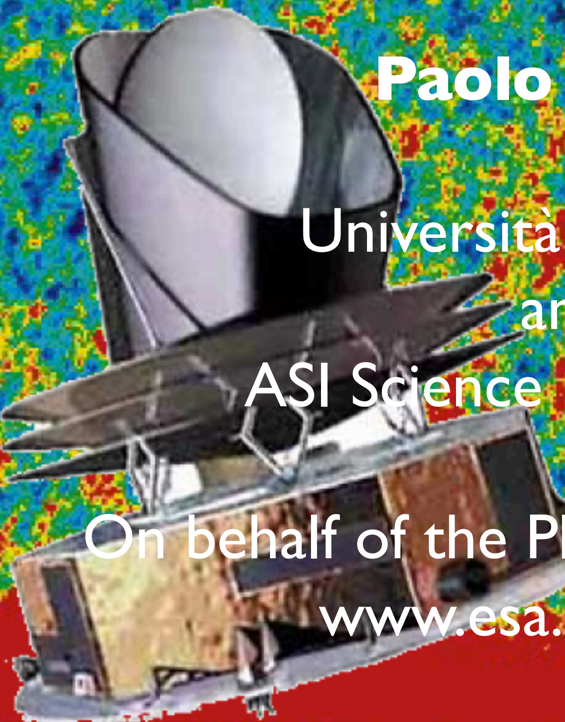
Planck: results and cosmological perspectives

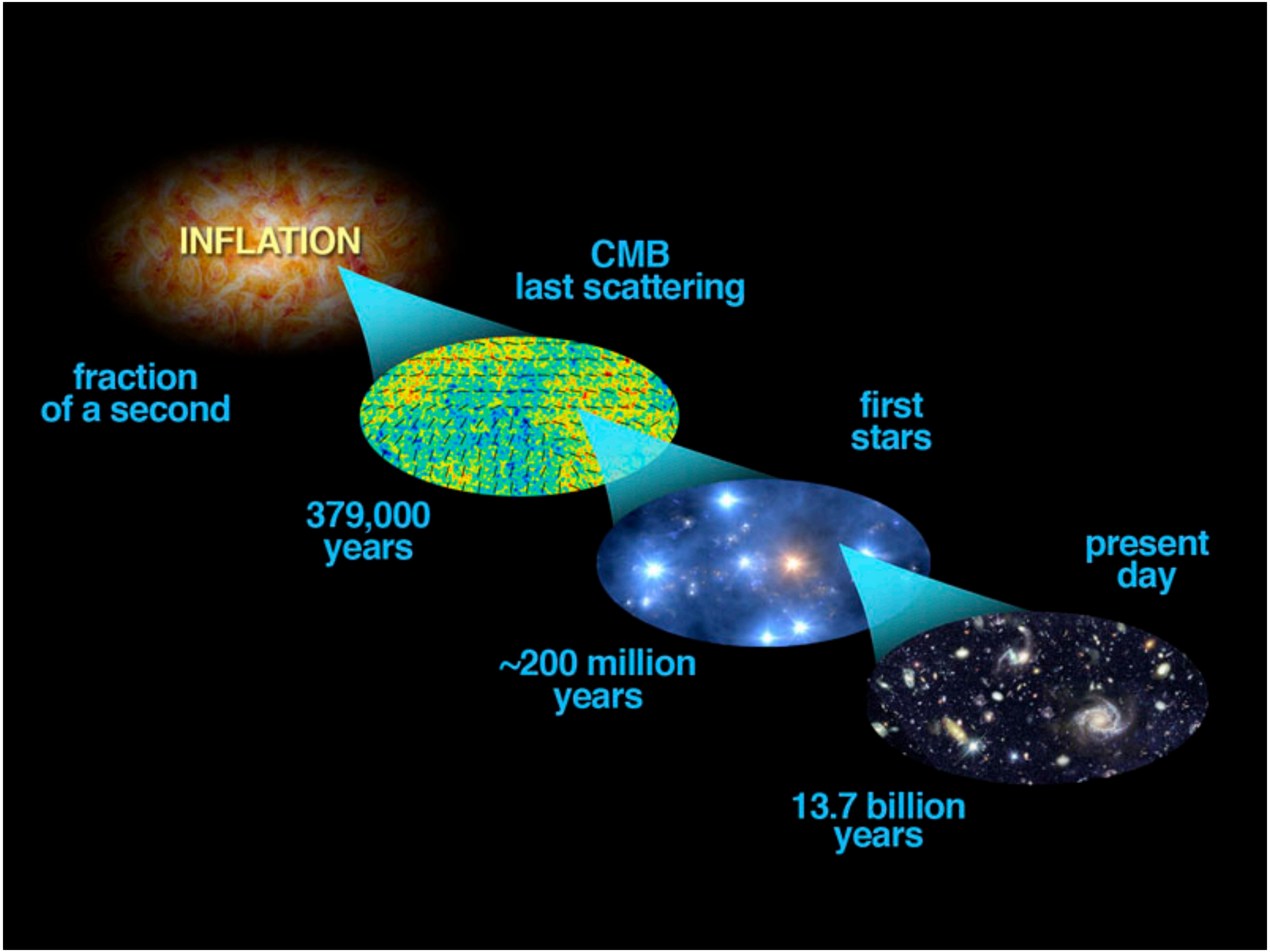


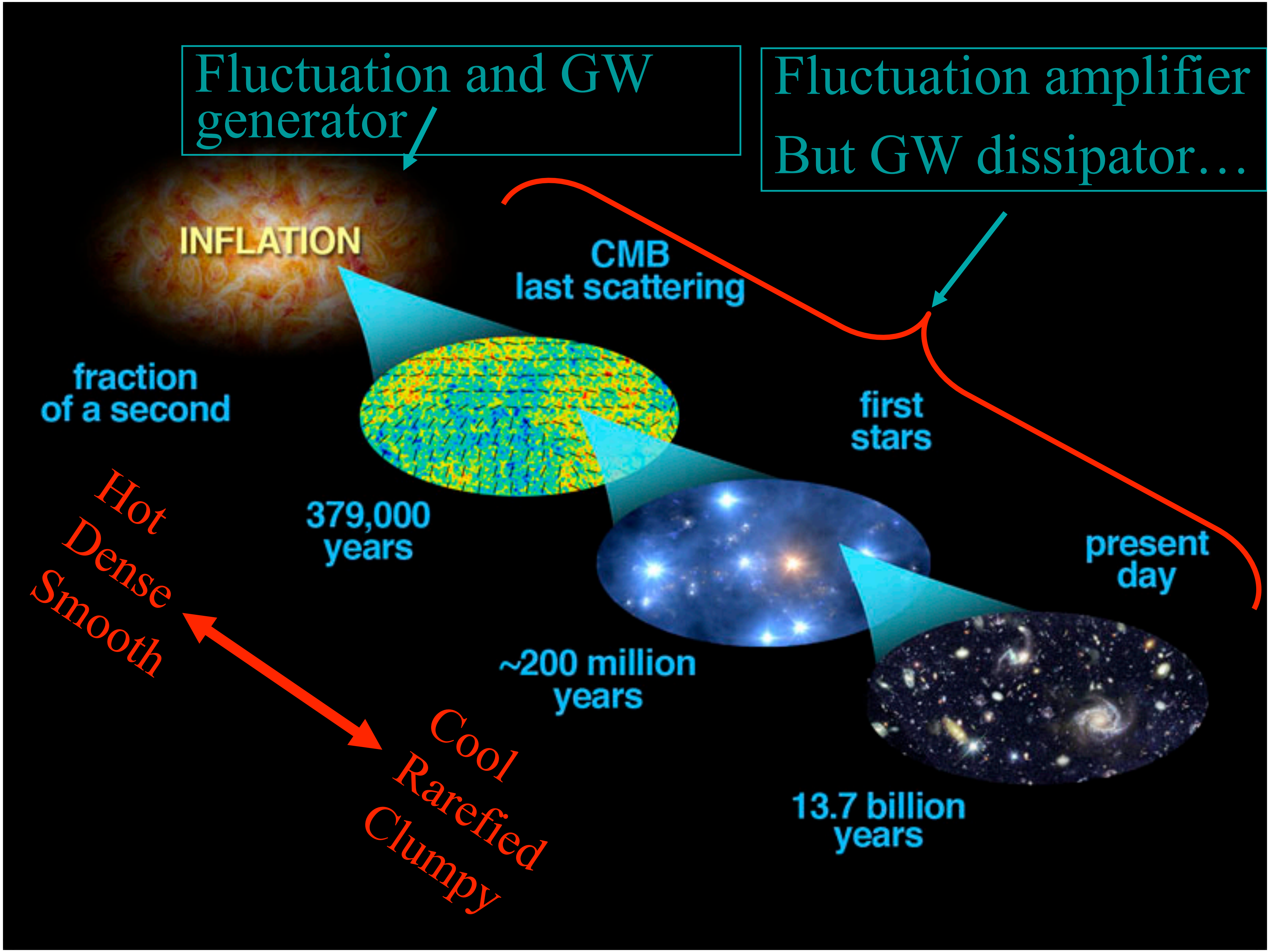
Paolo Natoli

Università di Ferrara
and
ASI Science Data Center

On behalf of the Planck collaboration
www.esa.int/planck

XXVI Rencontres de Physique de La Vallée d'Aoste – La Thuile, 27 Feb 2012

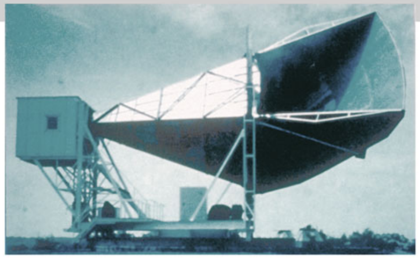

INFLATION
fraction
of a second
CMB
last scattering
379,000
years
first
stars
~200 million
years
present
day
13.7 billion
years

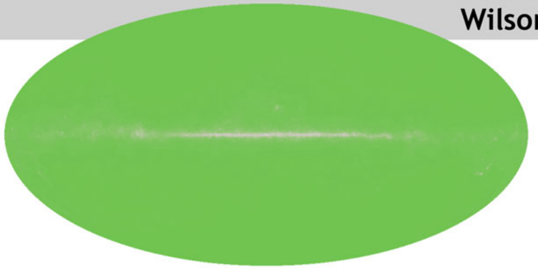

Fluctuation and GW generator
Fluctuation amplifier
But GW dissipator…
INFLATION
fraction of a second
CMB last scattering
379,000 years
first stars
~200 million years
present day
13.7 billion years
Hot
Dense
Smooth
Cool
Rarefied
Clumpy

Cosmic Microwave Background Radiation Overview

The oldest light or the first light of the Universe

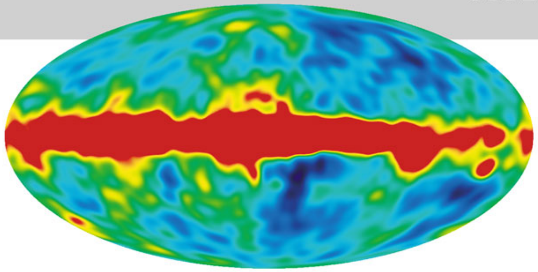
1965 Penzias and Wilson





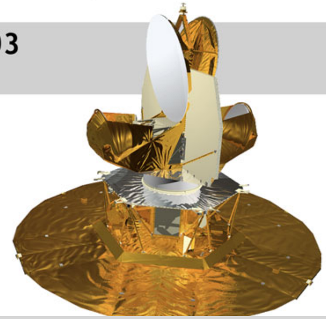
Discovered the remnant afterglow from the **Big Bang**.
→ **2.7 K**

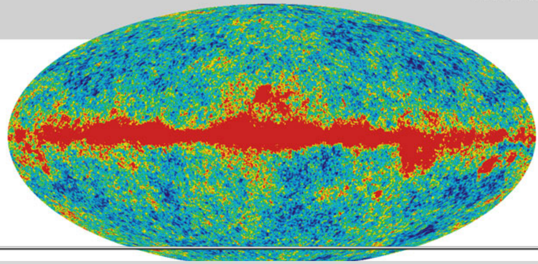
1992 COBE



Blackbody radiation, Discovered the patterns (**anisotropy**) in the afterglow.
→ **angular scale ~ 7°** at a level $\Delta T/T$ of 10^{-5}

