Fundamental Physics with Planck (expectations) and results from other experiments

Nazzareno Mandolesi

on behalf of the Fundamental Physics with Planck proposers

Cosmological parameters

WMAP constraints

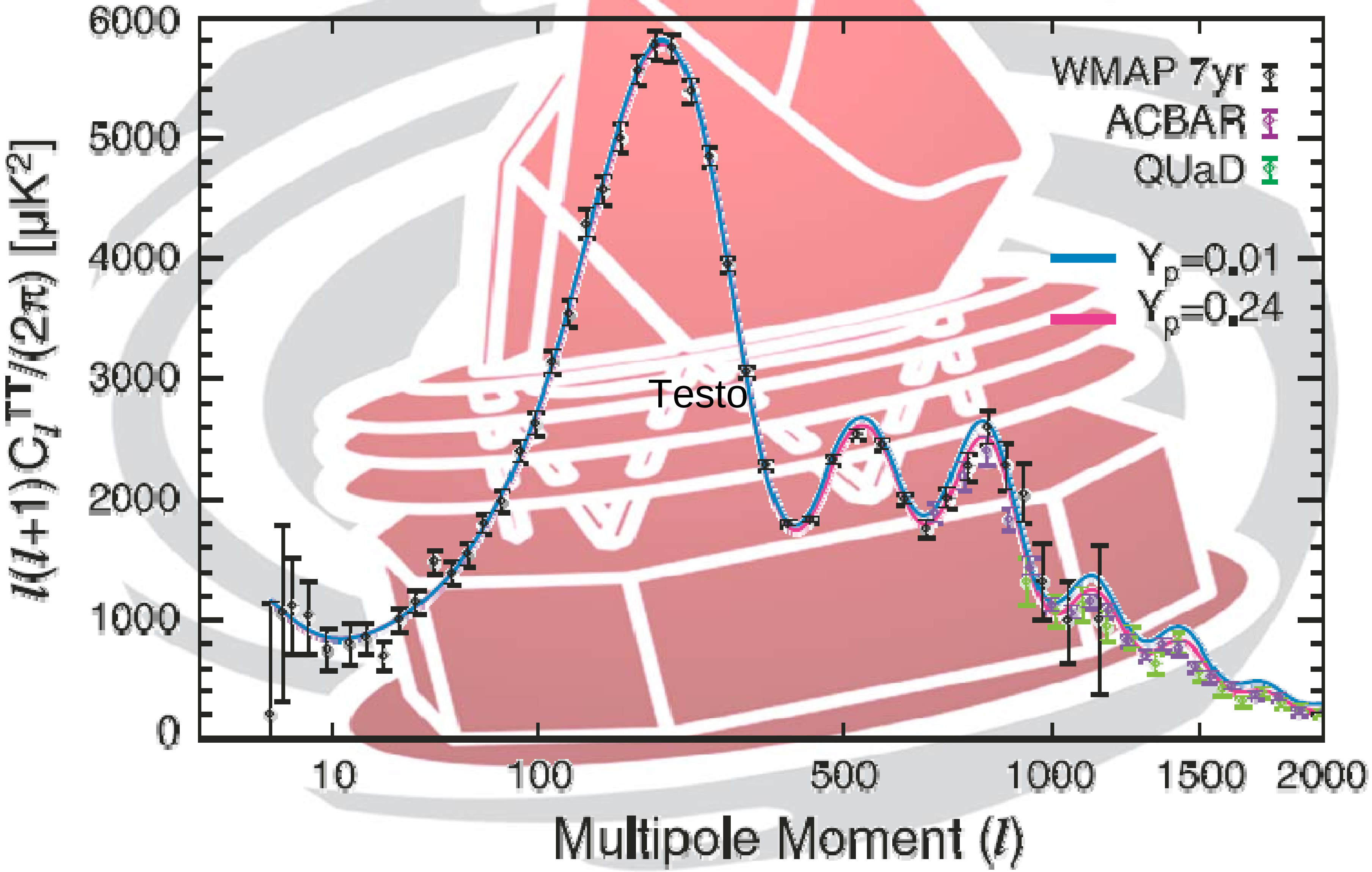
Table 3
Six-Parameter ΛCDM Fit [a]

Parameter	7-year Fit	5-year Fit
Fit parameters		
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	2.273 ± 0.062
$\Omega_c h^2$	0.1109 ± 0.0056	0.1099 ± 0.0062
Ω_Λ	0.734 ± 0.029	0.742 ± 0.030
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014	$0.963^{+0.014}_{-0.015}$
τ	0.088 ± 0.015	0.087 ± 0.017
Derived parameters		
t_0	13.75 ± 0.13 Gyr	13.69 ± 0.13 Gyr
H_0	71.0 ± 2.5 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
σ_8	0.801 ± 0.030	0.796 ± 0.036
Ω_b	0.0449 ± 0.0028	0.0441 ± 0.0030
Ω_c	0.222 ± 0.026	0.214 ± 0.027
z_{eq}	3196^{+134}_{-133}	3176^{+151}_{-150}
z_{reion}	10.5 ± 1.2	11.0 ± 1.4

New Measurements, More Parameters !

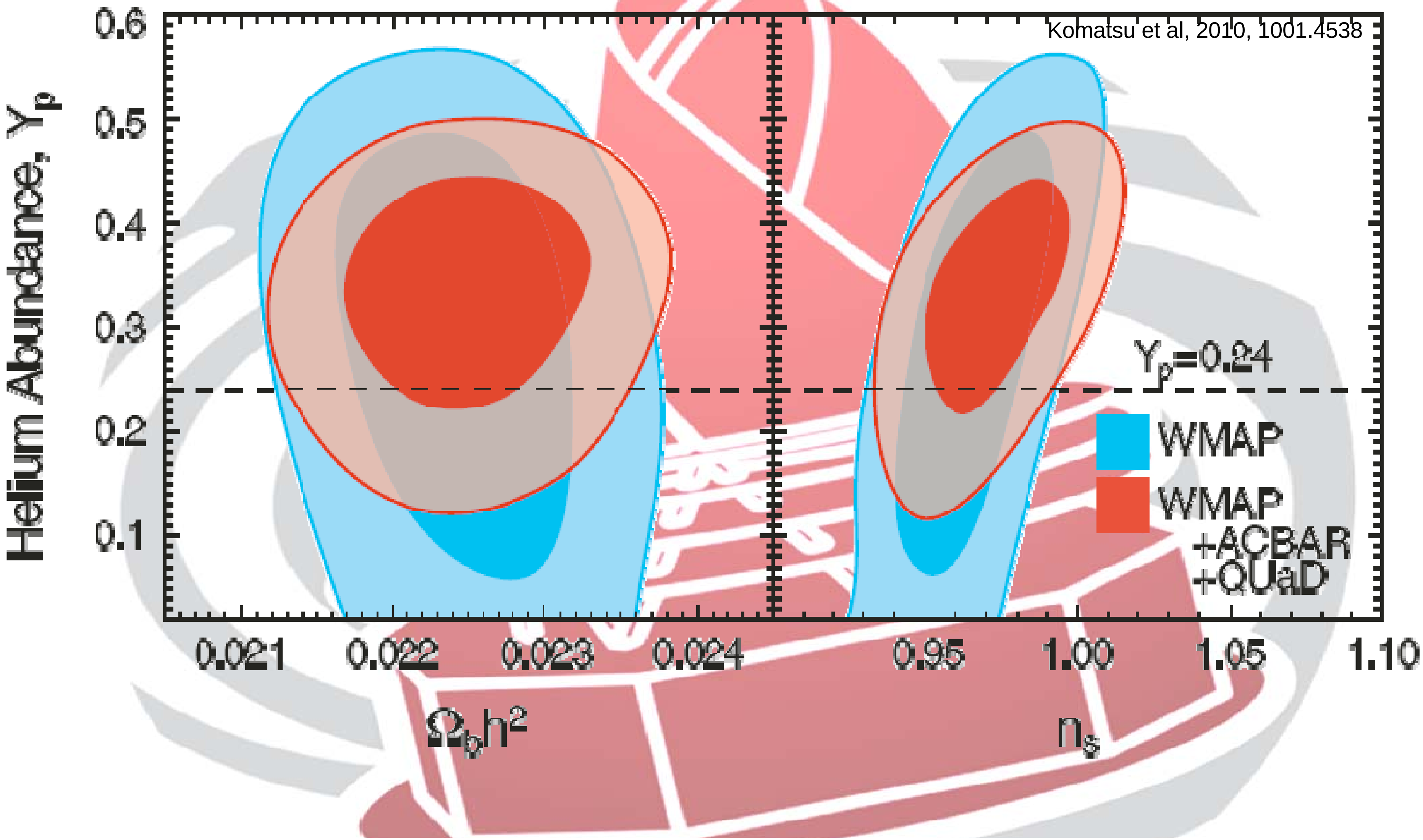
- Neutrino masses Σm_ν
- Neutrino effective number N_ν^{eff}
- Primordial Helium Y_P

Small scale CMB can probe Helium abundance at recombination.



