Foreground challenge to detect primordial B-modes using ECHO - A fourth generation CMB space mission

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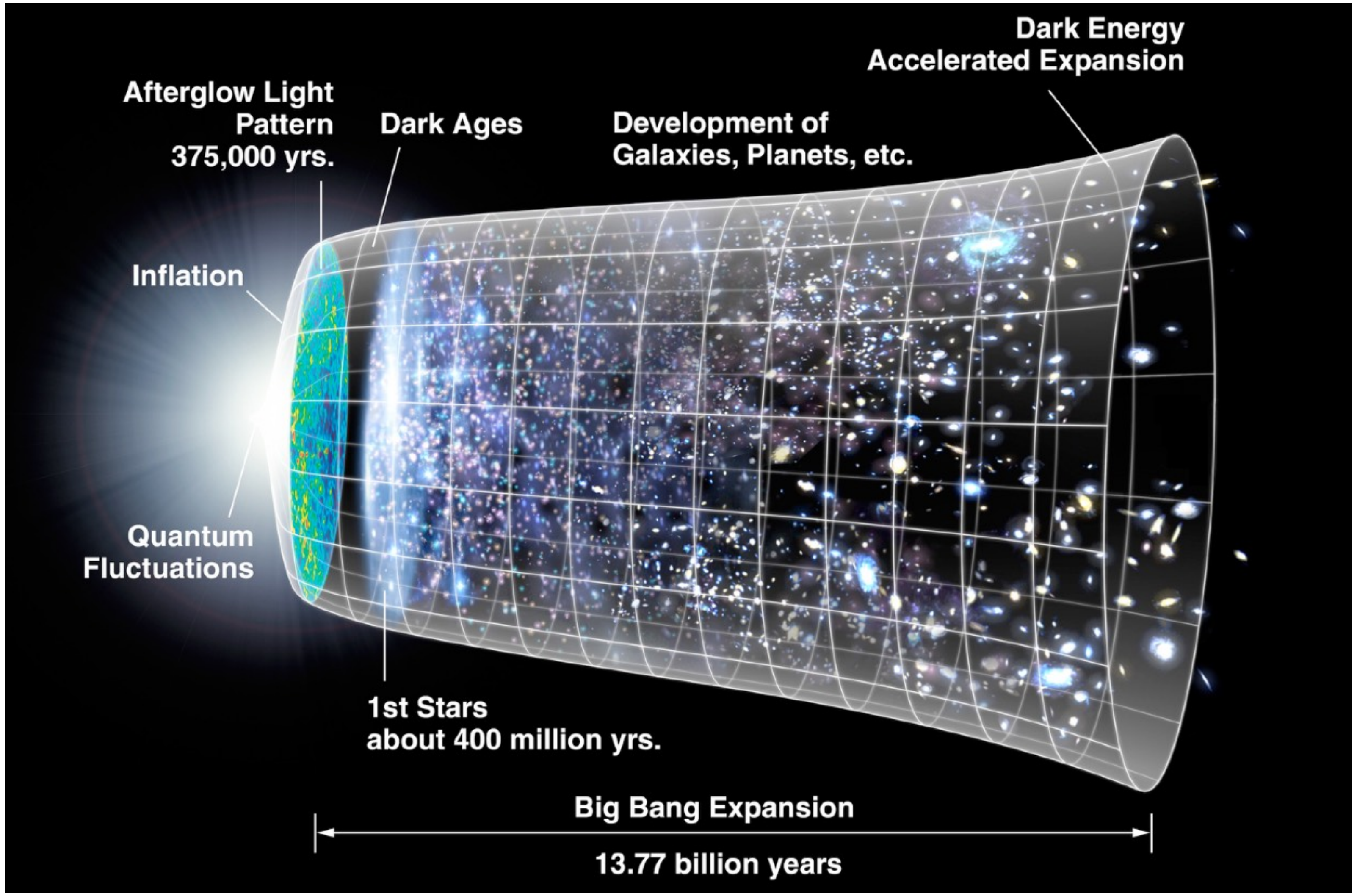
Next CMB mission: Why ?



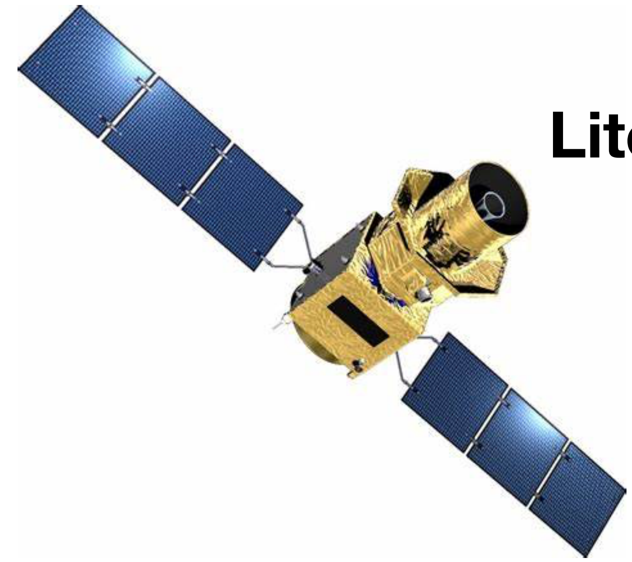
CMB is the oldest and cleanest cosmological probes of the universe

Planck mission has extracted ~ 100 % information from CMB temperature

But only a small fraction (10%) of the rich CMB polarization information

Unsolved problem: Inflation ? ? —> Primordial B-modes in CMB polarization

Future CMB satellites aim to detect r ~ 0.001

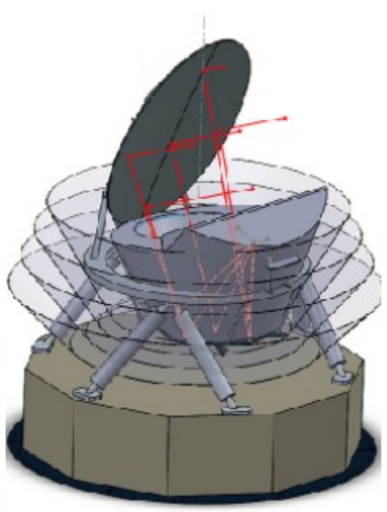


LiteBIRD (JAXA - Selected)

Matsumura et al, 2013

40 – 402 GHz

2.5 μK.arcmin



PICO (NASA?)