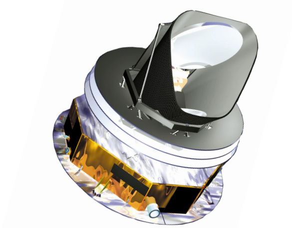
2003 WMAP

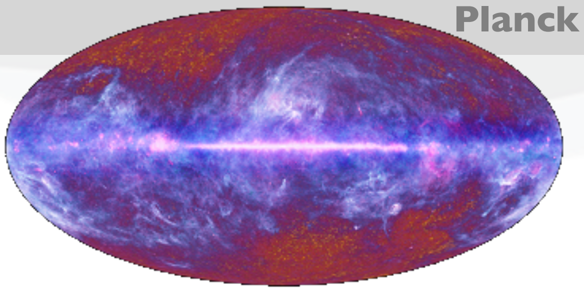




(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15'**

2009 Planck





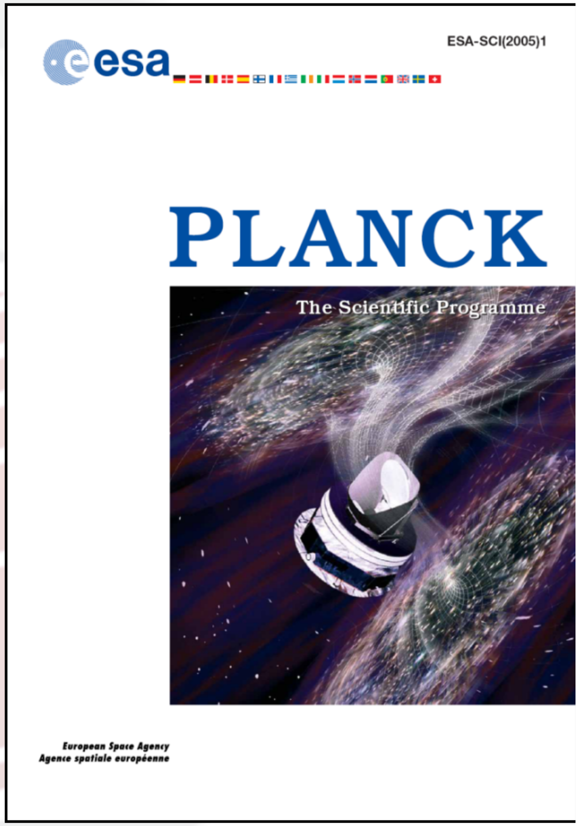
→ **angular scale ~ 5',**
$\Delta T/T \sim 2 \times 10^{-6}$, 30~867 Hz

Science with Planck

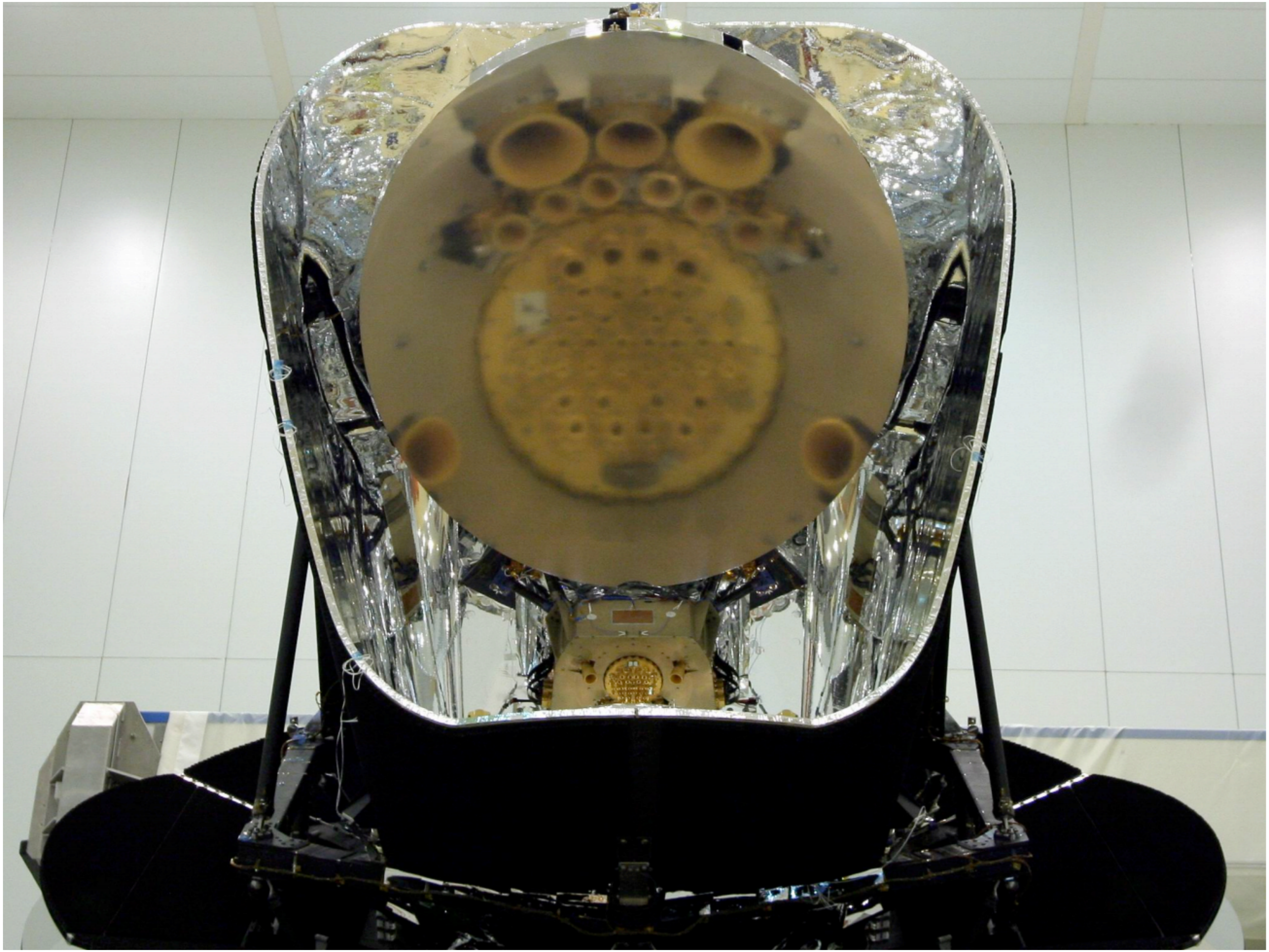
Determining cosmological parameters to high accuracy:

  - Geometry, Contents, Dynamics of Universe
  - Epoch of reionisation: birth of the first stars
  - Constraining dark energy, neutrino mass, …

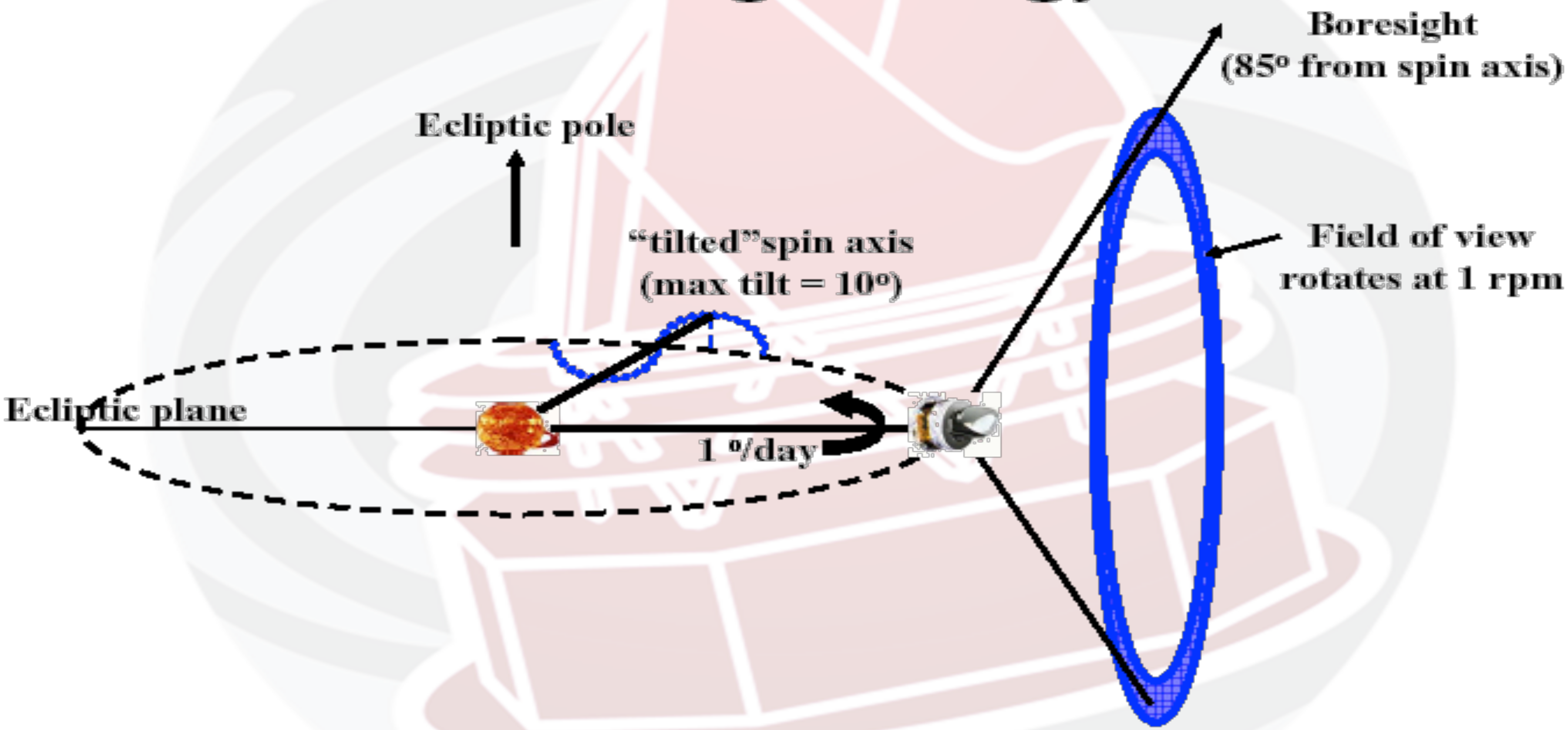
- Testing inflation:
  - Constraining the inflaton potential
  - Finding signatures of primordial gravitational waves
- Finding primordial non-Gaussianity in primordial perturbations:
  - Testing different inflationary scenario
- Evolution of structure and nature of dark matter
- Testing fundamental symmetries: P, CPT
- **Astrophysics (Galactic & Extragalactic)**

