Probing extended Starobinsky inflation with CMB & 21cm intensity mapping

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(TM, T. Plehn, L. Röver, and B. M. Schäfer, B. Schosser, arXiv: 2210.05698;
TM, T. Plehn, L. Röver, and B. M. Schäfer, SciPostPhys. Core ’22)

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Overview

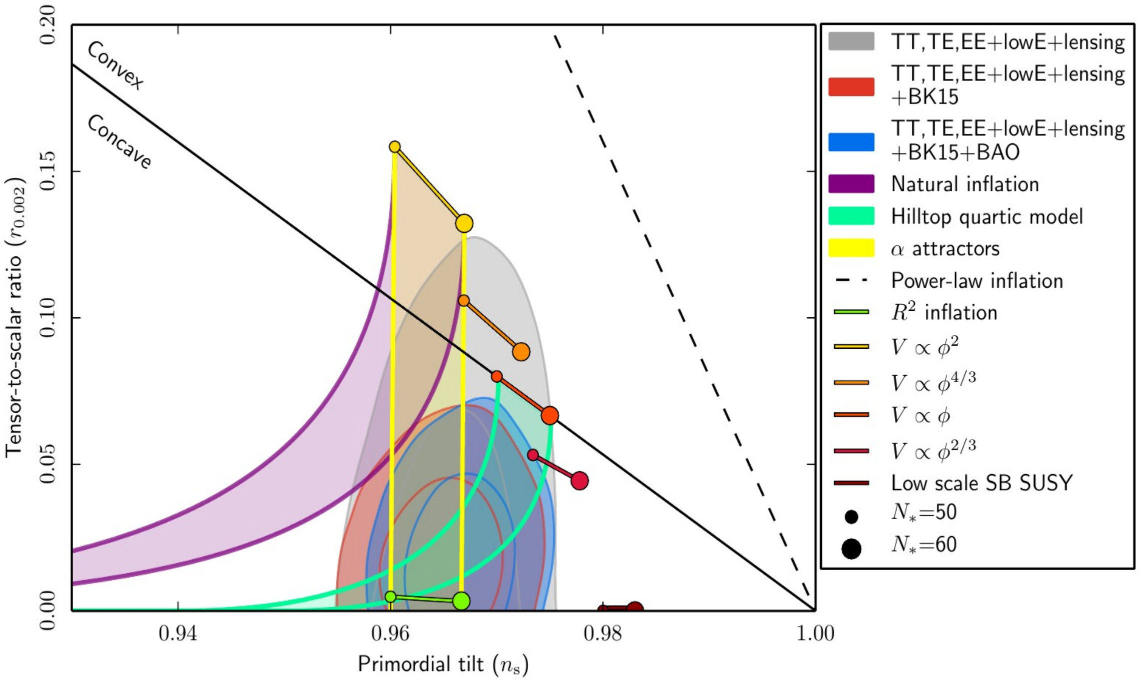
Cosmic inflation

Inflation in a nutshell

- Flatness, horizon, absence of exotic relics problems
- Seeds the primordial density fluctuations

Two inflationary models

- Starobinsky inflation
- Slow-roll parameters



(Planck 2018)

Starobinsky inflation

Starobinsky Model

Action in different frames

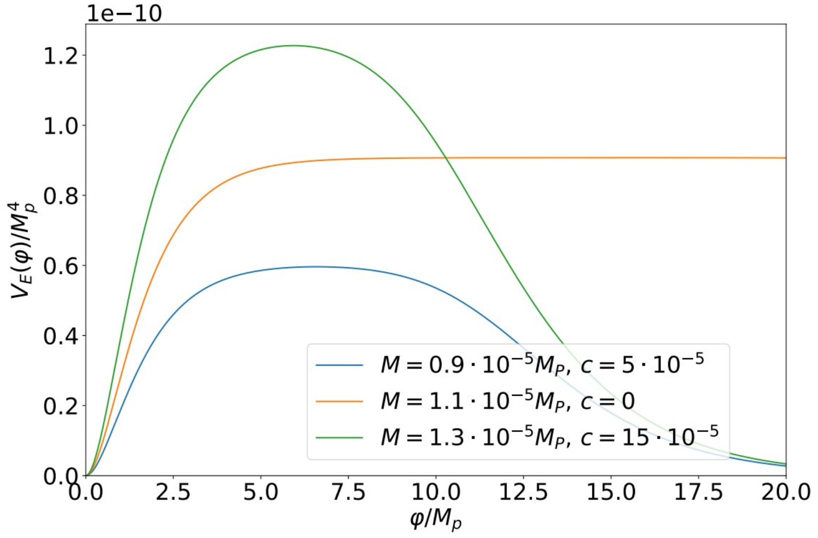
$$S_J = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g_J}\, f(R),$$

$$f(R) = M_P^2\left(R + \frac{1}{6M^2}R^2 + \frac{c}{36M^4}R^3\right)$$

$$S_E = \int \mathrm{d}^4x\sqrt{-g_E}\,\left[\frac{M_P^2}{2}R_E - \frac{1}{2}g^{\mu\nu}{}_E\left(\nabla_\mu\varphi\nabla_\nu\varphi\right) - V_E(\varphi)\right]$$

Potential

$$V_E(\varphi) = \frac{M_P^2\left(\frac{cs(\varphi)^3}{M^2}+3s(\varphi)^2\right)}{36M^2\left(1+\frac{s(\varphi)}{3M^2}+\frac{cs(\varphi)^2}{12M^4}\right)^2}$$



Inflationary dynamics

The background and perturbation

$$\varphi(x^\mu) = \bar{\varphi}(t) + \delta\varphi(x^\mu)$$

$$\ddot{\bar{\varphi}} + 3H\dot{\bar{\varphi}} + V_{E,\bar{\varphi}} = 0$$

$$\ddot{Q} + 3H\dot{Q} + \left[\frac{k^2}{a^2} + V_{E,\bar{\varphi}\bar{\varphi}} - \frac{1}{M_P^2 a^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{a^3}{H}\dot{\bar{\varphi}}^2\right)\right]Q = 0 \text{ and, } \quad v_k'' + \left(k^2 - \frac{a''}{a}\right)v_k = 0$$

Power spectrum

$$\mathcal{R} = \frac{H}{\dot{\bar{\varphi}}}Q; \quad \mathcal{P}_\mathcal{R}(t;k) = \frac{k^3}{2\pi^2}|\mathcal{R}(k)|^2$$

$$\mathcal{P}_\mathcal{T}(t;k) = 8\frac{k^3}{2\pi^2}|v_k|^2$$

$\delta\varphi \to \mathcal{R} \to \mathcal{P}_\delta \to$

- CMB temperature and polarisation fluctuations
- Mapped onto neutral hydrogen density to 21cm brightness fluctuation

Baseline parameters

$\{\omega_\mathrm{b},\ \omega_\mathrm{cdm},\ h,\ \tau_\mathrm{reio},\ M,\ c,\ N_*\}$ MCMC: MontePython+CLASS

