Institute for Theoretical Particle Physics and Cosmology
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Inferring cosmological parameters from galaxy and dark sirens cross-correlation

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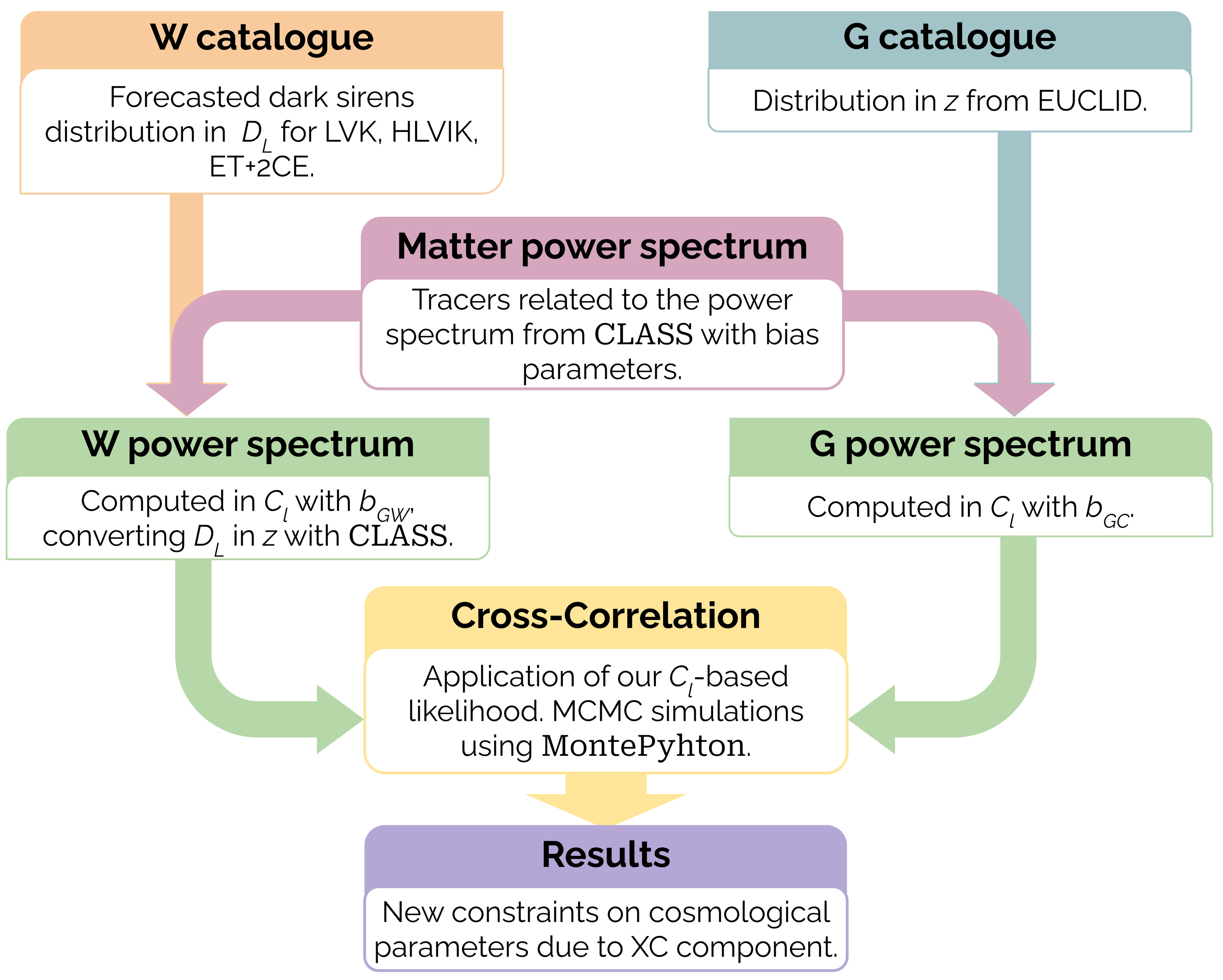
Dark sirens

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) survey, 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** (XC) these two observable: e.g. the Hubble constant

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

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



Cross-Correlation

→ C_l-based likelihood

$$-2\ln\mathcal{L}(\vec{D}|\vec{\theta}) = \left(\vec{D}-\vec{T}(\vec{\theta})\right)^T C^{-1}\left(\vec{D}-\vec{T}(\vec{\theta})\right)$$

