SEARCHING FOR A SMOKING GUN OF MAGNETIC FIELDS IN THE EARLY UNIVERSE:
A NAPOLEONIC TACTIC FOR THE CMB!

Daniela Paoletti

Background images Carlo Sa design for HBO

About myself

I am a mythological creature in the Italian National Institute of Astrophysics (INAF)
The «Precaria Highlander»
A INAF-Bologna postodoc for 14 years, under INAF contract for 18...
Not really immortal but with a nice couple of swords!

I work in cosmology, from study of inflation to the reionization, passing through modified gravity and cosmic birefringence.

I have been working on Primordial Magnetic Fields since my master thesis in 2006

I have been the leader of the Planck working group dedicated to primordial magnetic fields from 2013 until the end of the collaboration

I am currently the leader of the project study group of LiteBIRD dedicated to primordial magnetic fields

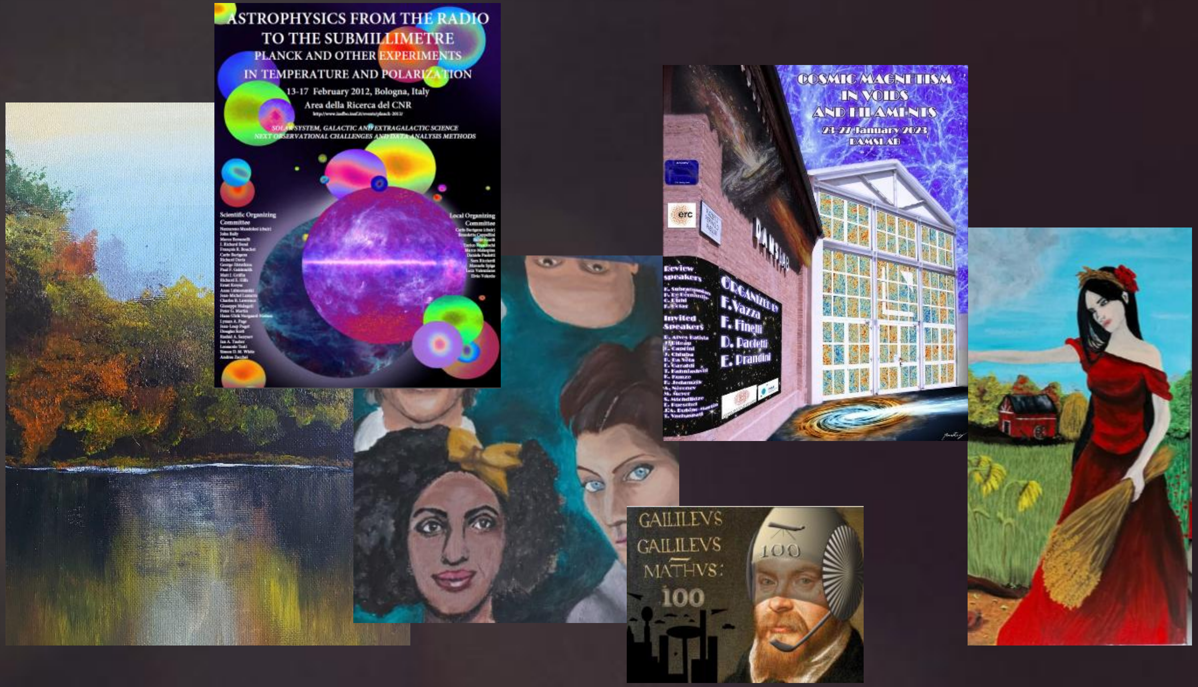
I am the coordinator of the Good OMENS, Good Old Magnetism in the Early uNiverSe, program in INAF

Alter Ego..second job

I am also an artist, classical and digital (2 and 3D), with the pseudonym Peracturus

And also here enter magnetic fields
My current challenge is answering the question

How do you paint Primordial Magnetic Fields like Van Gogh painted the sky and Monet the dawns?



Third Mission...third job

Inventing totally crazy and unthinkable games and VR experiences for education and outreach within

PLAY INAF

https://play.inaf.it/accendi-la-tua-stella/

LiteBIRD PMF Group

- J.A. Rubino-Martin *IAC- La Laguna*
- M. Shiraishi *Suwa University of Science*
- D. Molinari *Cineca*
- J. Chluba *Manchester University*
- F. Finelli *INAF-OAS Bologna*
- C. Baccigalupi *Sissa*
- J. Errard *APC-Paris*
- A. Gruppuso *INAF-OAS Bologna*
- A. Lonappan *San Diego University*
- A. Tartari *INFN-Pisa*
- L. Porcelli *INFN-Frascati*

Non-LiteBIRD Group and Collaborators

- Fabio Finelli *INAF-OAS Bologna*
- Alex Ciabattoni *INAF-OAS Bologna*
- Kandu Subramanian *IUCAA*
- J.A. Rubino-Martin *IAC- La Laguna*
- J. Chluba *Manchester University*
- Franco Vazza *Unibo*
- Adam Andrews *INAF-OAS Bologna*
- Dhiraj Hazra *IMSC Chennai*
- Chiara Caprini *Geneve University*
- C. Baccigalupi *Sissa*
- E. Prandini *Unipd*
- Matteo Viel *Sissa*
- ...

So basically what I do for good part of my days is chasing the giant Cosmic Elephant (in the cosmology room) Called Primordial Magnetism Through the Cosmic Microwave Background

CMB

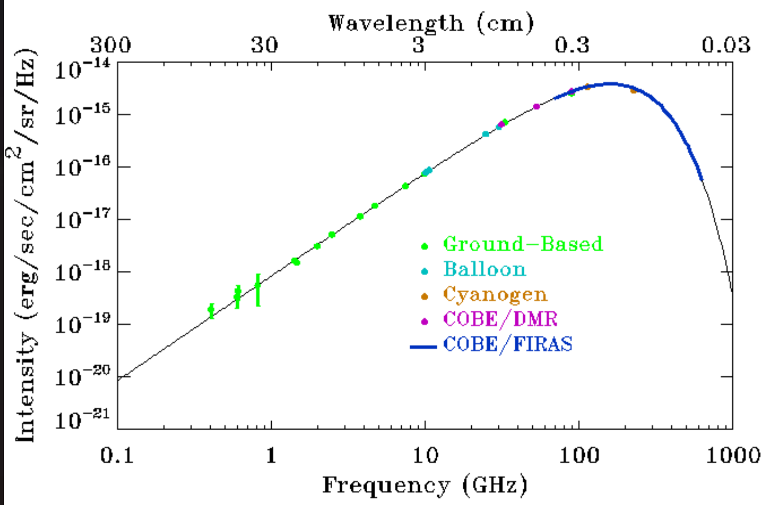
And other cosmological probes

THE CMB

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
Clusters of galaxies
Galaxy
Solar System
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
1 billion years
10 billion years
13.82 billion years
POLICE BOX

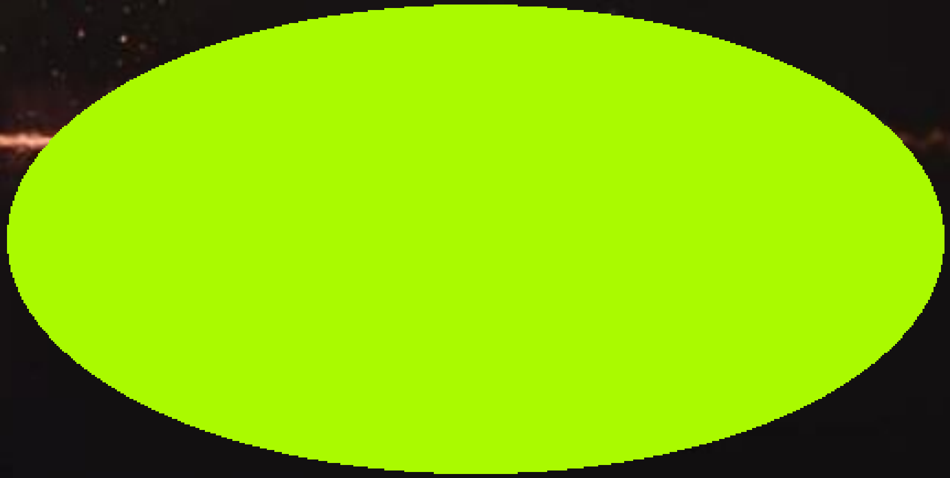
You are here!

CMB is the only perfect (almost) black body known in nature
Its spectrum is the mirror of the equilibrium between matter and radiation at its emission



Possible deviations from the BB are called spectral distortions and may trace poorly known processes as the recombination or exotic mechanisms of energy injections as the annihilation of dark matter particles or indeed PMFs

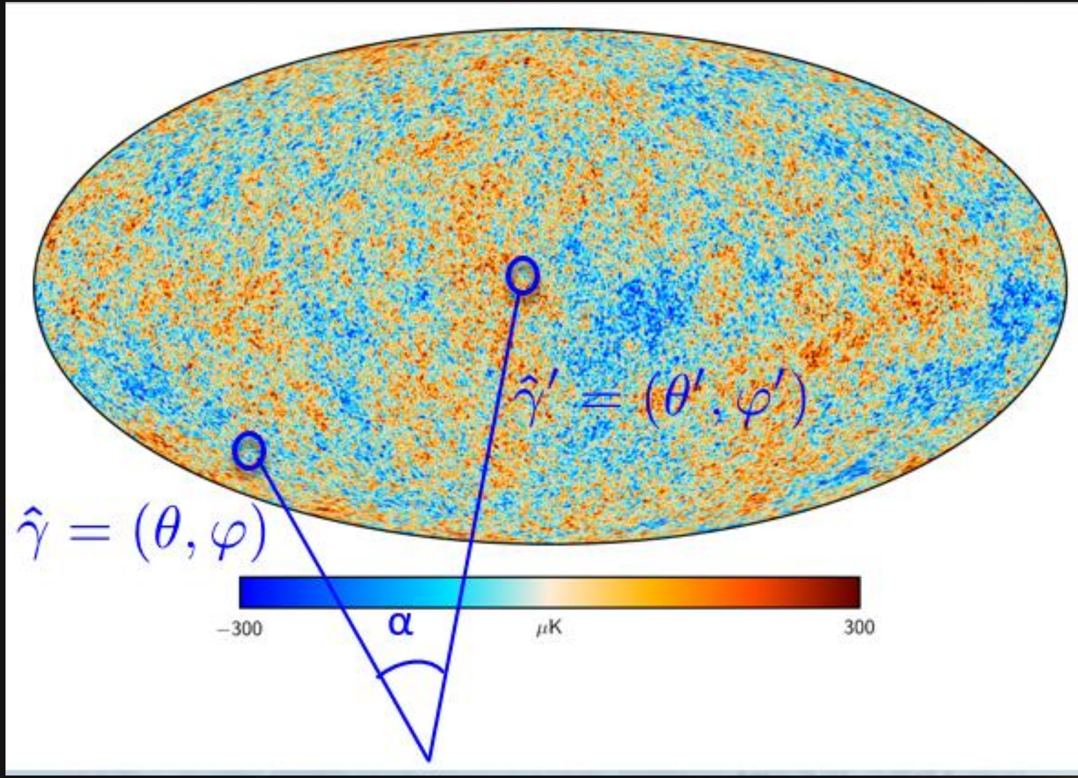
MONOPOLE



$\mathbf{T_0 = 2.7255 \pm 0.0006\ K}$

$\mathbf{Tr = 2.725(1 + z)}$

$\mathbf{Freq_{peak} = 160.24\ GHz}$

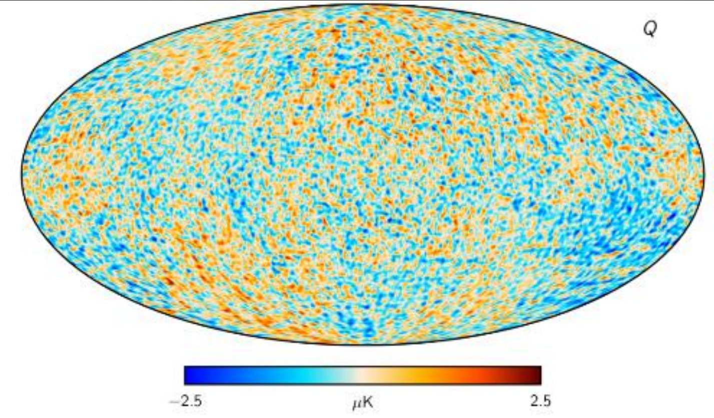


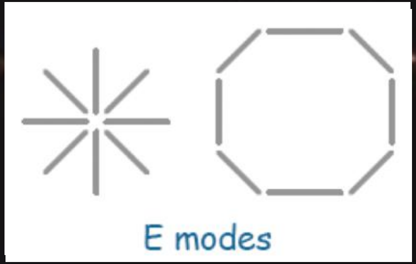
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}')\right\rangle$$

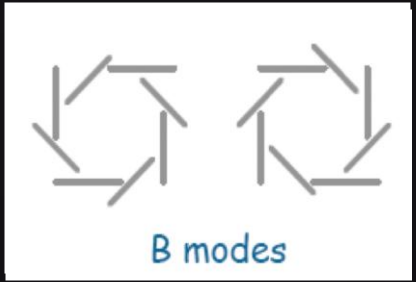
$$\Delta T(\vec{x},\hat{n},\tau) = \Sigma_{l=1}^{\infty}\Sigma_{m=-l}^{l} a_{lm}(\vec{x},\tau)Y_{lm}(\hat{n})$$

$$C_l = \frac{1}{2l+1}\Sigma_m \langle a_{lm}^{*} a_{lm}\rangle$$

POLARIZATION





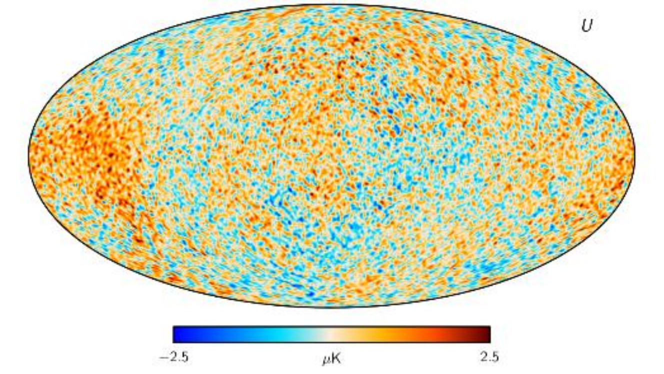


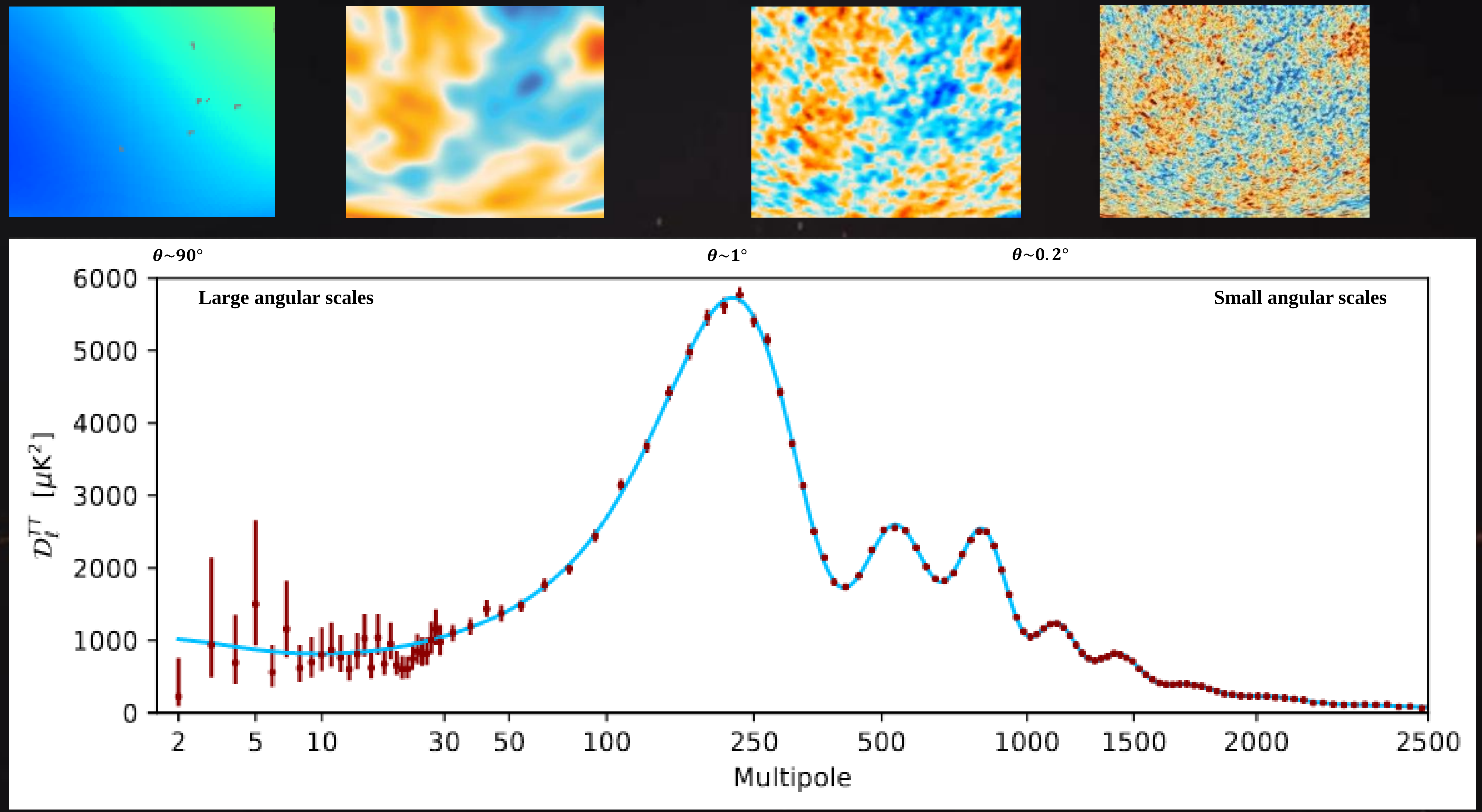
Weakly polarized
Q and U stokes are replaced by rotationally invariant E and B

