix} m_{1,\mathrm{det}} \\ m_{2,\mathrm{det}} \\ d_L \\ \vec{s}_1 \\ \vec{s}_2 \\ \cdots \end{pmatrix} \begin{pmatrix} m_{1,\mathrm{det}} \\ m_{2,\mathrm{det}} \\ d_L \\ \vec{s}_1 \\ \vec{s}_2 \\ \cdots \end{pmatrix} \bullet \bullet \bullet \begin{pmatrix} m_{1,\mathrm{det}} \\ m_{2,\mathrm{det}} \\ d_L \\ \vec{s}_1 \\ \vec{s}_2 \\ \cdots \end{pmatrix}$$

GW #1 GW #2 GW #n

first inference
(parameter estimation, PE)
to estimate **θ**, 11 parameters, the
individual properties of each event

Hierarchical inference

For a single CBC event:

PE

choice of models (z, m_s, spins, merger rate...)

marginalise over the true (unkown) parameters of the CBC

$$\mathcal{L}(x_{\rm GW}|\Lambda) \propto \frac{\int \boxed{\mathcal{L}(x_{\rm GW}|z,\theta,\Lambda)}\, \boxed{p(z|\Lambda)\, p(\theta|\Lambda)}\, \boxed{\mathrm{d}z\, \mathrm{d}\theta}}{\boxed{\int_{\rho \geqslant \rho_{\rm thr}} p(\det|z,\theta,\Lambda)\, p(z|\Lambda)\, p(\theta|\Lambda)\, \mathrm{d}z\, \mathrm{d}\theta}}$$

the denominator corrects for the selection effect

Bright siren

associated EM counterpart, $z^{\rm GW} = z_{\rm host}^{\rm EM}$, only 1 event since 2015

$$p(z|\Lambda) = \delta(z - z^{\rm EM}_{\rm host})$$

Spectral siren

structures in the detector-frame mass spectra, agnostic z prior

$$m_{\rm det} = (1+z)m_s$$

uniform comoving

$$p(z|\Lambda) \propto \frac{\mathrm{d}V_c}{\mathrm{d}z}$$

Dark siren

structures in the detector-frame mass spectra, z from a catalog

$$m_{\rm det} = (1+z)m_s$$

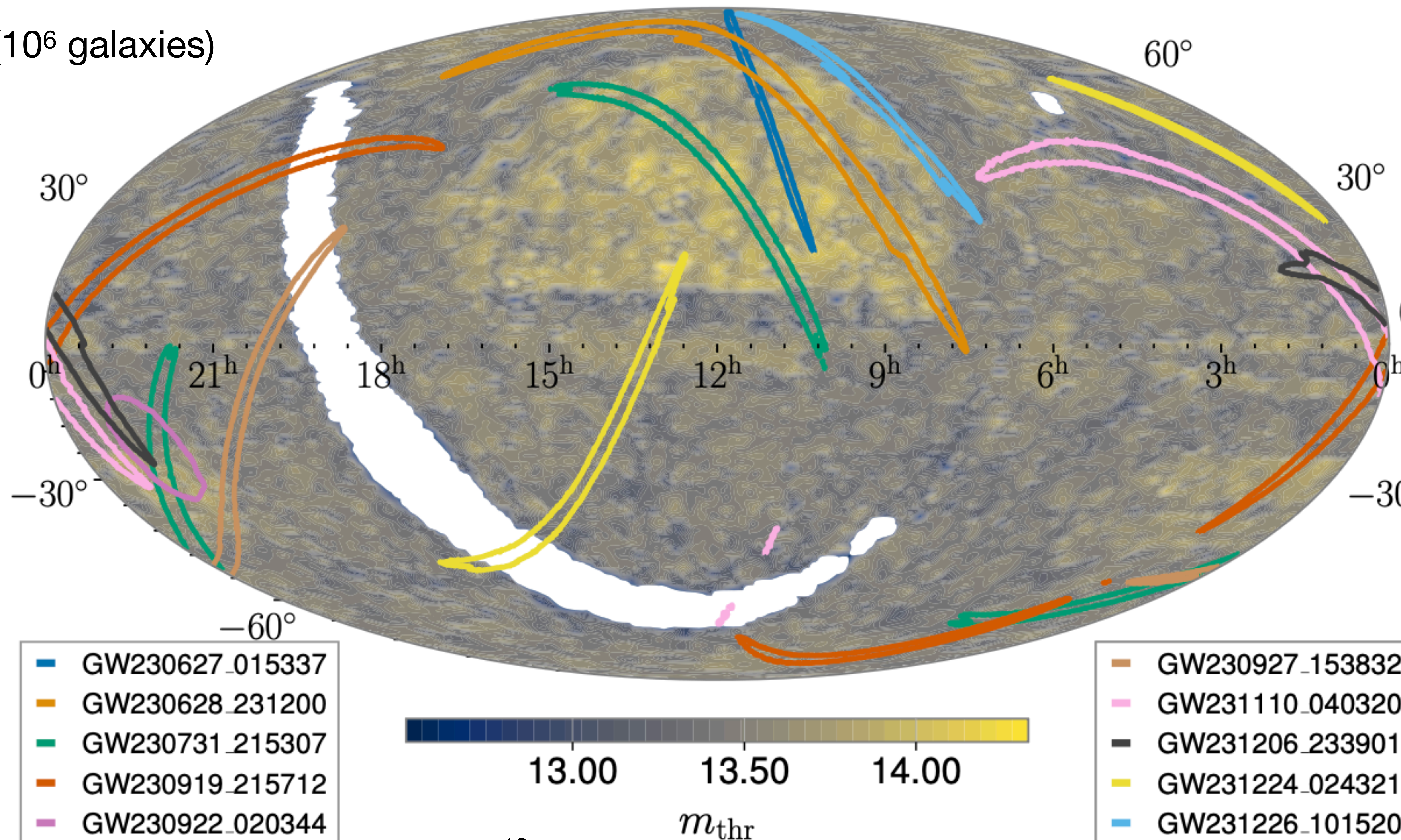
$$p(z|\Lambda) \propto p_{\rm EM\ catalog}(z)$$

Galaxy catalog for the dark sirens analysis

Use GLADE+ Dálya et al., MNRAS 479, 2374 (2018) and 514, 1403 (2022):

GLADE+, full sky, 22 millions of galaxies: GWGC, 2MPZ, 2MASS XSC, HyperLEDA, and WISExSCOSPZ galaxy catalogues, and the SDSS-DR16Q quasar catalogue

Choose the K-band (10^6 galaxies)

