

Dark sirens

We are currently witnessing exponential growth in gravitational wave (W) detection, thanks to rapidly advancing technology. The most common resolved signals come from compact binary coalescence, whose electromagnetic counterpart is not detected: **dark sirens**. A comprehensive catalogue of these objects is expected to be available in the near future and can be used in cosmology as a **tracer of matter overdensities**. Together with the **galaxy clustering (G)** or CMB surveys, they represent two independent and complementary measurements of distance, **luminosity distance D_L** and **redshift z** , of the same fluctuations. Models and parameters can be constrained by **cross-correlating** these two observable: e.g. the Hubble constant H_0 ,

$$D_L = a(t_0)(1+z) \int_0^z \frac{cdz'}{a(t_0)H(z')}$$

This project presents the improvement in **inferring cosmological parameters** with a forecasted dark sirens catalogue and shows the strength of cross-correlation.

Gravitational waves data

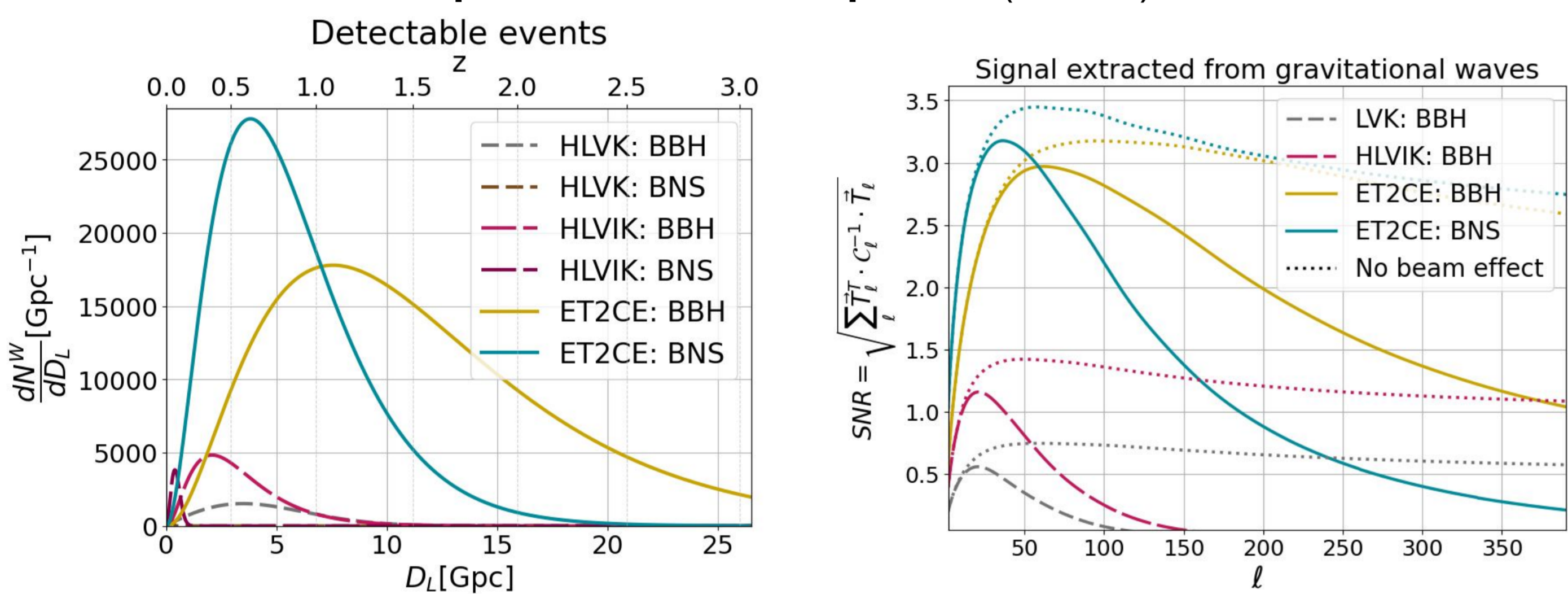
Distribution of detectable events dN/dD_L

Forecasted distribution of the detections over **10 years** for different sources:

- ◆ **binary black holes (BBH)**;
- ◆ **binary neutron stars (BNS)**;

based on the sensitivities of 3 different detector configurations:

- ◆ **LIGO** (both Hanford and Livingston), **Virgo** and **Kagra** (HLVK);
- ◆ HLVK and **LIGO India** (HLVIK);
- ◆ **Einstein Telescope** and **2 Cosmic Explorers** (ET2CE).