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

→ Covariance matrix

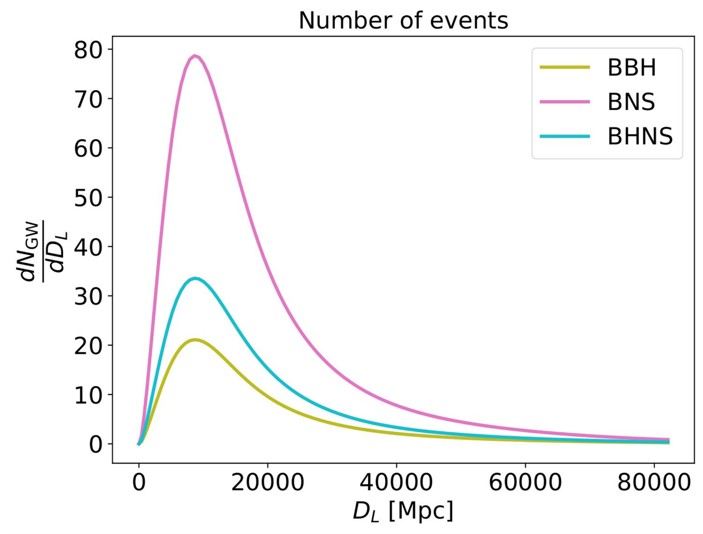
$$C(l=l') = \begin{bmatrix} (GG,GG) & (GG,GW) & (GG,WG) & (GG,WW) \\ (GW,GG) & (GW,GW) & (GW,WG) & (GW,WW) \\ (WG,GG) & (WG,GW) & (WG,WG) & (WG,WW) \\ (WW,GG) & (WW,GW) & (WW,WG) & (WW,WW) \end{bmatrix}$$

- GG: **Galaxy clustering auto-correlation**
- WW: **Gravitational waves auto-correlation**
- XC: **Cross-correlation only**
- GG WW XC: **Full matrix**
- Each block is computed as follows:

$$(AB,CD)_{ij,kn}(l,l') = \frac{\delta_{ll'}}{(2l+1)f_{\rm sky}\Delta l} \times \left(C^{AC}_{ik}(l)C^{BD}_{jn}(l') + C^{AC}_{in}(l)C^{BD}_{jk}(l')\right)$$

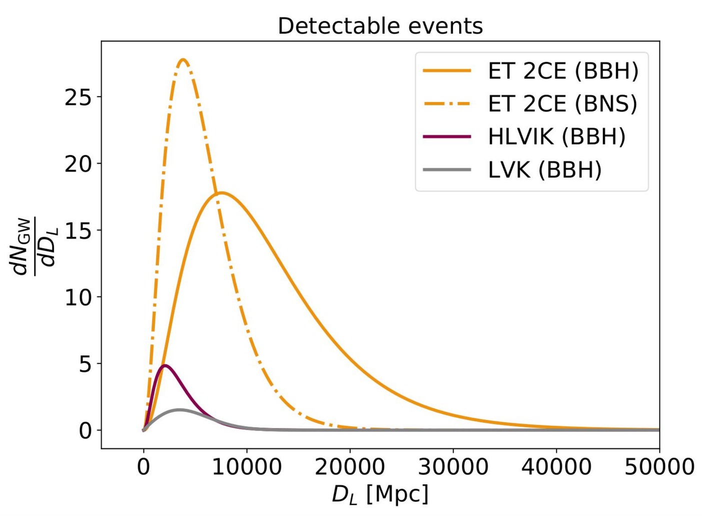
→ Run Markov Chain Monte Carlo (MCMC)
The cosmology and its parameters are inferred using CLASS and by running the simulations with MontePython.

Gravitational waves data



→ Total distribution of GW events
Predicted total number of mergers from 3 different sources:
- **binary black holes** (BBH)
- **binary neutron stars** (BNS)
- black hole and neutron star binary (BHNS).

→ Distribution of detectable events dN/dD_L
Forecasted distribution of the detections for relevant binaries, over **10 years** of observations, based on the sensitivities of 3 different detector configurations:
- **Ligo** (both Hanford and Livingston), **Virgo** and **Kagra** (LVK),
- LVK and **Ligo India** (HLVIK)
- **Einstein Telescope** (ET) and **2 Cosmic Explorers** (CE).



Power spectra C_l

→ Angular power spectrum
C_l are computed using Limber approximation between sources A and B (either GW or GC) and various redshift bins i and j.

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

- $W^A_i(z)$ is the window function.

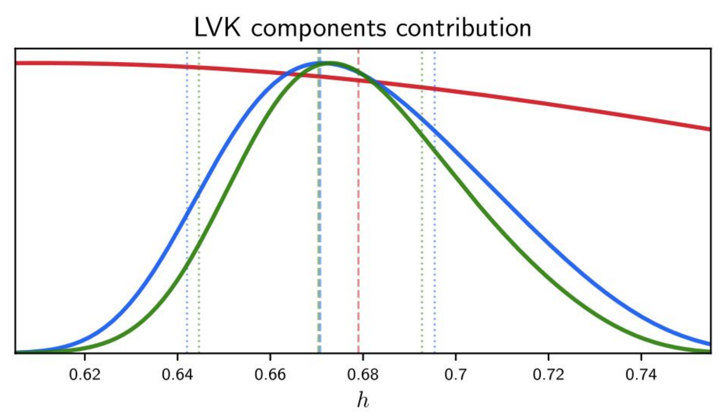
$$W^A_i(z) = \frac{dN^A_i}{dz}\frac{H(z)}{c}b^A(z)$$