E-modes: even under parity

B-modes: odd under parity

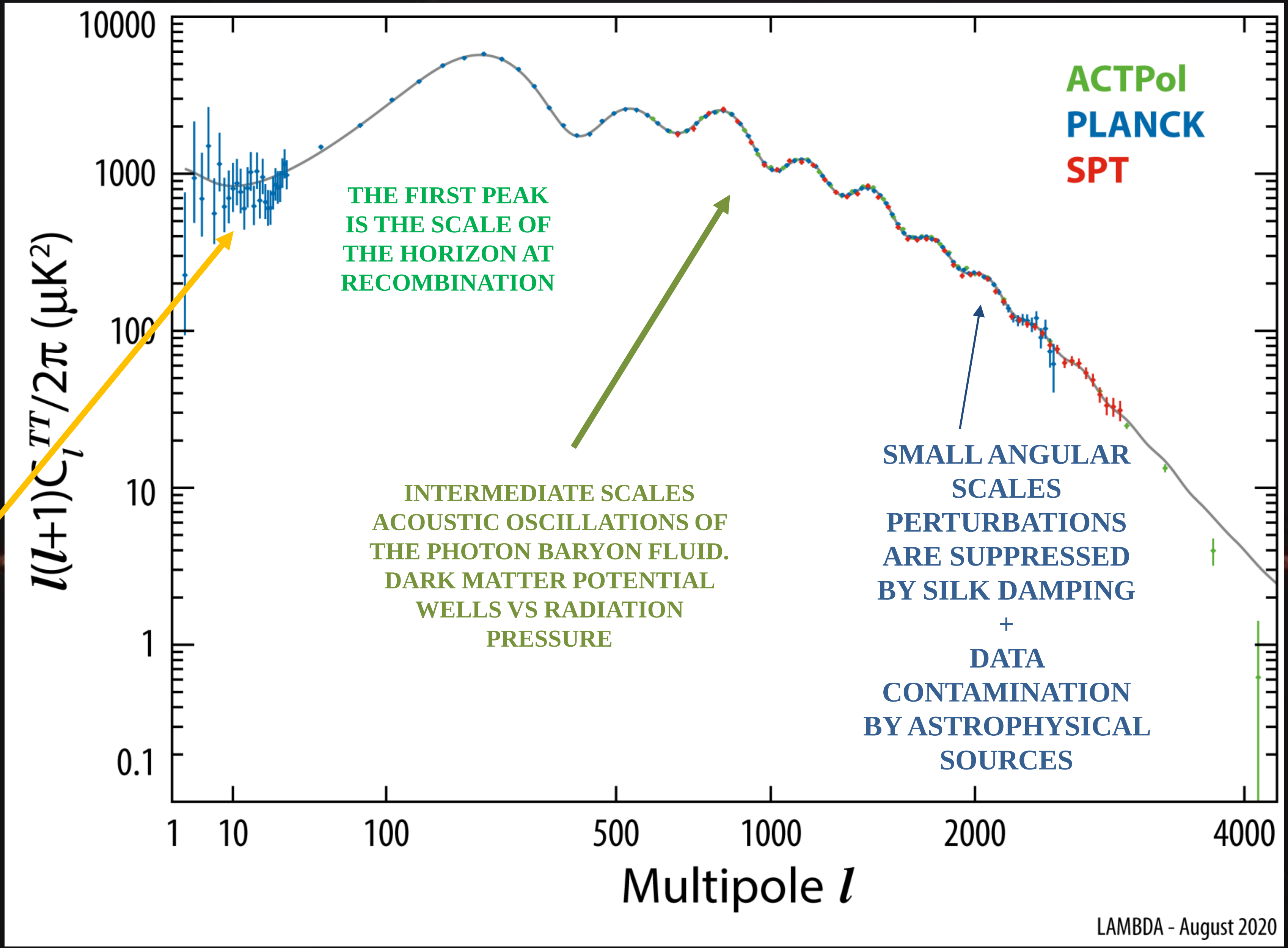
Remember: E-modes are produced by normal fluctuations. B-modes are produced only by additional contributions as inflation or PMF!





θ~90°
θ~1°
θ~0.2°
Large angular scales
Small angular scales
$\mathcal{D}_\ell^{TT}$ [μK^2]
Multipole

Temperature

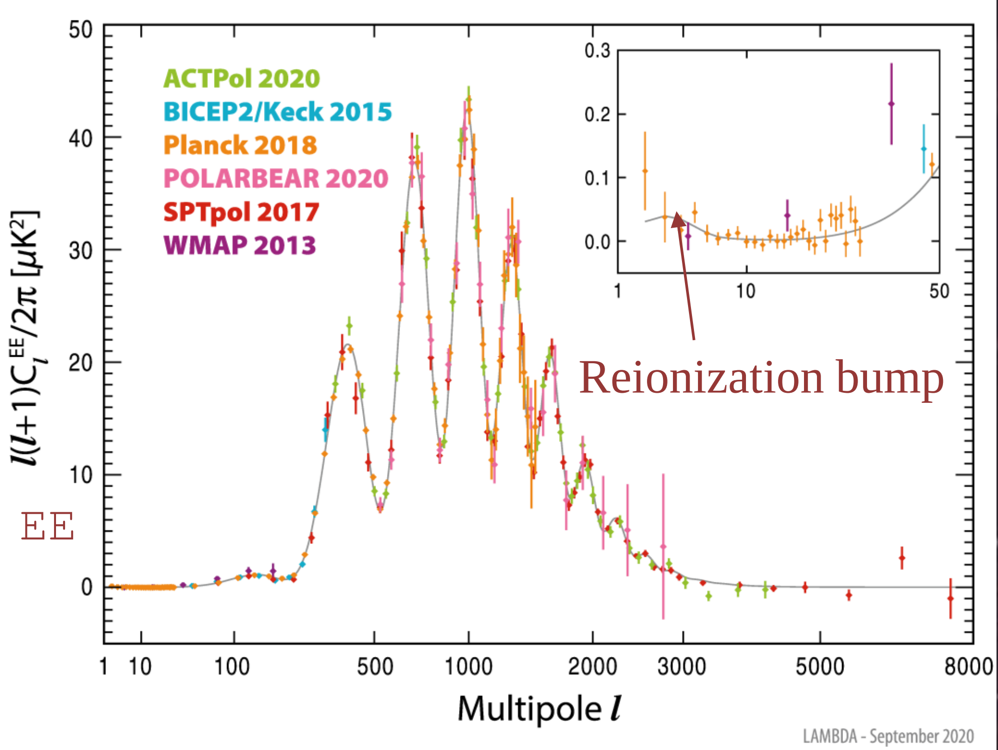


LARGE ANGULAR SCALES ARE SCALES OUTSIDE THE HORIZON AT RECOMBINATION. ONLY GRAVITY

Since Planck has almost exhausted the power of temperature
we are now entering in a new era
where the new physics lies hidden

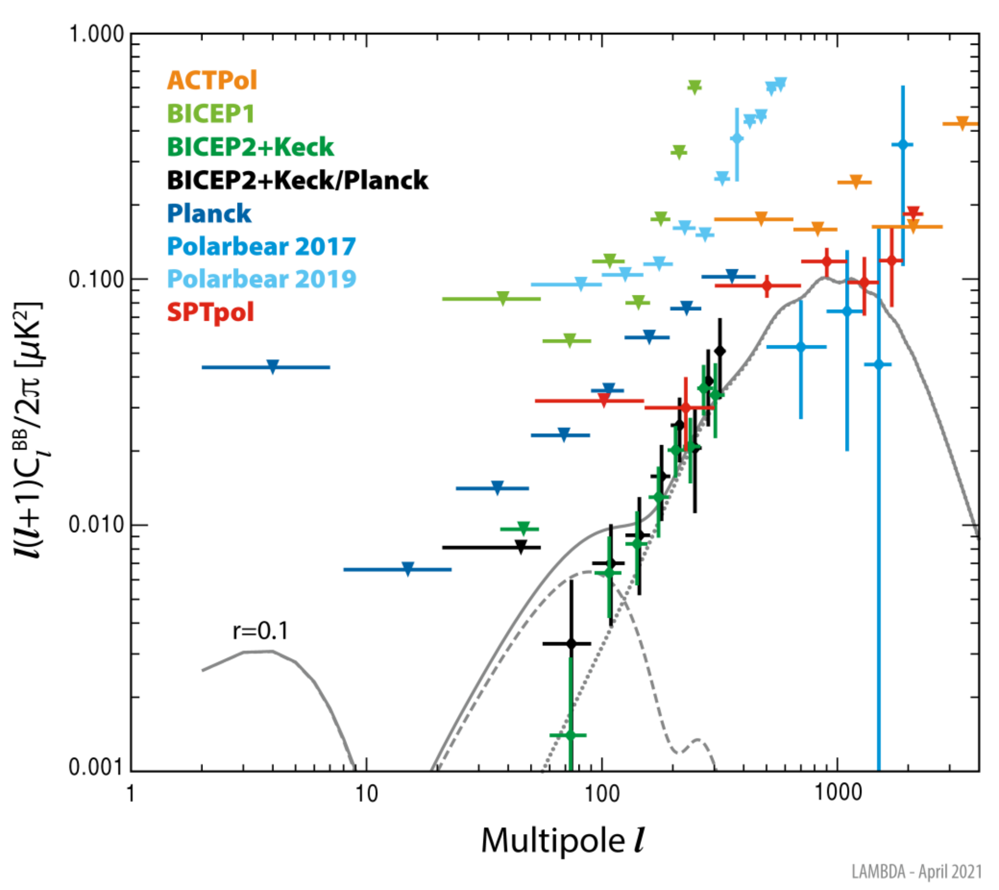
The era of CMB polarization

...that is not as easy as temperature...



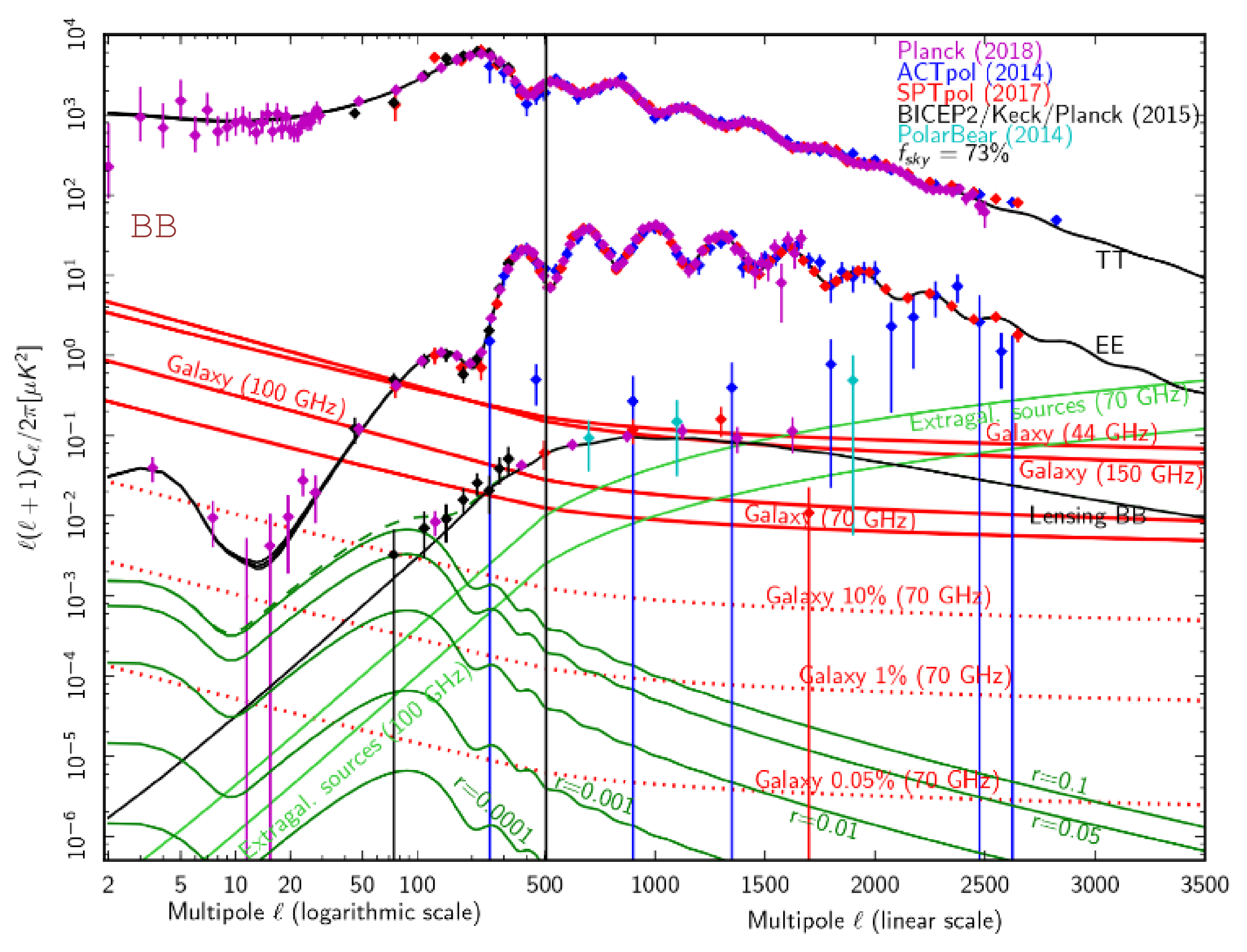
E-mode polarization is less contaminated by FG at small angular scales and the sharpness of the peaks in the future will allow to provide even stronger constraints than temperature in many parameters.

Tracer of reionization



B-Mode not generated by scalar fluctuations...either inflation...or exotic physics as primordial magnetic fields or birefringence

Courtesy of Molinari, Mandolesi, Burigana



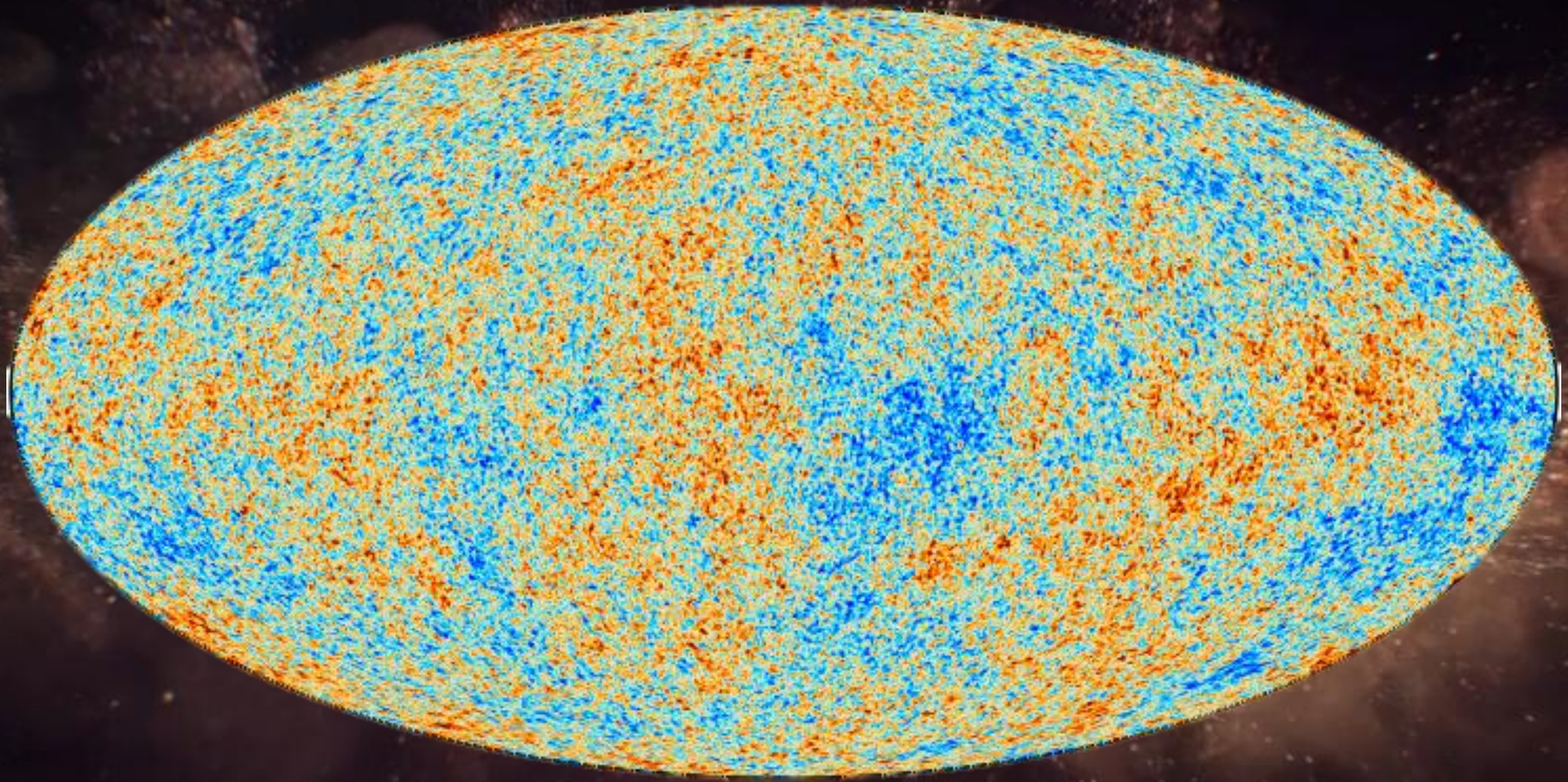
B-modes are related to the primordial tensor mode and in particular to the energetic scale of inflation and its dynamics.

B-MODES ARE BASICALLY THE HOLY GRAIL OF INFLATION

MAYBE..

