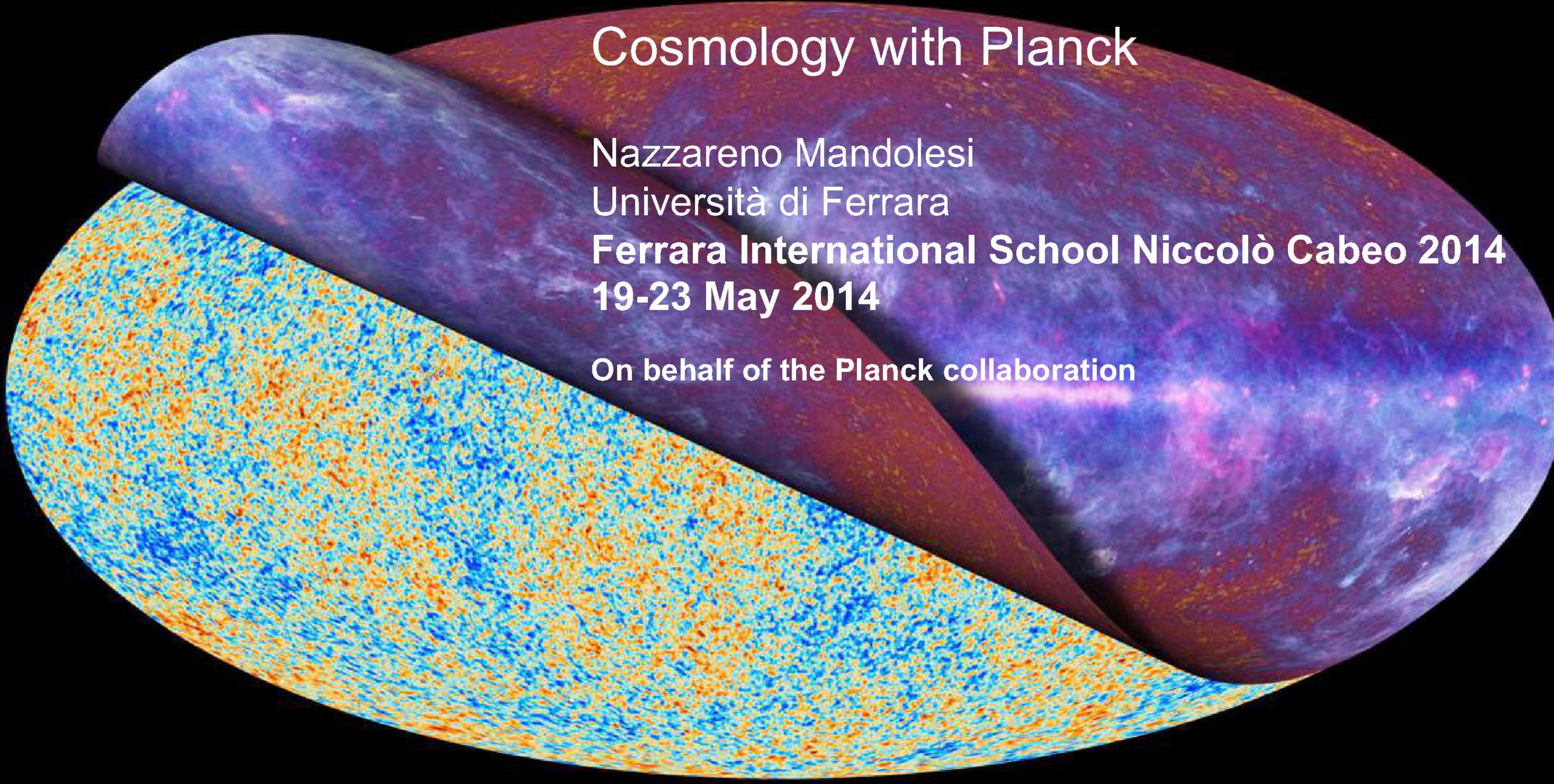
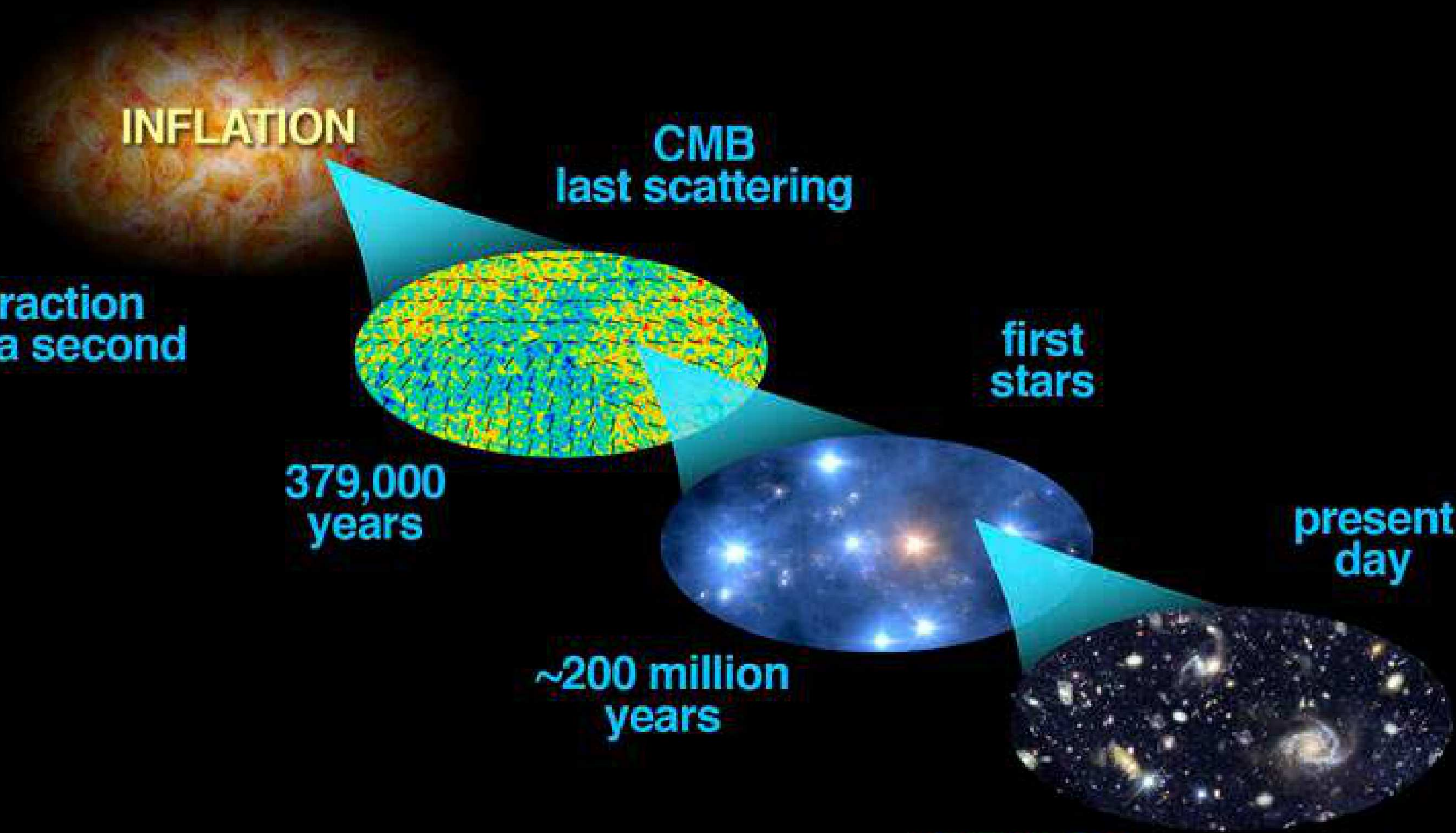


Cosmology with Planck

Nazzareno Mandolesi
Università di Ferrara
Ferrara International School Niccolò Cabeo 2014
19-23 May 2014

On behalf of the Planck collaboration

Planck unveils the Cosmic Microwave Background



INFLATION

fraction
of a second

CMB
last scattering

379,000
years

first
stars

~200 million
years

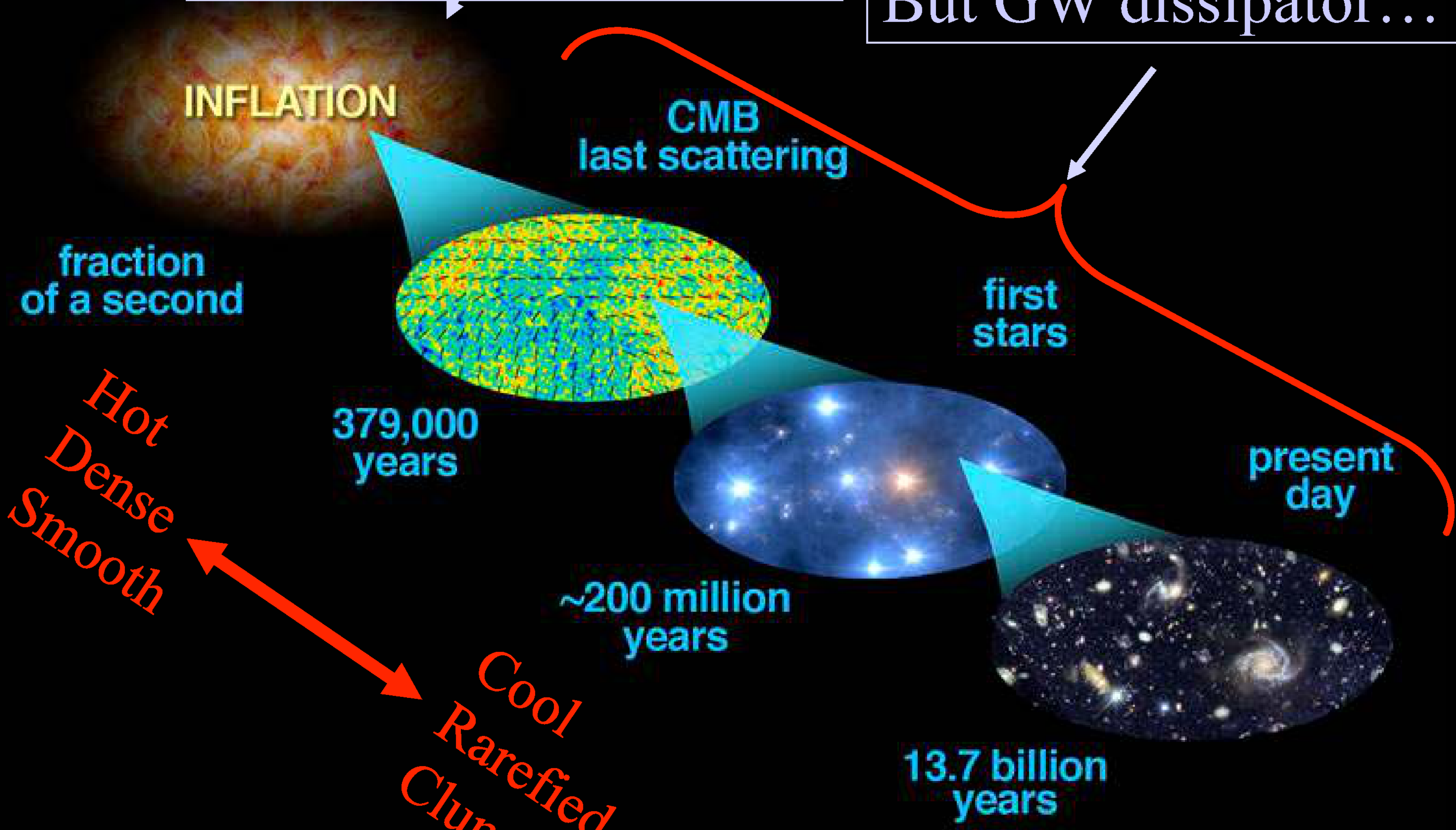
present
day

13.7 billion
years

Fluctuation and GW generator

Fluctuation amplifier

But GW dissipator…



Hot

Dense

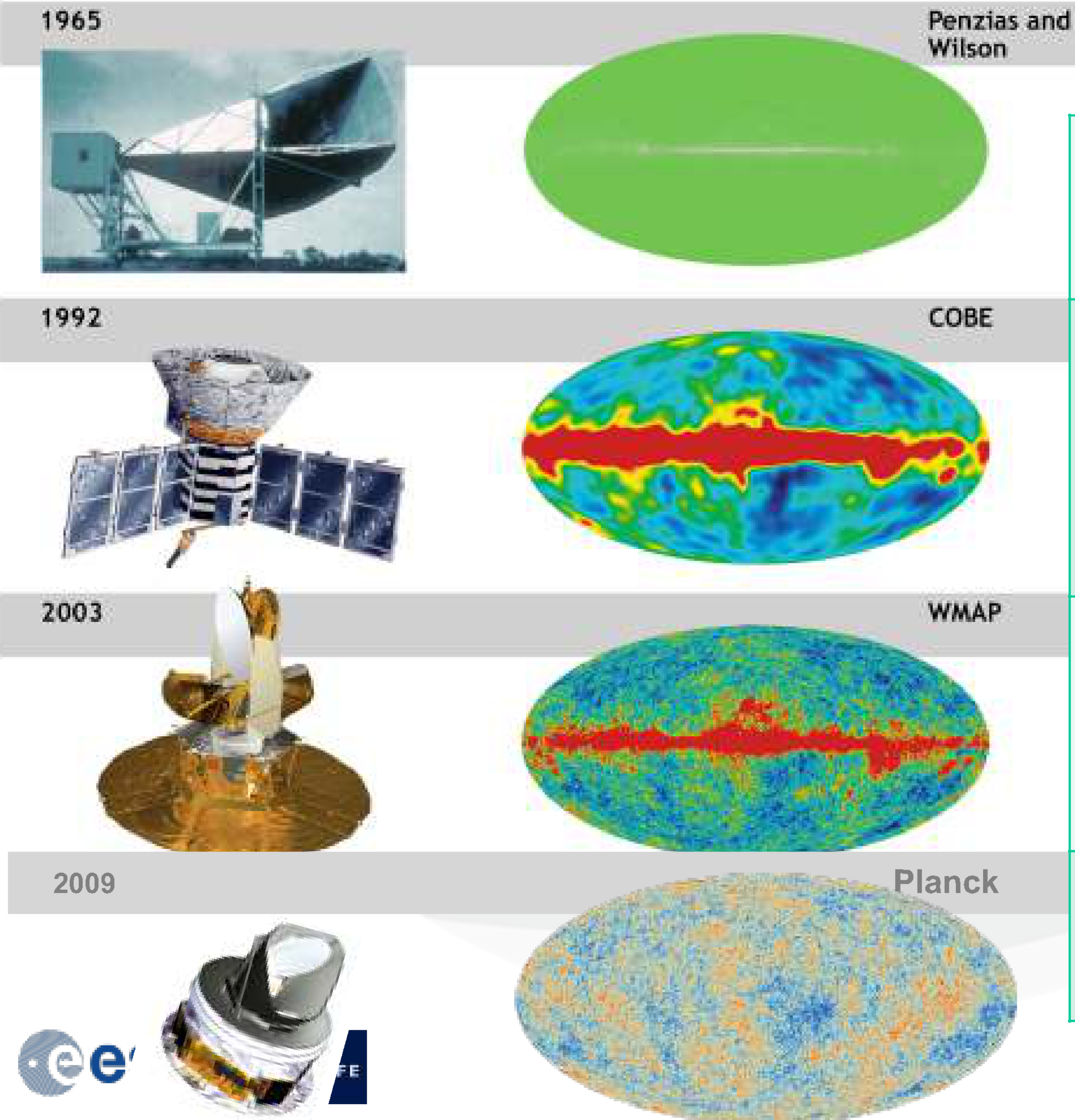
Smooth

Cool

Rarefied

Clumpy

Cosmic Microwave Background Radiation Overview



The oldest light or the first light of the Universe

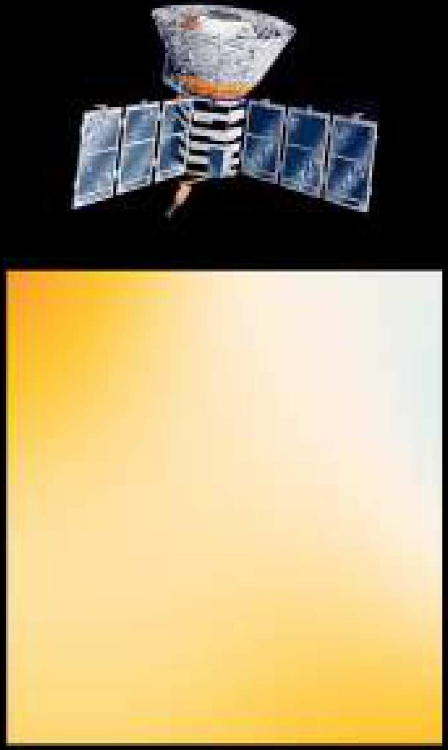
Discovered the remnant afterglow from the **Big Bang**.
→ **2.7 K**

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

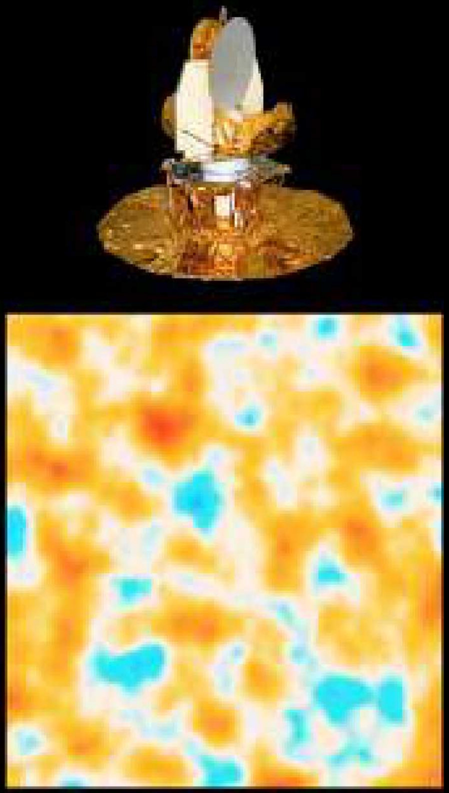
(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15'**

→ **angular scale ~ 5'**,
ΔT/T ~ 2×10^{-6}, 30~867 Hz

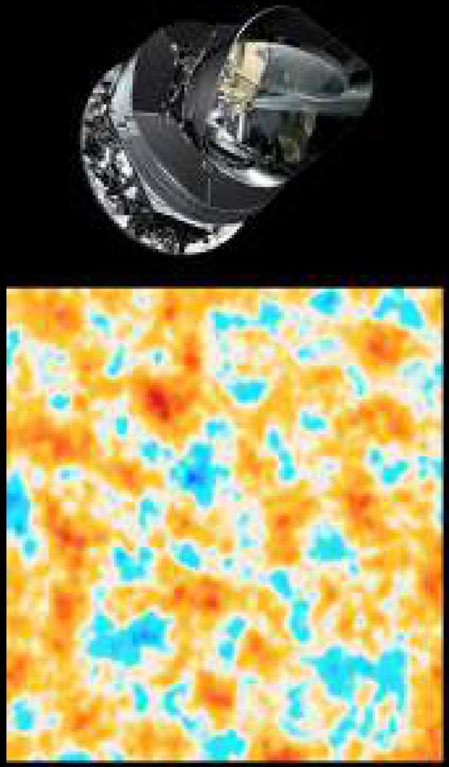
Comparison with forerunners



COBE



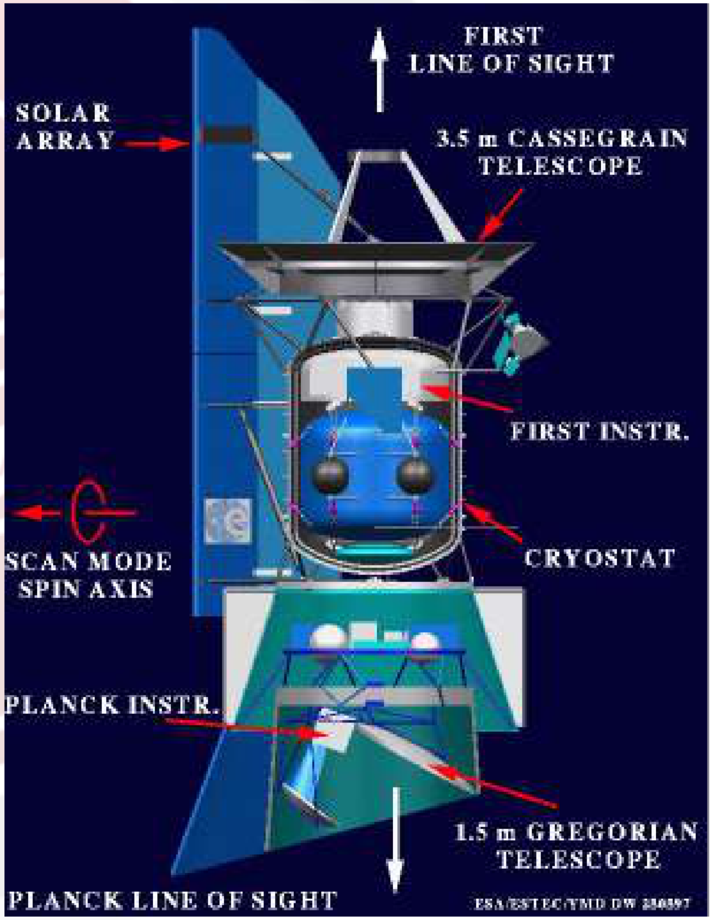
WMAP



Planck

A brief history of Planck

- **1993**: COBRAS & SAMBA proposals for M3 « Horizon 2000 » launch slot [2003]
- (1996: WMAP selected by NASA)
- **1996**: selection of COBRAS/SAMBA, then named Planck [2004]
- **1997**: instrument AO + selection LFI&HFI [2006]
- **1998**: The program runs into financial/ programmatic difficulties, merging FIRST(Herschel)/Planck studies [2007]
- (2001 WMAP launch)
- lots of technical problems solved and work …
- **2009** Planck **launch** [2009]
- **2013** 1st Planck Cosmological data release
- **2014** 2nd Planck Cosmological data release
- **2015** 3rd Planck Cosmological data release

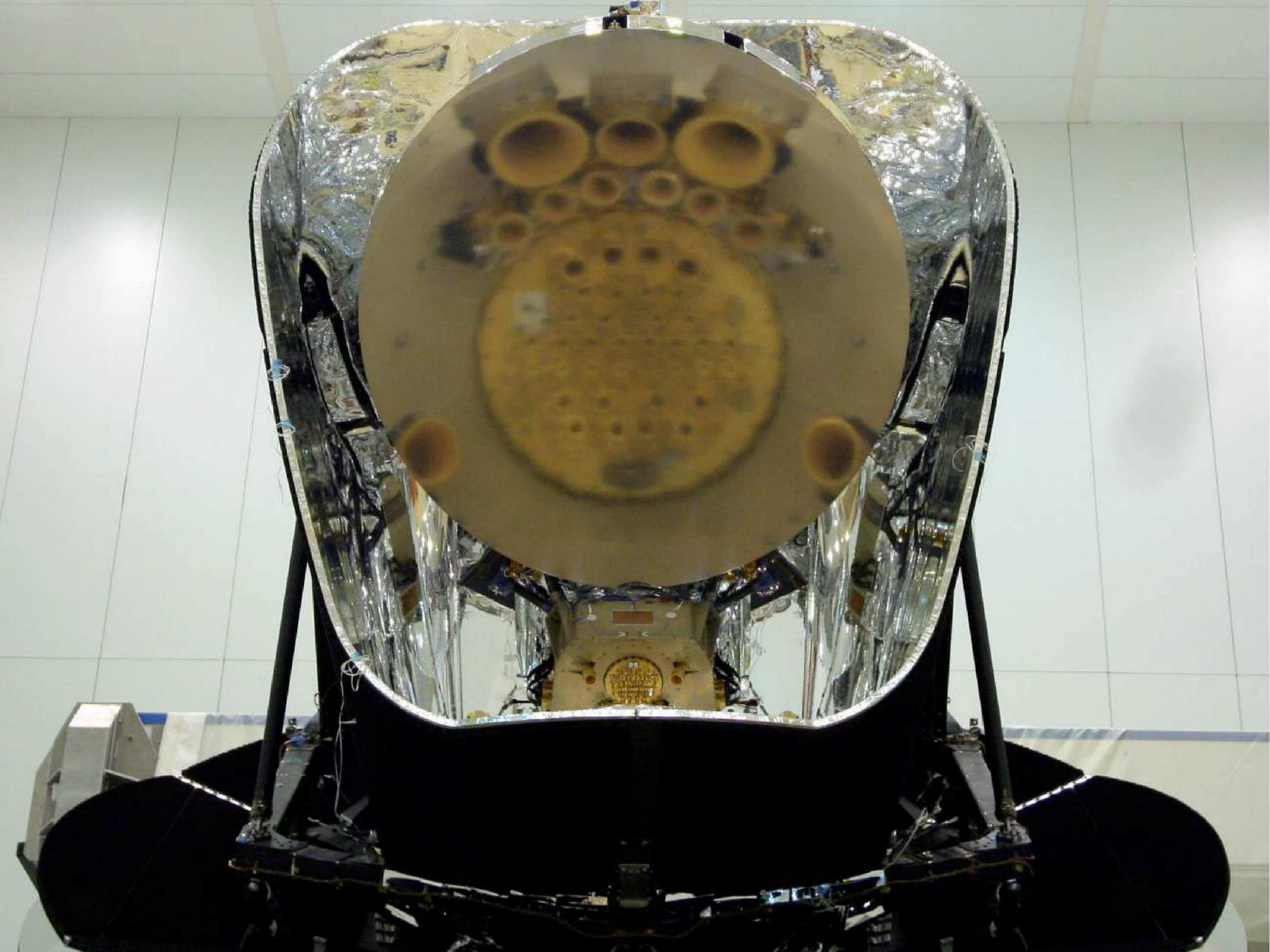


esa

UNIFE

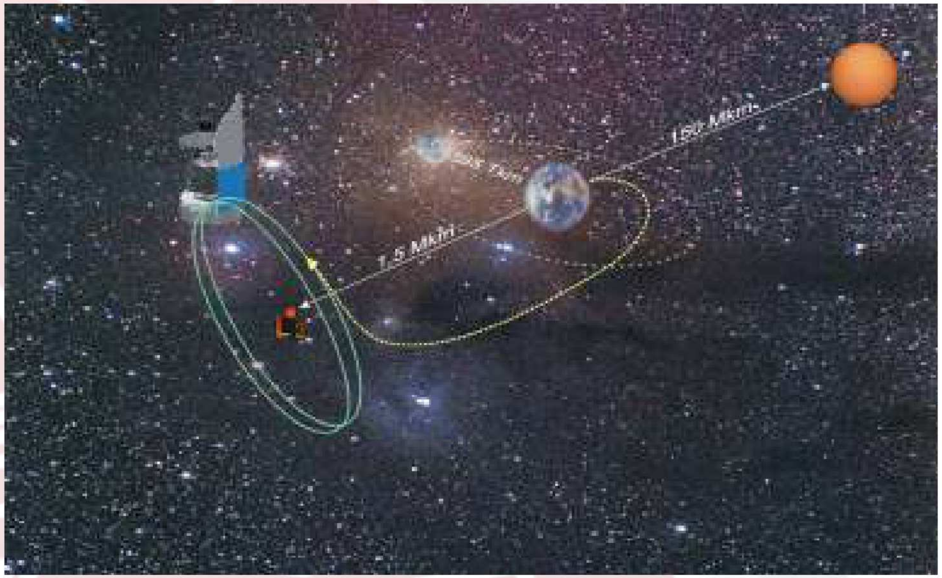
agenzia spaziale italiana

INAF ISTITUTO NAZIONALE DI ASTROFISICA

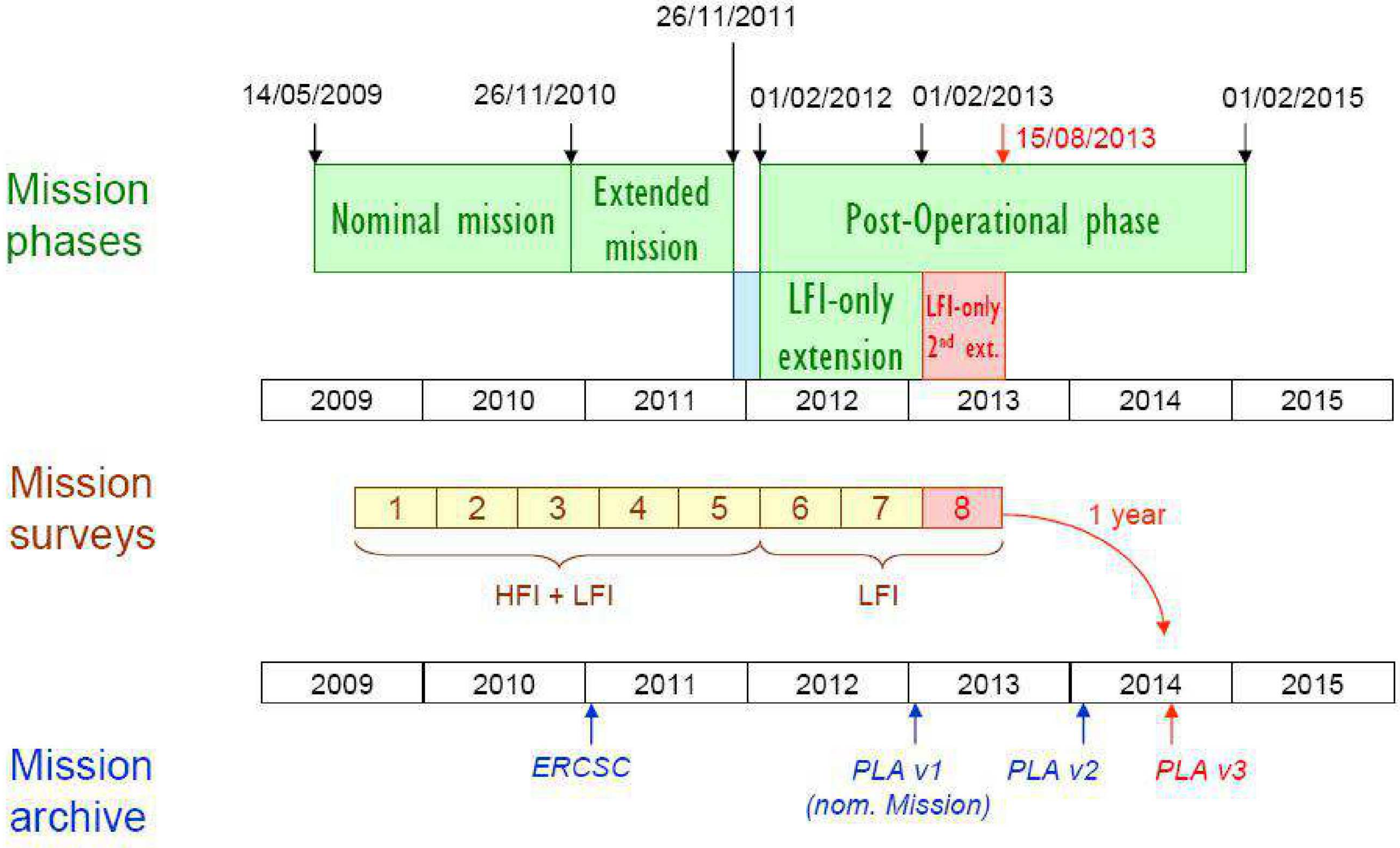


The Planck mission

14 May 2009
13:12:02 UTC



Planck’s operational timeline



26/11/2011

14/05/2009

26/11/2010

01/02/2012

01/02/2013

15/08/2013

01/02/2015

Mission phases

Nominal mission

Extended mission

Post-Operational phase

LFI-only extension

LFI-only 2nd ext.

