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Probing the ΛCDM Universe and Beyond with Present and Future 21cm Intensity Mapping Surveys

Hydrogen Through Cosmic Time

Recombination
$z \sim 1100$

Reionization
$6 < z < 20$

LSS
(galaxies)

Neutral Hydrogen
(HI)

Our work

CMB
photons

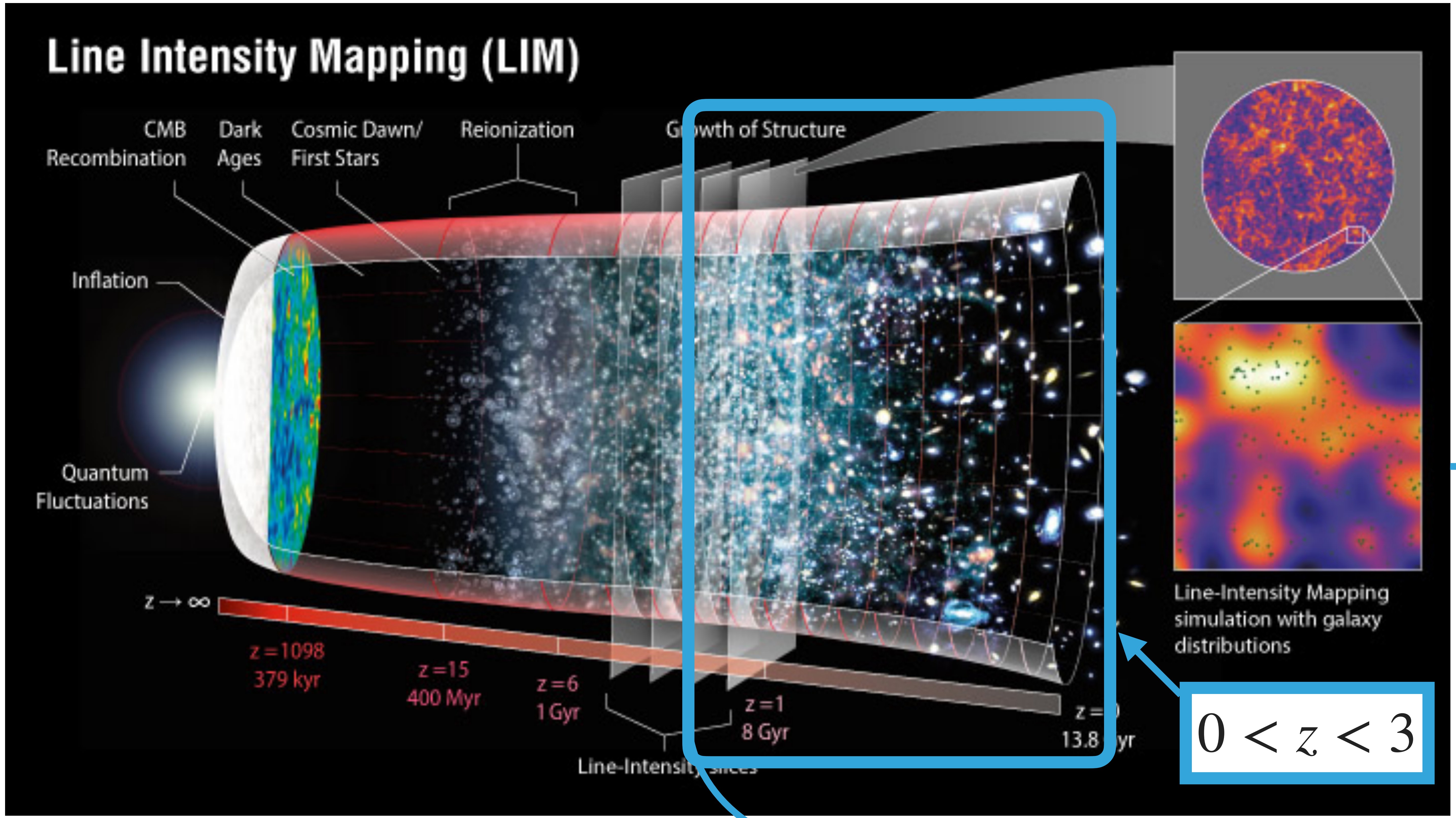
Cosmic Dawn
$z \sim 20$

Late Universe
Galaxy evolution
$z < 6$

Credit: ESA

21cm Line Intensity Mapping

Credit: *NASA / LAMBDA Archive Team*



$0 < z < 3$

total intensity of the 21cm emission line in a **large pixel** (low spatial resolution)

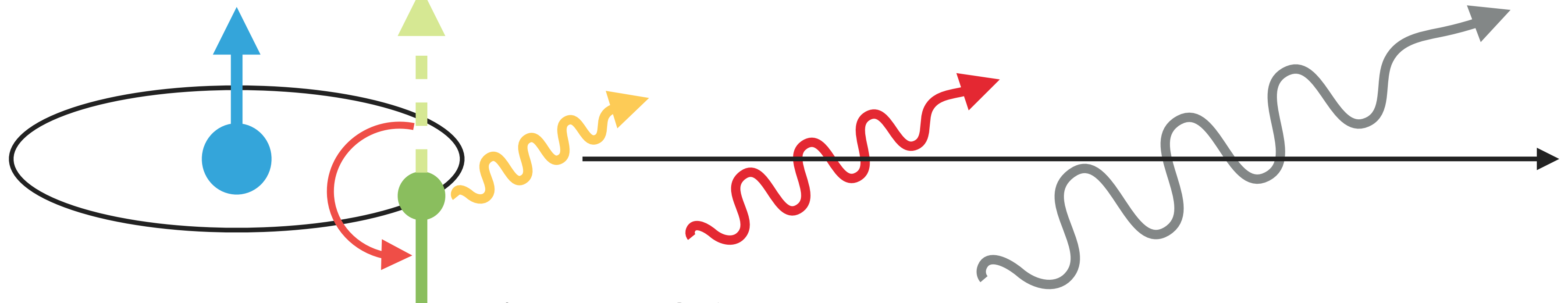
↓

Integrated emission from multiple galaxies

↓

Brightness Temperature

$T_b(x, z)$



$\lambda_{em} = 21\text{cm}$
$\nu_{em} = 1420\text{Mhz}$

$$1 + z = \frac{\nu_{em}}{\nu_{obs}}$$

TOMOGRAPHY

high spectral resolution

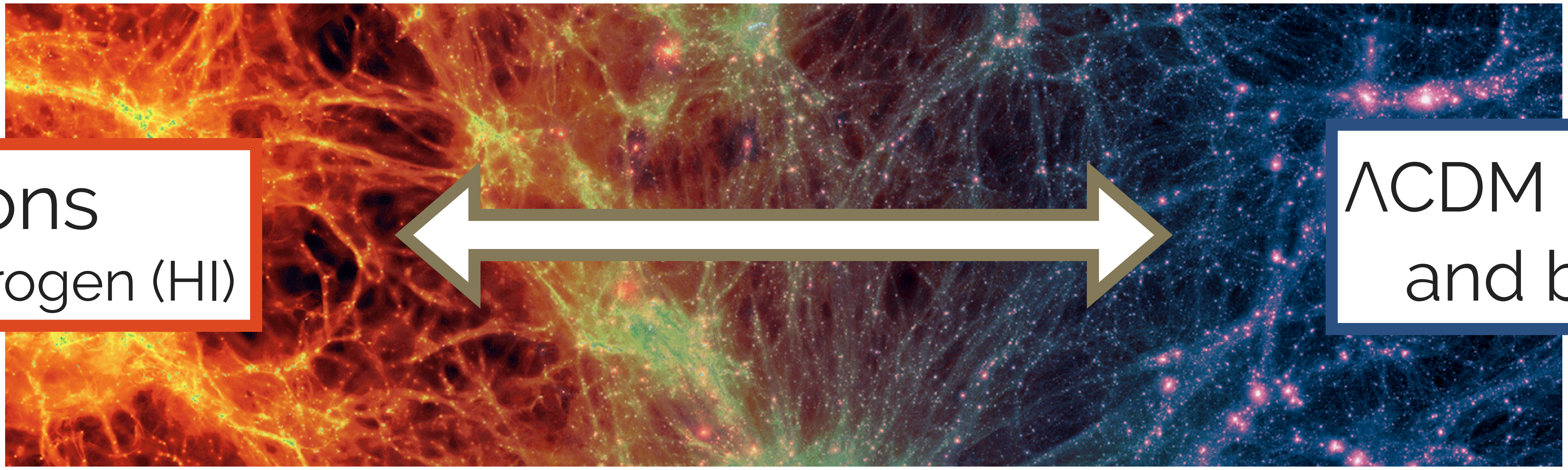
Open Questions

What is Dark Matter?

What is the link between galaxies and dark matter halo?

Can alternative models solve the tensions simultaneously?

Credit: Illustris



Baryons
Neutral Hydrogen (HI)

ΛCDM Universe and beyond

What can cosmology tell us about neutrinos?

What is Dark Energy?

Does the CMB lensing anomaly hide not understood systematics?

Are the Hubble and the growth tension an indication of new physics?

Overview

The 21cm observable

- Theoretical modelling
- Forecasted data sets
- Numerical methods

Probing the ΛCDM Universe

- Cosmological parameters constraints
- 21cm combined with CMB data

Probing the beyond ΛCDM Universe

Constraints on Dark Energy

Constraints on the neutrino mass

References

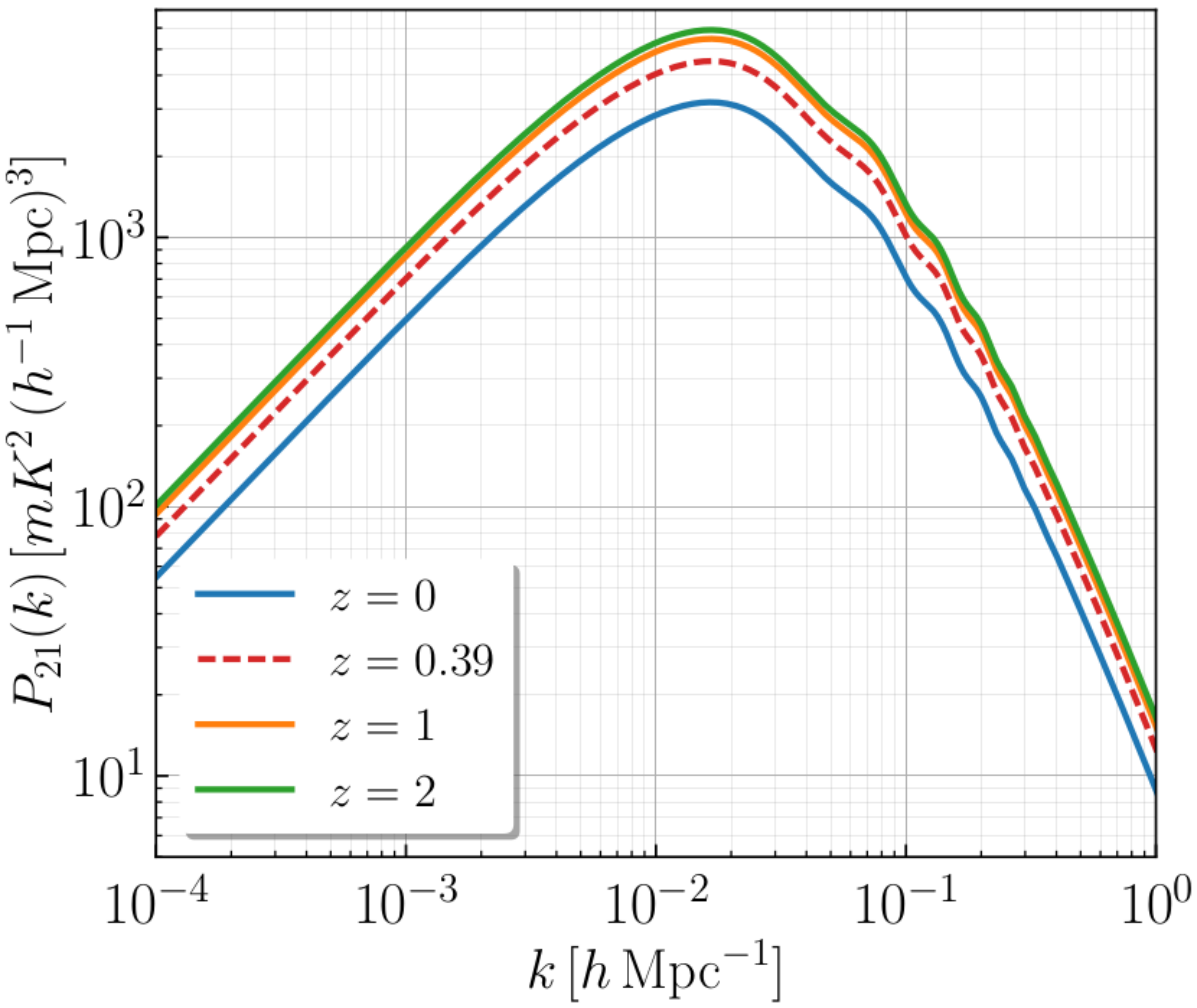
M. Berti, M. Spinelli, B. S. Haridasu, M. Viel, A. Silvestri, JCAP 01.01 (2022), ArXiv:*2109.03256*.

