planck

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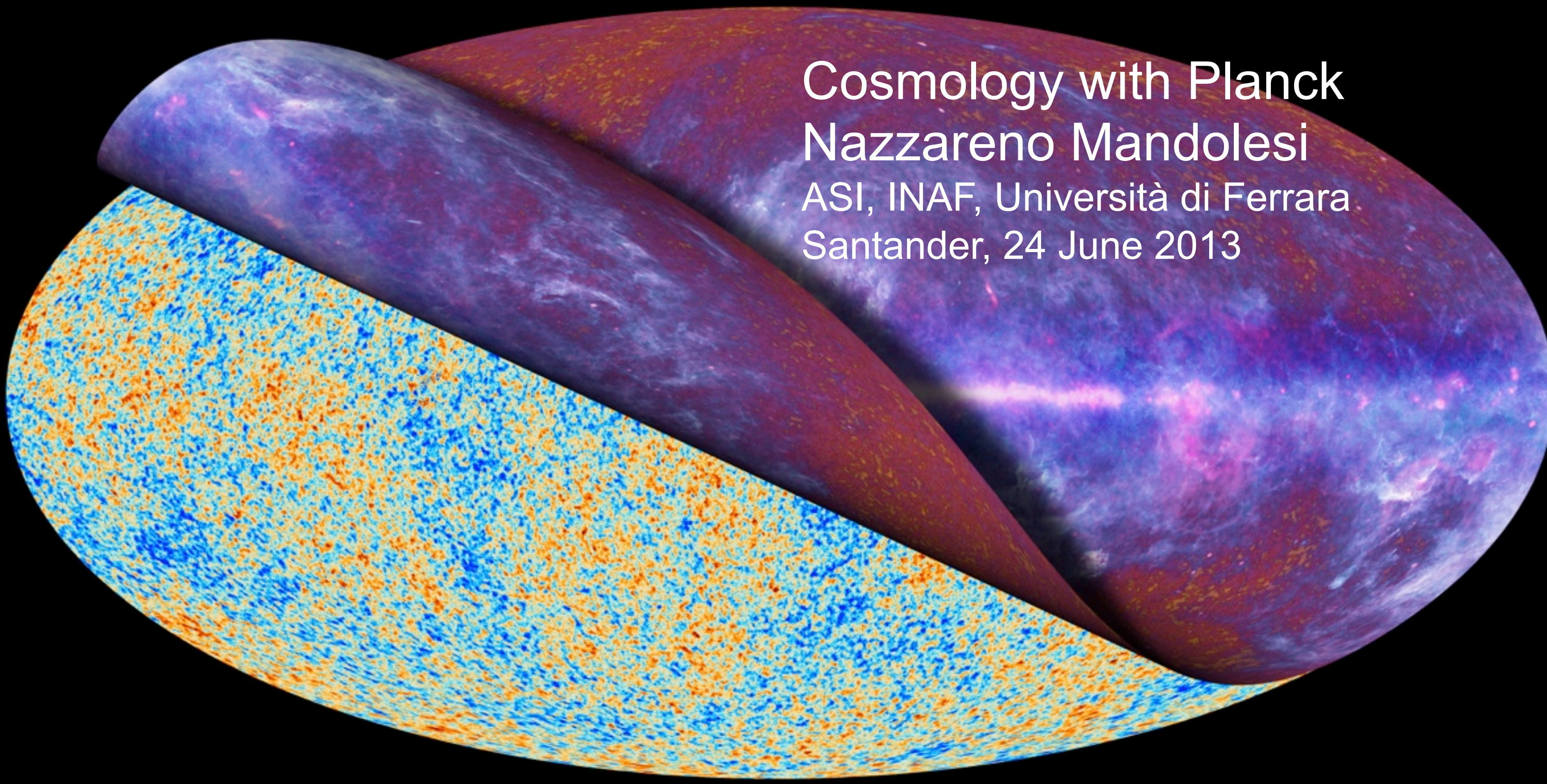
