Primordial magnetic fields: what's new?

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Outline

1. Magnetic fields in the Universe
2. Primordial magnetic fields
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   - Impact on PS
   - Magnetically-induced non-Gaussianities
   - Faraday rotation
   - Magnetically-induced breaking statistical isotropy
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Observational evidence

- Magnetic fields (MF) are present in many astrophysical objects: from smaller (planets) to larger scales (cluster of galaxies)
- **Nearby galaxies:** MF strengths are of tens μG coherent on scales up to ten kpc (e.g. Beck & Wielebinski 2013)
- Also observed in **high-redshift galaxies** (Bernet et al. 2008)
- **Cluster of galaxies:** MF strenghts of few μG correlated on scales of ten kpc (e.g. Ferreti et al. 2012)
- **IGM, low density intracluster regions, voids:** MF strengths of $> 10^{-15} - 10^{-18}$ G on Mpc scales (Nerenov & Vovk 2010, Nerenov et al. 2013)

MF in collapsed objects as galaxies or clusters could be explained by a dynamo but... what about a primordial origin for these fields?

Mechanisms for generating MF

- Hydrodynamical proccesses as adiabatic compression and turbulent shock flows would amplify the primordial seeds during the structure formation
- Possible mechanisms to produce primordial seeds are:
  - Inflation (Ratra 1992), (Turner & Widrow 1988)
  - Phase transitions (Vachaspati 1991)
  - Other processes as: cosmic strings, cosmic defects...
- Imprints on: BBN, LSS, ionization history of the Universe, spectral distortions, CMB

PMF model

- **Homogeneous PMF** $\rightarrow$ isotropy-breaking $\rightarrow$ EB, TB modes predictions
- **Stochastic PMF background** with a non-helical (symmetric) and a helical part (anti-symmetric)
- Two-point correlation function in the Fourier space

$$\langle B_i^*(\mathbf{k}) B_j(\mathbf{k}')\rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k} - \mathbf{k}')[P_{ij} P_B(k) - i\epsilon_{ijl}\hat{k}_l P_H(k)] \quad (1)$$

- Power spectrum of the magnetic field given by

$$P_B(k) = Ak^{n_B} = \frac{(2\pi)^{n_B+5}}{2k_\lambda^{n_B+3}} \frac{B_\lambda^2}{\Gamma\left(\frac{n_B}{2}+\frac{3}{2}\right)} k^{n_B}, \text{(for } k < k_D), \quad (2)$$

and

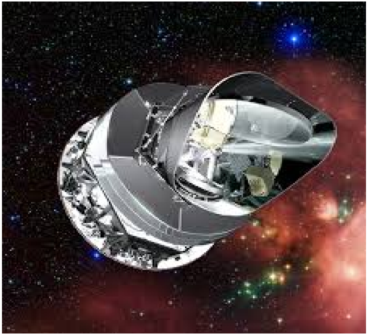
$$P_H(k) = A_H k^{n_H} = \frac{(2\pi)^{n_H+8}}{2k_\lambda^{n_H+3}} \frac{H_\lambda^2}{\Gamma\left(\frac{n_H}{2}+2\right)} k^{n_H}, \quad (3)$$

with $k_\lambda = 2\pi/\lambda$, B_λ smoothed on a comoving scale λ $(f_\lambda = Nexp(-x^2/2\lambda^2))$

- The $\tau_{\mu\nu}^{mag}$ sources scalar, vector and tensor pertubations
- Magnetic-induced perturbations could be distinghised from other sources
- Three different initial conditions can be considered to solve the Einstein-Boltzmann equations: passive, compensated and inflationary modes
  - Passive-modes: includes the magnetic contribution before neutrino decoupling. No compensation of the PMF anistropic stress is produced without neutrino free streaming. It is a logarithmical growing mode.
  - Compensated-modes: includes the magnetic contribution after neutrino decoupling. The magnetic metric perturbations are compensated by the fluid ones to leading order.
- Both are independent of the generation mechanism

Planck 2015 results

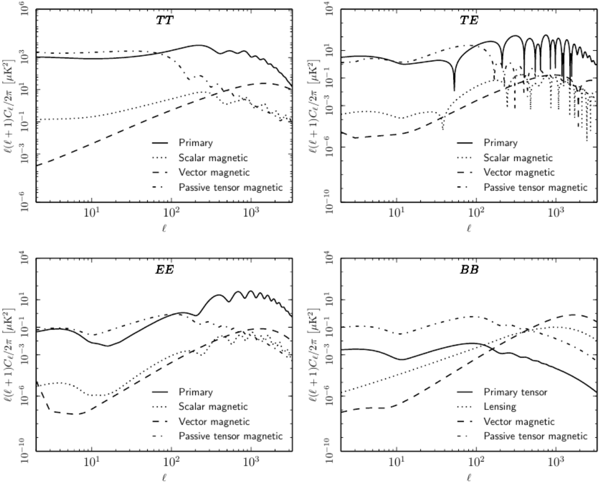
Planck Col. XIX: Constraints on primordial magnetic fields (arXiv:1502.01594)



