Tracing Large Scale Structure with angular cross-correlation of GWs and HI line for cosmology

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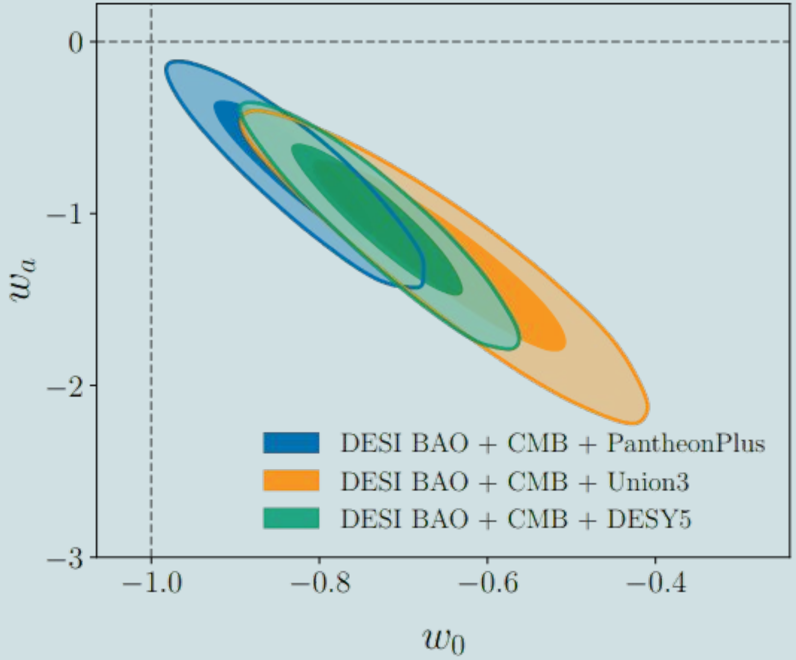
Current Cosmological Framework

ΛCDM incredibly successful

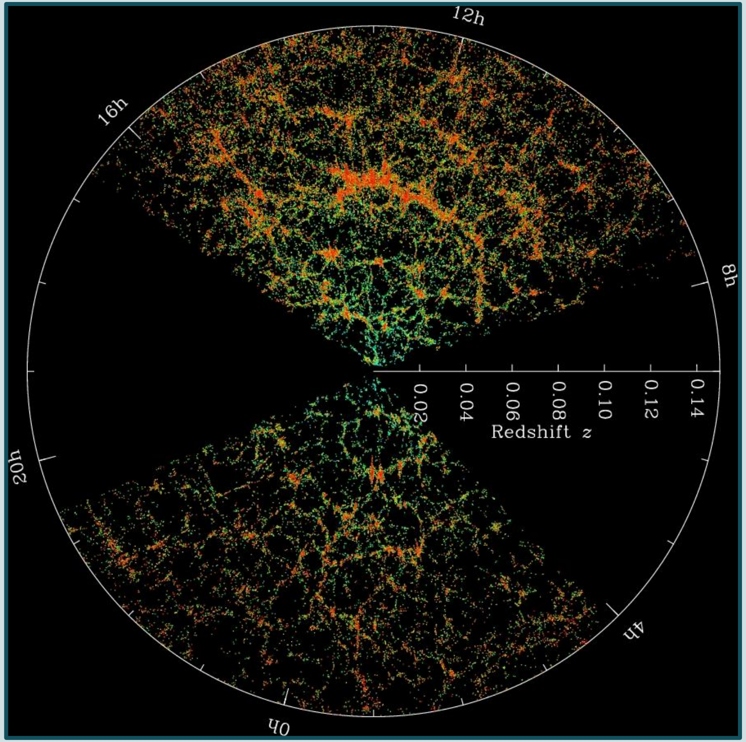
Dark sector remains unknown, giving rise to discrepancies

Developing alternative well-motivated models to restore cosmological concordance.

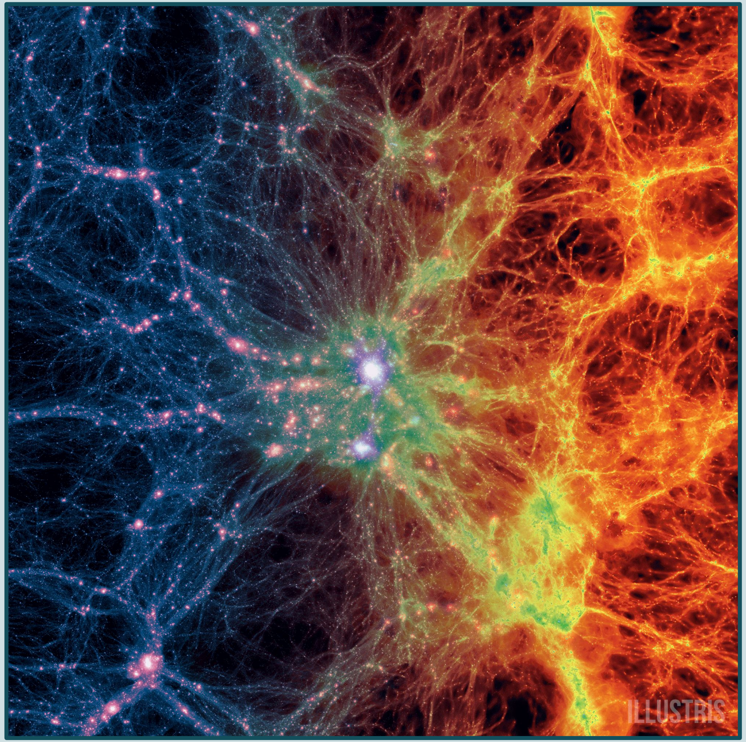
[DESI Collaboration, 2025]



Large Scale Structure (LSS)



[M. Blanton, Sloan Digital Sky Survey]



[Illustris Project]

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

Key point of the approach

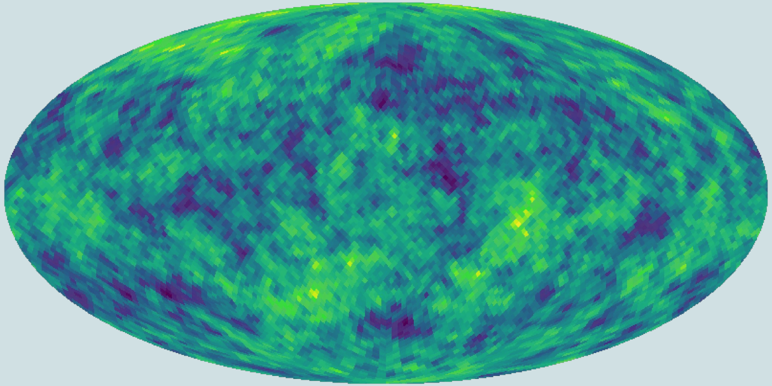
Access to properties of **two different** tracers of the **same underlying** density field in **two different spaces**

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

⇩

Constraints on cosmological parameters

Using neutral hydrogen intensity mapping as new LSS tracer



Why HI is interesting?

1) Covers large cosmological volumes with respect to resolved galaxy surveys, in fast and inexpensive way;
2) Spectroscopic precision in redshift distribution;
3) Precise measurement of matter abundance thank to intensity of the line;
4) Upcoming future observatory (SKAO)

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

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

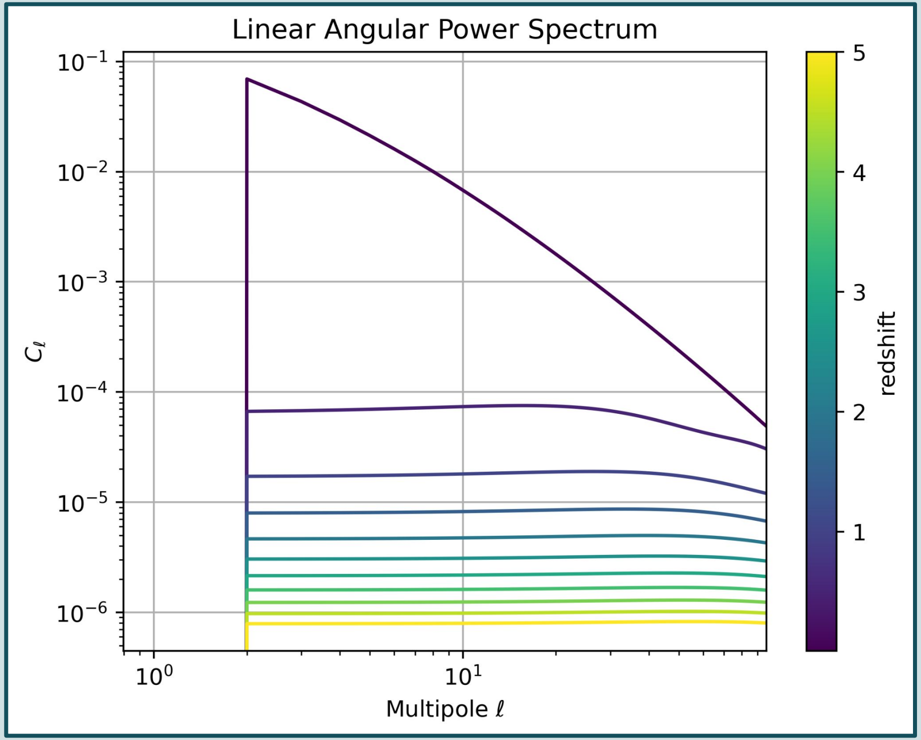
$$\delta^X(\theta,\phi,x) = \sum_{\ell=0}^{+\infty}\sum_{m=-\ell}^{\ell} a^X_{\ell m}(x) Y_{\ell m}(\theta,\phi)$$

