CMB CONSTRAINTS ON PRIMORDIAL MAGNETIC FIELDS FROM THE POST-RECOMBINATION IONIZATION HISTORY

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Cosmic Orbital and Suborbital Microwave ObservationS

COSMIC MAGNETISM
Looking backward approach

Magnetic fields are observed everywhere up to the largest scales of the known Universe

Their origin is still debated

Astrophysical origin with turbulent dynamo from stars
together with AGN feedback in the IGM
or
Amplification during the LSS formation of pre-existing fields

COSMIC MAGNETISM
Looking forward approach

In the early Universe a series of processes may have generated magnetic fields prior to and during the recombination

Different mechanisms provide fields with different characteristics

Primordial fields may have evolved to present days in the fields of the LSS

If structure formation -almost- erases the memory of the field original state FERMI satellite provided a -not so unexpected- way out

Magnetic fields in the voids of the LSS evolved almost passively through the Universe evolution and have memory of their primordial state
Future target of experiments like CTA

COSMIC MAGNETISM
Either way you look it is interesting

Primordial magnetic fields represent a unique observational window on the early Universe

Using the constraints on their characteristic and discriminating between different generation mechanisms may shed light on the physics of the early Universe

Inflation dynamics, phase transitions, second order perts.
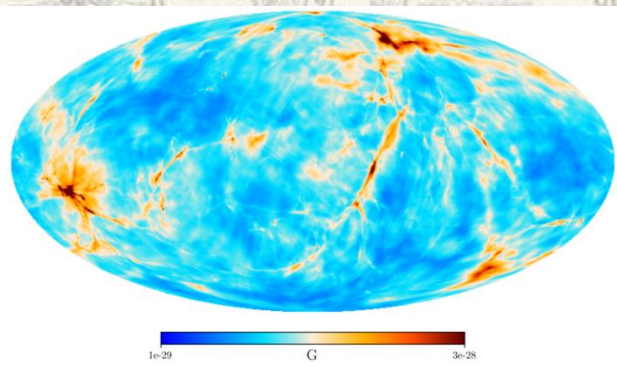
Magnetic field in our local backyard generated by the Harrison mechanism before recombination
Hutschenreuter, Dorn, Jasche, Vazza, Paoletti, Lavaux, Enßlin (2018)

Primordial magnetic fields may hold the key in understanding the magnetic Universe we observe today

We are just at the dawn of this cosmology field

Fields in voids may hold the witness of the primordial universe and its evolution through cosmic time

Thanks to improved simulations we can now realiably look through time

MAGNETIC FIELDS AND THE CMB

GRAVITATIONAL EFFECTS

Magnetically induces Scalar Vector and Tensor perturbations depend on the PMF characteristics and may strong increase the power on small angular scales n T and P inducing also a B-mode polarization which may relevant for scale invariant PMFs

FARADAY ROTATION

PMFs induce a rotation of the polarization plane generating B-modes from E-modes and viceversa.
The effect has a peculiar frequency dependence and may be identified and disentangled from birefringence thanks to it.
Relevant for future low-frequency experiments

NON GAUSSIANITIES

A stochastic background of PMF with its energy momentum tensor quadratic in the fields have a fully non Gaussian impact on CMB anisotropies.
Non zero bispectra with shapes depending on the PMF characteristics and magnetically induced initial conditions

MAGNETIC FIELDS AND THE CMB: IMPACT ON THE IONIZATION HISTORY

Magneticallly induced perturbations survive Silk damping thanks to magnetosonic waves but the PMFs are suppressed on smaller scales by radiation viscosity

$$\frac{k_D}{\text{Mpc}^{-1}} = \frac{\sqrt{5.5 \times 10^4}(2\pi)^{\frac{n_B+3}{2}}}{\sqrt{\langle B^2 \rangle}/nG\sqrt{\Gamma[(n_B+5)/2]}}\sqrt{h\frac{\Omega_b h^2}{0.022}}$$

Around and after recombination the fields are suppressed by two additional mechanisms which arise thanks to the reduced ionization fraction

MHD DECAYING TURBULENCE
AMBIPOLAR DIFFUSION

Both effect induce a dissipated energy injection in the plasma heating the matter and modifying the ionization history and as a consequence CMB anisotropies