2009 2010 2011 2012 2013 2014 2015

Mission surveys

1 2 3 4 5 6 7 8

1 year

HFI + LFI

LFI

2009 2010 2011 2012 2013 2014 2015

Mission archive

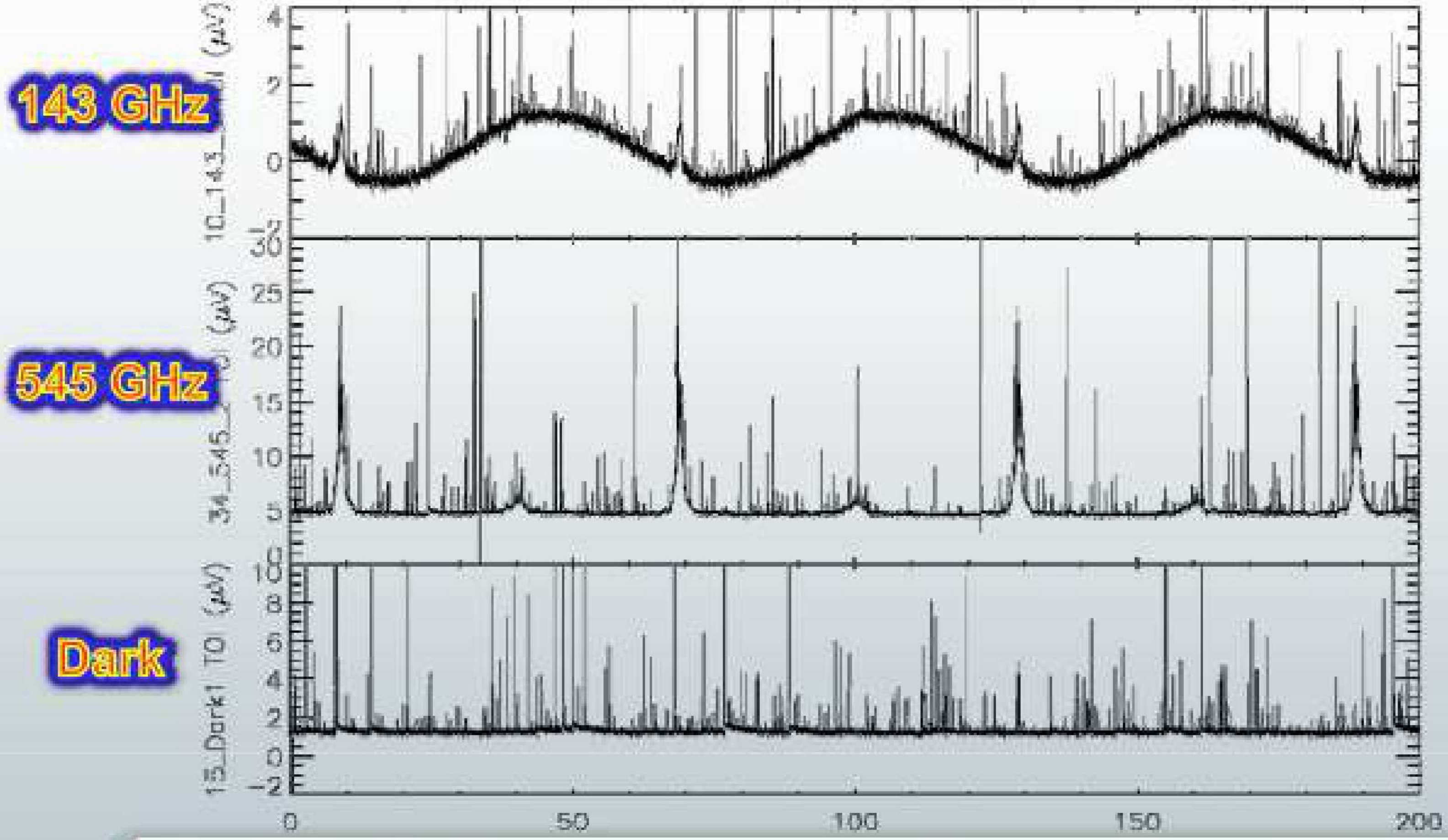
ERCSC

PLA v1 (nom. Mission)

PLA v2

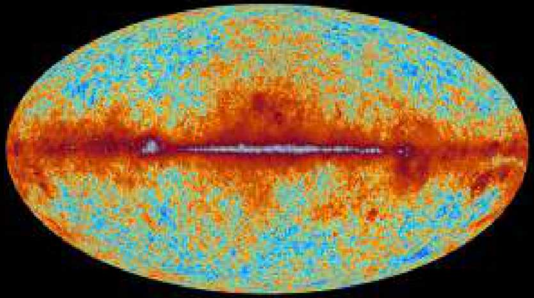
PLA v3

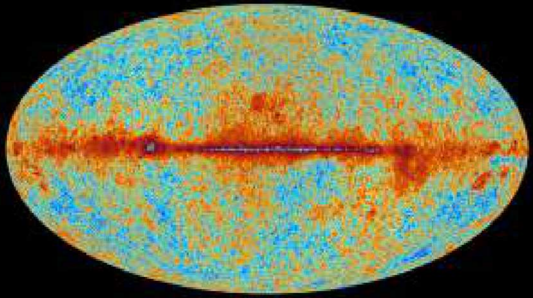
Raw data stream

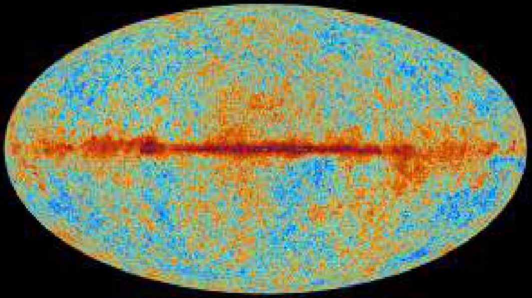


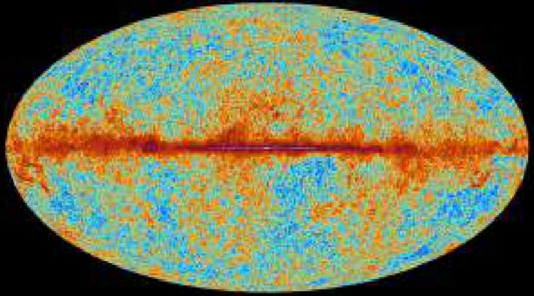
3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

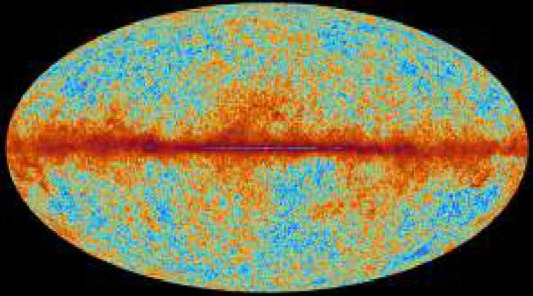
The sky as seen by Planck

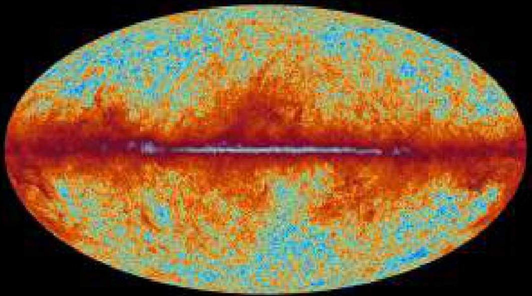

30 GHz

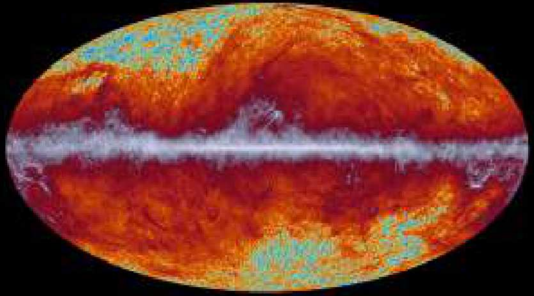

44 GHz

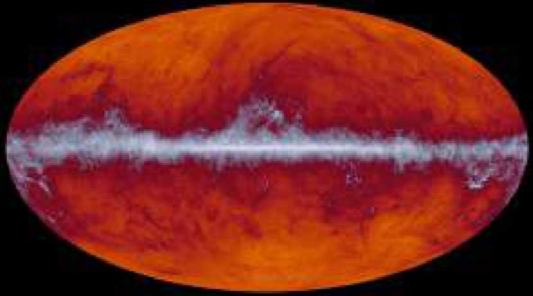

70 GHz

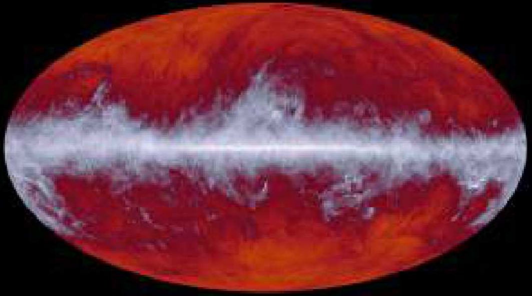

100 GHz


143 GHz


217 GHz

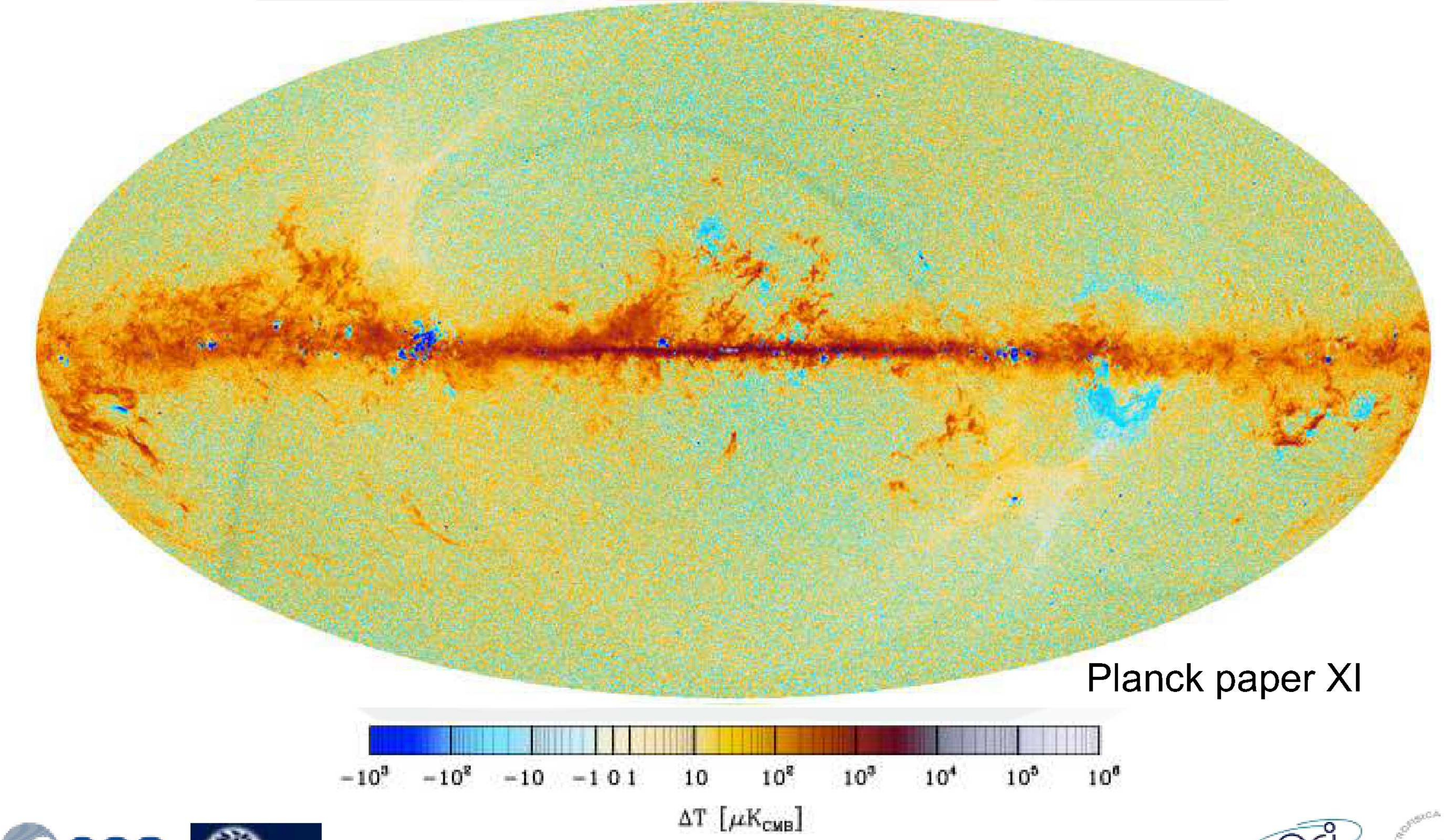

353 GHz


545 GHz


857 GHz

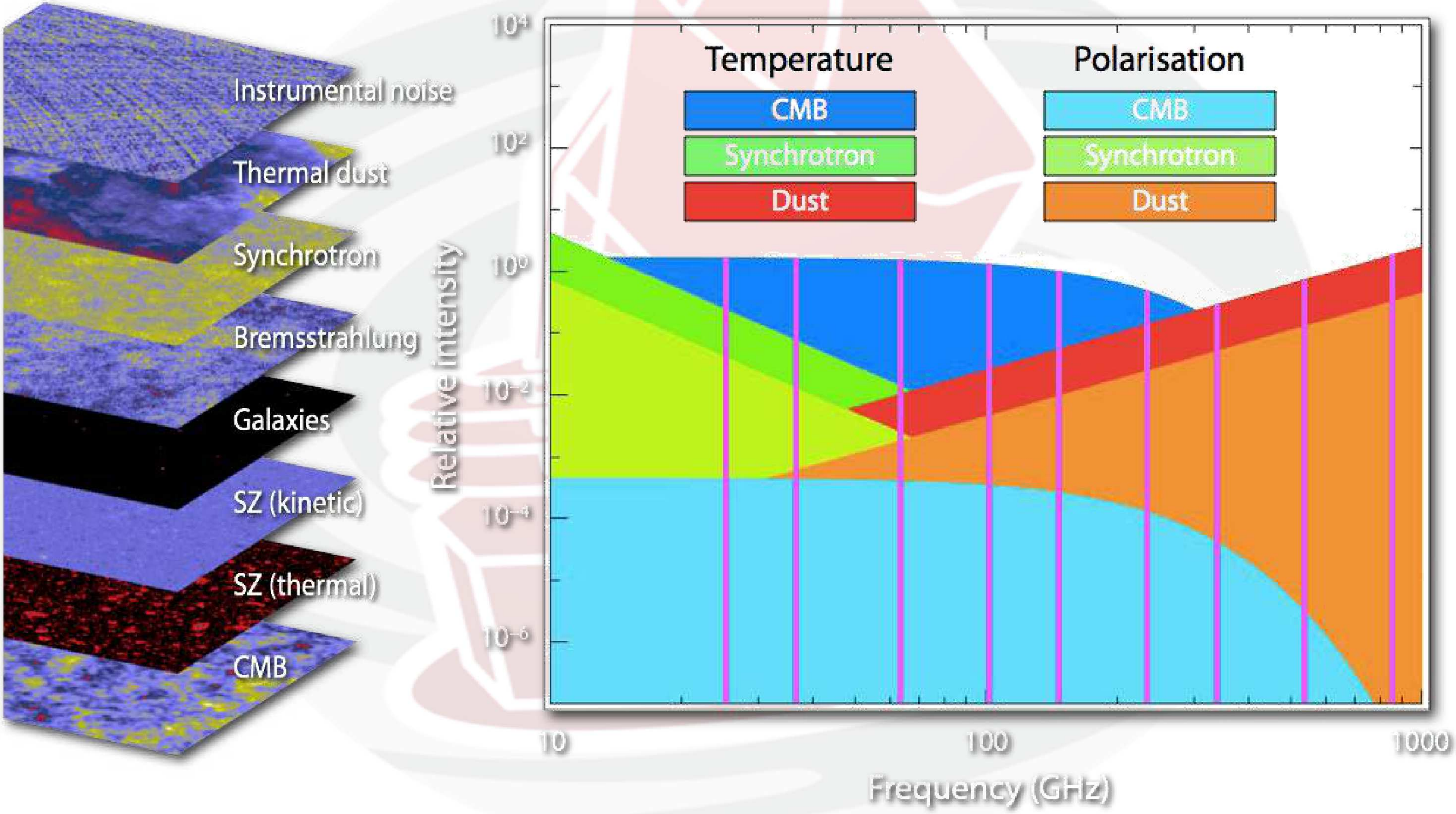
Consistency: HFI 100 GHz – LFI 70 GHz

Red is mostly CO, Blue is mostly free-free. CMB is gone!



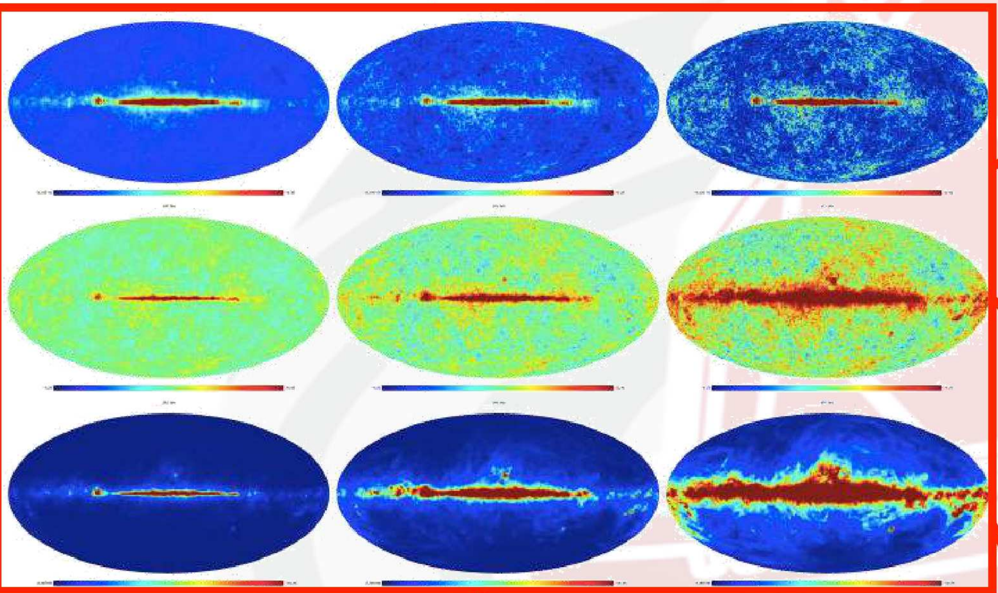
Planck paper XI

Layers on the sky

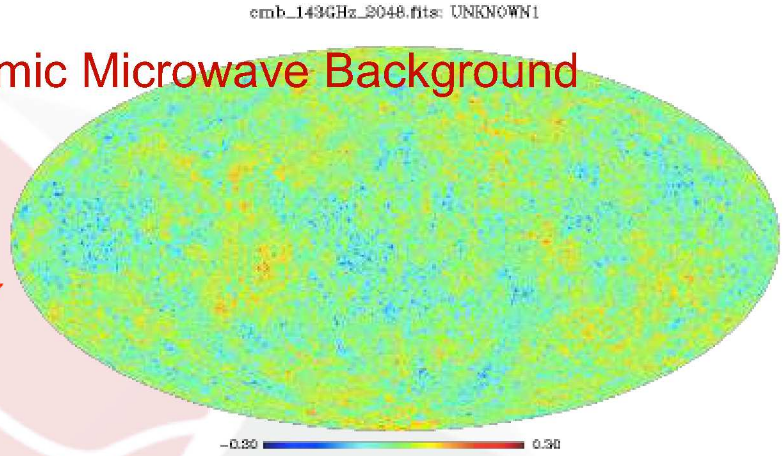


Expected results from simulations

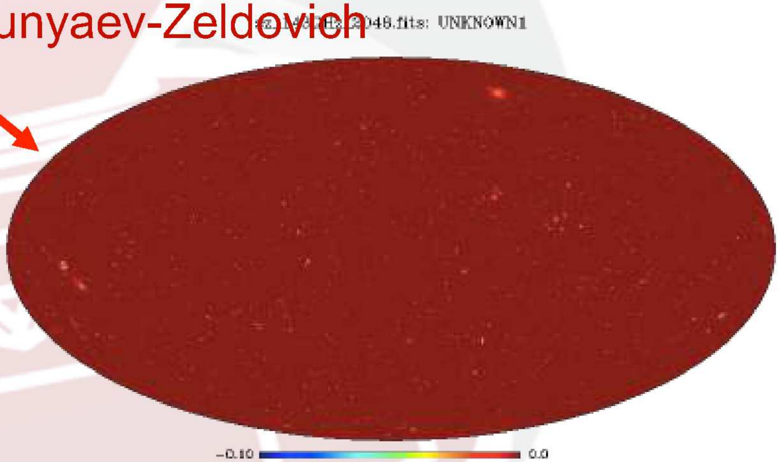
30, 44, 70, 100, 143, 217, 353, 545, 857 GHz – I, Q, U at all channels
Except 545 & 857 GHz