S. Hannany, priv. comm.

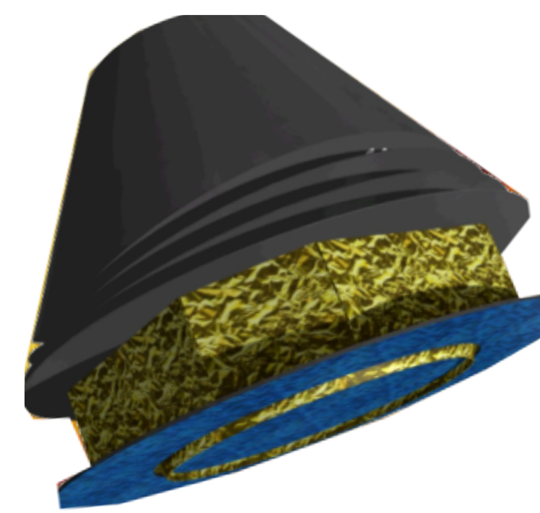
21 – 800 GHz

1 μK.arcmin

CMB -Bharat (ISRO?)

23 - 850 GHz

1.7 μK.arcmin



CMB - Bharat in Brief

- *European CMB proposal CORE (Cosmic Origins Explorer), a 'near- ultimate' CMB polarization mission.*
- *Did not pass the screening by ESA in January 2017.*
  - *cost did not fit within ESA's M-class mission.*

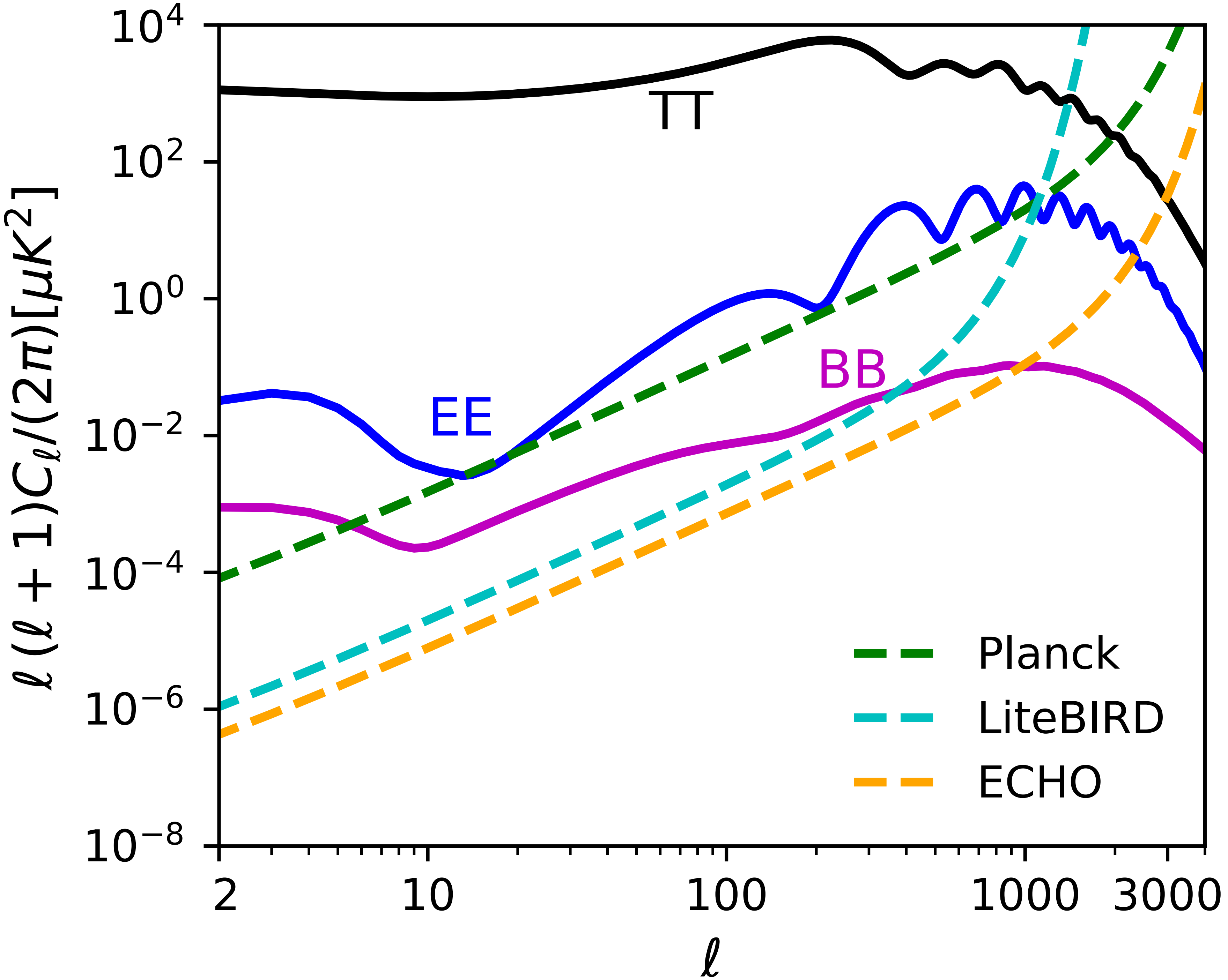
ESA encouraged to consider a joint proposal with a major international partner

➢**CMB-Bharat:** *Cross-institutional Indian cosmology consortium was set up formally on Jan 9th 2018 at ISRO HQ meet ~ 90 members from ~15 institutes*

