Cornering Extended Starobinsky Inflation with CMB and SKA

Benedikt Schosser together with Tanmoy Modak, Tilman Plehn, Lennart Röver, Björn Malte Schäfer

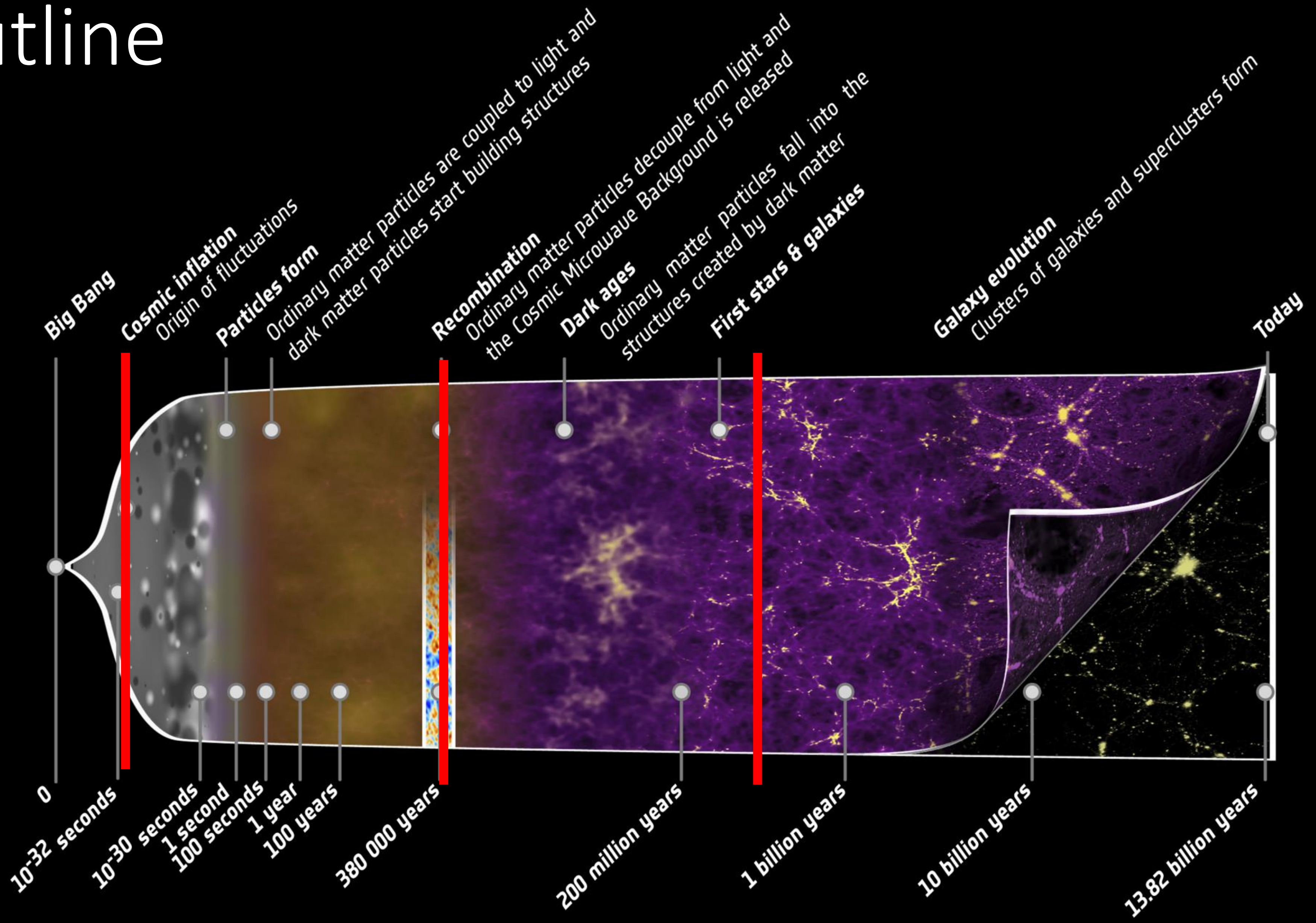
Universität Heidelberg

arXiv:2210.05695

IRN Terascale

Nantes, 19 October 2022

Outline


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Motivation

Goal: Explain inflation with gravity

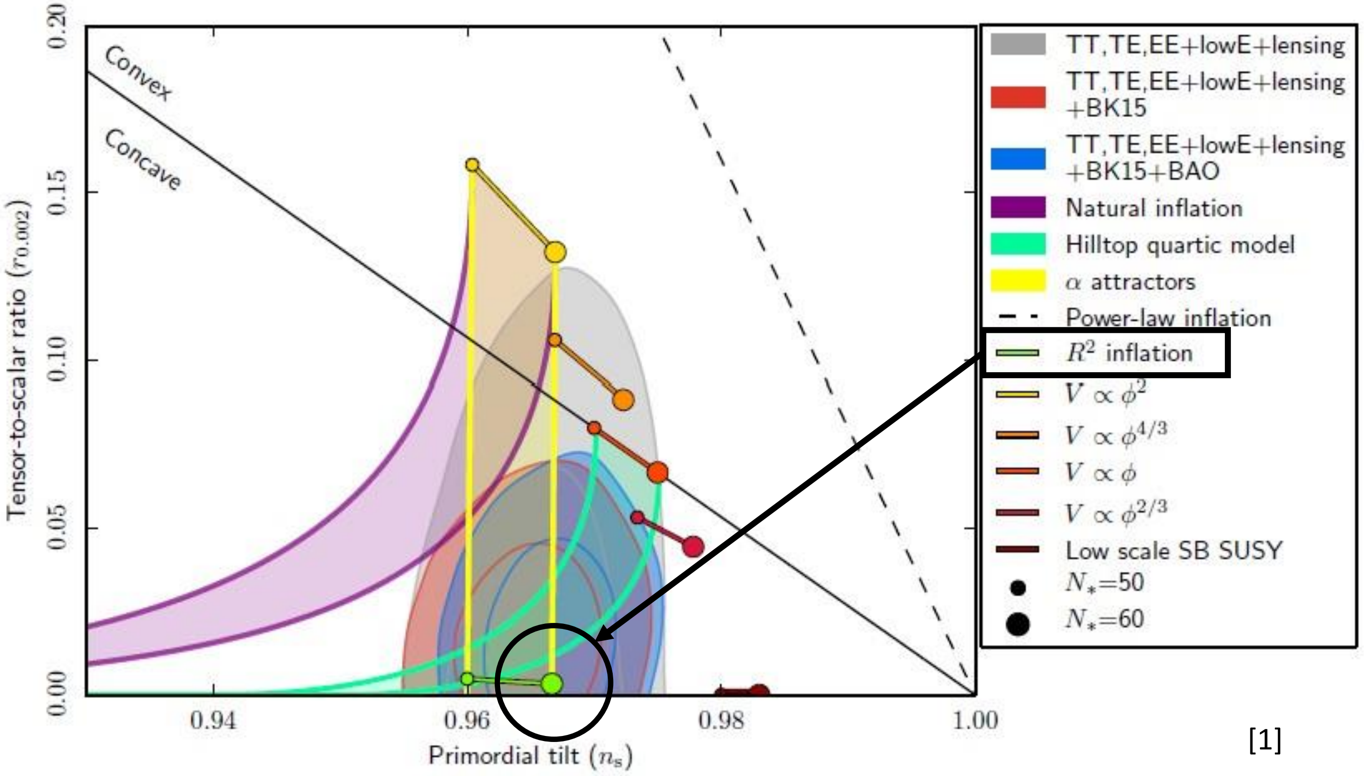
$$\mathcal{L}_{EH} = \frac{M_P^2}{2}\sqrt{-g}R$$

Starobinsky-inflation is the best-fit model

$$\mathcal{L}_{St} = \frac{M_P^2}{2}\sqrt{-g}\left(R + \frac{1}{6M^2}R^2\right)$$

Include higher order terms: $f(R)$-gravity

$$\mathcal{L}_{(3)} = \frac{M_P^2}{2}\sqrt{-g}\left(R + \frac{1}{6M^2}R^2 + \frac{c}{36M^4}R^3\right)$$



[1]

[1] Planck 2018 results. X. Constraints on inflation, arXiv:1807.06211v2

Einstein-Jordan duality

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

Legendre transformation ⬇ s : scalar field

$$S_J = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g_J}[f(s) - f'(s)(R-s)] \equiv \int \mathrm{d}^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\Omega^2 R - V(s)\right],$$

$$\Omega^2 = \frac{f'(s)}{M_P^2} = 1 + \frac{1}{3M^2}s + \frac{c}{12M^4}s^2,\ V(s) = \frac{1}{2}[sf'(s) - f(s)]$$

Change from Jordan-frame to Einstein-frame ⬇ Weyl transformation: $g_{\mu\nu,E} = \Omega^2 g_{\mu\nu,J}$

