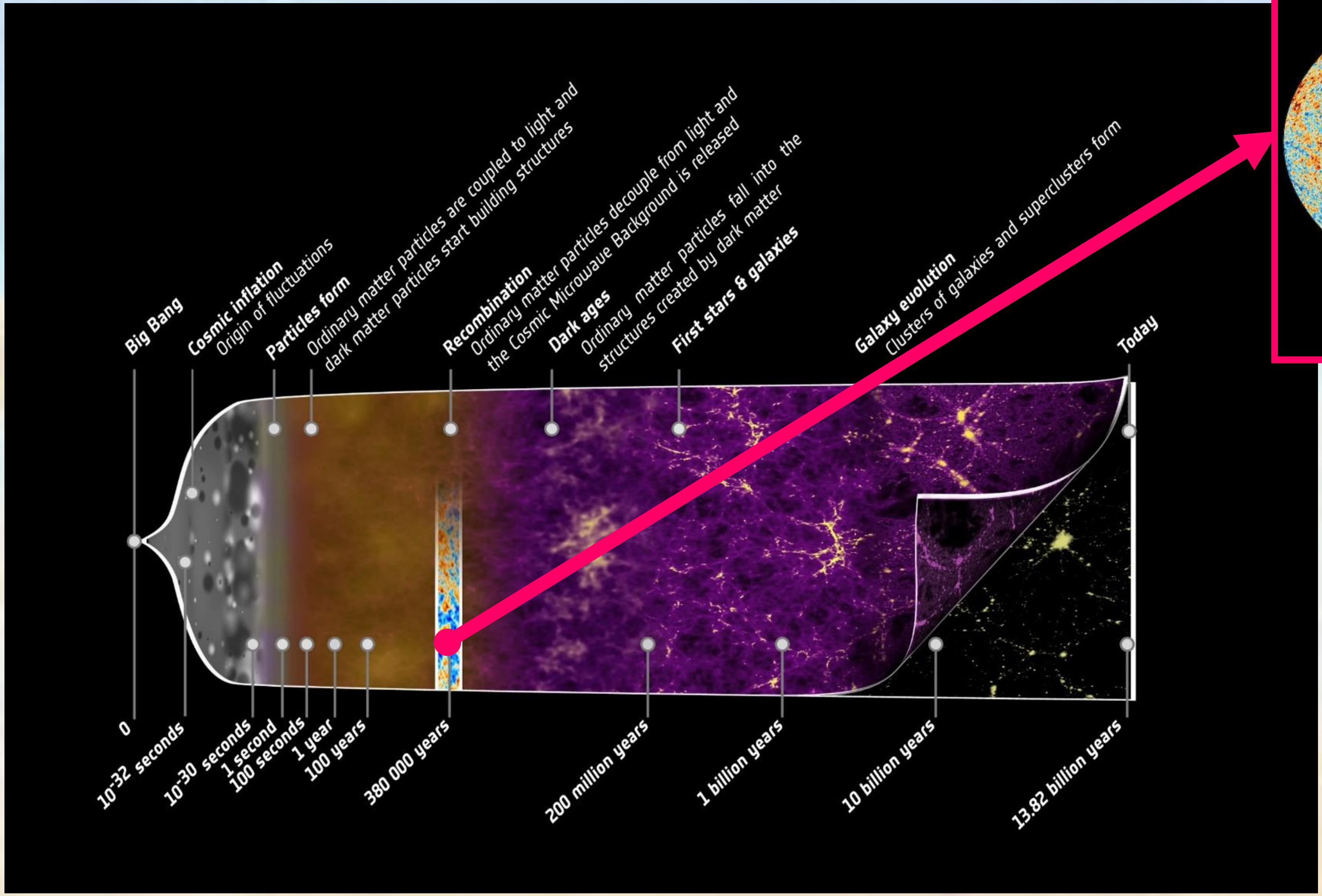
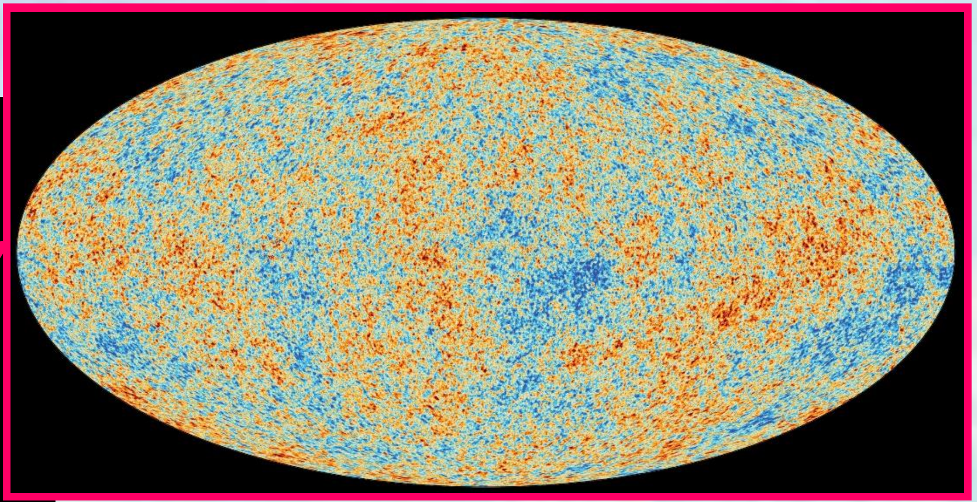
COSMOLOGY
WITH THE
COSMIC MICROWAVE BACKGROUND
@OAS

OAS days 17-18 December 2018

Cosmic Microwave Background in pills





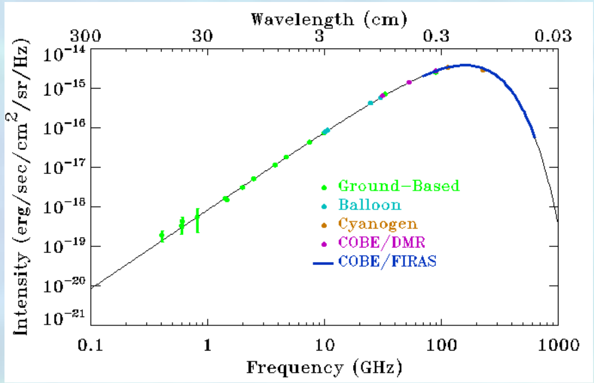
THE RELIC RADIATION OF THE BIG BANG

After the Big Bang, the expansion cools down the Universe up to a point when it is neutralized by the formation of Hydrogen atoms.

This period is called **RECOMBINATION**

The Universe becomes optically thin and the relic photons from the Big Bang are free to propagate

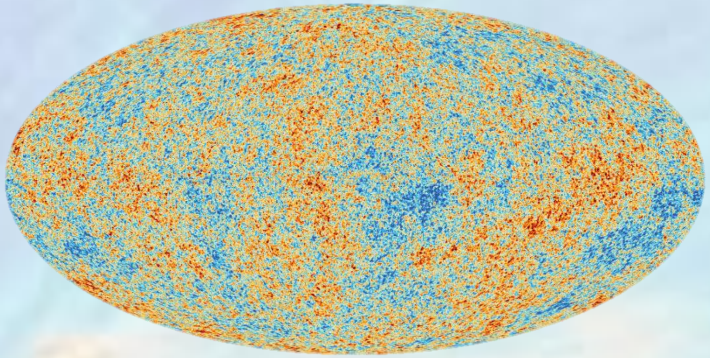
These photons are the first light of the Universe called CMB



Probably the best black body in nature

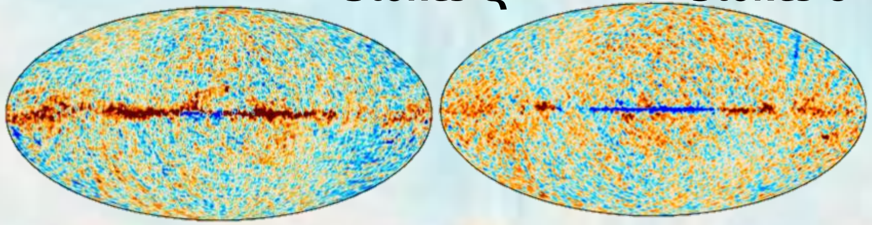
$T_{CMB} = 2.72548 \pm 0.00057$ *(Fixen 2009)*

Planck 2018 Temperature map



Isotropic but not completely. Small anisotropies of the order of $\frac{\Delta T}{T} \sim 10^{-5}$ are the imprints of primordial fluctuations generated after inflation which grew up forming the large scale structure we observe in the Universe

Stokes Q **Stokes U**



Planck 2018 polarization maps

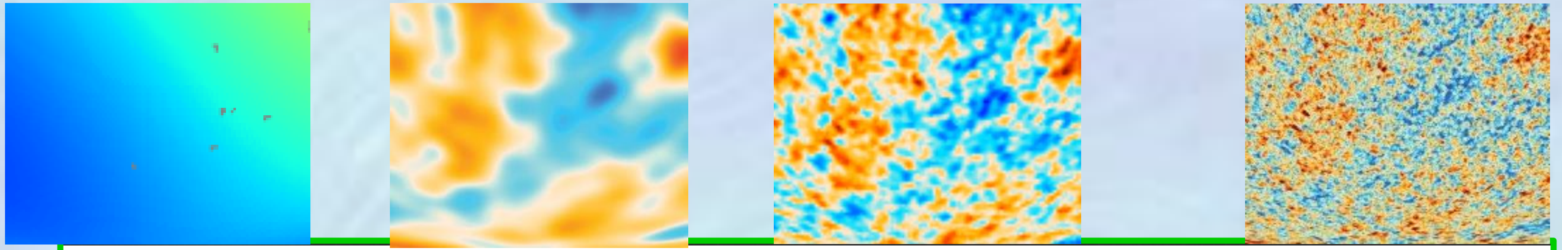
The CMB is polarized and the polarization anisotropies carry an additional information. Polarization is analised through combinations of Q and U Stokes parameters named E and B.

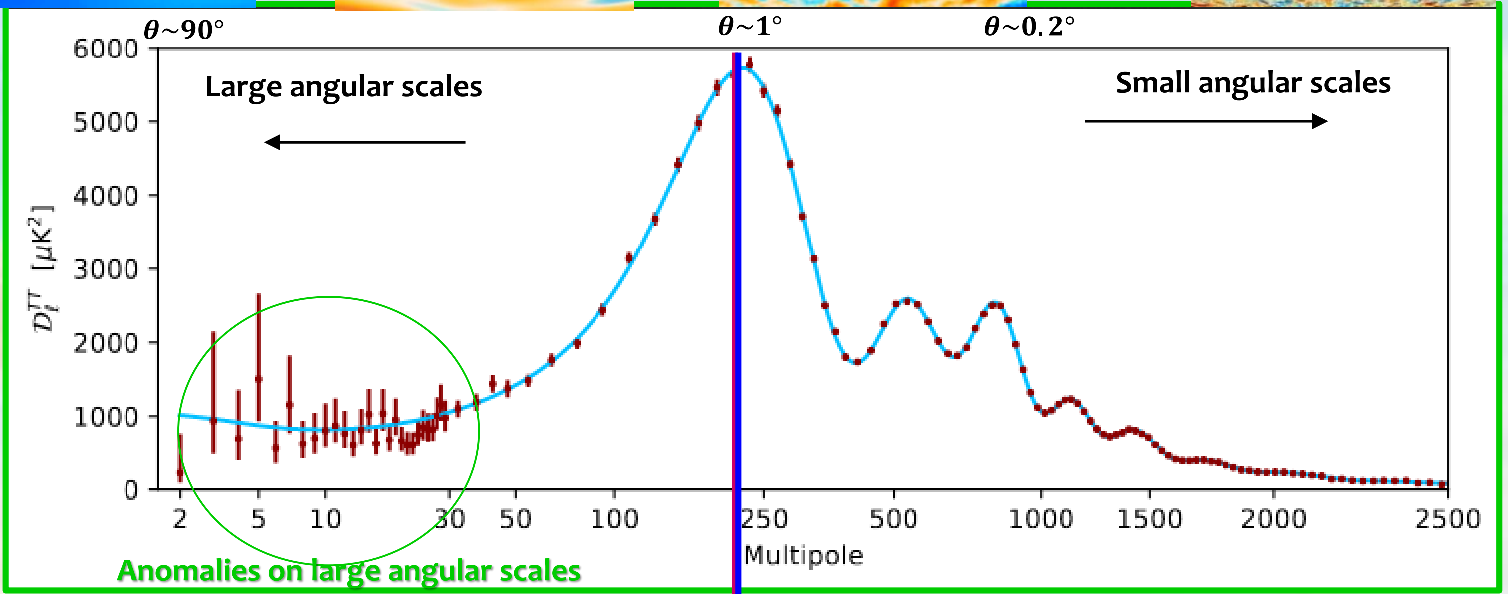
$$\Delta T(\vec{x}, \hat{n}, \tau) = \Sigma_{l=1}^{\infty} \Sigma_{m=-l}^{l} a_{lm}(\vec{x}, \tau) Y_{lm}(\hat{n})$$

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

The statistical properties of the anisotropies depend on both early and late cosmology. Their analysis is done using the angular power spectra which contains all the information if the primordial fluctuations are Gaussian.

