Korea-Italy Workshop on Multi-messenger Astrophysics and Cosmology

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Cosmology beyond Standard Sirens: Cross-correlation of Gravitational Waves and Neutral Hydrogen Intensity Mapping

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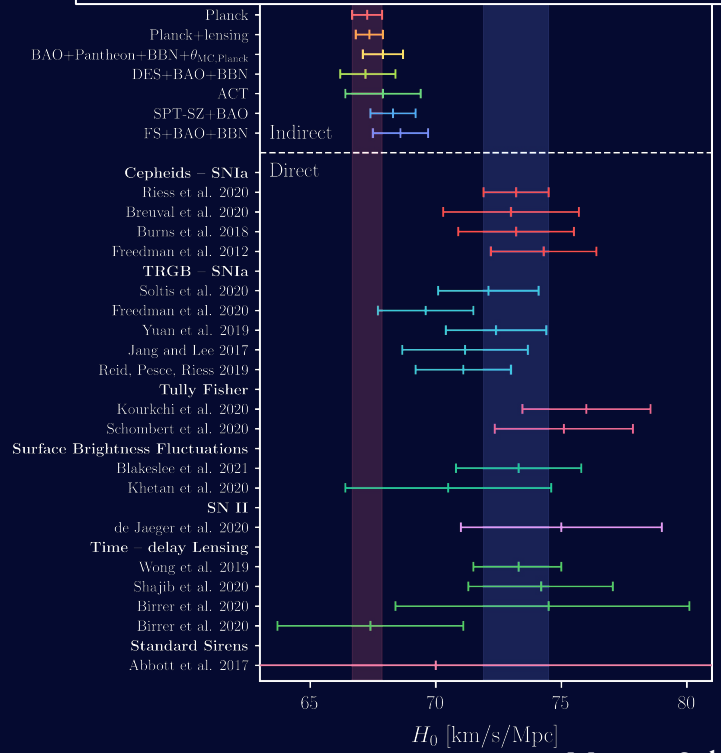
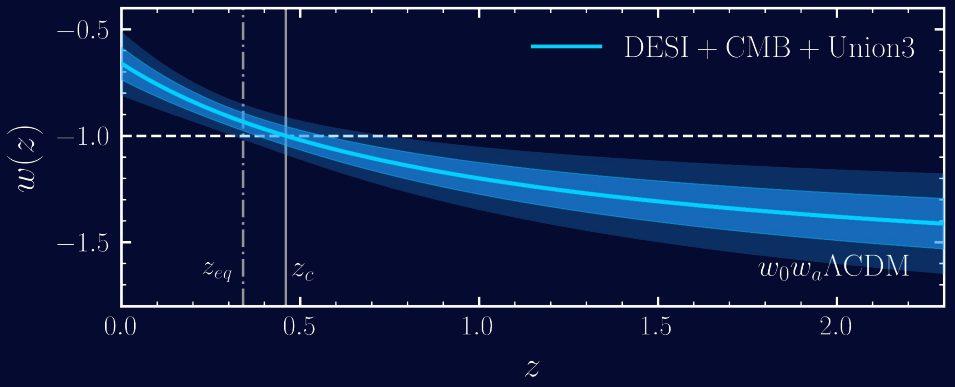
Current Cosmological Framework

Hubble (cosmic calibration) Tension



Hints on Dynamical Dark Energy by DESI



Standard Sirens

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

Bright Sirens	Dark Sirens	Spectral Sirens
The sources of GW events emit also some electromagnetic signal	GWs event are associated to a potential host galaxy from which z is inferred	Features in spectrum of the GWs population pinpoint the source z
⇨ Multi-messenger approach	⇨ Multi-tracer approach	⇨ Statistical approach

Using cross-correlation as independent approach

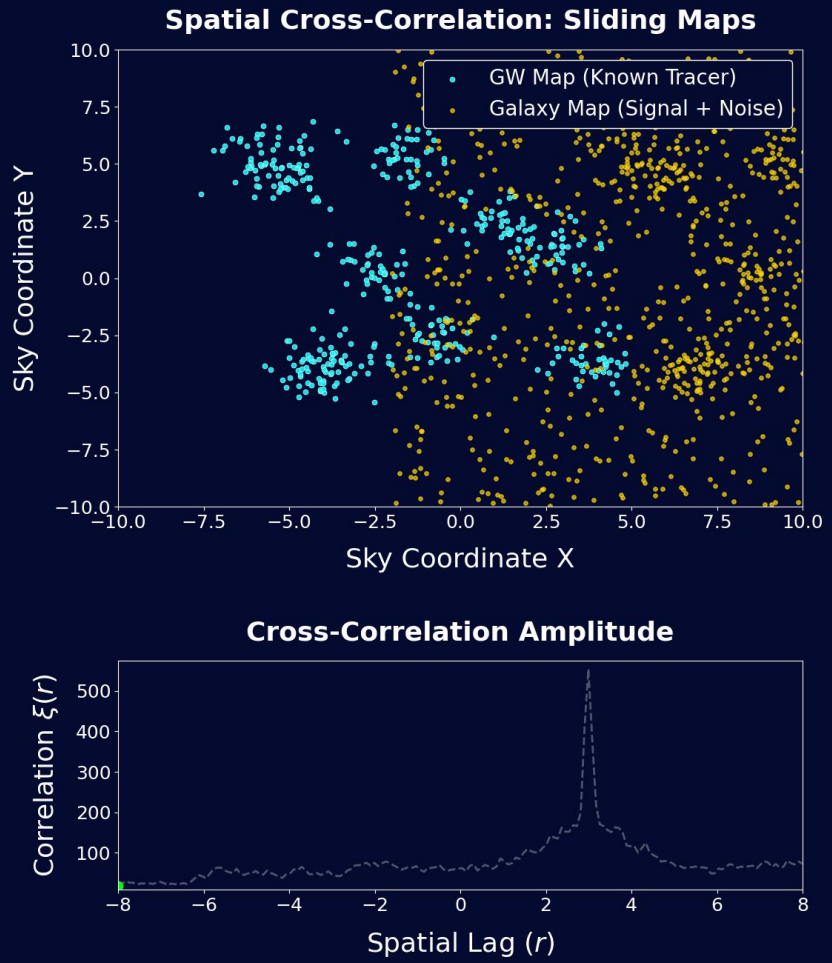


Standard Approach: GW x Galaxy Surveys

→ **Fundamental assumption:**
Both GW sources and galaxy population follow the same underlying DM distribution

- **Galaxy Surveys:**
  Clustering statistics in redshift space;
- **GWs:**
  Clustering statistics in luminosity distance space

} Cross-correlation in a multi-tracer perspective to unlock cosmological information