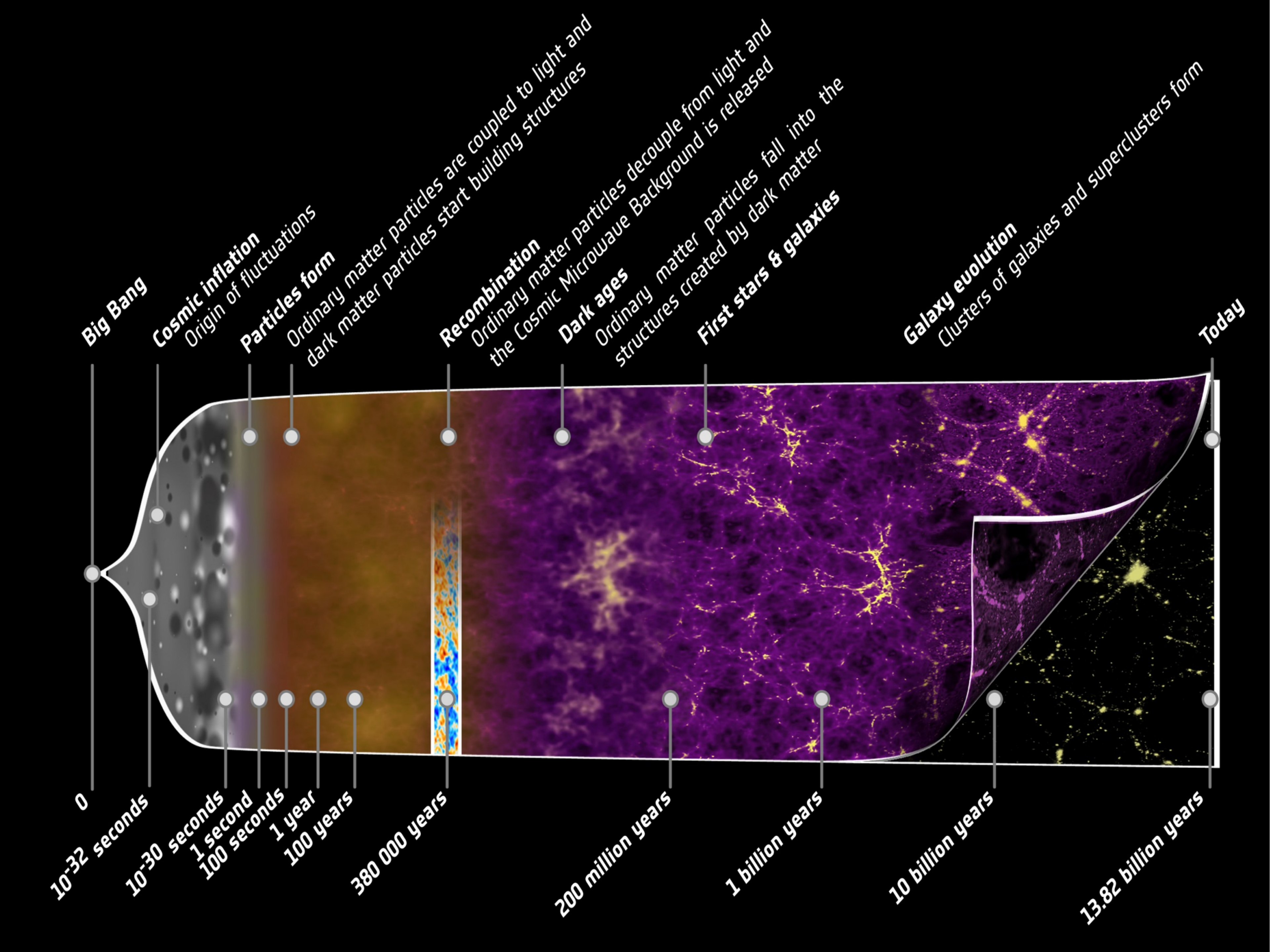
Cosmology with Planck

