Primordial Magnetic Fields

…or…

How I learned to sometimes stop worrying about inflation and love exotic cosmological models

D. Paoletti for the PMF crew

D. Paoletti is funded by ASI-LiteBIRD

THE REASON BEHIND PRIMORDIAL MAGNETIC FIELDS IMPORTANCE

Primordial Magnetic Fields (PMFs) can provide the seeds to the generation of the Cosmic Magnetism observed on cosmological scales in the large scale structure and its voids.

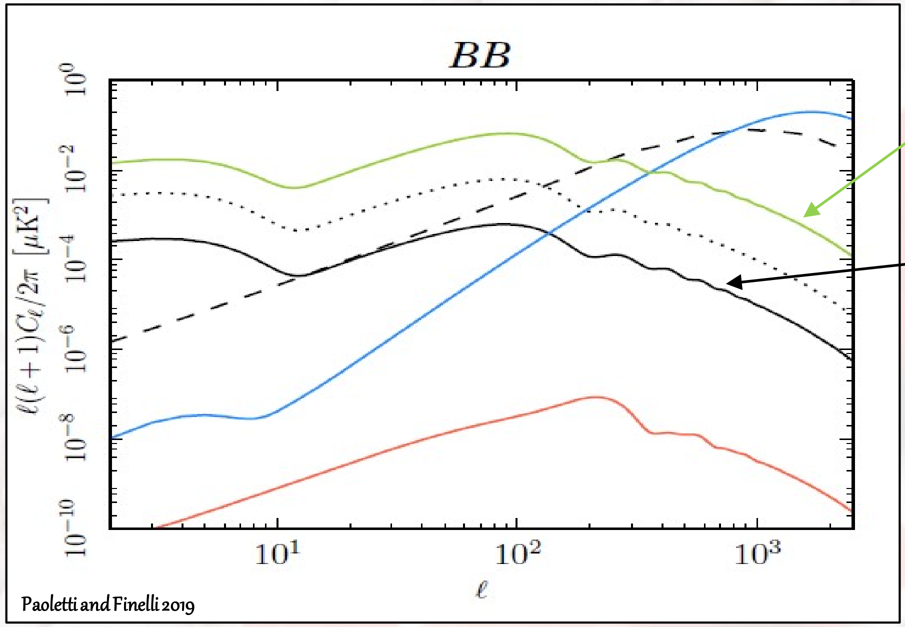
Astrophysical observations keep pointing more and more towards a primordial origin for the cosmic magnetism but such primordial magnetism has to leave imprints in all the history of the Universe

PMFs to be generated require peculiar conditions in the early Universe, a smoking gun of non standard fundamental physics at these energies.

PMFs with their characteristics can shed light and be an unconventional window on the secret wonderland of fundamental physics at high energies

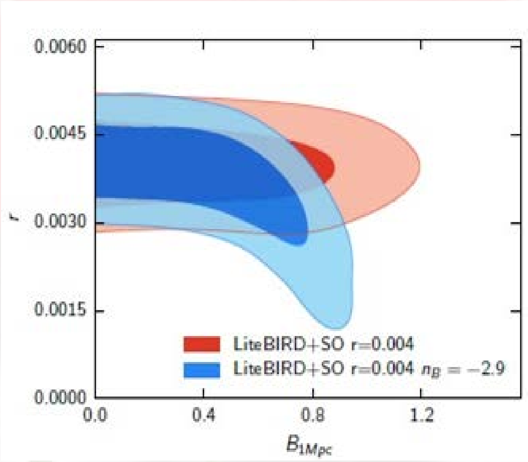
BUT PMFs are particularly important for LiteBIRD also for a different reason

PMF can contaminate B-modes with signals very similar to the ones expected from inflation



These are PMFs

This is your inflation signal



PMFs have many different imprints on CMB anisotropies and only putting all the different probes within the CMB we can be capable of disentangling the inflationary and PMF signals

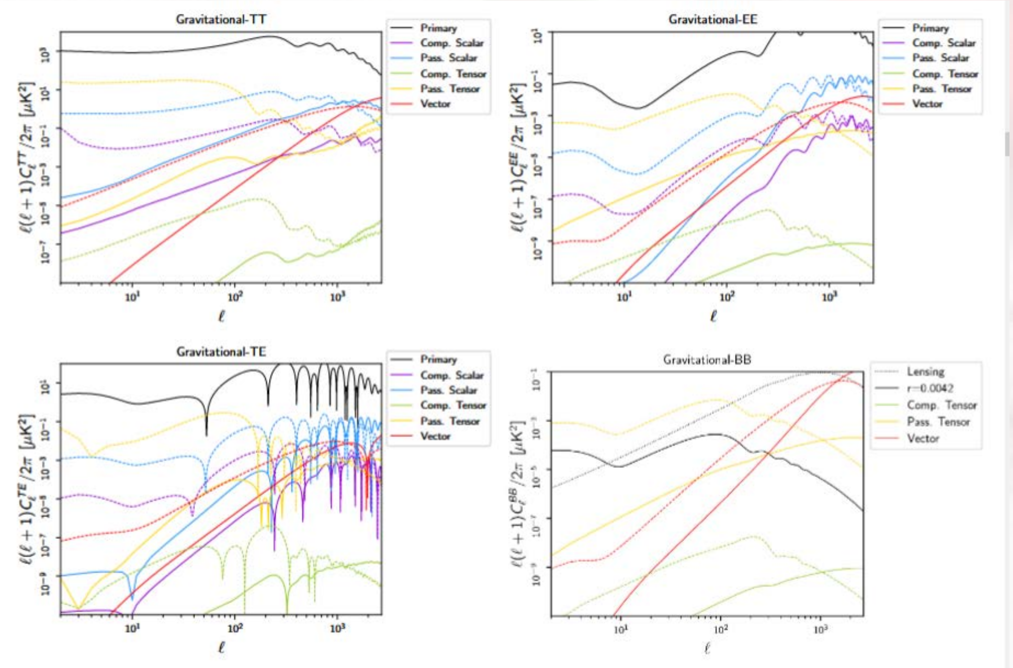
THIS IS BASICALLY THE SCOPE OF OUR PSG, PUT TOGETHER ALL THE DIFFERENT PROBES OF PRIMORDIAL MAGNETISM IN THE CMB WITH LITEBIRD

MAGNETIC CMB SCENARIO

PMFs have a whole variety of effects on CMB anisotropies affecting both absolute spectrum (not relevant for LB), angular power spectra in temperature and polarization, bispectra, trispectra (we will see for this one)+....