Cross-Correlation

→ C_ℓ -based likelihood

$$-2\ln\mathcal{L}(\vec{D}|\vec{\theta}) = \sum_{\ell=\ell_{\min}}^{\ell_{\max}} (\vec{D}_\ell - \vec{T}_\ell(\vec{\theta}))^T C_\ell^{-1} (\vec{D}_\ell - \vec{T}_\ell(\vec{\theta}))$$

- ◆ θ : variable cosmological parameters;
- ◆ D : data from fiducial file (mock data);
- ◆ T : theory data from inferred cosmological parameters.

→ Covariance matrix

- ◆ **GG**: Galaxy clustering auto-correlation;
- ◆ **WW**: Gravitational waves auto-correlation;
- ◆ **XC**: Cross-correlation only;
- ◆ **GG WW XC**: Full matrix;

$$C_\ell = \begin{pmatrix} (\overrightarrow{GG}_\ell, \overrightarrow{GG}_\ell) & (\overrightarrow{GG}_\ell, \overrightarrow{WG}_\ell) & (\overrightarrow{GG}_\ell, \overrightarrow{WW}_\ell) \\ (\overrightarrow{WG}_\ell, \overrightarrow{GG}_\ell) & (\overrightarrow{WG}_\ell, \overrightarrow{WG}_\ell) & (\overrightarrow{WG}_\ell, \overrightarrow{WW}_\ell) \\ (\overrightarrow{WW}_\ell, \overrightarrow{GG}_\ell) & (\overrightarrow{WW}_\ell, \overrightarrow{WG}_\ell) & (\overrightarrow{WW}_\ell, \overrightarrow{WW}_\ell) \end{pmatrix}$$

◆ Each covariance matrix block component is computed as follows:

$$\text{Cov} [C^{A_i B_j}(\ell), C^{C_k D_n}(\ell')] = \frac{\delta_{\ell\ell'}}{(2\ell+1)f_{\text{fov}}\Delta\ell} (C^{A_i C_k}(\ell)C^{B_j D_n}(\ell) + C^{A_i D_n}(\ell)C^{B_j C_k}(\ell))$$