If not higher order momenta like the bispectrum or trispectrum are non-negligible and provide additional probes.



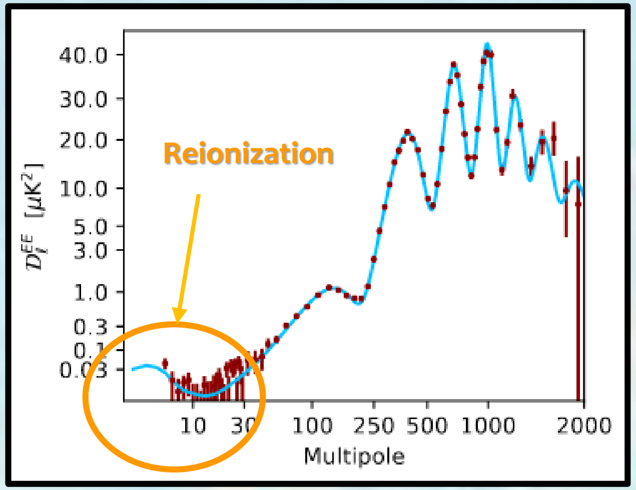


Outside the causal connection when CMB was generated. Representative of the initial conditions after inflation.

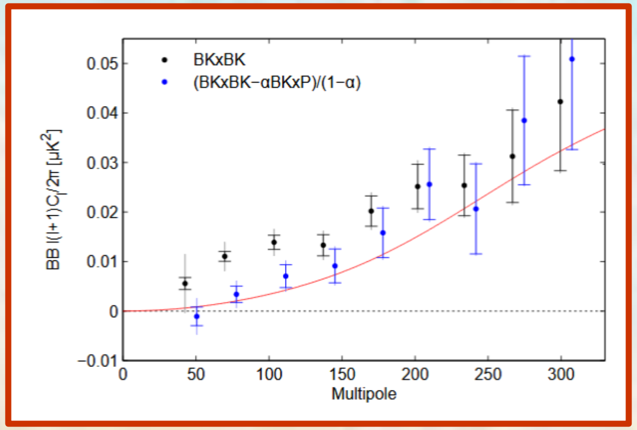
Power Spectrum of primordial fluctuations A_s n_s

Causal physics: acoustic oscillations of the baryon photon fluid and Silk damping. Matter content of the Universe, neutrino's physics, power spectrum tilt n_s…

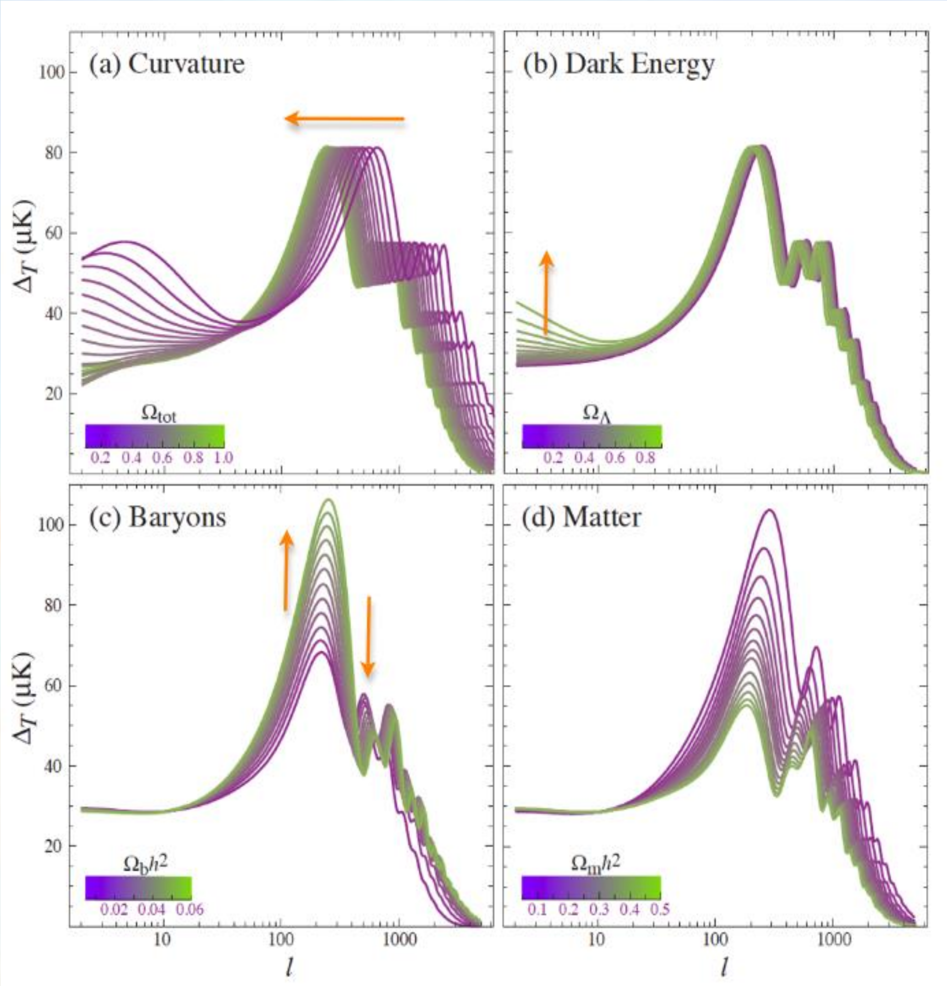
E-Mode Polarization



B-Mode Polarization



COSMOLOGICAL PARAMETERS



Hu & Dodelson 2002

Parameter	TT+lowE	EE+lowE	TE+lowE	TT,TE,EE+lowE	TT,TE,EE+lowE+lensing
$\Omega_b h^2$	0.02212 ± 0.00022	0.0240 ± 0.0012	0.02249 ± 0.00025	0.02236 ± 0.00015	0.02237 ± 0.00015
$\Omega_c h^2$	0.1206 ± 0.0021	0.1158 ± 0.0046	0.1177 ± 0.0020	0.1202 ± 0.0014	0.1200 ± 0.0012
$100\theta_{MC}$	1.04077 ± 0.00047	1.03999 ± 0.00089	1.04139 ± 0.00049	1.04090 ± 0.00031	1.04092 ± 0.00031
τ	0.0522 ± 0.0080	0.0527 ± 0.0090	0.0496 ± 0.0085	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073
$\ln(10^{10}A_s)$	3.040 ± 0.016	3.052 ± 0.022	$3.018^{+0.0020}_{-0.0018}$	3.045 ± 0.016	3.044 ± 0.014
n_s	0.9626 ± 0.0057	0.980 ± 0.015	0.967 ± 0.011	0.9649 ± 0.0044	0.9649 ± 0.0042
H_0	66.88 ± 0.92	69.9 ± 2.7	68.44 ± 0.91	67.27 ± 0.60	67.36 ± 0.54
Ω_m	0.321 ± 0.013	$0.289^{+0.026}_{-0.033}$	0.301 ± 0.012	0.3166 ± 0.0084	0.3153 ± 0.0073
σ_8	0.8118 ± 0.0089	0.796 ± 0.018	0.793 ± 0.011	0.8120 ± 0.0073	0.8111 ± 0.0060

```
[%]

0.7
1
0.03
13
0.7
0.4

0.8
2.3
0.7
```

Table 2. Confidence limits for the cosmological parameters in the base-ΛCDM model from *Planck* temperature, polarization, and temperature-polarization cross-correlation separately and combined, in combination with the EE measurement at low multipoles.

Planck TT, TE, EE + lowE + lensing is the 2018 baseline (Planck 2018)

COSMOLOGY FROM THE CMB

A&A 594, A18 (2016)
DOI: 10.1051/0004-6361/201525829
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Planck 2015 results

Astronomy & Astrophysics
Special feature

Planck 2015 results
XVIII. Background geometry and topology of the Universe

A&A 594, A14 (2016)
DOI: 10.1051/0004-6361/201525814
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Planck 2015 results

Astronomy & Astrophysics
Special feature

Planck 2015 results
XIV. Dark energy and modified gravity

A&A 594, A16 (2016)
DOI: 10.1051/0004-6361/201526681
© ESO 2016

Planck 2015 results

Planck 2015 results
XVI. Isotropy and statistics of the CMB

A&A 594, A17 (2016)
DOI: 10.1051/0004-6361/201525836
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Planck 2015 results

Astronomy & Astrophysics
Special feature

Planck 2015 results
XVII. Constraints on primordial non-Gaussianity

A&A 594, A20 (2016)
DOI: 10.1051/0004-6361/201525898
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Planck 2015 results

Astronomy & Astrophysics
Special feature

Planck 2015 results
XX. Constraints on inflation

A&A 596, A110 (2016)
DOI: 10.1051/0004-6361/201629018
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Astronomy & Astrophysics

Planck intermediate results
XLIX. Parity-violation constraints from polarization data

A&A 594, A19 (2016)
DOI: 10.1051/0004-6361/201525821
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Planck 2015 results