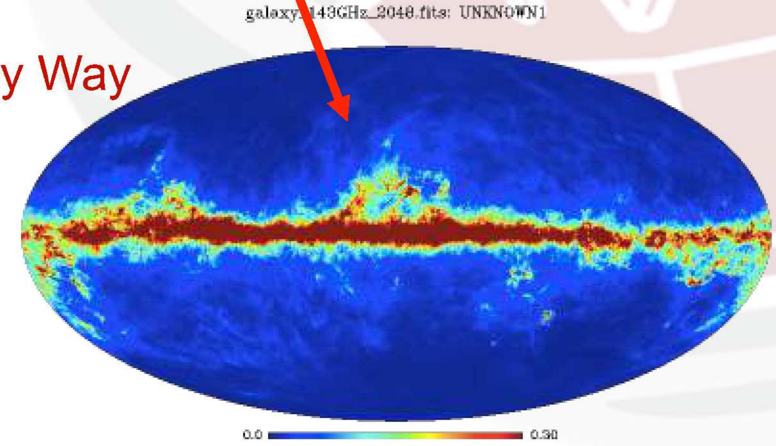
Cosmic Microwave Background



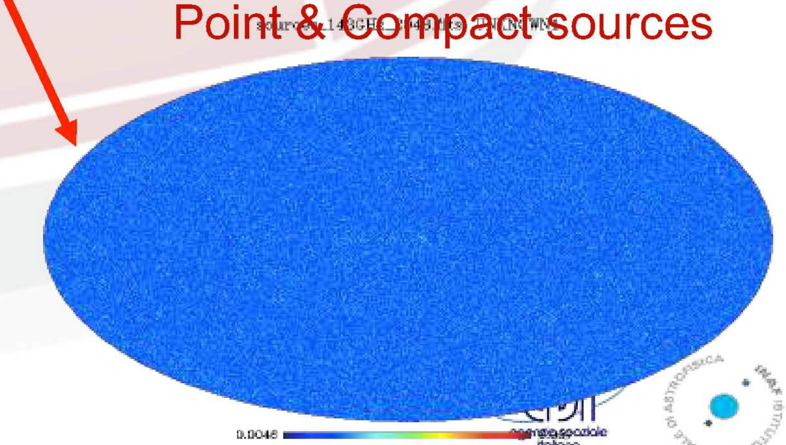
Sunyaev-Zeldovich



The Milky Way

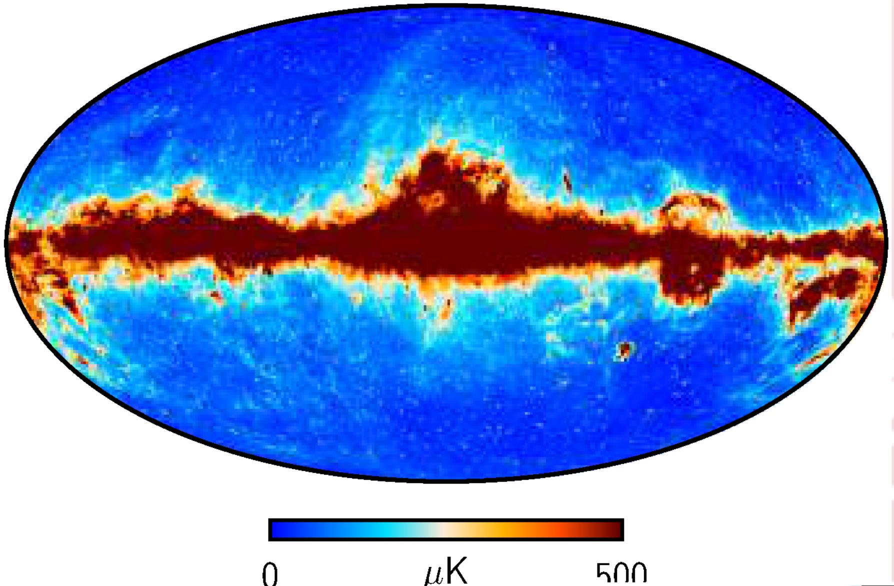


Point & Compact sources

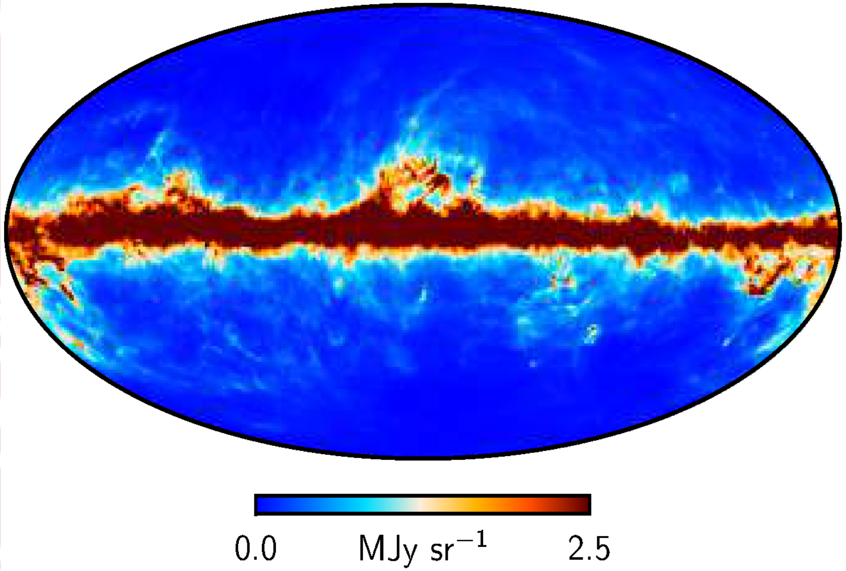


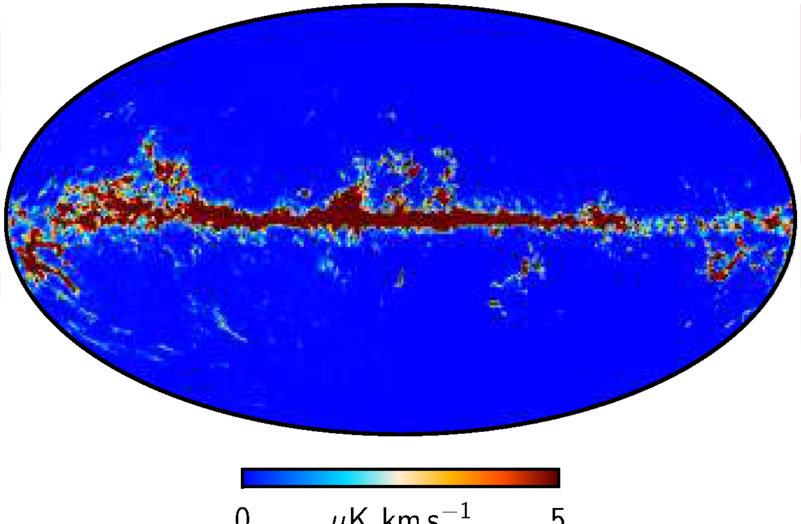
Emission from the Milky Way

Non-thermal radio emission



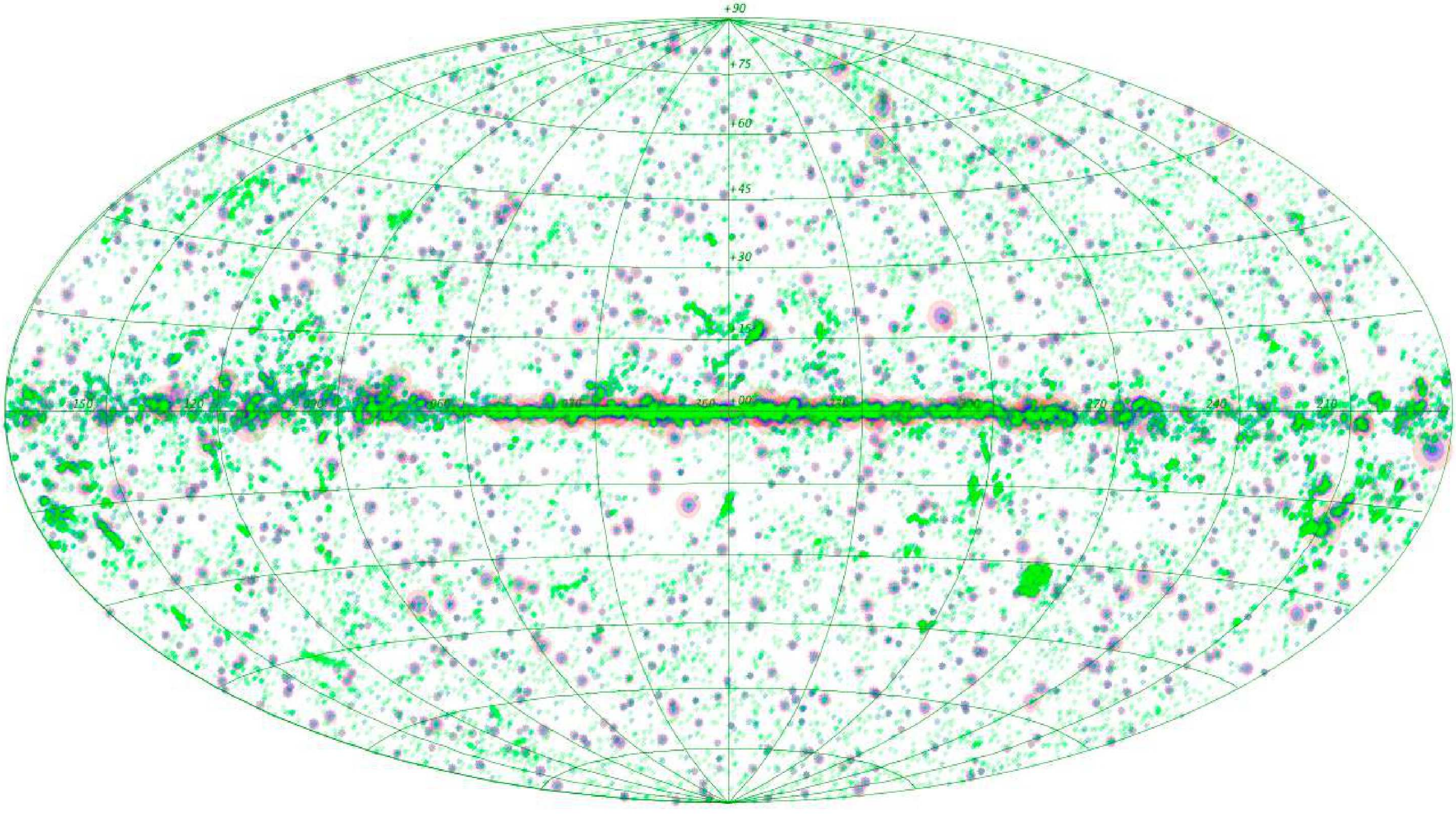
Thermal dust emission



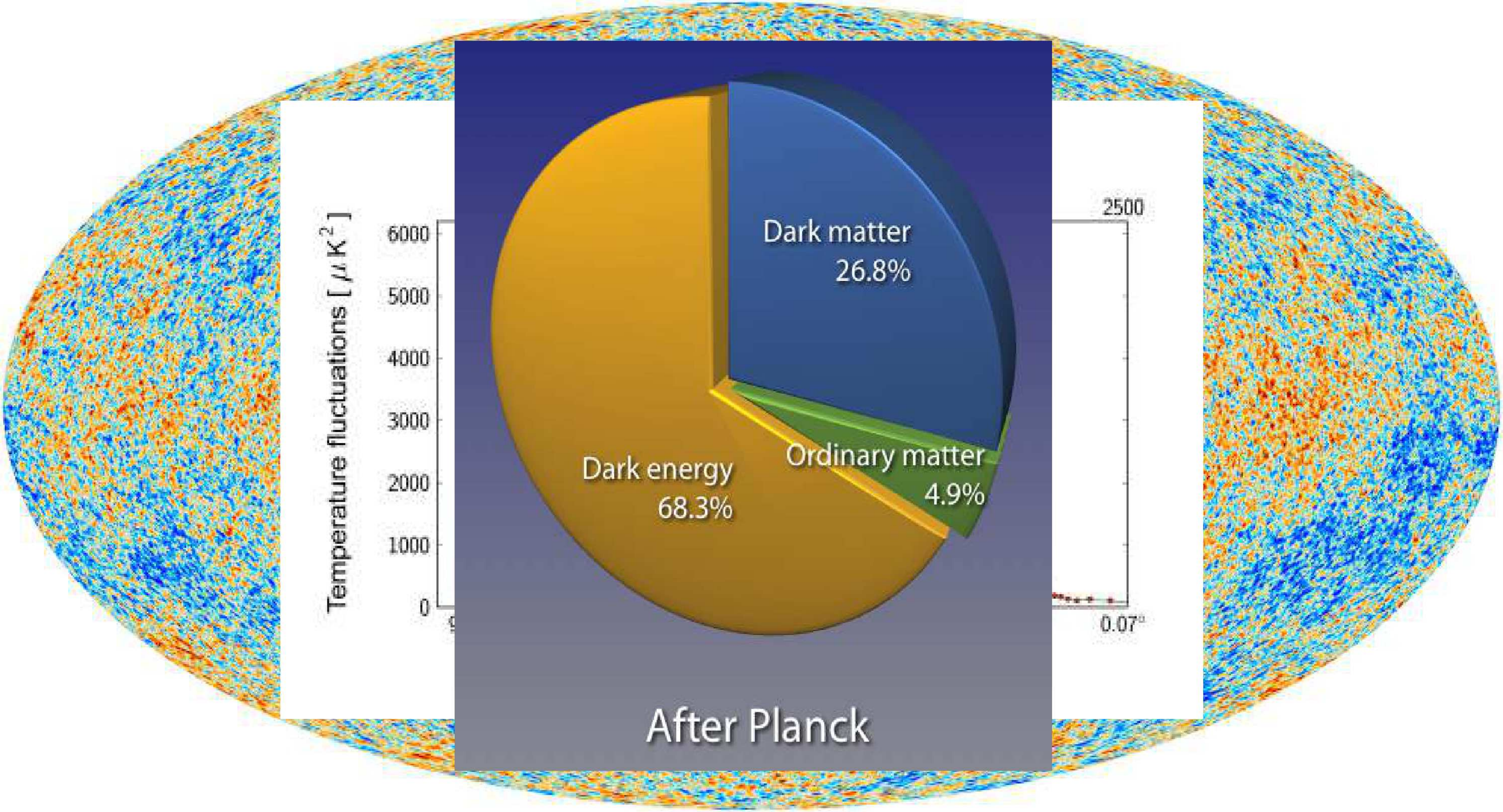


Carbon monoxide

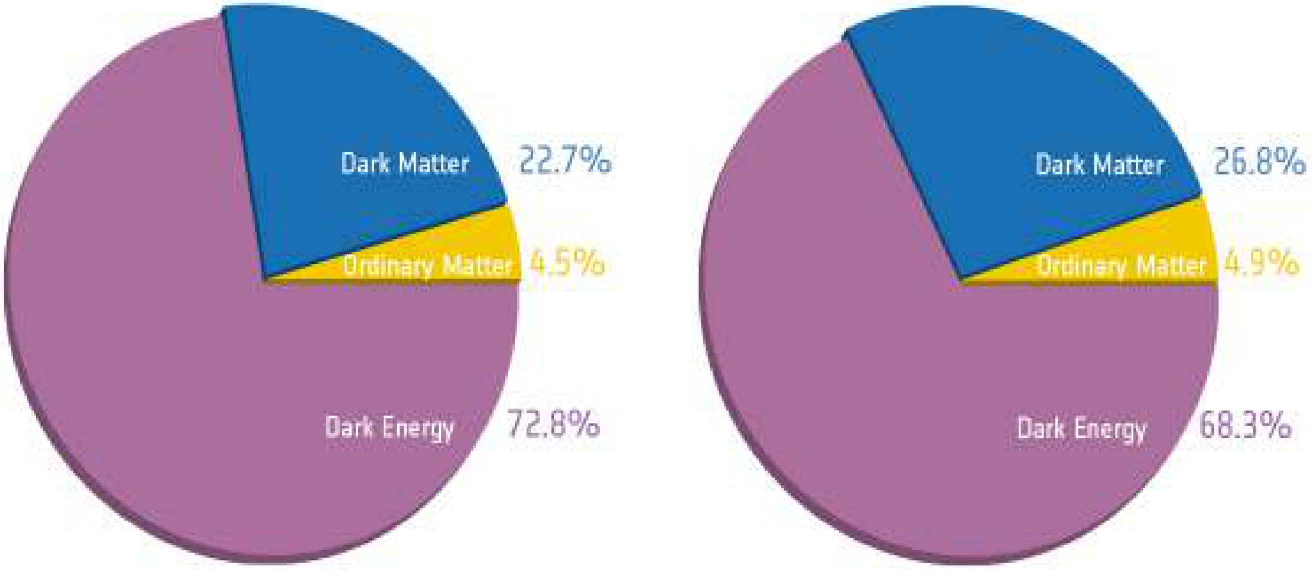
Compact galactic and extragalactic sources



The anisotropies of the CMB



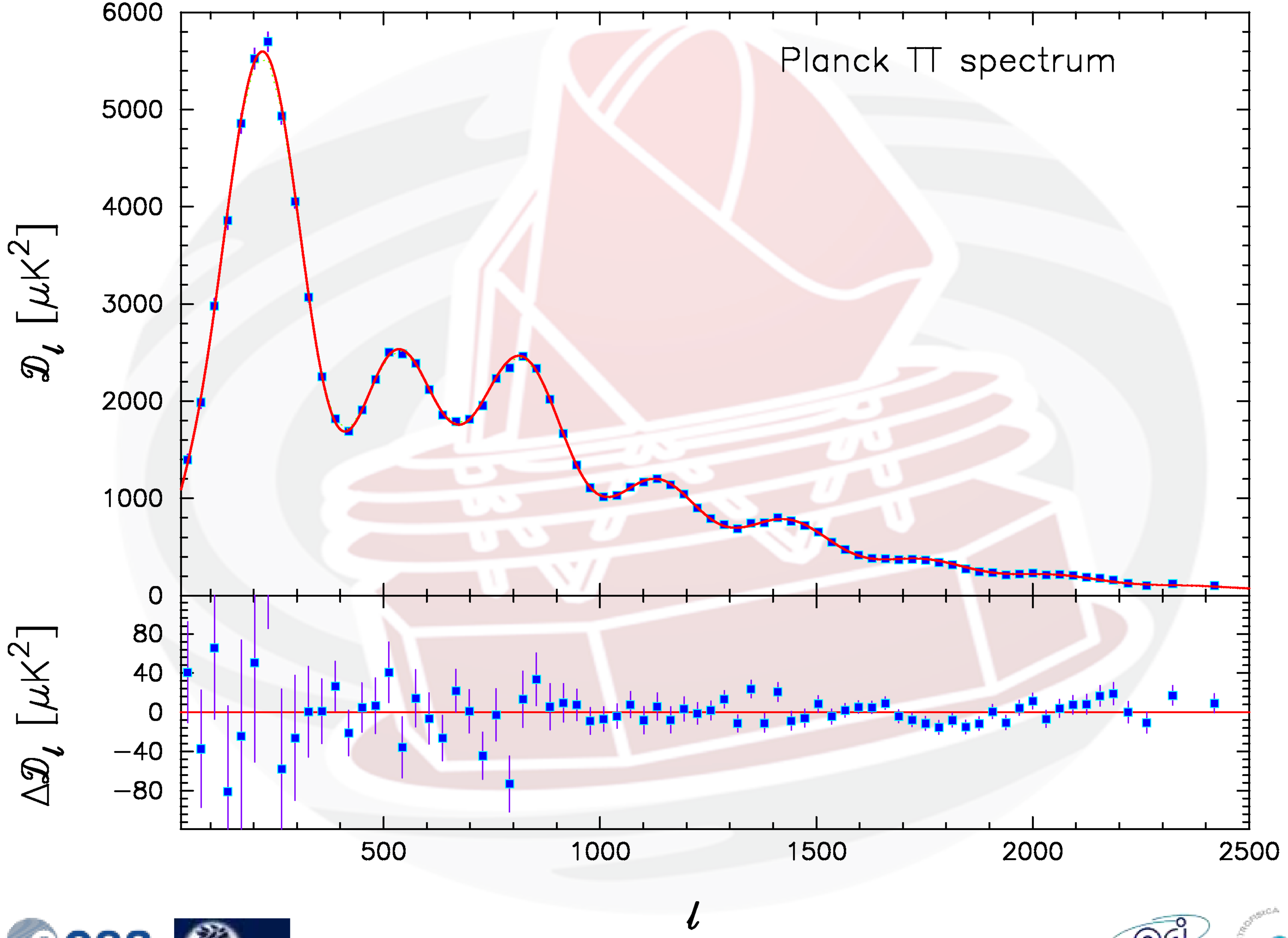
The basic content of the Universe



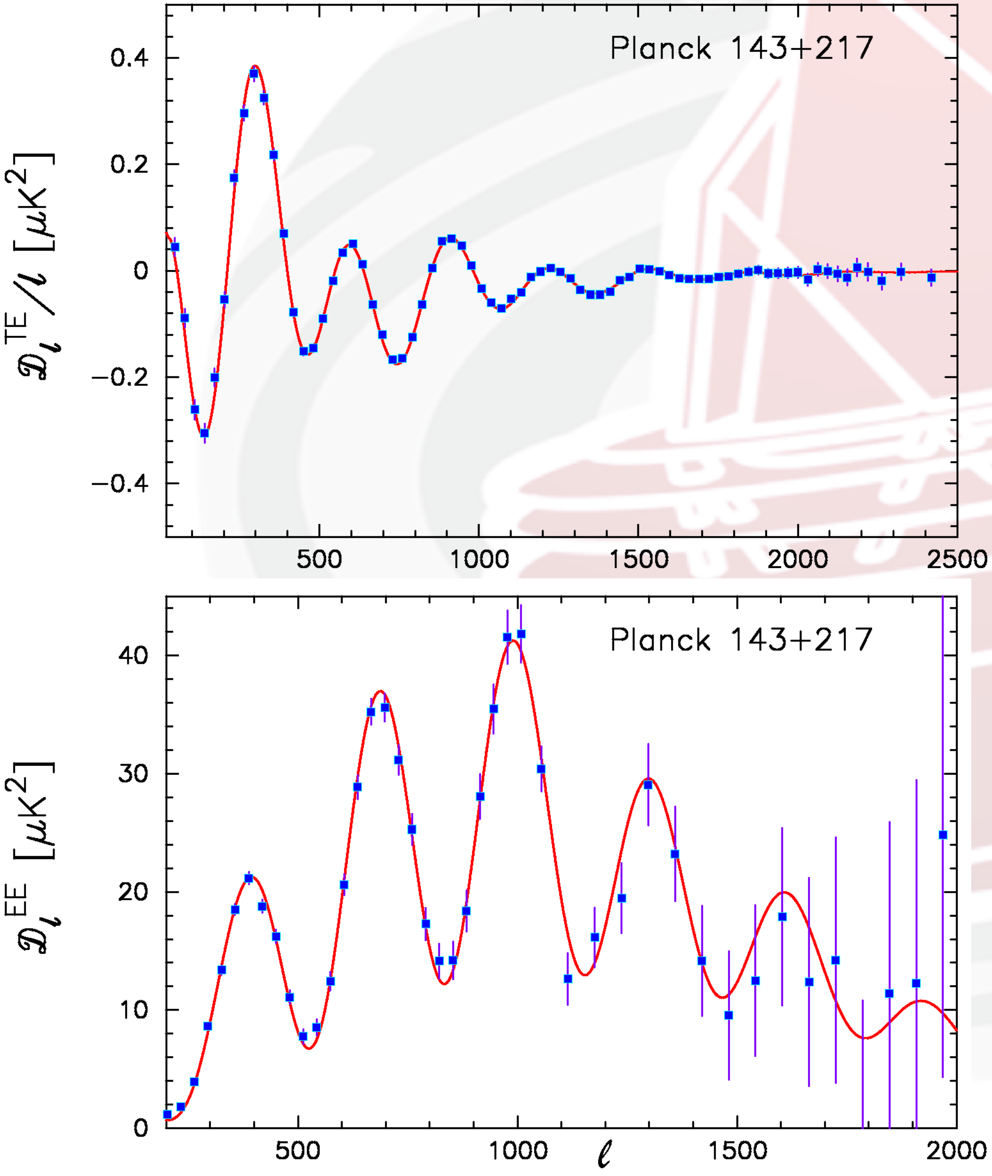
Before Planck

After Planck

...has changed!


Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
80
40
0
−40
−80
$\Delta\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
500
1000
1500
2000
2500
ℓ

CMP polarization with Planck



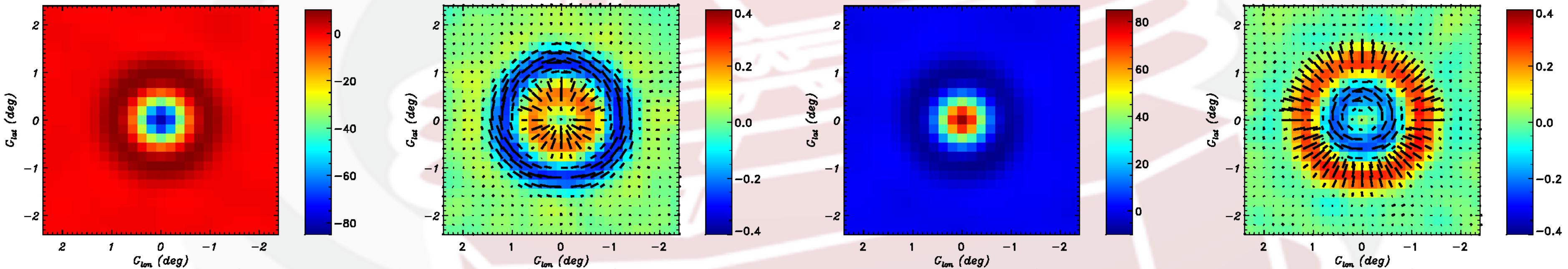
Polarization non delivered in 2013. Large angular scales need better cleaning. Small angular scale are already in good shape as shown.

The red line is not a fit to the polarization data, but the predicted curve from the ΛCDM model assuming the temperature data!

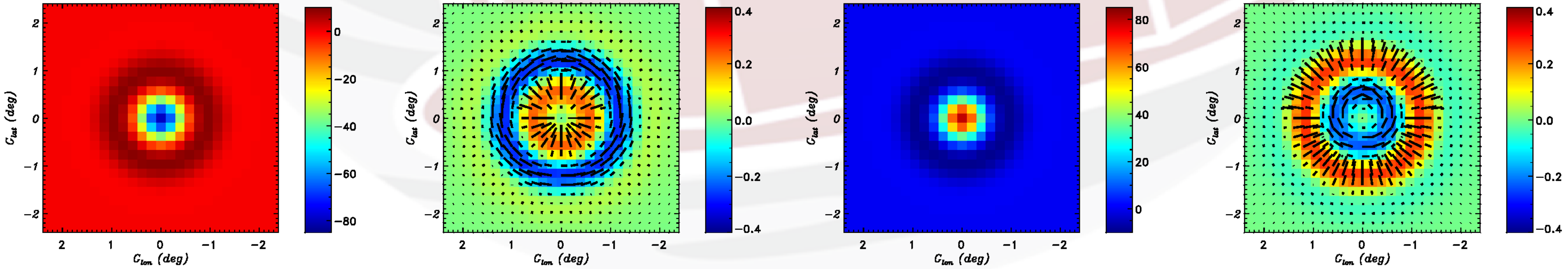
Polarization and hot spots

Stack hot/cold spots in the CMB. See the TE correlation in real space!

Remarkable proof of inflation: existence of super-horizon fluctuations



Intensity (cold spots) Q$_r$ (cold spots) Intensity (hot spots) Q$_r$ (hot spots)



The ΛCDM model of the Universe

ΛCDM = « Lambda-cold-dark-matter » model

- General Relativity [lots of laboratory test]
- Isotropic and homogeneous Universe [CMB, Copernican principle]
- Expanding space (hot big bang) → **H_0** ($h = H_0/[100\mathrm{km/s/Mpc}]$)
- Contents:
  - Ordinary (baryonic) matter → **Ω_b** [probes the physics of early universe]
  - Cold dark matter → **Ω_c** [galaxy rotation curves, slows down expansion]
  - Dark energy → **Ω_Λ** [distance scale measurements, accelerated expansion]
- Small Gaussian initial fluctuations → **A_s** (amplitude), **n_s** (tilt) [inflation]
- Space is flat → $\Omega_b + \Omega_c + \Omega_\Lambda = 1$ [inflation]
- Late-time reionization → **τ** → **6 parameters in total** [τ is WMAP provided for now]

BASE ΛCDM MODEL (Planck + WP + HL) - 2013

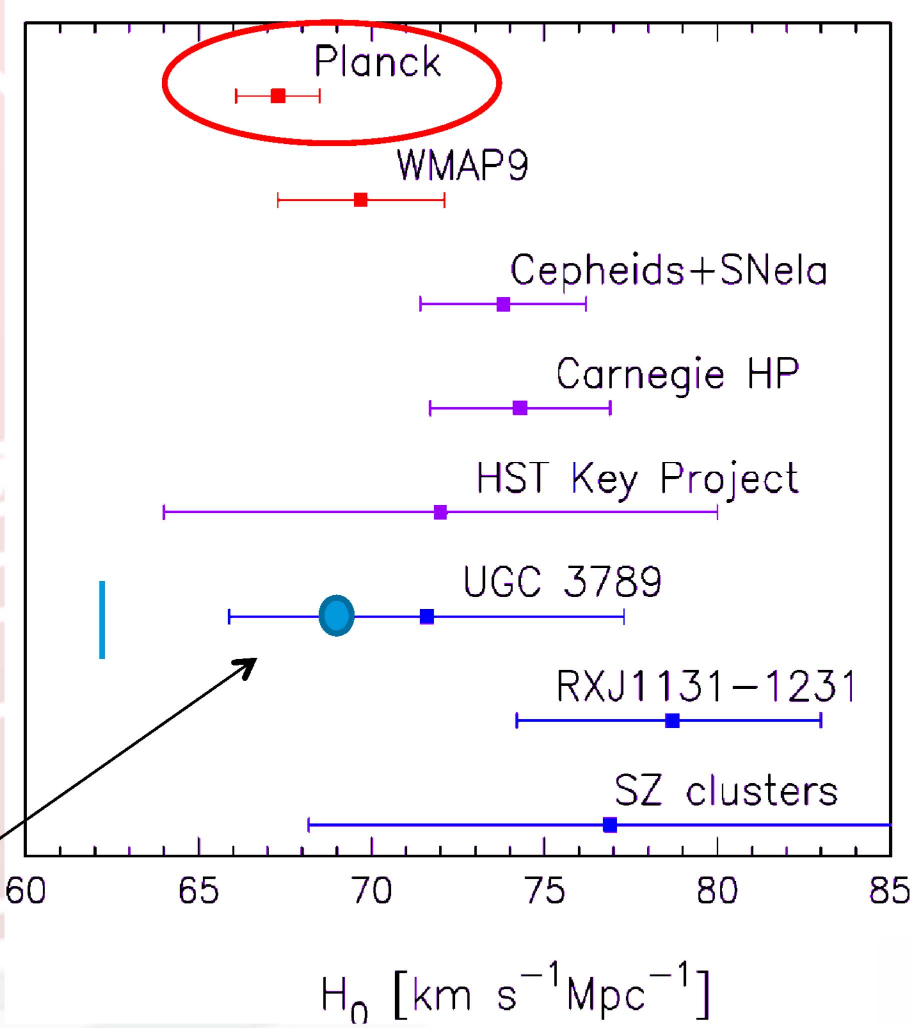
Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)
H_0	67.3±1.2 (is it low?)
Ω_Λ	0.685±0.017
σ_8	0.828±0.012
z_{re}	11.1±1.1

Tension with Hubble Constant astrophysical measurements

Planck value for the Hubble constant is in at tension with several other measurements (most notably the HST determination).

Systematics in luminosity distance measurements can be clearly there, however this tension could be also hinting towards new physics.

The determination of H0 from Planck is indeed **model dependent**.