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

MHD DECAYING TURBULENCE

The high radiation viscosity in the pre-recombination plasma over-damps the velocity
fluctuations maintaining the Reynold number low
Around and after recombination when the radiation viscosity drops it allows for the
development of large Reynold numbers and MHD turbulence
Energy is transferred from large to small angular scales where it is dissipated into heat

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

(Sethi and Subramanian 2009)

$$m = 2(n_B + 3)/(n_B + 5)$$

$$t_i/t_d \approx 14.8(\langle B^2\rangle^{1/2}/\text{nG})^{-1}(k_D/\text{Mpc}^{-1})^{-1}$$

$$\rho_{\text{B}}(z) = \langle B^2\rangle(1 + z)^4/(8\pi) \approx 9.5 \times 10^{-8}(\langle B^2\rangle/\text{nG}^2)\,\rho_\gamma(z)$$

It depends on the energy density of the field.

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.

$$\Gamma_{am} \approx \frac{(1 - X_p)}{\gamma X_p \rho_b^2} \langle \mathbf{L}^2 \rangle$$

(Sethi & Subramanian 2005; Schleicher et al. 2008)

$$\langle \mathbf{L}^2 \rangle = |(\nabla \times \mathbf{B}) \times \mathbf{B}|^2 / (4\pi)^2$$

$$|(\nabla \times B) \times B|^2 = 16\pi^2 \rho_B^2(z) \, l_D^{-2}(z) \, g_L(n_B + 3)$$

$$g_L(x) = 0.6615[1 - 0.1367x + 0.007574x^2] \, x^{0.8874}$$

$$l_D = a/k_D$$

Lorentz force derived from the exact solution to the convolution integral in Finelli et al. And Paoletti et al. 2010

IT ALL LOOKS FINE AND EASY JUST INSERT THE RATES IN COSMOREC AND IT'S DONE.....

TOO MUCH HEAT!!!

CONVERGENCE IS JUST A DREAM!!!

REALITY ARE NUMERICAL INSTABILITIES!!!

PANIC!!!!!!!!!!!!!!!!!!!!!!!!!

MHD TURBULENCE

The heating rises very sharpely at recombination. Although the injection rate is continuous it presents a cusp which gives rise to numerical instabilities
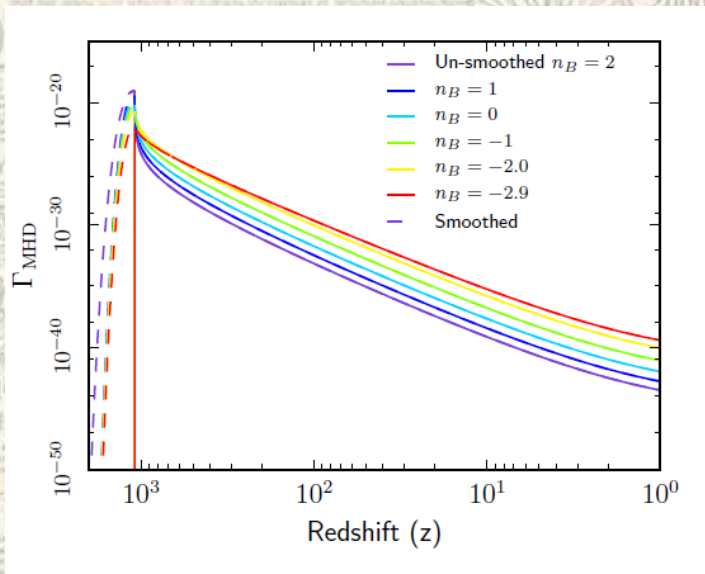
AMBIPOLAR

PMFs with power on small scales produce too much heating to be numerically handled by the common version of cosmorec

IT WAS NOT POSSIBLE TO CONSTRAIN FIELDS WITH POSITIVE SPECTRAL INDICES

Previous treatments were limited to either scale invariant case like in Planck XIX 2016 and Chluba et Al. 2015 or at most added -2.5 and -1.5 like in Komatsu & Kunze 2015

