A global view of the inflationary landscape in future experiments

Tanmoy Modak
10 August 2024
CHEP, IISc

Cosmic inflation

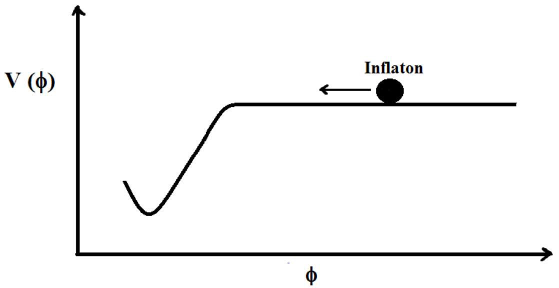
Inflation in a nutshell

Flatness, horizon, absence of exotic relics problems

Dynamics

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

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

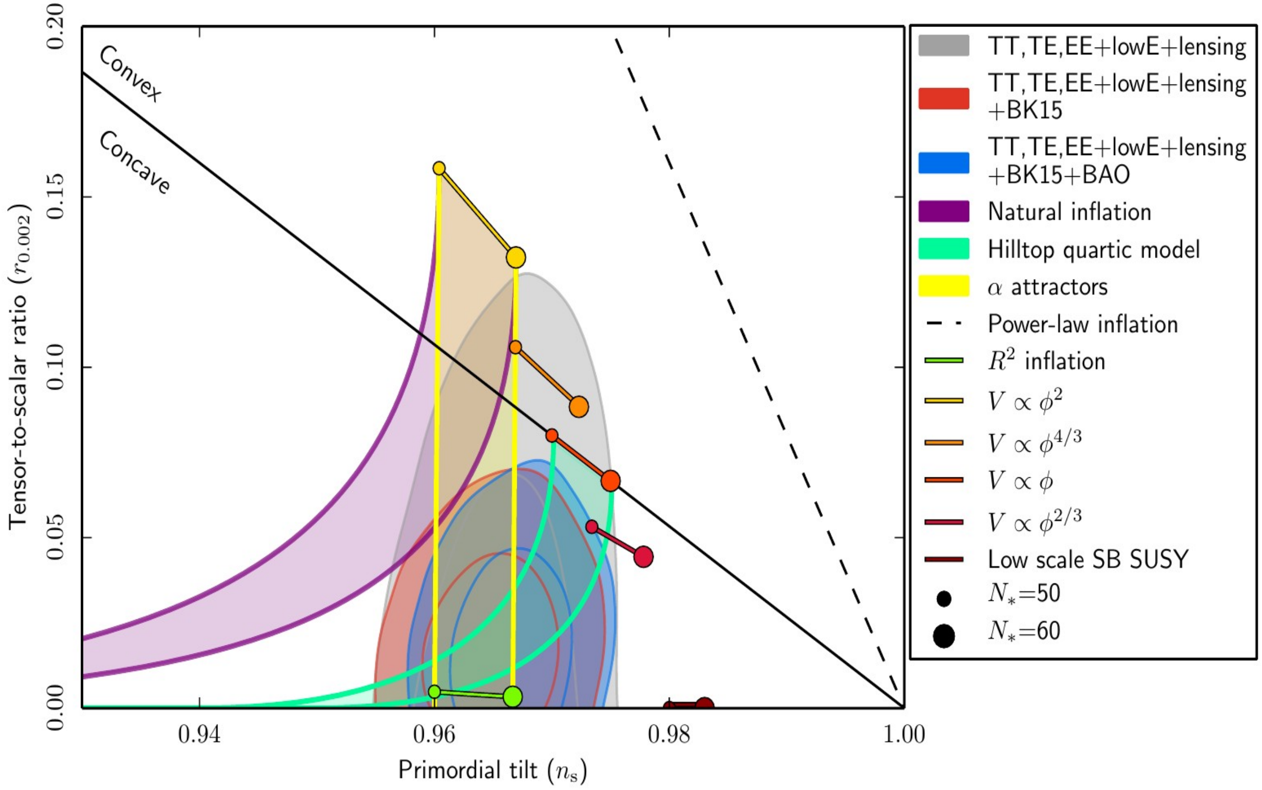


Perturbation

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

- CMB temperature and polarisation fluctuations
- Neutral hydrogen density to 21cm brightness fluctuation

The Zoo

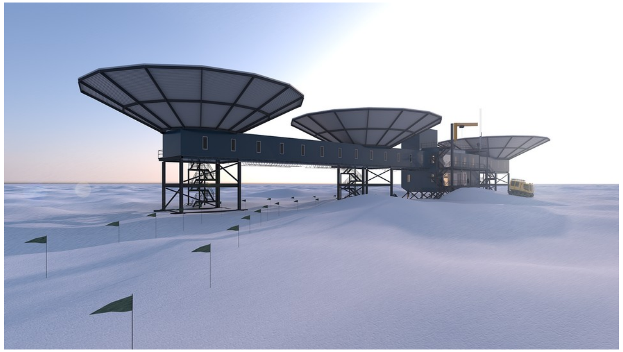


(Planck 2018)

CMB

CMB-S4

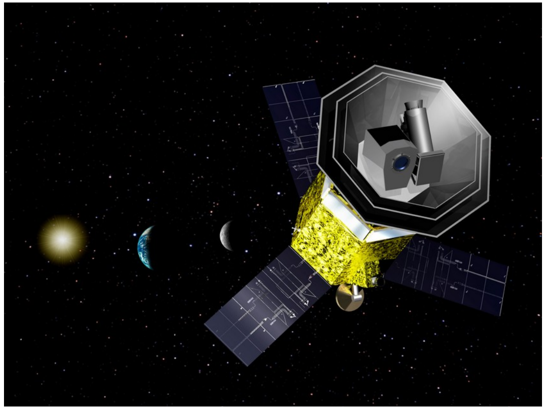
12 telescopes: 500,000 cryogenically-cooled superconducting detectors in South Pole and in the Chilean Atacama desert



(CMB-S4 South pole preliminary; Credit: CMB-S4)

LiteBIRD

Second Lagrange point, 1.5 million kilometers from Earth



(LiteBIRD concept art: Credit ISAS/JAXA)

Current and future of CMB experiments

- 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 by SKA

Brightness temparture T_b (TM, T. Plehn, L. Röver, and B. M. Schäfer, B. Schosser, SciPost Phys. 15, 047 (2023))

Resonant interaction of CMB photons & the hyperfine transition

$$\nu_0 = 1420.405752\ \mathrm{MHz},\ \lambda_0 = 21.11\ \mathrm{cm}$$

Differential brightness temperature

$$\Delta T_b = \tau \frac{T_b(z) - T_\gamma(z)}{1+z} \quad \text{, optical depth:} \tau \ll 1$$

Power Spectrum

$$\overline{\Delta T_b} \simeq 189 \left[\frac{H_0\,(1+z)^2}{H(z)} \right] \Omega_{\mathrm{HI}}(z)\, h\ \mathrm{mK}$$

(Sprenger et al. JCAP'19)