M. Berti, M. Spinelli, M. Viel, Mon. Not. Roy. Astron. Soc. 521.3 (2023), ArXiv:*2209.07595*.

The 21cm Observable

Theoretical 21cm Linear Power Spectrum

Berti et al. (2022)



We model it as[1]

$$P_{21}(z,k,\mu) = \bar{T}_b^2(z)\left[\,b_{\mathrm{HI}}(z) + f(z)\,\mu^2\,\right]^2 P_{\mathrm{m}}(z,k)$$

where

- $\bar{T}_b^2(z)$ is the mean brightness temperature
- $b_{\mathrm{HI}}(z)$ is the HI bias
- $f(z)$ is the growth rate
- $\mu = \hat{k} \cdot \hat{z}$
- $P_{\mathrm{m}}(z,k)$ is the matter power spectrum

✓ in good agreement with hydrodynamical simulations results (*Villaescusa-Navarro et al., 2018*)

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[1] *Kaiser (1987), Bacon et al. (2019)*

Power Spectrum Multipoles Expansion

$$\boxed{P_{21}(z,k,\mu) = \bar{T}_{\rm b}^2(z)\ \left[b_{\rm HI}(z) + f(z)\,\mu^2\right]^2 P_{\rm m}(z,k)}$$

Expand in μ

$$P_{21}(k,\mu) = \Sigma_\ell\, P_\ell(k)\mathscr{L}_\ell(\mu)$$

where the Legendre polynomials are

$$\mathscr{L}_0(\mu) = 1$$

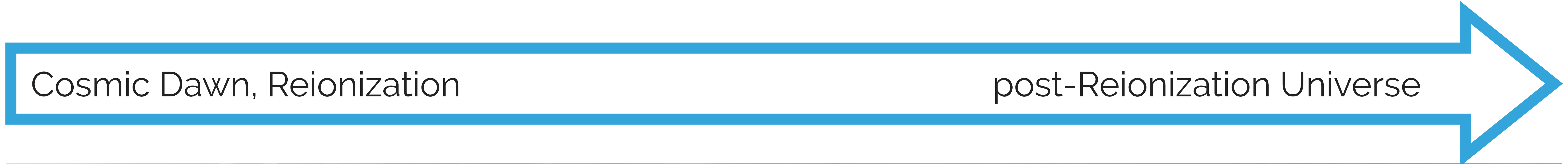
$$\mathscr{L}_2(\mu) = \frac{3\mu^2}{2} - \frac{1}{2}$$

$$P_\ell(z,k) = \frac{(2\ell+1)}{2}\int_{-1}^{1} {\rm d}\mu\, \mathscr{L}_\ell(\mu) P_{21}(z,k,\mu)$$

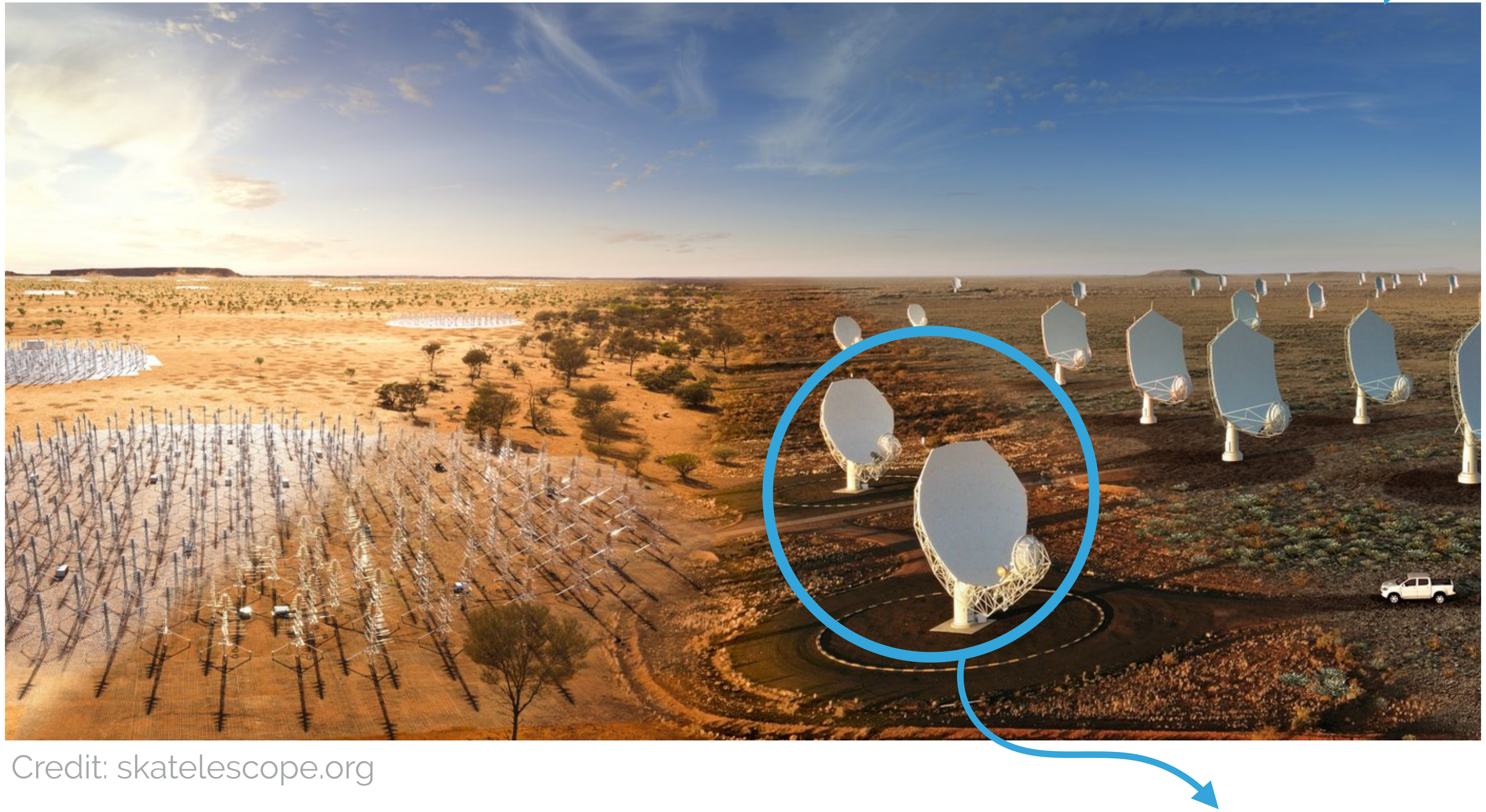
$$\boxed{P_\ell(z,k) = \frac{(2\ell+1)}{2}\,\bar{T}_{\rm b}^2(z)\, P_{\rm m}(z,k)\int_{-1}^{1} {\rm d}\mu\, \mathscr{L}_\ell(\mu)\ \left[b_{\rm HI}(z) + f(z)\,\mu^2\right]^2}$$

→ We forecast observations for the power spectrum $P_{21}(z,k,\bar{\mu})$ and the multipoles $P_\ell(z,k)$

SKA Observatory (SKAO)



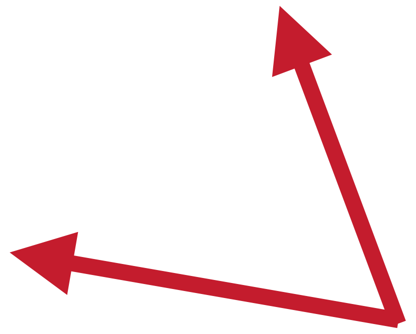
SKA-LOW
50 MHz - 350 MHz
$30 > z > 3$



Credit: skatelescope.org

SKA-MID
350 MHz - 13.5 GHz
$3 > z > 0$

MeerKAT
(SKA pathfinder)
$1.5 > z > 0$



→ Radio frequencies

→ Covers all the relevant frequencies with unprecedented sensitivity

Modelling SKAO Observations

I. Instrumental Noise

$$P_{\rm N}(z) = \frac{T_{\rm sys}^2 4\pi f_{\rm sky}}{N_{\rm dish} t_{\rm obs} \delta\nu} \frac{V_{\rm bin}(z)}{\Omega_{\rm sur}}$$

SKAO specifications

Parameter		Value
$D_{\rm dish}$ [m]	SKAO dish diameter	15
$N_{\rm dish}$	SKAO dishes	133
$t_{\rm obs}$ [h]	observing time	10000
$T_{\rm sys}$ [K]	system temperature	25
$\delta\nu$ [MHz]	frequency range	1
$\Omega_{\rm sur,1}$ [sr]	survey area (Band 2)	1.5
$\Omega_{\rm sur,2}$ [sr]	survey area (Band 2)	6.1
$f_{\rm sky,2}$	covered sky area (Band 2)	0.12
$f_{\rm sky,1}$	covered sky area (Band 1)	0.48
Δz	width of the redshift bins	0.5

SKAO Red Book (2018)

II. Beam Effects

$$\tilde{B}(z,k,\mu) = \exp\left[\frac{-k^2 R_{\rm beam}{}^2(z)(1-\mu^2)}{2}\right]$$

$$R_{\rm beam}(z) = \frac{\theta_{\rm FWHM}}{2\sqrt{2\ln 2}} r(z)$$

beam physical size

III. Covariance Between Multipoles

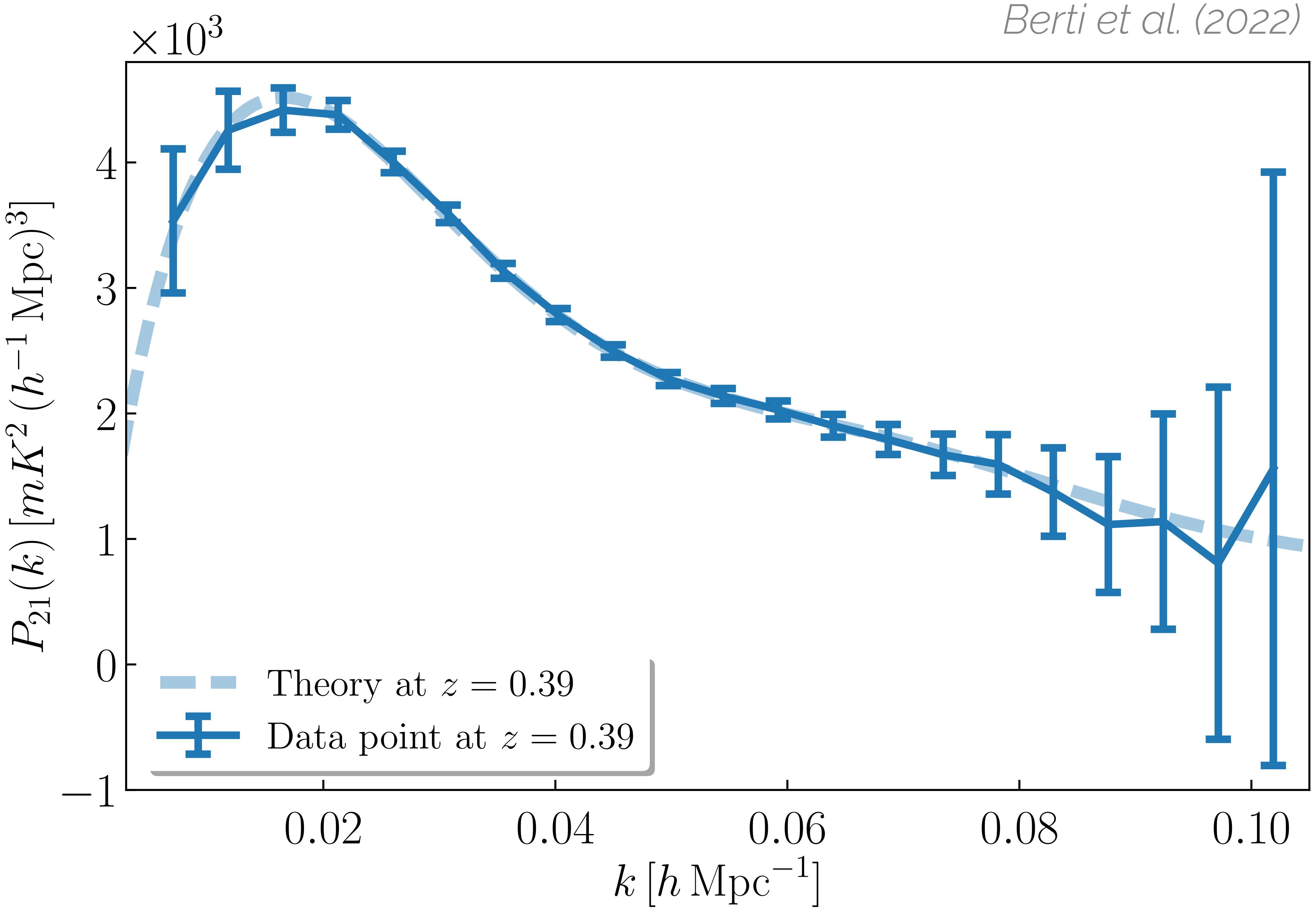
$$C_{\ell\ell'}(z,k) = \frac{(2\ell+1)(2\ell'+1)}{2} \int_{-1}^{1} {\rm d}\mu\, \mathscr{L}_\ell(\mu)\, \mathscr{L}_{\ell'}(\mu)\, \sigma^2(z,k,\mu)$$