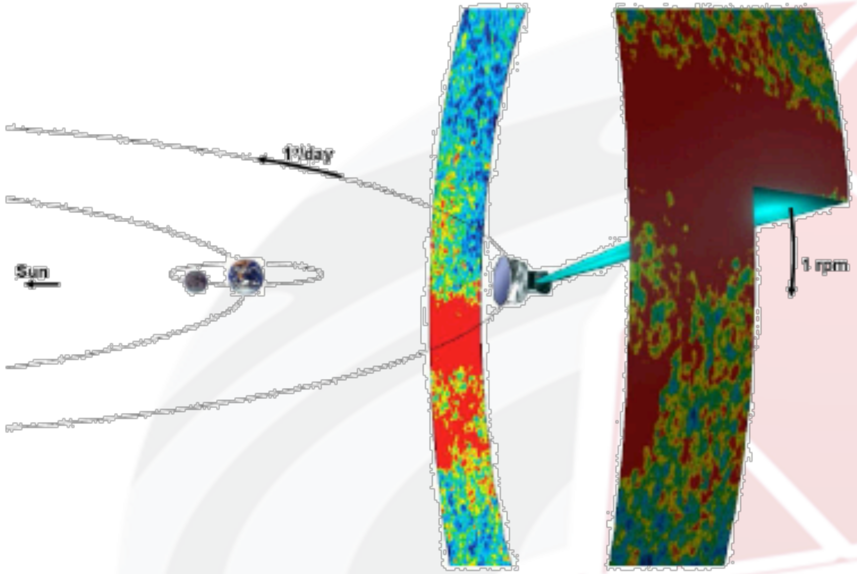


http://www.rssd.esa.int/Planck



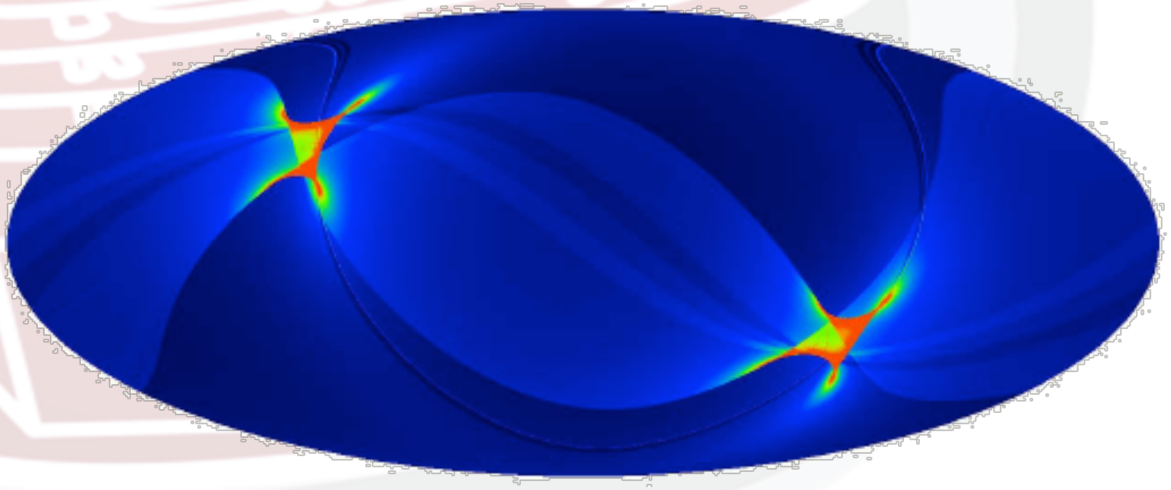
Observing strategy





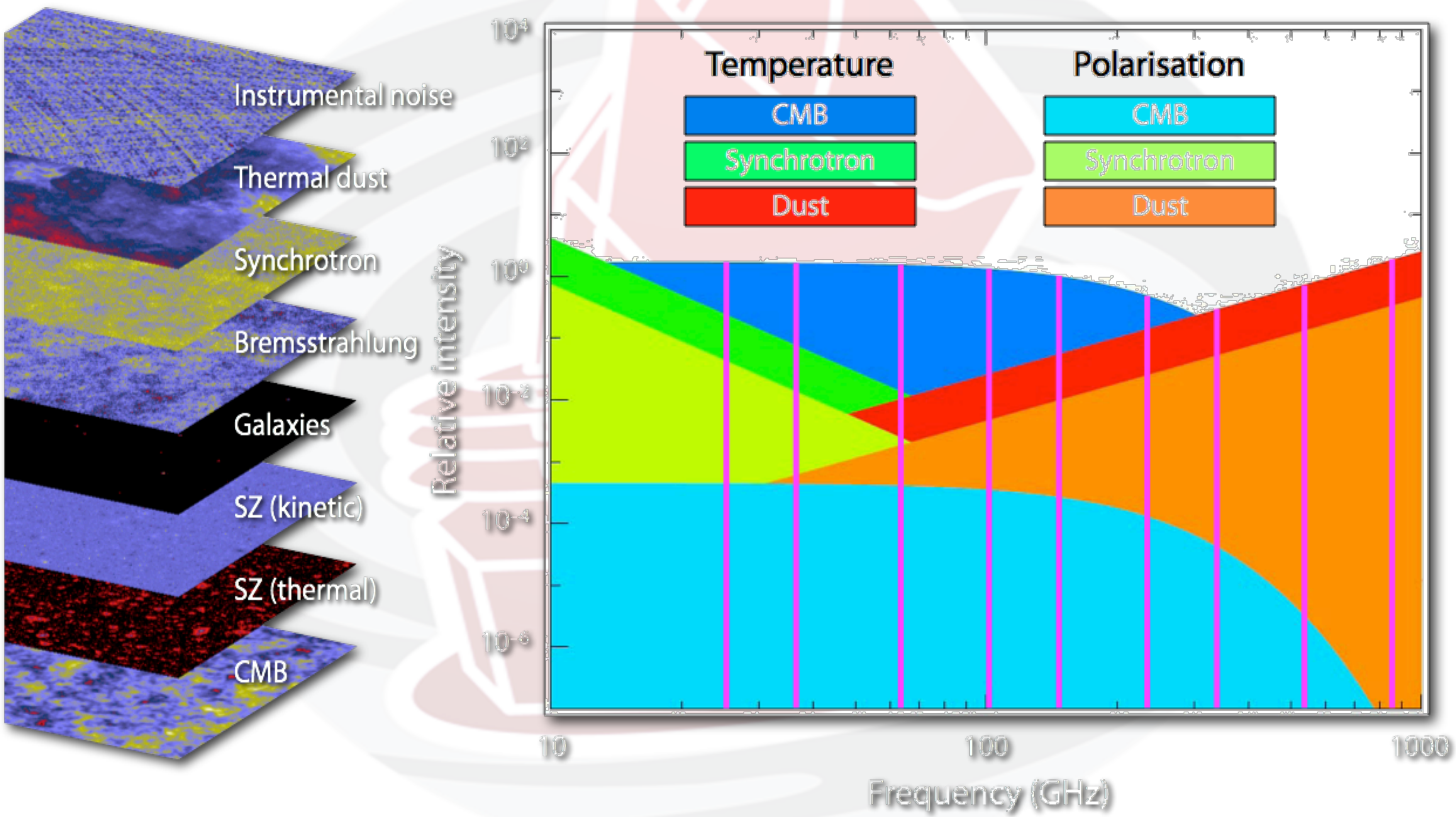
Planck is a survey mission

About 6 months are needed to cover ~95% of the sky.



Current Status

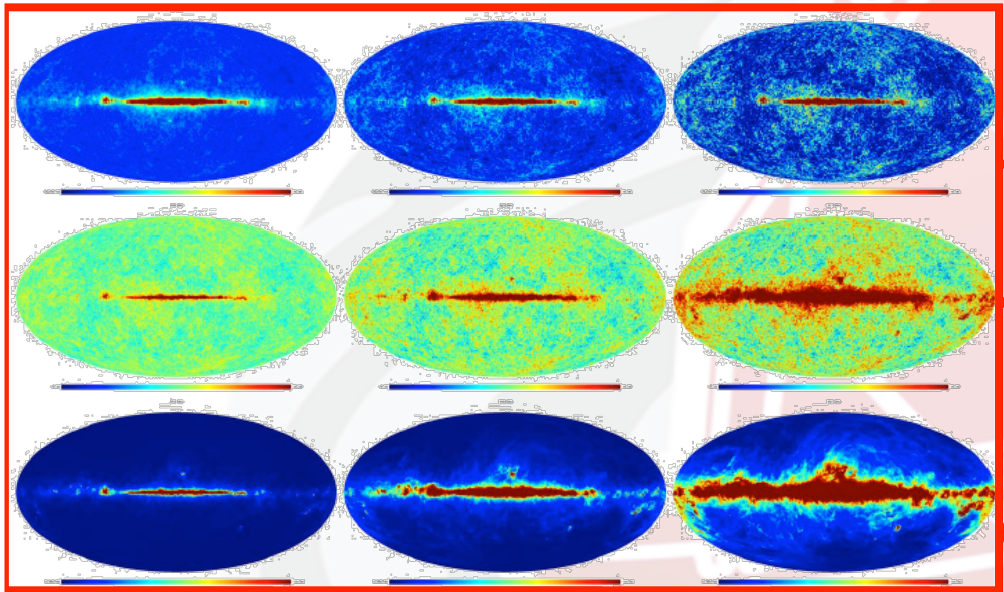
- 1019 days since launch.
- Satellite and instruments have been working nominally and continuously since start of sky surveys (mid August 2009)
  – HFI ran out of He on 14 Jan 2012 and stopped taking scientifically useful data
  – LFI still data gathering (several months)
- All the sky has been surveyed about five times with both instruments. LFI is already into its sixth sky survey.



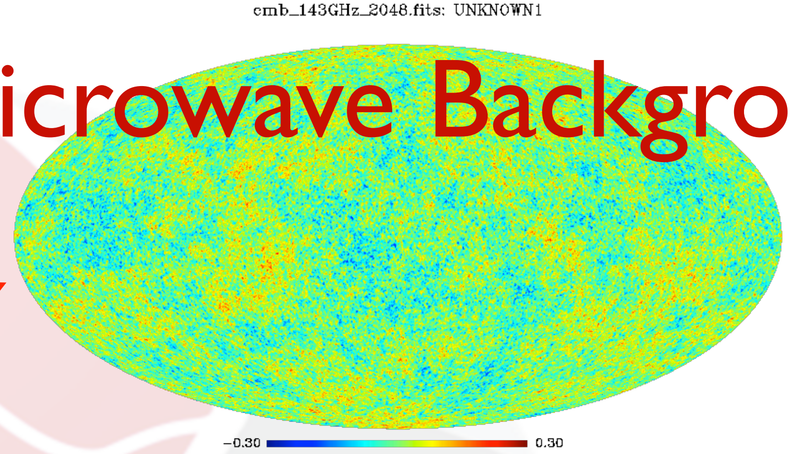
Instrumental noise
Thermal dust
Synchrotron
Bremsstrahlung
Galaxies
SZ (kinetic)
SZ (thermal)
CMB
Temperature
CMB
Synchrotron
Dust
Polarisation
CMB
Synchrotron
Dust
Relative intensity
Frequency (GHz)
10
100
1000

Expected results from simulations

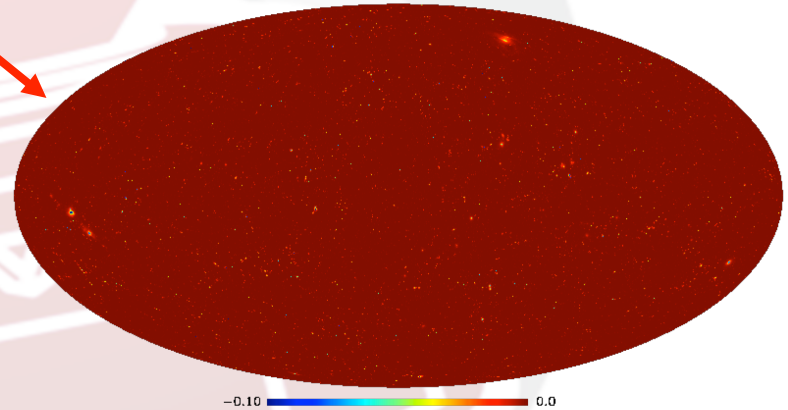
30, 44, 70, 100, 143, 217, 353, 545, 857 GHz – I, Q, U at all channels
Except 545 & 857 GHz