CMB and 21cm intensity mapping

CMB

- Planck
- CMB-S4: $(\ell \in [30, 3000])$
- LiteBIRD: $(\ell \in [2, 1350])$
- LiteBIRD low-ℓ + CMB-S4 high-ℓ: $(\ell \in [2, 50]) + [50, 3000])$

(Brinckmann et al. JCAP'19)

21cm intensity mapping

- Resonant reaction between CMB photon and hyperfine transition neutral hydrogen
- Differential brightness temperature:

$$\Delta T_b = \tau \frac{T_b(z) - T_\gamma(z)}{1+z}$$

- Observable: Mean differential brightness temperature:

$$\overline{\Delta T_b} \simeq 189 \left[\frac{H_0 \ (1+z)^2}{H(z)} \right] \Omega_{\rm HI}(z) \ h \ {\rm mK}, \ {\rm with}, \quad \Omega_{\rm HI}(z) = \frac{\rho_{\rm HI}}{\rho_c} \propto x_{\rm HI}(z)$$

(Sprenger et al. JCAP'19, Brax et al.JCAP'13)

21cm power spectrum

$$P_{21}(k,\mu,z) \propto (b_{HI}\overline{\Delta T_b})^2 \times P_\delta(\hat{k},z)$$

$$P_N(z) = \frac{4\pi T_{\rm sys}^2 f_{\rm sky}\lambda^2 y D_A^2}{A\Omega f_{\rm cover} t_{\rm obs}}$$

$$P_{21}^{\rm obs}(k,\mu,z) = P_{21}(k,\mu,z) + P_N(z)$$

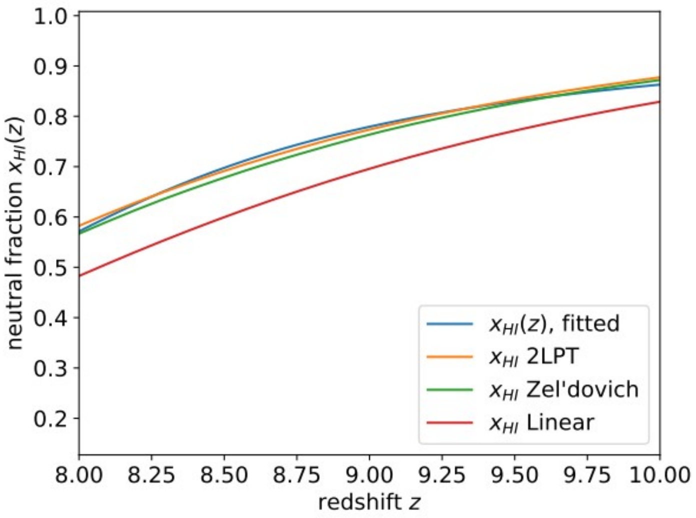
Square Kilometre Array

- SKA1-LOW: $z \in [8, 10]$ and $0.01\ \mathrm{Mpc}^{-1} < \mathrm{k} < 0.2\ \mathrm{Mpc}^{-1}$

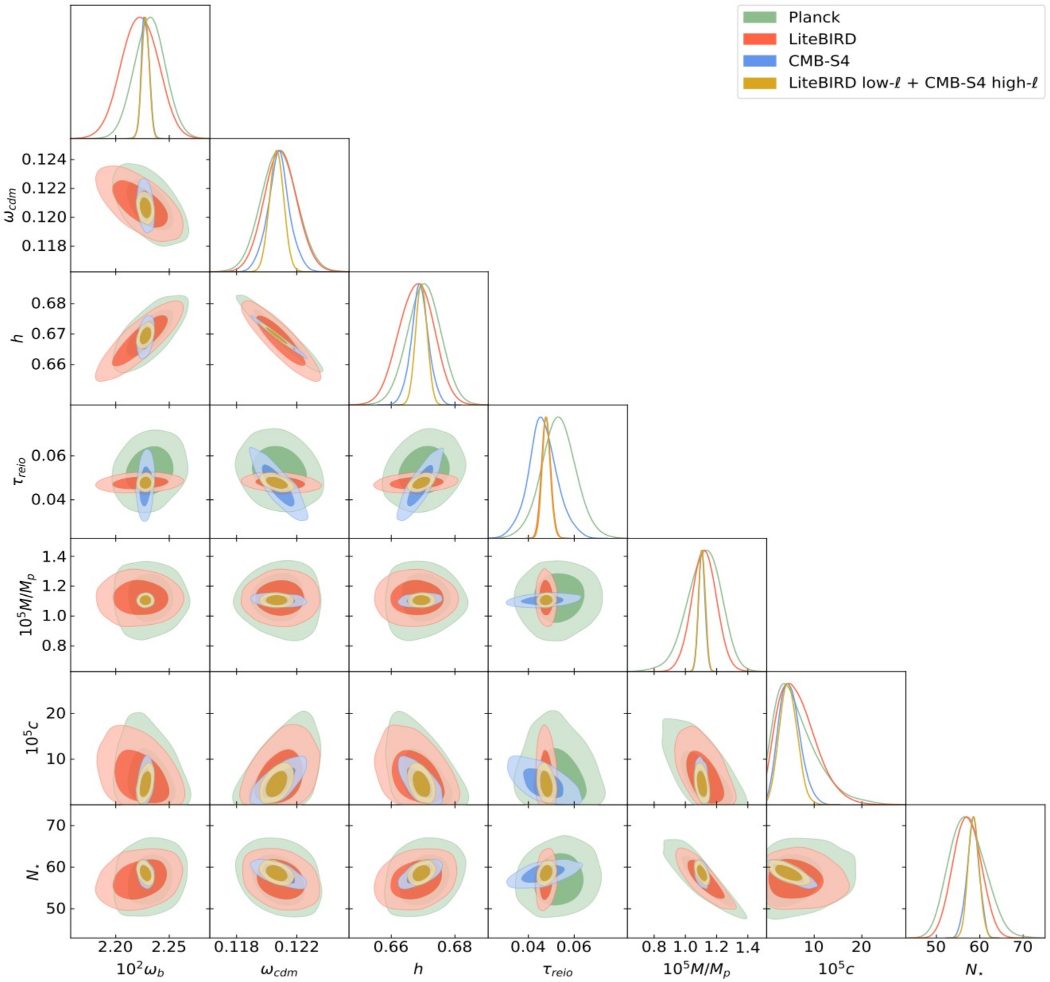
Neutral hydrogen fraction

$$x_{\rm HI}(z) = \frac{1}{2}\left[1 + \frac{2}{\pi}\tan^{-1}\left(\delta_1(z-\delta_2)\right)\right]$$