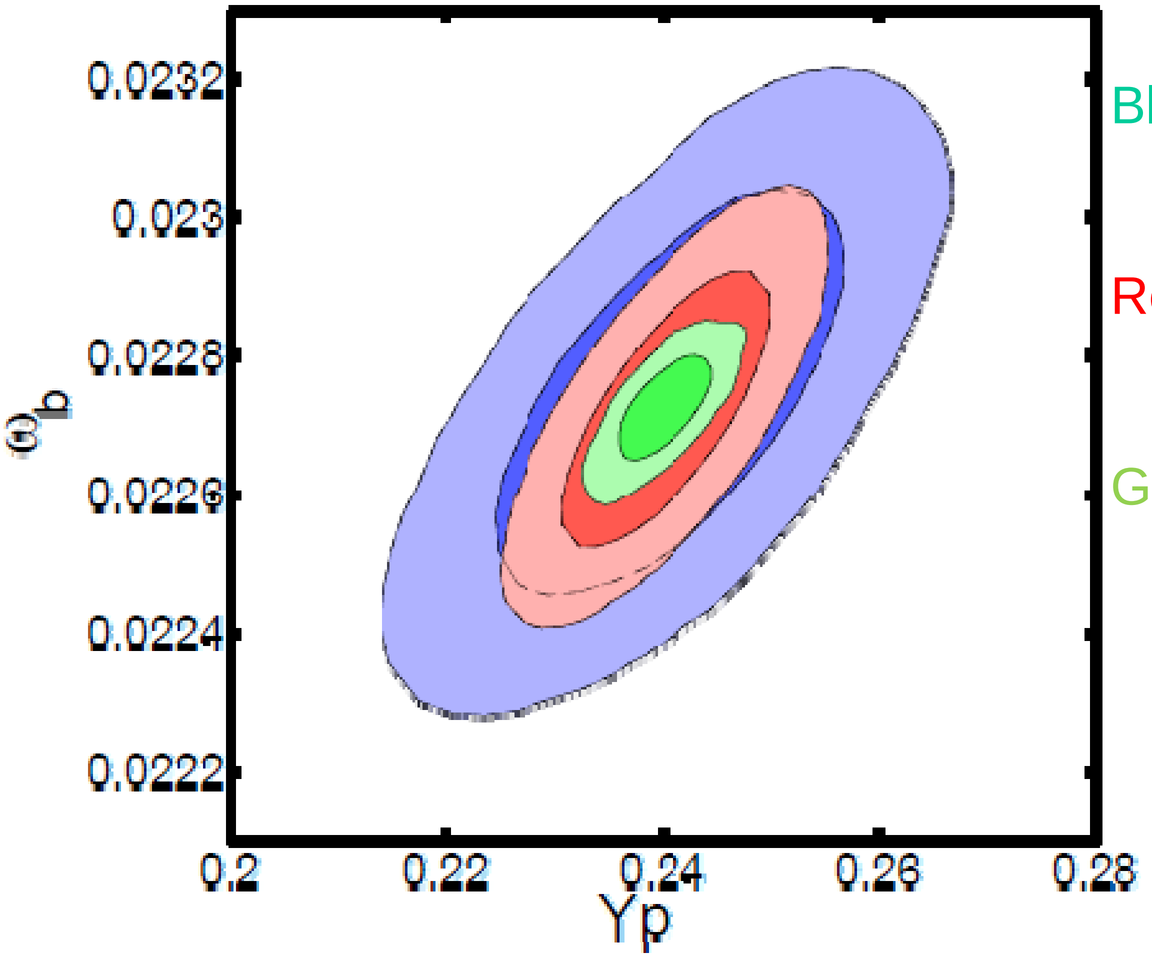
Nazzereno Mandolesi

WMAP constraints



	WMAP only	*WMAP*+ACBAR+QUaD
Y_p	< 0.51 (95% CL)	$Y_p = 0.326 \pm 0.075$ (68% CL)[b]

Forecasts on Helium Abundance

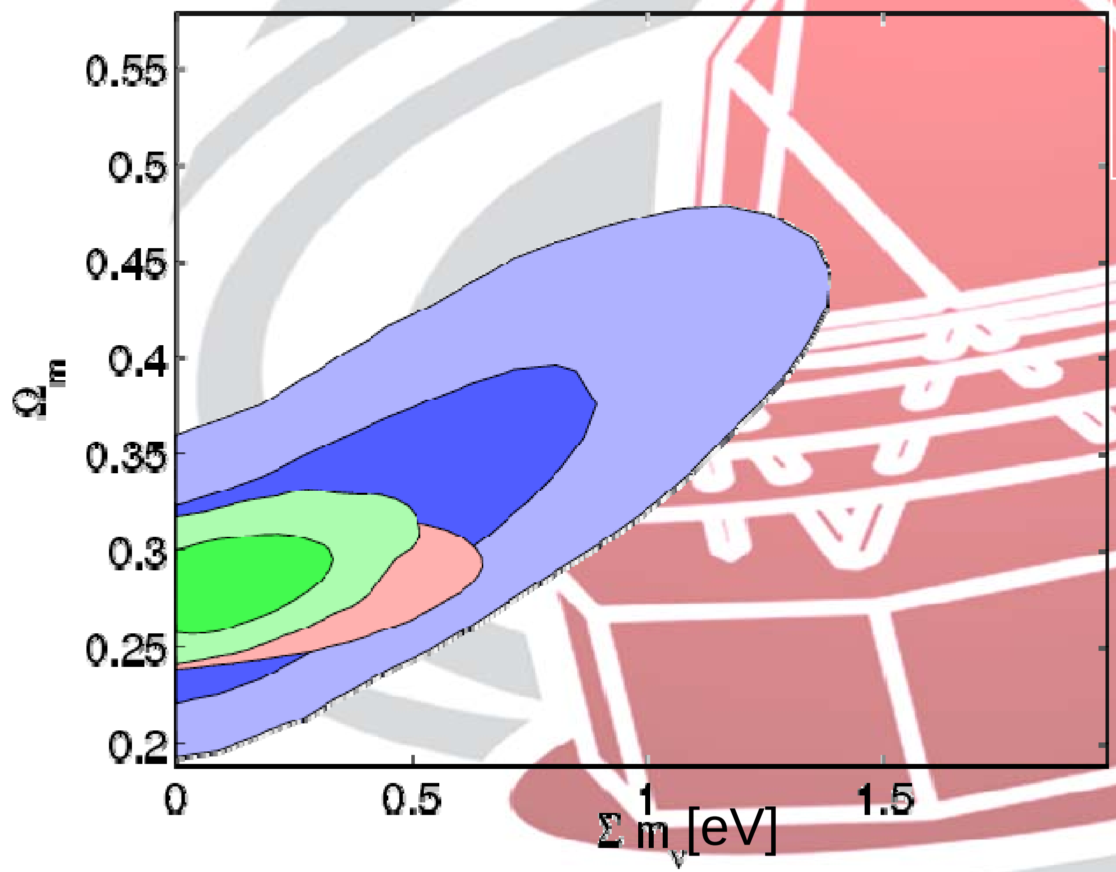


Blue: Planck ΔYp=0.01

Red: Planck+ACTpol ΔYp=0.006

Green: COrE

Current constraints on neutrino mass from Cosmology



Blue: WMAP-7
Red: w7+SN+Bao+H0
Green: w7+CMBsuborb+SN+LRG+H0

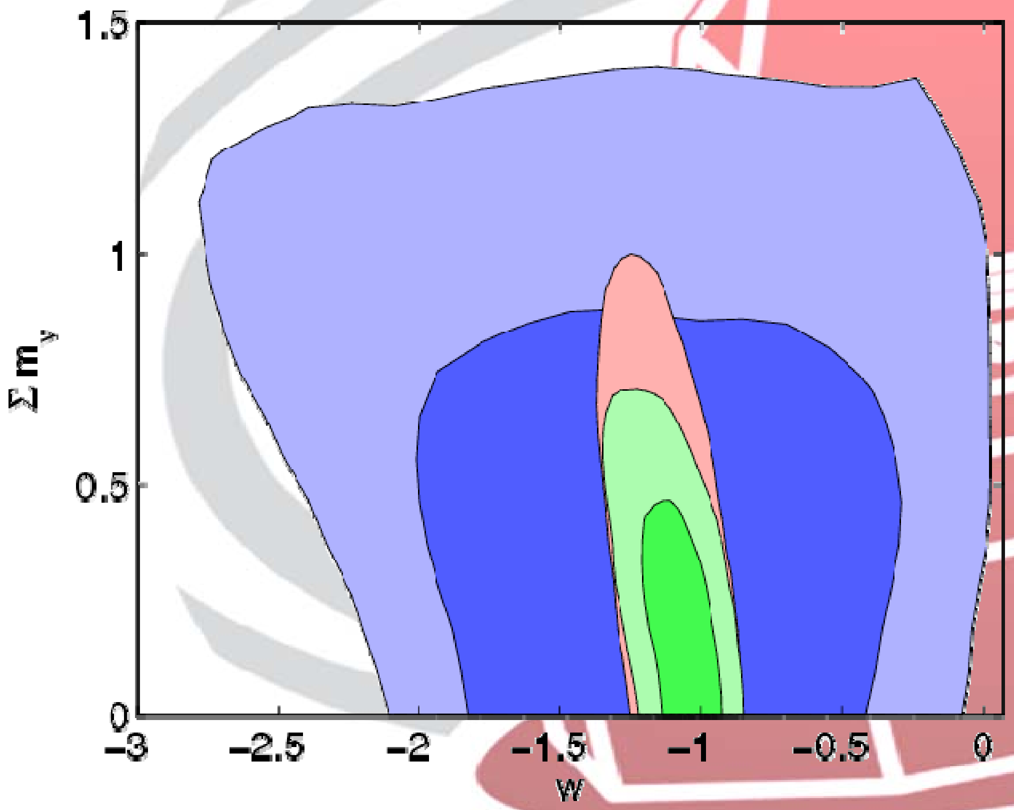
Current constraints (assuming ΛCDM):

$\Sigma\, m_\nu < 1.2$ [eV] CMB

$\Sigma\, m_\nu < 0.7\text{-}0.5$ [eV] CMB+other

$\Sigma\, m_\nu < 0.3$ [eV] CMB+LSS (extreme)