GRAVITATIONAL- MAGNETICALLY INDUCED PERTURBATIONS

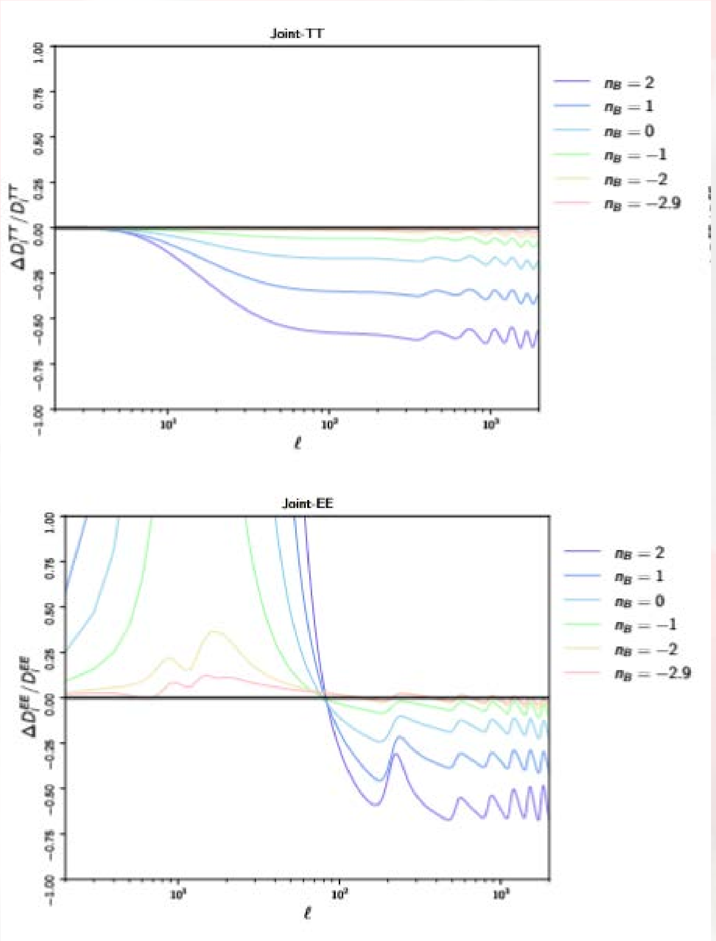
Additional contributions to the angular power spectra in all even channels



NON-GAUSSIANTIES non vanishing BBB bispectrum

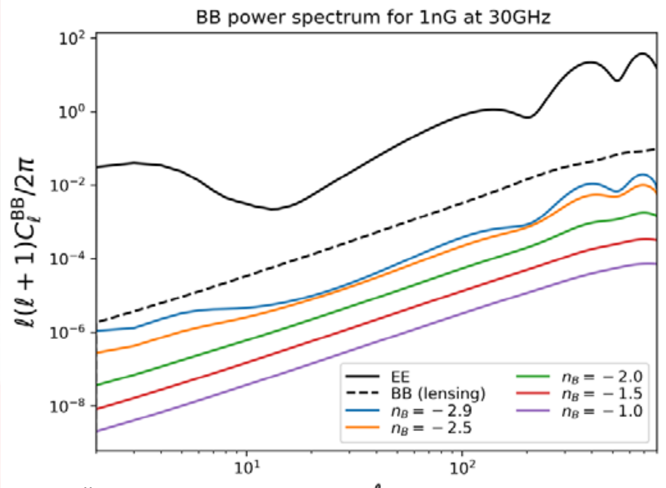
THERMAL-IONIZATION DISSIPATION EFFECT

Modifies primary CMB in all channels



FARADAY ROTATION

Generation of B-mode signal from E-modes through rotation of the pol plane. Colored!



From Alberto

PMFs are pretty sensitivity to whatever strangeness you have in you spectra and/or likelihood..are a very good diagnostic

MAGNETIC CREW

We are relatively few but collect some of the best world expertise in all aspects of PMFs and CMB

CARLO BACCIGALUPI

JENS CHLUBA

JOSQUIN ERRARD

FABIO FINELLI

ALESSANDRO GRUPPUSO

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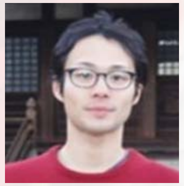


ANDREA TARTARI

THE PSG

Our wikipage:
https://wiki.kek.jp/display/cmb/Project+Paper%3A+Primordial+Magnetic+Fields

2 papers proposed
Original proposal

Paper I – Constraints on PMFs

Constraints on non-helical PMFs by using their different effects on CMB anisotropies:

- Gravitational
- Impact on the ionization history
- Non-Gaussianities
- Faraday rotation

RELYING ON TT-TE-EE-BB

Paper II – Constraints on helical PMFs

Focus on the role of helicity, a mandatory condition for causally generated magnetic fields. Apart from Planck 2015 few things are around on constraining helical PMFs with CMB.

Some theoretical work still to be done – 6-8 months after first paper

RELYING ON TT-TE-EE-BB but also TB and EB. Helical PMFs are a good target for odd cross-correlators

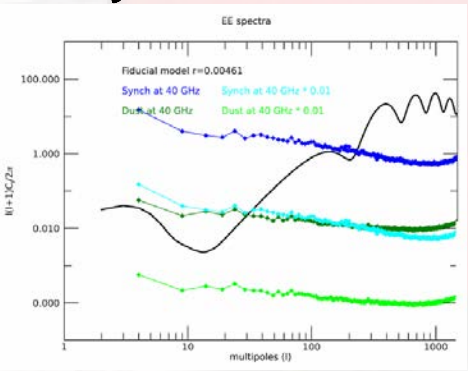
PAPER 1

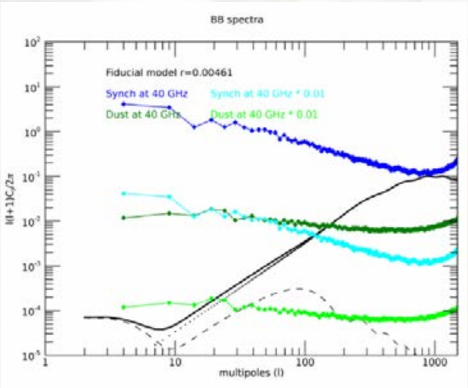
INPUTS and METHOD FOR GRAVITATIONAL, HEATING AND NG - Power Spectra - PTEP-like Baseline settings:

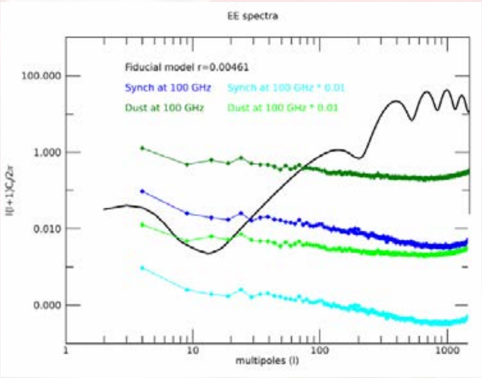
- Instrumental white noise: inverse noise variance weighting of channels from 78 to 195 GHz channels, best FWHM where overlaps, version IMOv1 from PTEP.
- TT and EE are with only instrumental noise (only available option until short time ago). For EE we agreed to provide dedicated results investigating the effect of FG residuals for the E-mode paper.
- FG and systematics: provided by FG JSG and Hirokazu (again PTEP-like)
- Planck: mock data realization with boosted noise in different ell ranges in TT and EE to reproduce the same error bars fro LCDM as Planck 2018
- Standard Inverse Wishart likelihood (exact likelihood provided in cosmomc package)

