Connecting Cosmic Inflation to Particle Physics with LiteBIRD, CMB S4, EUCLID and SKA

Lei Ming

Sun Yat-Sen University, Guangzhou

2023/11/09 @UBB seminar

Contact: minglei@mail.sysu.edu.cn

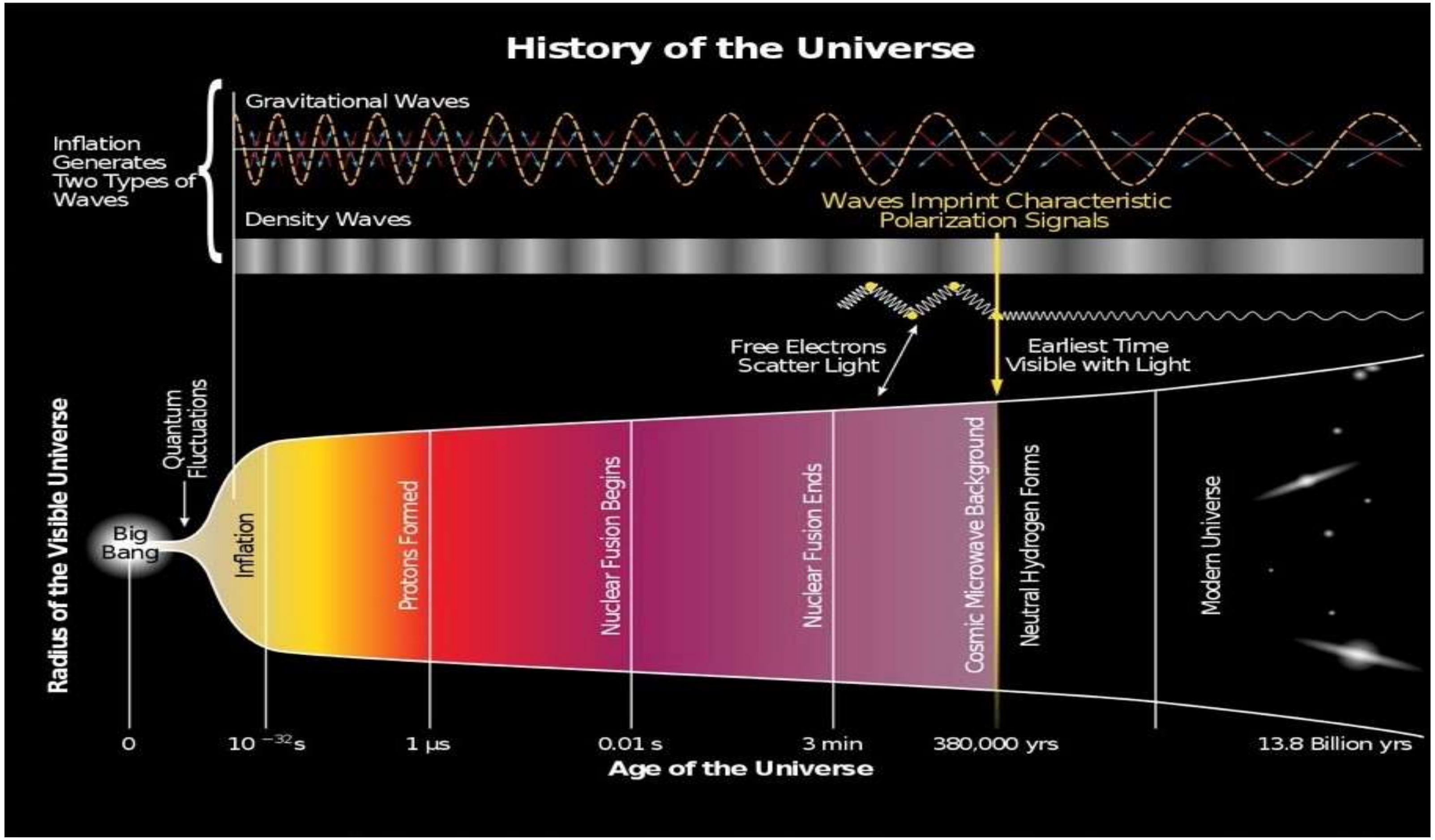
Based on arxiv: 2208.07609 and 2303.13503
with Marco Drewes and Isabel Oldengott

Content

1. Inflation and CMB
2. Imprint of reheating in CMB
3. Measuring the inflaton coupling
4. Bayesian analysis
5. Application to specific models
6. Summary and Outlook

1

Inflation and CMB



$a \sim e^{Ht}$

Cosmic Microwave Background

homogeneity, isotropy and special flatness

Inflation models: a long list

A.1 Higgs Inflation (HI)
A.2 Radiatively Corrected Higgs Inflation (RCHI)
A.3 Large Field Inflation (LFI)
A.4 Mixed Large Field Inflation (MLFI)
A.5 Radiatively Corrected Massive Inflation (RCMI)
A.6 Radiatively Corrected Quartic Inflation (RCQI)
A.7 Natural Inflation (NI)
A.8 Exponential SUSY Inflation (ESI)
A.9 Power Law Inflation (PLI)
A.10 Kähler Moduli Inflation I (KMII)
A.11 Horizon Flow Inflation at first order (HF1I)
A.12 Colemann-Weinberg Inflation (CWI)
A.13 Loop Inflation (LI)
A.14 $R + R^{2p}$ Inflation (RpI)
A.15 Double Well Inflation (DWI)
A.16 Mutated Hilltop Inflation (MHI)
A.17 Radion Gauge Inflation (RGI)
A.18 MSSM Inflation (MSSMI)
A.19 Renormalizable Inflection Point Inflation (RIPI)
A.20 Arctan Inflation (AI)
A.21 Constant n_s A Inflation (CNAI)
A.22 Constant n_s B Inflation (CNBI)
A.23 Open String Tachyonic Inflation (OSTI)
A.24 Witten-O'Raifeartaigh Inflation (WRI)
A.25 Small Field Inflation (SFI)
A.26 Intermediate Inflation (II)
A.27 Kähler Moduli Inflation II (KMIII)
A.28 Logamediate Inflation (LMI)
A.29 Twisted Inflation (TWI)
A.30 GMSSM Inflation (GMSSMI)
A.31 Generalized Renormalizable Inflection Point Inflation (GRIPI)
A.32 Brane SUSY breaking Inflation (BSUSYBI)
A.33 Tip Inflation (TI)
A.34 β Exponential Inflation (BEI)
A.35 Pseudo Natural Inflation (PSNI)
A.36 Non Canonical Kähler Inflation (NCKI)
A.37 Constant Spectrum Inflation (CSI)
A.38 Orientifold Inflation (OI)
A.39 Constant n_s C Inflation (CNCI)
A.40 Supergravity Brane Inflation (SBI)
A.41 Spontaneous Symmetry Breaking Inflation 1 (SSBI1)
A.42 Spontaneous Symmetry Breaking Inflation 2 (SSBI2)
A.43 Spontaneous Symmetry Breaking Inflation 3 (SSBI3)
A.44 Spontaneous Symmetry Breaking Inflation 4 (SSBI4)
A.45 Spontaneous Symmetry Breaking Inflation 5 (SSBI5)
A.46 Spontaneous Symmetry Breaking Inflation 6 (SSBI6)
A.47 Inverse Monomial Inflation (IMI)
A.48 Brane Inflation (BI)
A.49 KKLT Inflation (KKLTI)
A.50 Running Mass Inflation 1 (RMI1)
A.51 Running Mass Inflation 2 (RMI2)
A.52 Running Mass Inflation 3 (RMI3)
A.53 Running Mass Inflation 4 (RMI4)
A.54 Valley Hybrid Inflation (VHI)
A.55 Dynamical Supersymmetric Inflation (DSI)
A.56 Generalized Mixed Inflation (GMLFI)
A.57 Logarithmic Potential Inflation 1 (LPI1)
A.58 Logarithmic Potential Inflation 2 (LPI2)
A.59 Logarithmic Potential Inflation 3 (LPI3)
A.60 Constant n_s D Inflation (CNDI)