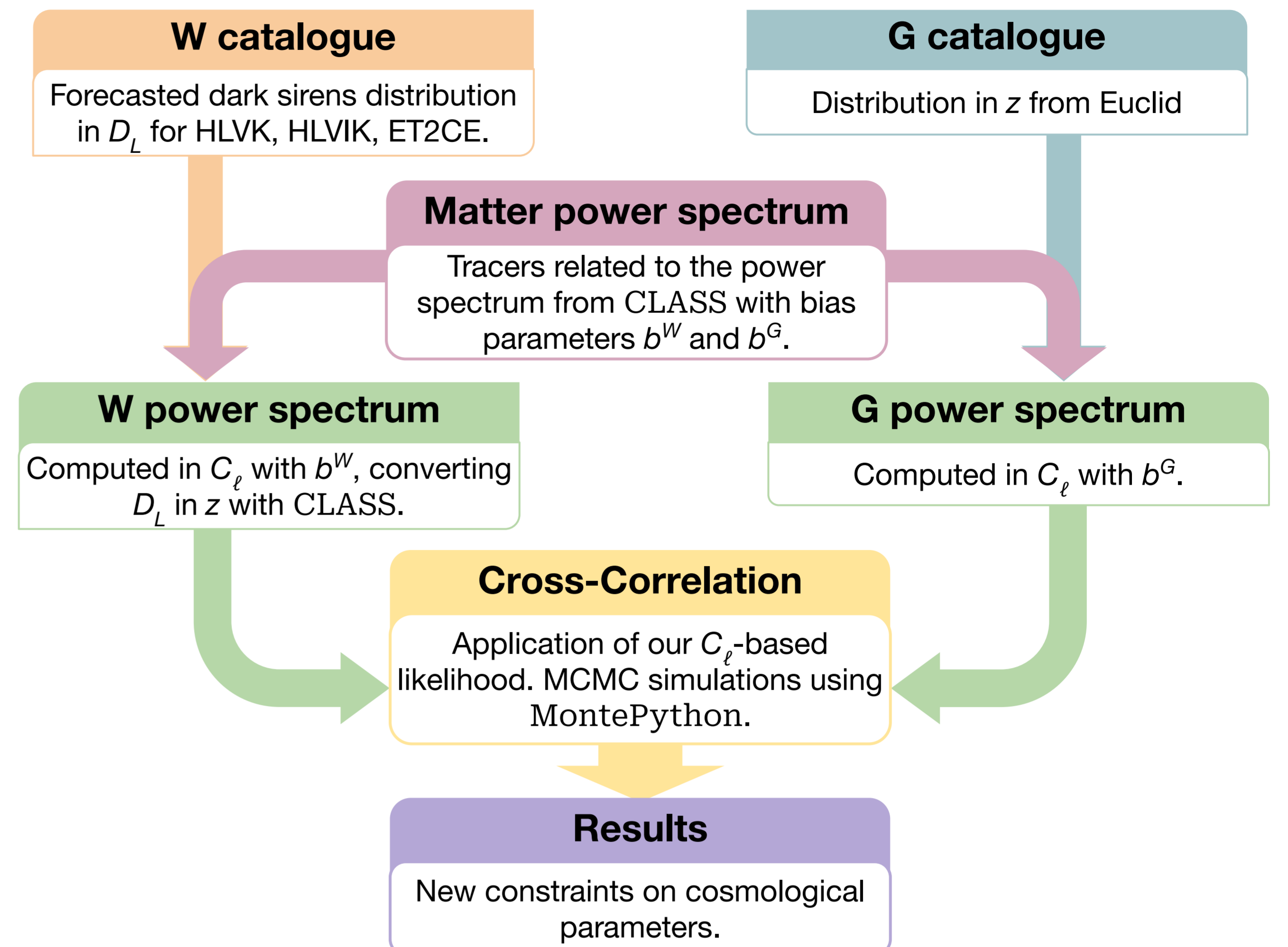
→ Run Markov Chain Monte Carlo (MCMC)

The cosmology and its parameters are inferred using CLASS and by running the simulations with MontePython.

Conclusions

- New decomposable model-independent, full likelihood analysis to infer cosmological parameters and estimate the potential of cross-correlation;
- Only ET2CE increased sensitivity will allow us to detect a sufficiently large sample of dark sirens to take advantage of the cross-correlation with galaxy clustering;
- ◆ H_0 can be constrained to better than 1% at 1σ ;
- Additional cross-correlation analysis, e.g. with CMB, can further improve the constraints on other parameters or cosmological models.

