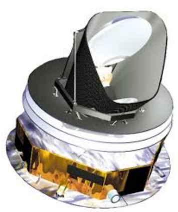
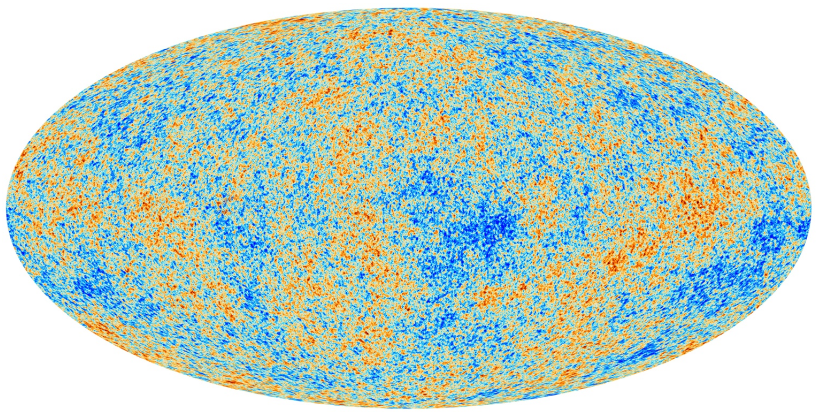
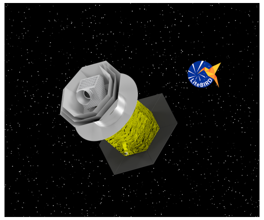
CMB constraints on inflation and perspectives for future observations







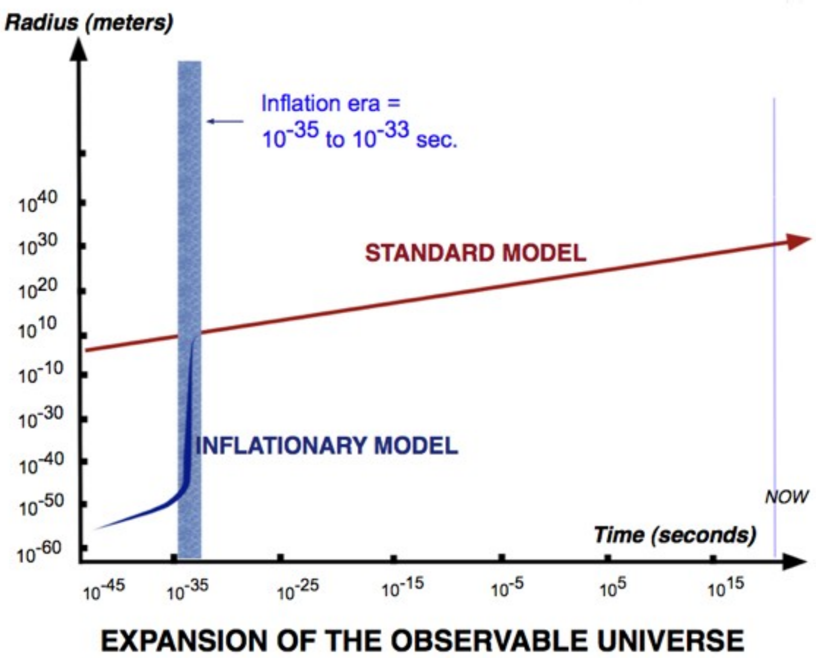
Fabio Finelli

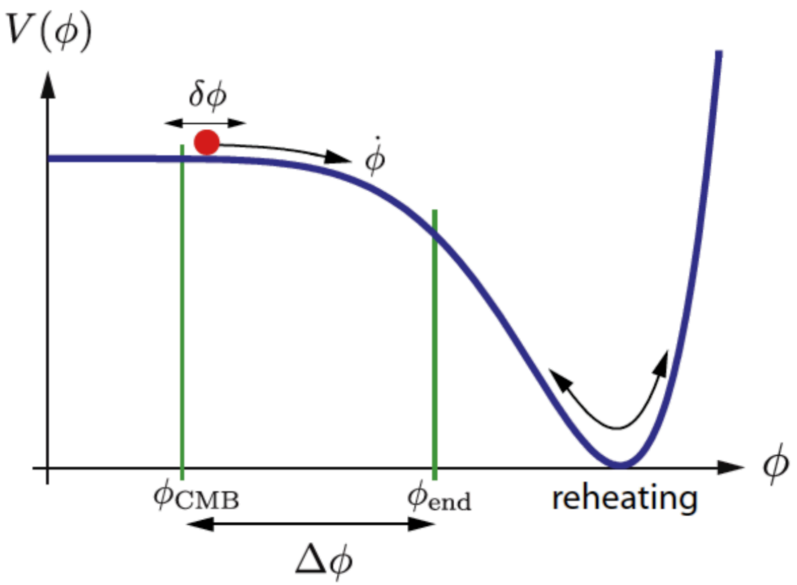
INAF OAS Bologna

INFN Sezione di Bologna

Inflation 2025, IAP, Dec. 1-5, 2025

Cosmic Inflation





Minimal early universe framework which solves puzzles of the Standard Hot Big Bang cosmology such as the flatness, horizon, structure formation, monopole problems by postulating a nearly exponential expansion before the thermal era.

An exponential expansion driven a cosmological constant would address all these problems but would continue forever. The simplest example for cosmic inflation is therefore given by a standard scalar field which slowly rolls down a sufficiently flat potential. The *nearly* exponential expansion during a stage in which the potential term dominates over the kinetic energy term is called slow-roll regime, which ends in the coherent oscillation regime when the inflation starts decaying in additional particles.

Generation of fluctuations

By a nearly exponential expansion, cosmic inflation also provides a unified generation mechanism for nearly scale invariant primordial spectra of gravitational waves and of curvature (i.e. density) perturbations from quantum fluctuations.

Tensor perturbations (gravitational waves)

$$\mathcal{P}_{\rm t}(k) = A_{\rm t}\left(\frac{k}{k_*}\right)^{n_{\rm t}+\frac{1}{2}\frac{{\rm d}n_{\rm t}}{{\rm d}\ln k}\ln(\frac{k}{k_*})+\dots}$$

$$A_{\rm t} \simeq \frac{2H^2}{\pi^2 M_{\rm pl}^2} \approx \frac{2V}{3\pi^2 M_{\rm pl}^4}$$

$$n_{\rm t} \simeq -2\epsilon_1 \approx -\frac{M_{\rm pl}^2 V_\phi^2}{V^2}$$

$$\epsilon_1 = -\frac{\dot H}{H^2} << 1$$

$$\frac{{\rm d}n_{\rm t}}{{\rm d}\ln k} \simeq -2\epsilon_1\epsilon_2$$

$$\epsilon_2 = -\frac{\dot\epsilon_1}{H\epsilon_1} << 1$$

Scalar perturbations

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\frac{1}{2}\frac{{\rm d}n_{\rm s}}{{\rm d}\ln k}\ln(\frac{k}{k_*})+\dots}$$

$$A_{\rm s} \approx \frac{V^3}{12\pi^2 M_{\rm pl}^6 V_\phi^2}$$

$$n_{\rm s} - 1 \simeq -2\epsilon_1 - \epsilon_2 \approx -3\frac{M_{\rm pl}^2 V_\phi^2}{V^2} + 2\frac{M_{\rm pl}^2 V_{\phi\phi}}{V}$$

$$\frac{{\rm d}n_{\rm s}}{{\rm d}\ln k} \simeq -2\epsilon_1\epsilon_2 - \epsilon_2\epsilon_3$$

$$r = \frac{\mathcal{P}_{\rm t}(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \simeq 16\epsilon_1 \simeq -8n_{\rm t}$$

Generation of fluctuations: 2

The generation of quantum fluctuation is not only characterized by the two-point correlation function

$$\langle \mathcal{R}(\mathbf{k}_1)\ \mathcal{R}(\mathbf{k}_2)\rangle = (2\pi)^3\ \frac{2\pi^2}{k^3}\mathcal{P}_{\mathcal{R}}(k)\ \delta^3(\mathbf{k_1}+\mathbf{k_2})$$

but also from higher order correlations due to non-linearity in the inflation potential:

$$\langle \mathcal{R}(\mathbf{k_1})\ \mathcal{R}(\mathbf{k}_2)\ \mathcal{R}(\mathbf{k}_3)\rangle = (2\pi)^3 B_{\mathcal{R}}(k_1,k_2,k_3)\delta^3(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})$$

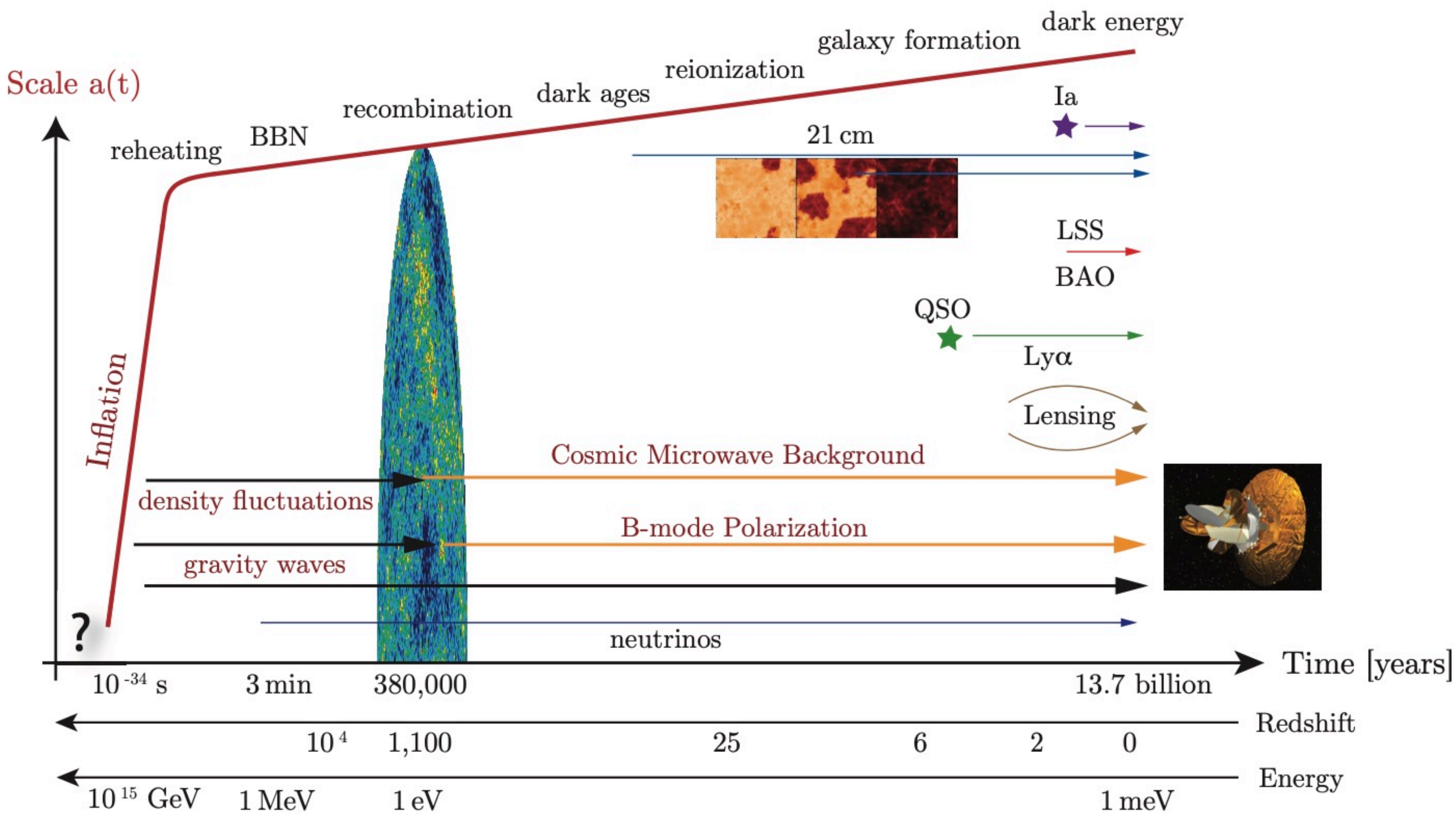
$$B_{\mathcal{R}}(k_1,k_2,k_3) \propto f_{\rm NL} F(k_1,k_2,k_3)$$

The non-Gaussianity parameter $f_{\rm NL}$ generated in single field slow-roll inflation with a kinetic term with vacuum initial conditions for quantum fluctuations is $f_{\rm NL} \sim \mathcal{O}(\epsilon_1\,,\epsilon_2)$, i.e. at an undetectable level and smaller than other general relativistic contributions, such as the cross-correlation between the integrated Sachs-Wolfe effect and the gravitational lensing of the CMB.

For a general scalar field Lagrangian or for multi-field inflation, the non-Gaussian contribution can be large enough to be measured:

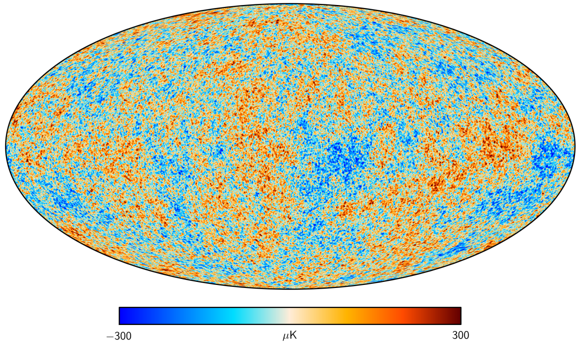
$$f_{\rm NL}^{\rm equil} \sim \mathcal{O}\left(\frac{1}{c_s^2}-1\right) \qquad \mathcal{L} = P(\phi, X) \qquad c_{\rm s}^2 = \frac{P_{,X}}{P_{,X}+2XP_{,XX}}$$

The CMB anisotropy pattern as a fantastic laboratory for cosmic inflation



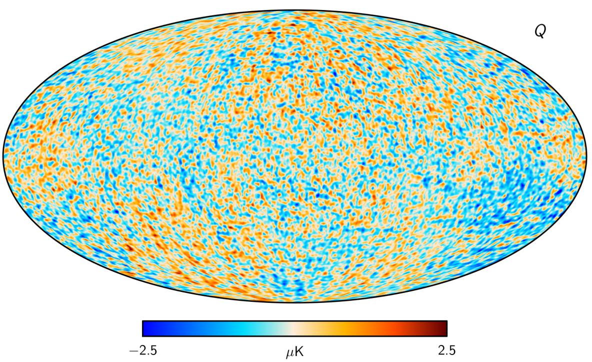
Credits: D. Baumann, TASI Lectures on Inflation

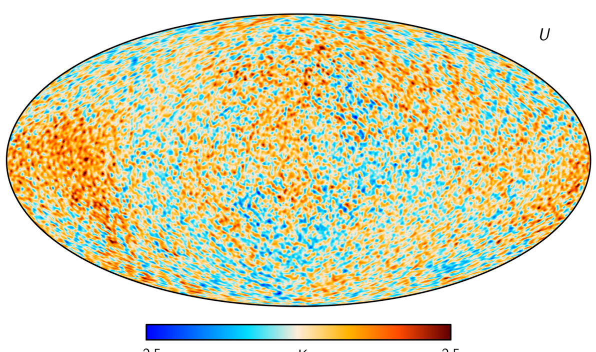
The CMB anisotropy pattern as a fantastic laboratory for cosmic inflation

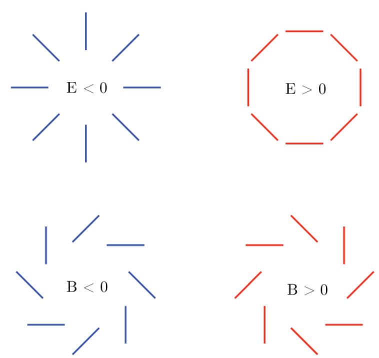


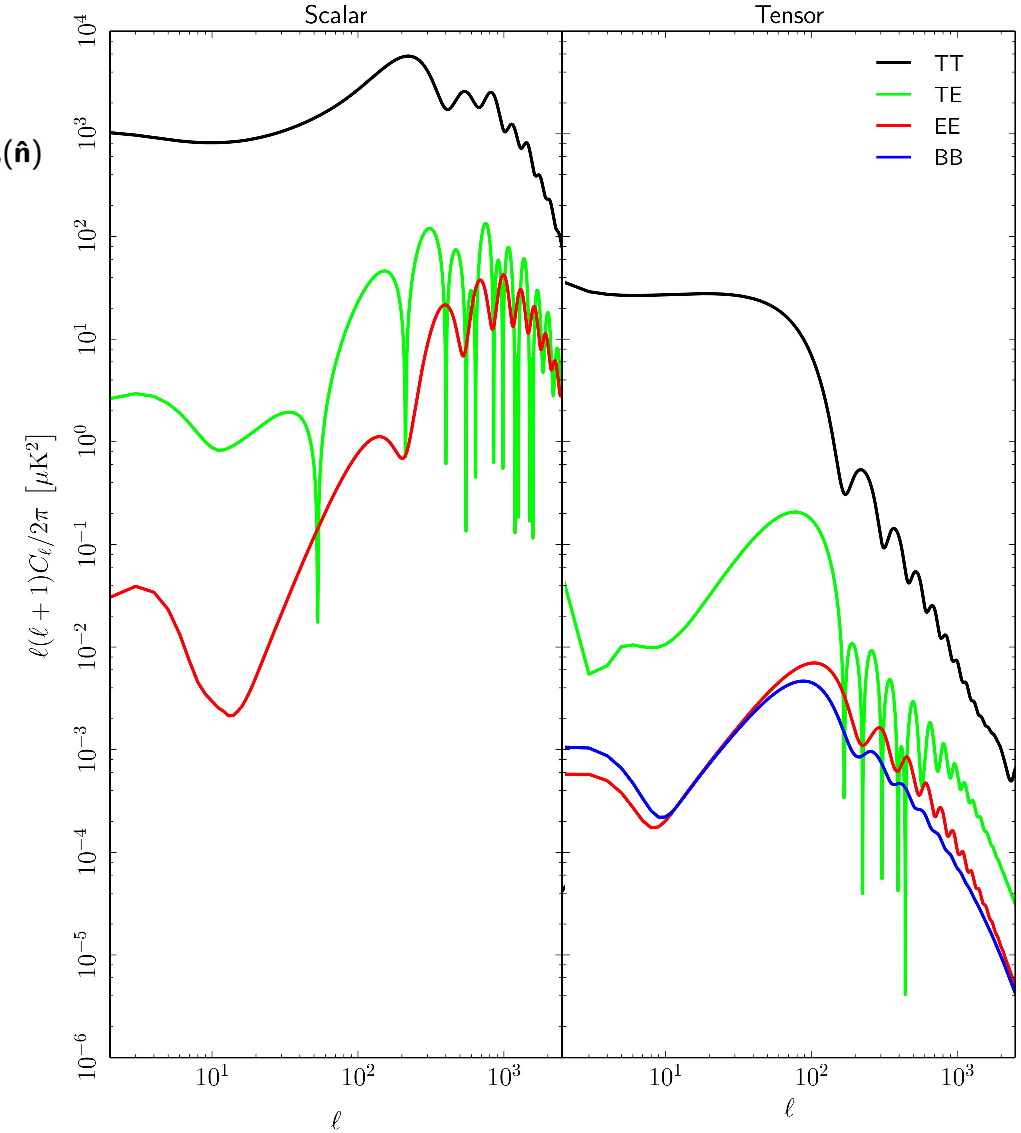
$$\Delta_T(\hat{\mathbf{n}}) = \frac{\Delta T}{T}(\hat{\mathbf{n}}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$$C_\ell \equiv \langle |a_{\ell m}|^2 \rangle$$