"*Encyclopædia Inflationaris*" Phys.Dark Univ. 5-6 (2014) 75-235

Even more……

Future observation

- South Pole Observatory
- Simmons Observatory

$\delta r \sim 3 \times 10^{-3}$

- JAXA's LiteBIRD
- CMB-S4

$\delta r \sim 10^{-3}$ for $r = 0$

- EUCLID
- Square Kilometre Array (SKA)

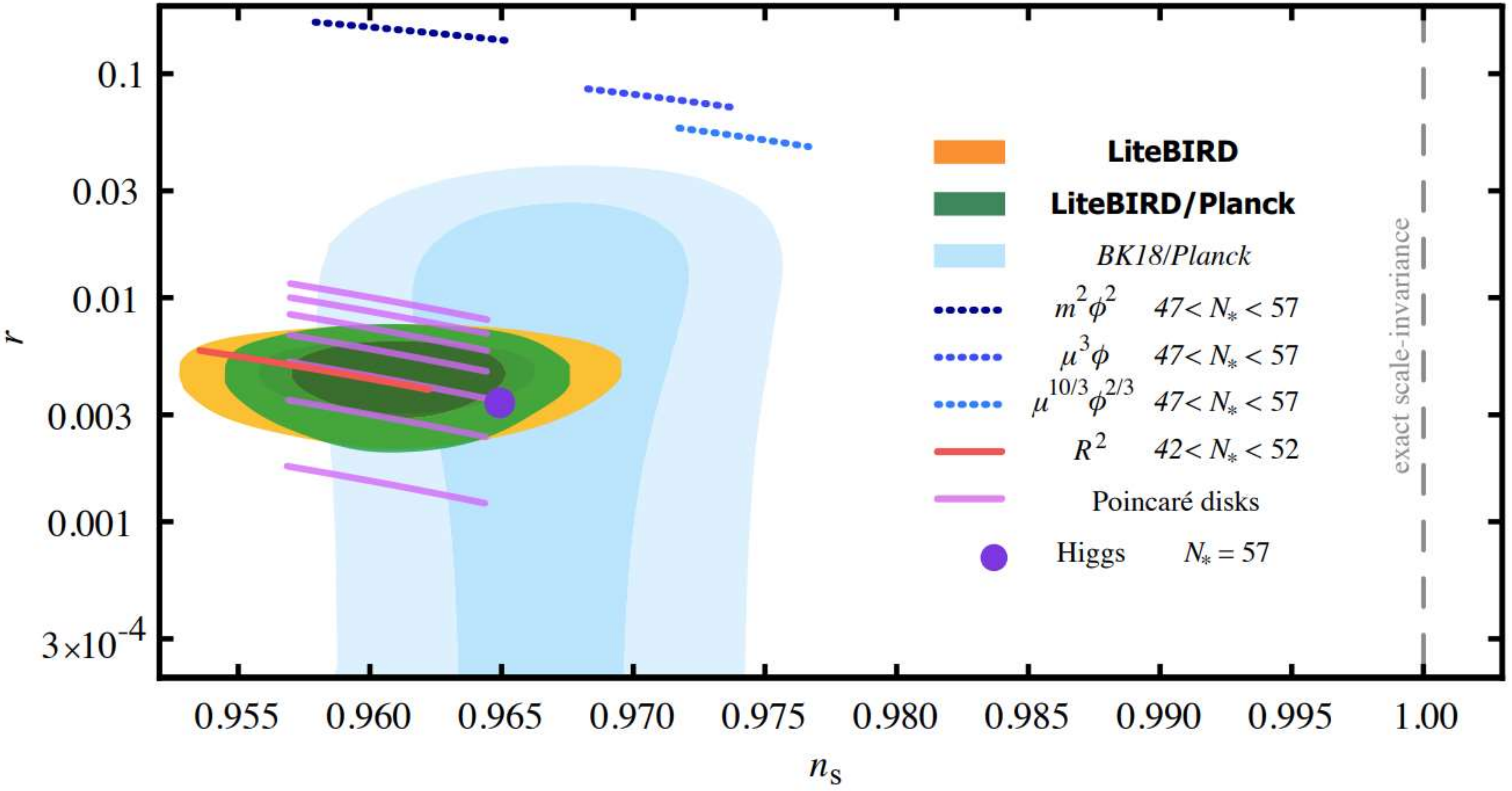
$\delta n_s \sim 0.00085$

- …

The primordial spectrum

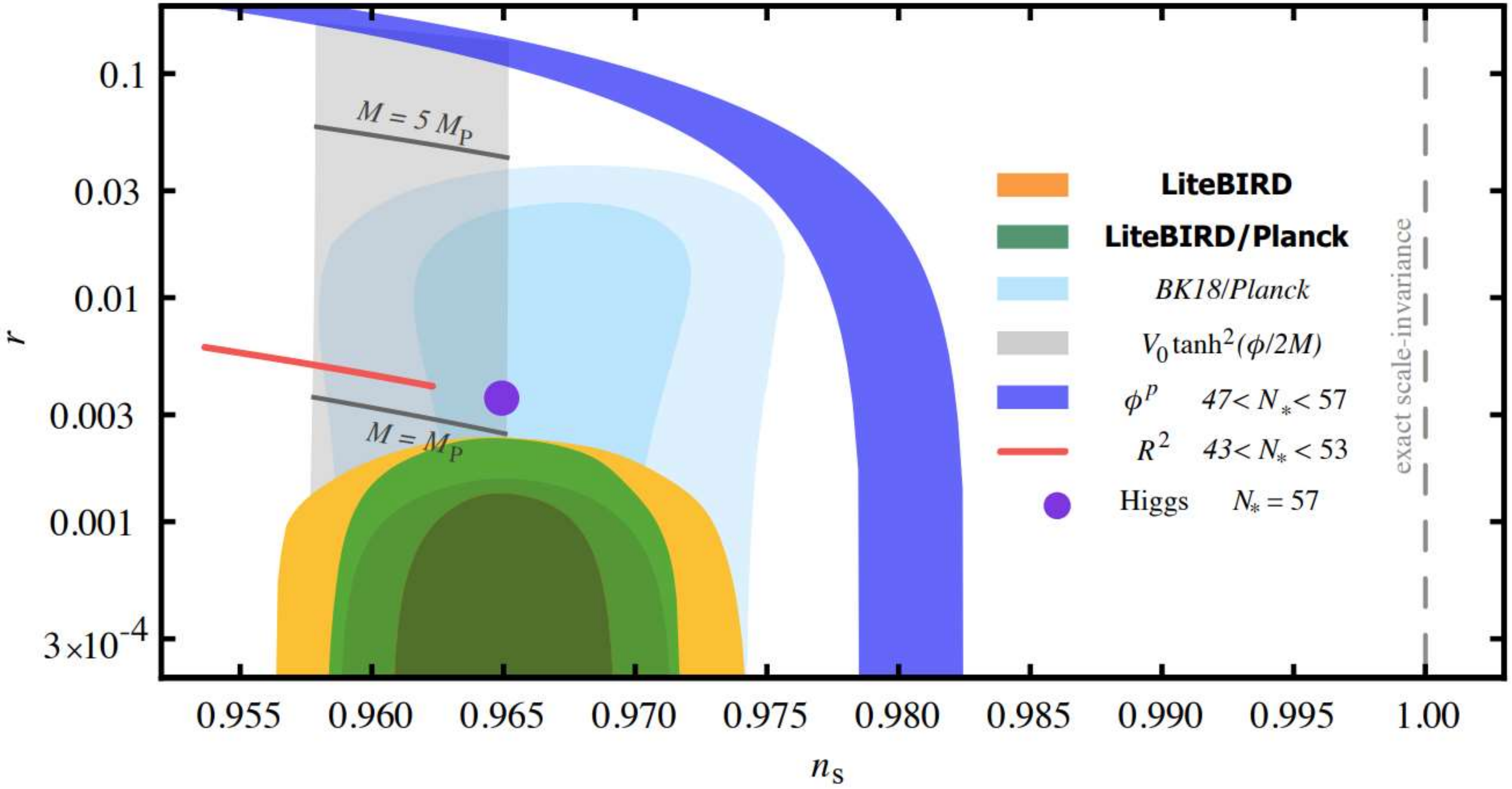
- scalar perturbations $$P_s(k) = A_s \left(\frac{k}{0.05\,\mathrm{Mpc}^{-1}} \right)^{n_s - 1}$$
- tensor perturbations $$P_t(k) = A_t \left(\frac{k}{0.05\,\mathrm{Mpc}^{-1}} \right)^{n_t}$$
- tensor-to-scalar ratio $$r \equiv \frac{P_t(0.05)}{P_s(0.05)} = \frac{A_t}{A_s}$$

$k_* = 0.05/\mathrm{Mpc}$ is the standard pivot scale of e.g. the Planck and BICEP collaborations