Current constraints on neutrino mass from Cosmology



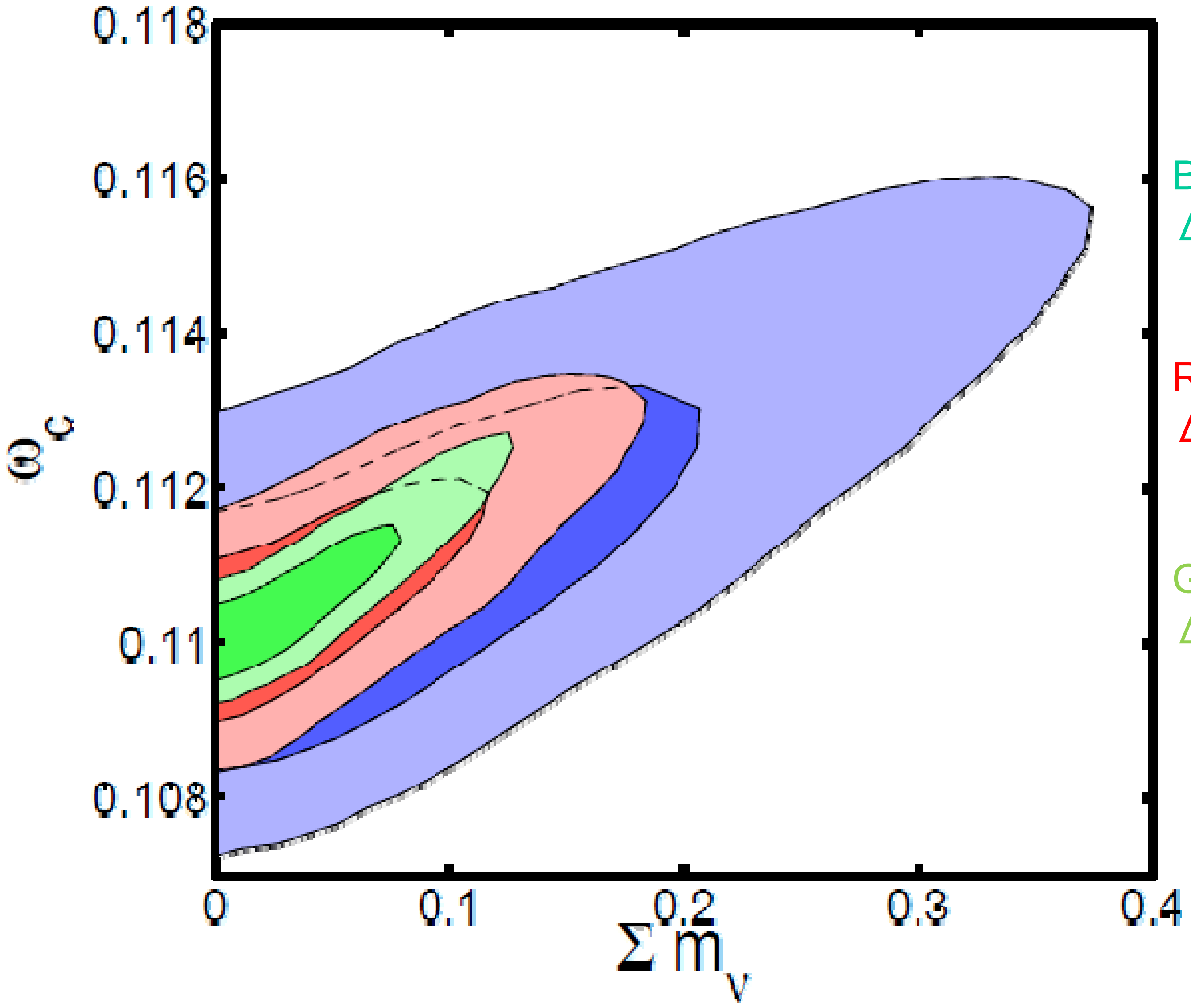
Blue: WMAP-7

Red: w7+SN+Bao+H0

Green: w7+CMBsuborb+SN+LRG+H0

Constraints weaken by 30-50% when «dark energy» is included.

Forecasts on Neutrino Mass

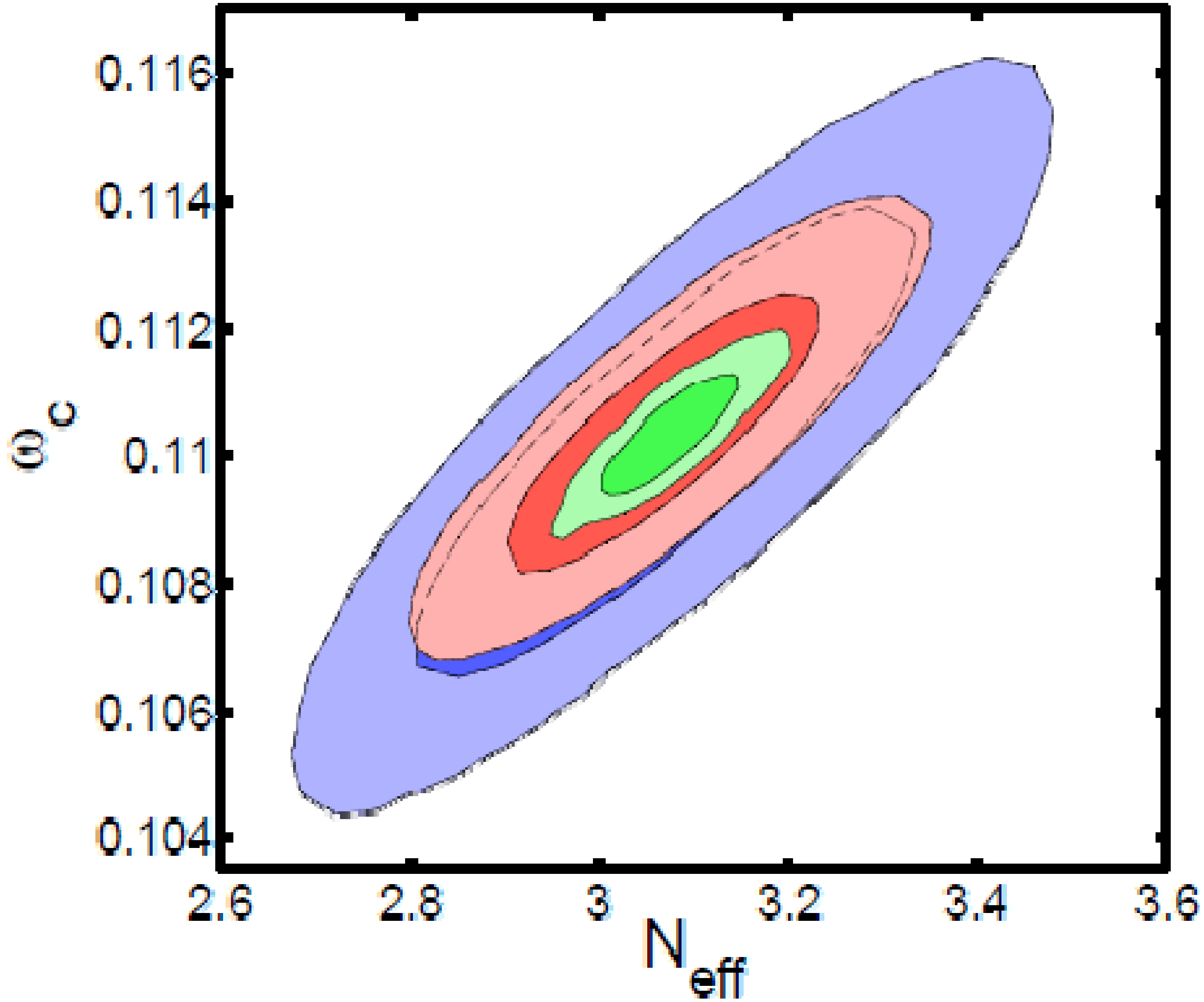


Blue: Planck
$\Delta \Sigma m_\nu = 0.16$

Red: Planck+ACTpol
$\Delta \Sigma m_\nu = 0.08$

Green: COrE
$\Delta \Sigma m_\nu = 0.05$

Forecasts on Neutrino Number



Blue: Planck $\Delta N_\nu = 0.18$

Red: Planck+ACTpol $\Delta N_\nu = 0.11$

Green: CMBPol $\Delta N_\nu = 0.044$

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, PRD submitted, **arXiv:1005.3808** 2010

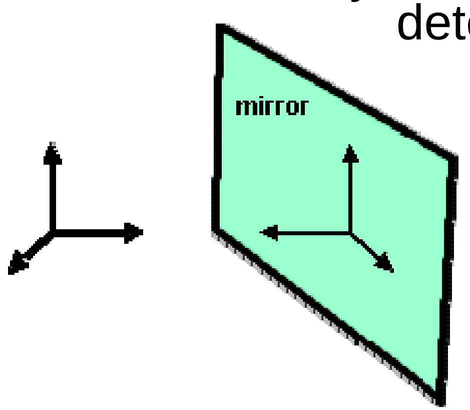
Fundamental Symmetries

Parity

Birefringence angle (Tracer of CPT violations)

What is the Parity Transformation?

It is the transformation that is applied when we look at the world in a mirror.
In math it is the flip of sign of one spatial coordinate.
In three dimensions it is equivalent to the flips of all the 3 spatial dimensions (note that the flip of signs of 2 axes in 3 dimensions is equivalent to a rotation).
The determinant of a Parity transformation is -1 (whereas a Rotation has determinant =1)



$$\begin{cases} x \longrightarrow -x \\ y \longrightarrow -y \\ z \longrightarrow -z \end{cases}$$

If Physics equations are invariant under Parity then we say that Parity is conserved.