Nazzareno Mandolesi
ASI, INAF, Università di Ferrara

Santander, 24 June 2013



Planck unveils the Cosmic Microwave Background


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Planck History in Brief

- First conceived in 1992, proposed to ESA in 1993
- Payload approved in 1996
- Launched in May 2009, started to survey the sky in August of the same year
- Nominal mission completed at the end of 2010
  - but continued to gather data with the full payload until January 2012
  - … and it continues to gather data with LFI only until the fall (August end of 8 full sky survey)
- Planck is an ESA mission: ESA, European industries, and the international technological and scientific community have contributed to its realisation and success
- The Planck payload has been founded by the European members state Space Agencies and by NASA: ASI and CNES are the leading Agencies.
  - Thousands of engineers and scientists were involved from ~100 scientific institutes in Europe, the USA, and Canada
  - Two scientific Consorzia (LFI led by N. Mandolesi and HFI by Jean Loup Puget) were responsible for the delivery of the Instruments to ESA, the mission data analysis and the delivery of the data and results to the open scientific community

A proposal submitted in response to ESA M3 Call for Mission Ideas (May 1993)

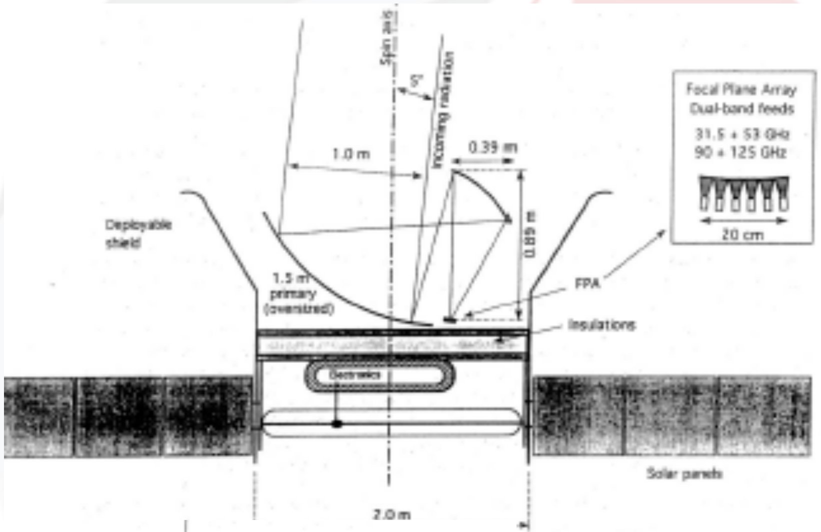
1993

COBRAS

COsmic Background Radiation Anisotropy Satellite

SAMBA

Satellite for Measurements of Background Anisotropies



...ian optical system assumed in our ...set from the spin axis (here assumed ... the details of the scan strategy. The ...lelobe pickup and cooling efficiency. ... feeds. Placing their apertures on a