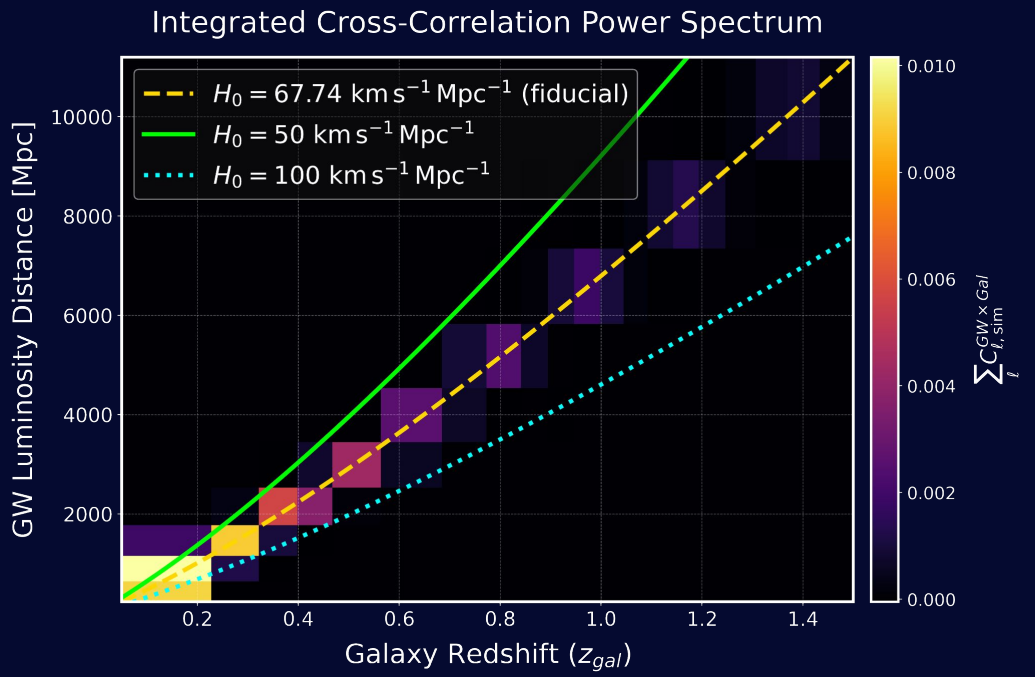


Cross-correlation automatically cancels out tracer-specific systematics

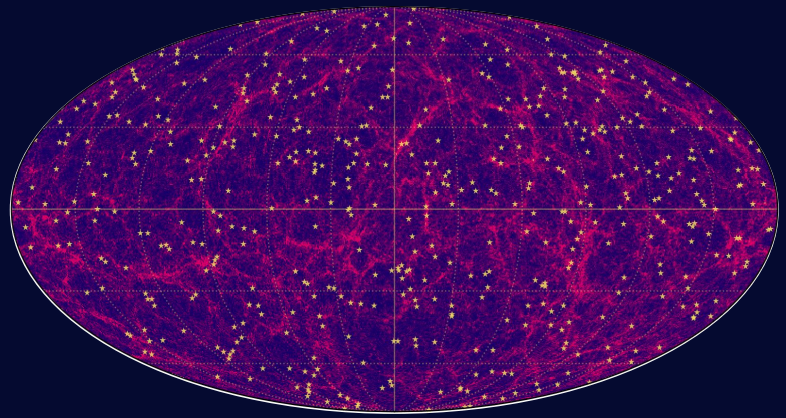
Cross-Correlation: Key point of the approach

Access to properties of **two different** tracers of the **same underlying** density field in **two different spaces**

Combination of data requires the conversion between z and d_L: Cross-correlation is maximised when the **correct distance-redshift relation is adopted**

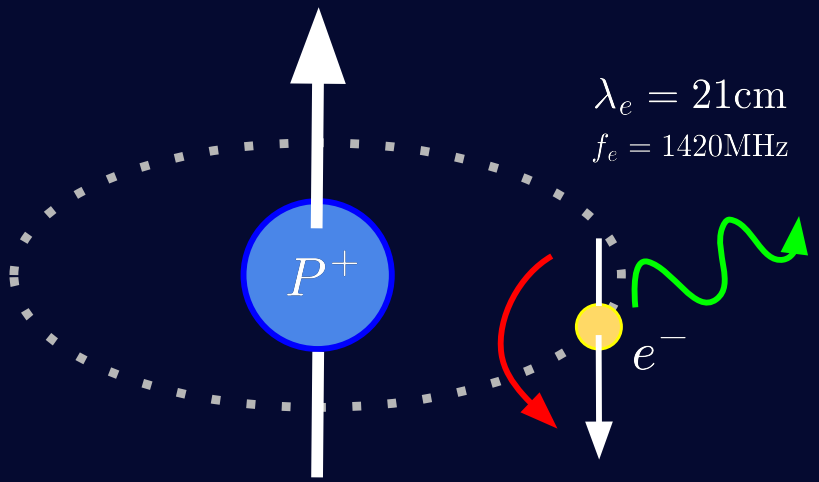


Using neutral hydrogen 21 cm line intensity mapping as LSS tracer



[credit: U. Dupletsa]