$$\sigma^2(z,k,\mu) \propto \left(P_{21}(z,k,\mu) + P_{\rm N}(z)\right)^2$$

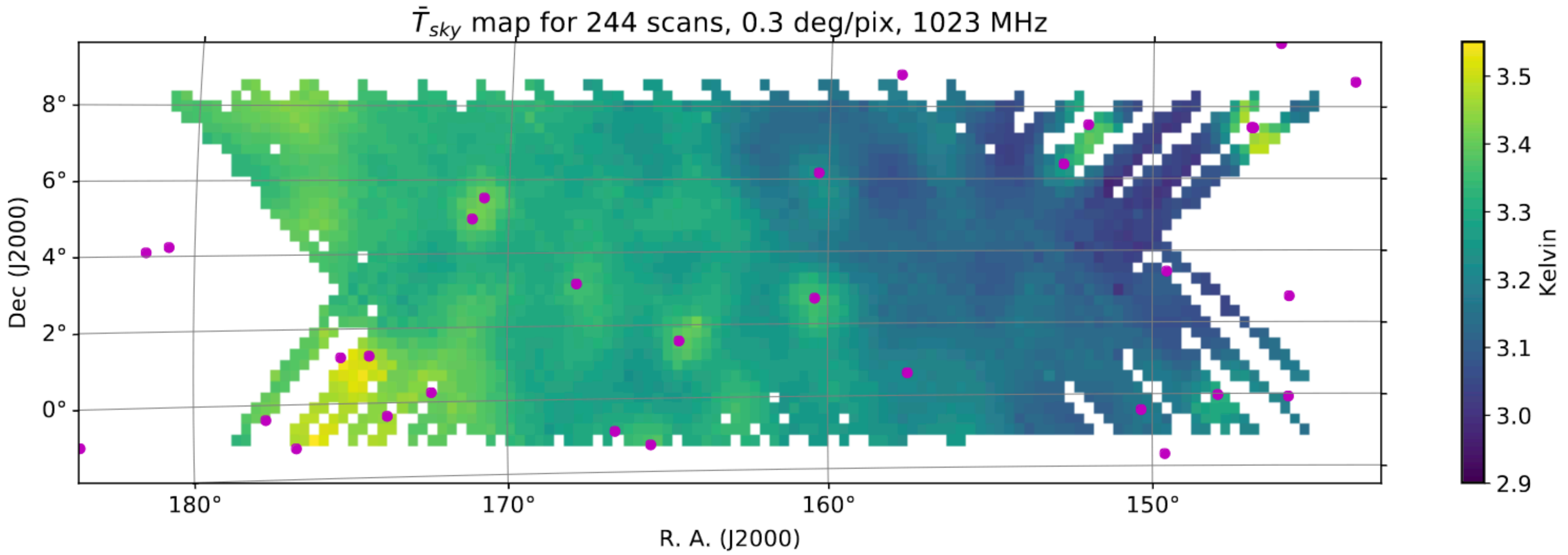
variance

The Power Spectrum Mock Data Set

Berti et al. (2022)



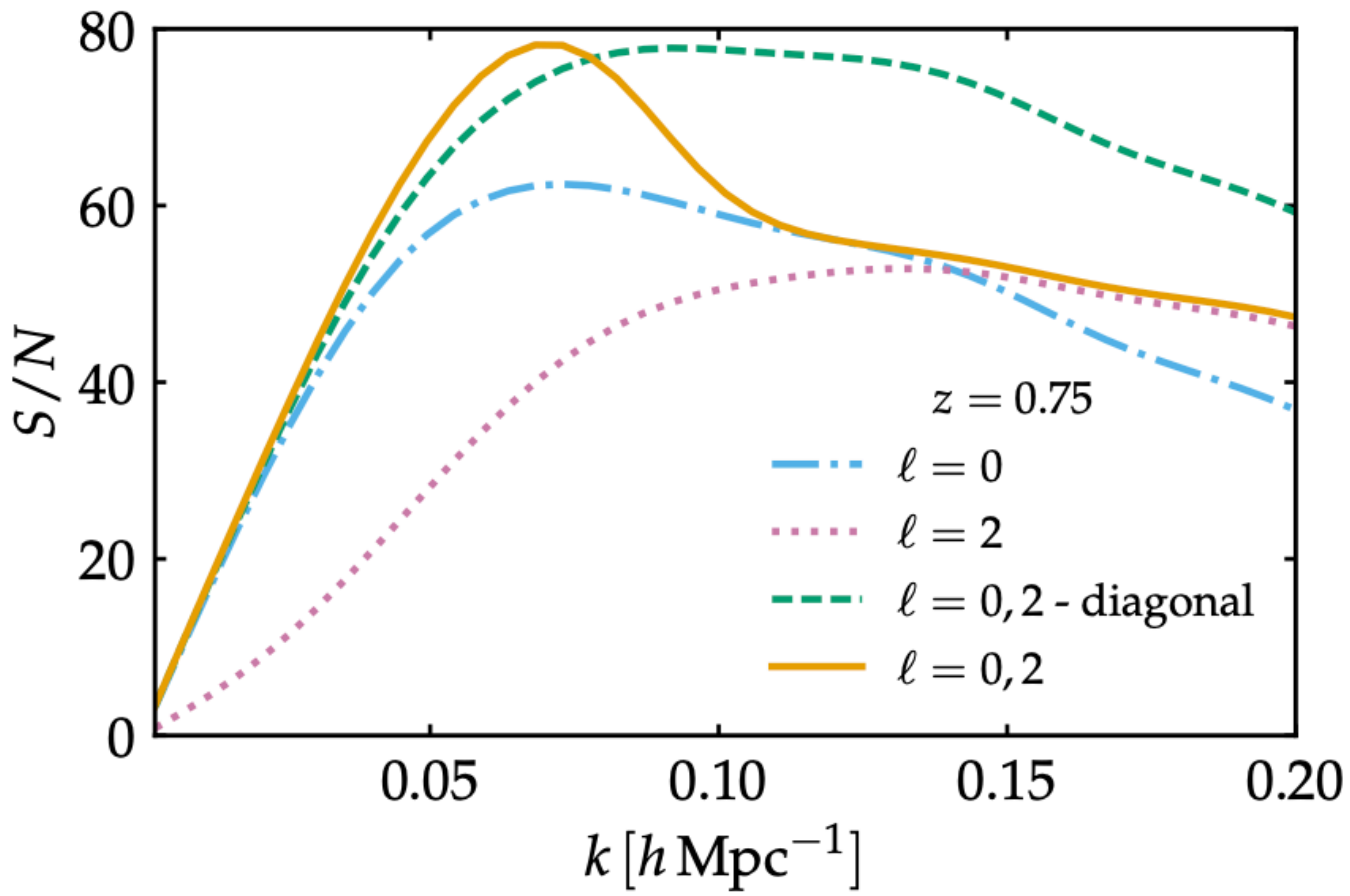
- MeerKAT like observations
- Auto-power spectrum
- One redshift bin
- More realistic measurement



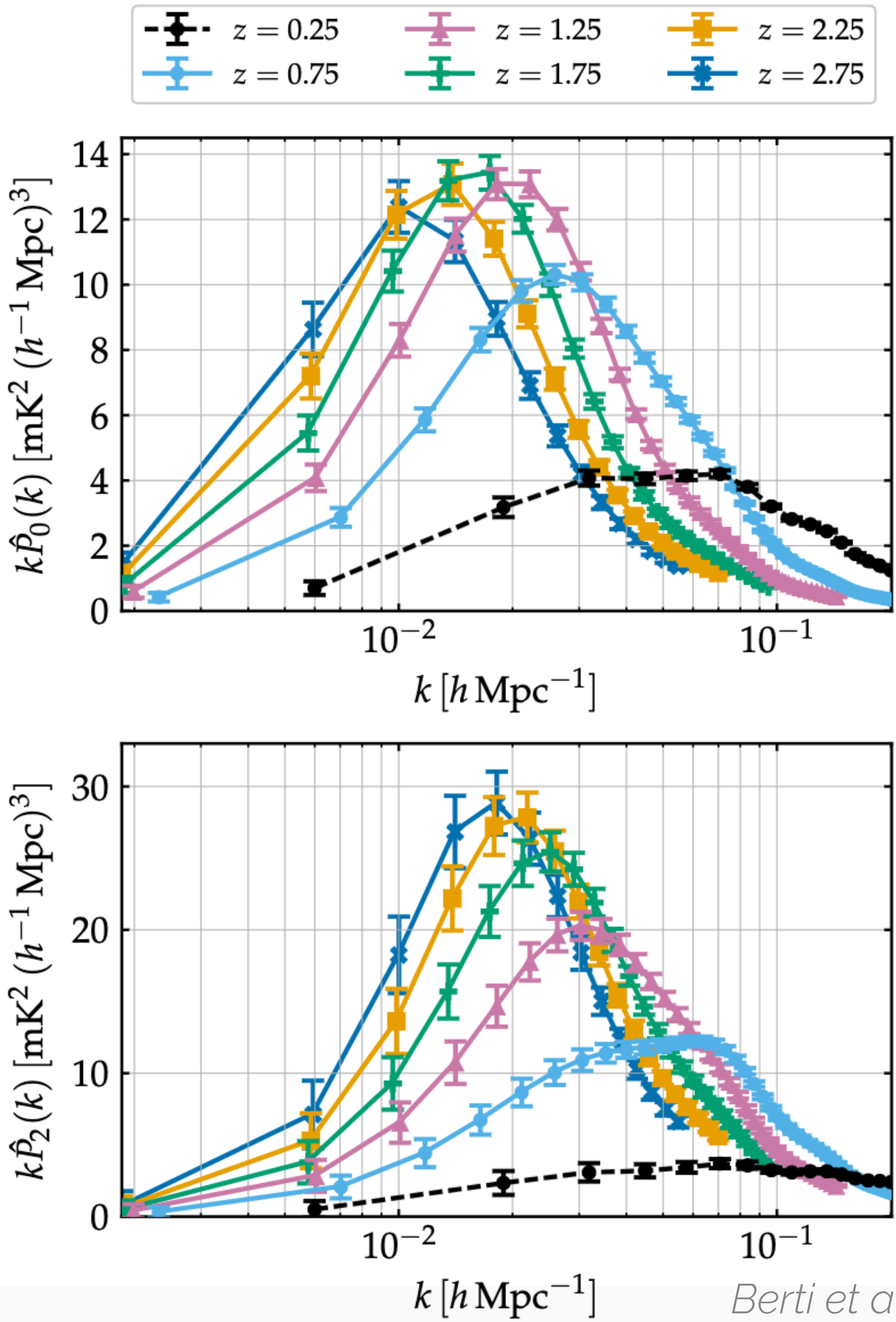
Wang et al. (2021)

The Multipoles' Mock Data Set

- SKAO like observations
- Monopole and quadrupole
- Observations within 6 redshift bins
- Beam's effect, multipole covariance