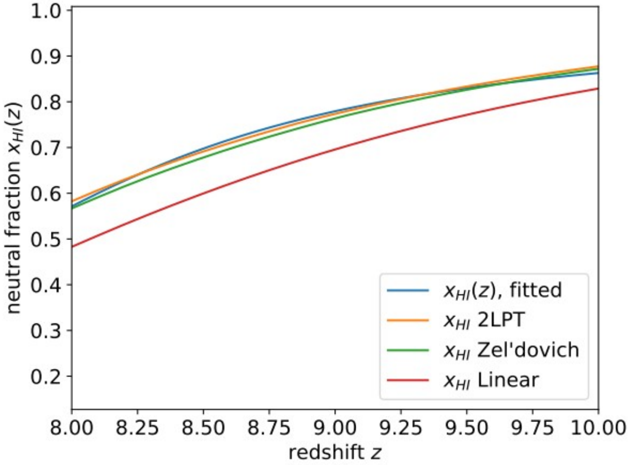
$$P_{21}(k,\mu,z) = f_{\mathrm{AP}}(z) \times f_{\mathrm{res}}(k,\mu,z) \times f_{\mathrm{RSD}}(\hat{k},\hat{\mu},z) \times b_{21}^2(z) \times P_\delta(\hat{k},z)$$

$$b_{21} = \overline{\Delta T_b}(z) b_{\mathrm{HI}}(z)$$

Neutral hydrogen fraction

$$\Omega_{\mathrm{HI}}(z) = \frac{\rho_{\mathrm{HI}}}{\rho_c} = \Omega_b(1 - Y_P)\left(\frac{H_0}{H(z)}\right)^2 (1+z)^3\, x_{\mathrm{HI}}(z)$$

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



21cmFAST

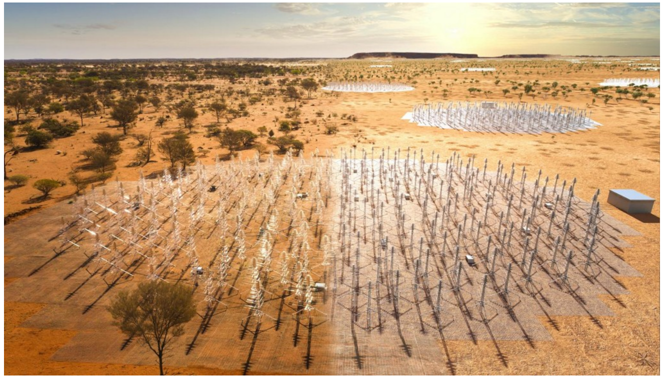
Fit values: $\delta_1 = 0.9755,\ \delta_2 = 7.7664$

three nuisance parameters: $\{b_{HI}, \delta_1, \delta_2\}$

SKA1-Low

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

The comoving radial distance line of sight to
z = 8: 8943.21 (Mpc)
z = 10: 9440.25 (Mpc)
The difference translates to 37.09 Mpc/h for 20 bins



(SKA-Low prototype antennas: Credit SKA)

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

SKA1-Low specifications

$t_{\mathrm{obs}} = 10000$ hrs, $\nu_0 = 1420.405752$ MHz, $\lambda_0 = 21.11$ cm, band $[50, 350]$ MHz, array of 224 stations, size of the station $D = 40$ each with 256 antennas with area $3.2\ m^2$.

Compared to LOFAR 25% better resolution, eight times the sensitivity, and will be able to survey the sky 135 times faster.

Hubble slow-roll parameters

(TM, T. Plehn, L. Röver, and B. M. Schäfer, B. Schosser, SciPost Phys. 15, 047 (2023);
TM, T. Plehn, L. Röver, and B. M. Schäfer, SciPostPhys. Core ’22)

- Inflationary dynamics: parametrized by expansion of Hubble parameter

The parameters

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

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

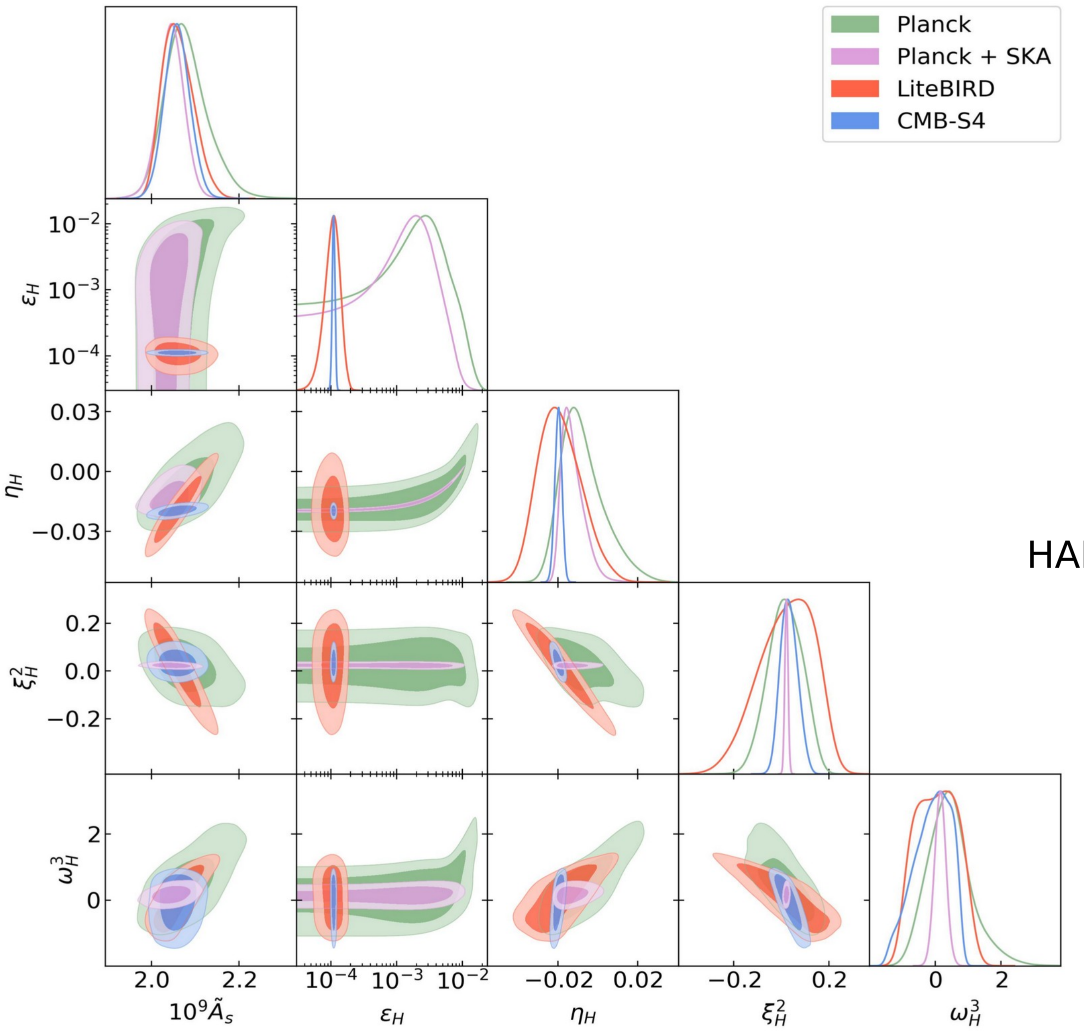
$$\eta_H = \frac{M_{\rm pl}^2}{4\pi}\left(\frac{H''}{H}\right), \ldots.$$