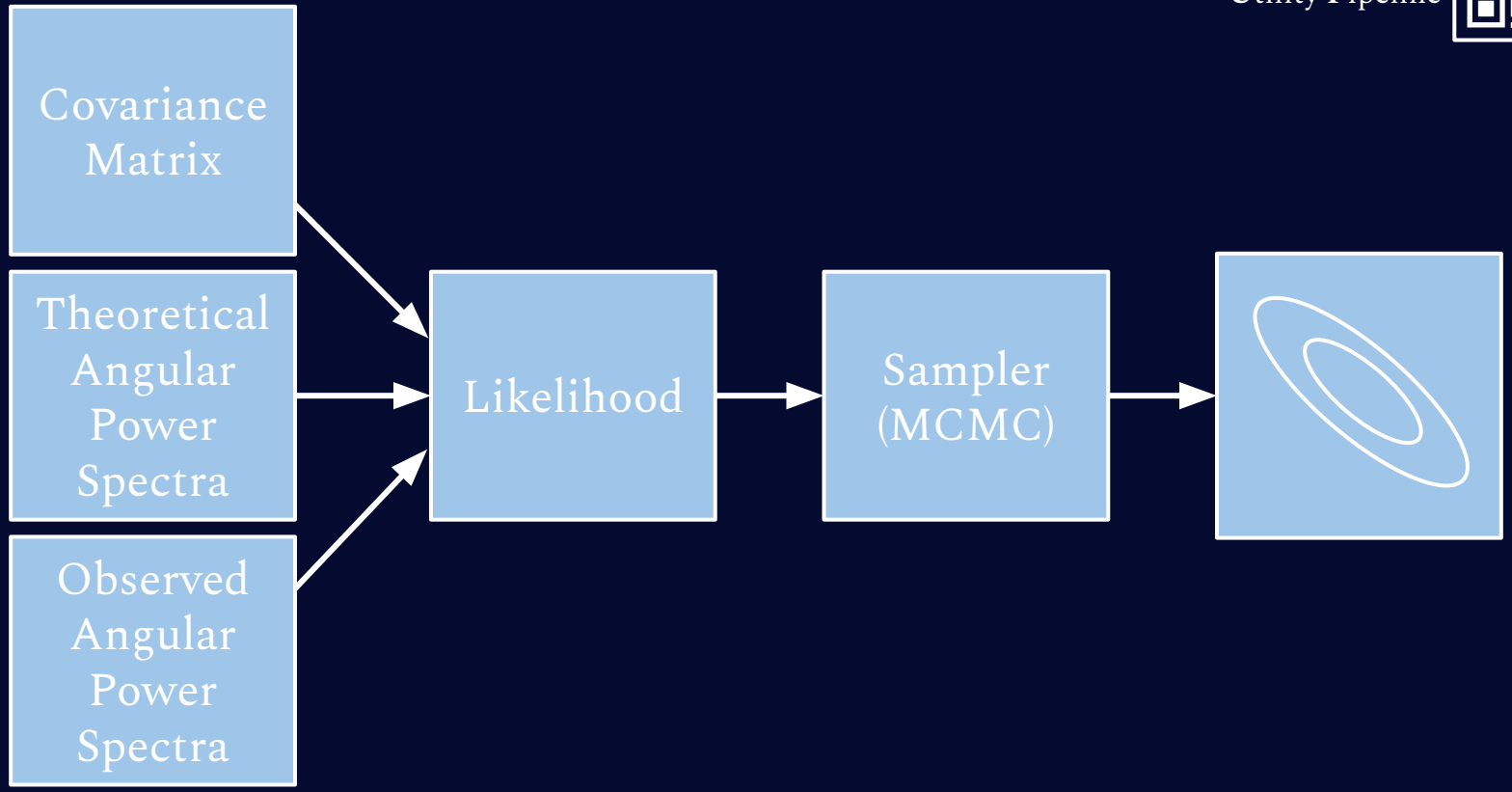
What is 21 cm emission and why it is promising



1) Covers large cosmological volumes with respect to resolved galaxy surveys, in fast and inexpensive way;
2) Spectroscopic precision in redshift distribution up to z $\lesssim$ 5;
3) Precise measurement of matter abundance thanks to intensity of the line;
4) Upcoming future observatory (SKA Observatory)

Likelihood Formalism

GWHICcUP:
GW x **HI** Cross-**c**orrelation
Utility **P**ipeline



Likelihood Formalism

Likelihood

$$\ln \mathcal{L}(\Lambda) = -\frac{1}{2} \sum_{ij} \sum_{i'j'} \sum_{\ell\ell'} \left(\tilde{C}_\ell^{ij} - C_\ell^{th,ij}(\Lambda) \right)^T \mathcal{C}_{\ell\ell'}{}^{-1} \left(\tilde{C}_{\ell'}^{i'j'} - C_{\ell'}^{th,i'j'}(\Lambda) \right)$$

Covariance Matrix

Full Matrix

$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

HIxHI

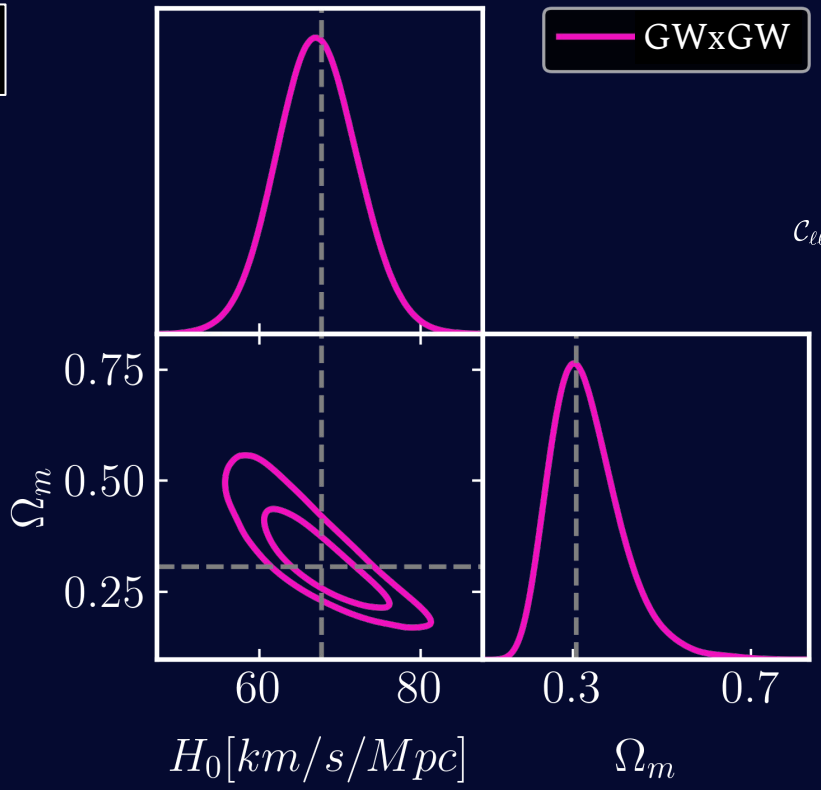
GWxHI

GWxGW

$$(AB_\ell, CD_{\ell'}) = Cov[C_\ell^{AB}, C_{\ell'}^{CD}] = \frac{\delta_{\ell\ell'}}{(2\ell+1) f_{sky}} \left[C_\ell^{A_i B_k} C_{\ell'}^{B_j D_n} + C_\ell^{A_i D_n} C_{\ell'}^{B_j C_k} \right]$$