21cmFAST: $\delta_1 = 0.9755$, $\delta_2 = 7.7664$

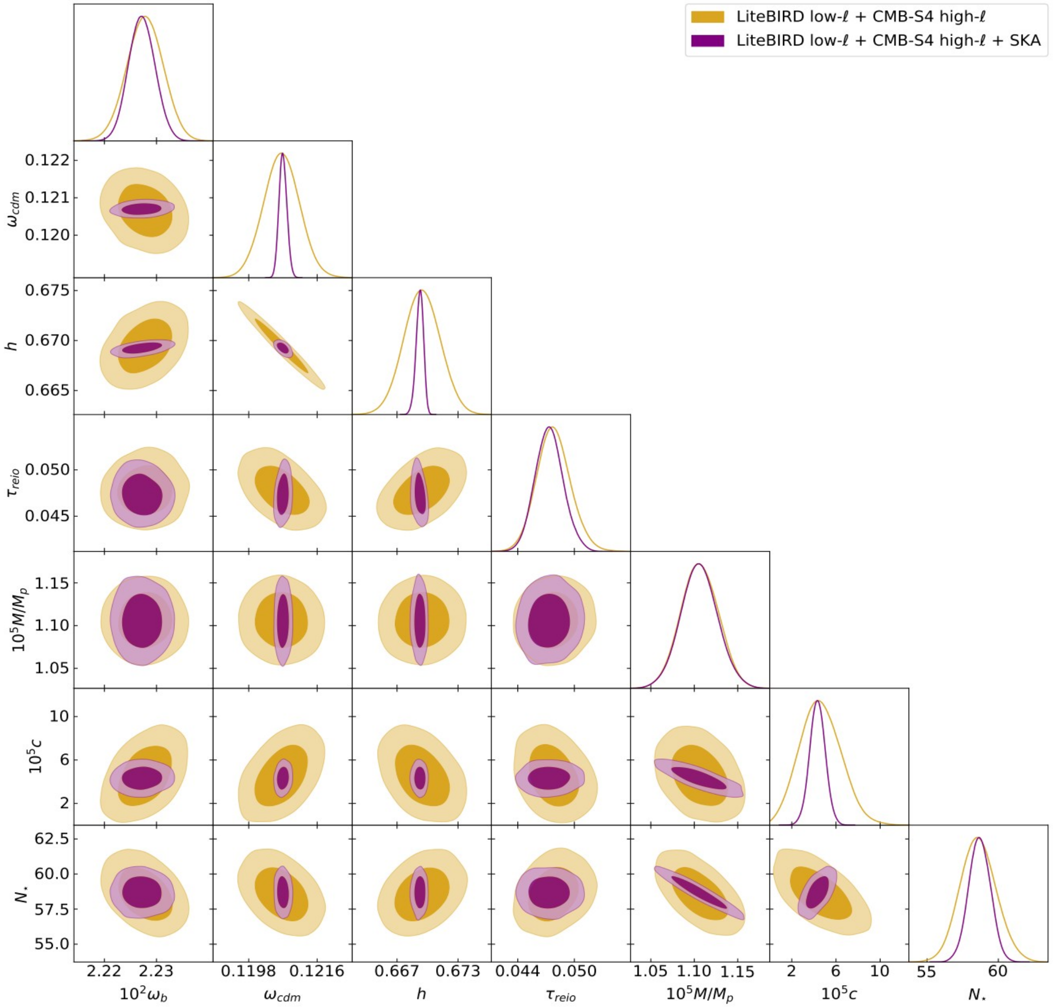


CMB


Planck
LiteBIRD
CMB-S4
LiteBIRD low-ℓ + CMB-S4 high-ℓ
ω_{cdm}
h
τ_{reio}
$10^5 M/M_p$
$10^5 c$
N_*
$10^2\omega_b$

Data	Parameters	Best-fit	Mean$\pm\sigma$	95% lower	95% upper
Planck (TT, TE,EE+low-ℓEE +low-ℓTT)	$100\ \omega_b$	2.228	$2.232^{+0.015}_{-0.015}$	2.203	2.26
	$\omega_{\rm cdm}$	0.1206	$0.1208^{+0.0012}_{-0.0012}$	0.1185	0.1232
	h	0.6696	$0.6703^{+0.0053}_{-0.0053}$	0.6600	0.6808
	$\tau_{\rm reio}$	0.04781	$0.05315^{+0.0074}_{-0.0077}$	0.03764	0.0687
	$10^5 M/M_P$	1.103	$1.119^{+0.117}_{-0.0987}$	0.9005	1.329
	$10^5 c$	4.135	$6.069^{+2.840}_{-5.402}$	—	< 15.96
	$N_\star$	58.24	$57.17^{+3.73}_{-4.47}$	49.65	65.24
LiteBIRD	$100\ \omega_b$	2.229	$2.223^{+0.018}_{-0.017}$	2.190	2.256
	$\omega_{\rm cdm}$	0.1204	$0.1209^{+0.001}_{-0.0011}$	0.1188	0.1231
	h	0.6705	$0.6679^{+0.0057}_{-0.0055}$	0.657	0.6785
	$\tau_{\rm reio}$	0.04735	$0.04775^{+0.002}_{-0.002}$	0.04391	0.05171
	$10^5 M/M_P$	1.144	$1.121^{+0.077}_{-0.077}$	0.9676	1.273
	$10^5 c$	2.633	$6.345^{+2.996}_{-4.801}$	—	< 14.62
	N_*	57.79	$57.08^{+3.18}_{-3.19}$	51.04	63.27
CMB-S4	$100\ \omega_b$	2.227	$2.228^{+0.004}_{-0.004}$	2.221	2.235
	$\omega_{\rm cdm}$	0.121	$0.1208^{+0.0007}_{-0.0007}$	0.1192	0.1223
	h	0.6681	$0.669^{+0.0027}_{-0.0027}$	0.6634	0.6749
	$\tau_{\rm reio}$	0.04478	$0.04634^{+0.0064}_{-0.0058}$	0.03258	0.05963
	$10^5 M/M_P$	1.098	$1.105^{+0.021}_{-0.021}$	1.065	1.145
	$10^5 c$	5.166	$4.794^{+1.923}_{-2.461}$	0.7769	9.543
	N_*	58.44	$58.45^{+1.45}_{-1.35}$	55.66	61.26
LiteBIRD low-ℓ + CMB-S4 high-ℓ	$100\ \omega_b$	2.227	$2.228^{+0.004}_{-0.004}$	2.221	2.235
	$\omega_{\rm cdm}$	0.1206	$0.1207^{+0.0005}_{-0.0005}$	0.1197	0.1216
	h	0.6696	$0.6695^{+0.0018}_{-0.0018}$	0.6659	0.673
	$\tau_{\rm reio}$	0.04829	$0.04779^{+0.0017}_{-0.0019}$	0.04425	0.05148
	$10^5 M/M_P$	1.108	$1.106^{+0.022}_{-0.021}$	1.064	1.147
	$10^5 c$	4.177	$4.573^{+1.786}_{-1.944}$	1.015	8.300
	N_*	58.71	$58.59^{+1.24}_{-1.25}$	56.15	61.08