MHD TURBULENCE

We have improved the transition in the rise of the MHD heating term in a way to be more representative of the rise of the effect during the recombination reducing the sharpness of the rate and as a consequence the numerical instabilities in the derivatives.
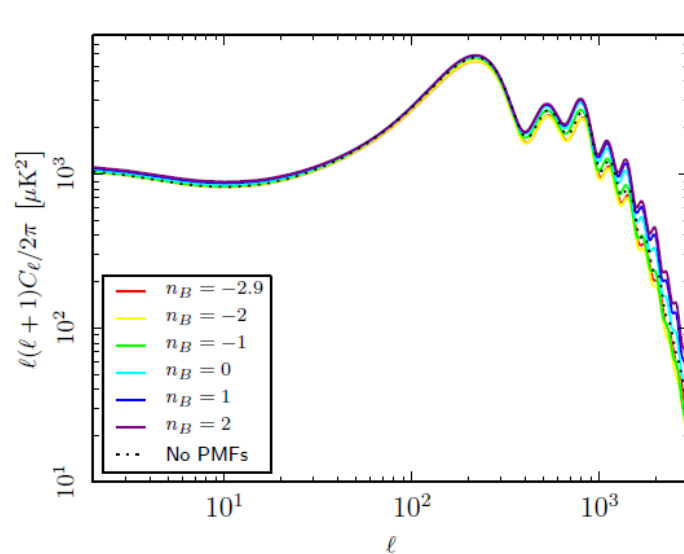

AMBIPOLAR

We have improved the numerical accuracy of the recombination code for the injection rate
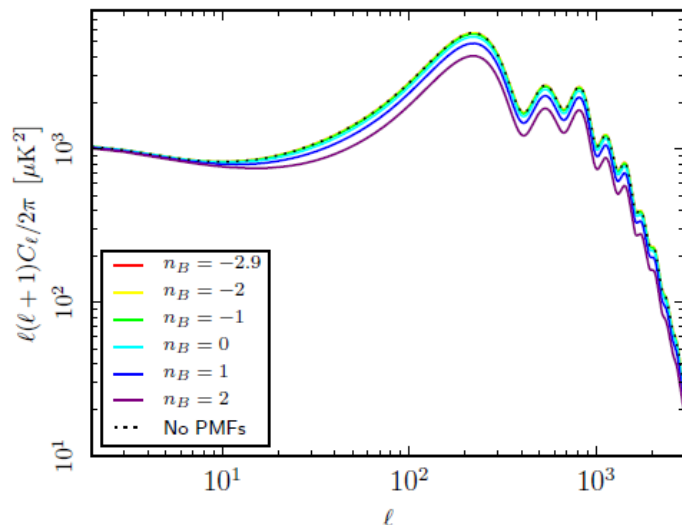
GENERAL

