CMB FROM SPACE
A LABORATORY FOR COSMOLOGY AND FUNDAMENTAL PHYSICS

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Milano - March 6 2019

Future CMB space experiments represent the best observational window on cosmology, fundamental physics and cosmic magnetism

Planck has shown the potential of space missions carrying out the best measurement ever of CMB temperature anisotropies in the region where the CMB is the dominant contribution

The next frontier is polarization. Future ground based measurements need to be complemented by full sky, large frequency coverage (especially on the high side) measurements in polarization. This can be achieved only by space

In order to design the road ahead optimizing the design of future missions to maximize the scientific outcome (also keeping the costs under control) it is necessary to do

Forecasts

One of the tasks of the WP 4-6X1 is to perform scientific forecasts for future generation of satellite missions for the CMB and also for their combination with LSS experiments

In this framework the expertise developed within the Planck collaboration in the working groups of inflation, primordial magnetic fields, cosmological parameter and likelihood has been the starting point of the work

Real data analyses and forecasts pipeline:

Theoretical models
Predictions for CMB observables

Current Data

- Real datata analysis with different combinations and setups
- Constrains on the cosmological parameters which characterize the model through Markov chain MonteCarlo algorithm

Forecasts

- Simulations of mock data including astrophysical contamination
- Forecasts on the cosmological parameters which characterize the model through Markov chain MonteCarlo algorithm

Main activities :

- **Planck legacy**
  - Release preparation
  - Post-release exploitation

- **Forecasts for the future experiments**
  - an expertise from the past – Core
  - Preparation for the future – LiteBIRD, Pristine

  - **Early Universe** How were the initial conditions?

  - **Cosmic Magnetism** What is the origin of cosmic magnetism?

  - **Reionization** When reionization started and how it happened?

  - **Dark Energy as a scalar-tensor gravity – New Isocurvatures mode** Are there viable alternatives to general relativity?

  - **CMB X correlation with LSS** Can CMBXLSS break degeneracies on the late Universe physics?

PLANCK LEGACY

Participation to the current Planck 2018 Legacy Release.
We are strongly involved in the inflation working group and in particular in the study of the constraints on slow roll inflationary models

Planck was a formidable experiment to probe the initial conditions and the physics of the Early Universe.

The Universe according to Planck:

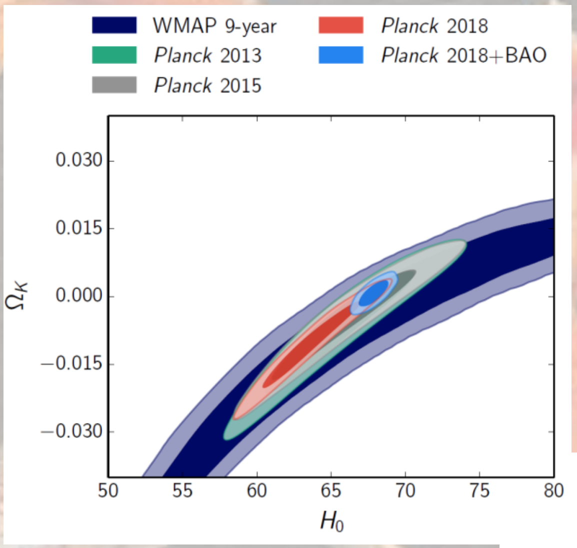
- **Flat** $\Omega_K = 0.0007 \pm 0.0037 \quad (95\,\%\ \mathrm{CL})$.
- **Primordial perturbations follow a power law power spectrum n_s = 0.9649 ± 0.0042 at 68 %CL, 8.4 sigma from scale invariance with no scale dependence**

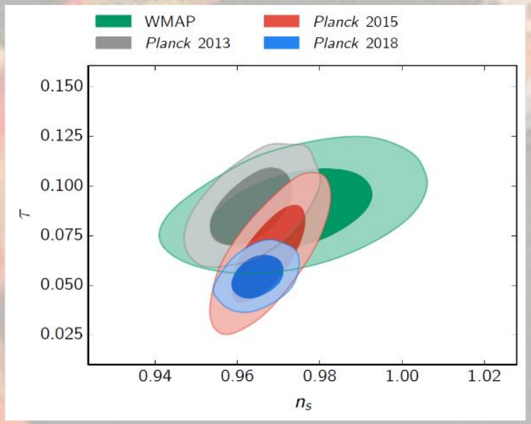
$$\frac{dn_s}{d\ln k} = -0.0045 \pm 0.0067$$

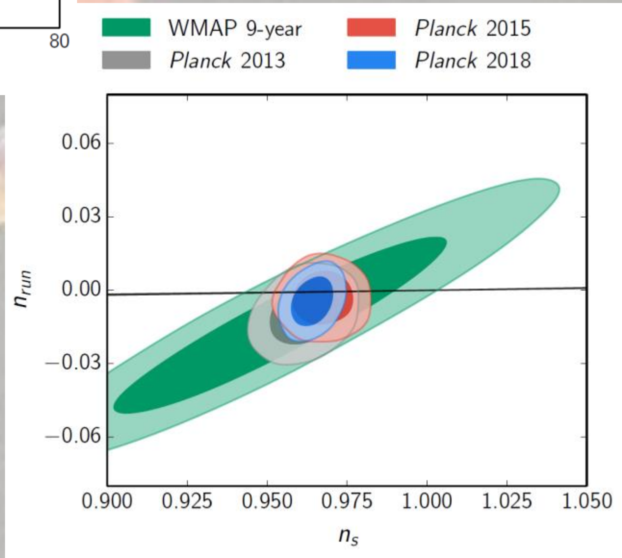
Or running of running spectral index

$$\begin{aligned} n_s &= 0.9587 \pm 0.0056\ (0.9625 \pm 0.0048)\,, \\ dn_s/d\ln k &= 0.013 \pm 0.012\ (0.002 \pm 0.010)\,, \\ d^2n_s/d\ln k^2 &= 0.022 \pm 0.012\ (0.010 \pm 0.013)\,, \end{aligned}$$

- **Gaussian**
- **Adiabatic**





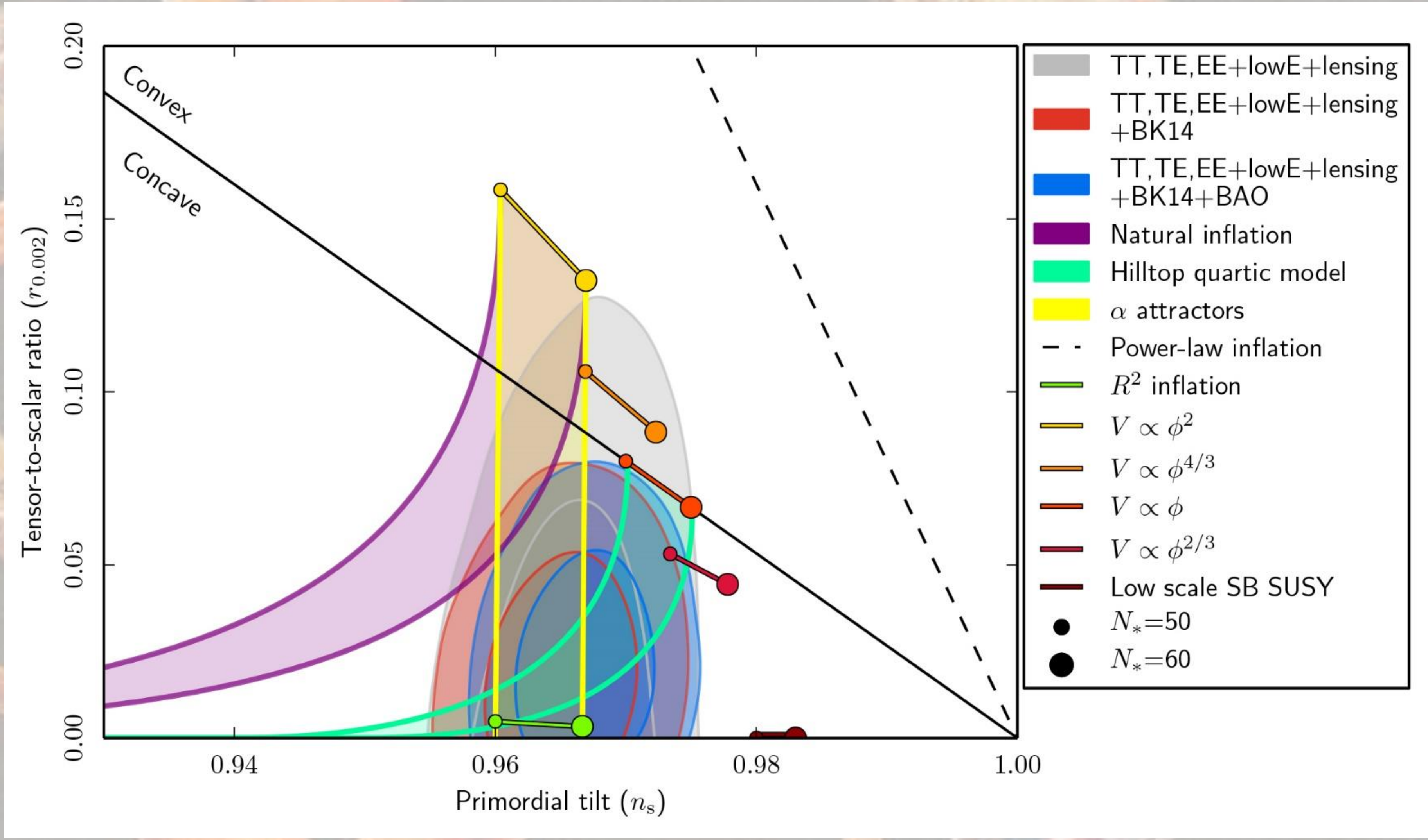


Constraints on the tensor to scalar ratio

Cosmological model ΛCDM+r	Parameter	*Planck* TT,TE,EE +lowEB+lensing	*Planck* TT,TE,EE +lowE+lensing+BK14	*Planck* TT,TE,EE +lowE+lensing+BK14+BAO
	r	< 0.11	< 0.070	< 0.070
	$r_{0.002}$	< 0.10	< 0.064	< 0.065
	n_s	0.9659 ± 0.0041	0.9653 ± 0.0041	0.9670 ± 0.0037
$+dn_s/d\ln k$	r	< 0.16	< 0.079	< 0.076
	$r_{0.002}$	< 0.16	< 0.077	< 0.072
	n_s	0.9647 ± 0.0044	0.9640 ± 0.0043	0.9658 ± 0.0038
	$dn_s/d\ln k$	-0.0085 ± 0.0073	-0.0071 ± 0.0068	-0.0065 ± 0.0066
$+N_{\rm eff}$	r	< 0.092	< 0.071	< 0.072
	$r_{0.002}$	< 0.085	< 0.065	< 0.067
	n_s	$0.9607^{+0.0086}_{-0.0084}$	$0.9606^{+0.0084}_{-0.0083}$	0.9660 ± 0.0070
	$N_{\rm eff}$	2.92 ± 0.19	2.93 ± 0.19	3.02 ± 0.17
$+m_\nu$	r	< 0.097	< 0.071	< 0.070
	$r_{0.002}$	< 0.091	< 0.065	< 0.065
	n_s	0.9654 ± 0.0044	0.9652 ± 0.0042	0.9669 ± 0.0037
	$\sum m_\nu$ [eV]	< 0.24	< 0.22	< 0.11
$+\Omega_K$	r	< 0.12	< 0.076	< 0.074
	$r_{0.002}$	< 0.12	< 0.072	< 0.068
	n_s	$0.9703^{+0.0045}_{-0.0046}$	$0.9699^{+0.0047}_{-0.0046}$	$0.9664^{+0.0045}_{-0.0046}$
	Ω_K	$-0.012^{+0.007}_{-0.006}$	$-0.012^{+0.007}_{-0.006}$	0.0006 ± 0.0019
$+w_0$	r	< 0.11	< 0.074	< 0.073
	$r_{0.002}$	< 0.10	< 0.069	< 0.068
	n_s	0.9675 ± 0.0042	0.9670 ± 0.0042	$0.9660^{+0.0039}_{-0.0040}$
	w_0	$-1.58^{+0.14}_{-0.34}$	$-1.58^{+0.14}_{-0.34}$	$-1.04^{+0.06}_{-0.05}$