THE CHALLENGE OF OBSERVING THE MICROWAVE SKY

WHAT WE WANT TO SEE



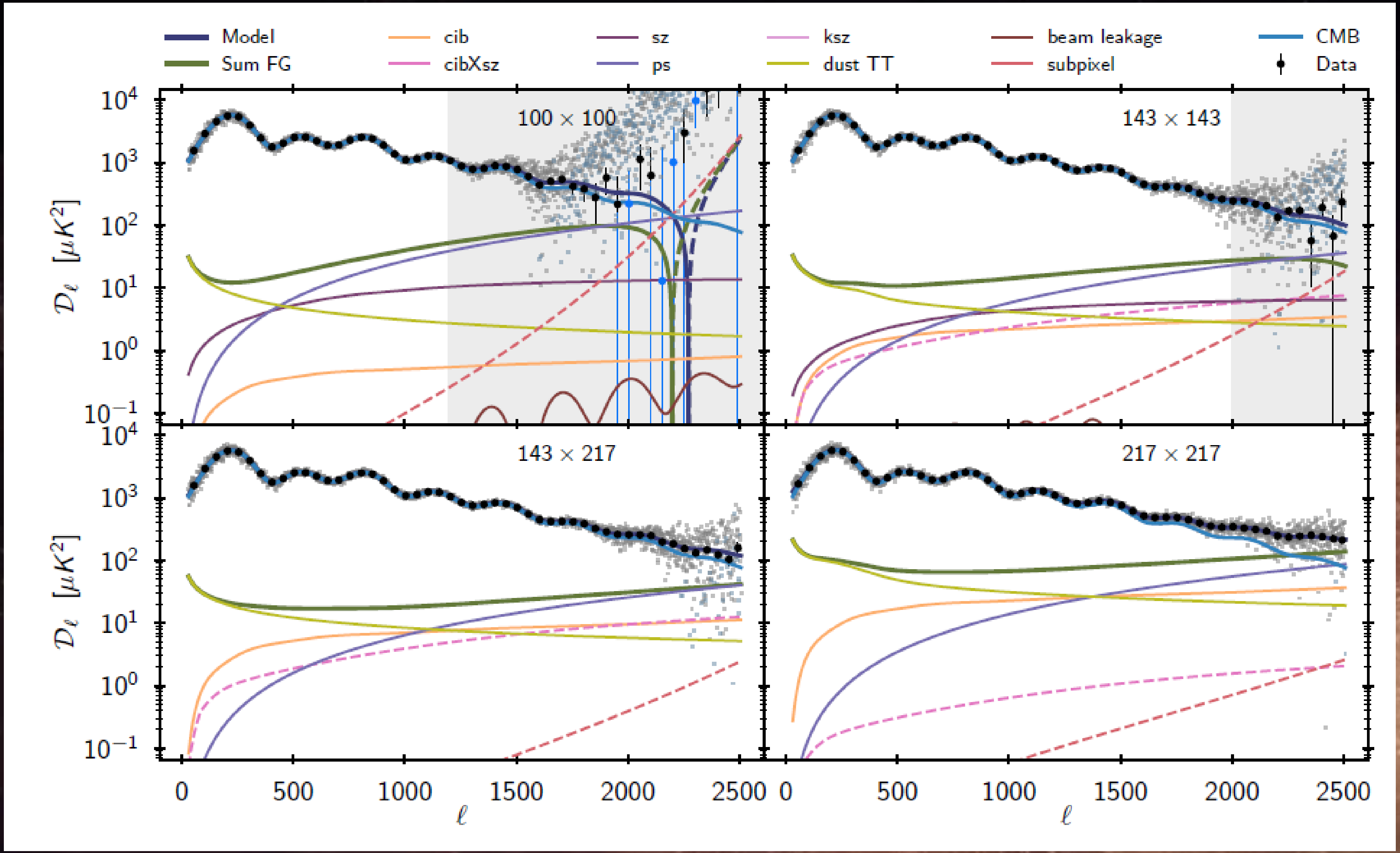
WHAT WE ACTUALLY SEE

WHAT WE NEED TO REMOVE

The microwave sky is a mess and we need to recognize the fleebe signal of the CMB in a sea of astrophysical and secondary anisotropies signals. This is done with likelihood template fitting for SZ and point sources; Component Separation algorithm for diffuse foregrounds and De-lensing for the lensing contribution

MAIN CONTRIBUTIONS (rated by the devilman scale of badness):

- **SUNYAEV ZELDOVICH:** Thermal is well known and subtractable; Kinetic contributes only on very high multipoles NOT POLARIZED 
- **POINT SOURCES NOT-DETECTED:** Poissonian term well known flat Cls depending on number counts; Cosmic Infrared Background contributes also with clustering term more complex but affects only temperature. POLARIZED (Radio sources on low and intermediate frequencies) 
- **LENSING:** deflection of CMB photons by large scale structure – produced B mode signal on intermediate and small scales 
- **CO LINES:** Planck provided an amazing map of the three transitions affecting the region around 100 GHz POLARIZED? 
- **SYNCHROTRON:** Dominant at low frequencies but contribution extends up to 100GHz POLARIZED 
- **GALACTIC DUST:** Is everywhere, is terribly bright and probably changes spectral shape at highest frequencies. POLARIZED 



Planck 2018 V

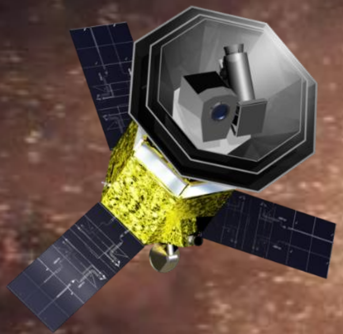
Observing the CMB

In order to perform the best possible measurement of the CMB we need in both temperature and polarization:

- sensitivity,
- resolution for the small scales,
- full sky coverage for the large angular scales and reduce the sample variance;
- wide frequency coverage to clean the signal from astrophysical contamination

SPACE

LiteBIRD



GROUND

2024 - #10000 detectors both large (fsky 0.4) and small aperture telescopes

Abitbol +2019

202X+ - #100000 detectors. Combination of ~~South Pole~~ and Atacama sites

Abazajian+2019

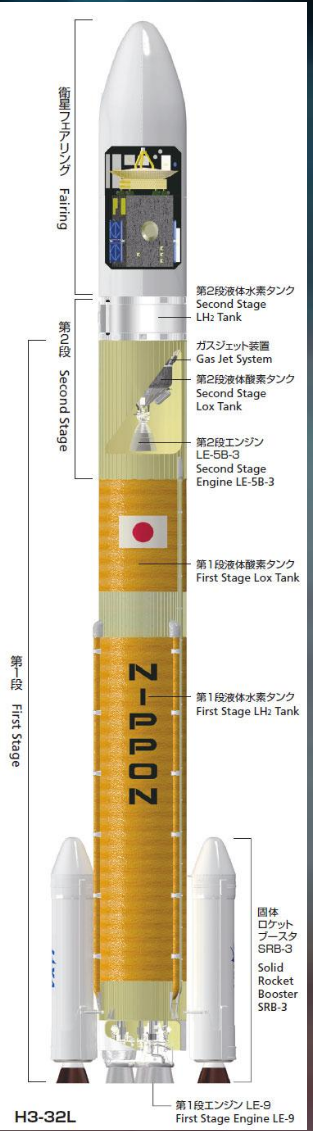
PUTTING TOGETHER SPACE AND GROUND 202X YEARS WILL SEE AN AMAZING MEASUREMENT OF CMB POLARIZATION ON THE WHOLE OBSERVATIONAL WINDOW

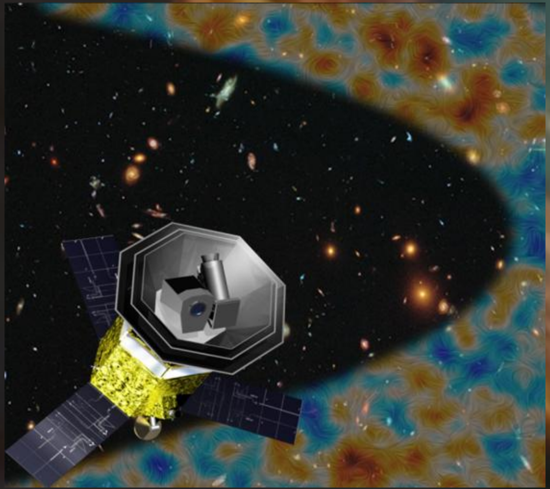

LITEBIRD

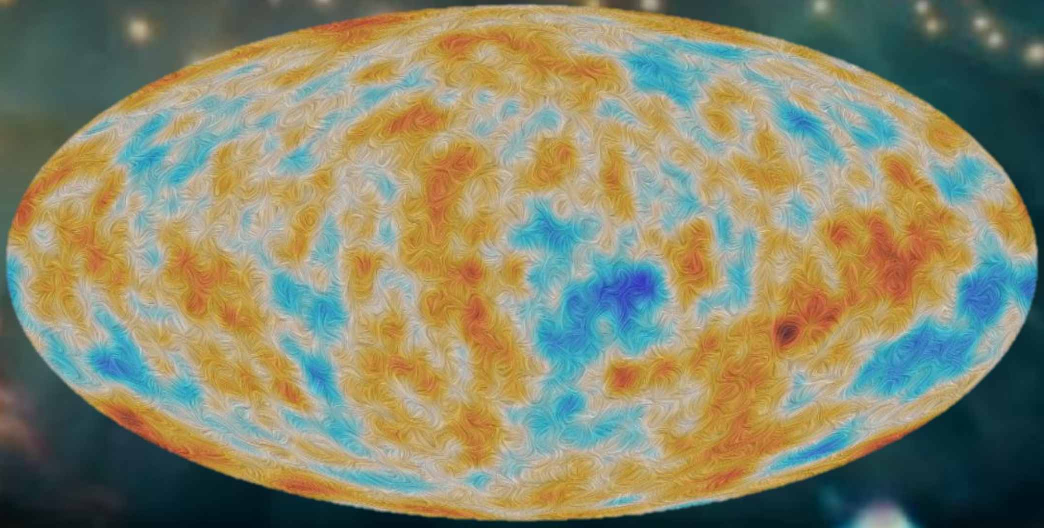
OVERVIEW

- Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in **JFY 2032** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB B-modes
- Final combined sensitivity: **2.2 μK·arcmin**

LiteBIRD collaboration PTEP 2023



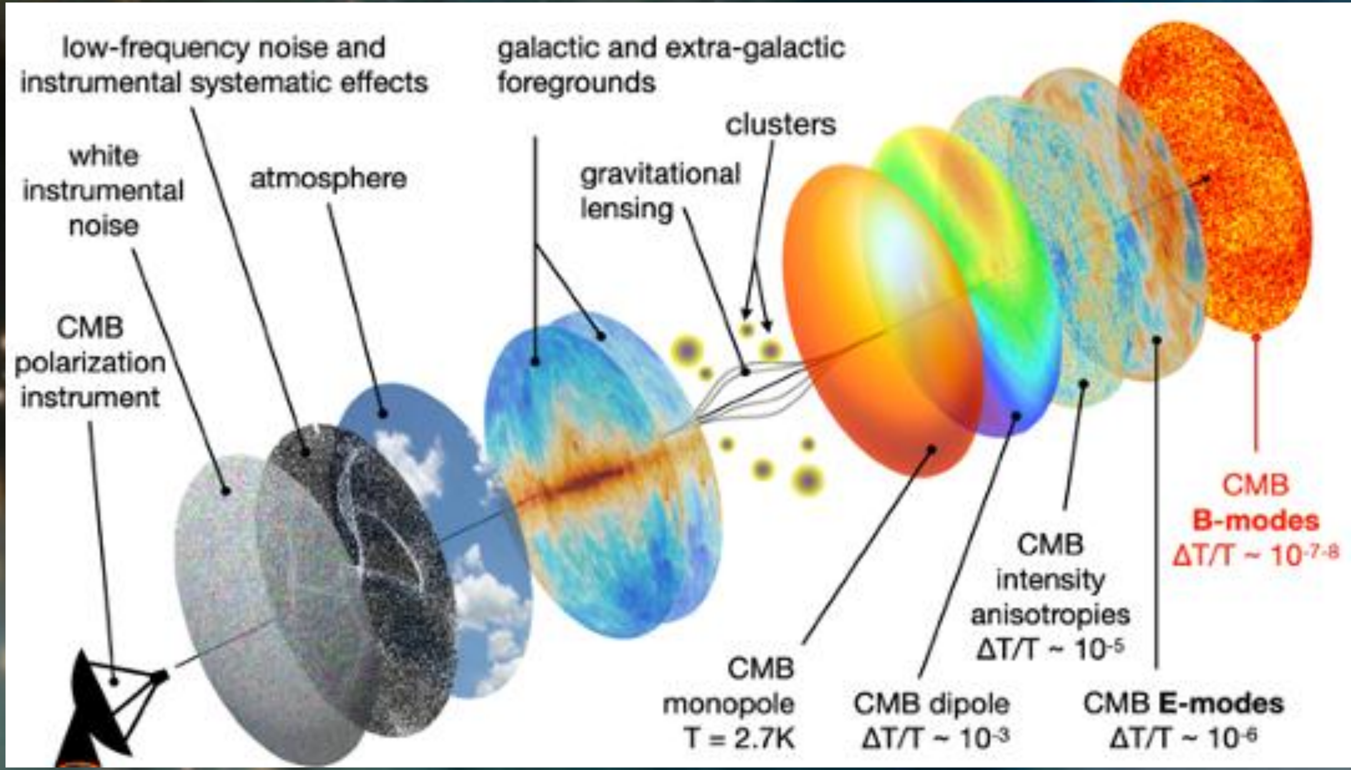




Credits: Peracturus

THE CHALLENGE OF MEASURING B-MODES

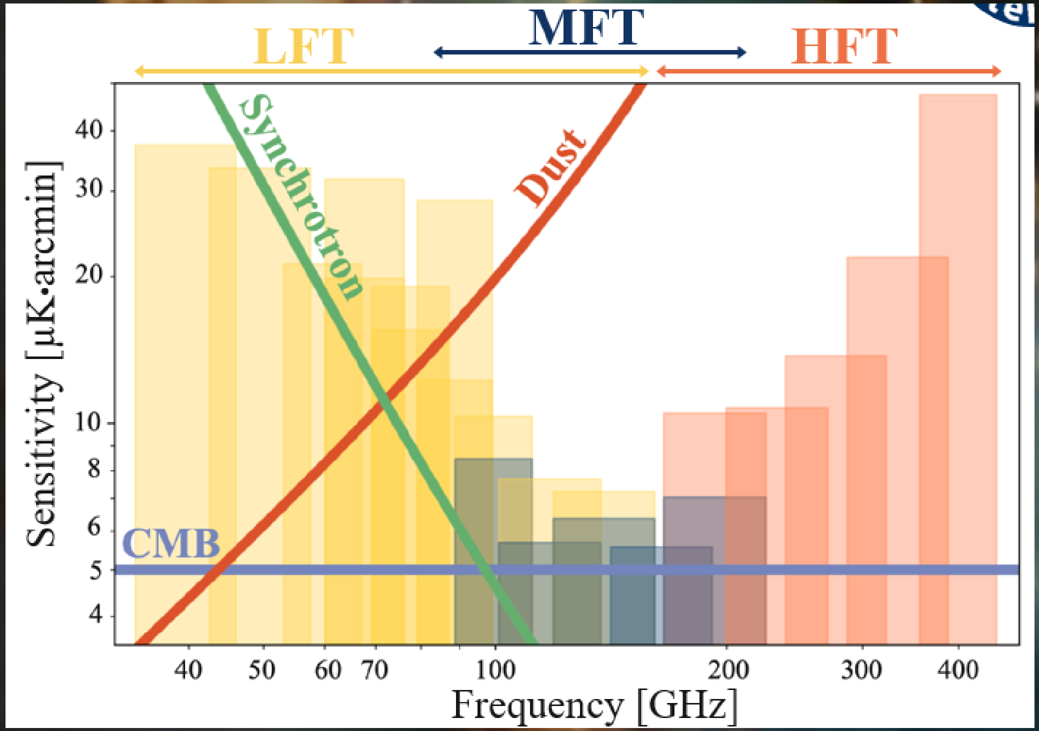
- The B-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- LiteBIRD is targeting a sensitivity level in polarization ~30 times better than Planck
- This extremely good statistical uncertainty must go in parallel with exquisite control of:
  - Instrument systematic uncertainties
  - Galactic foreground contamination
  - "Lensing B-mode signal" induced by gravitational lensing
  - Observer biases

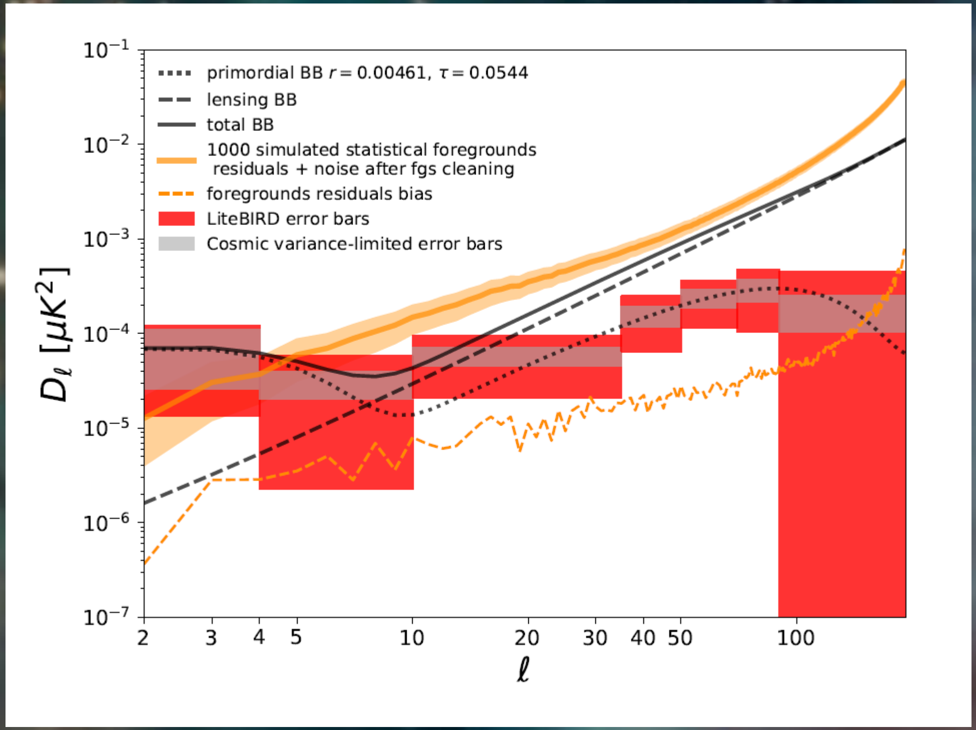


Credits: Josquin Errard

How can we face this challenge?

- Frequency coverage!
- Sensitivity!
- Systematics control!