Results: GWxGW

ET2L+CE



$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

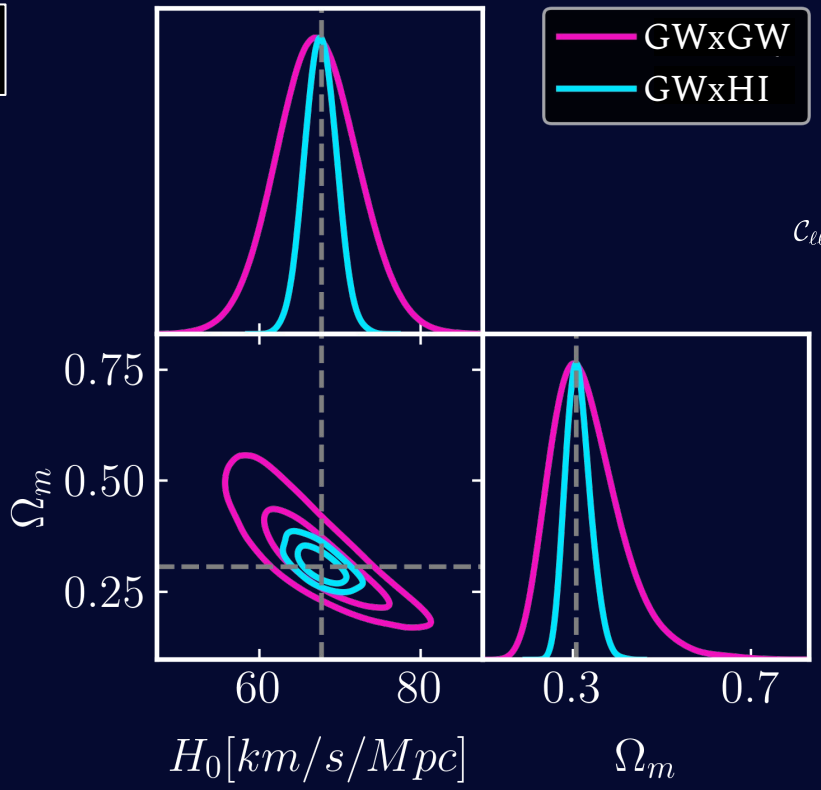
GWxGW

Injected cosmology is retrieved, but with large contours

[https://arxiv.org/abs/2607.26193]

Results: GWxGW + Cross-Correlation

ET2L+CE



$$C_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

GWxHI

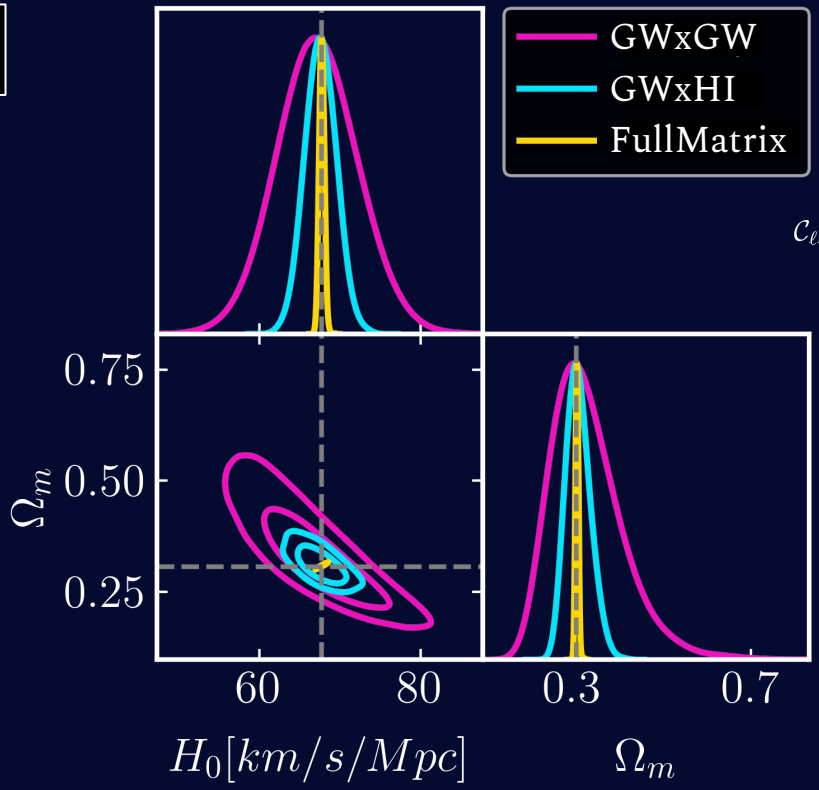
GWxGW

Cross-correlation adds significant constraining power

[https://arxiv.org/abs/2607.26193]

Results: Full Analysis

ET2L+CE



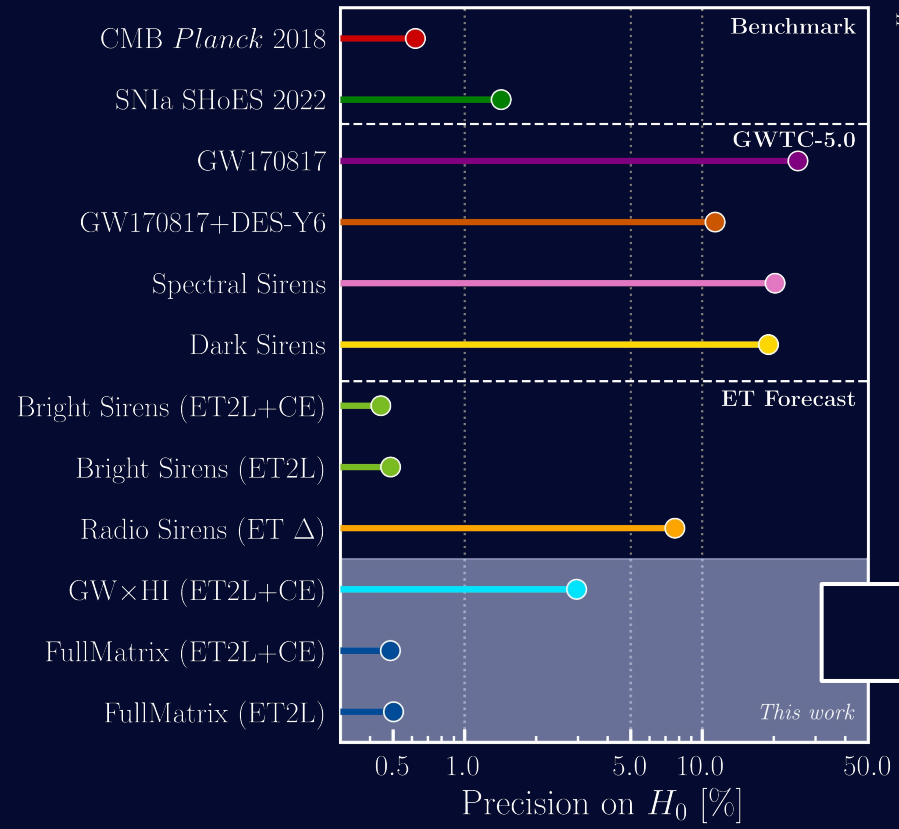
$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

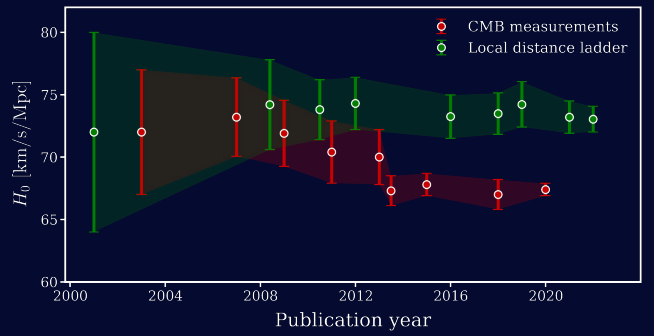
Full Matrix
HIxHI
GWxHI
GWxGW

Full information matrix provides the most stringent constraints

[https://arxiv.org/abs/2607.26193]