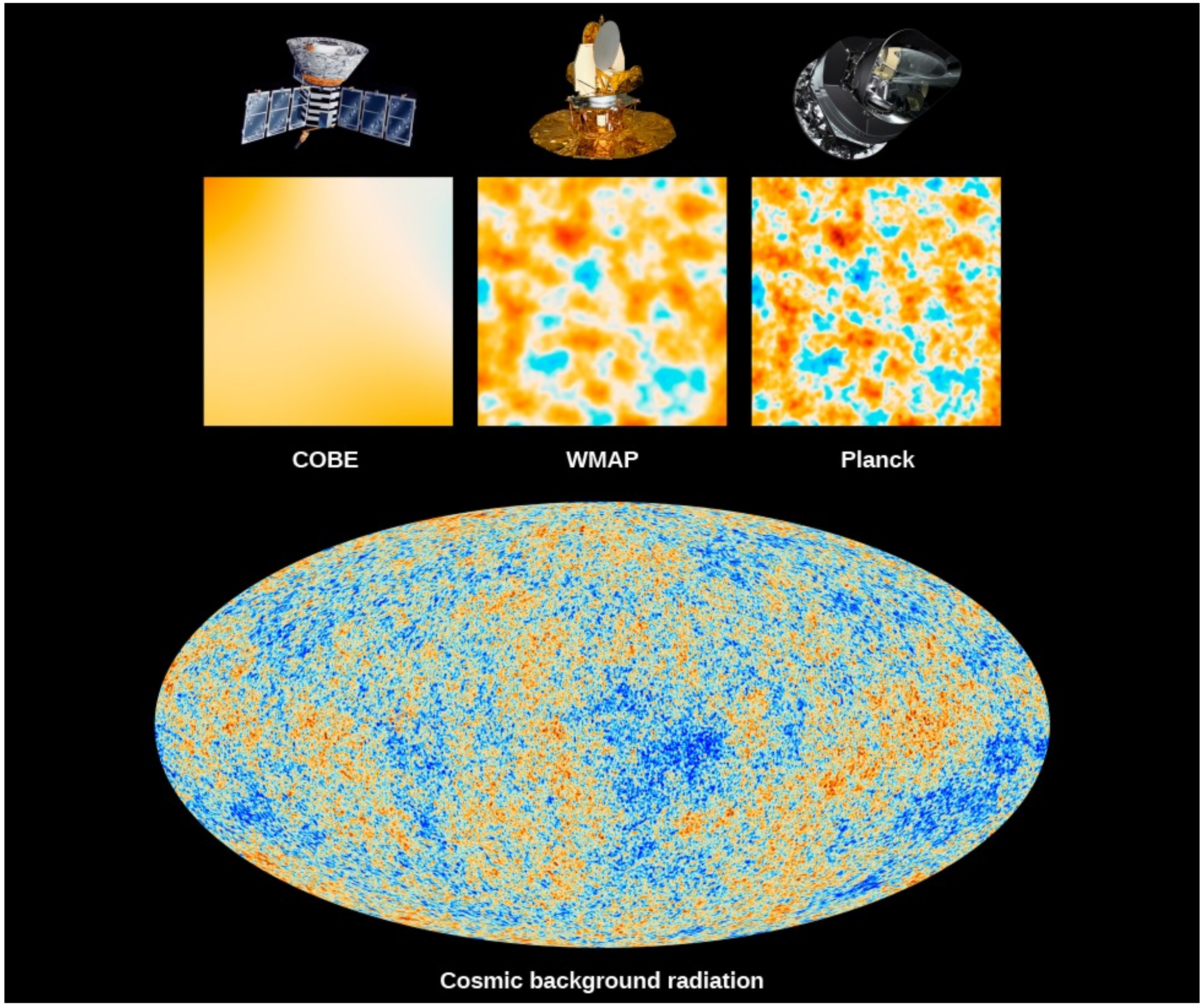




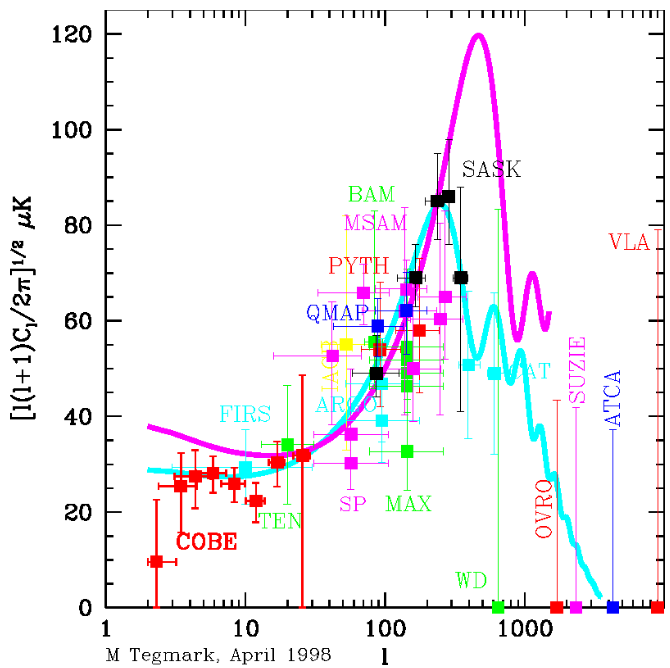


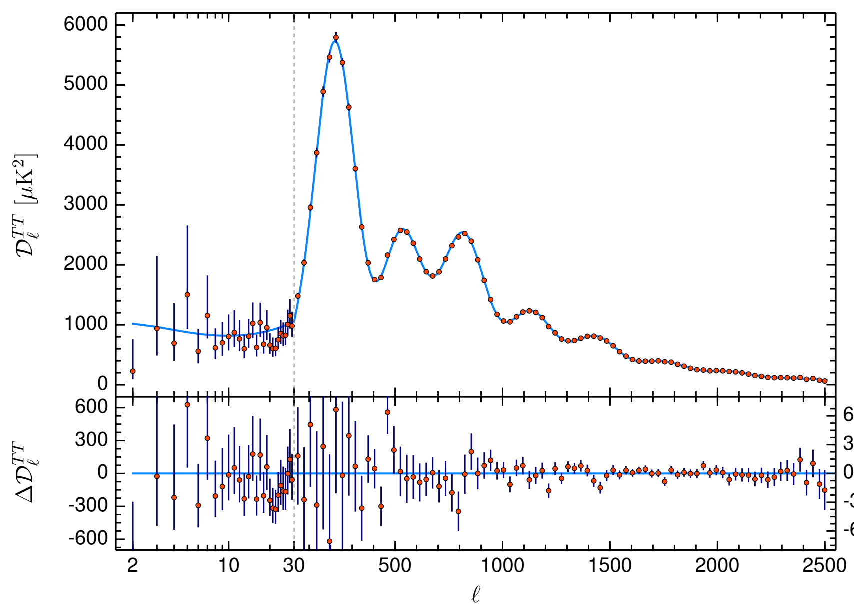


CMB anisotropies in historical perspectives



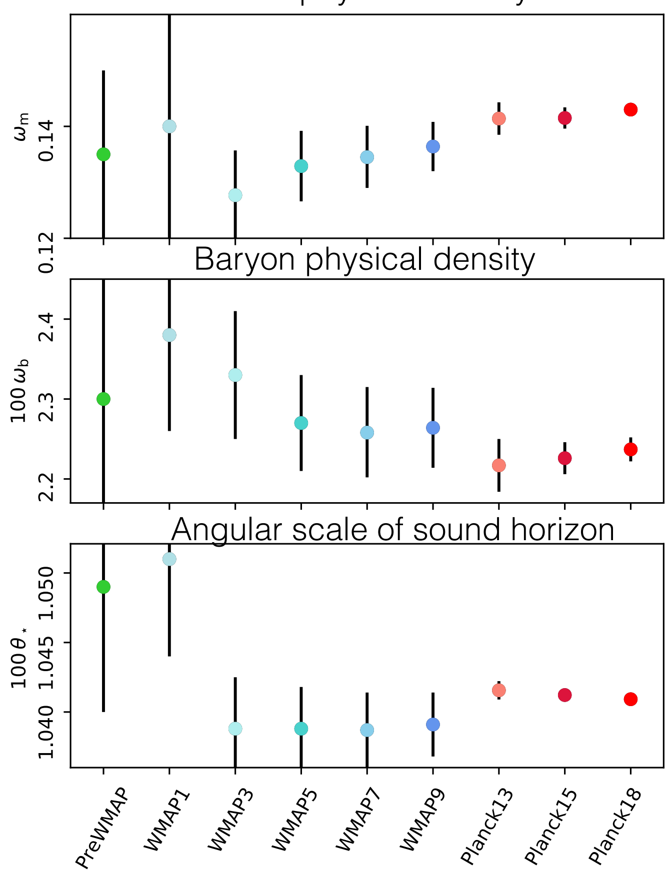
CMB anisotropies in historical perspectives

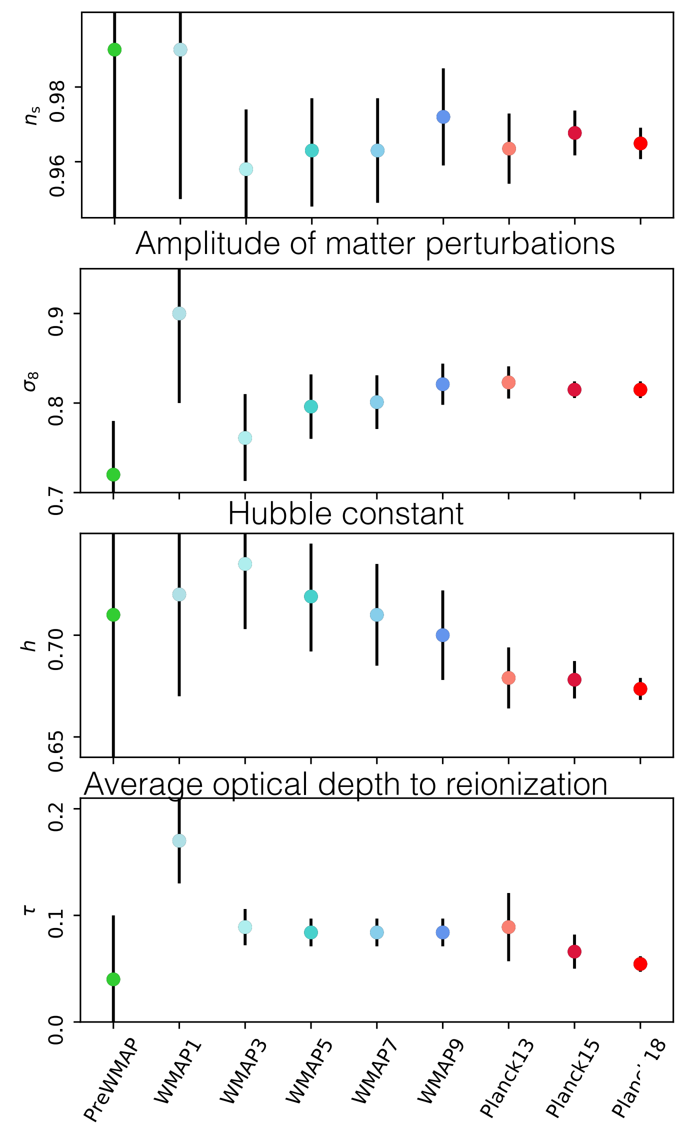




Planck collaboration

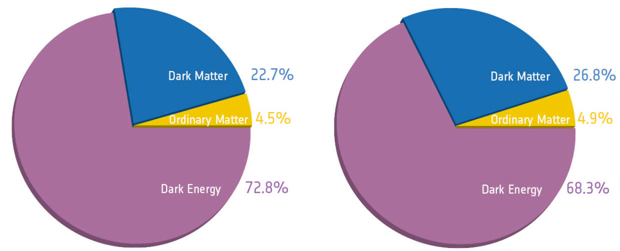
Cosmology in historical perspectives





Planck 2018 results. I. Overview and the cosmological legacy of Planck

Planck 2018 view of LambdaCDM



Before Planck   After Planck

Parameter	TT+lowE	EE+lowE	TE+lowE	TT,TE,EE+lowE	TT,TE,EE+lowE+lensing	[%]
$\Omega_b h^2$	0.02212 ± 0.00022	0.0240 ± 0.0012	0.02249 ± 0.00025	0.02236 ± 0.00015	0.02237 ± 0.00015	0.7
$\Omega_c h^2$	0.1206 ± 0.0021	0.1158 ± 0.0046	0.1177 ± 0.0020	0.1202 ± 0.0014	0.1200 ± 0.0012	1
$100\theta_{MC}$	1.04077 ± 0.00047	1.03999 ± 0.00089	1.04139 ± 0.00049	1.04090 ± 0.00031	1.04092 ± 0.00031	0.03
τ	0.0522 ± 0.0080	0.0527 ± 0.0090	0.0496 ± 0.0085	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	13
$\ln(10^{10} A_s)$	3.040 ± 0.016	3.052 ± 0.022	$3.018^{+0.0020}_{-0.0018}$	3.045 ± 0.016	3.044 ± 0.014	0.7
n_s	0.9626 ± 0.0057	0.980 ± 0.015	0.967 ± 0.011	0.9649 ± 0.0044	0.9649 ± 0.0042	0.4
H_0	66.88 ± 0.92	69.9 ± 2.7	68.44 ± 0.91	67.27 ± 0.60	67.36 ± 0.54	0.08
Ω_m	0.321 ± 0.013	$0.289^{+0.026}_{-0.033}$	0.301 ± 0.012	0.3166 ± 0.0084	0.3153 ± 0.0073	2.3
σ_8	0.8118 ± 0.0089	0.796 ± 0.018	0.793 ± 0.011	0.8120 ± 0.0073	0.8111 ± 0.0060	0.7

Table 2. Confidence limits for the cosmological parameters in the base-ΛCDM model from *Planck* temperature, polarization, and temperature-polarization cross-correlation separately and combined, in combination with the EE measurement at low multipoles.

Planck TT, TE, EE + lowE + lensing is the 2018 baseline (Planck 2018)

Subpercent precision for cosmological parameters (except for the optical depth)

Planck 2018 results and initial conditions:

concordance with key predictions of the simplest inflationary models

A nearly flat Universe $\Omega_K = -0.011^{+0.013}_{-0.012}$ 95%CL

(+BAO) $\Omega_K = 0.0007 \pm 0.0037$

A tilted power-law spectrum for density perturbations $n_s = 0.9649 \pm 0.0042$ 68%CL

No statistical evidence of running $dn_s/d\ln k = -0.0045 \pm 0.0067$ 68%CL

Nearly Gaussian perturbations (T , E)

Planck 2018 results. IX. Constraints on primordial non-Gaussianity

$f_{NL}^{local} = -0.9 \pm 5.1$

$f_{NL}^{equil} = -26 \pm 47$ 68%CL

$f_{NL}^{ortho} = -38 \pm 24$

No need for additional fields: nearly adiabatic fluctuations (axion) $\beta_{iso}^{axion} < 0.038$ 95%CL

(curvaton) $\beta_{iso}^{curvaton} < 0.001$

No strings and other topological defects $f_{10} < 0.020$ 95%CL

Planck 2015 results. XIII. Cosmological parameters

Planck 2018 results and initial conditions:

concordance with key predictions of the simplest inflationary models

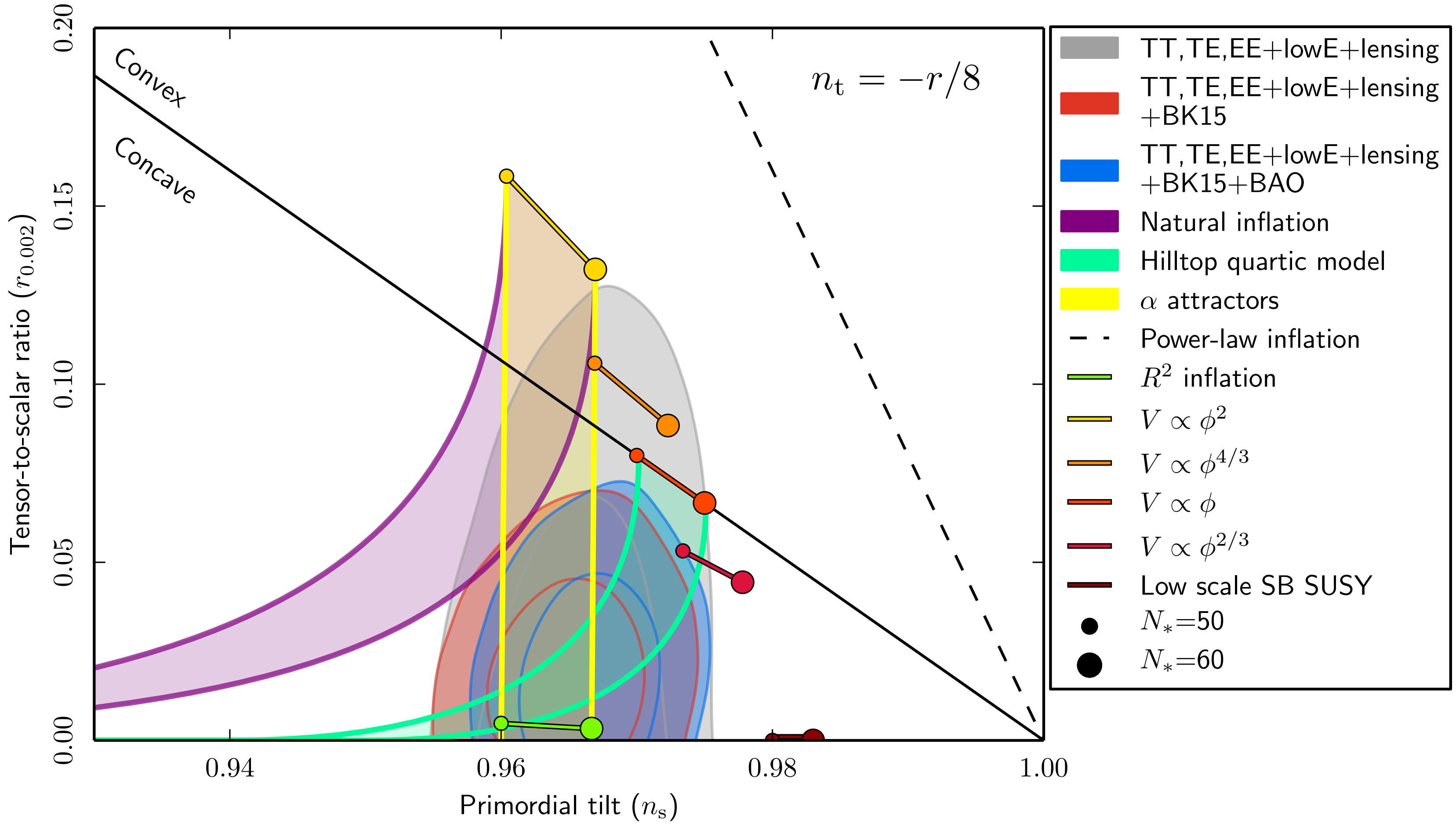
Small relative amount of gravitational waves ($n_t = -r/8$) $r_{0.002} < 0.10$

95%CL

($n_t = -r/8$, +BK15) $r_{0.002} < 0.056$

$$\left[\ V_* = \frac{3\pi^2 A_\mathrm{s}}{2}\, r\, M_\mathrm{Pl}^4 < (1.6 \times 10^{16}\ \mathrm{GeV})^4 \quad 95\,\%\ \mathrm{CL}\ \right]$$

Which inflationary models are best able to account the data?