UGC 3789 distance recalibrated, now $H_0 = 68.9 \pm 7.1$ Km/s/Mpc

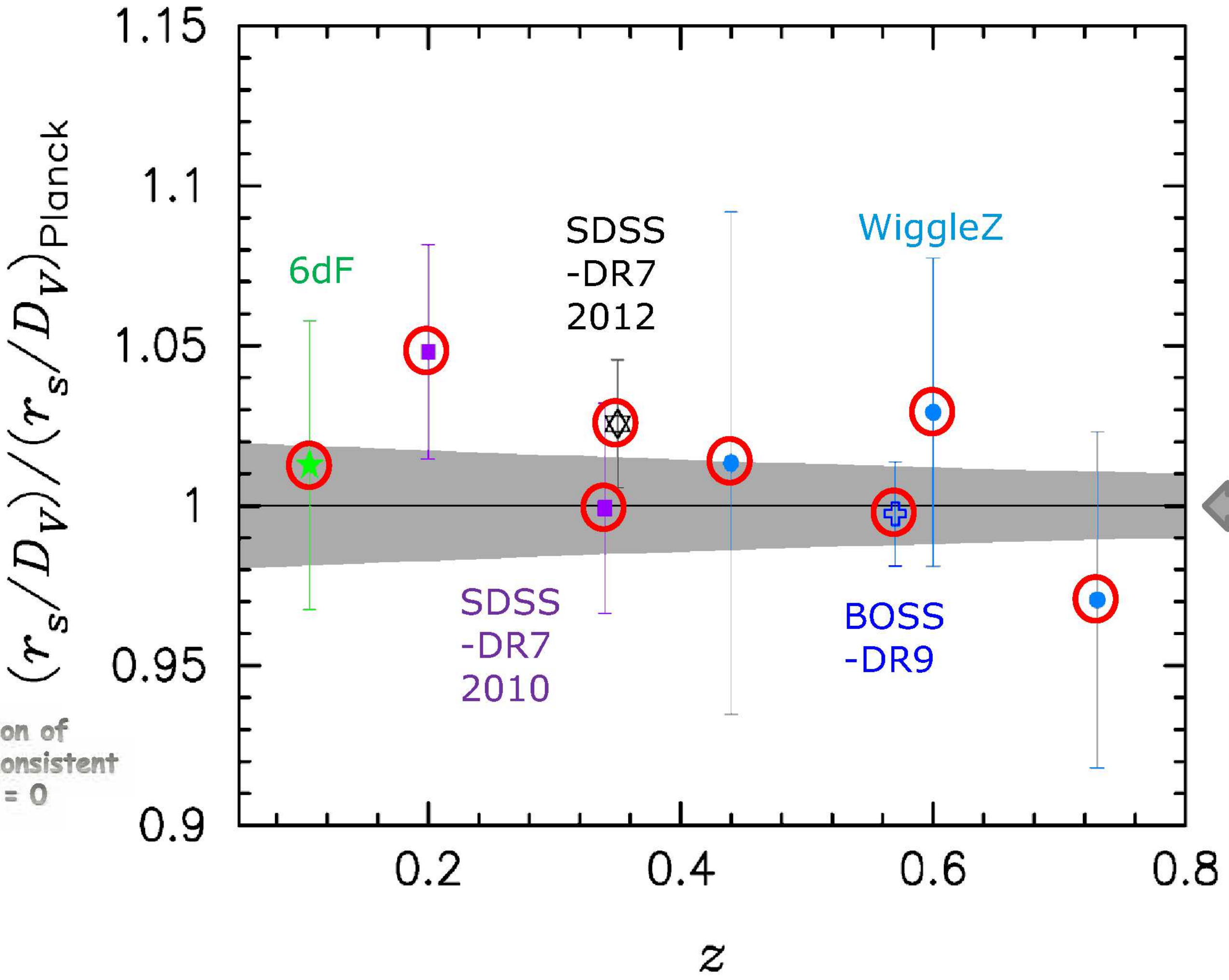
The Megamaser Cosmology Project: IV. A Direct Measurement of the Hubble Constant from UGC 3789

M. J. Reid, J. A. Braatz, J. J. Condon, K. Y. Lo, C. Y. Kuo, C. M. V. Impellizzeri, C. Henkel

(Submitted on 31 Jul 2012 (v1), last revised 22 Feb 2013 (this version, v2))

In Papers I and II from the Megamaser Cosmology Project (MCP), we reported initial observations of water masers in an accretion disk of a supermassive black hole at the center of the galaxy UGC 3789, which gave an angular-diameter distance to the galaxy and an estimate of Ho with 16% uncertainty. We have since conducted more VLBI observations of the spatial-velocity structure of these water masers, as well as continued monitoring of its spectrum to better measure maser accelerations. These more extensive observations, combined with improved modeling of the masers in the accretion disk of the central supermassive black hole, confirm our previous results, but with signifcantly improved accuracy. We find Ho = 68.9 +/- 7.1 km/s/Mpc; this estimate of Ho is independent of other methods and is accurate to +/-10%, including sources of systematic error. This places UGC 3789 at a distance of 49.6 +/- 5.1 Mpc, with a central supermassive black hole of (1.16 +/- 0.12) x 10^7 Msun.

BAO scale distance ratio



Planck
Prediction
(shaded area)

→ Planck & BAO are in tight agreement (and thus can be used jointly)

DE equation of state is consistent with 1+w = 0

Further tests of the standard model

- Sum of neutrino masses:
  - We know that neutrinos are massive (oscillations)
  - Minimum possible sum mass is around 0.07 eV
  - Planck: **no detection**, limit from all data is 0.23 eV
- Extra particles? **N_{eff} consistent with 3 neutrinos only, $N_{eff} < 4$ at 95%**
- Is 'Λ' really a cosmological constant ? **Consistent with $p = -W\rho$**
- Topology of the universe: **limits close to horizon size**
- decaying dark matter, varying constants: **no detections**
- tests of assumptions (isotropy, Gaussianity): **strong limits**, **some anomalies**
- **Tensor fluctuations: $r < 0.11$ (from temperature, model dependent, no B mode polarization so far). See later Bicep2 claim.**
- Tests of initial conditions for perturbations: **no surprises**
- Further constraints on inflation (running spectra index, etc) …

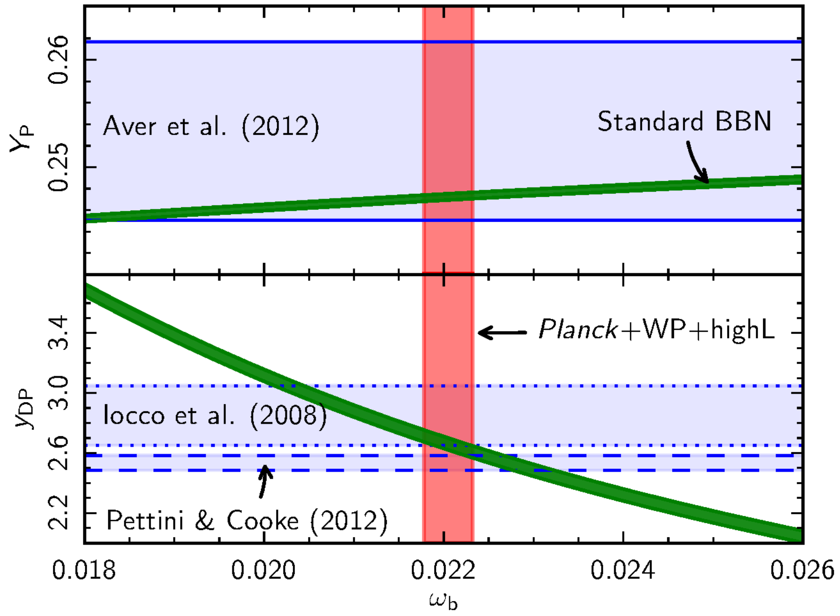
EXTENDED ΛCDM MODELS (Planck+BAO) - 2013

Parameter	Value (95%)
Ω_K	-0.0005 ± 0.0066
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30 ± 0.54
Y_P	0.267 ± 0.040
$dn_s/d\ln k$	-0.014 ± 0.017
$r_{0.002}$	<0.11
w	-1.13 ± 0.24

The first three minutes

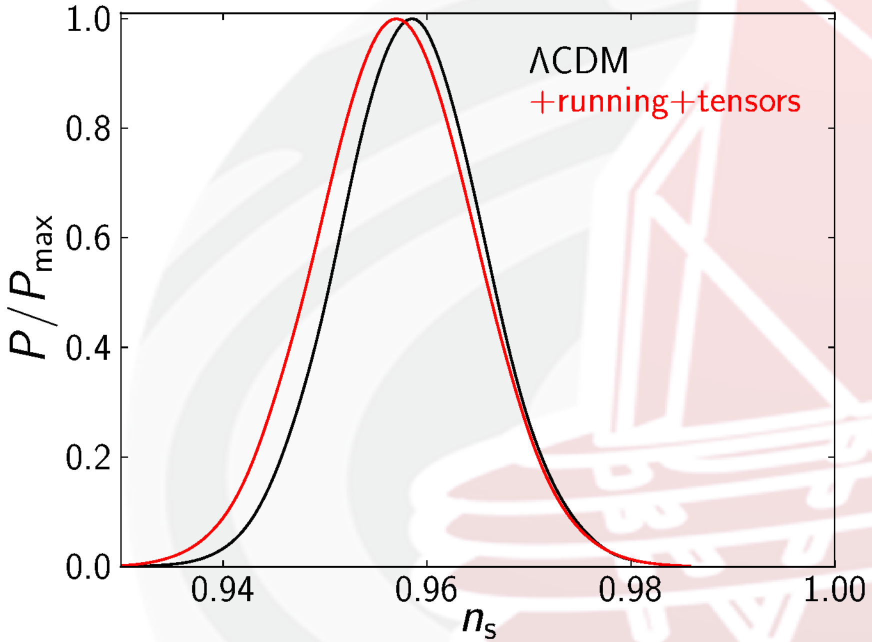
Looking into the fireball, back to the first three minutes

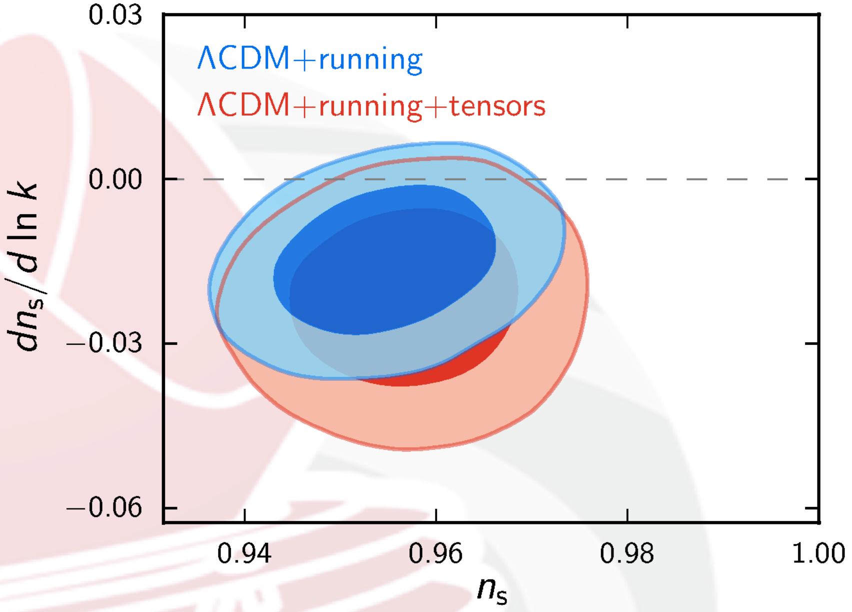
- at high energies the nuclei of heavier elements are kicked apart by the high energy photons, they can only form at ~ 0.1 MeV
- final abundance depends strongly on baryons to photon ratio
- CMB measures both, so can compare to direct observations!

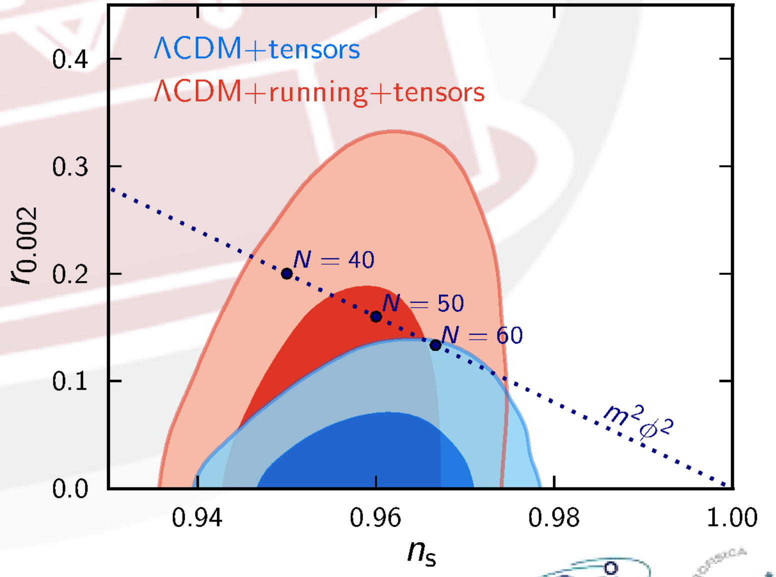


Great consistency test using known physics over most of the age of the universe!

Also tests for extra relativistic degrees of freedom, **N_{eff} = 3.36±0.34** (Planck+WP+highL, expected 3.05)

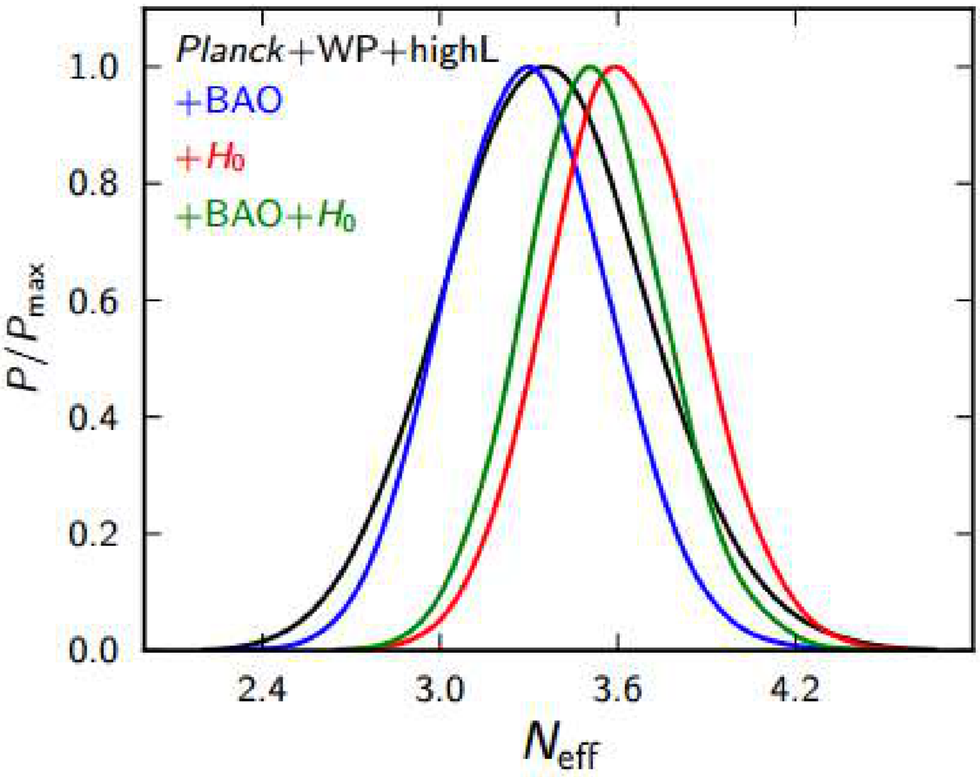

ΛCDM
+running+tensors
$P/P_{\rm max}$
1.0
0.8
0.6
0.4
0.2
0.0
0.94
0.96
0.98
1.00
$n_{\rm s}$


ΛCDM+running
ΛCDM+running+tensors
$dn_{\rm s}/d\ln k$
0.03
0.00
−0.03
−0.06
0.94
0.96
0.98
1.00
$n_{\rm s}$


ΛCDM+tensors
ΛCDM+running+tensors
$r_{0.002}$
0.4
0.3
0.2
0.1
0.0
$N = 40$
$N = 50$
$N = 60$
$m^2\phi^2$
0.94
0.96
0.98
1.00
$n_{\rm s}$

Example: extra degrees of freedom from Planck+HST ?

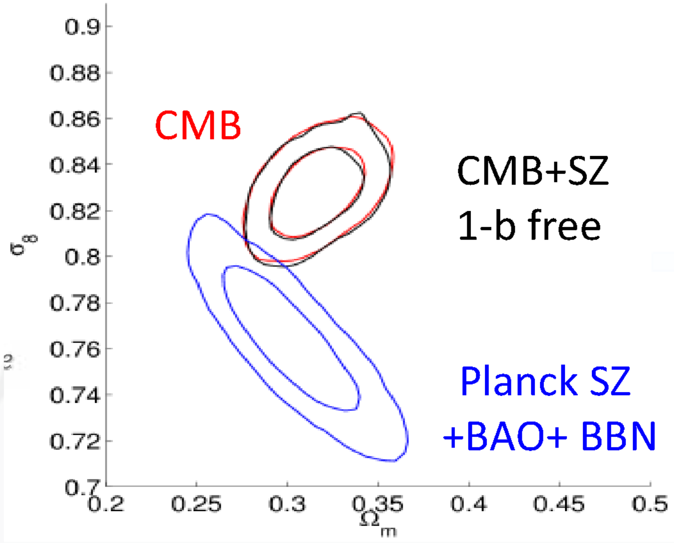
While the Planck+WP+highL dataset is consistent with the standard 3 neutrino families framework, when we include the HST value for the Hubble constant we see a preference for extra degrees of freedom at about 95% c.l. with Neff=3.6.

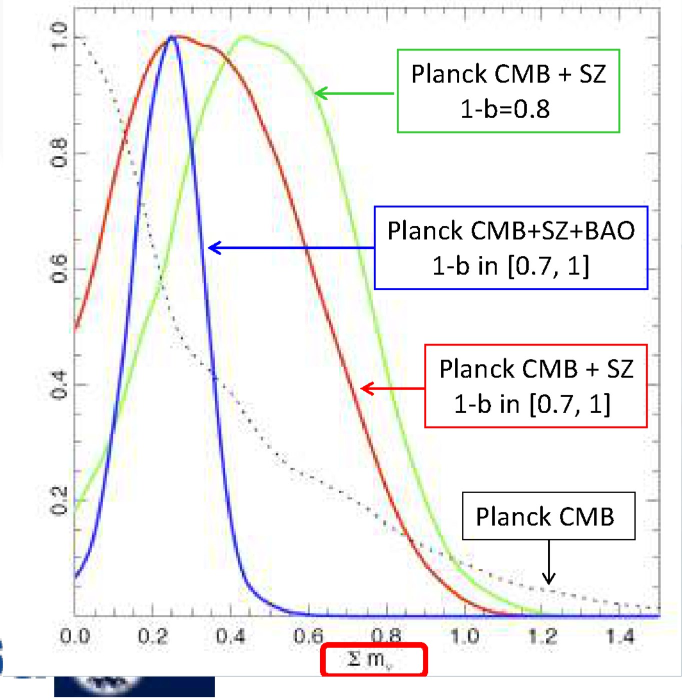


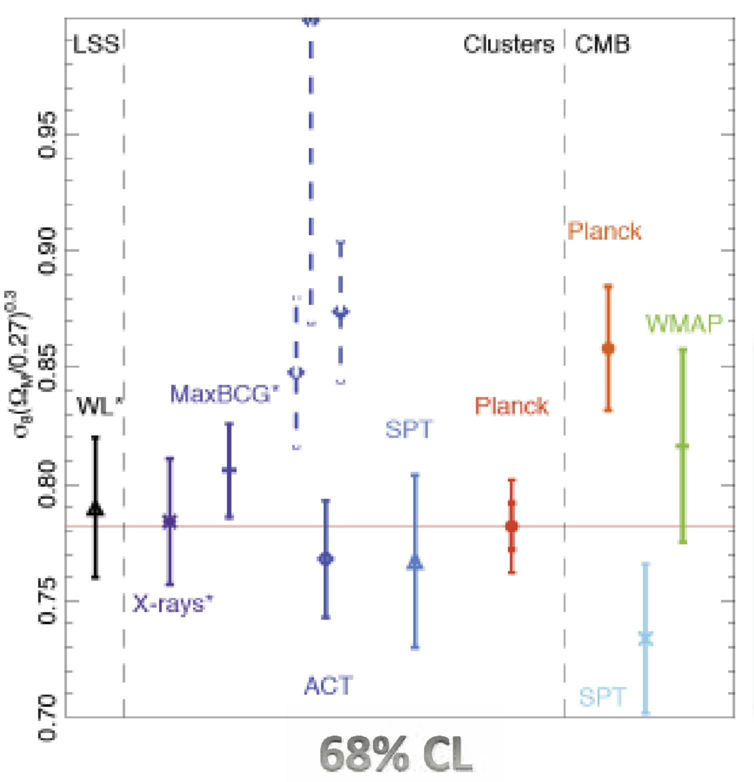
A sterile neutrino with non standard decoupling could explain this effect.

Other new physics mechanisms could explain this tension.

Planck clusters (SZ) vs CMB

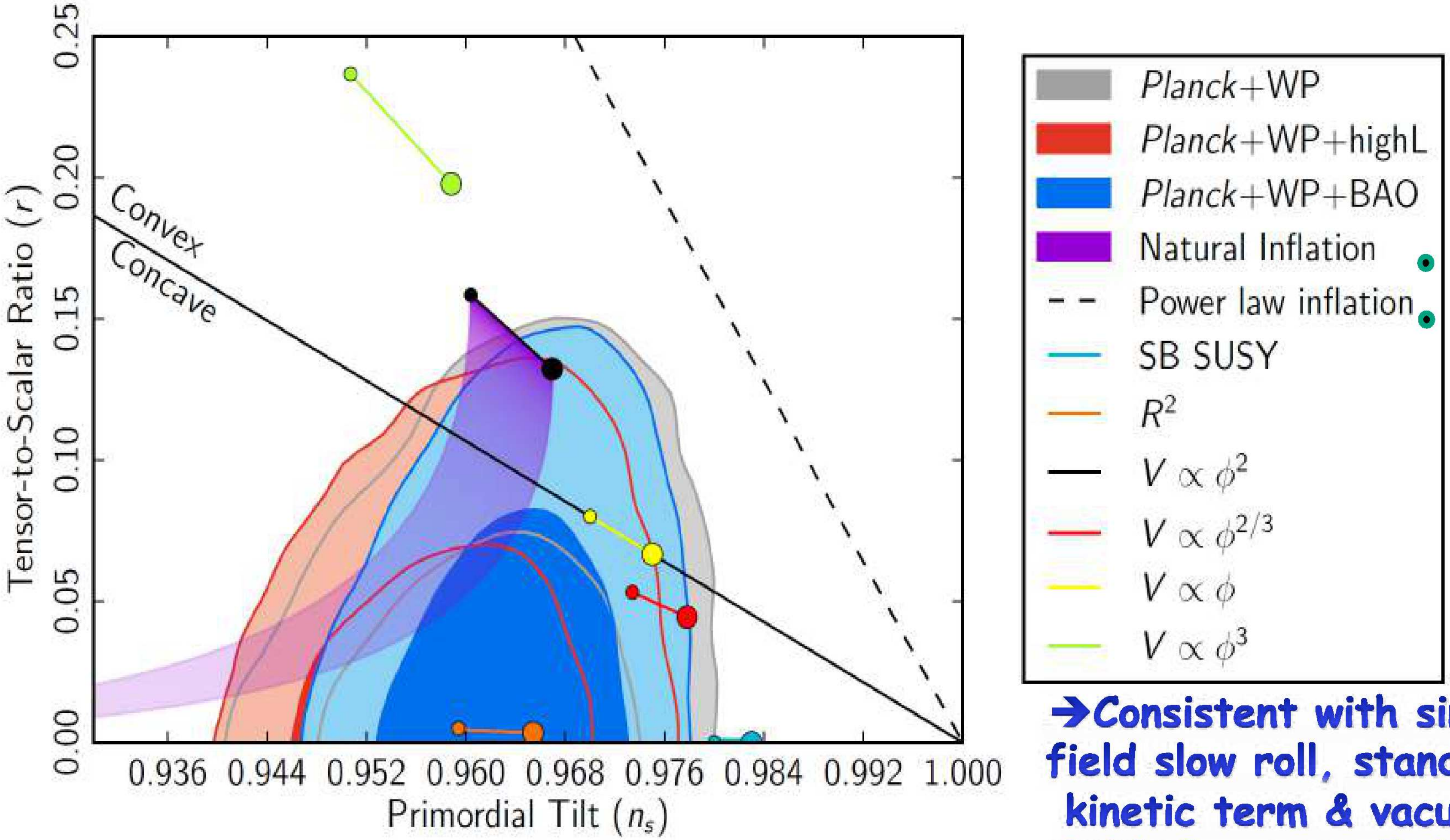






Corrected an error in Planck Cosmology from clusters paper: now m_nu > 0.06 consistently. Still a three sigma discrepancy.

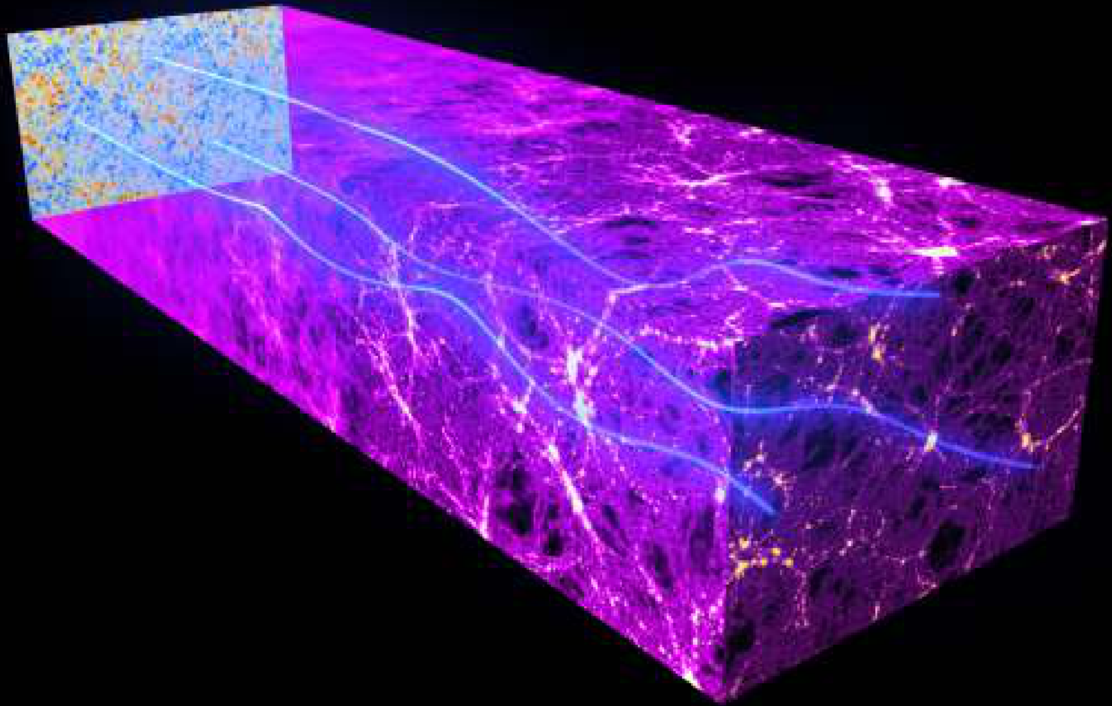
Main constraint on Inflation physics



→Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits).

