

2nd New Horizons for Psi Workshop

Constraints on Modified Gravity Theories of Dark Energy with the Latest LVK Data

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arXiv: 2509.04348, 2605.27227 with the LVK

arXiv: 2606.14549 with Jun Zhang



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• Introduction

- Dark energy can be explained by modified gravity.
- Toy model: a single scalar field

$$\mathcal{L}_\phi = X(\phi) - V(\phi)$$

$$w = \frac{P_{\text{DE}}}{\rho_{\text{DE}}} = \frac{X(\phi) - V(\phi)}{X(\phi) + V(\phi)}$$

- Horndeski-class scalar-tensor field theories (fixing speed of gravity to be c):

$$\mathcal{L} = \frac{1}{2} \underline{M_{\text{eff}}^2(\phi)} R + K(\phi, X) - G_3(\phi, X) \square \phi$$

Scalar field couples to gravitation tensor field

• Higher-dimensional theories

- In the Dvali-Gabadadze-Porrati (DGP) theory, the Universe consists of a 4D brane and a 5D bulk:

$$S = M_5^3 \int_{\mathcal{M}} d^5x \sqrt{-\gamma} R + \int_{\partial\mathcal{M}} d^4x \sqrt{-g} \left[-2M_5^3 K + \frac{M_4^2}{2} R - \sigma + \mathcal{L}_{\text{matter}} \right]$$

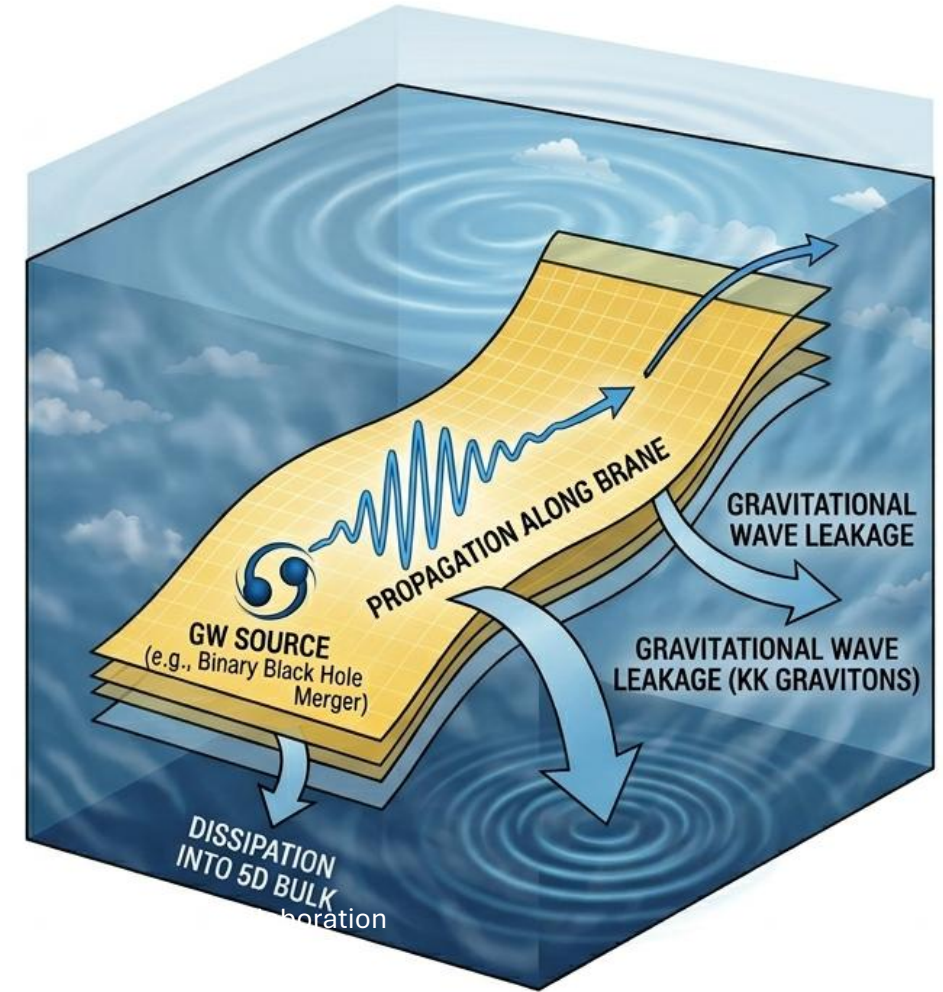
- Gravity leaks into the bulk at cosmological distances above a crossover scale:

$$R_c \sim \frac{M_4^2}{2M_5^3} \sim \frac{c}{H_0}$$

- Modified Friedmann equation:

$$H^2 + \frac{k}{a^2} = \left(\sqrt{\frac{\rho}{3M_P^2} + \frac{1}{R_c^2}} + \epsilon \frac{1}{2R_c^2} \right)^2$$

- For $\epsilon=1$, it leads to natural expansion of the 4D brane without the need of Λ .



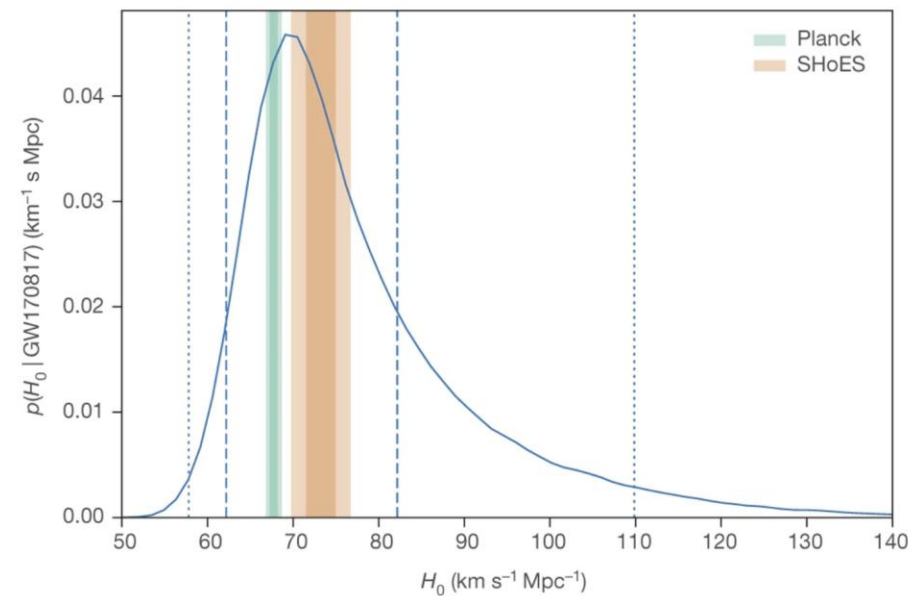
• Gravitational-wave cosmology

- New probe for cosmology: gravitational-wave sirens
 - Bright sirens: GW events with EM counterparts
 - Dark sirens: GW events without EM counterparts