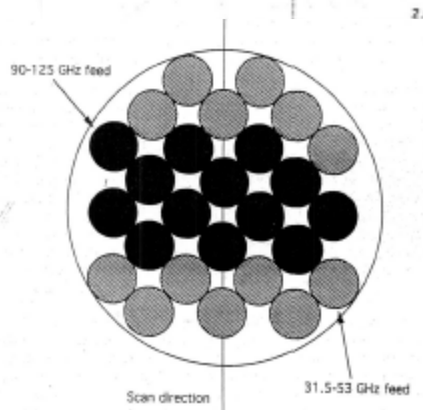
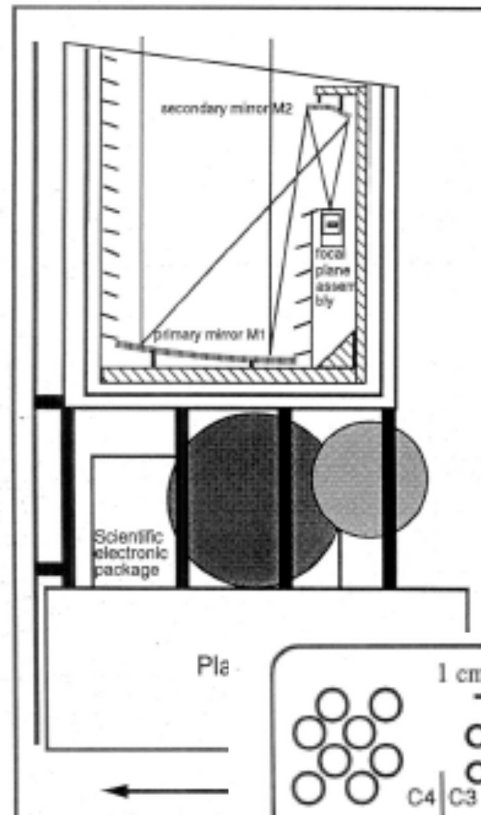
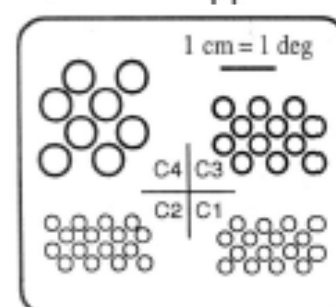
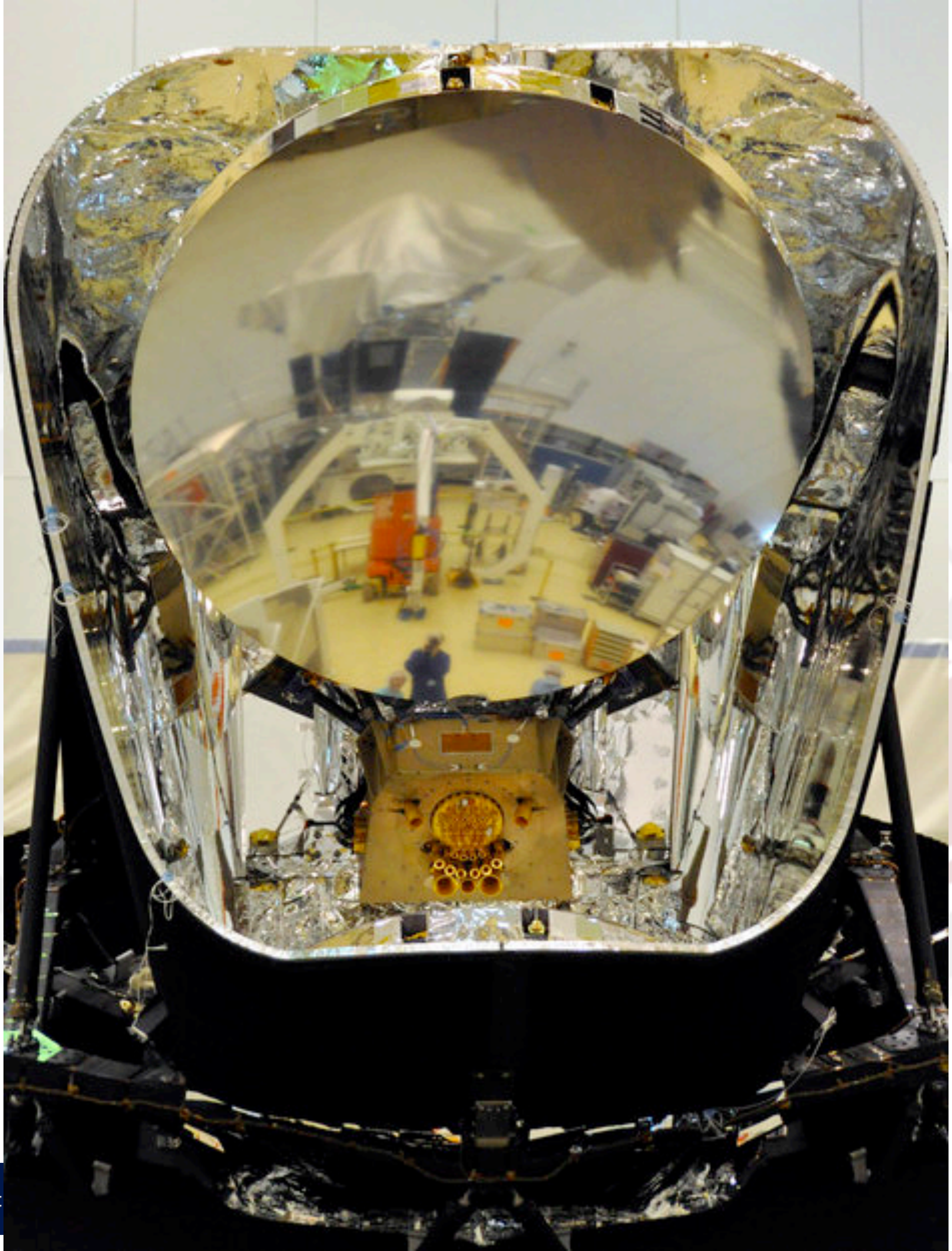