We have increased the time sampling of recombination in order to solve large scale numerical instabilities which were responsible of the sharp features at low multipoles observed in previous works
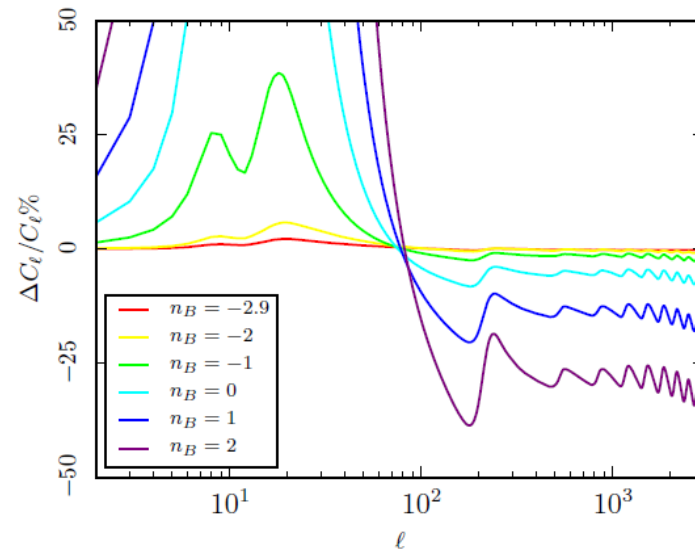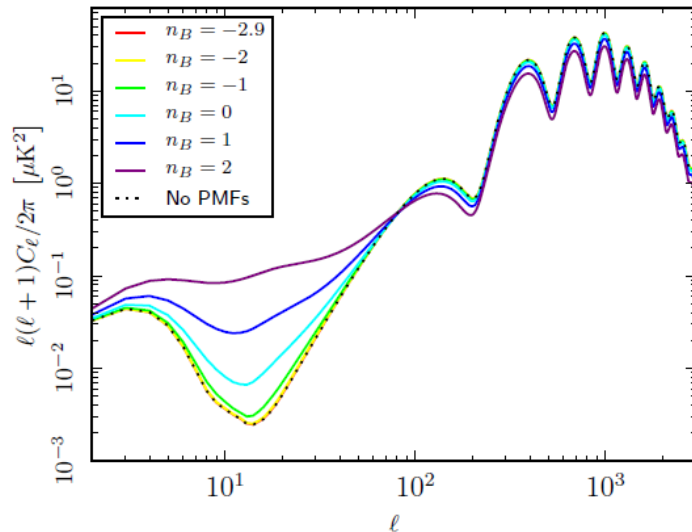