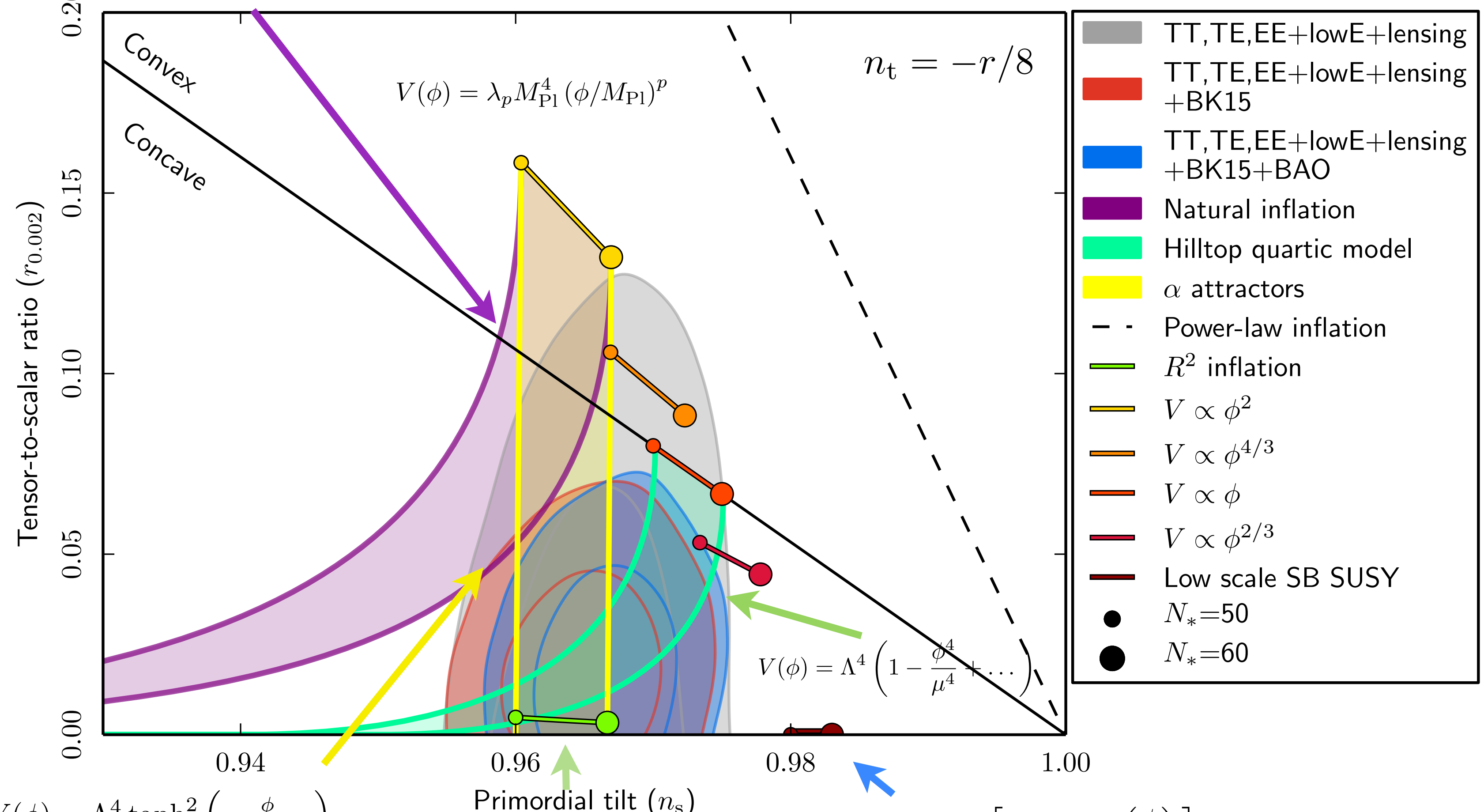
Planck 2018 results. X. Constraints on inflation

Which inflationary models are best able to account the data?

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

Freese et al. 1990

Planck 2018 results. X. Constraints on inflation



$$V(\phi) = \Lambda^4 \tanh^2\left(\frac{\phi}{\sqrt{6\alpha}M_{\rm pl}}\right)$$

Kallosh & Linde 2013

Starobinsky 1980

$$V(\tilde\phi) = \frac{\Lambda^4}{4}\left(1 - e^{-2\tilde\phi/\sqrt{6}M_{\rm pl}}\right)^2$$

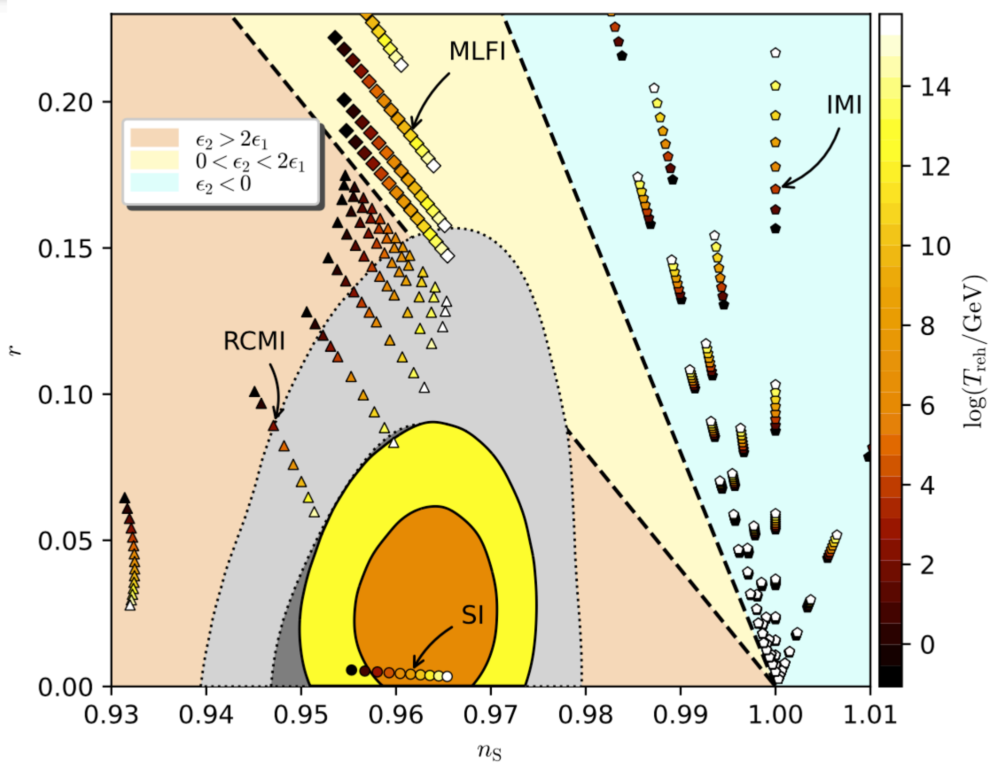
$$V(\phi) = \Lambda^4 \left[1 + \alpha_h \ln\left(\frac{\phi}{\mu}\right)\right]$$

Dvali et al. 1994

Which inflationary models are best able to account the data?

Inflationary model	Potential $V(\phi)$	Parameter range	$\Delta\chi^2$	$\ln B$
$R + R^2/(6M^2)$	$\Lambda^4\left(1 - e^{-\sqrt{2/3}\phi/M_{\rm Pl}}\right)^2$	...	...	...
Power-law potential	$\lambda M_{\rm Pl}^{10/3}\phi^{2/3}$	...	2.8	−2.6
Power-law potential	$\lambda M_{\rm Pl}^{3}\phi$	...	2.5	−1.9
Power-law potential	$\lambda M_{\rm Pl}^{8/3}\phi^{4/3}$	...	10.4	−4.5
Power-law potential	$\lambda M_{\rm Pl}^{2}\phi^{2}$	...	22.3	−7.1
Power-law potential	$\lambda M_{\rm Pl}\phi^{3}$	...	40.9	−19.2
Power-law potential	$\lambda\phi^{4}$	...	89.1	−33.3
Non-minimal coupling	$\lambda^4\phi^4 + \xi\phi^2 R/2$	$-4 < \log_{10}\xi < 4$	3.1	−1.6
Natural inflation	$\Lambda^4\left[1 + \cos(\phi/f)\right]$	$0.3 < \log_{10}(f/M_{\rm Pl}) < 2.5$	9.4	−4.2
Hilltop quadratic model	$\Lambda^4\left(1 - \phi^2/\mu_2^2 + \ldots\right)$	$0.3 < \log_{10}(\mu_2/M_{\rm Pl}) < 4.85$	1.7	−2.0
Hilltop quartic model	$\Lambda^4\left(1 - \phi^4/\mu_4^4 + \ldots\right)$	$-2 < \log_{10}(\mu_4/M_{\rm Pl}) < 2$	−0.3	−1.4
D-brane inflation ($p = 2$)	$\Lambda^4\left(1 - \mu_{D2}^2/\phi^p + \ldots\right)$	$-6 < \log_{10}(\mu_{D2}/M_{\rm Pl}) < 0.3$	−2.3	1.6
D-brane inflation ($p = 4$)	$\Lambda^4\left(1 - \mu_{D4}^4/\phi^p + \ldots\right)$	$-6 < \log_{10}(\mu_{D4}/M_{\rm Pl}) < 0.3$	−2.2	0.8
Potential with exponential tails	$\Lambda^4\left[1 - \exp(-q\phi/M_{\rm Pl}) + \ldots\right]$	$-3 < \log_{10} q < 3$	−0.5	−1.0
Spontaneously broken SUSY	$\Lambda^4\left[1 + \alpha_h \log(\phi/M_{\rm Pl}) + \ldots\right]$	$-2.5 < \log_{10}\alpha_h < 1$	9.0	−5.0
E-model ($n = 1$)	$\Lambda^4\left\{1 - \exp\left[-\sqrt{2}\phi\left(\sqrt{3\alpha_1^{\rm E}}M_{\rm Pl}\right)^{-1}\right]\right\}^{2n}$	$-2 < \log_{10}\alpha_1^{\rm E} < 4$	0.2	−1.0
E-model ($n = 2$)	$\Lambda^4\left\{1 - \exp\left[-\sqrt{2}\phi\left(\sqrt{3\alpha_2^{\rm E}}M_{\rm Pl}\right)^{-1}\right]\right\}^{2n}$	$-2 < \log_{10}\alpha_2^{\rm E} < 4$	−0.1	0.7
T-model ($m = 1$)	$\Lambda^4 \tanh^{2m}\left[\phi\left(\sqrt{6\alpha_1^{\rm T}}M_{\rm Pl}\right)^{-1}\right]$	$-2 < \log_{10}\alpha_1^{\rm T} < 4$	−0.1	0.1
T-model ($m = 2$)	$\Lambda^4 \tanh^{2m}\left[\phi\left(\sqrt{6\alpha_2^{\rm T}}M_{\rm Pl}\right)^{-1}\right]$	$-2 < \log_{10}\alpha_2^{\rm T} < 4$	−0.4	0.1

Table 5. Bayesian comparison for a selection of slow-roll inflationary models with $w_{\rm int}$ fixed (see text for more details). We quote 0.3 as the error on the Bayes factor. Models are strongly disfavoured when $\ln B < -5$.



Planck 2018 results. X. Constraints on inflation

Martin, Ringeval, Vennin (2013, 2018)

Post-2018 Planck maps/likelihoods (1)

New maps

- NPIPE-DR4 Fully independent pipeline with LFI and HFI data with different calibration and solar dipole determination. Planck Collaboration A&A 643, A42. Optical depth consistent with PR3.

- Beyond Planck (https://beyondplanck.science) Delivering next-generation processing of Planck LFI 30, 44 and 70 GHz frequency maps.

Low-l (l<30)

- SROLL2 SimAll algorithm but with in input results from improved map making algorithm SROLL2 which reduces the systematic uncertainties in the maps (eg ADC non-linearities &co.). Slightly improved error bars on large scale dependent parameters Delouis et al. 2019 A&A 629, A38 (2019), Pagano et al. (2020) A&A 635, A99 (2020)

- TQU pixel based likelihood using the LFI 70 GHz combined with WMAP Ka and V bands. Larger uncertainties wrt lowL+SimAll but full likelihood not sims based+ TE and l-l correlations Natale et al. 2020 A&A 644, A32 (2020)

Post-2018 Planck maps/likelihoods (2)

High-l (l≥30)

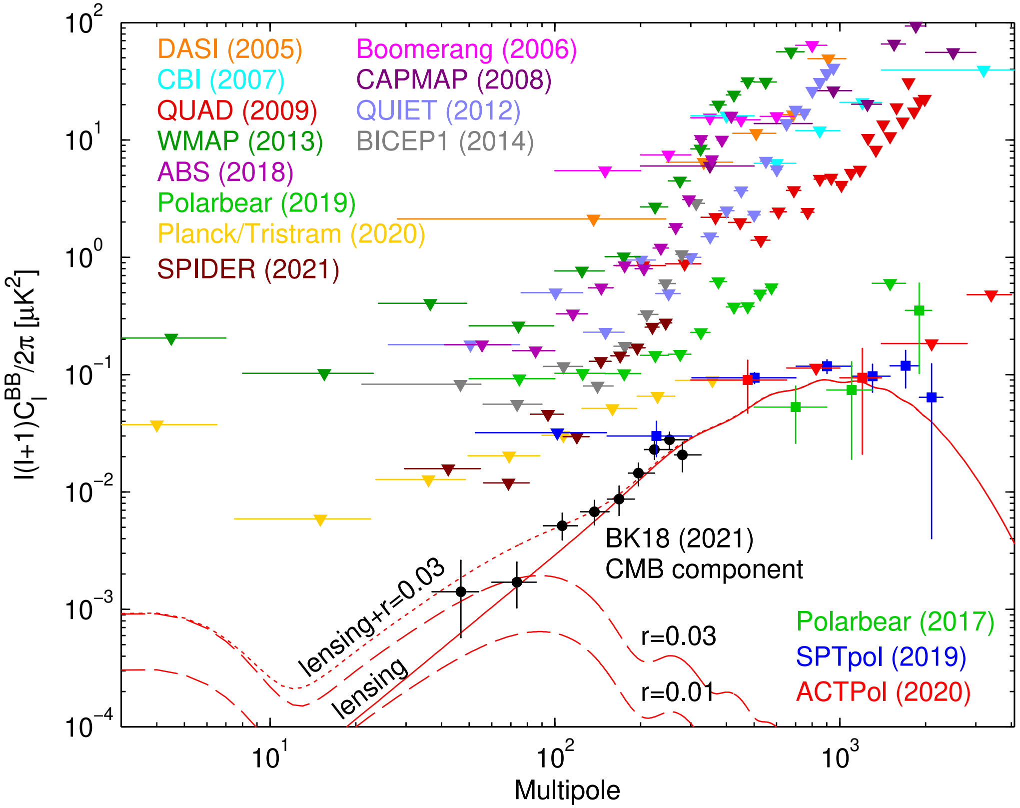
- Alternative high-l likelihood (Camspec) with an optimized mask fsky=0.8, different cleaning approach using direct maps subtraction instead of map based models for foregrounds, different algorithm. Slightly reduced tensions with no evidence beyond statistical fluctuations Efstathiou, Gratton 2019. Also used on NPIPE DR4 maps. Rosenberg, Efstathiou, Gratton 2022.

- Another high-l (HiLLiPoP) and low-l likelihood (LoLLiPoP) has been applied to NPIPE DR4 maps (Tristram et al. 2023) leading to consistent results with Camspec.

Lensing

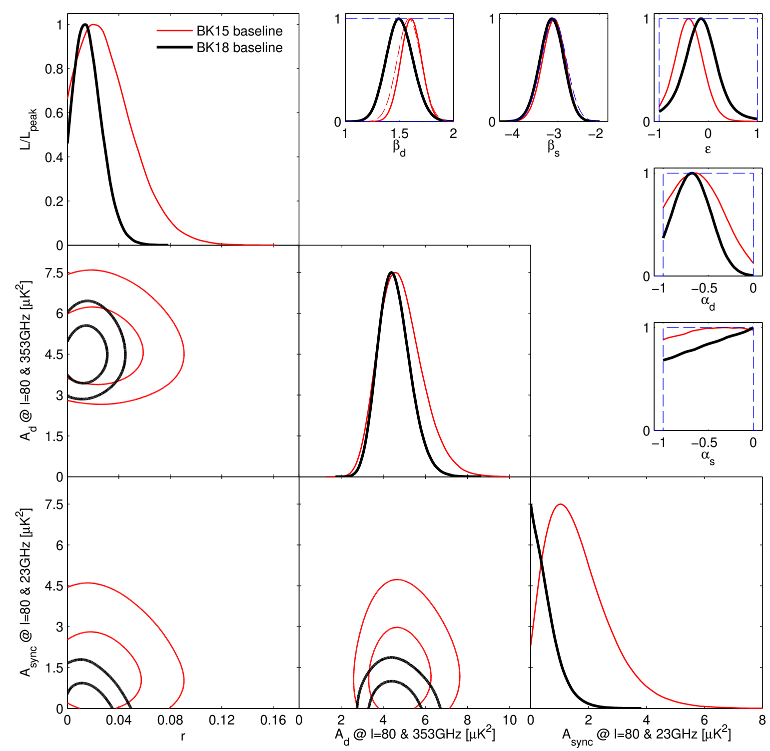
- Planck lensing likelihood from NPIPE DR4 maps (Carron, Mirmelstein, Lewis 2023) improving on 2018 results.