Currently updating to BK15

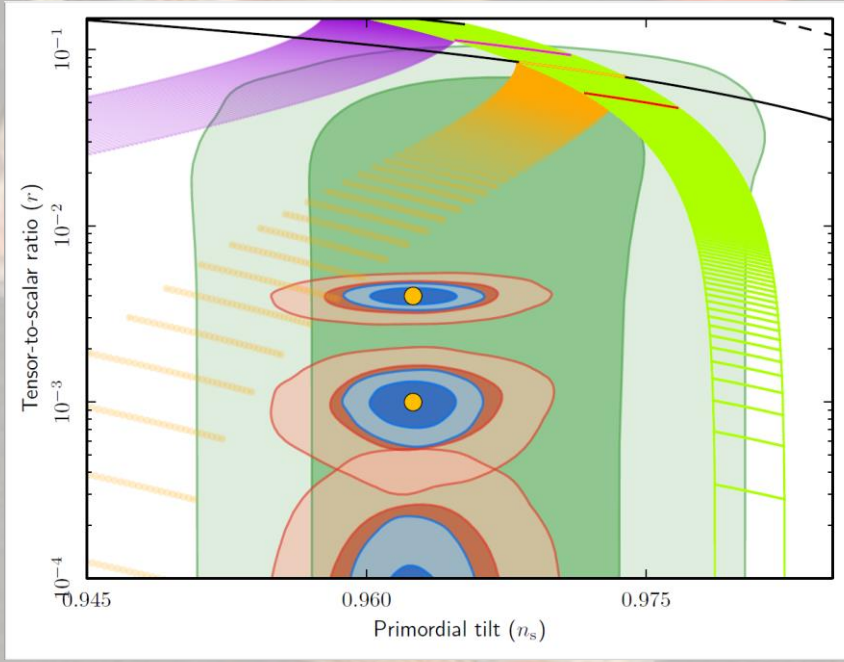
Constraints on slow roll models

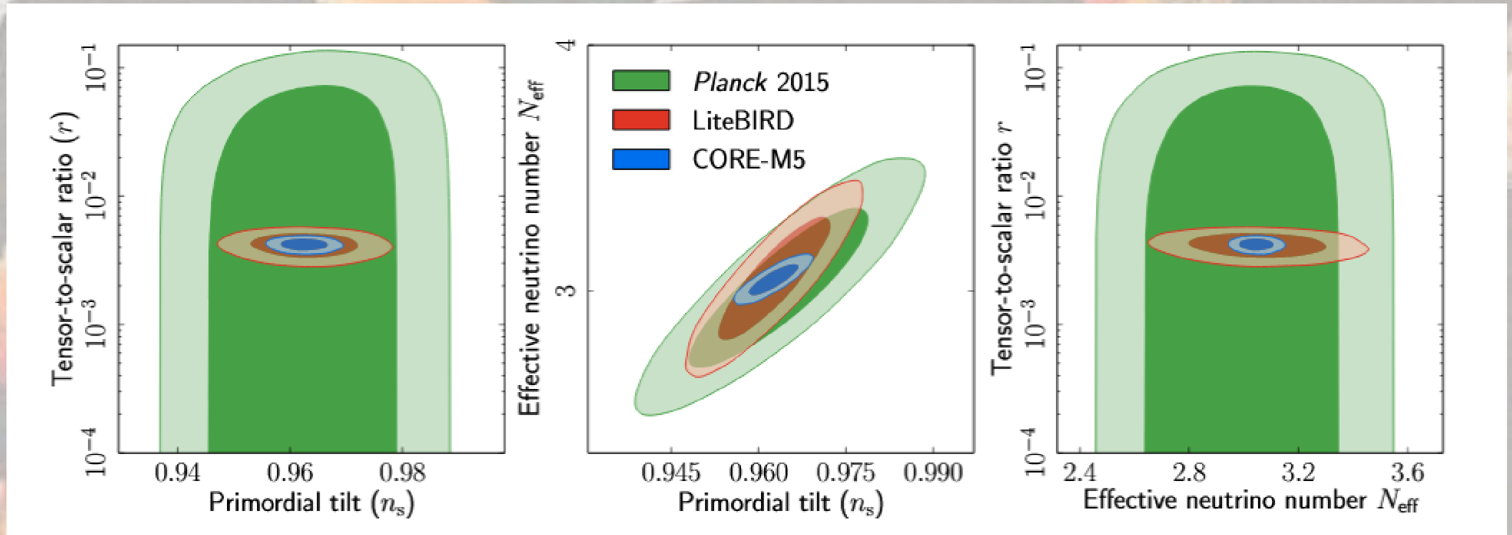


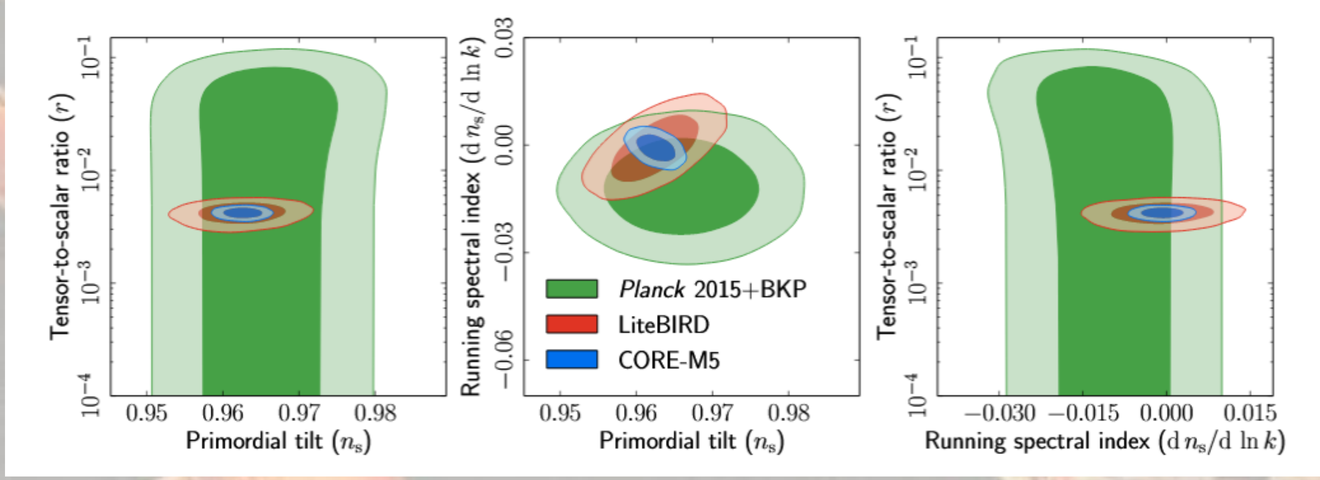
Planck improves the bound on the tensor to scalar ratio, i.e. $r < 0.10$ at 95 %CL at the pivot scale k=0.002 Mpc^{-1}. In combination with BK14, the bound tightens to $r < 0.064$ at 95 % CL. The analysis with the new data from BICEP-Keck collaboration (BK15, P.A.R. Ade et al., 2018) is ongoing

FORECASTS

Methods developed for the COrE forecasts in the inflation ECO paper







Core Coll. ECO paper on inflation

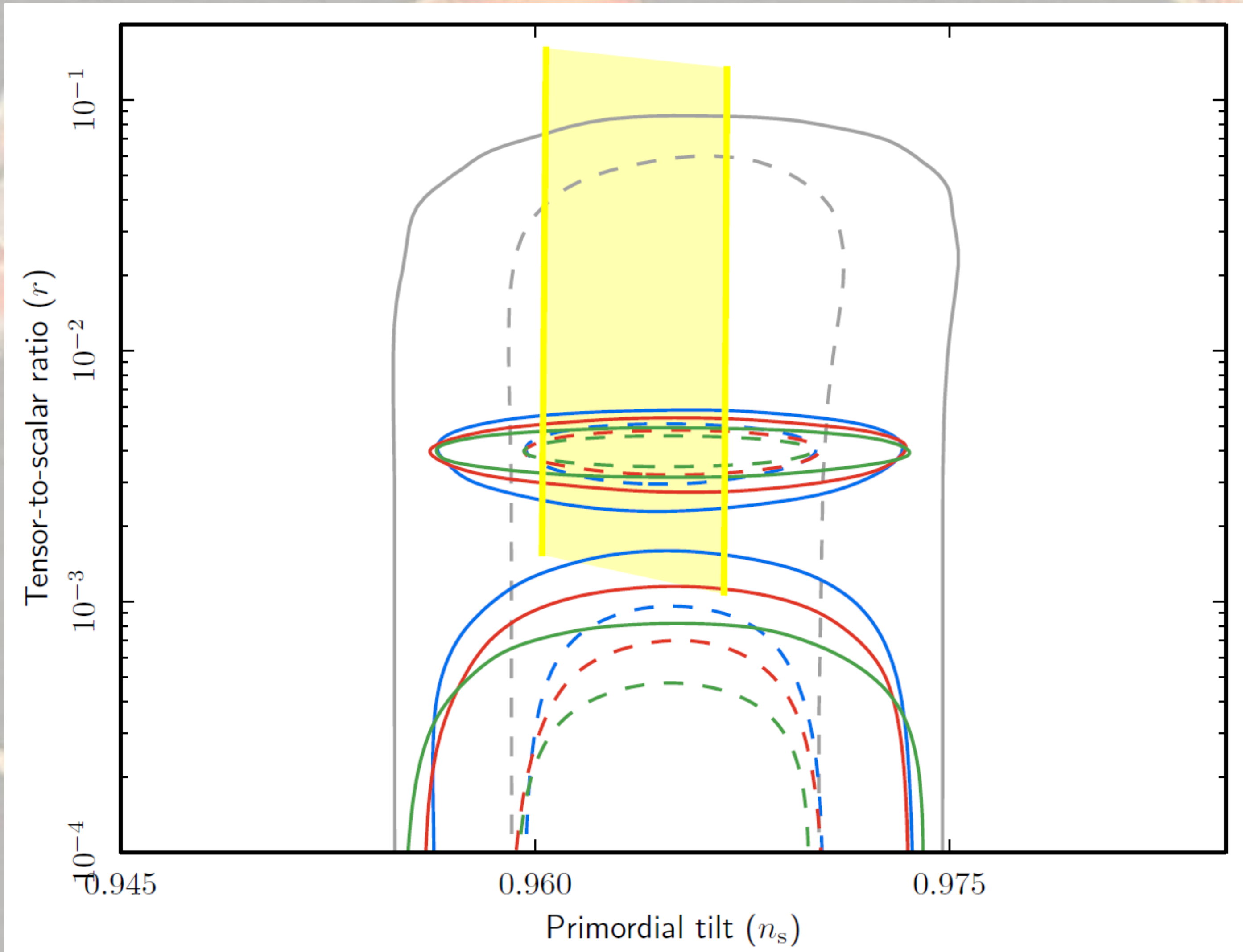
LiteBIRD

We performed the forecasts for the tensor to scalar ratio using a Markov chain MonteCarlo approach where all the cosmological parameters are varied together with r