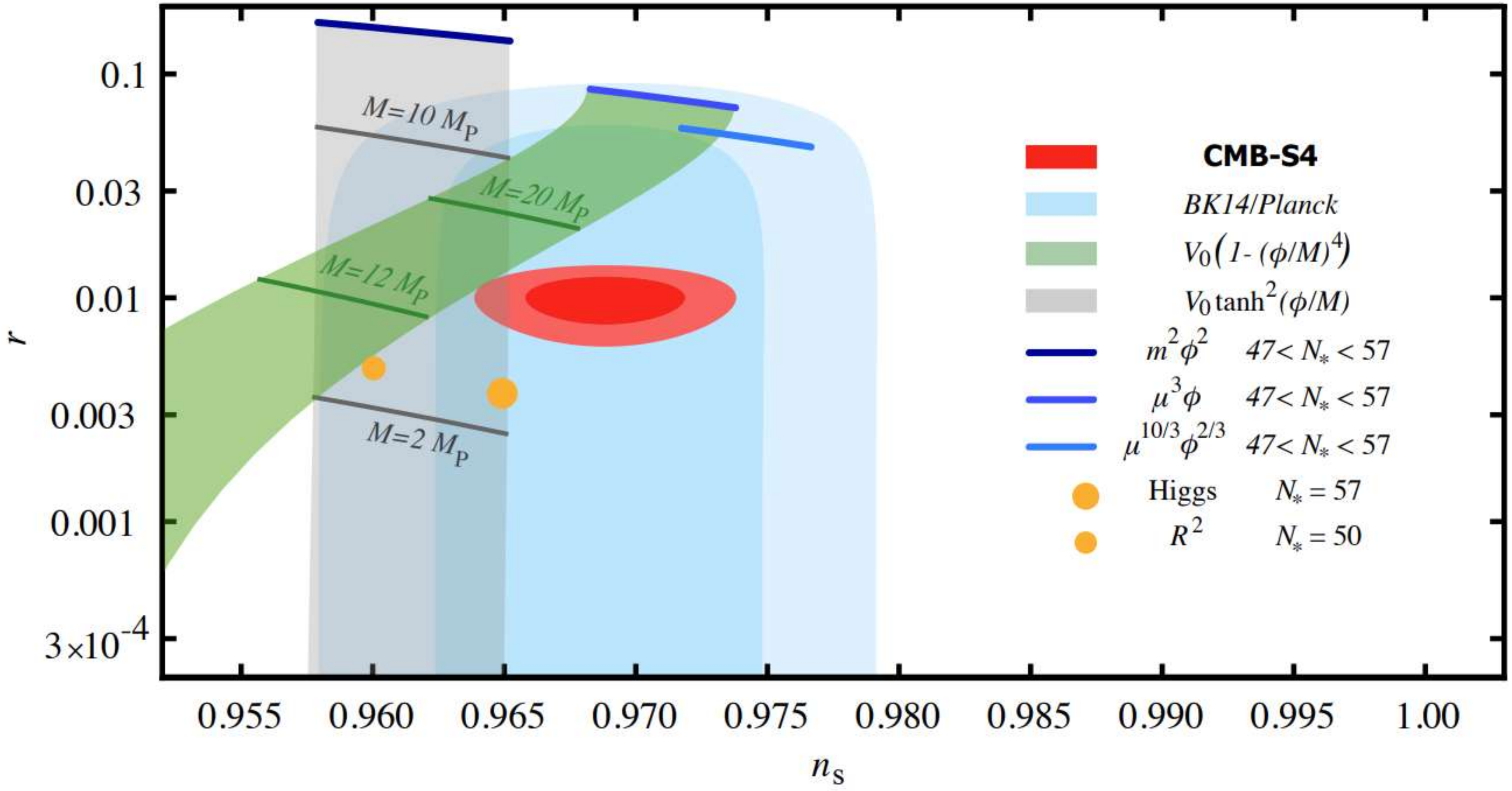
PTEP 2023 (2023) 4, 042F01

Fiducial model: Starobinsky's R^2



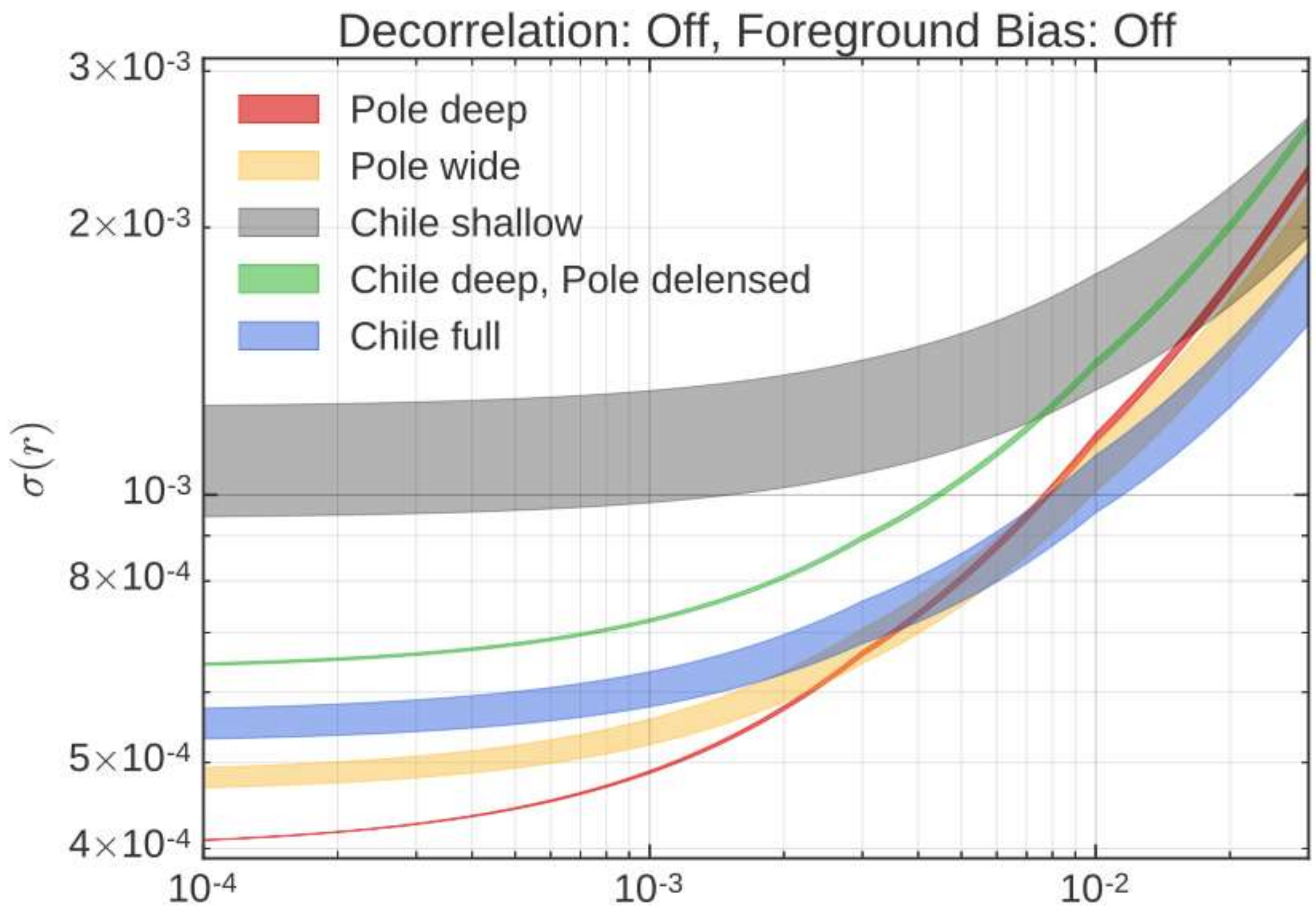
PTEP 2023 (2023) 4, 042F01

Fiducial model: $r = 0$



arxiv: 1610.02743

Fiducial model: $r = 0.01$



arxiv: 2008.12619

The relations between SRP and observables

$$n_s = 1 - 6\epsilon_k + 2\eta_k \ , \quad r = 16\epsilon_k$$

$$H_k^2 = \frac{\mathcal{V}(\varphi_k)}{3M_{pl}^2} = \pi^2 M_{pl}^2 \frac{rA_s}{2}$$

where the slow-roll parameters for a given (single field) inflation model, i.e., the effective potential $V(\varphi)$, are

$$\epsilon = \frac{M_{pl}^2}{2}\left(\frac{\partial_\varphi V}{V}\right)^2$$

and

$$\eta = M_{pl}^2 \frac{\partial_\varphi^2 V}{V}$$

2

Imprint of reheating in CMB

The expansion history of universe

- duration of the reheating epoch

$$N_{\rm re} = \frac{4}{3\bar{w}_{\rm re}-1}\left[N_k + \ln\left(\frac{k}{a_0 T_0}\right) + \frac{1}{4}\ln\left(\frac{40}{\pi^2 g_*}\right) + \frac{1}{3}\ln\left(\frac{11 g_{s*}}{43}\right) - \frac{1}{2}\ln\left(\frac{\pi^2 M_{pl}^2 r A_s}{2\sqrt{\mathcal{V}_{\rm end}}}\right)\right]$$

- average equation of state during reheating

$$\bar{w}_{\rm re} = \frac{1}{N_{\rm re}}\int_0^{N_{\rm re}} w(N)dN$$

where $N_k = \ln\left(\frac{a_{\rm end}}{a_k}\right)$ is the e-folding number between horizon crossing of the k mode and the end of inflation, $\epsilon = 1$.