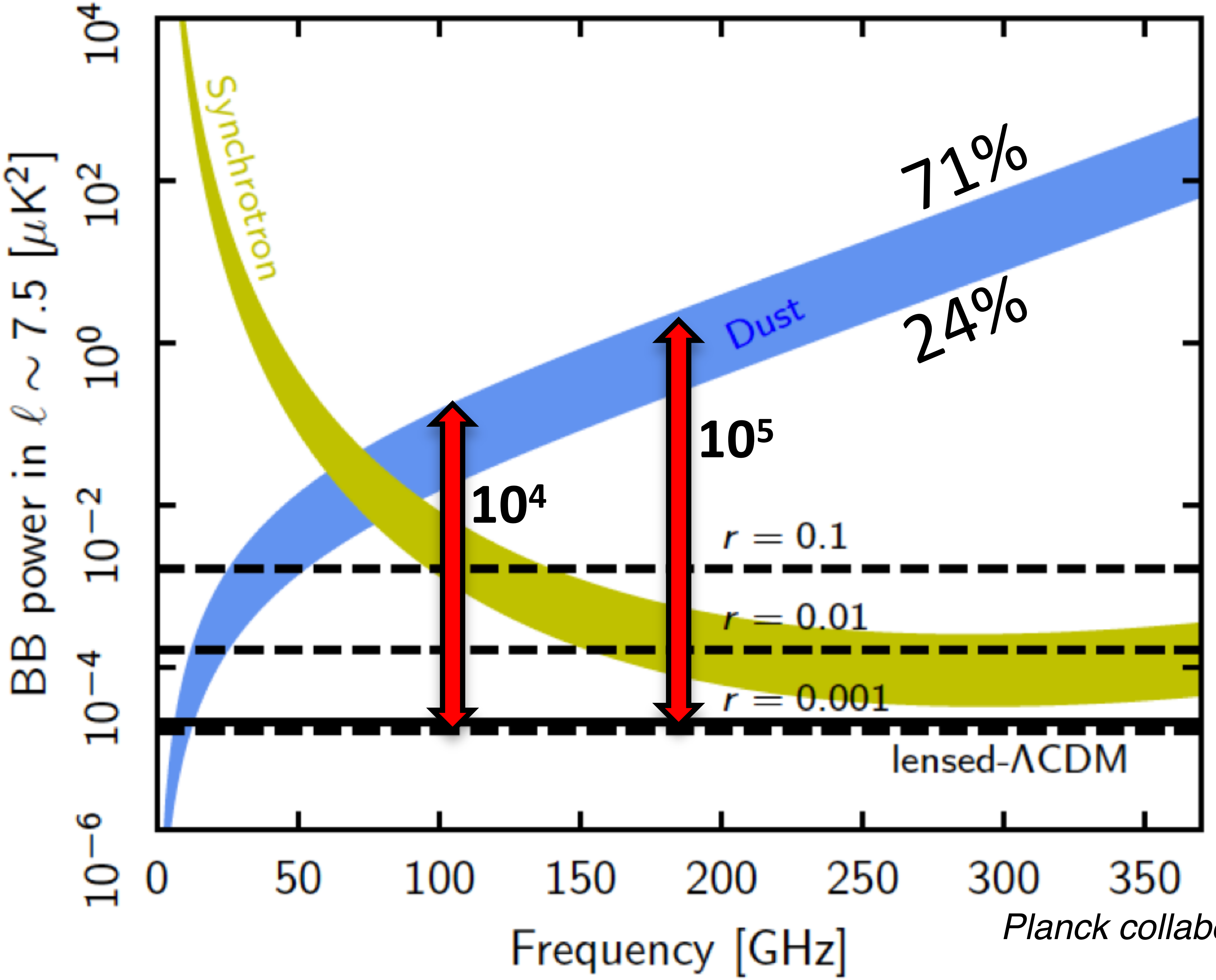
- *Consortium submit the proposal of CMB- mission "Exploring Cosmic History and Origins (ECHO)" to ISRO on 16th April, 2018*

A "near-ultimate" CMB polarization survey

(1-2μK.arcmin sensitivity, ~20 bands in 28-850 GHz)



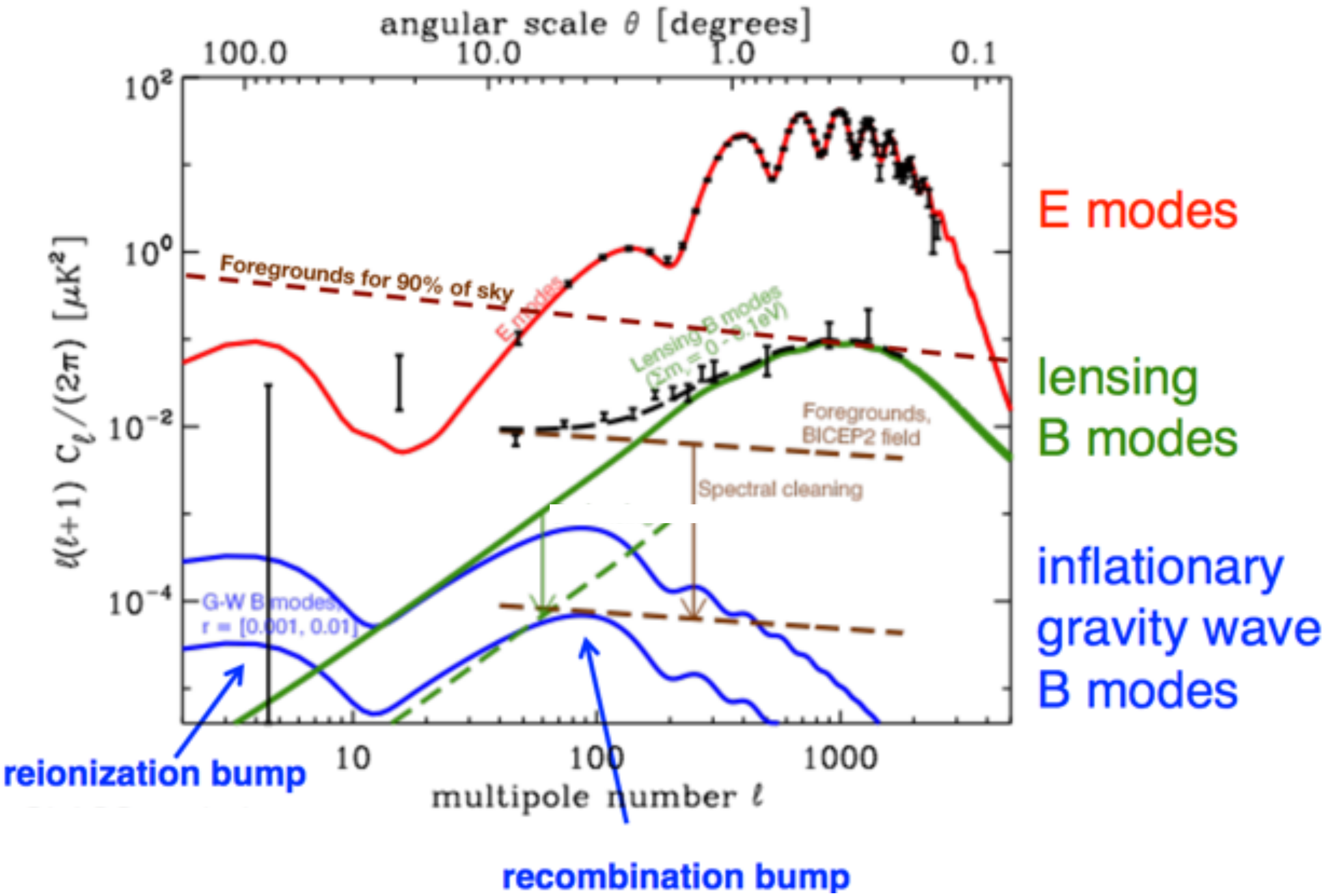
Foreground contamination



Planck collaboration XI (2018)

- *Spinning dust/AME can be 1- 2% (Dickinson et al. 2011) polarized*
- *Point sources can be 1.5-4.8% (Ricci, R. et al. (2004)) polarized.*

Lensed B-modes



Key target

Delensing is important to reduce uncertainty of r measurement

CMB-Bharat research – '*r*' recovery

- To detect r ~ 10^{-3} at 3σ significance
- Full-sky maps
- 20 frequency bands between 28 and 850 GHz
- CMB polarization sensitivity: 1-2 uK.arcmin
- Few arcmin resolution allows for delensing

Table 1. ECHO instrument specification as proposed in the CMB-Bhārat proposal.