....with SKA



LiteBIRD low-ℓ + CMB-S4 high-ℓ
LiteBIRD low-ℓ + CMB-S4 high-ℓ + SKA
ω_{cdm}
h
τ_{reio}
$10^5 M/M_p$
$10^5 c$
N_*
$10^2\omega_b$
0.122
0.121
0.120
0.675
0.670
0.665
0.050
0.045
1.15
1.10
1.05
10
6
2
62.5
60.0
57.5
55.0
2.22 2.23
0.1198 0.1216
0.667 0.673
0.044 0.050
1.05 1.10 1.15
2 6 10
55 60

Data	Parameters	Best-fit	Mean$\pm\sigma$	95% lower	95% upper
	$100\ \omega_b$	2.228	$2.227^{+0.003}_{-0.003}$	2.222	2.232
LiteBIRD low-ℓ	$\omega_{\rm cdm}$	0.1206	$0.1207^{+0.0001}_{-0.0001}$	0.1205	0.1209
+	h	0.6694	$0.6692^{+0.0004}_{-0.0003}$	0.6685	0.670
CMB-S4 high-ℓ	$\tau_{\rm reio}$	0.04792	$0.04734^{+0.0014}_{-0.0016}$	0.04445	0.05033
+	$10^5 M/M_P$	1.100	$1.106^{+0.023}_{-0.023}$	1.064	1.148
SKA	$10^5 c$	4.350	$4.325^{+0.692}_{-0.690}$	2.891	5.734
	N_*	58.95	$58.68^{+0.77}_{-0.75}$	57.20	60.18

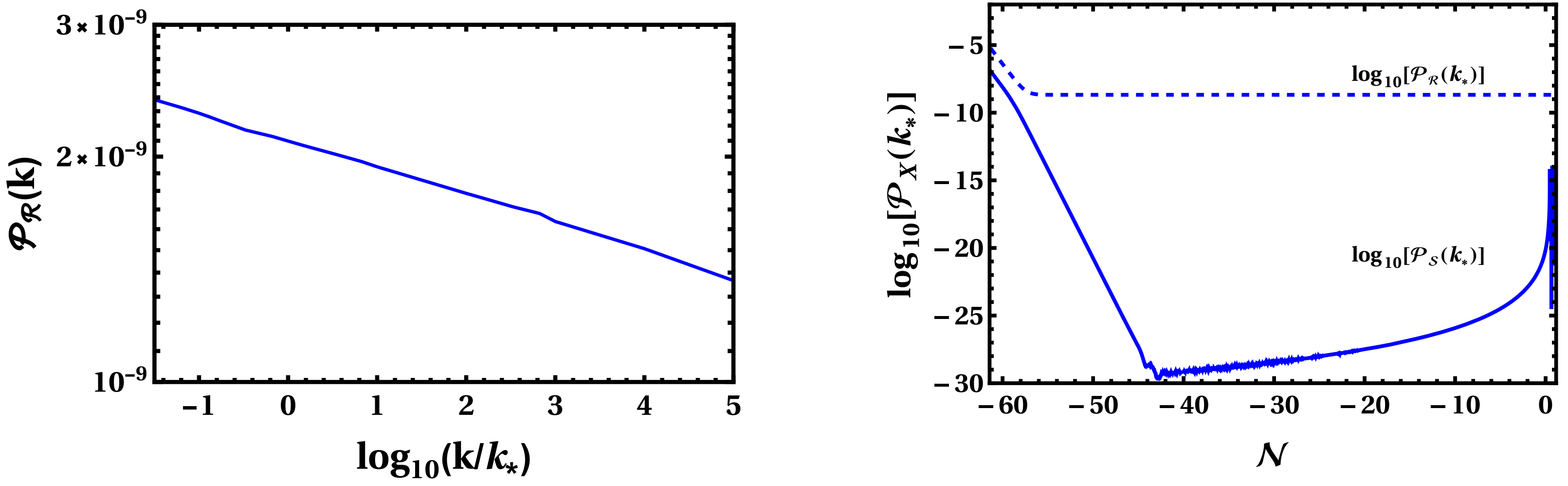
R^2-Higgs inflation

$$S_E = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{1}{2}e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}\left(\sum_i(\partial_\mu\rho_i)^2\right) - V_E\right]$$

$$V_E(\varphi,\rho_1,\rho_2,\rho_3) = \frac{1}{8}e^{-2\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}\left[V(\rho_1,\rho_2,\rho_3)+2\frac{M_P^4}{\xi_R}\left(e^{\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}-1-\frac{\xi_{11}}{M_P^2}\rho_1^2\right)^2\right]$$

$r_{\varphi*} \approx 3.3\times10^{-3},\ n_{s*} = 0.965$

(S.M.Lee, TM, K.y. Oda, T. Tomo, EPJC'22;
TM, K.y. Oda, EPJC'21)



Hubble Slow-roll

Hubble slow-roll parameters

- Inflationary dynamics: parametrized by expansion of Hubble parameter
- Scalar and tensor modes: constrained by given Hubble parameter

The parameters

(Lesgourgues et al. JCAP'08, Planck'18)

$$H(\bar{\varphi}) = \sum_{n=0}^{N} \frac{1}{n!} \frac{d^n H}{d\bar{\varphi}^n}\bigg|_{\bar{\varphi}_*} (\bar{\varphi} - \bar{\varphi}_*)^n$$

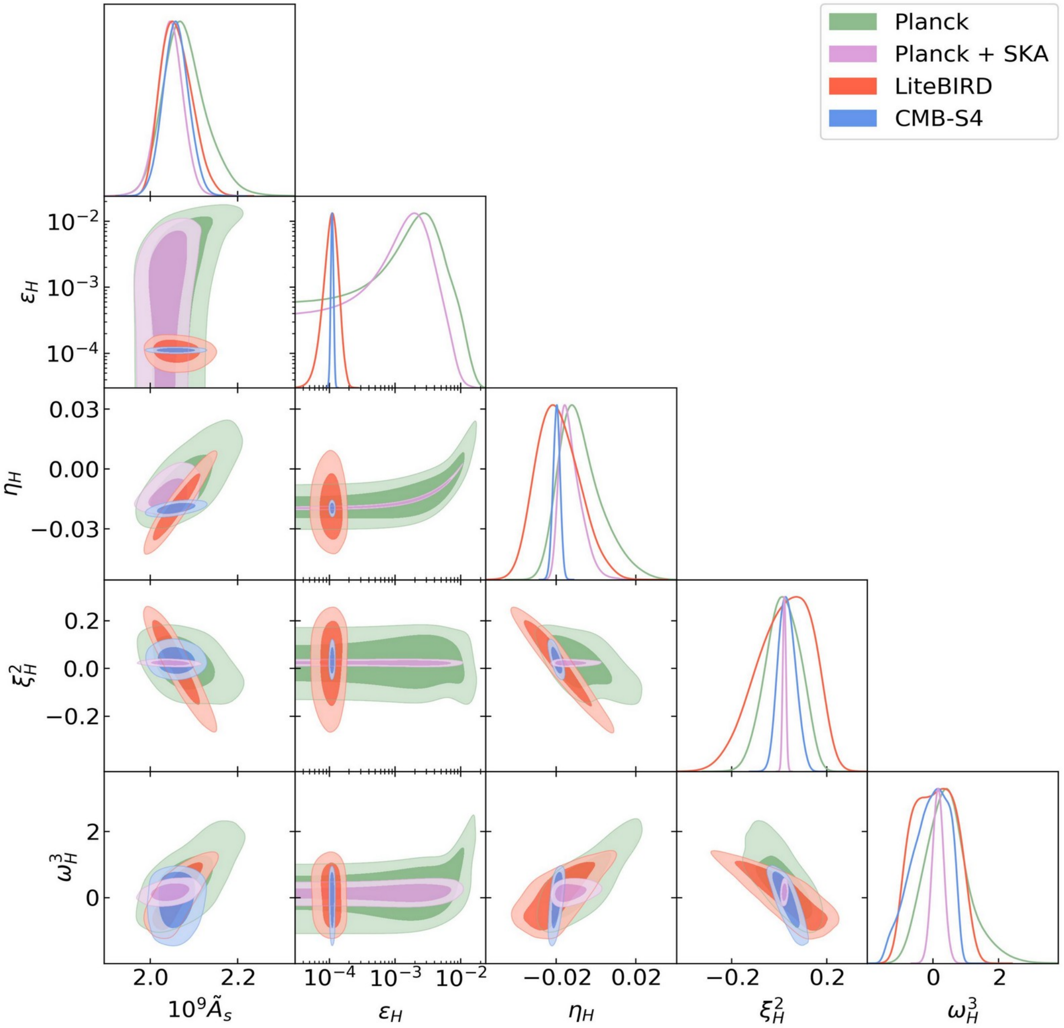
$$\epsilon_H = \frac{M_{\rm pl}^2}{4\pi} \left(\frac{H'}{H}\right)^2,$$