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

[Baumann 2022]

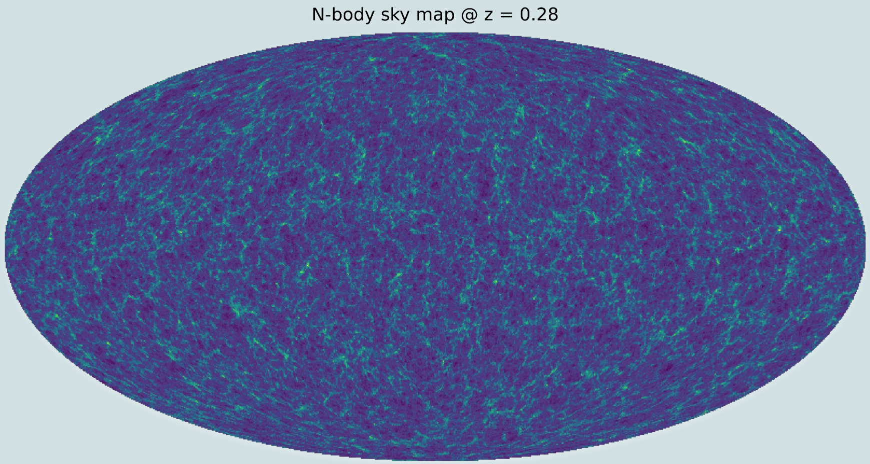
Simulating the maps

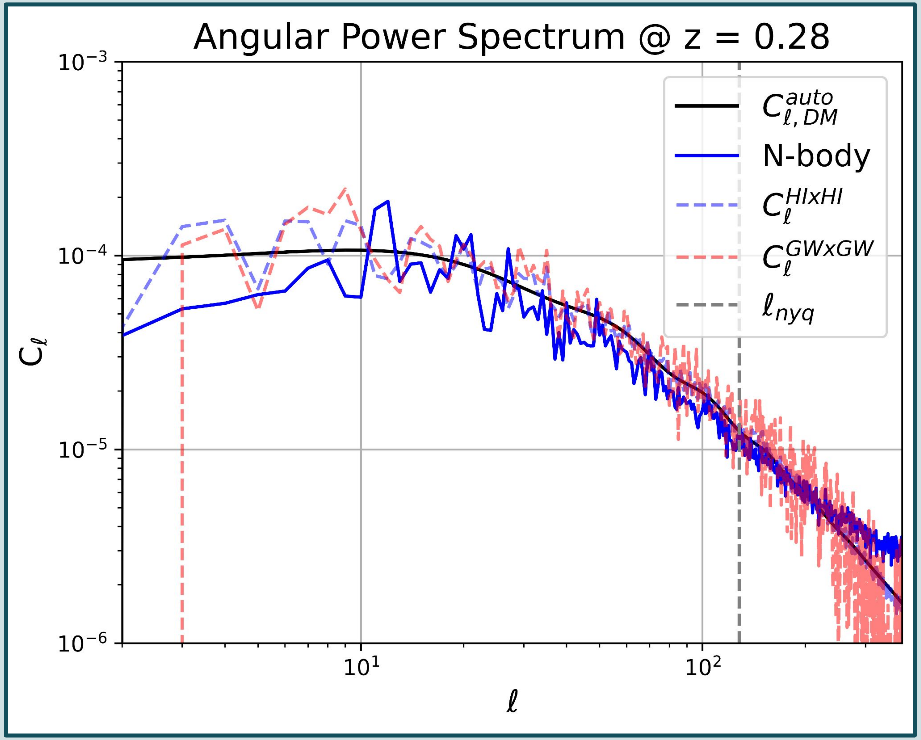
CLASS simulates the evolution of **linear perturbations** and provides the angular power spectrum of the **underlying dark matter distribution** for each redshift bin



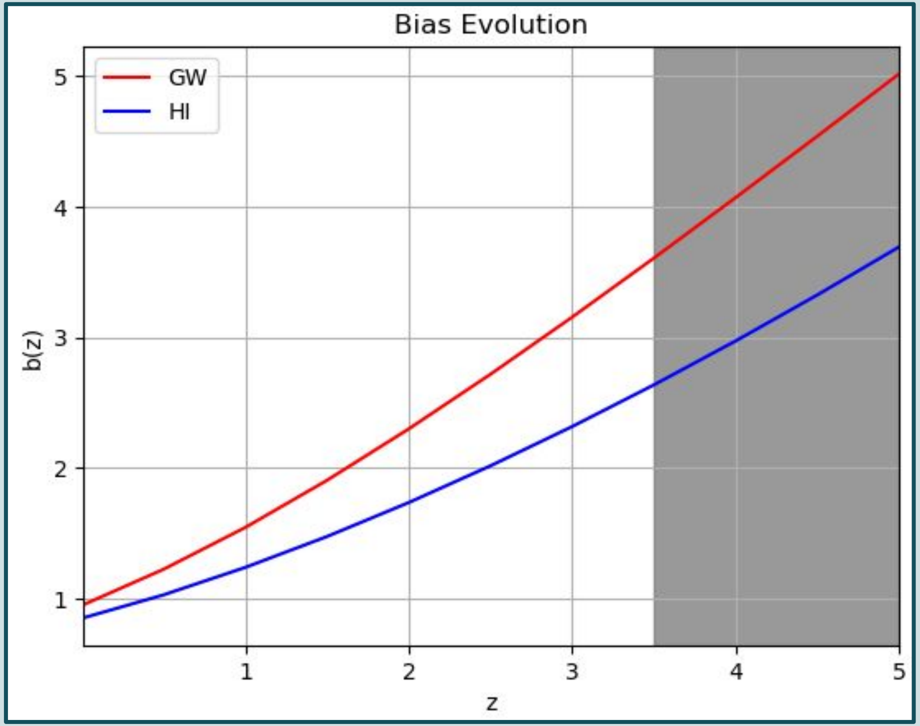
[Blas, Lesgourgues, Tram 2011]