Figure 7 - The proposed geometrical disposition of the feed elements in the focal plane array is shown. The higher frequency elements (90–125 GHz) are more sensitive to beam distortion effects and have been clustered near the center of the array. Our preliminary study shows that coma lobes of the most de-centered elements are expected to be below -40 dB (10^{-4}) at 125 GHz and below -55 dB ($10^{-5.5}$) at 30 GHz.






NORD



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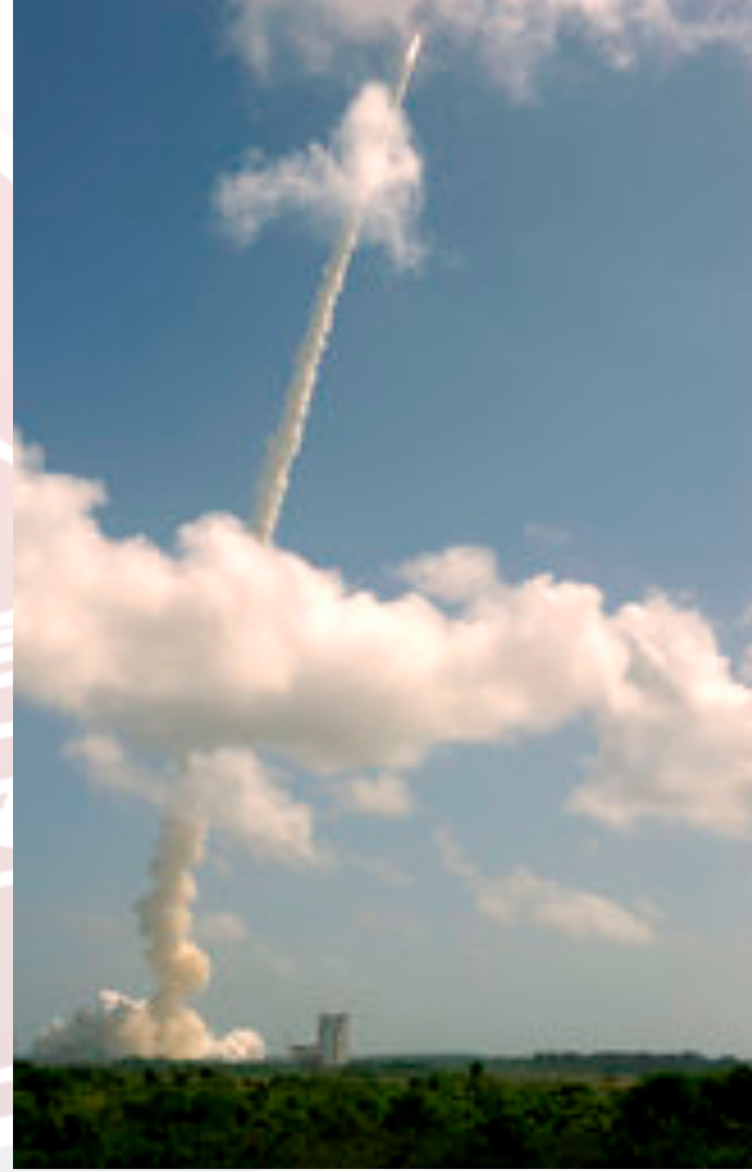