Mock data:

- **Baseline is the noise based on the instrumental characteristics**
- **foreground residuals and post component separation noise (provided by J. Errard)**
- **impact of delensing based on external data support for two extreme cases:**

  - **optimistic on long timescale - CIB+WISE combined with high-resolution ground-based CMB data**
  - **more pessimistic but on a shorter timescale -Planck CIB+WISE data which already exists**



Planck 2018+BK14
baseline+FG+post-CS Noise
pessimistic delensing
optimistic delensing

To be updated with the most recent instrumental configuration

PRISTINE

We applied a similar approach to estimate the tensor to scalar ratio for the Pristine proposal for an ESA F-mission

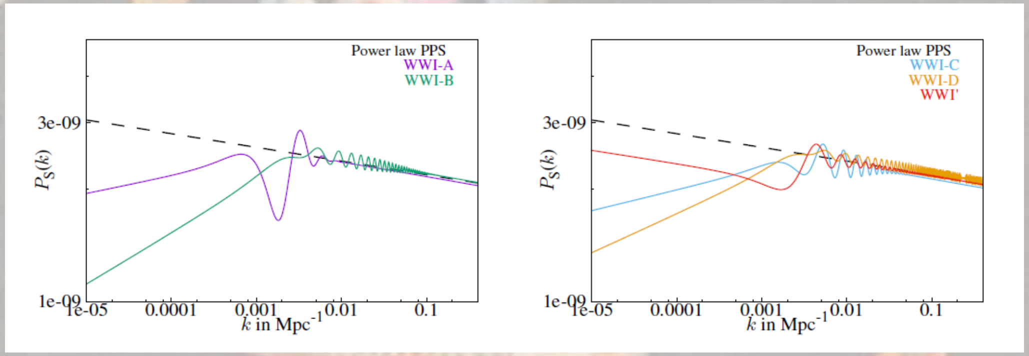
REIONIZATION AND THE EARLY UNIVERSE

Alternatives to/violations of the standard slow roll inflation model represent a possible solution to the large scale anomalies observed. The search of features in the primordial power spectrum is one of the most active fields especially in the light of Planck data.

But features may be obscured by the confusion due to the uncertainty in the reionization model.

Different reionization models may impact the significance of the detection of primordial features.

We investigated this issue considering a Wiggle Whipped Inflation framework where we allow for different modelling of discontinuity in the inflaton potential or its derivative.

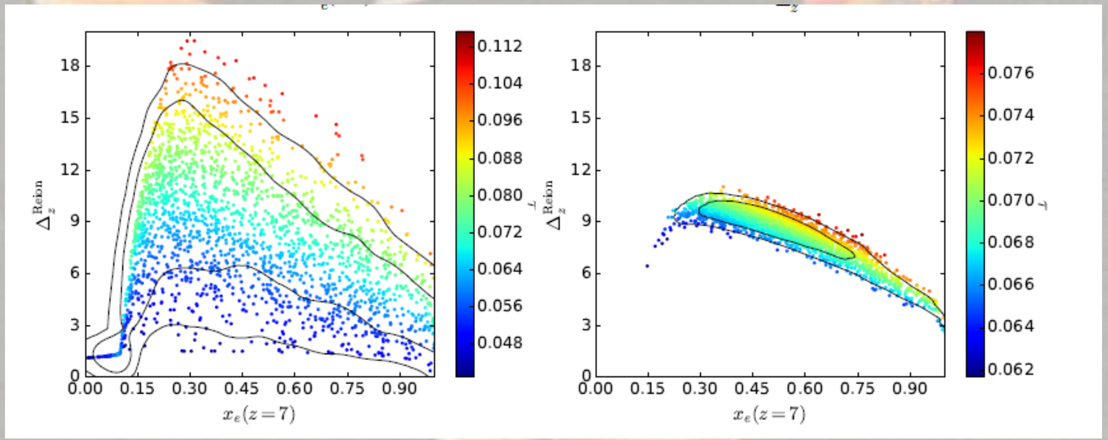


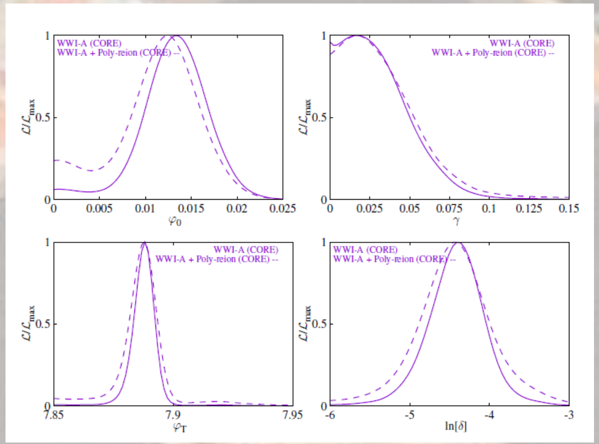
Hazra, Paoletti, Ballardini, Finelli, Shafieloo, Smoot, Starobinsky 2018

For the reionization, together with the standard tanh model we consider the Polyreion model (Hazra &Smoot 2017) where the history of reionization is parametrized by two additional extra parameters: an intermediate position in redshift and the free electron fraction at that redshift.

$$x_e(z) = (1 + F_{\mathrm{He}}) f(z),$$

With f(z) a PCHIP polynomial. 4 nodes @ z=0,5.5, 7 and zero ionization fraction



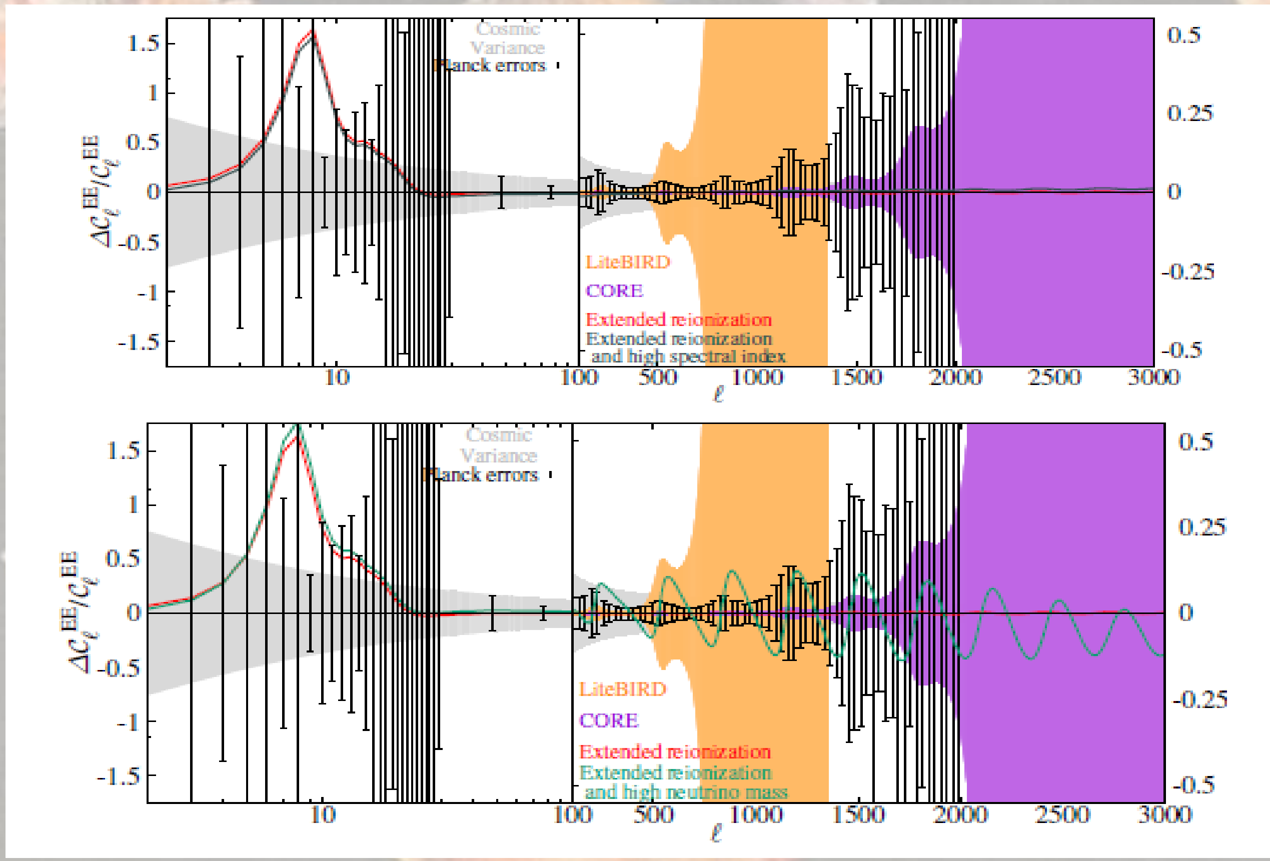


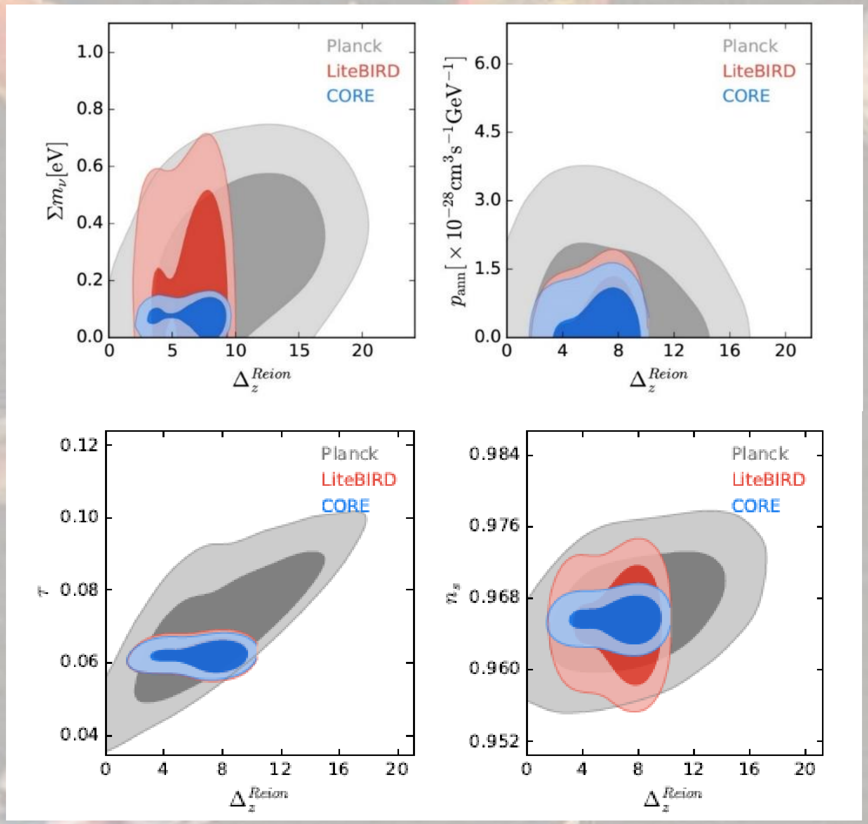
We have shown how a Core-like experiment will be not significantly affected by the confusion of the reionization model

REIONIZATION IN DETAILS

Future E-mode observations from space have the capability to discriminate among different models of reionization.

