Cosmological parameter constraints from HI Intensity Mapping lognormal simulations

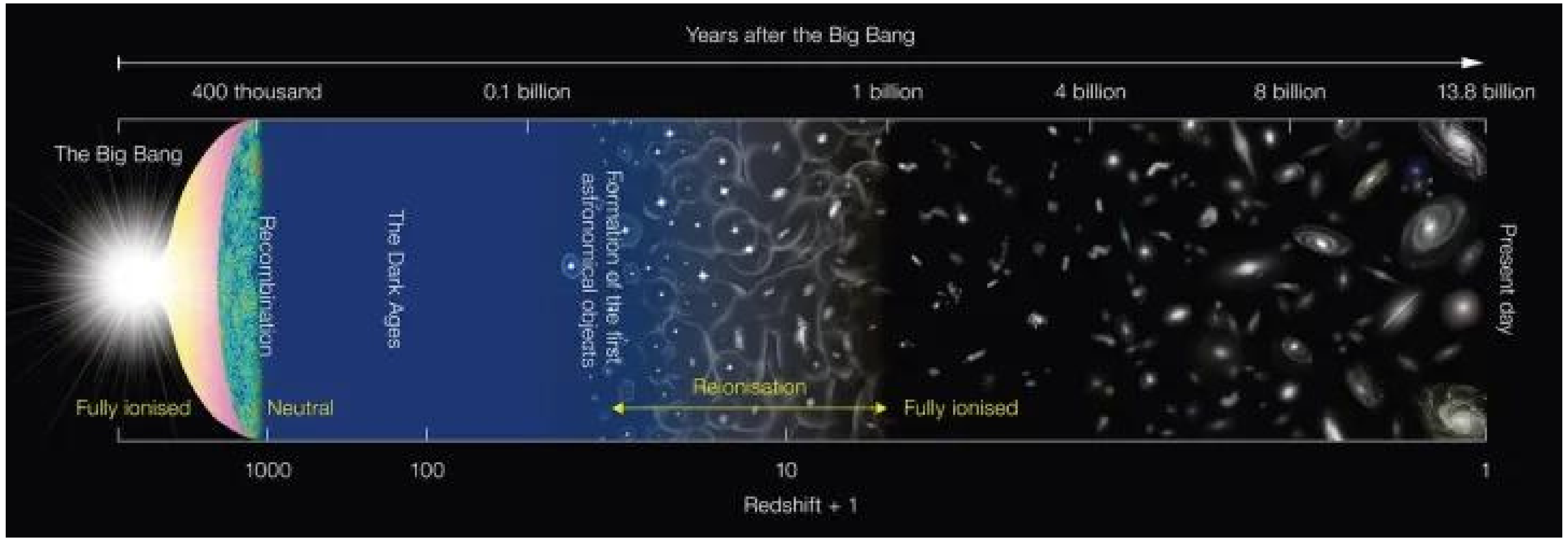
PABLO MOTTA

UNIVERSIDADE DE SÃO PAULO
NETHERLANDS INSTITUTE FOR RADIO ASTRONOMY

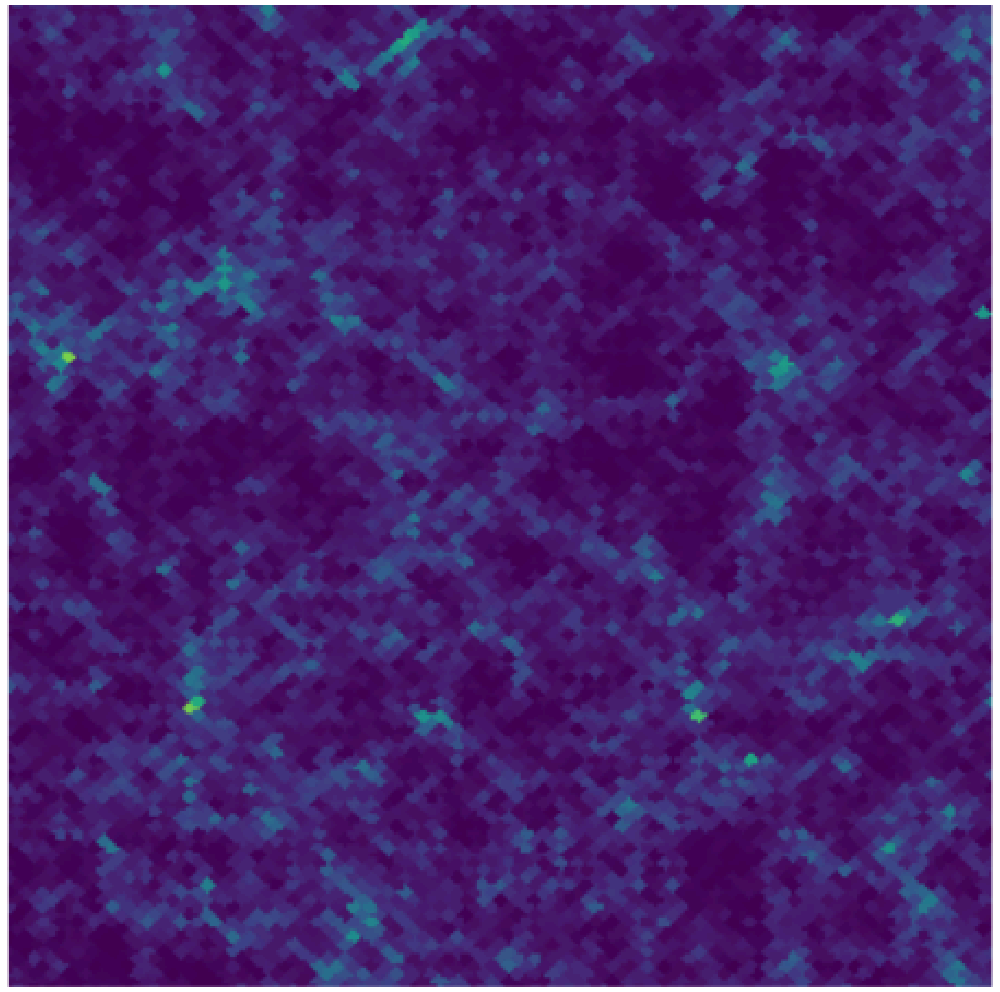
BINGO Collaboration Meeting 2023-12-07

Introduction

- The main science goal of BINGO is cosmology.
- BINGO is a radio Hi Intensity Mapping (IM) experiment. The IM technique measures the full intensity field, the brightness temperature, from the 21−cm emission.
- BINGO will constrain cosmology using HI as a tracer of the matter density in our Universe.
- BINGO will improve the constraints on current cosmological parameters in combination with other experiments, such as CMB measurements.



Cosmic expansion

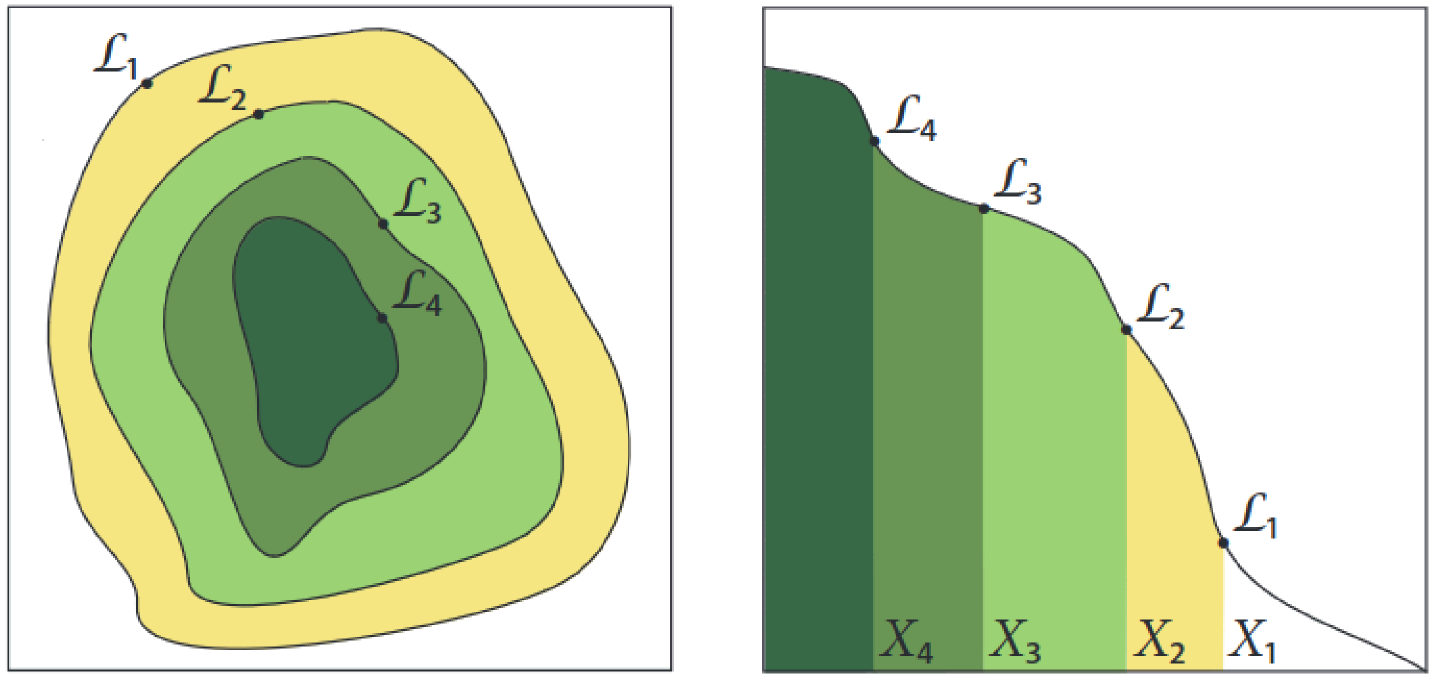


HI brightness temperature: a tracer of the underlying matter

Bayesian inference

- Bayes Theorem state that (conditional probabilities)

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$



(a) (b)

- For parameter inference

$$P(\Theta|\mathcal{D}) = \frac{P(\mathcal{D}|\Theta)P(\Theta)}{P(\mathcal{D})}$$

Prior distribution (initial beliefs)

Evidence or marginal likelihood (normalizes the posterior)

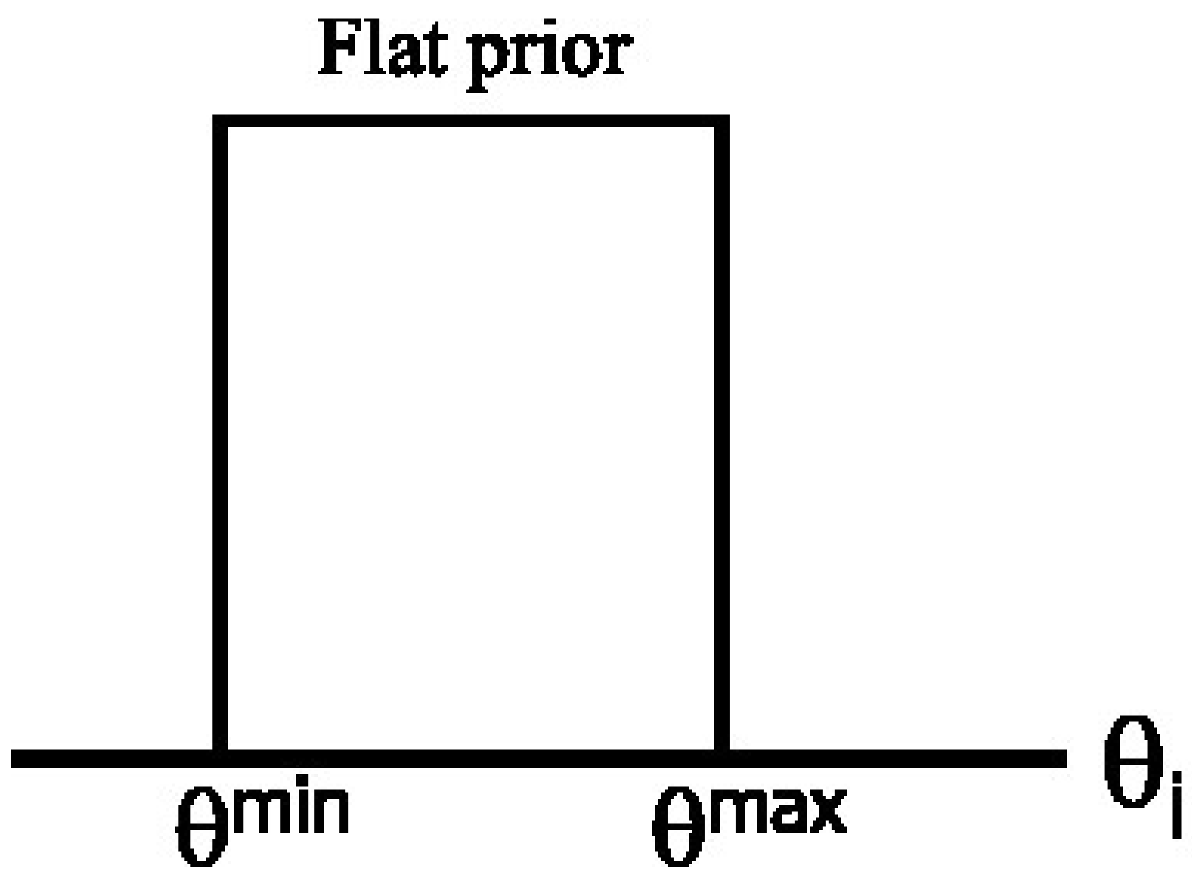
Posterior: probability of the parameters given the data