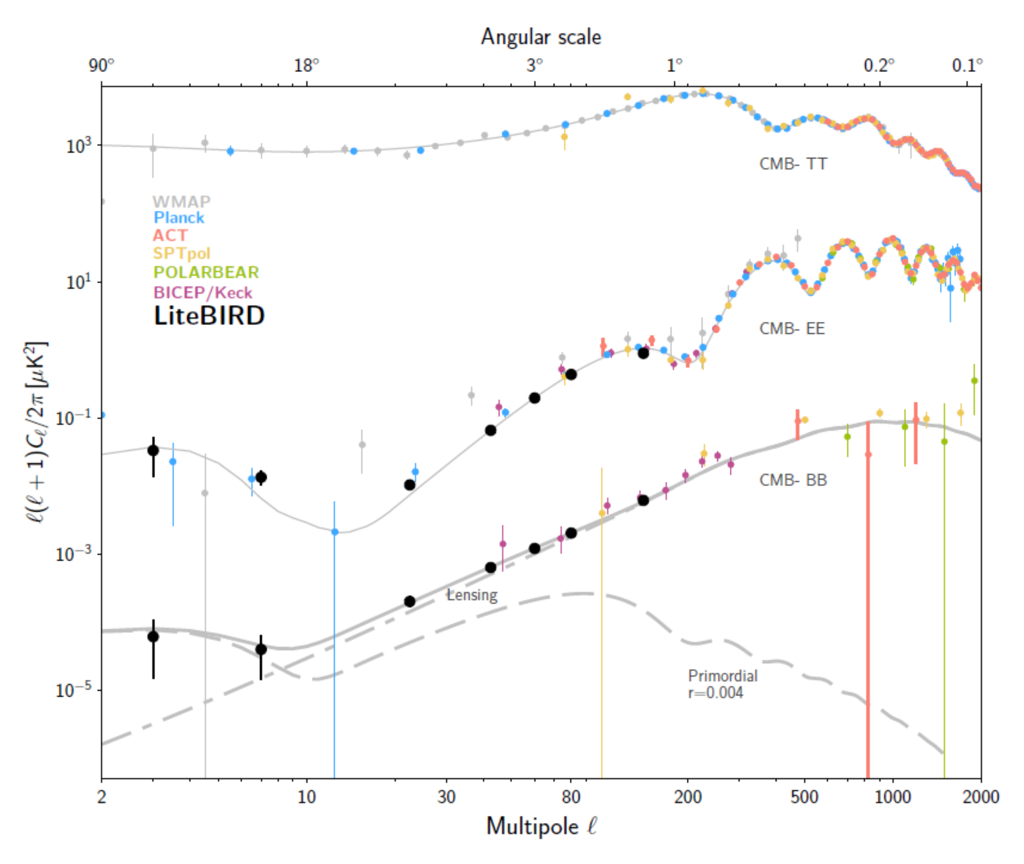




LiteBIRD Coll. PTEP 2023

LiteBIRD main science goals

- **Definitive search for the B-mode signal from cosmic inflation in the CMB polarization**
- Making a discovery or ruling out well-motivated inflationary models Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) B-mode power is proportional to the tensor-to-scalar ratio, r
- Current best constraint: r < 0.032 (95% C.L.) *Tristram+ 2021, combining BK18 and Planck PR4*
- **LiteBIRD will improve current sensitivity on r by a factor ~50**
- L1-requirements (no external data):
  - For r = 0, total uncertainty of δr < 0.001
  - For r = 0.01, 5-σ detection of the reionization (2 < ℓ < 10) and recombination (11 < ℓ < 200) peaks independently
- L2-requirements:
  - σstat < 6×10-4 and σsys < 6×10-4
  - Additional security margin of σmargin < 6×10-4



LiteBIRD Coll. PTEP 2023

PRIMORDIAL MAGNETIC FIELDS
AND
THE CMB

THE QUEST FOR OUR SMOKING GUN IS OPEN

PRIMORDIAL MAGNETIC FIELDS IN THE EARLY UNIVERSE

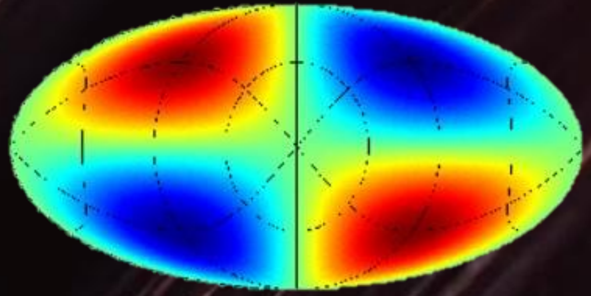
On one side, seeds for cosmic magnetism
On the other, smoking gun of violations of standardness of fundamental physics, weird things, ultraweird things
Indeed generating MFs in the early Universe is tricky, for example we can have

- Weird things in fundamental physics in the causal Universe with first order phase transition with the **CAUSAL MECHANISMS** – and then start an inverse cascade to solve the small coherence length issue, probably implying helical fields *Sigl+ 1997, Boyanovsky and de Vega 2005, Ellis+ 2019 , Zhanget+ 2019, Vachaspati 1991, Quashnock+ 1989, Hindmarsh and Everett 1998, Grasso and Riotto 1998, Ahonen and Enqvist 1998, Baymet+ 1996,Tevzadze+ 2012 , Caprini+ 2009..* ***CAUSAL MECHANISMS ARE BOUNDED TO SCALE DEPENDENCES WITH SPECTRAL INDEX EQUAL OR GREATER THAN 2***

- Weird things in fundamental physics in the inflationary Universe with additional fields, couplings with the inflaton, breaking of conformal invariance – **INFLATIONARY MECHANISMS** -and then solve the strong coupling and the back reaction problems, BUT COHERENCE LENGTH IS FINE! *Turner and Widrow 1988 , Ratra 1992, Giovannini and Shaposhnikov 2000, Tornkvist+ 2001, Bamba and Yokoyama 2004, Ashoorioon and Mann 2005, Demozzi+ 2009, Kanno+ 2009, Caldwell+ 2011, Jain+ 2014, Fujita+ 2015 ...list totally uncomplete.*
  SPECTRAL INDEX RELATED TO THE SPECIFIC MECHANISM

Either ways stay weird!

MODEL AND PARAMETRIZATION



HOMOGENEOUS FIELD:

- **PRO:** Easiest field possible
- **CONS**: Most complex Universe possible.
  Very difficult to generate with local processes

STOCHASTIC BACKGROUND:

- **PRO:** Can be generated by local processes
  Random fields Gaussianly distributed
  Same old FLRW Universe
- **CONS:** Parametrizations are pretty variable. Result representation depends on it

Ideal MHD Limit

$$P_B(k) = A_B\, k^{n_B}$$

$$\vec{B}^{(\mathrm{phys})}(\vec{x},\tau) = \vec{B}(\vec{x})/a(\tau)^2,$$

$$\left\langle B_i(\vec{k})\, B_j^*(\vec{k}')\right\rangle = \frac{(2\pi)^3}{2}\,\delta^{(3)}(\vec{k}-\vec{k}')\left(\delta_{ij}-\hat{k}_i\hat{k}_j\right) P_B(k),$$

$$B_\lambda^2 = \int_0^\infty \frac{dk\,k^2}{2\pi^2}\, e^{-k^2\lambda^2} P_B(k) = \frac{A_B}{4\pi^2\lambda^{n_B+3}}\,\Gamma\left(\frac{n_B+3}{2}\right)$$

$$\langle B^2(k)\rangle = \frac{A_B}{2\pi^2}\frac{k_D^{n_B+3}}{n_B+3}$$

$$k_D = (5.5\times 10^4)^{\frac{1}{n_B+5}}\left(\frac{B_\lambda}{\mathrm{nG}}\right)^{-\frac{2}{n_B+5}}\left(\frac{2\pi}{\lambda/\mathrm{Mpc}}\right)^{\frac{n_B+3}{n_B+5}} h^{\frac{1}{n_B+5}}\left(\frac{\Omega_b h^2}{0.022}\right)^{\frac{1}{n_B+5}}\Big|_{\lambda=1\,Mpc}\mathrm{Mpc}^{-1}$$

Subramanian & Barrow 1998, Jedamzik+1998, Mack+2002

Sharp cut off due to suppression of magnetosonic waves by radiation viscosity

THE MAIN EFFECTS OF PMFs ON THE CMB

GRAVITATIONAL : PMFs are an extra relativistic component in the plasma. They generate independent cosmological perturbations and additional angular power spectra in TT-TE-EE-BB *Subramanian & Barrow 1998, 2002; Durrer+2000; Kahniashvili+2001; Mack+2002; Caprini & Durrer 2002; Subramanian+2003; Lewis 2004; Giovannini 2004; Caprini 2006; Kahniashvili & Ratra 2007; Yamazaki et al 2007, 2008; Finelli, Paci, DP 2008; Giovannini & Kunze 2008,2008,2008; Paoletti+2009; Bonvin & Caprini 2010; Bonvin 2010; Kunze 2011; Shaw & Lewis 2010, Planck Coll. 2015, DP+LiteBIRD 2024-*

HEATING EFFECT: PMFs are dissipated after recombination and the energy injection modifies the ionization history *Subramanian & Barrow 1998, Jedamzik+ 2000, Sethi & Subramanian 2005, Schleicher+ 2008,Kunze & Komatsu 2014, Chluba, DP+ 2015, Kunze and Komatsu 2015, Planck 2015 Results XIX, Paoletti+ 2019, DP+LiteBIRD 2024-*

FARADAY ROTATION: PMFs diffuse on the line of sight of CMB induce a Faraday rotation of the CMB polarization generating B-modes from E-modes *Kosowsky & Loeb 1996, Kosowsky+ 2005, Kahniashvili+ 2009, Pogosian+ 2009 , Planck 2015 Results XIX, DP+LiteBIRD Coll 2024-*

NON GAUSSIANITIES: PMFs modelled as a stochastic background have a chisqr distribution leading to non-zero bi and tri spectra *Brown & Crittenden, Trivedi+ 2010, Shiraishi+ 2011, 2012; Shiraishi 2013, Seshadri & Subramanian 2009, Caprini, Finelli, DP, Riotto 2009, Cai+ 2010, Shiraishi+ 2010, Kahniashvili & Lavrelashvili 2010;Trivedi+ 2012, 2014; Planck 2015 results XIX, DP+LiteBIRD 2024 –*

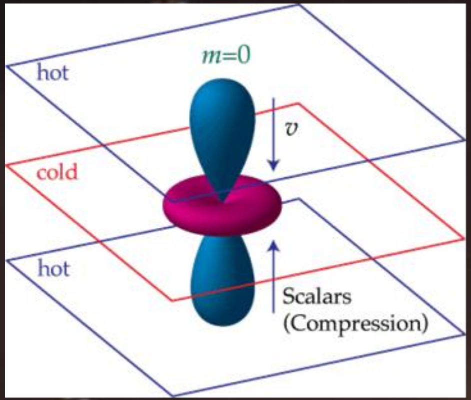
PARITY VIOLATING CORRELATORS: if PMFs have an helical component TB and EB cross correlations become non zero *Caprini+ 2004, Kahniashvili+ 2005, Kahniashvili & Ratra 2014, Ballardini, Finelli, DP 2015, Planck 2015 Results XIX*

THE GRAVITATIONAL EFFECT

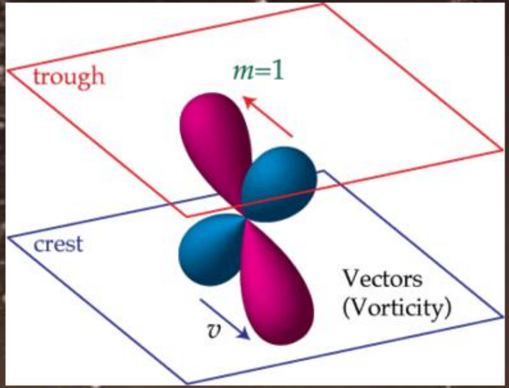
MAGNETICALLY INDUCED MODES

PMF excite all types of perturbations:

- **SCALARS:** TT-TE-EE modes generated by magnetic energy density+anisotropic pressure+Lorentz force
- **VECTORS:** TT-TE-EE-**BB** Vector projection of the anisotropic pressure and Lorentz force
- **TENSORS:** TT-TE-EE-**BB** Tensor projection of the anisotropic pressure