We studied the capabilities of future experiments to constrain extended models of reionization, Polyreion in this case, also in the presence of extended cosmological models





Hazra, Paoletti, Finelli, Smoot 2018

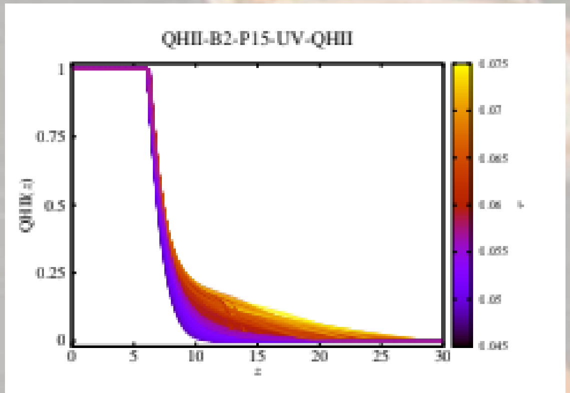
Our study shows that LiteBIRD and CORE are able to remove the degeneracies of reionization parameters with CORE more sensitive to the duration of reionization

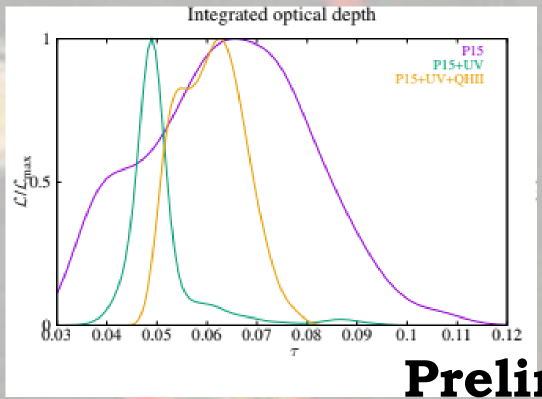
FREE FORM RECONSTRUCTION

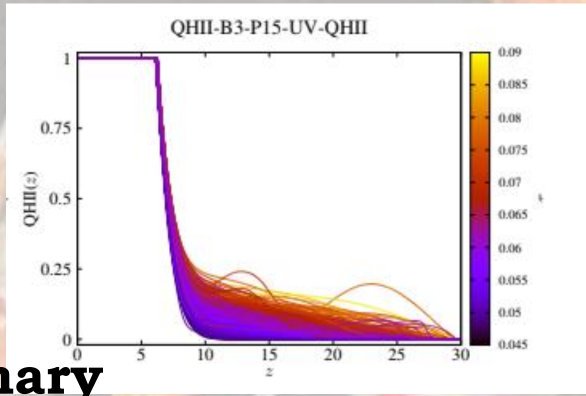
We are currently extending our analysis
Instead of using a phenomenological model we directly solve the ionization equations.
This allows a free form reconstruction of the ionization epoch with different number of bins.

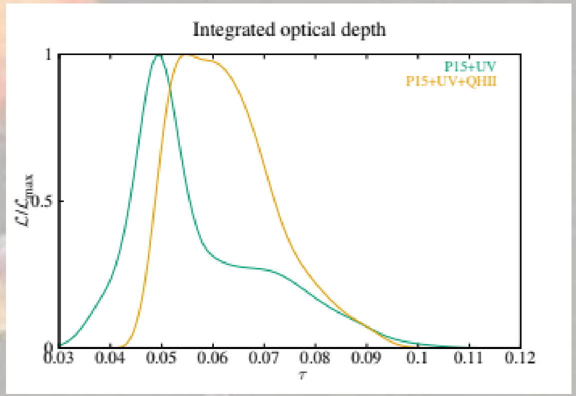
With this approach we can complement CMB data with external datasets:

- **Planck**
- **UV luminosity density from Hubble Freontier Fields z=6-11 Bouwens et al 2015, Ishigaki et al. 2018**
- **Lyman-alpha z=6-8 Fan et al. 2006, Schroeder et al. 2014, Schenker et al 2015 (HII regions around Quasars)**







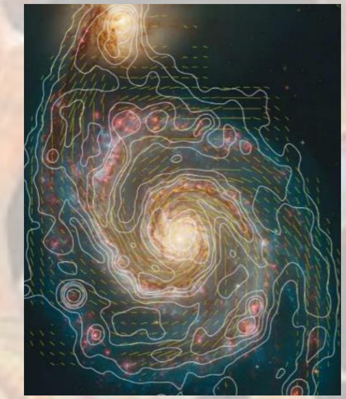


Preliminary

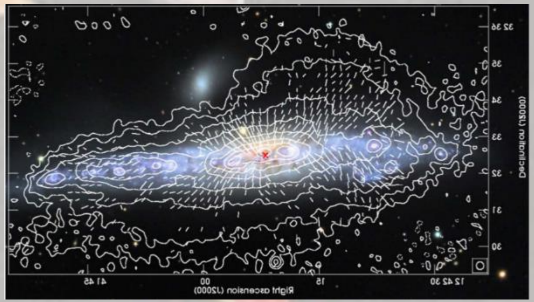
Hazra, Paoletti, Finelli and Smoot in prep.

COSMIC MAGNETISM

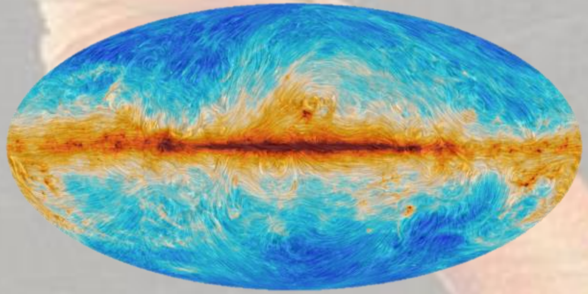
The hypothesis that the magnetic fields we observe today on cosmological scales are seeded by primordial magnetic fields (PMFs) is one of the most interesting since magnetic fields can be generated before recombination by several mechanisms.



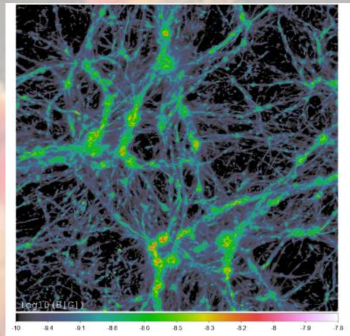
Fletcher et al 2011



Mora and Krause 2013



Planck 2015 Results I



Sims from Vazza et al. 2014

On the other hand Cosmic Magnetic fields may keep the memory, especially in the voids and filaments of the LSS of their primordial progenitors.
Since different generation mechanisms lead to fields with different characteristics it is possible use PMF as a unconventional window on the early Universe to investigate inflationary mechanims or phase transitions physics

Within our group we have developed a long time experience in primordial magnetic fields and their impact on CMB anisotropies (including the leadership of the Planck dedicated project in the 2015 release by Paoletti)
CMB represents one of the best laboratory to test PMFs

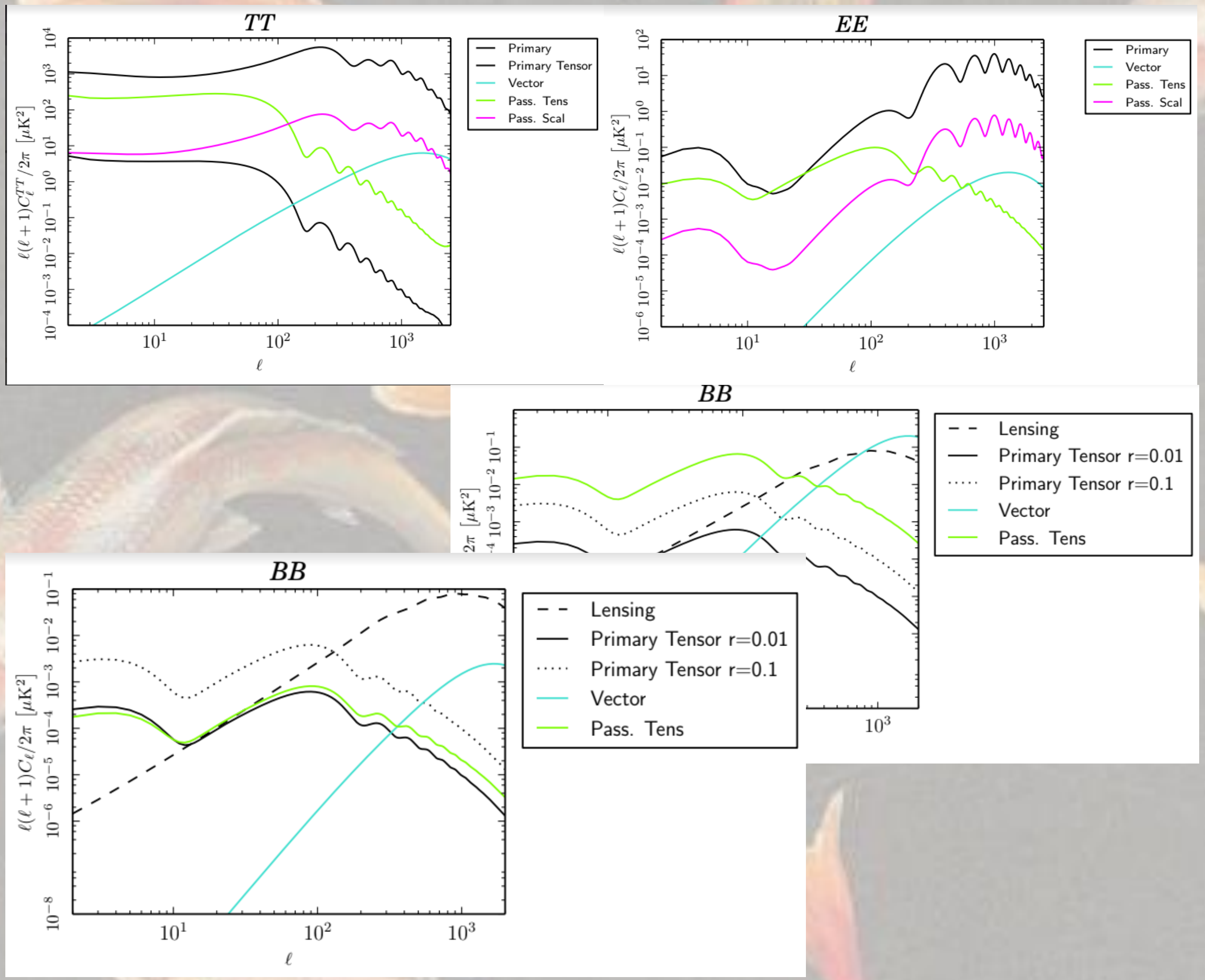
GRAVITATIONAL EFFECT

PMFs energy momentum tensor is at the same order of cosmological perts. It adds to the source term of pertubed Einstein equations