$$\eta_H = \frac{M_{\rm pl}^2}{4\pi} \left(\frac{H''}{H}\right), \ldots.$$

Baseline model parameters

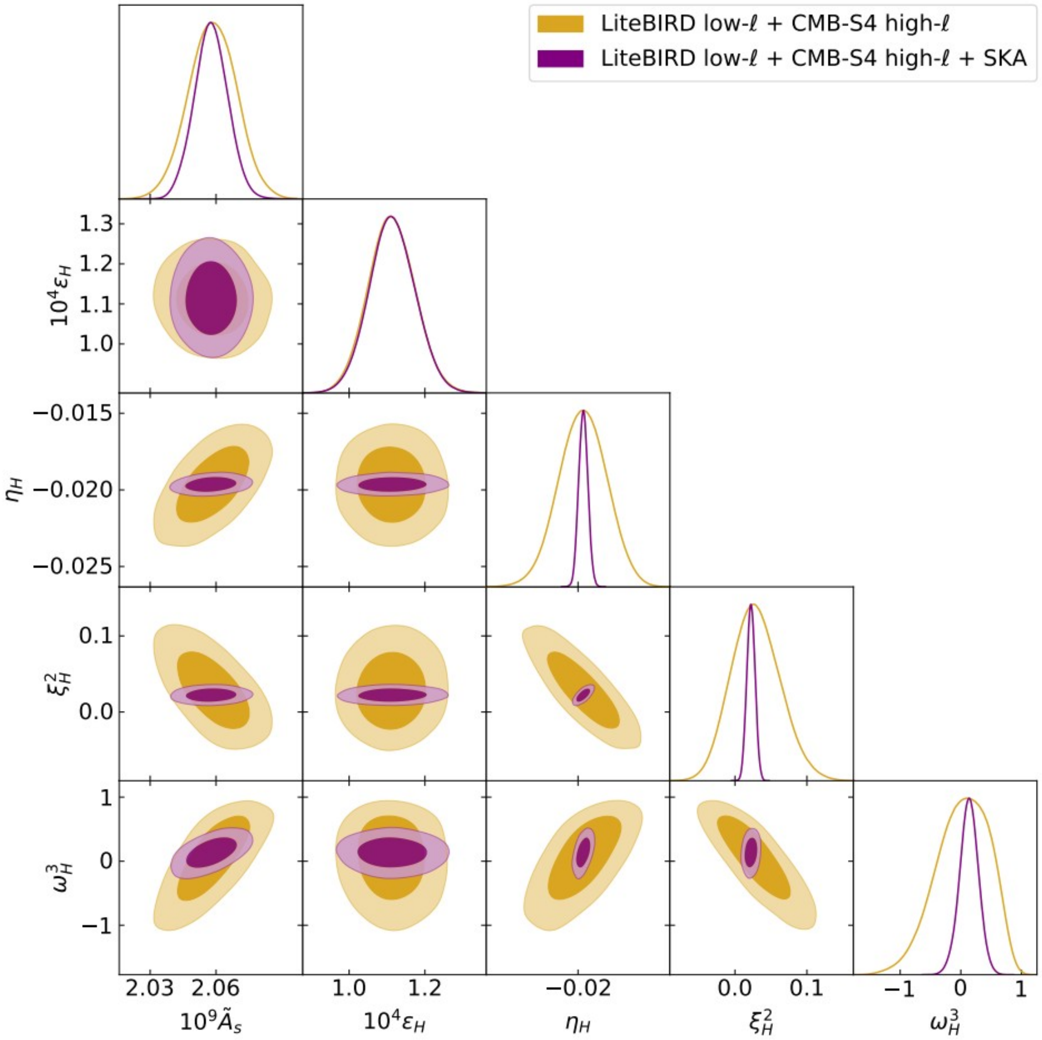
$$\{\omega_{\rm b},\, \omega_{\rm cdm},\, h,\, \tau_{\rm reio},\, n_s,\, \tilde{A}_s,\, \epsilon_H,\, \eta_H,\, \xi_H^2,\, \omega_H^3\}$$

CMB



Planck
Planck + SKA
LiteBIRD
CMB-S4
$10^9\tilde{A}_s$
ϵ_H
η_H
ξ_H^2
ω_H^3

....with SKA


LiteBIRD low-ℓ + CMB-S4 high-ℓ
LiteBIRD low-ℓ + CMB-S4 high-ℓ + SKA
$10^4\epsilon_H$
η_H
ξ_H^2
ω_H^3
$10^9\tilde{A}_s$
$10^4\epsilon_H$
η_H
ξ_H^2
ω_H^3

Summary & outlook

- Starobinsky inflation: One of the bestfit model
- Extension with higher order terms
- Future CMB experiments: offers excellent probes
- CMB-S4+LiteBIRD+SKA: may discover higher order terms
- Impact of astro parameters: MCMC too difficult. Machine Learning