Frequency (GHz)	Beam FWHM (arcmin)	Q & U noise r.m.s (μK.arcmin)
28	39.9	16.5
35	31.9	13.3
45	24.8	11.9
65	17.1	8.9
75	14.91	5.1
95	11.7	4.6
115	9.72	3.1
130	8.59	3.1
145	7.70	2.4
165	6.77	2.5
190	5.88	2.8
220	5.08	3.3
275	4.06	6.3
340	3.28	11.4
390	2.86	21.9
450	2.48	43.4
520	2.14	102.0
600	1.86	288.0
700	1.59	1122.0
850	1.31	9550.0

Adak et al (arXiv:2110.12362)

Summary of the foreground components

Table 2. Summary of the sky components and their parametric model used in simulations.

Component	Emission law	Nomenclature	Additional information/Templates	
CMB	Blackbody with scaling, $a_\nu = \frac{dB_\nu(T)}{dT}\|_{T_{CMB}}$; $T_{CMB} = 2.725\text{K}$		$r = 0$	
Thermal dust	MBB modified black body spectrum	GNILC − dust	*Planck* GNILC maps at 353 GHz from Planck Collaboration XLVIII (2016)	No dust decorrelation
		TD − dust	HI based dust polarization model at high galactic latitude developed in Ghosh et al. (2017) and Adak et al. (2020) at 353 GHz	Includes dust decorrelation
		Gines − dust	Multi-layer dust model based on dust extinction maps developed in Martínez-Solaeche et al. (2018)	Includes dust decorrelation
Synchrotron	Power-law, spatially varying spectral index with $\langle\beta_s\rangle = -3$	Power − law	SMICA Q, U maps from Planck Collaboration IV (2018) at 30 GHz	
	Frequency dependent spectral index; $\beta_s = -3.11 + C\log(\frac{\nu}{23})$ with curvature, $C = -0.3$ at 23 GHz	Curved−power−law	SMICA Q, U maps from Planck Collaboration IV (2018) at 30 GHz	
	GALPROP scaling; $(\frac{\nu}{30})^2 \frac{f_s(\frac{\nu}{\alpha})}{f_s(\frac{30}{\alpha})}$ with constant $\alpha = 0.26$ and $f_s(\nu)$ is taken from external template generated from GALPROP code	GALPROP	SMICA Q, U maps from Planck Collaboration IV (2018) at 30 GHz	
Spinning dust	CNM emission law with 1% polarization fraction and dust polarization angle		*Planck* thermal dust intensity at 353 GHz (Planck Collaboration XLVIII 2016) scaled at 23 GHz with correlation coefficient of 0.91 K/K	
Point-sources	Sources from radio surveys extrapolated with power laws;		Radio sources have median polarization fraction of 2.7% and 4.8% for two class of power-laws;	
	IRAS survey modelled with modified blackbody emission laws.		IR sources are taken from IRIS data and having mean polarization fraction of 1.5%	

Adak et al (arXiv:2110.12362)

Set of sky simulations

Table 3. Set of simulations used in the analysis. The tick and cross symbols indicate which components are added and excluded respectively for different sets. The dust and synchrotron models used are identified using nomenclatures listed in Table 2.

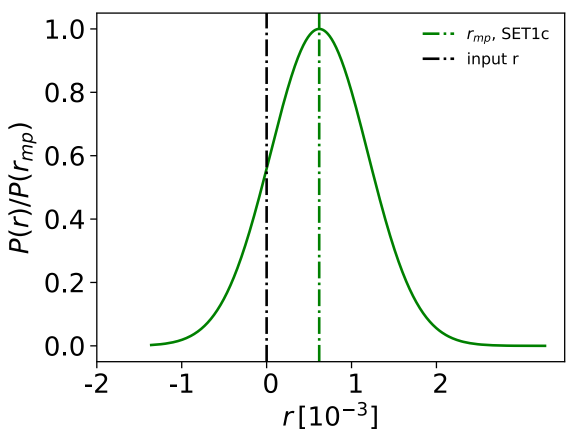
Sim.ID	Pipeline		Dust	Synchrotron emission law	AME	point-sources	delensing	Decorrelation
	Commander	NILC						
SET1a	✓	✓	GNILC – dust	GALPROP	✗	✗	✗	✗
SET1b	✓	✓	GNILC – dust	GALPROP	✓	✗	✗	✗
SET1c	✓	✓	GNILC – dust	GALPROP	✓	✓	✗	✗
SET1d	✓	✓	GNILC – dust	GALPROP	✗	✗	✓(84 %)	✗
SET1e	✓	✓	GNILC – dust	Power – law	✓	✓	✗	✗
SET1f	✓	✓	GNILC – dust	Curved–power–law	✓	✓	✗	✗
SET2a	✓	✓	Gines – dust	GALPROP	✓	✓	✗	✓
SET2b	✓	✓	Gines – dust	Power – law	✓	✓	✗	✓
SET2c	✓	✓	Gines – dust	Curved–power–law	✓	✓	✗	✓
SET3a	✓	✗	TD – dust	GALPROP	✓	✓	✗	✗
SET3b	✓	✗	TD – dust	GALPROP	✓	✓	✗	✓