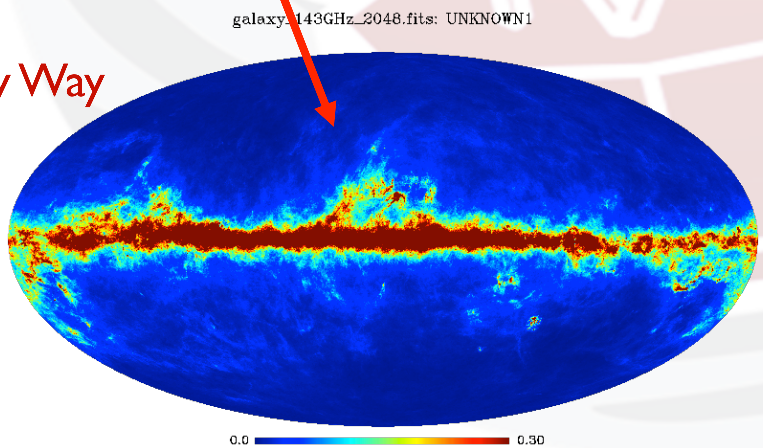
Cosmic Microwave Backgro



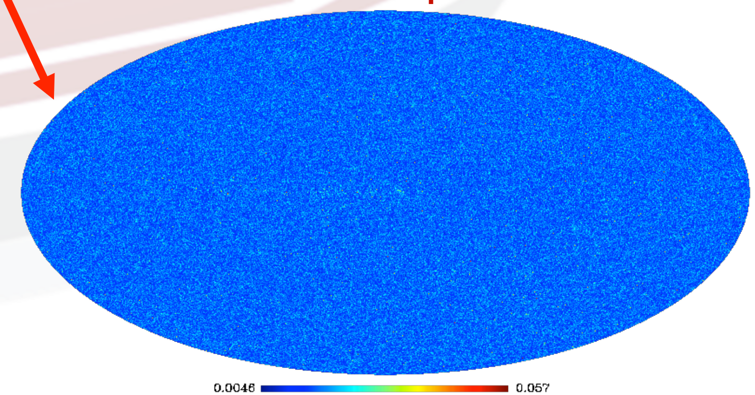
Sunyaev-Zeldovich

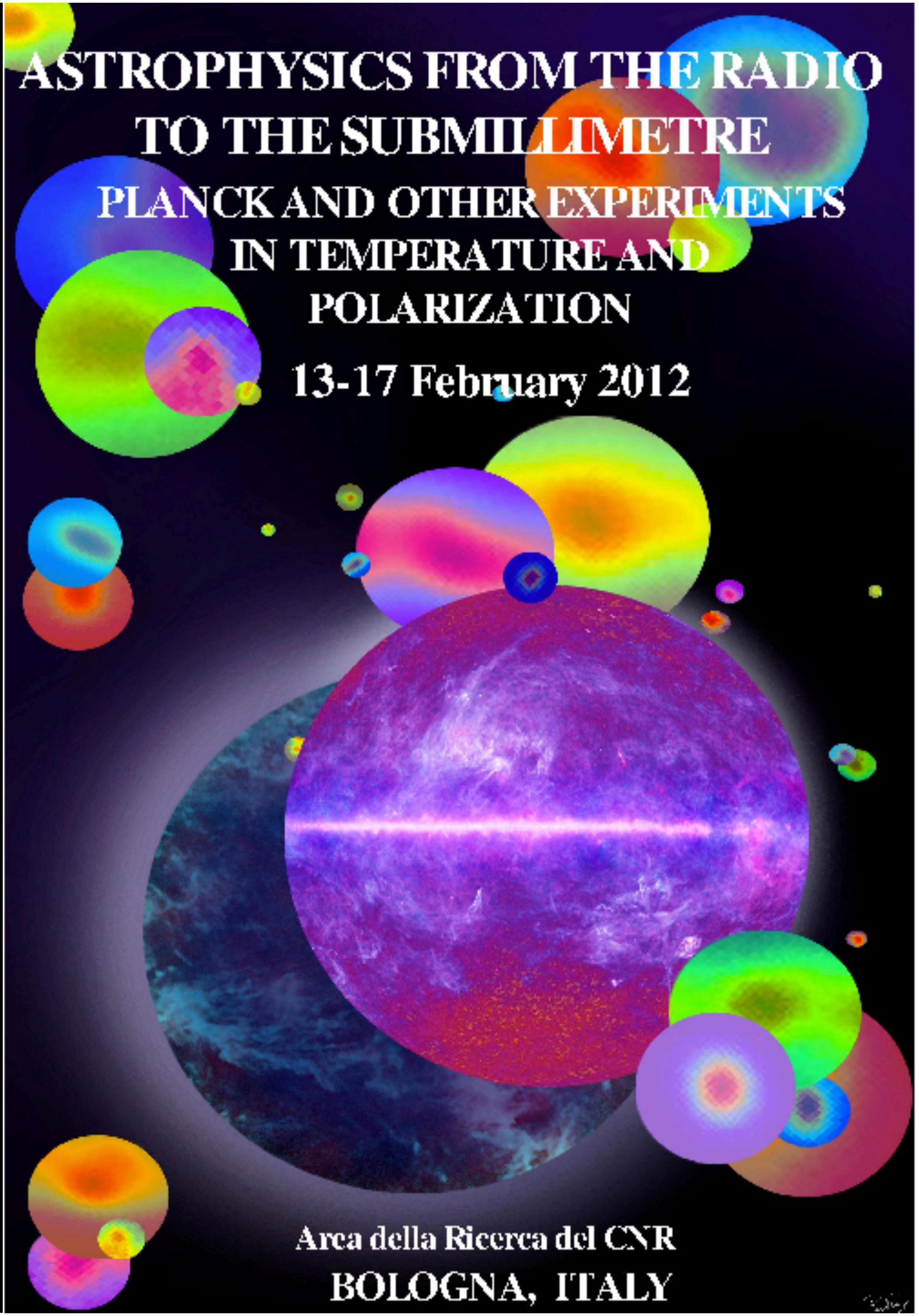


The Milky Way

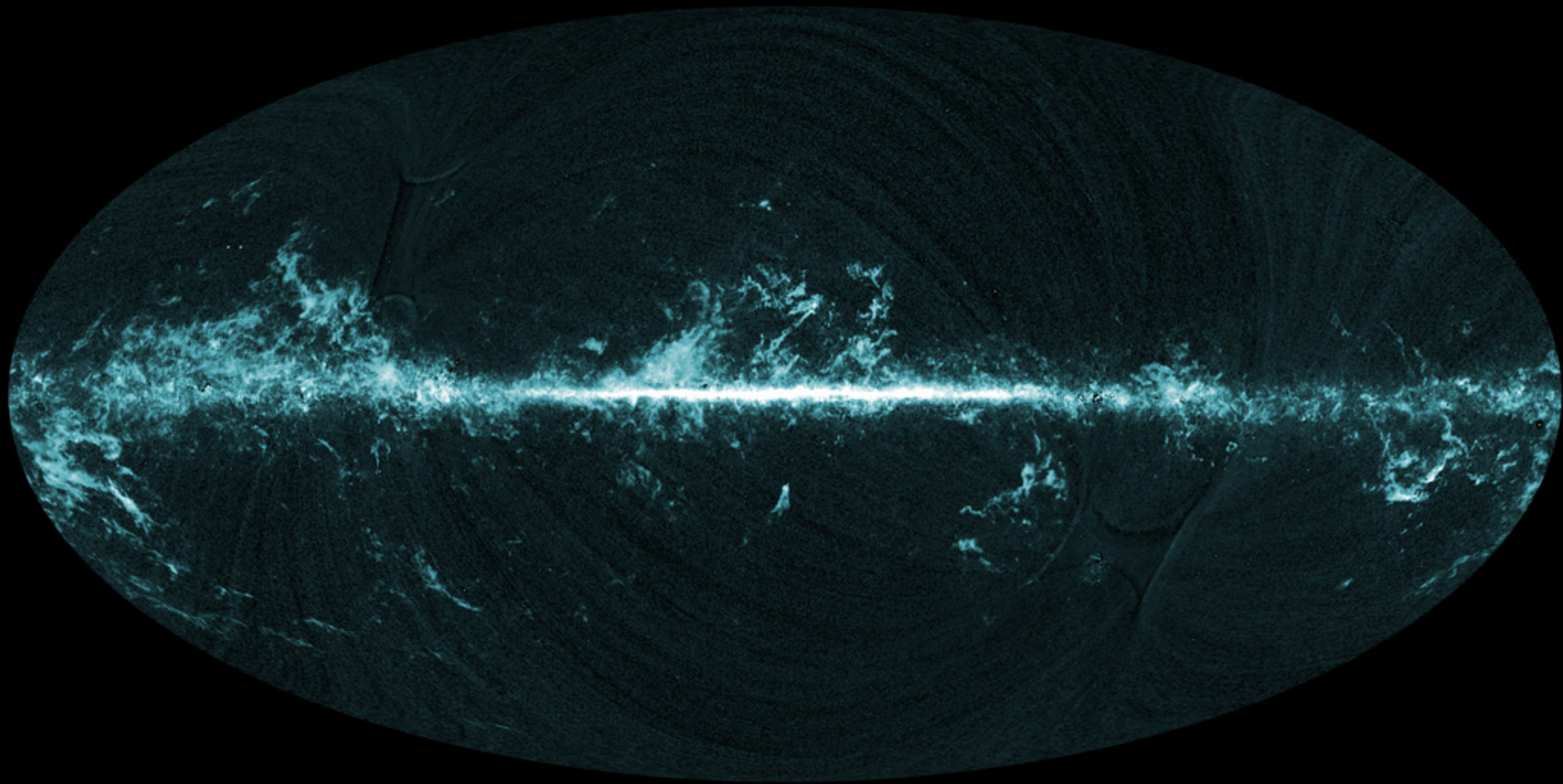


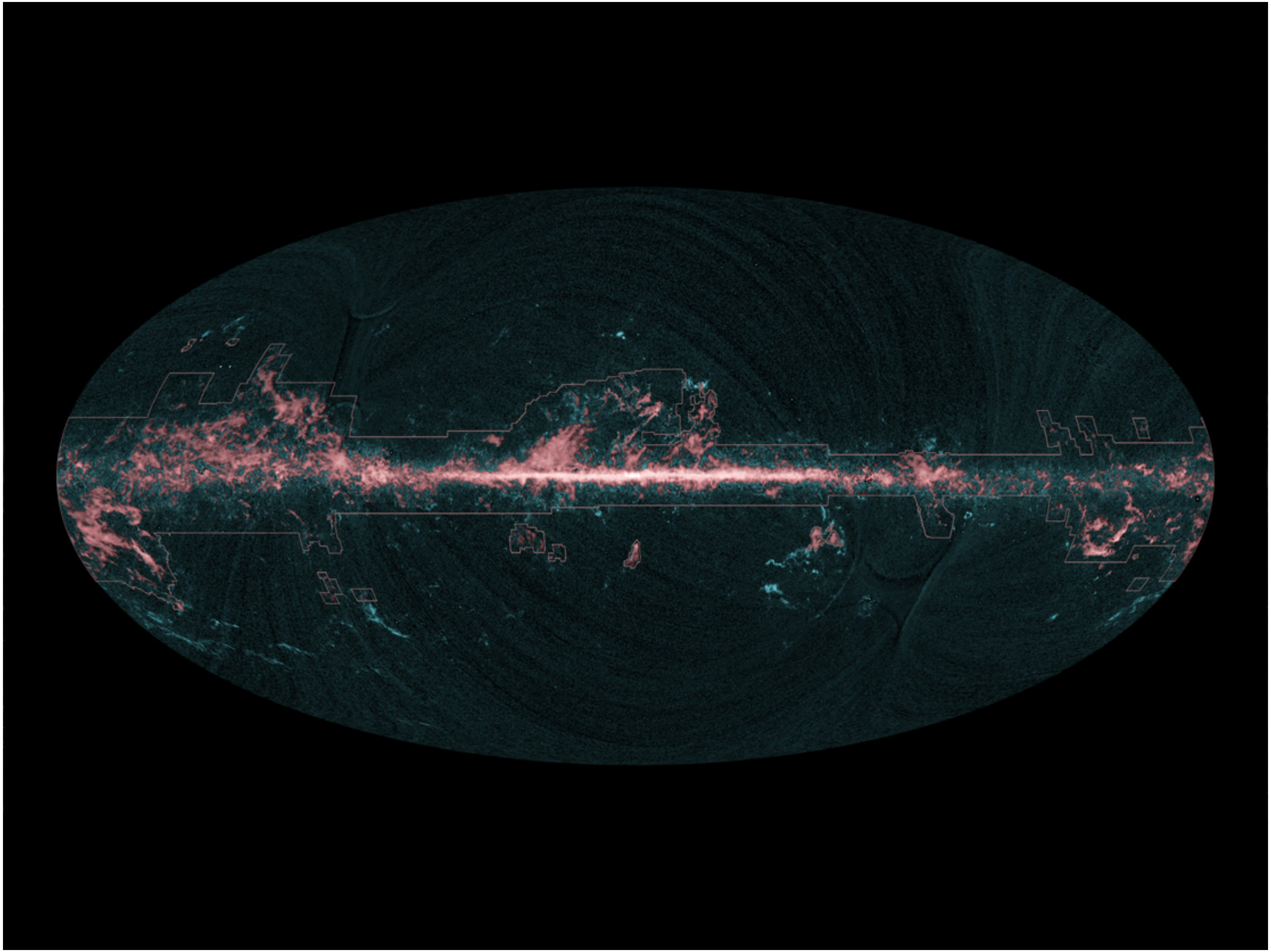
Point & Compact sources




ASTROPHYSICS FROM THE RADIO
TO THE SUBMILLIMETRE
PLANCK AND OTHER EXPERIMENTS
IN TEMPERATURE AND
POLARIZATION
13-17 February 2012
Area della Ricerca del CNR
BOLOGNA, ITALY