Likelihood: probability of the data given the parameter value

Priors

- Assumed a uniform distribution (flat priors)

Parameter	Prior
Ω_b	0.03, 0.07
Ω_{cdm}	0, 0.7
h	0.5, 1
n_s	0.87, 1.07
$\ln 10^{10} A_s$	0.5, 5
τ_r	0.01, 0.2
b^i_{HI}	0.8, 1.2
$\Omega^i_{HI} b^i_{HI}$	$2 \times 10^{-4}, 4 \times 10^{-4}$



Likelihood

- Assuming flat priors, the posterior distribution is obtained from a sample of the likelihood function.
- We sample the likelihood using a Monte Carlo method that converges towards the region in parameter space with higher likelihood.
- The likelihood is computed with the formula bellow. **It depends on the theoretical angular power spectrum and the measured one from the (simulated) data.**

$$\mathcal{L}_G(\mathbf{\Theta}) = \frac{1}{\sqrt{|2\pi\mathcal{C}|}} \exp\left(-\frac{1}{2}\chi^2(\mathbf{\Theta})\right)$$

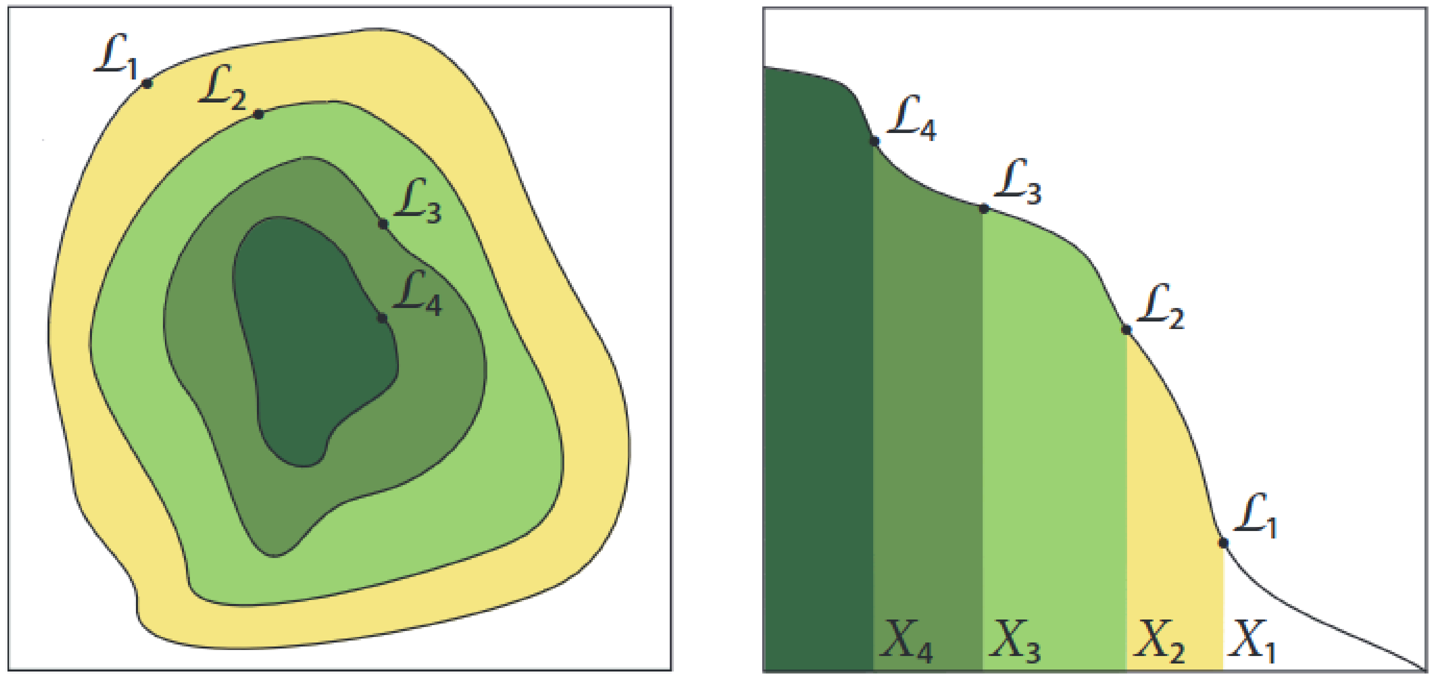
where

$$\chi^2(\mathbf{\Theta}) = \left[\hat{S}_b - S_b^{th}(\mathbf{\Theta})\right]^T \mathcal{C}^{-1} \left[\hat{S}_b - S_b^{th}(\mathbf{\Theta})\right]$$

Measurement

Theory

Covariance

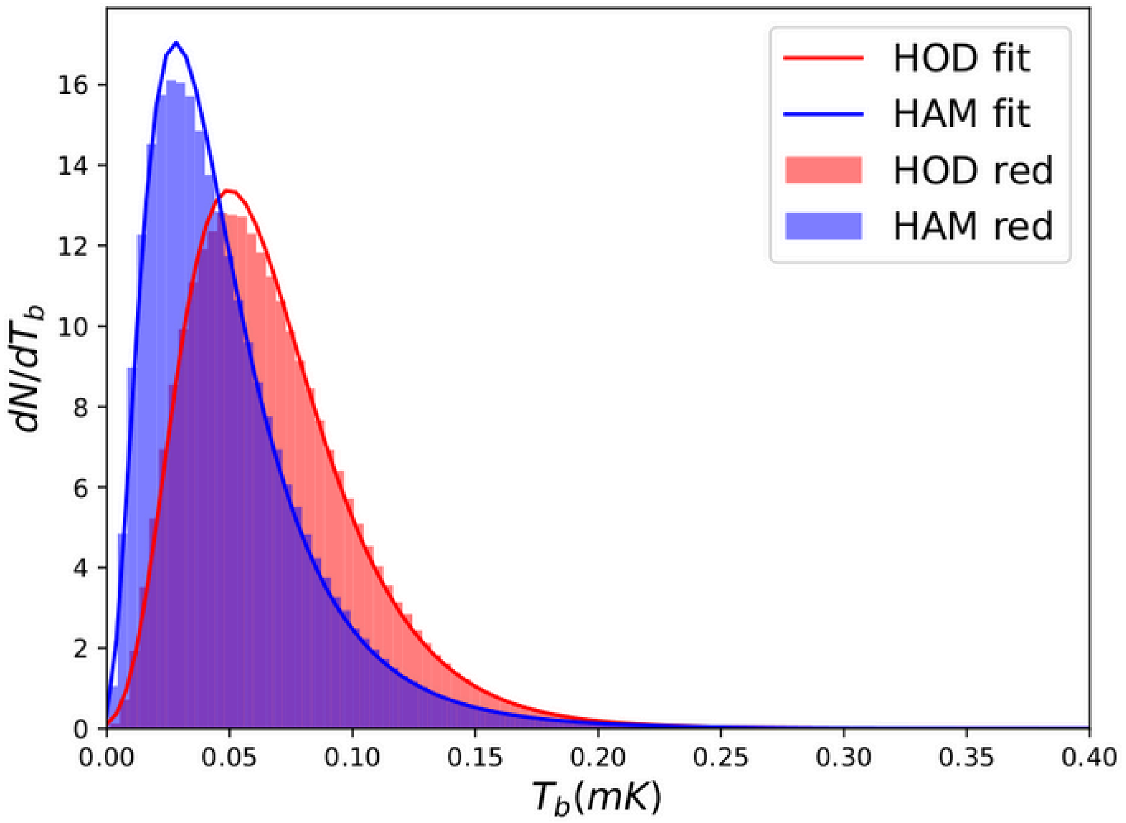


(a) (b)

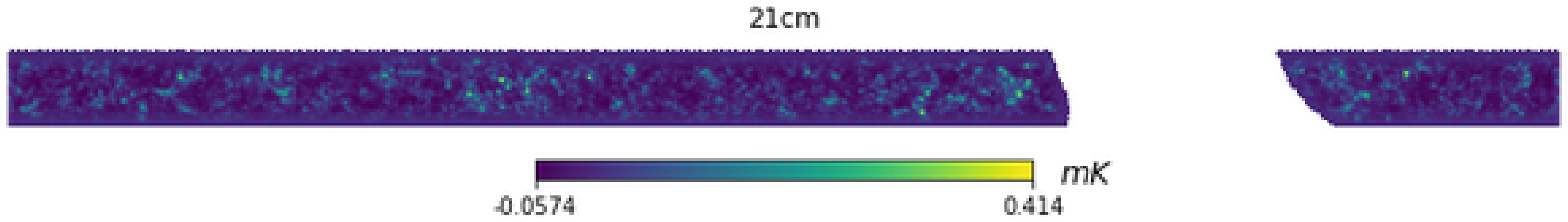
BINGO simulations

21cm simulation

- We created random lognormal maps of the 21cm brightness temperature.
- The lognormal distribution was fitted from the Zhang at al (N−body) mock maps[1].



Brightness temperature histogram from Zhang at al.