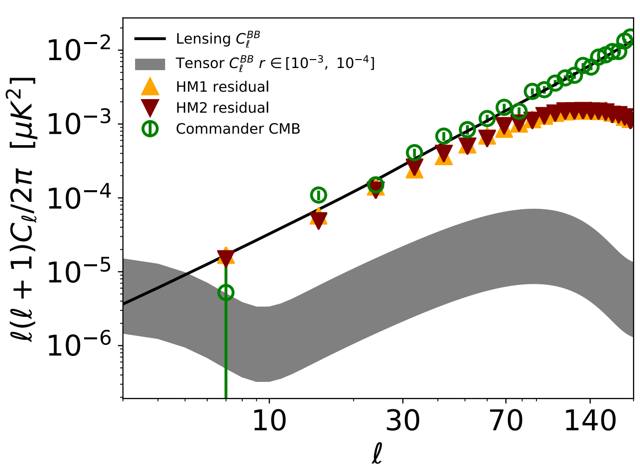
Foreground cleaning

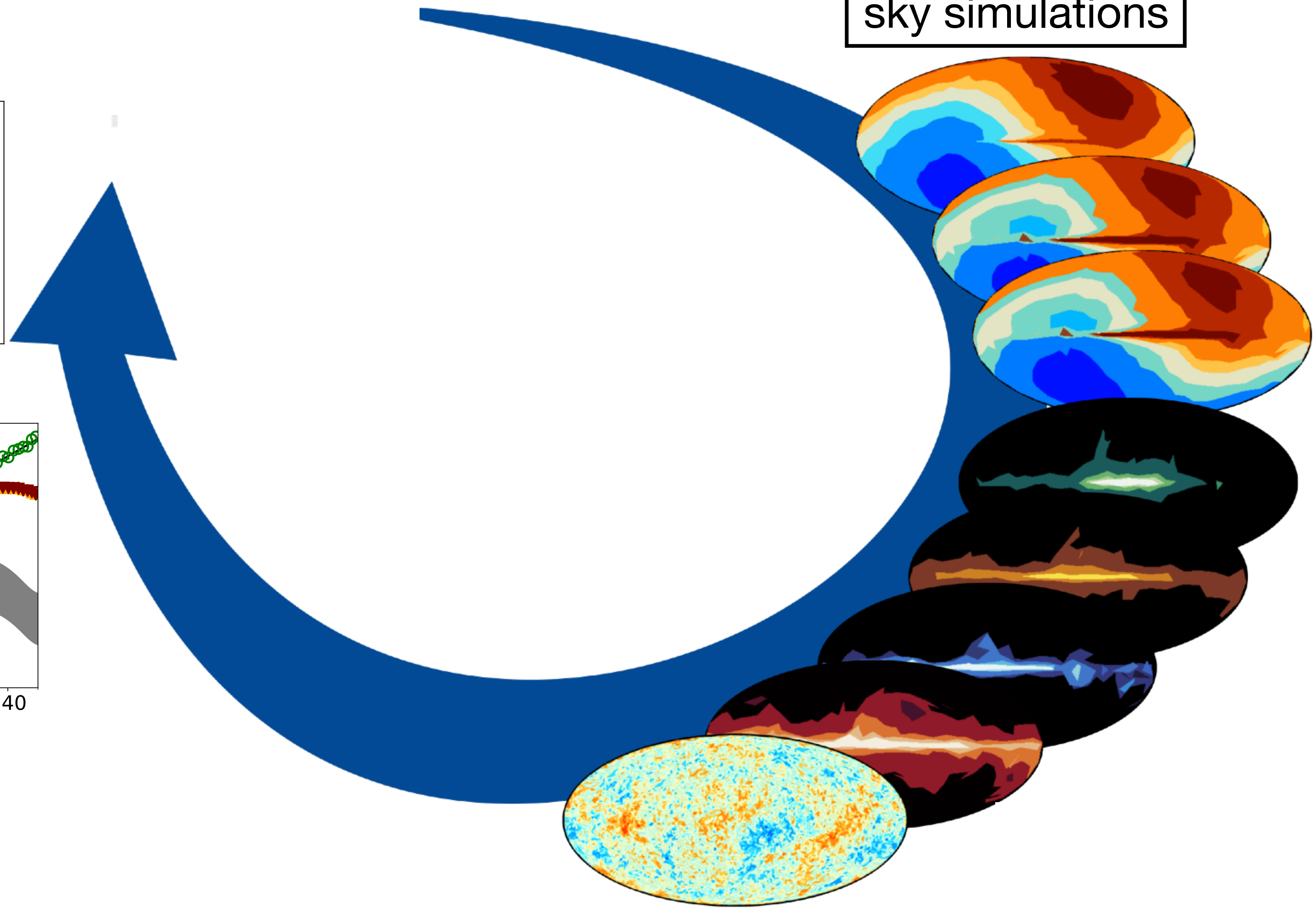
Likelihood analysis / r estimation

$$-2\mathcal{L} = constant + \sum_{k,k'} \left[\hat{C}_k^{BB} - C_k^{BB,model}(r, A_L)\right] \Sigma_{k,k'}^{-1} \left[\hat{C}_{k'}^{BB} - C_{k'}^{BB,model}(r, A_L)\right]$$

sky simulations







✓ Needless Internal Linear Combination (NILC) method - minimum-variance estimator in spherical wavelet basis - *Delabrouille et al. 2009, Basak et al. 2012, 2013.*

✓ *COMMANDER – Bayesian multi-component spectral fit in pixel space through* Gibb's sampling *– Eriksen et al. 2004, 2008*