Astronomy & Astrophysics
Special feature

Planck 2015 results
XIX. Constraints on primordial magnetic fields

Planck 2015 results
XIII. Cosmological parameters

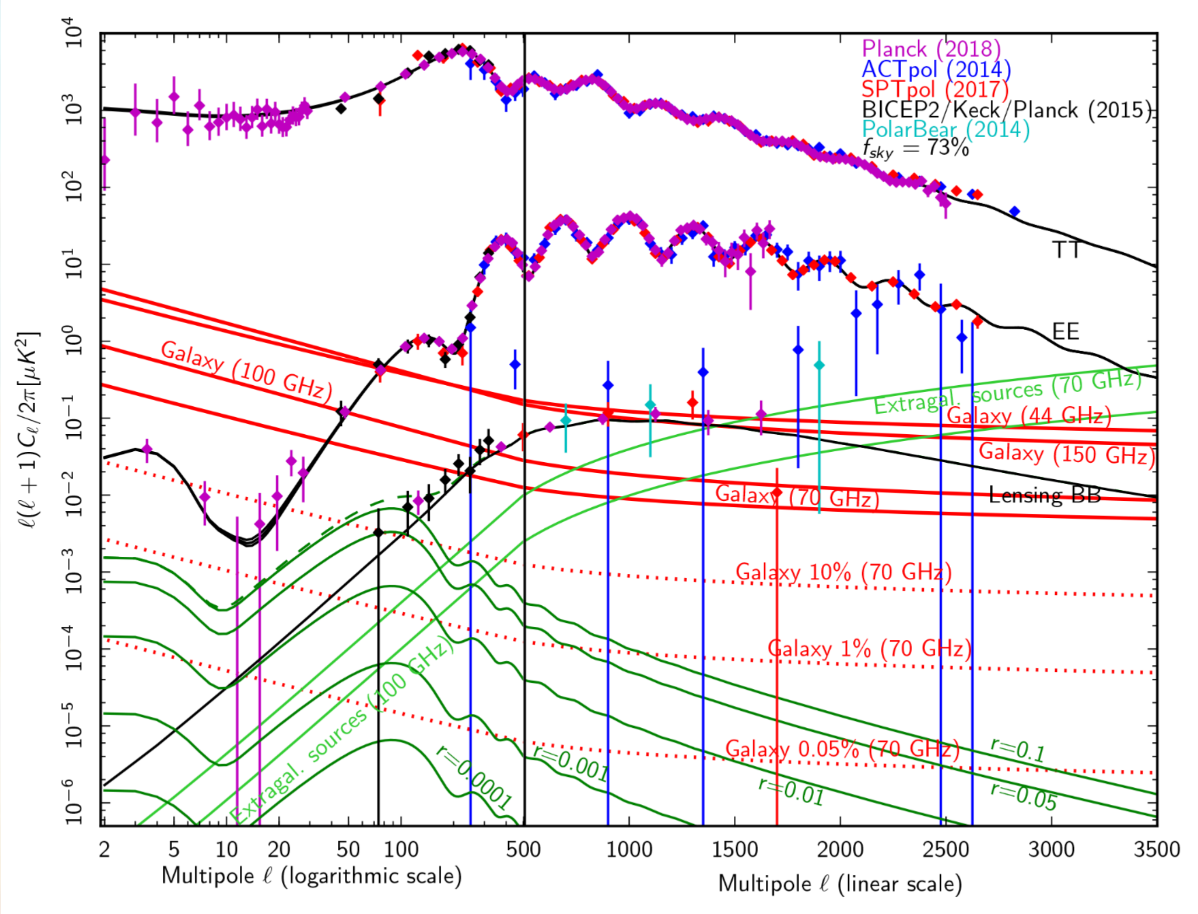
Planck Collaboration: P. A. R. Ade[105], N. Aghanim[71], M. Arnaud[87], M. Ashdown[83,7], J. Aumont[71], C. Baccigalupi[103], A. J. Banday[117,12], R. B. Barreiro[78], J. G. Bartlett[1,80], N. Bartolo[38,79], E. Battaner[120,121], R. Battye[81], K. Benabed[72,116], A. Benoît[69], A. Benoit-Lévy[29,72,116], J.-P. Bernard[117,12], M. Bersanelli[41,58], P. Bielewicz[97,12,103], J. J. Bock[80,14], A. Bonaldi[81], L. Bonavera[78], J. R. Bond[11], J. Borrill[17,109], F. R. Bouchet[72,107], F. Boulanger[71], M. Bucher[1], C. Burigana[57,39,59], R. C. Butler[57], E. Calabrese[112], J.-F. Cardoso[88,1,72], A. Catalano[89,86], A. Challinor[75,83,15], A. Chamballu[87,19,71], R.-R. Chary[68], H. C. Chiang[33,8], J. Chluba[28,83], P. R. Christensen[98,44], S. Church[111], D. L. Clements[67], S. Colombi[72,116], L. P. L. Colombo[27,80], C. Combet[89], A. Coulais[86], B. P. Crill[80,14], A. Curto[78,7,83], F. Cuttaia[57], L. Danese[103], R. D. Davies[81],

AFTER PLANCK…

Planck has performed the final temperature measurement on scales which the CMB dominates. Planck legacy will be one of the stress tests of cosmology for years to come.

Polarization is the new frontier of CMB cosmology with many proposals for future experiments dedicated to it. Lower amplitude, lesser known contamination by astrophysical signals represent a big observational and data analysis challenge but it is worth it:

Courtesy of Molinari, Mandolesi, Burigana



- **Characterization of the reionization process**
- **Revealing anomalies on large angular scales**
- **Energy scale of inflation**
- **Parity violations**
- **Cosmic magnetism**
- **Exotic physics**
- ……

Personnel

PERMANENT STAFF

- **Fabio Finelli** - *Senior Researcher*

- **Alessandro Gruppuso** - *Researcher*

- **Nazzareno Mandolesi** - *Research Director («in quiescenza»)*

- **Luca Valenziano** - *Senior Researcher*

TEMPORARY STAFF

- **Daniela Paoletti** *(TD ASI-COSMOS funds)*

PHD STUDENTS

- **Josè Bermejo Climent**

- **Matteo Billi**

- **Matteo Braglia**

CLOSE COLLABORATORS

Mario Ballardini - *University of the Western Cape, Cape Town*
Carlo Burigana – *IRA*
Adriano De Rosa – *OAS-Bo*
Matteo Galaverni - *Specola vaticana*
Dhiraj Hazra - *INFN-Bologna*
Massimiliano Lattanzi – *INFN Ferrara*
Diego Molinari - *Università di Ferrara*
Michele Moresco - *Unibo*
Lauro Moscardini - *Unibo*
Paolo Natoli - *Università di Ferrara*
Augusto Sagnotti - *Scuola Normale Superiore*
George F. Smoot – *APC Paris*
Alexei A. Starobinsky - *Landau Institute and Russian Academy of Sciences, Russia*
Caterina Umiltà - *University of Cincinnati*
Franco Vazza - *Unibo*

Research Activities

Long tradition in

- CMB science, data analysis, development and optimization of algorithms for theoretical predictions/estimators/simulations

- Theoretical cosmology

- Cosmology conference organization (planned for 2019 «Concordances and challenges in cosmology after Planck», Sesto, Italy - «Cosmocruise 2019» Adriatic and Aegean Sea)

The CMB activities obviously stem from the Planck project (Planck ASI funding is ending but its science, data, team,… legacy will continue) and continue in other CMB experiments in preparation and proposal for future CMB experiments.

The expertise in CMB physics, data analysis and science interpretation allows us to contribute to other experiments which are in sinergy with CMB, such as galaxy surveys in preparation which will be of key importance in cosmology in the next years. Beyond the obvious combination of different measurements and likelihoods, cosmological information is contained in cross-correlation between CMB and these galaxy surveys.

PROJECTS

PLANCK

This is definitely the longest project we have been involved into. With the final Planck legacy release of data and scientific results to be completed by early next year the funding is almost over but not the scientific work! The exploiting of the full scientific legacy of Planck will require years!

RESPONSABILITIES

We have been massively involved in the Planck mission, starting from the PI of the low frequency instrument, Reno Mandolesi, to the contribution to the experimental part of the satellite (see also Villa, Morgante talk), data analysis, scientific interpretation and management. Here I highlight the main leaderships on the scientific part. We have also contributed to the cosmological results in power spectrum, likelihood, parameters, isotropy and statistics, non-gaussianities.

- INFLATION - F. Finelli (co-lead of Planck 2013 results. XXII, Planck 2015 results. XX, Planck 2018 results. X. Constraints on inflation)
- PARITY VIOLATIONS - A. Gruppuso (lead of of Planck Intermediate Results XLIX. Parity-violation constraints from polarization data)
- PRIMORDIAL MAGNETIC FIELDS - D. Paoletti (lead of Planck 2015 results. XIX. Constraints on primordial magnetic fields)
- Core team area on cosmological models and parameters - F. Finelli (LFI lead, 2007-2013, 2015-2018)

PROJECTS (cont'd)

ASI COSMOS

Project funded by ASI for a three year study on the cosmic microwave background.
It is structured in 11 nodes (7 universities, 2 INAF institutes and 2 INFN sections).
Scientific goal is the study of the physics of the early Universe and fundamental physics through the observations of the microwave sky and the definition of an Italian road map in the field of the CMB research for the next decade (years)

CMB experiments

We are involved in important international collaborations for future CMB experiments:

- LITEBIRD: phase A1 study of JAXA for a satellite dedicated to CMB polarization
- LSPE: joint balloon - ground experiment for CMB polarization on large angular scales
- PRISTINE: proposal for an F mission dedicated to CMB high frequency polarization
- CORE: ESA M5-M4-L2-M3 proposals for a medium-large size CMB mission

Euclid

Luca Valenziano is the INAF responsible for Euclid (see Auricchio's talk).
We are members of the CMBXC (CMB cross-correlation) and COTH Euclid SWGs (Finelli lead of WP4 Initial conditions). These activities are funded through ASI-INAF agreement (PI, Valenziano), INAF premiale MITIC and INAF.

PROJECTS (cont'd)

SKA

Members of the SKA collaborations, participants to PGR (Progetto di Grande Rilevanza) Italia – Sud Africa e PRIN SKA. Interest in cosmology and CMBXC

INFN (Gr. II & IV)

Members of the project Gr. IV InDark (Inflation, Dark Matter and Large Scale Structure, PI N. Bartolo, local coordinator within INFN Bologna, F. Finelli). Travel funds and postdoc position for foreign researchers.

SEARCHING FOR ANSWERS TO OPEN QUESTIONS

Planck has provided an amazing precise picture of our Universe, which is actually pretty boring, but still, some open questions may lead us towards exciting scenarios. One of our objectives is to pursue these avenues and search for the answers.

How were the initial conditions?

When reionization started and how did it happen?

What is the origin of Cosmic Magnetism?

There are CMB anomalies on large scales and what is their nature?

Are there parity violations?

Are there viable alternatives to general relativity?

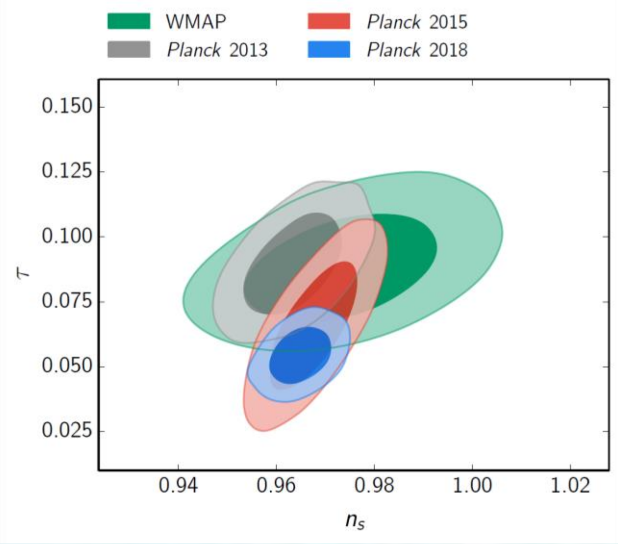
The CMB and its combination and cross correlation with other probes represents one of the best laboratories to search for these answers.