-Subramanian & Barrow 1998, 2002; Durrer et al. 2000; Kahniashvili et al. 2001; Mack et al. 2002; Caprini & Durrer 2002; Subramanian et al. 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 et al. 2009; Bonvin & Caprini 2010; Bonvin 2010; Kunze 2011; Shaw & Lewis 2010-

Modes

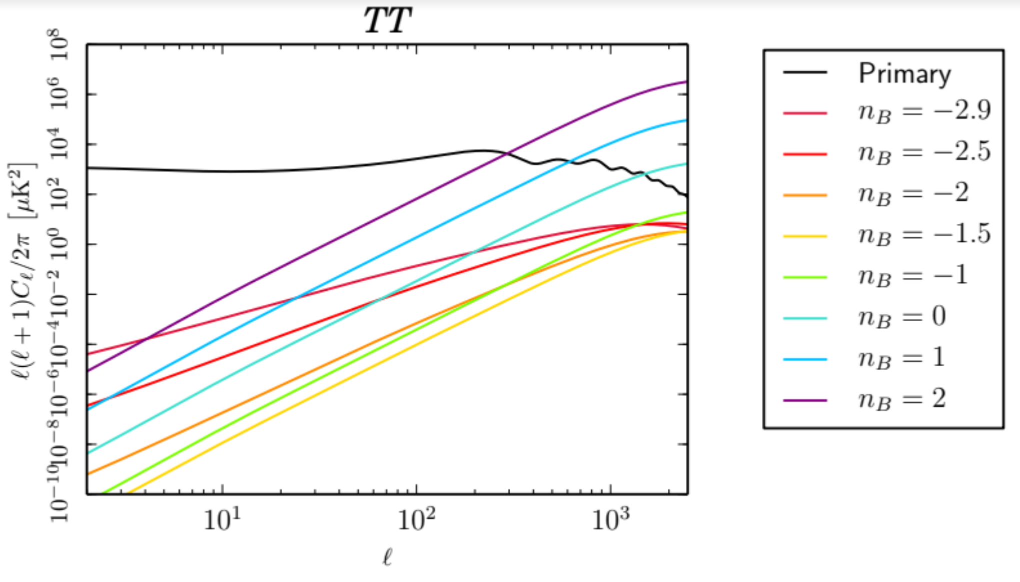
- **SCALARS:** TT-TE-EE modes generated by magnetic energy density+anisotropic pressure+Lorentz force
- **VECTORS:** TT-TE-EE-**BB** Vector projection of the anisotropic pressure and Lorentz force
- **TENSORS:** TT-TE-EE-**BB** Tensor projection of the anisotropic pressure

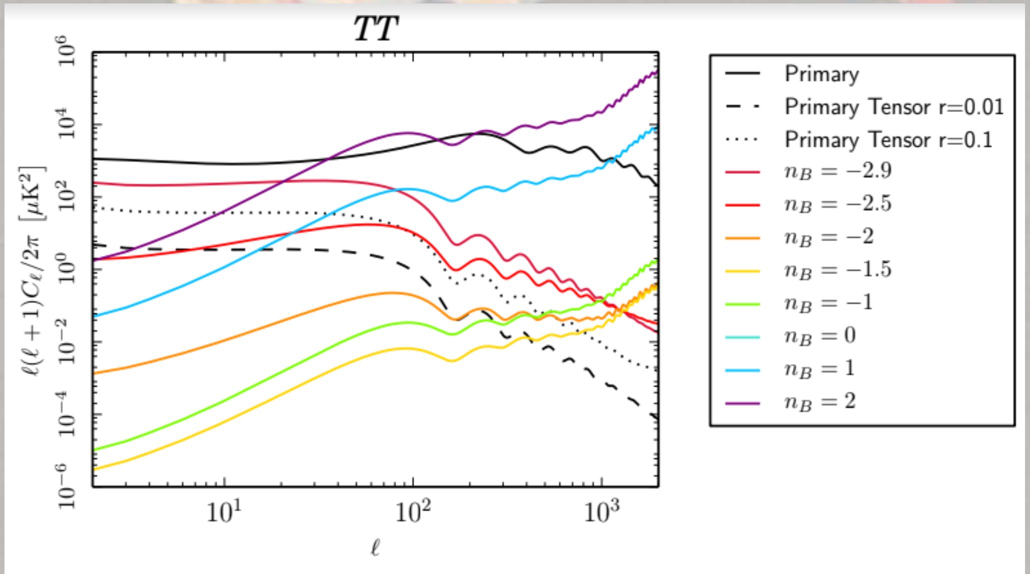


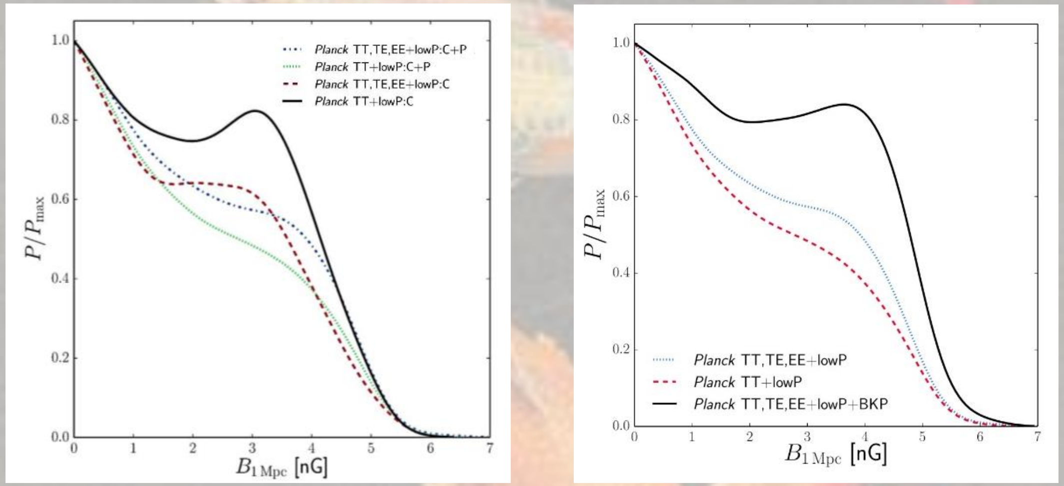
Initial Conditions

- **COMPENSATED:** standard mode. Neutrino anisotropic pressure and relativistic species densities compensate magnetic terms.
- **PASSIVE:** Residual of pre-neutrino decouplign mode. Inflationary type with magnetic amplitude.
- **INFLATIONARY:** stricly dependent on the type of coupling. Still in development *- Bonvin & Caprini 2010 -*

CONSTRAINTS ON PMFs AMPLITUDE



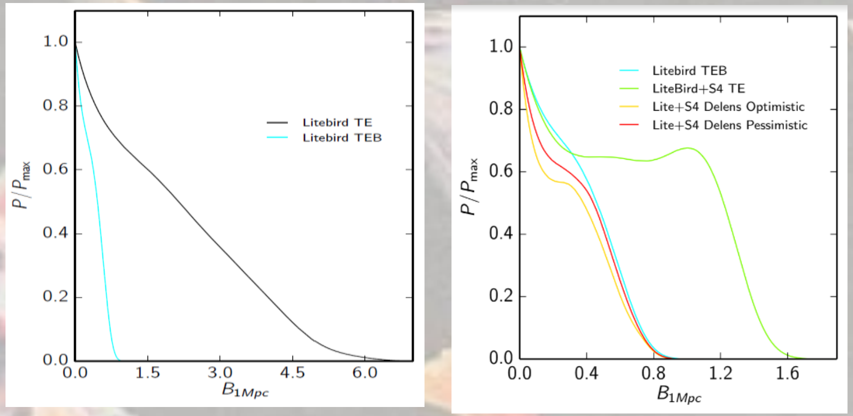




Planck 2015 Results XIX

Improvements of the Einstein-Boltzmann code with the contribution of PMFs (developed by Paoletti) and the fitting functions to the PMFs EMT components lead to a precision in the predictions of a part over 100000.

Currently working on forecasts for future experiments

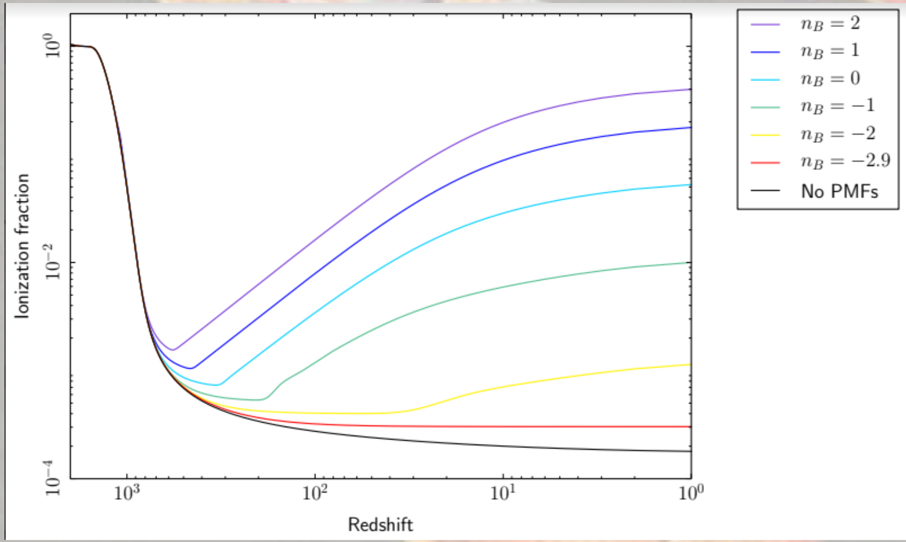


Paoletti et Al. In prep.