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UNIFE

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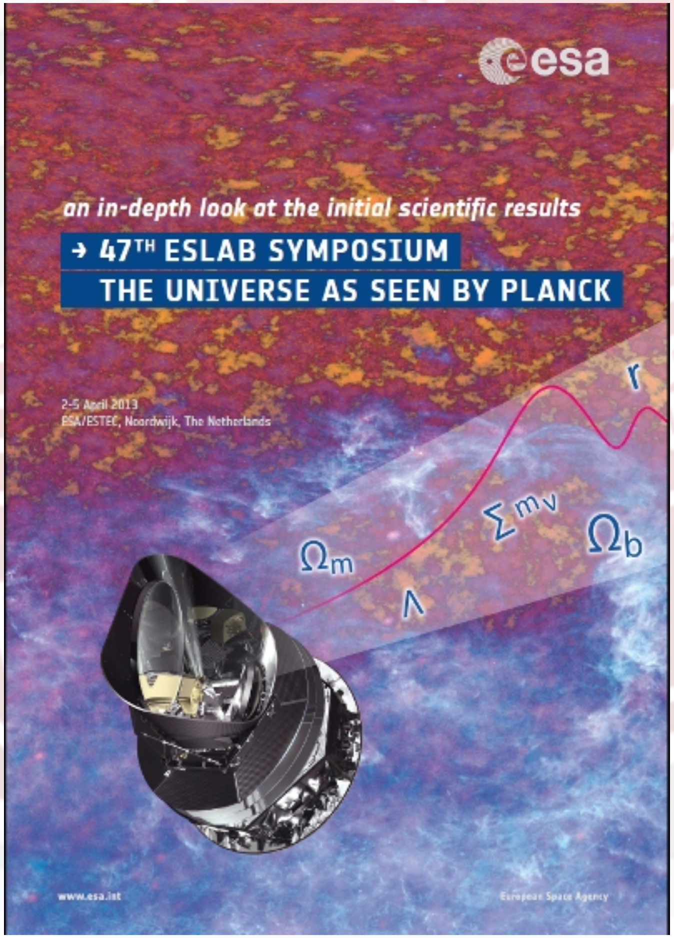
INAF ISTITUTO NAZIONALE DI ASTROFISICA

21 March 2013:
29 papers delivered
About 1000 pages all together



Planck newspaper coverage, March 21–22, 2013


"All the News That's Fit to Print"