Linear theory vs. N-body





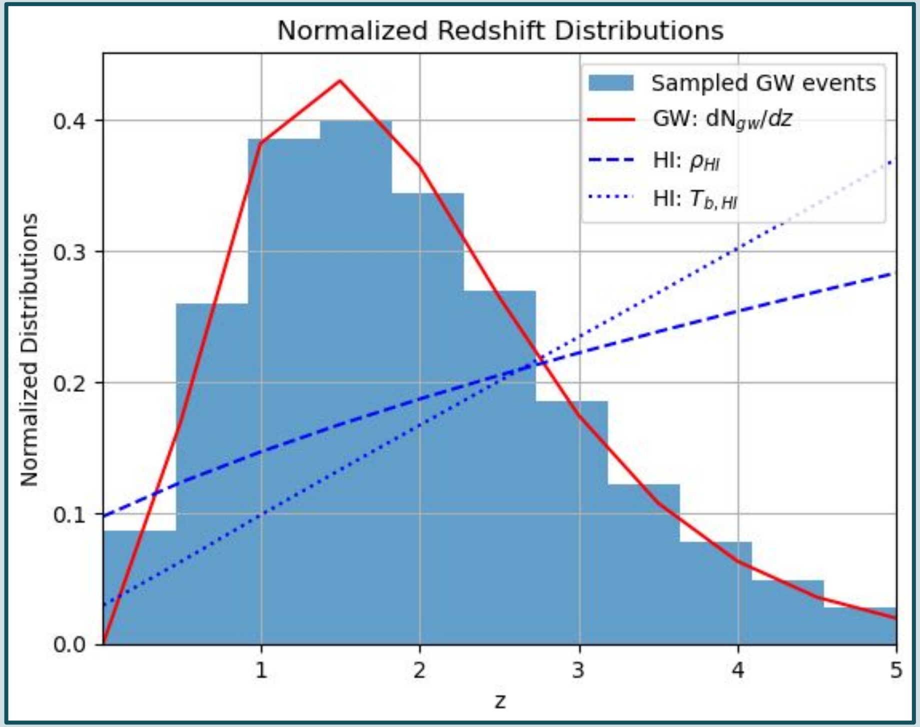
Maps creation: bias



$$bias_{GW}(z) = a_{gw} exp(b_{gw} z^{d_{gw}}) + z^{c_{gw}}$$

$$bias_{HI}(z) = a_{hi}(1+z)^{b_{hi}} + c_{hi}$$

Maps creation: tracers redshift distribution

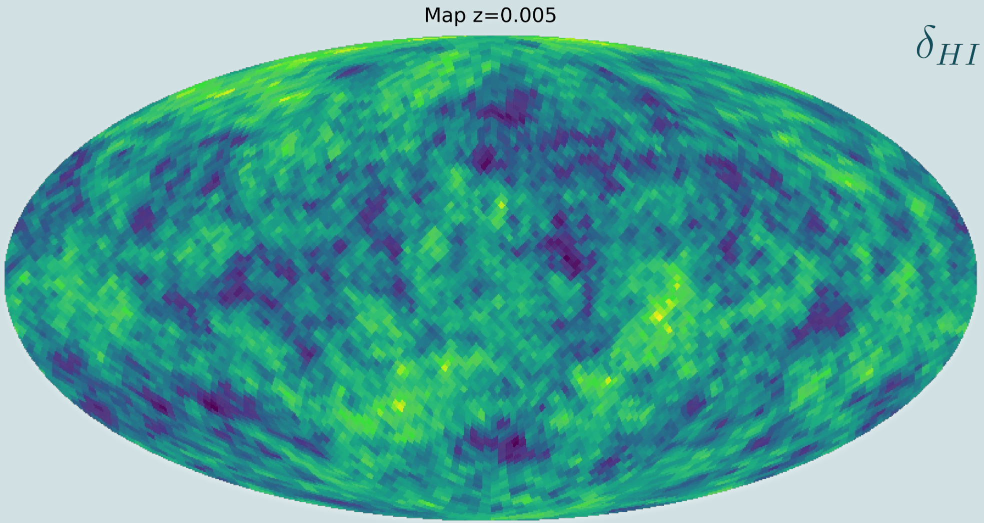


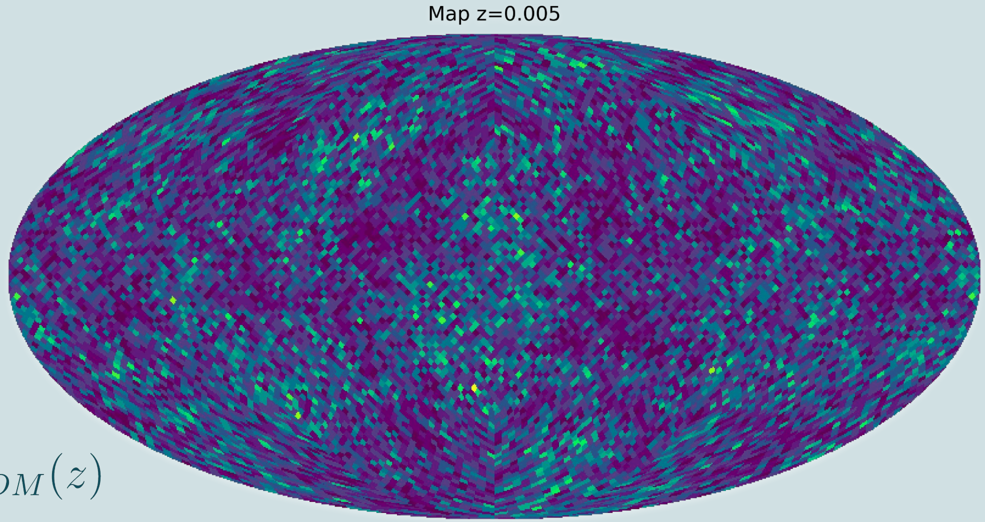
$$\frac{dN_{gw}}{dz} = A_{gw} z^{B_{gw}} \exp(-C_{gw} z)$$

$$\rho_{HI}(z) = 4 \times 10^{-4} (1+z)^{0.6} \rho_{crit,0}$$

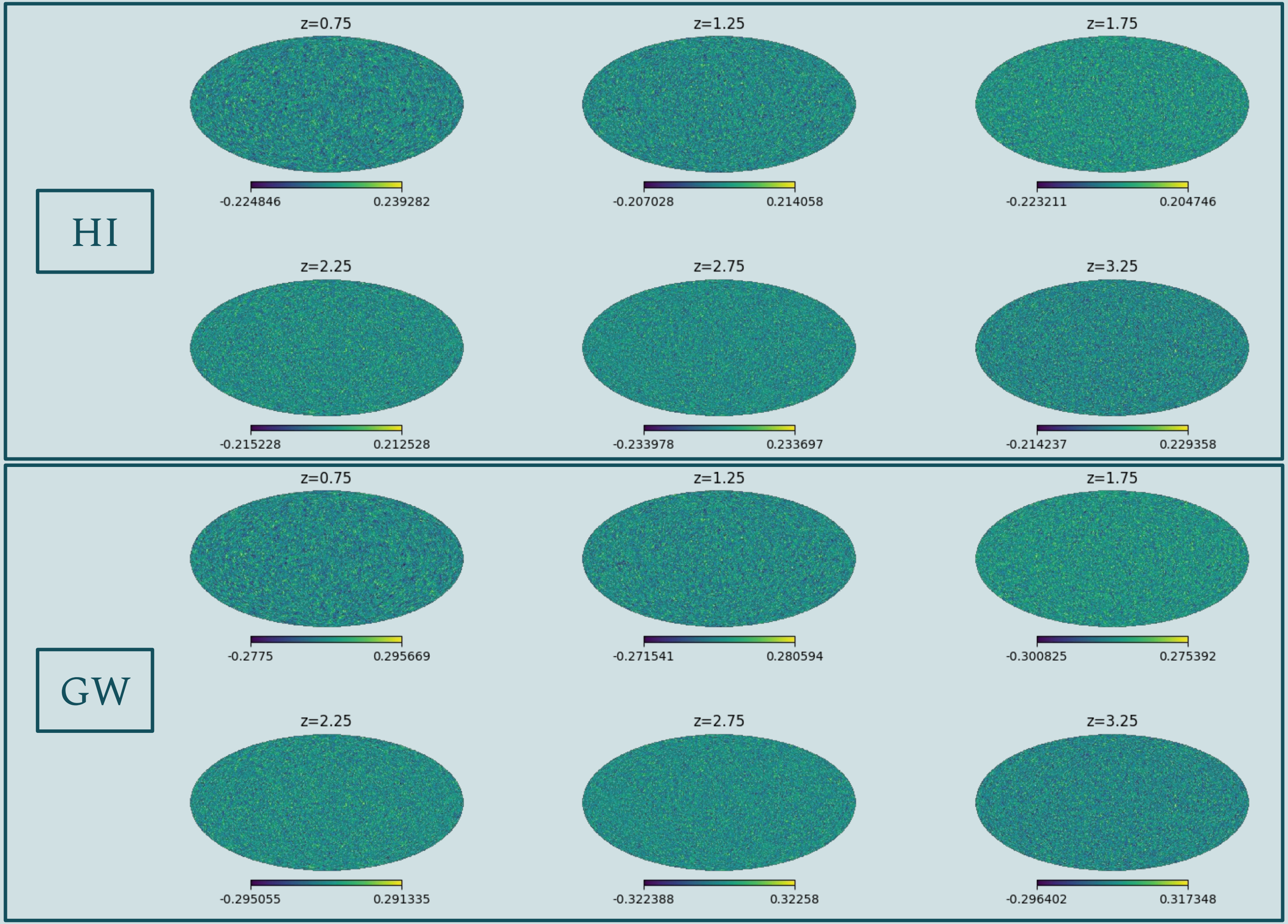
$$T_{B,HI}(z) = 44 \mu T \left(\frac{\rho_{HI}(z) h}{2.45 \times 10^{-4} \rho_{crit,0}} \right) \frac{(1+z)^2}{E(z)}$$