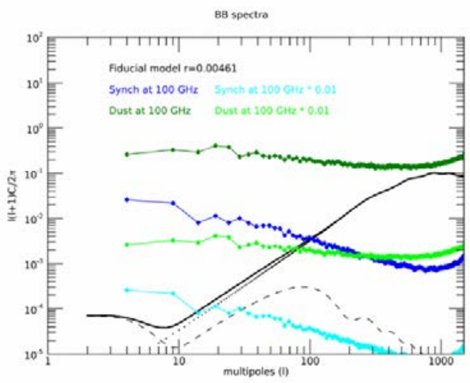
INPUTS FOR FARADAY- Foreground reduced power spectra FOR SINGLE FREQUENCY:

- Produced internally by Diego - Starting from dust and synchrotron maps at 100 GHz (provided by Nicoletta) Diego derived the spectra, applying de-apodized HFI mask, and rescaled for the frequencies of interest for Faraday (<100 GHz). We mimic the cleaning by CS by reducing of a factor 100 the FG contamination.
- Chisqr likelihood









Current Status of Paper I

Completed

Since end of March 2023

We kept a tight schedule since DP contract was expiring on May 1st 2023 and OAS director refused to renew it. New «concorso» was pending with delays, problems, issues, all possible.
DP choice was to complete everything before the end of contract.

Due to this hard deadline we tried from the beginning of PSGs to have feedback on issues as what to do with temperature…E-mode residuals etc…. but it was too early to have a full coordination..

So we sticked to what requested: PTEP-like

Beginning of April we have been asked to include the 1/f in temperature for all analyses…Unfeasible since paper I burned about 1M cpu hours of DP personal HPC projects on CINECA and now just few tens K left..

Trade off agreement: delay the paper of a couple of months for the new allocation of cpu hours and include the 1/f as additional worst case scenario in just the main analyses

CURRENT STATUS OF PAPER I

HANGING

WAITING FOR 1/f*

Recent developments on 1/f seem to indicate it is very low so we agreed to first perform a test and on the basis of the results decide if go on with original plan or with the trade off agreeement

LiteBIRD Paper Project: Constraints on Primordial Magnetic Fields

Bastian Balthazar Bux[1] Agnes Nutter[2] Will Parry[3] Akira Fudo[4] Ryo Saeba[5] Andrè Grandier[6] etc

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[4]Devilish office for human-demon hybrids protection, Tokyo
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[6]De Jarjayes residence, servants apartments

Abstract. We present the forecasts for the constraints on the characteristics of Primordial Magnetic Fields (PMFs) we can provide with the LiteBIRD satellite via some of their diverse imprints on CMB anisotropies and in particular on polarization. We focus on the most known effects of PMFs on CMB anisotropies: the gravitational effects of magnetically-induced perturbations, the effects on the thermal and ionization history, the Faraday rotation and non-Gaussianities. LiteBIRD represents a tremendous probe for primordial magnetism with all the diverse effects relying on different data aspects and products making them perfectly complementary. We explore different levels of complexity both for LiteBIRD data and PMF configuration, considering also possible degeneracies with primordial gravitational waves from inflation. With LiteBIRD we will be able to improve in all the effects with respect to current results on intermediate and large scales by Planck. In particular, thanks to the accurate B-mode polarization measurement, LiteBIRD will improve the constraints on infrared configurations for the gravitational effect giving $B_{1Mpc}^{n_B=-2.9} < 0.8$ nGauss and the possibility to detect with high significance nanoGauss fields, whereas we observe a significant reduction on the limits for the standard case marginalized over the spectral index which provides $B_{1Mpc}^{Marg} < 2.2$ nG. From the thermal history effect which relies mainly on E-mode polarization we have a strong improvement for all PMF configurations with the marginalized case giving $\sqrt{\langle B^2\rangle^{Marg}} < 0.50$. Faraday rotation taking advantage of the LiteBIRD wide coverage of the low frequencies and the high sensitivity in B-modes, improves by orders of magnitude with respect to current results giving $B_{1Mpc}^{n_B=-2.9} < 1.9$ nGauss at 68% CL. Finally, the non-Gaussianity using the B-mode polarization bispectrum can detect PMF at the level of 1 nanoGauss, again improving significantly current bounds from Planck. All together these forecasts represent a multivaried collection of complementary conservative limits on PMF characteristics, based on widely tested methodologies, that we can provide with the LiteBIRD satellite.

Contents

1 Introduction

Magnetic fields are ubiquitous in the Universe, from the smallest scales in stars and planets, representing indeed a necessary condition for the development of life, up to the largest scales observable, filling the entire Universe in both structures and voids.

Magnetic fields are observed in Galaxies, and in particular in the Milky Way since 1949 when two independent observations of polarized optical light [1, 2] were later interpreted as the result of dust grain alignment due to a diffuse magnetic field in the Galaxy [3]. Afterwards Zeeman line splitting and Faraday rotation confirmed the presence of a Galactic

PAPER 1 HIGHLIGHTs

GRAVITATIONAL EFFECT

Depends an all even channels TT-TE-EE-BB

TT and EE are instrument noise. Progressive complexity for B-modes

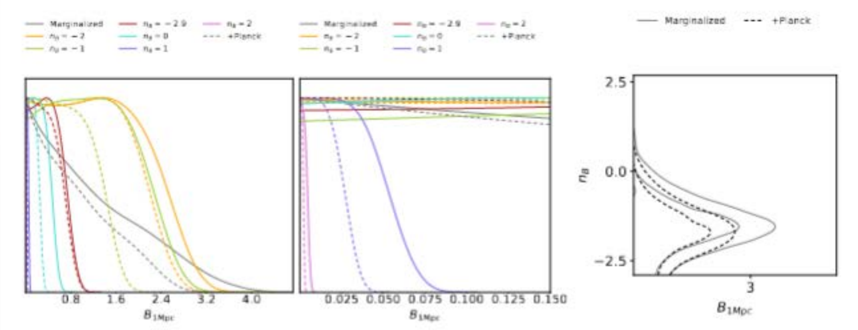
- instrument white noise
- PTEP like
- Lensing in signal cofitted
- Lensing and FG bias
- Lensing, FG and systematic bias
- TBC 1/f in temperature