BK18



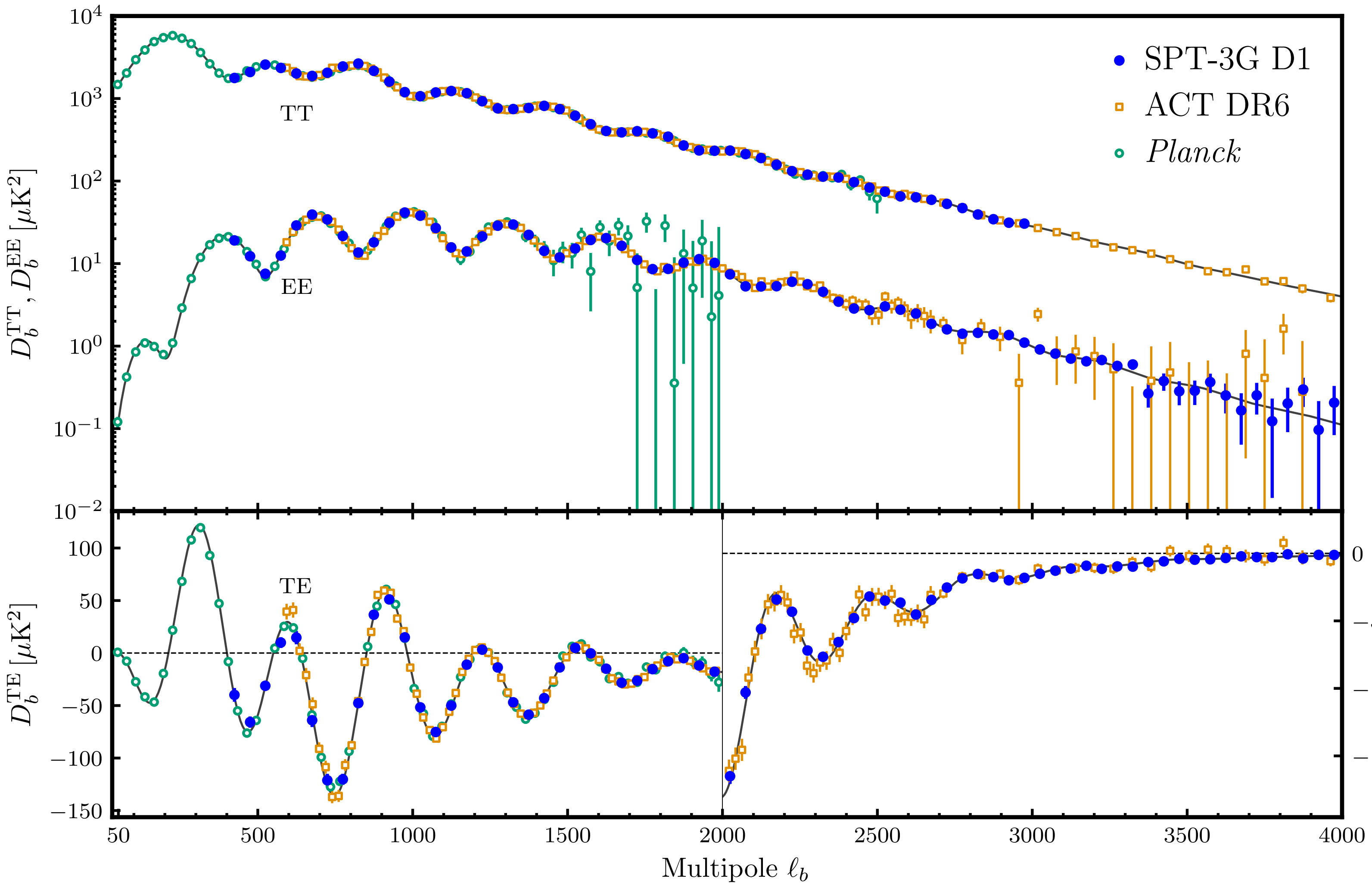
$$\text{BK15}: r_{0.05} < 0.07$$

$$\text{BK18}: r_{0.05} < 0.036 \qquad (95\% \text{ CL})$$



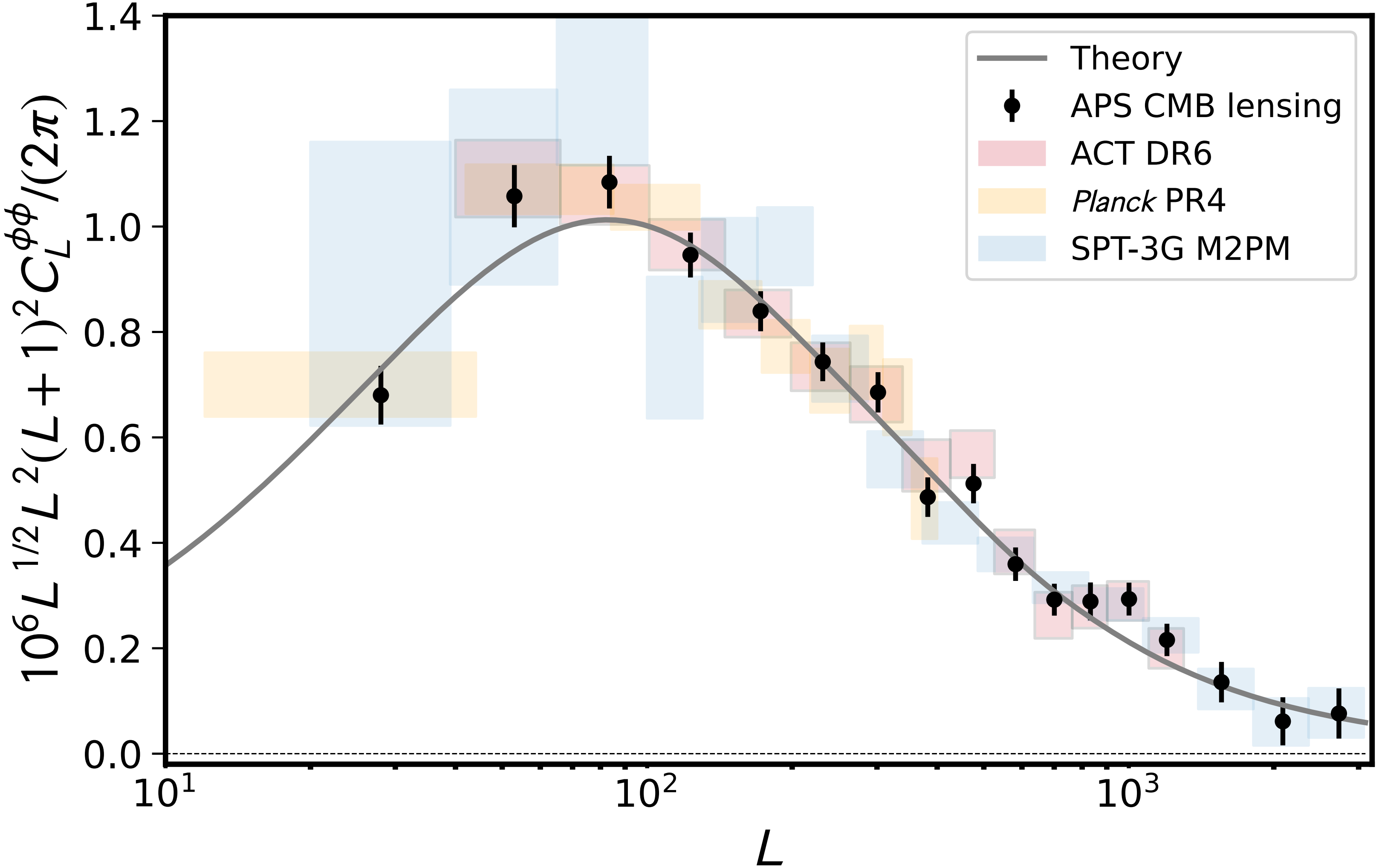
P.A.R. Ade et al.: BICEP and Keck Coll., Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season (2021)

ACT DR 6 - SPT 3G D1



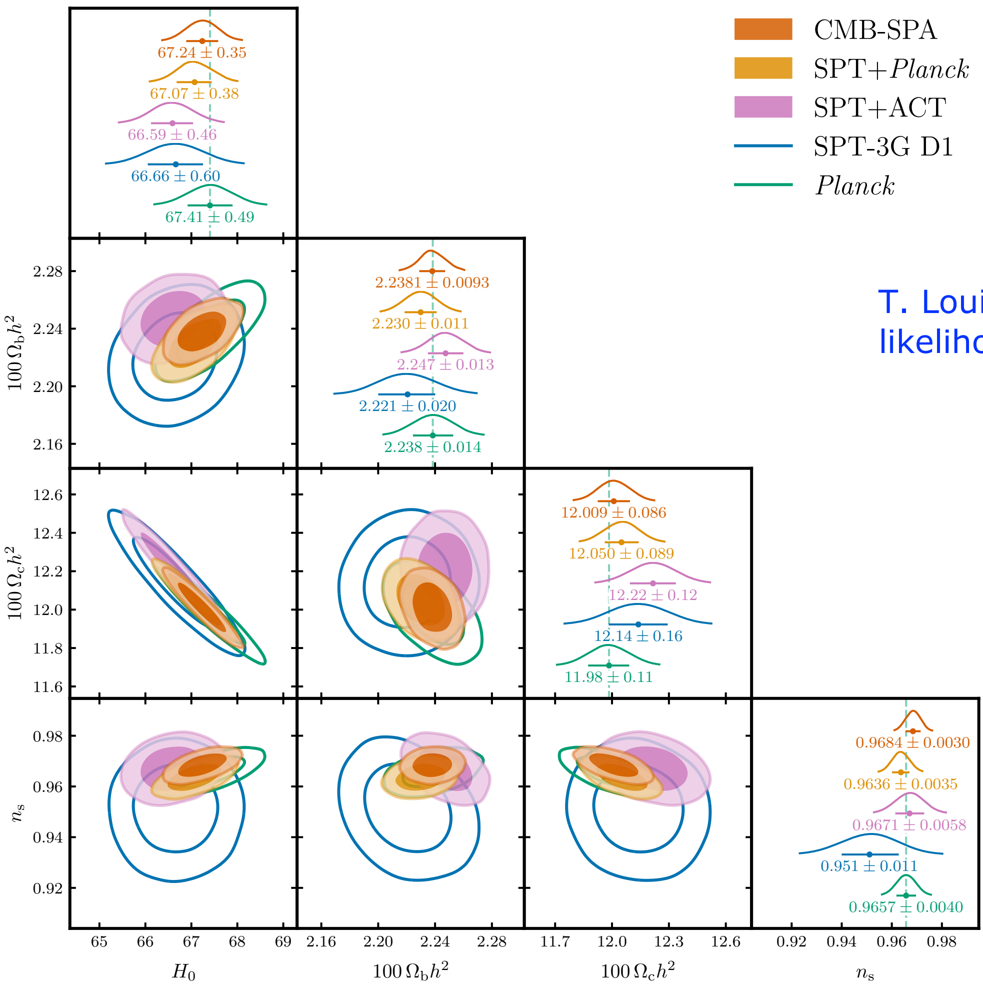
Camphuis et al., SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field (2025)

ACT DR 6 - SPT 3G D1



Qu et al., SPT-3G D1: Unified and consistent structure growth measurement from joint ACT, SPT and Planck CMB lensing (2025)

ACT DR 6 - SPT 3G D1



$$n_s^{\rm ACT} = 0.9666 \pm 0.0077 \quad (68\,\%{\rm CL},\ {\rm ACT\,DR6} + \tau\,{\rm prior\,SROLL2})$$

$$n_s^{\rm P-ACT} = 0.9709 \pm 0.0038 \quad (68\,\%{\rm CL},\ {\rm P-ACT})$$

T. Louis et al., The Atacama Cosmology Telescope: DR6 power spectra, likelihoods and LCDM parameters (2025)

$$n_s^{\rm SPT} = 0.951 \pm 0.011 \quad (68\,\%{\rm CL},\ {\rm SPT-3G\,D1} + \tau\,{\rm prior\,PR4})$$

$$n_s^{\rm SPT-P} = 0.9636 \pm 0.0035 \quad (68\,\%{\rm CL},\ {\rm SPT-3GD1} + Planck)$$

$$n_s = 0.9649 \pm 0.0042 \quad (68\,\%\,{\rm CL}\,,\, Planck\,{\rm DR3})$$

Camphuis et al., SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field (2025)

CMB circa 2025 and initial conditions:

concordance with key predictions of the simplest inflationary models

A nearly flat Universe $\Omega_K = -0.0088 \pm 0.0048 \quad (68\,\%\ \mathrm{CL},\ \mathrm{SPA})$

A tilted power-law spectrum for density perturbations $n_\mathrm{s} = 0.9684 \pm 0.0030 \quad (68\,\%\ \mathrm{CL},\ \mathrm{SPA})$

M. Tristram et al. (2025) $n_\mathrm{s} = 0.9669 \pm 0.0037 \quad (68\,\%\ \mathrm{CL},\ \mathrm{SPA\ reanalysis\ T, E\ only})$

No statistical evidence of running $dn_\mathrm{s}/d\ln k = 0.0060 \pm 0.0055\,(68\,\%\ \mathrm{CL},\ \mathit{Planck}\ +\ \mathrm{ACT\ DR6})$

E. Calabrese et al., ACT DR6 (2025)

Nearly Gaussian perturbations (T , E)

$$f_\mathrm{NL}^\mathrm{local} = -0.1 \pm 5.0$$

$$f_\mathrm{NL}^\mathrm{equil} = 6 \pm 46 \qquad (68\,\%\mathrm{CL},\ \mathrm{PR4})$$

$$f_\mathrm{NL}^\mathrm{ortho} = -8 \pm 21$$

G. Jung et al. (2025)

No need for additional fields: nearly adiabatic fluctuations

E. Calabrese et al., ACT DR6 (2025)

Similar results to *Planck* from *Planck* + ACT DR6

CMB circa 2025 and initial conditions:

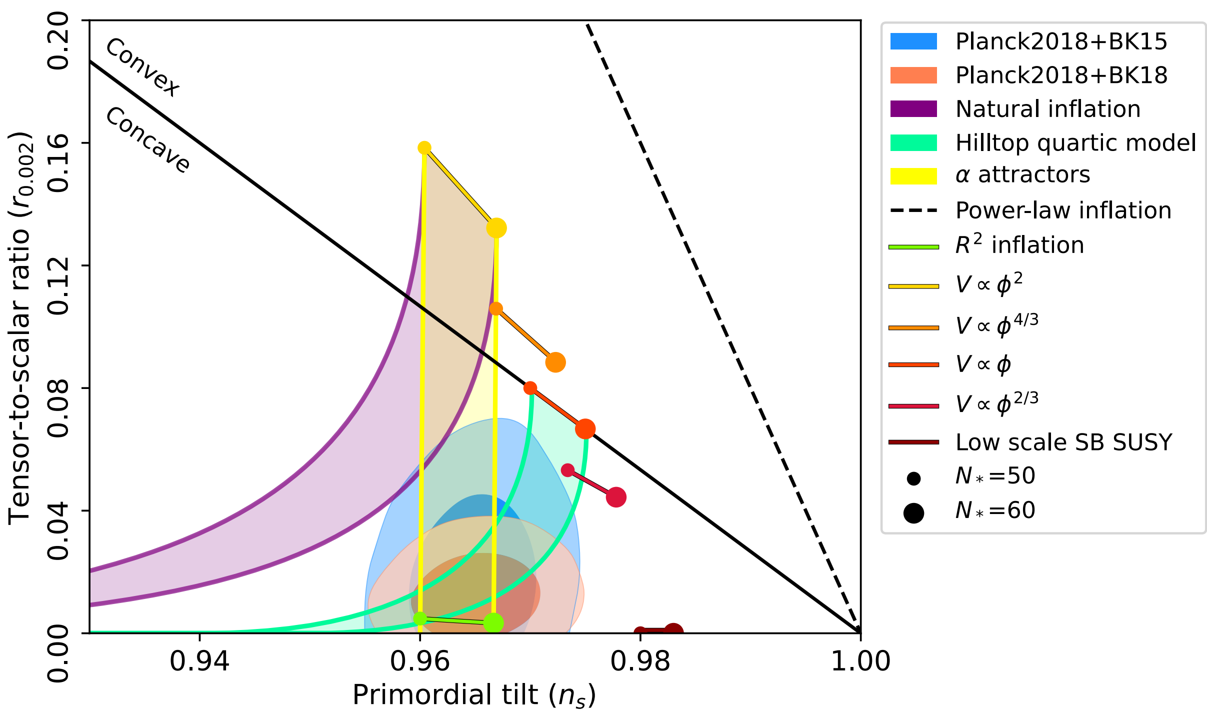
concordance with key predictions of the simplest inflationary models

Small relative amount of gravitational waves ($n_t = -r/8$, +BK18) $r_{0.05} < 0.035$ (95% CL)

BICEP/Keck-Array 18 (2021)

$$\left[\ V_* = \frac{3\pi^2 A_s}{2}\, r\, M_{\rm Pl}^4 < (1.4\times 10^{16}\ {\rm GeV})^4 \quad (95\,\%\ {\rm CL})\ \right]$$

$$\left[\ \frac{H_*}{M_{\rm Pl}} < 2.0\times 10^{-5} \quad (95\%\ {\rm CL})\ \right]$$



Paoletti, Finelli, Valiivita, Hazumi (2022)

See also $r_{0.05} < 0.032$ (95% CL)

Tristram et al (2022)

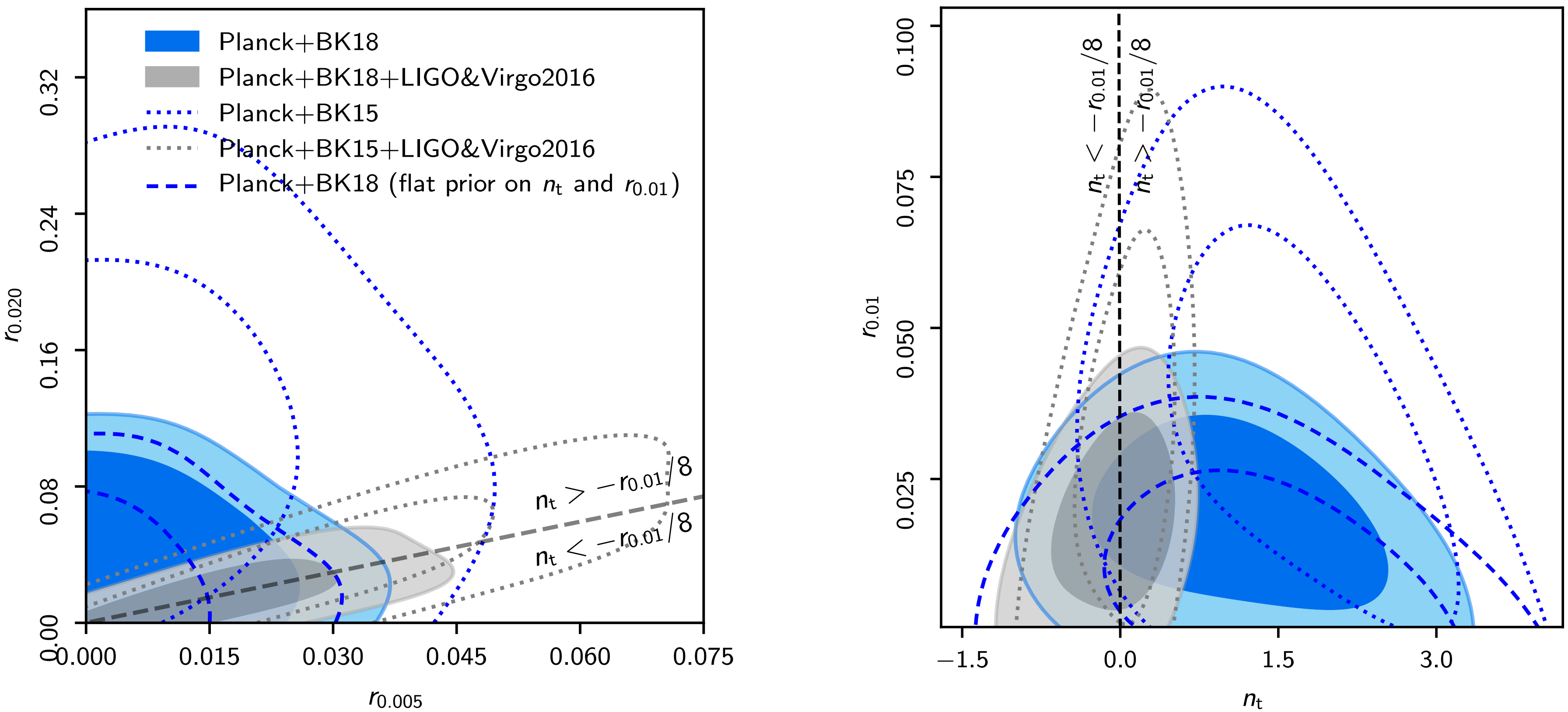
See e.g. Ballardini (2023)

CMB circa 2025 and initial conditions:

concordance with key predictions of the simplest inflationary models

Small relative amount of gravitational waves (n_t not fixed +BK18)

$$\mathcal{P}_{\rm t}(k) = \exp\left\{ \frac{\ln k - \ln k_1}{\ln k_2 - \ln k_1} \ln\left[r_2 \mathcal{P}_{\mathcal{R}}(k_2)\right] - \frac{\ln k - \ln k_2}{\ln k_2 - \ln k_1} \ln\left[r_1 \mathcal{P}_{\mathcal{R}}(k_1)\right] \right\} \qquad (r_1\,, r_2) \to (r_{0.01}, n_{\rm t})$$



Paoletti, Finelli, Valiivita, Hazumi (2022)

CMB circa 2025 and initial conditions:

"… (All) And then a step to the right" (The Time Warp)

ACT DR 6 favors a scalar spectral index larger than Planck

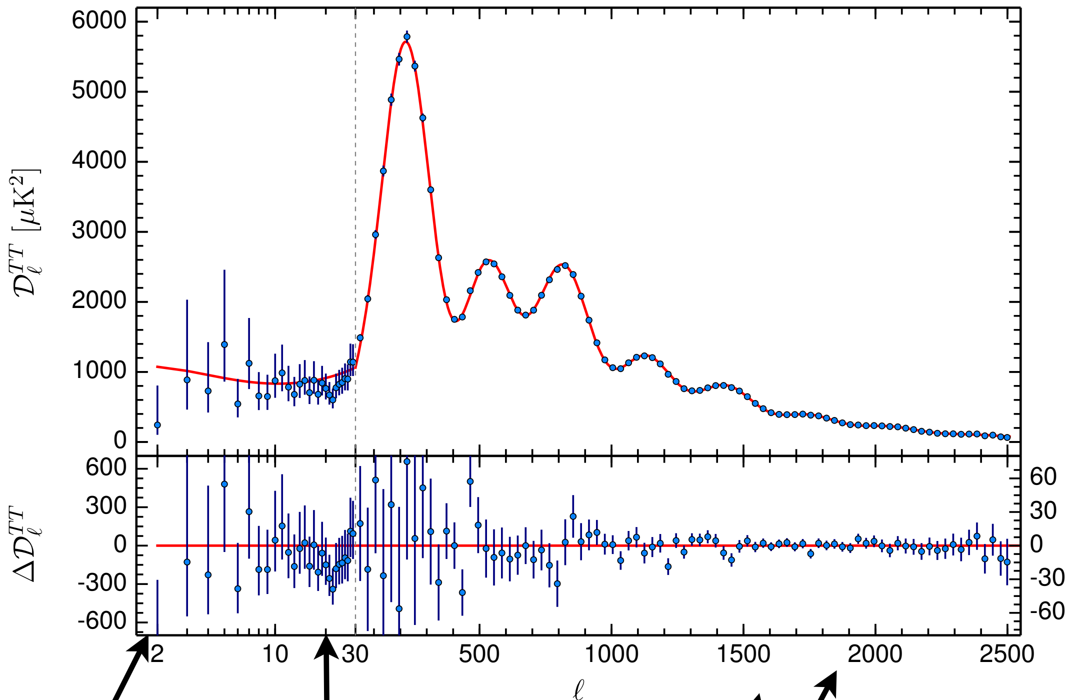
The combination with BAO data has turned now into a tension with DESI for LCDM (3.1 sigma with Planck DR3). A manifestation of this tension in ns with updated CMB is

$$n_{\rm s} = 0.9739 \pm 0.0034 \quad (68\,\%\ \mathrm{CL},\ \mathrm{P-ACT-LB\,(DESI\,DR1\,BAO)})$$

$$n_{\rm s} = 0.9728 \pm 0.0027 \quad (68\,\%\ \mathrm{CL},\ \mathrm{SPA\ +\ DESI\,DR2\,BAO})$$

See L. Balkenhol's talk

Is there evidence for features in the PPS?