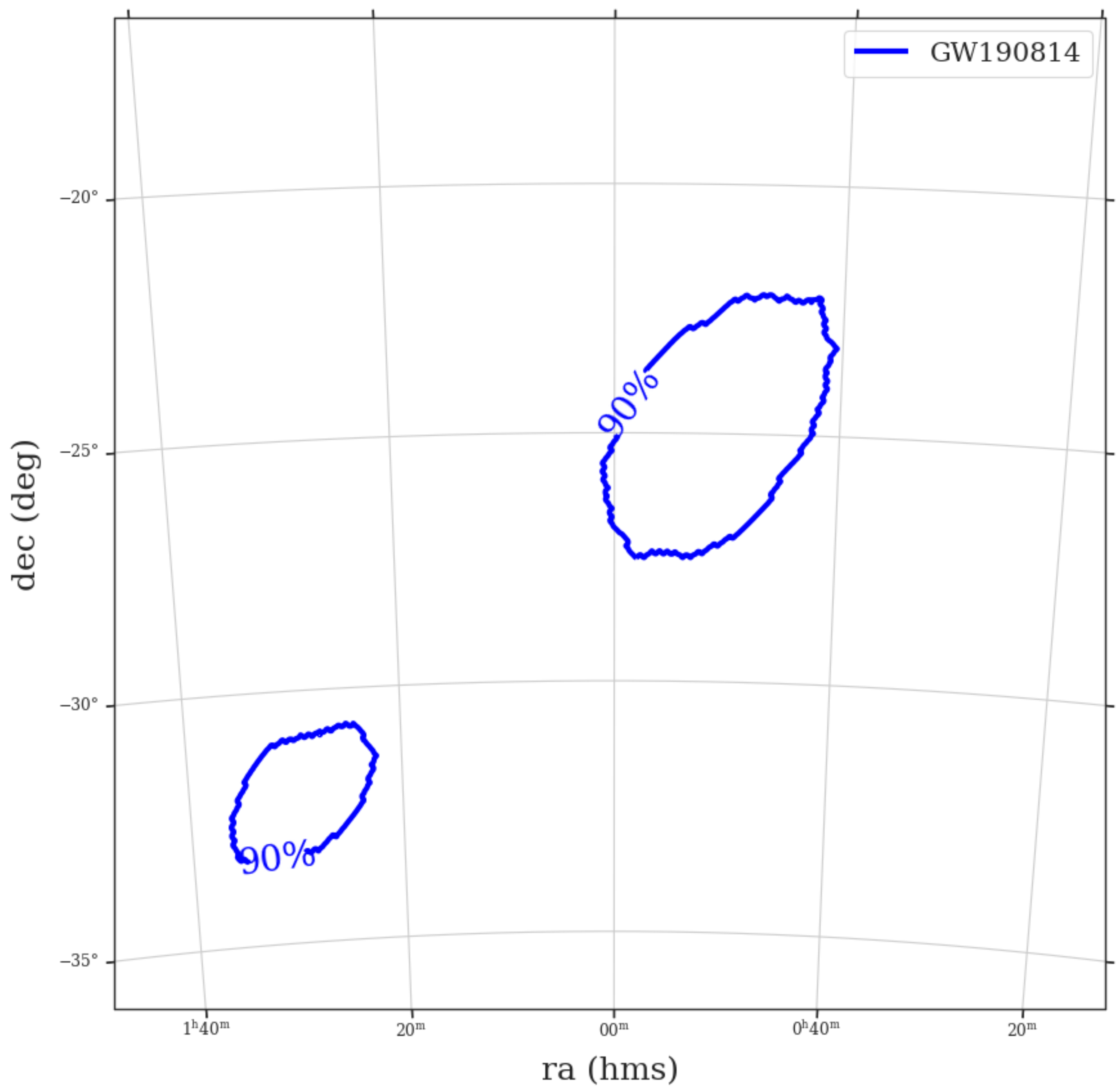


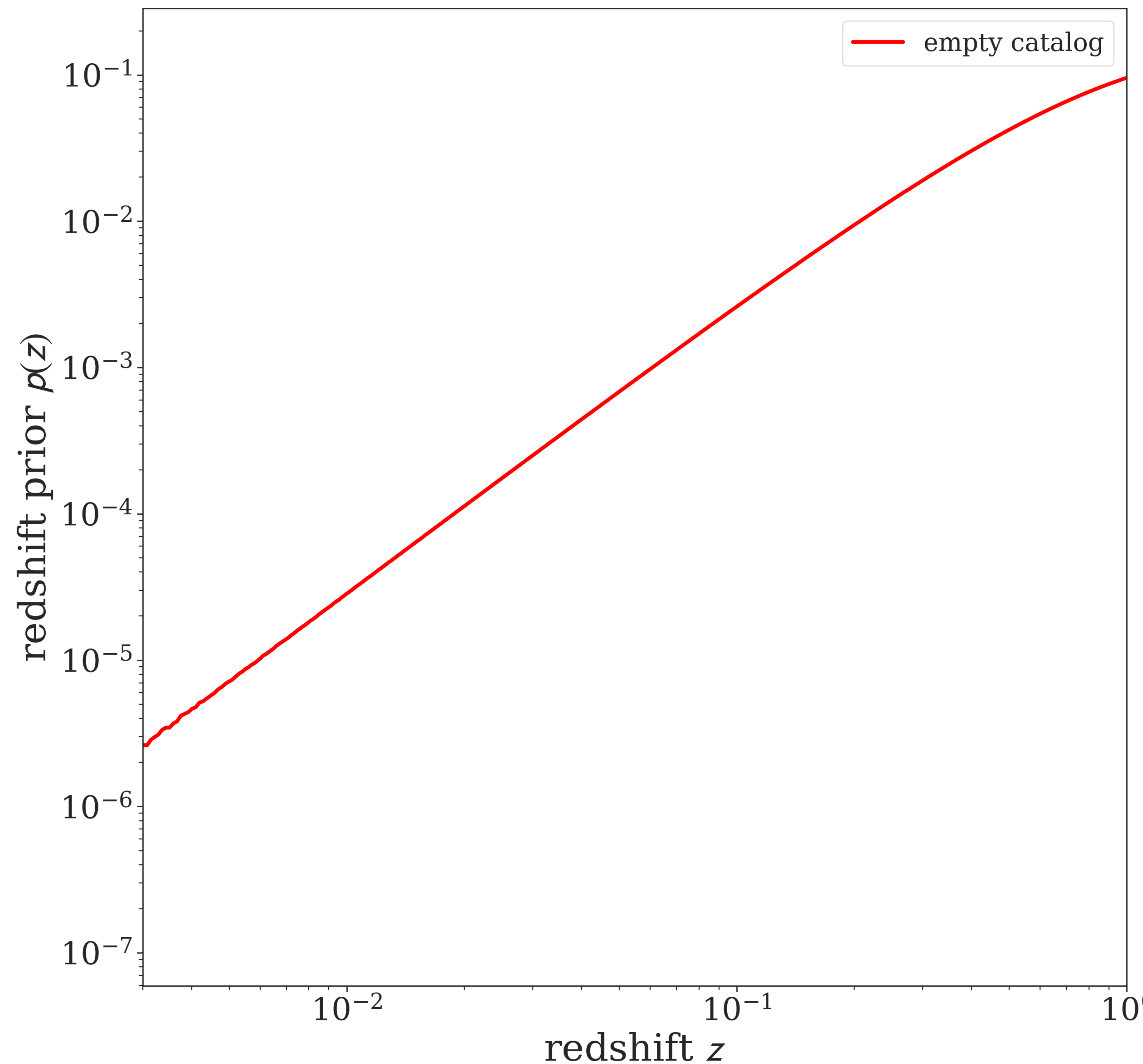
https://arxiv.org/abs/2509.04348

Constructing the redshift prior using the GLADE+ catalog

Dálya et al., MNRAS 479, 2374 (2018) and 514, 1403 (2022)

GW190814: d_L ~ 230 Mpc





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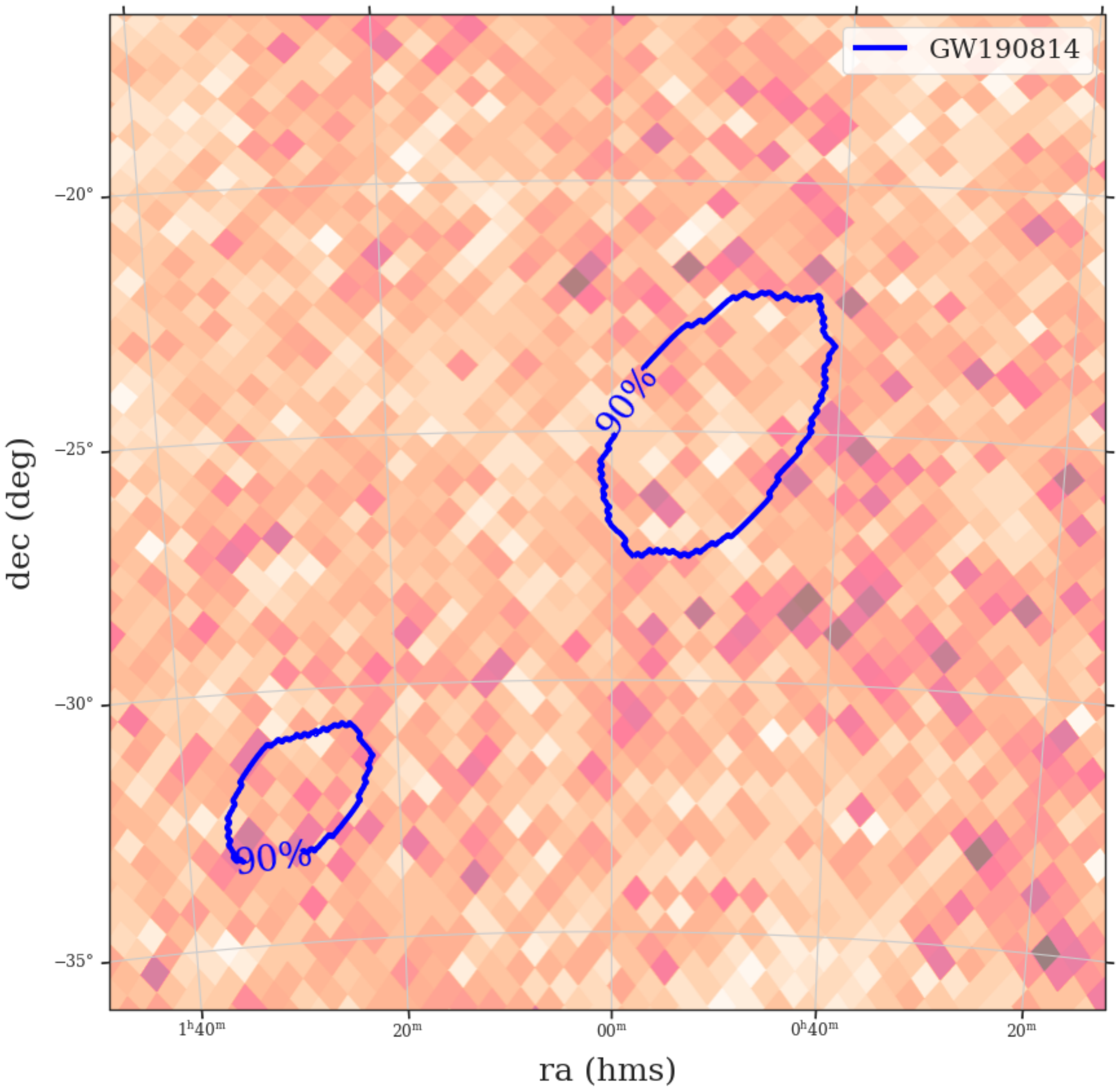
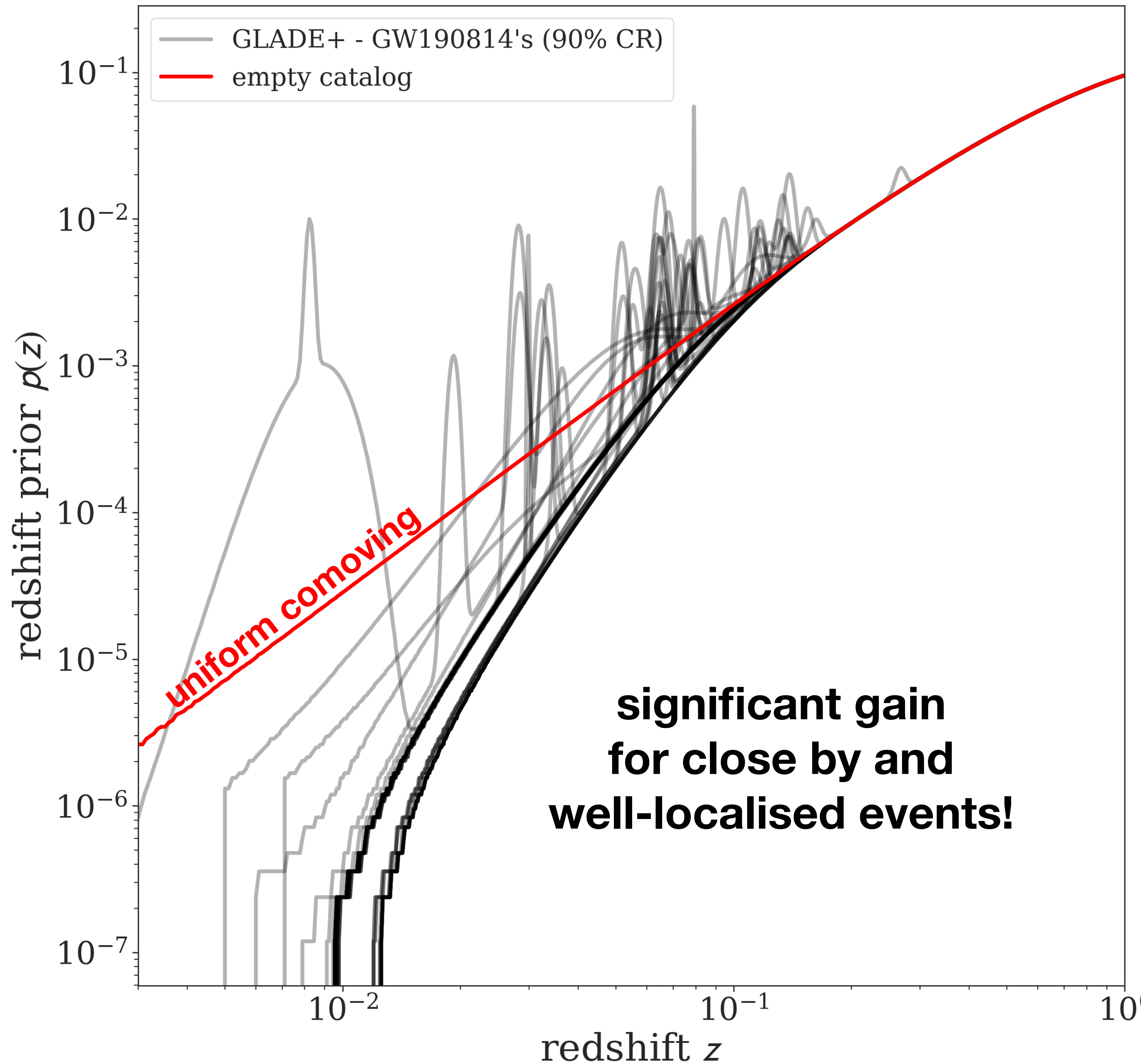