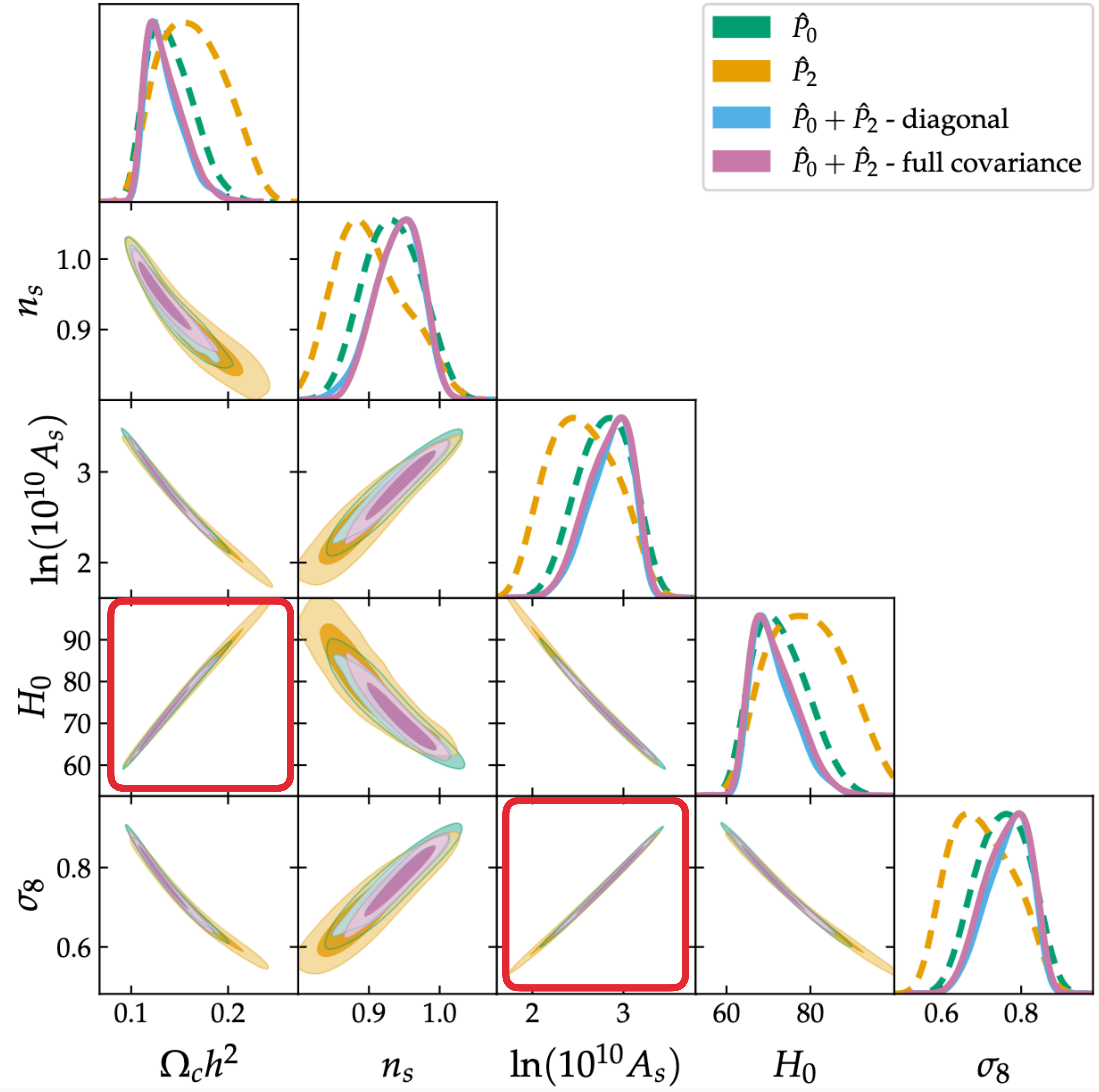
$$\hat{P}_\ell(z,k) = \frac{(2\ell+1)}{2}\int_{-1}^{1} \mathrm{d}\mu\, \mathscr{L}_\ell(\mu)\tilde{B}^2(z,k,\mu)P_{21}(z,k,\mu)$$



Berti et al. (2023a)

Probing the ΛCDM Universe

Constraints From the 21cm Signal



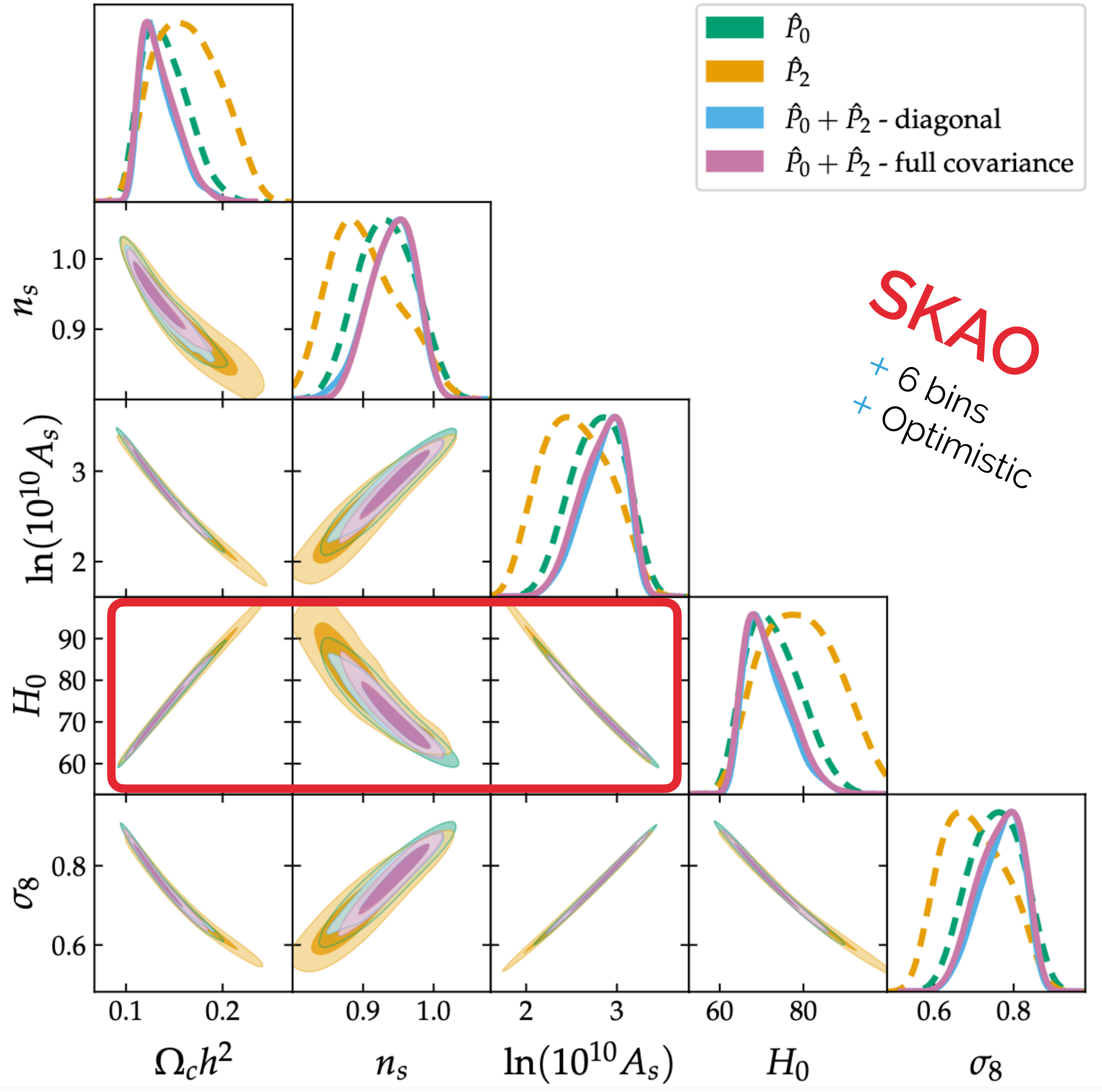
Berti et al. (2023a)

Analysis set up

- Full MCMC analysis
- Implement a new likelihood code integrated with CosmoMC
- Varying the full set of cosmological parameters $\{\Omega_b h^2, \Omega_c h^2, \tau, \theta_{\rm MC}, A_s, n_s\}$
- Test the constraining power of the 21cm signal alone and combined with CMB

- Multiples' mock data set - 6 bins
- 21cm alone has a good constraining power on the cosmological parameters
- Marked correlations ($\Omega_c h^2 - H_0$ and $\sigma_8 - A_s$)

SKAO vs MeerKAT Forecasts

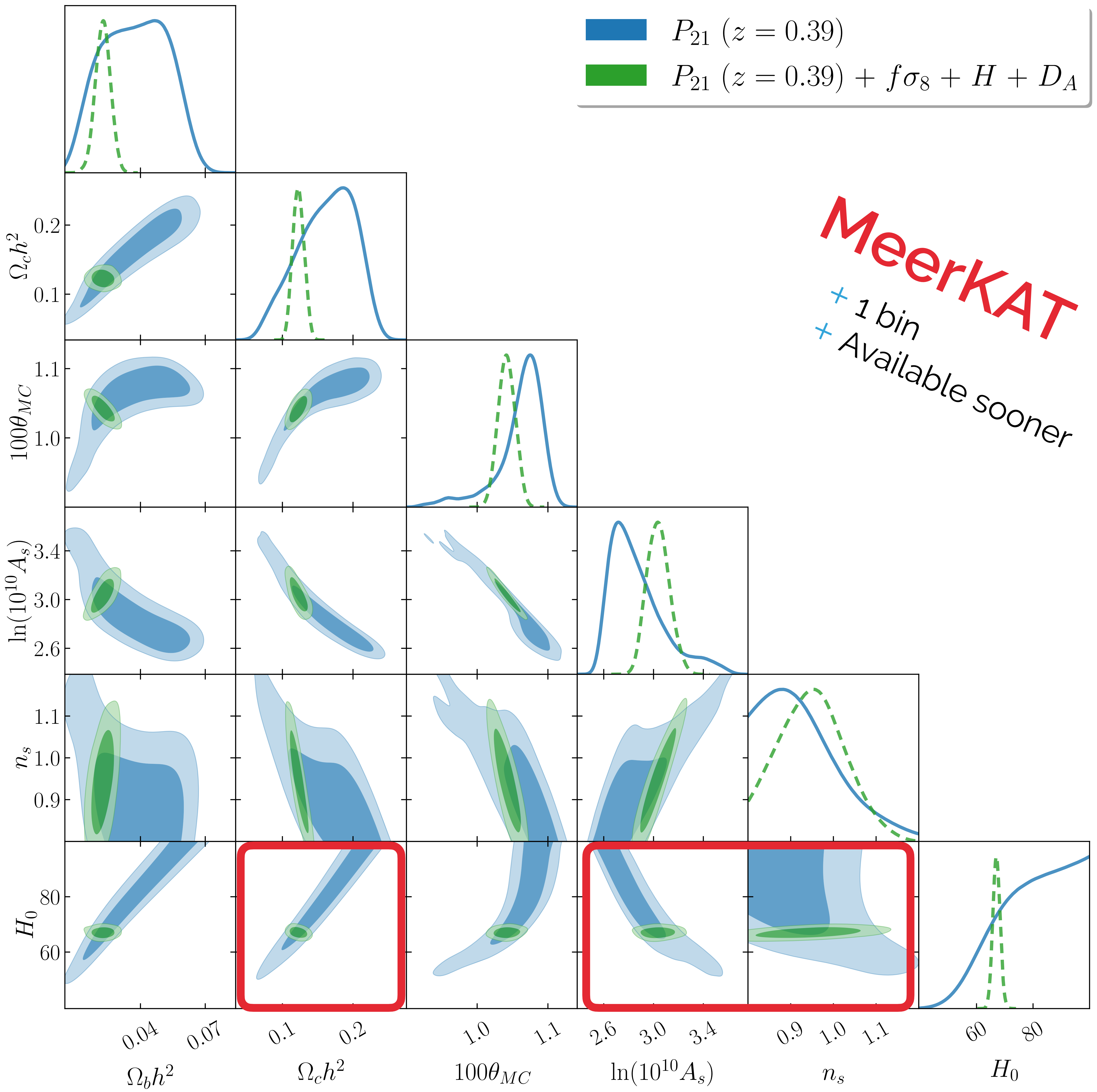


SKAO

+ 6 bins

+ Optimistic

Berti et al. (2023a)