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_M + \Omega_\Lambda}}$$

From GW waveform
 $|h| \sim 1/d_L$

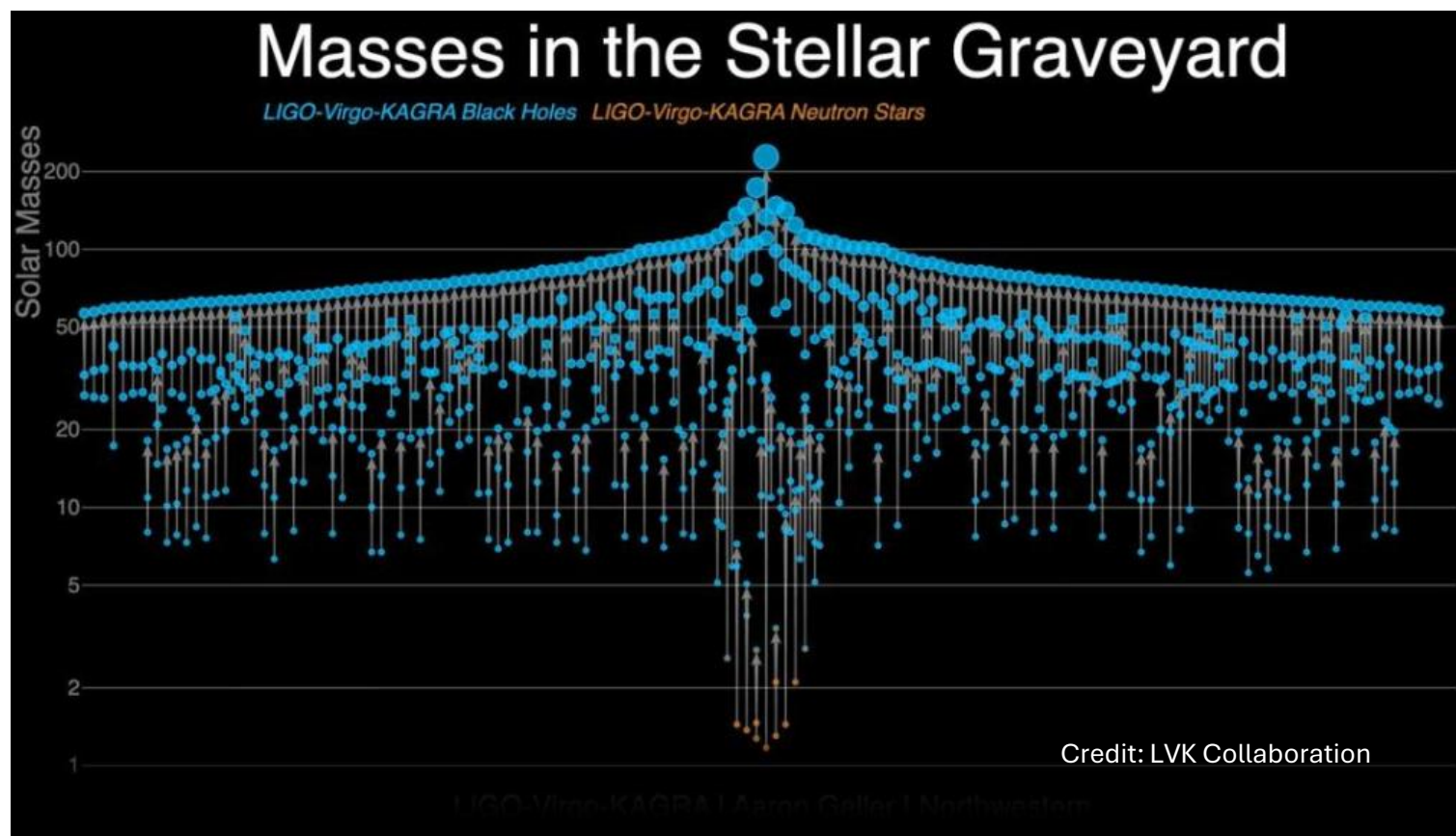
Need to know redshift
Bright siren: GW170817
Redshift from host galaxy



Credit: Abbot et al, 2017

• Gravitational-wave cosmology

- The latest GWTC-5 catalogue from LIGO-Virgo-KAGRA (LVK) contains 390 binary mergers. All are dark sirens except GW170817.



• Method: extra GW damping

- GW propagation effects can test modified gravity theories of dark energy.

$$\tilde{h}''(k) + 2\mathcal{H}[1 - \delta(\eta)]\tilde{h}'(k) + c^2 k^2 \tilde{h}(k) = 0$$

- It leads to deviation in GW luminosity distance

$$d_L^{\text{GW}}(z) = d_L^{\text{EM}}(z) \exp \left[- \int_0^z \frac{dz'}{1+z'} \delta(z') \right]$$

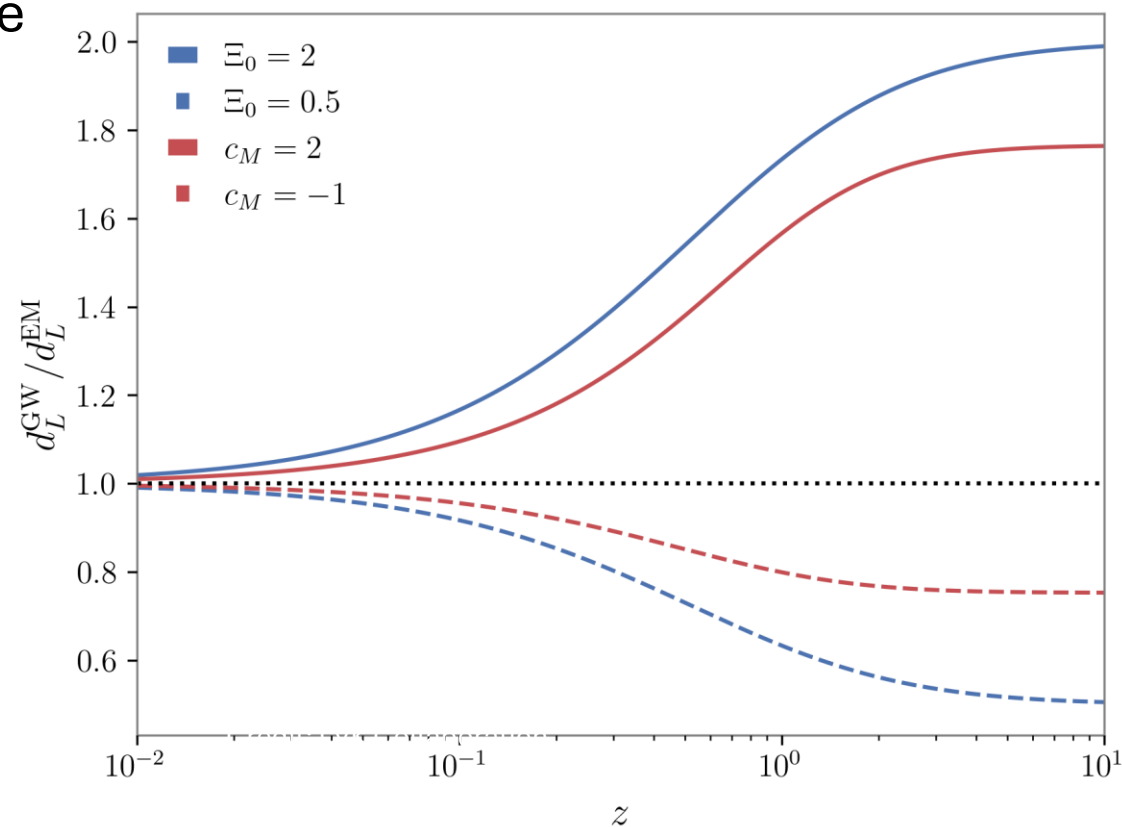
- Example: Horndeski scalar-tensor theories,

$$\delta(z) = -\frac{\alpha_M(z)}{2} = -\frac{1}{2} \frac{d \ln M_{\text{eff}}^2}{d \ln a}$$

$$\alpha_M(z) = c_M \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda 0}}$$