Specifically **Parity is conserved in electromagnetic interactions** (as well as in gravity and strong interactions) whereas is broken in weak interactions.

CMB physics is purely electromagnetic. Therefore through CMB anisotropies we can study whether the Lagrangian of the photon is Parity conserved as we expect. This analysis might help in constraining Parity-violating terms that can be introduced.

Algebraic Properties for Testing Parity in CMB Temperature Map

spherical harmonics expansion for **T anisotropies**	Parity		Property
$a_{T,\ell m} = \int d\Omega \, Y^{\star}_{\ell m}(\hat{n}) \, T(\hat{n})$	$\hat{n} \rightarrow -\hat{n}$	$\Rightarrow$	$a_{T,\ell m} \rightarrow (-1)^{\ell} a_{T,\ell m}$

behavior of T coefficients of spherical harmonics under parity symmetry (i.e. even multipoles are invariant under parity whereas odd multipoles acquire a “-1”)

CMB physics does not distinguish between even and odd multipoles.
For example at low ell the TT power spectrum is given
by the so called Sachs - Wolfe plateau that reads:

$$\ell(\ell+1)C_{\ell}^{TT} \sim const$$

Therefore it is possible to divide each T map in two subsets corresponding to even and odd multipoles, satisfying two different transformation under P symmetry. Considering the angular power spectrum contained in the two subsets it is possible to study the consistency with P symmetry

Algebraic Properties for Testing Parity in CMB Polarization Maps

spherical harmonics expansion for **Pol anisotropies**

$$a_{\pm 2,\ell m} \equiv \int d\Omega\, Y^{\star}_{\pm 2,\ell m}(\hat{n})\left(Q(\hat{n}) \pm iU(\hat{n})\right)$$

Parity

$$\hat{n} \rightarrow -\hat{n}$$

Property

$$a_{E,\ell m} \equiv (-1)^{\ell} a_{E,\ell m}$$

$$a_{B,\ell m} \equiv (-1)^{\ell+1} a_{B,\ell m}$$

$$a_{E,\ell m} \equiv -(a_{2,\ell m} + a_{-2,\ell m})/2$$

$$a_{B,\ell m} \equiv -(a_{2,\ell m} - a_{-2,\ell m})/2i$$

Similar consideration previously expressed for T can be applied to the E mode and (potentially) to the B mode

Moreover the opposite behavior of B w.r.t. T or E, forces the cross-correlations <T B> and <E B> to be vanishing in order to be consistent with Parity symmetry!

Testing parity (P) symmetry: definition of estimators

For X = TT, TE, EE and BB:

$$R^X = C_+^X / C_-^X$$

$$D^X = C_+^X - C_-^X$$

$$C_{+/-}^X \equiv \frac{1}{(\ell_{max}-1)} \sum_{\ell=2,\ell_{max}}^{+/-} \frac{\ell(\ell+1)}{2\pi} \hat{C}_\ell^X$$

(Kim & Naselsky, 2010)

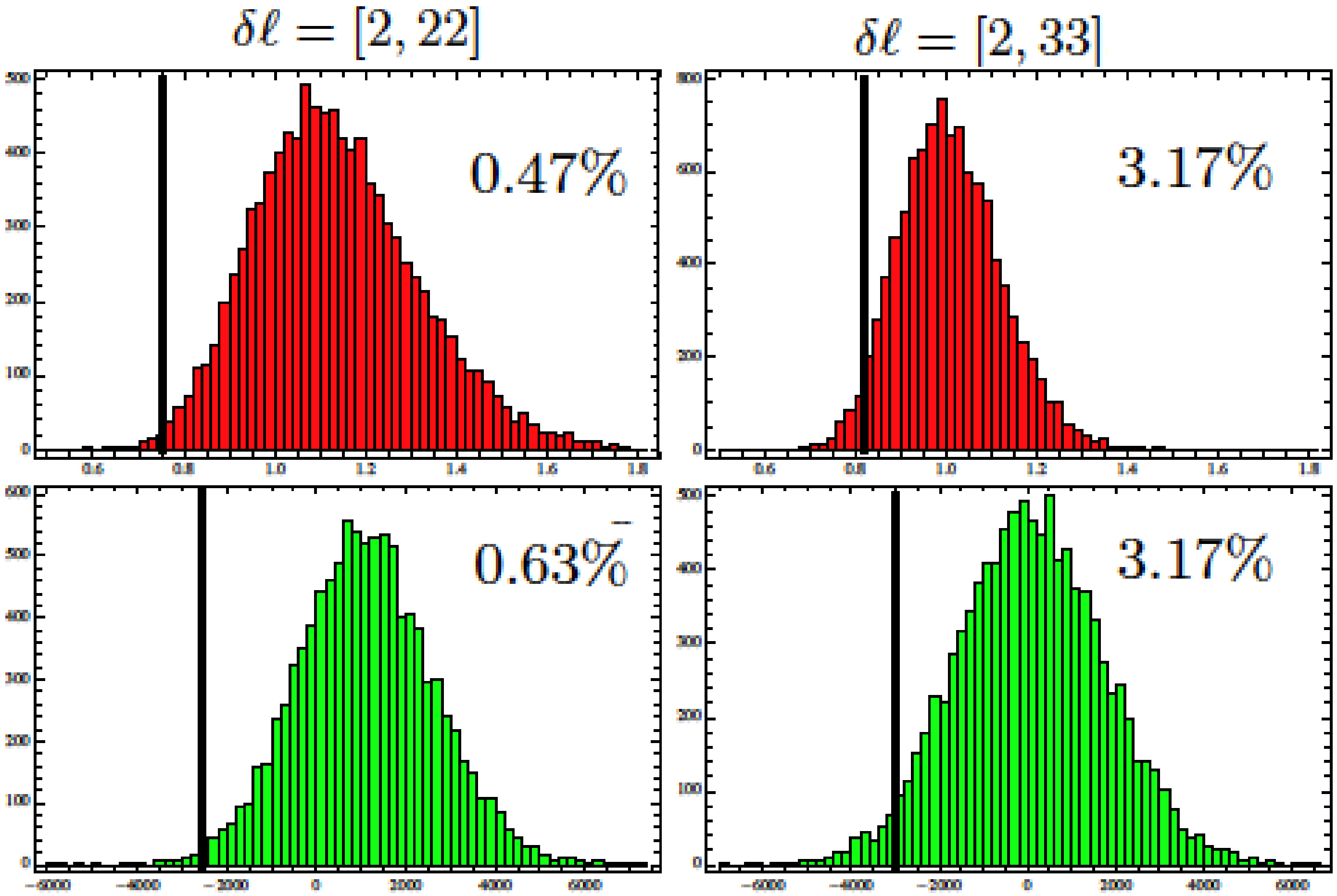
•For X = TB and EB:

$$C^X \equiv \frac{1}{(\ell_{max}-1)} \sum_{\ell=2,\ell_{max}} \frac{\ell(\ell+1)}{2\pi} \hat{C}_\ell^X$$

these estimators have been computed at large angular scale considering an optimal APS estimator. A MC of 10000 realizations with realistic noise (both for WMAP 7 and Planck) has been performed

(Gruppuso et al., MNRAS, 2010)

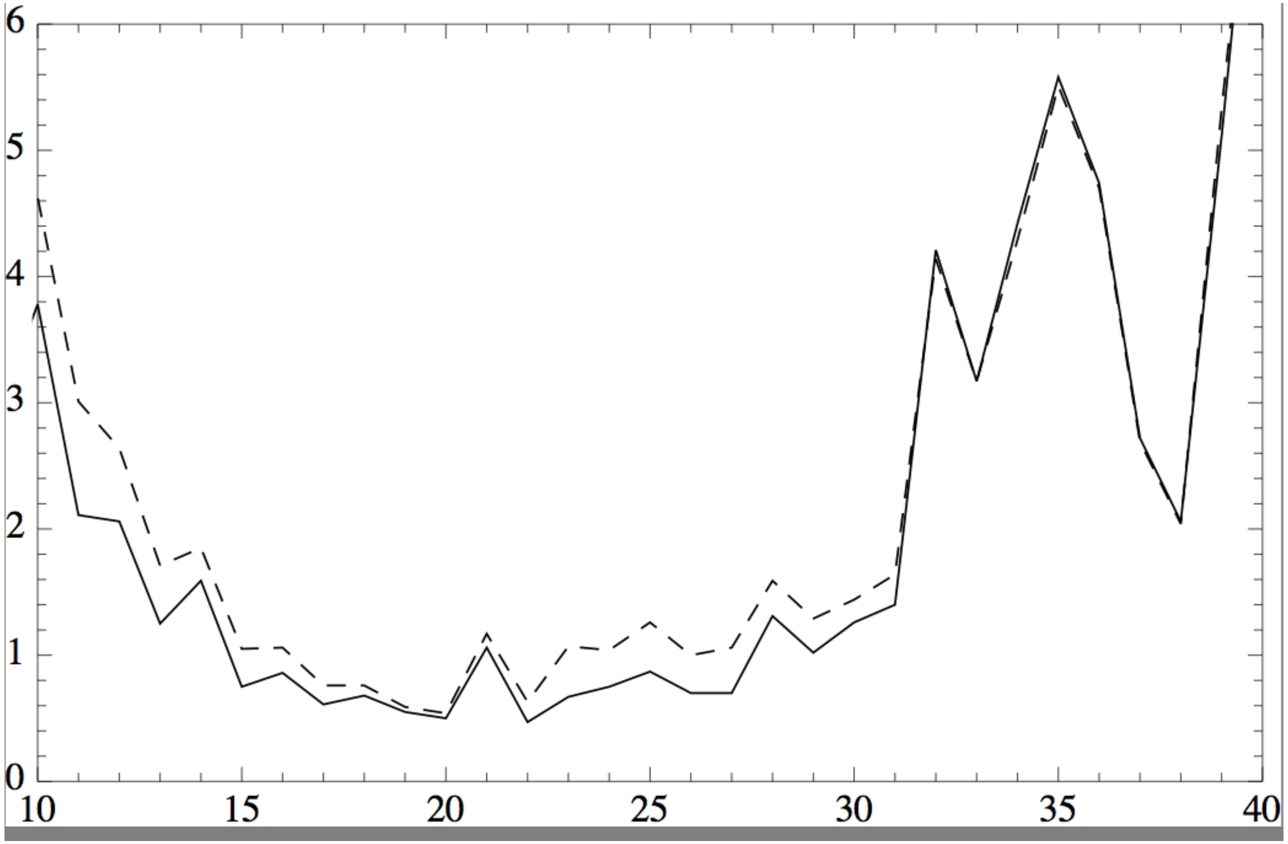
TT results (WMAP 7)



- R
- D

Percentage vs angular scale

%



solid line: R estimator

dashed line: D estimator

l max

this plot suggests the existence of a characteristic scale lying in the range between 15 and 24 for which the estimators might be considered “anomalous” (<1%)

Considerations on this Parity analysis

TT anomaly detected @ large angular scale with a confidence level of 99.5% in the WMAP 7 data.