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

Parameters of

$$\{\tilde{A}_s,\, \epsilon_H,\, \eta_H,\, \xi_H^2,\, \omega_H^3\}$$

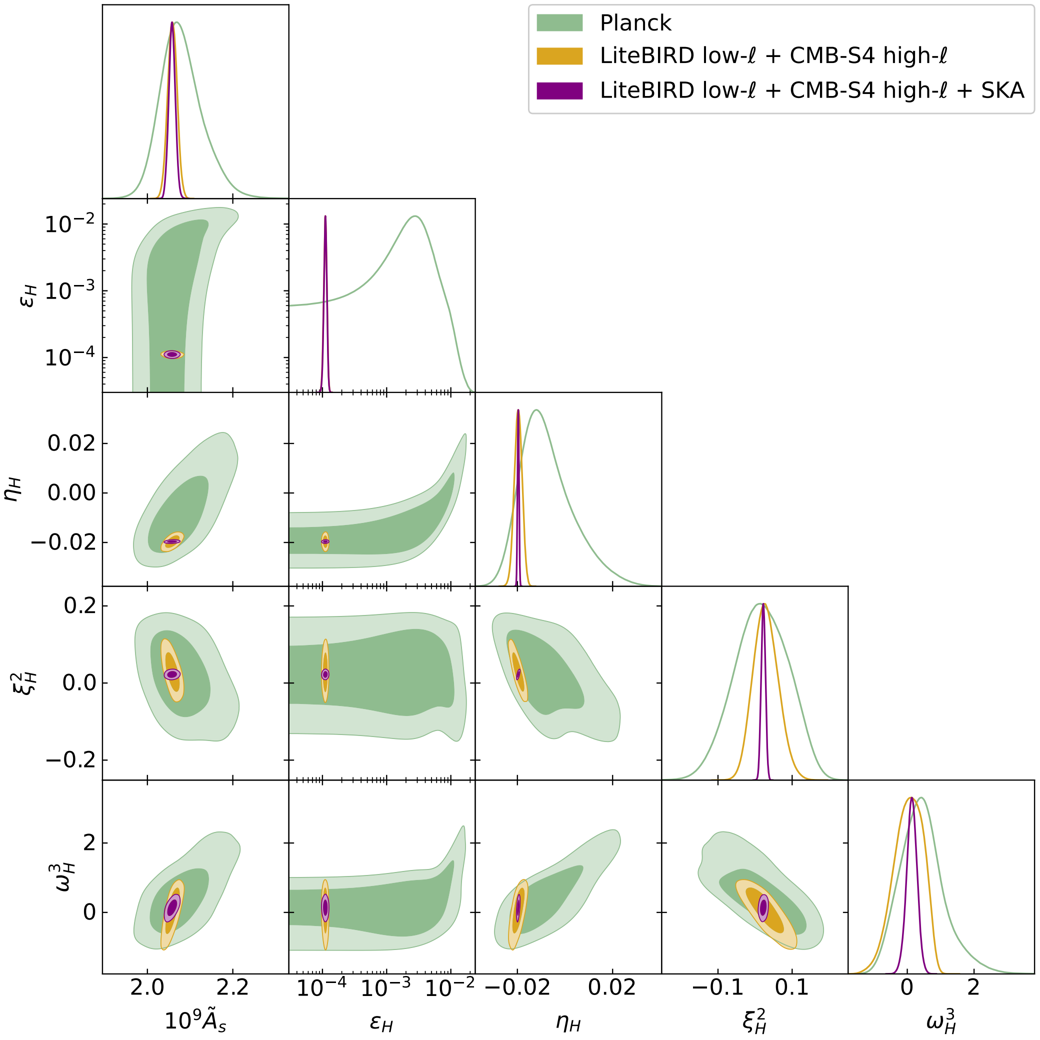
CMB



Class+MontePython

HALOFIT: For nonlinear corrections

With SKA



Planck
LiteBIRD low-ℓ + CMB-S4 high-ℓ
LiteBIRD low-ℓ + CMB-S4 high-ℓ + SKA
$10^9\tilde{A}_s$
ϵ_H
η_H
ξ_H^2
ω_H^3
2.0
2.2
10^{-4}
10^{-3}
10^{-2}
−0.02
0.00
0.02
−0.2
0.0
0.2
−0.1
0.1
0
2

Modified ΛCDM

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

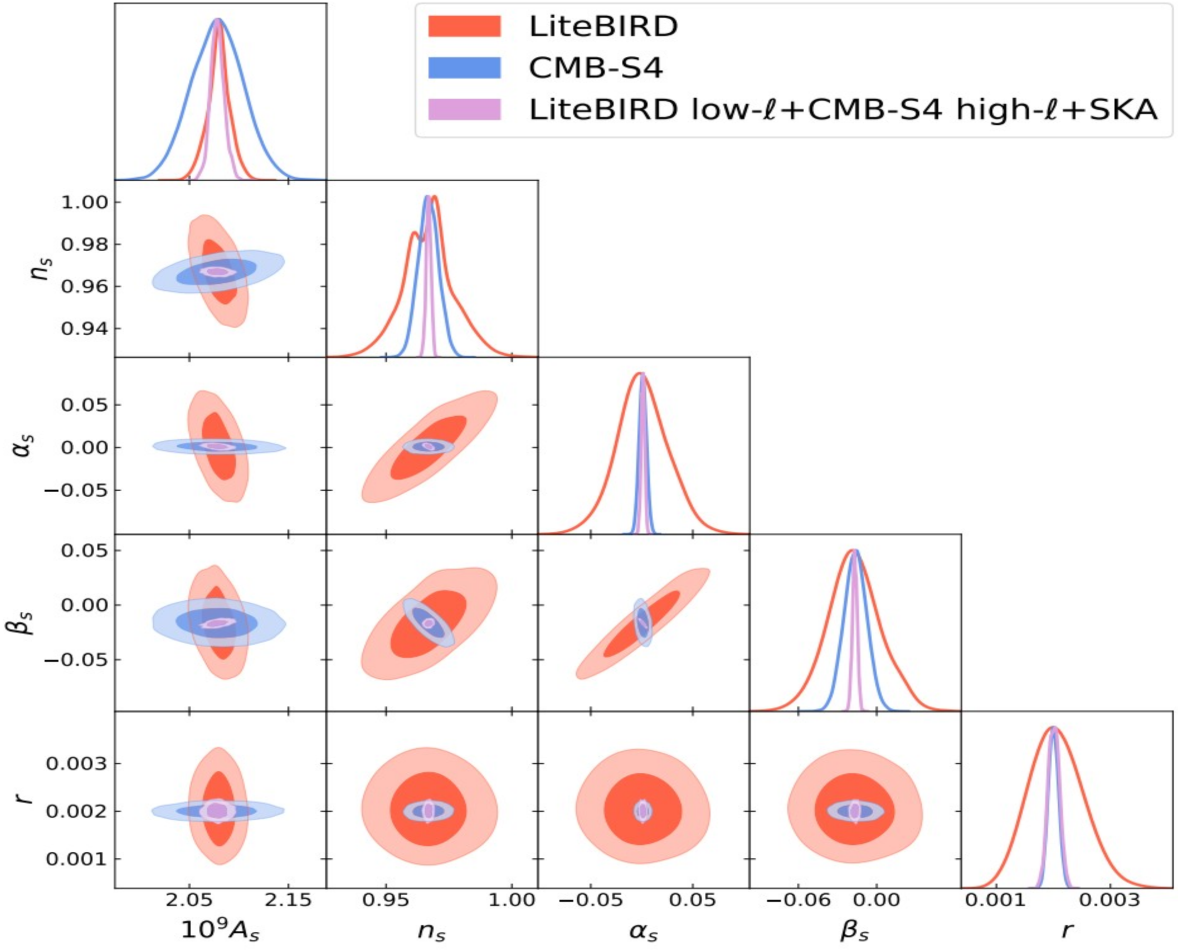
spectral index: $n_s = 1 + d\mathcal{P}_{\mathcal{R}}(k)/d\ln k$