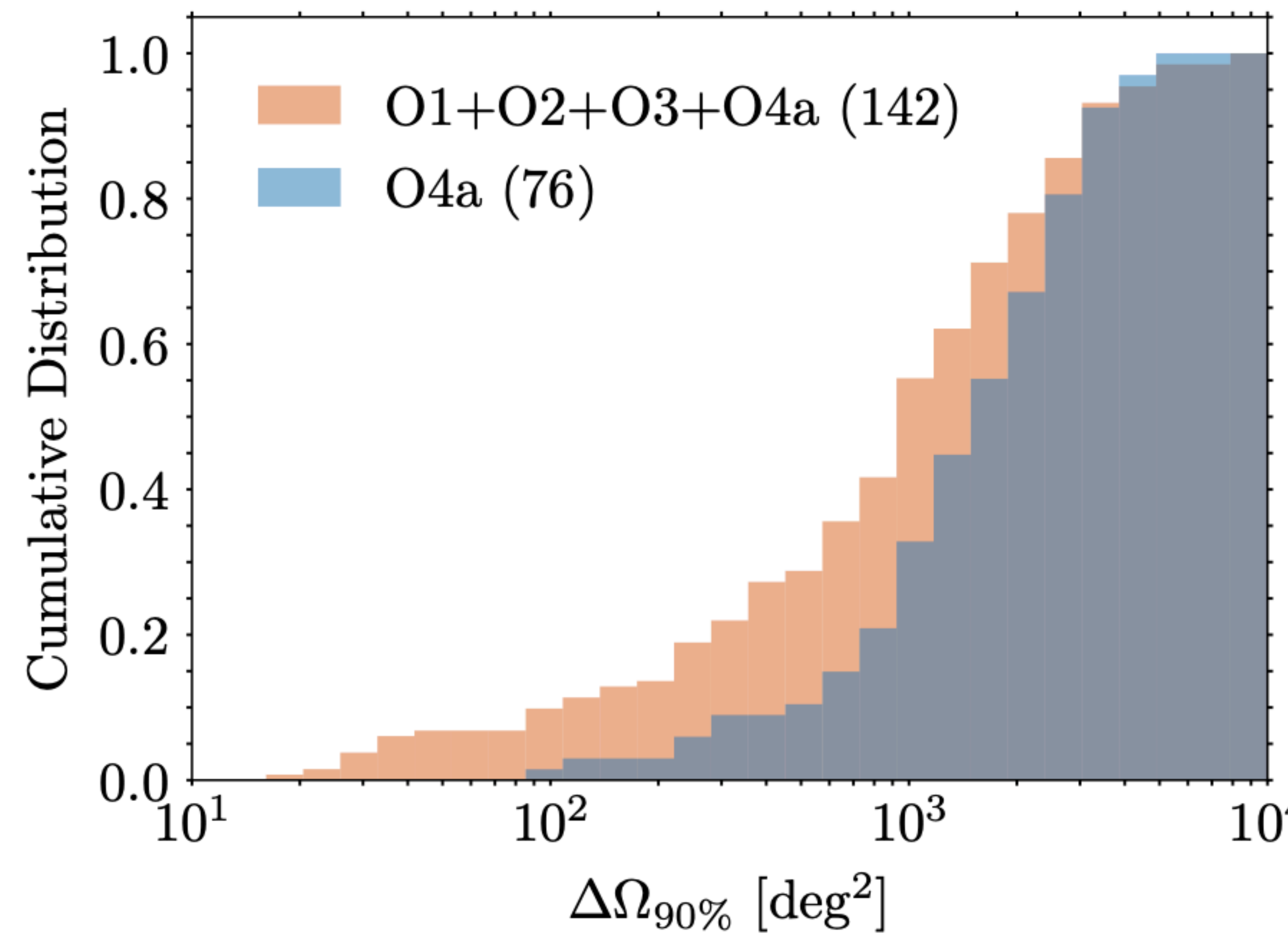
significant gain for close by and well-localised events!

3. Cosmological constraints with GWTC-4.0

with GWTC-3: R. Abbott et al 2023 ApJ 949 76
with GWTC-4.0: arXiv:2509.04348

The data set: **142 CBCs, 141 dark sirens + the bright siren GW170817**
using a False Alarm Rate < 1/ (4 years)

2509.04348v1



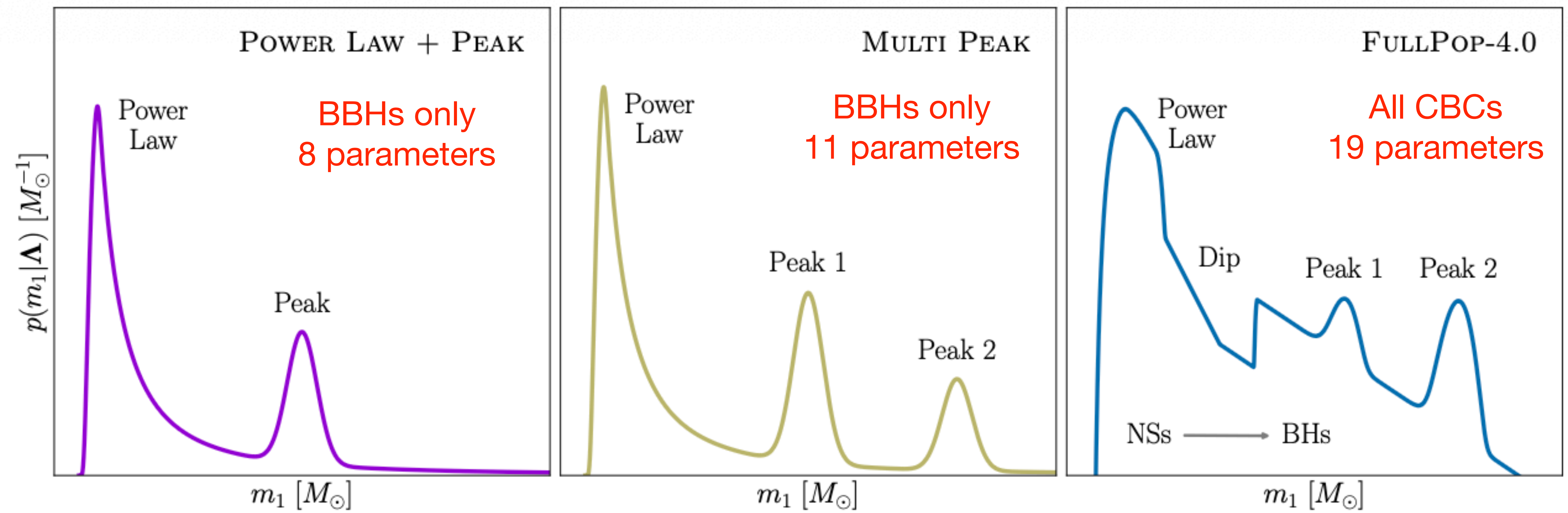
Sky localisation is worse during O4a (Virgo not running):
<u>don't expect a large difference between the spectral/dark analyses</u>

Two independent analysis pipelines:

- gwcosmo Gray et al, JCAP 12 (2023) 023, Gray et al, MNRAS 512 (2022) 1127
- icarogw Mastrogiovanni et al, A&A 682 (2024) A167 Mastrogiovanni et al, PRD, 104, 062009