PMFs AND THE IONIZATION HISTORY

Two mechanisms that take place after recombination dissipate the fields:
ambipolar diffusion and MHD decaying turbulence
The dissipation injects energy in the plasma
The Plasma is heated
Aside from spectral distortions which are negligible for current data *-Kunze & Komatsu 2014-*
The heating of the Plasma modifies the temperature and ionization fraction with a huge impact on CMB E-mode polarization

–Subramanian & Barrow 1998, Jedamzik et al. 2000, Sethi & Subramanian 2005, Schleicher et al. 2008, Kunze & Komatsu 2014, Chluba, DP et al. 2015, Kunze and Komatsu 2015, Paoletti et al. 2019-



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

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

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

MHD Turb

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

Ambipolar diffusion

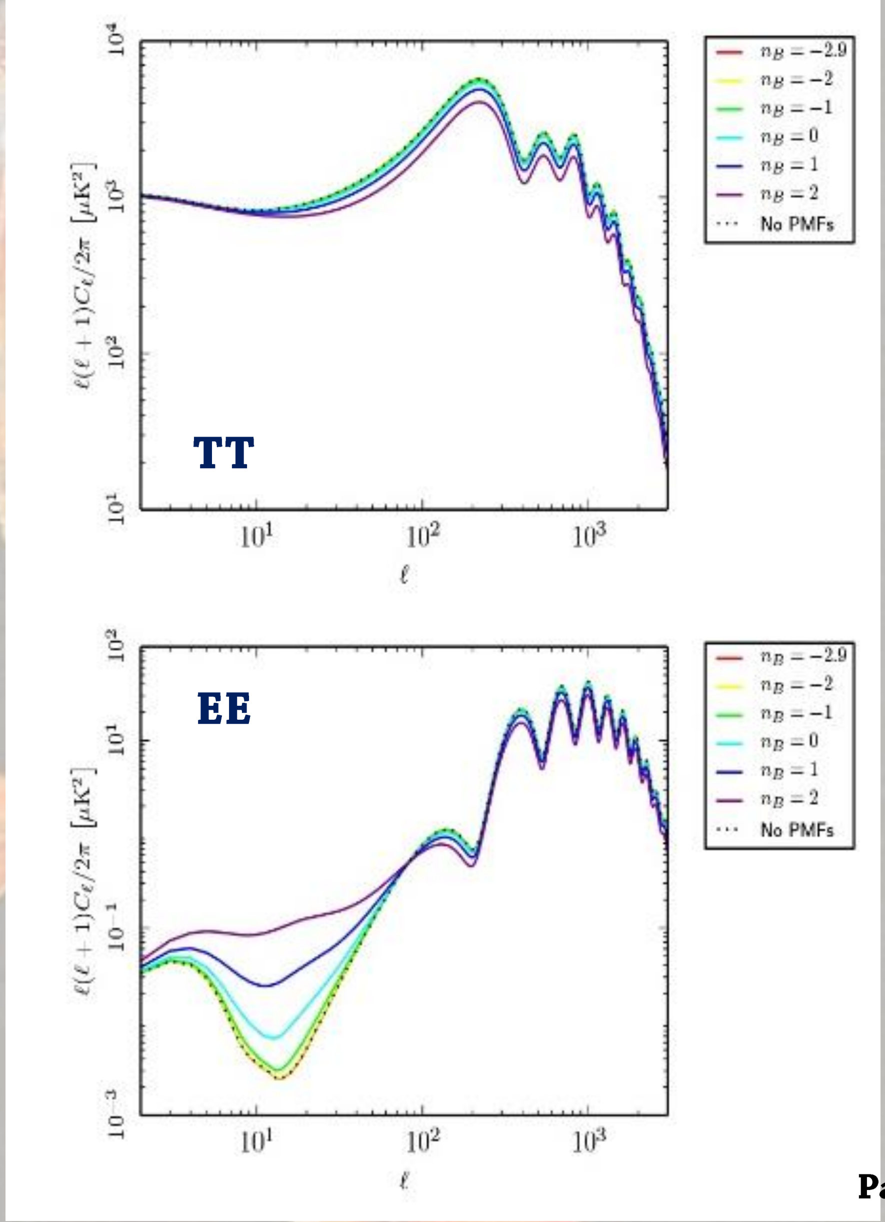
$$|(\nabla \times B)\times B|^2 == 16\pi^2 \rho_B^2(z)\, l_D^{-2}(z)\, g_L(n_B+3)$$

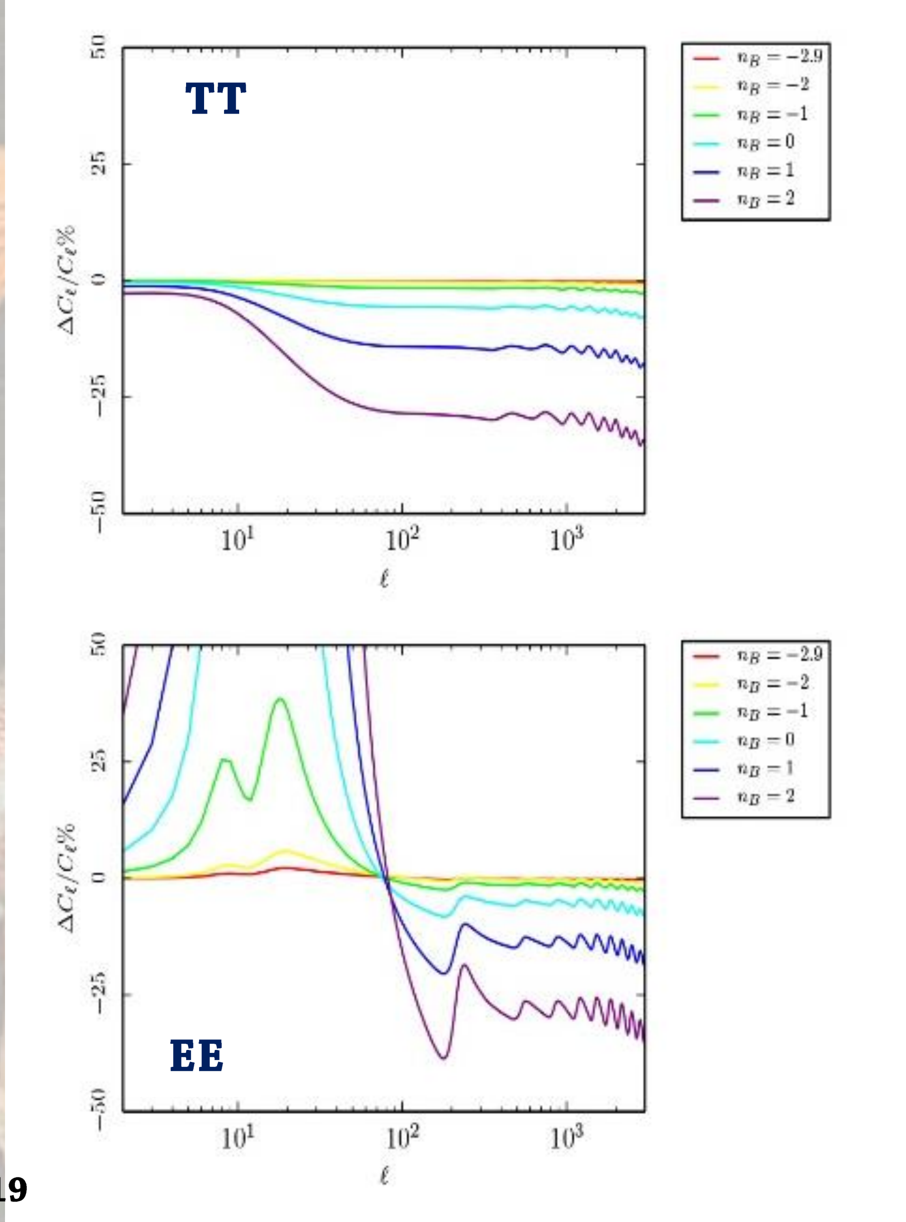
$$g_L(x) = 0.6615[1 - 0.1367x + 0.007574x^2]\, x^{0.8874}$$

$$l_D = a/k_D$$

The Lorentz force is derived following Finelli et al 2009 and Paoletti et al 2010

EFFECT ON CMB ANISOTROPIES

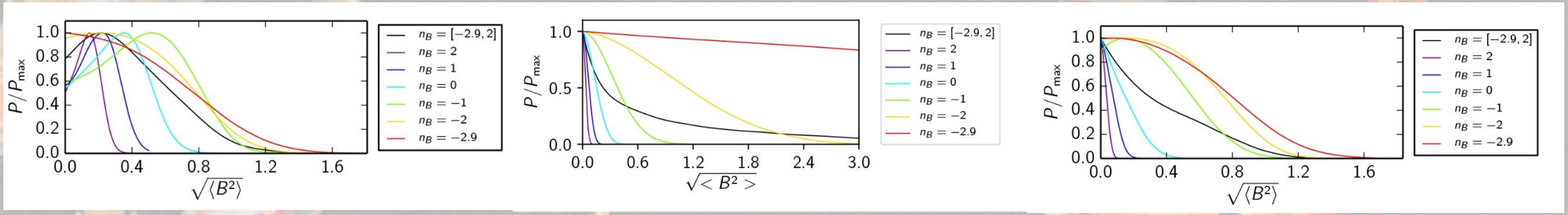




Paoletti et Al. 2019

CONSTRAINTS ON PMFs :Planck 2015

MHD **AMBIPOLAR** **COMBINATION**



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	< 0.86*

The result show the constraining power of this effect. The constraints for positive spectral indices are dominated by the ambipolar diffusion term which as shown in the angular power spectra induce a very strong effect especially in polarization.

Currently working in the development of the theoretical treatment of the heating rates using also support from numerical sims