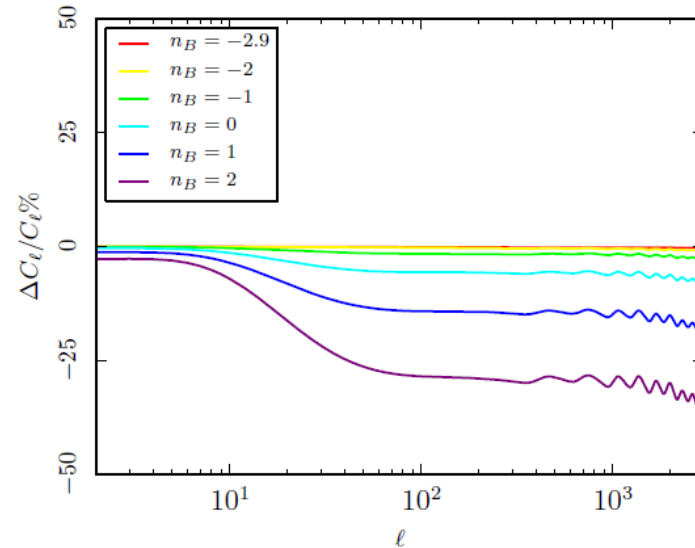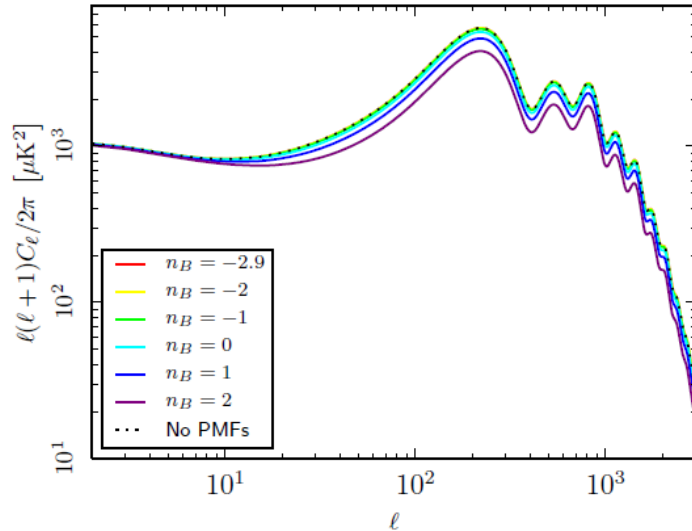
MHD TURBULENCE
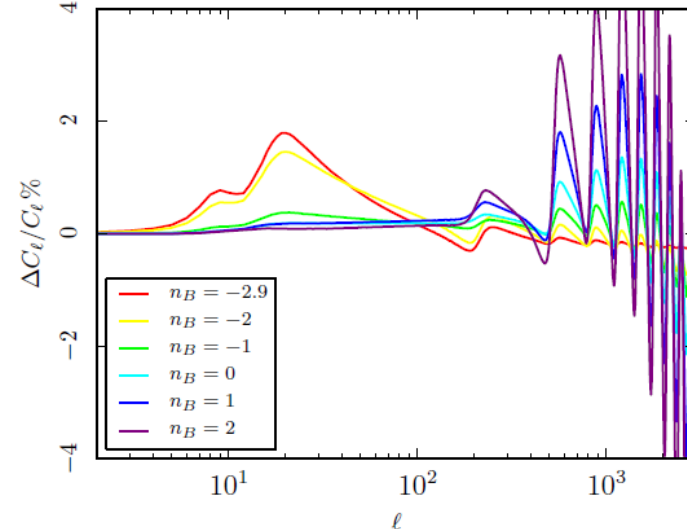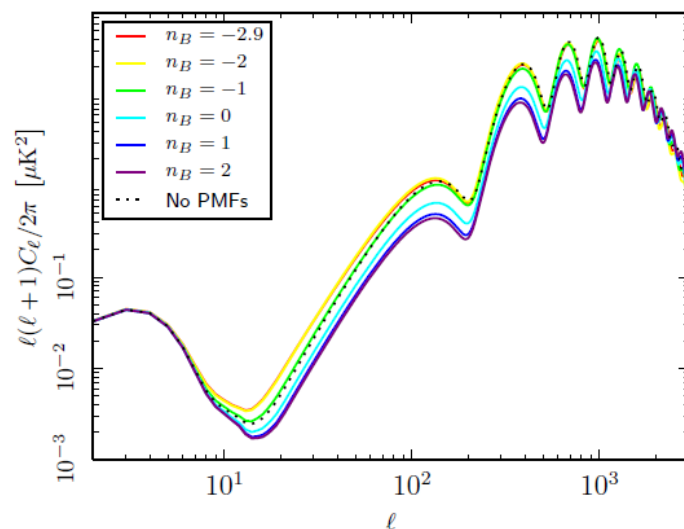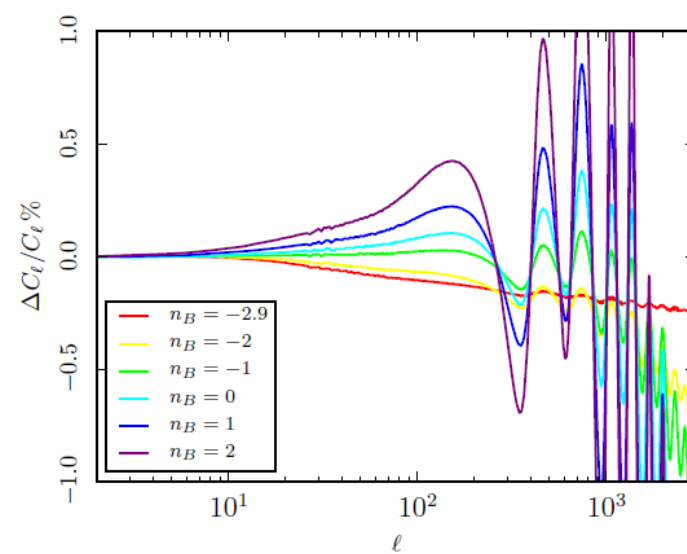
Paoletti, Chluba, Finelli, Rubino-Martin 2018