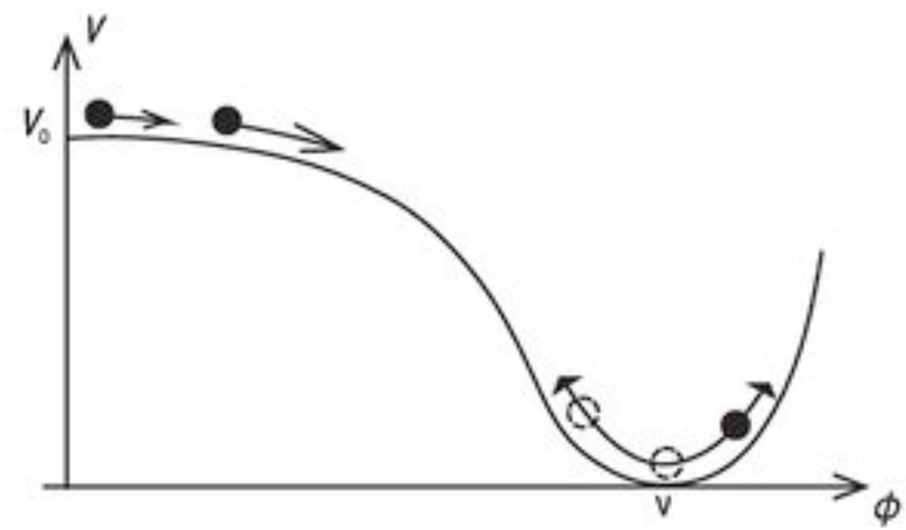
Lowest multipoles

Feature at

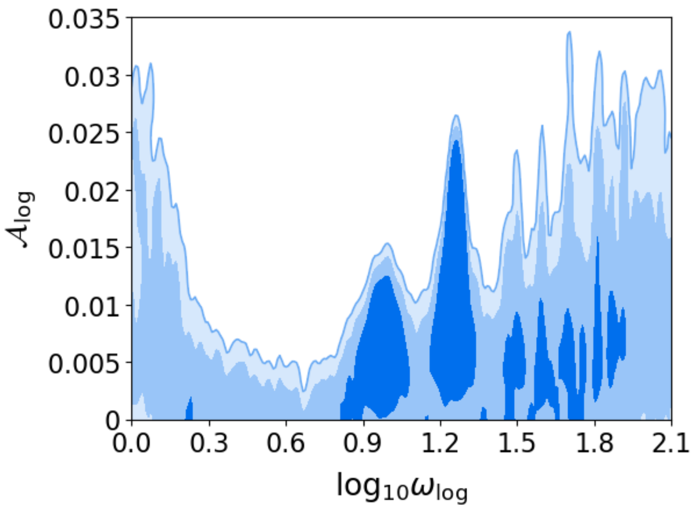
$\ell \sim 20$

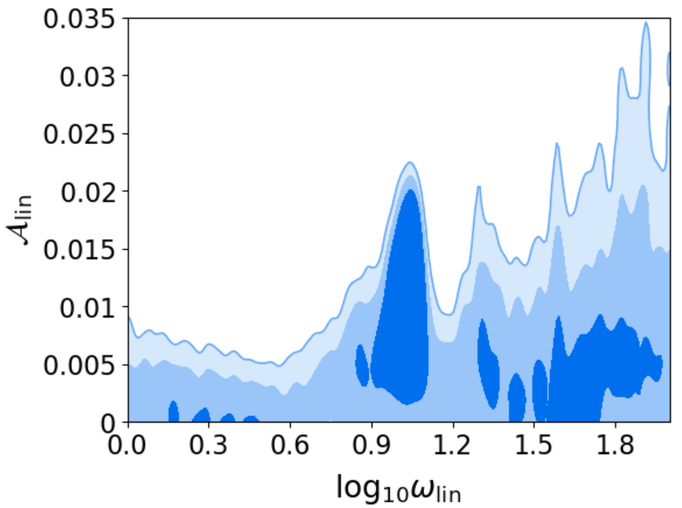
Intermediate and high multipoles

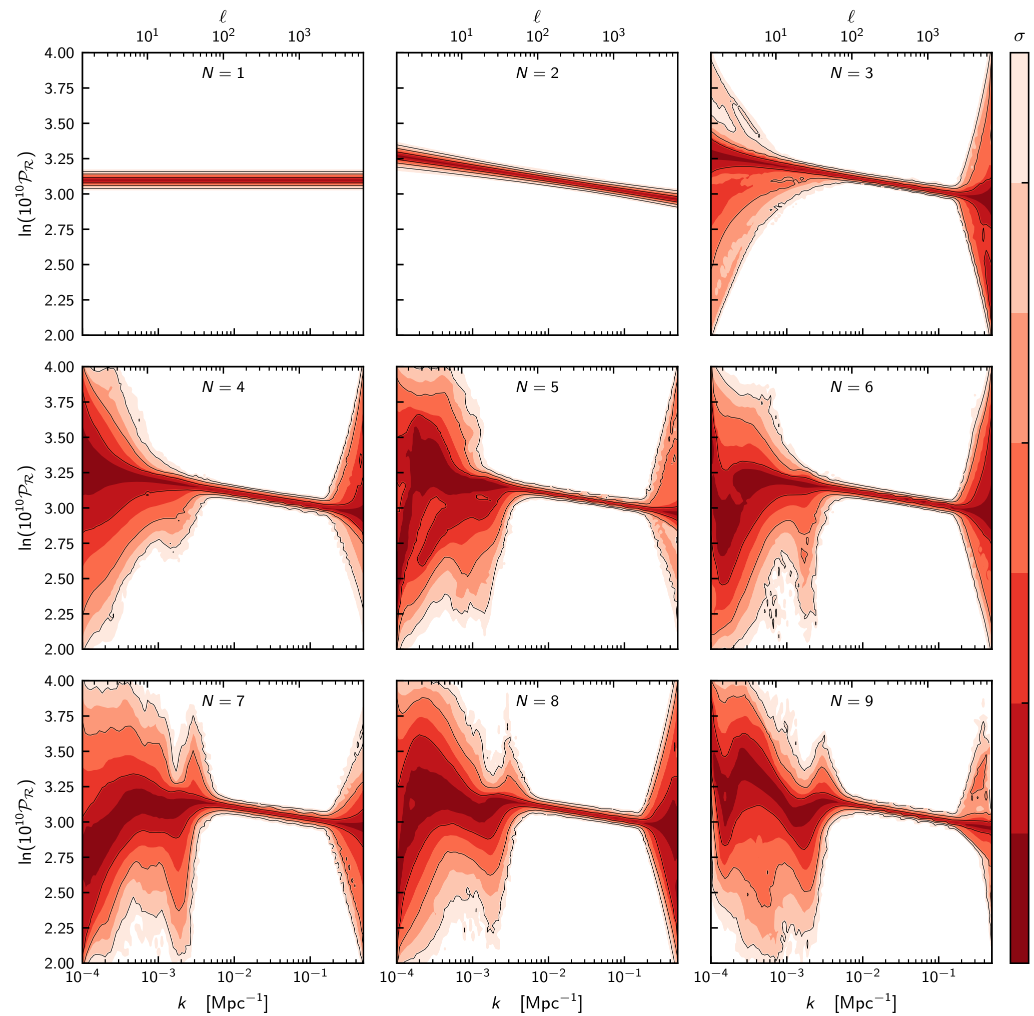
Slow roll?



Is there evidence for features in the PPS?



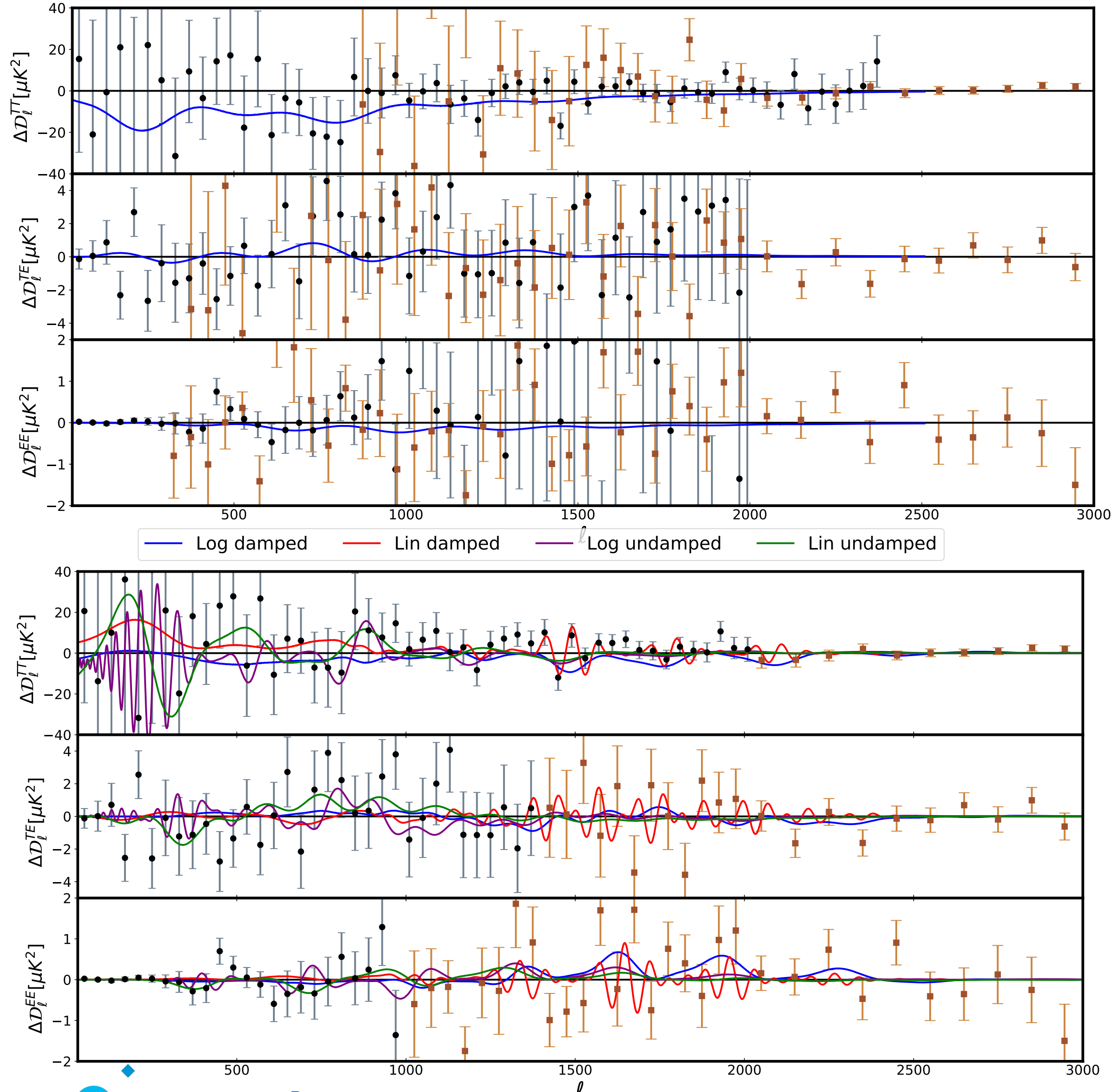




Planck 2018 results. X. Constraints on inflation

See A. Raffaelli's talk

Planck + SPT 3G



Planck

SPT-3G

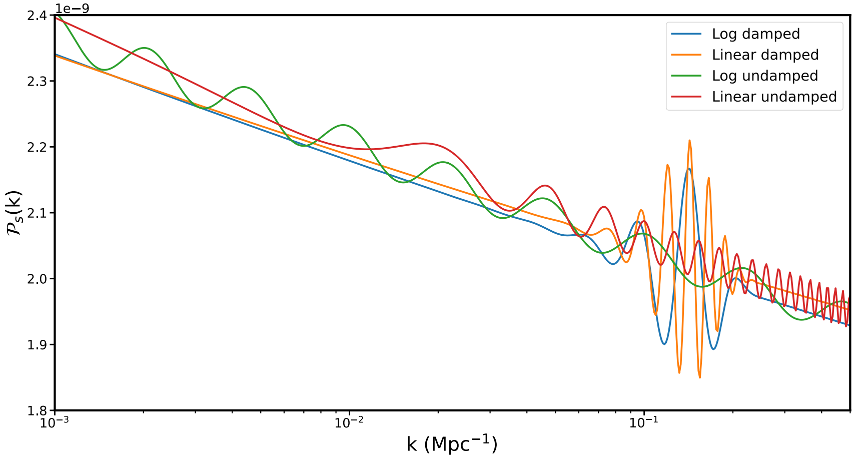
1 - Best-fit$_{SPT}$ / Best-fit$_{Planck}$

Antony, Finelli, Hazra, Paoletti, Shafieloo,

A search for super-imposed oscillations to the PPS in Planck and SPT-3G data (2024)

A search for primordial features in Planck and SPT-3G data

Models	$\Delta\chi^2_{\rm P18}$	$\ln B_{\rm P18}$	$\Delta\chi^2_{\rm SPT}$	$\ln B_{\rm SPT}$	$\Delta\chi^2_{\rm P18+SPT}$	$\ln B_{\rm P18+SPT}$
Lin undamped	-11.8	-2.6 ± 0.3	-7.0	-1.8 ± 0.3	-12.0	-4.5 ± 0.4
Log undamped	-9.3	-2.9 ± 0.3	-12.0	-1.2 ± 0.3	-14.3	-6.0 ± 0.4
Lin damped	-11.8	-2.0 ± 0.3	-7.7	0.0 ± 0.3	-14.7	-1.8 ± 0.3
Log damped	-10.0	-1.8 ± 0.3	-12.0	-0.4 ± 0.3	-17.5	-3.1 ± 0.4



Planck + SPT-3G $\alpha^{\rm lin}_{\rm P18+SPT} \lesssim 0.031$

Planck $\alpha^{\rm lin}_{\rm P18} \lesssim 0.036$

Planck + SPT-3G $\alpha^{\rm log}_{\rm P18+SPT} \lesssim 0.023$

Planck $\alpha^{\rm log}_{\rm P18} \lesssim 0.031$

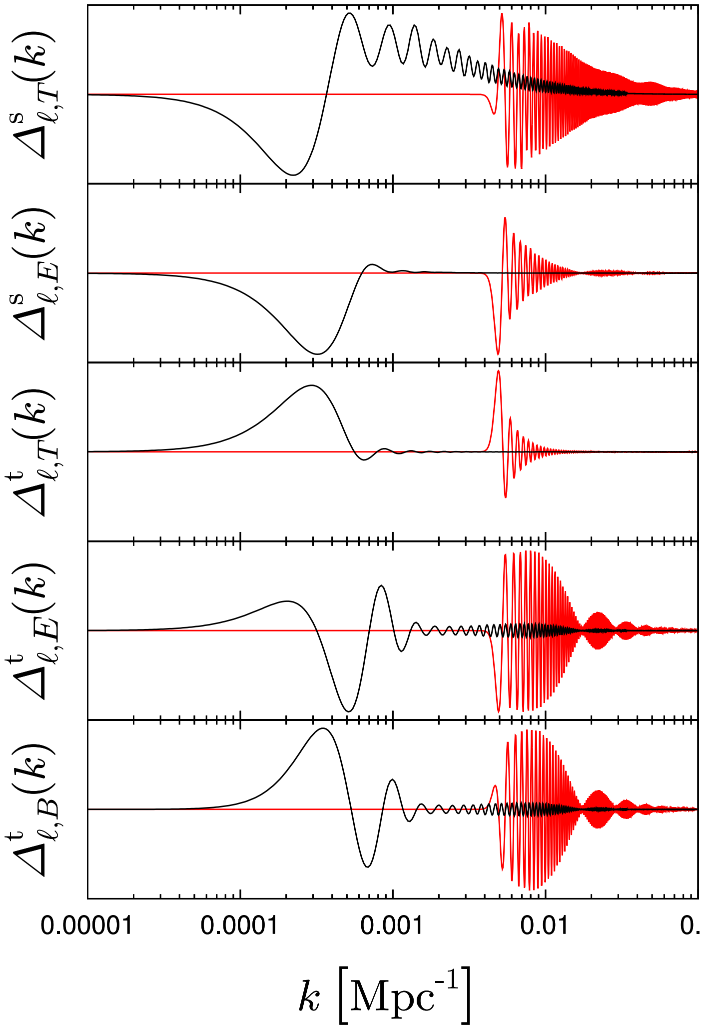
95%CL

See similar analysis by Peng et al. (2025) on Planck+ACT DR6+SPT-3G DR1

Antony, Finelli, Hazra, Paoletti, Shafieloo,

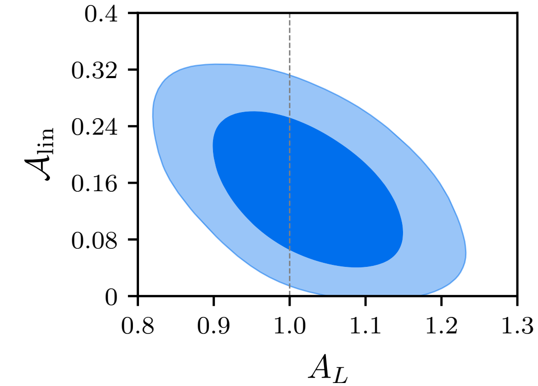
A search for super-imposed oscillations to the PPS in Planck and SPT-3G data (2024)

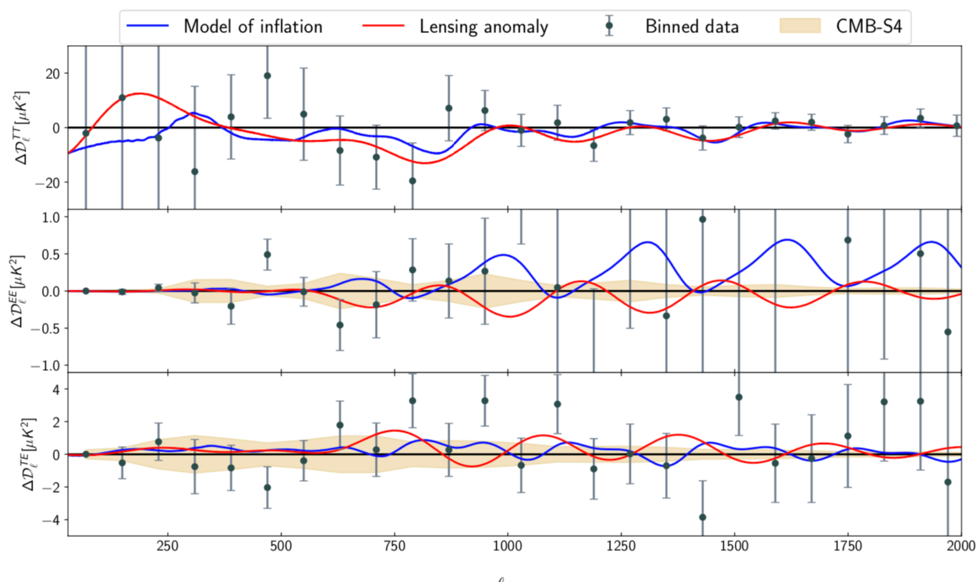
CMB polarisation and features



Planck 2018 results. X. Constraints on inflation

The sharpness of the CMB polarization transfer function can be powerful to test the primordial origin of these features - see also Chluba, Hamann, Patil (2015) for a review.