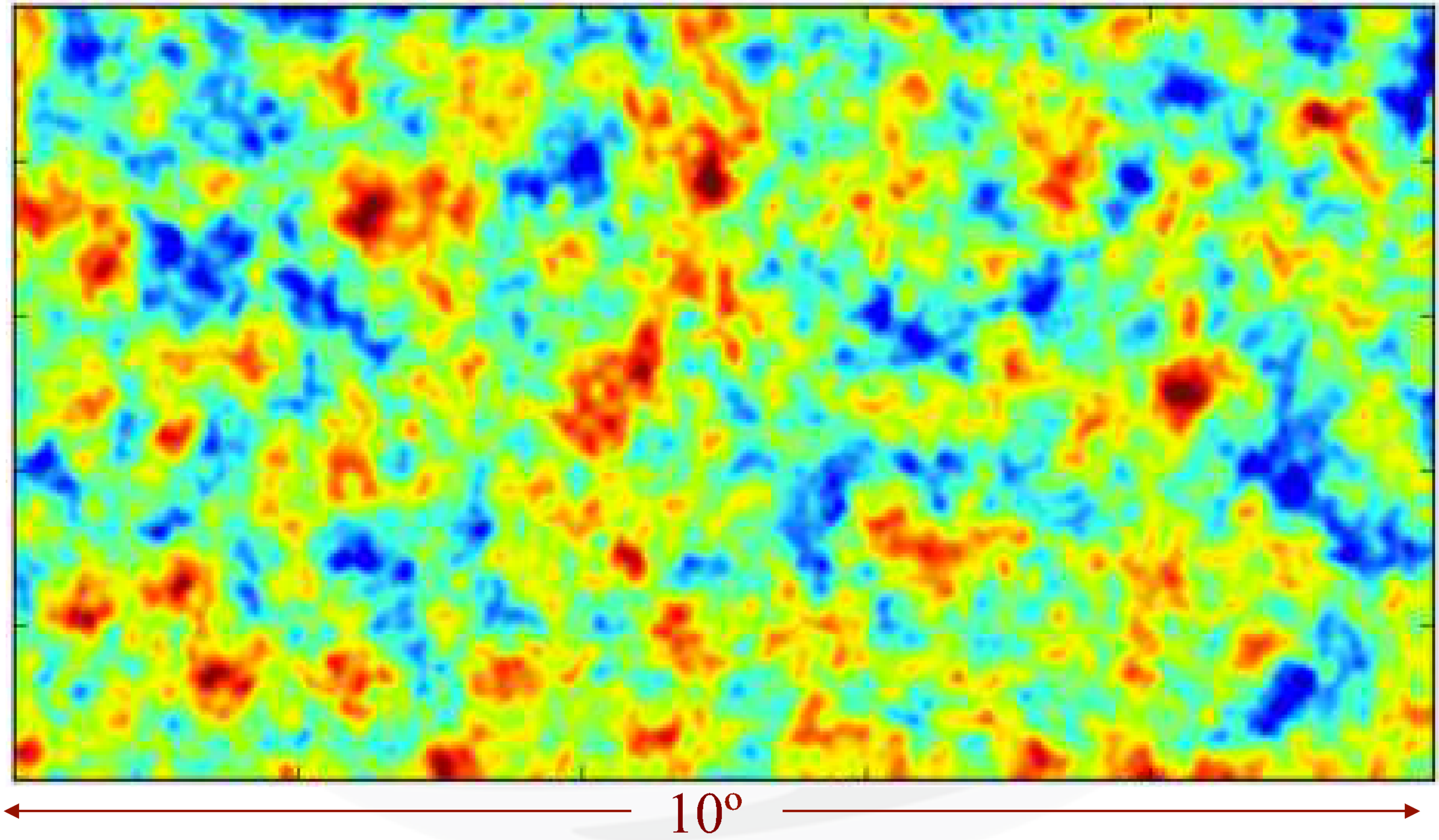
PLANCK PROBES AND EXPLOITS CMB LENSING

The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB



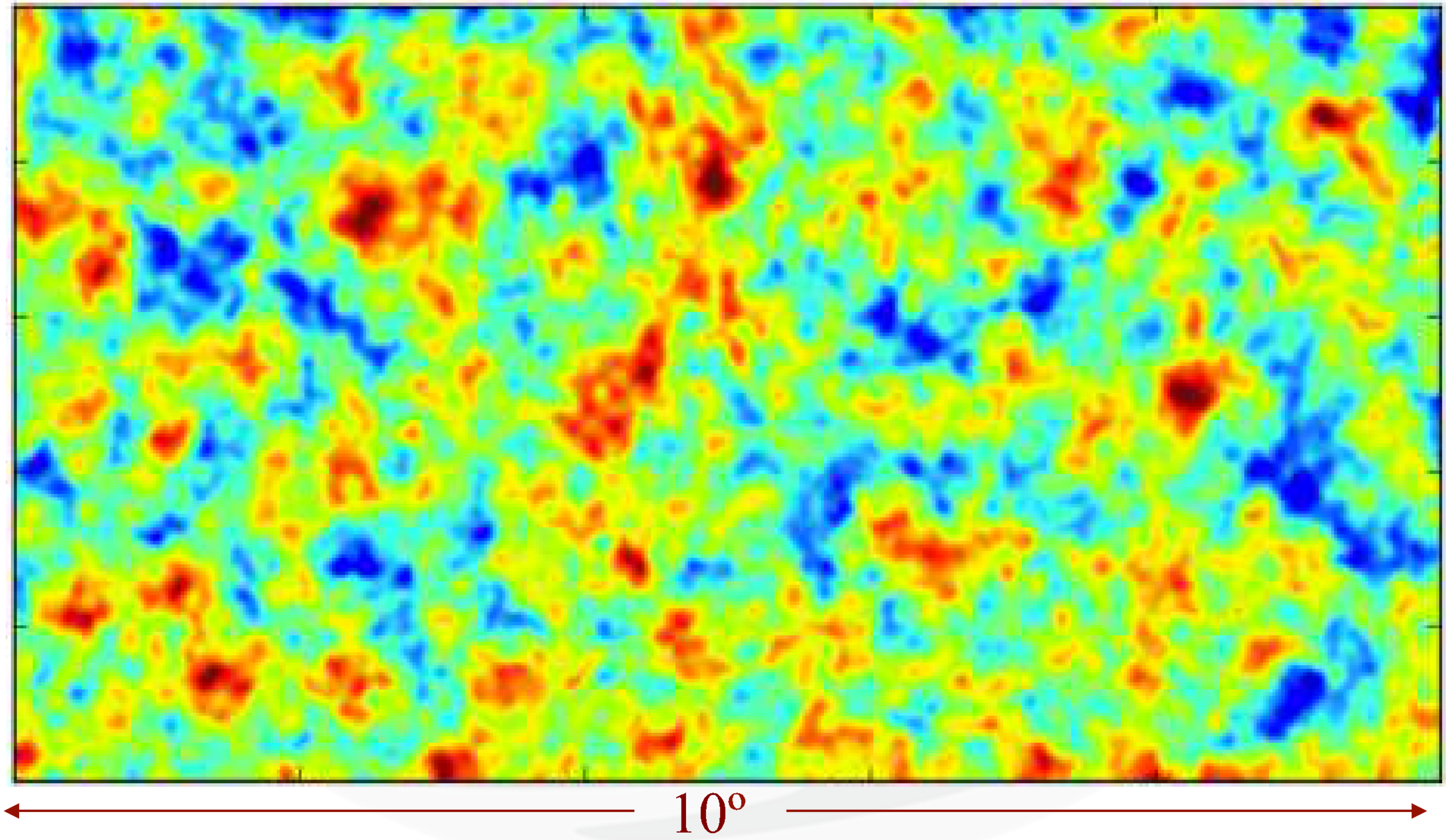
GRAVITATIONAL LENSING OF THE CMB

A simulated patch of CMB sky – **before lensing**

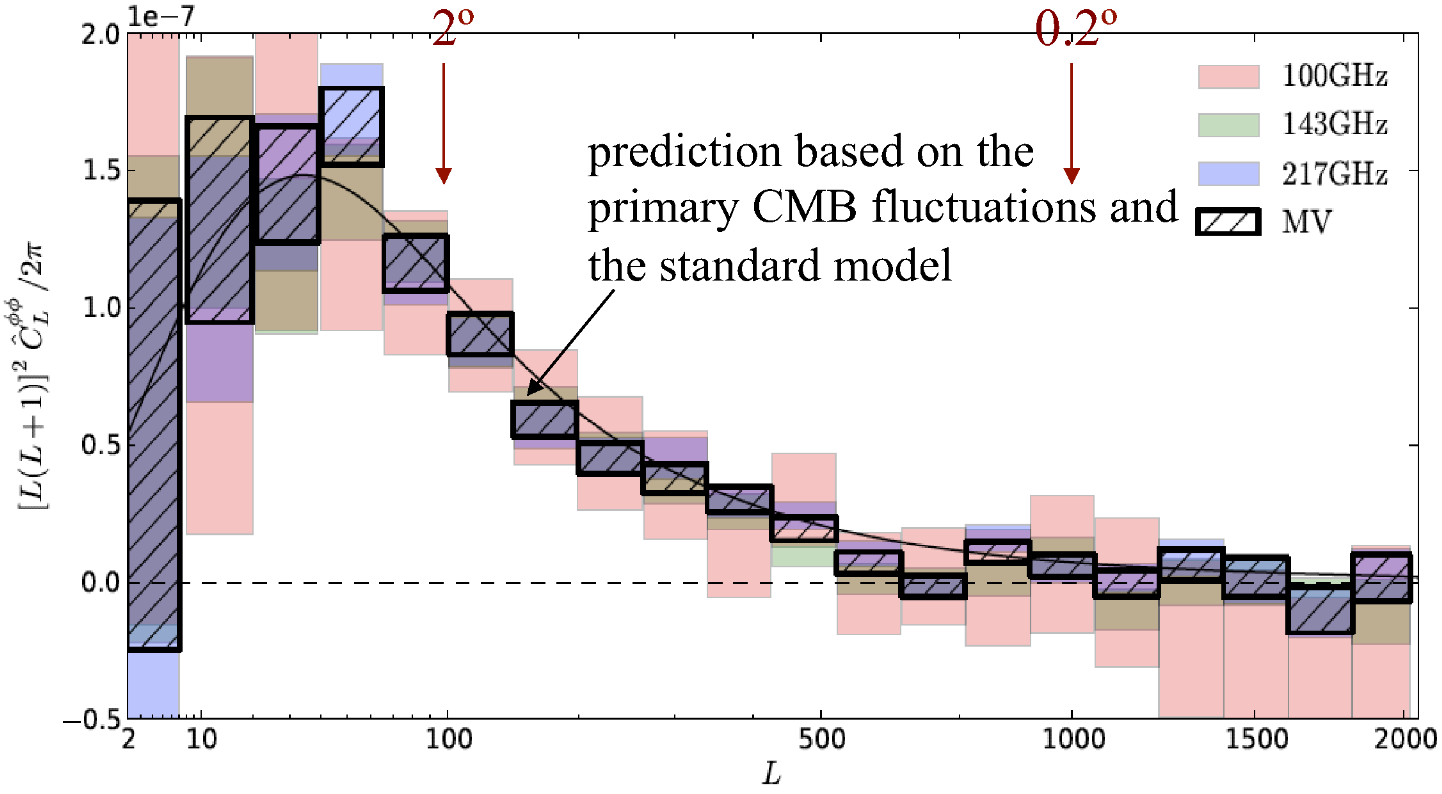


GRAVITATIONAL LENSING OF THE CMB

A simulated patch of CMB sky – **after lensing**



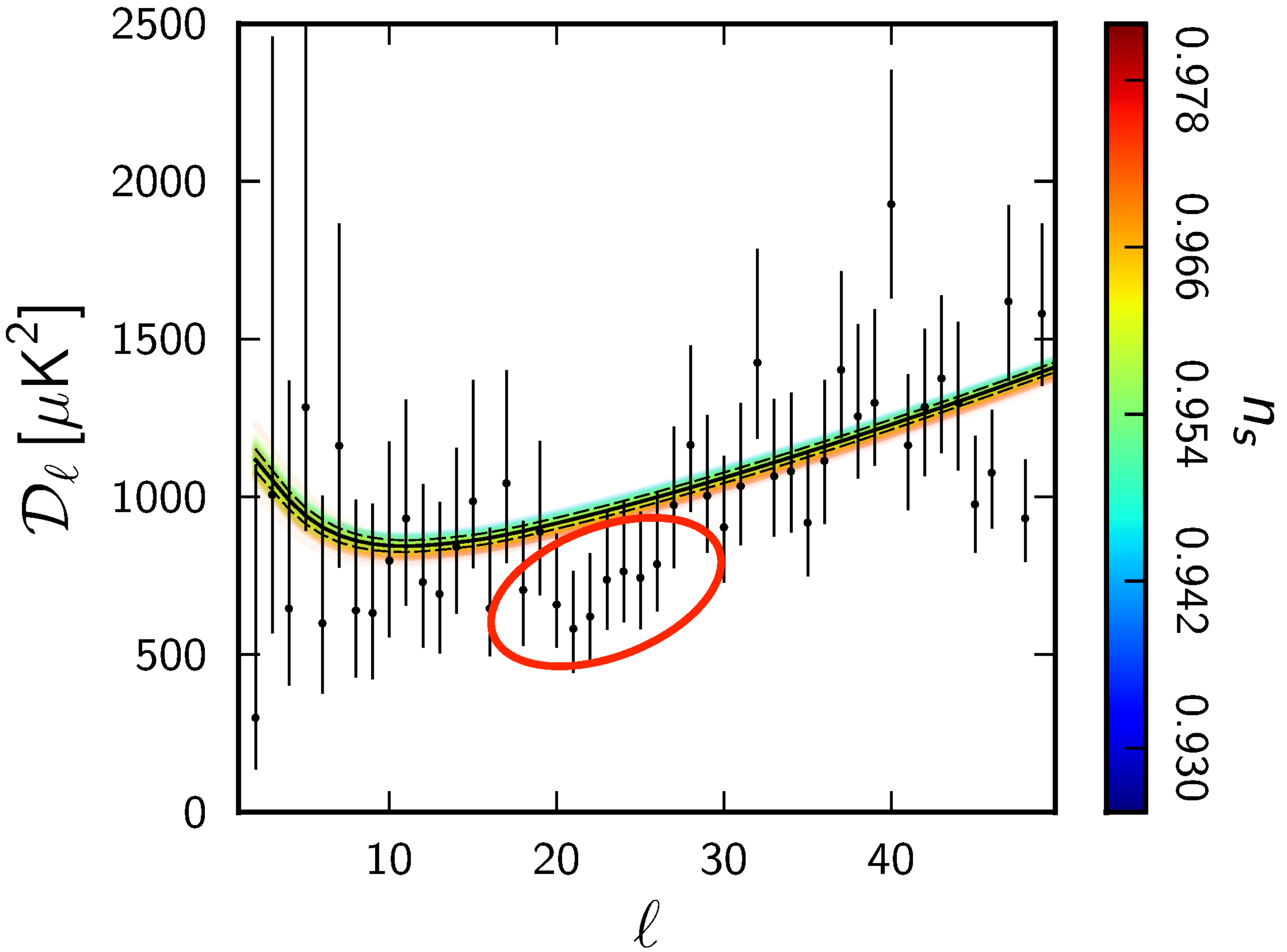
PLANCK LENSING POTENTIAL POWER SPECTRUM

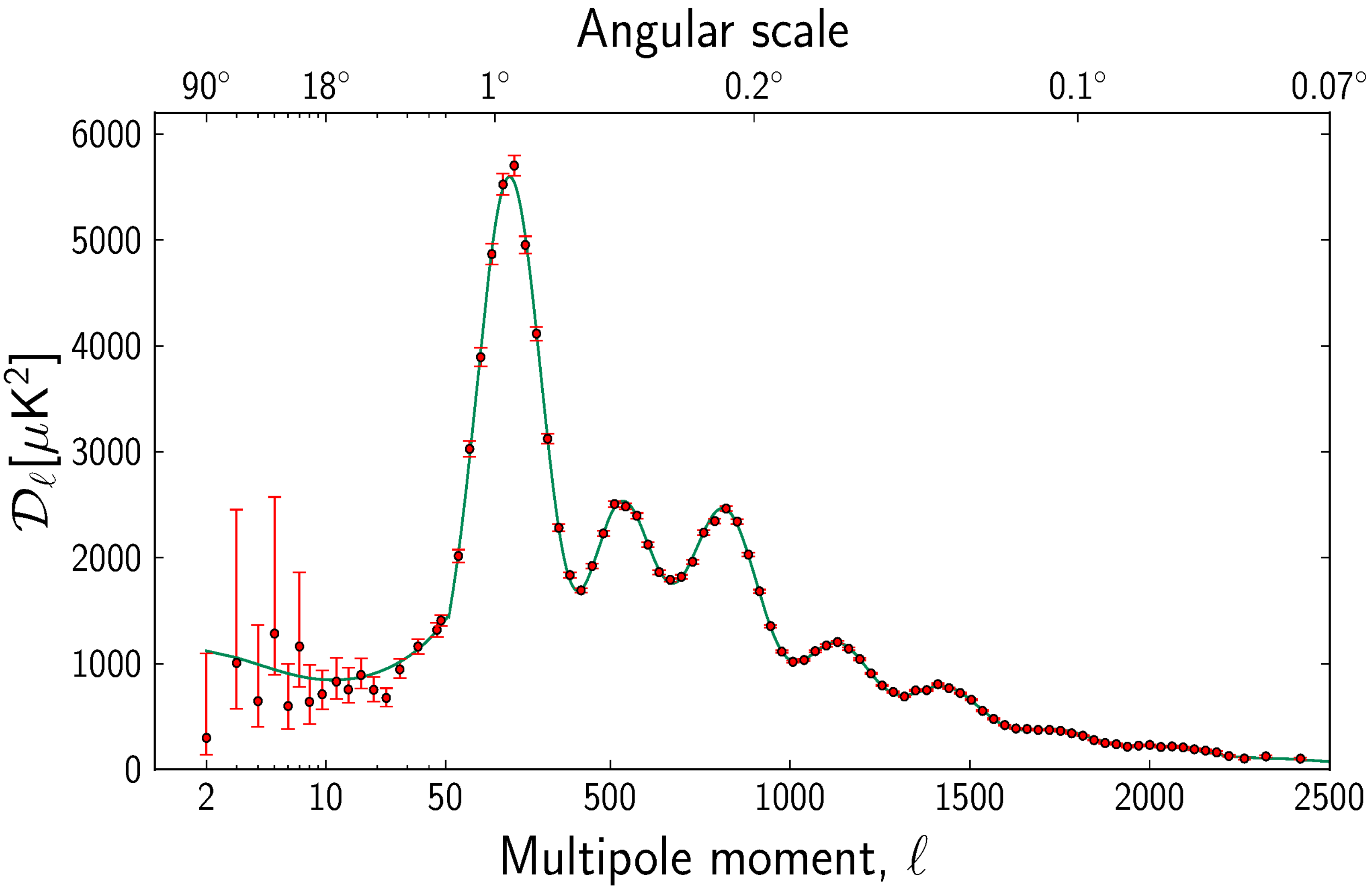


prediction based on the primary CMB fluctuations and the standard model

It is a 25 sigma effect!!

No surprises?





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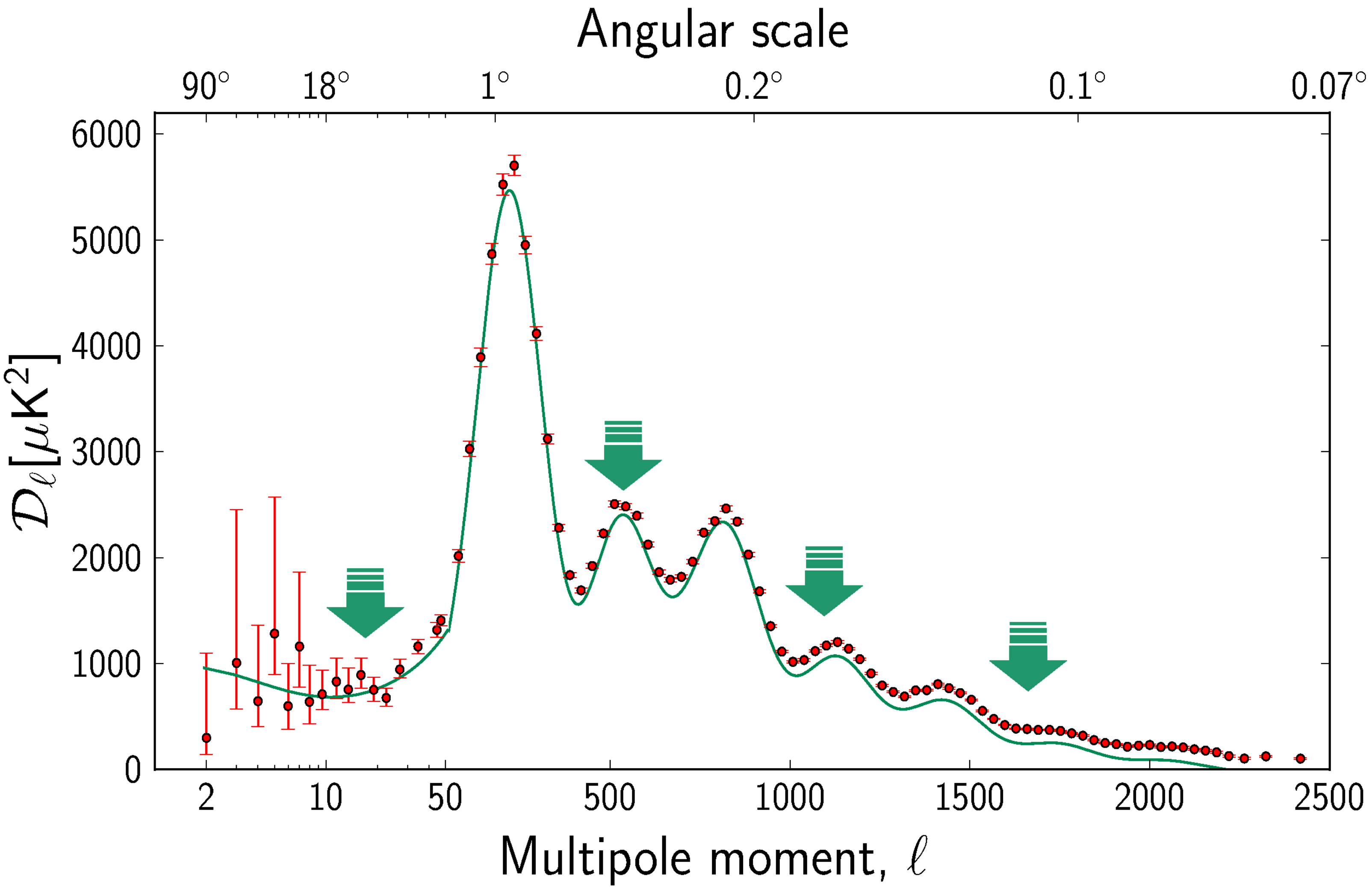
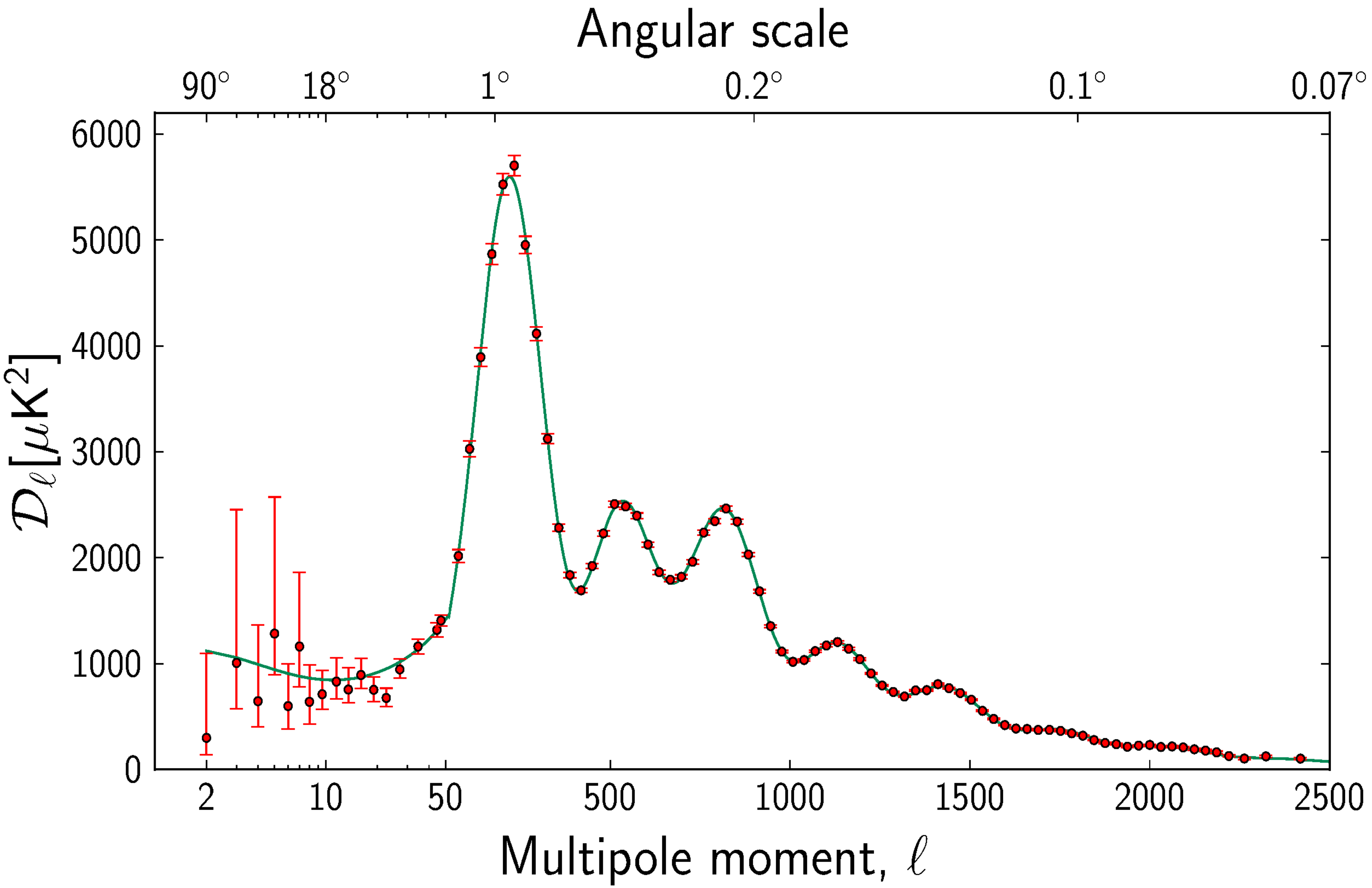
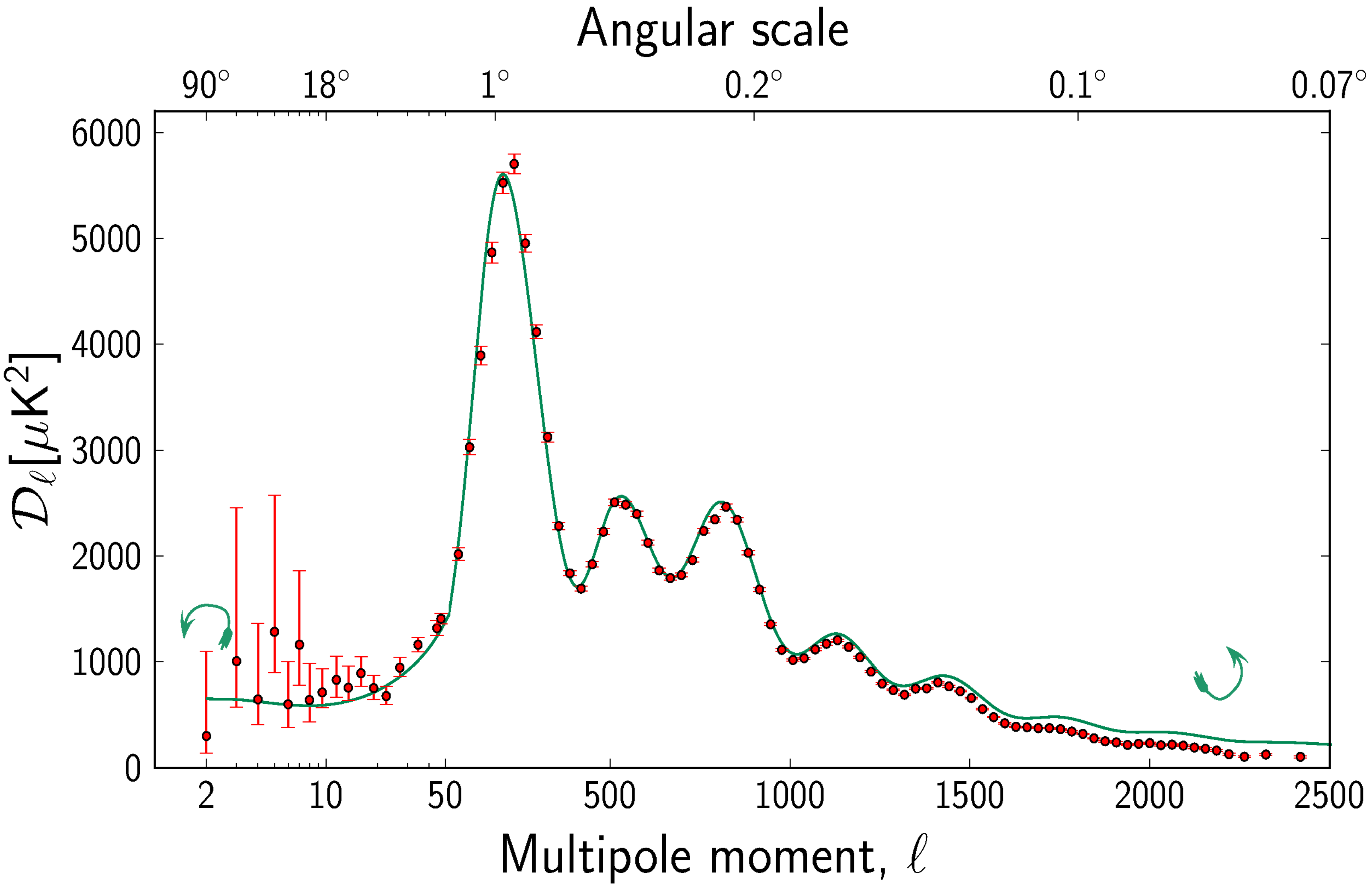
The low-l anomaly



The low-l anomaly



The low-l anomaly

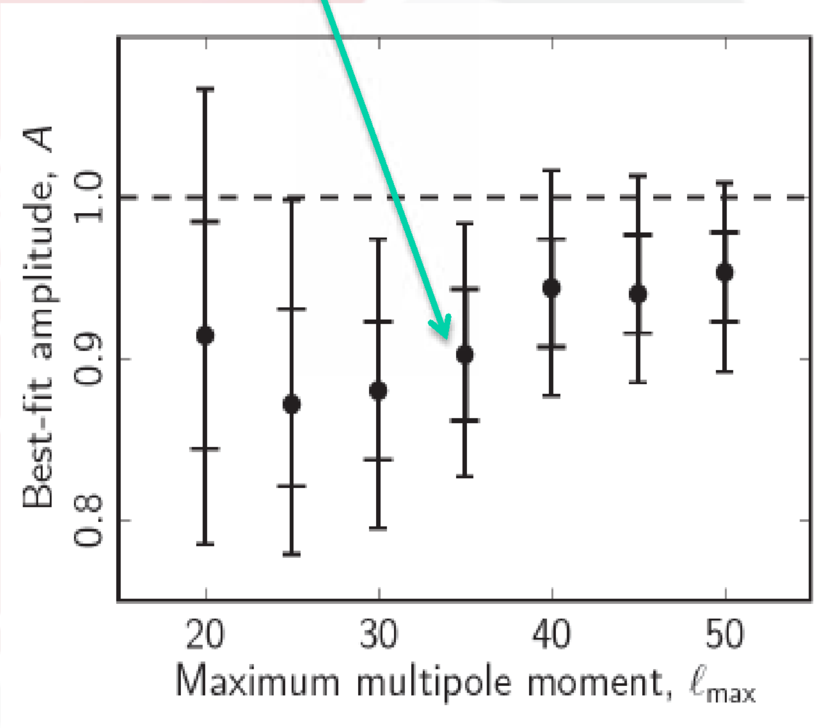


A simple amplitude test

- Rescale the power spectrum in amplitude:

$$C_\ell(A) = A\ C_\ell^{\Lambda CDM}$$

- Find the best-fit A as a function of maximum multipole l.
- There is a 99% “anomaly” for l_{max}=30.
- The anomaly fades away at higher multipoles → where theory and data agree remarkably well.