Planck 2015 results establish constraints on a stochastic PMF based on:

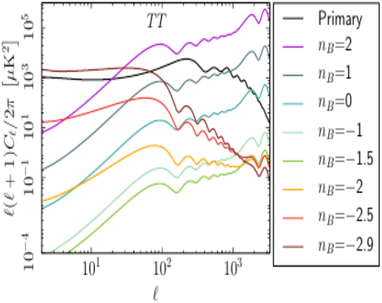
- the impact of magnetic-induced perturbations on CMB temperature and polarization power spectra
- the magnetic-induced non-Gaussianities and non-zero bispectrum
- the Faraday rotation of the angular power spectra of CMB polarization
- the magnetic-induced breaking of statistical isotropy (Alfvén waves)

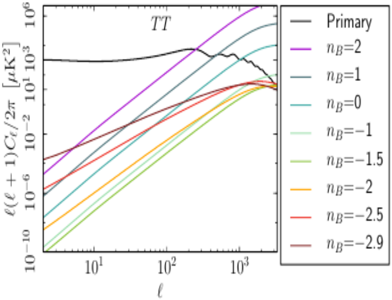
Behaviour of the compensated/passive modes



For $B_{1Mpc} = 4.5$nG, $n_B = -2.9$

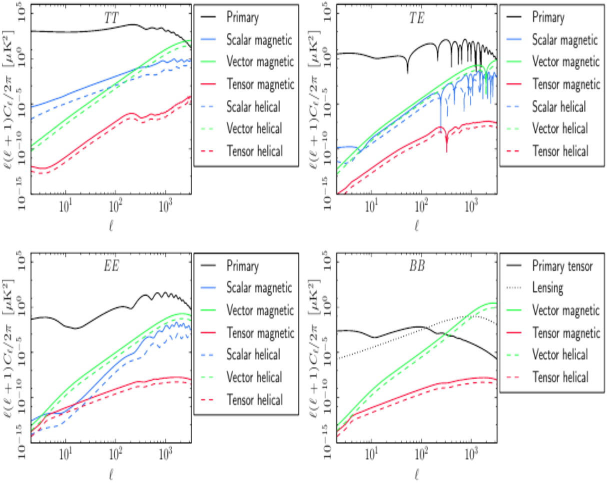
n_B dependence for compensated modes: scalar and vector





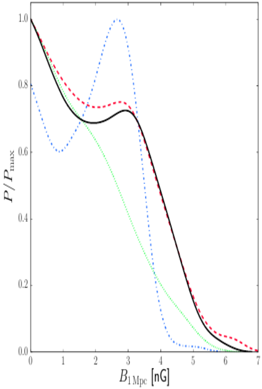
For $B_{1Mpc} = 4.5$nG

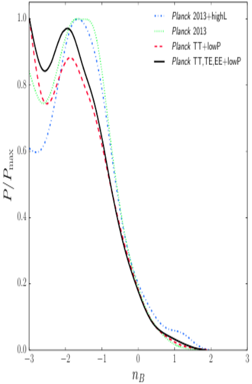
Comparison non-helical vs helical PMFs



For $B_{1Mpc} = 4.5$nG, $n_B = -1$

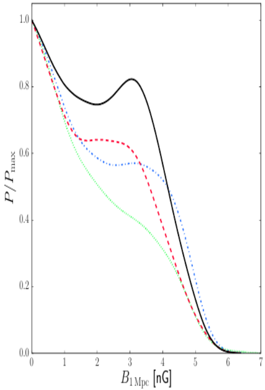
Constraints with compensated scalar and vector contributions

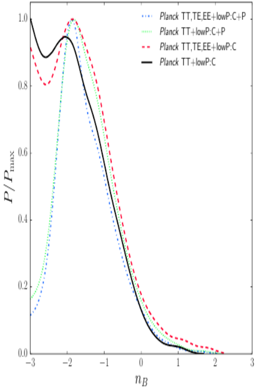




Results: $B_{1Mpc} < 4.4$ nG, $n_B < -0.31$ (95% CL)

Constraints with compensated + passive contributions





Results: With P: $B_{1Mpc} < 6.5$ nG (95% CL). C+P: $B_{1Mpc} < 4.5$ nG (95% CL)

PMF parameters

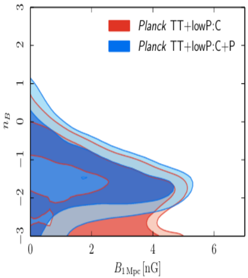


Fig. 8. PMF amplitude versus the spectral index for the baseline *Planck* 2015 case. C+P denotes the case where both compensated and passive modes are considered, whereas C indicates the case with only compensated modes. The two contours represent the 68 % and 95 % confidence levels.