AMBIPOLAR DIFFUSION

TOTAL

Paoletti, Chluba, Finelli, Rubino-Martin 2018
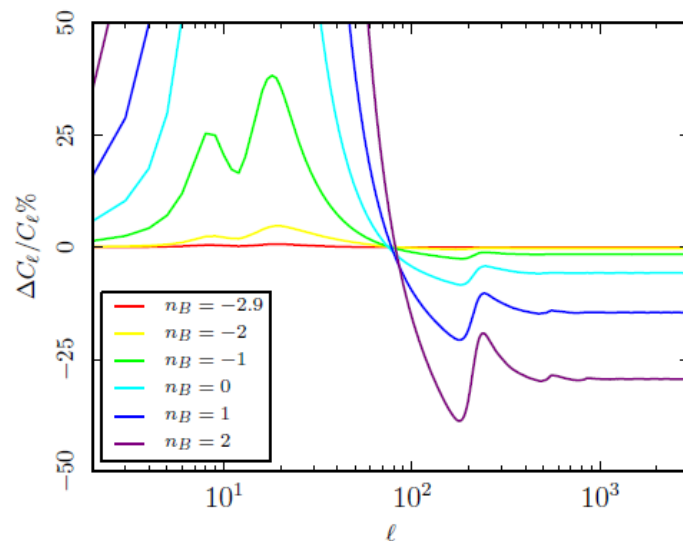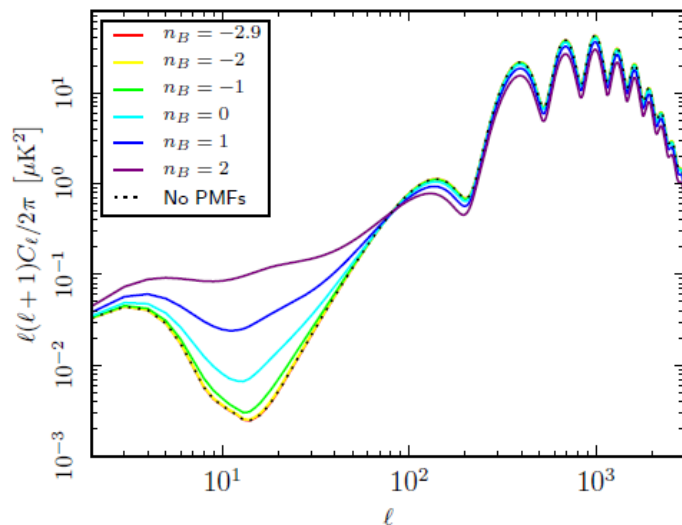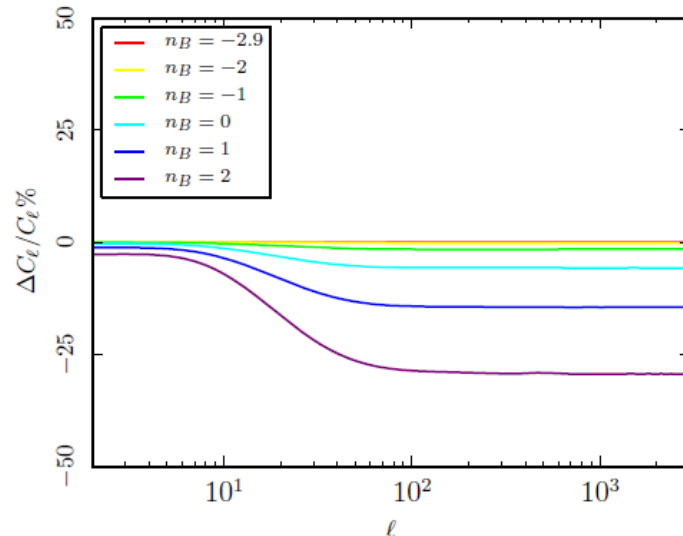
CONSTRAINTS ON PMFs

We developed a modified version of COSMOREC and Recfast++ to include the heating terms by PMFs (Chluba , Paoletti, Finelli & Rubino-Martin 2015).
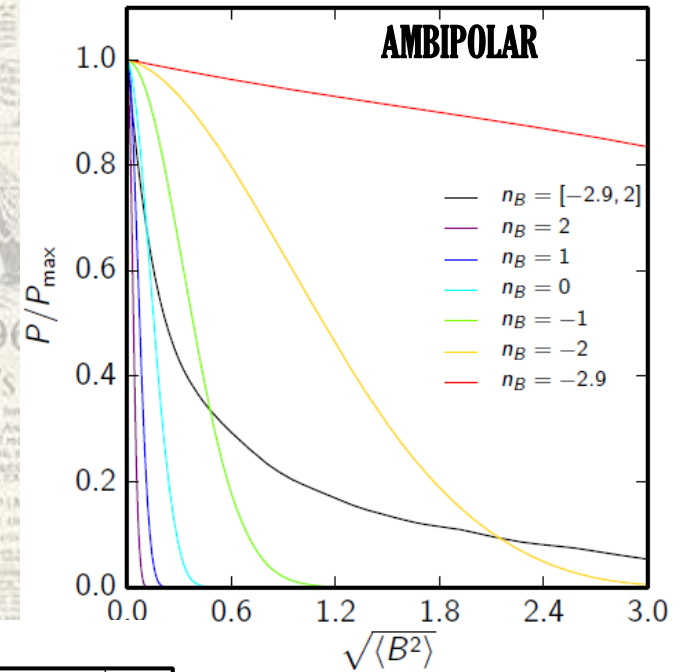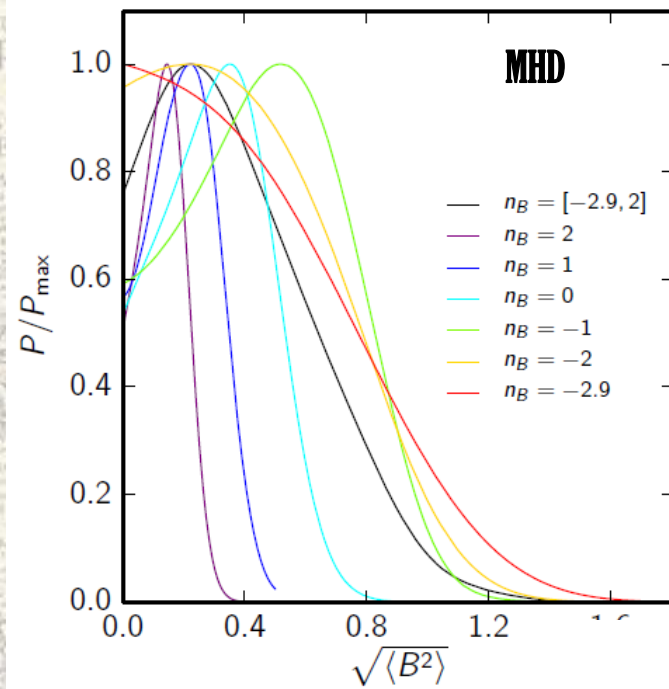We have implemented the numerical solutions and derived the constraints on the PMFs