< 1 at more then two σ

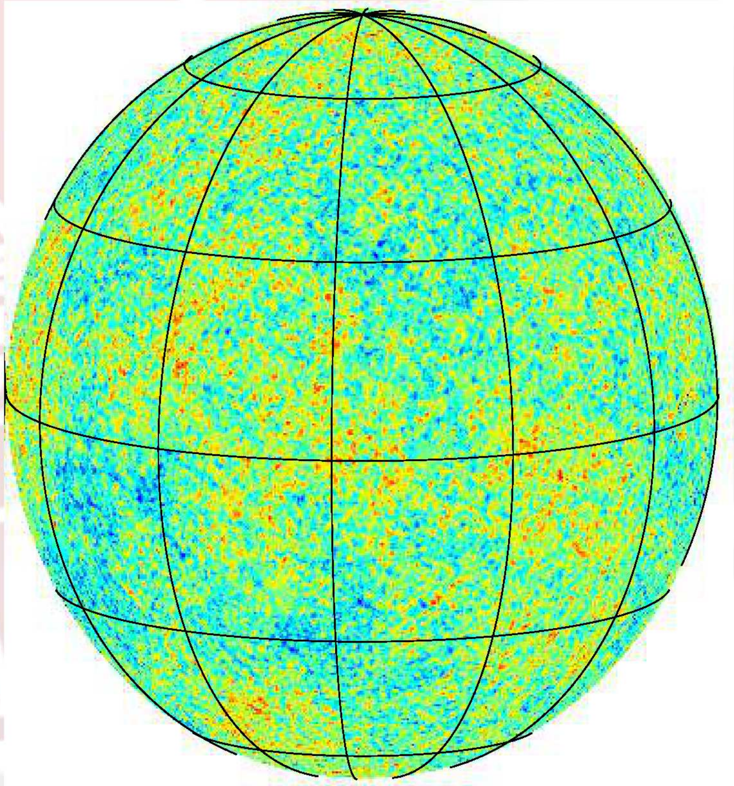
Non Gaussianity in the CMB

Nearly perfectly Gaussian fluctuation are a prediction of the inflation.

$$\frac{\Delta T}{T} \approx 10^{-5}$$

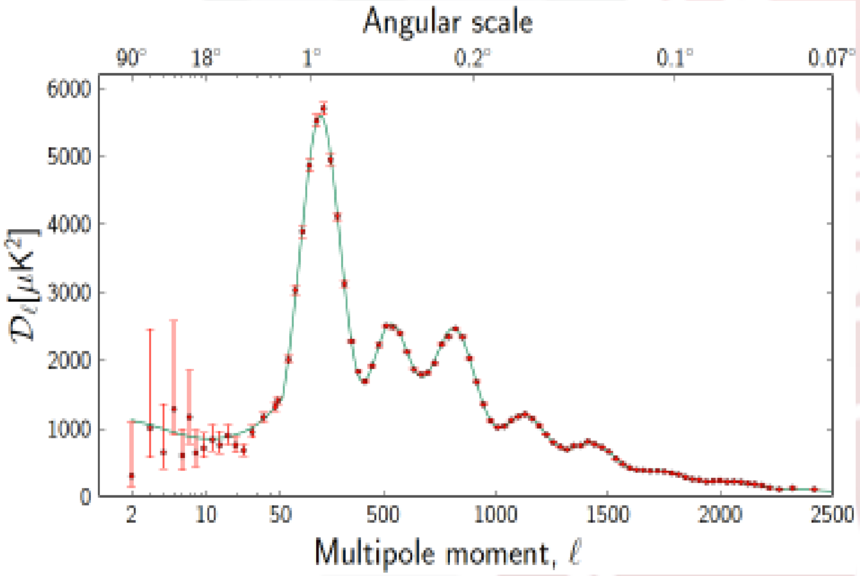
$$\frac{\Delta T}{T} + \text{const.} \times f_{NL} \left(\frac{\Delta T}{T} \right)^2$$

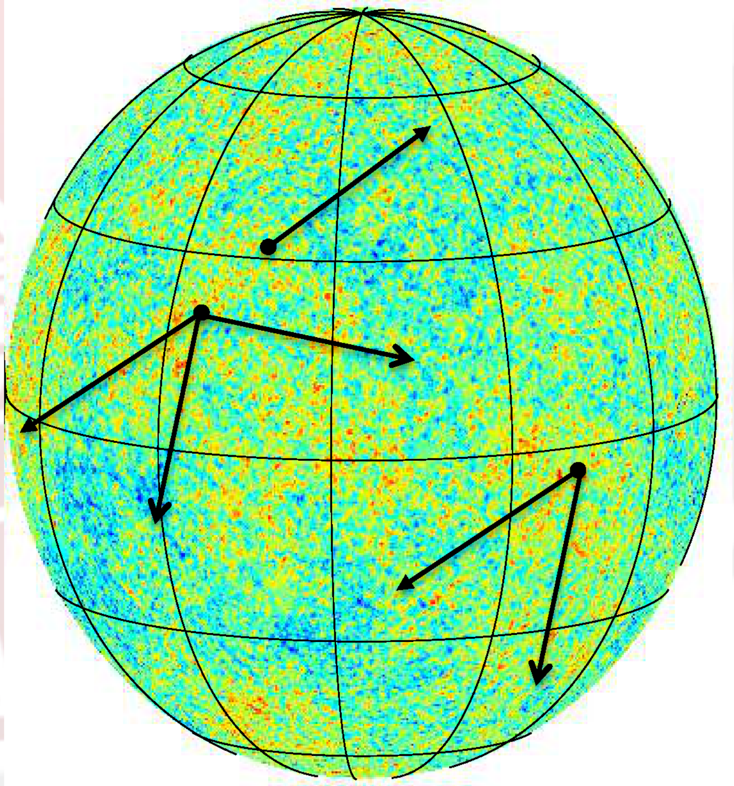
$$\left(\frac{\Delta T}{T} \right)^2 \approx 10^{-10}$$



How test for Gaussianity? And how?

The power spectrum compares two points separated by one angle (TT):

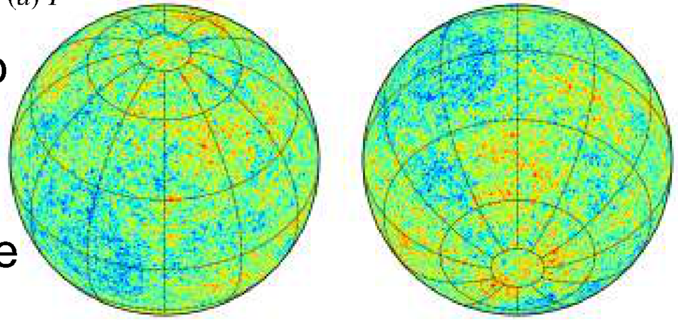




To check for non Gaussianity you can compare three points at more angles: the “power” bispectrum (TTT) and trispectrum (TTTT).

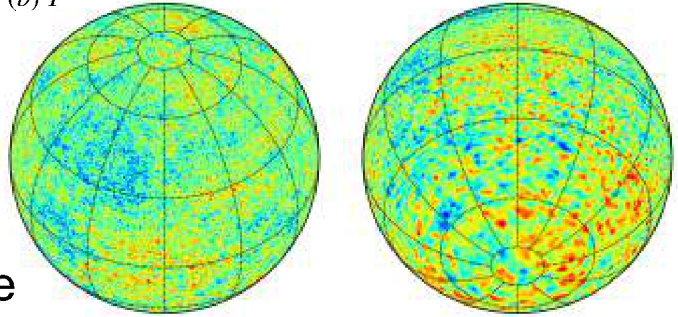
Doppler boosting of the CMB: eppur si muove!

- Planck is sensitive enough to measure the tiny doppler boosting effect on the anisotropies due to the observer peculiar velocity (we are not perfectly comoving observers!)
- Tiny effect: order $\beta = v/c \sim 1/1000$
- Two main effects: aberration and dipole modulation
- This yielded the first measure of the Earth velocity independent from the CMB dipole (observed since 1977):
- V=384 ± 78 (stat) ± 115 (sys) Km/s



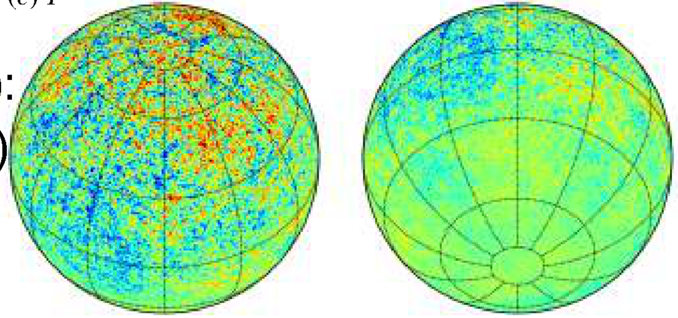
(a) $T^{\mathrm{PRIMORDIAL}}$

Simulated CMB



(b) $T^{\mathrm{ABERRATION}}$

Aberration for β=0.85



(c) $T^{\mathrm{MODULATION}}$

Modulation for β=0.85

Summary and what to expect in 2014

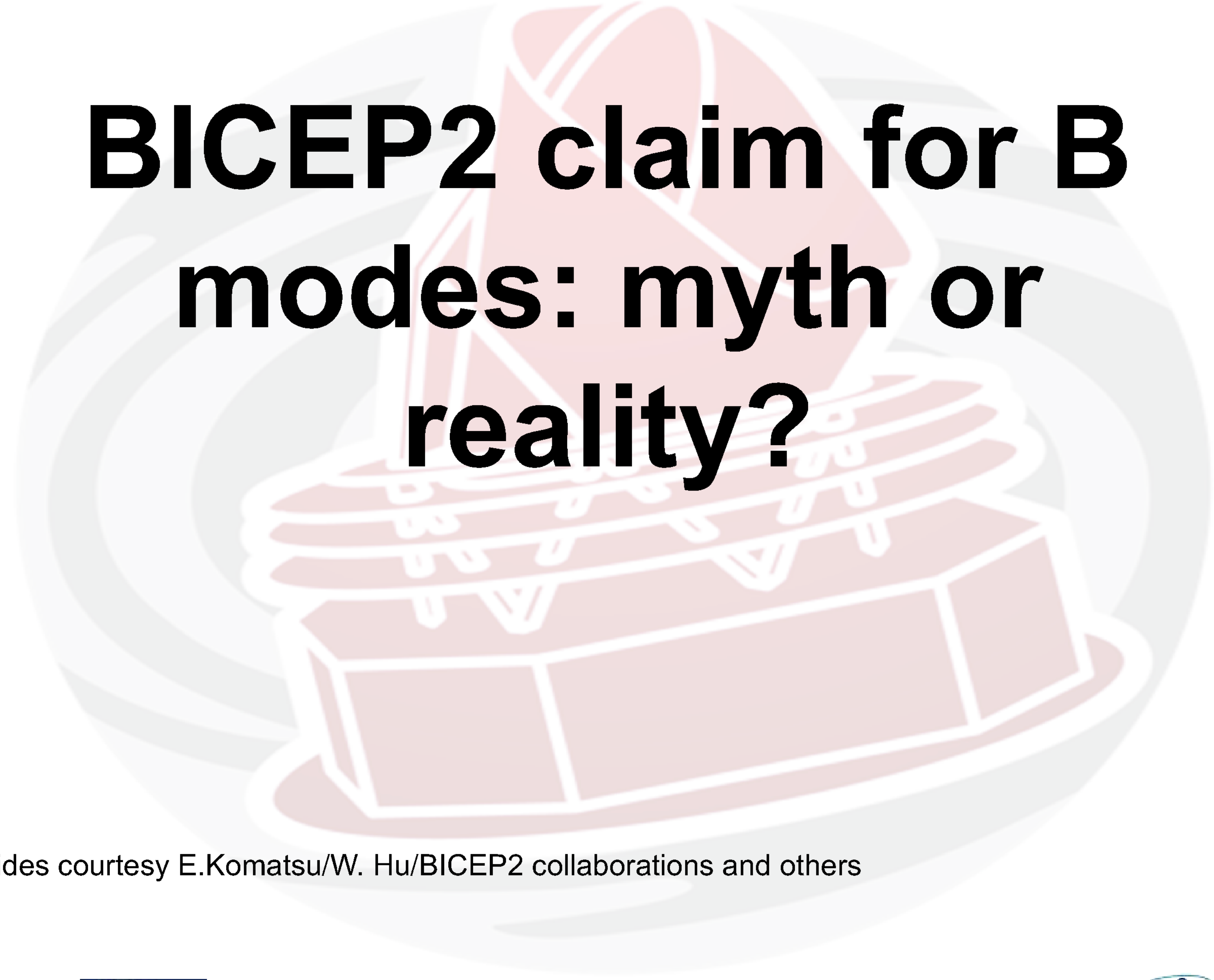
Planck has worked very well:

- Will leave us with the ***definitive*** CMB temperature for many years to come (after 2014)
- Very good consistency with the flat **ΛCDM** model (but few hints of anomalies, stay tuned for what it might come out)
- Strongly supports the **inflationary** scenario (Guassianity, primordial spectrum)
- Precision constraints on model parameters (typically < 1%)

Planck 2014 will deliver:

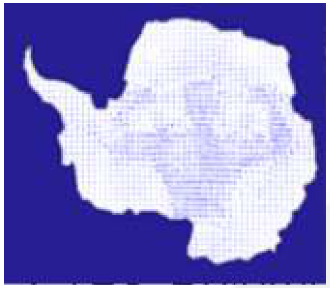
- Twice as much data (HFI) and almost Three times as much data (LFI)
- Improved instrument models, calibrations, dipole (amplitude&direction), LFI/HFI consistency, etc.
- Polarization at large and small angular scales:
  - Planck's own measure of the optical depth at reionazation (presently still using WMAP)
  - Improved constraints on GW from inlfation through primordial polarization B modes (no detection promised of course!)

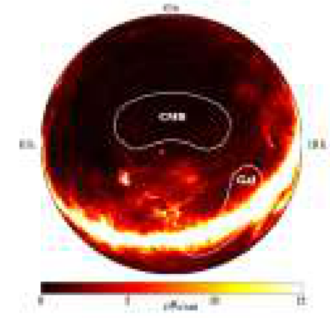
(*: uses extra non-CMB data, limit is 0.85eV else)



BICEP2 claim for B modes: myth or reality?

Several slides courtesy E.Komatsu/W. Hu/BICEP2 collaborations and others





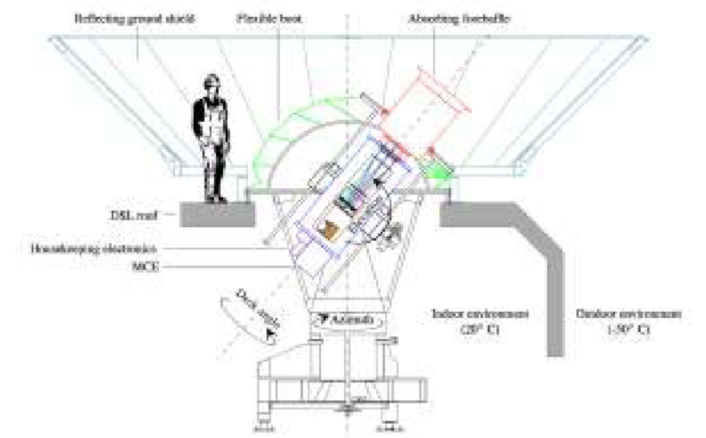
Meet BIC

Small (26 cm) refractive microwave telescope op
designed to do B-mode science

Deep integration on low Galactic emission small p
87 nK per 1 deg pixel in polarization)

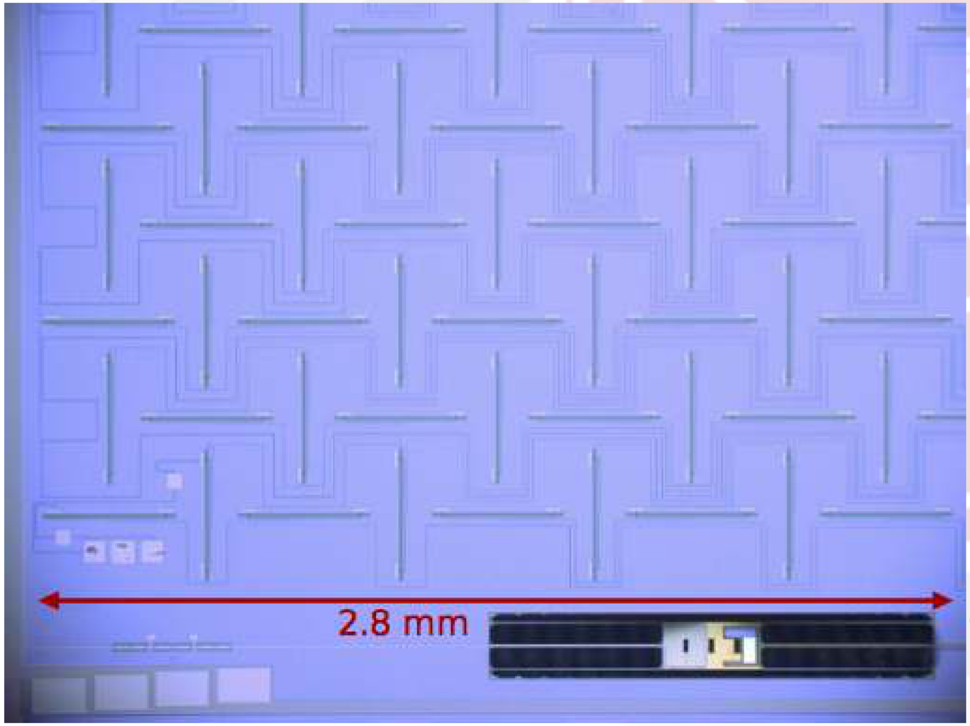
Array of 512 TES Bolometers (one order of magnit

Single frequency at 150 GHZ, operated from to 2
(also 100 GHz), follower BICEP3. Keck array (5
GHz in operation within same facility from 2014.



How does BICEP2 measure polarization?

Taking the difference between two detectors (A&B), measuring two orthogonal polarization states



Horizontal slots
-> A detector

Vertical slots
-> B detector

These slots are co-located, so they look at approximately same positions in the sky

CMB Polarization

Necessary and sufficient conditions for producing polarization in CMB are:

CMB photons are scattered by electrons

An electron is surrounded by quadrupole temperature anisotropy

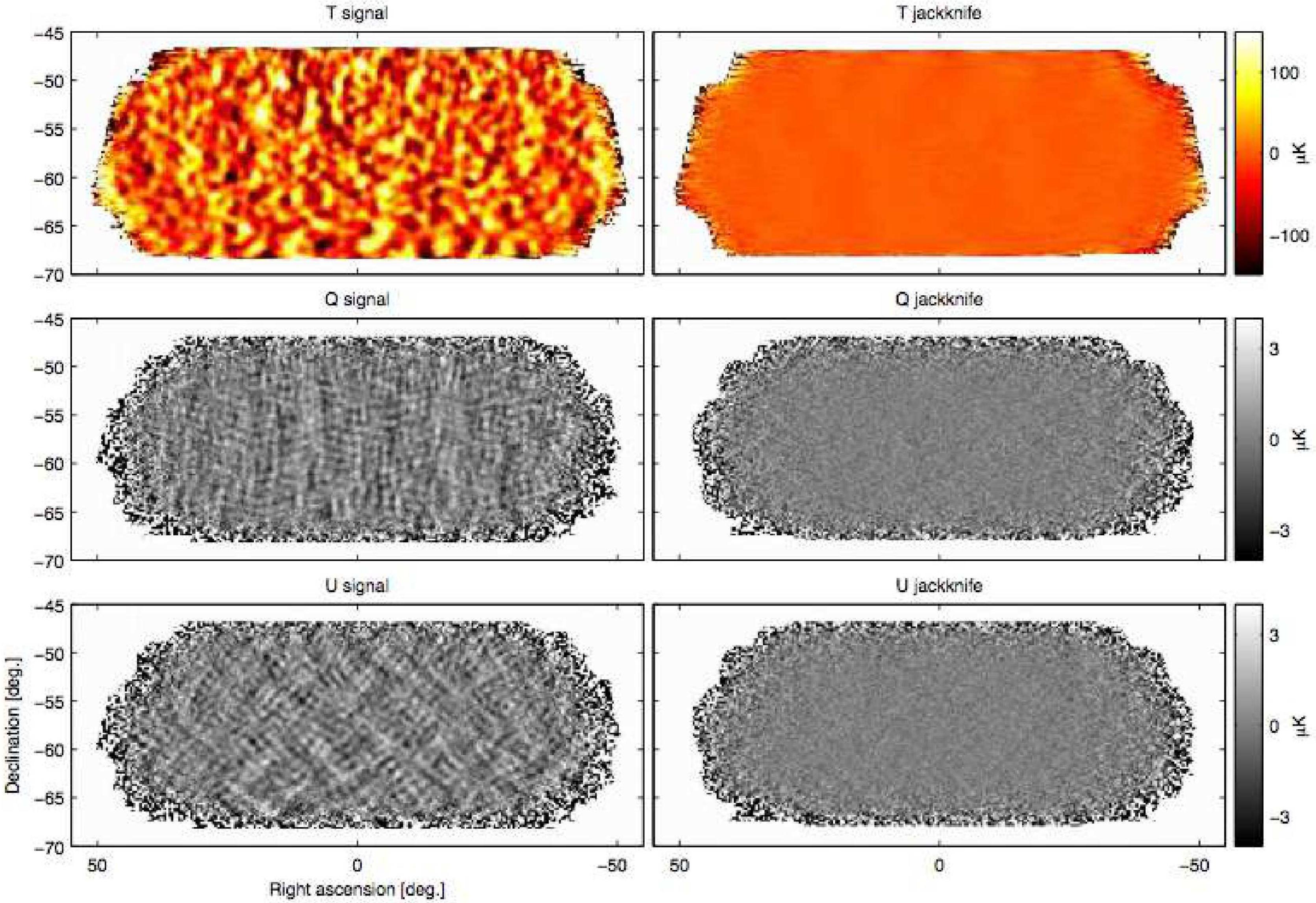


FIG. 1.— BICEP2 T, Q, U maps. The left column shows the basic signal maps with 0.25° pixelization as output by the reduction pipeline. The right column shows difference (jackknife) maps made with the first and second halves of the data set. No additional filtering other than that imposed by the instrument beam (FWHM 0.5°) has been done. Note that the structure seen in the Q&U signal maps is as expected for an E-mode dominated sky.

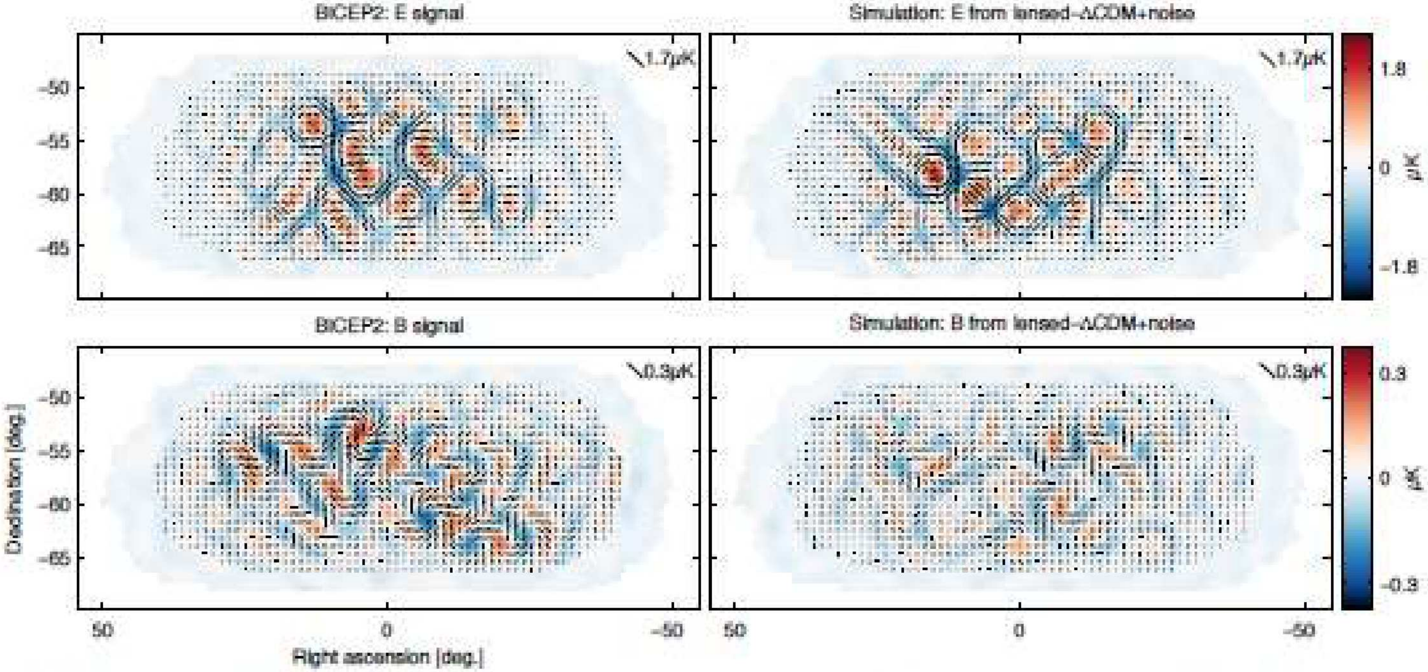
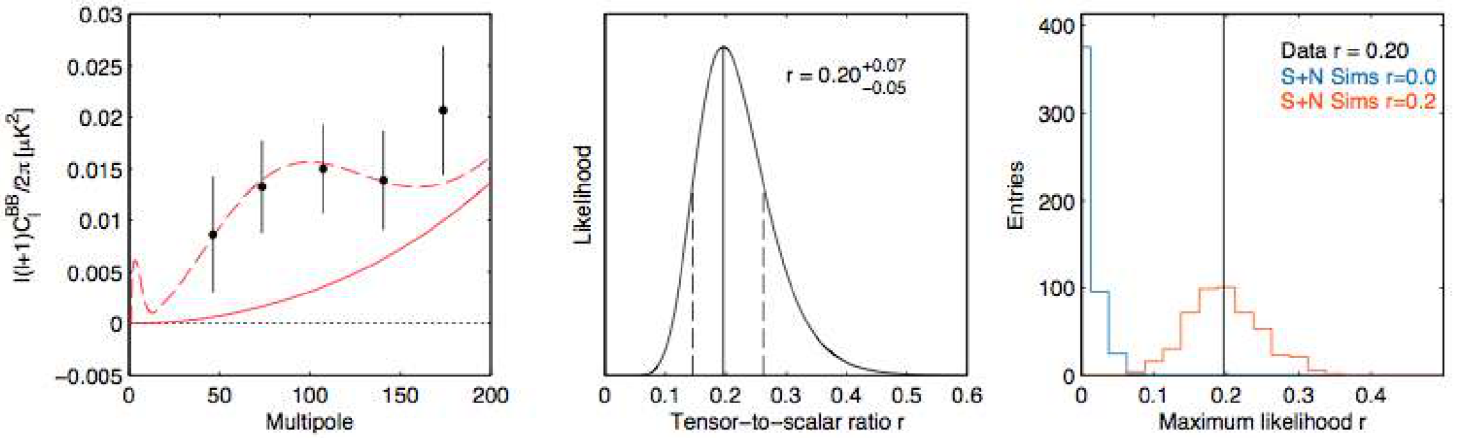


FIG. 3.— *Left:* BICEP2 apodized *E*-mode and *B*-mode maps filtered to 50 < < 120. *Right:* The equivalent maps for the first of the lensed- CDM+noise simulations. The color scale displays the *E*-mode scalar and *B*-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess *B*-mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at 70). (Also note that the *E*-mode and *B*-mode maps use different color/length scales.)