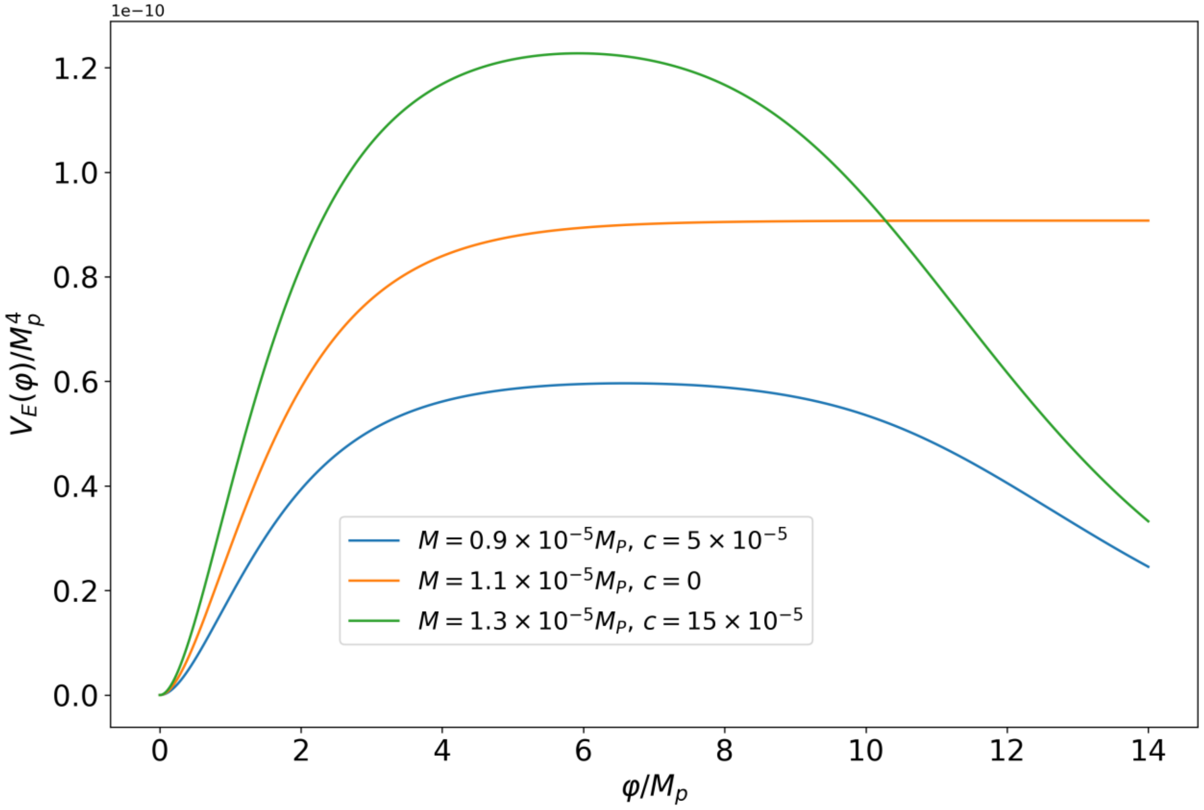
$$S_E = \int \mathrm{d}^4x\sqrt{-g_E}\left[\frac{M_P^2}{2}R_E - \frac{1}{2}g_E^{\mu\nu}\nabla_\mu\varphi\nabla_\nu\varphi - V_E(\varphi)\right],\ \varphi \equiv \sqrt{\frac{3}{2}}M_P\ln\Omega^2$$

Inflaton Potential

$$e^{\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}} = 1 + \frac{1}{3M^2}s + \frac{c}{12M^4}s^2$$

$$\Rightarrow s(\varphi) = \begin{cases} \frac{2M^2}{c}\left\{\sqrt{1+3c\left(e^{\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}-1\right)}-1\right\}, \ c>0 \\ -3M^2\left(1-e^{\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}\right), \ c=0 \end{cases}$$

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



Inflaton Potential

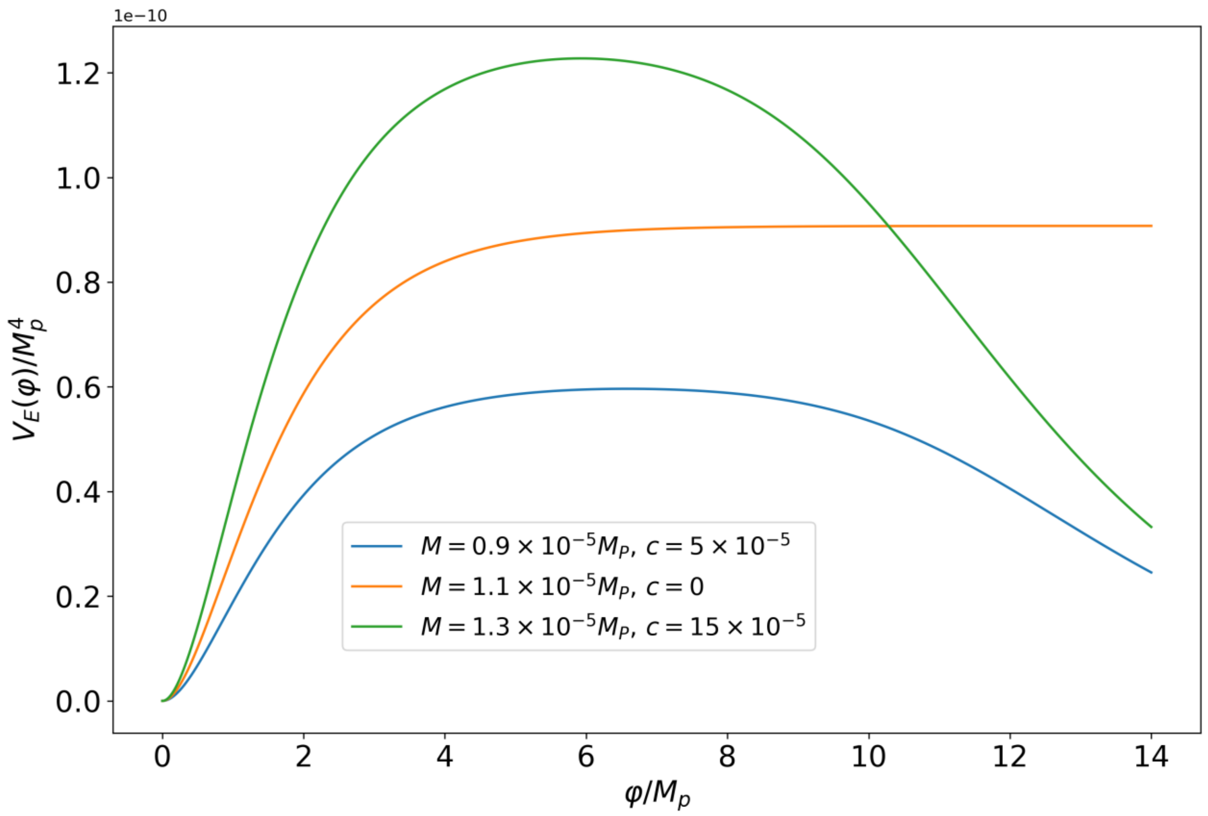
<u>Reminder</u>: How to get accelerated expansion