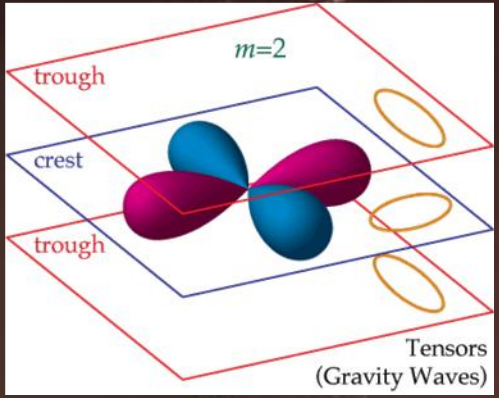


SOURCED BY ENERGY DENSITY AND ANISOTROPIC STRESS



SOURCED BY

ANISOTROPIC STRESS

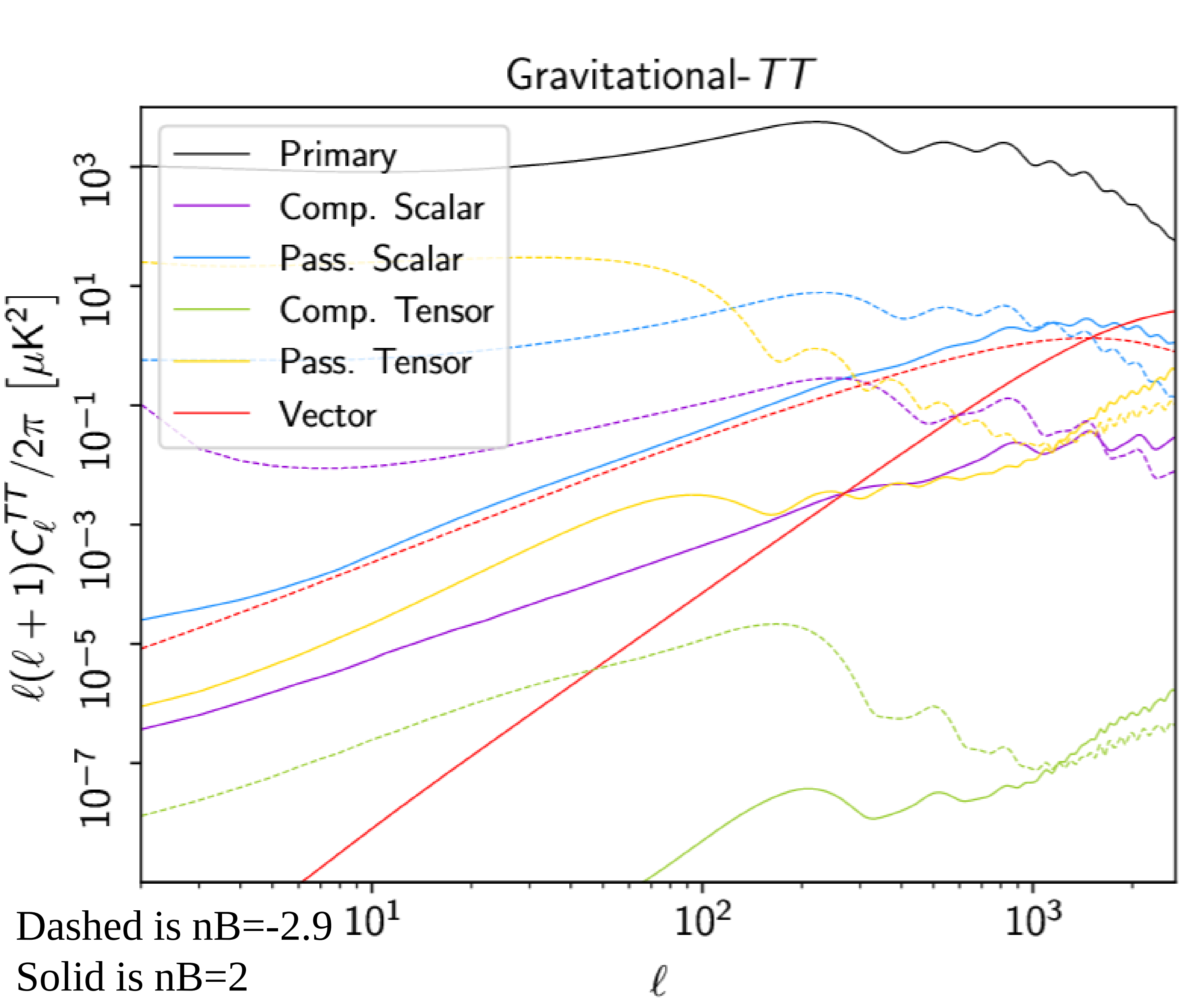


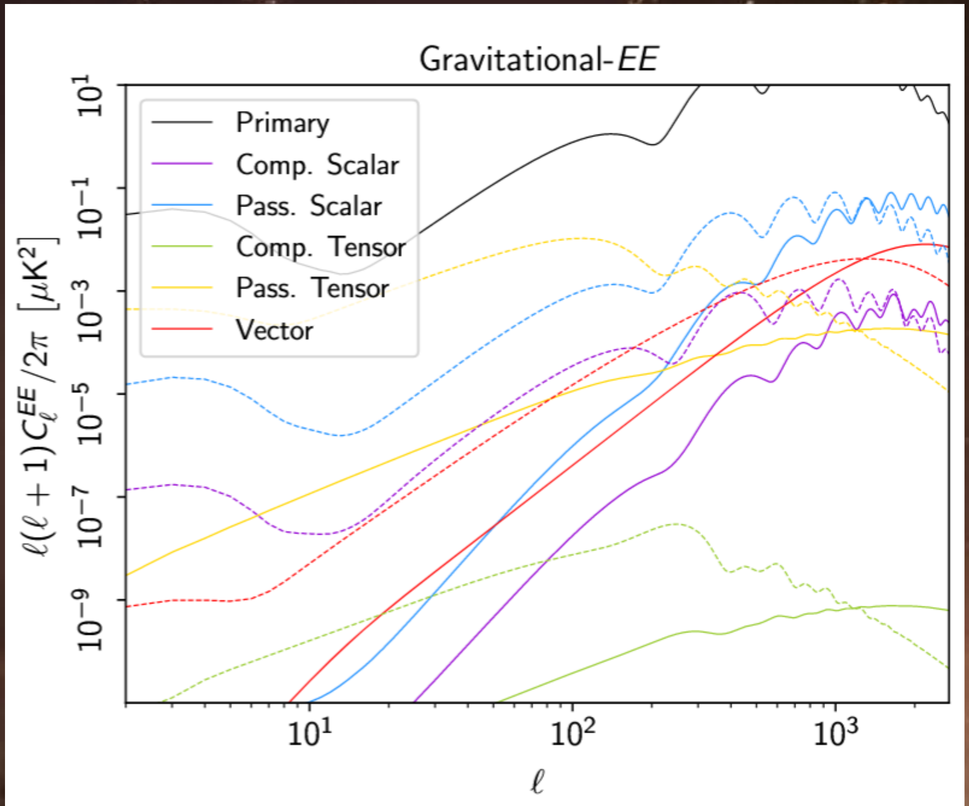
SOURCED BY ANISOTROPIC STRESS

PMFs source 3 additional signals in CMB:
Scalar, Vector and Tensor

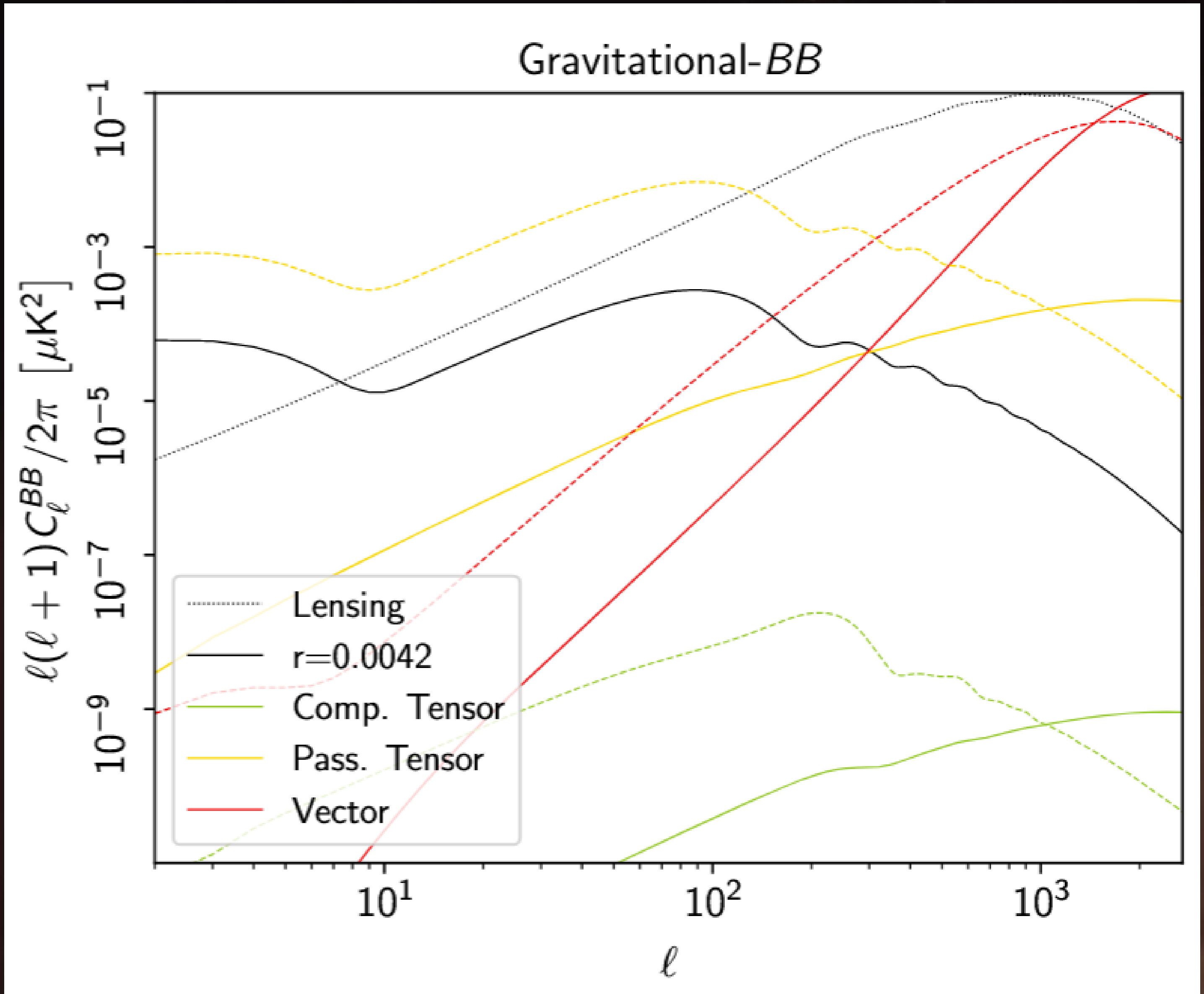
Scalar and Tensor come with two kind of initial conditions:
Compensated (isocurvature), Passive

FOR A TOTAL OF 5 ADDITIONAL POWER SPECTRA





Paoletti+ (LiteBIRD Coll.) 2024



Paoletti+ (LiteBIRD Coll.) 2024

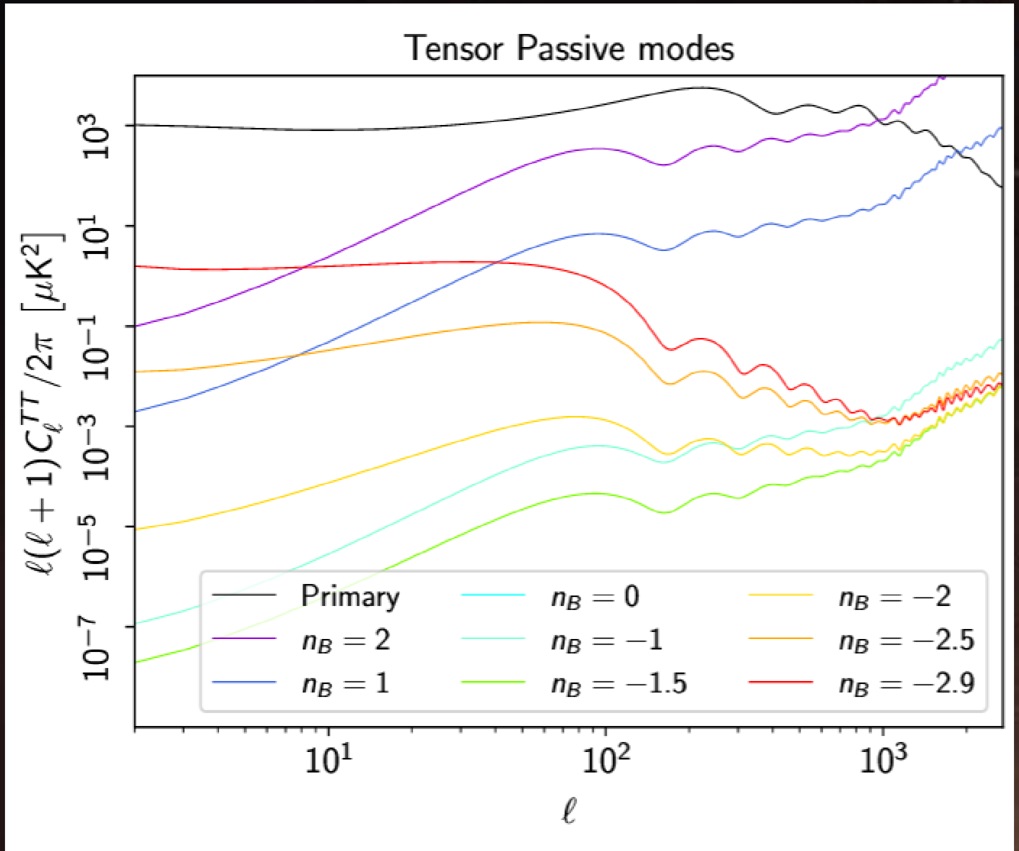
B-modes are the holy grail of inflation

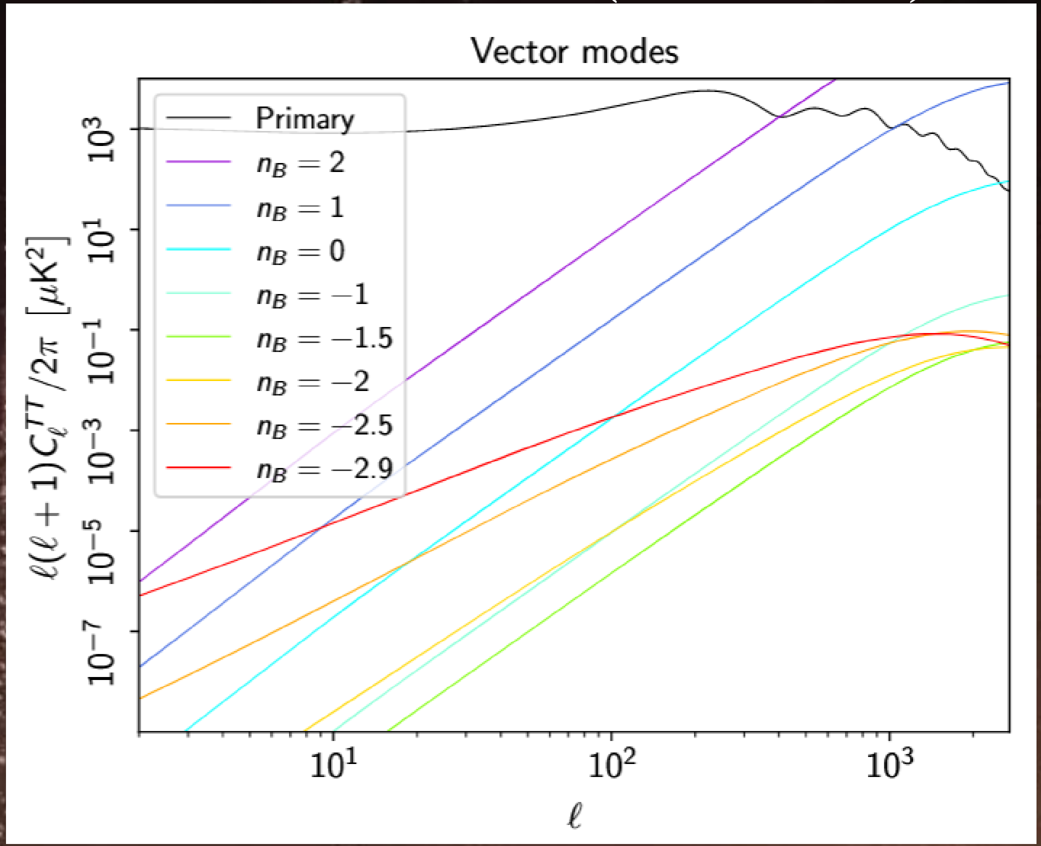
or

PMFs

DEPENDENCE ON THE PMF CONFIGURATION

Paoletti+ (LiteBIRD Coll.) 2024

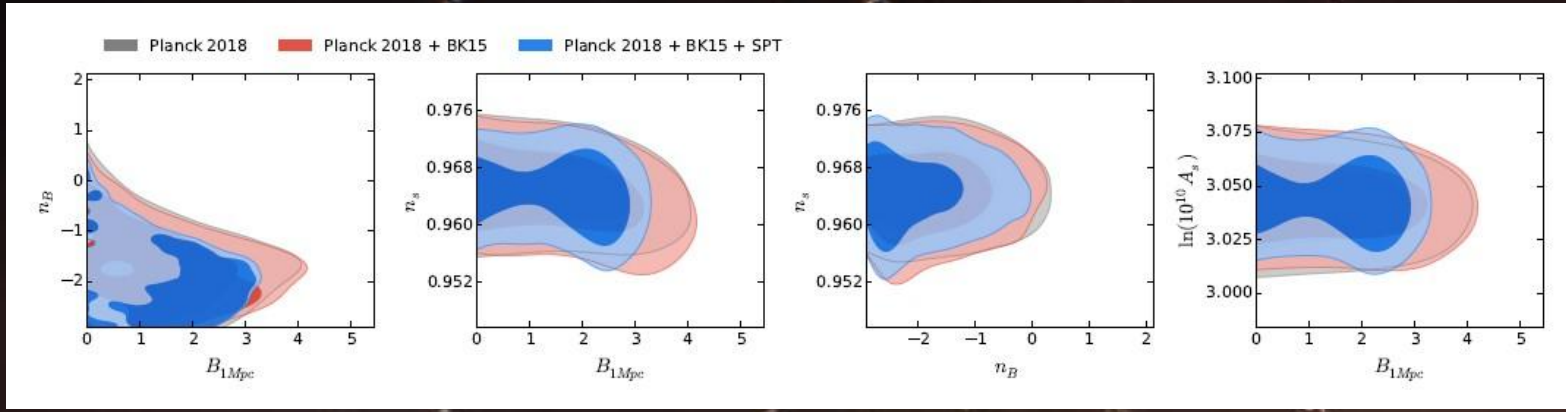


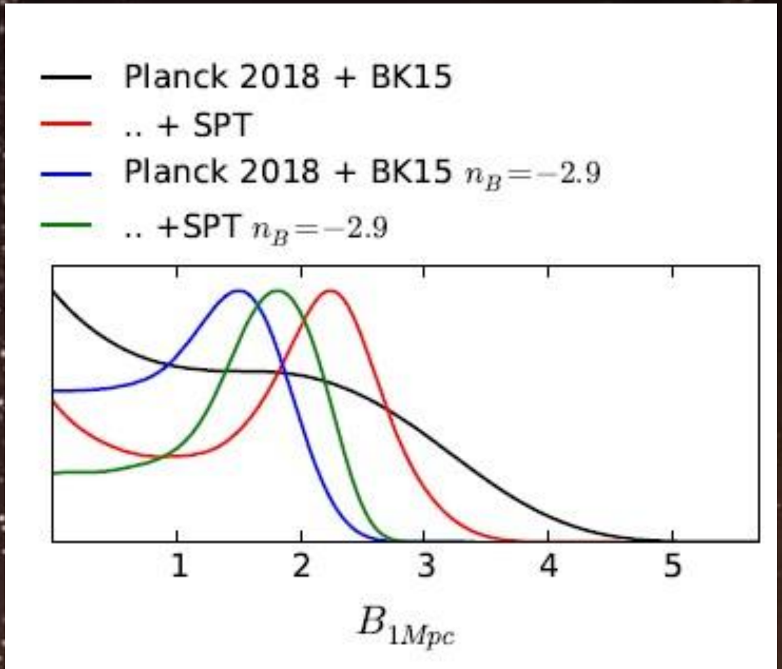


Causal PMFs (nB>2) have a strong impact on intermediate and small angular scales
Infrared PMFs (Inflation born) impact the large scales
The behaviour is driven by the magnetic source terms which are white noise for nB>-1.5 and k^(2n+3) for -3<nB<-1.5

CURRENT STATUS OF GRAVITATIONAL EFFECT

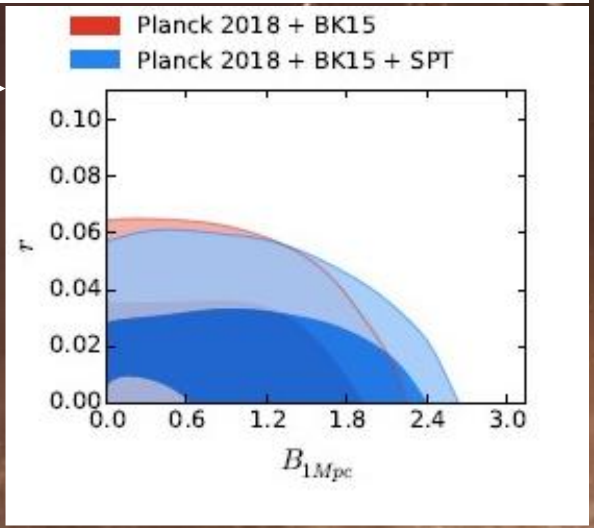
Parameter/Data	Planck 2018	Planck 2018+BK15	Planck 2018 + BK15+SPT Pol
$B_{1\,\mathrm{Mpc}}$ [nG]	<3.4	<3.5	<2.8
n_B	<-0.2	<-0.3	<-0.6





$$B_{1\,\mathrm{Mpc}} = 1.5^{+0.9}_{-1.4}\ \mathrm{nG}$$

Almost scale invariant (nB=-2.9) →



$$B_{1\,\mathrm{Mpc}} < 3\ \mathrm{pG}$$

Causal fields (nB=2)

Paoletti and Finelli 2019

LiteBIRD FORECASTS

In order to test different scenarios in an increase of complexity from the ideal case to the more realistic we use different setups for LiteBIRD data.:

- Ideal: only instrumental noise for TT-TE-EE-BB, lensing BB is considered as an additional noise component.
- Baseline: we add the contribution of statistical foreground residuals to the noise for l<191 (assumption of perfect cleaning)
- Realistic: noise includes instrument and statistical FG, the fiducial BB signal includes all contributions, CMB+lensing BB+FG residual bias+systematics bias which are fitted with nuisance amplitudes

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	< 0.50	< 0.51	< 0.27
-1	< 2.4	< 2.4	< 1.5
-2	< 2.5	< 2.7	< 2.3
-2.9	< 0.6	< 0.8	< 0.8

Paoletti+ (LiteBIRD Coll.) 2024

LiteBIRD with all biases					
Fiducial	Only lensing marginalization		Lensing and biases marginalization		
n_B	$B_{1\,\mathrm{Mpc}}$ [nG]	A^{BB}_{Lens}	$B_{1\,\mathrm{Mpc}}$ [nG]	A^{BB}_{Lens}	$A^{BB}_{\mathrm{FG-syst-bias}}$
Marginalized	< 3.38	0.987 ± 0.020	< 3.51	0.985 ± 0.021	...
2	< 0.007	0.987 ± 0.021	< 0.007	0.985 ± 0.020	...
1	< 0.072	$0.986^{+0.021}_{-0.020}$	< 0.074	$0.985^{+0.020}_{-0.021}$	...
0	< 0.55	0.988 ± 0.021	< 0.57	0.986 ± 0.021	...
-1	< 2.70	0.987 ± 0.020	< 2.79	0.985 ± 0.020	...
-2	< 3.30	0.985 ± 0.022	< 3.21	$0.984^{+0.020}_{-0.021}$	...
-2.9	< 0.89	0.988 ± 0.020	< 0.83	0.988 ± 0.021	$0.946^{+0.438}_{-0.806}$

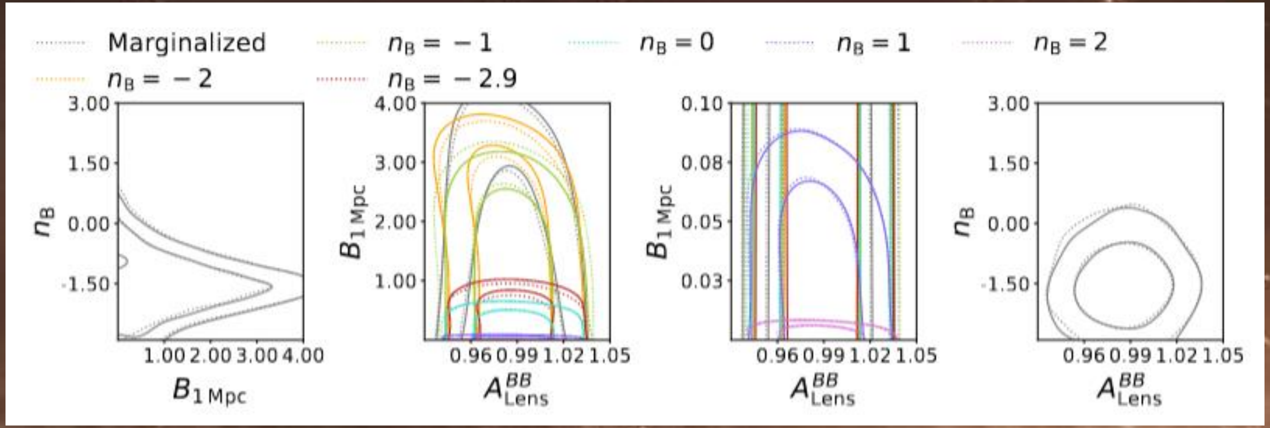
Testing to the extreme, we include everything, lensing, systematics, residual bias..