→ <u>We combine their results</u>

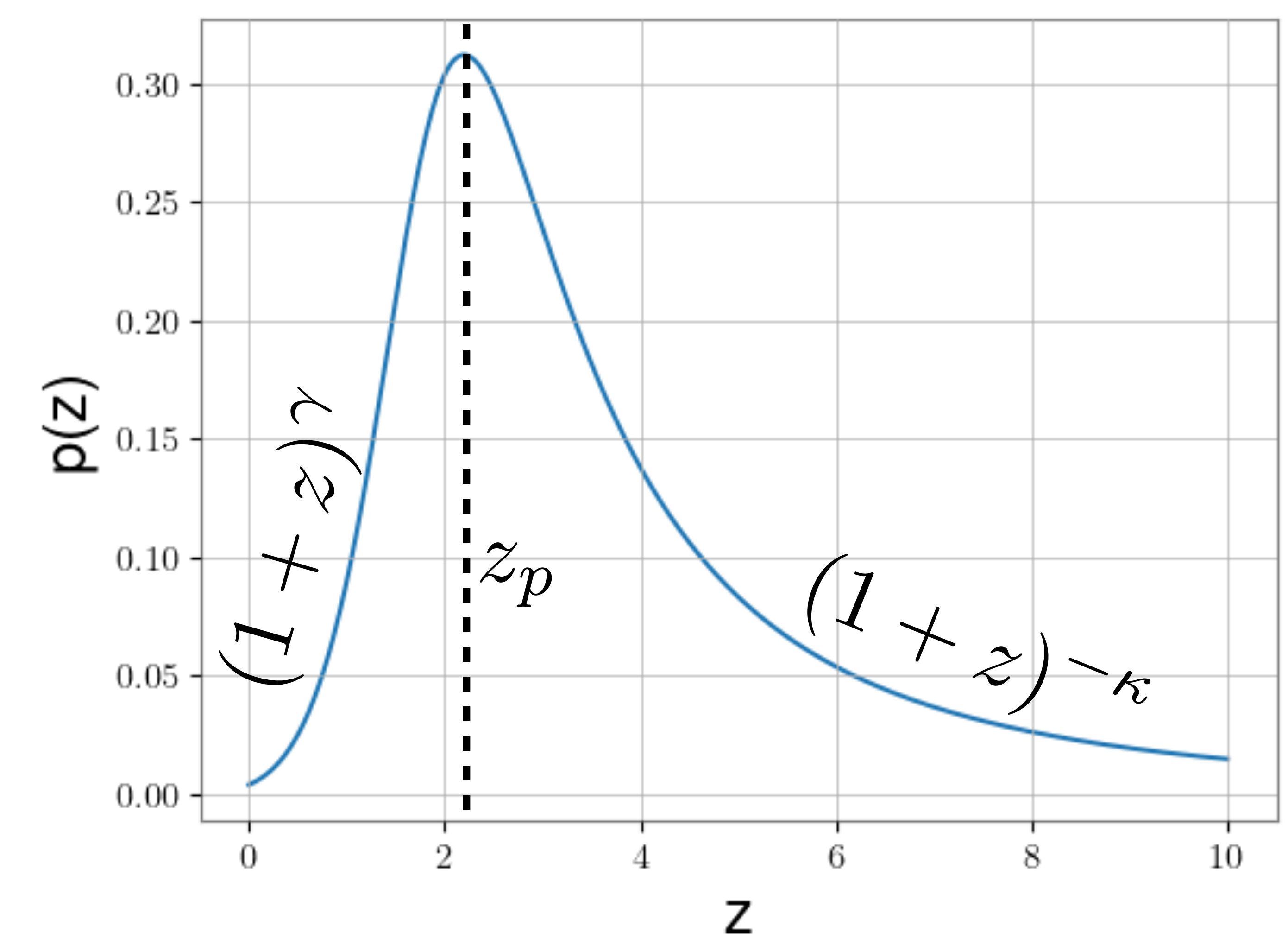
Choice of mass models:



Choice of a generic merger-rate model, Madau-Dickinson (SFR):

$$p(s|z) = R_0\,\psi(z|\gamma,\kappa,z_p) = R_0\,\frac{\left(1+\frac{1}{(1+z_p)^{\gamma+\kappa}}\right)(1+z)^{\gamma}}{1+\left(\frac{1+z}{1+z_p}\right)^{\gamma+\kappa}}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

3 parameters



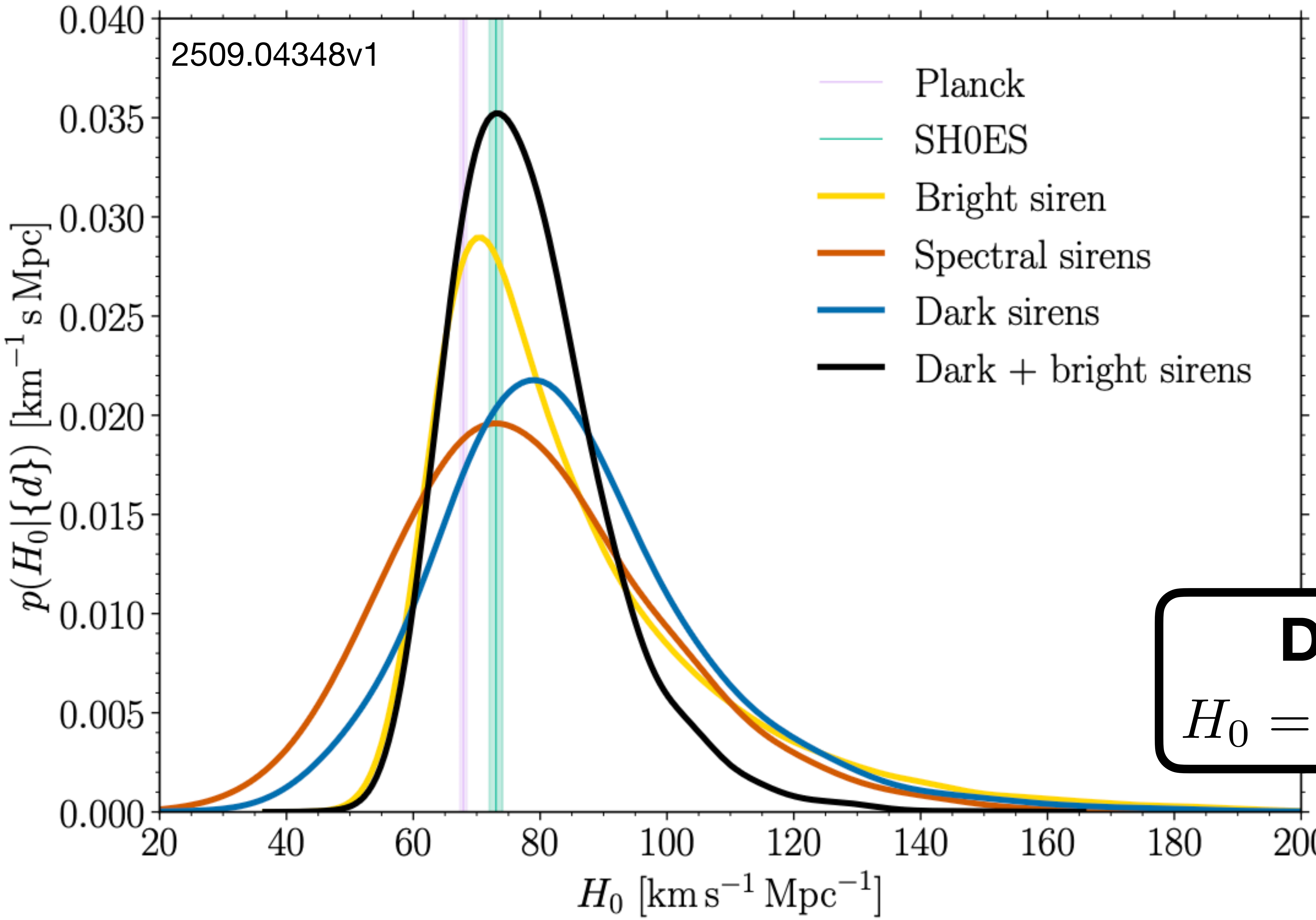
Choice of the redshift prior: spectral or dark analysis

Choice of the host galaxies/luminosity relation:

$$p(\text{hosting CBC}|L) \propto 1$$
$$p(\text{hosting CBC}|L) \propto L$$

H_0 from GWTC-4.0

H_0 posterior after marginalisation over 22 hyper-parameters (mass and rate models)



GW170817 alone:

$$H_0 = 78.4^{+25.7}_{-12.0}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Dark sirens only:

$$H_0 = 81.6^{+21.5}_{-15.9}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Spectral sirens only:

$$H_0 = 76.4^{+23.0}_{-18.1}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Dark+bright sirens:

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

Modified gravity

Many modified-gravity models:

→ modify the GW propagation equation (friction)
→ change the GW amplitude wrt GR
→ change the attributed distance d_L^{GW}

The ratio **d_L^{GW} / d_L^{EM}** is a convenient probe of departures from GR.

We consider 2 parameterisations:

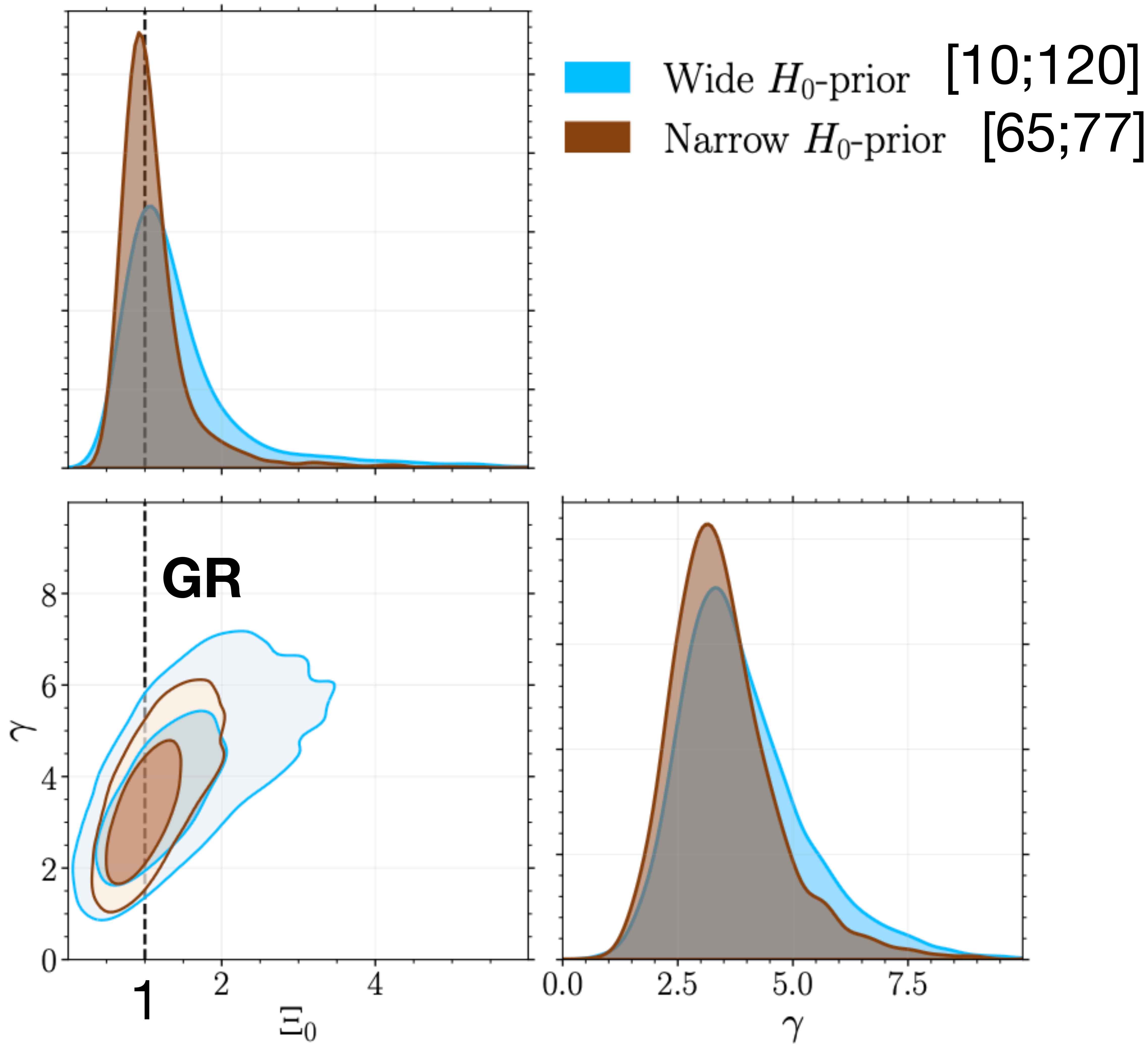
$$\frac{d_L^{\mathrm{GW}}}{d_L^{\mathrm{EM}}} = \begin{cases} \Xi_0 + \frac{1-\Xi_0}{(1+z)^n} \\ \exp\left(\int_0^z \frac{c_M \, \mathrm{d}z'}{E^2(z')(1+z')}\right) \end{cases}$$

Phenomenological approach
(Belgacem, E., et al. 2019b, JCAP, 07, 024)

Horndeski gravity, running Planck mass
(Horndeski, G. W. 1974, Int. J. Theor. Phys., 10, 363)

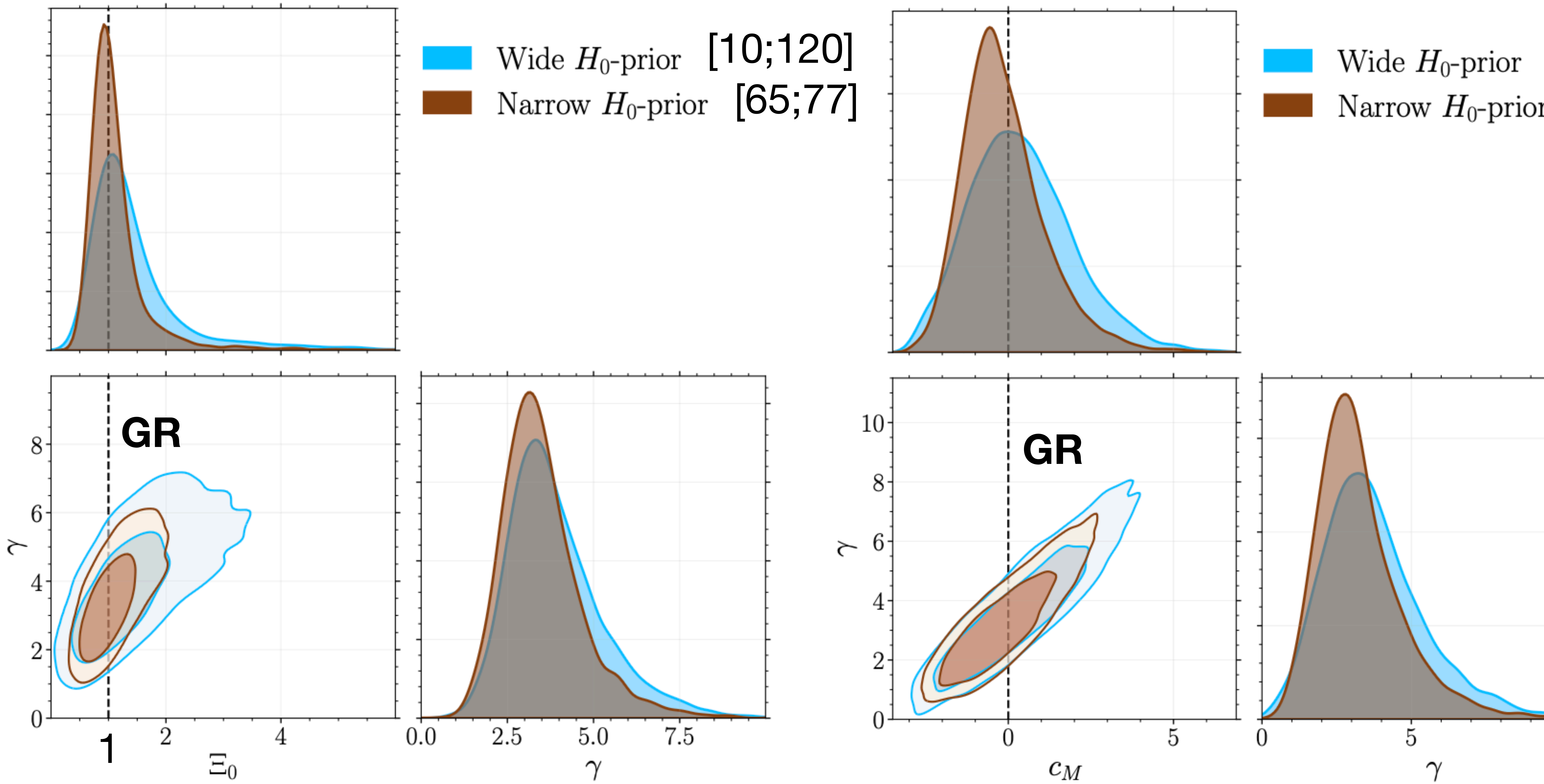
GR: $\Xi_0 = 1$ and $c_M = 0$

Modified gravity



Strong correlation with γ as the detectability of GWs can be due to a change of d_L^{GW} or to a change in the merger rate (γ at low z): $p(s|z) \propto (1+z)^{\gamma}$

Modified gravity



Strong correlation with γ as the detectability of GWs can be due to a change of d_L^{GW} or to a change in the merger rate (γ at low z): $p(s|z) \propto (1+z)^\gamma$

Conclusions

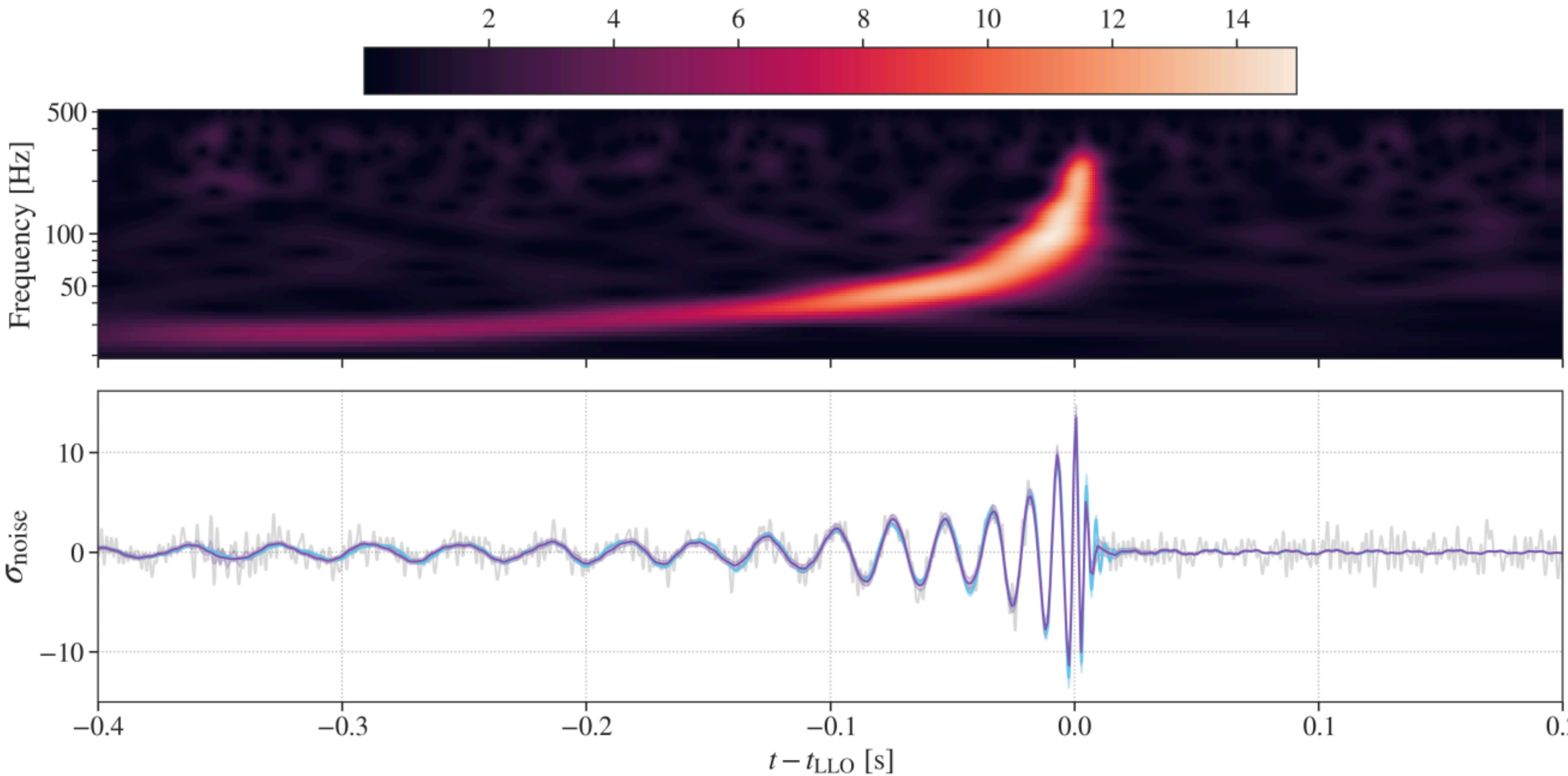
- Our best constraint (68%) with GWTC-4.0 on H_0 is $H_0 = 76.6^{+13.0}_{-9.5}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$
- Improvement vs GWTC-3: 60% better for the spectral analysis (~3.3x more events + better mass model)
- Not yet competitive with the CMB/Standard candles measurements
- No departure from GR after tests on some modified gravity models
- Virgo was NOT participating in O4a: expect better constraints with O4b
- UpGLADE: add Pan-STARRS DR2, PS-STRM, CatWISE, Legacy Survey, Duncan22, much more complete catalog