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

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

Baseline parameters

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


LiteBIRD
CMB-S4
LiteBIRD low-ℓ+CMB-S4 high-ℓ+SKA
n_s
α_s
β_s
r
$10^9 A_s$
n_s
α_s
β_s
r

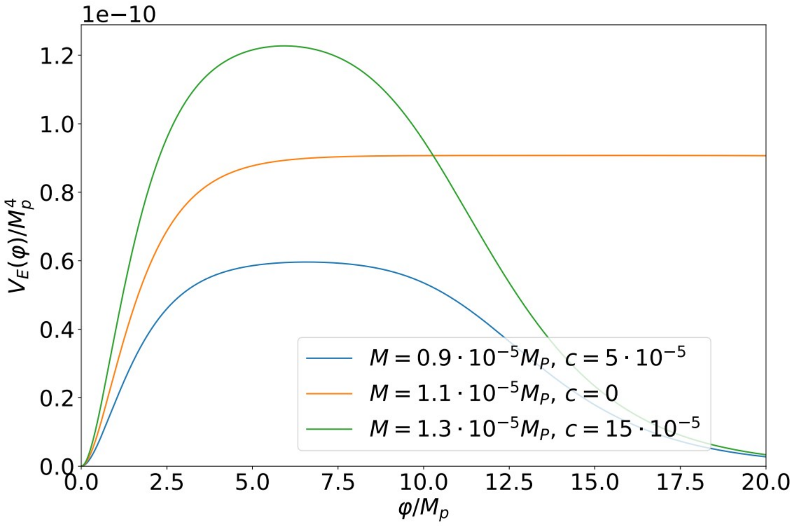
Starobinsky inflation

Action in different frames

$$S_J = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g_J}\, f(R),$$
$$f(R) = M_P^2\left(R + \frac{1}{6M^2}R^2 + \frac{c}{36M^4}R^3\right)$$

Potential

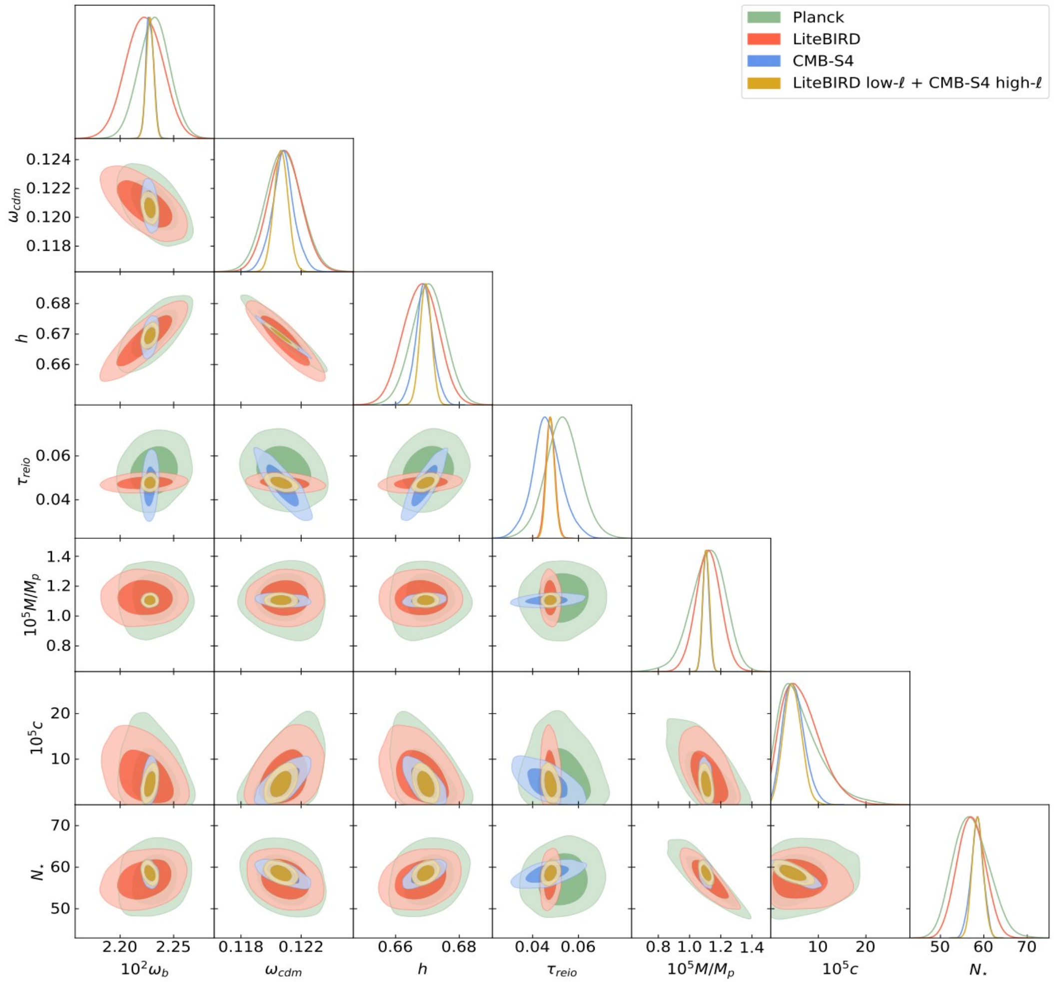
$$V_E(\varphi) = \frac{M_P^2\left(\frac{cs(\varphi)^3}{M^2} + 3s(\varphi)^2\right)}{36M^2\left(1 + \frac{s(\varphi)}{3M^2} + \frac{cs(\varphi)^2}{12M^4}\right)^2}$$