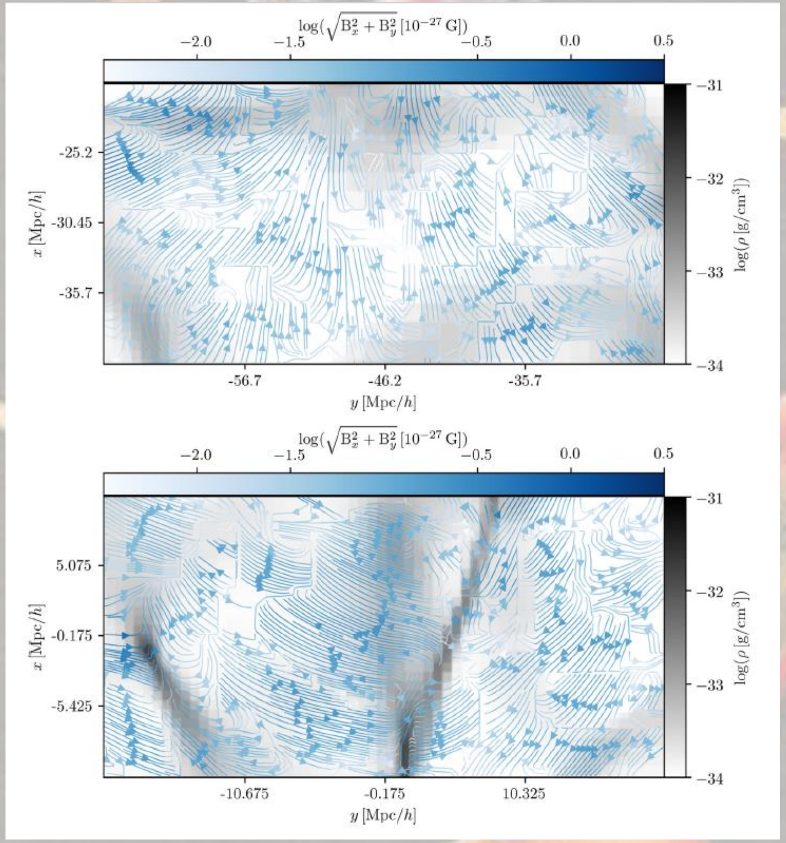
Paoletti et Al. 2019

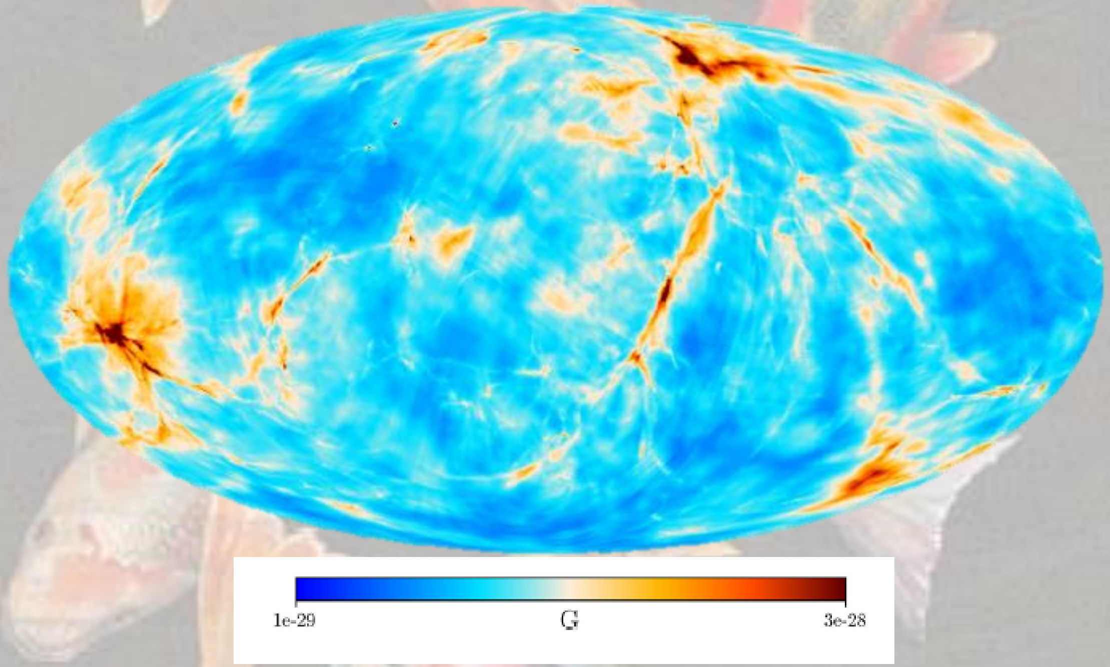
THE MAGNETIC FIELD IN OUR BACKYARD

S. Hutschenreuter, S. Dorn, J. Jasche, F. Vazza, D.P., G. Lavaux, T. A. Enßlin 2018

Reconnect with numerical simulations the primordial fields with the ones observed now
Circular technique: start from a local density field observations 2M++.
Reconstruct the matter density field with BORG *-Lavaux and Jasche 2016-*
Estimate the magnetic field @recombination from Harrison mechanism with second order perts.
Evolve the local structure including the magnetic field estimated with ENZO *–Enzo Coll. 2014-*

Galactic center





The fields from Harrison are too weak but similar analysis with ENZO are ongoing for primordial fields as constrained at recombination with the CMB

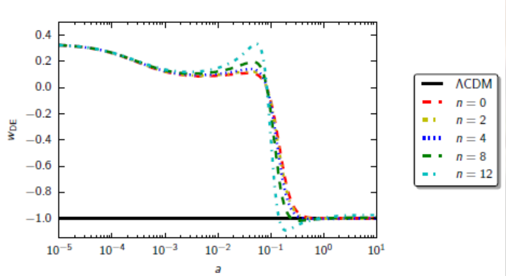
DEVIATIONS FROM GENERAL RELATIVITY

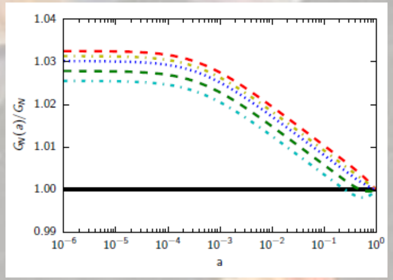
We study an extended Jordan-Brans-Dicke model of gravity which provides also a solution for dark energy

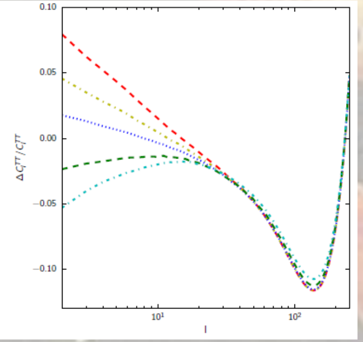
Perrotta et al. (1999), Chiba (1999), Uzan (1999), Bartolo et al. (2000), Boisseau et al. (2000), Baccigalupi et al. (2000), Umiltà et al (2015)

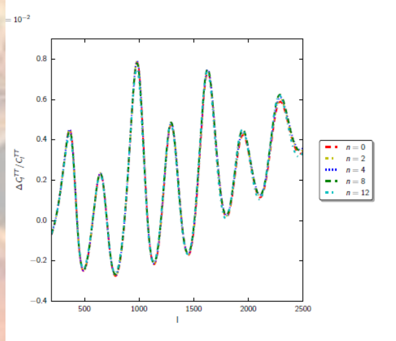
$$S = \int d^4x\sqrt{-g}\left[\frac{\gamma\sigma^2 R}{2} - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma) + \mathcal{L}_m\right]$$

$$V(\sigma) = \lambda_n\sigma^n$$









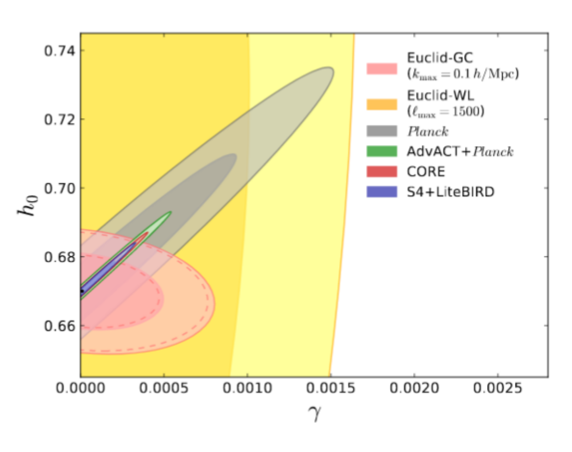
Einstein-Boltzmann code validated within the Euclid TWG (Bellini et al 2018)

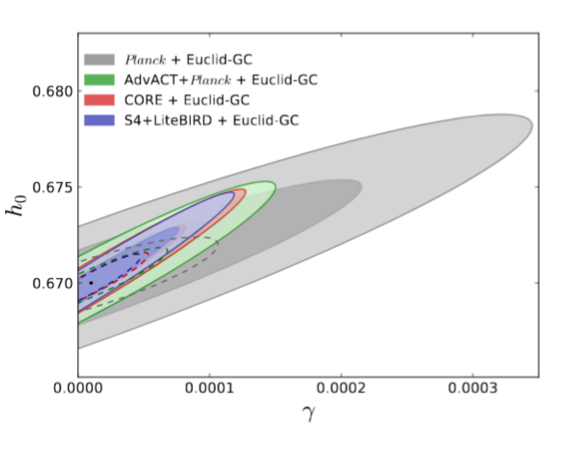
The associated constraints with CMB (Umiltà, Ballardini, Finelli, Paoletti 2015; Ballardini, Finelli, Umiltà, Paoletti 2016)

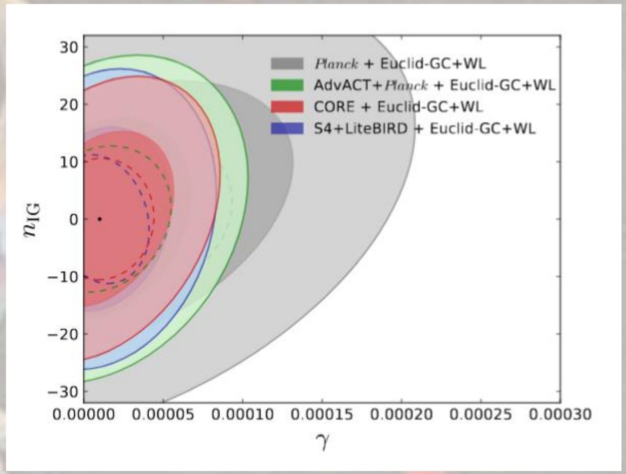
$$\gamma < 0.0017 \;\; (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT,TE,EE} + \mathrm{lowP} + \mathrm{lensing})$$

$$\gamma < 0.00075 \;\; (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT,TE,EE} + \mathrm{lowP} + \mathrm{lensing} + \mathrm{BAO})$$

We extend our previous constraints by forecasting the capabilities of the next generation of CMB experiments -AdvACT, CORE-like, S4+LiteBIRD







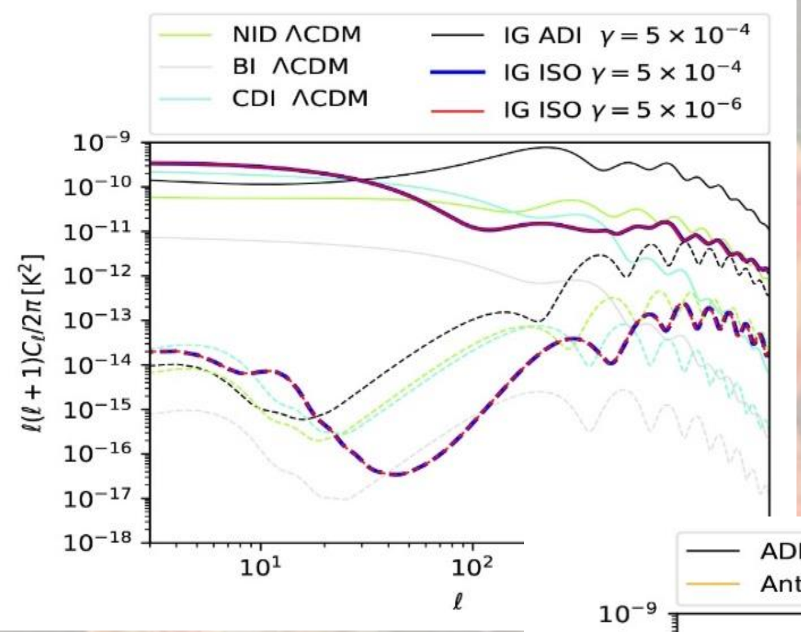
Ballardini, Sapone, Umiltà, Finelli, Paoletti 2019

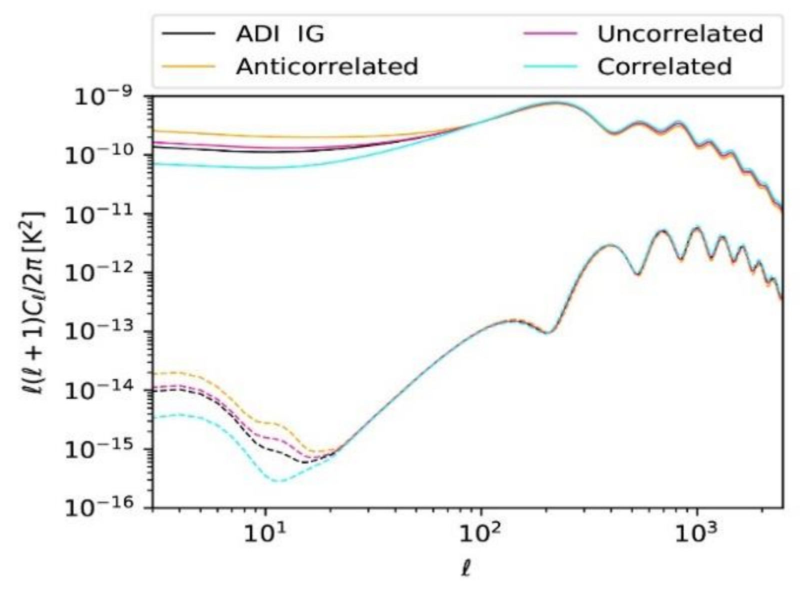
NEW ISOCURVATURE MODE

Within the scalr-tensor gravity model described we have identified and constrained a new isocurvature mode (a kind of perturbation which is not adiabatic and is generated in multifield models of inflation)