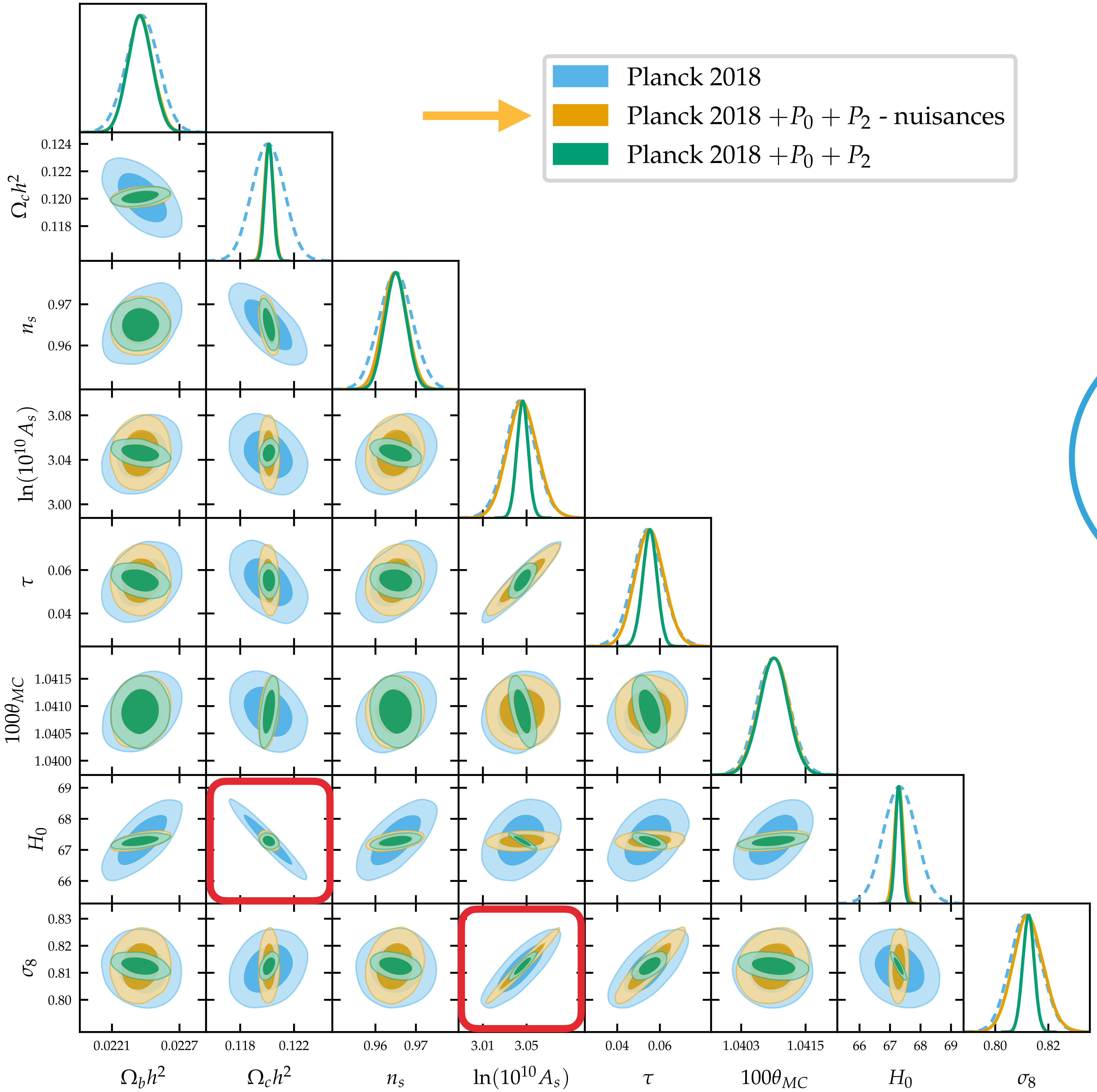
MeerKAT

+ 1 bin

+ Available sooner

Berti et al. (2022)

Constraints in Combination With CMB



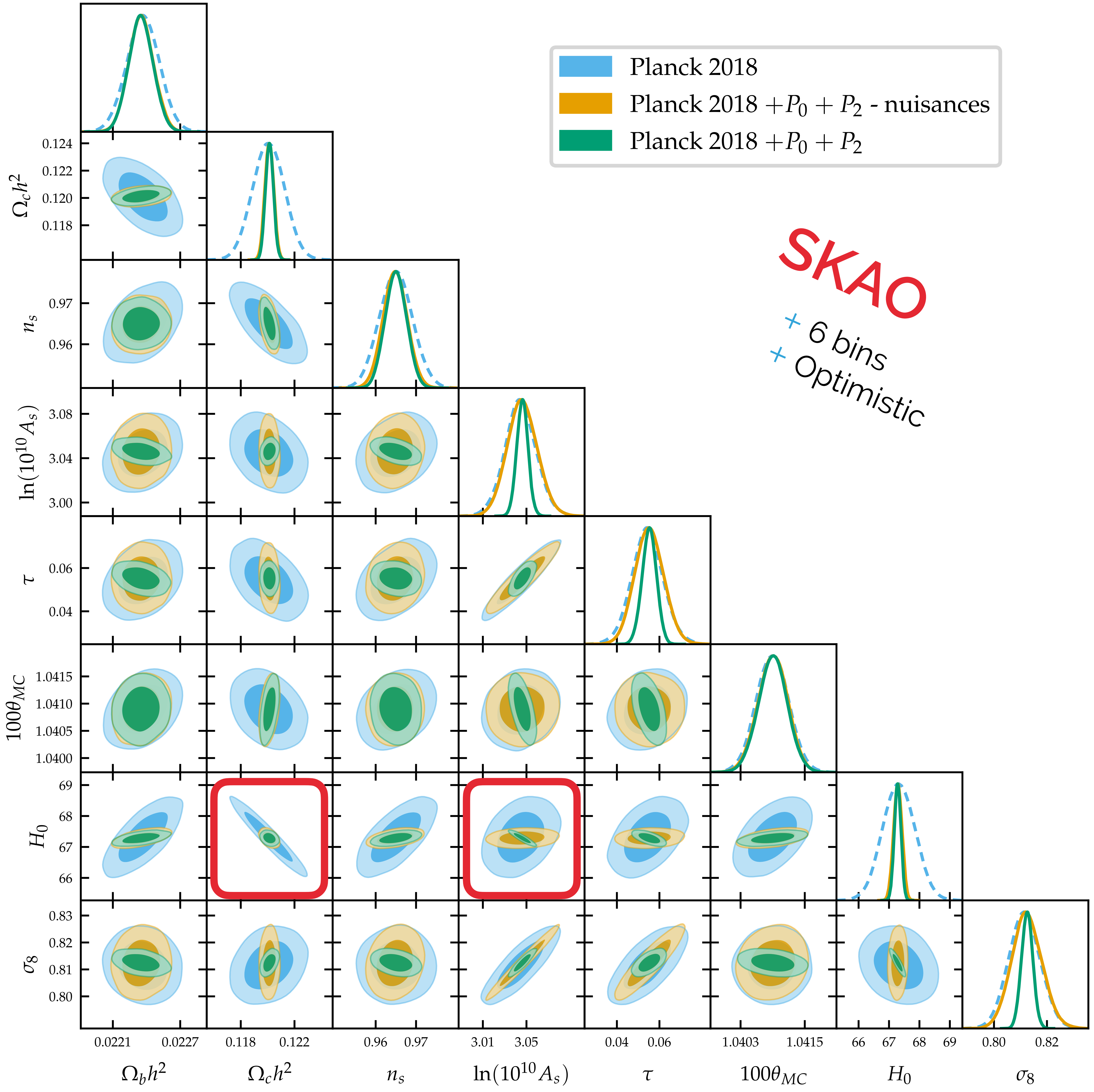
Berti et al. (2023a)

Planck TT, TE, EE + lowE + lensing

Parameter	Planck 2018	$+P_0+P_2$
$\Omega_b h^2$	0.64%	0.49%
$\Omega_c h^2$	0.99%	0.25%
n_s	0.42%	0.27%
$\ln(10^{10}A_s)$	0.46%	0.17%
τ	13.44%	6.09%
$100\theta_{MC}$	0.03%	0.03%
H_0	0.79%	0.16%
σ_8	0.73%	0.26%

- Constraints are significantly improved with respect to Planck alone
- Removed degeneracies
- We loose constraining power when introducing astrophysical nuisances

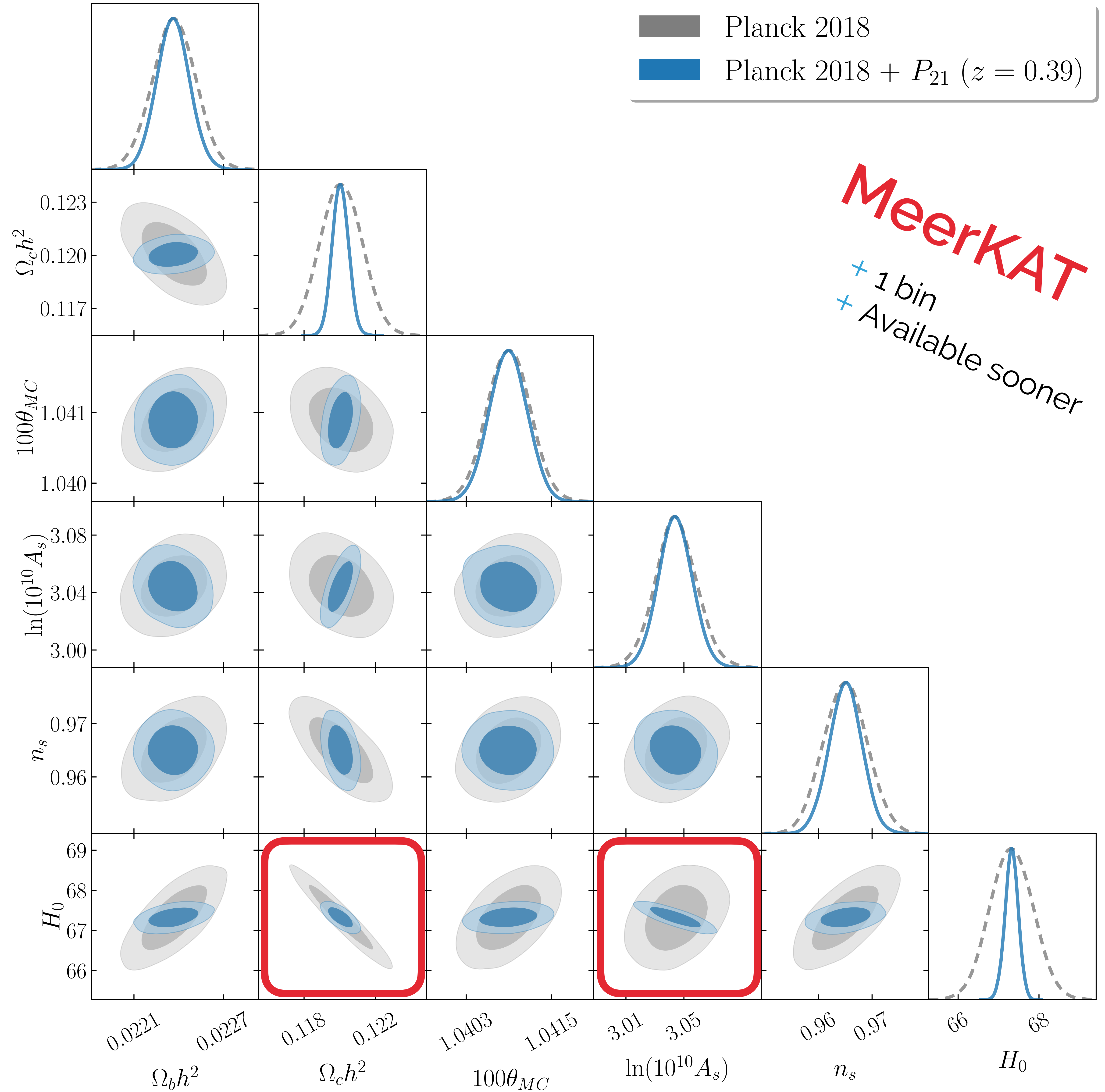
SKAO vs MeerKAT Forecasts



SKAO

+ 6 bins
+ Optimistic

Berti et al. (2023a)