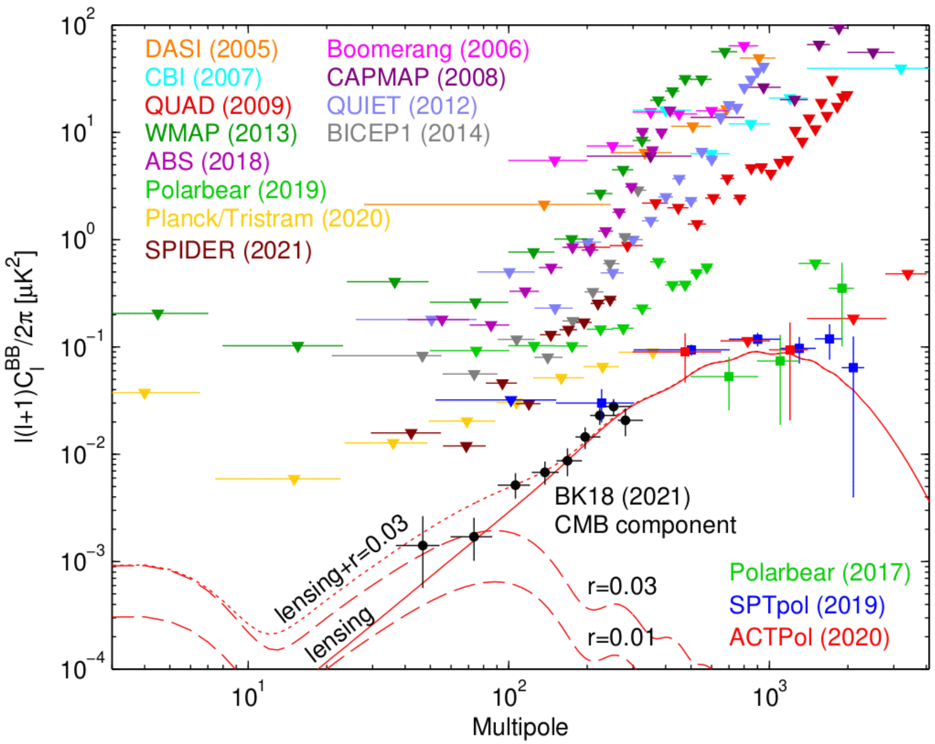




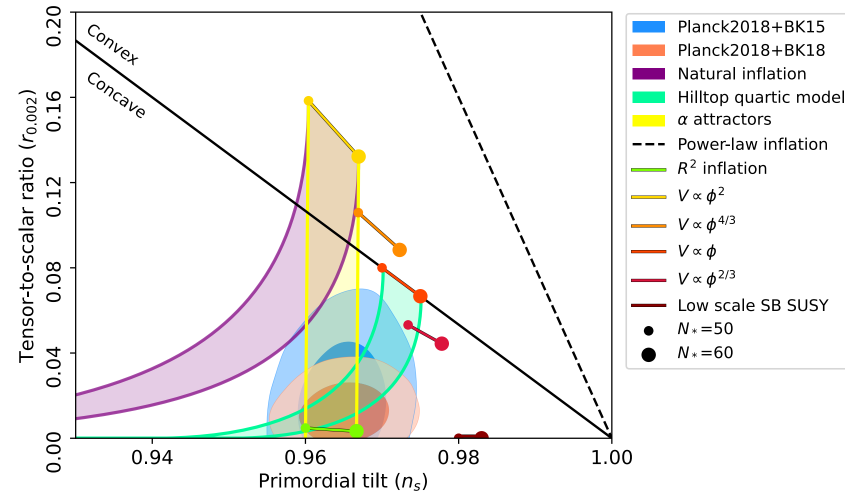
$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R},0}(k)\left[1 + \mathcal{A}_{\rm lin} e^{-\frac{(k-\mu_{\rm env})^2}{2\sigma_{\rm env}^2}} \cos\left(\omega_{\rm lin}\frac{k}{k_*} + \phi_{\rm lin}\right)\right]$$

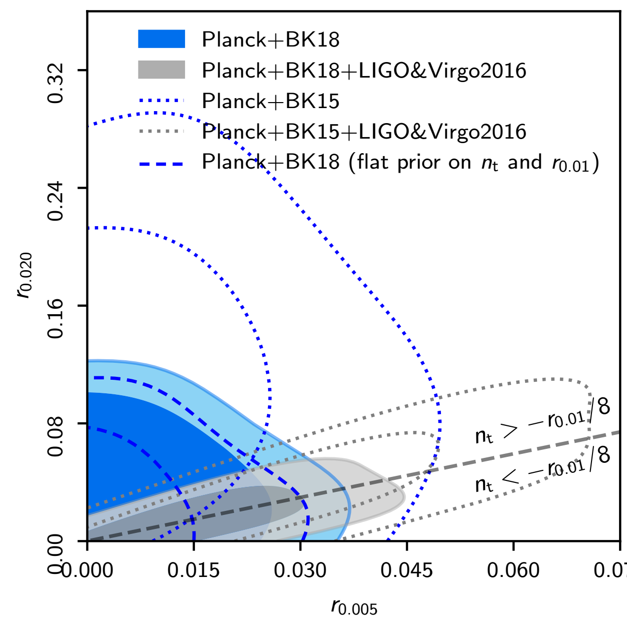
Antony, FF, Hazra, Shafieloo (2022)

B - modes



P.A.R. Ade et al., BK18 (2021)



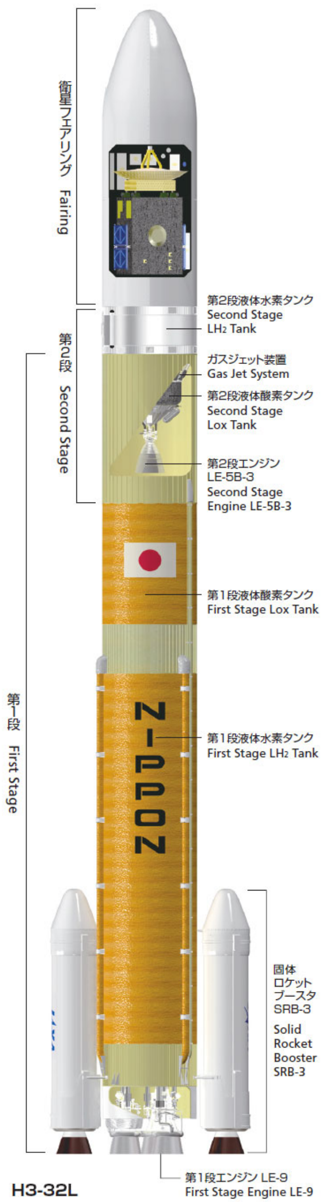


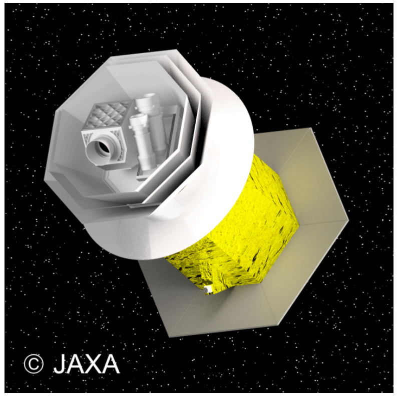
Paoletti, Finelli, Valiivita, Hazumi (2022)

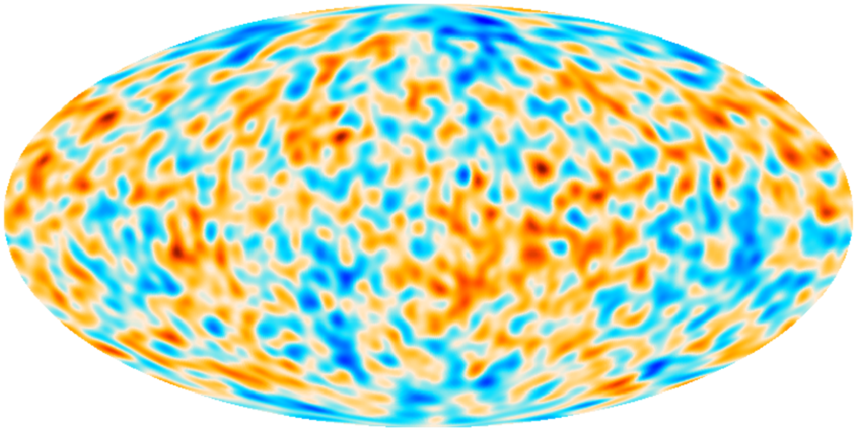
LiteBIRD

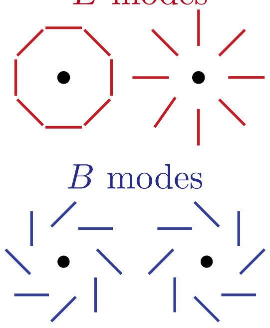
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes** both in the reionization and recombination bump
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023









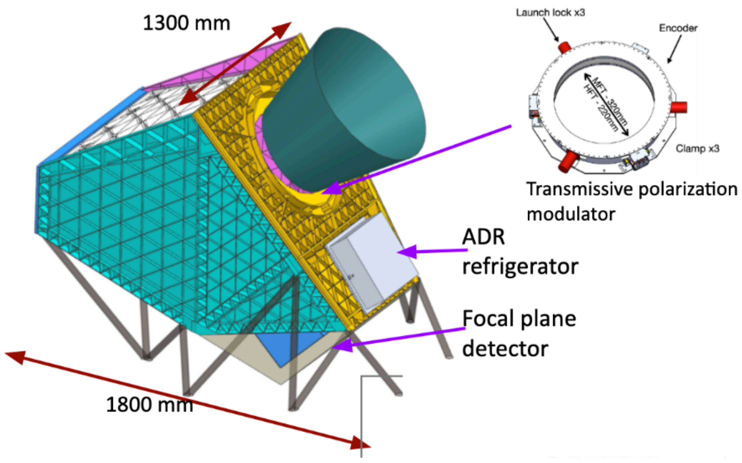
LiteBIRD reformation phase

- *LiteBIRD* has been under **rescope studies to consolidate the mission's feasibility while keeping the same scientific objectives**
  - Revisit the error budget
  - **Simplify the mission configuration** (one single telescope instead of three; try to use existing technologies)
  - **Simplify the cryogenic chain**
  - Detectors to be procured by Europe
  - New HWP design based on stacking 6 plates in Pancharatnam configuration, providing large bandwidth
- JAXA Key Decision Point #2 passed successfully (Sept 2025)
- JAXA Mission Definition Review #2 scheduled for July 2026

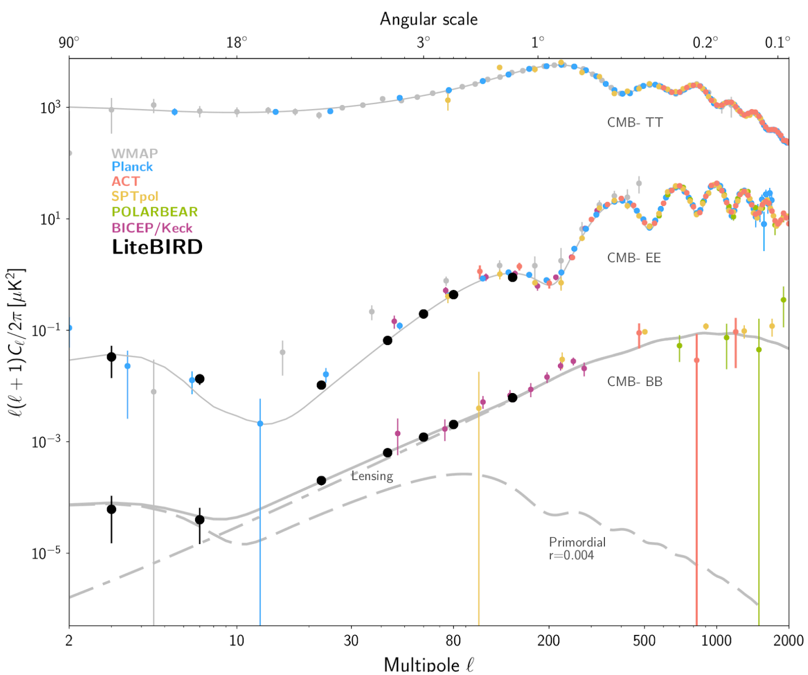
- **Two different configuration options** now being considered, both based on single Crossed-Dragone reflective telescope
- Option 1 (no HWP) requires a faster spin rate to minimize 1/f noise
- Option 2 is based on the possibility of using a wider-band HWP

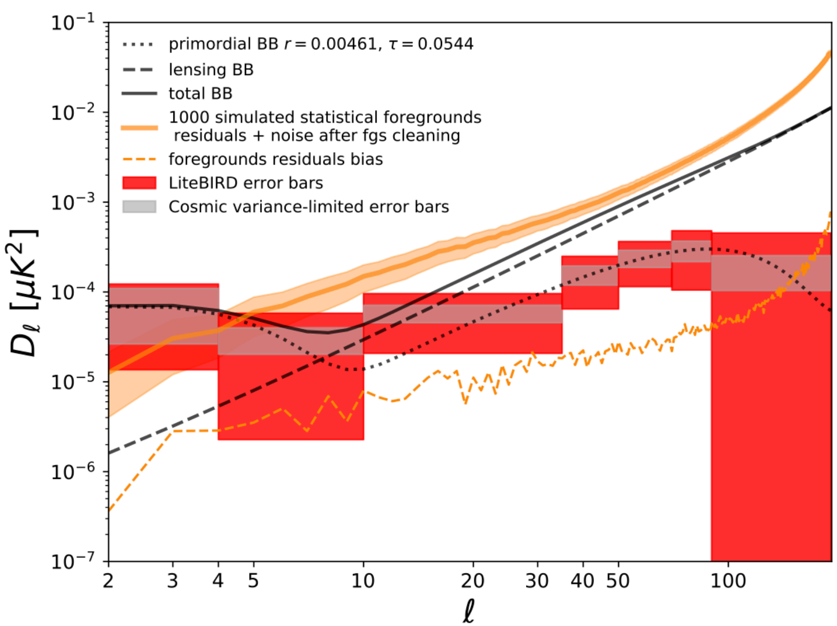
Option 1
- Aperture 500 mm
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

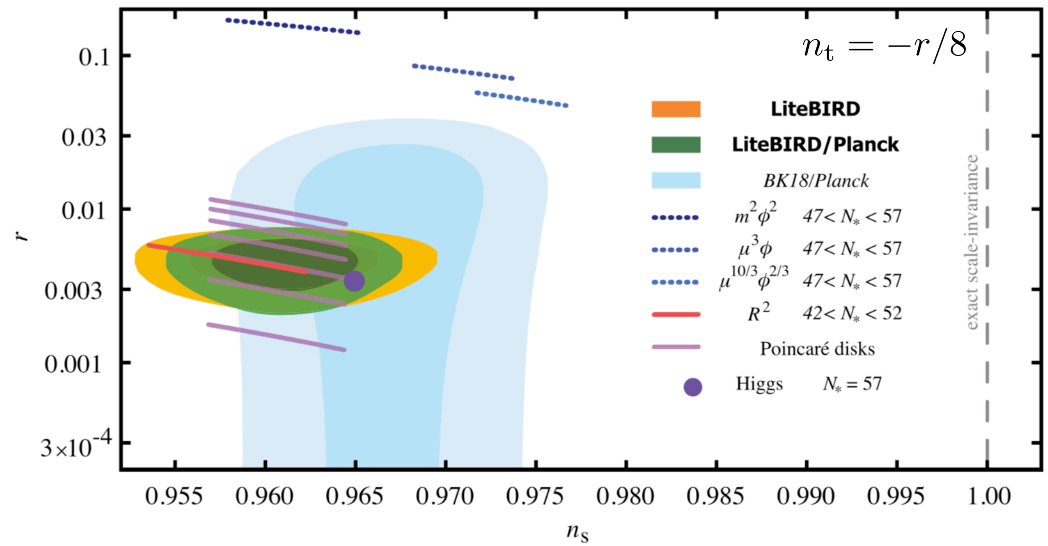
Option 2
- Aperture 500 mm
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm

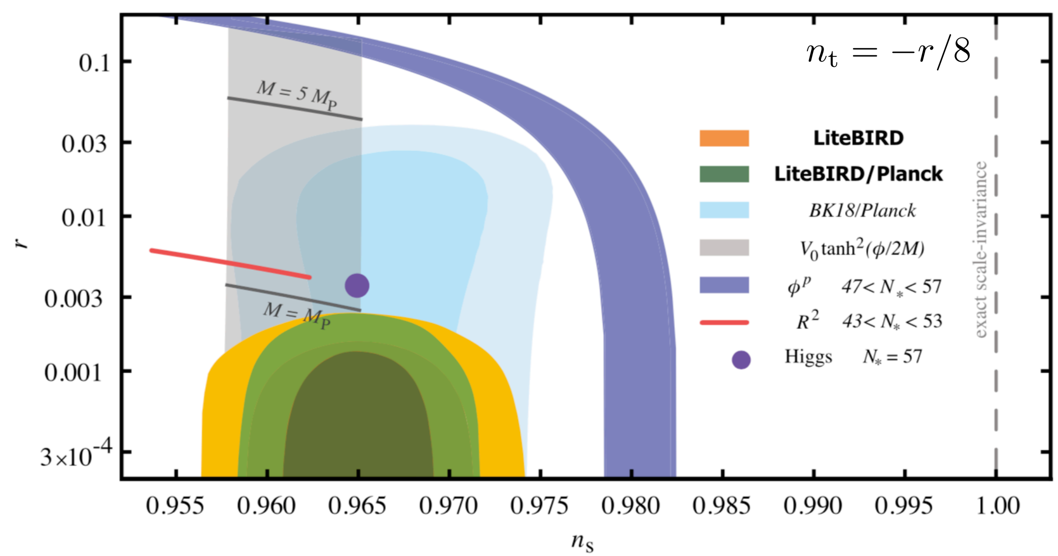


LiteBIRD Tests of Cosmic Inflation





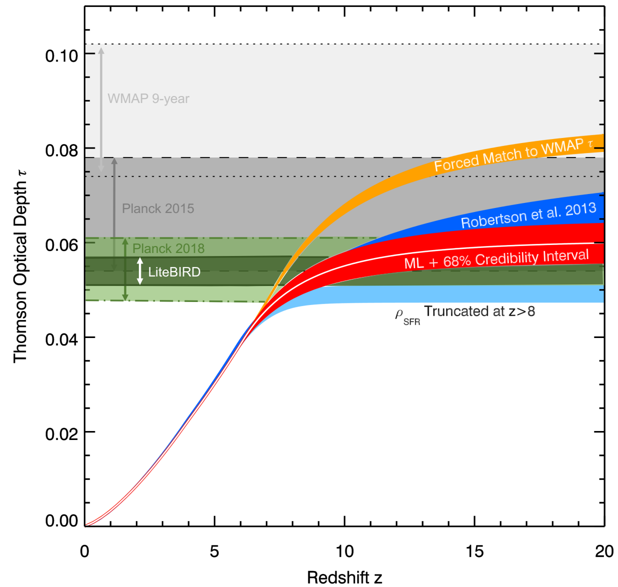




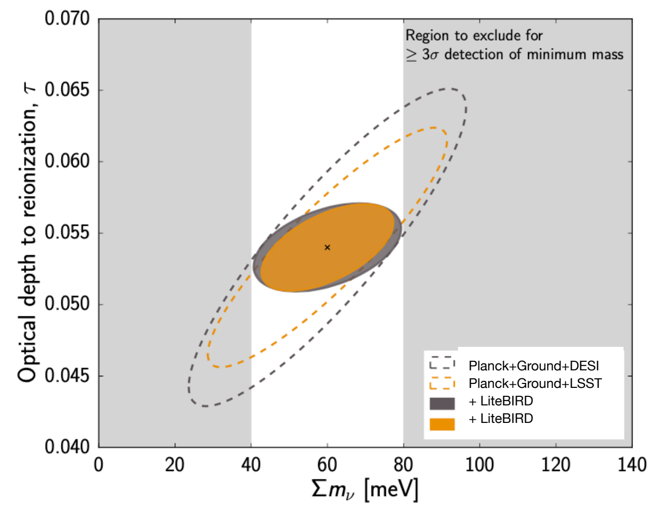
LiteBIRD Coll. Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey, PTEP (2022)