First full sky CO Map





Cosmological parameters

Cosmological parameters

WMAP constraints

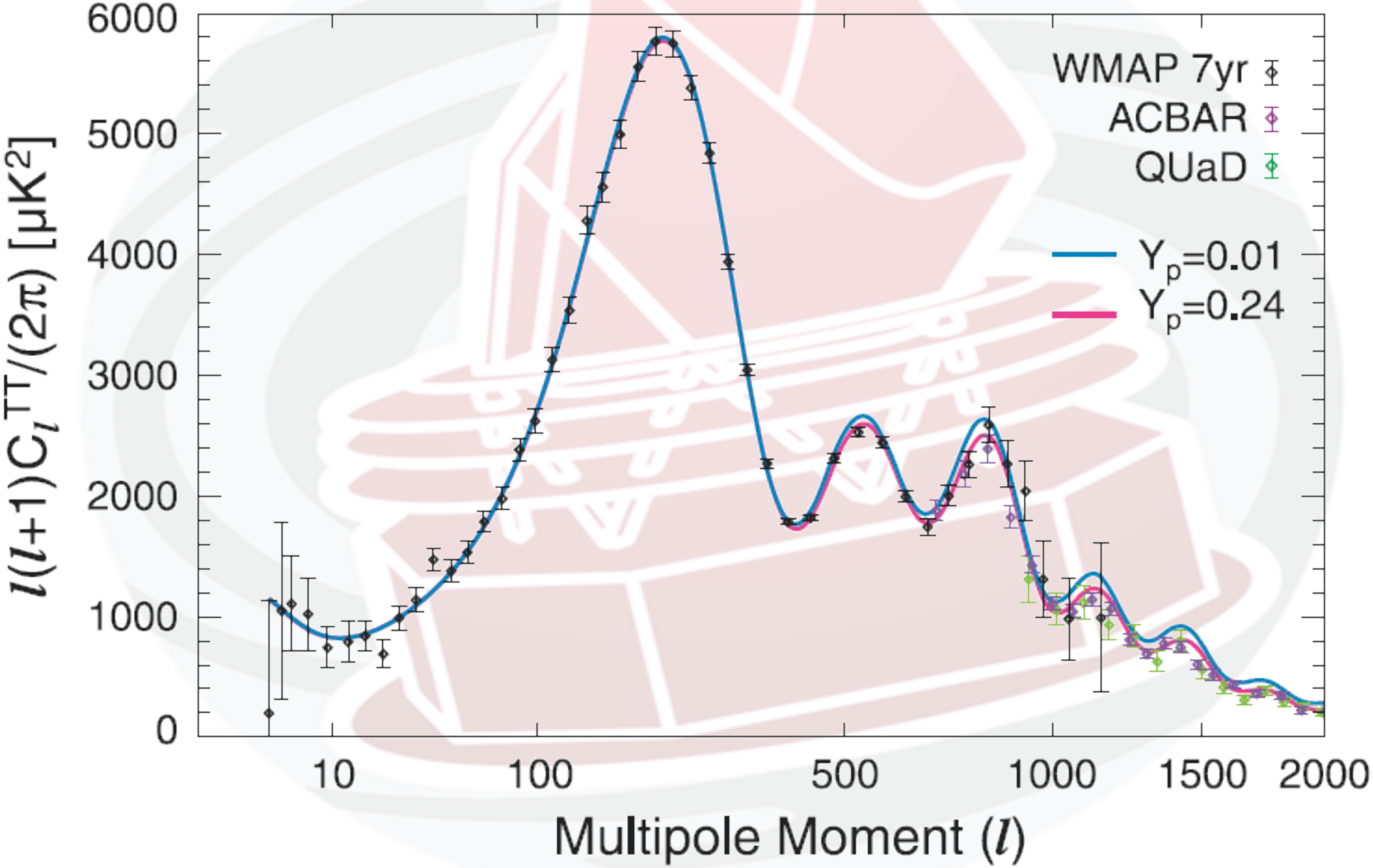
Table 3
Six-Parameter ΛCDM Fit [a]

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
$z_{\rm eq}$	3196^{+134}_{-133}	3176^{+151}_{-150}
$z_{\rm reion}$	10.5 ± 1.2	11.0 ± 1.4

New Measurements, Tighter Constraints for More Parameters!

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

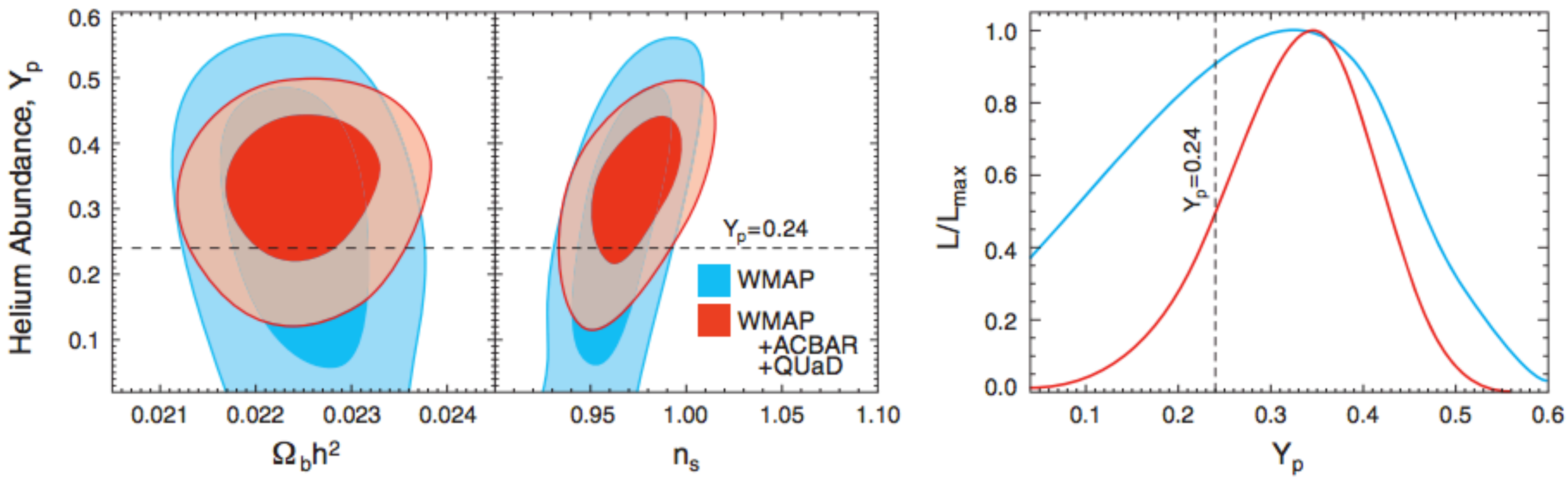
Small scale CMB can probe Helium abundance at recombination.



Nazzereno Mandolesi

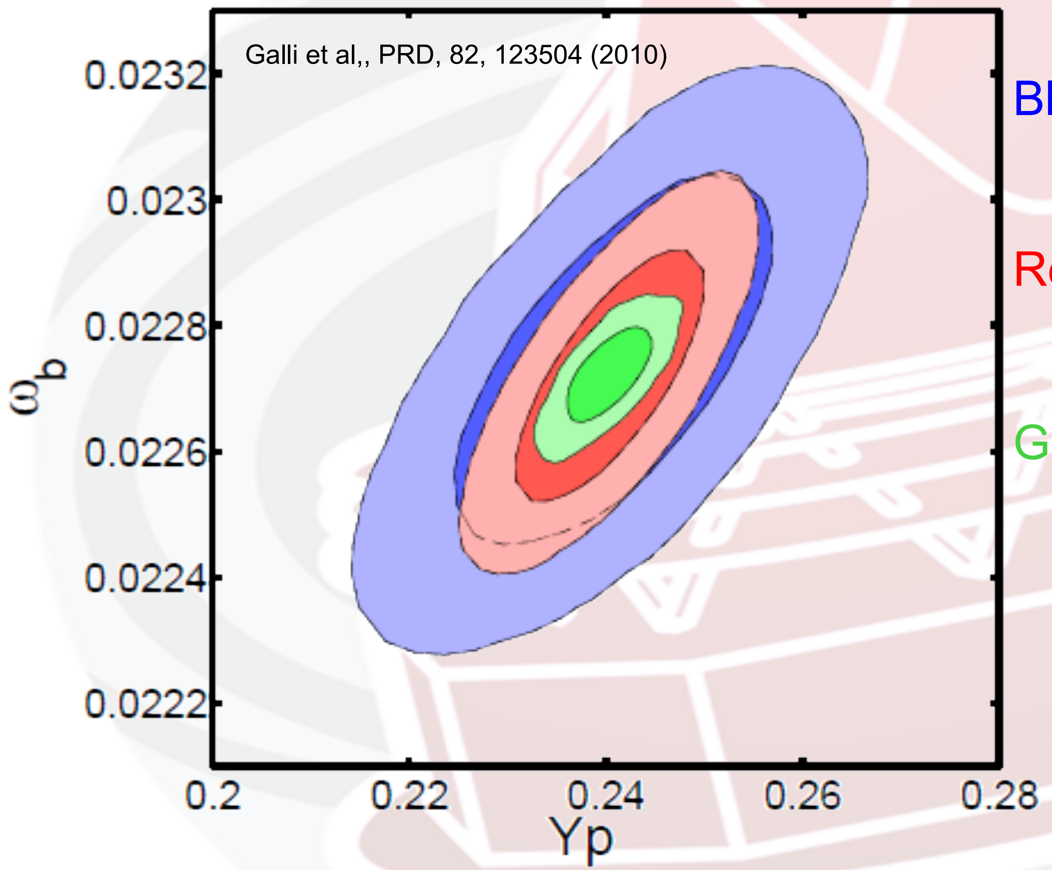
WMAP constraints on Helium

Komatsu et al, ApjS, 192, 18 (2011)