Results: Constraints on H_0





[https://arxiv.org/pdf/2605.27227]

[https://arxiv.org/pdf/2411.02490]

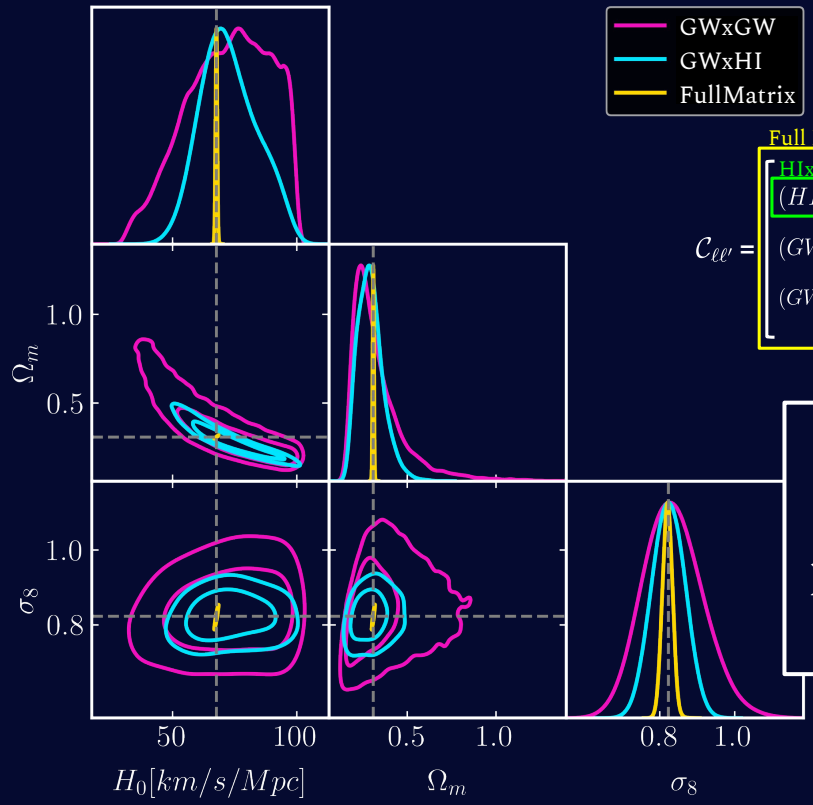
[https://arxiv.org/pdf/2605.12606]

$\lesssim 1\,\%$ precision for H_0

[https://arxiv.org/abs/2607.26193]

Results: Constraints on gravitational clustering

ET2L+CE



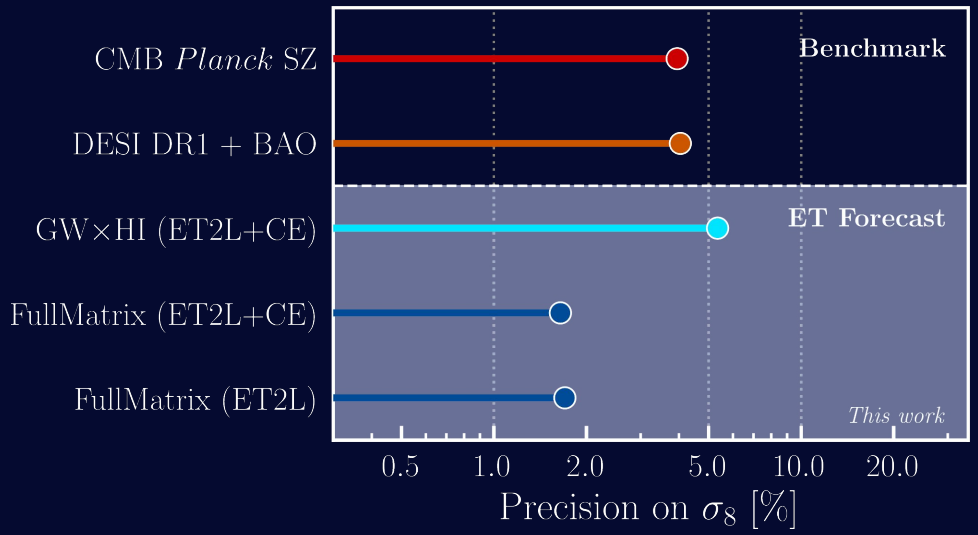
Full Matrix

$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} \text{HIxHI} & & \\ (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ & \text{GWxHI} & \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ & & \text{GWxGW} \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

GWxHI cross-correlation can probe the matter power spectrum

[https://arxiv.org/abs/2607.26193]

Results: Constraints on σ_8



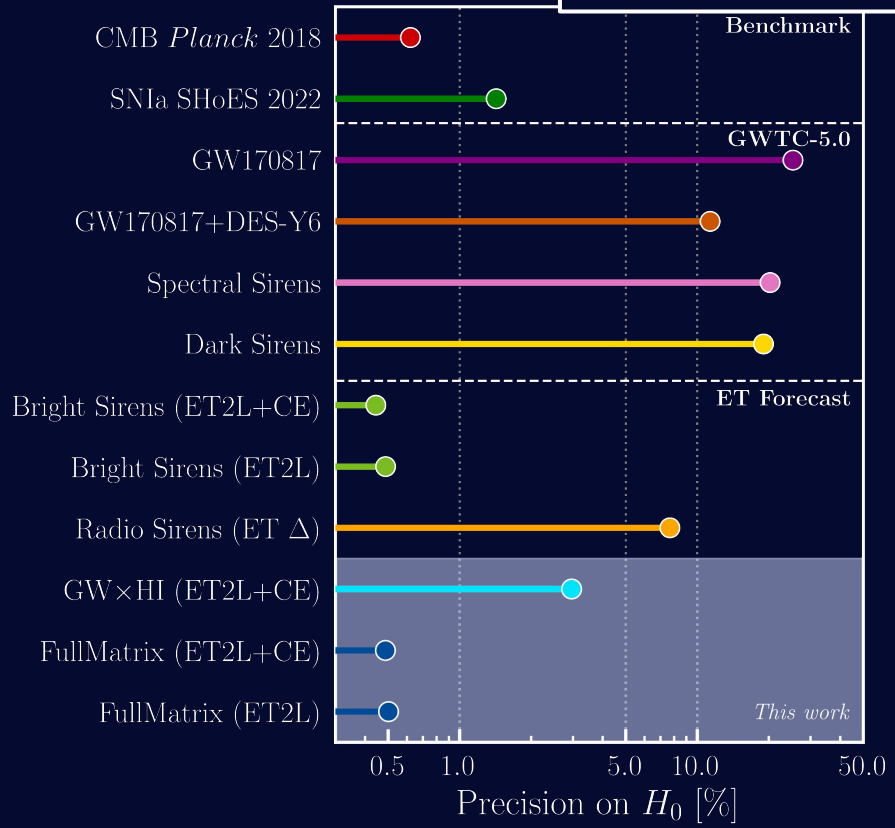
[https://arxiv.org/pdf/1502.01597]