1. matter of taste if such percentage is to be considered anomalous
2. It is still unknown whether such a result comes from fundamental physics or if it is due to some not perfectly removed astrophysical foreground or systematic effect

Polarization analysis of the WMAP 7 data does not show any deviation from Parity symmetry but:

1. This might be due to the large WMAP 7 noise level that make the signal sinking
2. If ell_max is too large the considered estimators are testing the Parity of the WMAP noise

Planck data are awaited with great interest in this respect because:

1. Planck is observing the sky with a totally different scanning strategy wrt WMAP (benefit from the point of view of systematic effects analysis)
2. Confirm TT anomaly and extend the Polarization analysis

Planck forecasts (e.g. 143 GHz channel)

- Standard deviations for D

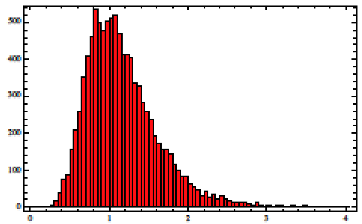
σ_D	WMAP 7 year	Planck
TT	1517.17	1509.21
TE	20.19	9.08
EE	0.65	0.10
BB	0.69	0.04

- Standard deviations for C

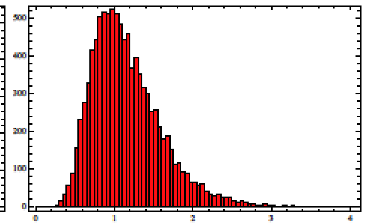
σ_C	WMAP 7 year	Planck
TB	0.95	0.19
EB	0.023	0.001

Planck is much more sensitive to polarization estimators

- R on EE



$\delta\ell = [2, 22]$



$\delta\ell = [2, 16]$

Testing CPT Symmetry

if terms like Chern-Simons have to be added to the standard electrodynamic Lagrangian, than Lorentz, P and CPT symmetries will be violated. This will induce a rotation of the polarization direction of each photon as it propagates from the LSS to us. This effect is called "Cosmic Birefringence"

$$C_\ell^{\mathrm{TE,obs}} = C_\ell^{\mathrm{TE}} \cos(2\Delta\alpha),$$

$$C_\ell^{\mathrm{TB,obs}} = C_\ell^{\mathrm{TE}} \sin(2\Delta\alpha),$$

$$C_\ell^{\mathrm{EE,obs}} = C_\ell^{\mathrm{EE}} \cos^2(2\Delta\alpha),$$

$$C_\ell^{\mathrm{BB,obs}} = C_\ell^{\mathrm{EE}} \sin^2(2\Delta\alpha),$$

$$C_\ell^{\mathrm{EB,obs}} = \tfrac{1}{2}(C_\ell^{\mathrm{EE}}) \sin(4\Delta\alpha).$$

alpha = Birefringence angle

From these equations it is possible to build estimators for alpha (as long as it is zero these violating terms are excluded)

Current constraints

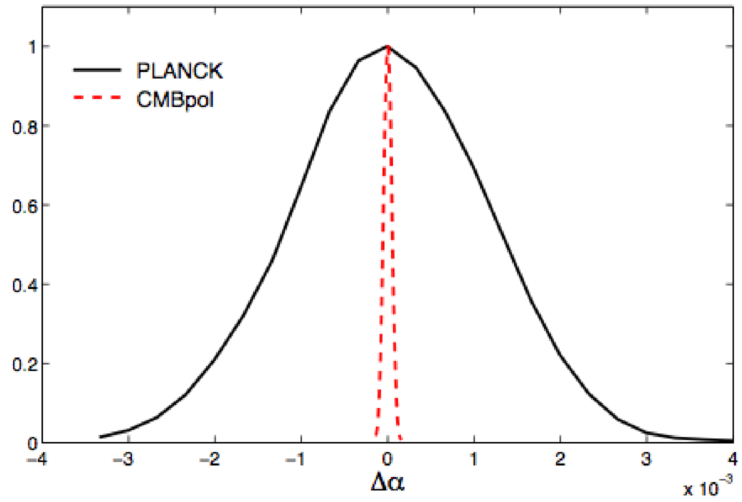
•WMAP 7 (Komatsu et al. 2010, in press in ApJS)

$$\Delta\alpha = -0.9^\circ \pm 1.4^\circ \qquad 23 < \ell < 800$$
$$\Delta\alpha = -3.8^\circ \pm 5.2^\circ \qquad 2 \leq \ell \leq 23$$

•QUAD (Wu et al. 2010, PRL)

$$\Delta\alpha = 0.83^\circ \pm 0.94^\circ \pm 0.5^\circ \quad 200 < \ell < 2000$$

Planck and CMBPol forecast



Xia et al. (2009), IJMPD

$$\sigma = 0.057^\circ \qquad \text{Planck}$$

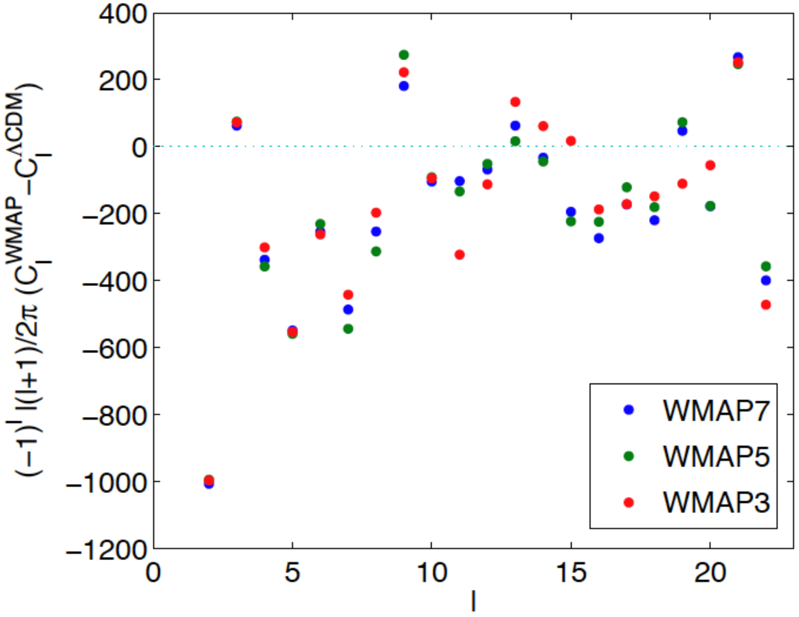
$$\sigma = 2.57^\circ \times 10^{-3} \qquad \text{CMBPol}$$

Testing parity symmetry

$$a_{T,\ell m} = \int d\Omega\, Y^{\star}_{\ell m}(\hat{n})\, T(\hat{n})$$

$$\hat{n} \to -\hat{n}$$

$$a_{T,\ell m} \to (-1)^{\ell}\, a_{T,\ell m}$$



Kim & Naselsky, 2010

$$a_{\pm 2,\ell m} = \int d\Omega\, Y^{\star}_{\pm 2,\ell m}(\hat{n})\, (Q(\hat{n}) \pm iU(\hat{n}))$$

$$a_{E,\ell m} = -(a_{2,\ell m} + a_{-2,\ell m})/2$$

$$a_{B,\ell m} = -(a_{2,\ell m} - a_{-2,\ell m})/2i\,.$$

$$\boxed{\begin{aligned} a_{E,\ell m} &\to (-1)^{\ell}\, a_{E,\ell m}, \\ a_{B,\ell m} &\to (-1)^{\ell+1}\, a_{B,\ell m} \end{aligned}}$$

COSMIC BIREFRINGENCE

We call **birefringence angle** (**BA**) the rotation angle of the polarization direction of each photon traveling in the universe.

If the Maxwell theory of electromagnetism is valid than the BA is zero.

If terms (like Chern-Simons) have to be added to the standard electrodynamics than the BA is different from zero (and Lorentz, CPT symmetries will be violated).

Considering CMB photons the APS of CMB anisotropies will be modified as follows:

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

where α is the birefringence angle

From these equations it is possible to build estimators for alpha. **Measuring alpha it is then possible to test the fundamental theory of electromagnetism** and constraining the amplitude of the terms that violate CPT symmetries.