- A general parameterization:

$$d_L^{\text{GW}}(z) = d_L^{\text{EM}}(z) \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n} \right]$$



• Extra GW damping in higher-dimensional theories

- In FLRW metric we can define GW luminosity distance as

$$d_L^{\text{GW}} \propto (1+z)(a_0 r_N)^{(D-2)/2}$$

- For light travelling in 4D spacetime,

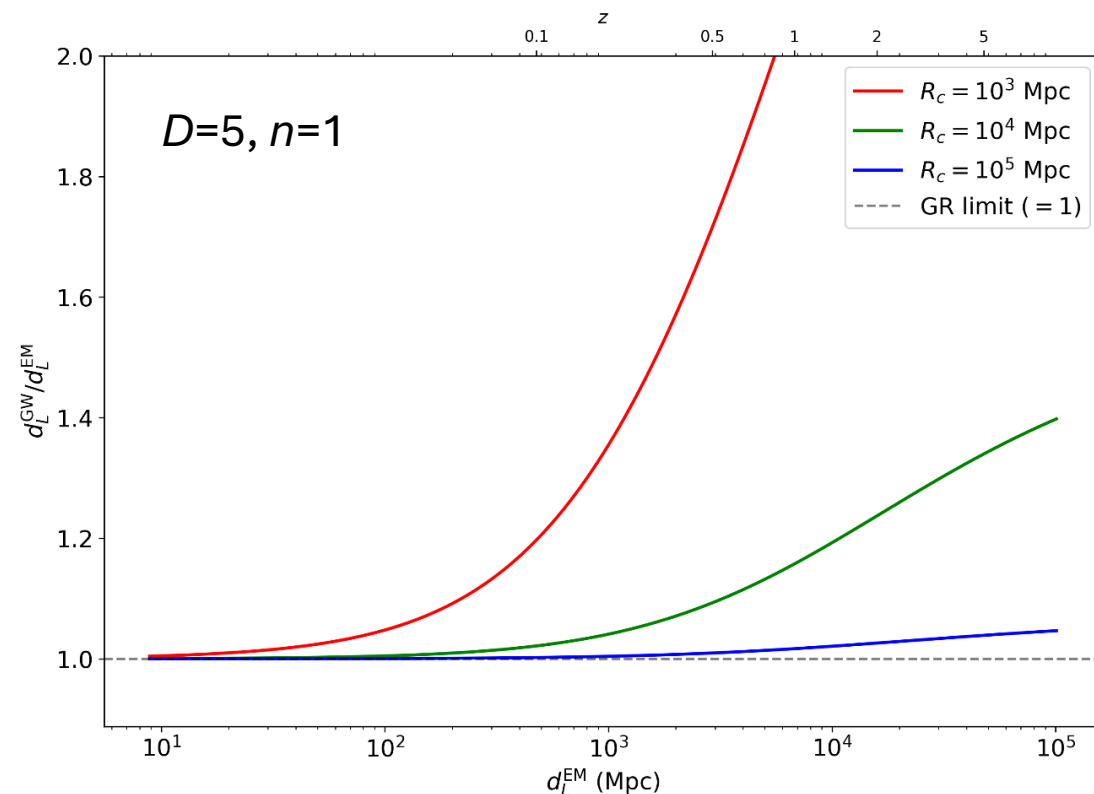
$$d_L^{\text{EM}} = (1+z)a_0 r_3$$

- Considering GW and EM travel along the same null geodesic $r_N = r_3$,

$$d_L^{\text{GW}} \propto (1+z)(a_0 r_3)^{(D-2)/2} \propto d_L^{\text{EM}} \left(\frac{d_L^{\text{EM}}}{1+z} \right)^{(D-4)/2}$$

- The phenomenological form including the crossover scale R_c gives

$$d_L^{\text{GW}} = d_L^{\text{EM}} \left[1 + \left(\frac{d_L^{\text{EM}}}{R_c(1+z)} \right)^n \right]^{\frac{D-4}{2n}}$$



• Method – Dark siren Bayesian analysis

- Hierarchical Bayesian framework to compute posterior on cosmological parameters Λ_c jointly with GW population parameters Λ :

$$p(\Lambda_c, \Lambda | \{d\}, N_{\text{det}}) \propto \pi(\Lambda_c) \pi(\Lambda) p(N_{\text{det}} | \Lambda_c, \Lambda) \underbrace{\xi(\Lambda_c, \Lambda)^{-N_{\text{det}}}}_{\text{Population prior}} \underbrace{p(\{d\} | \Lambda_c, \Lambda)}_{\text{Likelihood}}$$

- Marginalized likelihood over waveform parameters θ_i :

$$\underbrace{p(\{d\} | \Lambda_c, \Lambda)}_{\text{Likelihood}} = \prod_{i=1}^{N_{\text{det}}} \int d\theta_i^{\text{det}} \frac{p(\theta_i^{\text{det}} | d_i)}{\pi_{\text{PE}}(\theta_i^{\text{det}})} \left[\left| \frac{d\theta_i^{\text{det}}(\theta, \Lambda_c)}{d\theta_i} \right|^{-1} \underbrace{p_{\text{pop}}(\theta_i | \Lambda_c, \Lambda)}_{\text{Population prior}} \right]_{\theta_i = \theta_i(\theta_i^{\text{det}}, \Lambda_c)}$$