The mode is not present in LCDM and represents a new solution for the initial conditions in modified gravity.

$$
\begin{aligned}
\delta_\gamma &= \delta_\nu = C\left[-\frac{2}{3}k^2\tau^2 + \frac{2\omega}{15}k^2\tau^3\right] + D\left[-1 - \frac{2\omega}{3}\tau + \frac{3(15\gamma+2)\omega^2 + 4k^2}{24}\tau^2\right] \\
\delta_b &= C\left[-\frac{k^2}{2}\tau^2 + \frac{\omega}{10}k^2\tau^3\right] + D\left[-\frac{\omega}{2}\tau + \frac{1}{8}\left(\frac{3(15\gamma+2)\omega^2}{4k} + k\right)k\tau^2\right], \\
\delta_c &= C\left[-\frac{k^2}{2}\tau^2 + \frac{\omega}{10}k^2\tau^3\right] + D\left[-\frac{1}{2}\omega\tau + \frac{3}{32}(15\gamma+2)\omega^2\tau^2\right], \\
\delta_\nu &= C\left[-\frac{2}{3}k^2\tau^2 + \frac{2}{15}k^2\tau^3\omega\right] + D\left[-1 - \frac{2\omega}{3}\tau + \frac{3(15\gamma+2)\omega^2 + 4k^2}{24}\tau^2\right], \\
h &= C\left[k^2\tau^2 - \frac{1}{5}\omega k^2\tau^3\right] + D\left[\omega\tau - \frac{3}{16}(15\gamma+2)\omega^2\tau^2\right], \\
\eta &= C\left[2 - \frac{(4R_\nu+5)}{6(4R_\nu+15)}k^2\tau^2\right] + D\left[-\frac{\omega}{6}\tau + \frac{16k^2(R_\nu+5) + 3(15\gamma+2)(4R_\nu+15)\omega^2}{36(4R_\nu+15)}\tau^2\right] \\
\frac{\delta\sigma}{\sigma_i} &= C\left[-\frac{1}{4}\gamma\omega k^2\tau^3 + \frac{\gamma\omega^2}{40}(4+15\gamma)k^2\tau^4\right] + D\left[-\frac{1}{2} + \frac{3}{4}\gamma\omega\tau\right],
\end{aligned}
$$





Paoletti, Braglia, Finelli, Ballardini, Umiltà 2018

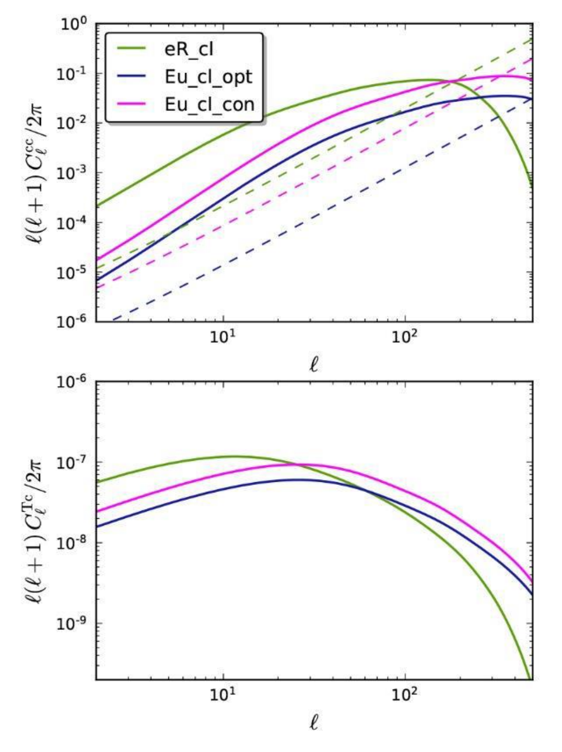
Constraints with Planck 2015

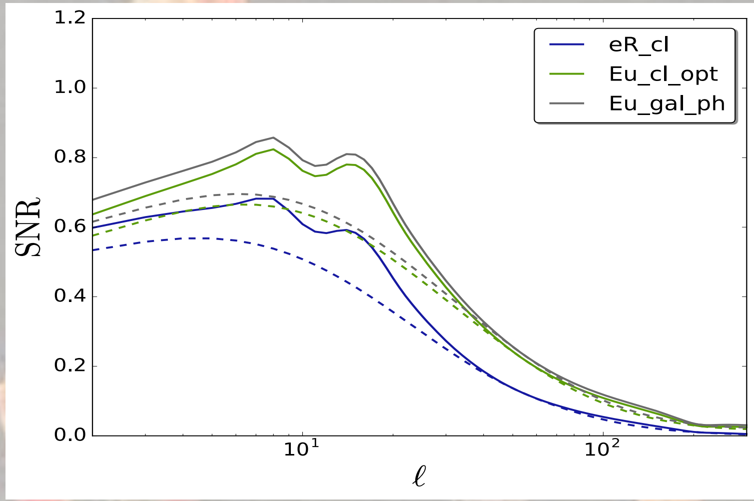
Case	$\gamma = 5\times10^{-4}$
Fully Anticorrelated	$f_{ISO} < 0.07$
Uncorrelated	$f_{ISO} < 0.31$
Fully Correlated	$f_{ISO} < 0.12$

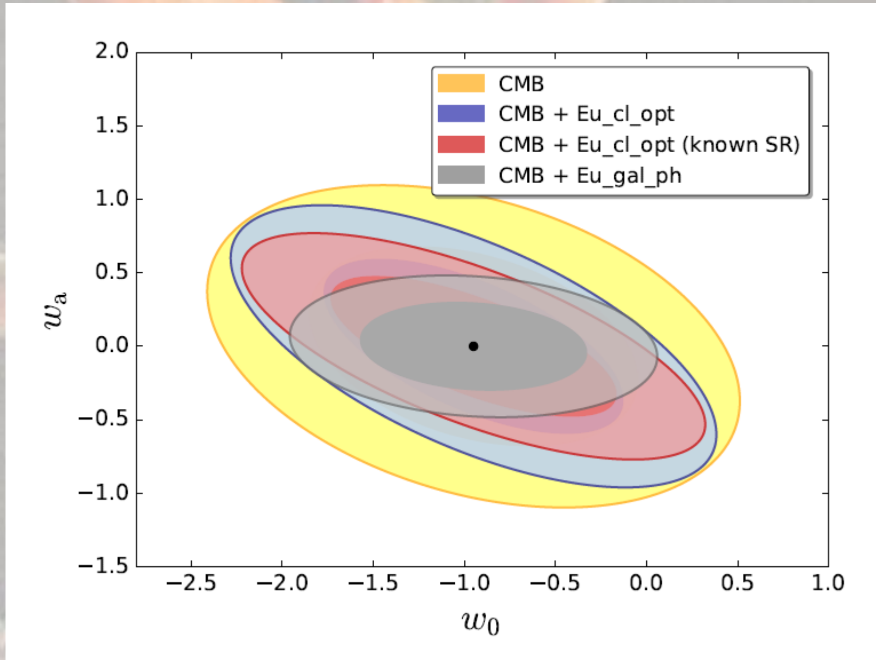
CMB X LSS

CMB sensitivity to late Universe parameters like the Dark Energy model is limited by the cosmic variance.
A possible solution is represented by the cross correlation with LSS observables.

As part of the Euclid collaboration we investigate the capabilities of such cross correlation for different probes like the galaxy number counts and the cluster number counts.
For the cluster number counts we estimated the signal to noise ratio for the ISW detection and derived Fisher forecasts for the cosmological parameters.







Ballardini, Paoletti, Finelli, Moscardini, Sartoris, Valenziano, MNRAS 482 (2019)

CONCLUSIONS

With an hybrid approach of theoretical modelling, numerical predictions and finally data analysis for current data and forecasts for the future ones we are able to investigate and constrain a variety cosmological models and test the capabilities of future experiments in improving the scenario

Future space CMB missions will be crucial

If Planck opened the era of precision cosmology with future missions we will go deeper and open the era of precision fundamental and particle cosmophysics

Our main work is to add pieces in the puzzle towards this target

DP in Pills :

- 2008 Master degree Astrophysics and Cosmology @Università di Bologna
- 2011 PhD in Astroparticle Physics @Università di Ferrara and in ecole doctorale Particules, Noyaux, Cosmologie @ Universitè Paris VII Paris
- 2011 – 2014 AdR @INAF-IASF-Bologna
- 2015 – 2018 Fellowship @INAF-IASF Bologna
- TD COSMOS Bologna started on the 02 May 2018

International collaborations:

- Planck – Scientist and Core2- 2015 Primordial Magnetic Fields paper leader
- Core-PRISM-Core+-COrE
- Euclid
- Pristine
- LiteBIRD

BACK UP SLIDES

- **GRAVITATIONAL :** **PMFs are an extra relativistic component in the plasma. They generate independent cosmological perts. and additional angular power spectra**
- **IONIZATION HISTORY :** **PMFs are dissipated after recombination and the energy injection modifies the ionization history** *–Subramanian & Barrow 1998, Jedamzik et al. 2000, Sethi*
- *& Subramanian 2005, Schleicher et al. 2008,Kunze & Komatsu 2014, Chluba, DP et al. 2015, Kunze and Komatsu 2015, Planck 2015 Results XIX, Paoletti et al. 2019-*
- **NON GAUSSIANITIES:** **PMFs modelled as a stochastic background has a chisqr distribution leading to non-zero bi and tri spectra** *- Brown & Crittenden, Trivedi et al. 2010, Shiraishi et al. 2011, 2012; Shiraishi 2013, Seshadri & Subramanian 2009, Caprini, Finelli,DP,Riotto 2009, Cai et al.2010, Shiraishi et al. 2010, Kahniashvili & Lavrelashvili 2010;Trivedi et al. 2012, 2014; Planck 2015 results XIX-*
- **FARADAY ROTATION:** **MFs diffuse on the line of sight of CMB induce a Faraday rotation of the CMB polarization generating B-modes from E-mode (freq. dep. disentangle from birefringence)** *–Kosowsky & Loeb 1996, Kosowsky et al 2005, Kahniashvili et al. 2009, Pogosian et al. 2009 , Planck 2015 Results XIX-*
- **PARITY VIOLATING CORRELATORS:** **if PMFs have an helical component TB and EB cross correlators becomes non zero** *-Caprini et al. 2004, Kahniashvili et al. 2005, Kahniashvili & Ratra 2014, Ballardini, Finelli, DP 2015, Planck 2015 Results XIX-*
- **HARMONIC SPACE CORRELATIONS :** **PMFs induce correlation between multipoles in the harmonic space. The correlation is related to the combination of PMF amplitude and Alfven velocity** *–Kahniashvili et al. 2008, Planck 2015 Results XIX-.*
- **TRANSVERSE:** **IMPACT ON BBN** *-Grasso & Rubinstein 1995, Kahniashvili et al. 2010-*, **LSS** *-Shaw & Lewis 2012, Fedeli & Moscardini 2012-*