This material is in part based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Backup

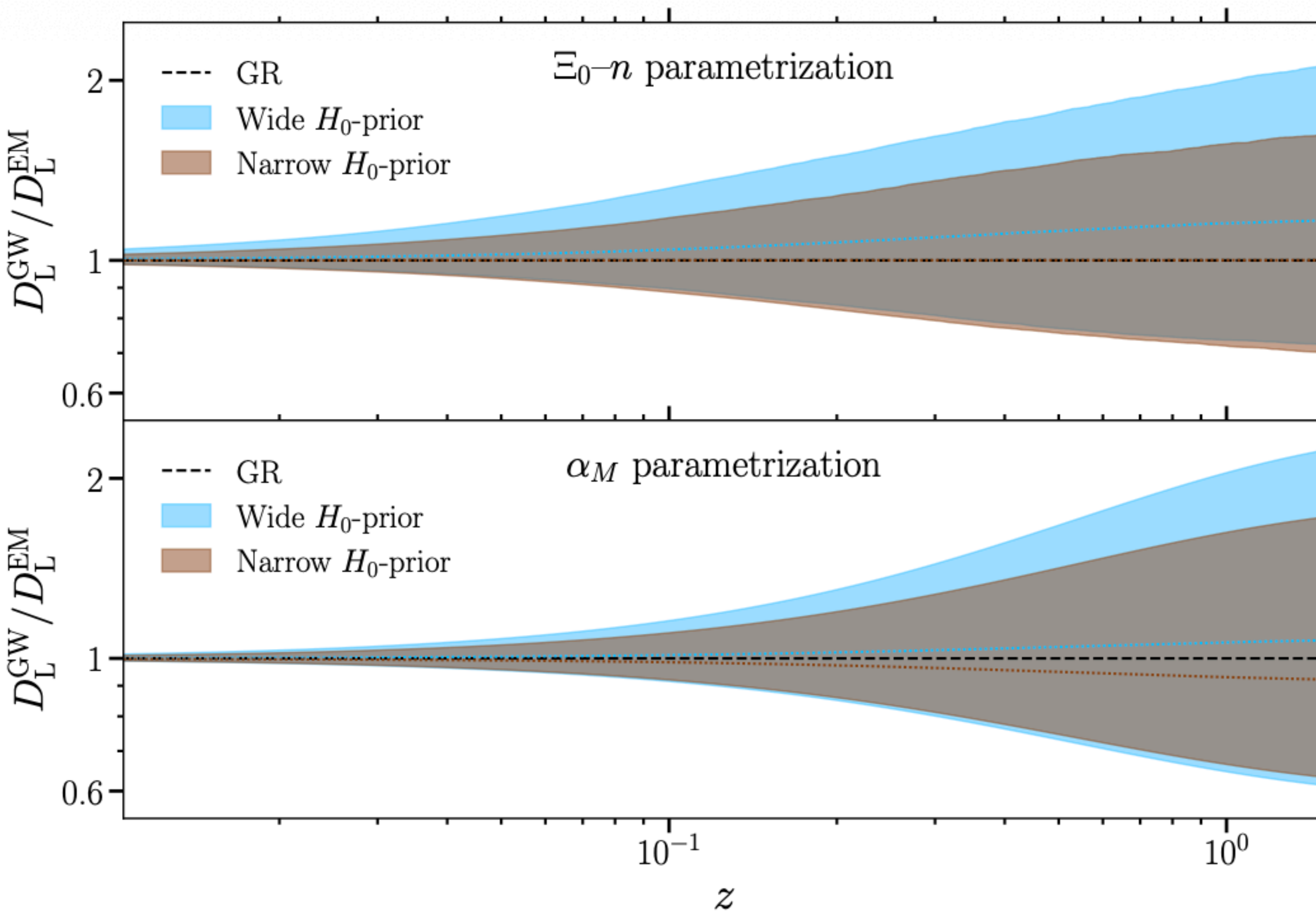
The data: GWTC-4.0

Largest SNR so far: GW230814_230901
SNR = 42.4

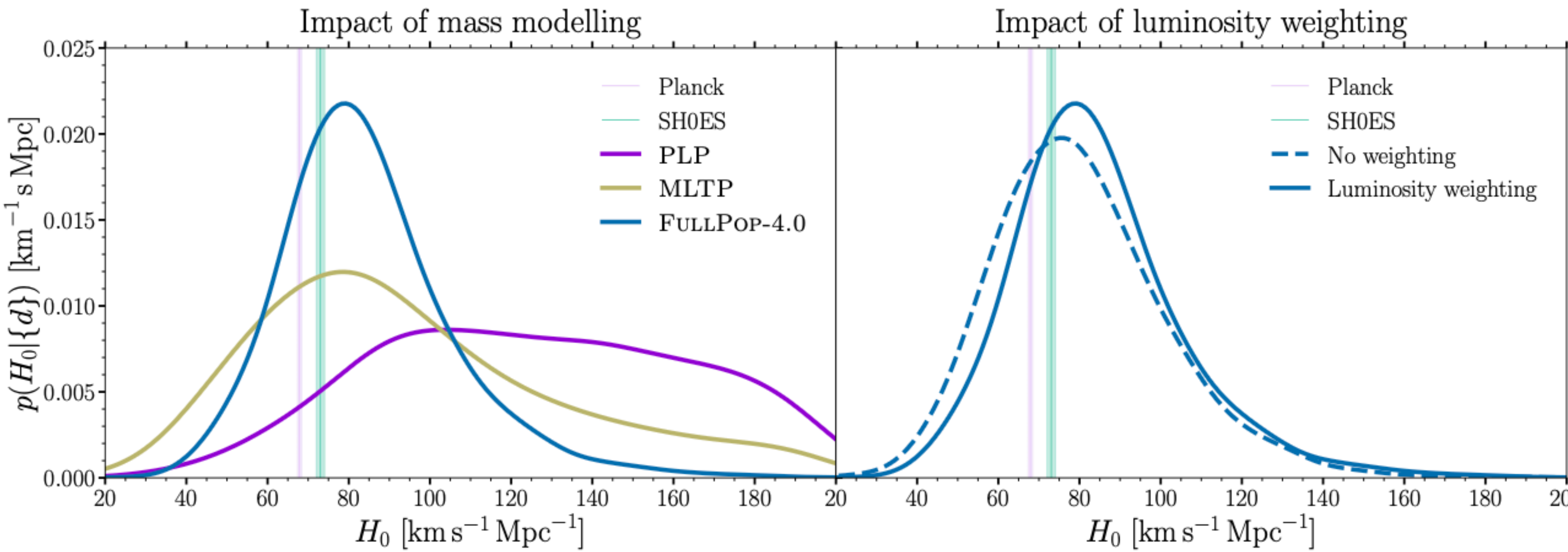


https://arxiv.org/pdf/2509.07348

Modified gravity



90% CR



Huge impact of mass modelling
the PLP model is strongly
disfavored by the Bayes factor