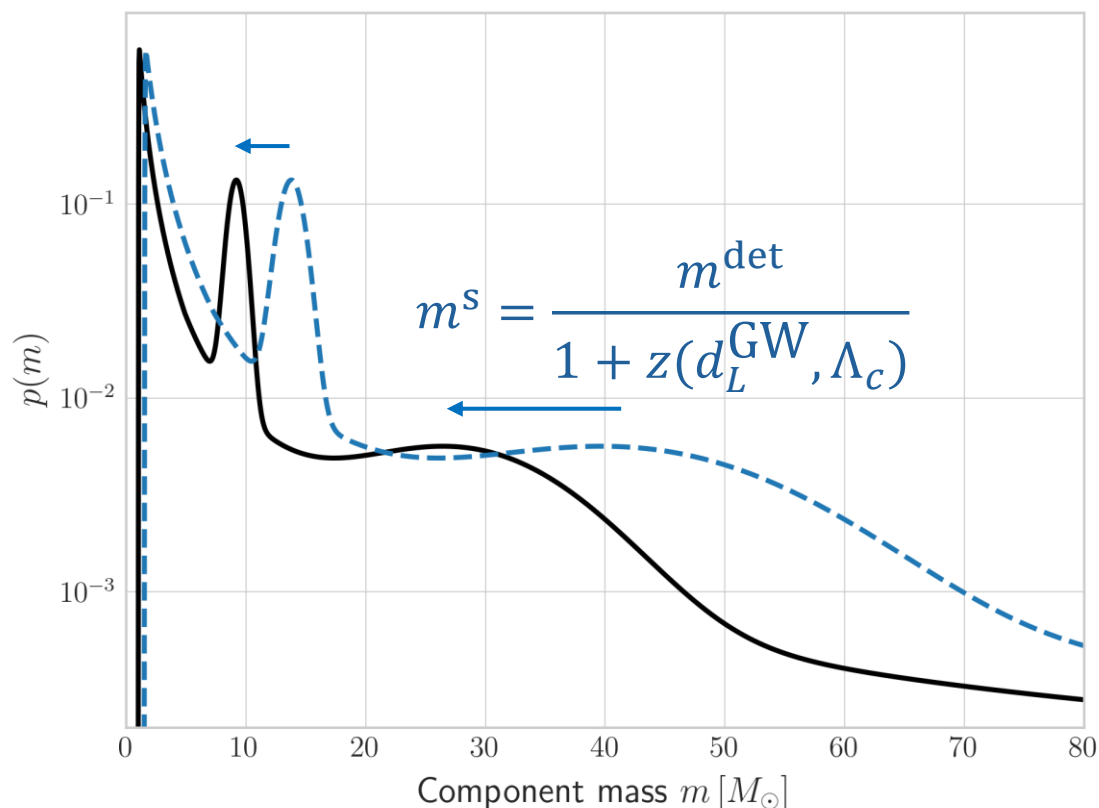
- Selection effects – simulated by multiple injections:

$$\underbrace{\xi(\Lambda_c, \Lambda)}_{\text{Population prior}} = \int d\theta^{\text{det}} P(\text{det} | \theta^{\text{det}}) \left[\left| \frac{d\theta^{\text{det}}(\theta, \Lambda_c)}{d\theta} \right|^{-1} \underbrace{p_{\text{pop}}(\theta | \Lambda_c, \Lambda)}_{\text{Population prior}} \right]_{\theta = \theta(\theta^{\text{det}}, \Lambda_c)}$$

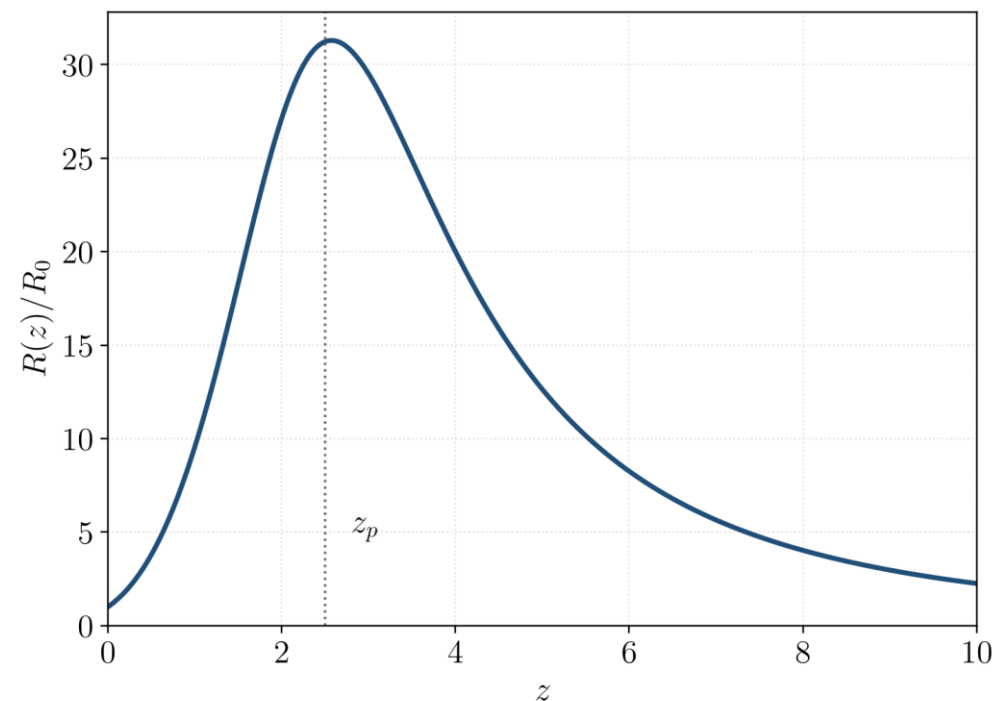
• Method – Dark siren Bayesian analysis

- Population prior distribution $p_{\text{pop}}(m_1^s, m_2^s, z|\Lambda_c, \Lambda)$, parameterized by $\{\Lambda\}$.

NS+BH full range mass distribution:

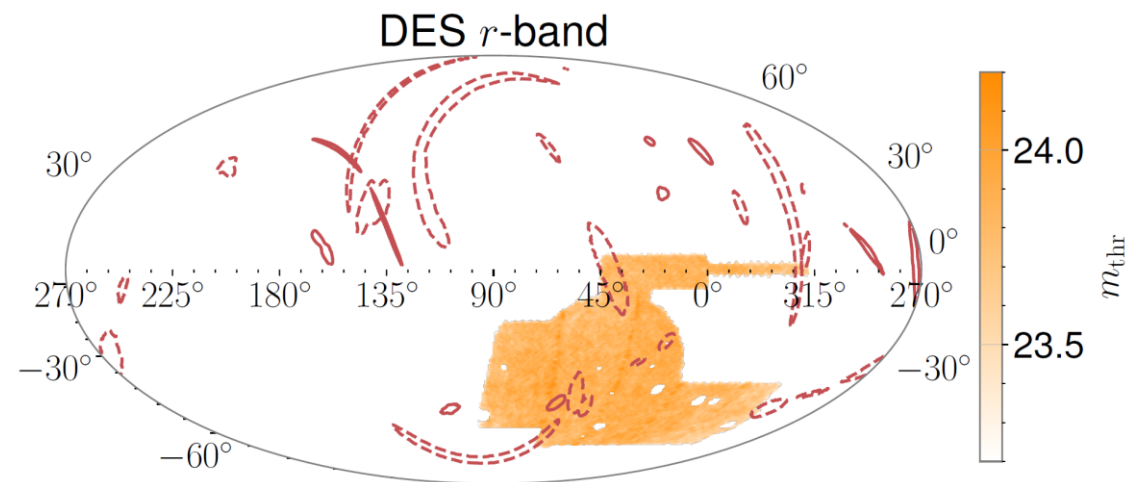
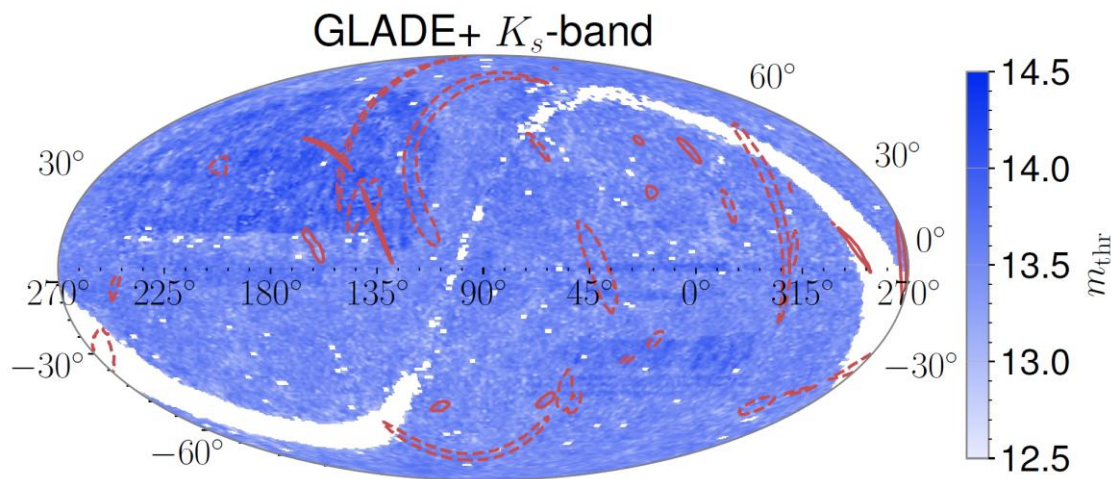