The New York Times

Late Edition

NEW YORK, FRIDAY, MARCH 22, 2013

The Cosmos, Back in the Day

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

By MARK LANDLER

Bronx Inspector, Secretly Taped, Suggests Race Is a Factor in Stops

By JOSEPH GOLDSTEIN

Officer Pedro Serrano

Once Few, Women Hold More Power in Senate

By JENNIFER STEINHAUER

Fast-Growing Brokerage Firm Often Tangles With Regulators

By NATHANIEL POPPER

Mood Darkens in Cyprus Ahead of Bailout Deadline

O Revelations! Letters, Once Banned, Flesh Out Willa Cather

By JENNIFER SCHUESSLER

Struggle Over Drone Program

Kurds Seek Truce With Turkey

No Progress on Border Data

54 Chicago Schools Closing

Risë Stevens, Star at the Met

School and Abuse Victims Talk

iPhone Inquiry in Europe

Computers at a New Level

New Legal Tactic for Baseball

Paul Krugman

Cartier

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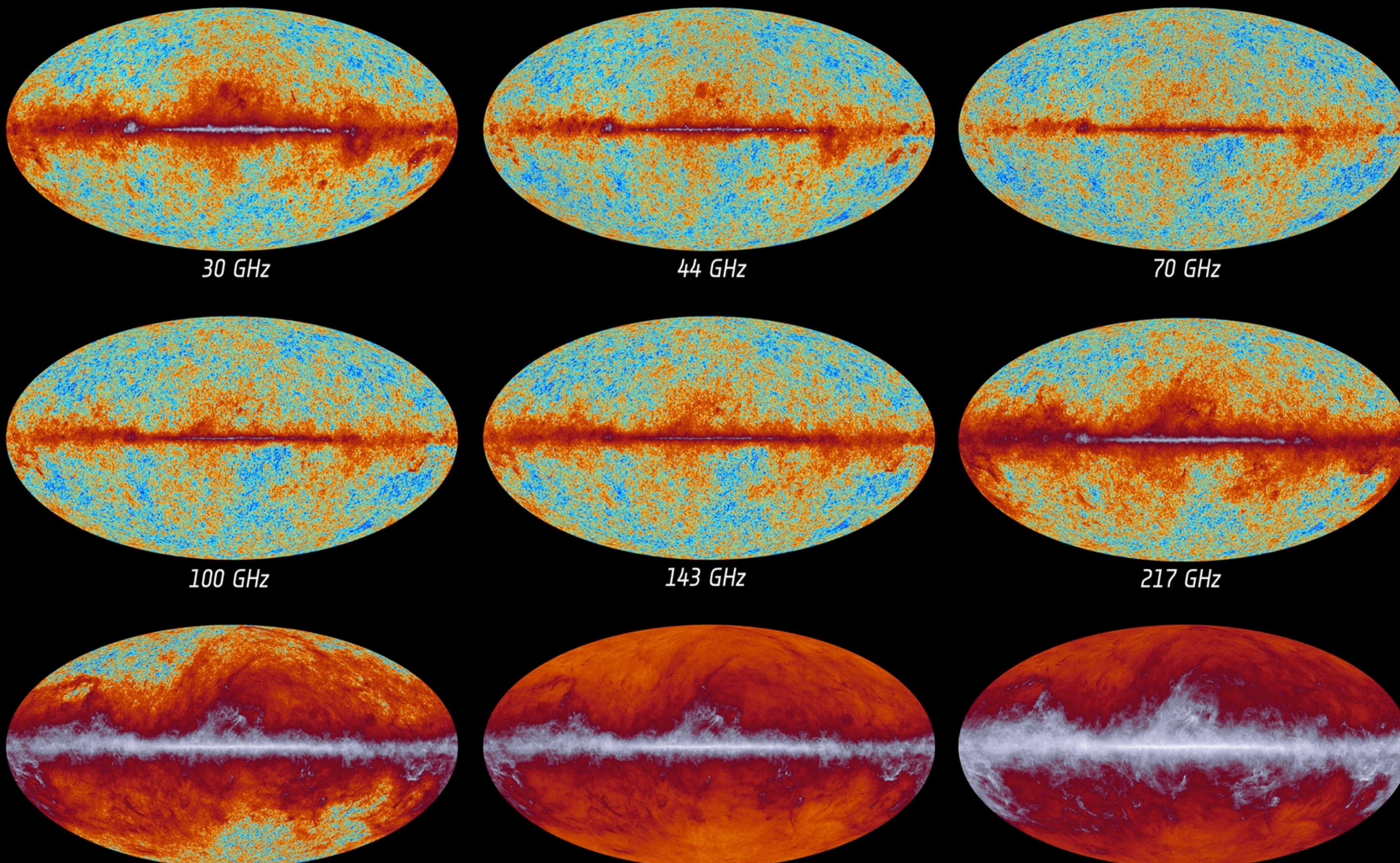
The visible night sky

