A robust cosmic standard ruler from the cross-correlations of galaxies and dark sirens

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Introduction

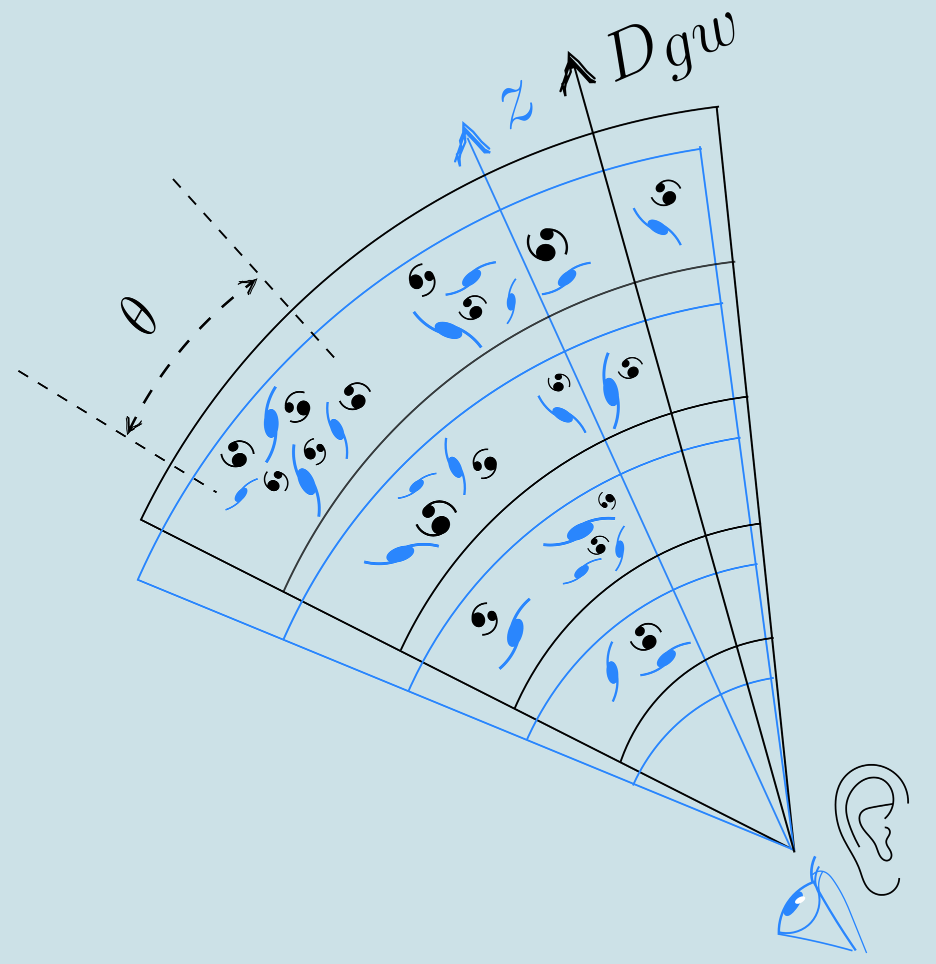

Figure 1: When a redshift shell coincides with a shell in distance, the correlation between the maps is maximal.

- Galaxies and binary black hole (BBH) mergers offer complementary radial information: redshift and luminosity distance, respectively. The relationship between these two quantities depends on the cosmological model, particularly on H_0:

$$D_L(z) \cong (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} \tag{1}$$

- Since these objects trace the same large-scale structure, their angular cross-correlation peaks when the redshift shells match the distance shells. This peak acts as a cosmic ruler, independent of tracer distributions, bias models, or non-linear structure evolution.

- This cross-correlation method avoids assumptions commonly made in other approaches regarding the astrophysical properties of BBHs, such as their merger rates and mass distribution, providing a robust and model-independent tool for constraining cosmological parameters.

Methods

- We used GLASS[1] to **simulate** 1000 full-sky light cones for both galaxies and BBHs, in very thin redshift bins with width $dz = 0.02$, for a given fiducial cosmology: $h = 0.7$, $\Omega_m = 0.3$.

- The galaxies follow a generic distribution for the next generation of spectroscopic surveys, while the distribution of BBH mergers were forecast with GWDALI[2] for a 3rd generation network of GW detectors (ET+2CE).

- To account for catalog incompleteness, all the host galaxies were removed.

- Weak lensing corrections ($D'_L = D_L/\sqrt{\mu}$) and Gaussian errors were added to the positions of each BBH, following the expected error distribution.

- A mask covering 1/3 of the sky was applied to the galaxy maps and the cross-correlation (Figure 2) was computed with NaMaster.