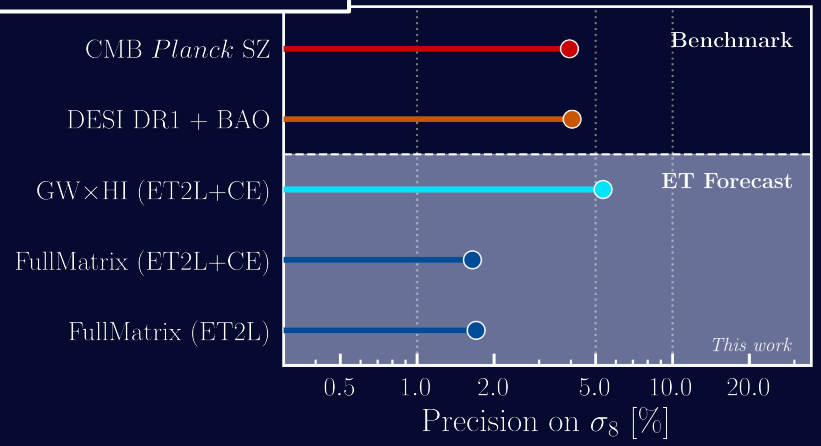
[https://arxiv.org/pdf/2411.12021]

Competitive precision on σ_8

Summary

GWs as emergent probe of LSS

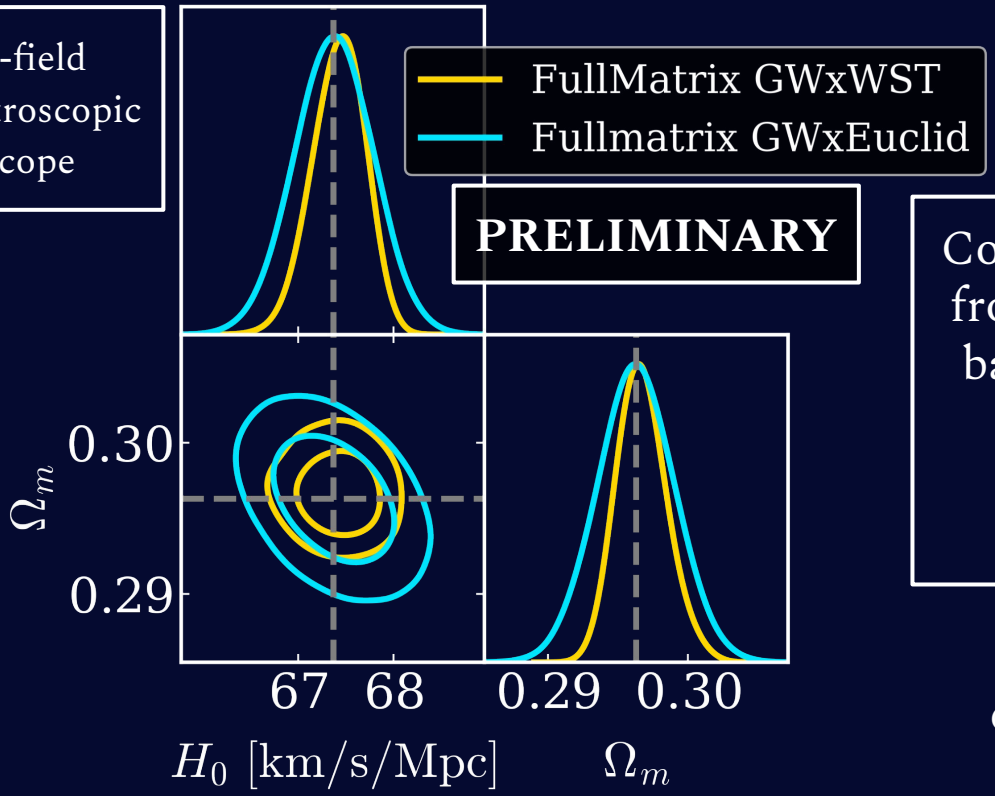




GWxHI cross-correlation can **jointly** probe the expansion history and matter power spectrum

Next steps: Spectroscopic Galaxy Catalogs

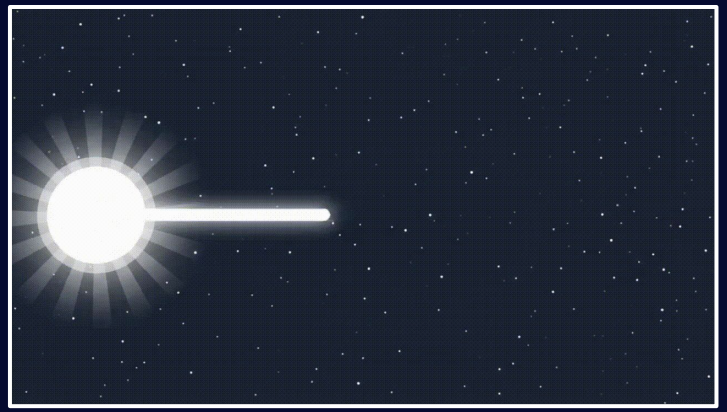
Wide-field Spectroscopic Telescope



Comparing constraints from galaxy clustering based on survey type:
Photometric
VS
Spectroscopic

In collaboration with
G. Sala (RWTH Aachen)

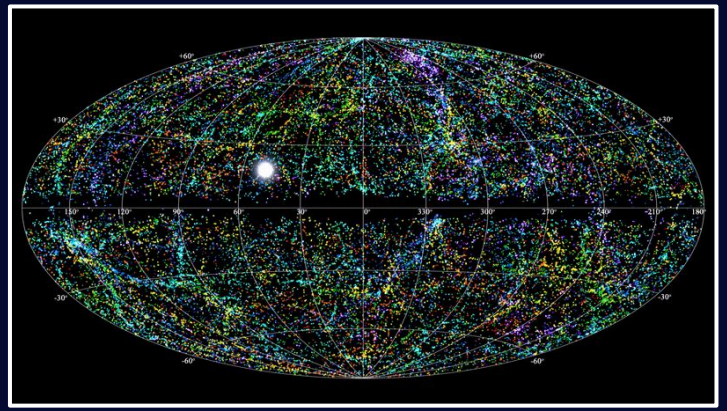
Future Developments: Alternative Tracers



Lyman-α forest:

probes high redshift, small non-linear scales

In collaboration with
M. Viel, G. Scelfo (SISSA)
N. Schoeneberg (LMU)



Fast Radio Bursts:

direct probe of the matter distribution via their dispersion measures

In collaboration with
M. Pili, M. Pilia (UniCA&OAC)

Full Joint Analysis:

Unified multi-tracer analysis to test Dark Energy and beyond Standard ΛCDM models

https://arxiv.org/abs/2607.26193

Thanks for the attention!