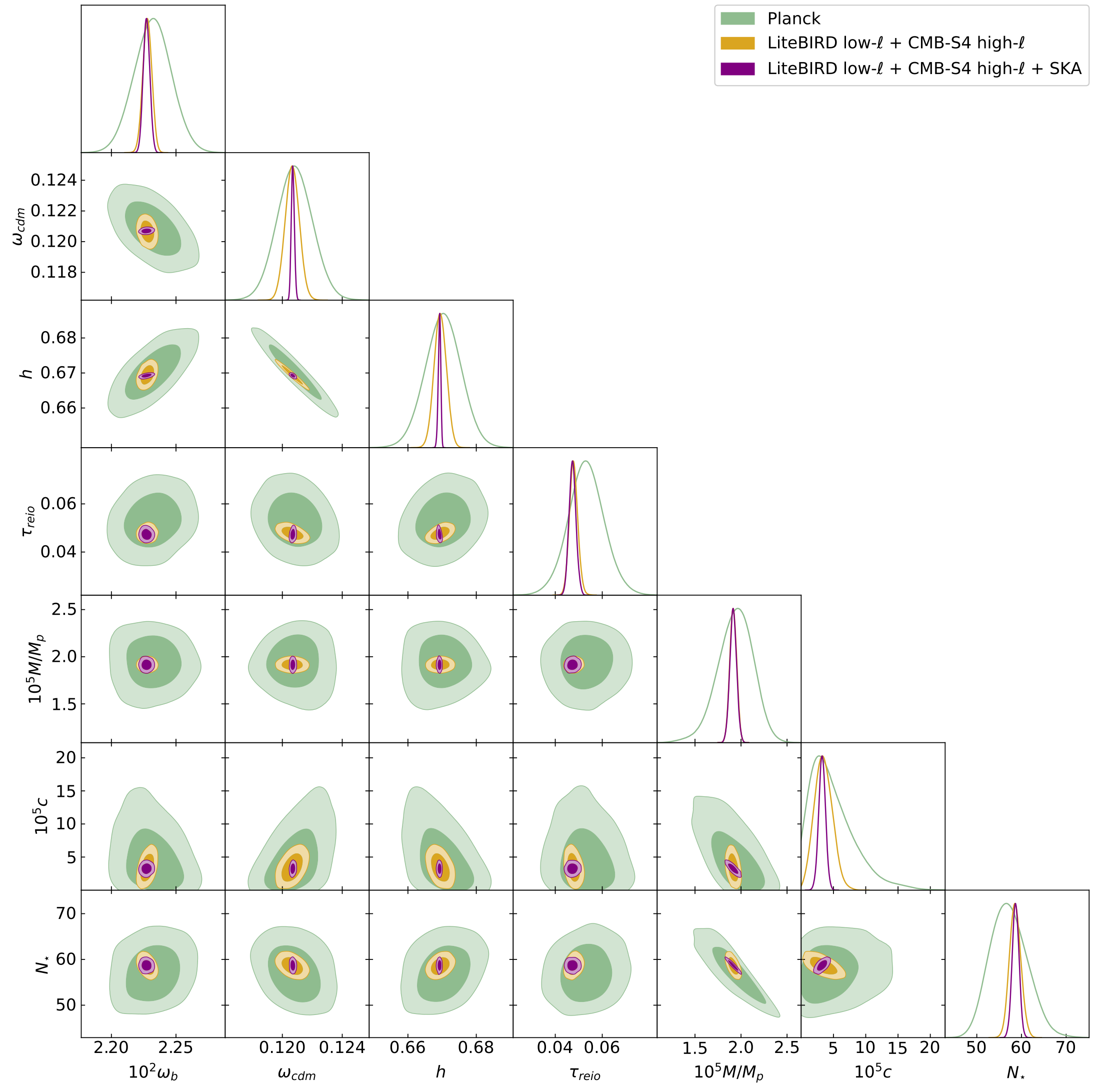
Baseline parameters

$$\{\omega_{\rm b},\ \omega_{\rm cdm},\ h,\ \tau_{\rm reio},\ M,\ c,\ N_*\}$$

CMB


Planck
LiteBIRD
CMB-S4
LiteBIRD low-ℓ + CMB-S4 high-ℓ
$10^2\omega_b$
ω_{cdm}
h
τ_{reio}
$10^5 M/M_p$
$10^5 c$
N_*
2.20 2.25
0.118 0.122
0.66 0.68
0.04 0.06
0.8 1.0 1.2 1.4
10 20
50 60 70
0.124 0.122 0.120 0.118
0.68 0.67 0.66
0.06 0.04
1.4 1.2 1.0 0.8
20 10
70 60 50

With SKA



Planck
LiteBIRD low-ℓ + CMB-S4 high-ℓ
LiteBIRD low-ℓ + CMB-S4 high-ℓ + SKA
$10^2\omega_b$
ω_{cdm}
h
τ_{reio}
$10^5 M/M_p$
$10^5 c$
$N_\star$
2.20 2.25
0.120 0.124
0.118 0.120 0.122 0.124
0.66 0.67 0.68
0.04 0.06
1.5 2.0 2.5
5 10 15 20
50 60 70

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

Few words on uncertainties at SKA

Biasing

Assumed linear biasing with a nuisance parameter $\boldsymbol{b_{HI}}$. Correct?

Neutral hydrogen fraction

Better modeling for the nutral hydrogen fraction instead of fitting function

High reshift galaxies observed by JWST

Foreground removal

Foreground: much higher than the actual signal

Assumed sufficiently smooth to be removed

Outlook

- Many models of inflation: Need narrow down or discover
- Future CMB experiments will provide sensitive probes
- 21cm inetnsity mapping by SKA: Complementary probes with CMB

Thank you!!

Additional Slides

Flatness problem

The curvature: $\Omega - 1 \propto \frac{1}{H^2 a^2}$, $\Omega = \frac{\rho}{\rho_c}$, $\rho_c = \frac{3H^2}{8\pi G}$

$\Omega - 1 = 0 \implies$ flat Universe

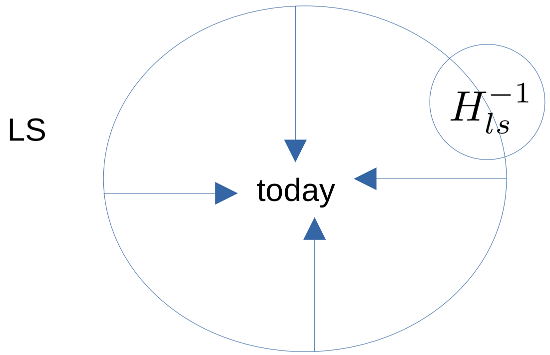
$$\text{Planck epoch: } \frac{|\Omega-1|_P}{|\Omega-1|_0} \approx \frac{a_{M_P}^2}{a_0^2} \approx \frac{T_0^2}{T_{M_P}^2} \approx \mathcal{O}(10^{-64});$$

$$\text{BBN: } \frac{|\Omega-1|_{BBN}}{|\Omega-1|_0} \approx \frac{a_{BBN}^2}{a_0^2} \approx \frac{T_0^2}{T_{BBN}^2} \approx \mathcal{O}(10^{-16});$$

$|\Omega - 1|_0 \sim 10^{-3} \implies$ small curvature at earliest epochs

Horizon problem

From epoch of last-scattering, photons free-stream and reach us untouched



$$\frac{(H_0^{-1})_{ls}^{-3}}{H_{ls}^{-3}} \sim 10^6 \text{ causally disconnected Hubble volumes}$$

CMB photons: $> 1^\circ$ or $\ell < 200$ no causal contact

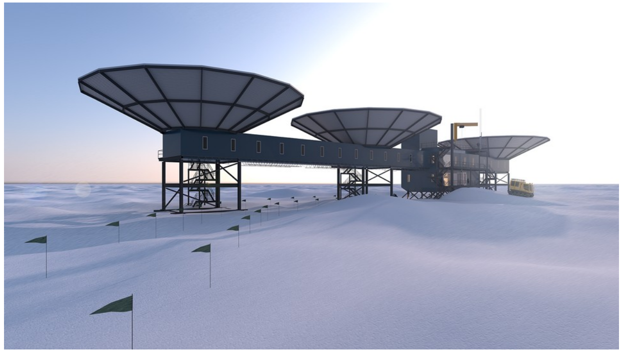
Excotic relic problem

Magnetic monopoles, ...