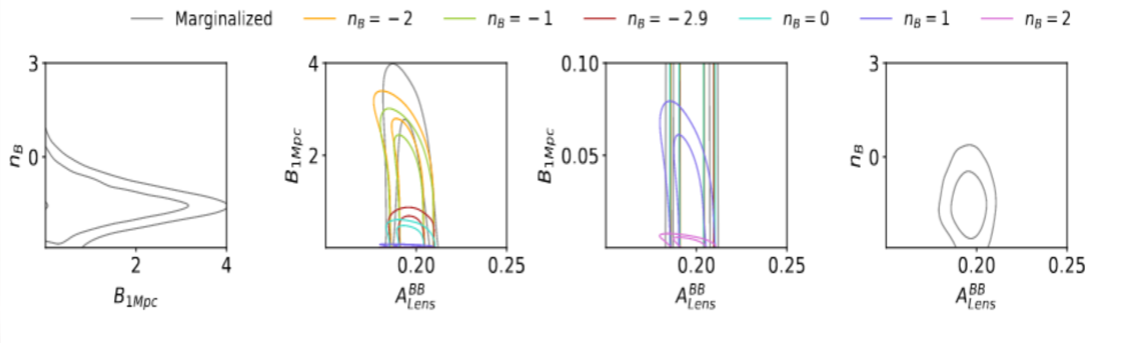
SEVERAL SCIENTIFIC CASES CONSIDERED

Data	LiteBIRD-ideal	LiteBIRD-baseline	LiteBIRD-baseline+Planck
n_B	$B_{1\,\mathrm{Mpc}}$ [nG]	$B_{1\,\mathrm{Mpc}}$ [nG]	$B_{1\,\mathrm{Mpc}}$ [nG]
Marginalized	< 2.9	< 2.9	< 2.2
2	< 0.005	< 0.005	< 0.003
1	< 0.06	< 0.06	< 0.031
0	< 0.05	< 0.05	< 0.27
-1	< 2.4	< 2.4	< 1.5
-2	< 2.5	< 2.7	< 2.3
-2.9	< 0.6	< 0.8	< 0.8

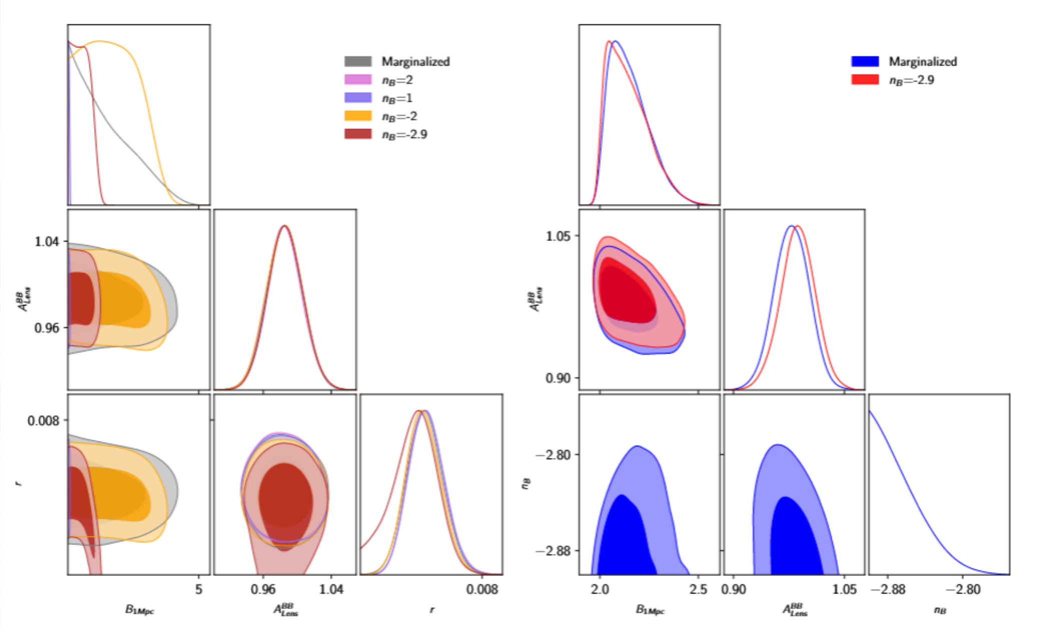
LiteBIRD with lensing Marginalization						
Lensing	Full		43% Delensed		80% Delensed	
n_B	$B_{1\,\mathrm{Mpc}}$ [nG]	A^{BB}_{Lens}	$B_{1\,\mathrm{Mpc}}$	A^{BB}_{Lens}	$B_{1\,\mathrm{Mpc}}$	A^{BB}_{Lens}
Marg.	< 3.5	0.985 ± 0.020	< 3.3	0.561 ± 0.012	< 3.3	$0.196^{+0.007}_{-0.006}$
2	< 0.007	0.985 ± 0.020	< 0.007	0.560 ± 0.013	< 0.006	0.195 ± 0.006
1	< 0.075	$0.985^{+0.021}_{-0.020}$	< 0.072	0.560 ± 0.013	< 0.067	0.195 ± 0.006
0	< 0.56	$0.986^{+0.020}_{-0.021}$	< 0.54	0.562 ± 0.012	< 0.51	0.196 ± 0.006
-1	< 2.75	$0.986^{+0.021}_{-0.020}$	< 2.67	0.561 ± 0.013	< 2.58	0.195 ± 0.006
-2	< 3.17	0.985 ± 0.021	< 3.06	0.560 ± 0.013	< 2.90	0.195 ± 0.006
-2.9	< 0.80	0.988 ± 0.020	< 0.76	0.563 ± 0.012	< 0.73	0.197 ± 0.006