$$0 < \frac{\ddot{a}}{(\dot{a})^2} = -\frac{\mathrm{d}}{\mathrm{d}t}(aH)^{-1} = -\frac{1}{a}\left(1 + \frac{\dot{H}}{H^2}\right)$$

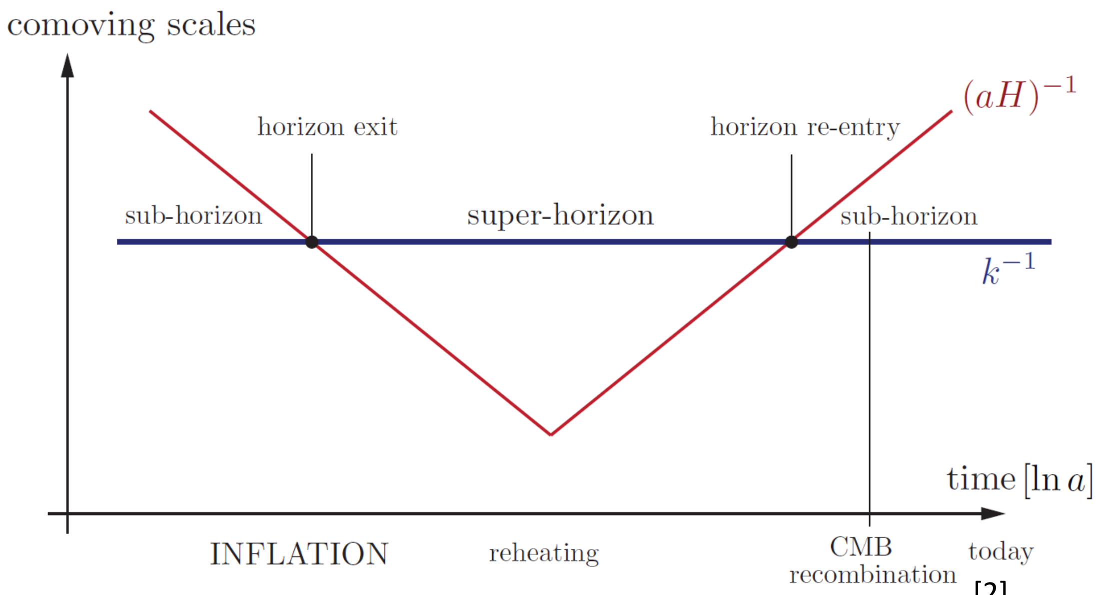
$$\Rightarrow 1 > -\frac{\dot{H}}{H^2} = \frac{3}{2}\left(1 + \frac{P}{\rho}\right)$$

$$\Rightarrow \omega = \frac{P}{\rho} = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)} < -\frac{1}{3}$$