Left, testing the unknown unknown hypothesis, we include everything in the data but fit only for PMFs and lensing.

Right, we try to marginalize over everything we included.

Even in the most complex data scenario we have a slight degradation but nevertheless we are able to strongly constrain especially inflationary PMFs

ENEMY NUMBER 1 IS CALLED LENSING
Delensing sensibly improves the constraints, see the paper



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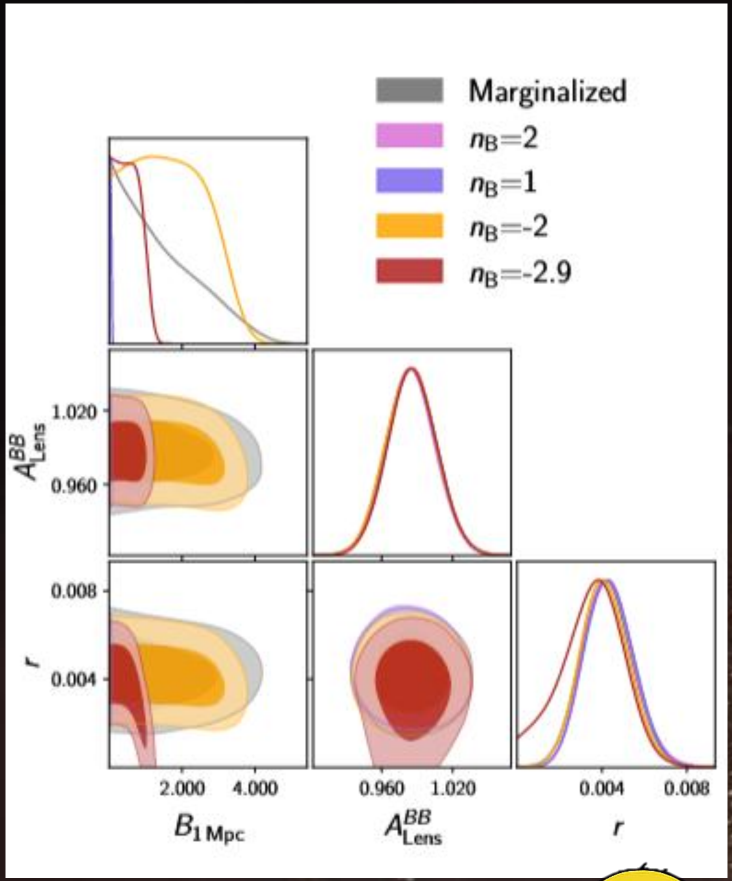
THE TRICKSTER FIELDS!



LiteBIRD with lensing Marginalization and non-zero inflationary signal			
Full lensing			
n_B	$B_{1\,Mpc}$ [nG]	A^{BB}_{Lens}	r
Marginalized	< 3.47	0.986 ± 0.021	$0.0042^{+0.0011}_{-0.0012}$
2	< 0.007	0.984 ± 0.0021	$0.0044^{+0.0010}_{-0.0013}$
1	< 0.075	0.985 ± 0.021	$0.0044^{+0.0010}_{-0.0013}$
0	< 0.553	0.987 ± 0.020	$0.0049^{+0.0011}_{-0.0013}$
-1	< 2.71	0.987 ± 0.020	$0.0049^{+0.0011}_{-0.0013}$
-2	< 3.27	0.985 ± 0.021	$0.0041^{+0.0010}_{-0.0012}$
-2.9	< 1.06	$0.986^{+0.021}_{-0.020}$	$0.0035^{+0.0017}_{-0.0013}$

When we consider the almost scale invariant case we observe a strong degeneracy with primordial GW from inflation (assumed r=0.0042).
So don't scream INFLATION too soon when we will measure B-modes

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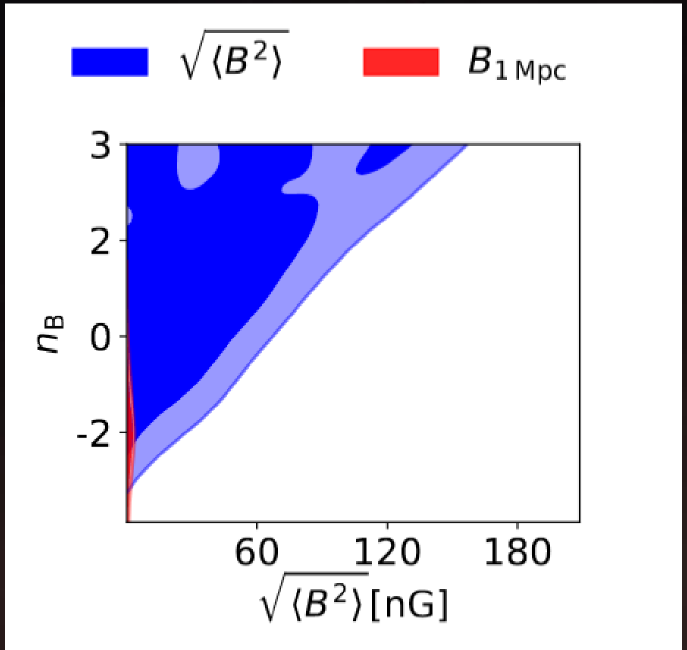
CHANGING PARAMETRIZATION



When moving from the 1 Mpc parametrization to the rms of the fields the representation of the results completely changes.

LiteBIRD with rms	
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

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THE HEATING EFFECT

PMFs AND THE IONIZATION HISTORY

Two mechanisms that take place after recombination dissipate the fields:

- ambipolar diffusion
- MHD decaying turbulence

THE DISSIPATION INJECTS ENERGY IN THE PLASMA

The heating of the Plasma modifies the temperature and ionization fraction

Subramanian & Barrow 1998, Jedamzik+ 2000, Sethi & Subramanian 2005, Schleicher+ 2008,Kunze & Komatsu 2014, Chluba, DP+2015, Kunze and Komatsu 2015, Paoletti+ 2019

It also causes spectral distortions of the absolute spectrum of CMB which are currently out of reach *-Kunze & Komatsu 2014-*

$$\frac{dT_e}{dt} = -2HT_e + \frac{8\sigma_T\, n_e \rho_\gamma}{3\, m_e c N_{tot}}(T_\gamma - T_e) + \frac{\Gamma}{(3/2)kN_{tot}},$$

MHD DECAYING TURBULENCE

On small scales PMFs subjected to non linear effect may develop magnetohydrodynamic turbulence

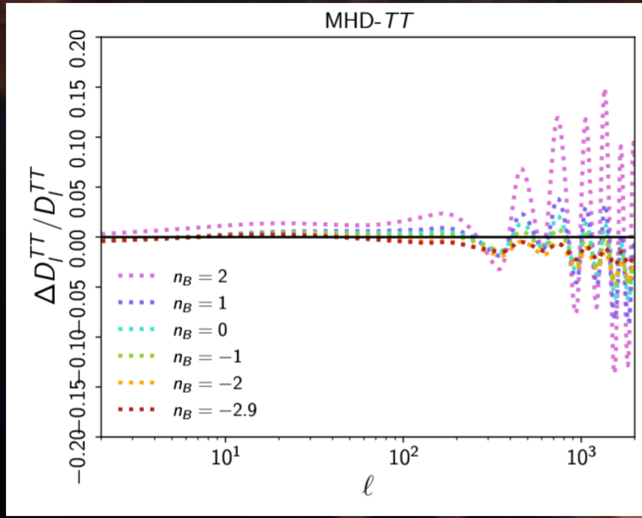
Before recombination the radiation viscosity over-damps the velocity fluctuations but when the radiation viscosity drops it allows for the development of large Reynold numbers and MHD turbulence

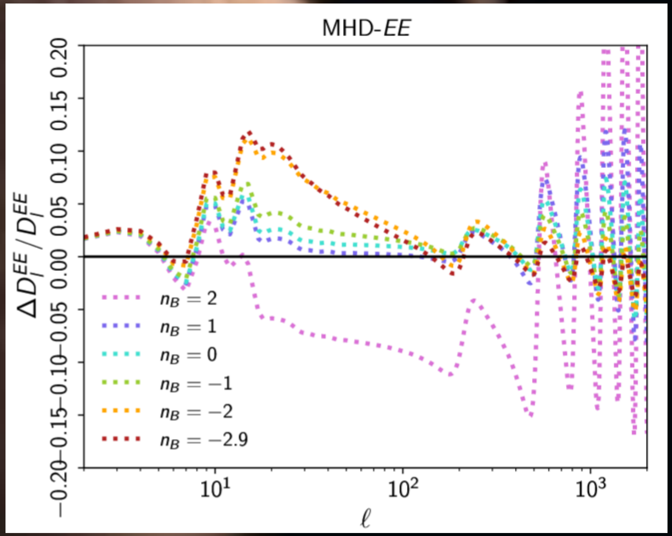
$$\Gamma_{\rm turb} = \frac{3m}{2} \frac{\left[\ln\left(1+\frac{t_i}{t_{\rm d}}\right)\right]^m}{\left[\ln\left(1+\frac{t_i}{t_{\rm d}}\right)+\frac{3}{2}\ln\left(\frac{1+z_i}{1+z}\right)\right]^{m+1}} H(z)\,\rho_{\rm B}(z).$$

$$\rho_{\rm B}(z) = \langle B^2\rangle(1+z)^4/(8\pi) \approx 9.5\times10^{-8}(\langle B^2\rangle/{\rm nG}^2)\,\rho_\gamma(z).$$

$$t_i/t_{\rm d} \approx 14.8(\langle B^2\rangle^{1/2}/{\rm nG})^{-1}(k_{\rm D}/{\rm Mpc}^{-1})^{-1}$$

$$m = 2(n_{\rm B}+3)/(n_{\rm B}+5)$$



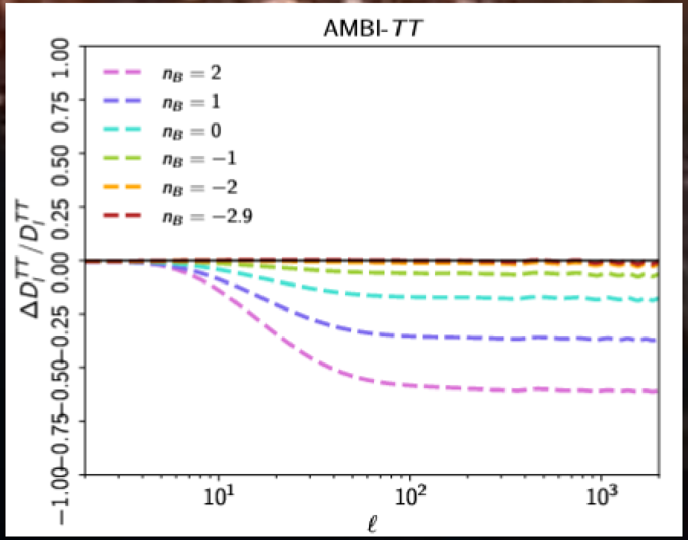


DRIVEN BY THE ENERGY DENSITY

Paoletti+ (LiteBIRD Coll.) 2024

AMBIPOLAR DIFFUSION

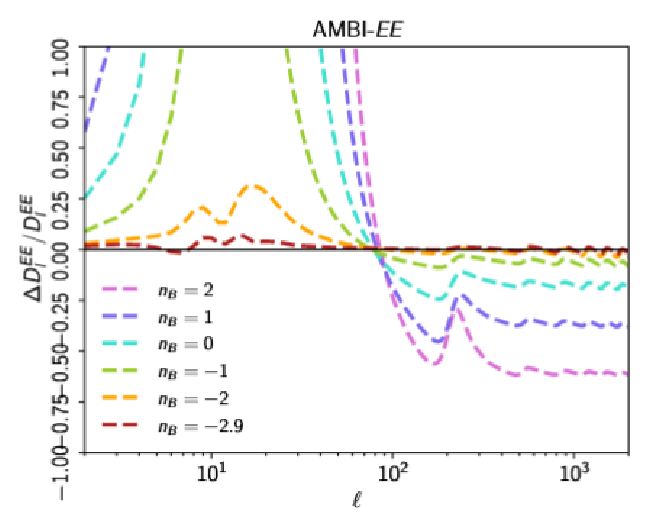
The ambipolar diffusion arises in partially ionized plasmas in the presence of magnetic fields
The Lorentz force acting only on ions induces a velocity difference with the neutral atoms.
Collisions between the two thermalize the energy transferring it to the neutral component



$$\Gamma_{\rm am} \approx \frac{(1 - X_{\rm p})}{\gamma X_{\rm p} \rho_{\rm b}^2} \langle \mathbf{L}^2 \rangle$$

The Lorentz force is derived following Finelli+ 2008 and Paolett+2009

DRIVEN BY THE LORENTZ FORCE



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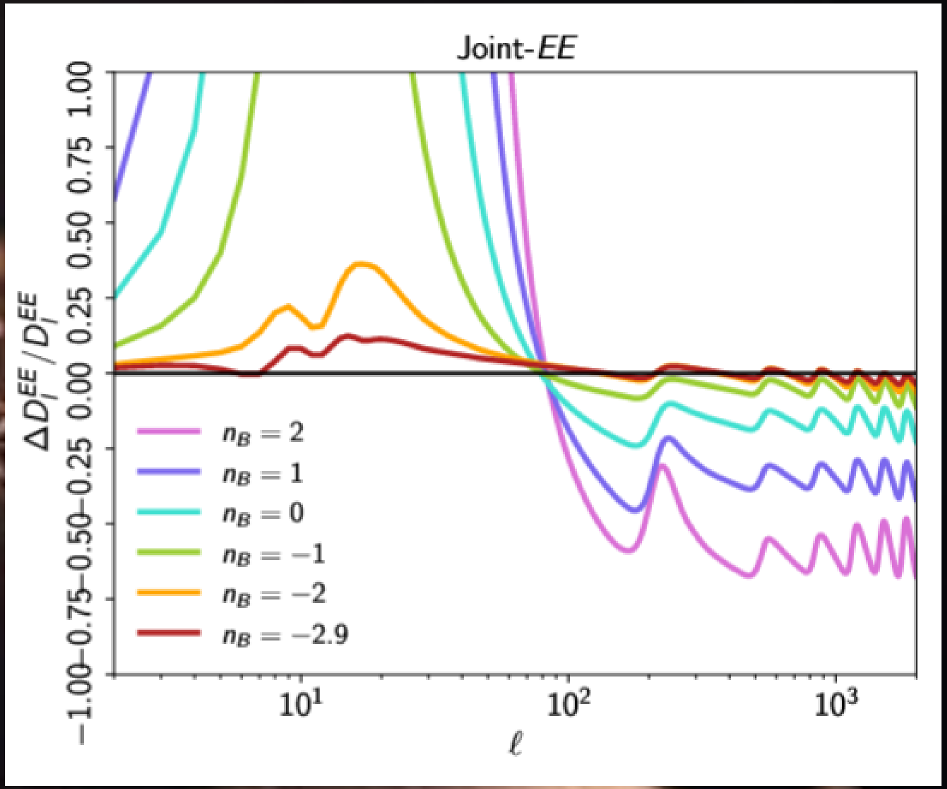