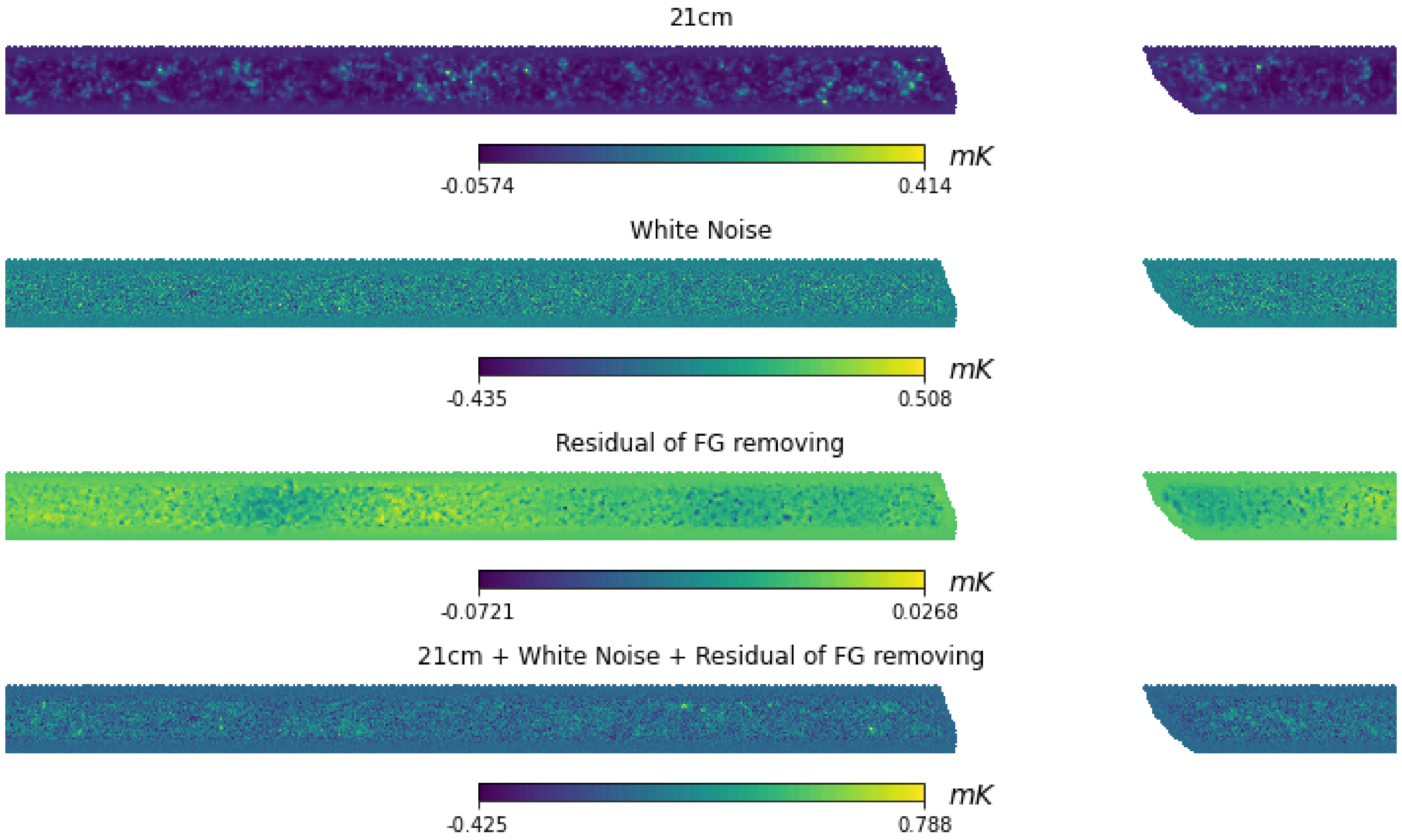
A random lognormal map of the pure 21cm signal

1. Zhang et al – *10.1051/0004-6361/202140887*

BINGO simulations

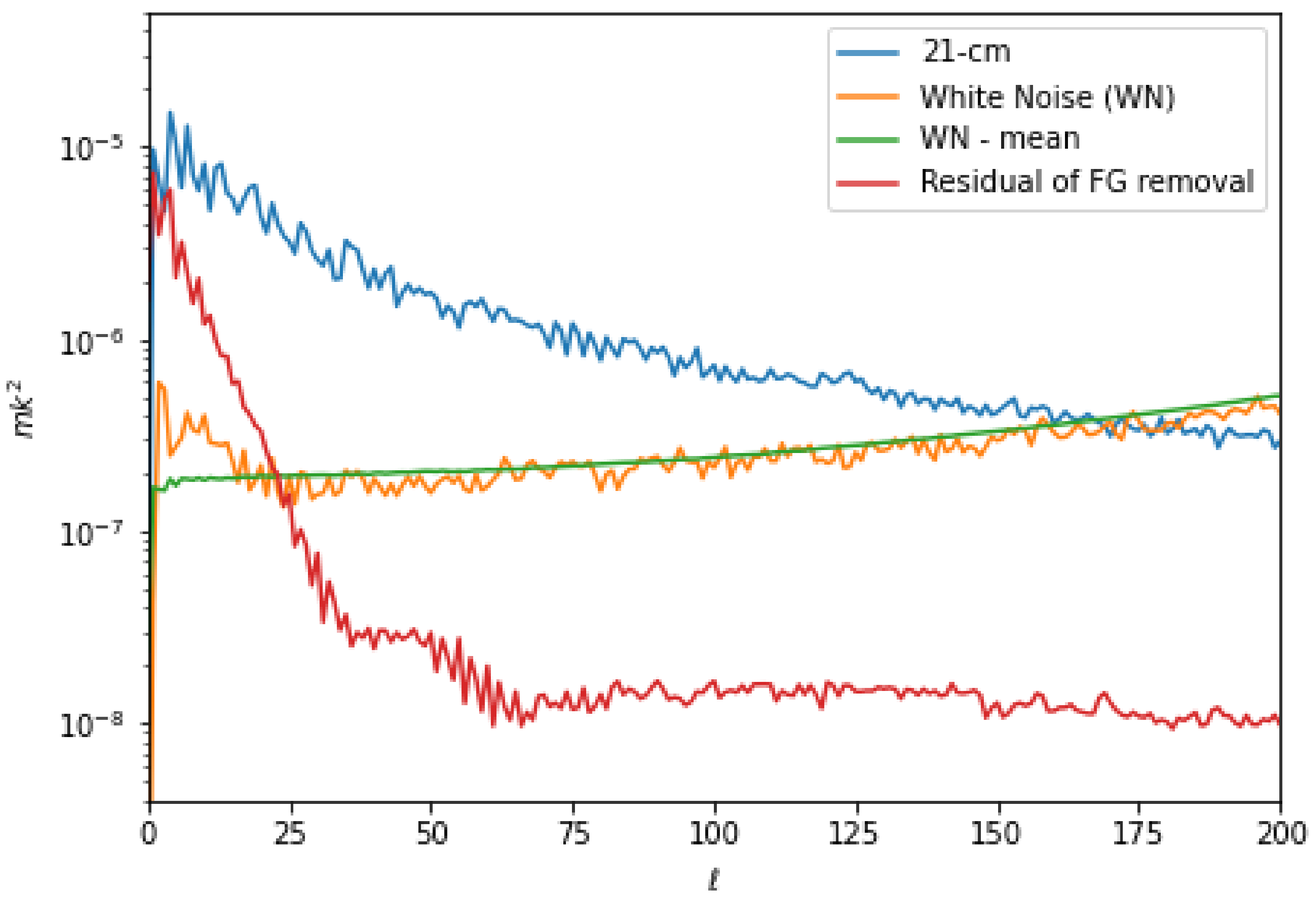
The BINGO simulation have three ingredients:

1. **Lognormal 21cm cosmological signal.**
2. **Gaussian White Noise (WN) map.** It is assumed BINGO phased I operation[2] and a 28 horns optical arrangement[3].
3. **Residual of Foreground (FG) removal.** It is assumed GNILC method with 07 components including Galactic synchrotron, free–free, thermal dust and others.[4]

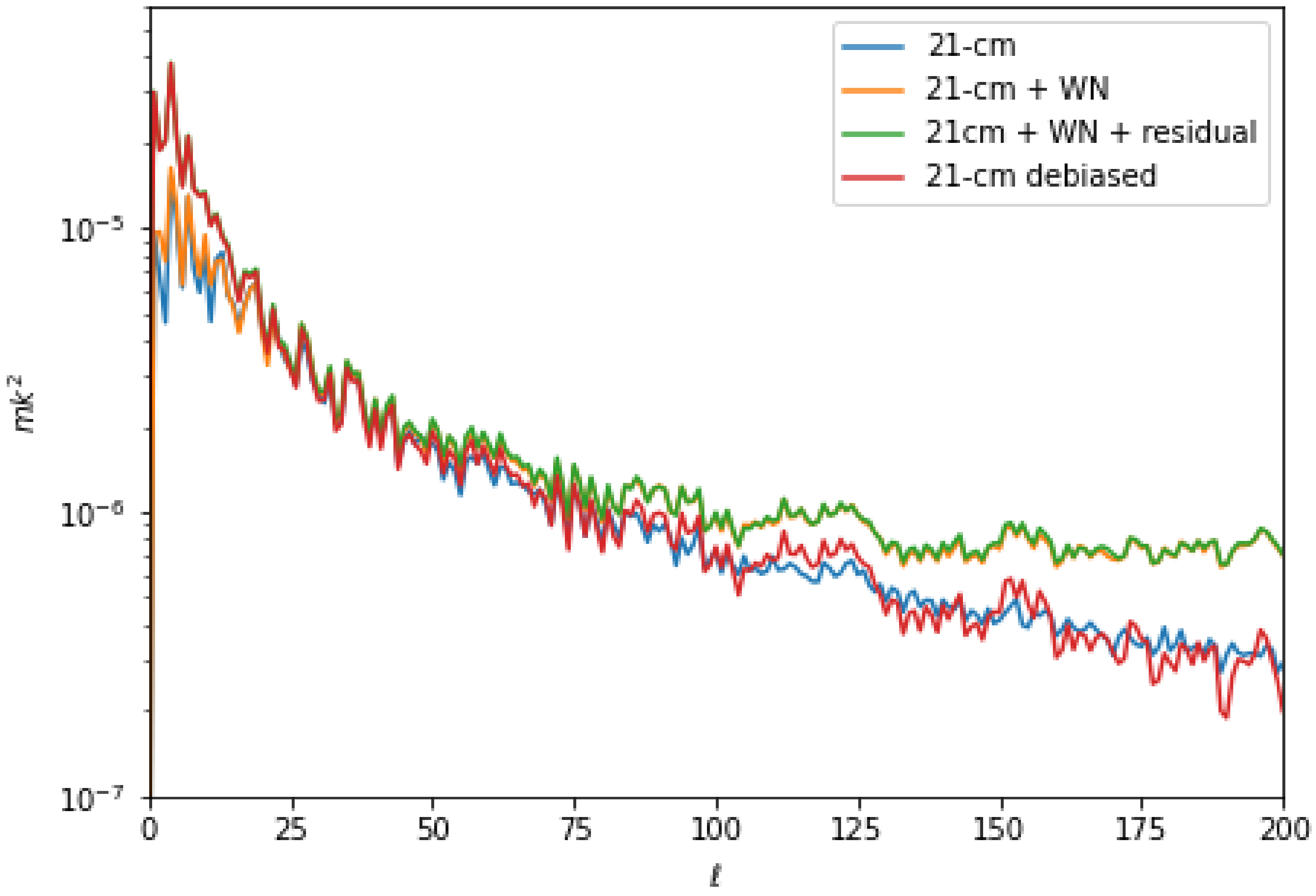


2. Wuensche et al – *10.1051/0004-6361/202039962*
3. Abdalla et al – *10.1051/0004-6361/202141382*
4. de Mericia et al – *10.1051/0004-6361/202243804*

APS measurements



The three ingredients of the simulation.