Potential energy has to surpass kinetic energy



Contact with Observations



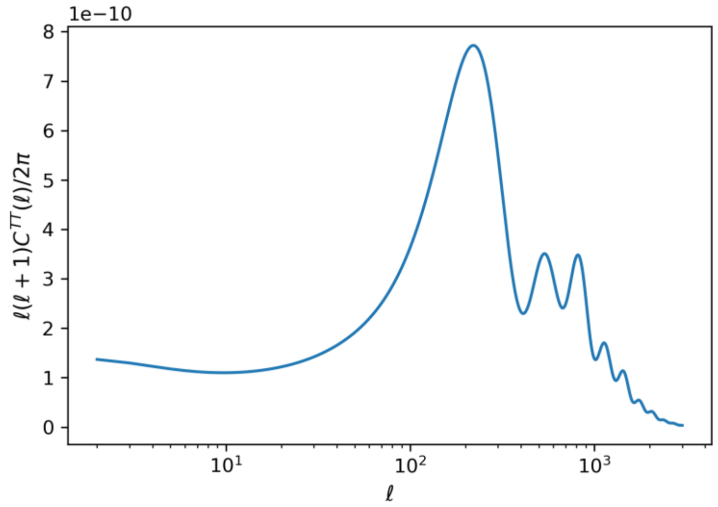
[2]

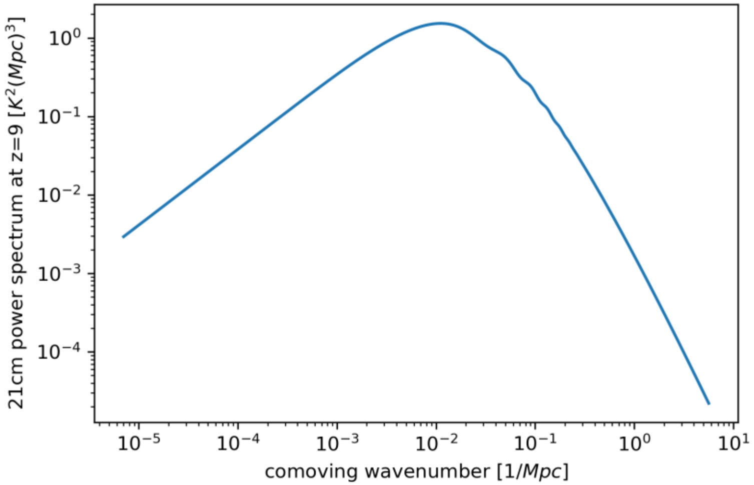
Quantum fluctuations in φ

$P_{\mathcal{R}}(k)$

CLASS[3]

$P_\delta(k)$





[2] Baumann: TASI Lectures on Inflation, arXiv:0907.5424v2
[3] The Cosmic Linear Anisotropy Solving System (CLASS), arXiv:1104.2932

21 cm intensity mapping

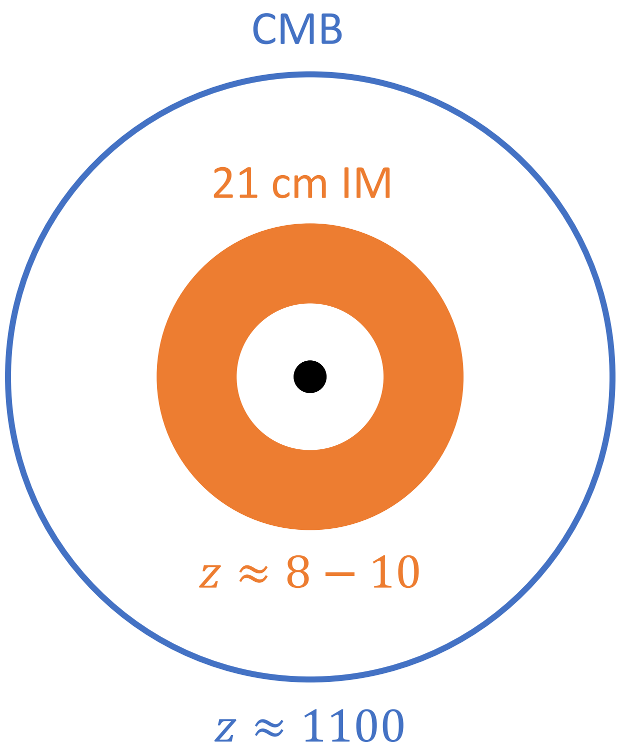
- Matter distribution at high redshift: $z = 8 - 10$

Simple reionization history

No position dependence of the spin temperature

- Measure 21cm hyperfine transition
- Find power spectrum
- 21cm power spectrum traces DM power spectrum

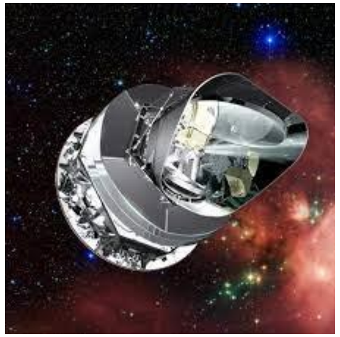
$$P_{21}(k) \Rightarrow P_\delta(k)$$



Experiments

Past | Future

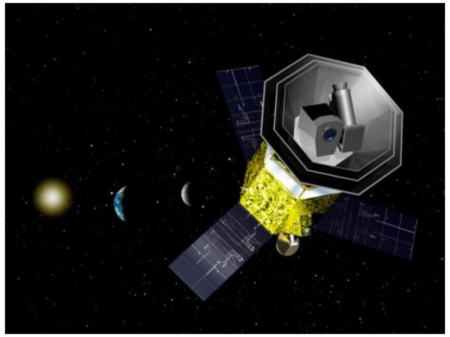
<u>Planck</u>



[4]