High and Low ell

This analysis is divided in high and low ell since CMB polarization arises at two distinct cosmological times:
the recombination epoch at z~1100
the re-ionization era at z ~<10

When CMB fields is expanded in spherical harmonics, the first signal mostly shows up at high multipole since polarization is generated through a causal process and the Hubble horizon at the last scattering surface subtends a degree size angle. The later re-ionization of the cosmic fluid at lower redshift impact low multipoles instead.

These two regimes need to be taken into account when probing for cosmological birefrigence, since they can be ascribed to different epochs and, hence, physical conditions.

Even though CMB photons are energetically weak, they are important for testing Lorentz and CPT symmetries for two reasons: first, CMB photons are generated during the early universe, when physics at the stake was not obviously identical to present and second, the long journey undertaken by CMB photons may make observable tiny violations to electromagnetic Lagrangian.

Small Angular Scale

QUAD EXPERIMENT
Wu et al. PRL 102 (2009)

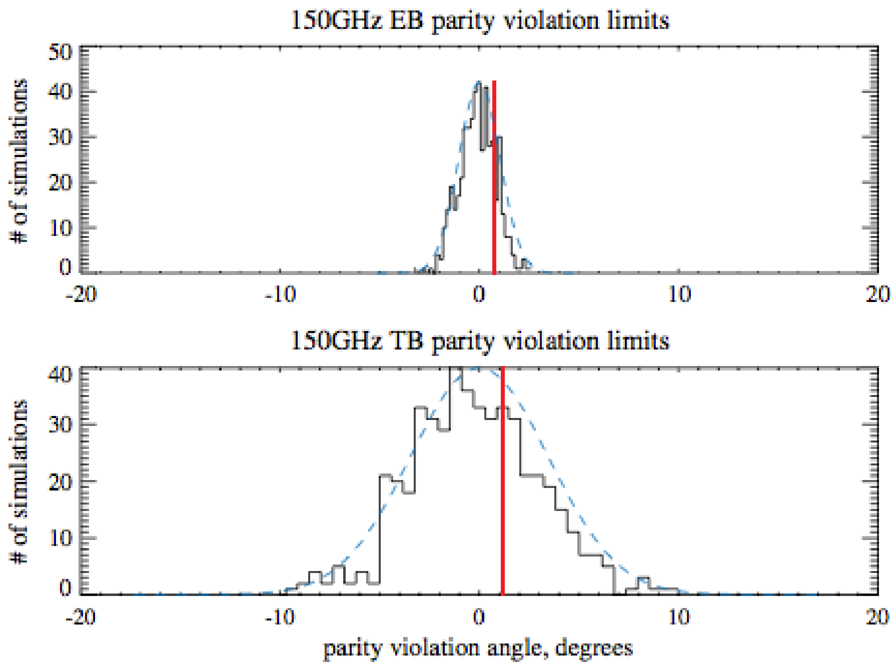
alpha = 0.55 +/- 0.82 (statistical) +/- 0.5 (systematic) [deg]

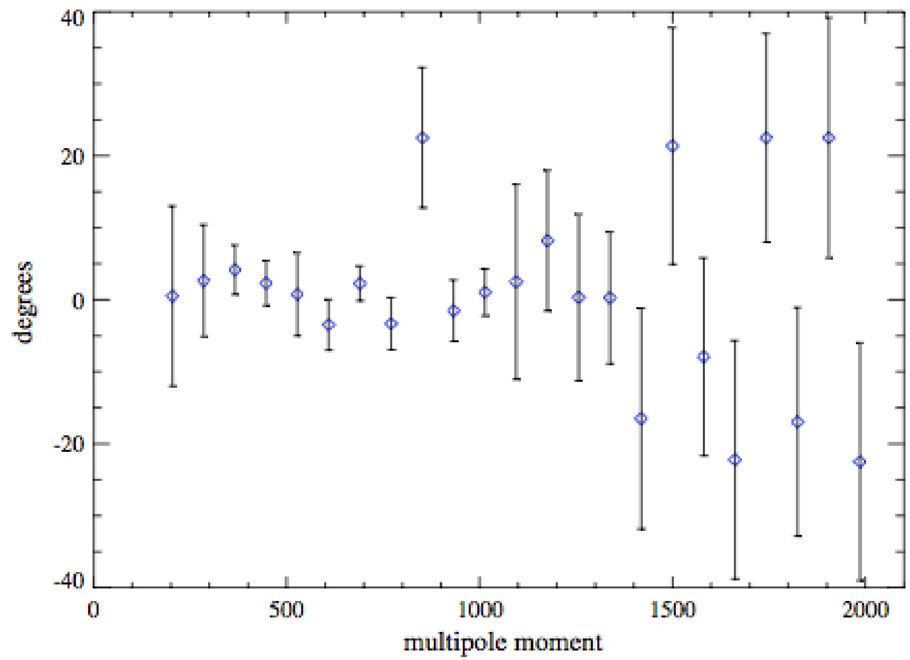
$$D_{\mathrm{TB},\ell} = C_\ell^{\mathrm{TB,obs}} \cos(2\Delta\alpha) - C_\ell^{\mathrm{TE,obs}} \sin(2\Delta\alpha),$$

$$D_{\mathrm{EB},\ell} = C_\ell^{\mathrm{EB,obs}} - \frac{1}{2}(C_\ell^{\mathrm{BB,obs}} + C_\ell^{\mathrm{EE,obs}}) \sin(4\Delta\alpha).$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{TB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{TB},\ell'},$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{EB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{EB},\ell'}.$$





Small Angular Scale

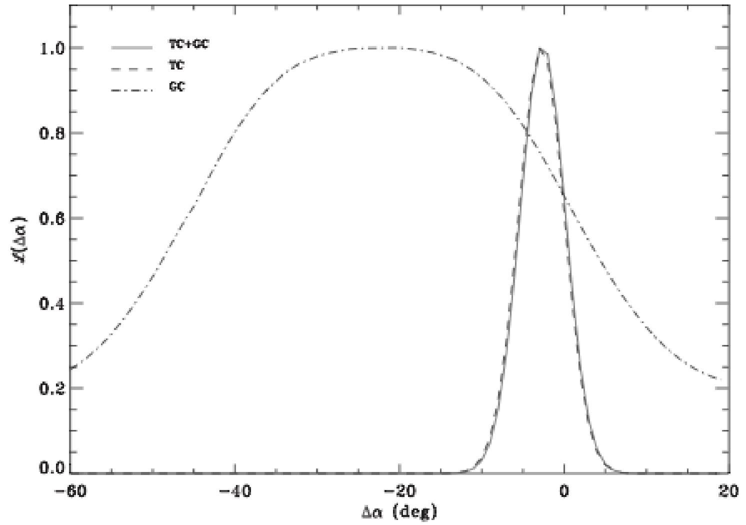
WMAP EXPERIMENT

using a pixel based likelihood code alpha = -1.1 +/- 1.2 (statistical) +/- 1.5 (systematic) [deg]

Komatsu et al. ApJSS 192 (2011) (WMAP 7YR)

using a wavelet analysis: alpha = -2.5 +/- 3 [deg] (WMAP 3YR)

Cabella, Natoli and Silk PRD76 (2007)



Large Angular Scale

WMAP EXPERIMENT

using a pixel based likelihood code alpha = -3.8 +/- 5.2 [deg] (WMAP 7YR)

Komatsu et al. ApJSS 192 (2011) $2 \leq \ell \leq 23$

not taking into account a systematic error of ~1.5 [deg]

using the following estimators (as Wu et al.)

Gruppuso et al. (2011) arXiv:1107.5548 alpha = -3.0 +/- 3.5 [deg] (WMAP 7YR)

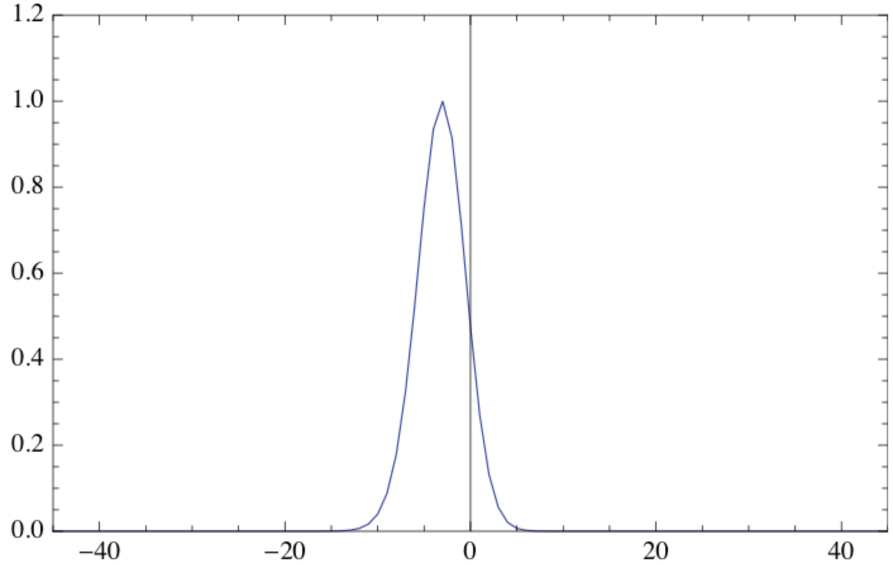
$2 \leq \ell \leq 23$

$$D_{\mathrm{TB},\ell} = C_\ell^{\mathrm{TB,obs}} \cos(2\Delta\alpha) - C_\ell^{\mathrm{TE,obs}} \sin(2\Delta\alpha),$$

$$D_{\mathrm{EB},\ell} = C_\ell^{\mathrm{EB,obs}} - \frac{1}{2}(C_\ell^{\mathrm{BB,obs}} + C_\ell^{\mathrm{EE,obs}}) \sin(4\Delta\alpha).$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{TB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{TB},\ell'},$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{EB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{EB},\ell'}.$$



Large Angular Scale

WMAP EXPERIMENT

using a pixel based likelihood code alpha = -3.8 +/- 5.2 [deg] (WMAP 7YR)

Komatsu et al. ApJSS 192 (2011)

$2 \leq \ell \leq 23$

not taking into account a systematic error of ~1.5 [deg]

using the following estimators (as Wu et al.)