$$\delta_{HI}(z) = bias_{HI}(z)\delta_{DM}(z)$$

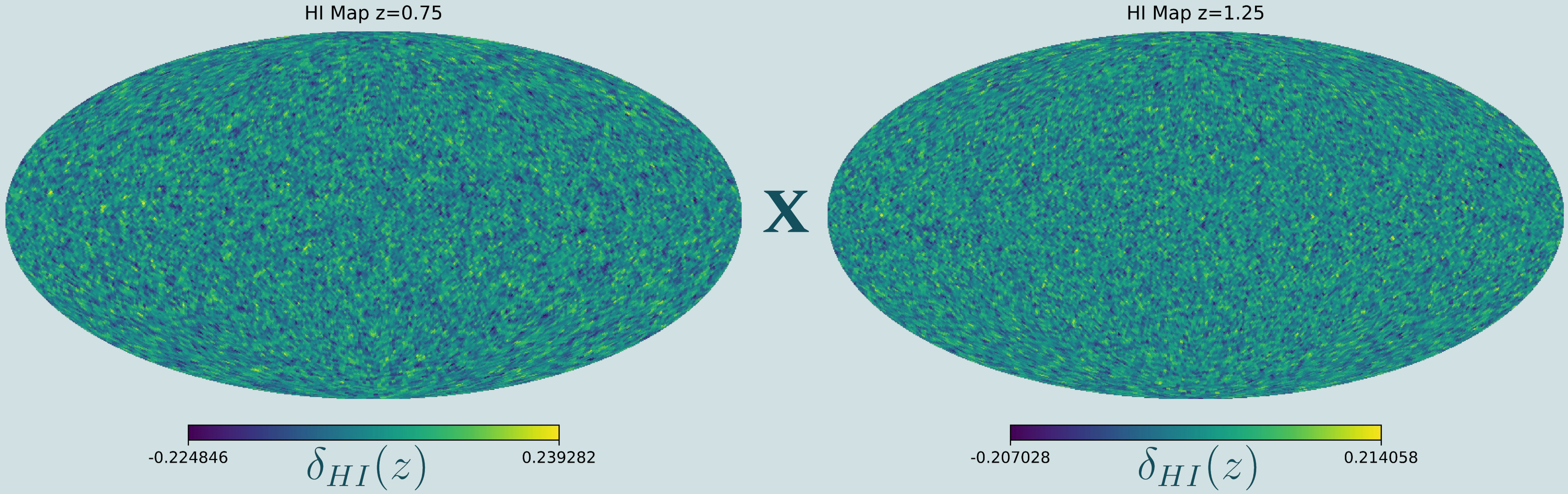


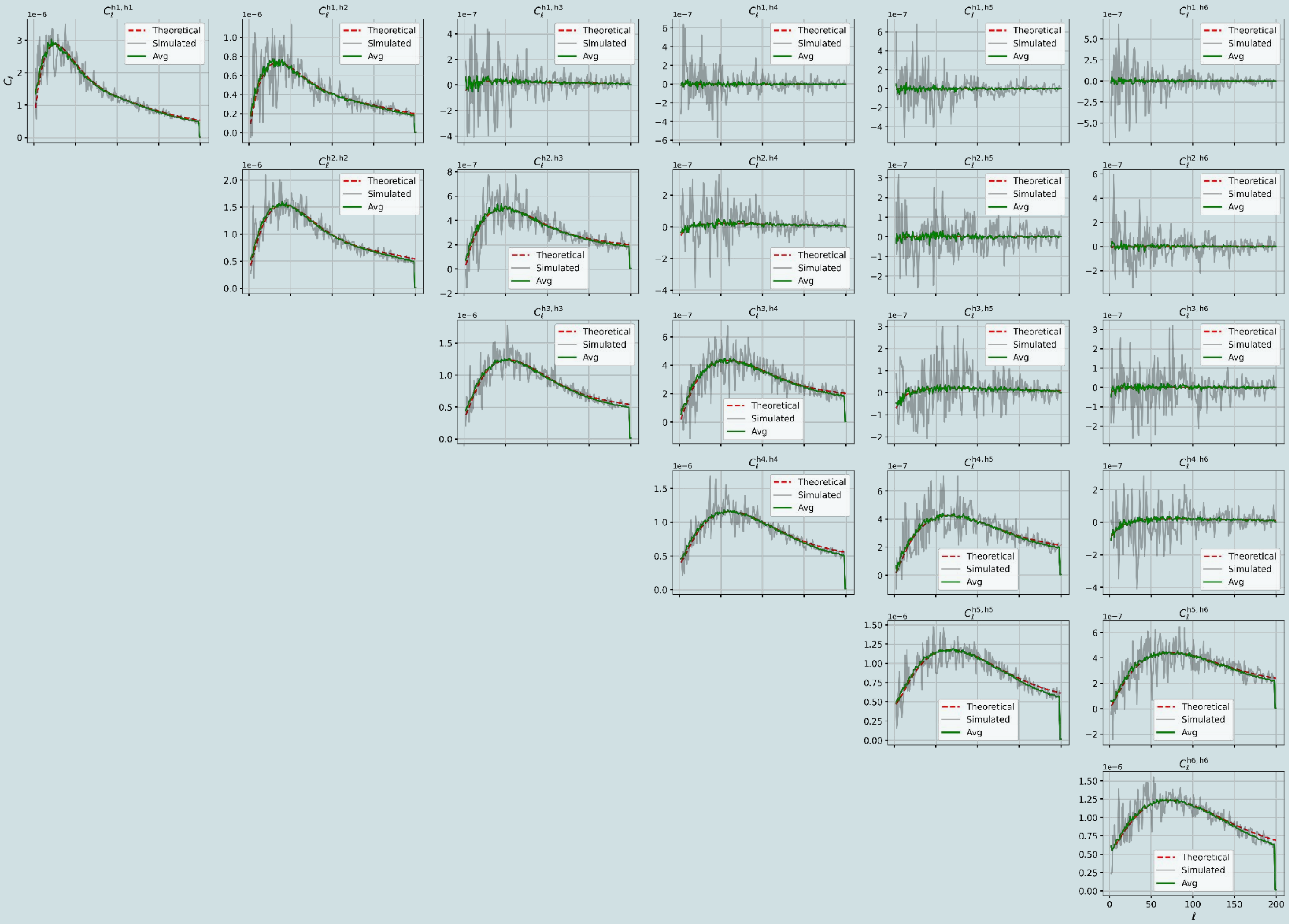


$$\delta_{GW}(z) = bias_{GW}(z)\delta_{DM}(z)$$


HI
z=0.75
-0.224846
0.239282
z=1.25
-0.207028
0.214058
z=1.75
-0.223211
0.204746
z=2.25
-0.215228
0.212528
z=2.75
-0.233978
0.233697
z=3.25
-0.214237
0.229358
GW
z=0.75
-0.2775
0.295669
z=1.25
-0.271541
0.280594
z=1.75
-0.300825
0.275392
z=2.25
-0.295055
0.291335
z=2.75
-0.322388
0.32258
z=3.25
-0.296402
0.317348

Extracting Correlations





$C_\ell^{h1,h1}$
$C_\ell^{h1,h2}$
$C_\ell^{h1,h3}$
$C_\ell^{h1,h4}$
$C_\ell^{h1,h5}$
$C_\ell^{h1,h6}$
$C_\ell^{h2,h2}$
$C_\ell^{h2,h3}$
$C_\ell^{h2,h4}$
$C_\ell^{h2,h5}$
$C_\ell^{h2,h6}$
$C_\ell^{h3,h3}$
$C_\ell^{h3,h4}$
$C_\ell^{h3,h5}$
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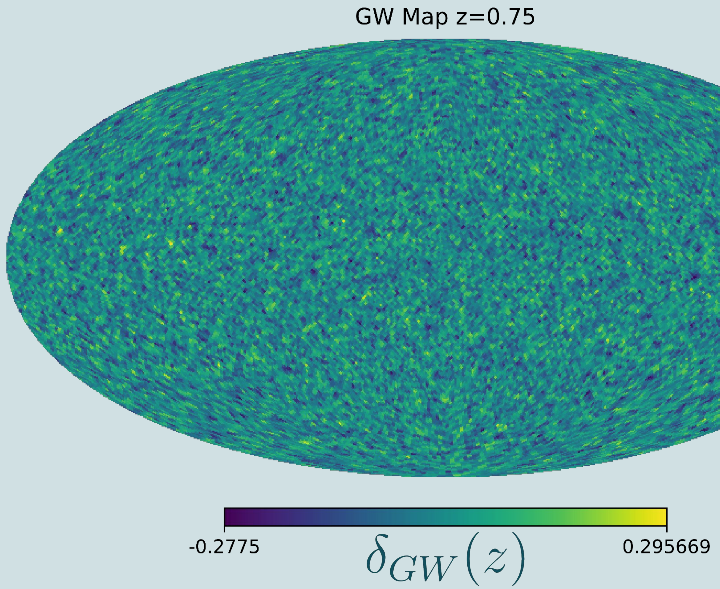
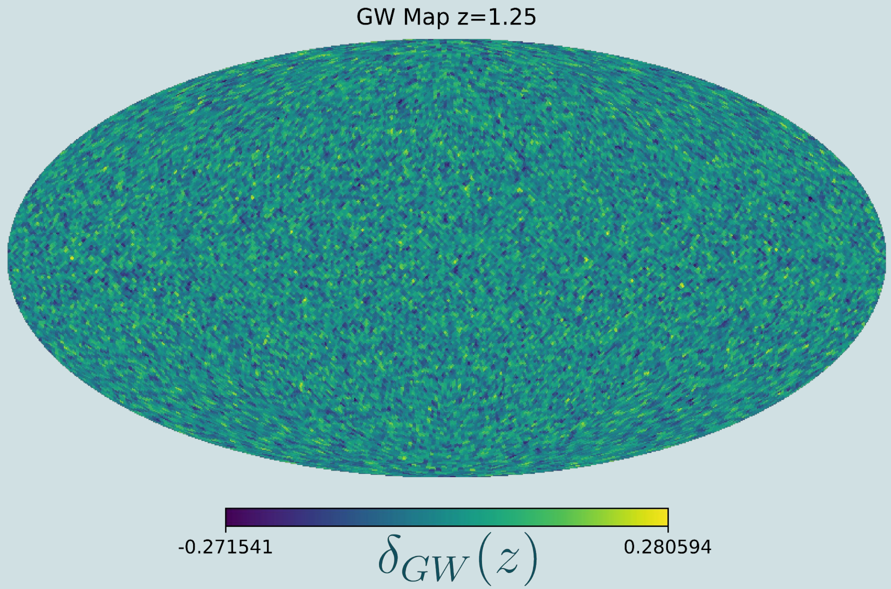
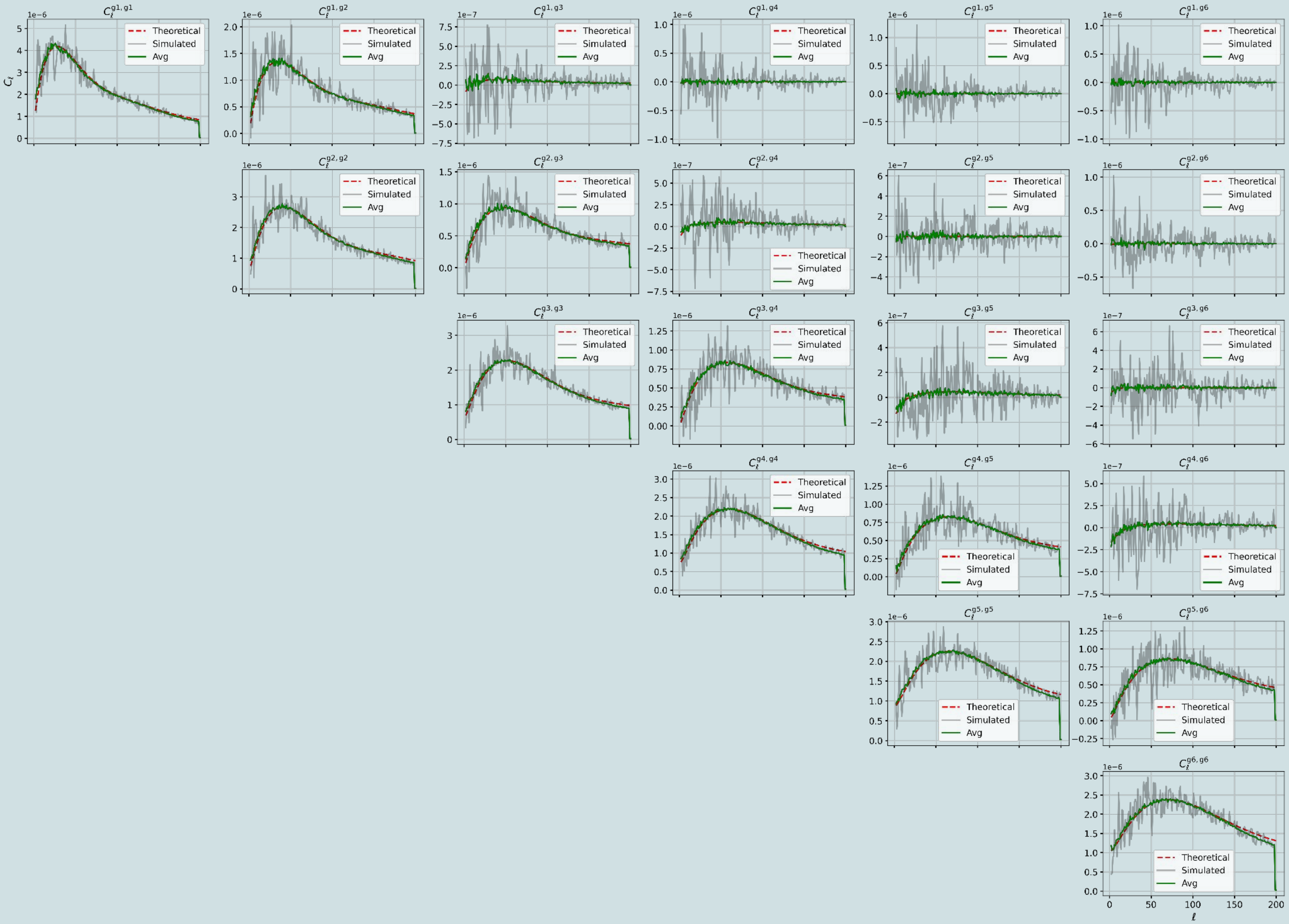
$C_\ell^{h4,h6}$
$C_\ell^{h5,h5}$
$C_\ell^{h5,h6}$
$C_\ell^{h6,h6}$
C_ℓ
ℓ
Theoretical
Simulated
Avg