The expansion history of universe

- The end of reheating $\Gamma = H$
- The Friedmann equation $H^2 = \frac{\rho}{3M_{pl}^2}$
- The redshift from a_{end}

$$\Gamma|_{\Gamma=H} = \frac{1}{M_{pl}}\left(\frac{\rho_{\text{end}}}{3}\right)^{1/2} e^{-3(1+\bar{w}_{\text{re}})N_{\text{re}}/2}$$

The expansion history of universe

- The effective reheating temperature

$$T_{\rm re} = \exp\left[-\frac{3(1+\bar{w}_{\rm re})}{4} N_{\rm re}\right] \left(\frac{40\mathcal{V}(\varphi_{\rm end})}{g_* \pi^2}\right)^{1/4}$$

3

Measuring the inflaton coupling

Three sets of microphysical parameters

- $\{v_i\}$: the coefficients of operators containing Φ alone
- $\{g_i\}$: the inflaton couplings between Φ and other fields
- $\{a_i\}$: all parameters other than $\{v_i\} \cup \{g_i\}$

e.g. $\Gamma = \frac{g^2 m_\phi}{\#}$ for reheating through elementary particle decays

Feedback effects

However, feedback effects on the reheating process introduce a dependence of Γ on $\{a_i\}$:

- resonant particle production during preheating phase
- thermal feedback during perturbative reheating

Conditions to constrain $\{g_i\}$ model-independently

$$g \ll \left(\frac{m_\phi}{\varphi_{\rm end}}\right)^{j-\frac{1}{2}} \min\left(\sqrt{\frac{m_\phi}{M_{pl}}}, \sqrt{\frac{m_\phi}{\varphi_{\rm end}}}\right)\left(\frac{m_\phi}{\Lambda}\right)^{4-D}$$

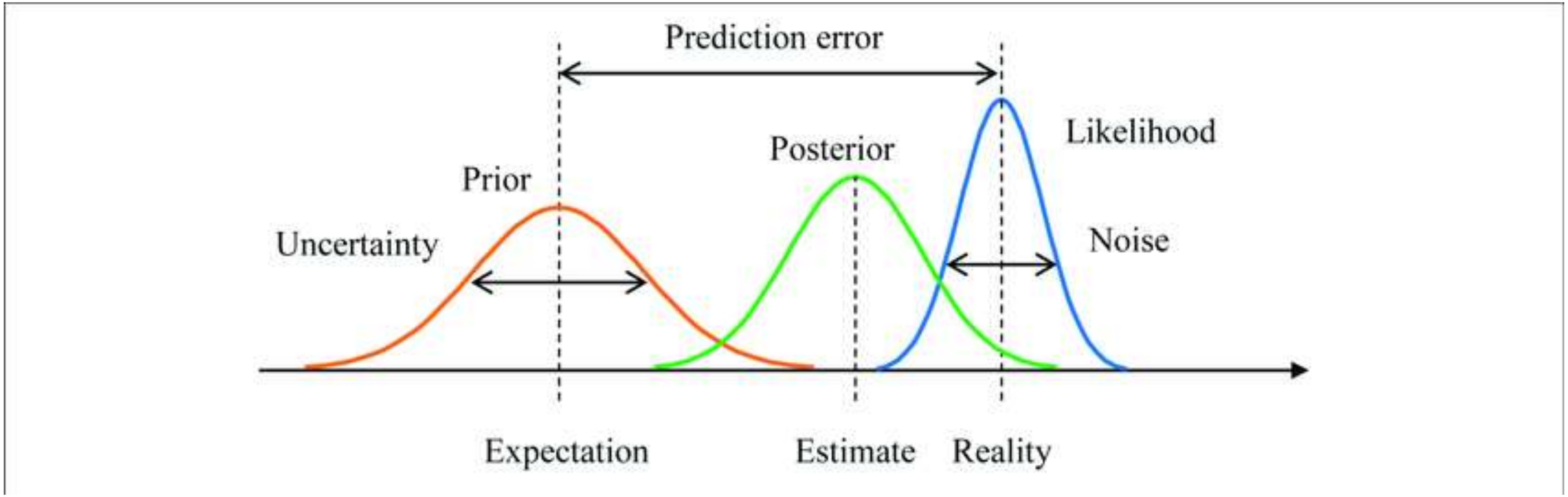
$$v_i \ll \left(\frac{m_\phi}{\varphi_{\rm end}}\right)^{j-\frac{5}{2}} \min\left(\sqrt{\frac{m_\phi}{M_{pl}}}, \sqrt{\frac{m_\phi}{\varphi_{\rm end}}}\right)\left(\frac{m_\phi}{\Lambda}\right)^{4-j}$$

$\{n_s, r, A_s\}$ ⟷ $\{M, \alpha, g\}$

4

Bayesian analysis

Prior, likelihood and posterior



Yanagisawa, Hideyoshi & Kawamata, Oto & Ueda, Kazutaka. (2019). 10.3389/fncom.2019.00002.

Prior, likelihood and posterior

- What we know prior to any measurements

$$N_{\rm re} > 0 \quad \text{and} \quad T_{\rm re} > T_{\rm BBN}$$

- Current and future observations

two-dimensional Gaussian

- Our predications

estimations for $\log_{10} g$ and $\log_{10} T_{\rm re}$ /GeV

Prior, likelihood and posterior

- The prior probability density function (PDF)

$$P(x) = c_1 \theta\big(T_{\rm re}(x) - T_{\rm BBN}\big)\ \gamma(x)\ \theta\big(N_{\rm re}(x)\big)$$

- The likelihood function

$$P(\mathcal{D}|x) = c_2 \mathcal{N}(n_s, r|\bar{n}_s, \sigma_{n_s}; \bar{r}, \sigma_r)\theta(r)\tilde{\gamma}(x)$$

- The posterior

$$P(x|\mathcal{D}) = P(\mathcal{D}|x)P(x)/P(\mathcal{D})$$

Likelihood

	$\bar{n}_s$	σ_{n_s}	$\bar{r}$	σ_r
Planck+BK18	0.967	0.005	0.01	0.018
CMB-S4/LiteBIRD	0.967	0.002	0.02	0.0012
CMB-S4+EUCLID	0.967	0.00085	0.02	0.0012

P. A. R. Ade et al. (BICEP, Keck), Phys. Rev. Lett. 127, 151301 (2021), arXiv:2110.00483[astro-ph.CO].
E. Allys et al. (LiteBIRD), (2022), arXiv:2202.02773[astro-ph.IM].
R. Laureijs et al. (EUCLID), (2011), arXiv:1110.3193[astro-ph.CO].