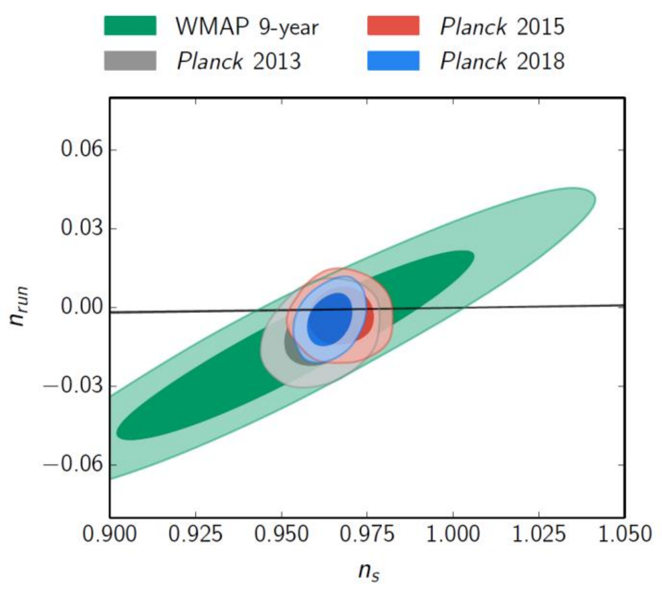
This is why we are now exploiting the Planck legacy data and their combination with Large Scale Structure data and why we are making the forecasts for future experiments CMB but also CMBxLSS. We still don't have answers now but we literally building the roadmap and paving the way for the near and far future

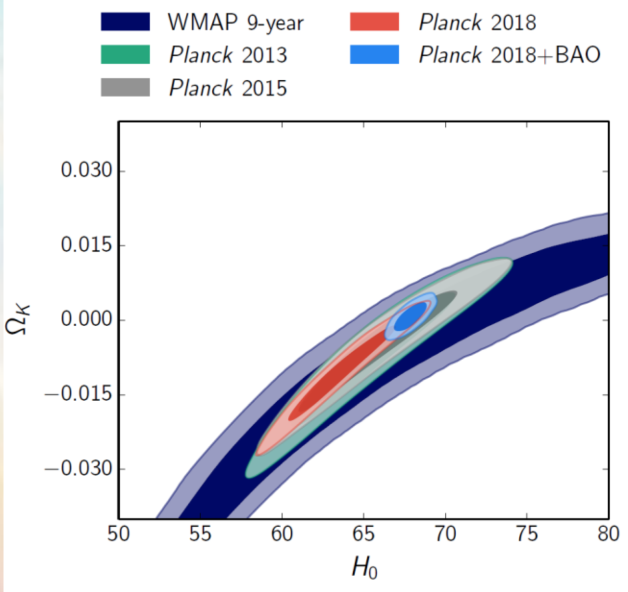
Planck was a formidable experiment to probe the initial conditions and the physics of the Early Universe.

Our Universe according to Planck is:

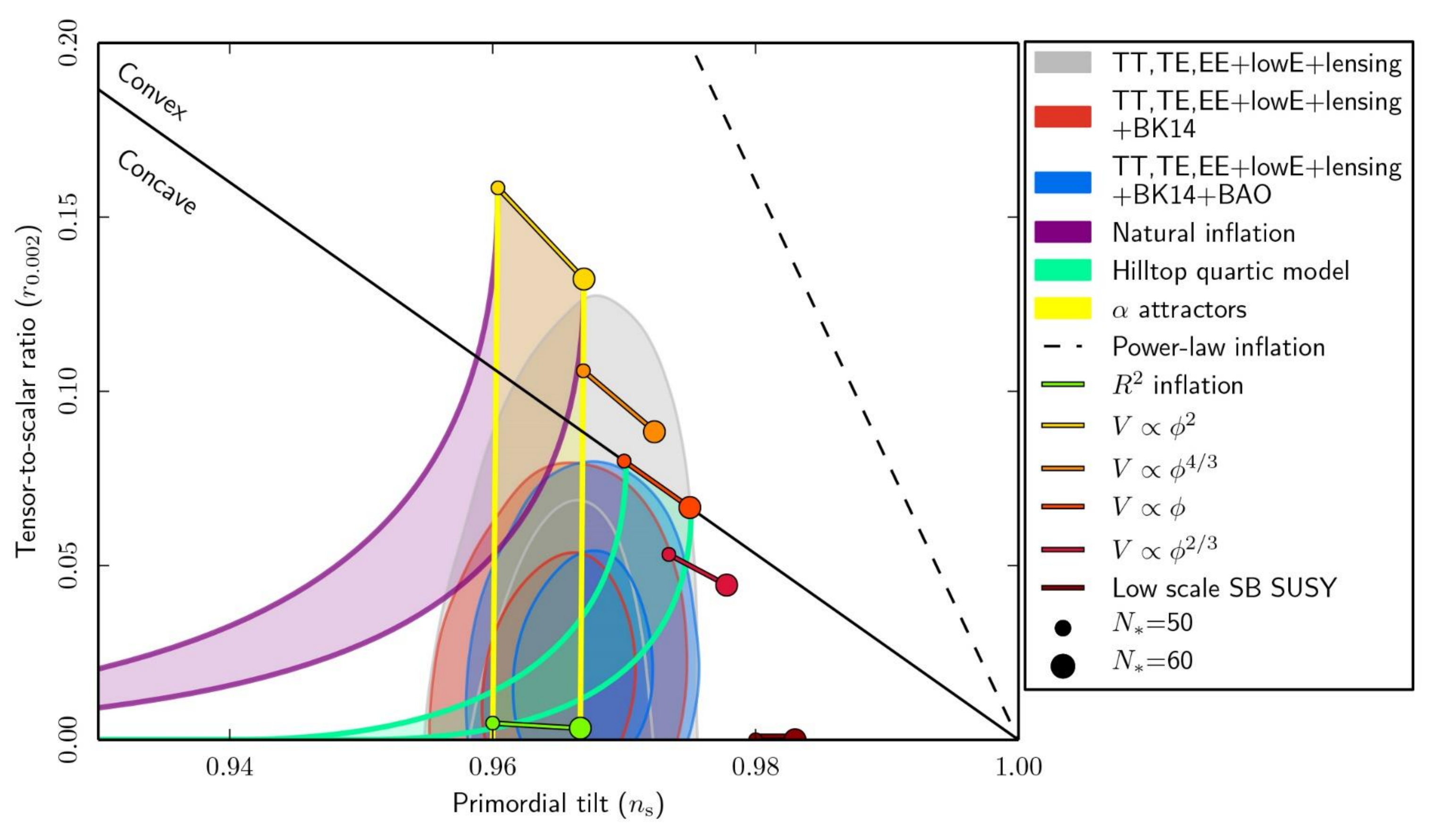
- Flat (Euclidean geometry) (OmegaK = 0.9649 ± 0.0042 at 68 %CL, Planck + BAO)
- Primordial perturbations follow a power law power spectrum, ns = 0.9649 ± 0.0042 at 68 %CL, 8.4 sigma from scale invariance
- Gaussian
- Adiabatic



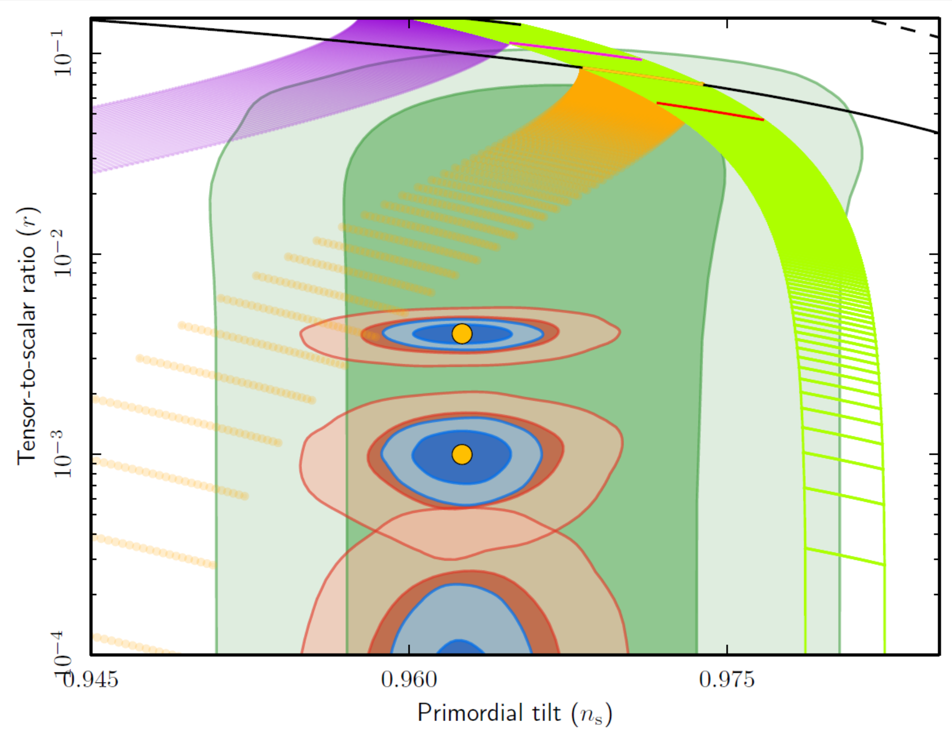




Planck 2018 results. X. Constraints on inflation



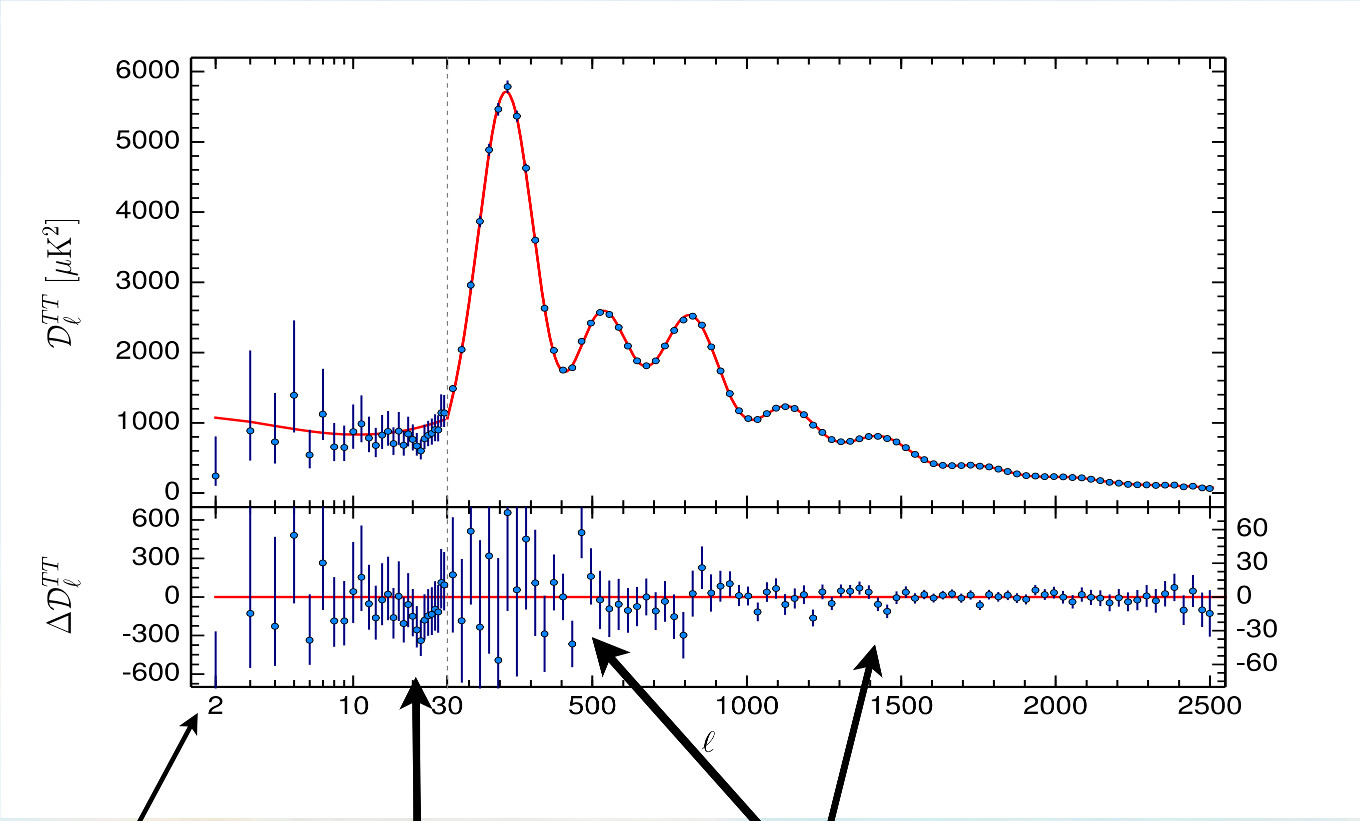
Future

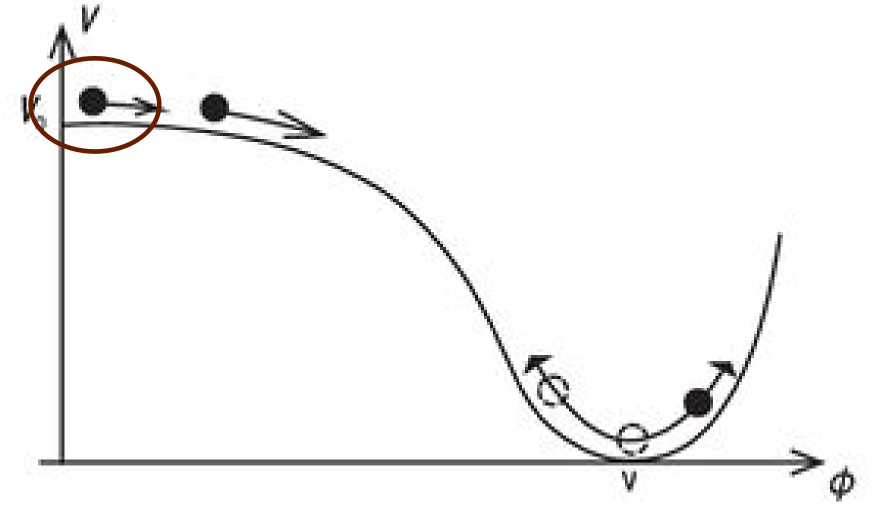


Planck improves the bound on the tensor to scalar ratio, i.e. r < 0.10 at 95 %CL at the pivot scale k=0.002 Mpc^{-1}. In combination with BK14, the bound tightens to r < 0.064 at 95 % CL. The analysis with the new data from BICEP-Keck collaboration (BK15, P.A.R. Ade et al., 2018) is ongoing