GW Map z=0.75
-0.2775
0.295669
$\delta_{GW}(z)$

X


GW Map z=1.25
-0.271541
0.280594
$\delta_{GW}(z)$


$C_\ell^{g1,g1}$
$C_\ell^{g1,g2}$
$C_\ell^{g1,g3}$
$C_\ell^{g1,g4}$
$C_\ell^{g1,g5}$
$C_\ell^{g1,g6}$
$C_\ell^{g2,g2}$
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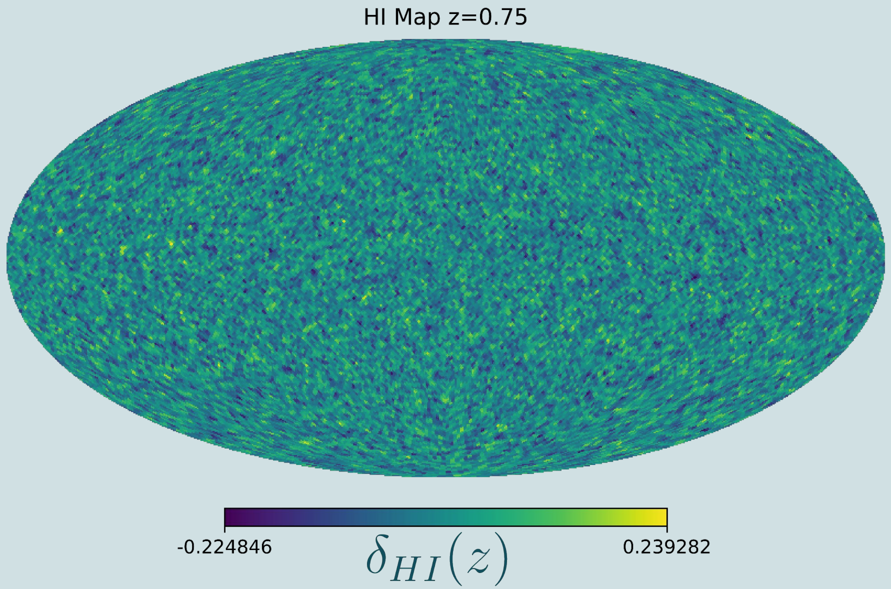
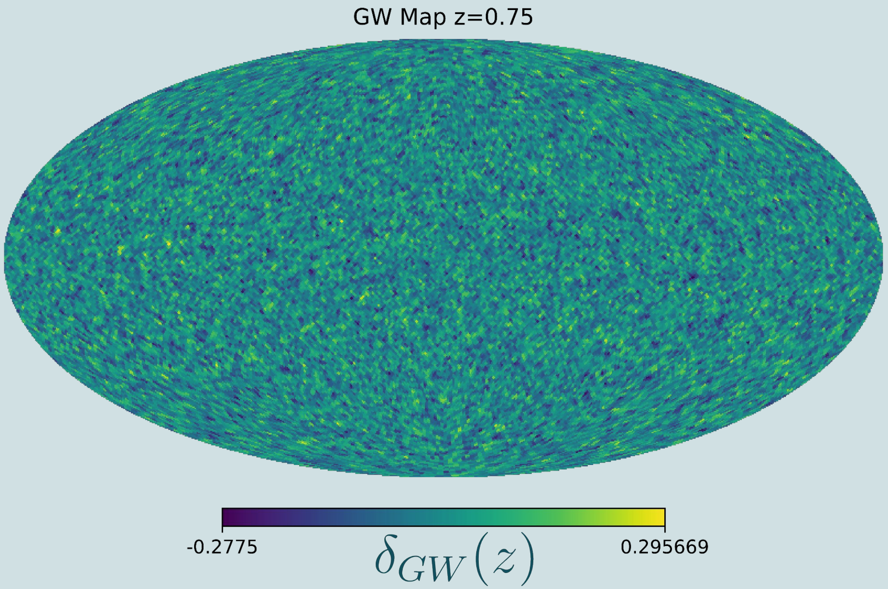
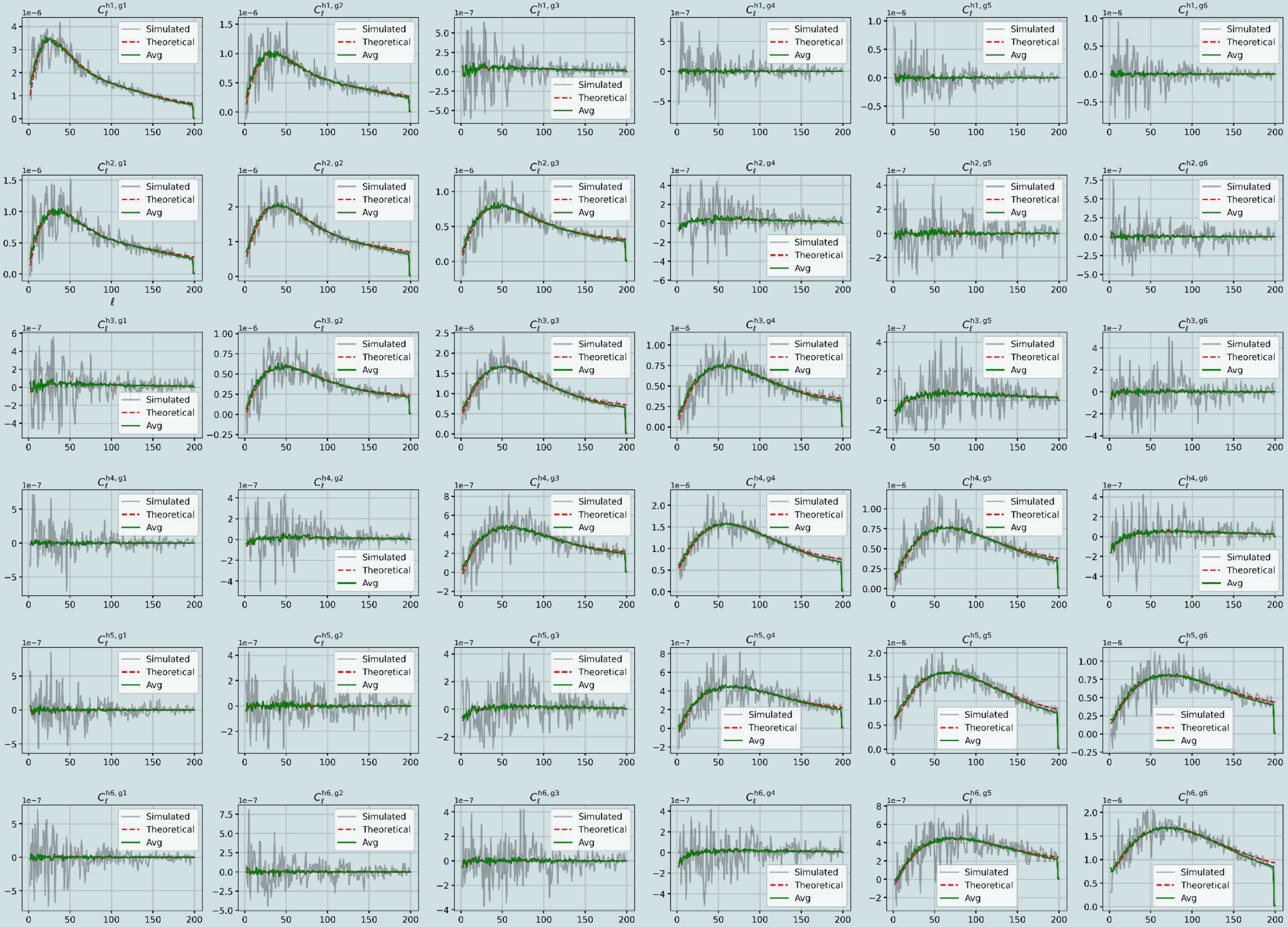
$C_\ell^{g3,g6}$
$C_\ell^{g4,g4}$
$C_\ell^{g4,g5}$
$C_\ell^{g4,g6}$
$C_\ell^{g5,g5}$
$C_\ell^{g5,g6}$
$C_\ell^{g6,g6}$
Theoretical
Simulated
Avg
C_ℓ
ℓ