Table 1. Mean parameter values and bounds of the central 68 %-credible intervals from *Planck TT,TE,EE* (left column) and *Planck TT* (right column). When consistent with zero, the upper bound of the 95 %-credible interval is reported. Note that H_0 is a derived parameter.

Parameter	*Planck TT,TE,EE* + lowP	*Planck TT* + lowP
ω_b	0.0222 ± 0.0002	0.0222 ± 0.0002
ω_c	0.1198 ± 0.0015	0.1197 ± 0.0022
θ	1.0408 ± 0.0003	1.0408 ± 0.0005
τ_{reion}	0.078 ± 0.017	0.075 ± 0.019
$\log[A_s 10^{-9}]$	3.09 ± 0.03	3.08 ± 0.04
n_s	0.963 ± 0.005	0.964 ± 0.007
H_0	$67.77^{+0.68}_{-0.67}$	$67.82^{+0.98}_{-1.00}$
$B_{1\,\mathrm{Mpc}}$/nG	< 4.4	< 4.4
n_B	< -0.008	< -0.31

Helical part

- Constraints on the helical part: generates TB and EB modes
- PMF strength $B_{1\,Mpc} < 5.6$ nG

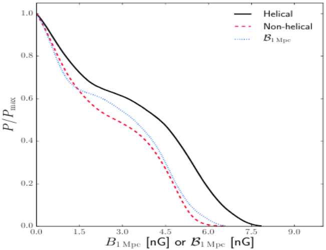


Fig. 12. PMF amplitude constraint for the helical case (solid black) compared with the non-helical case (dashed red). The dotted blue line shows the constraint on the amplitude of the helical component as an alternative interpretation of the constraints on the amplitude of PMFs with a helical component.

Others results: BICEP2/Keck/Planck

BICEP2/*Keck-Planck*

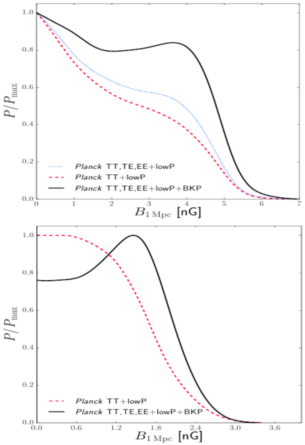
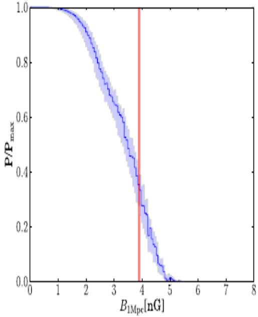


Fig. 11. Probability distributions for the PMF amplitude including the BICEP2/*Keck-Planck* cross-correlation, compared with the one based only on *Planck* data. *Top*: the case in which the spectral index is free to vary, *bottom*: the case with $n_B = -2.9$.

- PMF strength $B_{1\,Mpc} < 4.7$ nG
- PMF strength $B_{1\,Mpc} < 2.2$ nG for $n_B = -2.9$

POLARBEAR



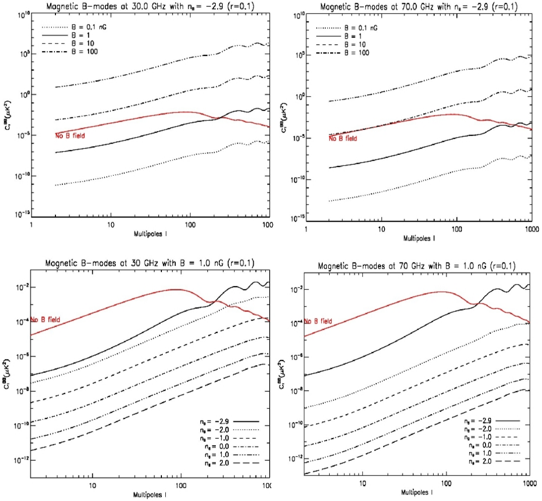
- Only for compensated modes
- Magnetically-induced vector modes: $B_{1Mpc} < 3.9$ nG (n_B unconstraint)

POLARBEAR, PRD (2015), 92, 123509 (arXiv:1509.02461)

Magnetically-induced non-Gaussianities

- They are generated by the quadratic terms of MF strength in the energy-momentum tensor
- Allow to provide constraints on PMF by computing the passive-mode bispectrum as well as the compensated-mode bispectrum
- Three results are presented by fixing $n_B = -2.9$:
  1. Magnetically-induced passive tensor bispectrum: $B_{1\,Mpc} < 2.8$ nG (95% CL)
  2. Magnetically-induced directional bispectrum: $B_{1\,Mpc} < 4.5$ nG (95% CL)
  3. Magnetically-induced compensated scalar bispectrum: $B_{1\,Mpc} < 2.97$ nG (95% CL)

Faraday rotation behaviour



FR of CMB polarization

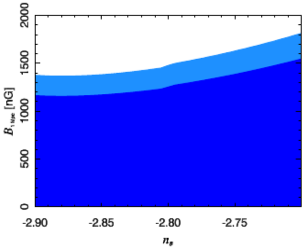


Fig. 13. Probability contours of PMF strength vs. spectral index of the PMF power spectrum as constrained by the 70 GHz observations.