MeerKAT

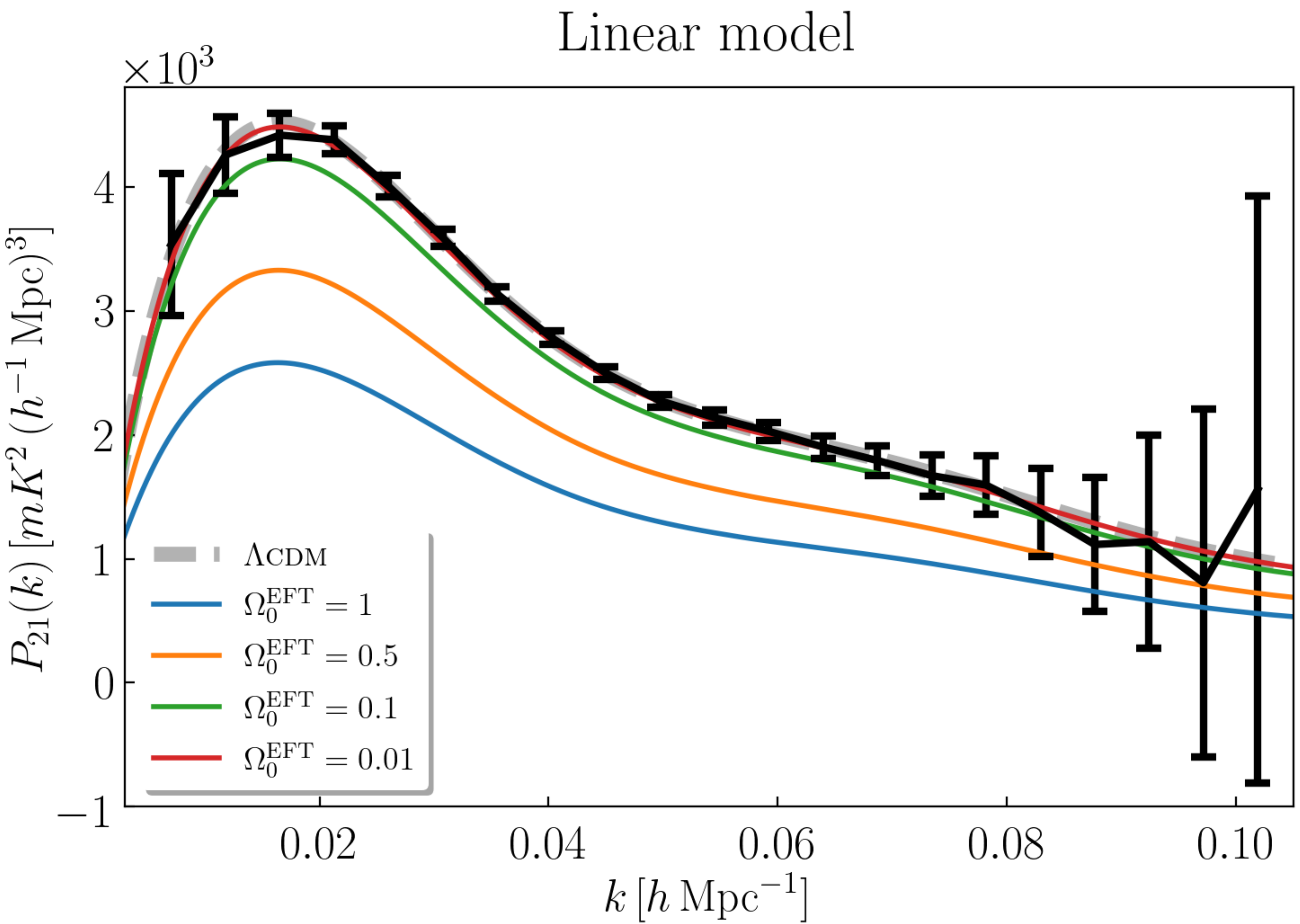
+ 1 bin
+ Available sooner

Berti et al. (2022)

Probing the Beyond ΛCDM Universe

Constraining Dark Energy With P_{21}

- MEERKAT forecasts for the 21cm power spectrum
- One redshift bin at $z = 0.39$
- More ideal multiple bins data set
- Study of DE → Effective Field Theory



Berti et al. (2022)

Effective Field Theory of Cosmic Acceleration

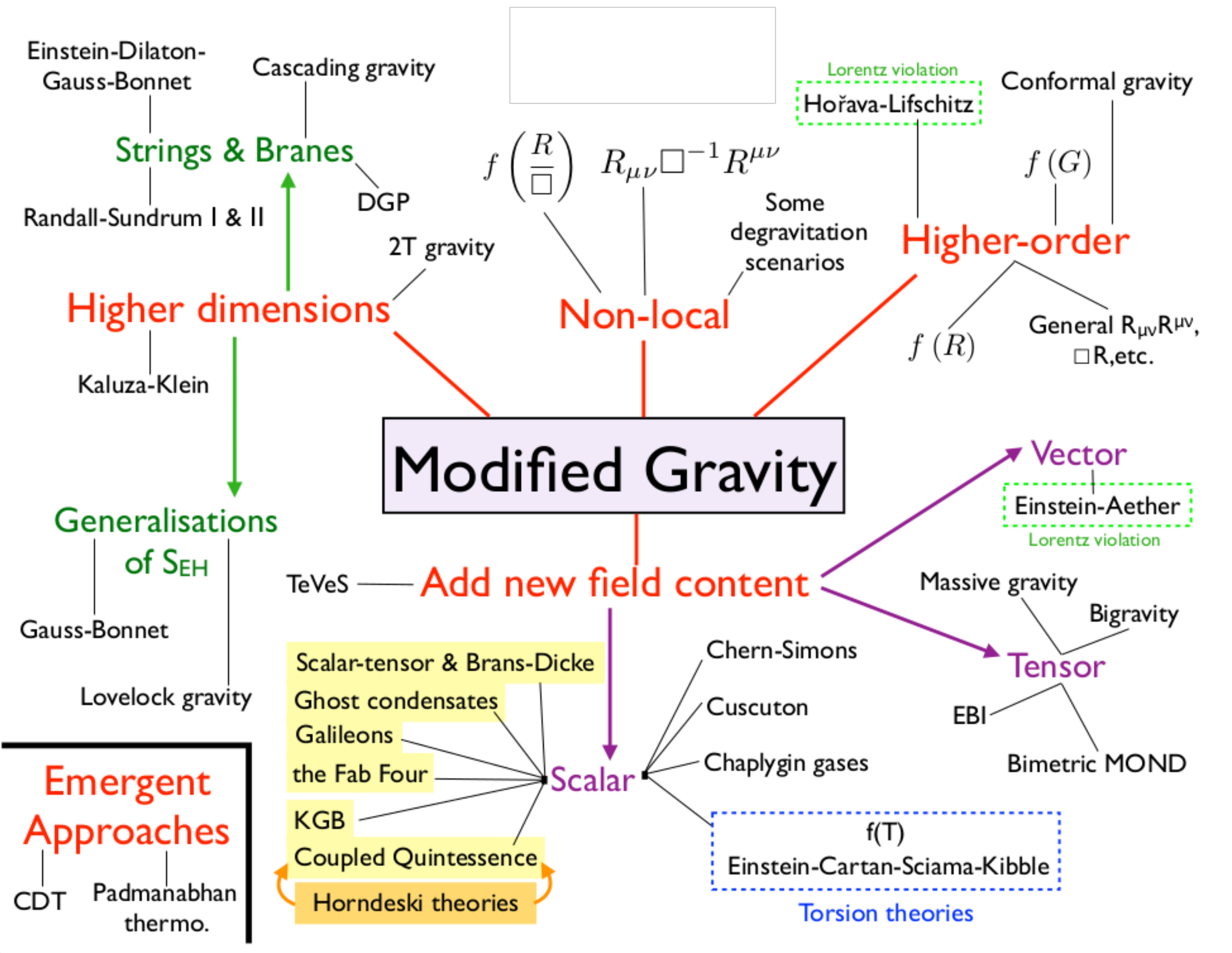
Introduced to describe INFLATION → Later applied to late time COSMIC ACCELERATION

Creminelli et al. (2006), Cheung et al. (2008)

Creminelli et al. (2009), Gubitosi et al. (2013), Bloomfield et al. (2013)

Construct the most general

ACTION



Bull et al. (2016)

Effective

Easily interfaced
with observations

Unifying

Must include as many DE/MG
models as special cases

Studied Models

Parametrise the evolution of the background EFT functions

$$S = \int d^4x\sqrt{-g}\left\{ \frac{m_0^2}{2}\left[1+\Omega^{\rm EFT}(\tau)\right] R+\Lambda(\tau) - c(\tau)a^2\delta g^{00} \right\} + S_m$$

We choose *pure*EFT models

Exponential parametrisation

$$\Omega^{\rm EFT}(a) = \exp\left(\Omega_0^{\rm EFT}a^{\beta}\right) - 1$$

Linear parametrisation

$$\Omega^{\rm EFT}(a) = \Omega_0^{\rm EFT}a$$

+

Fix background evolution

$$H(a)$$

to study only the impact on perturbations

Designer approach

$$\Lambda(a) = \Lambda(\Omega^{\rm EFT}(a), H(a))$$

$$c(a) = c(\Omega^{\rm EFT}(a), H(a))$$

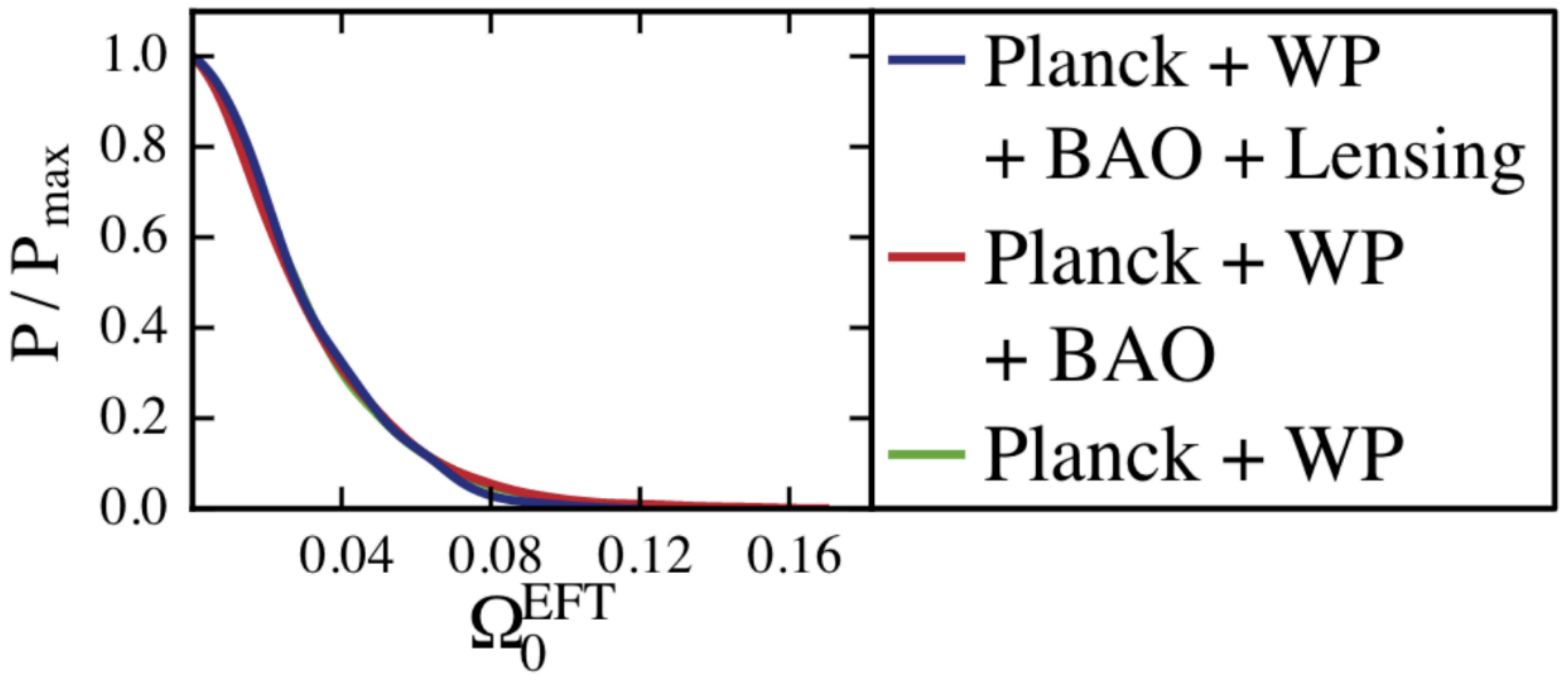
Latest Constraints on *pure*EFT Models

EffectiveFieldTheory with CAMB

Hu et al. (2014)

Linear

Raveri et al. (2014)