$$\dot{\phi}^2/2 << V$$

$$\ddot{\phi} << 3H\dot{\phi}\,, V_\phi$$





Lowest multipoles

Feature at $\ell \sim 20$

Intermediate and high multipoles

No physics beyond LambdaCDM is required at a statistically significant level, however these conclusions are mainly based on the Planck instrumental noise level and knowledge of foreground/systematics.

Future CMB polarization data (see for instance Hazra, Paoletti, Ballardini, Finelli, Shafieloo,Smoot & Starobinsky 2018) or galaxy surveys (Ballardini, Finelli, Fedeli, Moscardini, 2016) will confirm if these outliers in CMB temperature are explained by deviations from a power-law in the primordial spectra or are statistical fluctuations.

CMB anomalies

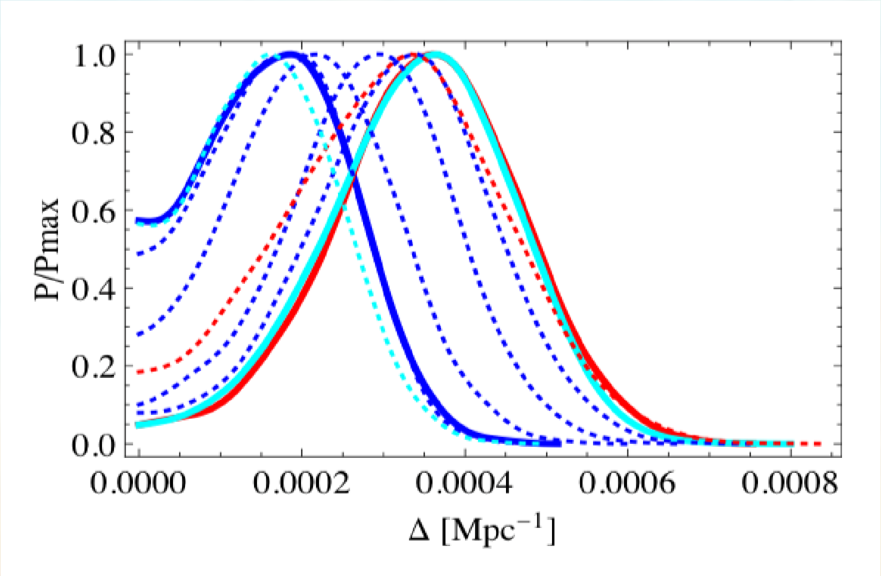
- CMB map (intensity map) at low ℓ shows some deviations from the ΛCDM model (power anomalies, directional anomalies, local anomalies). Significance of those are typically 2-3σ CL. There is a certain degree of correlation among those.

- Focus on the lack of power anomaly. This can be naturally described by an early departure from the inflation era. Such a departure is parameterised by an additional parameter Δ.

Planck 2015 data

Posterior distribution function of Δ versus sky fraction (Galactic mask)

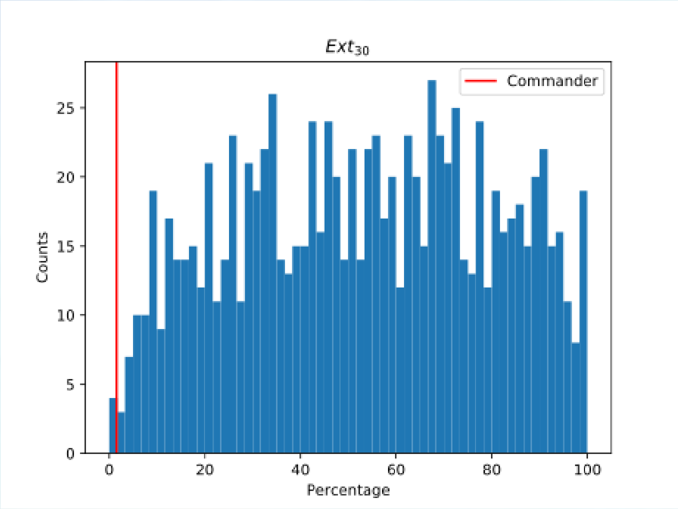
Most of the (low) power at large scale is localised around the Galactic plane, and some information is contained also in the polarisation maps



Gruppuso, Kitazawa, Mandolesi, Natoli, Sagnotti Phys.Dark Universe (2016)

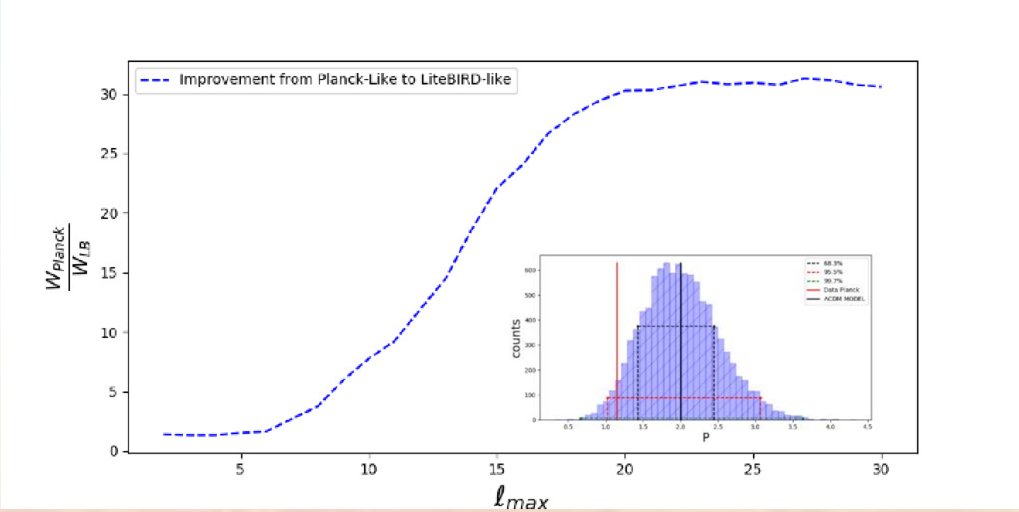
CMB anomalies

Natale, Gruppuso, Molinari, Natoli, in preparation (2018)



- we have built estimators aimed at testing how likely it is this low-ℓ behaviour in a ΛCDM model. Considering simulated CMB maps, which possess almost the same power as the one observed by Planck 2018, and performing random rotations of those, we find that only 4 out of 1000 show less variance at high Galactic latitude. This is a ~2.8 σ effect obtained with a frequentist approach and employing an optimal estimator for the angular power spectrum.

Billi, Gruppuso, Mandolesi, Moscardini, Natoli, to be submitted (2018)



- we have built a new one-dimensional estimator, namely P, which is capable to take into account jointly the TT, TE and EE CMB spectra. For Planck 2015 data this estimator can be fruitfully defined only up to the multipole l=6 (inner panel) beyond which it becomes noise dominated. However future CMB polarised measurements, which allow to consider few tens of multipoles at those large scales, can tight the empirical distribution of this new estimator up to a factor of ~30.

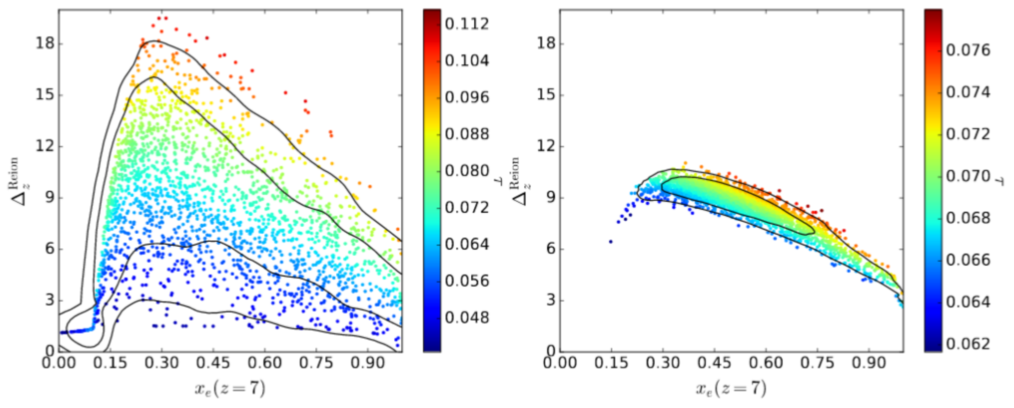
REIONIZATION WITH FUTURE CMB SPACE EXPERIMENTS

FUTURE E-MODE OBSERVATIONS FROM SPACE HAVE THE CAPABILITY TO DISCRIMINATE AMONG DIFFERENT MODELS OF REIONIZATION.

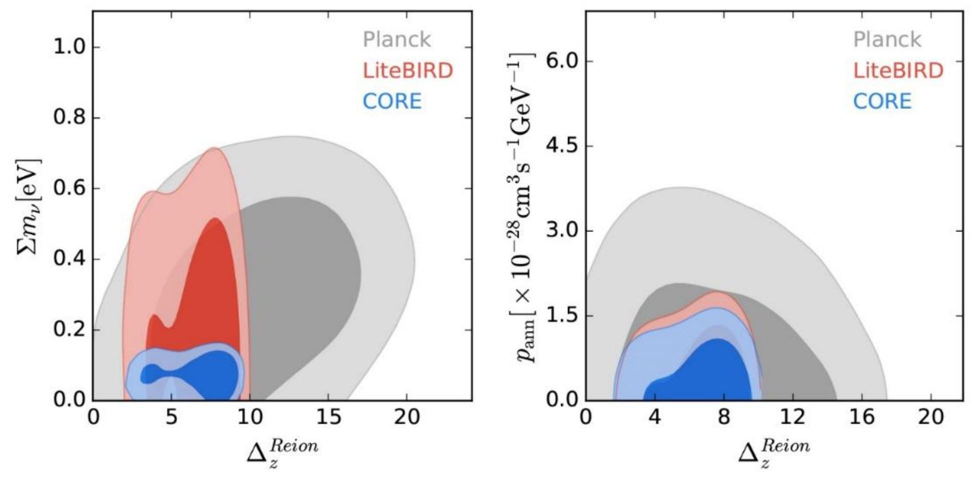
We Investigate the extended model where the history of reionization as parametrized by two additional extra parameters: an intermediate position in redshift and the free electron fraction at that redshift.

We investigated the capabilities of Planck, LiteBIRD (Matsumura et al. 2014 configuration) and a CORE-like (Core Collaboration, Delabrouille et al. 2016) experiment to break the degeneracies of the reionization history with the LCDM model and some of its extensions (Hazra et al. 2018-1, Hazra et al. 2018-2).