Correlation with Galaxy Clustering



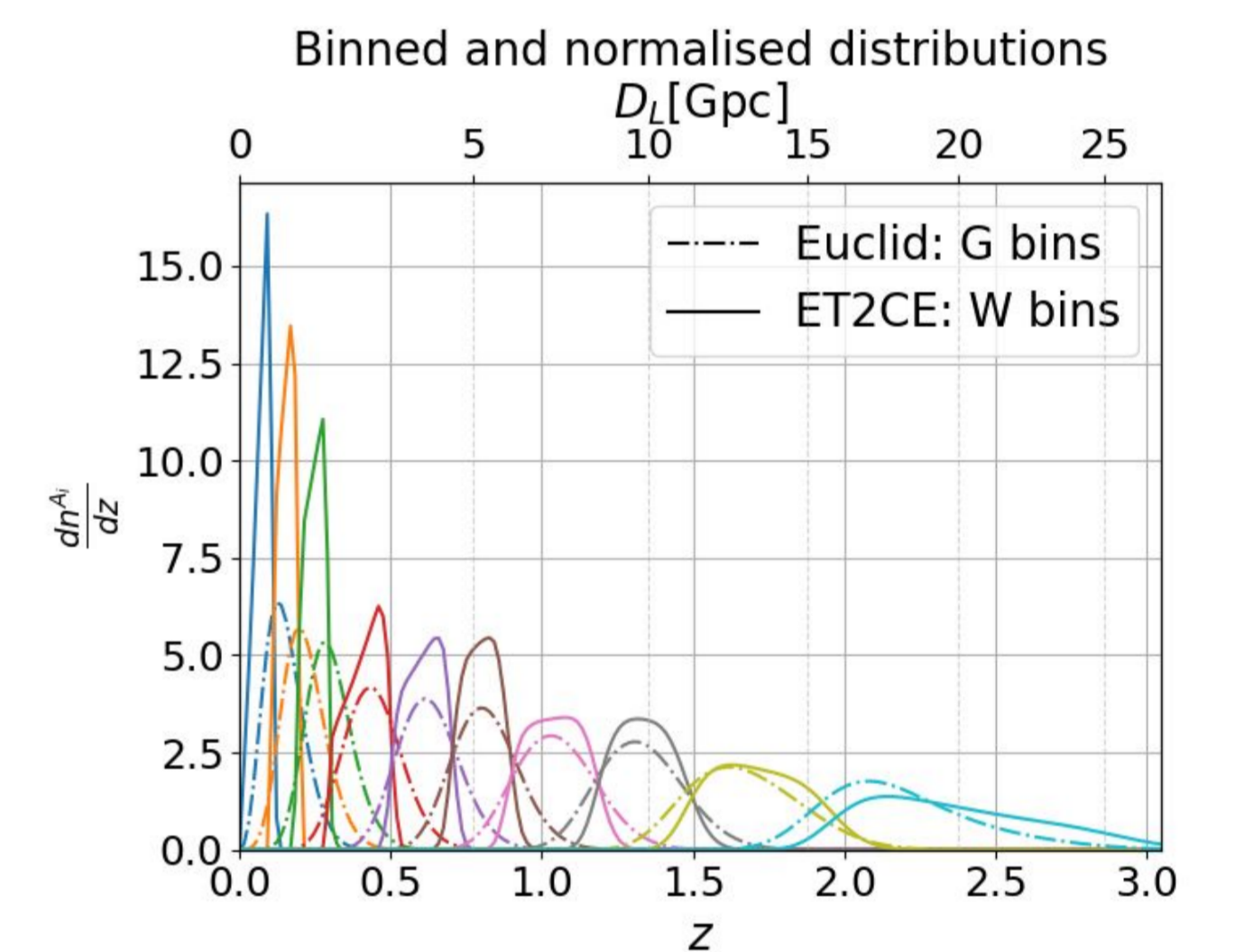
Power spectra C_ℓ

Angular power spectrum

C_ℓ between sources A and B (either W or G) are computed using Limber approximation and various redshift bins i and j , including the distance error,

$$C^{A_i B_j}(\ell) = \int_{z_{\min}}^{z_{\max}} dz \frac{W^{A_i}(z)W^{B_j}(z)}{H(z)r^2(z)} \times P_{\delta\delta} \left[k = \frac{\ell + 1/2}{r(z)}, z \right] + N^{A_i B_j}(\ell)$$

- ◆ $W^A(z)$ is the window function,
- ◆ $b^A(z)$ is the bias function between the matter power spectrum $P_{\delta\delta}$ and source A ,
- ◆ $N^{AB}(\ell)$ is the noise, which includes angular resolution and shot noise;
- ◆ dN^W/dD_L is converted to dN^W/dz with CLASS.