Gruppuso et al. (2011) arXiv:1107.5548 alpha = -1.6 +/- 1.7 [deg] (WMAP 7YR)

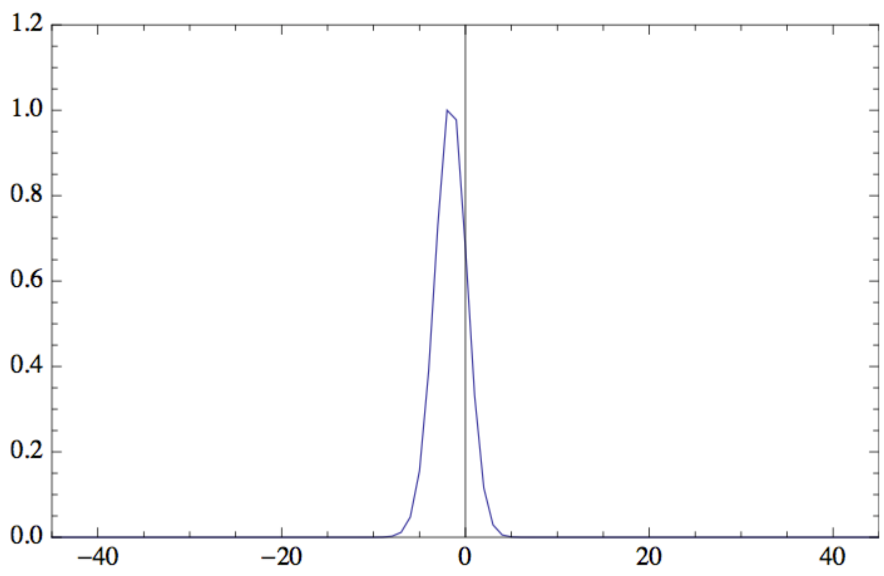
$2 \leq \ell \leq 47$

$$D_{\mathrm{TB},\ell} = C_\ell^{\mathrm{TB,obs}} \cos(2\Delta\alpha) - C_\ell^{\mathrm{TE,obs}} \sin(2\Delta\alpha),$$

$$D_{\mathrm{EB},\ell} = C_\ell^{\mathrm{EB,obs}} - \frac{1}{2}(C_\ell^{\mathrm{BB,obs}} + C_\ell^{\mathrm{EE,obs}}) \sin(4\Delta\alpha).$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{TB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{TB},\ell'},$$

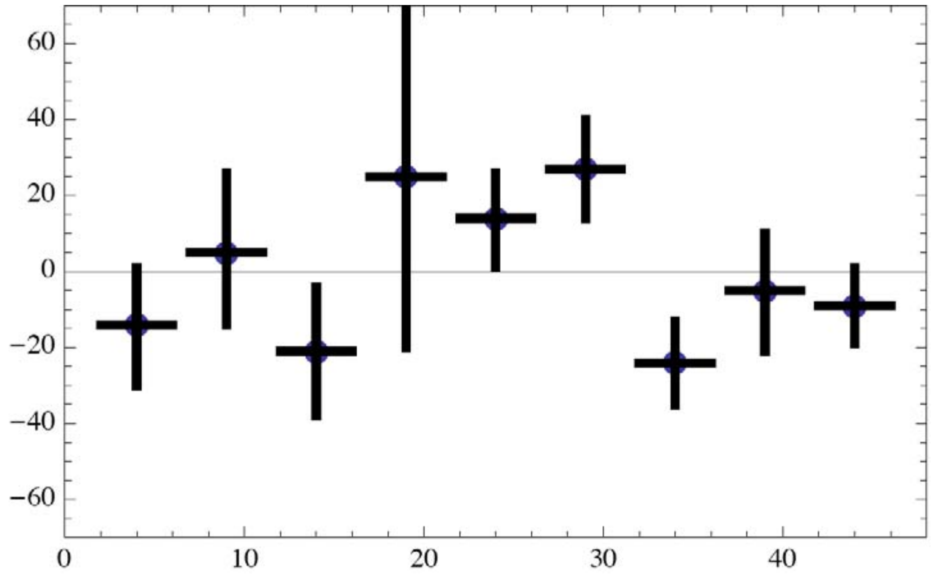
$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{EB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{EB},\ell'}.$$



Large Angular Scale

WMAP EXPERIMENT

Varying l_min and l_max, the D estimators allow to build the spectrum of the birefringence angle at large angular scale. This provides a scale dependent information on the birefringence angle. For example considering the DTB estimator:

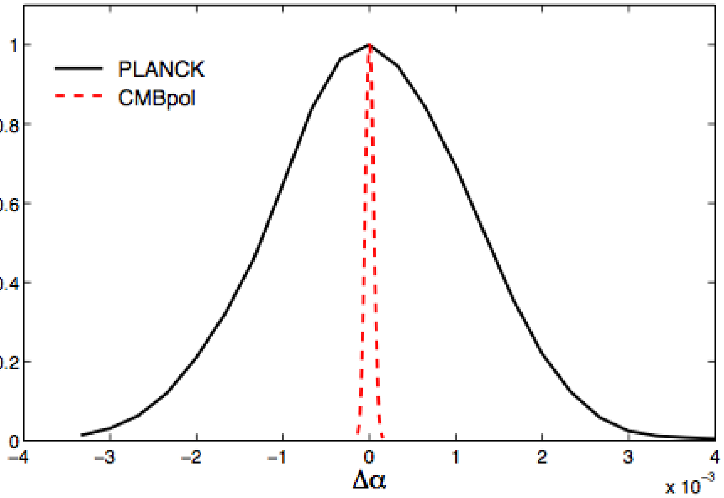


(WMAP 7YR)

Gruppuso et al. (2011) accepted for publication in JCAP. arXiv:1107.5548

Planck and CMBPol forecast

Small Angular Scale



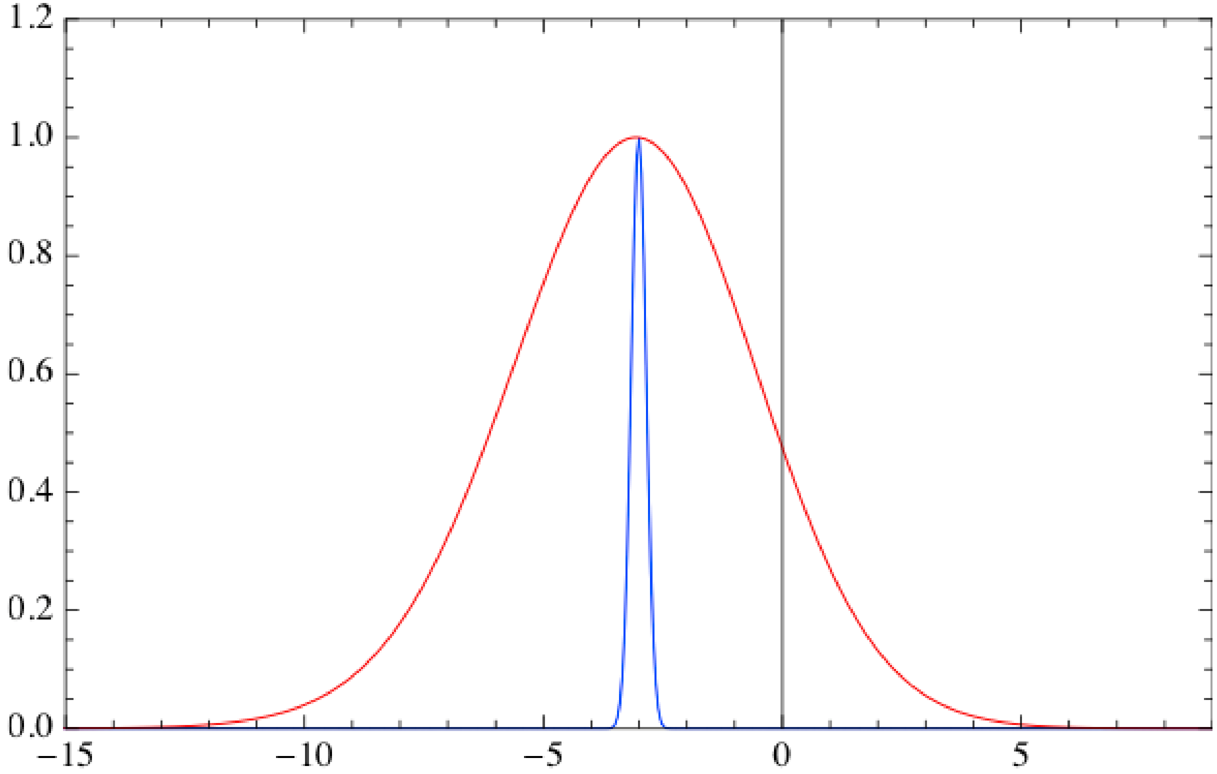
Xia et al. (2009), IJMPD

$\sigma = 0.057^\circ$ Planck

$\sigma = 2.57^\circ \times 10^{-3}$ CMBPol

Planck forecast

Large Angular Scale



Red = WMAP 7 year

Blue = Planck forecast

For example considering the joint estimator for the ell range [2,23] Planck should outnumber WMAP by a factor above 16 in terms of standard deviations

Testing birefringence at high energy (an example)

The rotation of polarization direction α can be written as follows

$$\alpha \simeq \xi \frac{p^2 d}{2M_{Pl}}$$

where p is the momentum of photons, d is the distance of the astrophysical source and M_Pl is the Planck scale. The parameter xi is the coupling to new terms in the dispersion relation

$$E^2 = p^2 \pm \frac{2\xi p^3}{M_{Pl}}$$

where the sign +/- depends on the chirality (or circular polarization) of the photons.