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



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



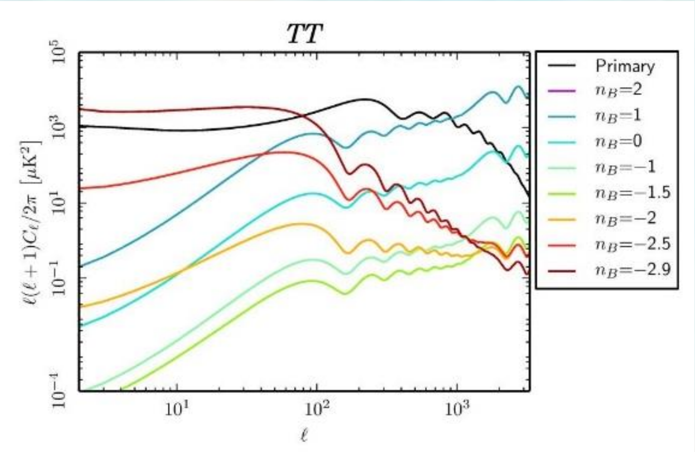
Hazra, Paoletti, Finelli, Smoot 2018

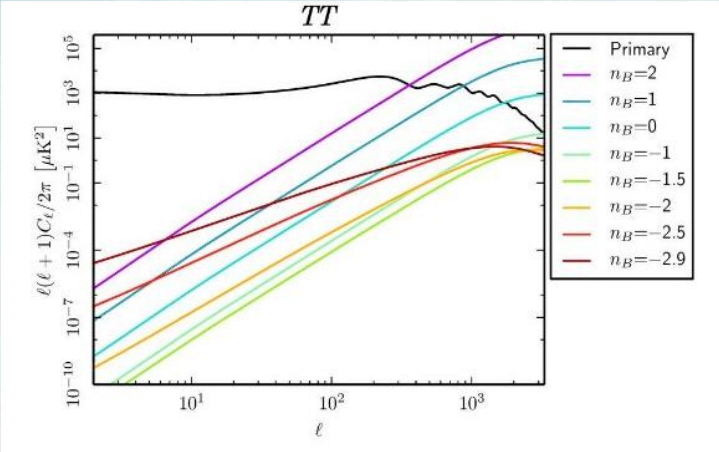
PRIMORDIAL MAGNETIC FIELDS

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

GRAVITATIONAL EFFECT

PMFs source magnetically-induced cosmological perturbations. Our group has done some of the reference works in the field being the first ones to compute analitically the magnetic source terms to cosmological perturbations (Finelli et al. 2008, Paoletti et al. 2009, Paoletti and Finelli 2011-2013, Planck 2015 Results XIX)





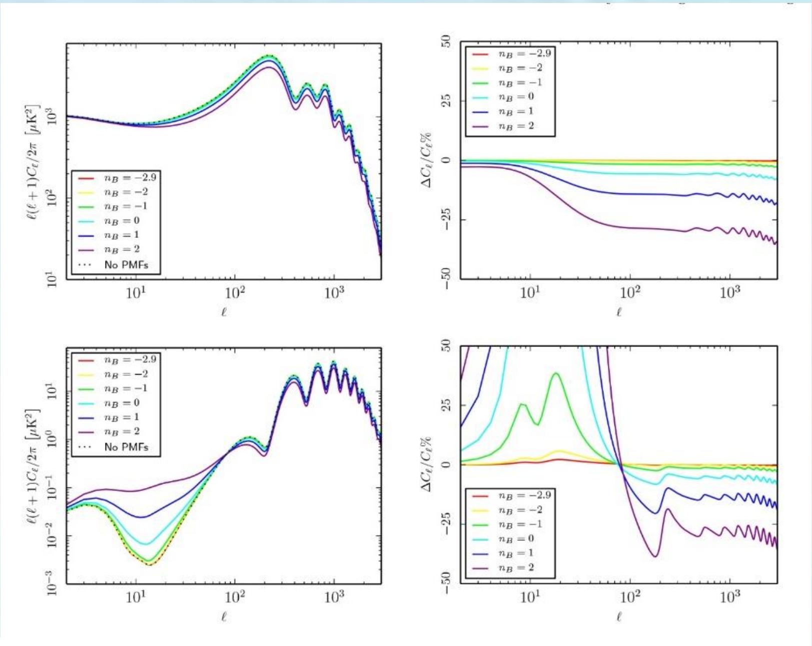
We can use the CMB to constrain the PMFs amplitude and spectral index (Paoletti and Finelli 2011-2013, Planck 2015 Results XIX) . Constraints from current CMB data are of few nG.

Forecasts for future experiments will allow to tighten the constraints below the nG level (Paoletti et al. In preparation).

EFFECT OF PMFs ON THE IONIZATION HISTORY

PMFs may affect also the ionization history leading to signatures on the CMB anisotropies in temperature and polarization thanks to the dissipation of the fields around and after recombination (Chluba, Paoletti, Finelli, Rubino-Martin 2015, Paoletti, Chluba, Finelli, Rubino-Martin 2018).

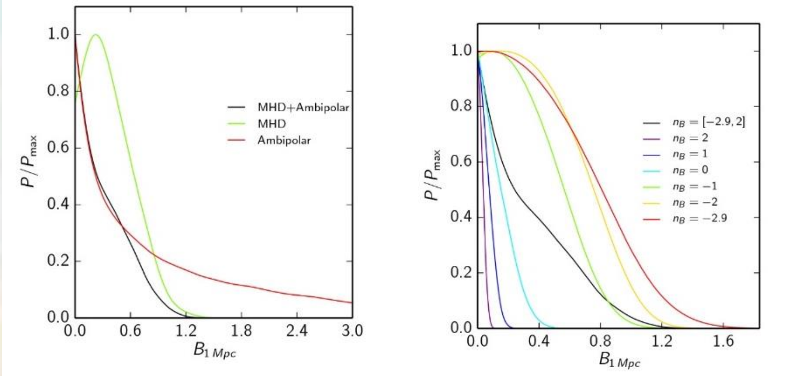
This effect is very competitive and it provides very good prospects in the light of future experiments targeted to e-mode polarization.



Paoletti, Chluba, Finelli, Rubino-Martin 2018

RECONNETING EARLY AND LATE

To really prove the primordial origin of the cosmic magnetism is necessary to have a realizability proof, namely that the fields we constrain at recombination with the CMB can really provide the fields we observe now.
We plan a collaboration with F. Vazza to pursue this objective through numerical simulations with initial conditions set up by the constraints from CMB.



Paoletti, Chluba, Finelli, Rubino-Martin 2018

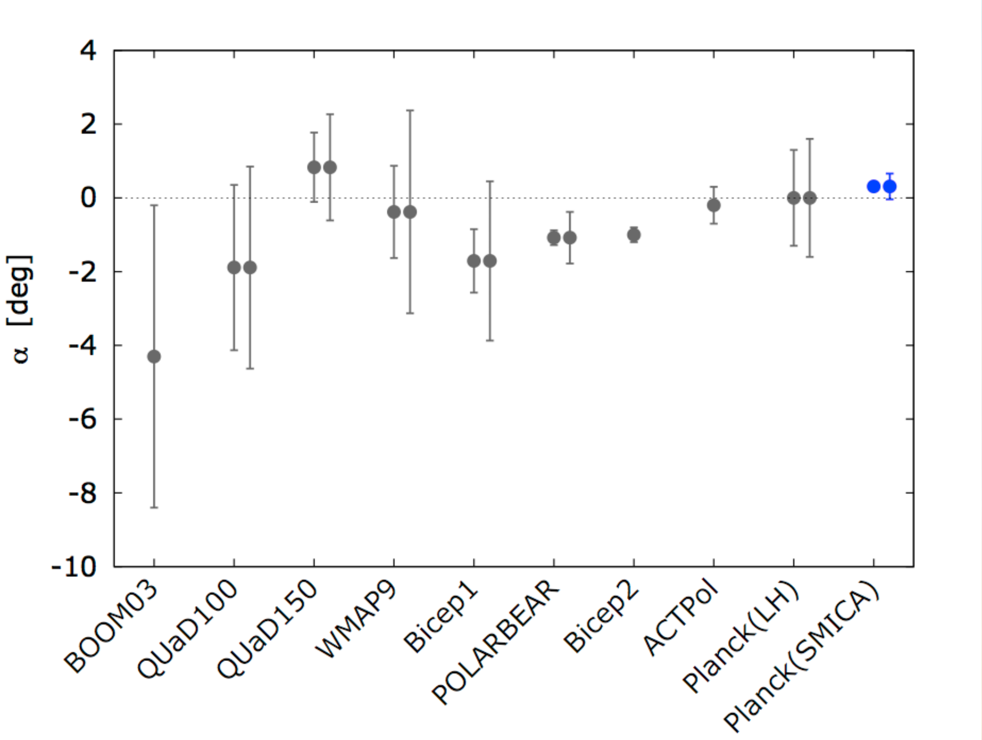
Parity violations studies

- Parity violating extensions of the standard model can be tested through CMB polarised anisotropies. New coupling terms in the Maxwell Lagrangian produce an effect known as Cosmic Birefringence: the rotation of the polarisation plane of a photon (also a CMB photon since CMB is polarised). A rotation is naturally parameterised by and angle.

isotropic birefringence

$$\begin{aligned}
C_\ell^{TE,obs} &= C_\ell^{TE}\cos(2\alpha)\,,\\
C_\ell^{TB,obs} &= C_\ell^{TE}\sin(2\alpha)\,,\\
C_\ell^{EE,obs} &= C_\ell^{EE}\cos^2(2\alpha) + C_\ell^{BB}\sin^2(2\alpha)\,,\\
C_\ell^{BB,obs} &= C_\ell^{BB}\cos^2(2\alpha) + C_\ell^{EE}\sin^2(2\alpha)\,,\\
C_\ell^{EB,obs} &= \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right)\sin(4\alpha)\,,
\end{aligned}$$

Planck collaboration, Astron. Astrophysics 596 (2016) A110



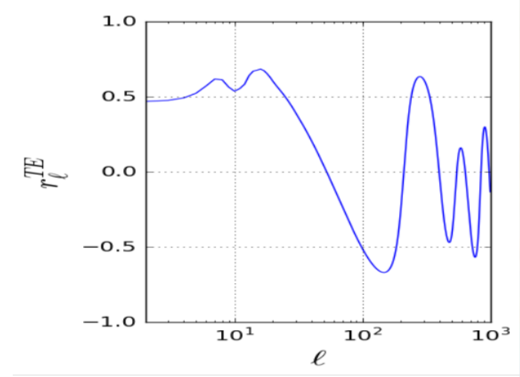
Anisotropic birefringence is the next frontier of this kind of research

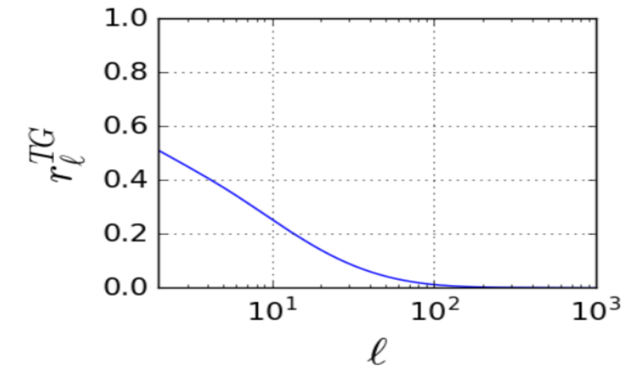
$$\boldsymbol{\alpha(\hat{n}) = \alpha + \delta\alpha(\hat{n})}$$

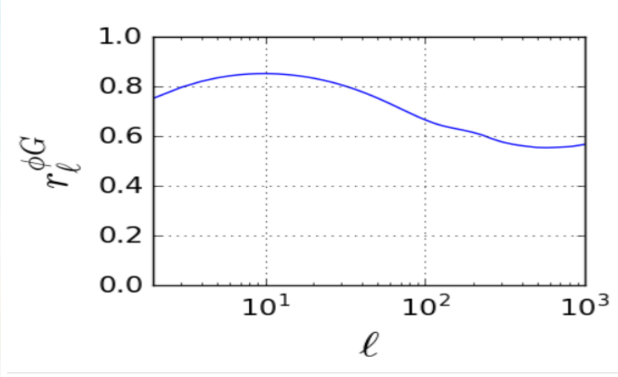
Anisotropies might come from fluctuations of the field which breaks P in the SM extension

CMBXC

- As for CMB primary intensity and polarization anisotropies, CMB secondary anisotropies are correlated with the growth of structures at low redshift.
- A contribution to CMB intensity fluctuations (integrated Sachs-Wolfe) is correlated with the time change of the gravitational potentials induced by the recent dominance of dark energy.
- The deflection of photons along the line of sight due to gravitational instability induces a correlation of the lensing effect in CMB fluctuations with structure formation (with a main contribution at low redshifts).