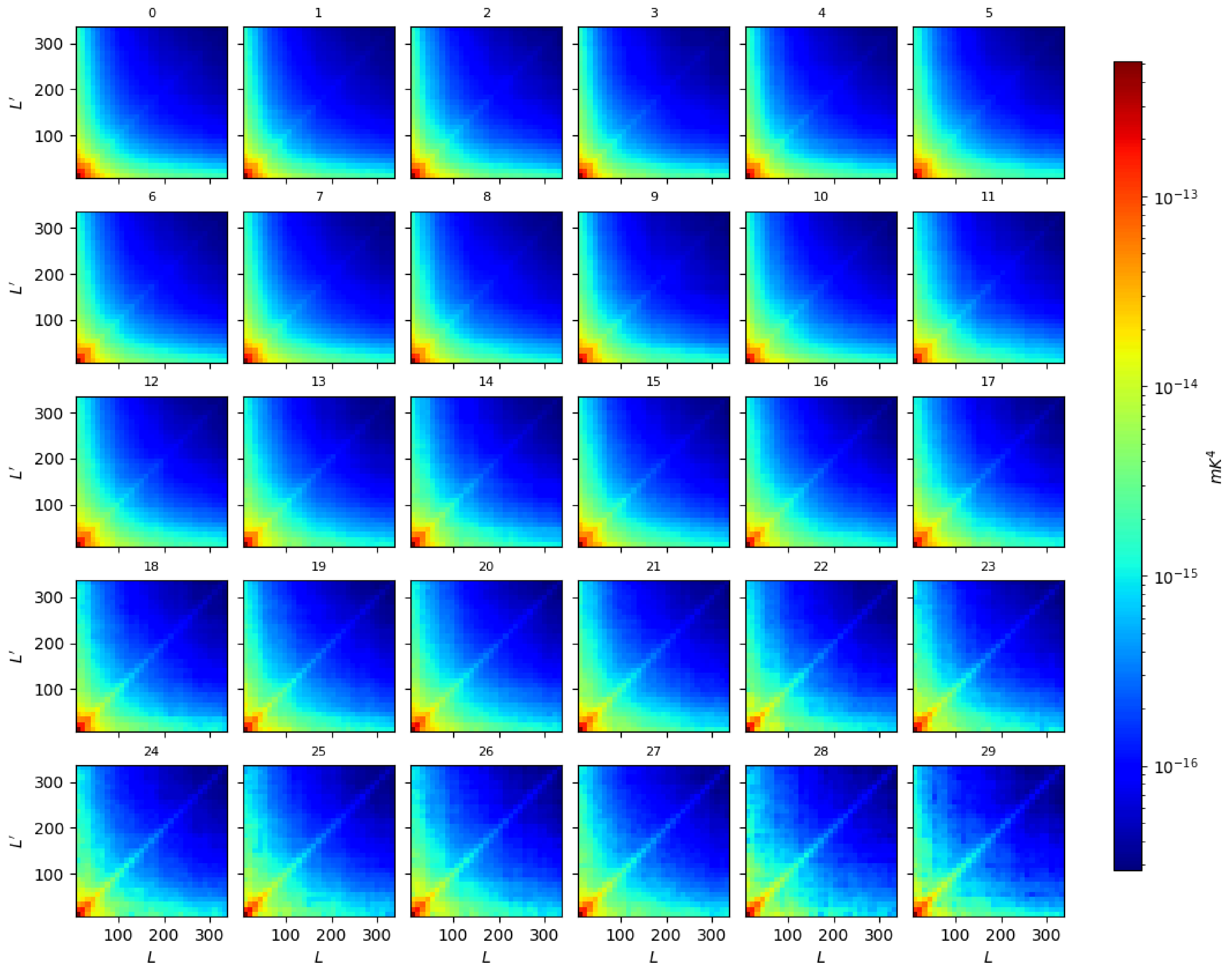


The three ingredients summed up.

- Debiasing is done by removing the expected White Noise contribution.

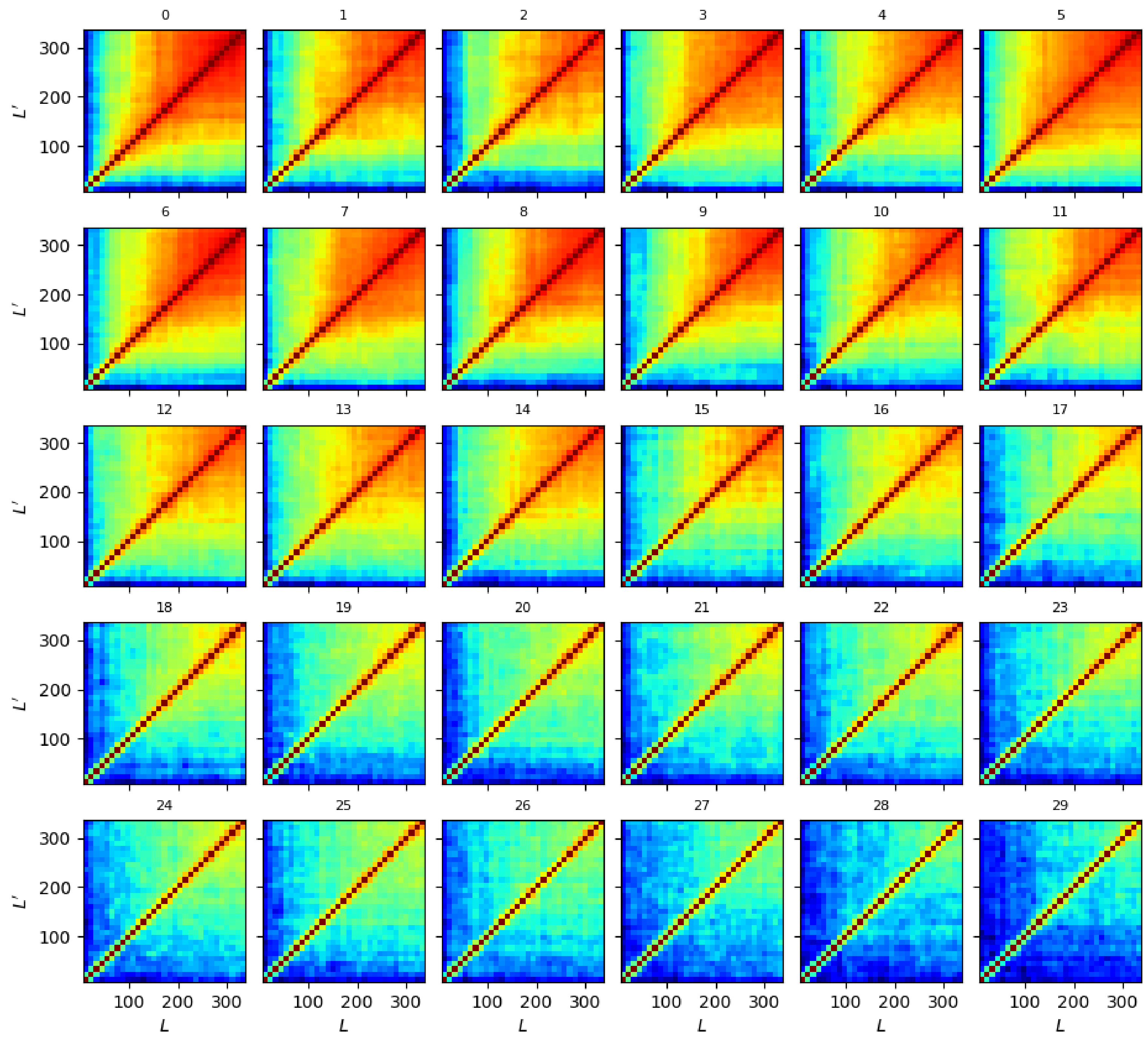
$$\hat{S}_\ell^{ij} = (d_\ell^{ij} - \hat{d}_\ell^{noise})/f_{sky}\, b_\ell^2 w_\ell^2$$

Covariance matrix

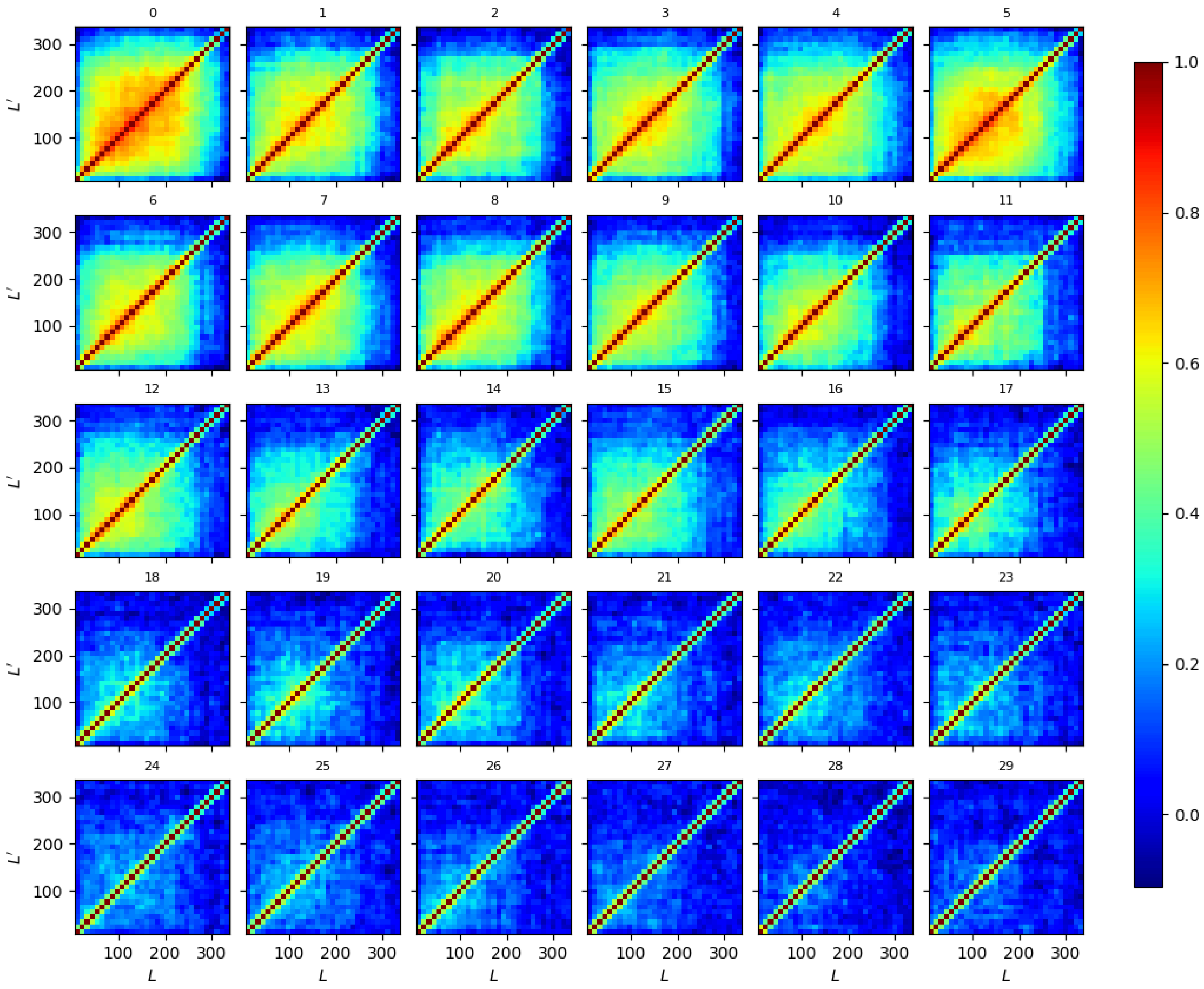


Covariance matrix

- We plot the covariance matrix in the form given by the Pearson correlation $P_{ij} = \frac{C_{ij}}{\sqrt{(C_{ii}C_{jj})}}$