5

Application to specific models

Two inflation models

The radion gauge inflation (RGI) and α-attractor T-models (α-T)

$$\mathrm{RGI}: \quad \mathcal{V}(\varphi) = M^4 \frac{(\varphi/M_{pl})^2}{\alpha + (\varphi/M_{pl})^2}$$

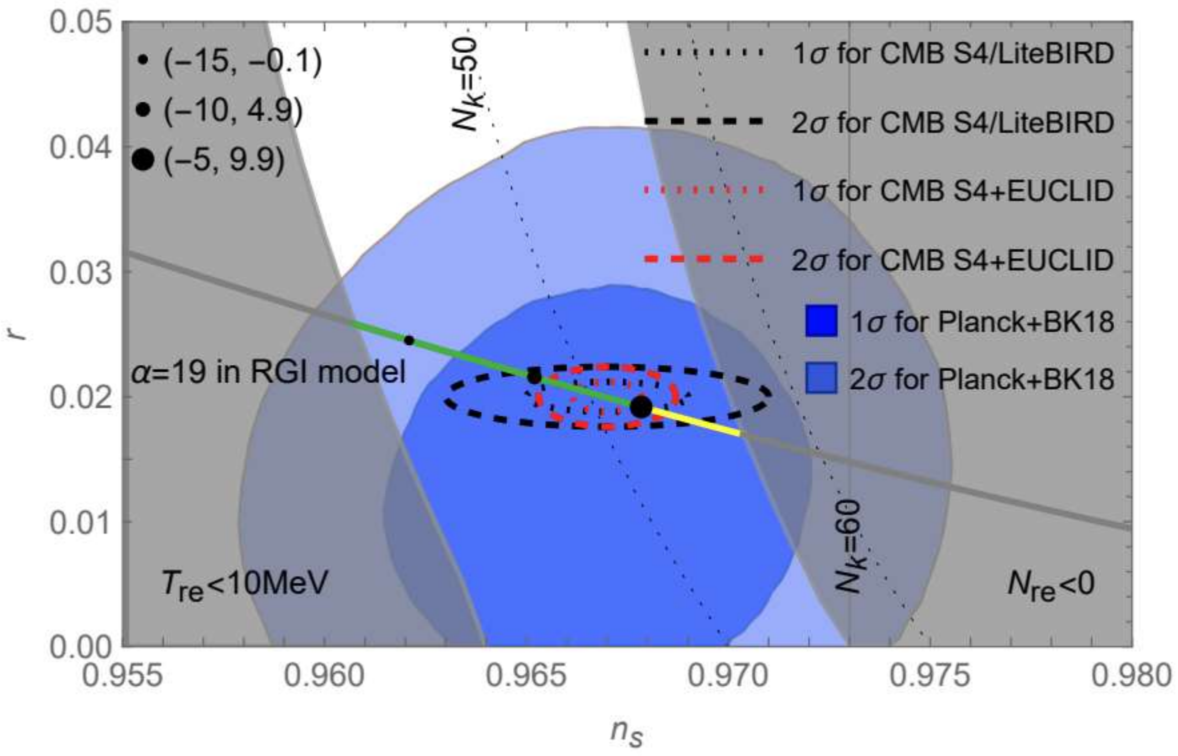
$$\alpha\!-\!\mathrm{T}: \quad \mathcal{V}(\varphi) = M^4 \tanh^{2n}\left(\frac{\varphi}{\sqrt{6\alpha}M_{pl}}\right)$$

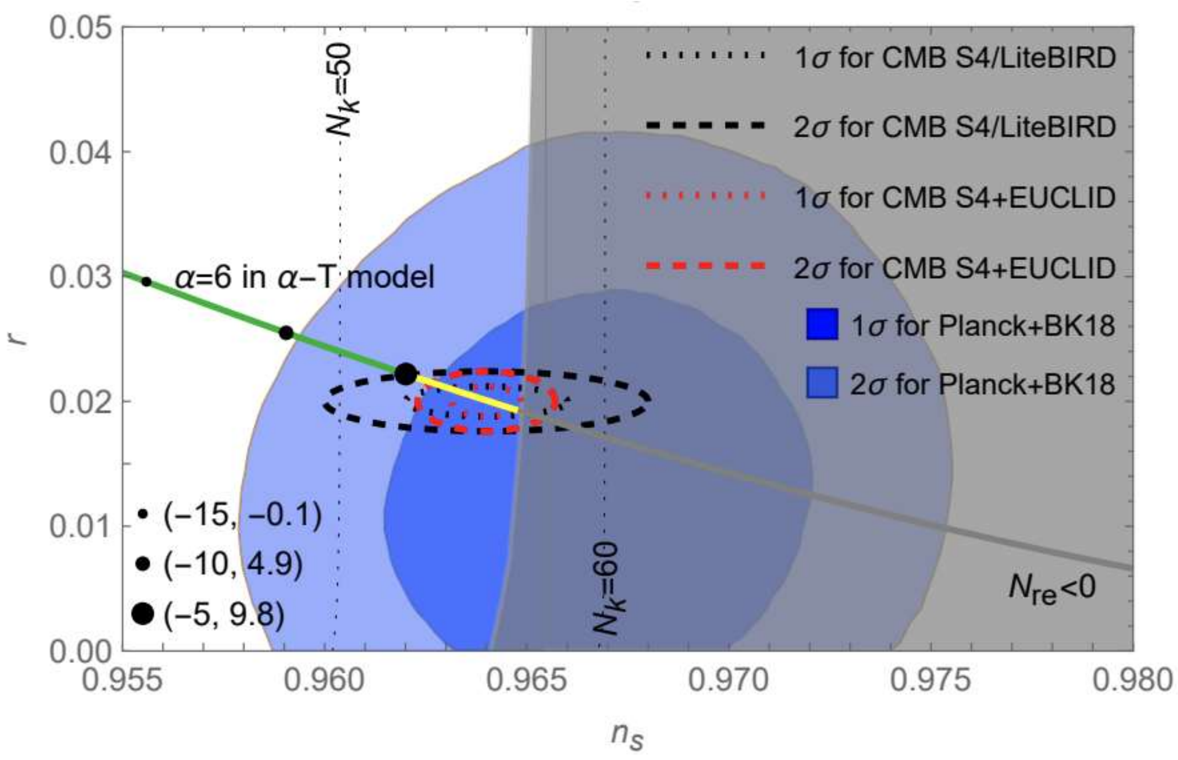
the normalization M can be expressed in terms of other parameters:

$$\mathrm{RGI}: \quad M = M_{pl}\left(\frac{3\pi^2}{2} r A_s \left(1 + \alpha\frac{M_{pl}^2}{\varphi_k^2}\right)\right)^{1/4},$$

$$\alpha\!-\!\mathrm{T}: \quad M = M_{pl}\left(\frac{3\pi^2}{2} A_s r\right)^{1/4} \tanh^{-\frac{n}{2}}\left(\frac{\varphi_k}{\sqrt{6\alpha}M_{pl}}\right)$$