Forecast results

Input $r = 0$

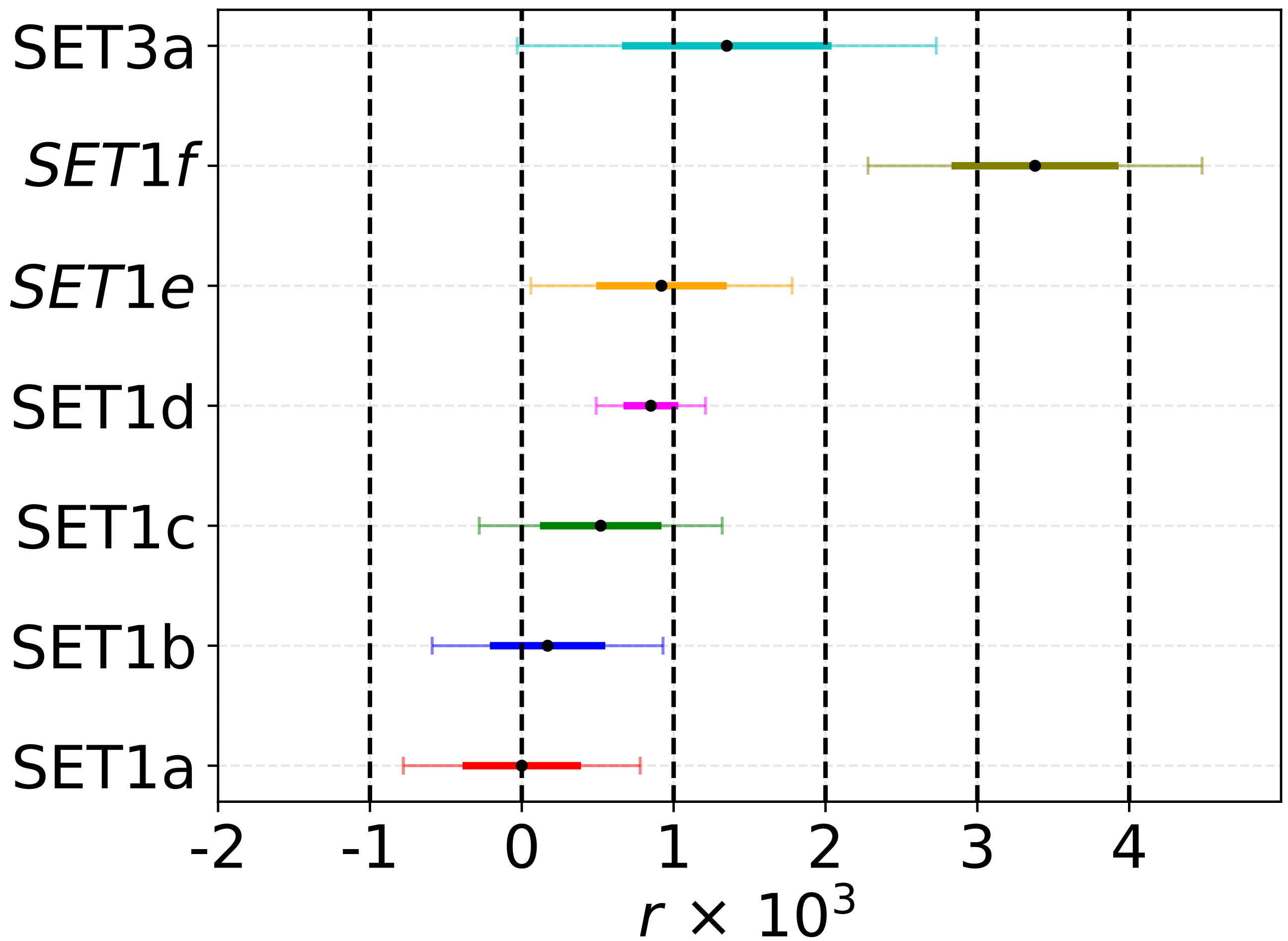
Sim ID	NILC r_{mp}	$\sigma(r_{mp})$	Commander r_{mp}	$\sigma(r_{mp})$
SET1a	-0.76×10^{-3}	0.67×10^{-3}	-0.08×10^{-3}	0.39×10^{-3}
SET1b	-0.55×10^{-3}	0.68×10^{-3}	-0.17×10^{-3}	0.38×10^{-3}
SET1c	0.81×10^{-3}	0.71×10^{-3}	0.52×10^{-3}	0.40×10^{-3}
SET1d	-0.49×10^{-3}	0.33×10^{-3}	0.44×10^{-3}	0.17×10^{-3}
SET1e	0.34×10^{-3}	0.81×10^{-3}	0.92×10^{-3}	0.43×10^{-3}
SET1f	0.54×10^{-3}	0.78×10^{-3}	3.38×10^{-3}	0.55×10^{-3}
SET2a	1.6×10^{-3}	1.1×10^{-3}	47.5×10^{-3}	1.5×10^{-3}
SET2b	0.6×10^{-3}	1.2×10^{-3}	51.1×10^{-3}	1.6×10^{-3}
SET2c	1.1×10^{-3}	1.2×10^{-3}	34.9×10^{-3}	1.4×10^{-3}
SET3a	-	-	1.3×10^{-3}	0.7×10^{-3}
SET3b	-	-	188×10^{-3}	6×10^{-3}

- SET1a: Baseline model
- SET1b: + AME
- SET1c: + point source
- SET1d: 84% delensing + baseline
- SET1e, SET1f: Synchrotron power-law and curved power law model
- SET2a–SET2c: Dust decorrelation included