Redshift distribution: $p(z) \sim R(z) \frac{dV_c(z)}{dz} \frac{1}{1+z}$
 $R(z)$ follows Madau-Dickinson star formation rate.



• Method – Dark siren Bayesian analysis

- Galaxy catalogue redshift prior $p(z|\Omega_j, \Lambda_c)$: line-of-sight distribution of galaxy in each pixel.
- GLADE+ and DES Year 6 Gold galaxy catalogue are used separately.
- If an empty galaxy catalogue is used ($p(z) \sim \frac{dV_c}{dz}$), Λ_c is constrained by compact object mass spectrum – “spectral siren”.



Abac et al, 2026

• Results – H_0 in Λ CDM

- Dark sirens with false alarm rate $< 0.25/\text{yr}$:
 - 142 in GWTC-4
 - 235 in GWTC-5

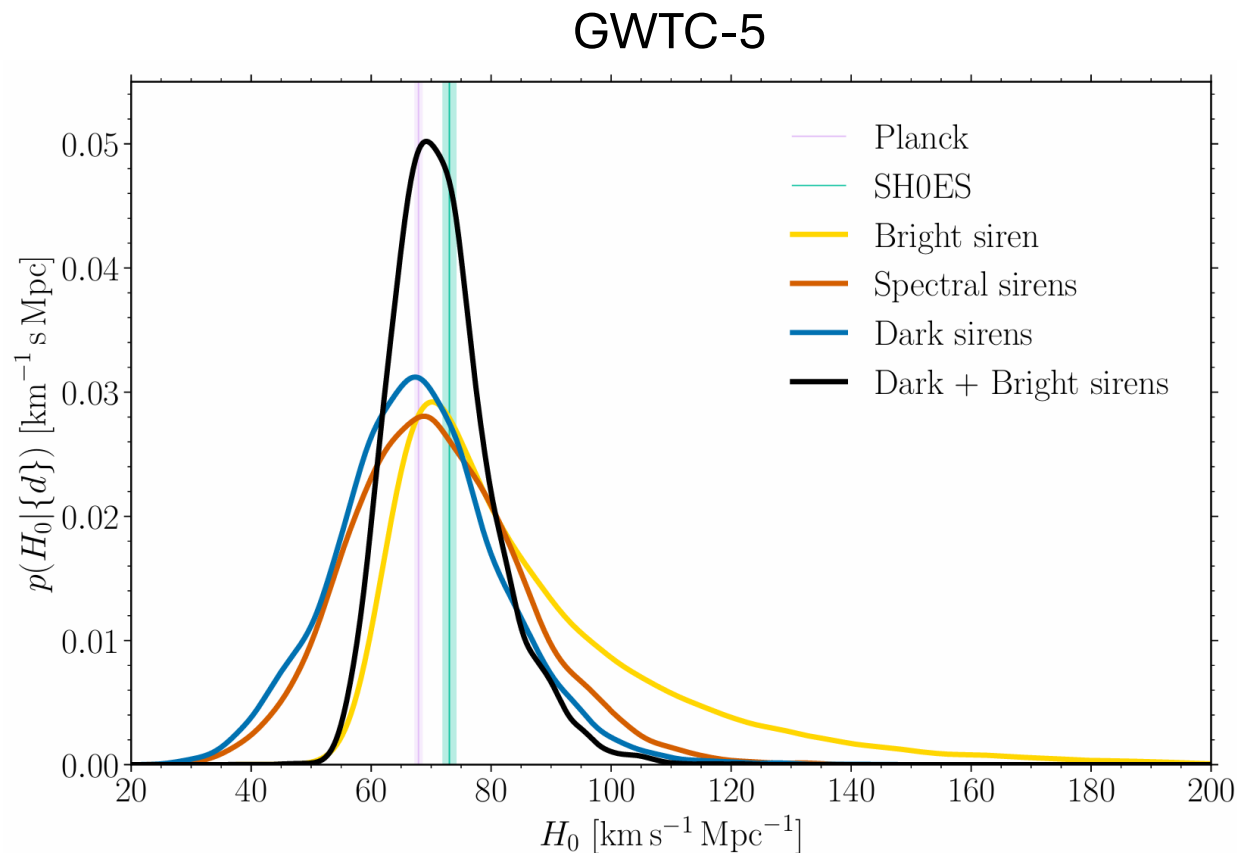
Marginalized posterior for H_0 in Λ CDM background with fixed Ω_{m0}

Dark siren constraint:

$$H_0 = 67.6_{-12.7}^{+13.6} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