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

Planck+ Forecasts on Helium Abundance

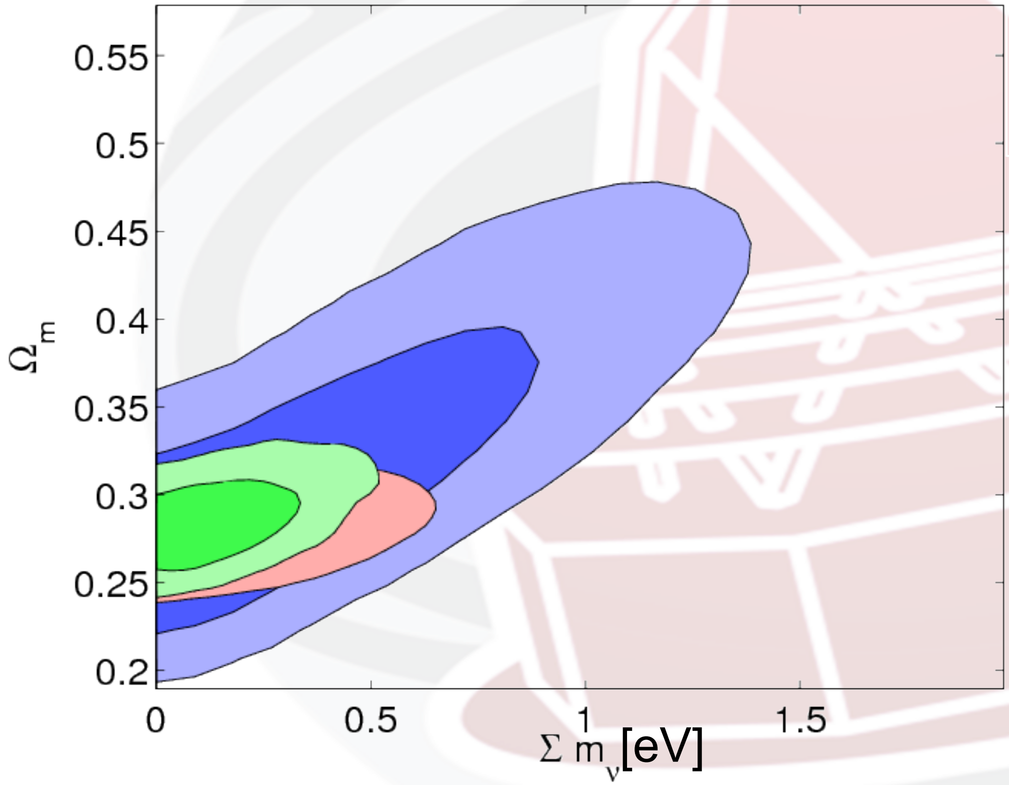


Blue: Planck $\Delta Yp=0.01$

Red: Planck+ACTpol $\Delta Yp=0.006$

Green: COrE $\Delta Yp=0.003$

Current constraints on neutrino mass from Cosmology



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

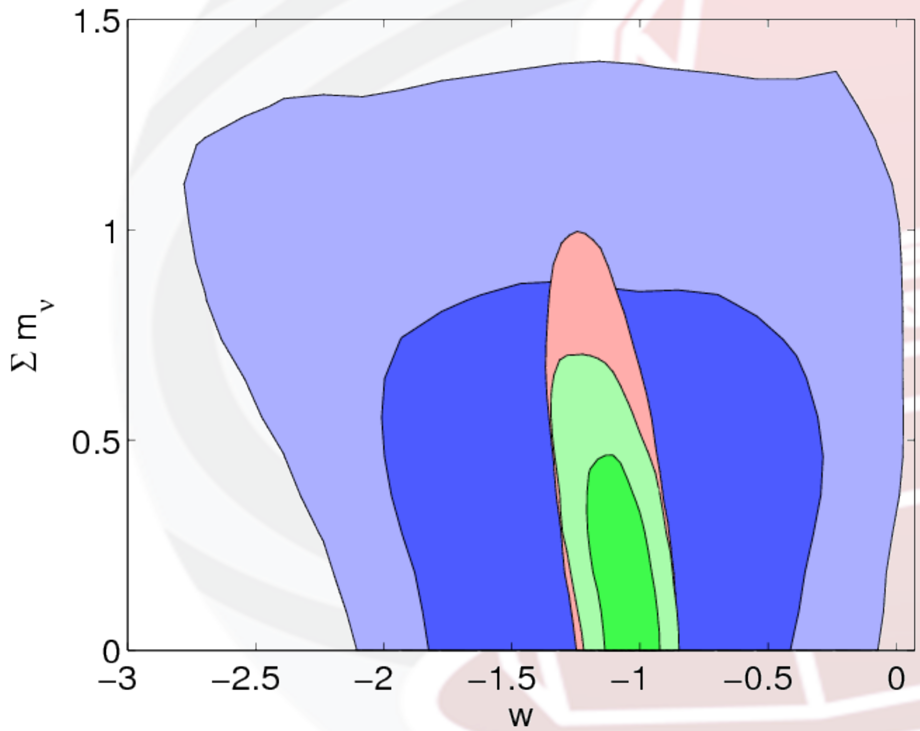
Current constraints (assuming ΛCDM):

Σm_ν<1.2 [eV] CMB

Σm_ν<0.7-0.5 [eV] CMB+other

Σm_ν<0.3 [eV] CMB+LSS (extreme)

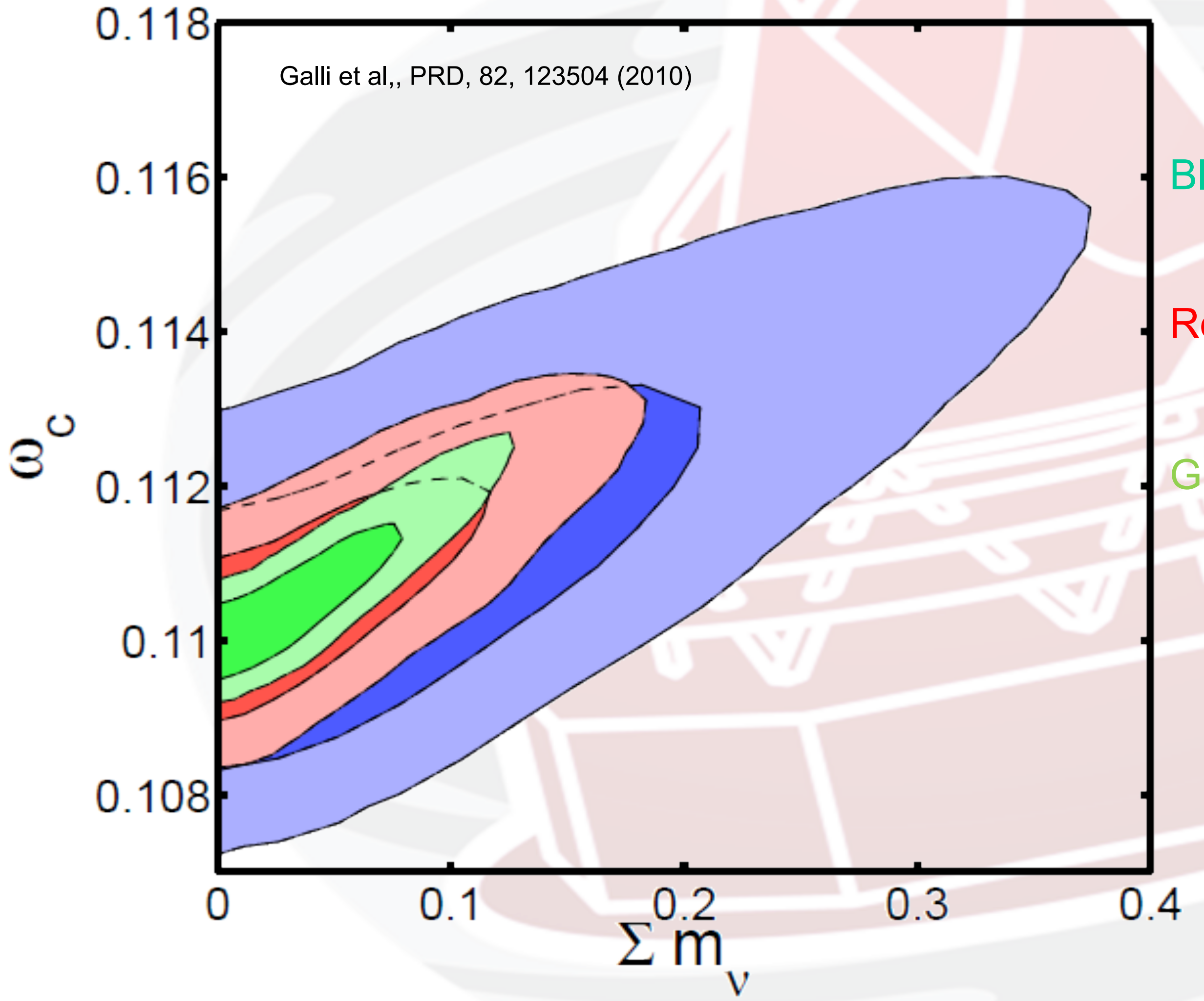
Current constraints on neutrino mass from Cosmology



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

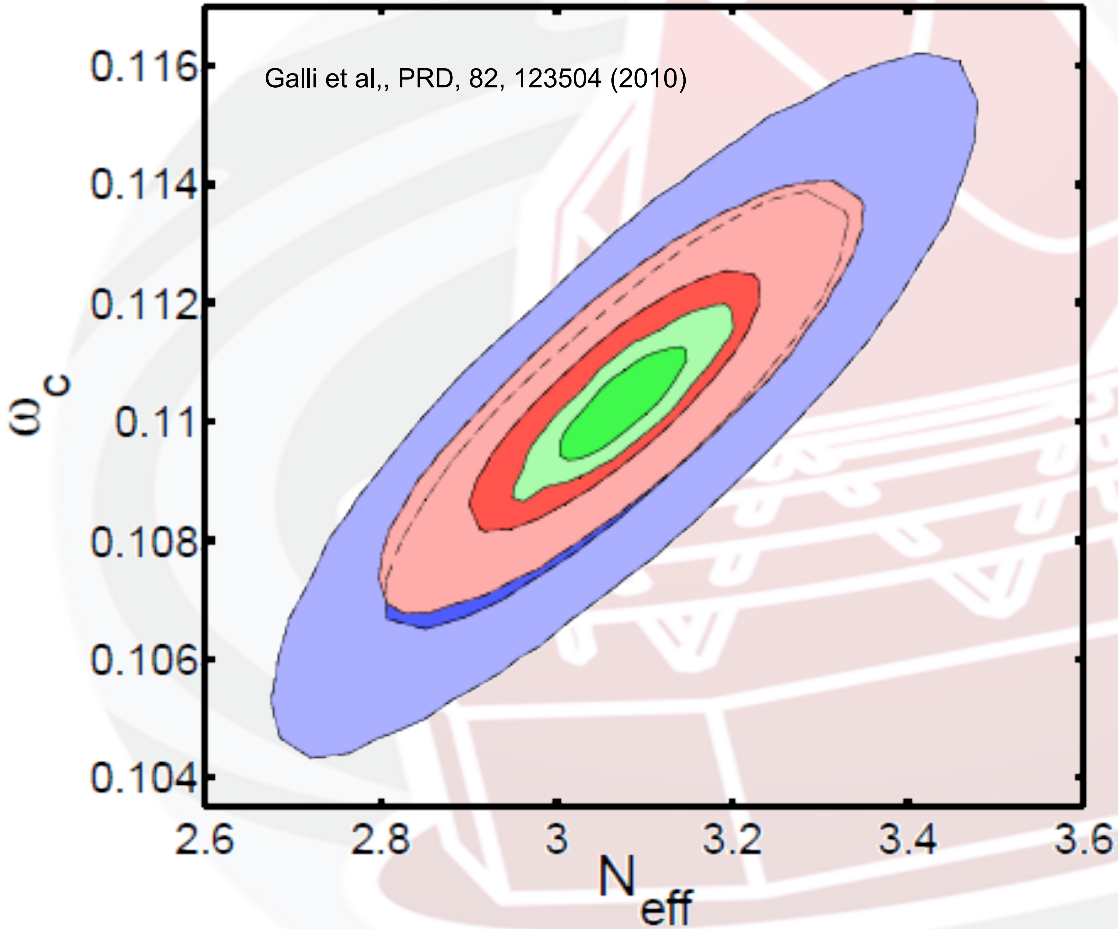


Blue: Planck $\Delta\Sigma m_\nu$=0.16

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 $\Delta N_\nu=0.11$

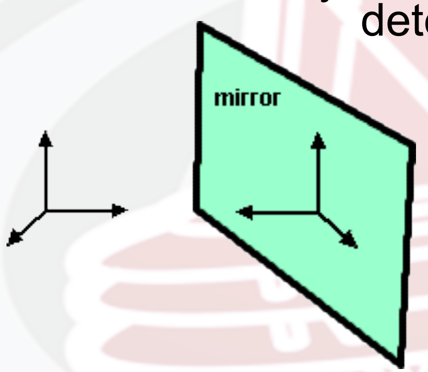
Green: COrE $\Delta N_\nu=0.044$

More Fundamental Physics

- Parity symmetry
- Birefringence and CPT constraints

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)