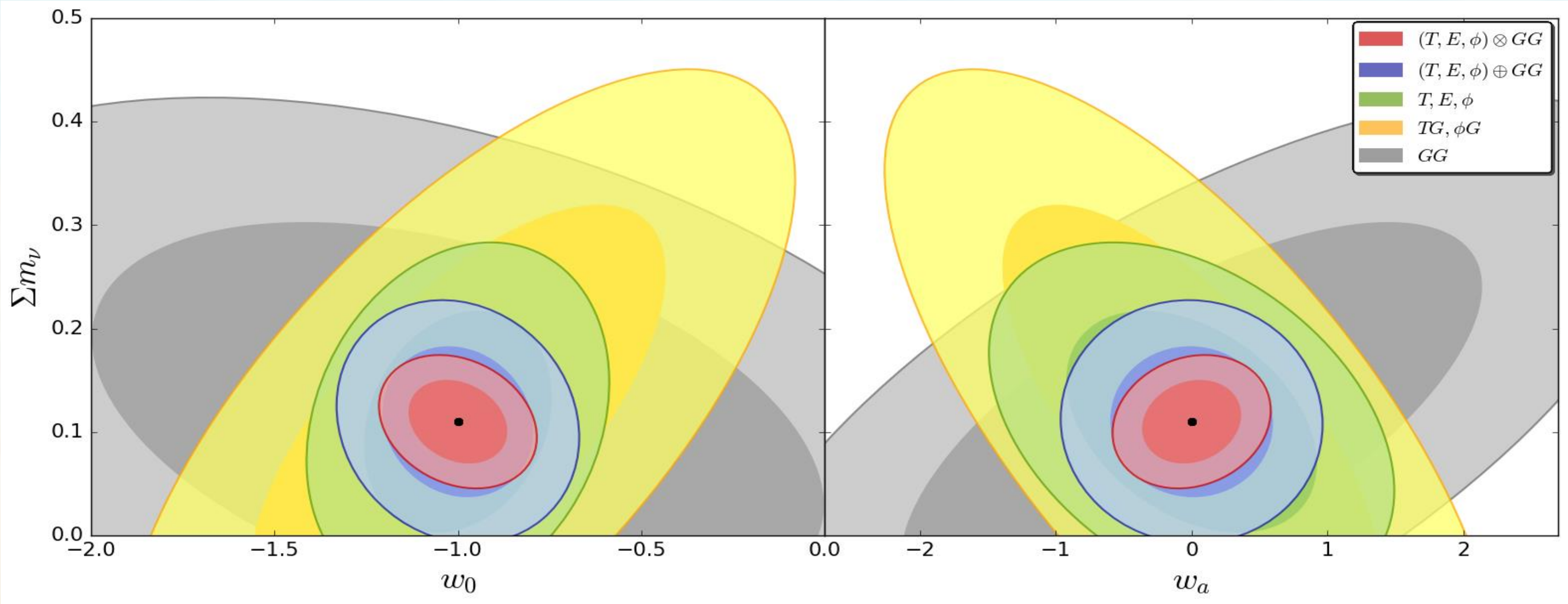


- The science of CMBXC will have an impulse from future galaxy surveys which will provide a larger number of counts and will cover a larger redshift volume.
- Euclid and SKA are obviously among these surveys.

What to expect from CMBXC from future galaxy surveys?

Extensive Fisher forecasts by a joint tomographic analysis using all 2D available power spectra with present (Planck) and future CMB experiments (AdvACTpol, S4) vs future galaxy surveys (Euclid, LSST, EMU and SKA).

CMBXC contains a lot of cosmological information (maximum S/N around 5 for TG, 250 for phiG for the surveys considered) and its inclusion is important for different cosmological parameters.

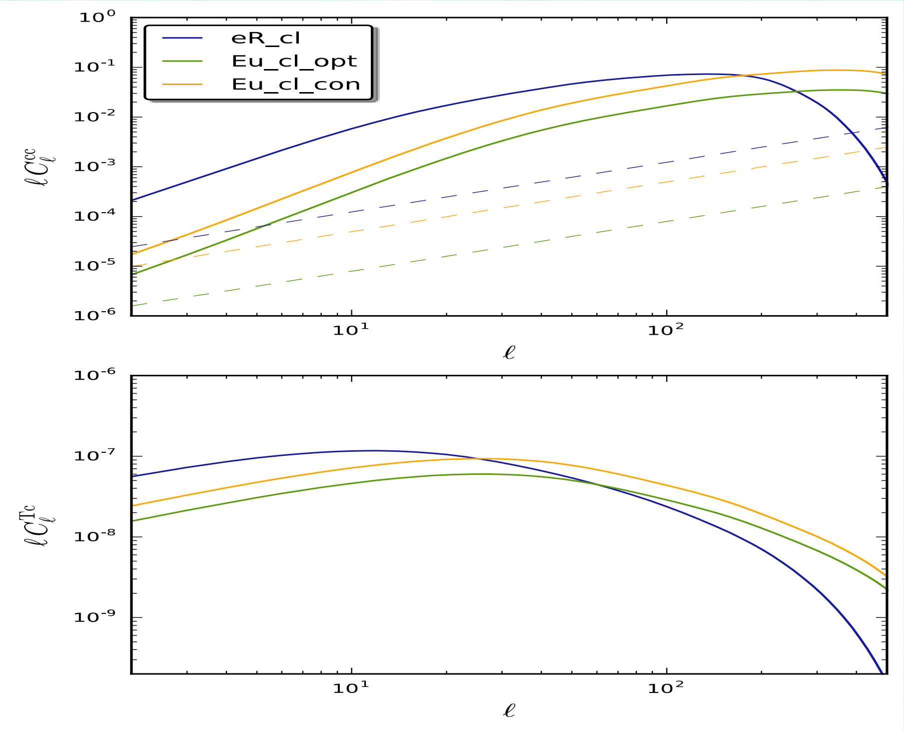


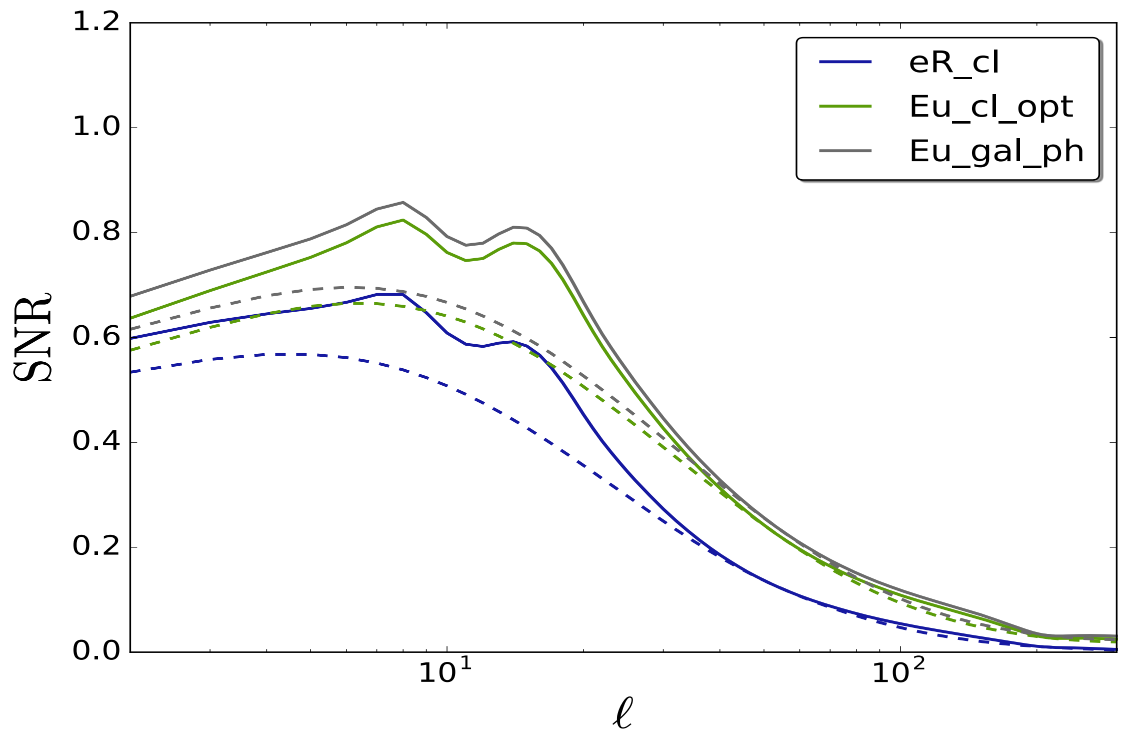
S4 and SKA

Bermejo-Climent, Ballardini, Finelli, Paoletti, Maartens, Rubino-Martin, Valenziano (2019)

ISW detection with clusters

Future surveys will provide cluster catalogues with a number of objects comparable with galaxy catalogues currently used for the detection of the ISW signal. By developing the predictions of the auto- and CMB cross-power spectra of cluster counts we show that the S/N potentially achievable with clusters is similar to the one of galaxies





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

Galaxy counts - CMB X-correlation

- **The Integrated Sachs-Wolfe effect (sensitive to Dark Energy) is detectable cross-correlating the CMB anisotropy pattern maps at large angular scale with Large Scale Structure Tracers.**

- **The signal is weak and therefore it is important to have estimators that do not introduce "extra" variance, or better to say, estimators that have the minimum variance as possible.**

- **Within Euclid XCMB activity a QML estimator for the TG APS has been built an put on test.**

See e.g. Schiavon, F, Finelli, F, Gruppuso, A, Marcos-Caballero, A, Vielva, P, Crittenden, RG, Barreiro, RB & Martinez-Gonzalez, E 2012

QML method

$y_{\ell'}$ vector, in harmonic space

$$\boxed{\hat{C}_\ell = F^{-1}_{\ell\ell'}\boxed{\left[x^t E_{\ell'} x - Tr[N E_{\ell'}]\right]}}$$

Sum on ℓ' is understood

total covariance, in pixel space

$$E_\ell = \frac{1}{2} C^{-1} P_\ell C^{-1} \qquad C = S(\{C_\ell^{fid}\}) + N$$

matrix E, for each multipole pixel space

$$P_\ell = \frac{\partial C}{\partial C_\ell^{fid}}$$

matrix P in pixel space, related to the Legendre polynomials

$$F_{\ell\ell'} = \frac{1}{2} Tr\left[C^{-1} P_\ell C^{-1} P_{\ell'}\right]$$

Fisher matrix, in harmonic space

x map, in pixel space

This estimator is **optimal** since it is "unbiased and minimum variance". They are minimum variance because they saturate the Fisher-Cramer-Rao inequality (under very general assumptions it is possible to show that the variance of a given estimator has a lower bound).