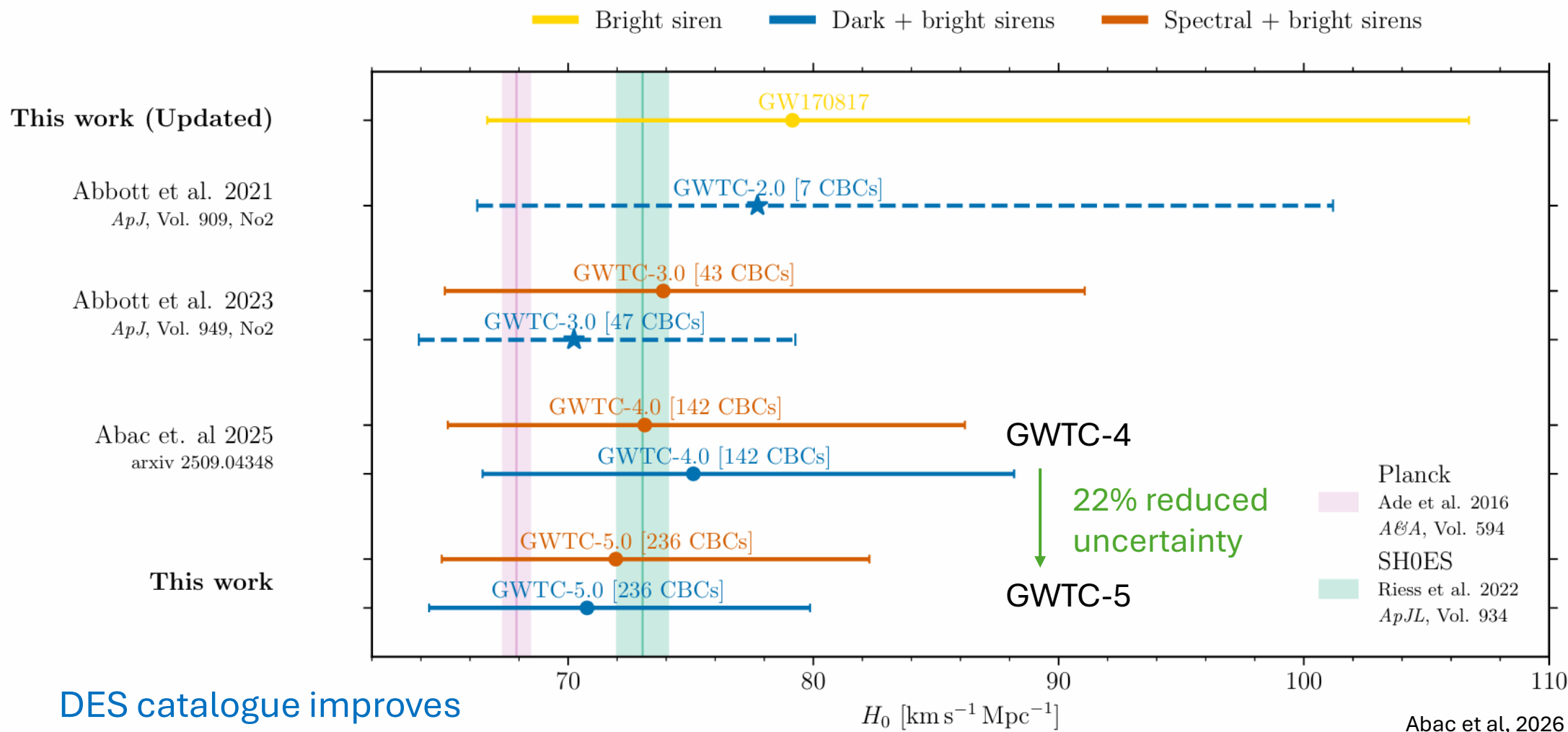
Dark siren + GW170817:

$$H_0 = 71.0_{-7.1}^{+9.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$



Abac et al, 2026

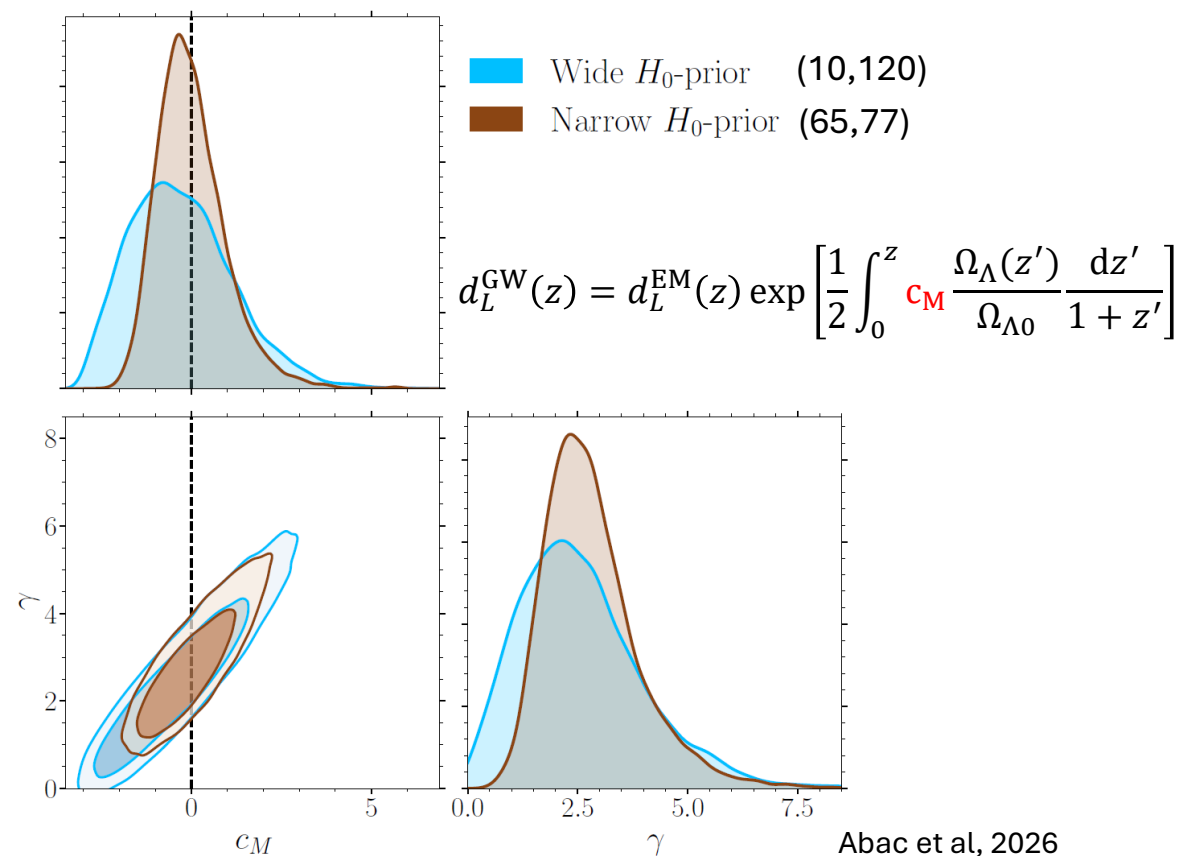
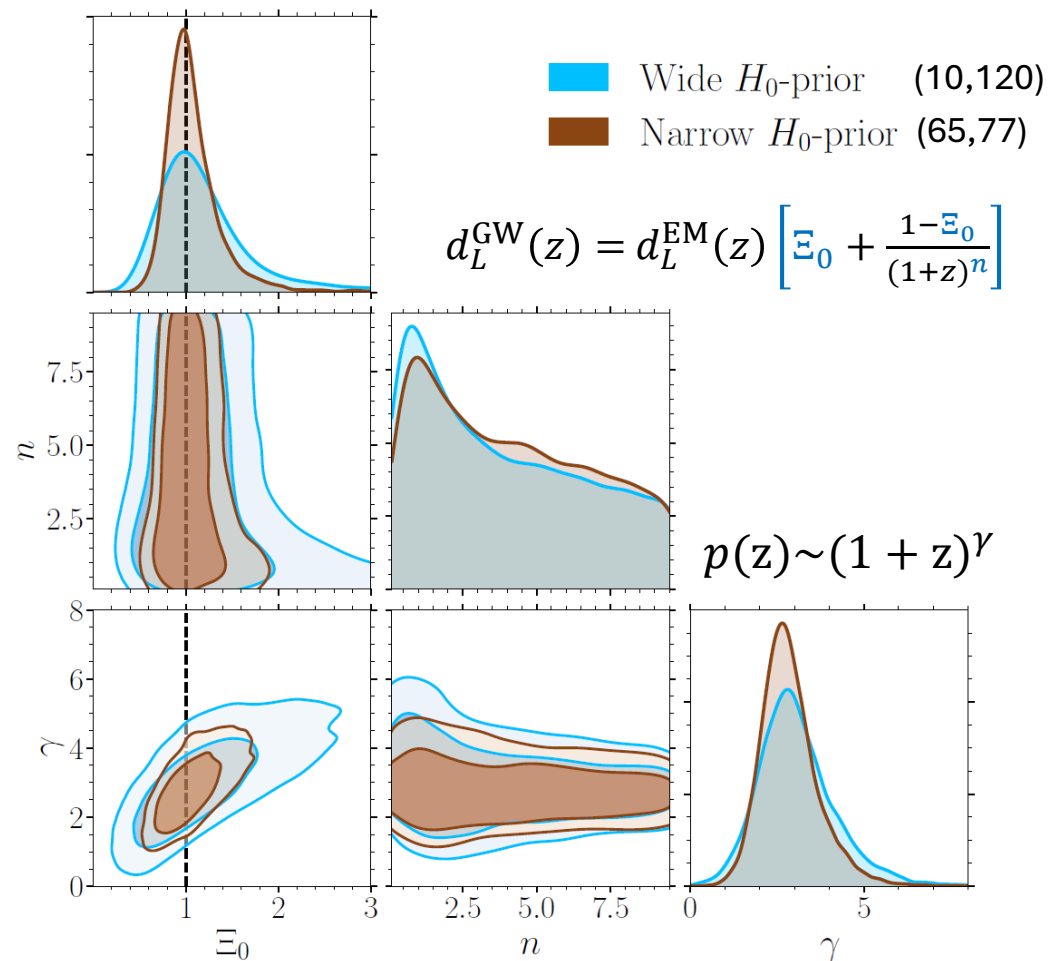
• Results – H_0 in Λ CDM