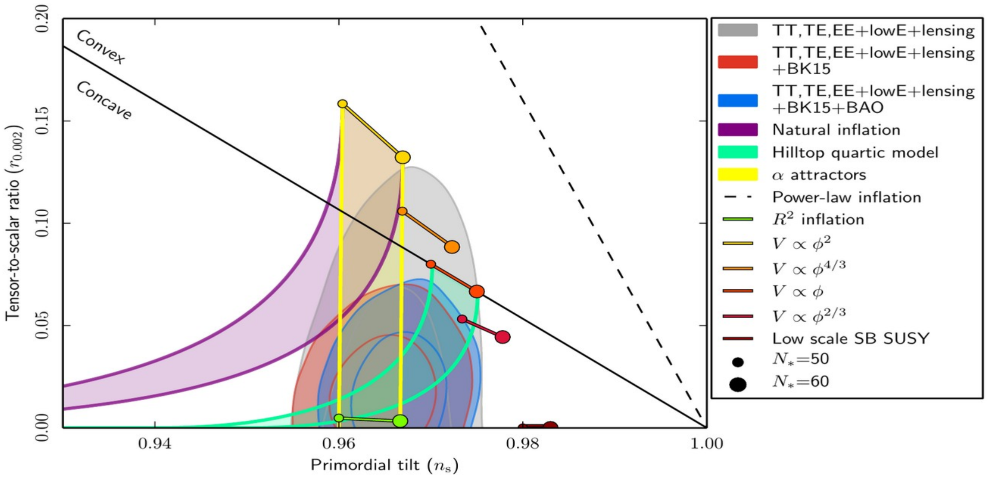
Additional Slides

LiteBIRD and CMB-S4

For LiteBIRD the angular scales are $\ell = 2$ ... 1350, the sky fraction is $f_{\rm sky} = 0.7$, while the channel is taken as 140 GHz with full-width-half-max or FWHM $= 31$ arcmin, $\Delta T = 4.1\ \mu$K arcmin, and $\Delta P = 5.8\ \mu$K arcmin (as per arXiv:1808.05955). The CMB-S4 specifications are $\ell = 30$ ... 3000, $f_{\rm sky} = 0.4$, 150 GHz channel, FWHM $= 3$ arcmin, $\Delta T = 1.0\ \mu$K arcmin and $\Delta P = 1.41\ \mu$K arcmin. We need to ensure that the two experiments cover mutually exclusive ℓ ranges, so just as in arXiv:1808.05955we combine low-ℓ from LiteBIRD data and high-ℓ CMB-S4 data, separated at $\ell \leq 50$. Noise is estimated through minimum variance estimator for both experiments. We use the HALOFIT model for the nonlinear corrections throughout this paper.

(Brinckmann et al. JCAP'19)

Modified ΛCDM



$\{\omega_{\rm b},\, \omega_{\rm cdm},\, h,\, \tau_{\rm reio},\, n_s,\, \mathcal{A}_s,\, \alpha_s,\, \beta_s,\, r\}$

power spectrum: $\mathcal{P}_\mathcal{R}(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{\alpha_s}{2!}\ln\left(\frac{k}{k_*}\right) + \frac{\beta_s}{3!}\ln\left(\frac{k}{k_*}\right)^2}$

tensor-to-scalar ratio: $r = \frac{\mathcal{A}_t}{\mathcal{A}_s}$

spectral index: $n_s = 1 + d\mathcal{P}_\mathcal{R}(k)/d\ln k$

Runnings of n_s: $\alpha_s = dn_s/d\ln k$ and $\beta_s = d^2 n_s/d\ln k^2$

SKA specifications

$$P_{21}(k,\mu,z) = f_{\rm AP}(z) \times f_{\rm res}(k,\mu,z) \times f_{\rm RSD}(\hat{k},\hat{\mu},z) \times b_{21}^2(z) \times P_\delta(\hat{k},z)$$
$$P_{21}^{\rm obs}(k,\mu,z) = P_{21}(k,\mu,z) + P_N(z)$$
$$P_N(z) = \frac{4\pi T_{\rm sys}^2 f_{\rm sky} \lambda^2 y D_A^2}{A\Omega f_{\rm cover} t_{\rm obs}}$$

$$T_{\rm sys} = T_{\rm sky} + T_{\rm rx}$$

$$\text{with} \quad T_{\rm sky} = 25\,{\rm K}\left(\frac{408\,{\rm MHz}}{\nu}\right)^{2.75} \quad \text{and} \quad T_{\rm rx} = 0.1 T_{\rm sky} + 40\ {\rm K}$$

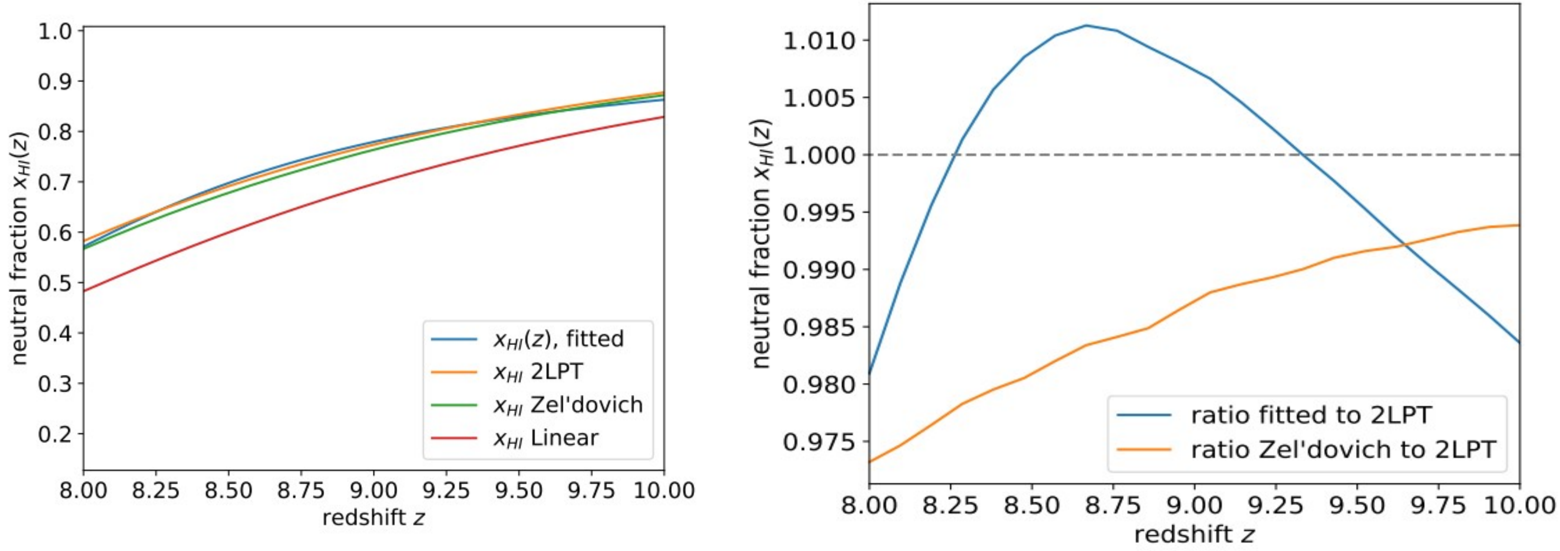
(SKA Red book)

$t_{\rm obs} = 1000$ hrs, $\nu_0 = 1420.405752$ MHz, $\lambda_0 = 21.11$ cm, band $[50, 350]$ MHz, array of 224 stations, size of the station $D = 40$ m, maximum baseline $D_{\rm base} = 1$ km, 64000 channels, $f_{\rm sky} = 0.58$, field of view of $\Omega = (1.2\lambda/D)^2$, an area $A = N_{\rm dish}\pi(D/2)^2$ per station, and the covering fraction $f_{\rm cover} = N_{\rm dish}(D/D_{\rm base})^2$.

at z= 8 the Comoving Radial Distance LoS to z is 8943.21 (Mpc) and at z= 10 the distance is 9440.25 (Mpc). The difference is 497.04 (cMpc) which translates to 741.85 Mpc/h. Now we have 20 bins so the difference translates to 37.09 Mpc/h.