We have used the Planck 2015 data:

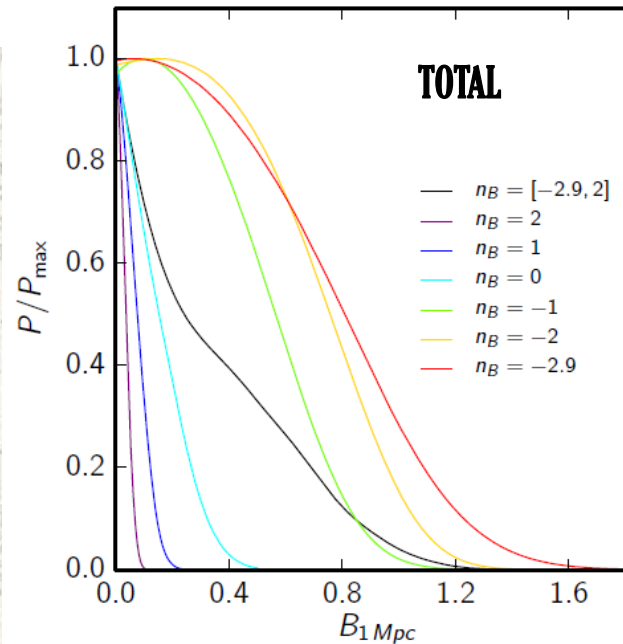Planck high-l likelihood based on cross spectra at 100, 143 and 217 GHz
Planck low-l likelihood in temperature based on the component separated map
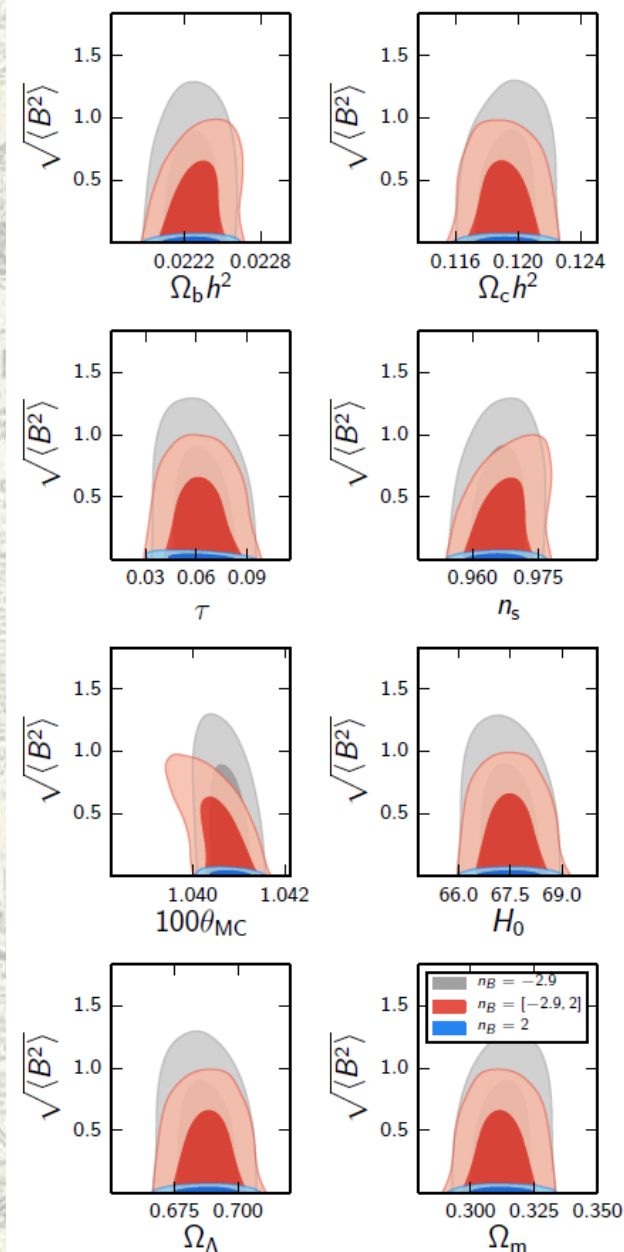Planck 2015 lensing likelihood with conservative range.
Optical depth prior based on Planck 2015 results.