$$\log_{10} \mathcal{B} = 2.3$$

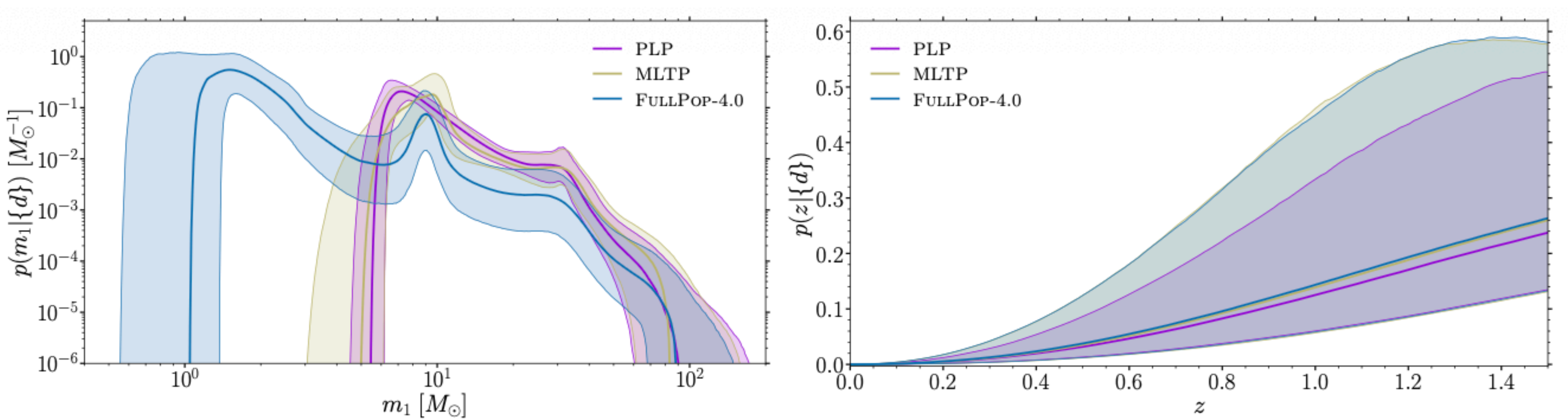
Small impact of luminosity weighting

$$p(s|M) \propto L(M)^{\epsilon}$$

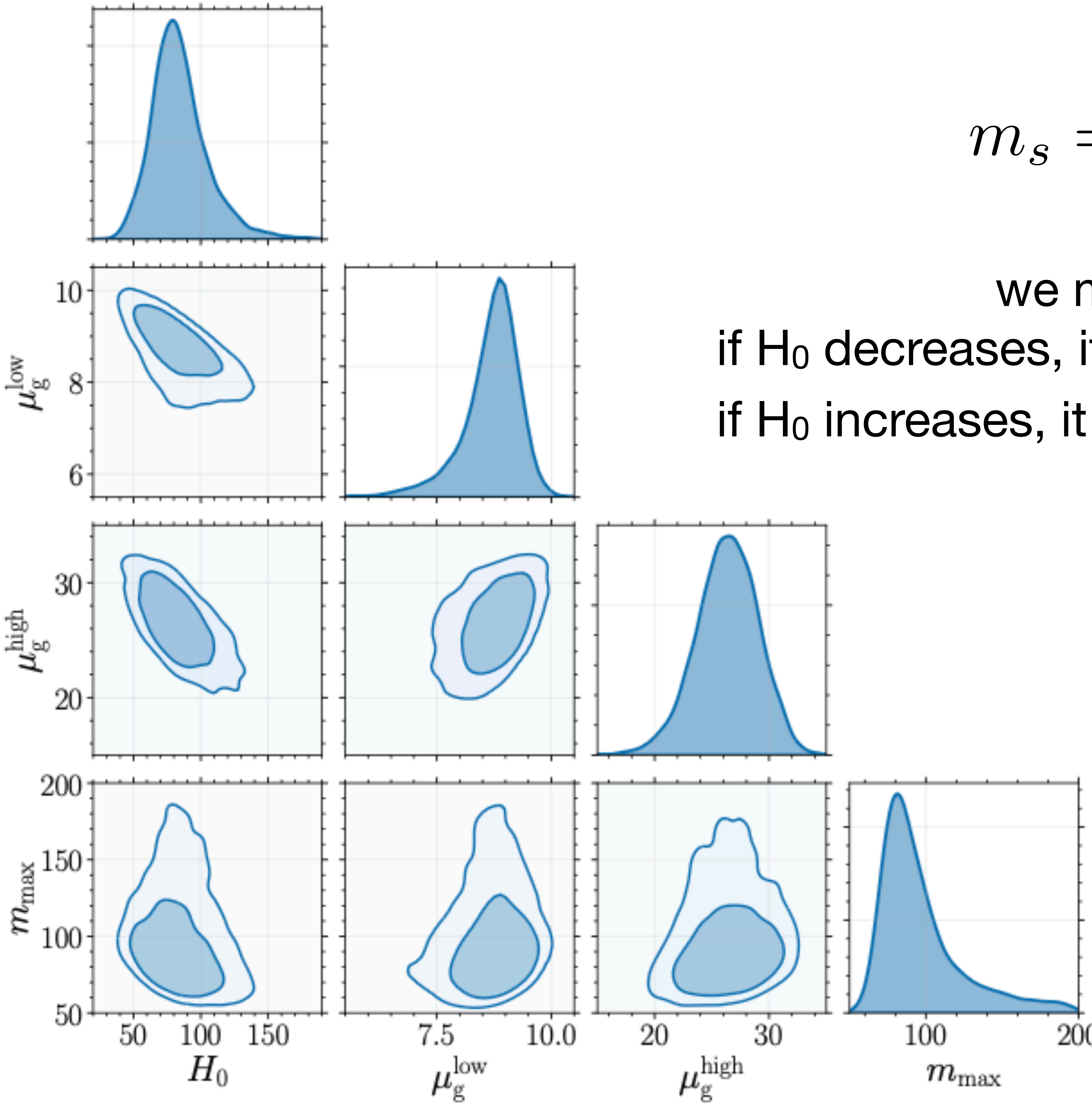
no weighting: $\epsilon = 0$
luminosity weighting: $\epsilon = 1$

no significant evidence for CBCs to occur in more luminous galaxies in the present data

Dark siren, GR, eps=1



Dark siren, GR, eps=1



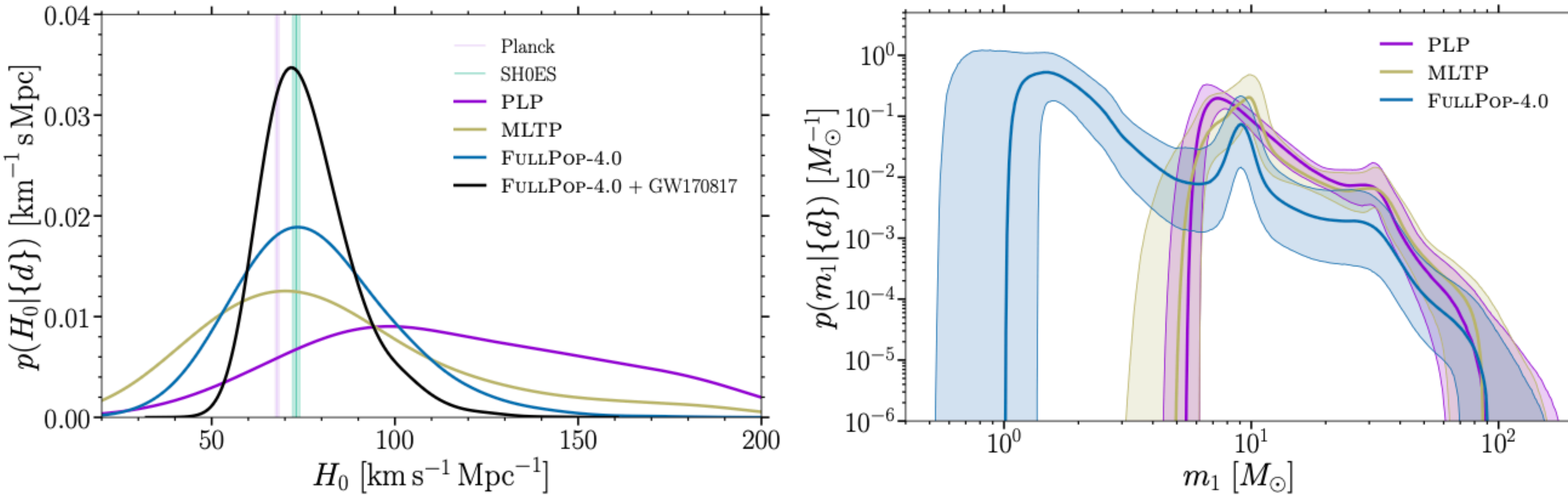
$$m_s = \frac{m_d}{1+z} = \frac{m_d}{1+\frac{H_0 d_L}{c}}$$

we measure m_d and d_L

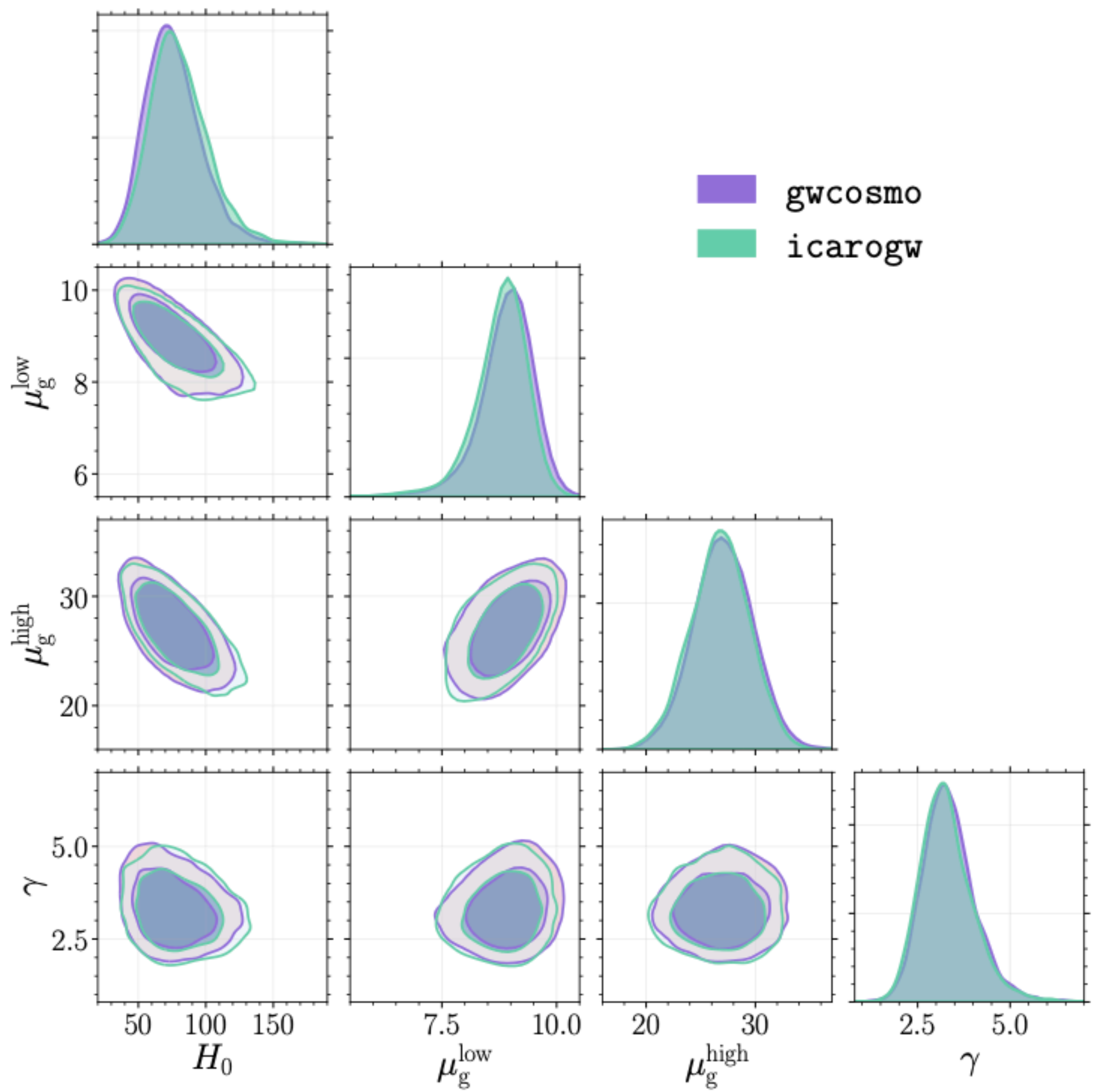
if H_0 decreases, it gives a larger m_s (**μ** increases)

if H_0 increases, it gives a larger m_s (**μ** decreases)