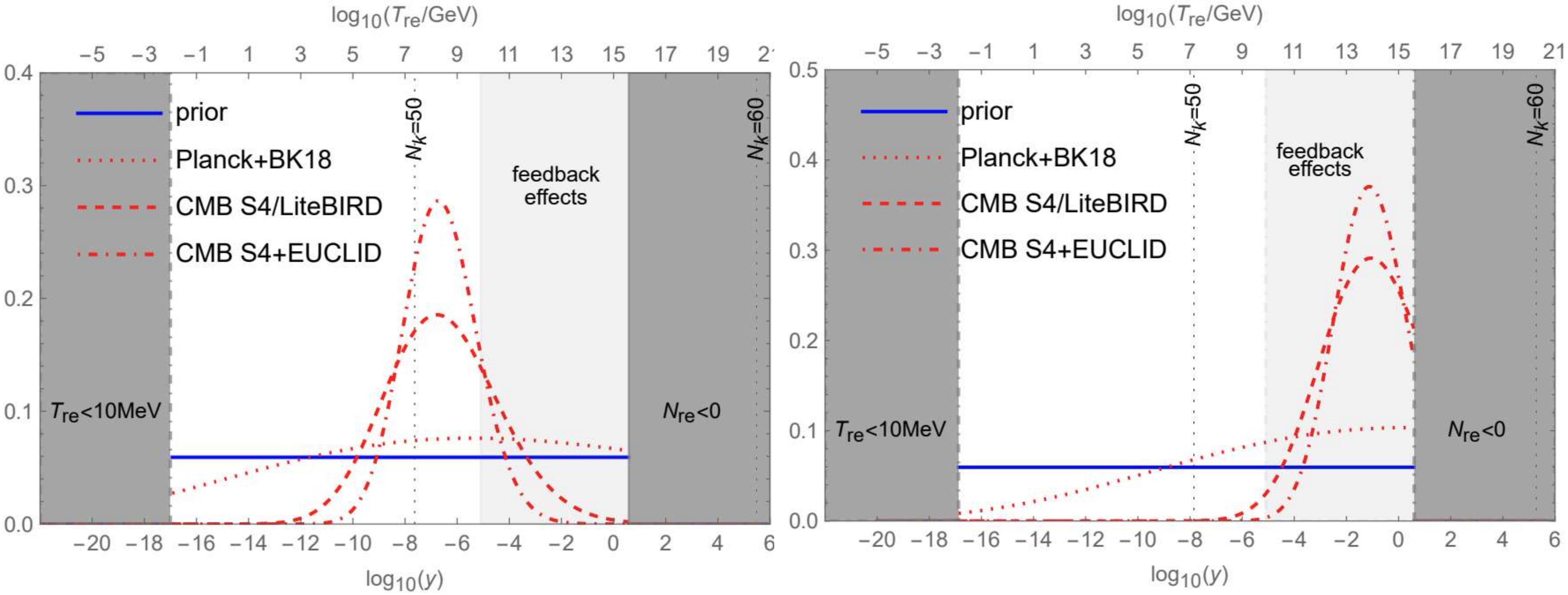
Predications





arxiv: 2208.07609

Prior and posteriors



arxiv: 2208.07609

Constraints on $\log_{10} g$ and $\log_{10} T_{\mathrm{re}}$ /GeV

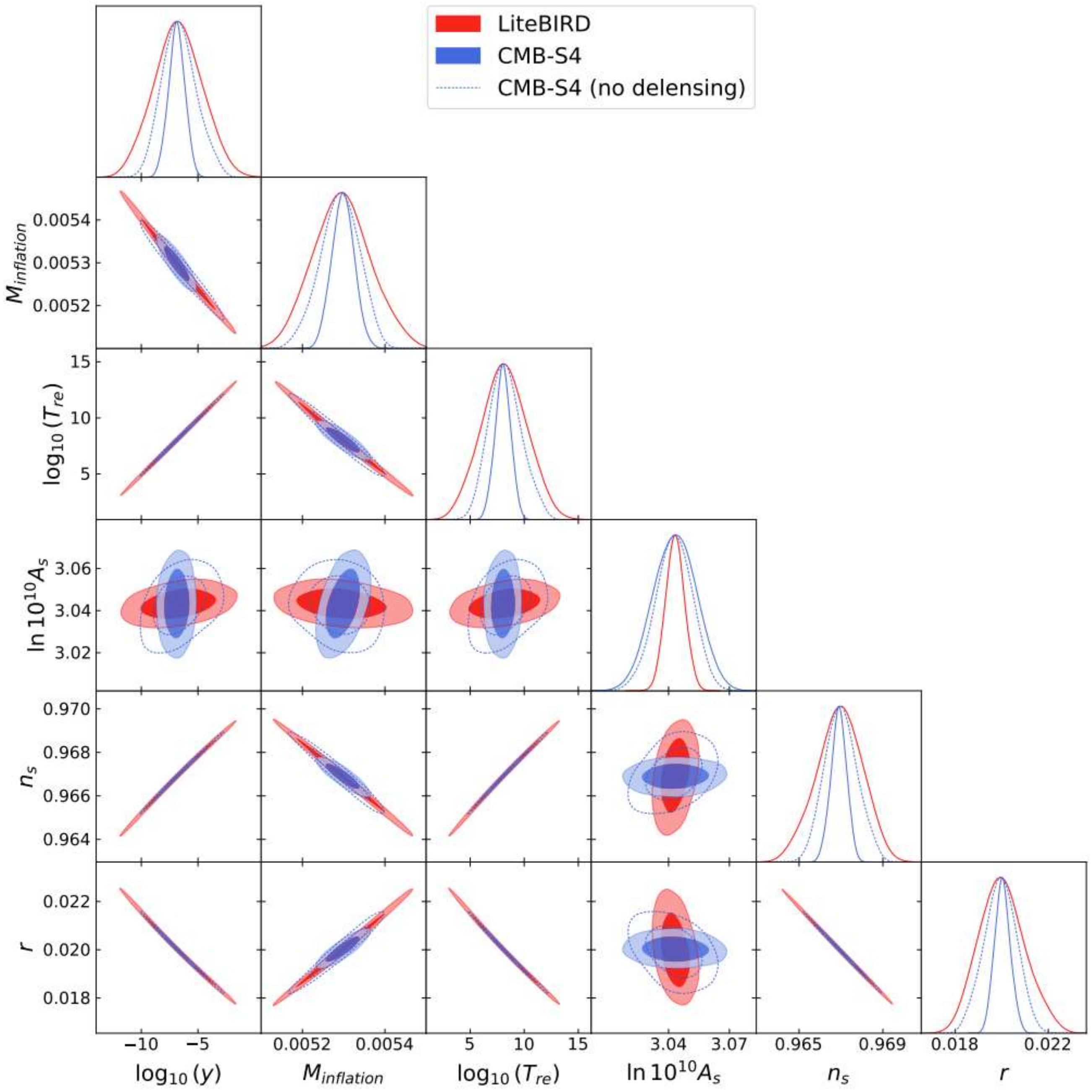
	RGI model		α-T model	
	$\log_{10} g$	$\log_{10} T_{\mathrm{re}}/\mathrm{GeV}$	$\log_{10} g$	$\log_{10} T_{\mathrm{re}}/\mathrm{GeV}$
flat prior	-8.2 ± 5.0	6.8 ± 5.0	-8.1 ± 5.0	6.7 ± 5.0
Planck+BK18	-7.2 ± 4.7	7.7 ± 4.6	-5.5 ± 4.2	9.3 ± 4.2
CMB-S4/LiteBIRD	-6.5 ± 2.2	8.4 ± 2.1	-1.7 ± 1.5	13.1 ± 1.4
CMB-S4+EUCLID	-6.6 ± 1.4	8.3 ± 1.4	-1.4 ± 1.1	13.5 ± 1.1