LiteBIRD with lensing Marginalization with Starobinky-like primordial									
Fiducial	Full Lensing			43% Delensed			80% Delensed		
n_B	$B_{1\,\mathrm{Mpc}}$	A^{BB}_{Lens}	r	$B_{1\,\mathrm{Mpc}}$	A^{BB}_{Lens}	r	$B_{1\,\mathrm{Mpc}}$	A^{BB}_{Lens}	r
Marginalized	< 3.47	0.986 ± 0.021	$0.0042^{+0.0011}_{-0.0012}$	< 3.30	0.569 ± 0.013	0.0042 ± 0.0010	< 3.31	$0.198^{+0.007}_{-0.006}$	0.0042 ± 0.0009
2	< 0.007	0.984 ± 0.0021	$0.0044^{+0.0010}_{-0.0013}$	< 0.007	0.568 ± 0.013	$0.0043^{+0.0009}_{-0.0010}$	< 0.0062	$0.197^{+0.007}_{-0.006}$	$0.0043^{+0.0008}_{-0.0009}$
1	< 0.075	0.985 ± 0.021	$0.0044^{+0.0010}_{-0.0013}$	< 0.071	0.568 ± 0.013	$0.0043^{+0.0009}_{-0.0011}$	< 0.067	0.198 ± 0.006	$0.0043^{+0.0008}_{-0.0009}$
0	< 0.553	0.987 ± 0.020	$0.0049^{+0.0011}_{-0.0013}$	< 0.547	0.569 ± 0.013	$0.0043^{+0.0009}_{-0.0010}$	< 0.514	0.199 ± 0.006	$0.0043^{+0.0008}_{-0.0009}$
-1	< 2.71	0.987 ± 0.020	$0.0049^{+0.0011}_{-0.0013}$	< 2.66	0.569 ± 0.013	$0.0043^{+0.0009}_{-0.0011}$	< 2.57	0.198 ± 0.0063	0.0042 ± 0.0008
-2	< 3.27	0.985 ± 0.021	$0.0041^{+0.0010}_{-0.0012}$	< 3.16	0.568 ± 0.013	0.0041 ± 0.0010	< 2.99	$0.198^{+0.007}_{-0.006}$	0.0042 ± 0.0009
-2.9	< 1.06	$0.986^{+0.021}_{-0.020}$	$0.0035^{+0.0017}_{-0.0013}$	< 1.04	0.570 ± 0.013	$0.0036^{+0.0015}_{-0.0011}$	< 1.03	0.200 ± 0.006	$0.0035^{+0.0015}_{-0.0009}$

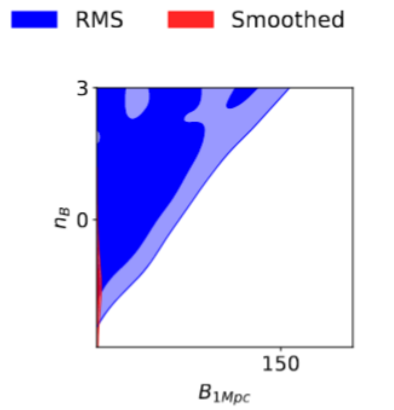




LiteBIRD with all biases					
Fiducial	Only Lensing Marginalization		Lensing and biases marginalization		
n_B	$B_{1\,Mpc}$ [nG]	A^{BB}_{Lens}	$B_{1\,Mpc}$ [nG]	A^{BB}_{Lens}	$A^{BB}_{FG-Syst-Bias}$
Marginalized	< 3.38	0.987 ± 0.020	< 3.46	0.987 ± 0.021	1.01 ± 1.0
2	< 0.007	0.987 ± 0.021	< 0.007	0.987 ± 0.020	1.00 ± 1.00
1	< 0.072	$0.986^{+0.021}_{-0.020}$	< 0.073	$0.986^{+0.020}_{-0.021}$	$1.02^{+0.98}_{-1.02}$
0	< 0.55	0.988 ± 0.021	< 0.54	$0.988^{+0.020}_{-0.021}$	1.00 ± 1.00
-1	< 2.70	0.987 ± 0.020	< 2.73	0.987 ± 0.020	$1.02^{+0.98}_{-1.02}$
-2	< 3.30	0.985 ± 0.022	< 3.32	0.986 ± 0.021	0.998 ± 1.00
-2.9	< 0.89	0.988 ± 0.020	< 0.89	0.988 ± 0.021	1.00 ± 1.00



FIRST TIME EVER IN LITERATURE

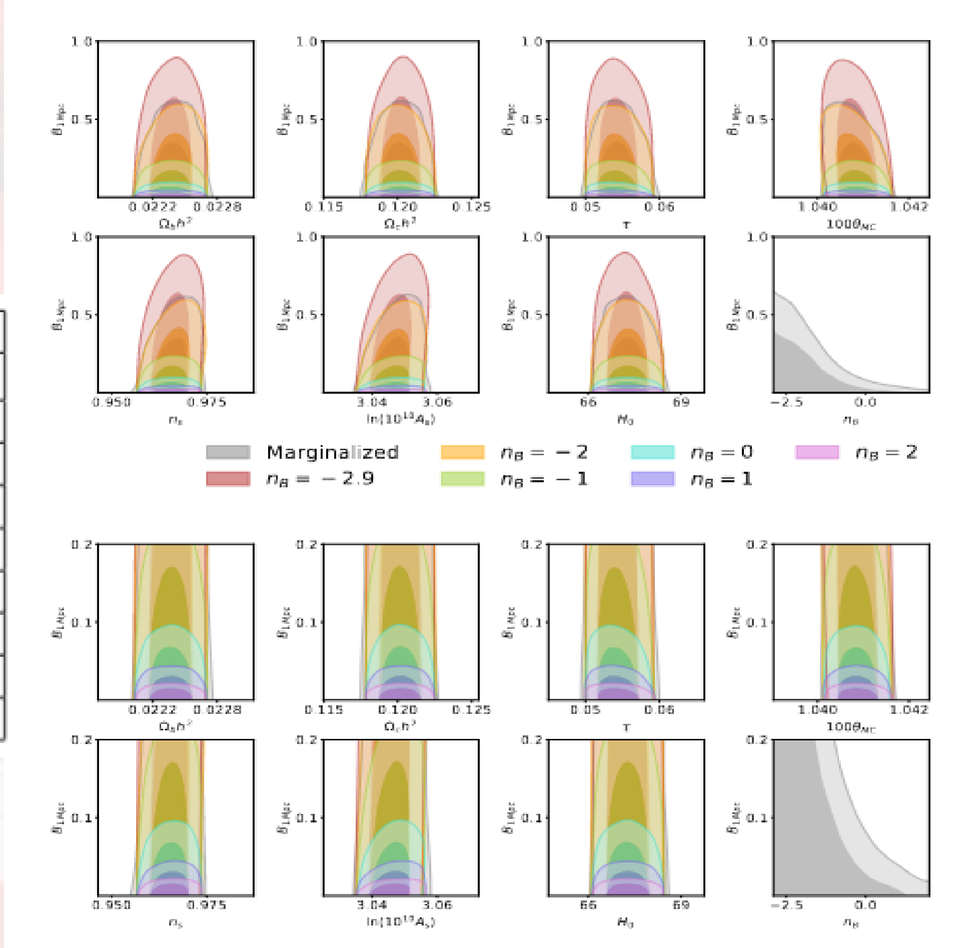


LiteBIRD with r.m.s.	
n_B	$\sqrt{\langle B^2 \rangle}$ [nG]
Marginalized	< 122.40
2	< 120.43
1	< 90.07
0	< 66.91
-1	< 43.45
-2	< 12.25
-2.9	< 0.76