HI Map z=0.75
-0.224846
0.239282
$\delta_{HI}(z)$

X


GW Map z=0.75
-0.2775
0.295669
$\delta_{GW}(z)$


$C_\ell^{h1,g1}$
$C_\ell^{h1,g2}$
$C_\ell^{h1,g3}$
$C_\ell^{h1,g4}$
$C_\ell^{h1,g5}$
$C_\ell^{h1,g6}$
$C_\ell^{h2,g1}$
$C_\ell^{h2,g2}$
$C_\ell^{h2,g3}$
$C_\ell^{h2,g4}$
$C_\ell^{h2,g5}$
$C_\ell^{h2,g6}$
$C_\ell^{h3,g1}$
$C_\ell^{h3,g2}$
$C_\ell^{h3,g3}$
$C_\ell^{h3,g4}$
$C_\ell^{h3,g5}$
$C_\ell^{h3,g6}$
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$C_\ell^{h4,g2}$
$C_\ell^{h4,g3}$
$C_\ell^{h4,g4}$
$C_\ell^{h4,g5}$
$C_\ell^{h4,g6}$
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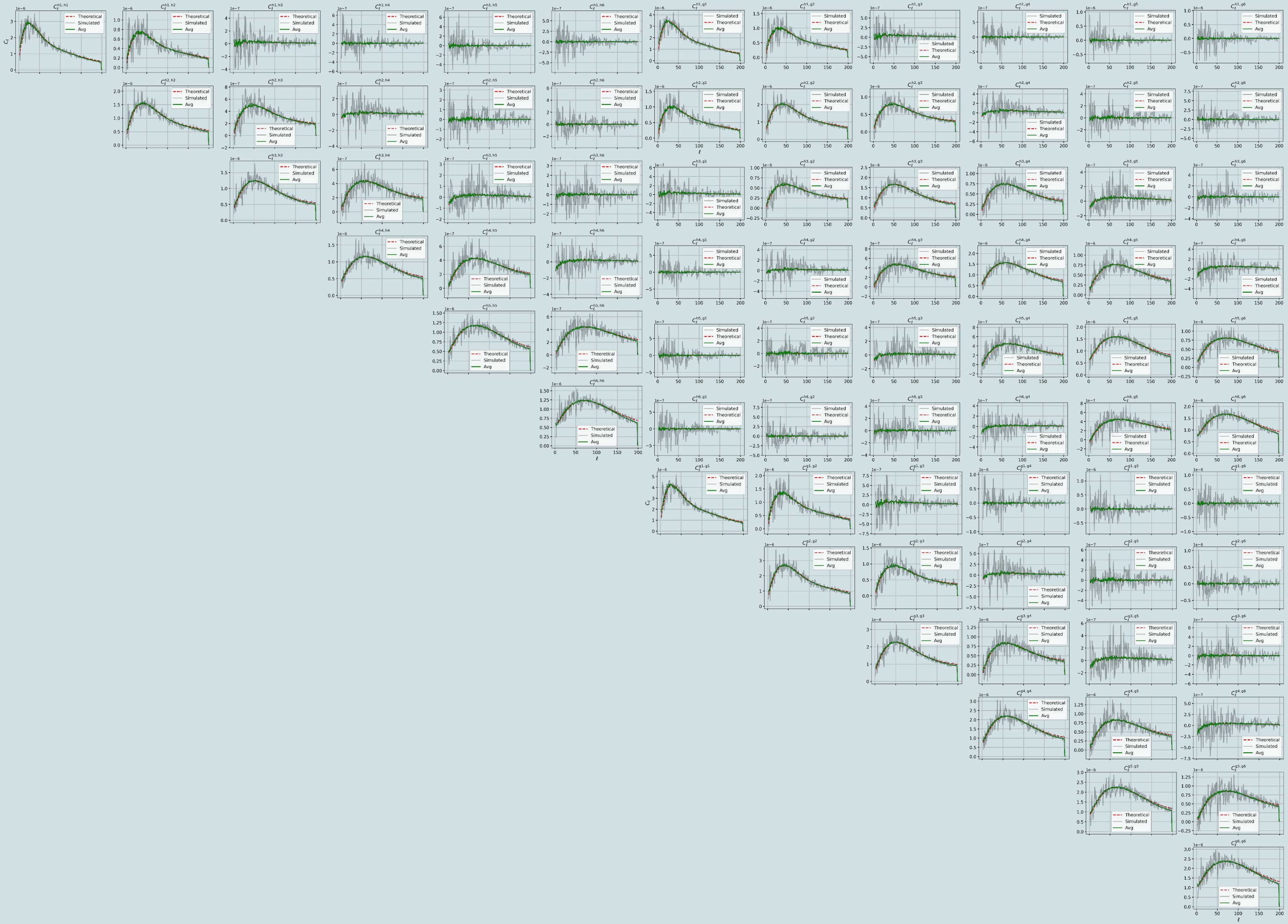
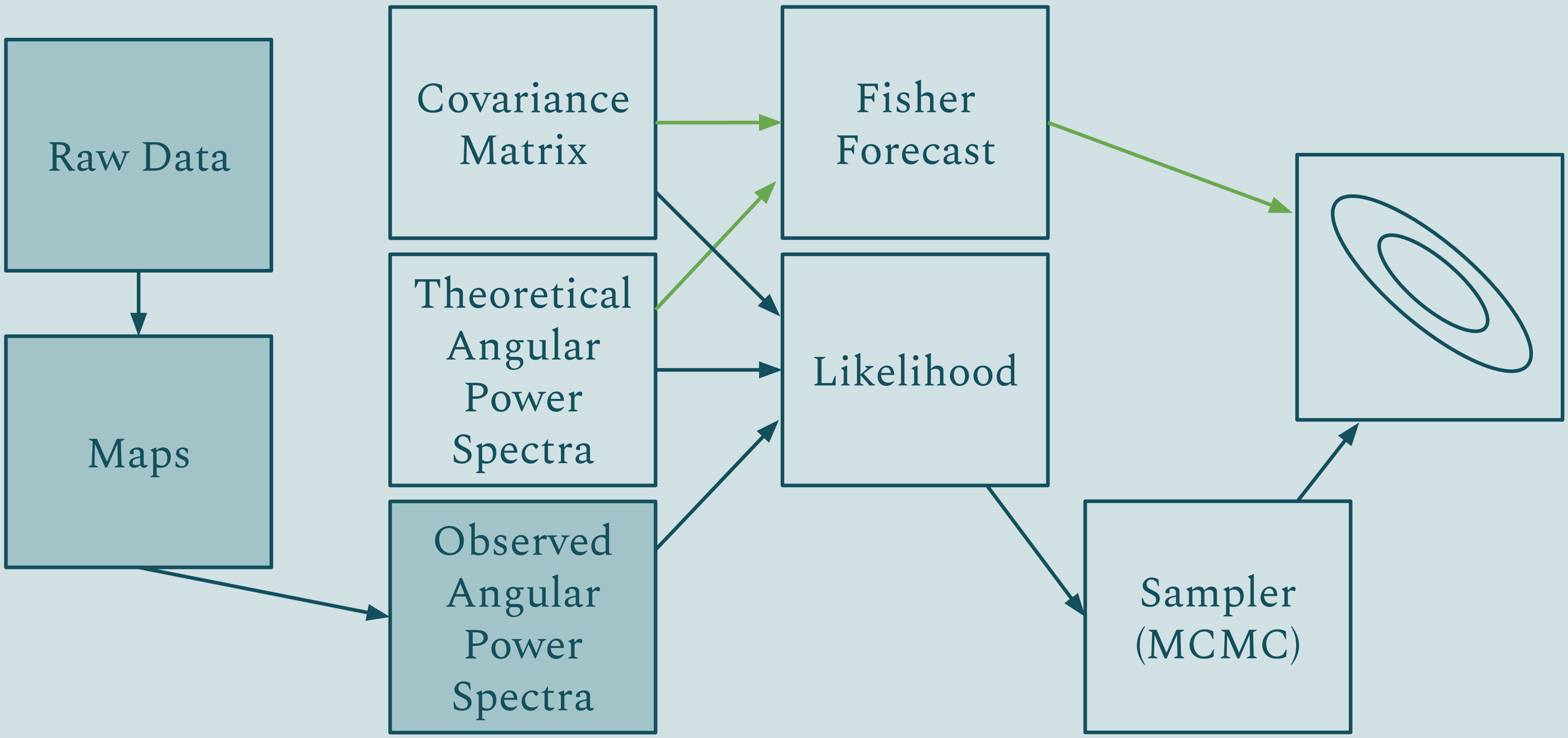
$C_\ell^{h6,g1}$
$C_\ell^{h6,g2}$
$C_\ell^{h6,g3}$
$C_\ell^{h6,g4}$
$C_\ell^{h6,g5}$
$C_\ell^{h6,g6}$
Simulated
Theoretical
Avg
ℓ