Considering INTEGRAL/IBIS observations of GRB041219A the measured α is compatible with zero as $\alpha = 21 \pm 47$ [deg] and imposing that the error on alpha is larger than the rotation computed above, one obtains a tight constrain on

$$\xi < 1.1 \times 10^{-14}$$ Laurent et al. PRD83(R) (2011)

where d=85 Mpc (z=0.02) and the photon energy is ~ 2-3 10^2 KeV.

Larger wrt what can be achieved with CMB!! However the constraint on xi cannot be so small.

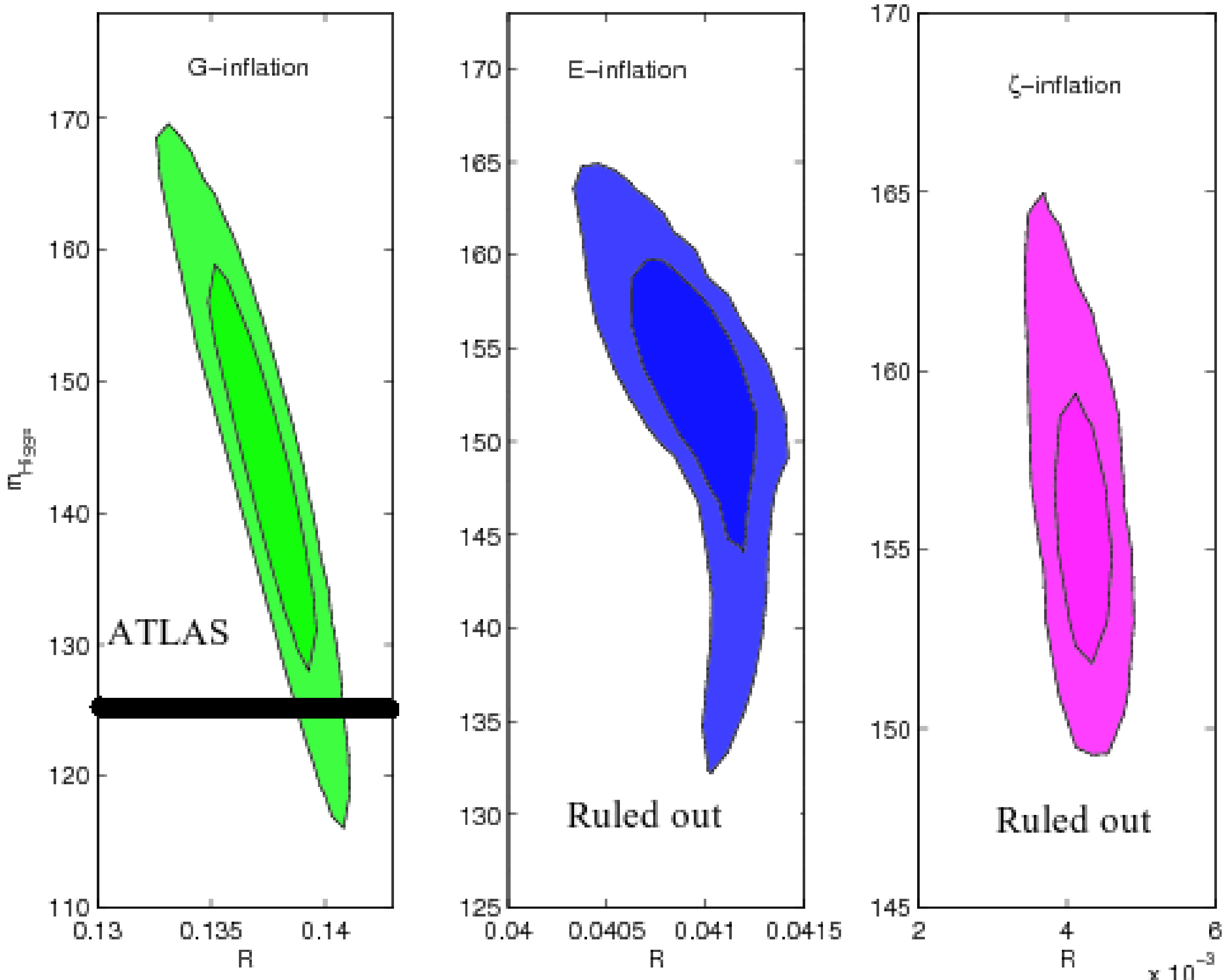
Higgs Boson

Bezrukov e Shaposhnikov, 2007: if gravity and Higgs boson are non minimally coupled then inflation field and Higgs boson can be unified.

In this theory the Inflaton and the Higgs boson (that gives mass to the particles of the Standard Model) would represent different stages of the the dynamical evolution of a single field.

CMB observations can constrain the inflationary parameters, and therefore for this model, also the Higgs mass.

Mass of Higgs boson vs R(tensor to scalar ratio)” for three models of the Higgs driven inflation. From the PLANCK mission we may expect to obtain better constrains on the R<0.05-0.1. However, as we can see, this model of inflation requires R~0.14. Thus, the PLANCK data would be crucial for these models



Popa, JCAP 2011

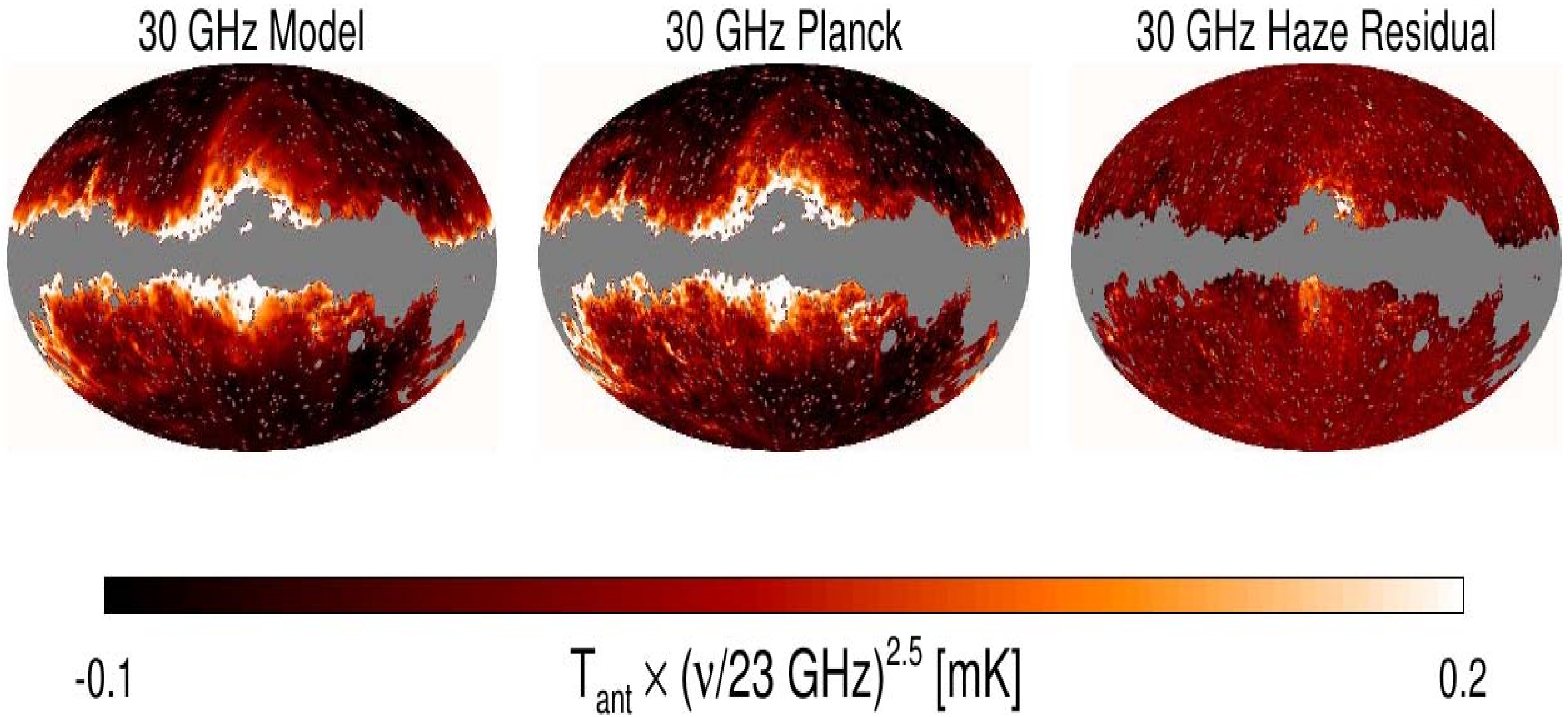
Motivation

- Planck has a well-known potential for fundamental physics.
- Several issues are well framed and have found the right place (e.g.: neutrino mass)
- Others, namely discrete symmetries (P, CPT...) still need to find the right place.
- I wanted to make the point that such topics deserve a science project of their own.

Moving to Planck

- Several groups are active both in LFI and HFI.
- We know that systematics (beams, detector orientation) are a BIG issue and will likely stand out in the final error budget. By how much, still to quantify.
- We need to sparkle LFI/HFI interaction on cross calibration of the two instruments

Haze



Is this due to high energy electrons, a new mechanism for CRs acceleration or something related to DM (or new Physics)?

It may be instead that all this will help Planck in dealing with tiny systematics of type unknown unknowns!!