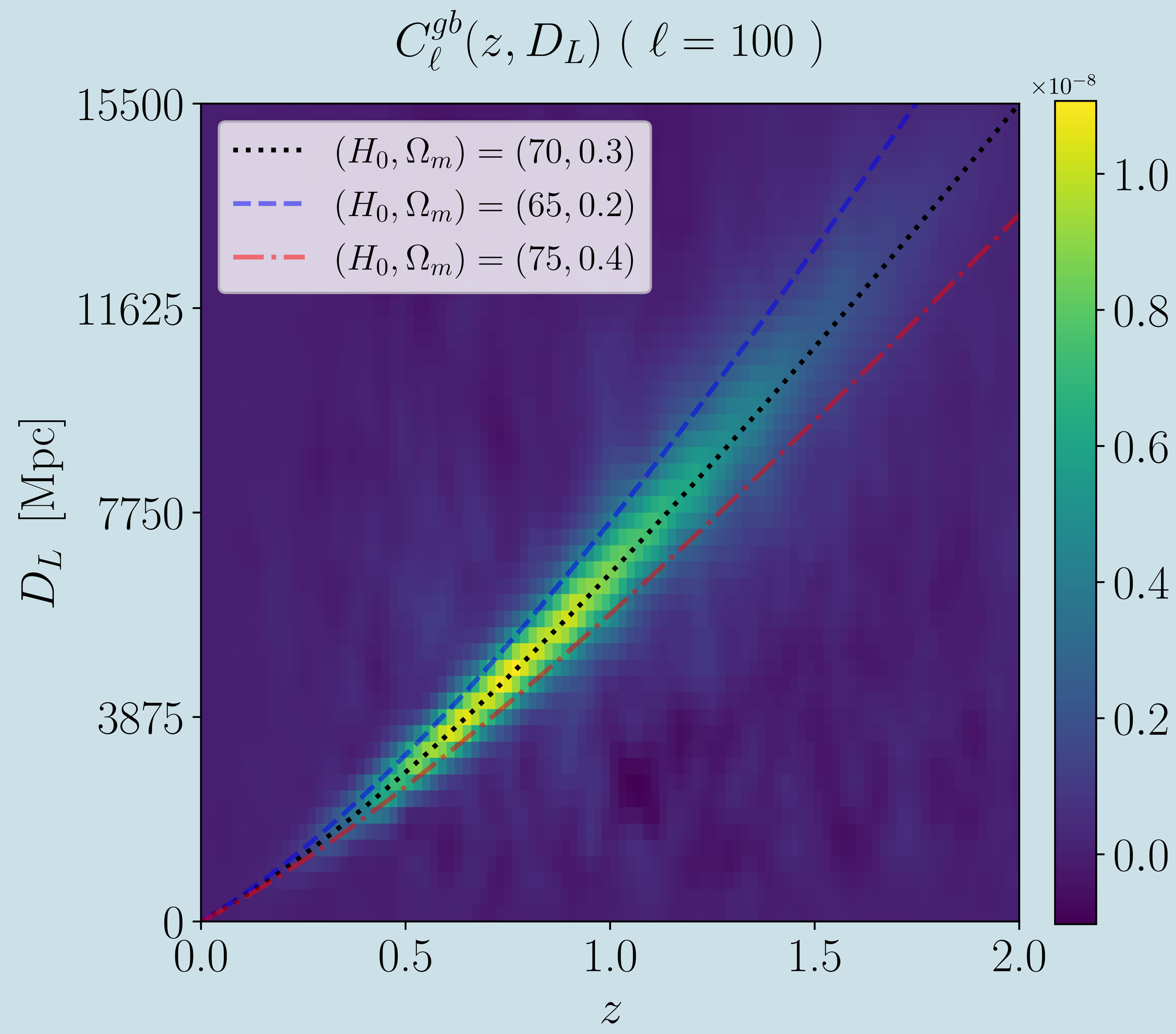

Figure 2: Average cross-correlation matrix of the 1000 simulated light cones.

Results

- The likelihood for some set of parameters θ^μ is given by

$$-2\log\mathscr{L} = \chi^2(\theta^\mu) = \sum_{i,j,i',j'}\sum_{\ell,\ell'} \Delta C_\ell^{ij}\, Cov^{-1}[C_\ell^{ij}, C_{\ell'}^{i'j'}]\,\Delta C_{\ell'}^{i'j'} \tag{2}$$

where

$$\Delta C_\ell^{ij} \equiv C_\ell^{ij,obs} - C_\ell^{ij}(\theta^\mu) \tag{3}$$

- The covariance matrix for our observable has $\approx \ell_{max} \times [(N_z+N_d)^2/2]^2$ degrees of freedom. Therefore, a numerical sample covariance with thin redshift bins is unfeasible, and we use the Gaussian approximation to compute its inverse[3]:

$$Cov^{-1}[C_\ell^{ij}, C_\ell^{i'j'}] = \frac{2\ell+1}{4}(2-\delta_{ij})(2-\delta_{i'j'})\left\{[\Gamma_\ell^{ii'}]^{-1}[\Gamma_\ell^{jj'}]^{-1} + [\Gamma_\ell^{ij'}]^{-1}[\Gamma_\ell^{i'j}]^{-1}\right\} \tag{4}$$