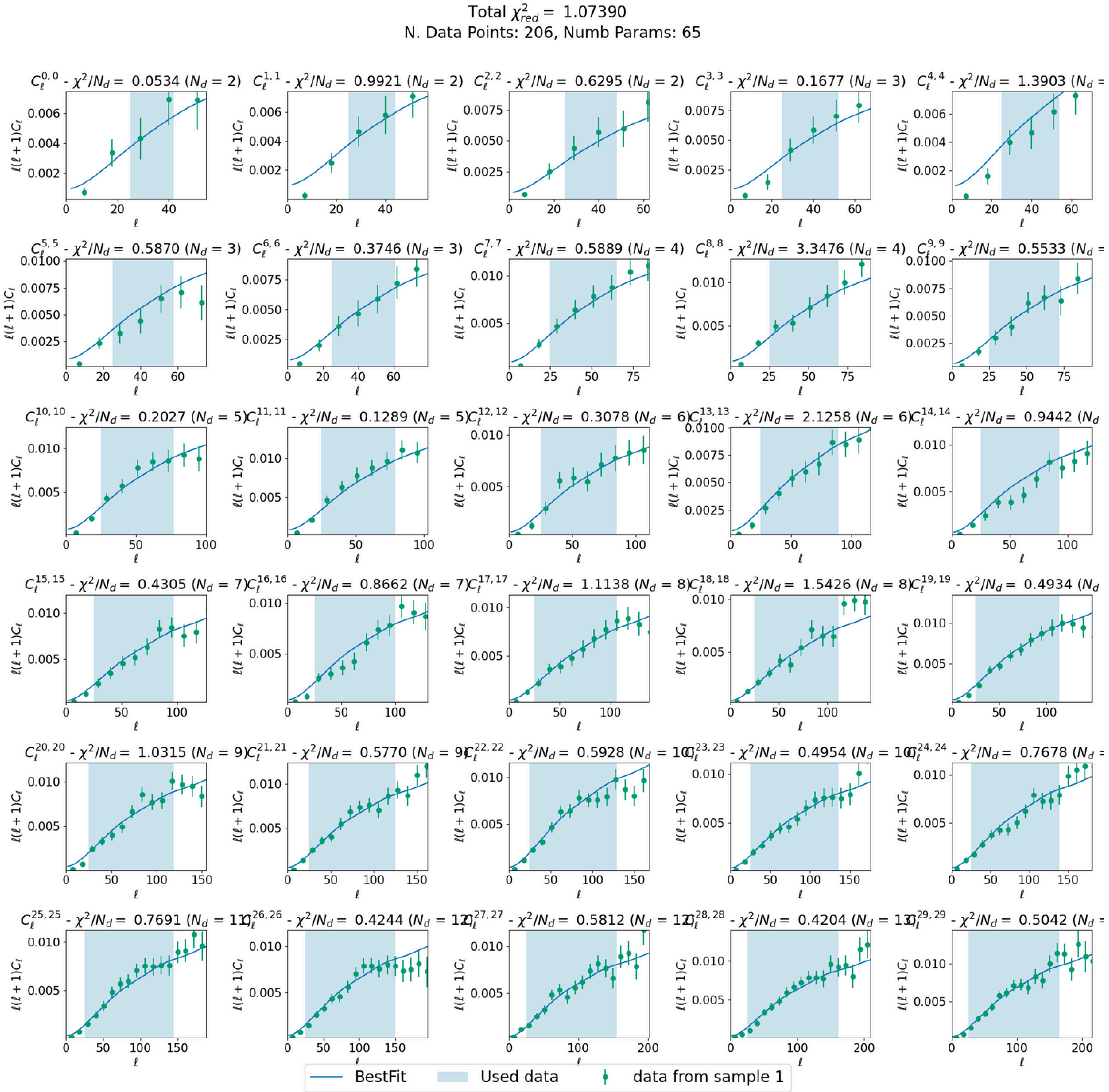
Pure 21cm



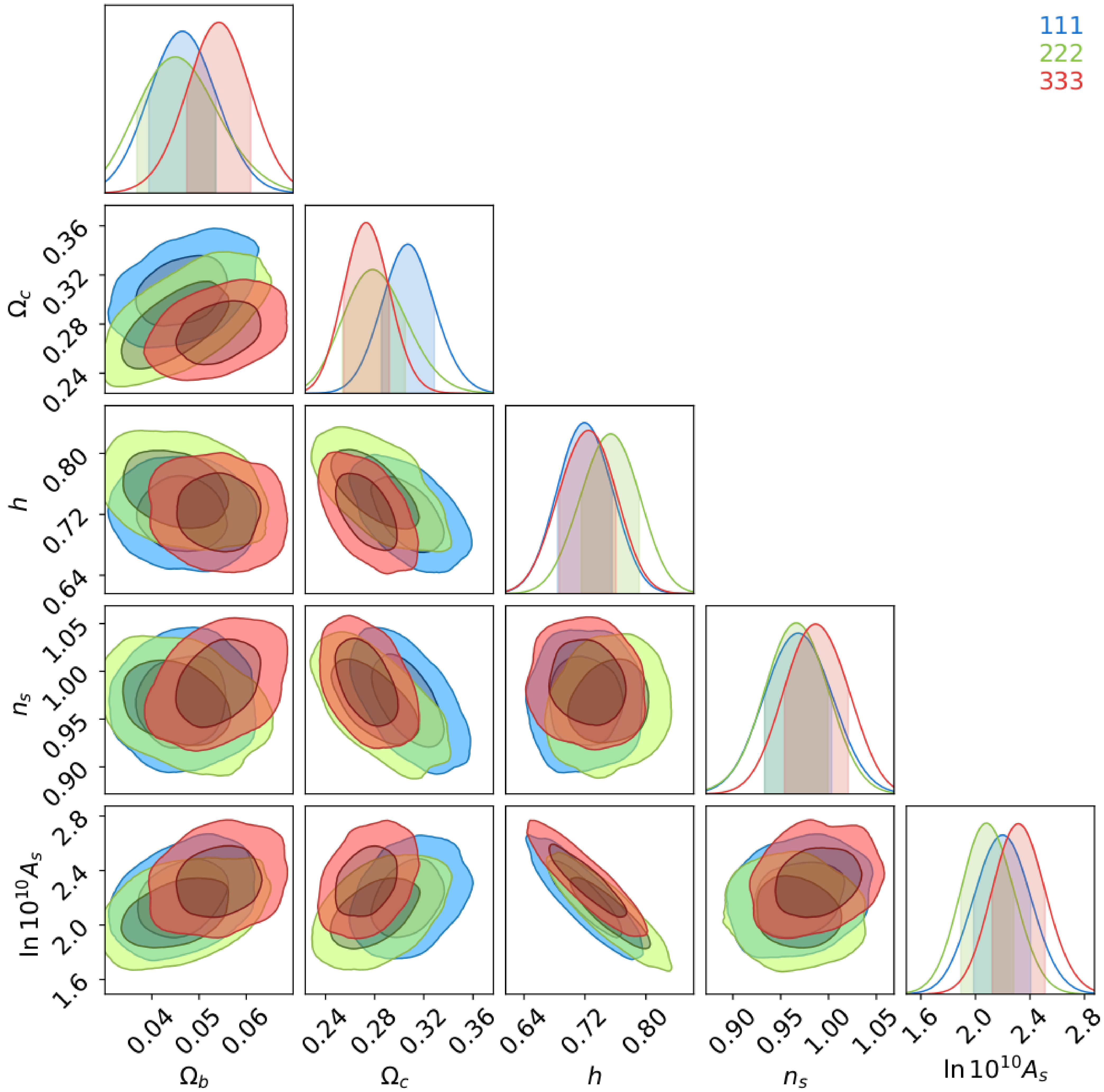
WN and FG res. included

Results

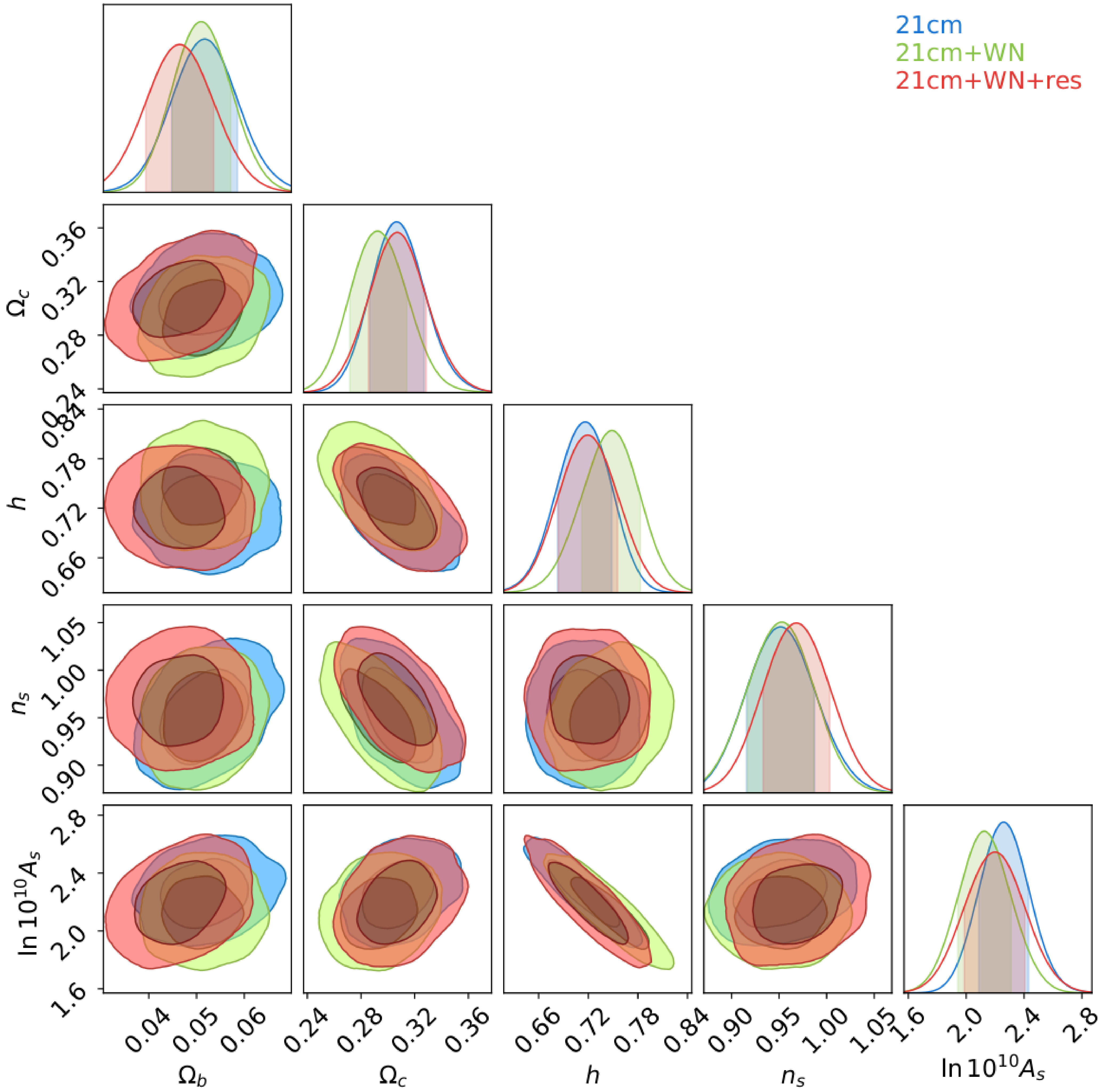
Best−fit curve



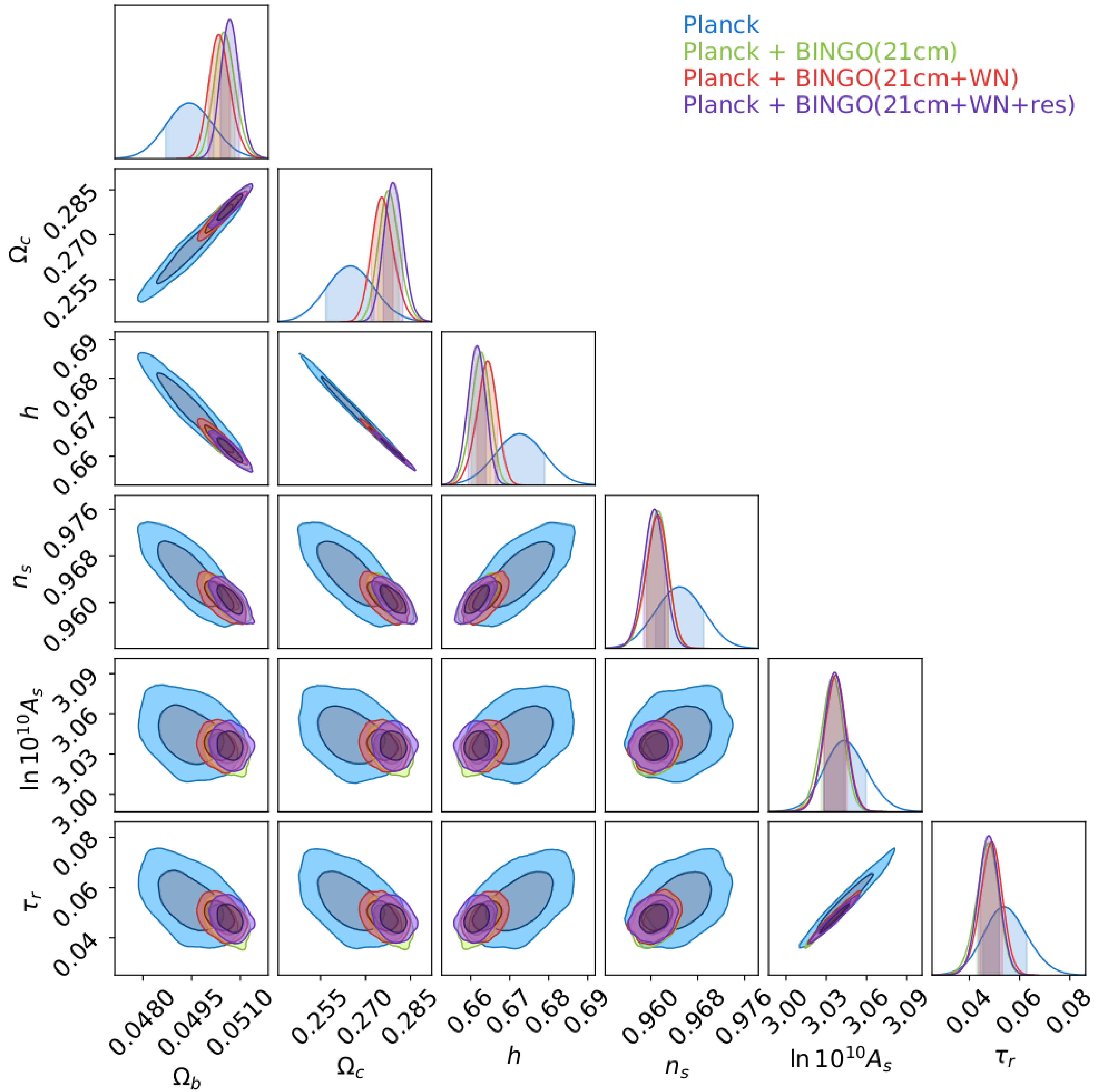
BINGO ΛCDM constraints: different realizations