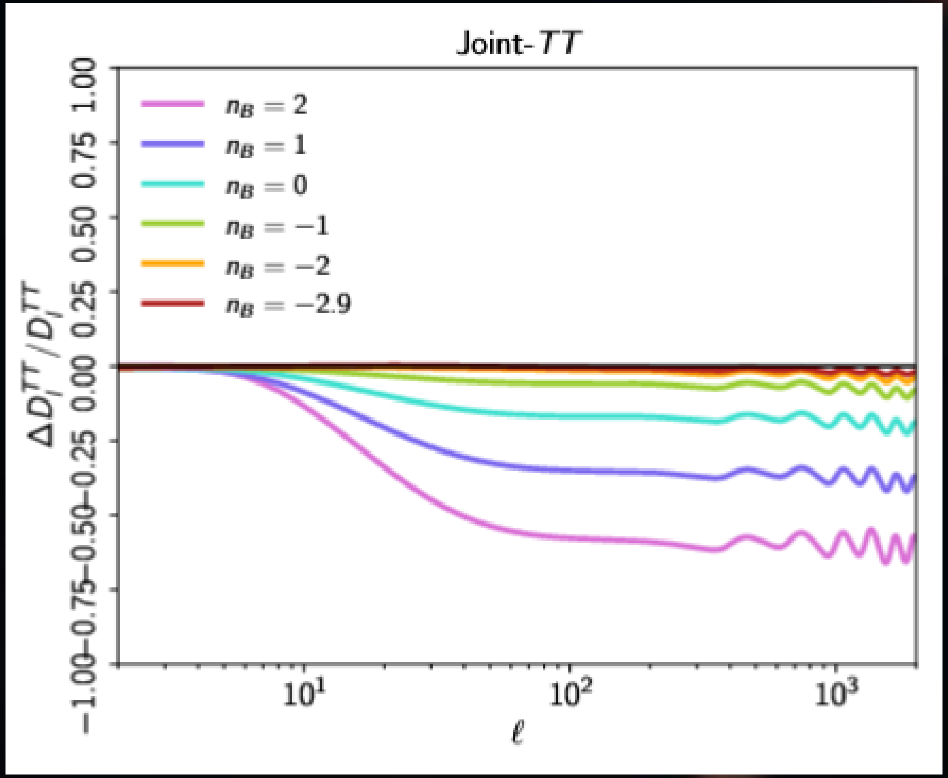

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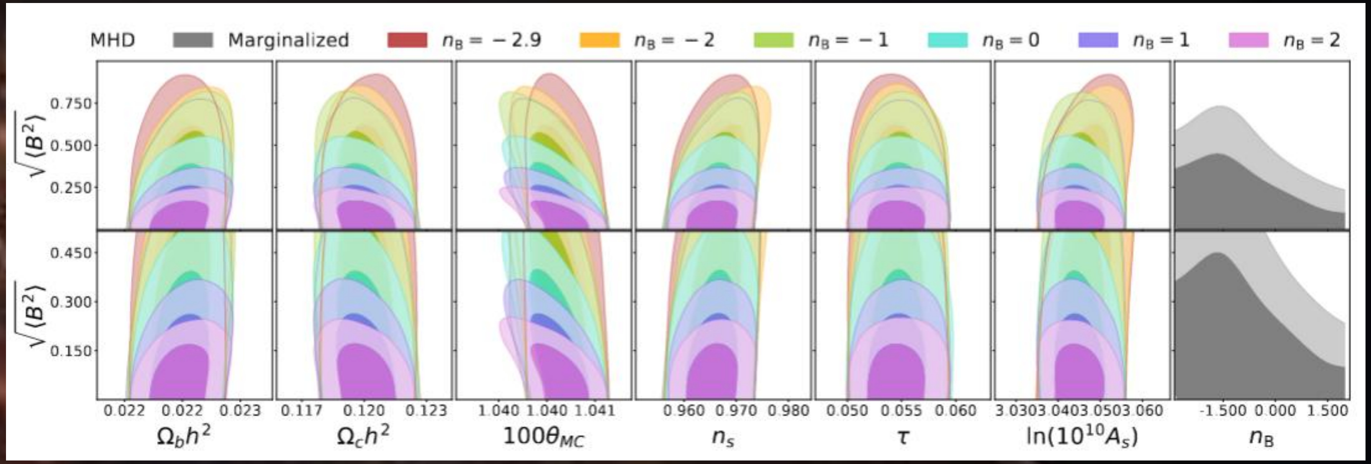
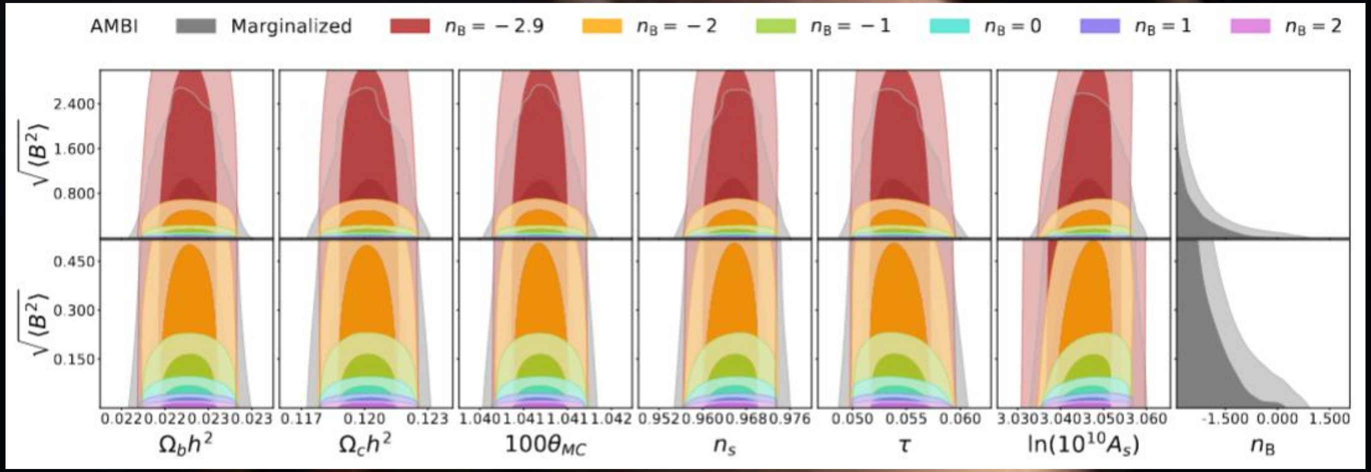
MHD decaying turbulence		
n_B	$\sqrt{\langle B^2 \rangle}$ [nG]	
Dataset	*LiteBIRD* (*Planck* 2018)	*LiteBIRD* + *Planck*
Marginalized	< 0.60 (< 0.68)	< 0.58
2	< 0.20 (< 0.18)	< 0.15
1	< 0.30 (< 0.27)	< 0.22
0	< 0.46 (< 0.41)	< 0.34
−1	< 0.67 (< 0.63)	< 0.54
−2	< 0.70 (< 0.79)	< 0.70
−2.9	< 0.76 (< 1.05)	< 0.72



Ambipolar diffusion		
n_B	$\sqrt{\langle B^2 \rangle}$ [nG]	
	LiteBIRD (*Planck*)	*LiteBIRD* +*Planck*
Marginalized	< 2.05 (< 3.40)	< 1.95
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



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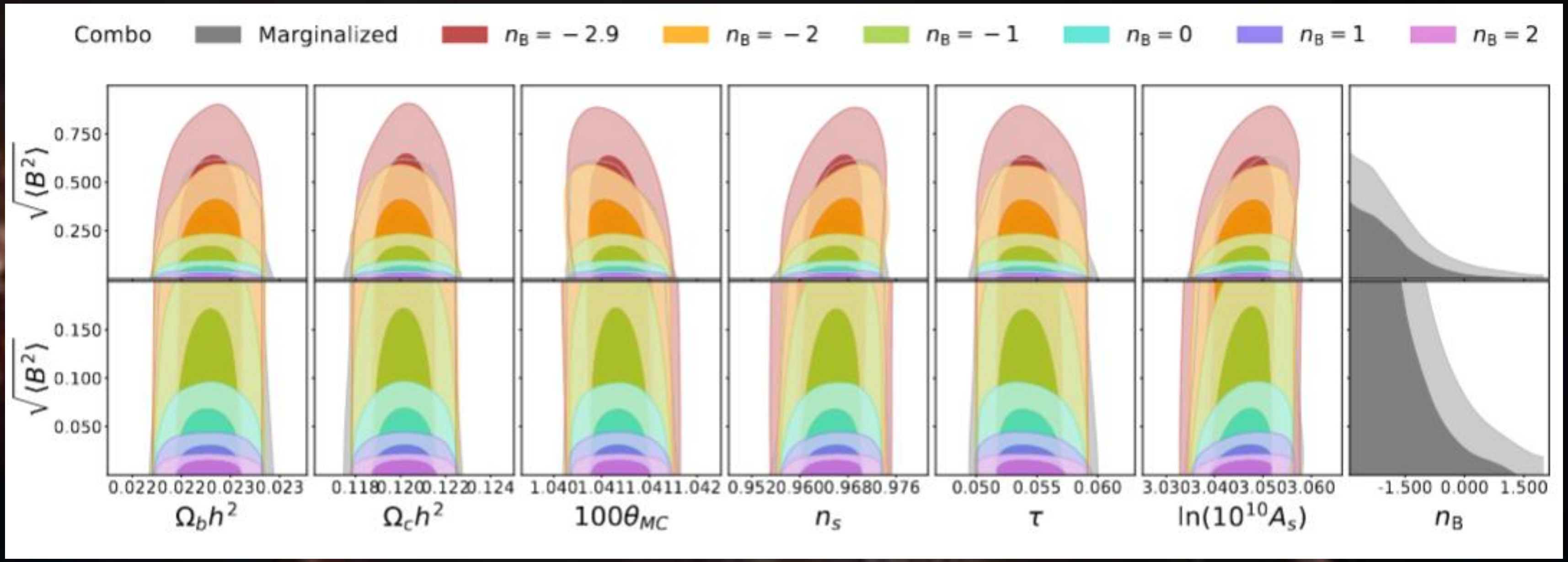

Combined effect		
n_B	$\sqrt{\langle B^2 \rangle}$ (nG)	
	LiteBIRD (*Planck*)	*LiteBIRD* +*Planck*
Marginalized	< 0.50 (< 0.69)	< 0.48
2	< 0.018 (< 0.06)	< 0.018
1	< 0.037 (< 0.12)	< 0.037
0	< 0.080 (< 0.26)	< 0.079
−1	< 0.20 (< 0.56)	< 0.19
−2	< 0.48 (< 0.79)	< 0.49
−2.9	< 0.73 (< 1.06)	< 0.69

Joint Gravitational and Heating constraints, useful only for almost scale invariant case provide $\sqrt{\langle B^2 \rangle} < 0.64$ nG

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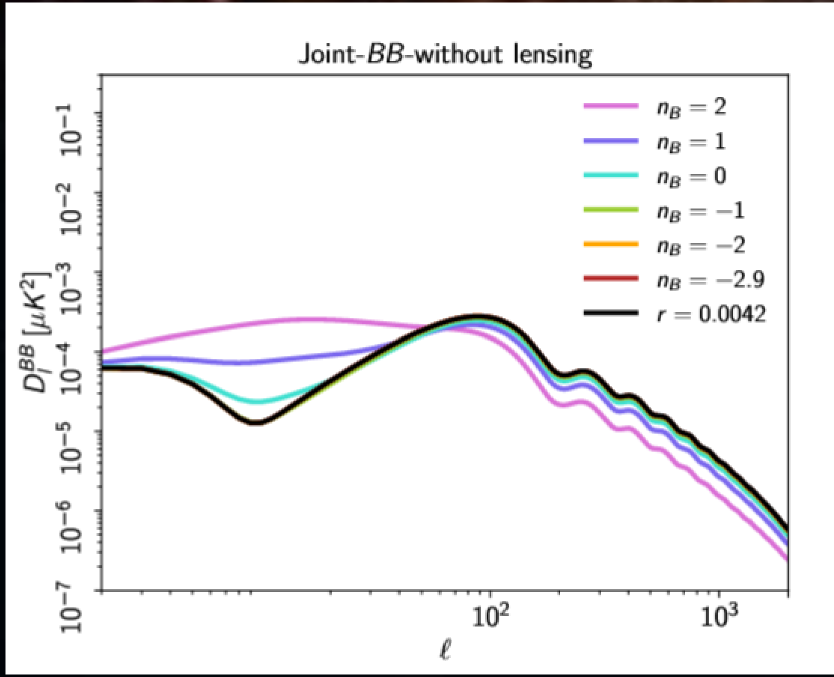
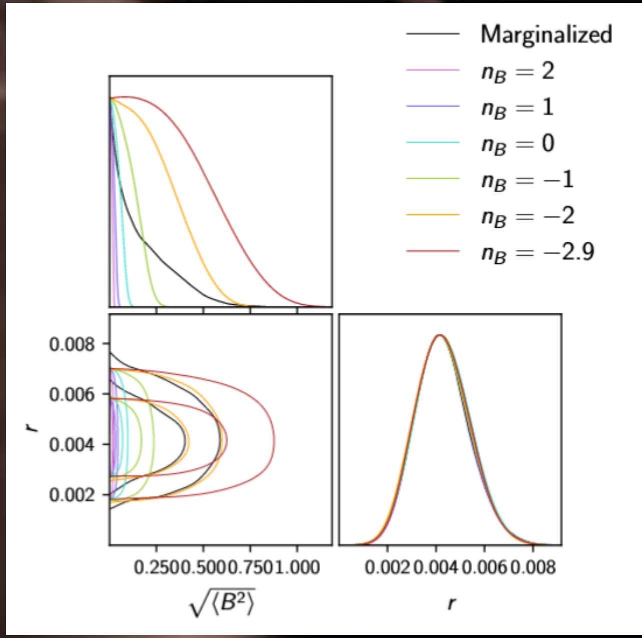
JOINT CONSTRAINTS WITH INFLATION GW



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	$0.0044^{+0.0010}_{-0.0012}$



Modifying primary CMB signals the heating effect modifies also B-modes from inflation. But in this case we can distinguish them

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THE FARADAY ROTATION

FARADAY ROTATION

The presence of PMFs induce a rotation of the polarization plane producing B-modes from E-modes

$$C_\ell^{BB} = N_\ell^2 \sum_{\ell_1,\ell_2} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi(2\ell+1)} N_{\ell_2}^2 K(\ell,\ell_1,\ell_2)^2 C_{\ell_2}^{EE} C_{\ell_1}^{\alpha} (C_{\ell_1 0 \ell_2 0}^{\ell 0})^2$$

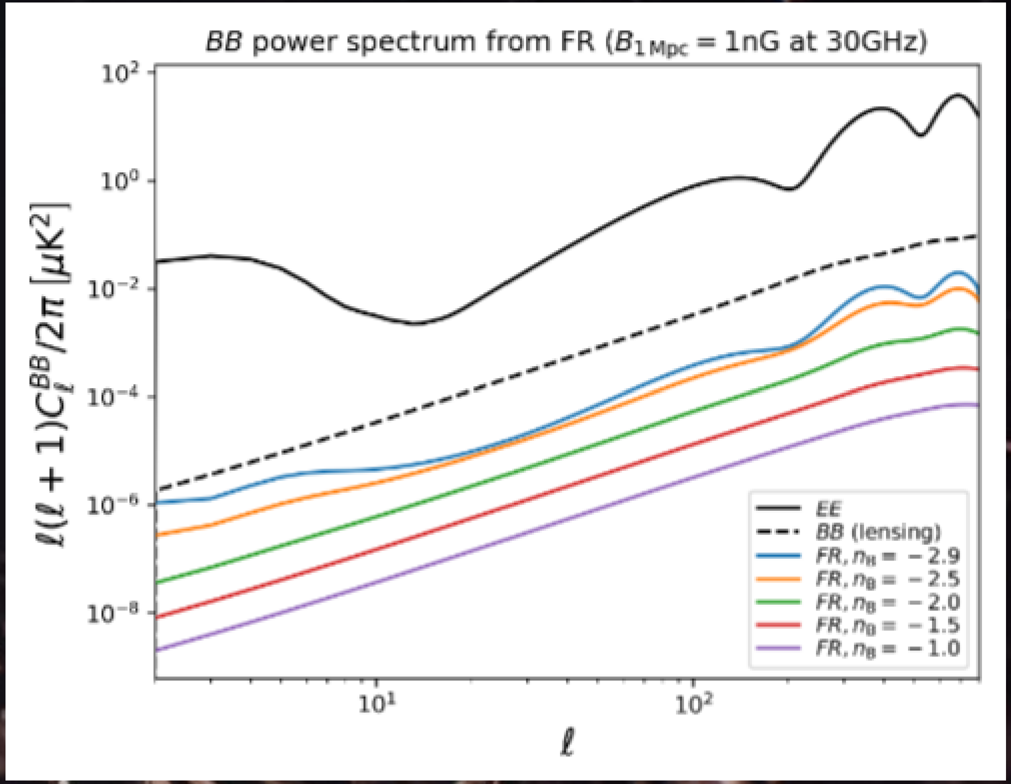
where $C_{\ell_1 0 \ell_2 0}^{\ell 0}$ are Clebsch-Gordan coefficients, $N_\ell = (2(\ell-2)!/(\ell+2)!)^{1/2}$ is a normalization factor, and $K(\ell,\ell_1,\ell_2) \equiv -1/2(L^2+L_1^2+L_2^2-2L_1L_2-2L_1L+2L_1-2L_2-2L)$ with $L \equiv \ell(\ell+1)$, $L_1 \equiv \ell_1(\ell_1+1)$

Kosowsky+2005

$$C_\ell^{\alpha} = \frac{9\ell(\ell+1)}{(4\pi)^3 e^2} \lambda_0^4 \frac{B_\lambda^2}{\Gamma(n_B+3/2)} \left(\frac{\lambda}{\eta_0}\right)^{n_B+3} \int_0^{x_D} dx\, x^{n_B} j_\ell^2(x),$$

$$x_D = k_D \eta_0.$$

FR scales as the inverse observational frequency to the fourth power!