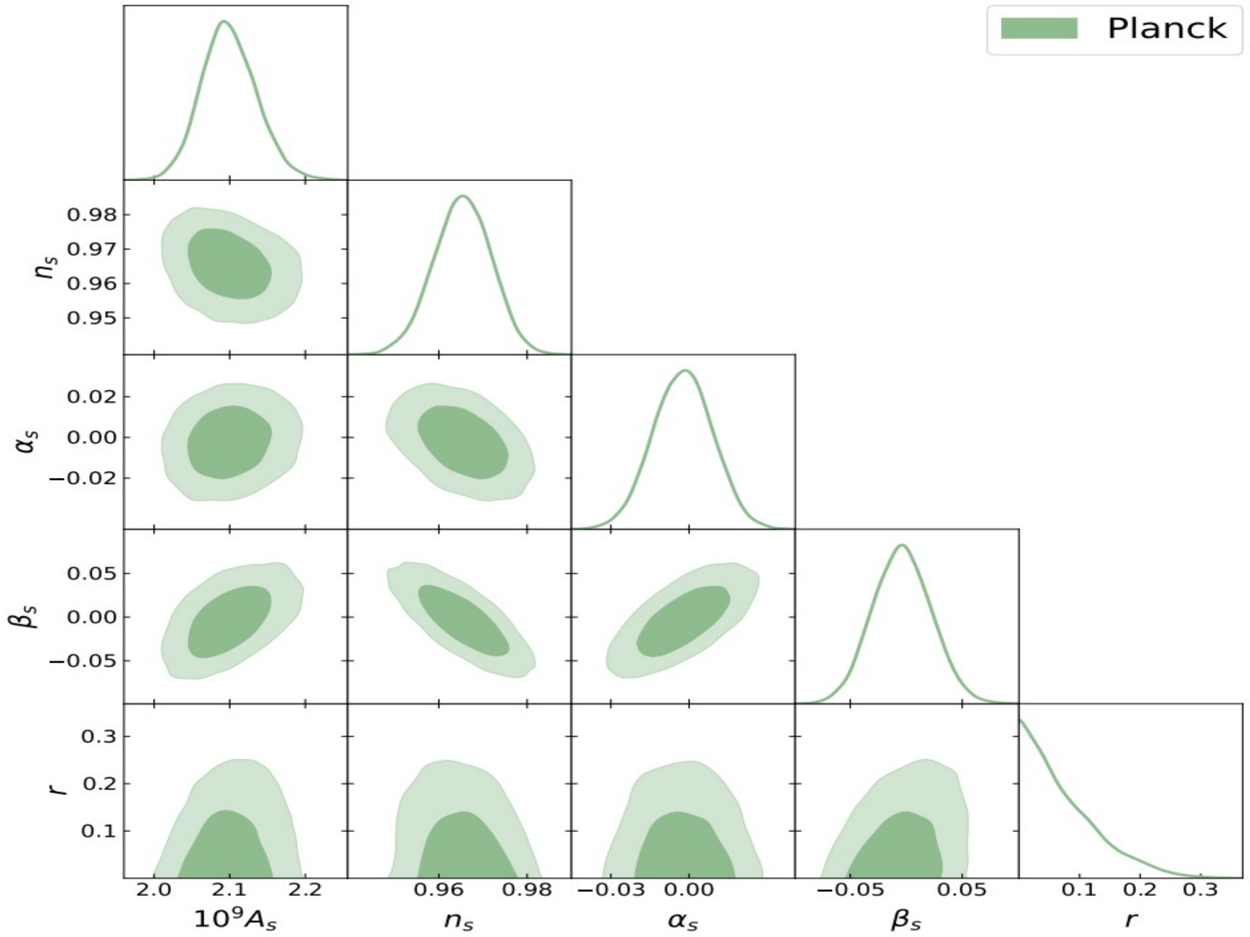
Avg. ionized patches few Mpc (Mellema et al. 1210.0197)

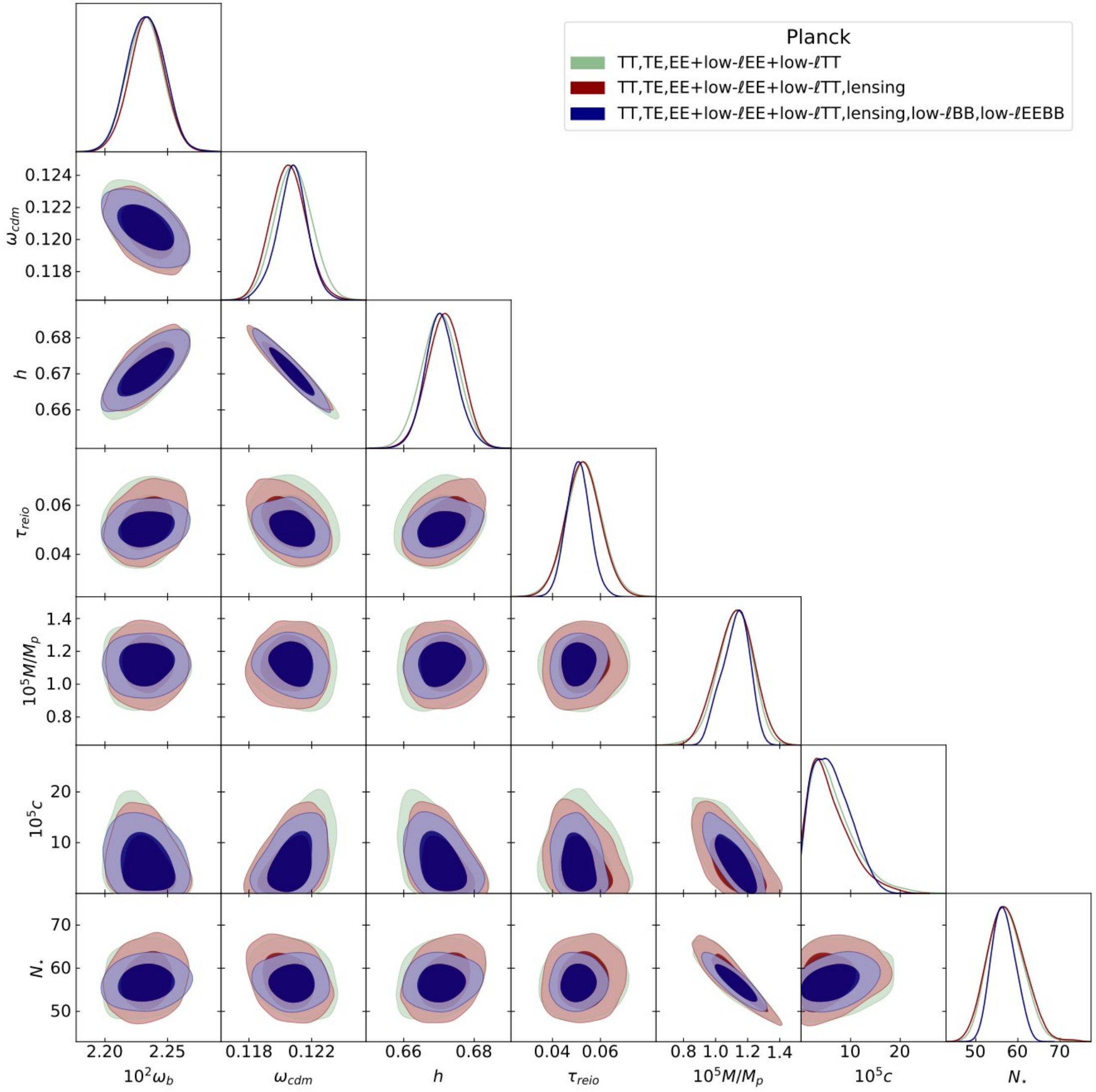
$$\Omega_{\rm HI}(z) = \frac{\rho_{\rm HI}}{\rho_c} = \Omega_b(1-Y_P)\left(\frac{H_0}{H(z)}\right)^2 (1+z)^3\, x_{\rm HI}(z)$$
$$P_{21}(k,\mu,z) = f_{\rm AP}(z) \times f_{\rm res}(k,\mu,z) \times f_{\rm RSD}(\hat{k},\hat{\mu},z) \times (b_{HI}\overline{\Delta T_b})^2 \times P_\delta(\hat{k},z)$$