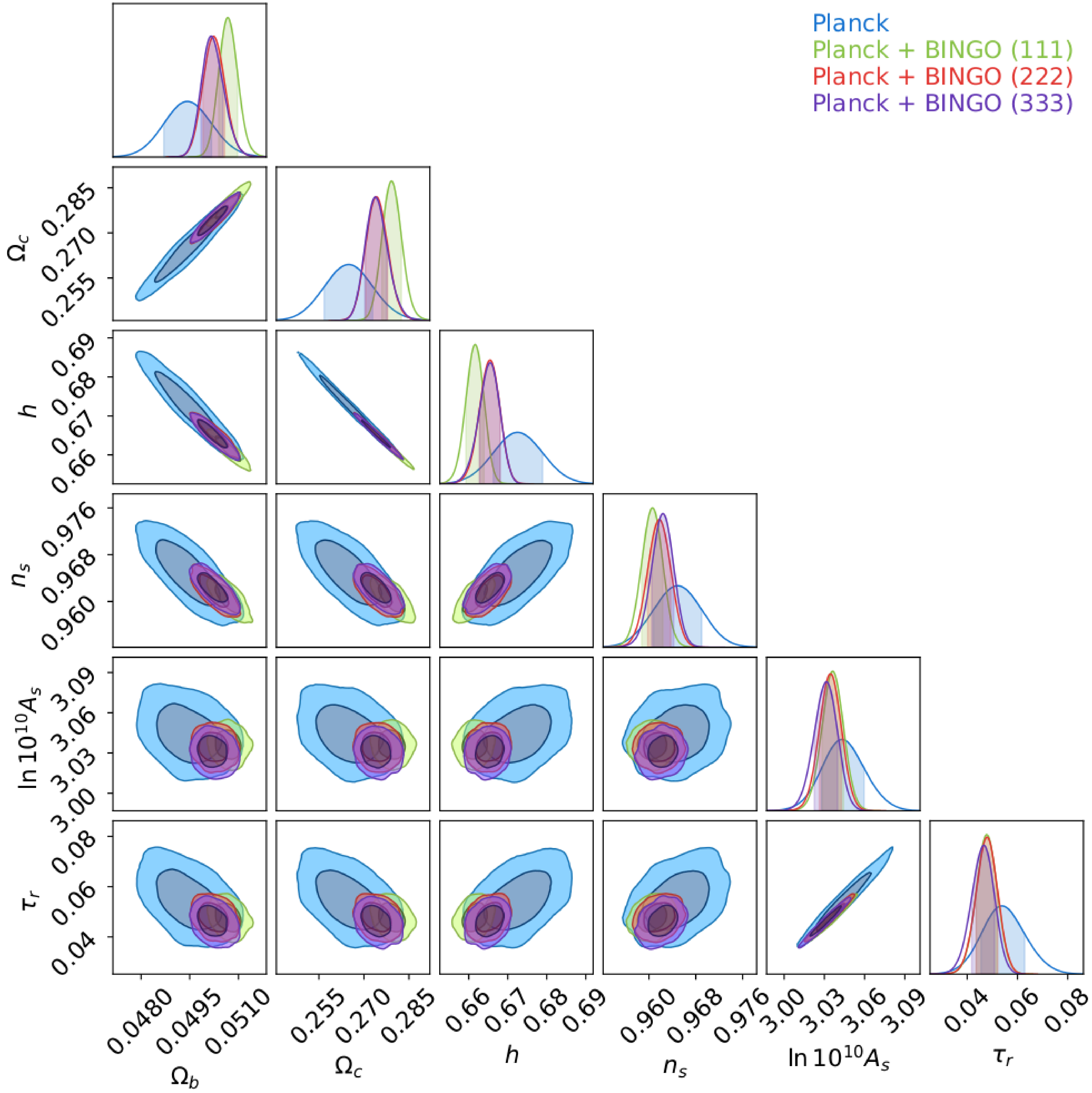
BINGO ΛCDM constraints: systematic effects



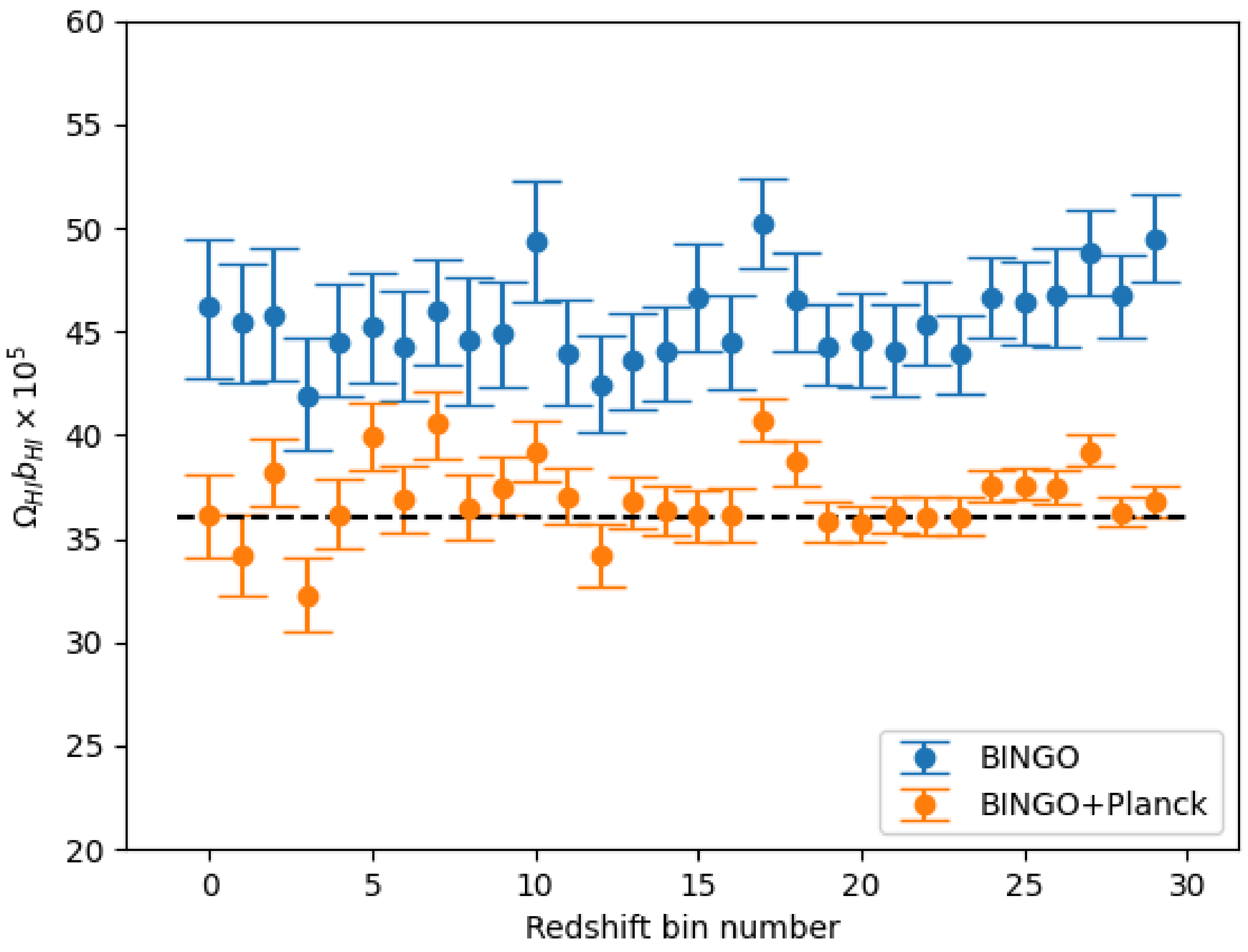
BINGO + Planck 2018 ΛCDM constraints: systematic effects

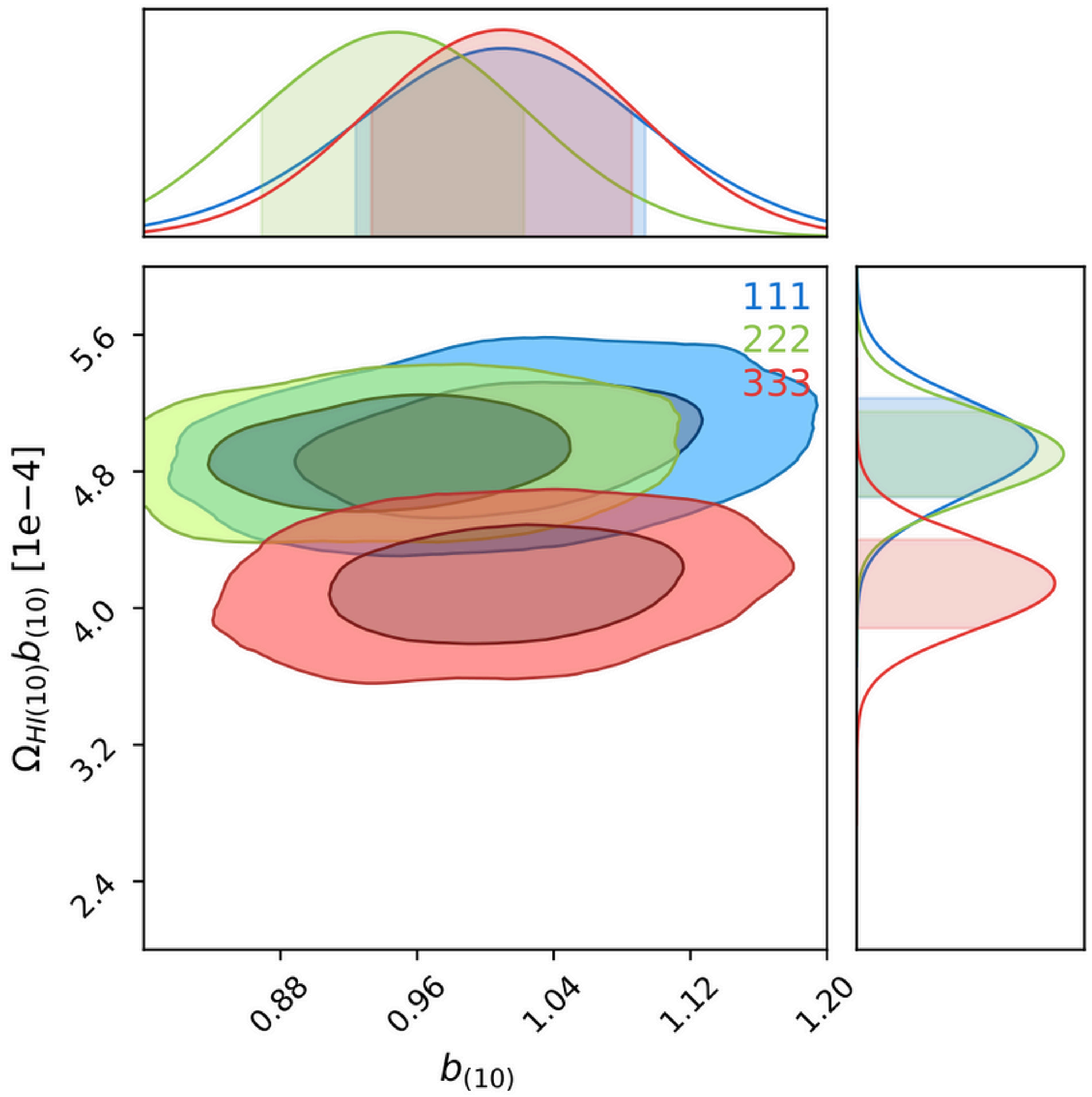


BINGO + Planck 2018 ΛCDM constraints: different realizations



Nuisance constraints





Chi2 values

Comparison between realizations

	sim 111	sim 222	sim 333	sim 444
BINGO	1.47	1.07	1.09	1.31
BINGO + Planck	1.52	1.13	1.12	1.48