Theoretical
Simulated
Avg

Likelihood Formalism



Likelihood Formalism and Evaluation

Theoretical Angular Power Spectra

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

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

Covariance Matrix

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

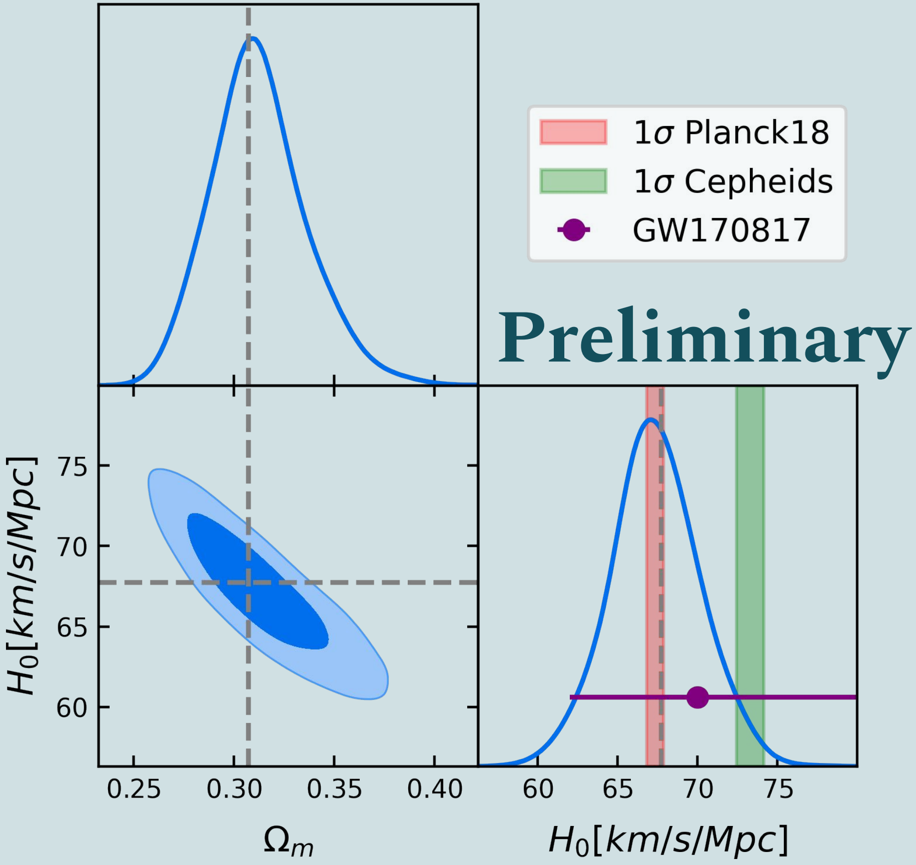
$$[Cov(\ell)]_{IJ} = C_\ell^{I_1 J_1} C_\ell^{I_2 J_2} + C_\ell^{I_1 J_2} C_\ell^{I_2 J_1}$$

Likelihood

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

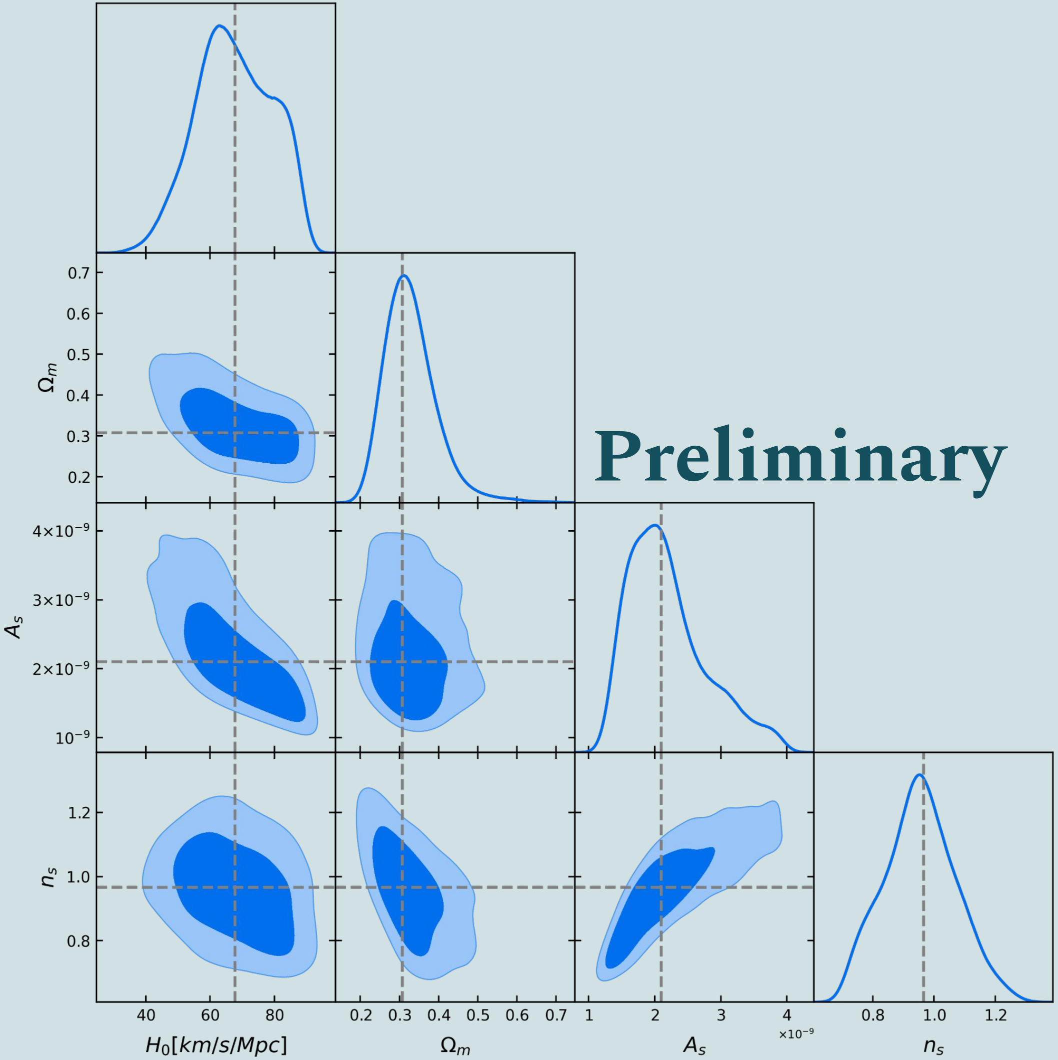
[A. Pedrotti et al. 2025; J. Ferri et al. 2025]