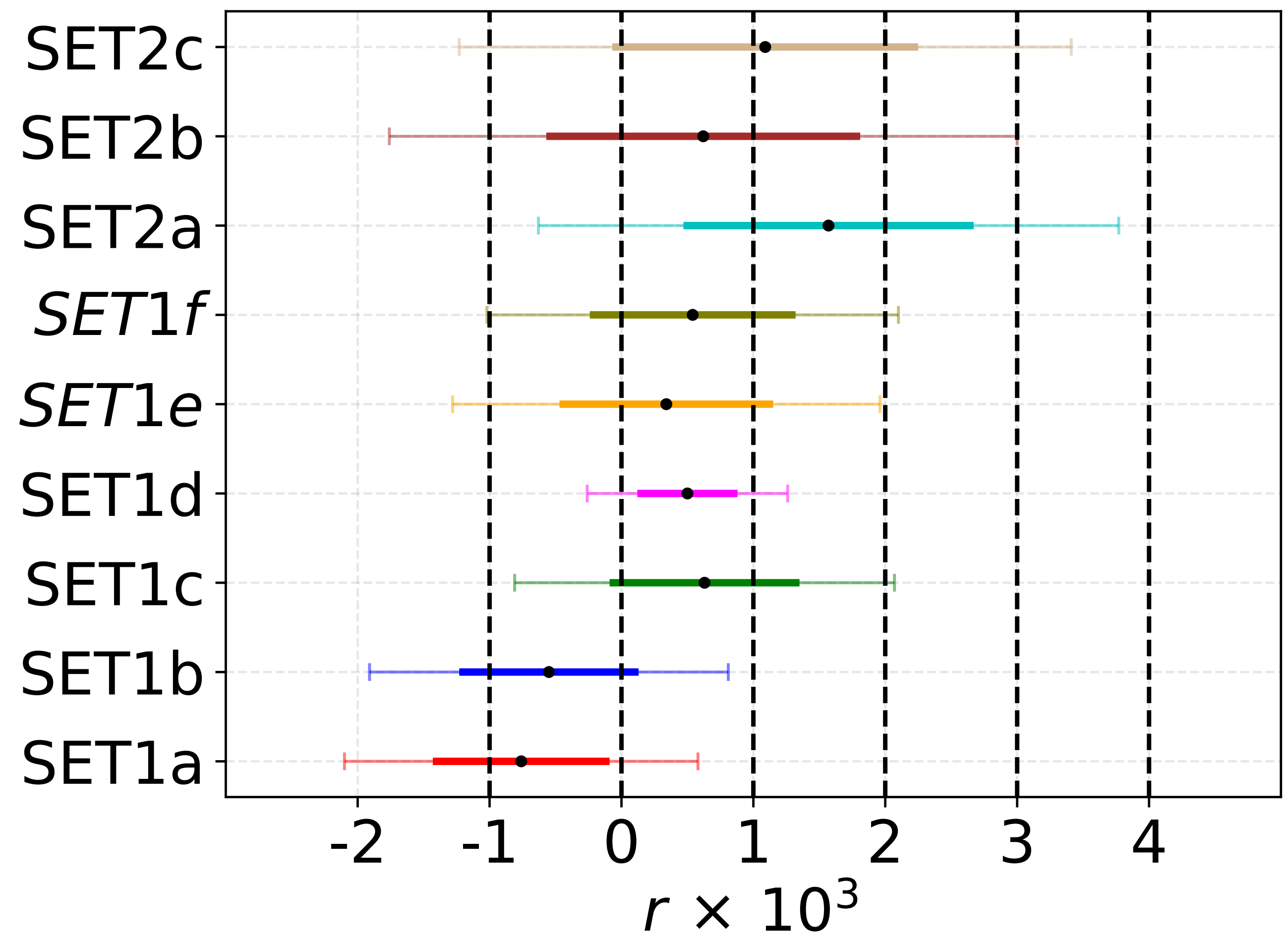
Summary plots

Input r = 0

Commander results

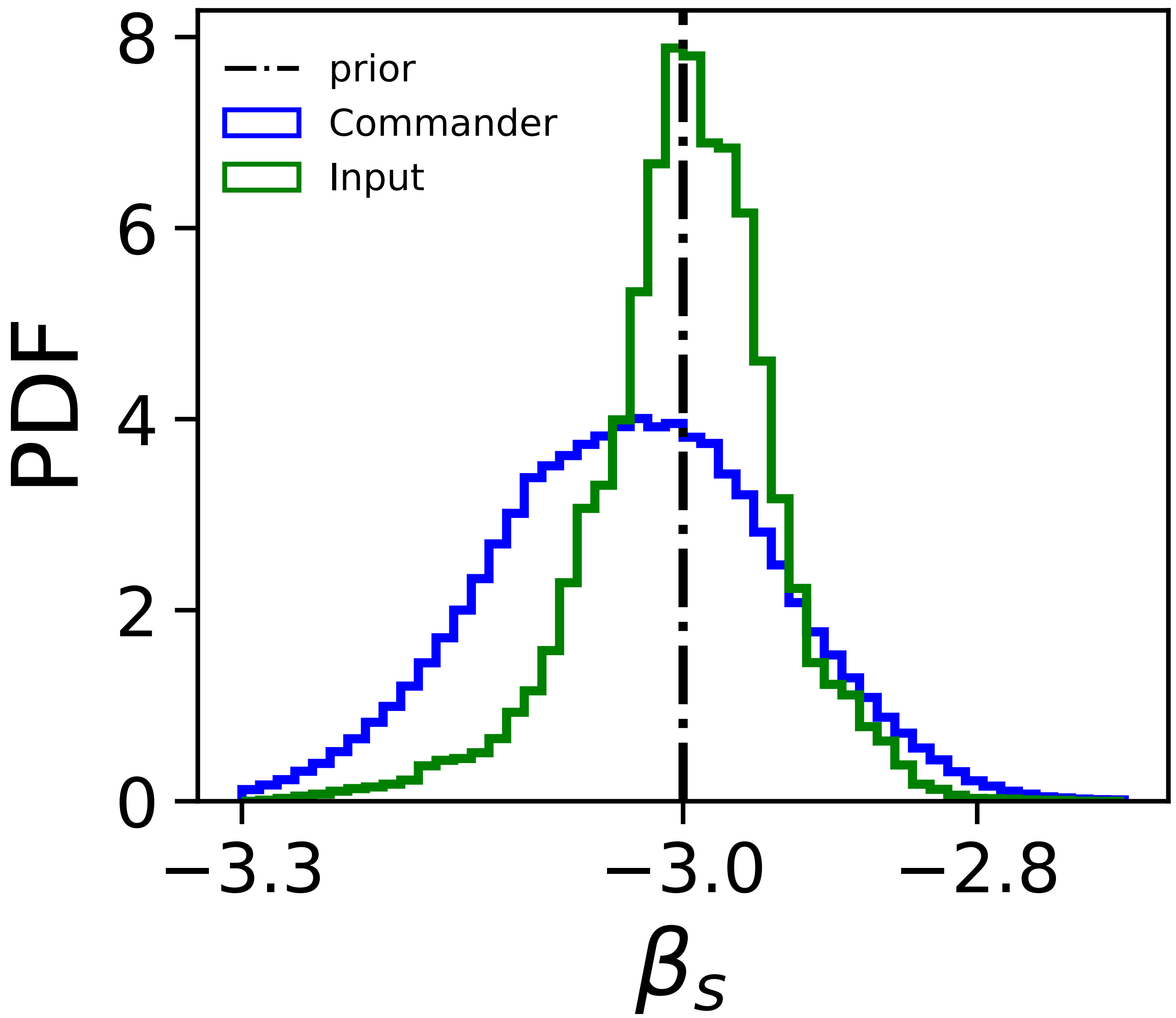


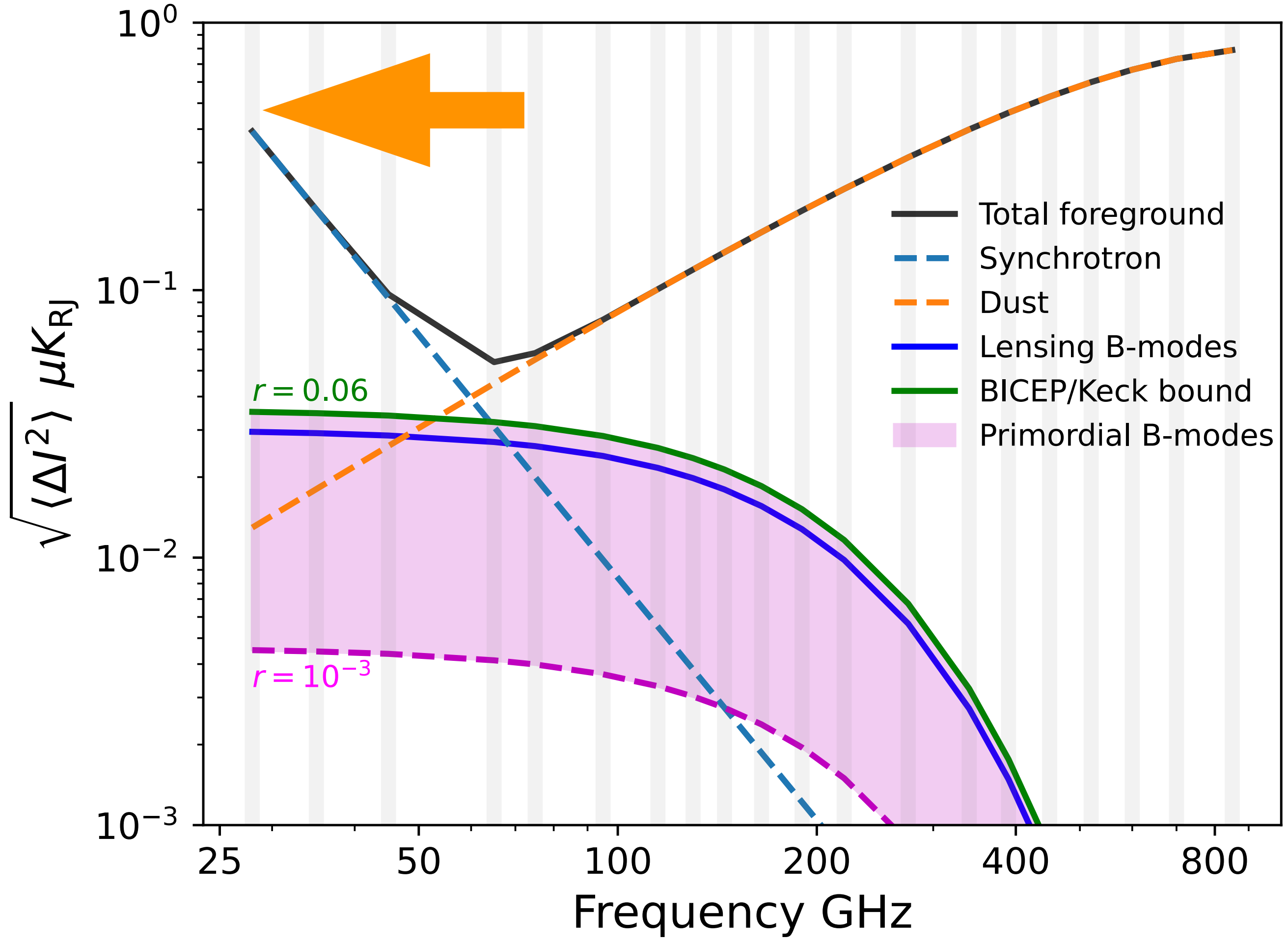
NILC results



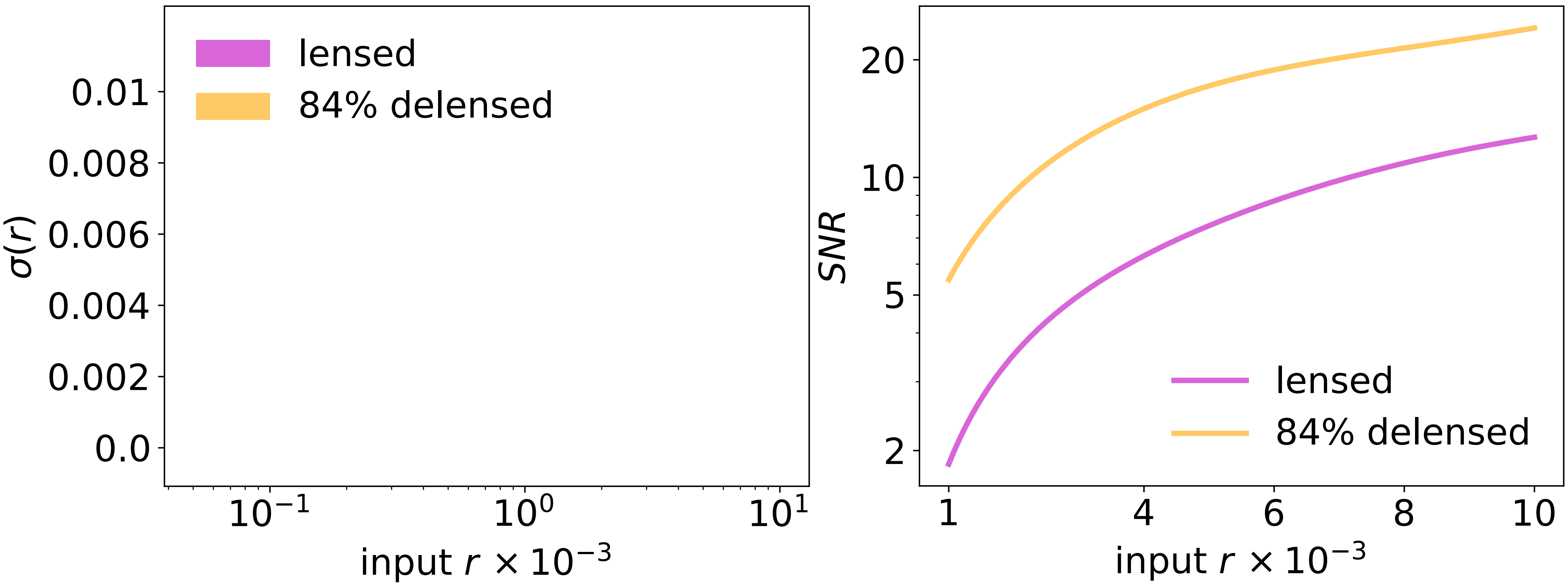
- ✓ COMMANDER returns biased *r* values for curved power-law synchrotron model (1f).
- ✓ COMMANDER returns biased *r* values in the presence of dust decorrelation(2a-c).
- ✓ NILC handles well different emission law models of synchrotron, e.g. curved power law.
- ✓ NILC returns larger errorbar on *r* in the presence of dust decorrelation (2a-c).

Lack of frequency channels





Detection significance : impact of delensing



- *84% delensing, increases SNR by more than two times*

Summary

- ECHO is the instrument with combination of full sky coverage, high resolution and sensitivity, large frequency coverage in a single platform.

- Huge discovery space: Inflation, particle physics, galactic and extragalactic astronomy
  - particularly designed to detect : r ~ 0.001.

- We consider 11 set of foreground complexities, including 84% delensing, and dust decorrelation.

- simple two-component (dust + synchrotron) foregrounds can easily be mitigated using existing component separation methods

- De-correlated dust requires new foreground cleaning method

- CMB Bharat (ECHO) alive in ISRO womb, needs a trigger!!!

Thank you