EFFECTS ON THE IONIZATION HISTORY

MHD decaying turbulence		
n_B	$\sqrt{\langle B^2\rangle}$ [nG]	
Dataset	LiteBIRD (Planck 2018)	LiteBIRD + Planck
2	< 0.20 (< 0.18)	< 0.15
1	< 0.30 (< 0.27)	< 0.22
0	< 0.46 (< 0.41)	< 0.34
-1	< 0.67 (< 0.63)	< 0.54
-2	< 0.70 (< 0.79)	< 0.70
-2.9	< 0.76 (< 1.05)	< 0.72
[-2.9,2]	< 0.6(< 0.68)	< 0.58

Only instrument noise for TT and EE

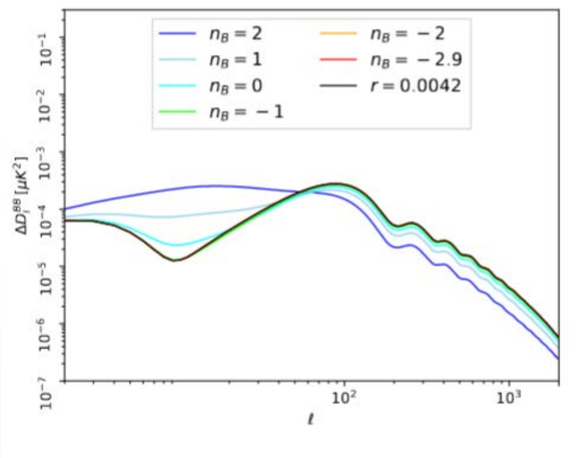


Combined effect		
n_B	$\sqrt{\langle B^2\rangle}$ (nG)	
	LiteBIRD (Planck)	LiteBIRD+Planck
2	< 0.018(< 0.06)	< 0.018
1	< 0.037(< 0.12)	< 0.037
0	< 0.080(< 0.26)	< 0.079
-1	< 0.20(< 0.56)	< 0.19
-2	< 0.48(< 0.79)	< 0.49
-2.9	< 0.73(< 1.06)	< 0.69
[-2.9,2]	< 0.50(< 0.69)	< 0.48

Ambipolar diffusion		
n_B	$\sqrt{\langle B^2\rangle}$ [nG]	
	LiteBIRD(Planck)	LiteBIRD+Planck
2	< 0.018(< 0.058)	< 0.018
1	< 0.037(< 0.12)	< 0.036
0	< 0.080(< 0.26)	< 0.078
-1	< 0.19(< 0.62)	< 0.19
-2	< 0.57(< 1.84)	< 0.58
-2.9	< 3.6(−)	< 3.6
[-2.9,2]	< 2.05(< 3.40)	< 1.95

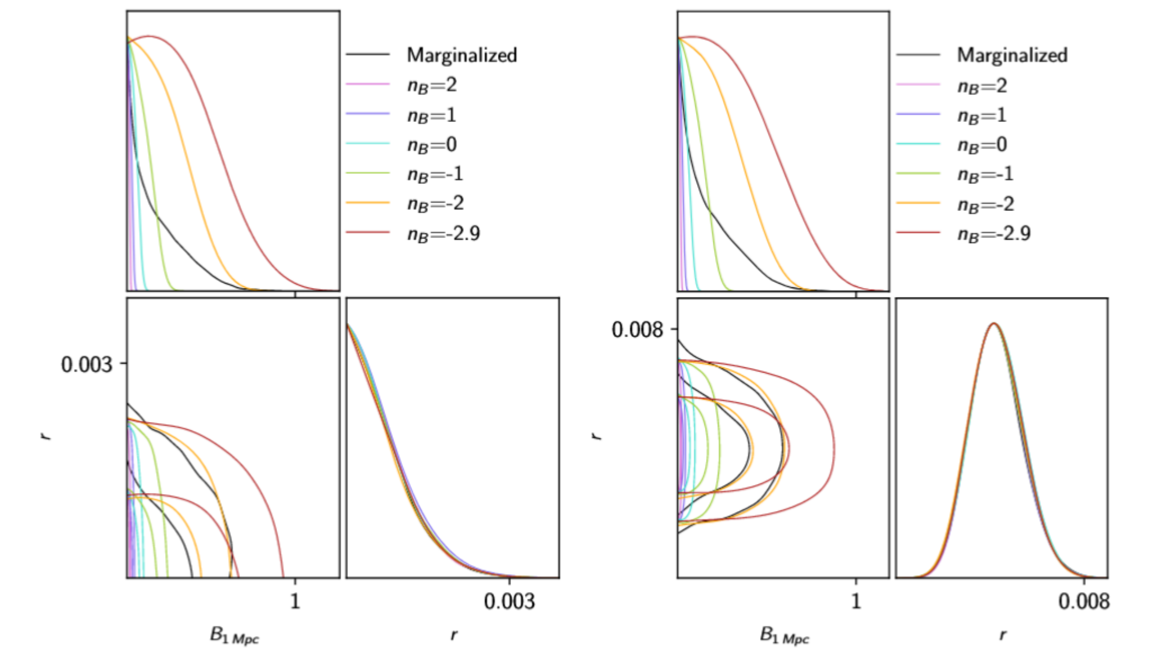
FIRST TIME IN LITERATURE – Effects on B-modes