Network	H_0 $[km\,s^{-1}Mpc^{-1}]$	Ω_m
LVK O5	$69.3^{+4.0}_{-4.4}$	$0.38^{+0.19}_{-0.15}$
LVK+ET	$69.99^{+0.52}_{-0.57}$	$0.300^{+0.012}_{-0.010}$
ET+2CE	$70.01^{+0.34}_{-0.26}$	$0.3000^{+0.0068}_{-0.0064}$

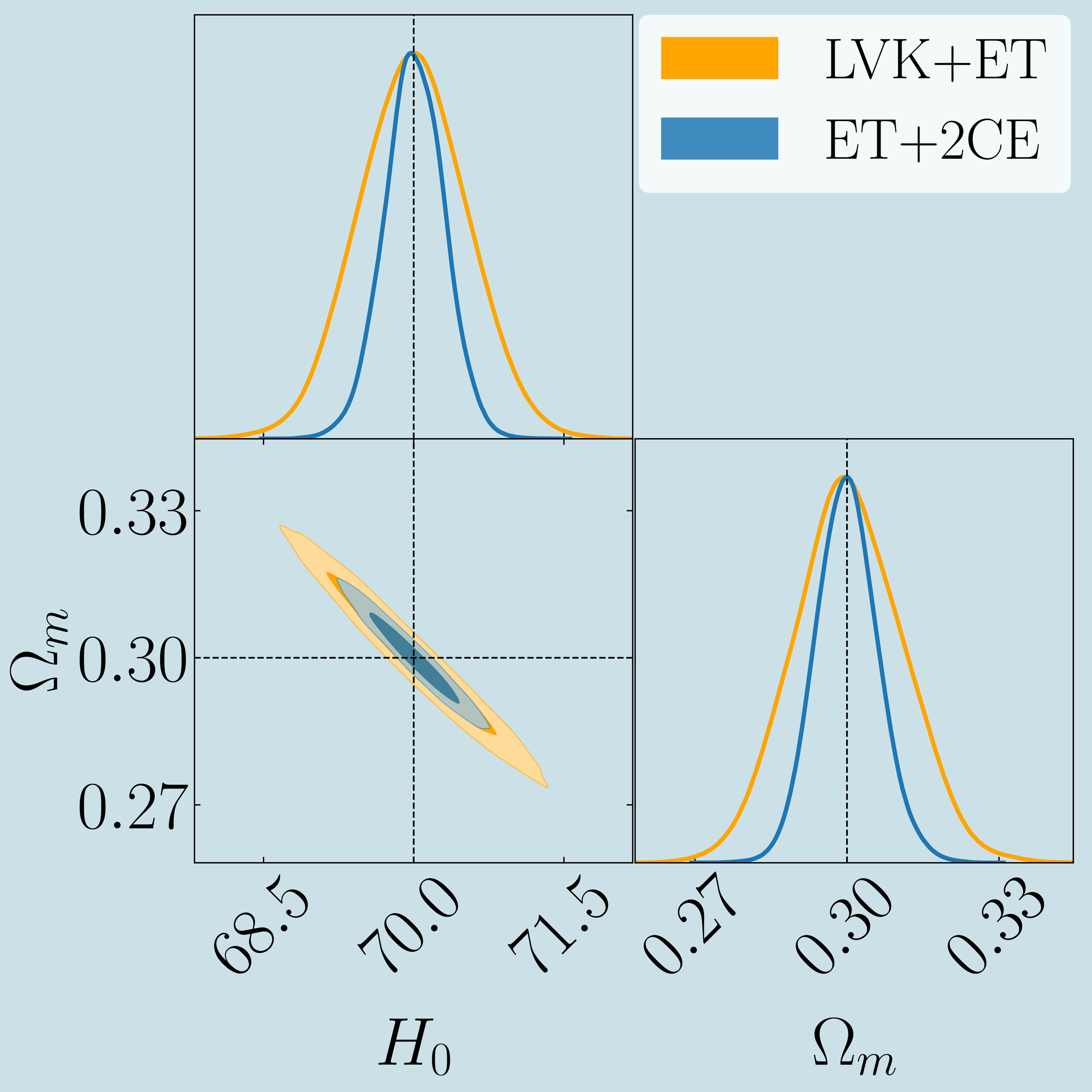

Figure 3: Posteriors on H_0 and Ω_m for the ET+2CE and LVK+ET networks.

References:
[1] N. Tessore et al. "GLASS: Generator for Large Scale Structure". arXiv: 2302.01942
[2] J. Mendonça and R. Sturani. "GWDALI: A Fisher-matrix based software for gravitational wave parameter estimation beyond Gaussian approximation". arXiv: 2307.10154
[3] R. Abramo et al. "Fisher matrix for the angular power spectrum of multi-tracer galaxy surveys". arXiv: 2204.05057

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