CMB

Current and future of CMB experiments

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



(CMB-S4 South pole preliminary)

CMB-S4

12 telescopes: 500,000 cryogenically-cooled superconducting detectors in South Pole and in the Chilean Atacama desert

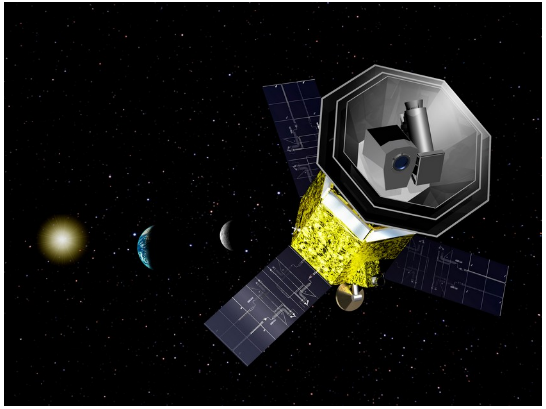
CMB-S4: $f_{\rm sky} = 0.4$, 150 GHz channel, FWHM = 3 arcmin, $\Delta T = 1.0\ \mu$K arcmin and $\Delta P = 1.41\ \mu$K arcmin.

LiteBIRD

Second Lagrange point, 1.5 million kilometers from Earth

LiteBIRD: Sky fraction: $f_{\rm sky} = 0.7$, Channel: 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

(Brinckmann et al. JCAP'19)



(LiteBIRD concept art: ISAS/JAXA)

Quantum fluctuations to CMB anisotropies

- Primordial fluctuation imprinted in CMB temperature and polarization anisotropies
- Scalar (density) perturbations create ***E***-modes but no ***B***-modes
- Vector (vorticity) perturbations not excited during inflation
- Tensor (gravitational waves) perturbations create both ***E-*** and ***B-***modes

E.g., the power spectrum of temperature and B-mode anisotropies:

$$C_\ell^{TT} \propto \int k^2 dk \mathcal{P}_\mathcal{R} \Delta_{T\ell}(k) \Delta_{T\ell}(k),$$

$$C_\ell^{BB} \propto \int k^2 dk \mathcal{P}_\mathcal{T} \Delta_{B\ell}(k) \Delta_{B\ell}(k),$$

Power spectrum

$$P_{21}(k,\mu,z) = f_{\rm AP}(z) \times f_{\rm res}(k,\mu,z) \times f_{\rm RSD}(\hat{k},\hat{\mu},z) \times (b_{HI}\overline{\Delta T_b})^2 \times P_\delta(\hat{k},z)$$

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

SKA1-Low

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

The comoving radial distance line of sight: z = 8: 8943.21 (Mpc); z = 10: 9440.25 (Mpc).
The difference translates to 37.09 Mpc/h.

Avg. ionized patches few Mpc

(Mellema et al. 1210.0197)

$t_{\rm obs} = 10000$ 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 $f_{\rm cover} = N_{\rm dish}(D/D_{\rm base})^2$.

(SKA Red book)

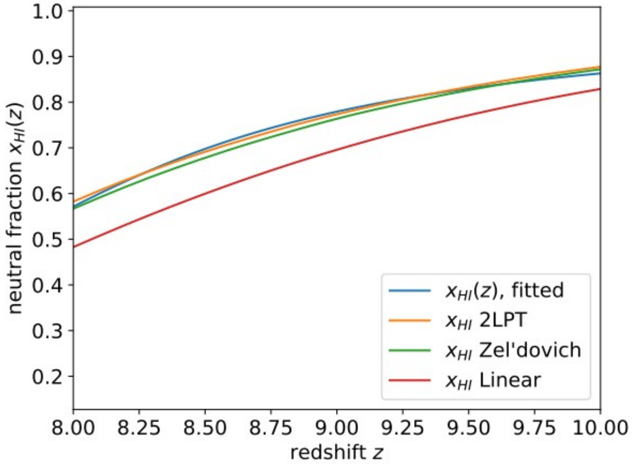
Neutral hydrogen fraction

$$\Omega_{\mathrm{HI}}(z) = \frac{\rho_{\mathrm{HI}}}{\rho_c} = \Omega_b(1 - Y_P)\left(\frac{H_0}{H(z)}\right)^2 (1+z)^3\, x_{\mathrm{HI}}(z)$$

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

Fitting

- 21cmFAST
- 1st order perturbative approx
- 2nd order 2LPT of velocity field



$$\text{Fit values: } \delta_1 = 0.9755,\ \delta_2 = 7.7664$$

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 $f_{\rm cover} = N_{\rm dish}(D/D_{\rm base})^2$.

Noise SKA

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

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

(SKA Red book)

SKA1-Low specification

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

$t_{\rm obs} = 10000$ 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 $f_{\rm cover} = N_{\rm dish}(D/D_{\rm base})^2$.

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, $\Delta T = 4.1$ μK arcmin, and $\Delta P = 5.8$ μK 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, $\Delta T = 1.0$ μK arcmin and $\Delta P = 1.41$ μK 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)

$\Omega_b = 0.0495.\ \ Y_P = 0.24672$

$$k = |\vec{k}| \qquad \text{and} \qquad \mu = \frac{\vec{k}\cdot\vec{r}}{kr}$$

$$\hat{k}^2 = \left[\frac{\hat{H}}{H}^2\mu^2 + \frac{D_A}{\hat{D}_A}(1-\mu^2)\right]k^2,$$

$$\hat{\mu}^2 = \frac{\hat{H}}{H}^2\mu^2\left[\frac{\hat{H}}{H}^2\mu^2 + \frac{D_A}{\hat{D}_A}(1-\mu^2)\right]^{-1}$$

$$f_{\mathrm{AP}}(z) = \frac{D_A^2\hat{H}}{\hat{D}_A^2 H}$$

$$f_{\rm res}(k,\mu,z)=\exp\left[-k^2\left(\mu^2(\sigma_\parallel^2-\sigma_\perp^2)+\sigma_\perp^2\right)\right]$$

$$\sigma_\parallel=\frac{c}{H}(1+z)^2\frac{\sigma_\nu}{\nu_0}\qquad\text{and}\qquad\sigma_\perp=(1+z)D_A\sigma_\theta\,,$$

$$\sigma_\theta=\frac{1}{\sqrt{8\ln 2}}\frac{\lambda_0}{D_{\rm base}}(1+z)z\quad\text{and}\qquad\sigma_\nu=\frac{\delta_\nu}{\sqrt{8\ln 2}}\,.$$

$$f_{\rm RSD}(\hat{k},\hat{\mu},z)=\left(1+\beta(\hat{k},z)\hat{\mu}^2\right)^2\ e^{-\hat{k}^2\hat{\mu}^2\sigma_{\rm NL}^2}\,,\qquad\text{with}\qquad\beta(\hat{k},z)=-\frac{1+z}{2b_{21}(z)}\frac{{\rm d}\log P_\delta(\hat{k},z)}{{\rm d}z}$$

$$\chi^2=\sum_{\text{bins }n}\int_{k_{\rm min}}^{k_{\rm max}}k^2{\rm d}k\int_{-1}^{1}{\rm d}\mu\,\frac{V_r(\bar{z}_n)}{2(2\pi)^2}\left[\frac{(\Delta P_{21}(k,\mu,\bar{z}_n))^2}{(P_{21}(k,\mu,\bar{z}_n)+P_N)^2+\sigma_{\rm th}^2(k,\mu,\bar{z}_n)}\right]$$

$$\sigma_{\rm th}(k,\mu,z) = \left[\frac{V_r(z)}{(2\pi)^2}k^2\Delta k\frac{\Delta z}{\Delta\bar{z}}\right]^{1/2}\alpha(k,\mu,z)\,P_{21}(k,\mu,z)\,.$$

The correlation length Δk is assumed to be 0.05 h/Mpc as a conservative choice, matching the BAO scale. We also choose $\Delta z = 1$, which is slightly lower than the whole redshift range probed by the experiment $z_{\rm max} - z_{\rm min} = 2$.