Extra slides

Distribution and Accessibility

GWHICcUP: **G**ravitational **W**ave x neutral hydrogen (**HI**) **C**ross-**c**orrelation **U**tility **P**ipeline

MultiCLASS

Montepython

Cobaya

Galaxy Catalogues

Measuring and resolve individual sources

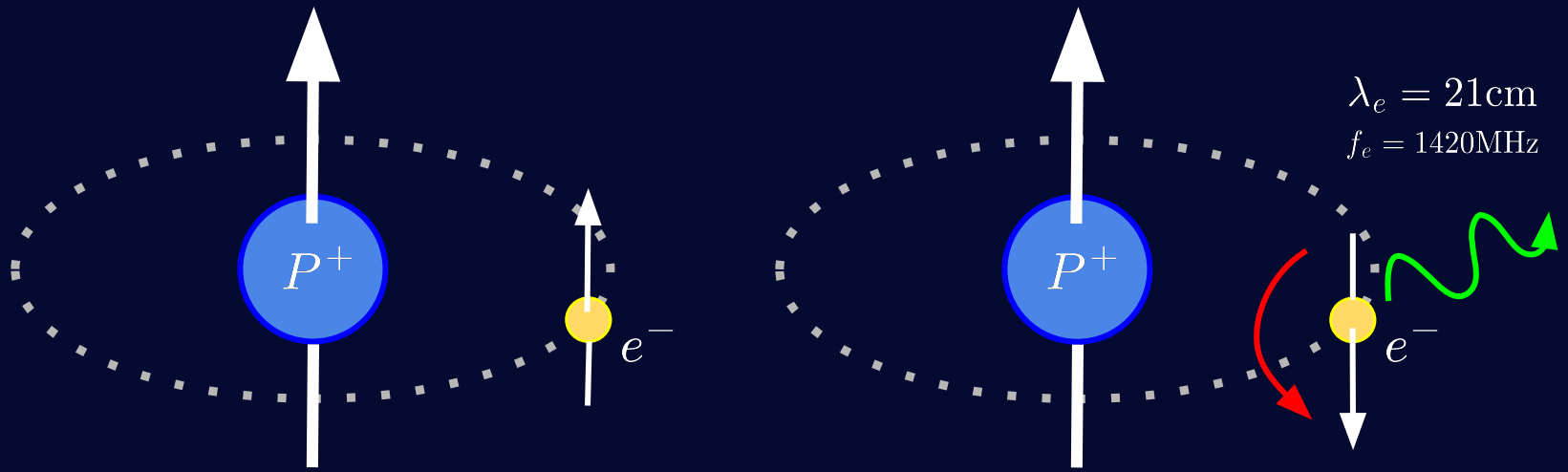


Intensity Mapping

Measures the cumulative, collective light coming from a broad region of space



Neutral Hydrogen



Neutral Hydrogen post Reionization

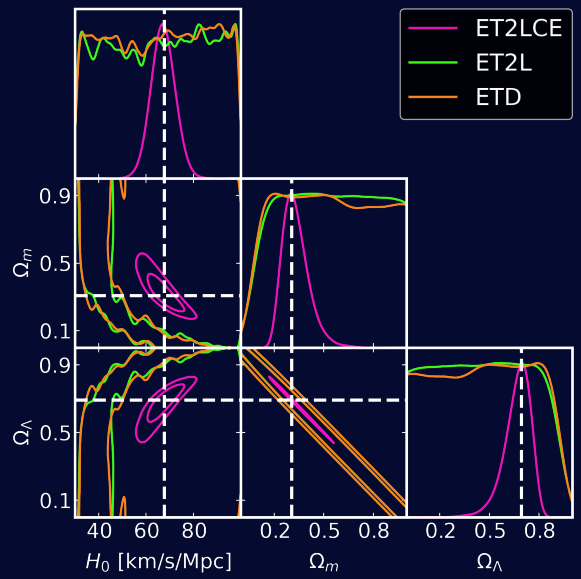
Post Reionization $z \lesssim 5$ the Universe is mostly ionized

- IGM is ionized → no emission of 21 cm;
- HI is “locked” inside galactic environments, i.e. inside dark matter halos
- HI distribution maps the dark matter distribution