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

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:

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

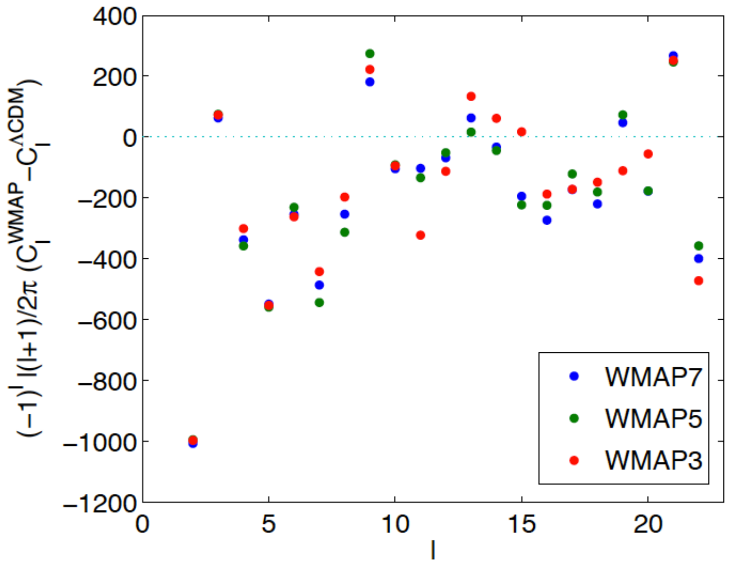
Therefore it is possible to divide each T map in two subsets corresponding to even and odd multipoles, satisfying two different transformation under P symmetry. Considering the angular power spectrum contained in the two subsets it is possible to study the consistency with P symmetry

Testing parity symmetry

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

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

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



Kim & Naselsky, 2010

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

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

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

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

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:

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

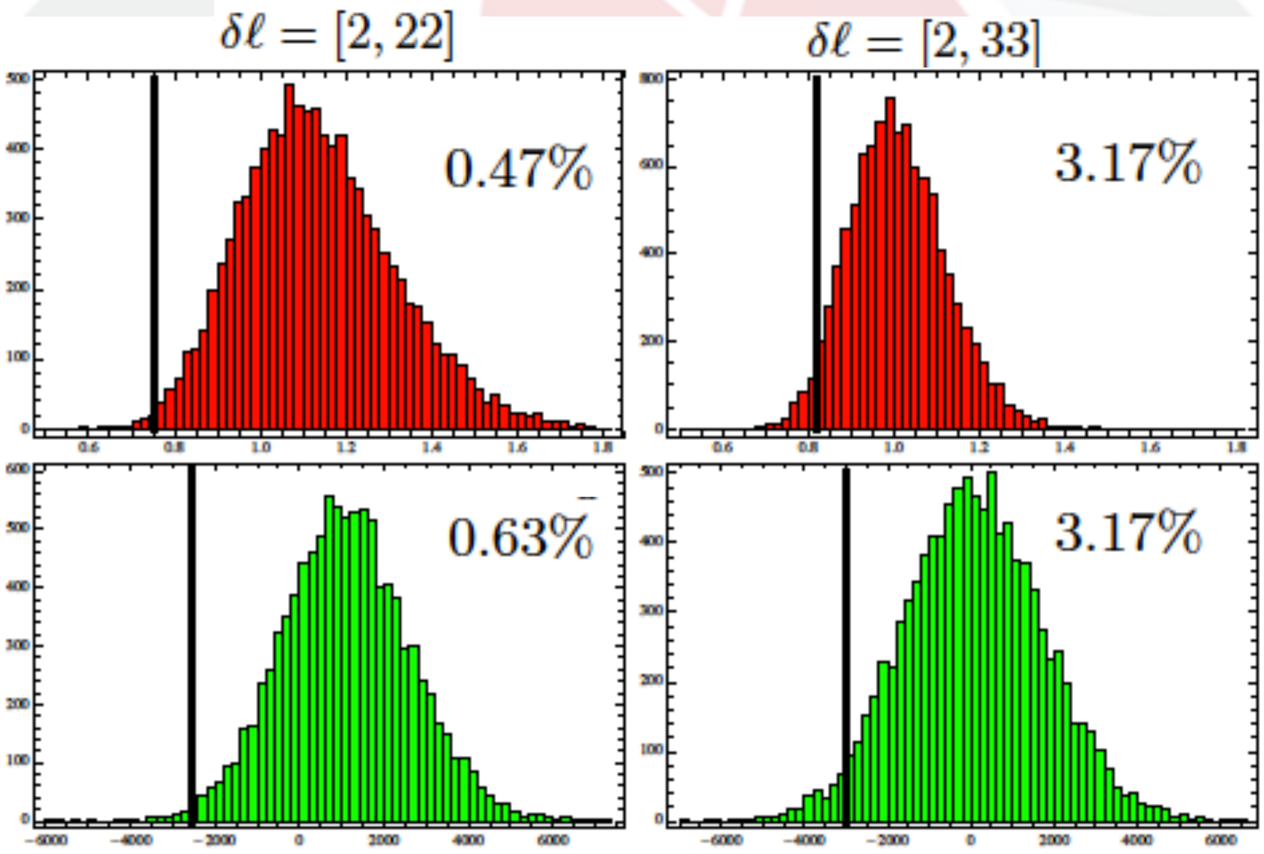
these estimators have been computed at large angular scale considering an optimal APS estimator.
A MC of 10000 realizations with realistic noise (both for WMAP 7 and Planck) has been performed

(Gruppuso et al., MNRAS, 2010)

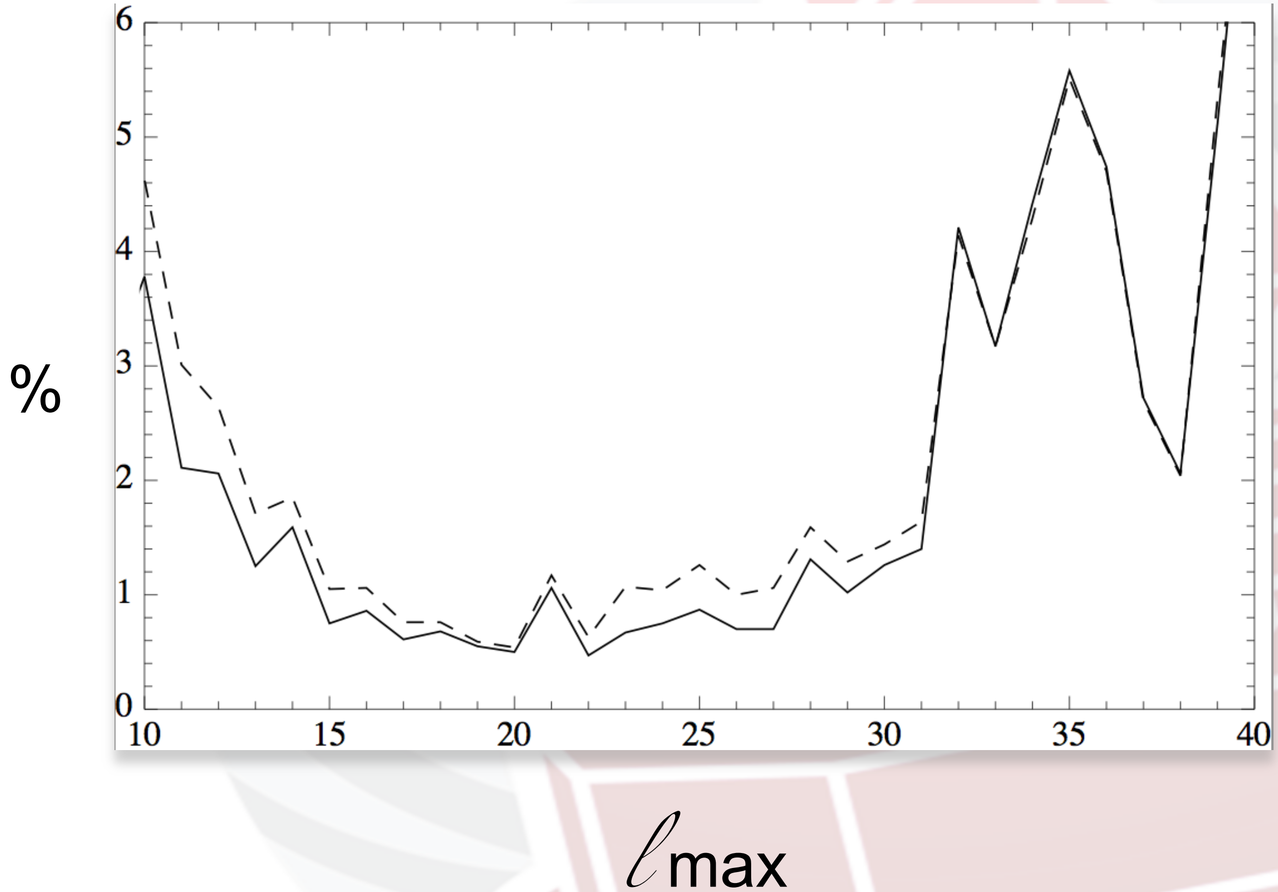
TT results (WMAP 7)

•R

•D



Percentage vs angular scale



solid line: R estimator

dashed line: D estimator

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%)

Planck forecasts (e.g. 143 GHz channel)

- Standard deviations for D

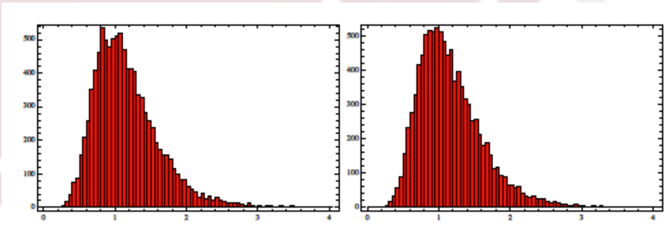
σ_D	WMAP 7 year	Planck
TT	1517.17	1509.21
TE	20.19	9.08
EE	0.65	0.10
BB	0.69	0.04

- 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



$\delta\ell = [2, 22]$ $\delta\ell = [2, 16]$

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:

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

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.