Non-linear Effects:

The prediction of the matter power spectrum, the bias, and RSD
0.33% error at $k = 0.01$ h/Mpc, a 1% error at $k = 0.3$ h/Mpc, and
a 3% error at $k = 10$ h/Mpc

$$\alpha(k,z) = \begin{cases} a_1 \exp\left(c_1 \log_{10}\frac{k}{k_1(z)}\right), & \text{for } \frac{k}{k_1(z)} < 0.3\,, \\ a_2 \exp\left(c_2 \log_{10}\frac{k}{k_1(z)}\right), & \text{for } \frac{k}{k_1(z)} > 0.3\,, \end{cases}$$

$$k_1(z) = 1\frac{h}{\rm Mpc}(1+z)^{\frac{2}{2+n_s}}\,,$$

with $a_1 = 1.4806\%$, $a_2 = 2.2047\%$, $c_1 = 0.75056$, and $c_2 = 1.5120$

Power spectrum

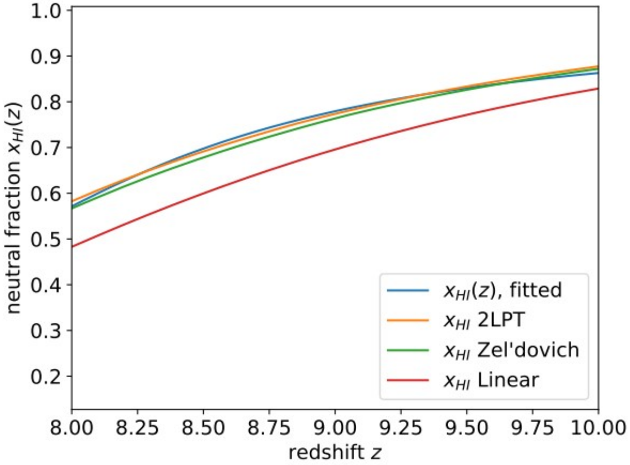
(TM, T. Plehn, L. Röver, and B. M. Schäfer, B. Schosser, SciPost Phys. 15, 047 (2023))

$$\mathrm{P}_{21}(k, \mu, z) \sim (b_{HI}\overline{\Delta T_b})^2 \times P_\delta(\hat{k}, z)$$
$$P_{21}^{\mathrm{obs}}(k, \mu, z) = P_{21}(k, \mu, z) + P_N(z)$$

Neutral hydrogen fraction

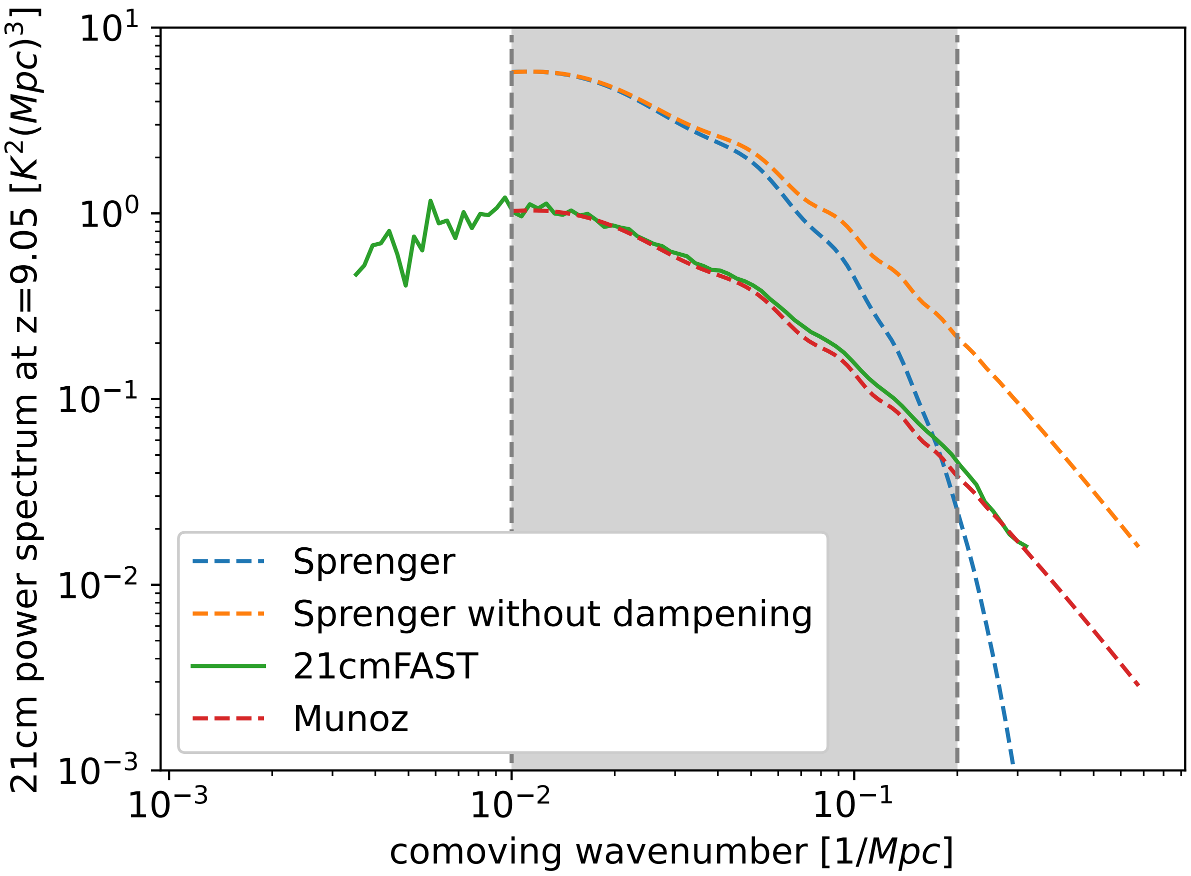
$$\Omega_{\mathrm{HI}}(z) = \frac{\rho_{\mathrm{HI}}}{\rho_c} = \Omega_b(1 - Y_P)\left(\frac{H_0}{H(z)}\right)^2 (1+z)^3\, x_{\mathrm{HI}}(z)$$
$$x_{\mathrm{HI}}(z) = \frac{1}{2}\left[1 + \frac{2}{\pi}\tan^{-1}\left(\delta_1(z - \delta_2)\right)\right]$$