Detector Setup

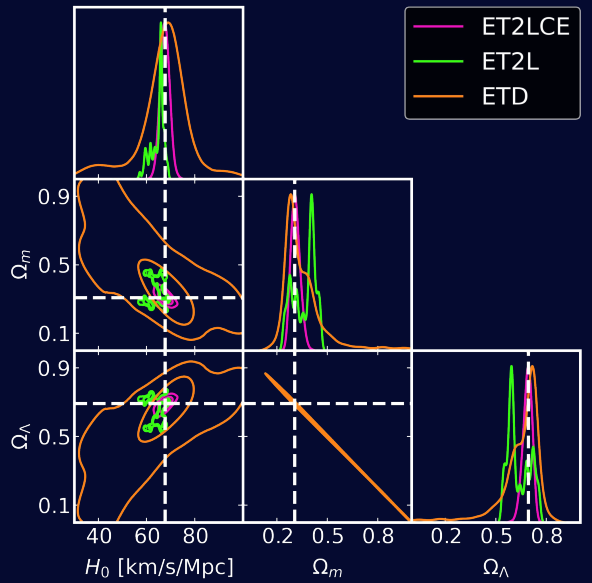


Detector Performance



$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

GWxGW

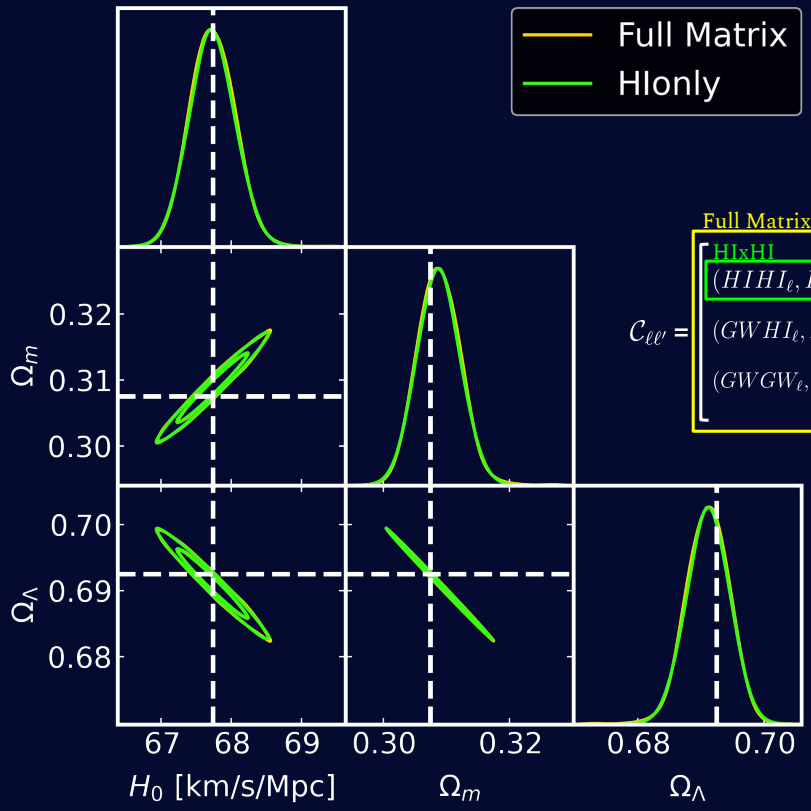


$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

GWxHI

HIxHI

ET2L+CE



Full Matrix

HIxHI

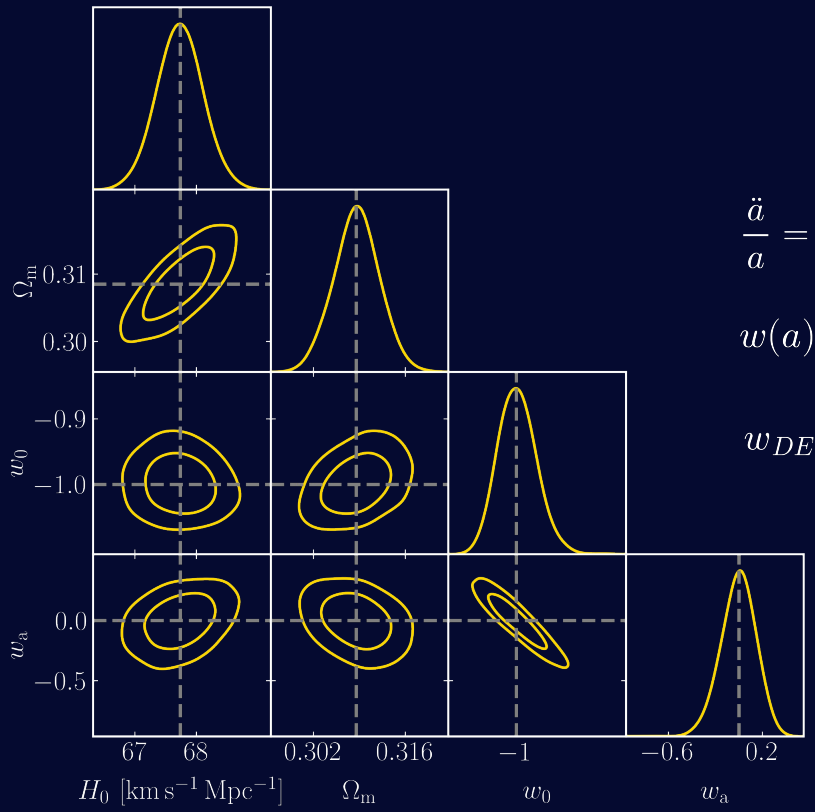
$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

[Schulz et al., in preparation]

Beyond Standard Cosmological Model

ET2L+CE

Extend the analysis to beyond the standard cosmological framework to test Dark Energy models



$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}[\rho_m + \rho_{DE}(1+3w(a))]$$

$$w(a) = \frac{p(a)}{\rho(a)}$$

$$w_{DE}(a) = w_0 + w_a(1-a)$$

Angular Power Spectrum Formalism

Computing tomographic cross-correlation by looking at the angular power spectrum: C_ℓ

→ advantage of naturally including effects coming from large angular separations, which are closely tied to cosmology and its evolution

$$\delta^X(\theta,\phi,x) = \frac{\rho^X(\theta,\phi,x) - \langle\rho^X\rangle(x)}{\langle\rho^X\rangle(x)}$$

$$\delta^X(\theta,\phi,x) = \sum_{\ell=0}^{+\infty}\sum_{m=-\ell}^{\ell} a^X_{\ell m}(x) Y_{\ell m}(\theta,\phi)$$

$$C^X_\ell(x) = \langle a^X_{\ell m}(x)^2\rangle = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} a^X_{\ell m}(x)^2$$

[Baumann 2022]

Likelihood Formalism and Evaluation

Theoretical Angular Power Spectra

$$C_l^{XY}(x_i, x_j) = \int_{z_{min}}^{z_{max}} \frac{cdz}{H(z)r^2(z)} \tilde{W}^X(z, x_i)\tilde{W}^Y(z, x_j) P\left(\frac{\ell + 1/2}{r(z)}, z\right)$$

$$\tilde{W}^X(z, x_i) = J_X(z) b_X(z) w^X(z, x_i) \frac{H(z)}{c} \qquad w^X(x, x_i) = W^X(x, x_i) \frac{dN^X_{obs}}{dx} \frac{1}{\int dx' W^X(x', x_i) \frac{dN^X_{obs}}{dx'}}$$

Covariance Matrix

$$C_\ell = \left(C_\ell^{XX}(x_1, x_{,1}), C_\ell^{XX}(x_1, x_{,2}), ..., C_\ell^{XX}(x_n, x_{,n}), C_\ell^{XY}(x_1, x_{,1}), ..., C_\ell^{XY}(x_n, x_{,m}), C_\ell^{YY}(x_1, x_{,1}), ..., C_\ell^{YY}(x_m, x_{,m})\right)^T$$

$$[Cov(\ell)]_{IJ} = C_\ell^{I_1 J_1} C_\ell^{I_2 J_2} + C_\ell^{I_1 J_2} C_\ell^{I_2 J_1}$$

Likelihood

$$\ln \mathcal{L}(\Lambda) = \frac{1}{2} \sum_{ij} \sum_{i'j'} \sum_{\ell\ell'} \left(\tilde{C}_\ell^{ij} - C_\ell^{th,ij}(\Lambda)\right) [Cov_{\ell\ell'}]^{-1} \left(\tilde{C}_{\ell'}^{i'j'} - C_{\ell'}^{th,i'j'}(\Lambda)\right)$$

 [A. Pedrotti et al. 2025; J. Ferri et al. 2025]