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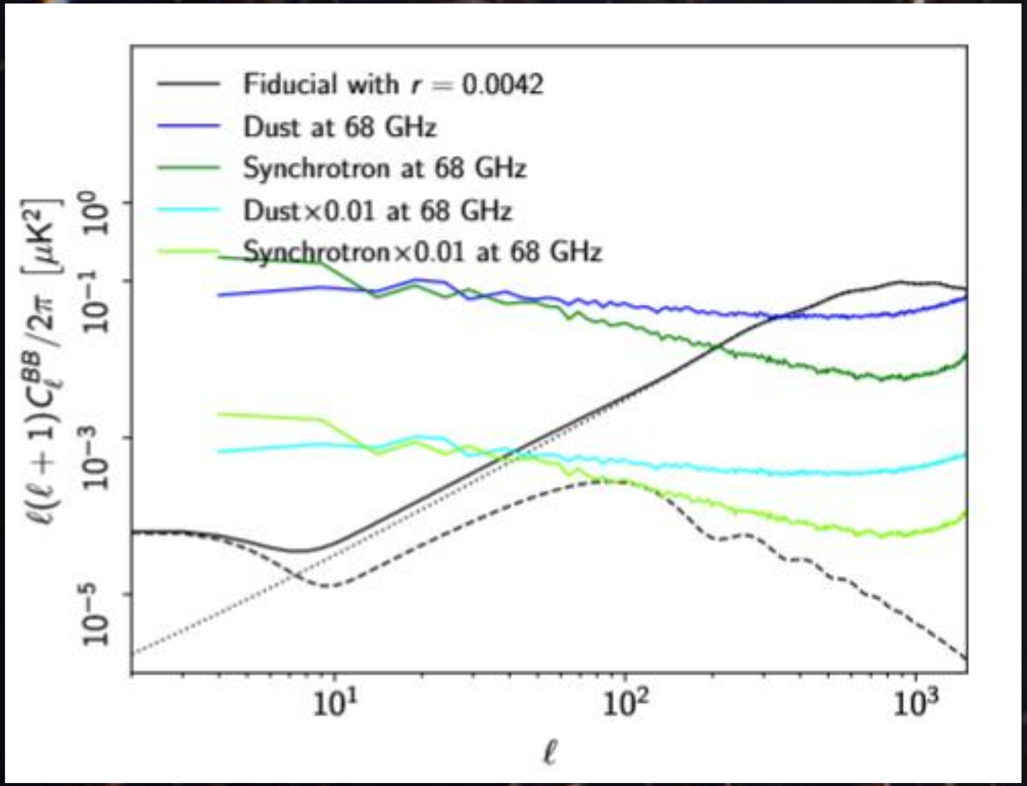
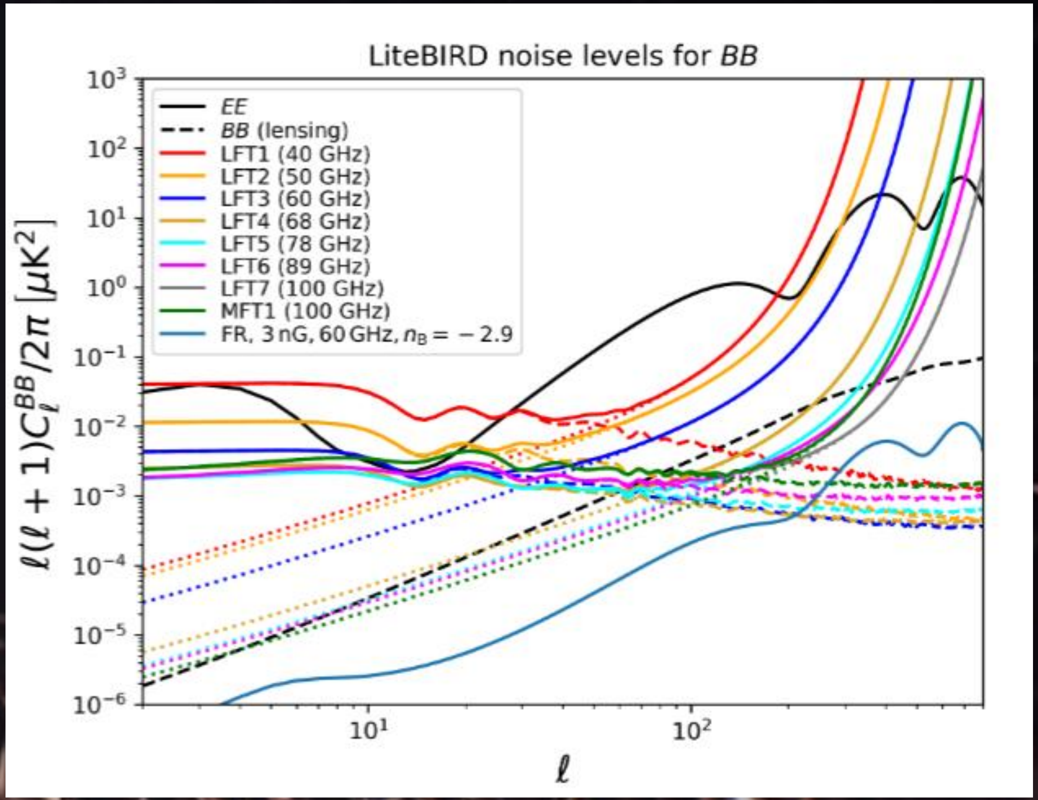
FARADAY INPUTS

We need single frequency FG reduced spectra. We assume the same sky as LiteBIRD Coll. PTEP2023 and assume a cleaning at 1% residual level





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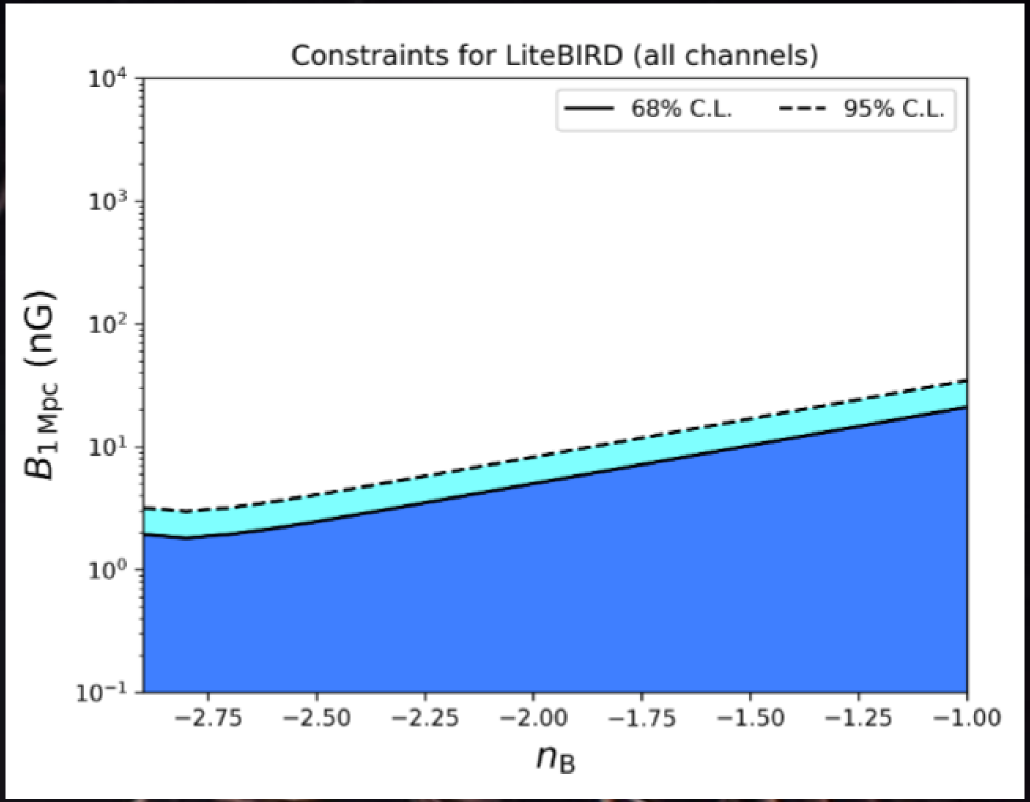
CONSTRAINTS FROM FARADAY ROTATION

n_B	$B_{1\,\mathrm{Mpc}}$ [nG] (68 GHz)	$B_{1\,\mathrm{Mpc}}$ [nG] (all)	$B_{1\,\mathrm{Mpc}}$ [nG] (no foreg.)
−2.9	< 4.5	< 3.2	< 3.0
−2.7	< 4.5	< 3.2	< 3.0
−2.5	< 5.7	< 4.1	< 3.8
−2.3	< 7.4	< 5.4	< 5.0
−2.1	< 9.8	< 7.2	< 6.6
−1.9	< 12.9	< 9.5	< 8.7
−1.7	< 17.1	< 12.7	< 11.6
−1.5	< 22.7	< 16.9	< 15.4
−1.3	< 30.2	< 22.5	< 20.5
−1.1	< 40.1	< 30.0	< 27.3



Improve by more than 2 orders of magnitude current best constraints

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THE NON GAUSSIANITIES

NON-GAUSSIANITIES

PMFs contribute to CMB anisotropieswith their energy momentum tensor which is quadratic in the fields.
If PMFs are modelled as a stochastic background this means a fully non-Gaussian impact on CMB
Non-vanishing high order statistical moments as bispectrum and trispectrum, respectively the three and four point correlation functions, are non-zero

As for the two point correlation function also for non-Gaussianity analysis we can consider different initial conditions and different modes.

- *Brown & Crittenden 2005*-> general treatment of magnetic NG
- *Brown 2008*->Ph.d Thesis
- *Seshadri & Subramanian 2009*-> Bispectrum of scalar magnetized mode
- *Caprini, Finelli, Paoletti & Riotto 2009*->Bispectrum of scalar magnetized mode
- *Trivedi, Subramanian & Seshadri 2010* ->Bispectrum from magnetic scalar passive mode
- *Shiraishi et Al. 2011*-> Bispectrum from vector magnetized mode
- *Shiraishi et Al. 2011/2* -> Bispectrum and constraints from magnetized passive tensor mode
- *Trivedi, Subramanian & Seshadri 2011* ->Trispectrum from magnetic scalar mode
- *Shiraishi et Al.2012*->Bispectrum from scalar & tensor passive modes
- ………………………..

PASSIVE TENSOR BISPECTRUM IN POLARIZATION

Out-horizon passive tensor mode is given by:

$$h_{ij}(\mathbf{k}) \approx -1.8 \frac{\ln(\tau_\nu/\tau_{\rm B})}{4\pi\rho_{\gamma,0}} \sum_{s=\pm2} e_{ij}^{(s)}(\hat{k}) e_{kl}^{(s)*}(\hat{k}) \int \frac{d^3p}{(2\pi)^3} B_k(\mathbf{p}) B_l(\mathbf{k}-\mathbf{p})$$

The BBB bispectrum is given by:

$$\langle a^B_{\ell_1 m_1} a^B_{\ell_2 m_2} a^B_{\ell_3 m_3} \rangle \propto \langle h_{i_1 j_1}(\mathbf{k}_1) h_{i_2 j_2}(\mathbf{k}_2) h_{i_3 j_3}(\mathbf{k}_3) \rangle$$

So it scales as the sixth power of the

$$A_{\rm bis} \equiv \left(\frac{B_{1\,\rm Mpc}}{1\,\rm nG}\right)^6 \left(\frac{\ln(\tau_\nu/\tau_{\rm B})}{\ln(10^{17})}\right)^3$$

For almost scale invariant fields the dominant configuration is the squeezed $\ell_1 \ll \ell_2 \approx \ell_3$,

+permutations

-Shiraishi+2011; Shiraishi+2012, Shiraishi2013, Shiraishi2019-

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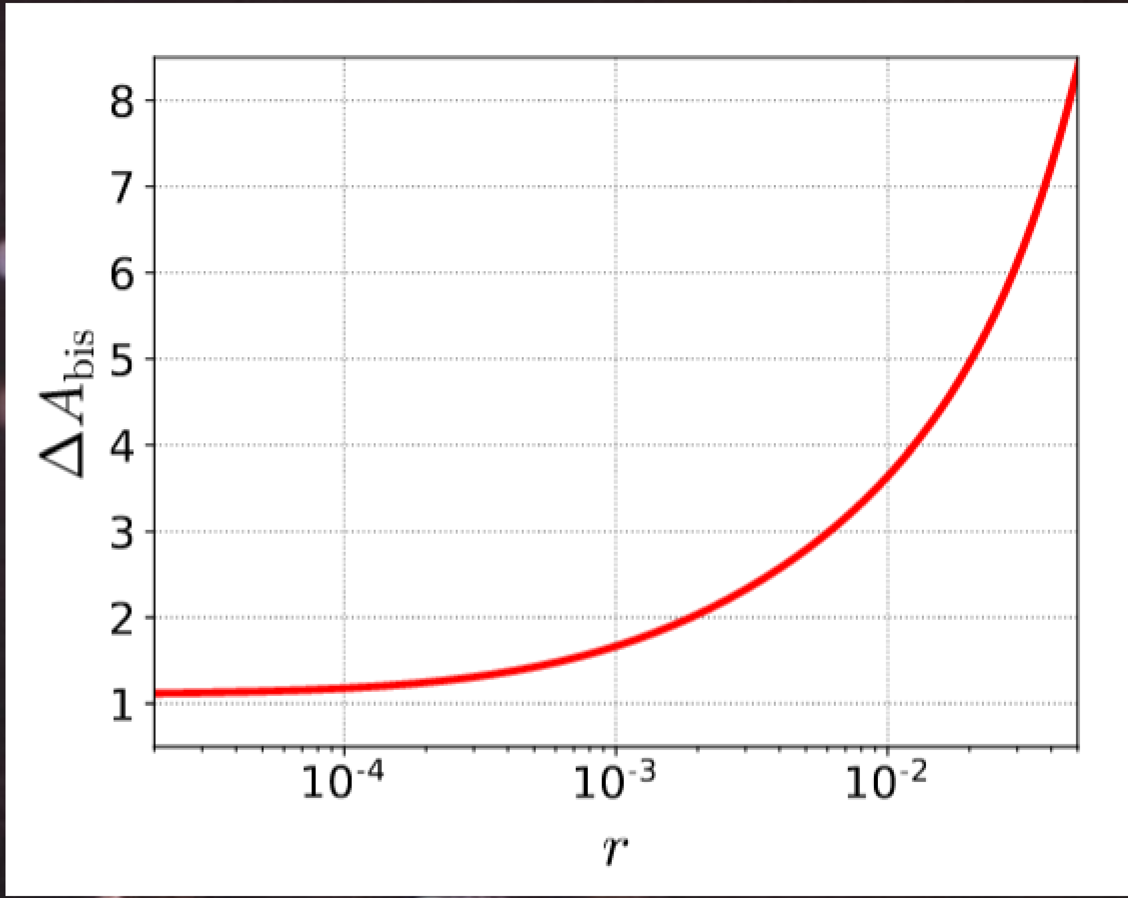
The noise setup is as the baseline case of the gravitational effect

$$F = f_{\rm sky} \sum_{\ell_1\ell_2\ell_3} \frac{|B_{\ell_1\ell_2\ell_3}|^2}{6C_{\ell_1}C_{\ell_2}C_{\ell_3}}$$

$$\Delta A_{\rm bis} = 1/\sqrt{F},$$

Below r=0.0001 the error on the bispectrum becomes dominated by noise and lensing therefore O(1) is the measurable limit of the bispectrum whatever the r improving previous results by 3 orders of magnitude



$B_{1\,\rm Mpc} \simeq 1\,\rm nG$ is a well measurable target with LiteBIRD

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SUMMARY

GRAVITATIONAL EFFECT: main improvement relying on **BB**

Improving especially infrared indices $B_{1\,\mathrm{Mpc}}^{n_B=-2.9} < 0.8\,\mathrm{nG}$ $B_{1\,\mathrm{Mpc}}^{\mathrm{marg}} < 2.2\,\mathrm{nG}$

HEATING EFFECT: main improvement relying on **EE**

Improving all indices $\sqrt{\langle B^2 \rangle}^{n_B=-2.9} < 0.7\,\mathrm{nG}$ $\sqrt{\langle B^2 \rangle}^{\mathrm{marg}} < 0.50\,\mathrm{nG}$

FARADAY ROTATION: single frequency BB spectra

Improving orders of magnitude $B_{1\,\mathrm{Mpc}}^{n_B=-2.9} < 3.2\,\mathrm{nG}$

NON-GAUSSIANITY: main improvement **BBB** bispectrum

Break the threshold $B_{1\,\mathrm{Mpc}} \simeq 1\,\mathrm{nG}$

Although important, numbers are not our main point...

What really stands is that with the CMB we have at least 4 probes of Primordial Magnetism based on different data products that will be available in the next years

This is crucial in more than one way, in fact we need to have a smoking gun of PMFs and this can only come with different coherent detections

In addition, if we find a B-mode polarization......all hell will get loose!!! We have seen it already with BICEP «supercazzola» of 2014!

Even if one is not interested into PMF we need to know how much they contribute to the B-mode signal and this can only be done with multiprobe

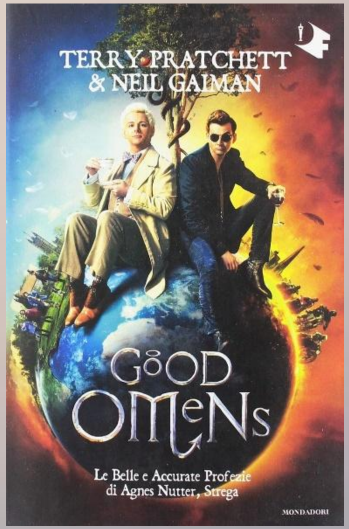
Like Napoleon used to defy much bigger armies attacking from different directions we will chase our Cosmic Elephant from at least 4 different angles

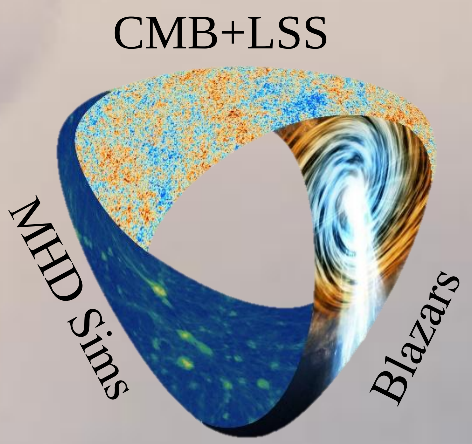
NEXT CHALLENGES

GOOD OMENS

GOOD Old Magnetism in the Early uNiverSe
INAF program–scheda inaf since 2022

This is a program that has the main target of bringing together all the different aspects – and communities- of the cosmic magnetism to finally understand its origin and the fundamental physics it involves in the early Universe.





CMB & LSS
Predictions of all the effects of PMFs on CMB anisotropies including gravitational effects, ionization history effects, helical fields in both, full non-linear treatment for the effects on the LSS; non-Gaussianities; treatment for homogeneous PMF and the anisotropic universe they come with.

Study of the interplay with extended cosmological models

Forecasts for future CMB and LSS experiments

MHD SIMULATIONS
Full MHD LSS formation will follow at each step of the CMB-LSS analises.

In fact each step will provide an increasing degree of realism to the initial conditions of the simulations.

The final result will be the status of the LSS and its observables with the contribution of the PMF we constrain or detect with future esperiments

ASTRO DATA
The simulations results will be compared with astrophysical data we will have available at the various steps.

Directly from sims we can extract radio data and cosmic rays predictions associated to the simulation.

The resulting MF will also be compared with the data on the magnetization of cosmic voids coming from high energy data

PEOPLE WITH GOOD OMENS!

INAF-OAS
COORDINATION
P.I. Daniela Paoletti
Members – F. Finelli, A. Andrews and A. Gruppuso
Developement of all the pipelines involving primordial magnetism: CMB-LSS effects, interplay with the cosmological model, forecasts, Local Universe simulations with Bayesian field inference, Homogeneus field

UNIVERSITA' PADOVA
Prof. Elisa Prandini
Comparison with gamma ray observations

SISSA
Prof. Carlo Baccigalupi
Forecasts development with realistic datasets
Prof. Matteo Viel
Impact on the LSS

UNIBO
Prof. Franco Vazza
MHD Simulations and obsevables

CINECA
Diego Molinari
Forecasts and the study of the interplay with the cosmological model

IMSC – Chennai
Prof. Dhiraj Hazra
Study of the interplay with the cosmological model

If you are interested in joining our Good OMENS just let us know.

We do not ask for FTE 😉

This effort is only meant to have INAF recognizing these activities and stress the importance of cosmological magnetic fields especially considering the strenght of the Italian community

Select as one of 7
INAF 2023 New IDEAS

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

Then as in all sad stories...the entire direction of INAF has been changed and the new ideas have been forgotten

BUT WE DON'T GIVE UP
AND THIS WORKSHOP
IS THE DEMONSTRATION
WE ARE GOING IN THE RIGHT DIRECTION
So let's keep working and make the cosmology room notice the elephant!