$$\text{Fit values: } \delta_1 = 0.9755,\ \delta_2 = 7.7664$$



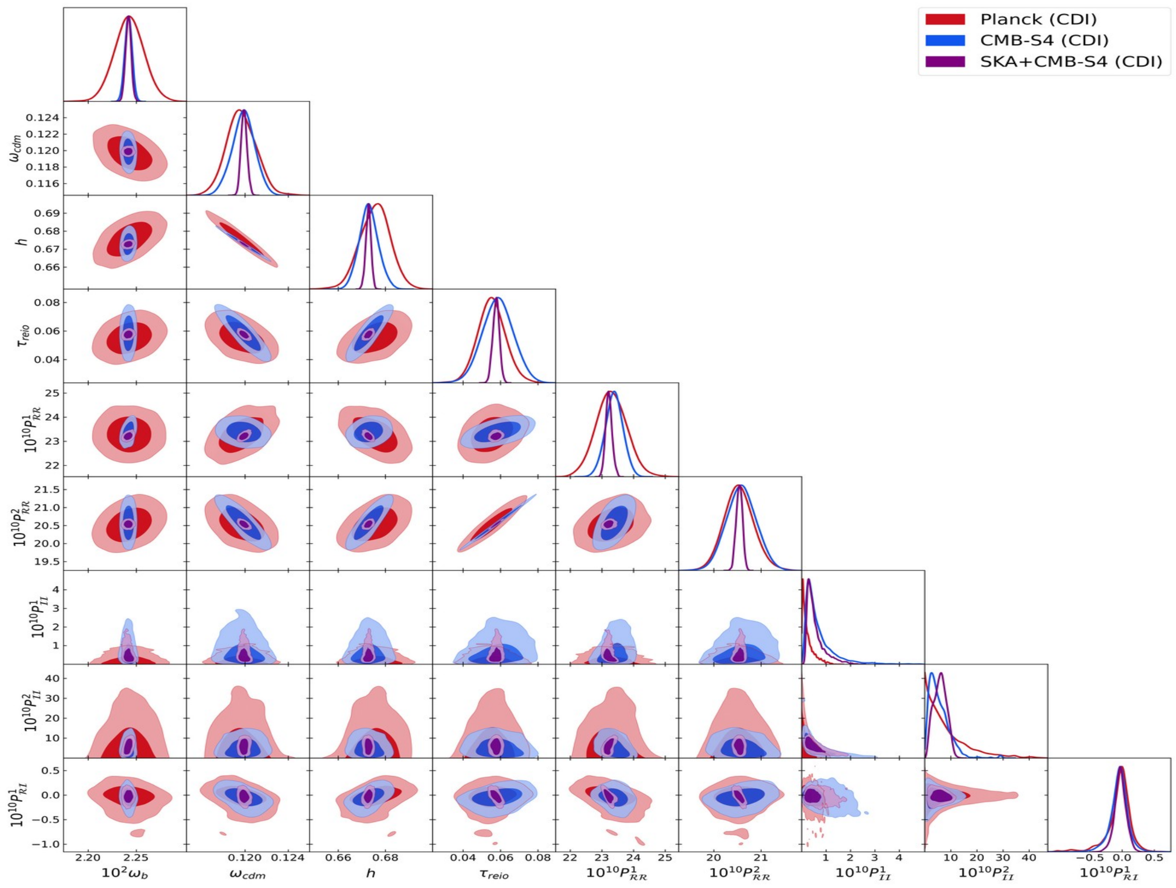
21cmFAST

$$\text{three nuisance parameters: } \{b_{HI}, \delta_1, \delta_2\}$$



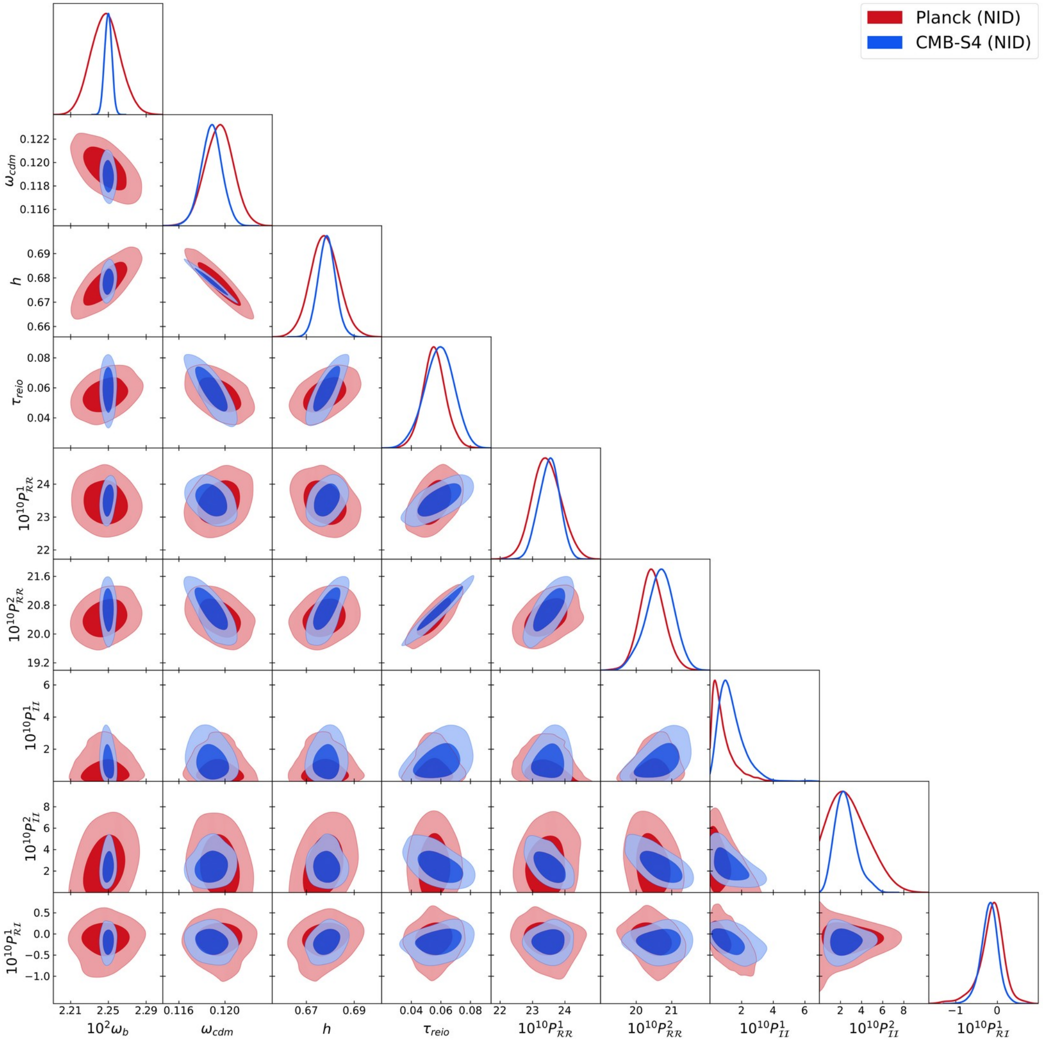
21cm power spectrum at z=9.05 [$K^2(Mpc)^3$]
comoving wavenumber [1/Mpc]
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
Sprenger
Sprenger without dampening
21cmFAST
Munoz

Generally correlated isocurvature mode



- Models with one adiabatic and one isocurvature mode
- Parameterized by power spectra of the 2x2 correlation matrix at a certain pivot scale $P_{\mathcal{R}\mathcal{R}}, P_{\mathcal{I}\mathcal{I}}, P_{\mathcal{R}\mathcal{I}}$

CDI = CDM isocurvature



Planck (NID)
CMB-S4 (NID)
$10^2\omega_b$
ω_{cdm}
h
τ_{reio}
$10^{10}P^1_{\mathcal{RR}}$
$10^{10}P^2_{\mathcal{RR}}$
$10^{10}P^1_{\mathcal{II}}$
$10^{10}P^2_{\mathcal{II}}$
$10^{10}P^1_{\mathcal{RI}}$