DES catalogue improves
the constraint by 7.4%.

• Results – modified gravity

- Spectral siren constraint on MG parameters (galaxy catalogue gives little improvements).



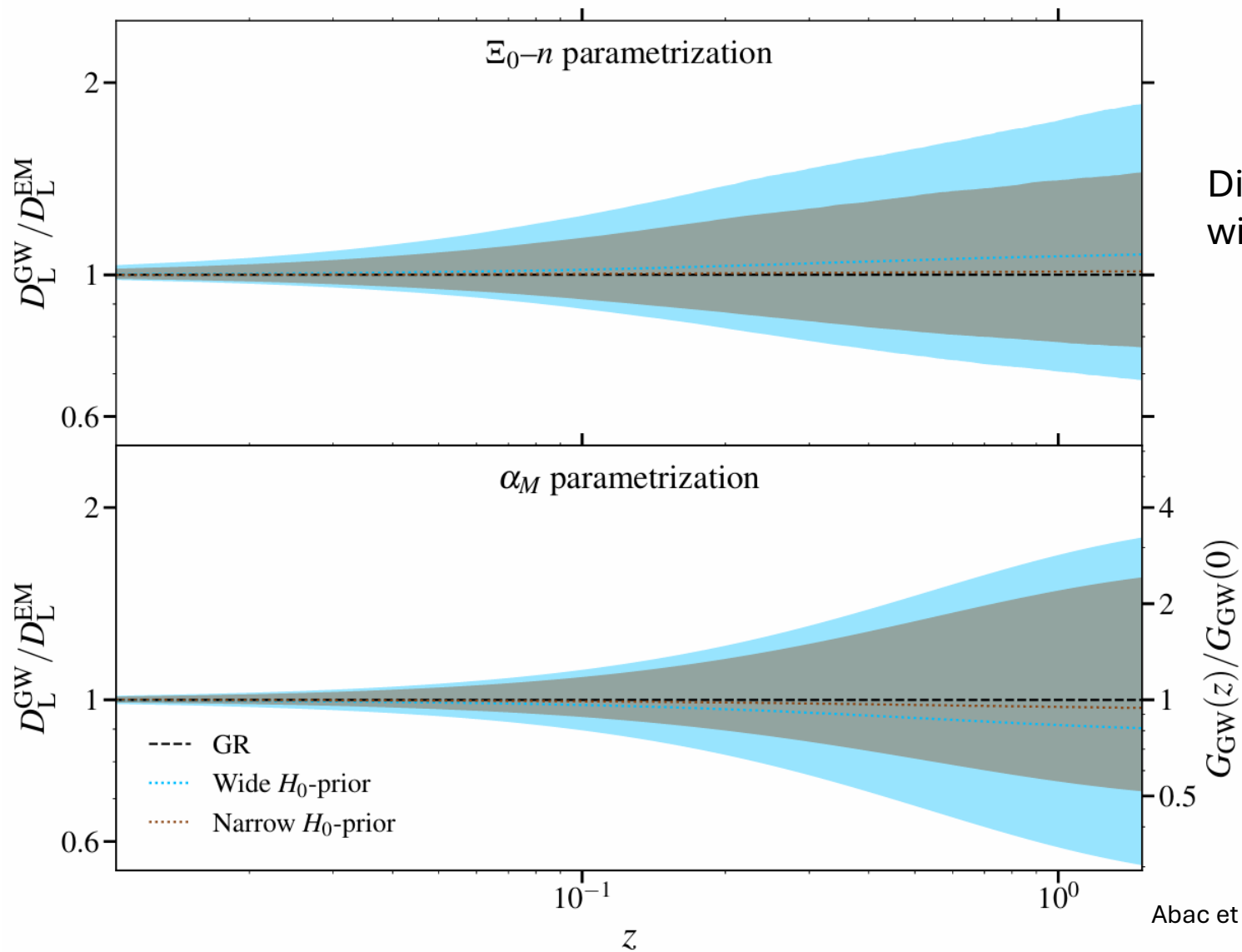
• Results – modified gravity

- Constraints with narrow H_0 prior:

	Ξ_0	c_M
GWTC-4	$1.0^{+0.4}_{-0.2}$	$-0.3^{+1.4}_{-1.0}$
GWTC-5	$1.0^{+0.3}_{-0.2}$	$-0.1^{+1.0}_{-0.8}$

- Constraint not as good as DESI + SNe + CMB: $c_M = 0.44^{+0.12}_{-0.43}$ (fix $\alpha_B = 0$), but it's getting closer.