BICEP2


0.03
0.025
0.02
0.015
0.01
0.005
0
−0.005
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
0
50
100
150
200
Multipole
Likelihood
$r = 0.20^{+0.07}_{-0.05}$
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor−to−scalar ratio r
400
300
200
100
0
Entries
Data r = 0.20
S+N Sims r=0.0
S+N Sims r=0.2
0
0.1
0.2
0.3
0.4
Maximum likelihood r

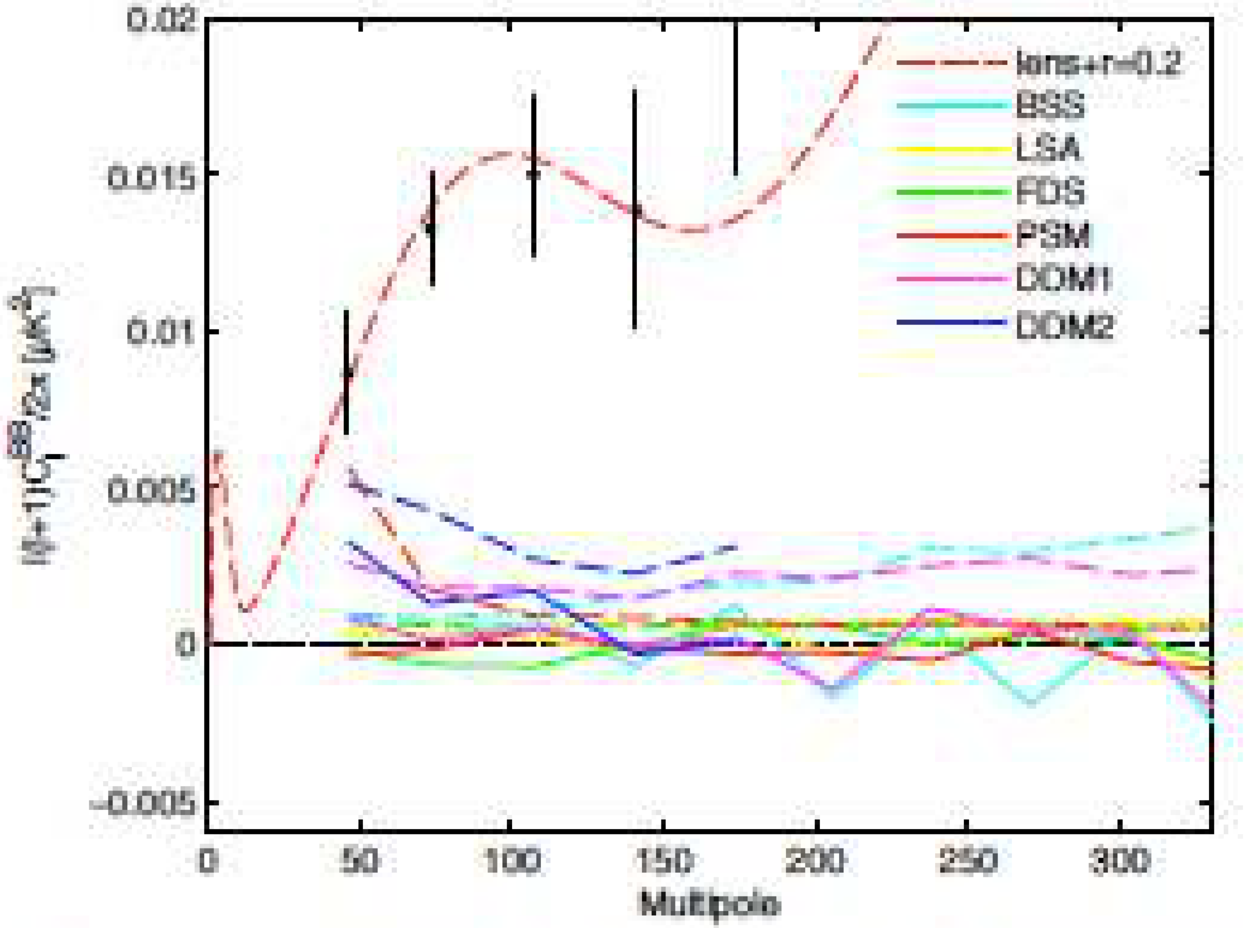
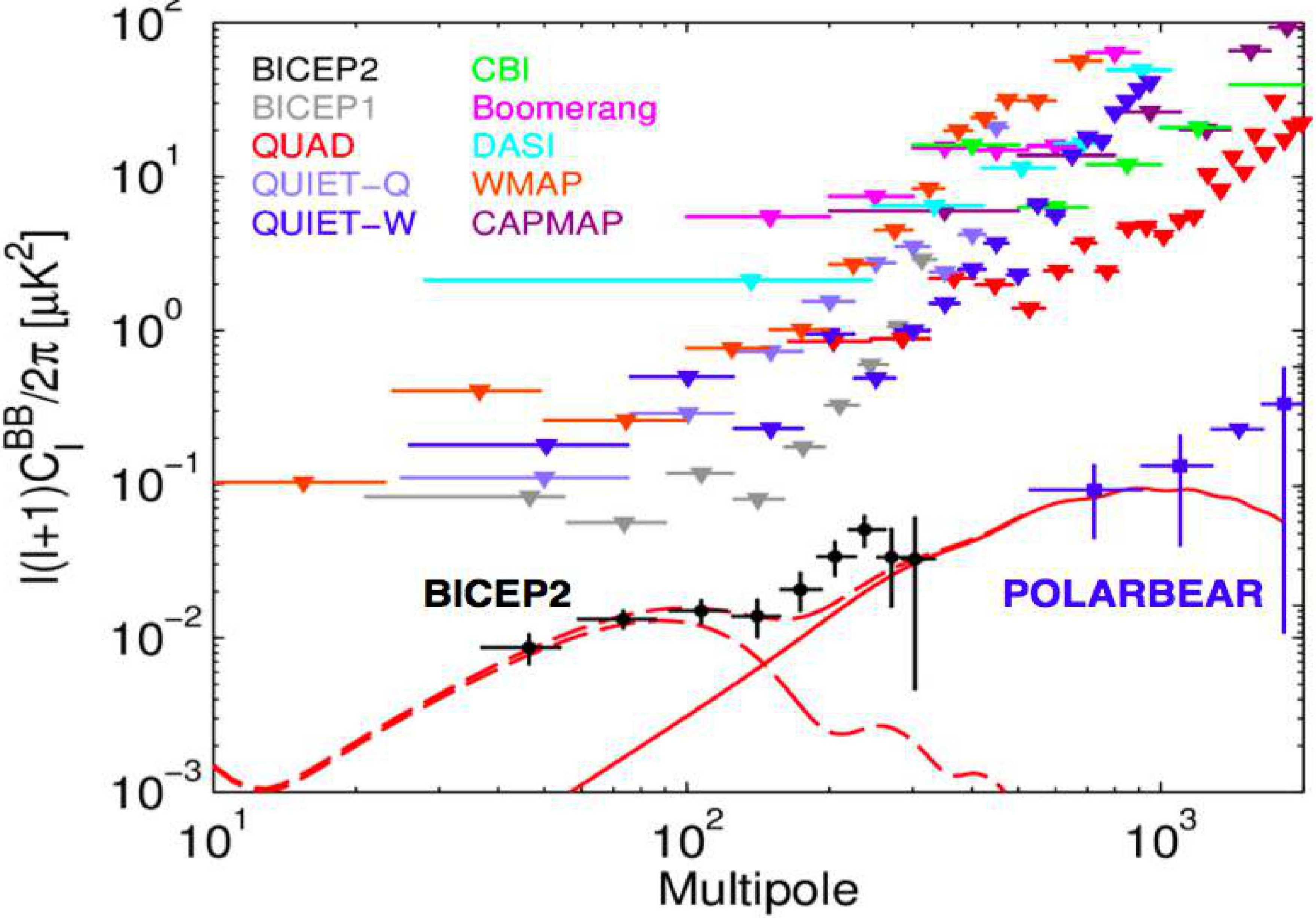
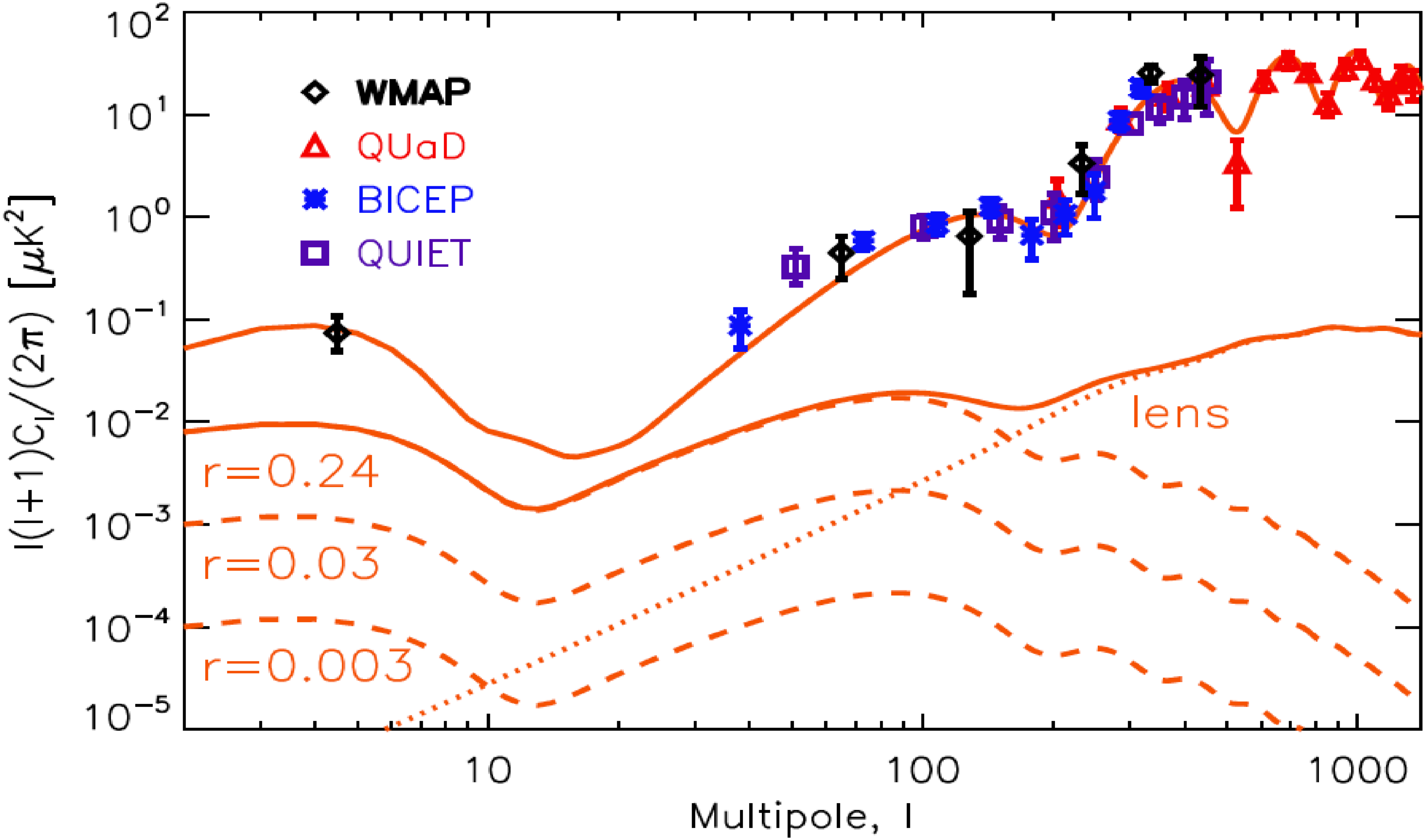
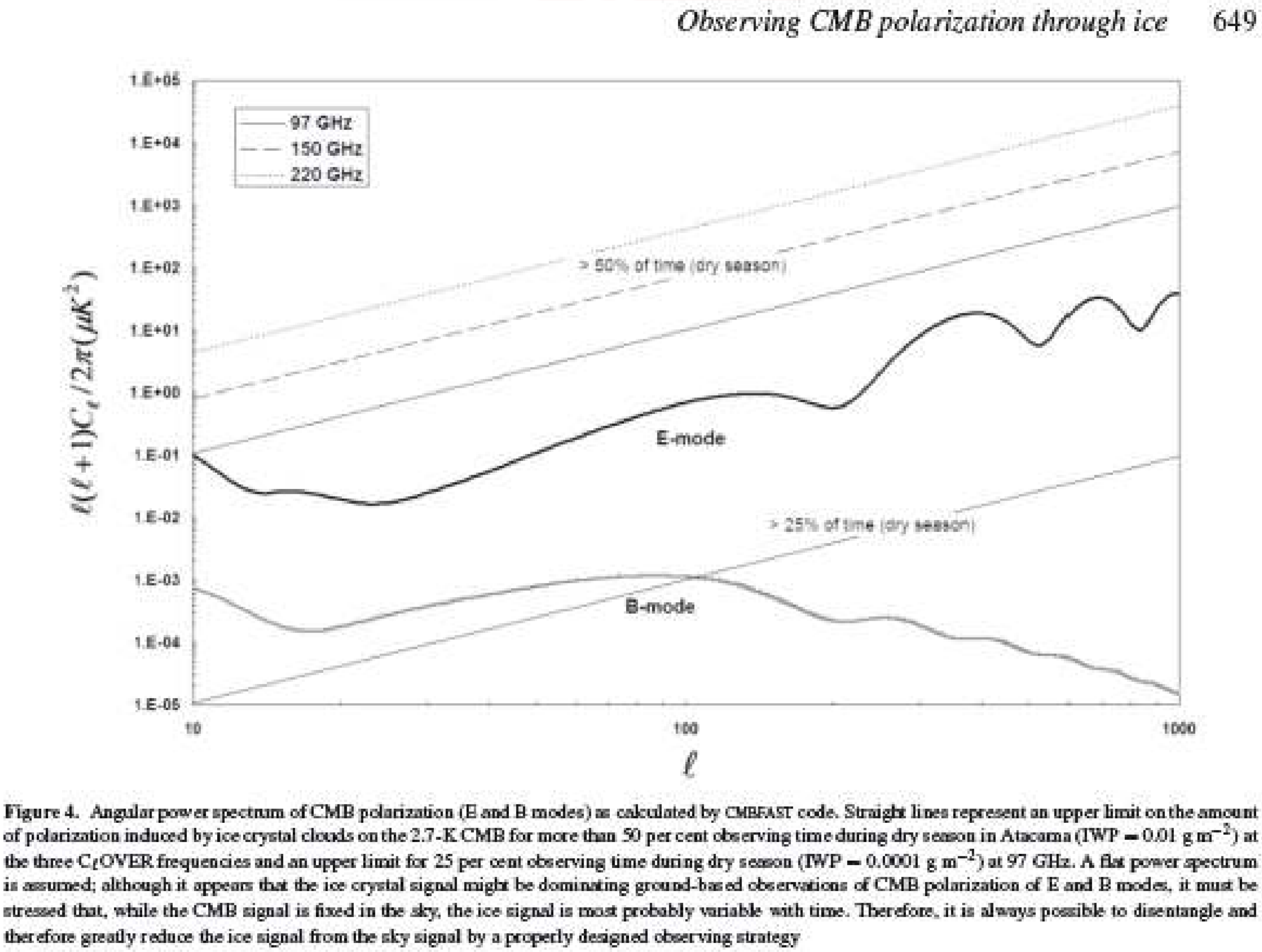


FIG. 6.— Polarized dust foreground projections for our field using various models available in the literature, and two new ones formulated using publically available information from *Planck*. Dashed lines show autospectra of the models, while solid lines show cross spectra between the models and the BICEP2 maps. The cross spectra are consistent with zero, and the DDM2 auto spectrum (at least) is noise biased high (and is hence truncated to < 200). The BICEP2 auto spectrum from Figure 2 is also shown with the lensed- CDM+$r = 0.2$ spectrum.


BICEP2
BICEP1
QUAD
QUIET-Q
QUIET-W
CBI
Boomerang
DASI
WMAP
CAPMAP
BICEP2
POLARBEAR
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
Multipole


◇ WMAP
▲ QUaD
✱ BICEP
□ QUIET
lens
r=0.24
r=0.03
r=0.003
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$l(l+1)C_l/(2\pi)$ [μK^2]
10
100
1000
Multipole, l

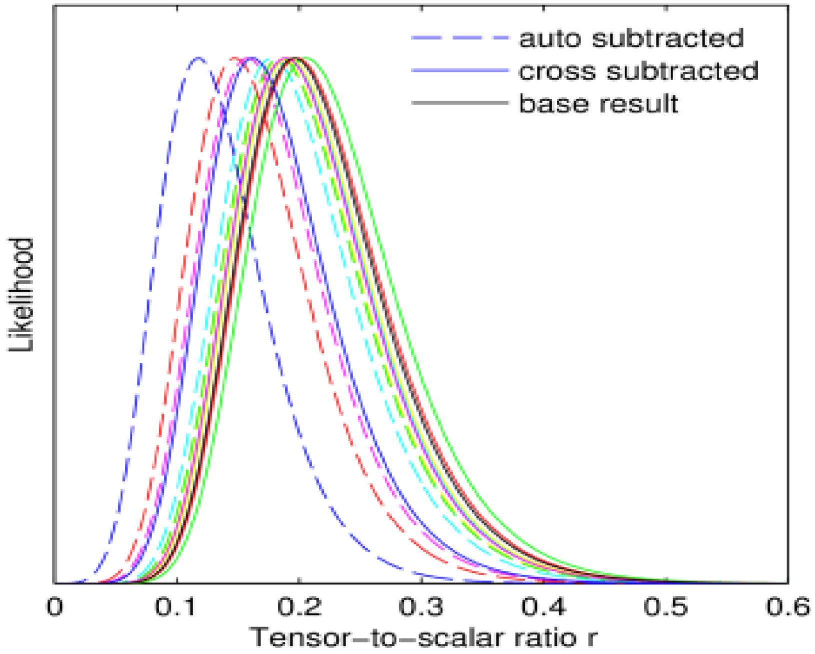
ICE CRYSTALS: polarization/de-polarization at microK level ?



Observing CMB polarization through ice 649

Figure 4. Angular power spectrum of CMB polarization (E and B modes) as calculated by CMBFAST code. Straight lines represent an upper limit on the amount of polarization induced by ice crystal clouds on the 2.7-K CMB for more than 50 per cent observing time during dry season in Atacama (IWP = 0.01 g m^{-2}) at the three CℓOVER frequencies and an upper limit for 25 per cent observing time during dry season (IWP = 0.0001 g m^{-2}) at 97 GHz. A flat power spectrum is assumed; although it appears that the ice crystal signal might be dominating ground-based observations of CMB polarization of E and B modes, it must be stressed that, while the CMB signal is fixed in the sky, the ice signal is most probably variable with time. Therefore, it is always possible to disentangle and therefore greatly reduce the ice signal from the sky signal by a properly designed observing strategy

Implications of the BICEP 2 claim (if confirmed!): 1

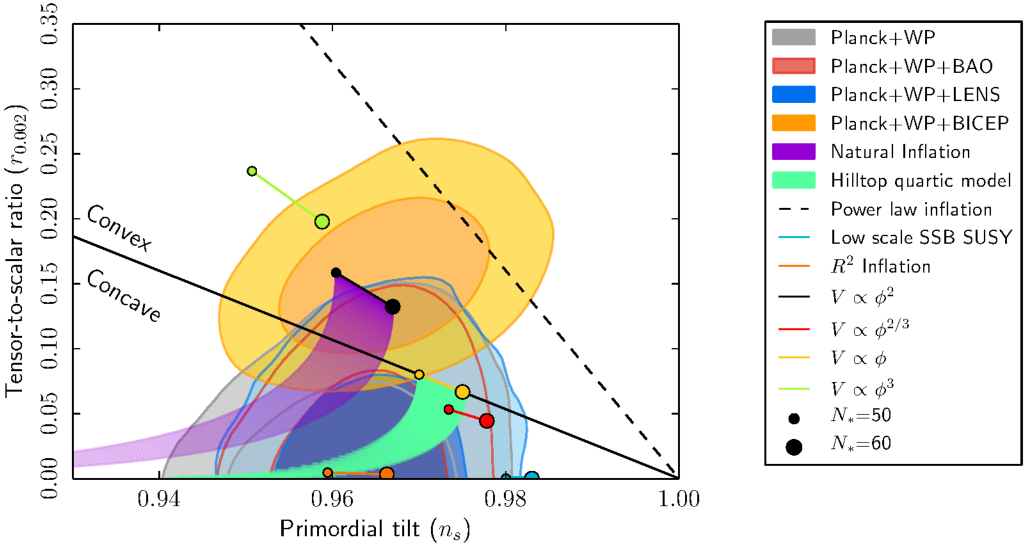


Interpretation of the B-mode signal as primordial strongly dependent on foreground uncertainties

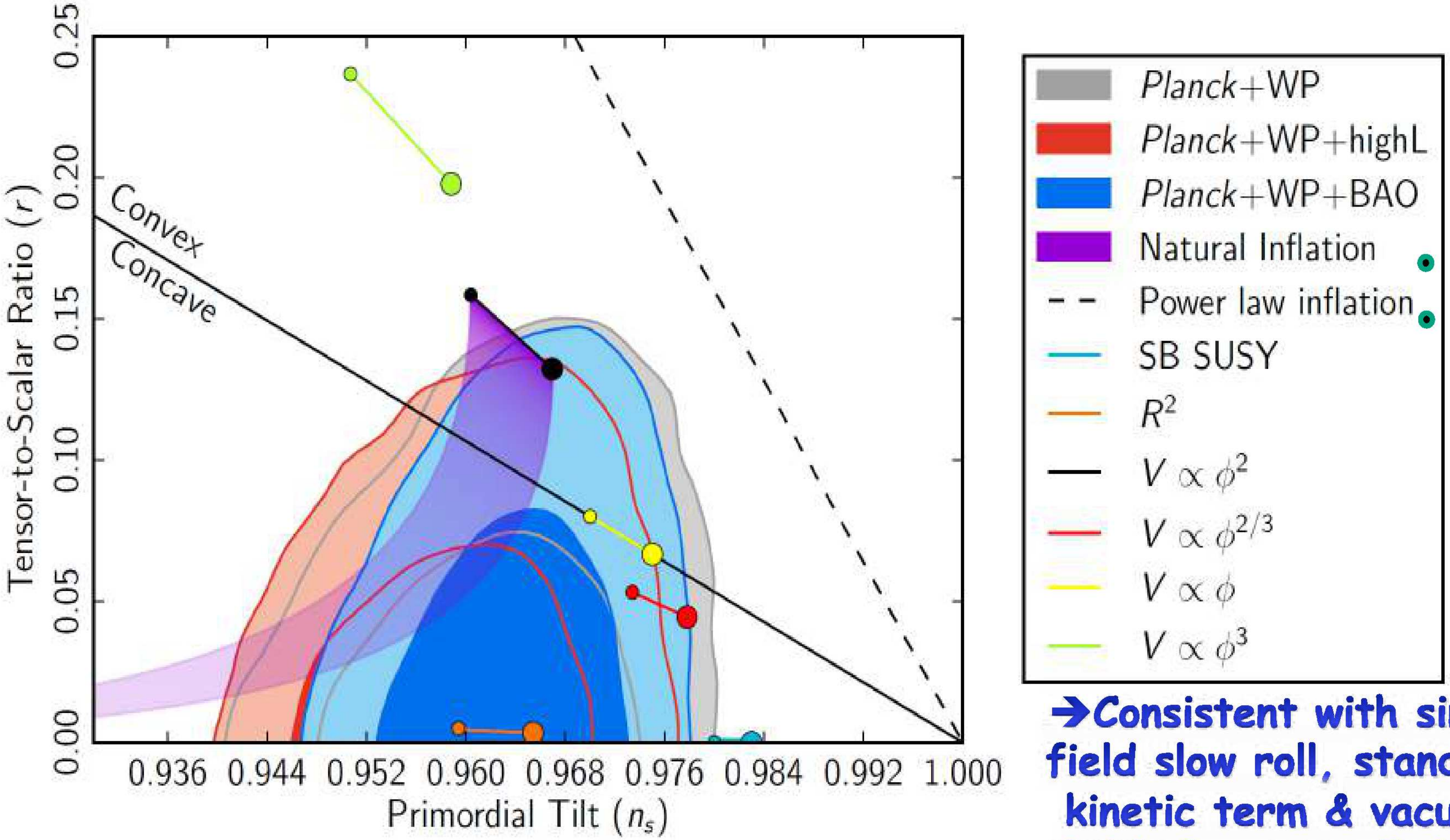
BICEP 2 arXiv:1403.3985 (2014)

Planck 2013 + BICEP 2

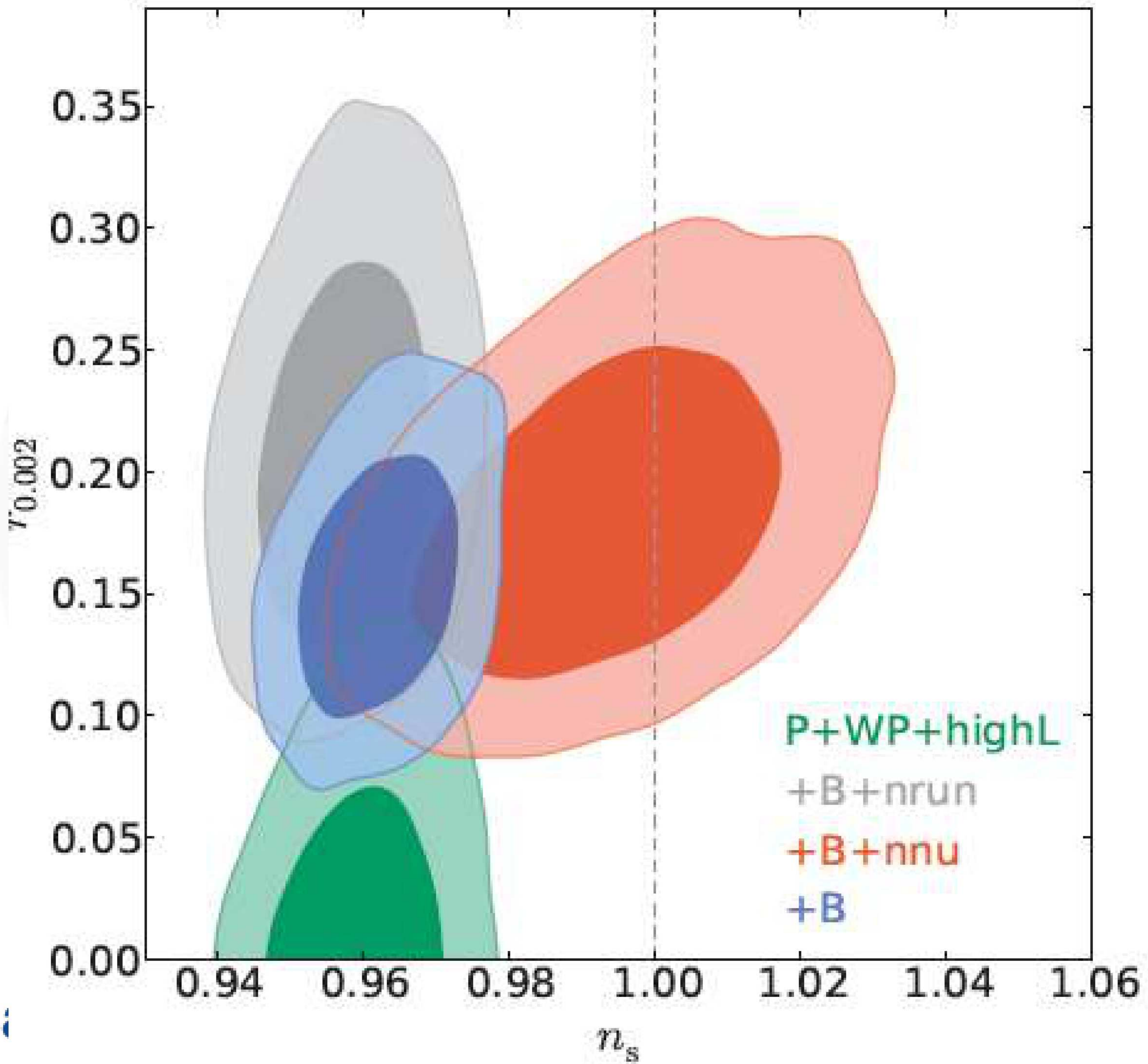
How Fig. 1 of the Planck 2013 results. XXII. Constraints on inflation would be modified with the addition of the BICEP 2 data publicly available



Main constraint on Inflation physics Planck + … (2013)



→Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits),


0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
$r_{0.002}$
0.94
0.96
0.98
1.00
1.02
1.04
1.06
n_s
P+WP+highL
+B+nrun
+B+nnu
+B

Implication of the measured tensor-to-scalar ratio

The measured r is directly connected to the potential energy of a field driving inflation.

r = 0.2 implies 2x10^{16} GeV

Grand Unification Scale! Inflation is a phenomenon of the high[est] energy physics

r = 0.2 also implies that a field driving inflation moved by ~10 x Planck Mass. A challenge to model building

CONCLUSIONS

Beautiful, unexpected measurement by BICEP2.