MHD

$n_B = [-2.9, 2]$
$n_B = 2$
$n_B = 1$
$n_B = 0$
$n_B = -1$
$n_B = -2$
$n_B = -2.9$

AMBIPOLAR

$n_B = [-2.9, 2]$
$n_B = 2$
$n_B = 1$
$n_B = 0$
$n_B = -1$
$n_B = -2$
$n_B = -2.9$

$$\langle B^2 \rangle = \frac{A_B}{2\pi^2} \int_0^{k_D} dk\, k^{2+n_B} = \frac{A_B}{2\pi^2(n_B+3)} k_D^{n_B+3}$$

TOTAL

$n_B = [-2.9, 2]$
$n_B = 2$
$n_B = 1$
$n_B = 0$
$n_B = -1$
$n_B = -2$
$n_B = -2.9$

Paoletti, Chluba, Finelli, Rubino-Martin 2018

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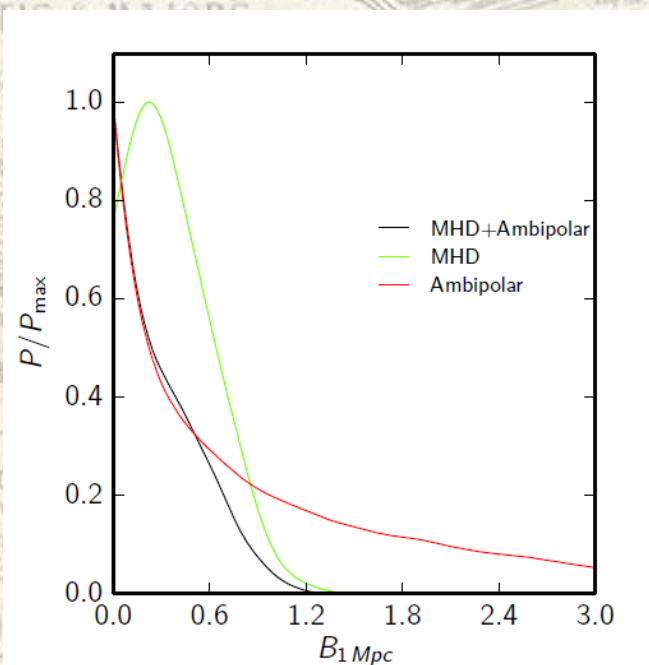
n_B	$\sqrt{\langle B^2 \rangle}$ (nG)		
	MHD turbulence	Ambipolar diffusion	Combination
2	< 0.25	< 0.06	< 0.06
1	< 0.37	< 0.12	< 0.13
0	< 0.58	< 0.26	< 0.30
-1	< 0.90	< 0.63	< 0.74
-2	< 0.93	< 1.88	< 0.90
-2.9	< 1.04	< 7.29	< 1.06
[-2.9,2]	< 0.87	< 2.52	< 0.83

Paoletti, Chluba, Finelli, Rubino-Martin 2018

PMFs generated prior to the recombination affect CMB anisotropies

Current constraints with the gravitational effects are at the level of few nanoGauss

The effect of the dissipation of the fields due to MHD turbulence and ambipolar diffusion has a strong impact on CMB anisotropies in temperature but also in polarization.

AMBIPOLAR diffusion dominates positive spectral indices
MHD is weakly dependent on the spectral index.

The constraints with Planck 2015 data are below the nanoGauss
Constraints for positive spectral indices are at the level of tens of picoGauss.

THE IMPACT OF PMFS ON THE IONIZATION HISTORY IS VERY STRONG AND REPRESENTS ONE OF THE BEST TARGET FOR THE FUTURE CMB DATA