- Satellite CMB experiment

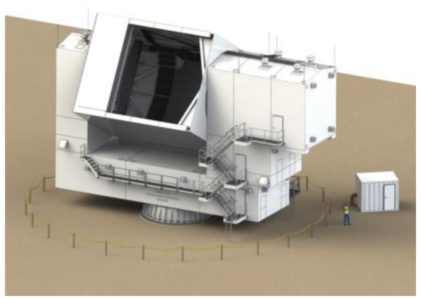
<u>LITEbird</u>



[5]

- Satellite CMB experiment
- Highest sensitivity for $2 < \ell < 1350$

<u>CMB-S4</u>



[6]

- Ground-based CMB experiment
- Highest sensitivity for $30 < \ell < 3000$

<u>Square Kilometre Array</u> (SKA)

[7]

- Ground-based
- 2 radio telescope arrays
- Observes large scale structure

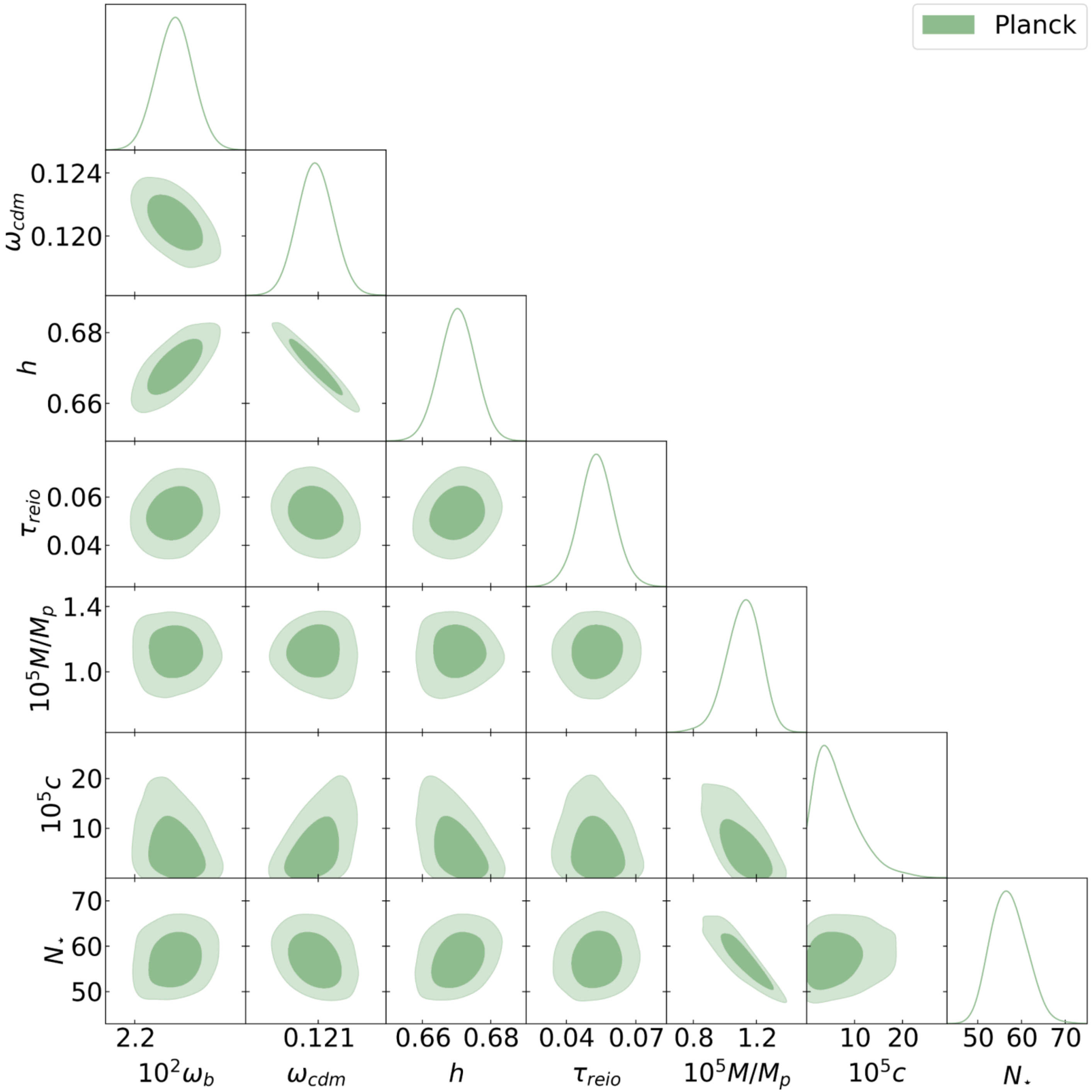
[4] https://www.nasa.gov/mission_pages/planck
[5] https://www.nist.gov/measuring-cosmos/litebird
[6] https://cmb-s4.org/experiment/telescopes/
[7] https://www.skao.int/en/explore/telescopes