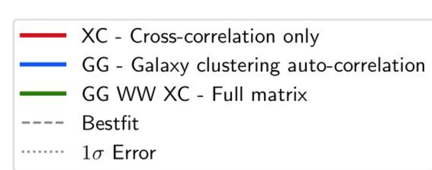
- $b^A(z)$ is the bias function that correlates the matter power spectrum $P_{\delta\delta}$ with the source A distribution.

$$b^W(z) = a^W_1(1+z)^{a^W_2} \qquad b^G(z) = a^G_1\sqrt{1+z}$$

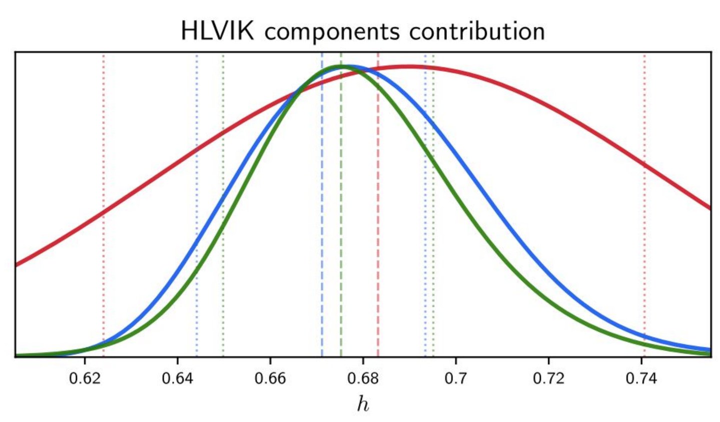
- For GW sources, dN/dD_L is converted to dN/dz with CLASS.

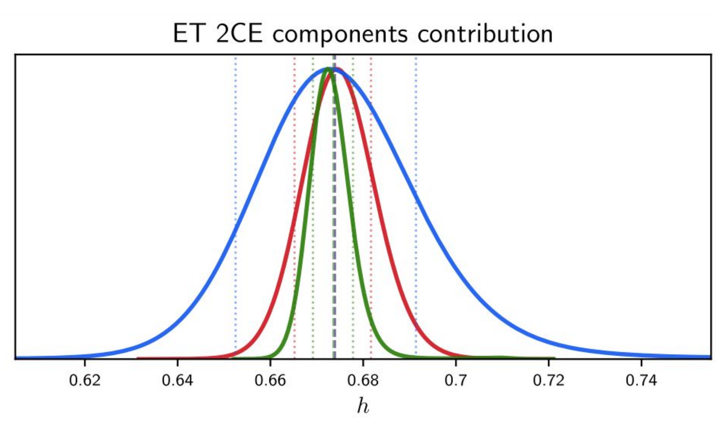
Results

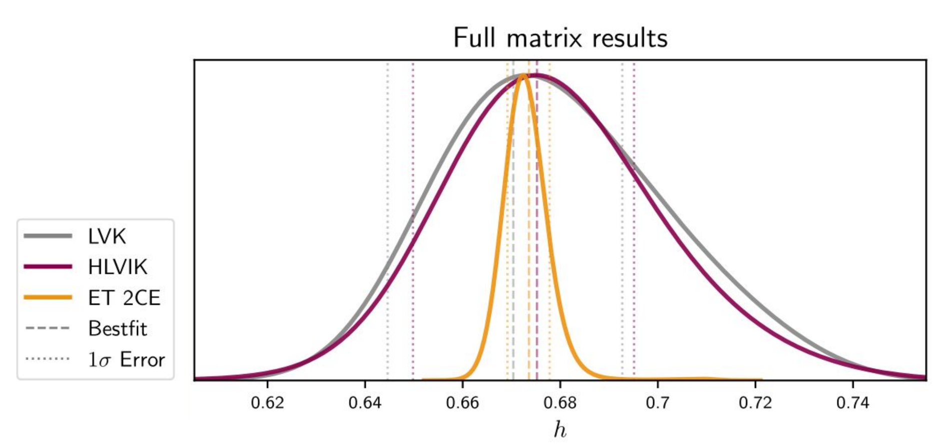




→ Contribution breakdown of h - 3 left plots
- **LVK** and **HLVIK** - top and middle plots: XC components do not improve the full matrix results, which are driven by GG.
- **ET 2CE** - bottom plot: The full matrix results are mainly driven by the XC component. Results are significantly improved compared to GG only.







→ Full matrix constraints on h - right plot
- **LVK** and **HLVIK** find the same constraints, driven by galaxy clustering.
- **ET 2CE** set a much stricter constraint on h.
  - The full matrix for ET 2CE on the left plot matches with ET 2CE results on the right.

Conclusions

→ New model-independent, full likelihood analysis to infer cosmological parameters;
→ Cross-correlation between galaxy clustering and gravitational waves from dark sirens has the potential to better constrain various;
- E.g. h can be constrained to better than 1%;

→ LVK and HLVIK do not have the capabilities to detect a sufficiently large sample of dark sirens;
→ ET 2CE increased sensitivity allows us to take advantage of cross-correlation potential by measuring many more gravitational wave events;
- BNS detection will be numerous and will play a relevant role.

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