LiteBIRD other science outcomes

- The mission specifications are driven by the required sensitivity on r
- Meeting those sensitivity requirements would allow to address other important scientific topics, such as:
  1. Characterize the B-mode power spectrum and search for source fields (e.g. scale-invariance, non-Gaussianity, parity violation, …)
  2. Power spectrum features in polarization
     - Large-scale ***E*-modes**
     - **Reionization** (improve $\sigma(\tau)$ by a factor of 3)
     - **Neutrino mass** ($\sigma(\sum m_\nu) = 12$ meV) including external data
  3. Constraints on **cosmic birefringence**
  4. **Gravitational lensing**
  5. **SZ effect** (thermal, diffuse, relativistic corrections)
  6. **Anisotropic distortions** of the CMB spectrum
  7. Constraints on **primordial magnetic fields**
  8. Elucidating **anomalies**
  9. Physics of **Galactic emission** mechanisms
  10. Catalogues of polarized **point sources**

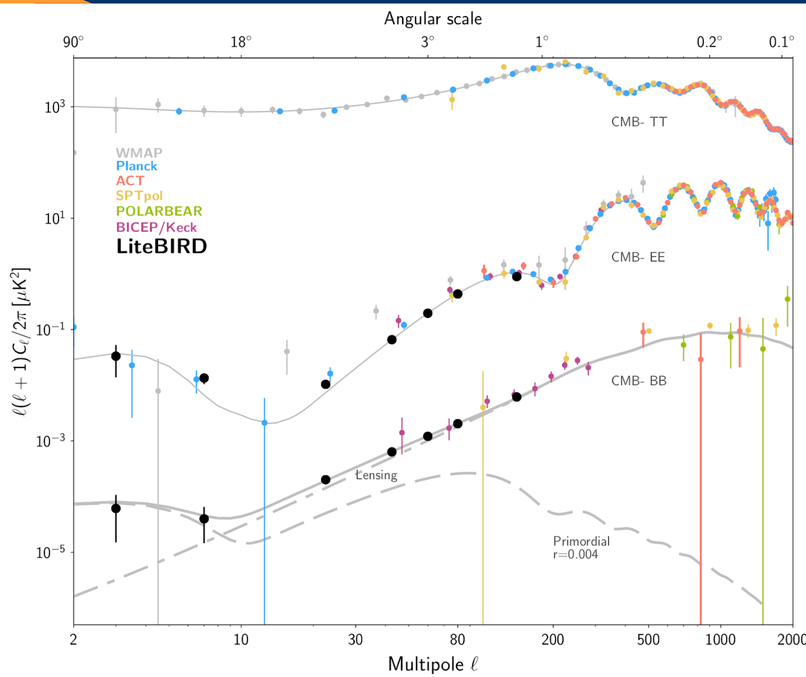


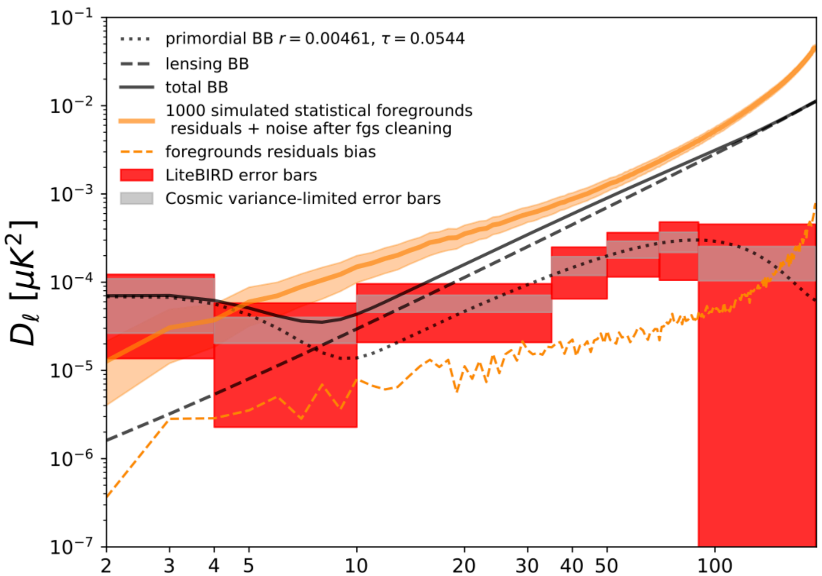
📖 Adapted from Robertson +2015



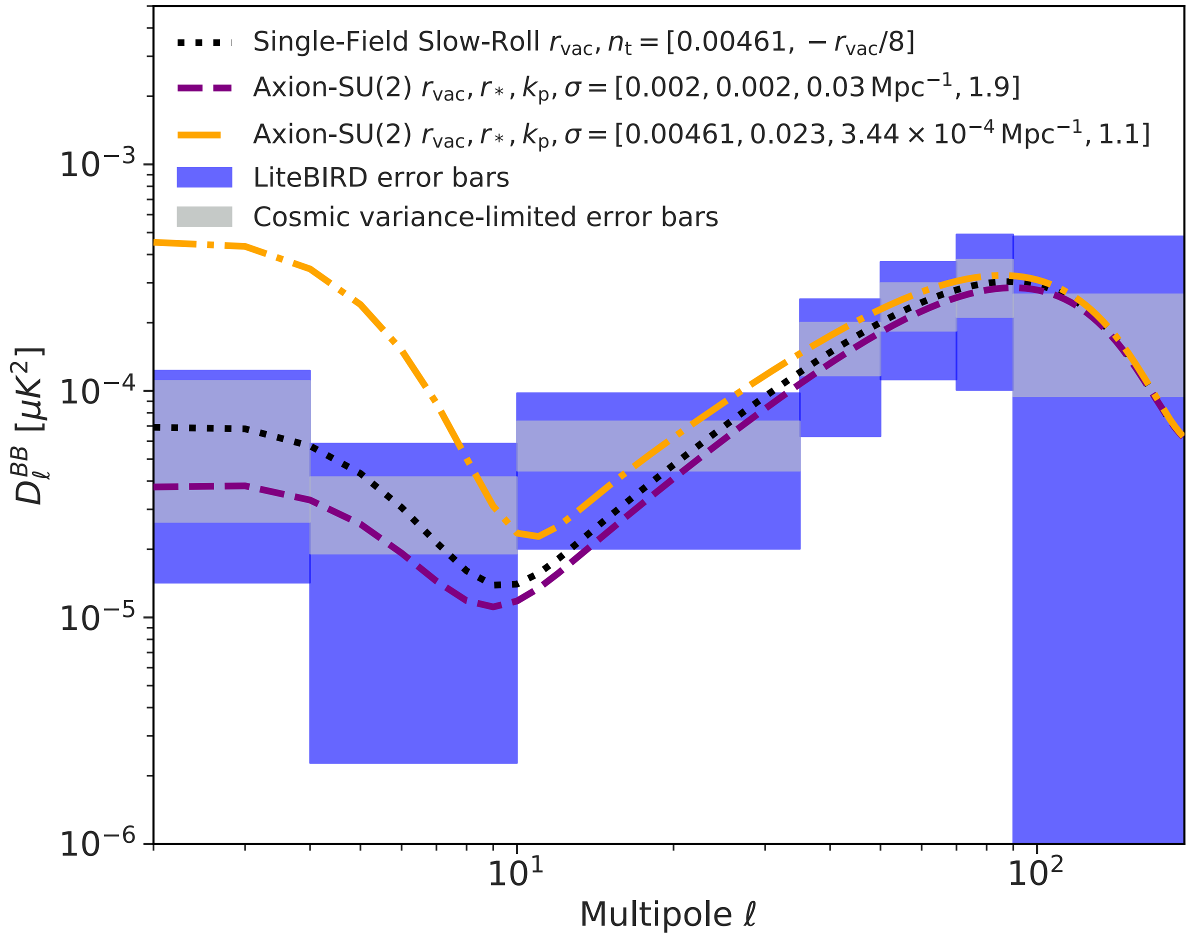
📖 LiteBIRD collaboration PTEP 2023

LiteBIRD Tests of Cosmic Inflation



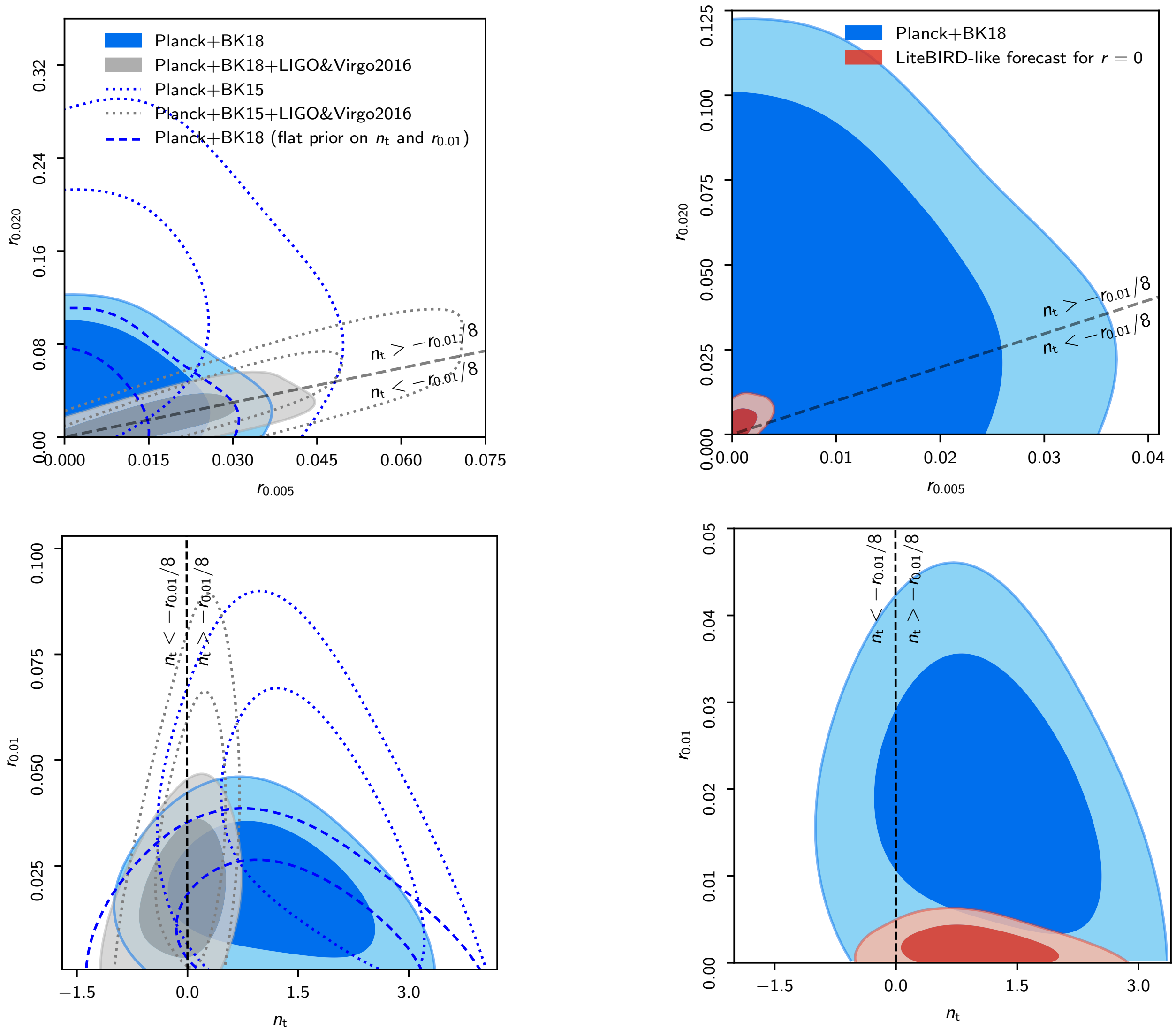


LiteBIRD Coll: Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey (2022)



LiteBIRD Coll: P. Campeti, E. Komatsu et al. LiteBIRD Science Goals and Forecasts. A Case Study of the Origin of Primordial Gravitational Waves using Large-Scale CMB Polarization (2024)

LiteBIRD

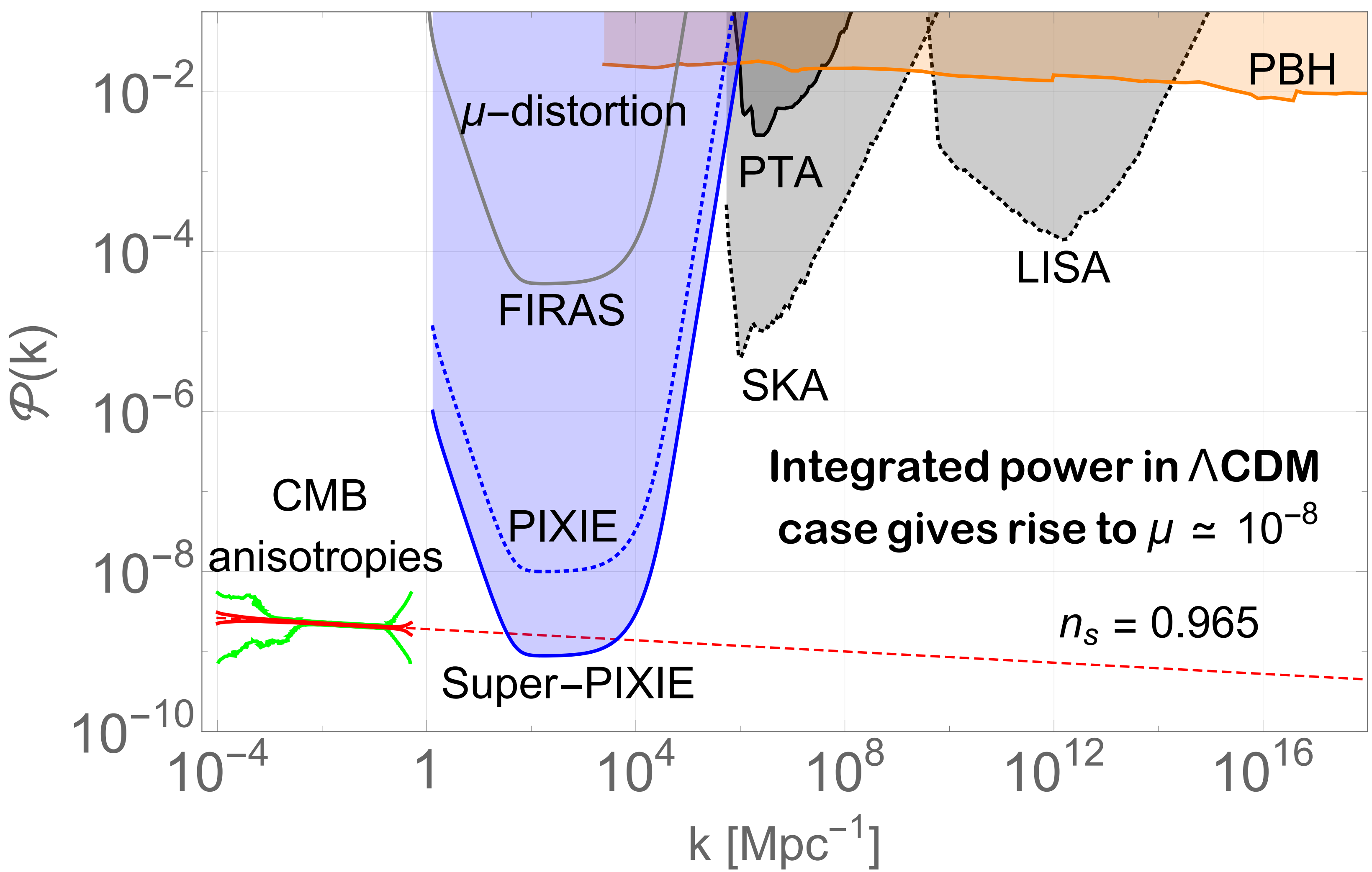


Conservative ‘unofficial’ LiteBIRD-like forecasts

Paoletti, Finelli, Valiivita, Hazumi (2022)

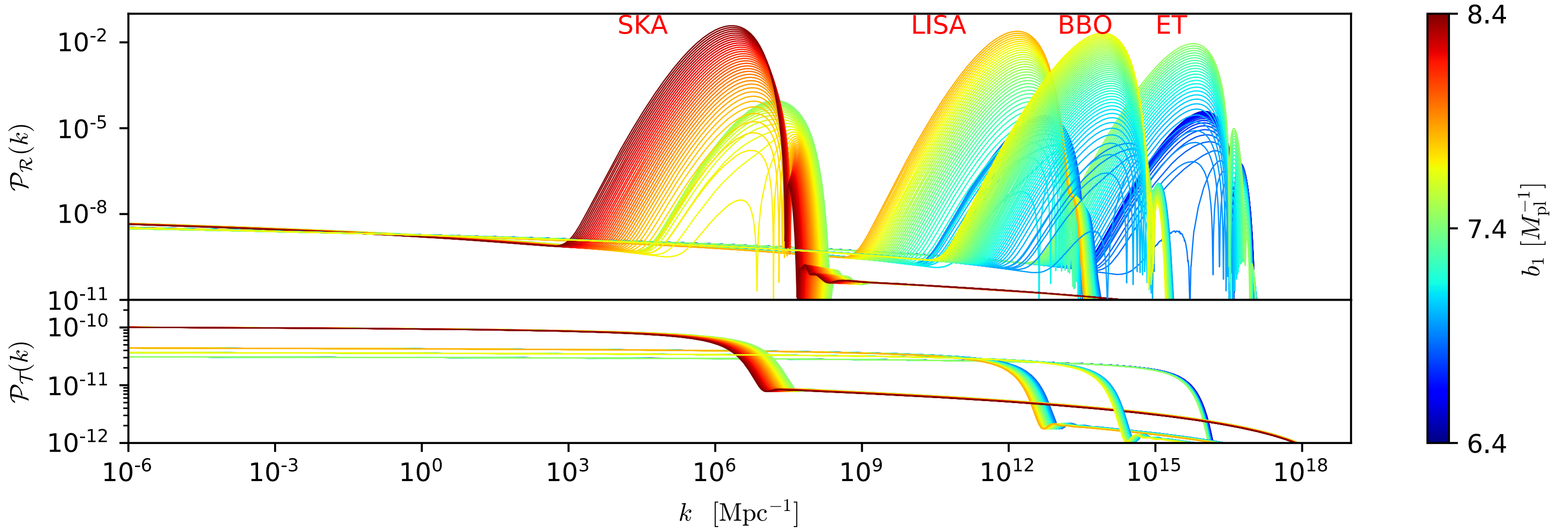
The golden rush to smaller scales

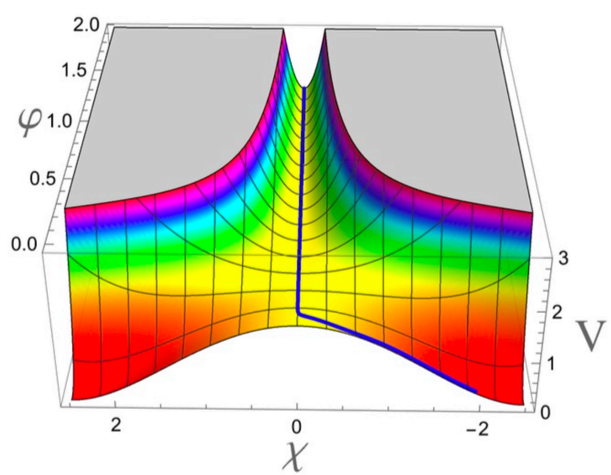
J. Chluba et al. white paper for ESA's Voyage 2050 call (2019)

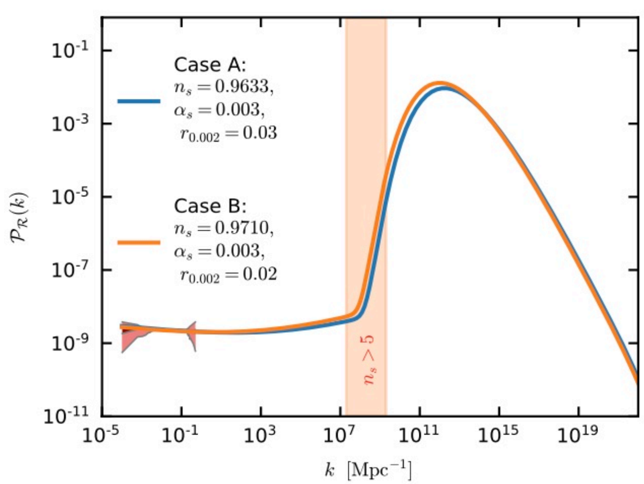


The golden rush to smaller scales

Braglia, Hazra, Finelli, Smoot, Sriramkumar, Starobinsky (2020) (see also Palma et al., Fumagalli et al.)