Results

<u>Method:</u>

- Sample the parameter-set $\{\omega_b, \omega_{cdm}, h, \tau_{reio}, M, c, N_\star\}$
- Calculate observables with CLASS
- Add gaussian prior with $\mu = 55, \sigma = 5$ for $N_\star$
- Use MCMC-tool MontePython [8] to get posterior

Parameter	95% limits
$10^5 M/M_p$	$1.12^{+0.21}_{-0.22}$
$10^5 c$	$6.1^{+9.9}_{-6.1}$
$N_\star$	57^{+8}_{-8}



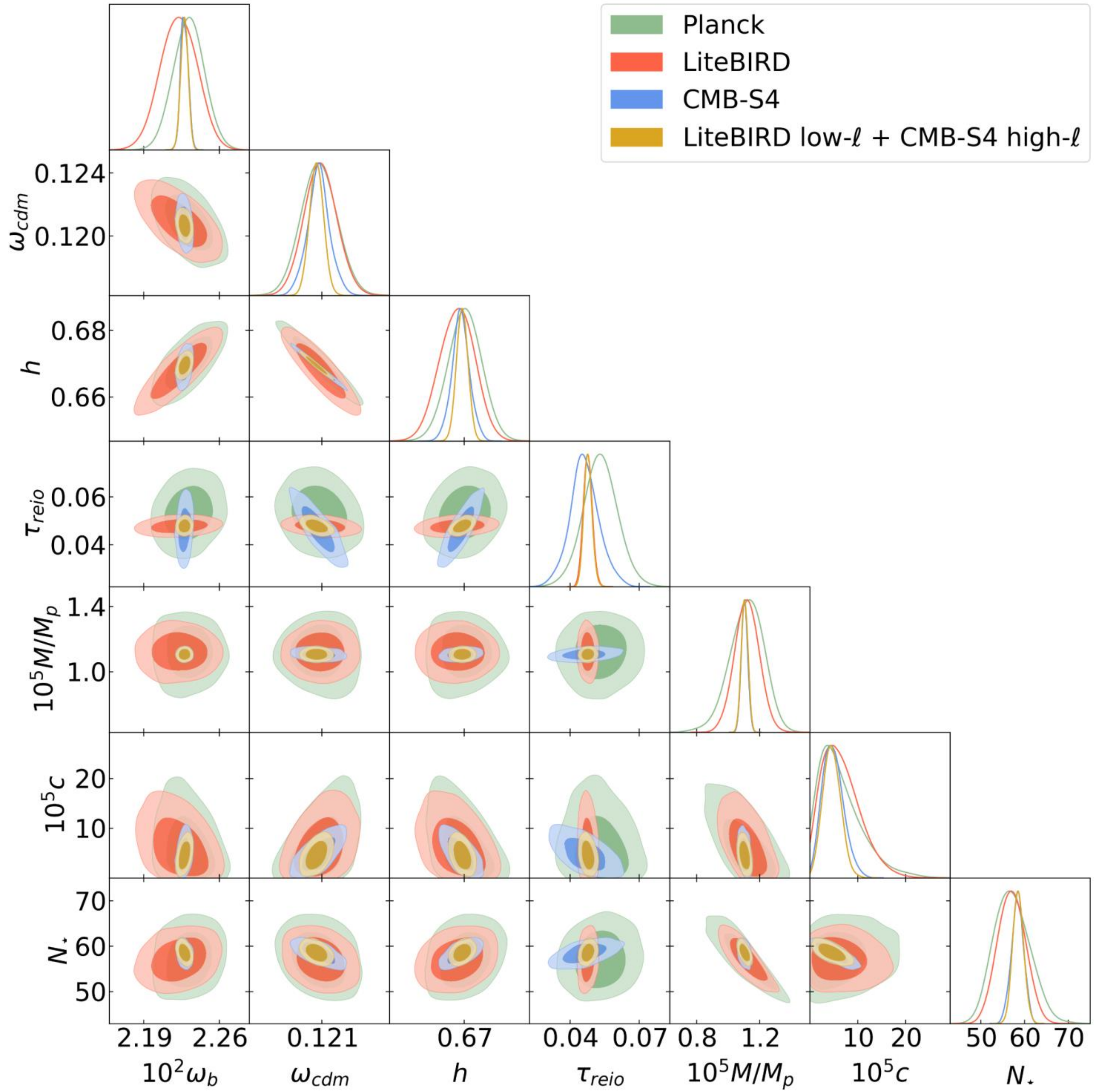
[8] MontePython 3: boosted MCMC sampler and other features, arXiv:1804.07261