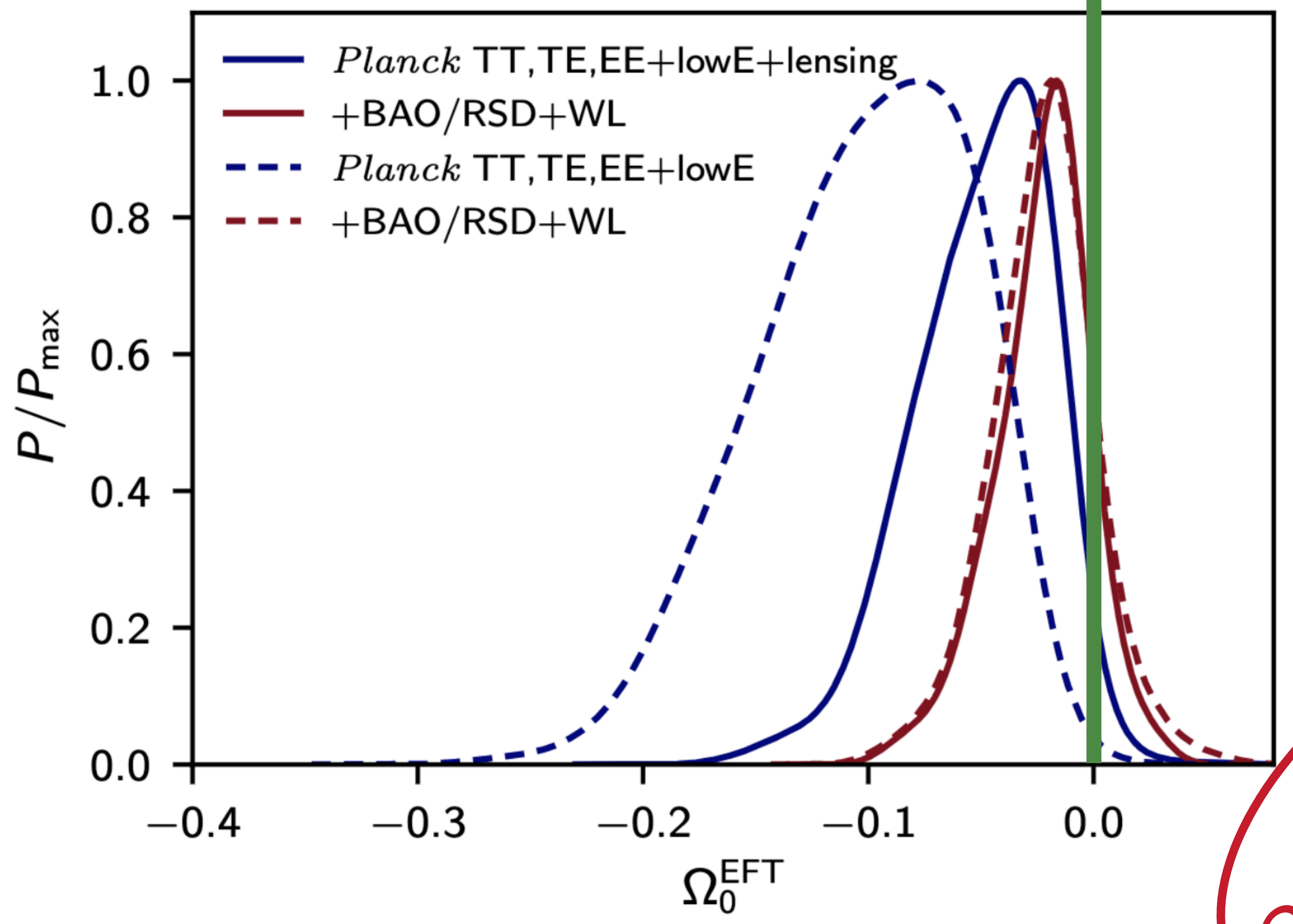


Parameter	Planck + all
$\Omega_0^{\rm EFT}$ . . .	< 0.061 (95% CL)
H_0	68.22 ± 0.75

Exponential

Planck collaboration (2018)

ΛCDM limit



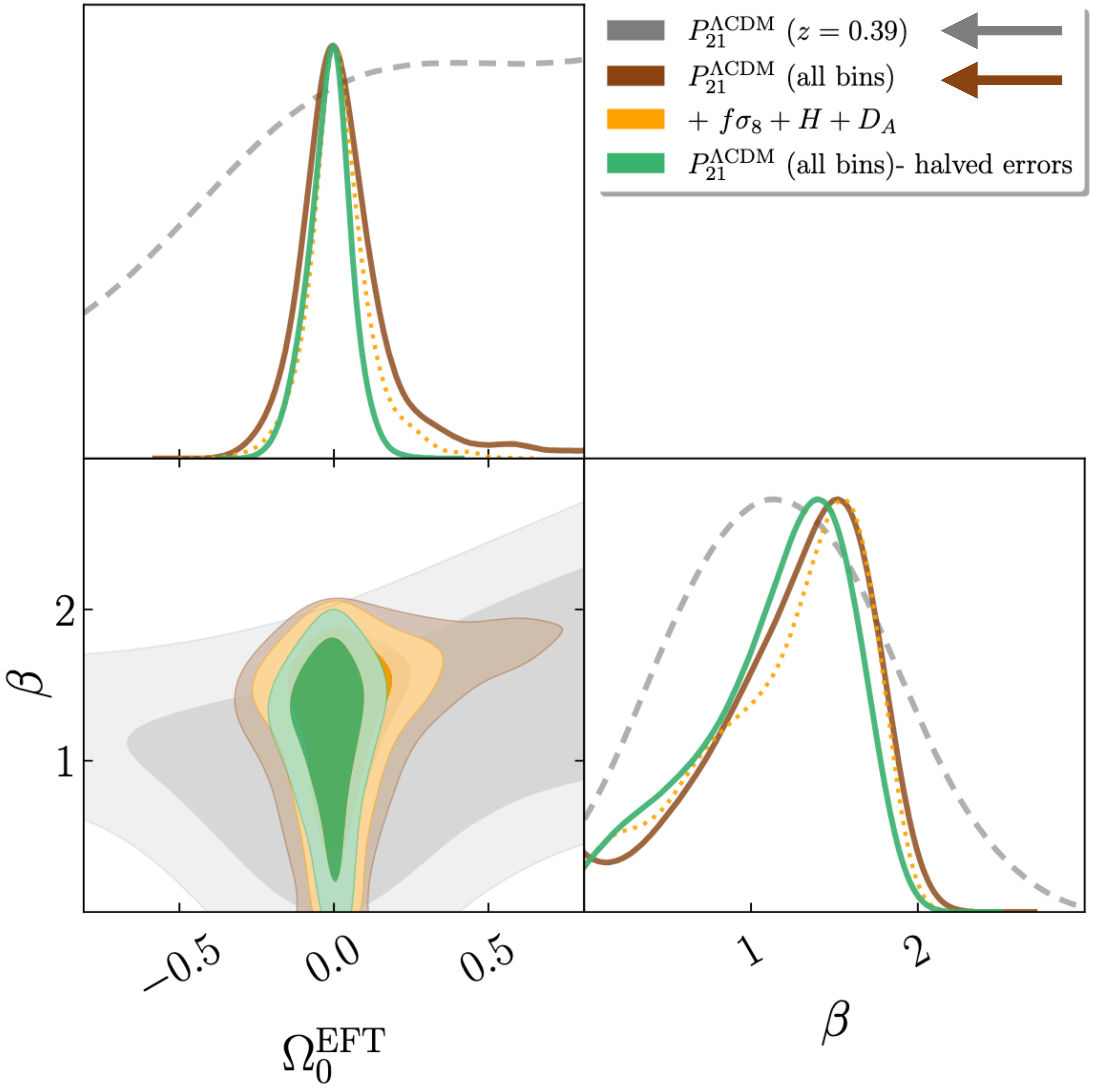
2.1σ away

Parameter	Planck 2018
$\Omega_0^{\rm EFT}$ . . .	$-0.101^{+0.059}_{-0.038}$
H_0	68.30 ± 0.71

Do We Expect To Be Sensitive?

Berti et al. (2022)

Exponential *pure*EFT Results - 21cm Alone

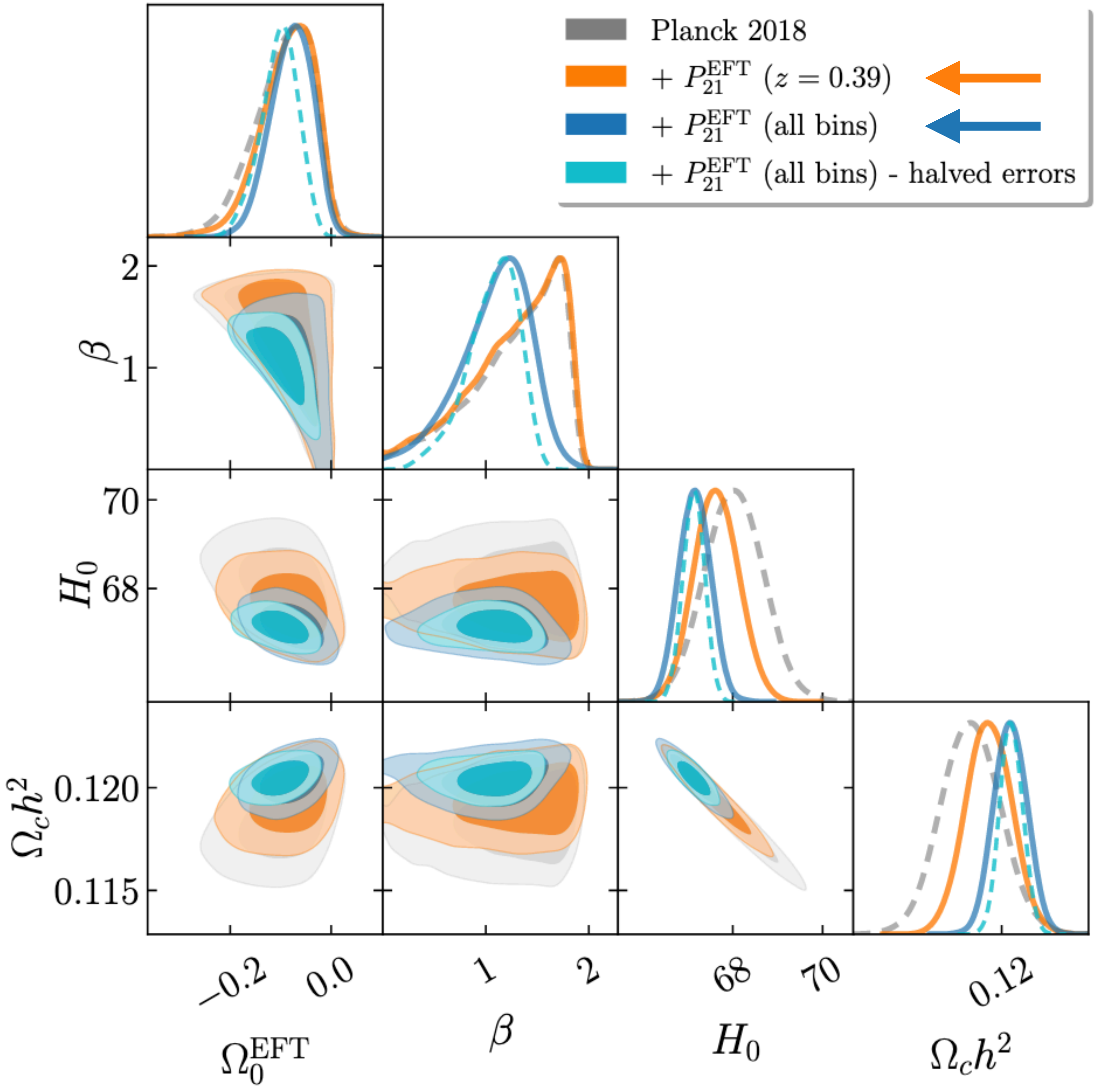


Par.	$P_{21}^{\Lambda\mathrm{CDM}}(z=0.39)$	$P_{21}^{\Lambda\mathrm{CDM}}$ (all bins)
Ω_0^{EFT}	—	$0.053^{+0.075}_{-0.17}$
β	1.21^{+57}_{-70}	1.26^{+50}_{-30}
H_0 ...	—	$74.1^{+8.1}_{-11}$

- Constraints on the cosmological parameters remain unaffected
- $P_{21}(z=0.39)$ alone has weak constraining power (realistic)
- Using multiple bins significantly improves the constraining power (ideal)

Berti et al. (2022)

Exponential *pure*EFT Results - 21cm + Planck



Berti et al. (2022)