B-modes in PTEP like mode



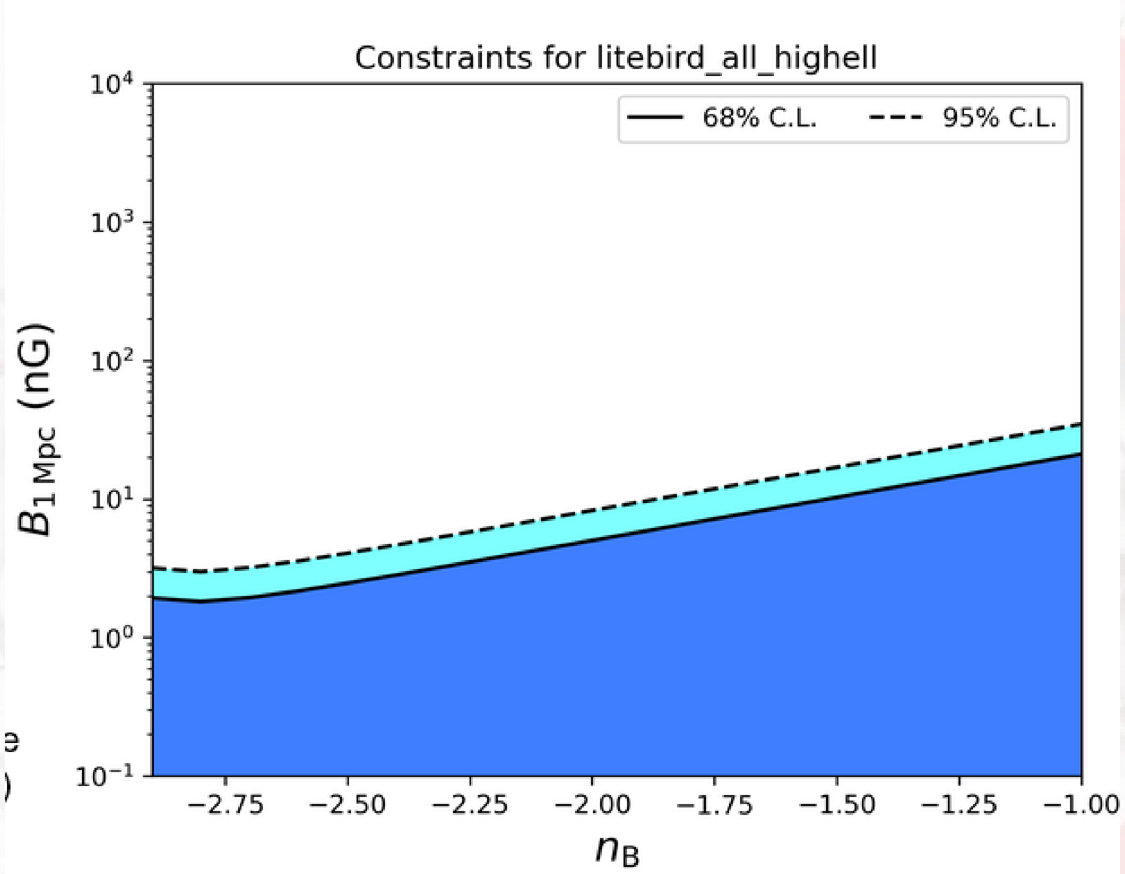
LiteBIRD TEB						
	AMBI		MHD		Combined	
n_B	$\sqrt{\langle B^2\rangle}$ (nG)	r [68%]	$\sqrt{\langle B^2\rangle}$ (nG)	r[68%]	$\sqrt{\langle B^2\rangle}$ (nG)	r[68%]
2	< 0.018	< 0.0018	< 0.20	< 0.0018	< 0.018	r < 0.0019
1	< 0.037	< 0.0018	< 0.30	< 0.0019	< 0.037	r < 0.0018
0	< 0.080	< 0.0017	< 0.46	< 0.0018	< 0.080	< 0.0018
-1	< 0.19	< 0.0018	< 0.65	< 0.0018	< 0.19	r < 0.0018
-2	< 0.58	< 0.0017	< 0.70	< 0.0018	< 0.50	r < 0.0018
-2.9	< 3.4	< 0.0018	< 0.75	< 0.0019	< 0.75	r < 0.0018
[-2.9,2]	< 1.82	< 0.0018	< 0.64	< 0.0018	< 0.49	r < 0.0018

Combined Heating and Inflation		
n_B	$\sqrt{\langle B^2\rangle}$ (nG)	r [68%]
Marginalized	< 0.47	$0.0043^{+0.0010}_{-0.0012}$
2	< 0.018	$0.0043^{+0.0010}_{-0.0012}$
1	< 0.037	$0.0043^{+0.0010}_{-0.0012}$
0	< 0.081	$0.0043^{+0.0011}_{-0.0012}$
-1	< 0.20	$0.0043^{+0.0010}_{-0.0012}$
-2	< 0.50	$0.0043^{+0.0011}_{-0.0012}$
-2.9	< 0.74	$0.0044^{+0.0010}_{-0.0012}$

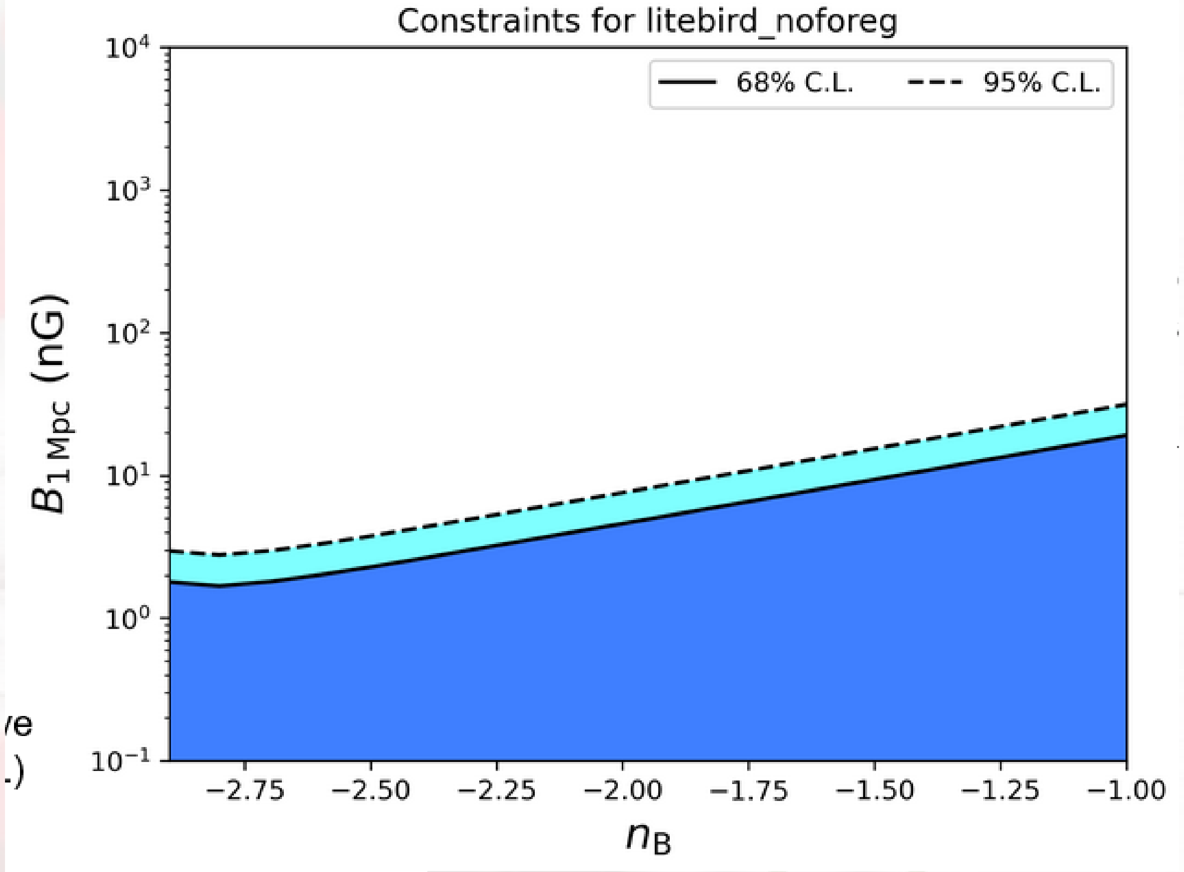


FARADAY ROTATION

Signal much brigther at lower frequencies, trade off with FG contamination we combine all channels with optimal weighting of channels below 100 GHz