Ten times more primordial GW than everybody would realistically conceive a few weeks ago.

Smoking gun of inflation, measures its energy scale

Potential issues with systematics -> need confirmation

Several experiments on their way: KECK, Polarbear, EBEX, Planck… We will see.

If measurement confirmed… Most likely ΛCDM will need retouching

Importance of B mode detection at degree scales

If the detected B mode polarization is primordial, and agrees with the prediction from a scale-invariant [but slightly red-tilted] gravitational wave spectrum, then:

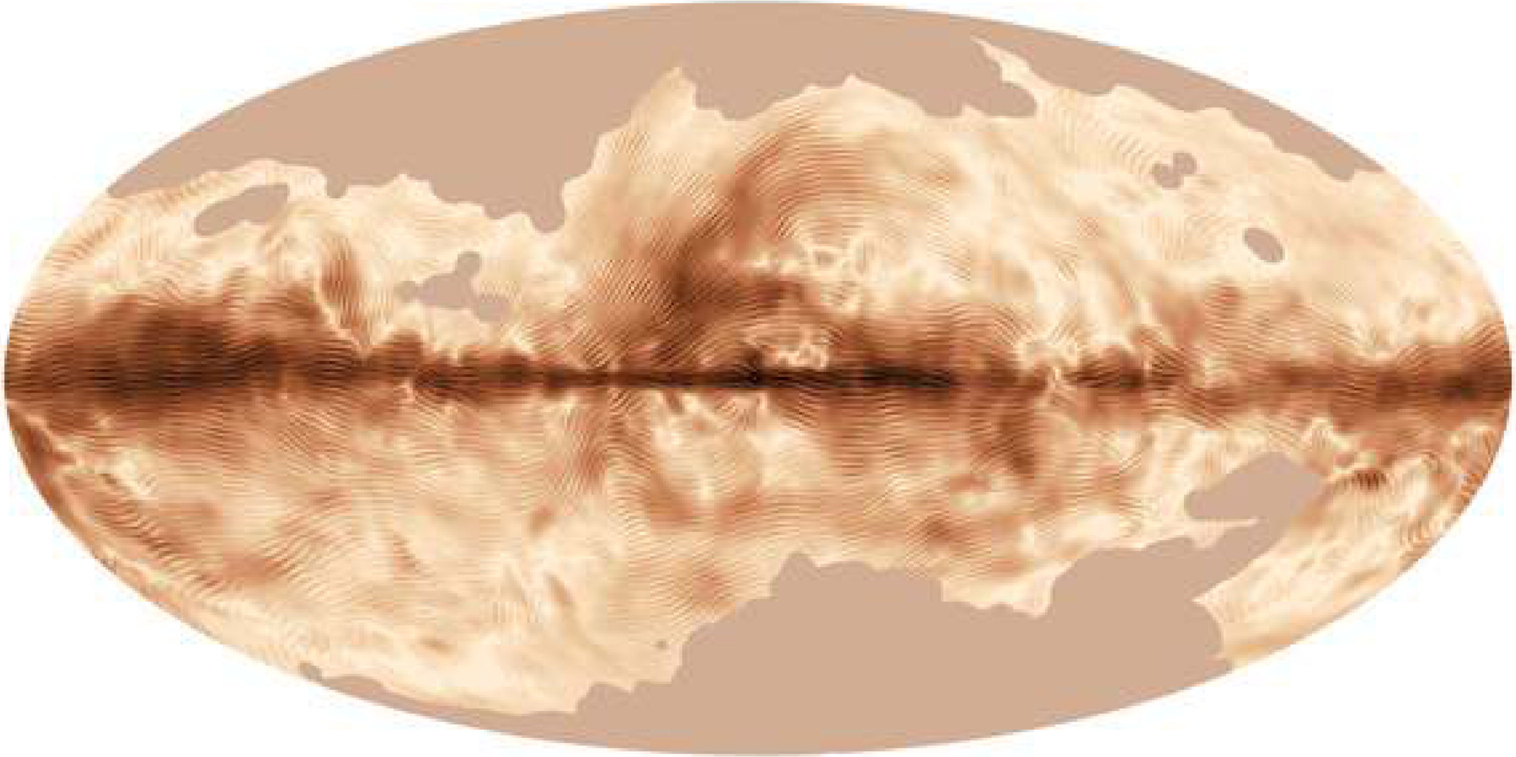
It proves inflation. Inflation generates these gravitational waves, whose wavelength has been stretched to cosmological scales. No astrophysics can do this.

This is a huge deal, if true but….

“I believe that if both Planck and the new results agree, then together they would give substantial evidence against inflation! I will quote Carl Sagan and say 'extraordinary claims require extraordinary evidence', and they don't have extraordinary evidence just yet." He reiterates that the BICEP2 and Planck/ WMAP discrepancies need to be resolved, and that result will be essential because "something has got to give". He urges other experiments to confirm the results and suggests that the combined observational results should then fit a simple yet detailed cosmological model before the BICEP2 observations can be thought of as proof of primordial gravitational waves or indeed inflation.

Neil Turok

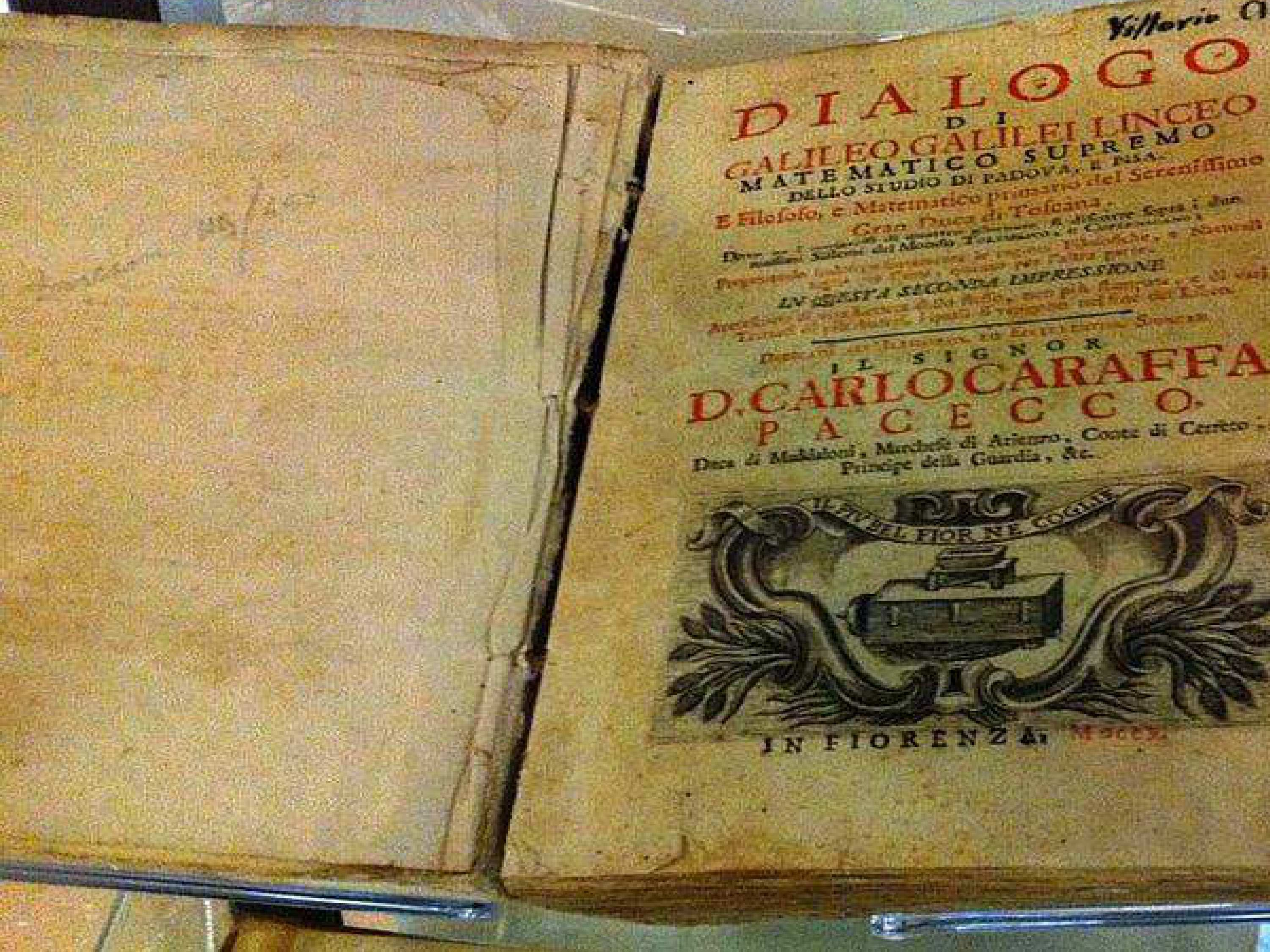
Milky Way Polarized Sky as seen by Planck



Mainly due to spinning dust in interstellar clouds
It reveals the galactic magnetic field

NEW PHYSICS?

- Standard Cosmological Model is in tension with experimental data?
- Standard Particle Model is in tension with experimental results?
- Lambda CDM ?
- Inflation?
- Higgs boson?
- Is the known Physics valid also at the extreme energies of the beginning?
- **Coupling General Relativity with Quantum Mechanics: is it a solved problem?**



Vittorio C

DIALOGO

DI

GALILEO GALILEI LINCEO

MATEMATICO SUPREMO

DELLO STUDIO DI PADOVA, E PISA,

E Filosofo, e Matematico primario del Sereniſſimo

Gran Duca di Toſcana.

IN QUESTA SECONDA IMPRESSIONE

IL SIGNOR

D. CARLO CARAFFA

PACECCO.

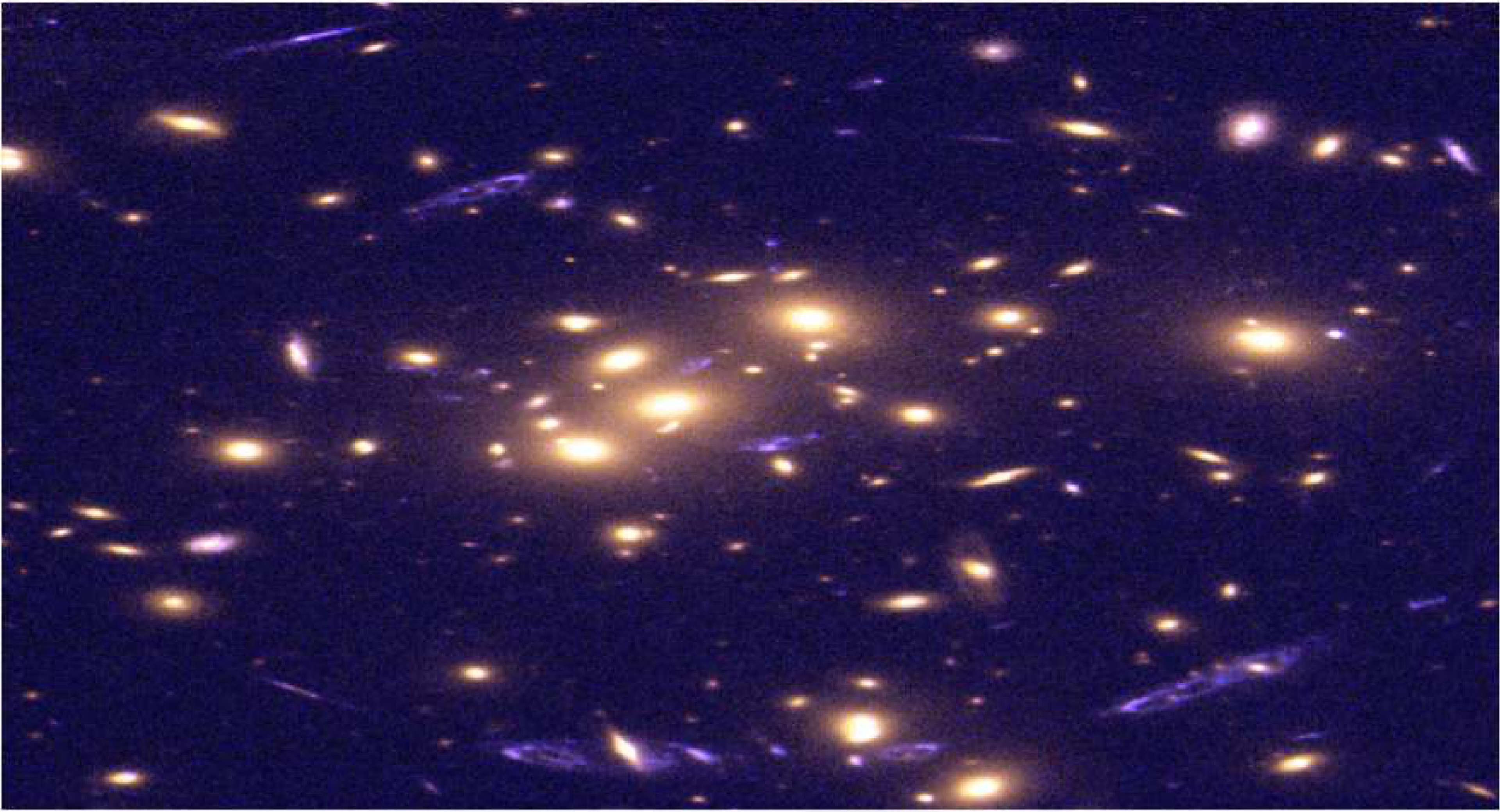
Duca di Maddaloni, Marcheſe di Arienzo, Conte di Cerreto, Principe della Guardia, &c.

IN FIORENZA. MDCCX.

- **Dialogo of Galileo Galilei**
- **Salviati: Who moveth the parts of the Earth downwards?**
- **Simplicius: The cause of this is most manifest and everyone knows that it is Gravity**
- **Salviati: No Simplicius, you are out. You should say that everyone knows it is called Gravity , I do not question you about the name but about the essence of the thing**

Gravity: An unfinished Problem

The Essence
of the thing

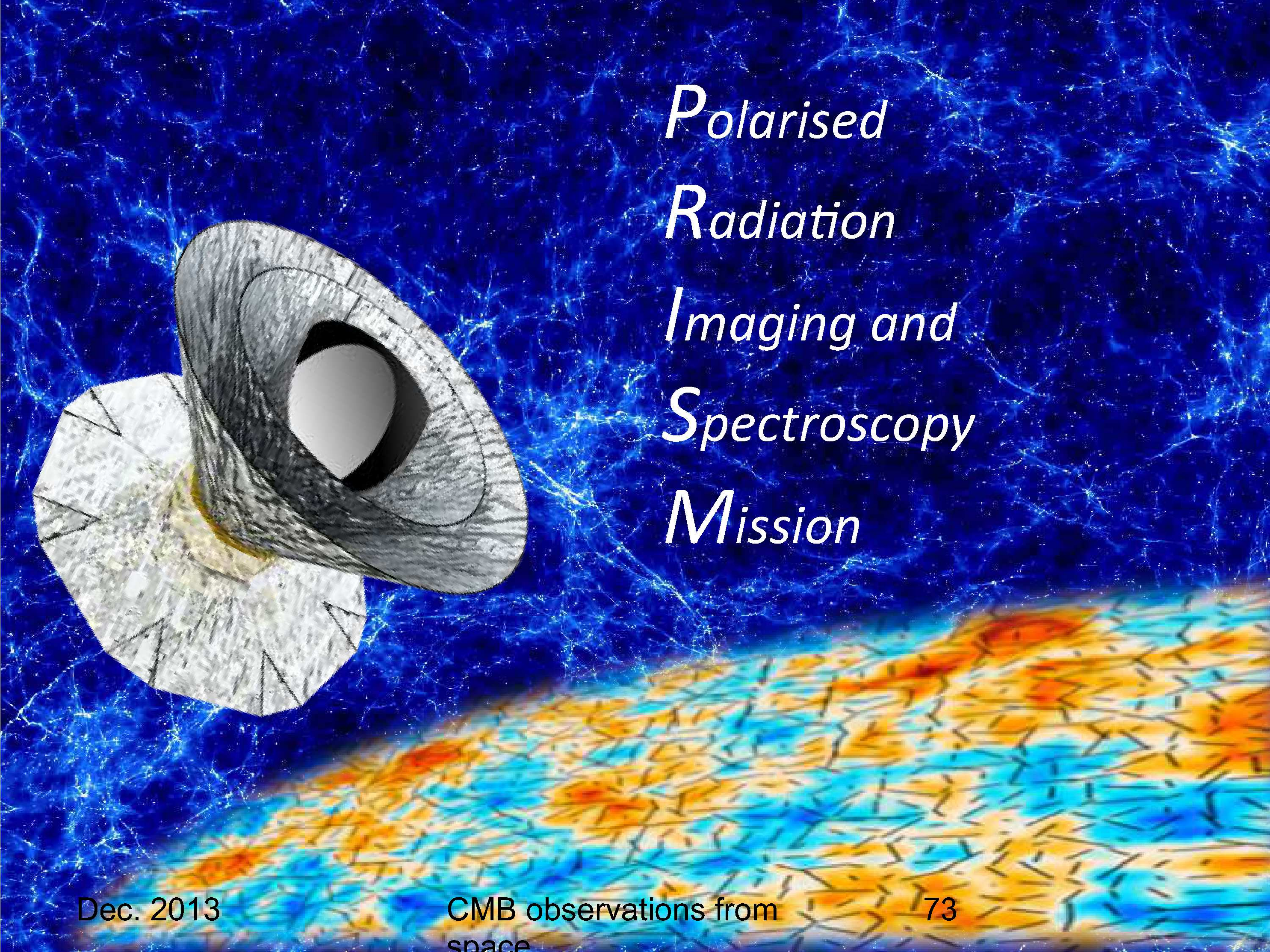


- A purely metric theory implies the Equivalence Principle
  - currently10^{-13} > Microscope 10^{-15}> long term target 10^{-18}
- The Gravitational Redshift changes the frequency of clocks
  - Currently tested to 7.10^{-5} > ACES on ISS 2.10^{-6} > future 5.10^{-10}

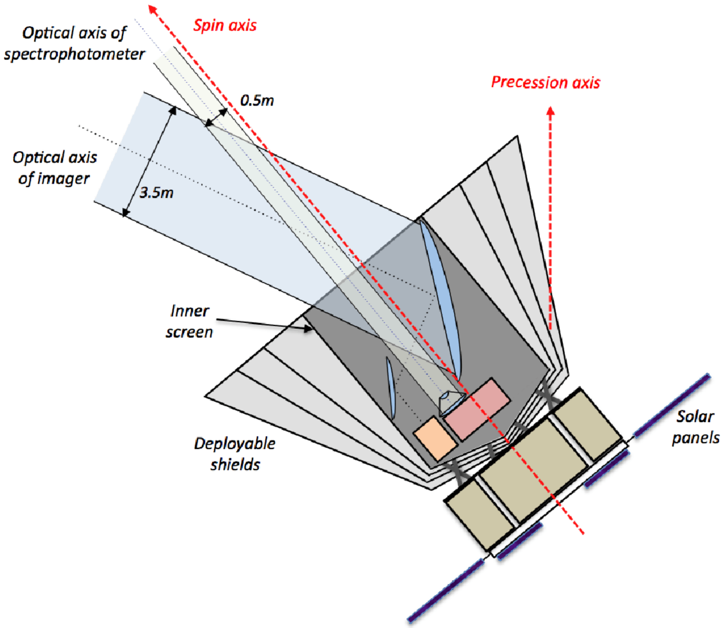
- Despite 70 or 80 years of the most serious theoretical work there is no known way of coupling General Relativity with Quantum Mechanics.
  - **This is the most pressing problem in Fundamental Physics**

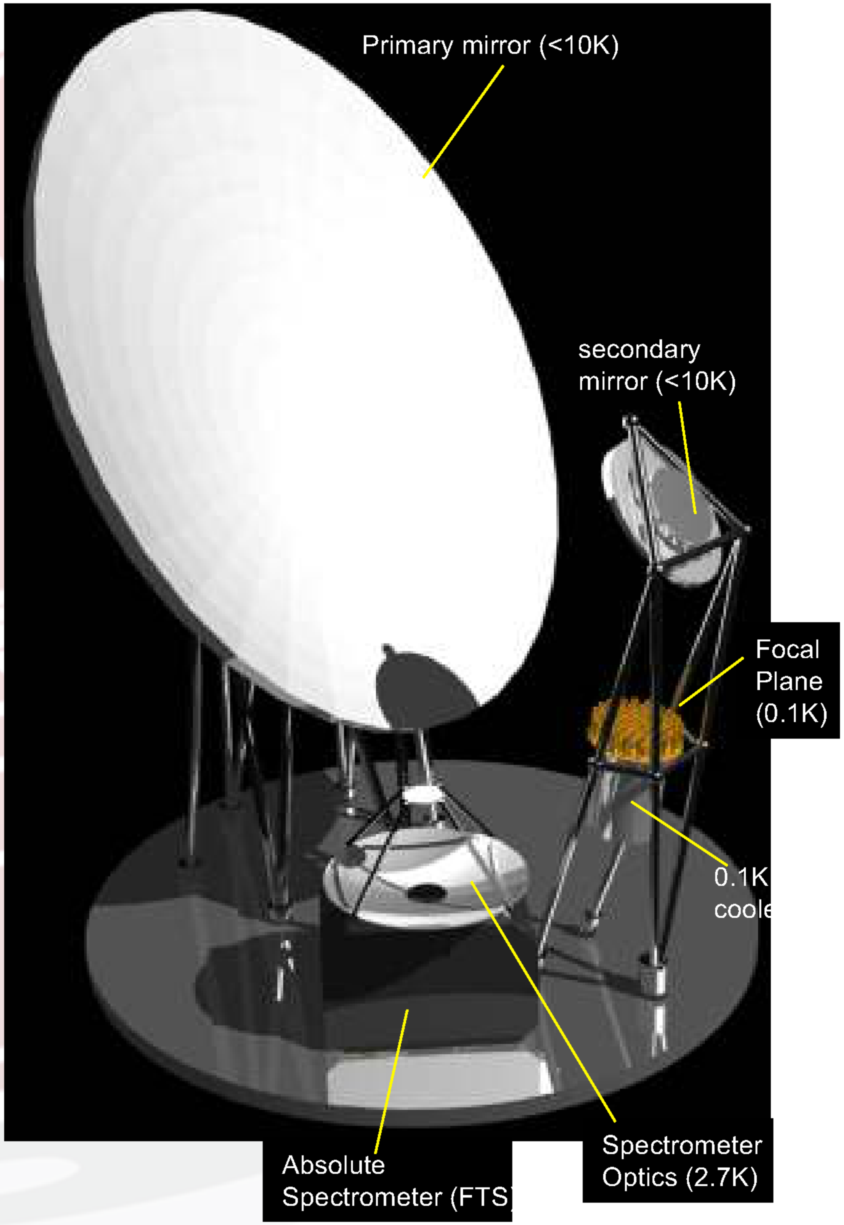
Key implications for GR

ATOMIC CLOCKS
ATOMIC INTERFEROMETERS



Polarised Radiation Imaging and Spectroscopy Mission



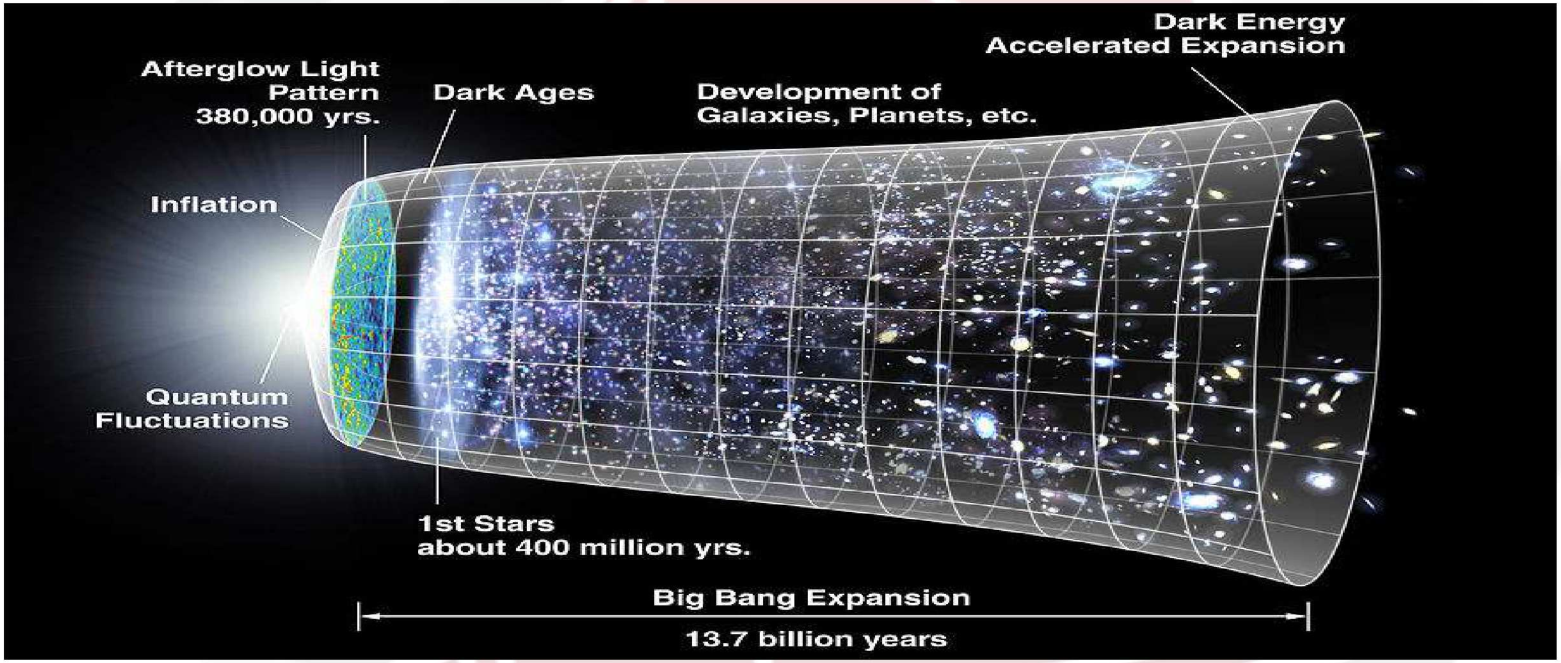


Polarimetric Imager

Think PLANCK + Full sky Herschel-SPIRE
- 10 – 100 times more sensitive
- Many more frequency channels
- Polarised
- 1-3 times better angular resolution

Absolute spectrophotometer

Think *COBE*/FIRAS
- 1000 times more sensitive
- 3 times better angular resolution


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 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.

A. Zacchei "Frequency maps

PLANCK 2014

THE MICROWAVE SKY IN TEMPERATURE AND POLARIZATION

1-5 December 2014, Palazzo Costabili, Ferrara, Italy

NEW RESULTS FROM PLANCK AND OTHER EXPERIMENTS ON COSMOLOGY, FUNDAMENTAL PHYSICS, GALACTIC AND EXTRAGALACTIC ASTROPHYSICS, DATA ANALYSIS AND NEXT OBSERVATIONAL CHALLENGES

SCIENTIFIC ORGANIZING COMMITTEE

LOCAL ORGANIZING COMMITEE

WHAT DO WE LOOK FOR?

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Thank you