Comparison between systematic error levels

	21cm	21cm+WN	21cm +WN+res
BINGO	1.23	1.21	1.47
BINGO + Planck	1.27	1.23	1.52

Next

Some extended analysis are on the way:

1. Dynamical DE and DE−DM interaction physics (Luiza Ponte et al)
2. Neutrino physics (Linfeng et al)
3. Modified gravity

Thank you

Extra slides

Overview

- **Objective:** Obtain cosmological parameter constraints using HI Intensity Mapping simulations for BINGO phase 1 operation.

- **Simulation components:** cosmological 21-cm signal modeled as a multivariate lognormal distribution, inclusion of main foreground sources within BINGO frequency range, incorporation of instrumental noise. Consideration of the effect introduced by a fixed instrumental beam resolution.

- **Methodology:** Application of Angular Power Spectrum (APS) formalism to BINGO simulations and adoption of a standard Bayesian analysis framework.

- **Results:** Derivation of cosmological parameter constraints for BINGO and BINGO + Planck 2018.

Multipole selection

Redshift bin	ℓ_{min}	ℓ_{max}
0	25	42
1	25	44
2	25	48
3	25	52
4	25	54
5	25	58
6	25	61
7	25	65
8	25	69
9	25	72
10	25	77
11	25	79
12	25	85
13	25	89
14	25	93
15	25	97
16	25	100
17	25	106
18	25	111
19	25	114
20	25	119
21	25	125
22	25	129
23	25	135
24	25	139
25	25	145
26	25	150
27	25	155
28	25	161
29	25	165

Table 3. Marginalised cosmological ΛCDM constraints and 68% credible intervals for BINGO simulations for the three cases: pure cosmological 21-cm signal; the cosmological signal added of white noise; the cosmological signal added of white noise and residuals of foreground removal.

Parameter	21cm	21cm+WN	21cm+WN+res
Ω_b	0.0517 ± 0.0069	$0.0509^{+0.0062}_{-0.0061}$	$0.0465^{+0.0071}_{-0.0072}$
Ω_c	0.307 ± 0.020	$0.292^{+0.022}_{-0.021}$	$0.307^{+0.022}_{-0.021}$
h	$0.716^{+0.032}_{-0.033}$	$0.748^{+0.034}_{-0.036}$	0.720 ± 0.036
n_s	0.951 ± 0.036	$0.953^{+0.034}_{-0.036}$	0.968 ± 0.035
$\ln 10^{10} A_s$	2.26 ± 0.17	$2.12^{+0.19}_{-0.18}$	2.20 ± 0.21

Table 4. Similar as Table 3 but for the BINGO + Planck 2018 likelihood.

Parameter	Planck	Planck + BINGO(21cm)	Planck + BINGO(21cm+WN)	Planck + BINGO(21cm+WN+res)
Ω_b	$0.04942^{+0.00074}_{-0.00072}$	$0.05049^{+0.00034}_{-0.00031}$	$0.05034^{+0.00034}_{-0.00033}$	$0.05067^{+0.00030}_{-0.00028}$
Ω_c	0.2648 ± 0.0081	$0.2777^{+0.0034}_{-0.0035}$	$0.2754^{+0.0038}_{-0.0036}$	0.2792 ± 0.0033
h	$0.6726^{+0.0064}_{-0.0063}$	0.6627 ± 0.00025	$0.6643^{+0.0026}_{-0.0027}$	$0.6617^{+0.0023}_{-0.0024}$
n_s	0.9649 ± 0.0041	$0.9612^{+0.0018}_{-0.0020}$	$0.9612^{+0.0018}-0.0020$	$0.9606^{+0.0018}_{-0.0019}$
$\ln 10^{10} A_s$	$3.043^{+0.016}_{-0.015}$	$0.30349^{+0.00080}_{-0.00087}$	$0.30371^{+0.00081}_{-0.00086}$	$0.30361^{+0.00082}_{-0.00079}$
τ_r	$0.0538^{+0.0090}_{-0.0084}$	$0.0477^{+0.0042}_{-0.0047}$	$0.0489^{+0.0044}_{-0.0045}$	0.0477 ± 0.0042

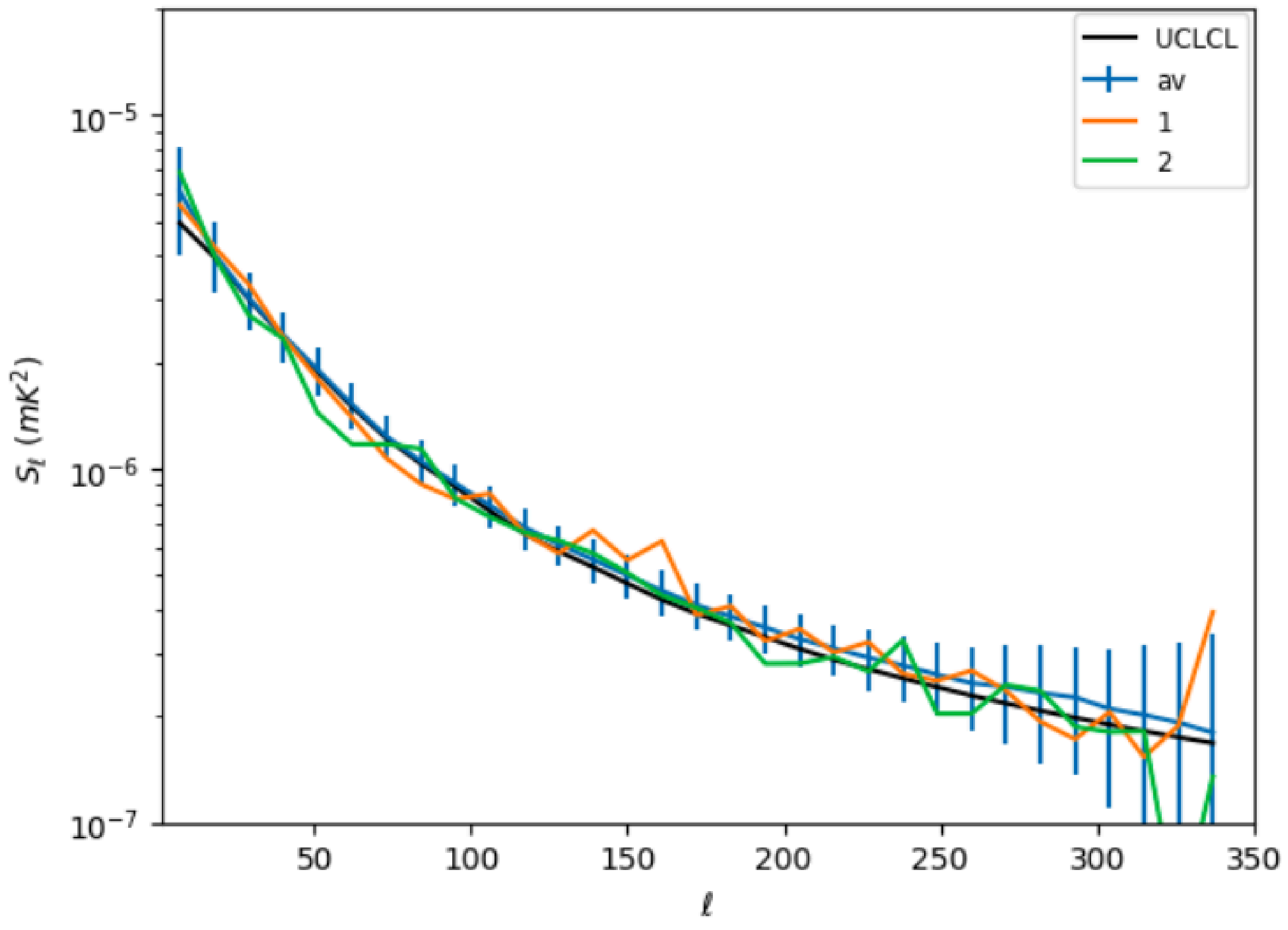
Table 5. Marginalised cosmological ΛCDM constraints and 68% credible intervals for different realizations of BINGO simulation. The numbers 111, 222 and 333 are just the number of the realization in the set of 500 simulations. white noise and foreground removal systematic errors effects are included.

Parameter	111	222	333
Ω_b	$0.0465^{+0.0071}_{-0.0072}$	$0.0451^{+0.0084}_{-0.0082}$	$0.0541^{+0.0068}_{-0.0067}$
Ω_c	$0.307^{+0.022}_{-0.021}$	$0.278^{+0.027}_{-0.024}$	$0.273^{+0.019}_{-0.018}$
h	0.720 ± 0.036	$0.754^{+0.037}_{-0.039}$	$0.725^{+0.036}_{-0.039}$
n_s	0.968 ± 0.035	$0.966^{+0.034}_{-0.033}$	$0.987^{+0.034}_{-0.033}$
$\ln 10^{10} A_s$	2.20 ± 0.21	$2.08^{+0.20}_{-0.19}$	$2.31^{+0.20}_{-0.19}$

Table 6. Similar as Table 3 but for the BINGO + Planck 2018 likelihood.