For n_B=-2.9, we have 1.93nG (@ 68% CL)

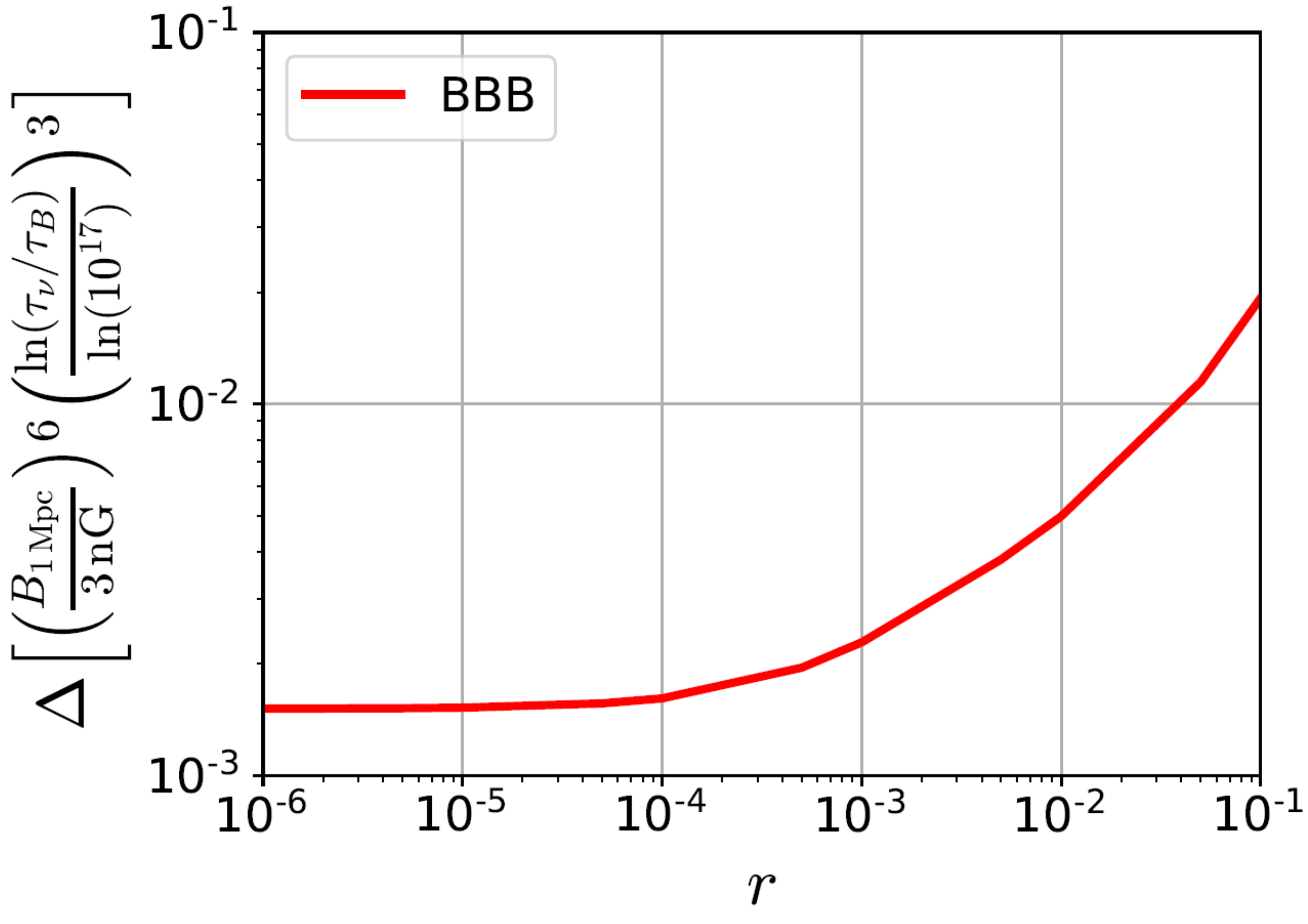


For n_B=-2.9, we have 1.79nG (@ 68% CL)

NON GAUSSIANITIES

1 sigma error on the magnetic bispectrum amplitude vs the tensor to scalar ratio, Includes all realistic bias (non-delensed lensing B-mode signal and residual foregrounds + instrumental noise) in the covariance and set fsky = 0.495.

BBB with LiteBIRD improves by 3 order of magnitude current constraints on the bispectrum amplitude breaking the nGauss level for the PMF amplitude.



PAPER II NOT FOLLOWING ORIGINAL PROPOSAL

LiteBIRD made the big mistake to put together some of the main experts in the PMF field discussing every other week..

Paper II will go much beyond inclusion of helicity which already is a breaktrhough in many analyses and LiteBIRD is one of the very little possibilities to improve on this side

We are now discussing extensions for all analyses including very cutting edge theoretical developments

We will include completely new approaches

Timescale will shift but we it will worth it!

PMFs CONTEXT IN ITALY AND BEYOND

Just two days after making DP sign a 1 year contract INAF selected DP proposal for a 10-year long program in the «NEW IDEAS» (7 selected in the whole INAF) presented at the INAF-GIORNATE NAZIONALI

Everyprobe, Everywhere, All Magnetic Fields at once

Daniela Paoletti *INAF-OAS*

Fabio Finelli *INAF-OAS*
Elisa Prandini *UniPd - associated INAF*
Franco Vazza *Unibo - associated INAF*
Carlo Baccigalupi *SISSA - associated INAF*
Dhiraj Hazra *IMSC Chennai - associated INAF*
Diego Molinari *Cineca - associated INAF*

The current INAF side of the magnetic force

It is a program which aims at reconstructing the history of Universe Magnetism from the Big Bang to our days and the implications this has for the fundamental physics in the early Universe

There are three main players into this game:

- Primordial Magnetic Fields and their impact on cosmological probes as Cosmic Microwave Background and Galaxy surveys and the associated constraints we can derive from them
- MHD Simulations of structure formation. Evolving initial magnetic fields into the ones we observe today (Challenges: large excursion in dynamical range and many different physical processes to account for)
- Observations of current Cosmic Magnetism from radio (LOFAR..SKA) to gamma rays (*Fermi*, MAGIC..CTA).

The sum is greater than its single addends.
If you put together the three you have

Everyprobe, Everywhere, All Magnetic Fields at Once

The new Idea is stricly related to the scheda INAF, 10 y program, «Good OMENS: Good Old Magnetism in the Early uNiverse». In March 2023 I submitted the proposal for a minigrant (20K over two years) «Gathering Good OMENS» crossed between the Good OMENS and the LiteBIRD scheda

If won (very bad omens) it will be dedicated to have visiting scientists in Bologna for developments crucial for LiteBIRD activities on PMFs.

THIS IS NOT THE END....