Results



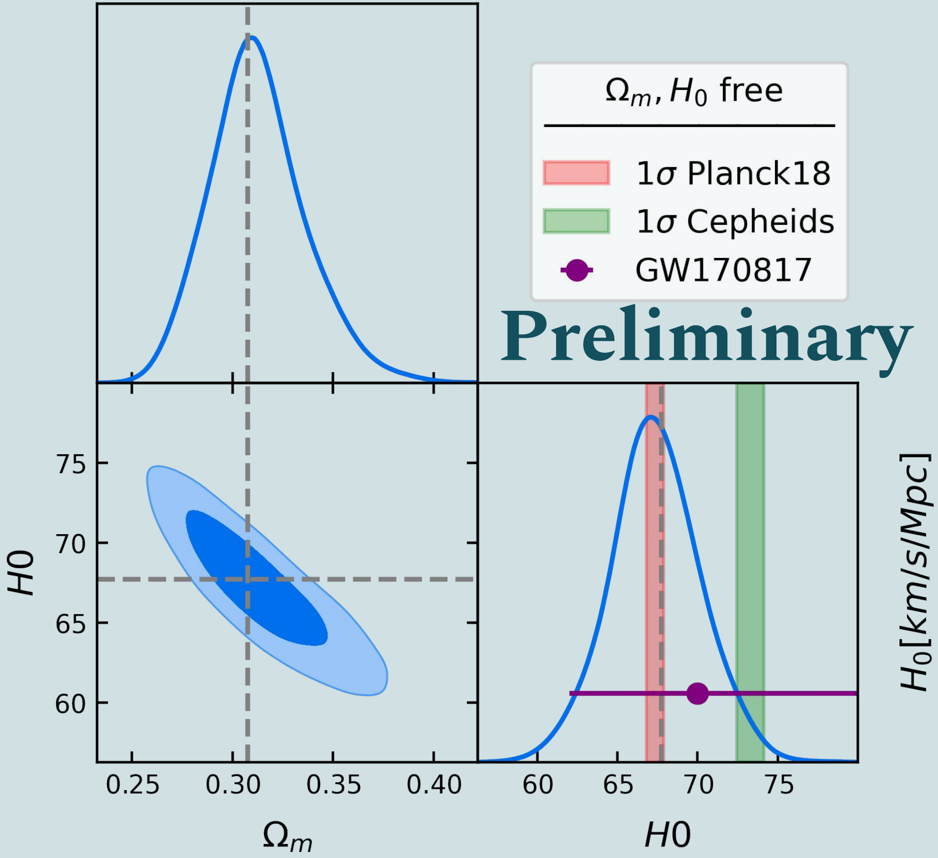
1σ Planck18
1σ Cepheids
GW170817
Preliminary
75
70
65
60
H0[km/s/Mpc]
0.25
0.30
0.35
0.40
Ωm
60
65
70
75
H0[km/s/Mpc]

Results

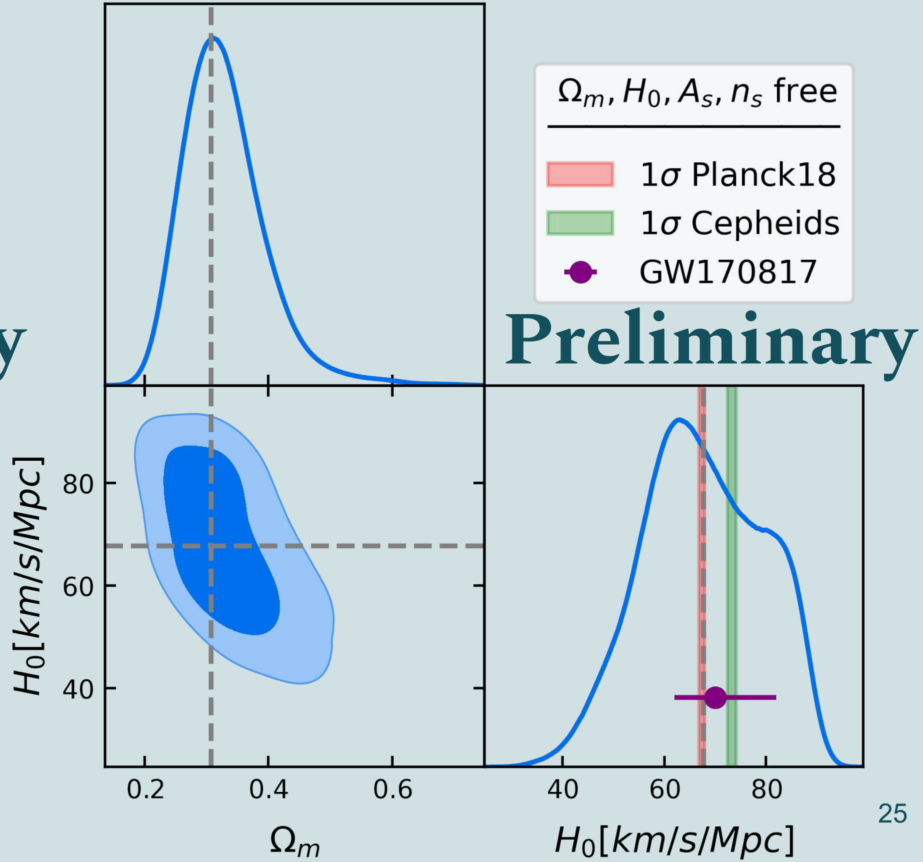


Preliminary

Results

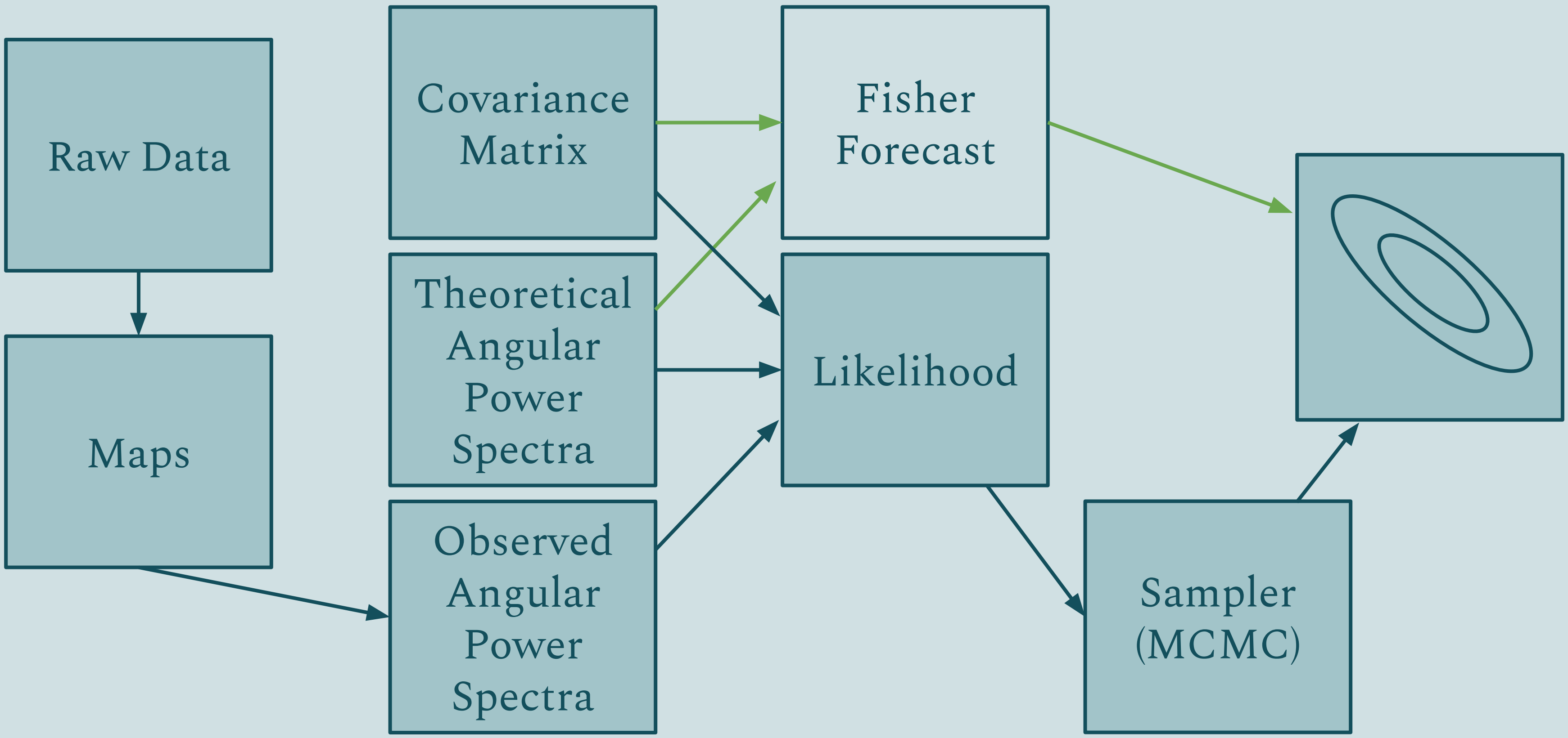


Ω_m, H_0 free
1σ Planck18
1σ Cepheids
GW170817
Preliminary
75
70
65
60
H0
0.25
0.30
0.35
0.40
Ω_m
60
65
70
75
H0



Ω_m, H_0, A_s, n_s free
1σ Planck18
1σ Cepheids
GW170817
Preliminary
80
60
40
H_0[km/s/Mpc]
0.2
0.4
0.6
Ω_m
40
60
80
H_0[km/s/Mpc]

Summary



Raw Data
Maps
Covariance Matrix
Theoretical Angular Power Spectra
Observed Angular Power Spectra
Fisher Forecast
Likelihood
Sampler (MCMC)

Future Developments

1) Release public available likelihood to perform forecast with custom method selection, e.g.: tracer (HI, GW, other), observational setup (detector network and sensitivity);

2) Extend the analysis to astrophysical parameter estimation, by fixing the cosmological model;

3) Parametric and non-parametric cosmological analysis in Λ-CDM and extended Dark Energy models;

4) Explore alternative cosmological tracers, such as Lyman-α forest.

Thanks for the attention!