arxiv: 2208.07609

Analytic and MCMC

(Monte Carlo Markov Chain)

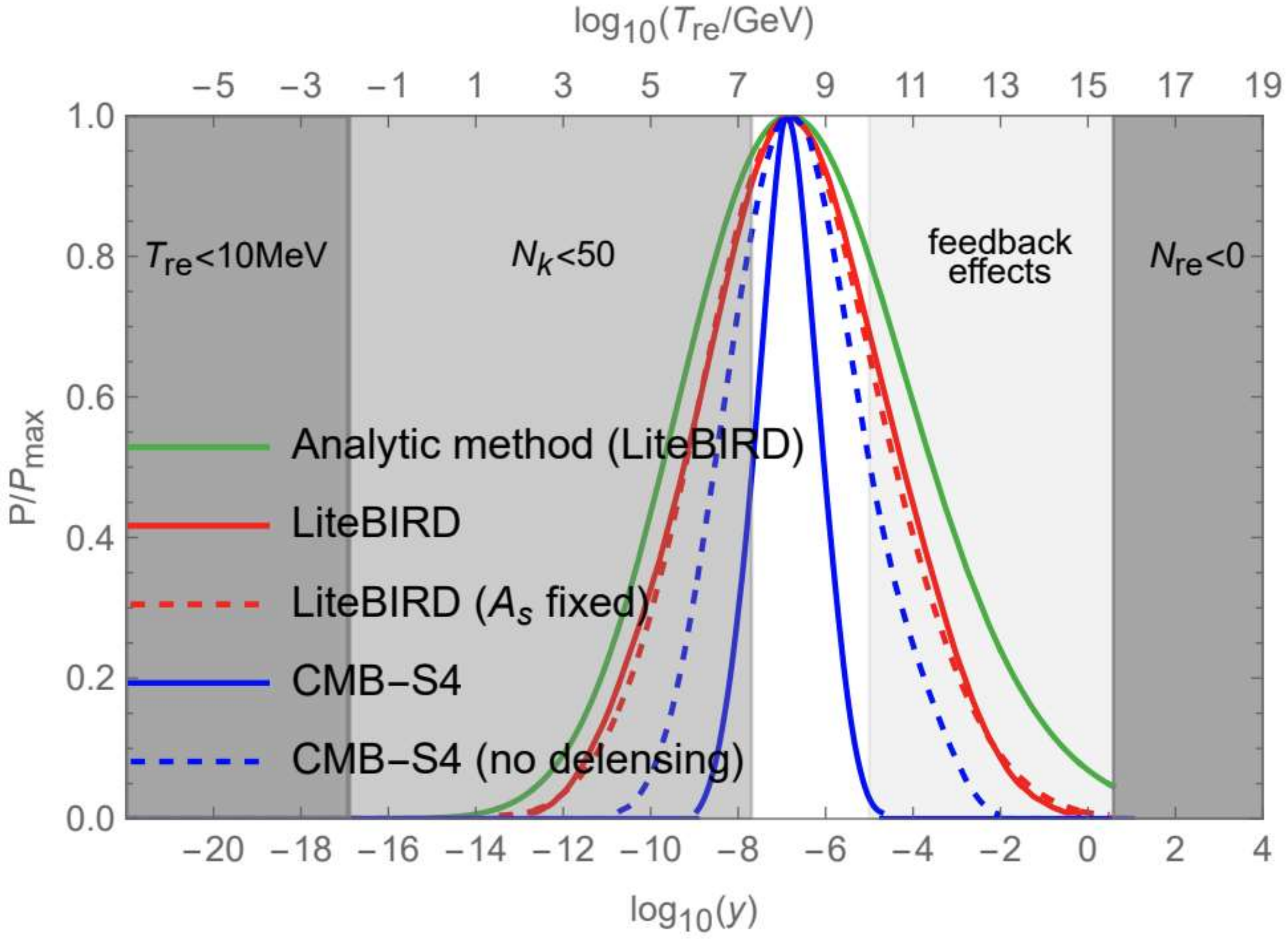
arxiv: 2303.13503



Analytic and MCMC

(Monte Carlo Markov Chain)

arxiv: 2303.13503



6

Summary and Outlook

- What we introduced:

  (1) a simple analytic method to quantify the information gain on the inflaton coupling g and the reheating temperature $T_{\rm re}$ from observational constraints on n_s and r

  (2) Monte Carlo Markov Chain based forecasts

- What will be considered:

  non-Gaussianities or the running of n_s

Thank you !