Braglia, Linde, Kallosh, Finelli (2022)

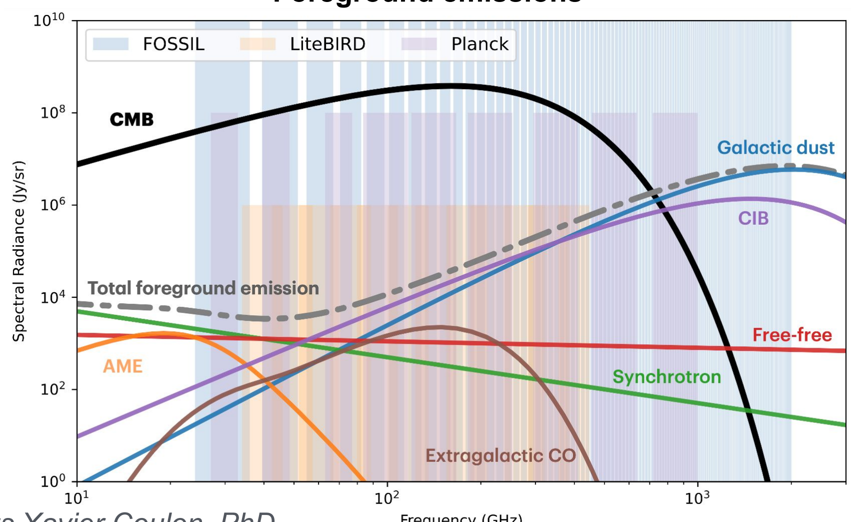
FOSSIL

FTS fOr CMB Spectral diStortIons expLoration

A mission concept for the ESA M8 call, PI: N. Aghanim (IAS)

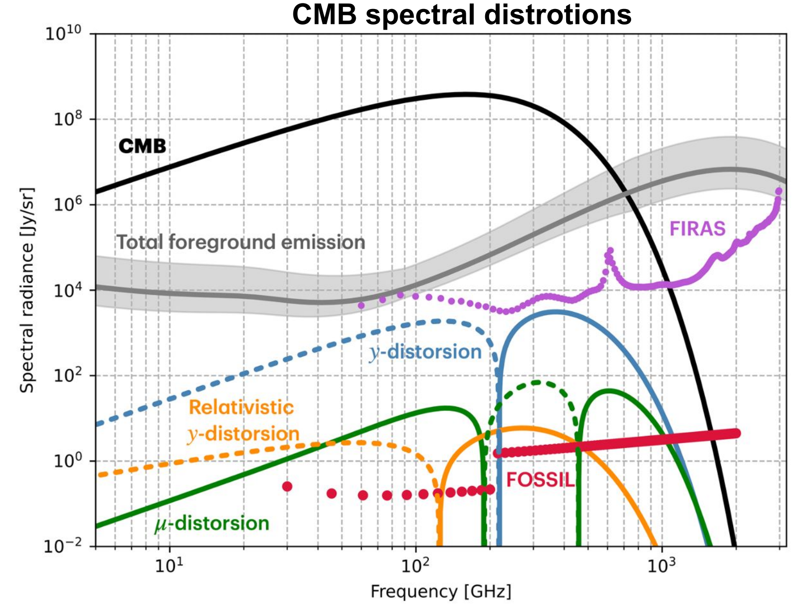
A NEW OBSERVATIONAL WINDOW & THREE TARGETS

Foreground emissions



Credits Xavier Coulon, PhD

CMB spectral distrotions



50 years after FIRAS, a **full-sky absolute spectrometric survey**

- ~130 frequency bands covering 30 GHz - 2 THz → Ideal for the challenge of foreground
- Monopole **y distortion >3 orders magnitude better** than FIRAS → at **hundreds σ**
- Average temperature of hot gas from relativistic SZ down to **kT_{eSZ} ≃ 1.3 keV at tens σ**
- μ distortions **~ a thousand times better** than FIRAS → **μ=2. 10^{-8} at ~4σ**

Courtesy of N. Aghanim

INAF ISTITUTO NAZIONALE DI ASTROFISICA OAS BOLOGNA

INFN BOLOGNA

FOSSIL

FTS fOr CMB Spectral diStortIons expLoration

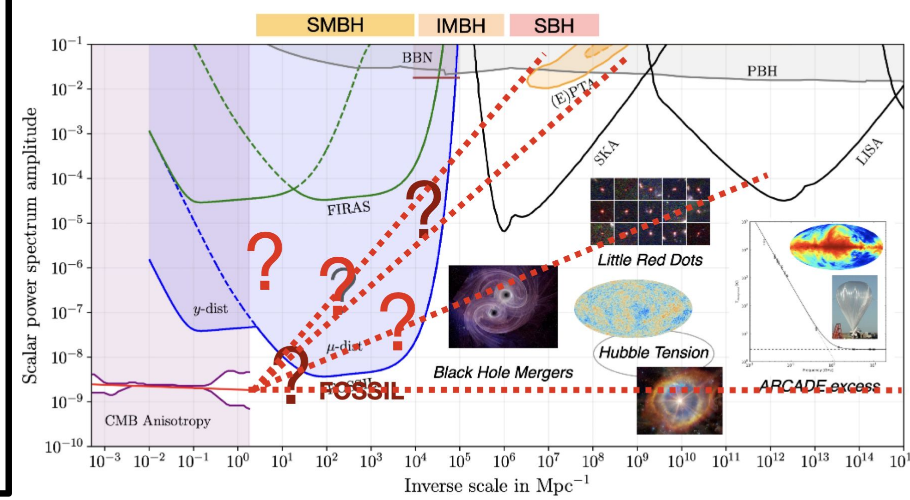
How did the universe begin & What is its content

Primary goal: Probing density perturbations

Dissipation of evolving initial perturbation from standard inflation → Spectral distortions **μ = 2. 10^{-8}**

- **Constrain & test inflation** → Departures from the prediction would out single-field slow-roll inflation
- **Probe primordial perturbations**→ Open a unique window at unexplored scales down to a few tens pc
- **Constrain origin of BHs** → Probe formation of primordial & intermediate-mass BHs

FOSSIL proposal, 2025; Adapted from Cyr+ '24



Primary goal: Probing the dark sector

Dark matter decay, annihilation and scattering with standard model particles → Spectral distortions

- **Constrain the nature of DM** by probing its interaction cross section with baryons & photons
- **Constrain photon to dark-photon conversion** kinetic mixing parameter

Courtesy of N. Aghanim

FOSSIL

FTS fOr CMB Spectral diStortIons expLoration

How did the universe evolve

FOSSIL

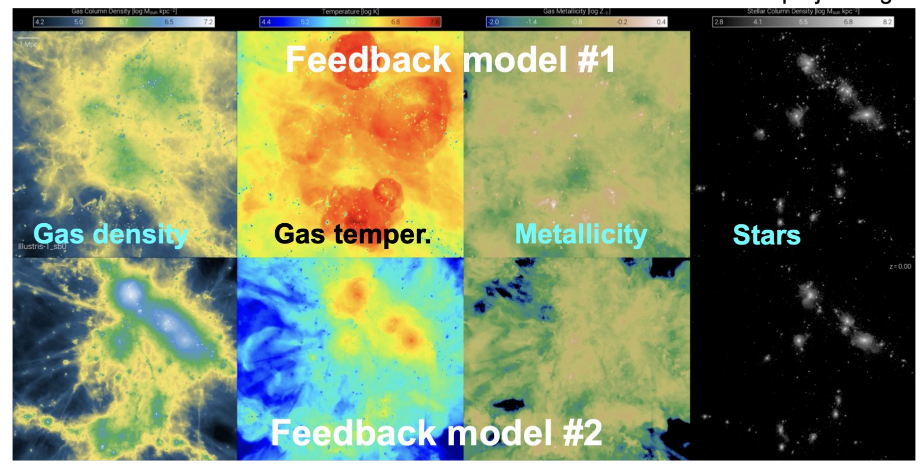
Primary goal: Probing the formation & evolution of the large-scale structure (LSS)

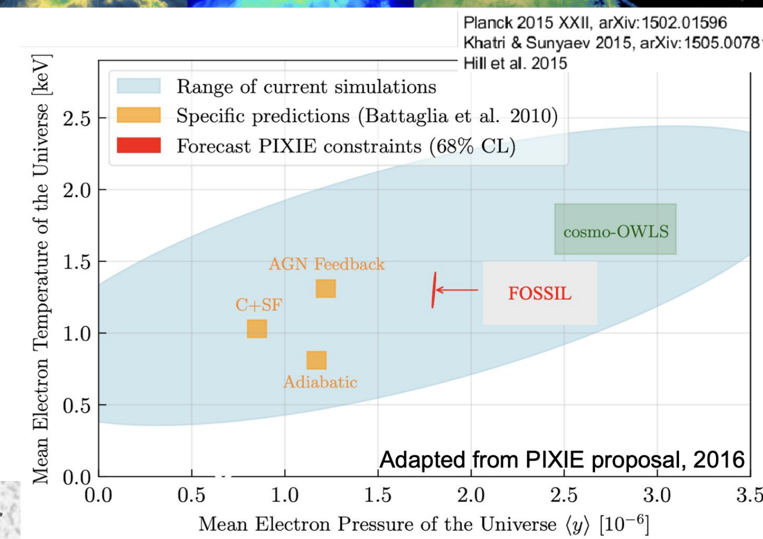
Energy release from collapse of baryons & feedback processes & reionisation → **y distortions** in relativistic & non-relativistic regimes

- Provide a **complete census of the thermal energy** from structure formation & reionisation
- Measure **temperature of hot gas** down to kT_{eSZ} ≃1.3 keV
- Put stringent constraints on total energy injected by **feedback from SuperMassive BHs**

Courtesy of N. Aghanim

Credits. TNG-project.org



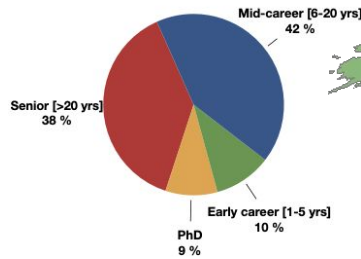


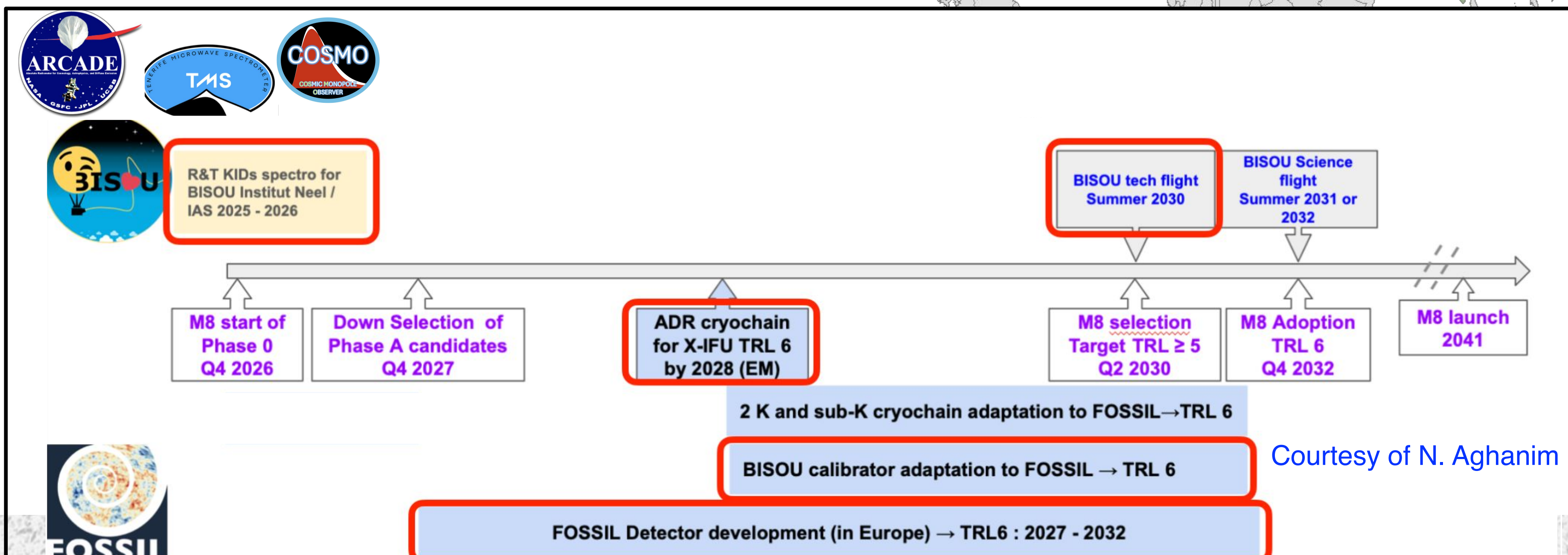
FOSSIL

FTS fOr CMB Spectral diStortIons expLoration

Getting prepared to FOSSIL

- 166 participants from 40 institutes & universities in 17 countries
- In theory, data analysis, instrumentation, demonstrators





Courtesy of N. Aghanim

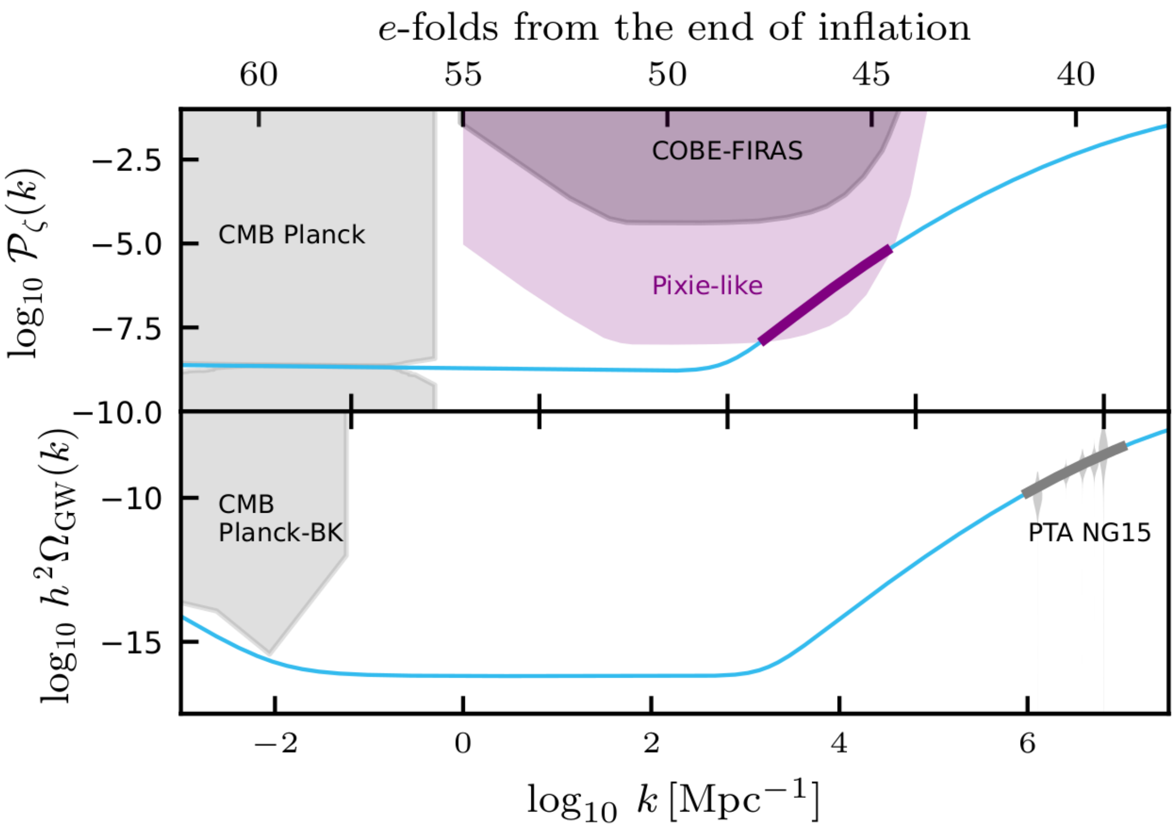
FOSSIL
FTS fOr CMB Spectral diStortIons expLoration

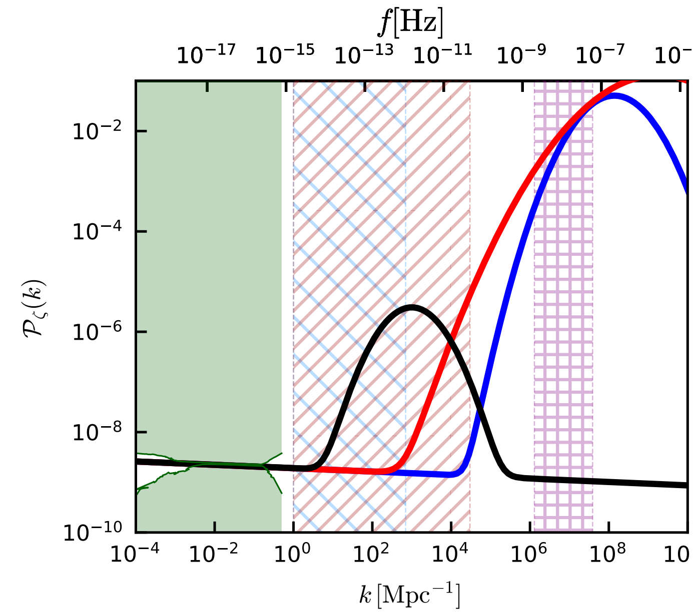
Enabled goals & Synergies

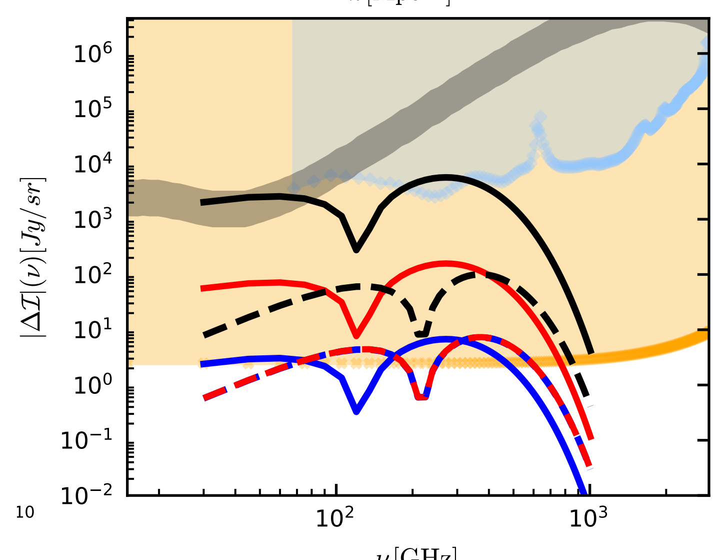
- Control foreground models with FOSSIL for **B-mode CMB polarisation measurements**
- Cross-correlation analyses with FOSSIL
  - Probe the first stages of galaxy formation in combination with **LIM experiments**
  - Provide absolutely-calibrated measurements of the y distortions from galaxy groups and clusters inaccessible from **CMB imagers**
  - Test models of the formation of the first structures in combination with **HI 21cm emission**

Courtesy of N. Aghanim

The quest for CMB SDs and PTA







$$\mathcal{P}_{\rm LN}(k) = \frac{A_\zeta}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2 k/k_*}{2\Delta^2}\right]$$

Tagliazucchi, Braglia, FF, Pieroni (2023)

Conclusions

The CMB anisotropy pattern has been the most decisive data set for inflation and has driven a significant progress on model building.

Either on CMB or LSS front, complementary data sets are reaching the same precision of Planck thanks to the information at small scales or low redshift. The combination of these datasets with Planck might change our view on the simplest inflationary models.

Future CMB experiments will be able to make progress in various directions. By chasing B-mode polarization we will probe the GUT energy scale by decreasing the uncertainty on the tensor-to-scalar ratio r by more than an order of magnitude wrt to BK18 (LiteBIRD, SO, SPO). By measuring CMB mu spectral distortions nearly three order of magnitudes below COBE FIRAS upper limits, we will explore small scales when these were still in the linear regime, and open a new window on primordial perturbations approximately between 10 Mpc^{-1} and 10 kpc^{-1} (FOSSIL).

Thanks for your attention!
Have a great meeting!