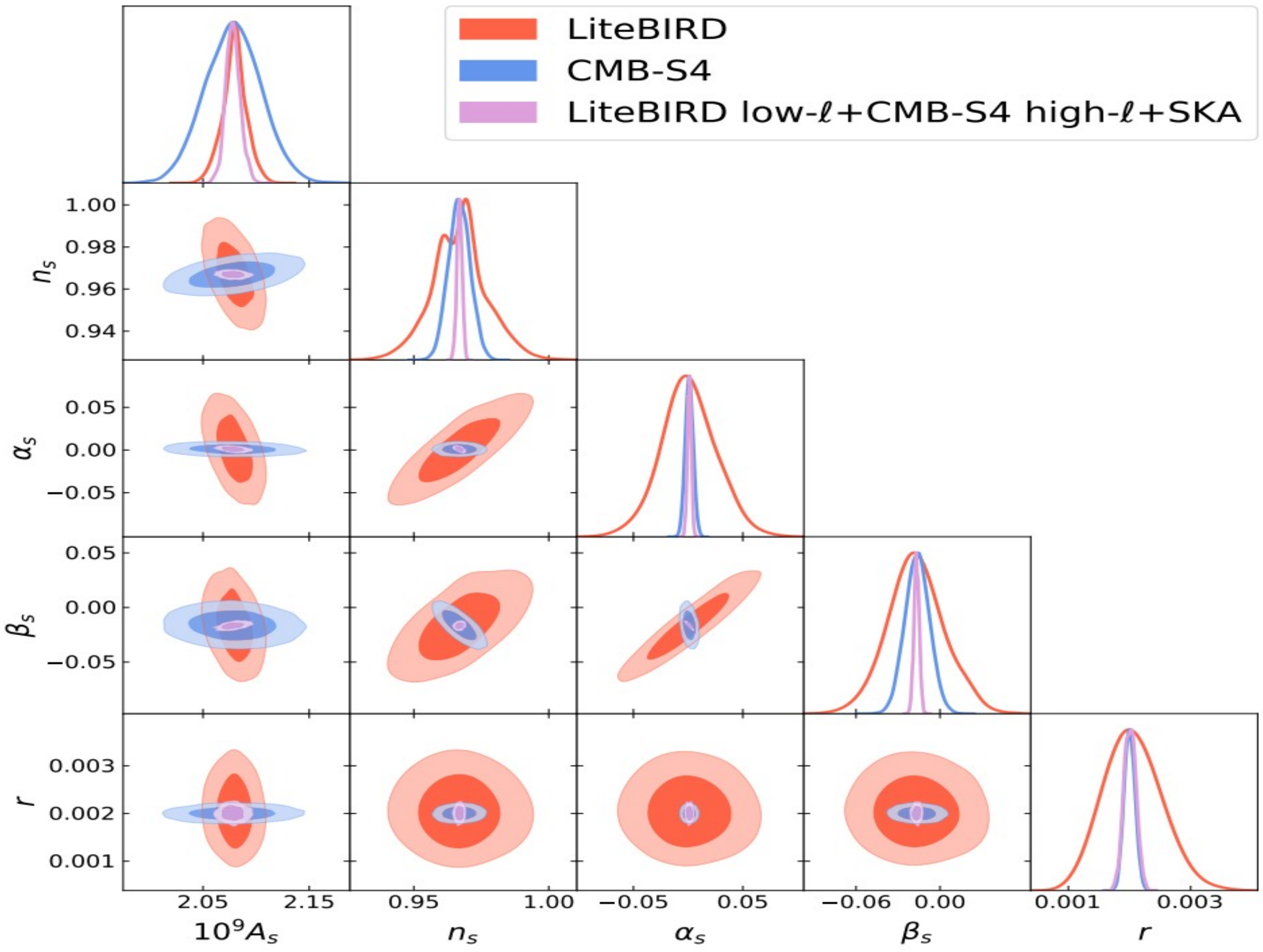
21cmFAST: First-order perturbative approximation (Zel'dovich's approximation) and a second-order 2LPT approximation to the linear velocity field.
Fit values: $\delta_1 = 0.9755$, $\delta_2 = 7.7664$

Modified ΛCDM





Planck
TT,TE,EE+low-ℓEE+low-ℓTT
TT,TE,EE+low-ℓEE+low-ℓTT,lensing
TT,TE,EE+low-ℓEE+low-ℓTT,lensing,low-ℓBB,low-ℓEEBB
ω_{cdm}
h
τ_{reio}
$10^5 M/M_p$
$10^5 c$
$N_\star$
$10^2\omega_b$



LiteBIRD
CMB-S4
LiteBIRD low-ℓ+CMB-S4 high-ℓ+SKA
1.00
0.98
0.96
0.94
n_s
0.05
0.00
−0.05
α_s
0.05
0.00
−0.05
β_s
0.003
0.002
0.001
r
2.05
2.15
$10^9 A_s$
0.95
1.00
n_s
−0.05
0.05
α_s
−0.06
0.00
β_s
0.001
0.003
r