Current constraints

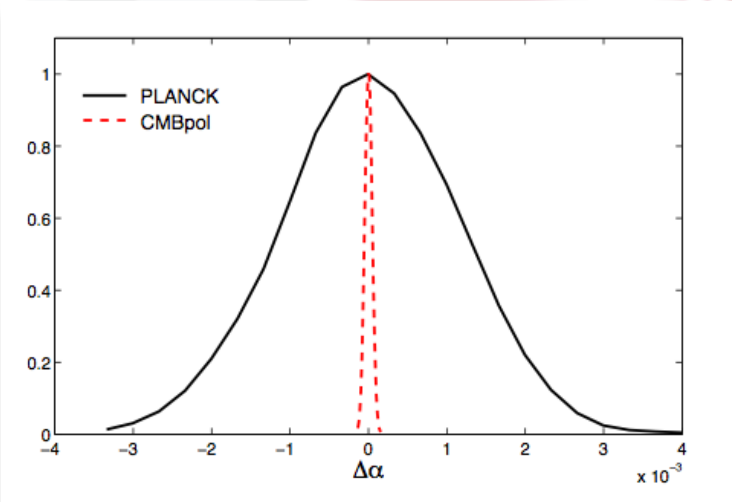
•WMAP 7 (Komatsu et al. 2010, in press in ApJS)

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

•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

$$\sigma = 0.057^\circ$$ Planck

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

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)

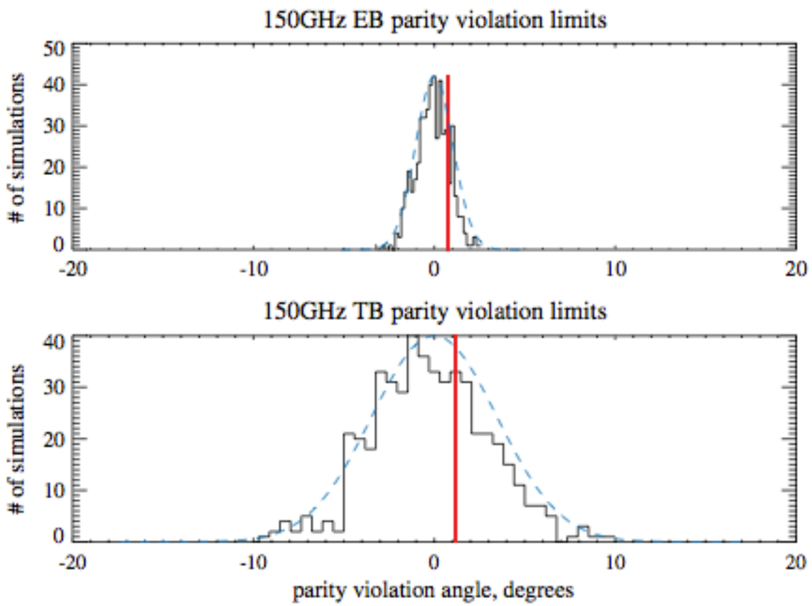
alpha = 0.55 +/- 0.82 (statistical) +/- 0.5 (systematic) [deg]

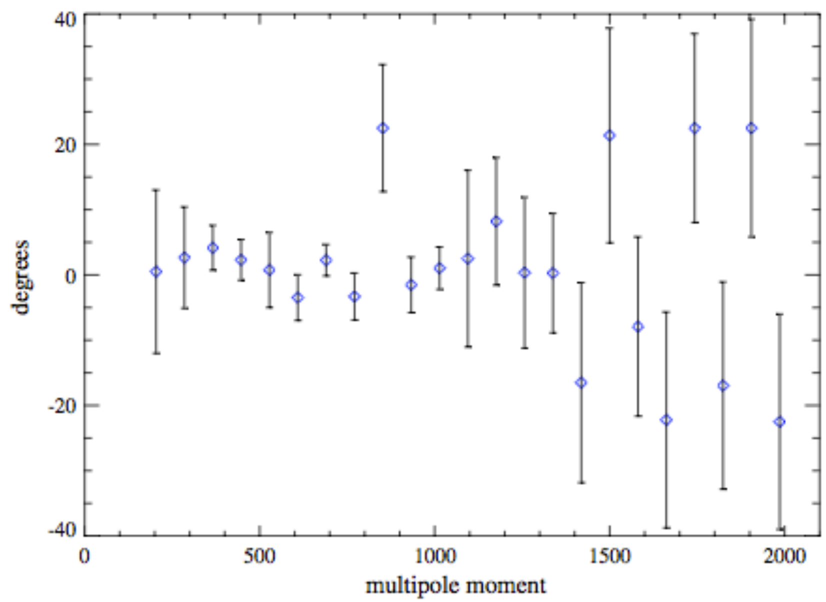
$$D_{\mathrm{TB},\ell} = C_\ell^{\mathrm{TB,obs}} \cos(2\Delta\alpha) - C_\ell^{\mathrm{TE,obs}} \sin(2\Delta\alpha),$$

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

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

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





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.)

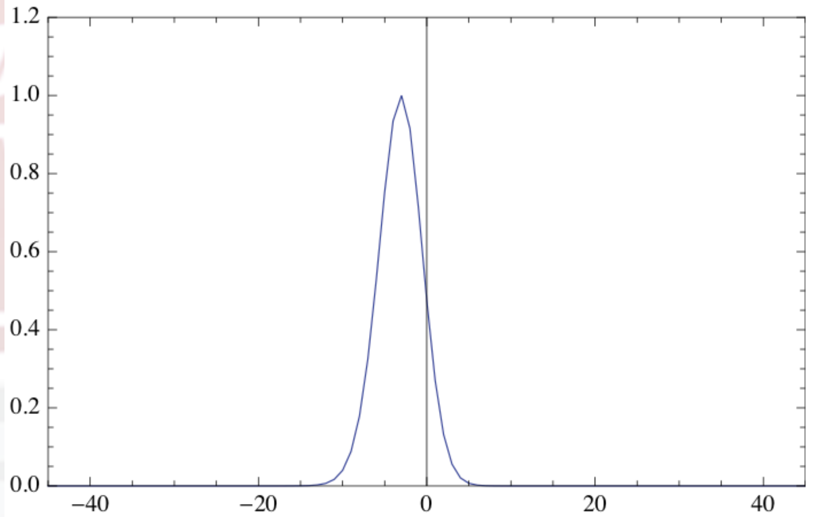
Gruppuso et al. (2011) arXiv:1107.5548 alpha = -3.0 +/- 3.5 [deg] (WMAP 7YR)
$2 \leq \ell \leq 23$

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

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

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

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



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)

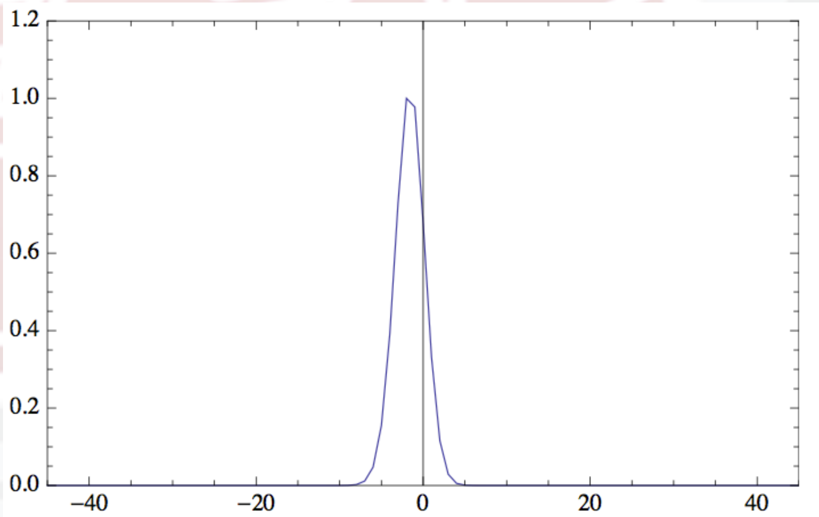
$2 \leq \ell \leq 47$

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

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

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

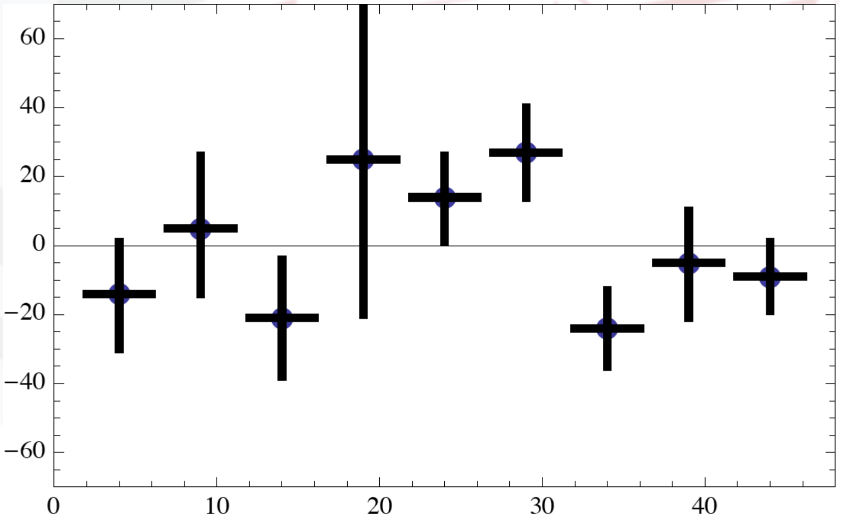
$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{EB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{EB},\ell'}.$$



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:

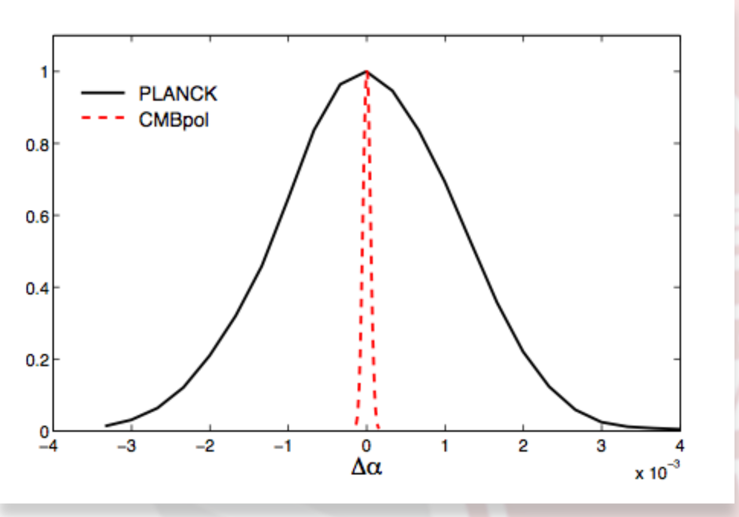


(WMAP 7YR)

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

Planck and CMBPol forecast

Small Angular Scale



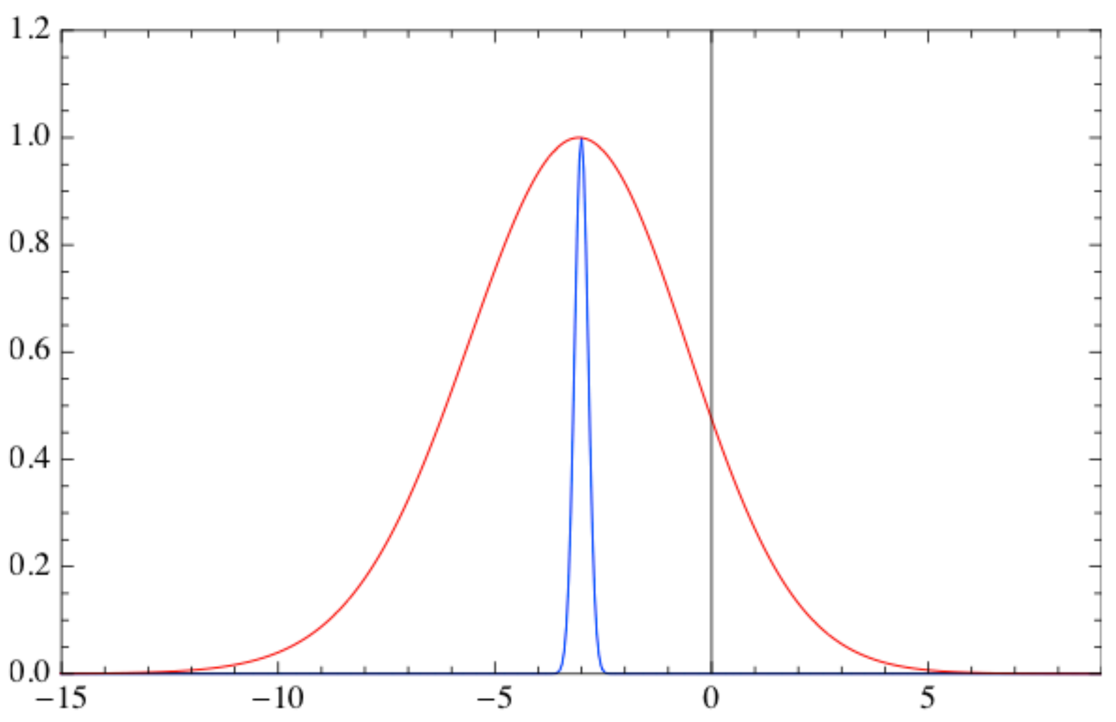
Xia et al. (2009), IJMPD

$$\sigma = 0.057^\circ$$ Planck

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

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

Conclusions

- **Planck has so far delivered results which mainly interest astrophycists.**
- **But the experiment has been built to do Cosmology: the "golden share" is yet to be seen (previewing from January 2013)**
- **Planck has some potential to deliver interesting fundamental physics, can complement "direct" measurements in HEP experiments.**

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA) and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.