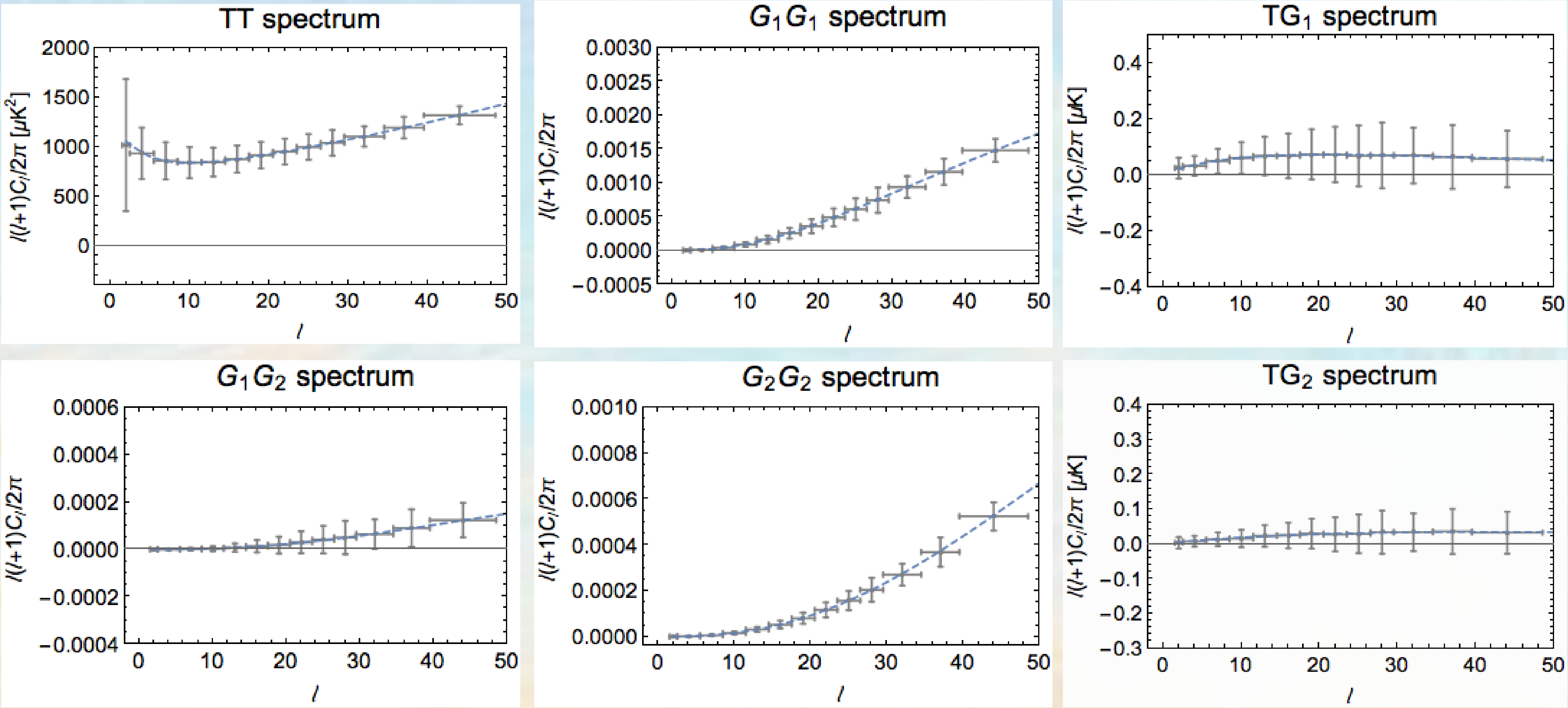
$$\langle \hat{C}_\ell \rangle = C_\ell$$

unbiased

$$\langle (\hat{C}_\ell - C_\ell)(\hat{C}_{\ell'} - C_{\ell'}) \rangle = F^{-1}_{\ell\ell'}$$

minimum variance

Gal CMB X-correlation



MC validation of the QML code at low res

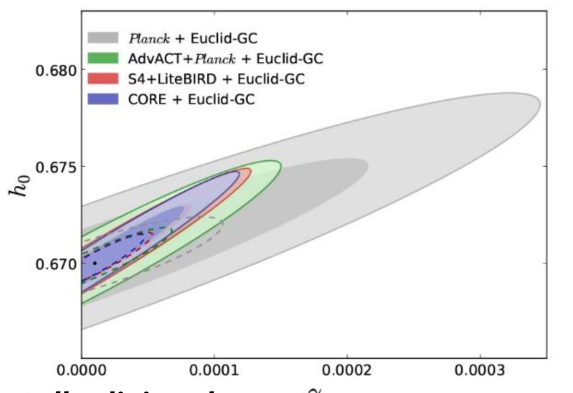
HOW COSMOLOGY CAN CONSTRAIN DEVIATIONS FROM GENERAL RELATIVITY

We study an extended Jordan-Brans-Dicke model of gravity which provides also a solution for dark energy with assocviated constraints with CMB (Umiltà, Ballardini, Finelli, Paoletti 2015; Ballardini, Finelli, Umiltà, Paoletti 2016)

$\gamma < 0.0017$ (95 % CL, *Planck* TT,TE,EE + lowP + lensing)

$\gamma < 0.00075$ (95 % CL, *Planck* TT,TE,EE + lowP + lensing + BAO)

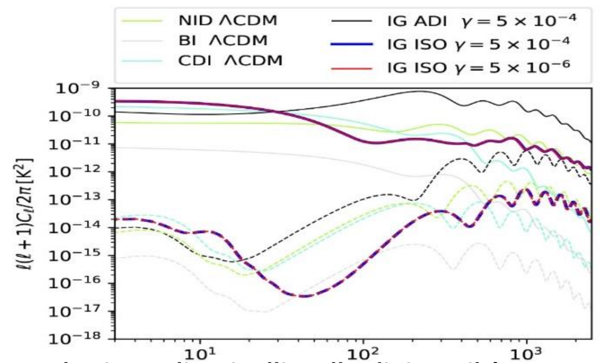
We extend our previous constraints by forecasting the capabilities of the next generation of CMB experiments -AdvACT, CORE-like, S4+LiteBIRD (Ballardini et al. in preparation).



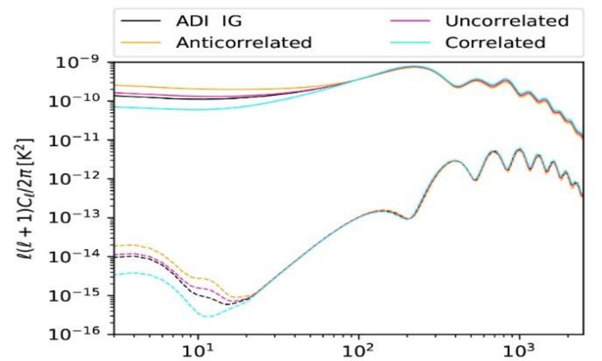
Ballardini et al. In prep.

We have also 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.

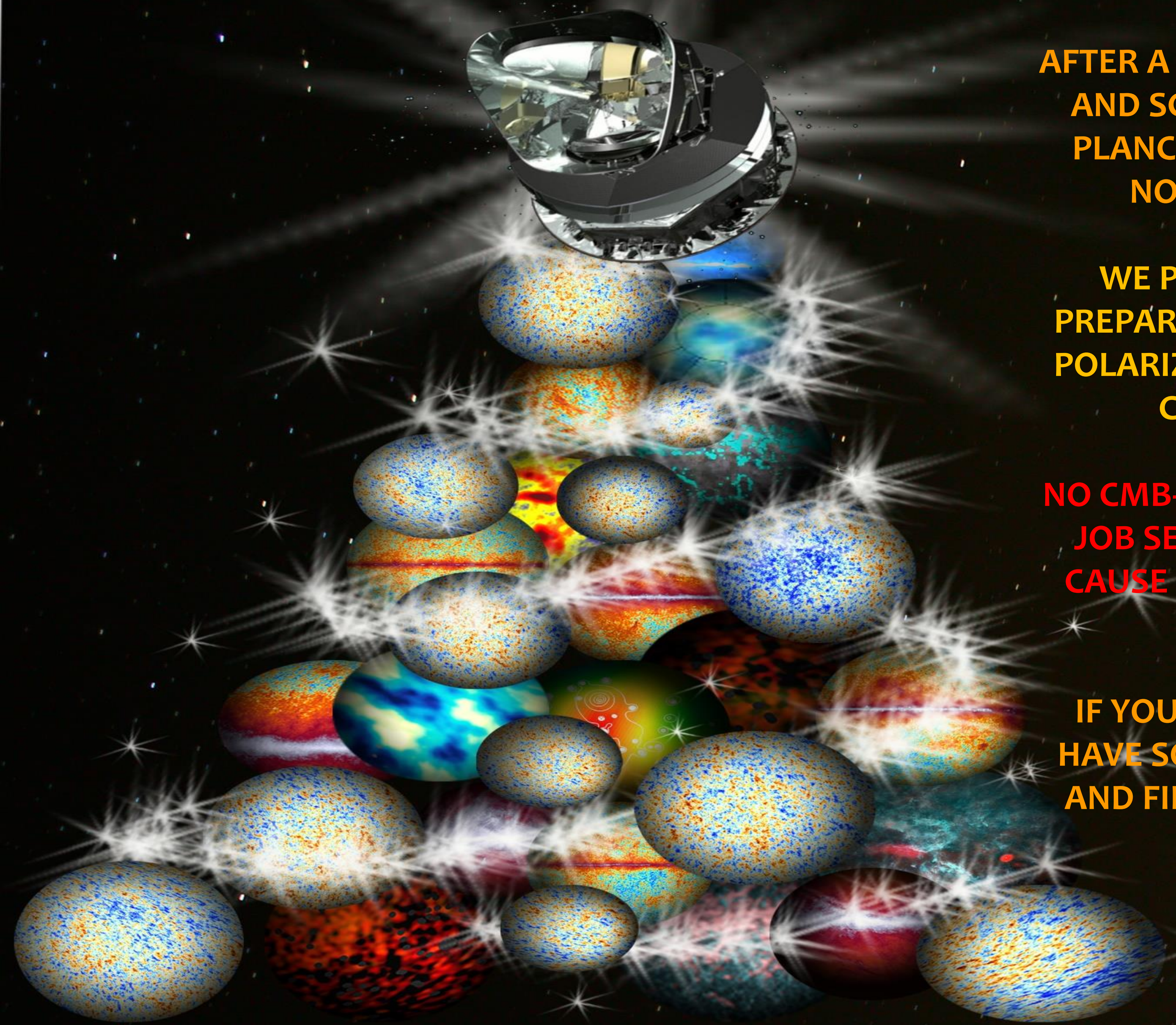


Paoletti, Braglia, Finelli, Ballardini, Umiltà 2018



Paoletti, Braglia, Finelli, Ballardini, Umiltà 2018

Case	$\gamma = 5 \times 10^{-4}$
Fully Anticorrelated	$f_{ISO} < 0.07$
Uncorrelated	$f_{ISO} < 0.31$
Fully Correlated	$f_{ISO} < 0.12$



AFTER A MAJOR INVOLVEMENT IN DATA ANALYSIS AND SCIENTIFIC INTERPRETATION WITHIN THE PLANCK COLLABORATION, THE CMB GROUP IS NOW INVOLVED IN THE LEGACY WORK

WE PARTICIPATE TO CMB EXPERIMENTS IN PREPARATION, PROPOSALS DEDICATED TO CMB POLARIZATION AND PROJECTS IN SINERGY WITH CMB, AS FUTURE GALAXY SURVEYS

NO CMB-CMBXC WAS CONSIDERED IN THE LATEST JOB SELECTIONS PROFILES. THIS CHOICE WILL CAUSE OAS TO LOSE THE ACQUIRED EXPERTISE AND COMPETITIVENESS

IF YOU WANT TO COLLABORATE OR YOU JUST HAVE SOME CURIOSITY WE ARE AT THE SECOND AND FIRST FLOOR @OAS-AREA DELLA RICERCA

THANK YOU