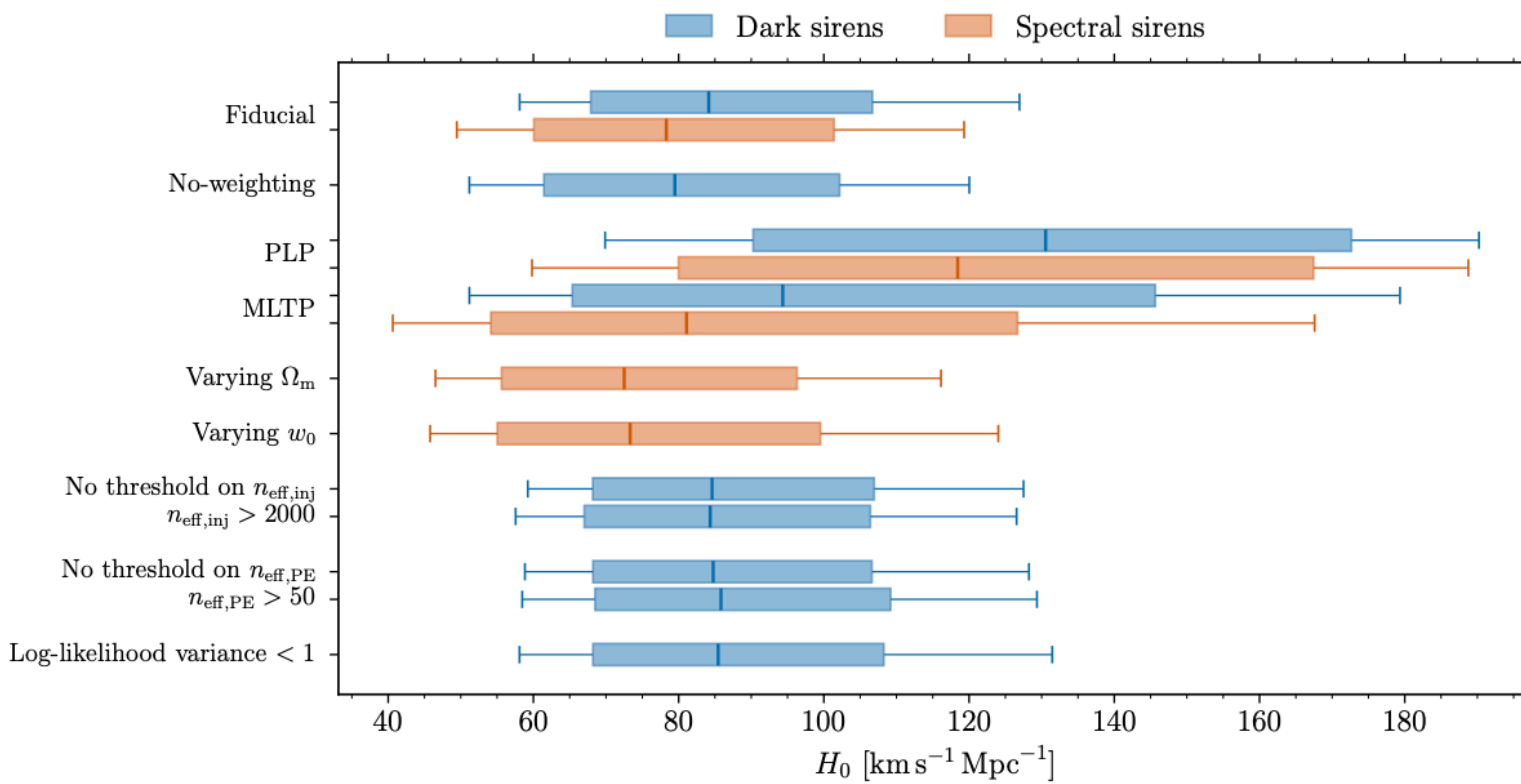
Spectral sirens - GR

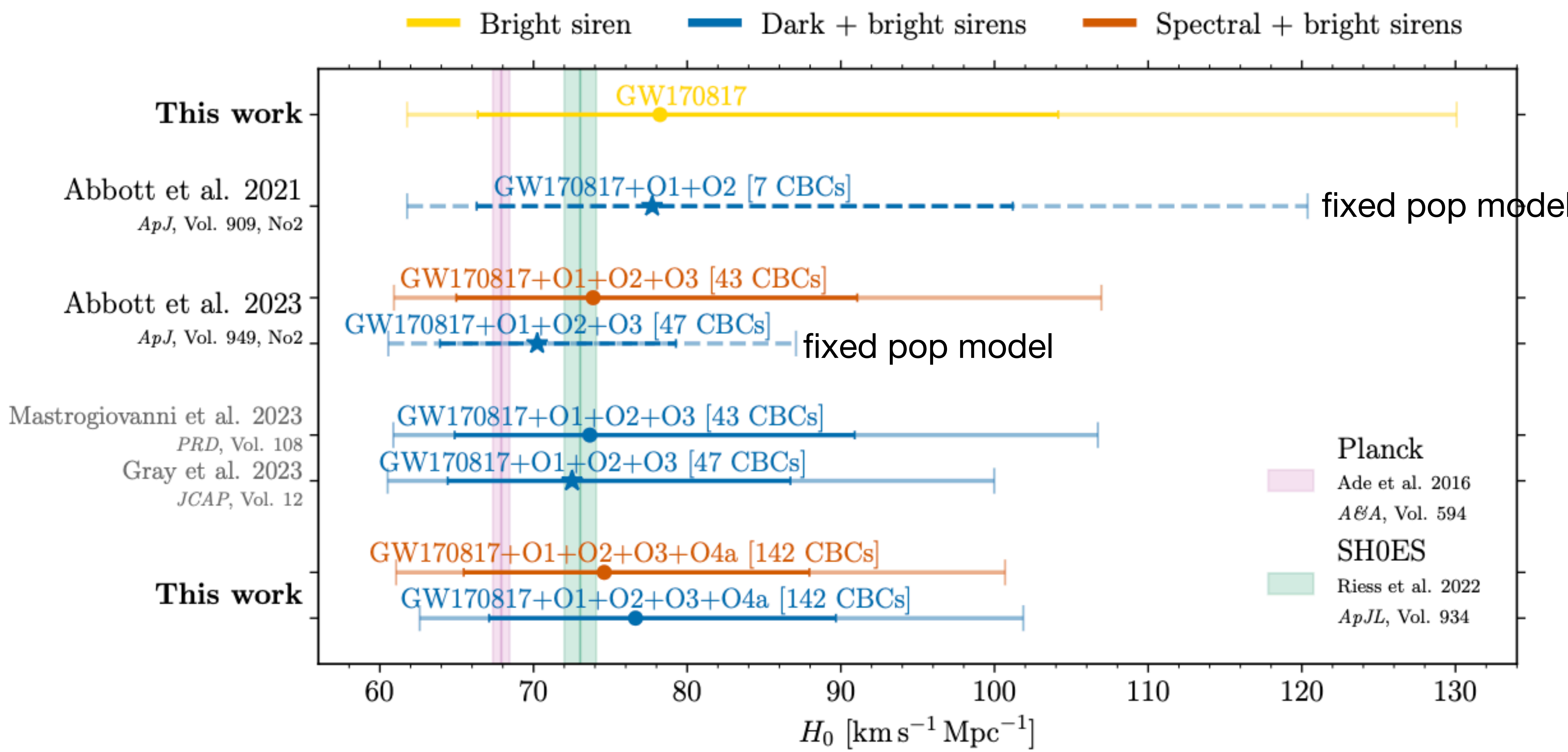


Spectral sirens - GR



Robustness tests





The current result corresponds to a marginalisation over all population and rate parameters, contrary to Abbott et al 2023 (47 CBCs only but using a fixed population and rate model)

The Line of Sight redshift prior: the full expression

$$p(z|\Omega_i,\Lambda,s,I) = \frac{1}{p(s|\Omega_i,\Lambda,I)}\Bigg[p(G|\Omega_i,\Lambda,I)\frac{1}{N_{\rm gal}(\Omega_i)}\sum_k^{N_{\rm gal}(\Omega_i)} p(z|\hat{z}_k)p(s|z,M(z,\hat{m}_k,\Lambda),\Lambda,I)$$
$$+\Bigg(\Theta[z_{\rm cut}-z]\int_{M(z,m_{\rm th}(\Omega_i),\Lambda)}^{M_{\rm max}(H_0)} p(z,M|\Lambda,I)p(s|z,M,\Lambda,I)\,dM$$
$$+\Theta[z-z_{\rm cut}]\int_{M_{\rm min}(H_0)}^{M_{\rm max}(H_0)} p(z,M|\Lambda,I)p(s|z,M,\Lambda,I)\,dM\Bigg)\Bigg].$$

https://doi.org/10.48550/arXiv.2308.02281

$$\Lambda = \{\Lambda_{\rm cosmo}, \Lambda_{\rm mass}, \Lambda_{\rm rate}\}$$

if no evolution of the mass models with z, discard the Lambda-mass
Lambda-rate appears in p(s|z,M...)
Lambda-cosmo appears in the m, M, z conversion