Parameter	Planck	Planck + BINGO (111)	Planck + BINGO (222)	Planck + BINGO (333)
Ω_b	$0.0004942^{+0.0000074}_{-0.0000072}$	$0.0005067^{+0.0000030}_{-0.0000028}$	$0.0005023^{+0.0000034}_{-0.0000033}$	$0.0005016^{+0.0000036}_{-0.0000031}$
Ω_c	0.2648 ± 0.0081	0.2792 ± 0.0033	$0.2741^{+0.0037}_{-0.0036}$	$0.2738^{+0.0039}_{-0.0035}$
h	$0.6726^{+0.0064}_{-0.0063}$	$0.6617^{+0.0023}_{-0.0024}$	$0.6655^{+0.0025}_{-0.0027}$	$0.6654^{+0.0026}_{-0.0027}$
n_s	0.9649 ± 0.0041	$0.9606^{+0.0018}_{-0.0019}$	0.9618 ± 0.0020	$0.9624^{+0.0018}_{-0.0020}$
$\ln 10^{10} A_s$	$3.043^{+0.016}_{-0.015}$	$0.0030361^{+0.0000082}_{-0.0000079}$	0.0030345 ± 0.0000083	$0.0030315^{+0.0000084}_{-0.0000091}$
τ_r	$0.0538^{+0.0090}_{-0.0084}$	0.0477 ± 0.0042	$0.0479^{+0.0043}_{-0.0044}$	$0.0466^{+0.0043}_{-0.0048}$

Cl measurements



21cm

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
relative error
2
0
−2
0
100
200
ℓ

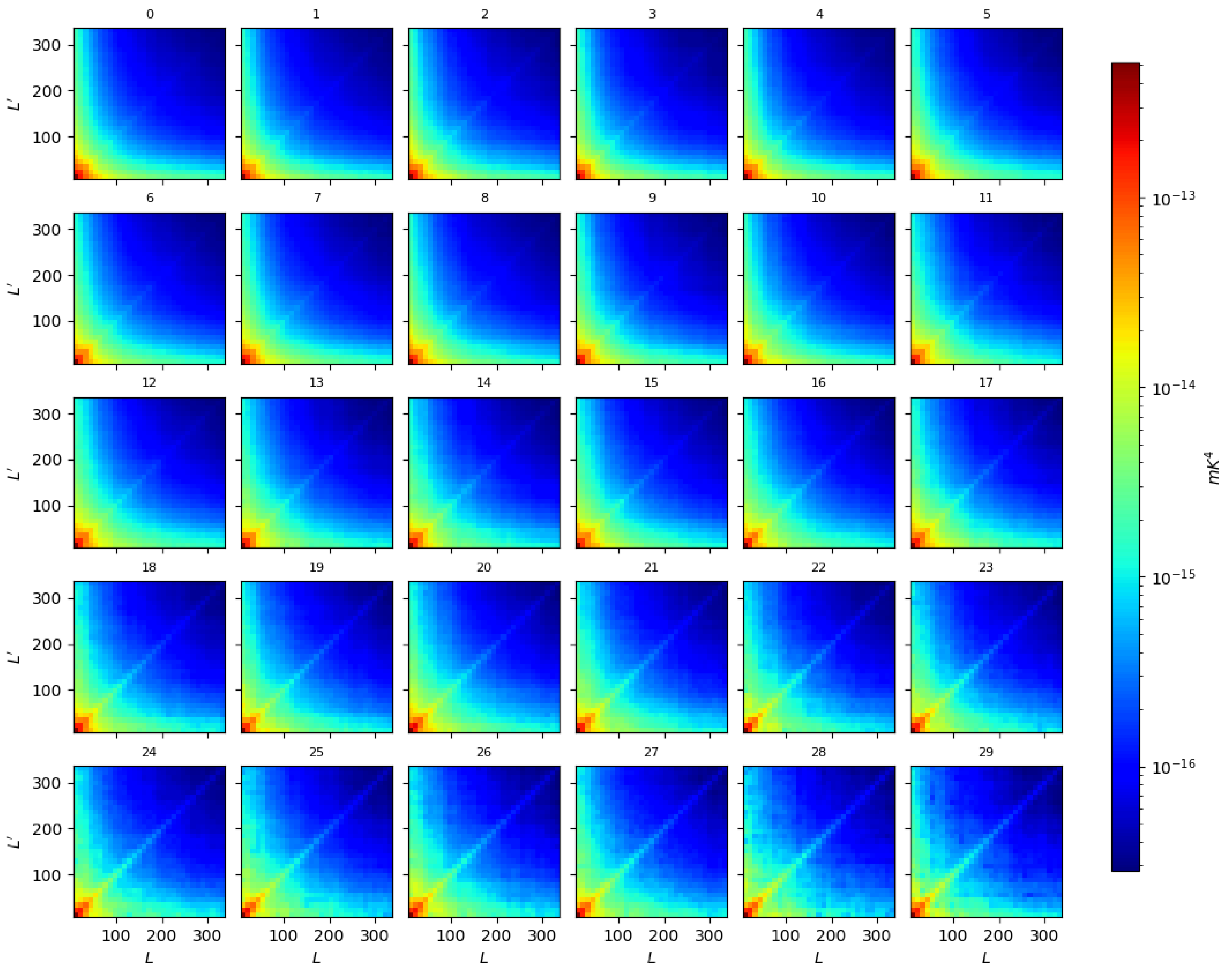
21cm + WN

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
relative error
2
0
−2
100
200
ℓ

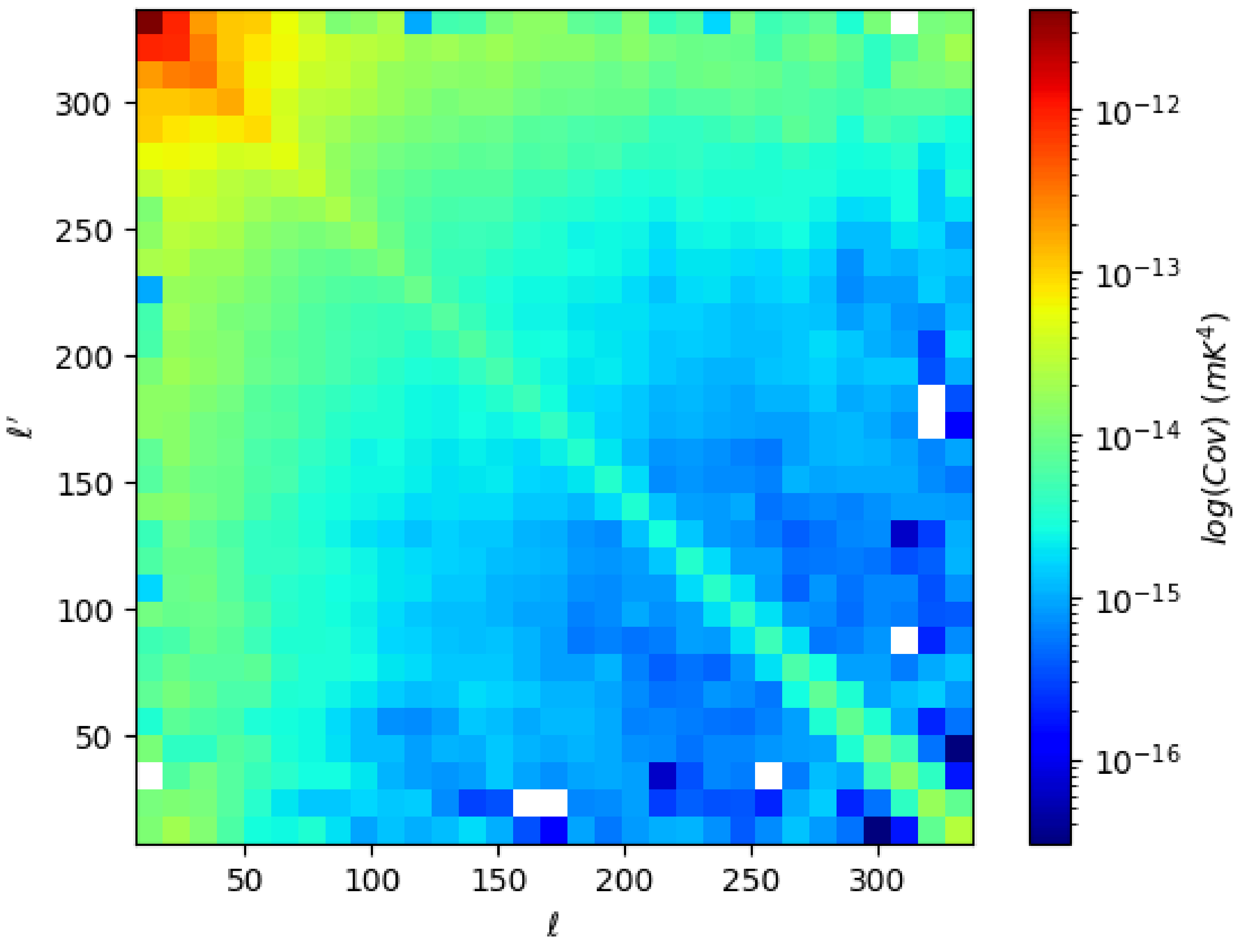
21cm + WN + res

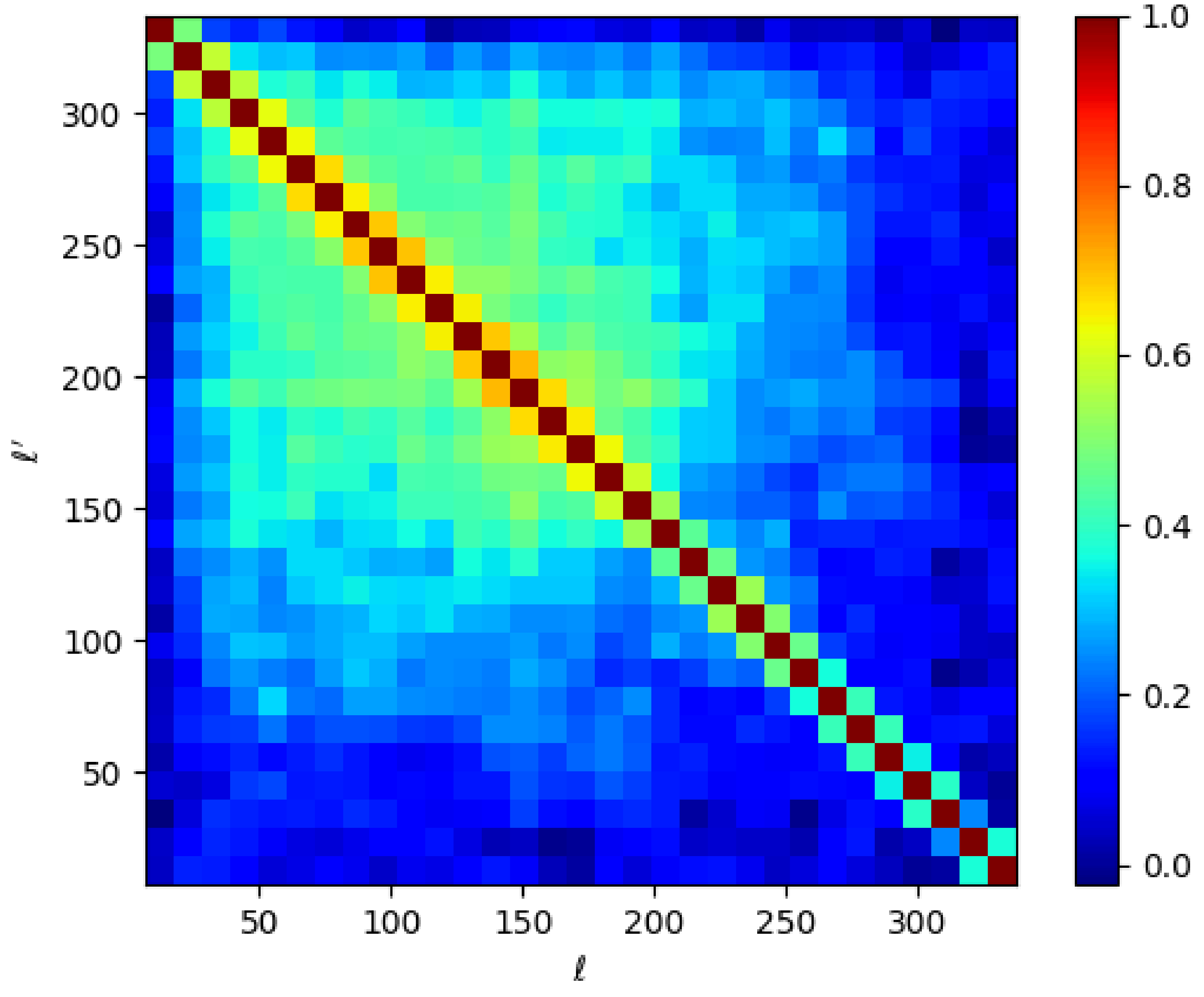
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
relative error
2
0
−2
0
100
200
ℓ

Covariance matrix



Covariance matrix and Pearson correlation





$$P_{ij} = \frac{C_{ij}}{\sqrt{(C_{ii} C_{jj})}}$$

Nuisance contour plots