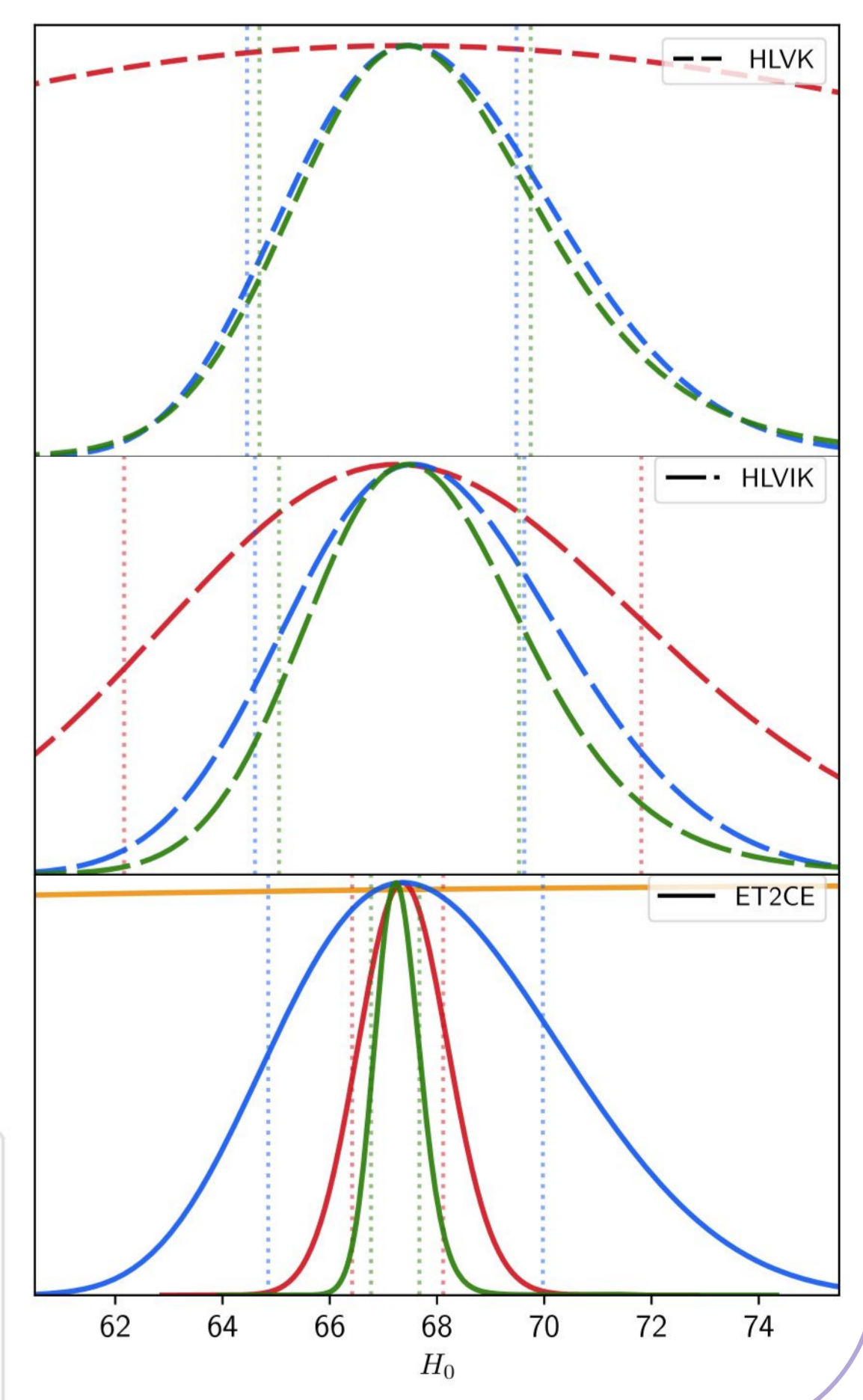
Results

→ Contribution breakdown of H_0

- ◆ **HLVK** and **HLVIK** - top and middle plots: **XC** components do not improve the **full matrix** results, which are driven by **GG**;
- ◆ **ET2CE** - bottom plot: The **full matrix** results are mainly driven by the **XC** component. Results are significantly improved compared to **GG** only. **WW** do not have any constraining power.

→ Dark sirens samples

- ◆ **BBH** only are considered for **HLVK** and **HLVIK**, the forecasted detections are too scarce improve any constraint with cross-correlation.
- ◆ Both **BBH** and **BNS** are considered for **ET2CE**. **BBH** sample has slightly more constraining power leading the combined results.



References

1. **Inferring cosmological parameters from galaxy and dark sirens cross-correlation [in preparation]**
Giona Sala¹, Alessandro Cuoco^{2,3}, Julien Lesgourgues¹, Kostantinos-Rafail Revis⁴, Lorenzo Valbusa Dall'Armi⁵, Santiago Casas¹.
2. **New information from cross-correlating gravitational waves and CMB [in progress]**
Giona Sala¹, Andrea Cozzumbo⁶, Julien Lesgourgues¹, Riccardo Murcia⁷.