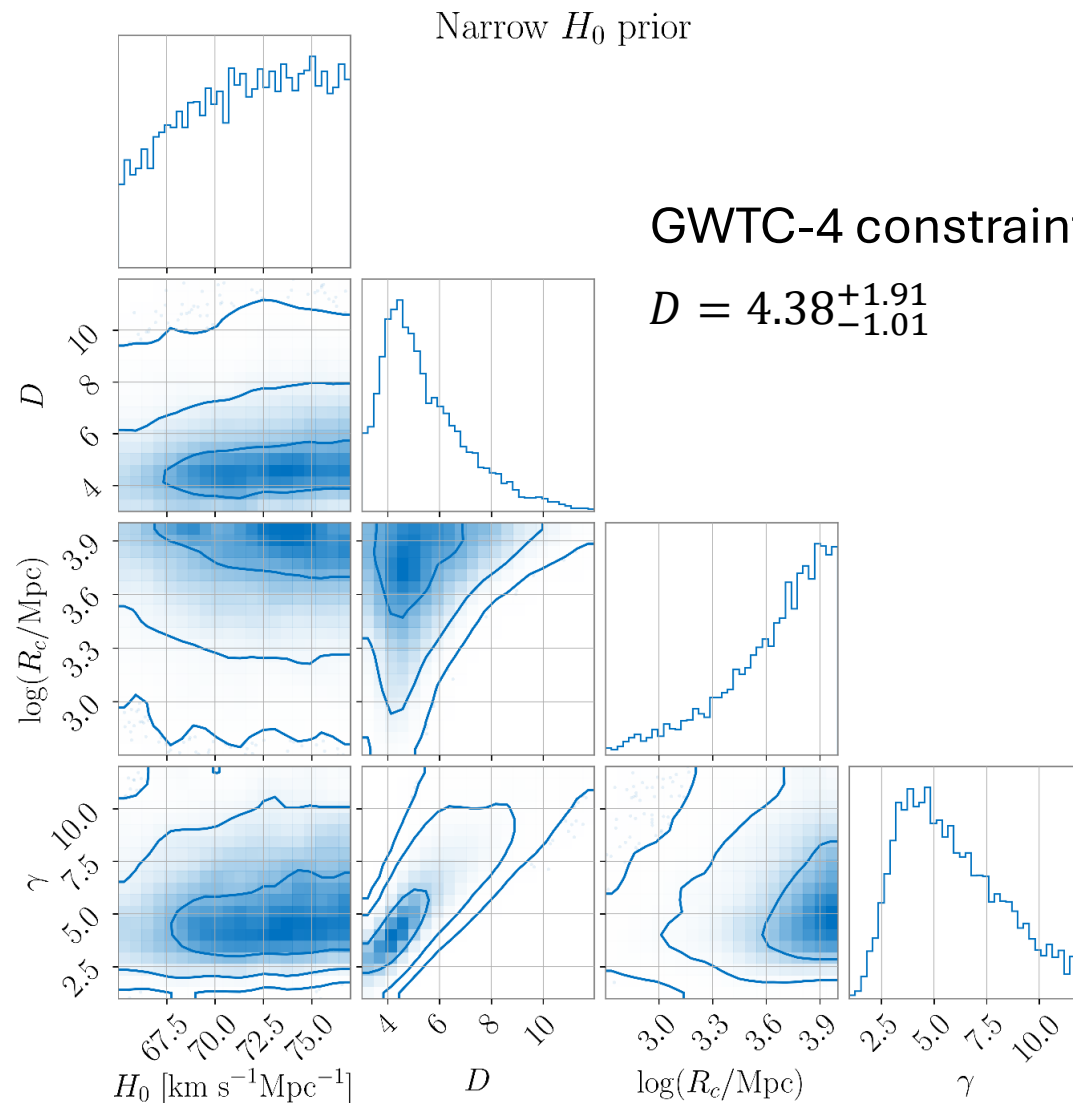
• Results – modified gravity



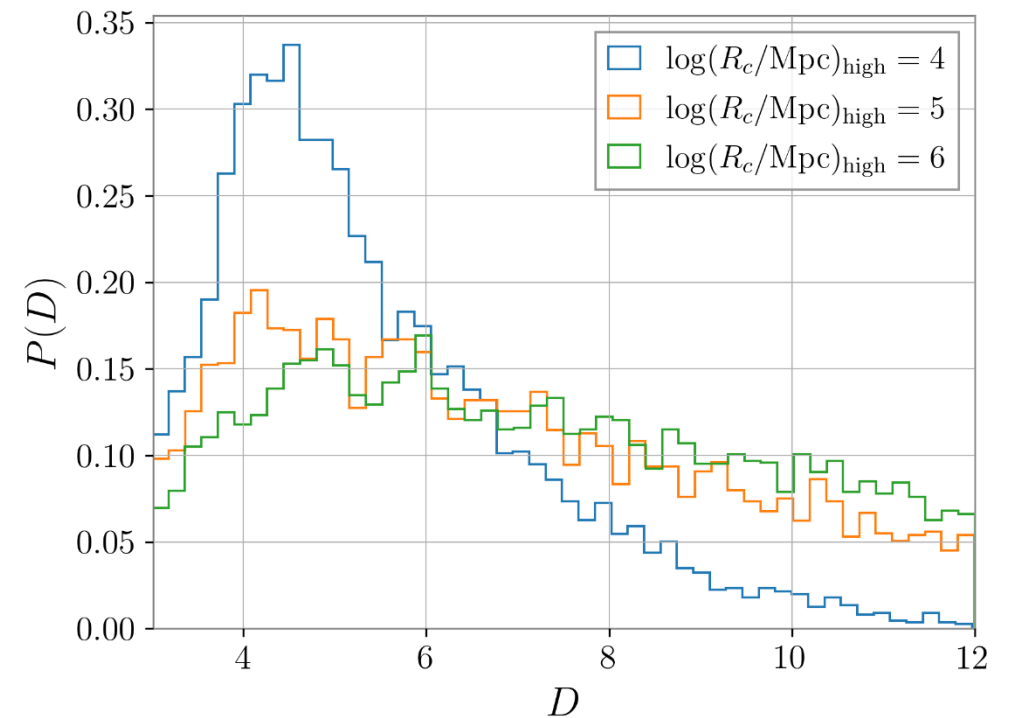
Distance ratio consistent with GR.

Abac et al, 2026

• Results – higher-dimensional theory



- Increasing R_c upper bound weakens the constraint on D .
- Modified gravity effect is suppressed at low redshift for high R_c .



Chen & Zhang, 2026

• Conclusions

- GWTC-5 gives the most stringent GW constraints on the Hubble constant and modified GW propagation to date.
 - Dark + bright siren: $H_0 = 71.0^{+9.0}_{-7.1} \text{ km s}^{-1} \text{ Mpc}^{-1}$.
 - 22% lower uncertainty than GWTC-4.
- Spectral siren component still dominates the constraint.
- GW luminosity distance remains consistent with GR, with constraints closer to EM probes.

Thank you!