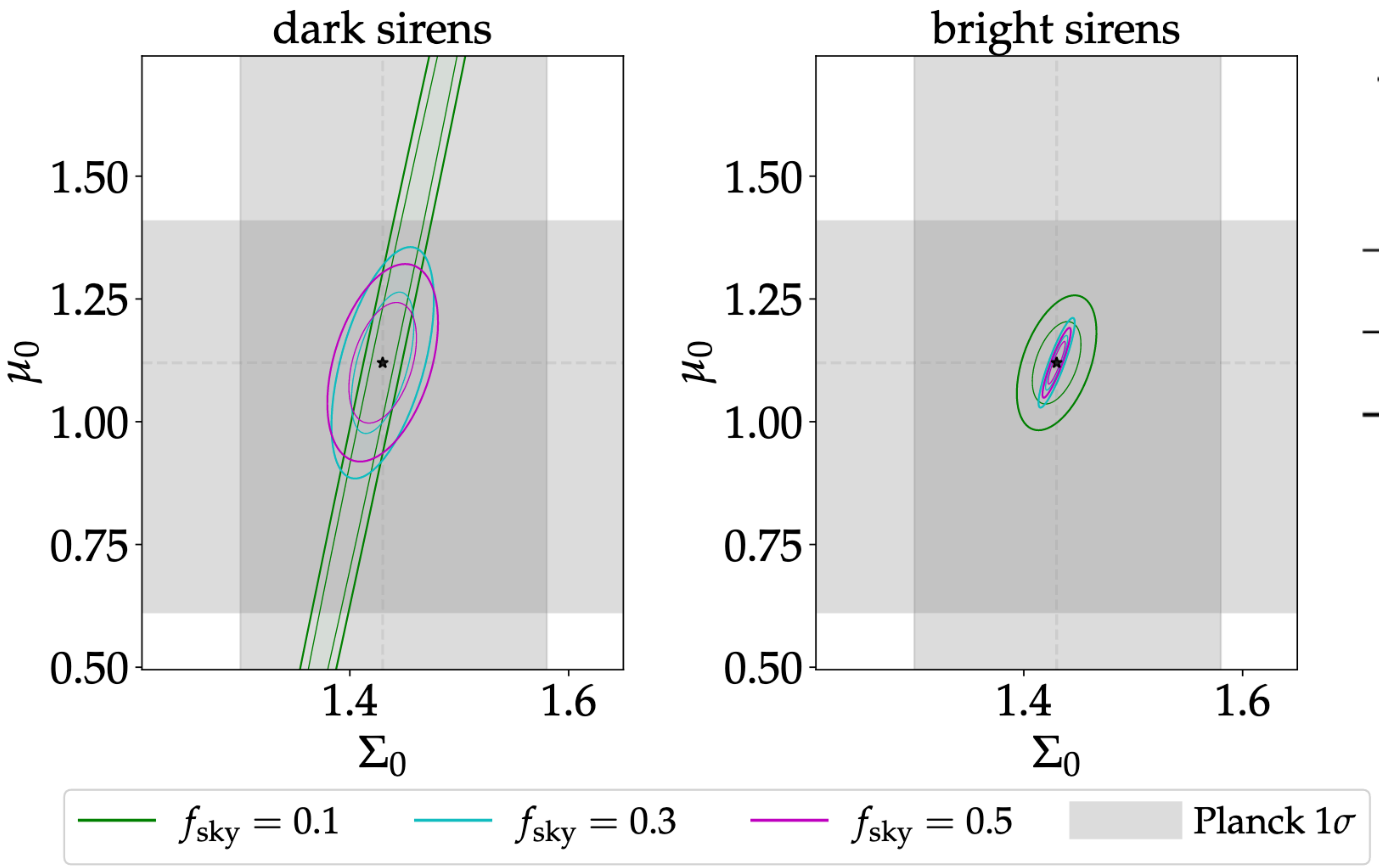
Par.	Planck 2018 + $P_{21}^{\rm EFT}(z = 0.39)$	Planck 2018 + $P_{21}^{\rm EFT}$ (all bins)
$\Omega_c h^2$.	0.1194 ± 0.0011 (-22%)	0.12042 ± 0.00080 (-43%)
$\Omega_0^{\rm EFT}$	$-0.086^{+0.064}_{-0.038}$ (-10%)	$-0.079^{+0.047}_{-0.036}$ $(-\mathbf{26}\%)$
β	$1.28^{+0.58}_{-0.22}$ $(+4\%)$	$1.08^{+0.42}_{-0.25}$ $(-\mathbf{13}\%)$
H_0 ...	67.63 ± 0.50 (-24%)	67.15 ± 0.36 (-46%)

- Planck 2018 + $P_{21}(z = 0.39)$ improvement at the 10% level (realistic)
- Planck 2018 + P_{21} improvement up to the 26% level and 35% level with halved errors (ideal)

Related Works

Testing gravity with gravitational waves x electromagnetic probes cross-correlations

G. Scelfo, **M. Berti**, A. Silvestri, M. Viel, JCAP 02 (2023), arXiv:2210.02460



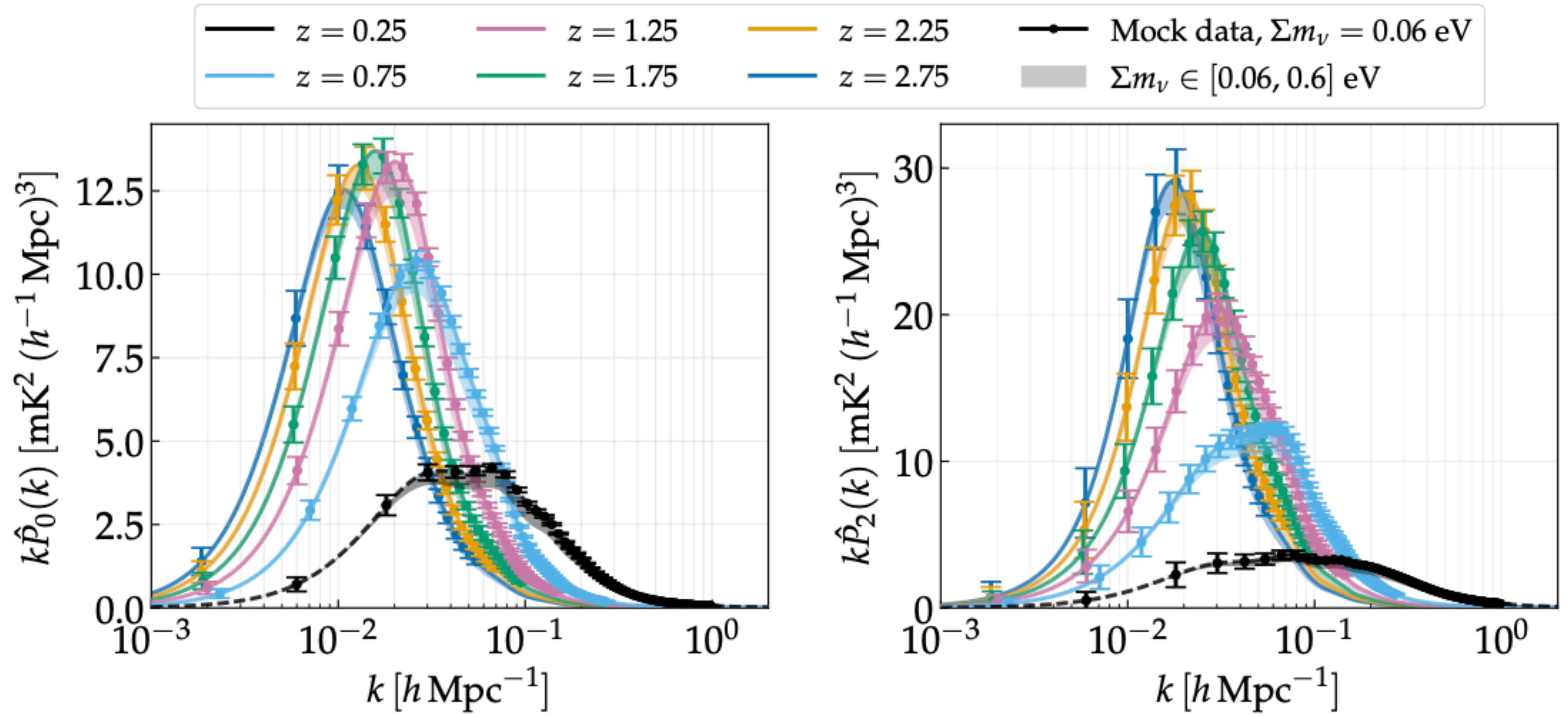
PROBE	σ_{μ_0}	σ_{η_0}	σ_{Σ_0}
Lensing	1.63	3.93	0.14
Clustering	0.09	0.50	0.29
L + C	0.03	0.06	0.01

Parameter	*Planck*
$\mu_0 - 1$	$0.10^{+0.30}_{-0.42}$
$\eta_0 - 1$	$0.22^{+0.55}_{-1.0}$
$\Sigma_0 - 1$	0.100 ± 0.093

Related Works

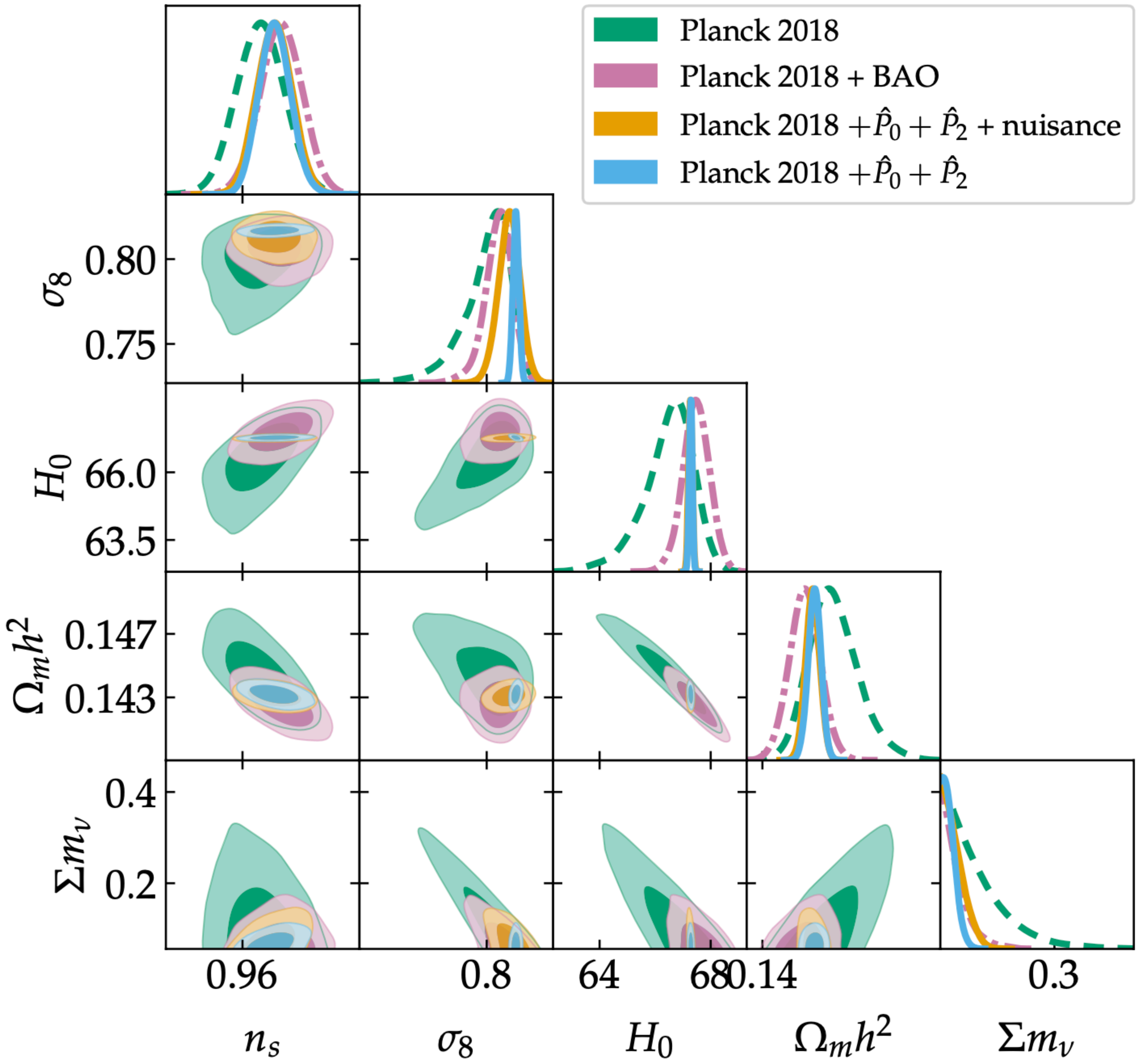
Latest perspectives on weighing the neutrinos with 21cm Intensity Mapping with the SKAO

M. Berti, M. Spinelli, B.S. Haridasu, M. Viel, in preparation.



Upper limits on Σm_ν

Planck 2018	< 0.259
$+ \hat{P}_0 + \hat{P}_2$	< 0.101
+ nuisance	< 0.129



Conclusions

Conclusions

1. The results we found are in agreement with similar works in the literature and confirm the key role of present and future late-time 21cm intensity mapping observations.

2. Combining 21cm power spectrum measurements to CMB observations leads to a substantial improvement of the constraints on $\Omega_c h^2$ and H_0.

3. Present-day surveys produced encouraging mild constraining power over beyond-ΛCDM extensions. More ideal 21cm signal SKAO observations within multiple redshift bins could potentially improve the knowledge of DE-MG theories.

4. 21cm intensity mapping SKAO measurements provide a new interesting cosmological probe, that carries rich information complementary to other high-precision cosmological observations.