Forecasts - CMB

Use Planck best-fit value as fiducial value for forecasts

↓

Next generation CMB experiments can exclude $c = 0$, if $c > 4 \cdot 10^{-5}$

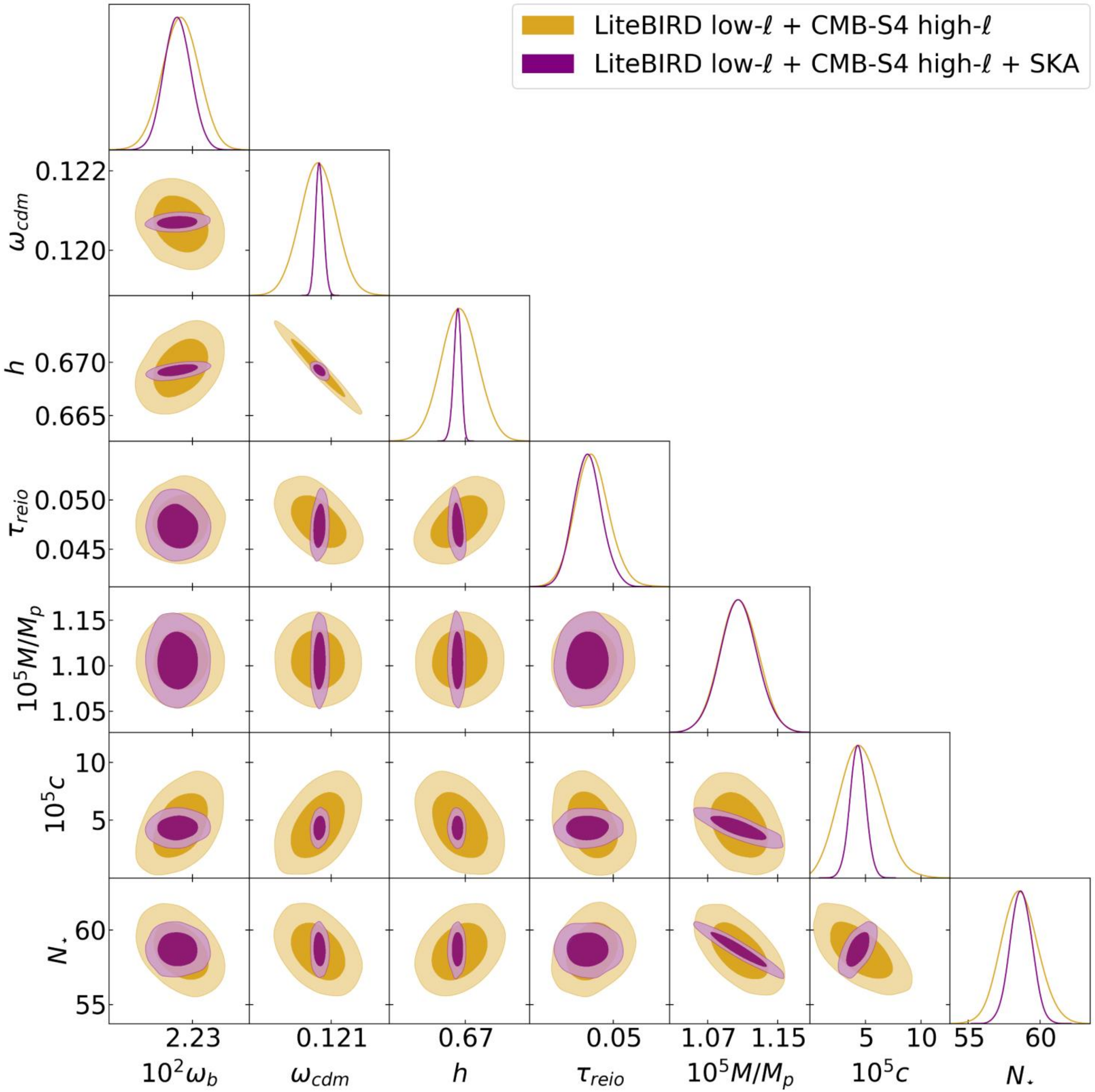


Forecasts - SKA

Use Planck best-fit value as fiducial value for forecasts

⬇

Next generation CMB and 21 cm experiments can exclude $c = 0$, if $c > 2 \cdot 10^{-5}$



Summary

- Extending Starobinsky-inflation to third-order $f(R)$ -gravity is natural
- Best-fit to the Planck measurements is for $c = 4.315 \cdot 10^{-5}$
- Combination of next generation CMB and 21cm experiments could exclude $c = 0$

$$\mathcal{L}_{(3)} = \frac{M_P^2}{2}\sqrt{-g}\left(R + \frac{1}{6M^2}R^2 + \frac{c}{36M^4}R^3\right)$$