- FR convert B-modes into E-modes and vice versa
- No helical contribution
- λ^4-dependece of B-modes and E-modes
- Results: $B_{1\,Mpc} < 1380$ nG (95% CL) for $\ell < 30$ at 70 GHz
- POLARBEAR: $B_{1\,Mpc} < 90$ nG (95% CL) for $\ell > 500$ at 148 GHz
- WMAP9 results: $B_{1Mpc} < 1700$ nG, $n_B < 0.58$ (95% CL)

Ruiz-Granados & Rubiño-Martín, 2016, *in preparation*

Magnetically-induced breaking statistical isotropy

- Stochastic PMF as source of primordial vector perturbations
- Alfvèn waves produces observables imprints on CMB via Doppler and the ISW effects
- Constraints are provided on the amplitude of the Alfvèn velocity: $B^2_{1\,Mpc} v_A^4/\bar{B}^2 < 1.7 \times 10^{-5}$ (95% CL) $\rightarrow$ no evidence of Alfvèn waves

Summary of constraints

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Table 1. Limits on primordial magnetic fields from magnetic mode contributions to the CMB power spectra, bispectra, trispectra, reionization, weak lensing, Lyman-α forest and Faraday rotation of background quasars.

Probe	Magnetic modes	Upper limit B_0 (nG)	Reference
CMB Power Spectra	Scalar, vector & tensor	4.4 (non helical, general)	Planck-2015
	Scalar, vector & tensor	5.6 (Helical, general)	Planck-2015
	Scalar, vector & tensor	2.1 (Scale invariant)	Planck-2015
	Ionization History	0.7	Planck-2015
CMB Polarization	Vector, B Mode	3.9	POLARBEAR
CMB Bispectrum	Energy density (Compensated scalar)	22	Seshadri and Subramanian (2009)
	Passive-scalar	2.4	Trivedi *et al* (2010)
	Compensated-scalar	3	Planck-2015
	Vector	10	Shiraishi *et al* (2010)
	Passive-tensor	3.2	Shiraishi and Sekiguchi (2014)
	Passive-tensor	2.8	Planck-2015
CMB Trispectrum	Energy density (Compensated scalar)	19	Trivedi *et al* (2014)
	Passive-scalar	0.6	Trivedi *et al* (2014)
	Magnetic inflationary mode Bonvin *et al* (2013)	0.05	Trivedi *et al* (2014)
Reionization	$n = -2.85$ to -2.95	0.059–0.358	Pandey *et al* (2015)
Weak lensing		~1–3	Pandey and Sethi (2012)
Lyman-α forest	$n \approx -3$	0.3–0.6	Pandey and Sethi (2013)
Faraday rotation	Uniform to 50 Mpc	1–6	Blasi *et al* (1999)
	Uniform to 1 Mpc	0.5–1.2 (2 σ)	Pshirkov *et al* (2015)
Absence of GeV halo from Tev Blazars		$B_0 \gtrsim 10^{-16}$ G	Neronov and Vovk (2010)
(Lower limit)		($l_B \gg l_{ic}$)	Tavecchio *et al* (2011)

Note: We quote limits derived for close to scale-invariant magnetic fields (except where we say general) and an early generation epoch (10^{14} GeV) for magnetic passive modes. The value B_0 refers to the magnetic field smoothed at a scale of 1 Mpc. The last row gives the approximate lower limit from γ-ray observations of TeV blazars.

Subramanian (2016), arXiv:1504.02311

Conclusions

- Magnetically-induced modes do not modified the cosmological parameters of the standard ΛCDM model
- High-ℓ T+P measurements allow to constrain the stochastic PMF background with high precision
- Main contribution comes from the vector perturbations in T
- Magnetically-induced modes are a natural source of non-Gaussinity that complement the constraints coming from the APS
- No Alfvén waves are observed
- Polarized PS at small scales and low frequencies are required to constrain the Faraday rotation. QUIJOTE+Planck(LFI) would be crucial for detecting this effect
- An additional CMB tool for detecting PMF is their impact on the ionization history as published in Chluba et al. (2015, arXiv:1503.04827) which obtain $B < 0.9$ nG and show the impact on the APS

THANK YOU VERY MUCH!