The sky as seen by Planck



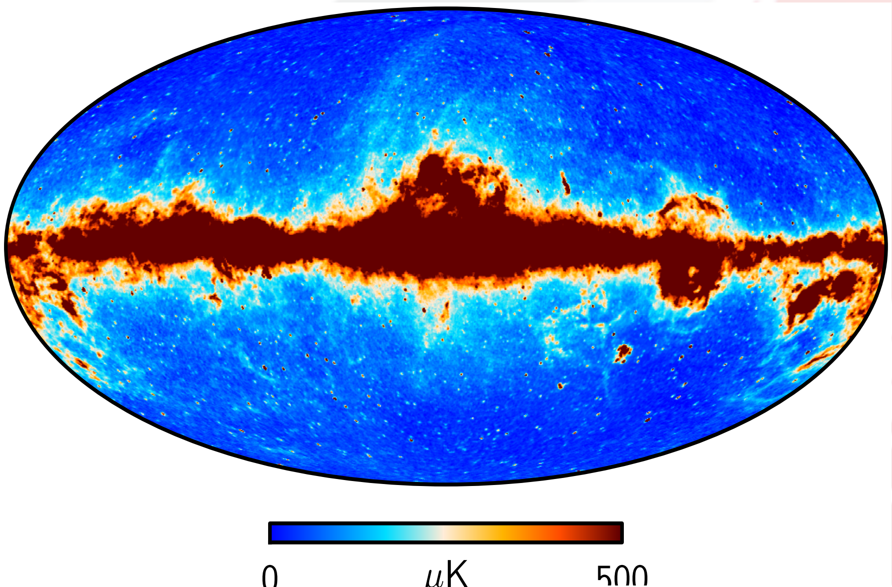
30 GHz | 44 GHz | 70 GHz

100 GHz | 143 GHz | 217 GHz

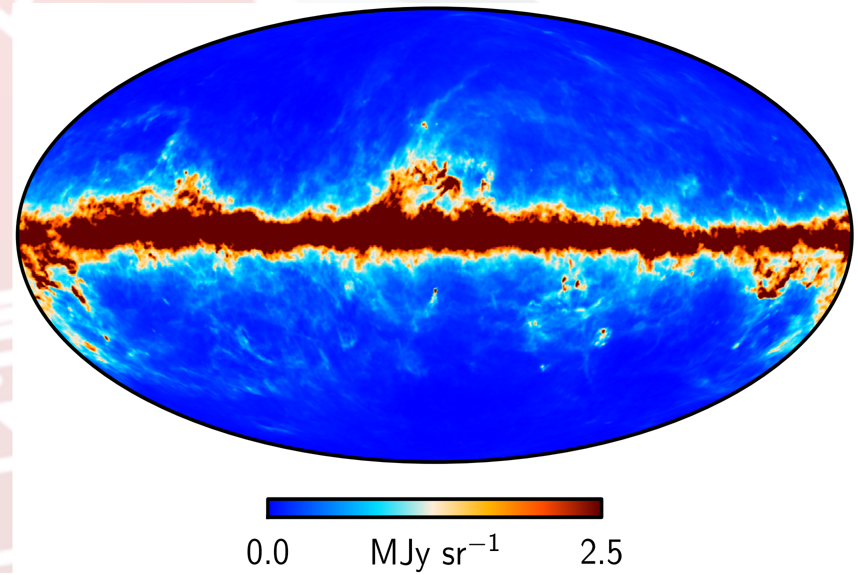
353 GHz | 545 GHz | 857 GHz

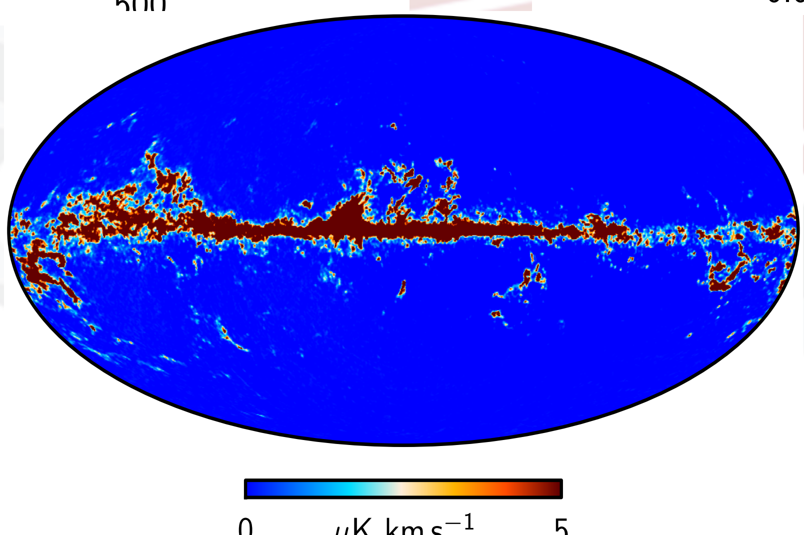
Emission from the Milky Way

Non-thermal radio emission



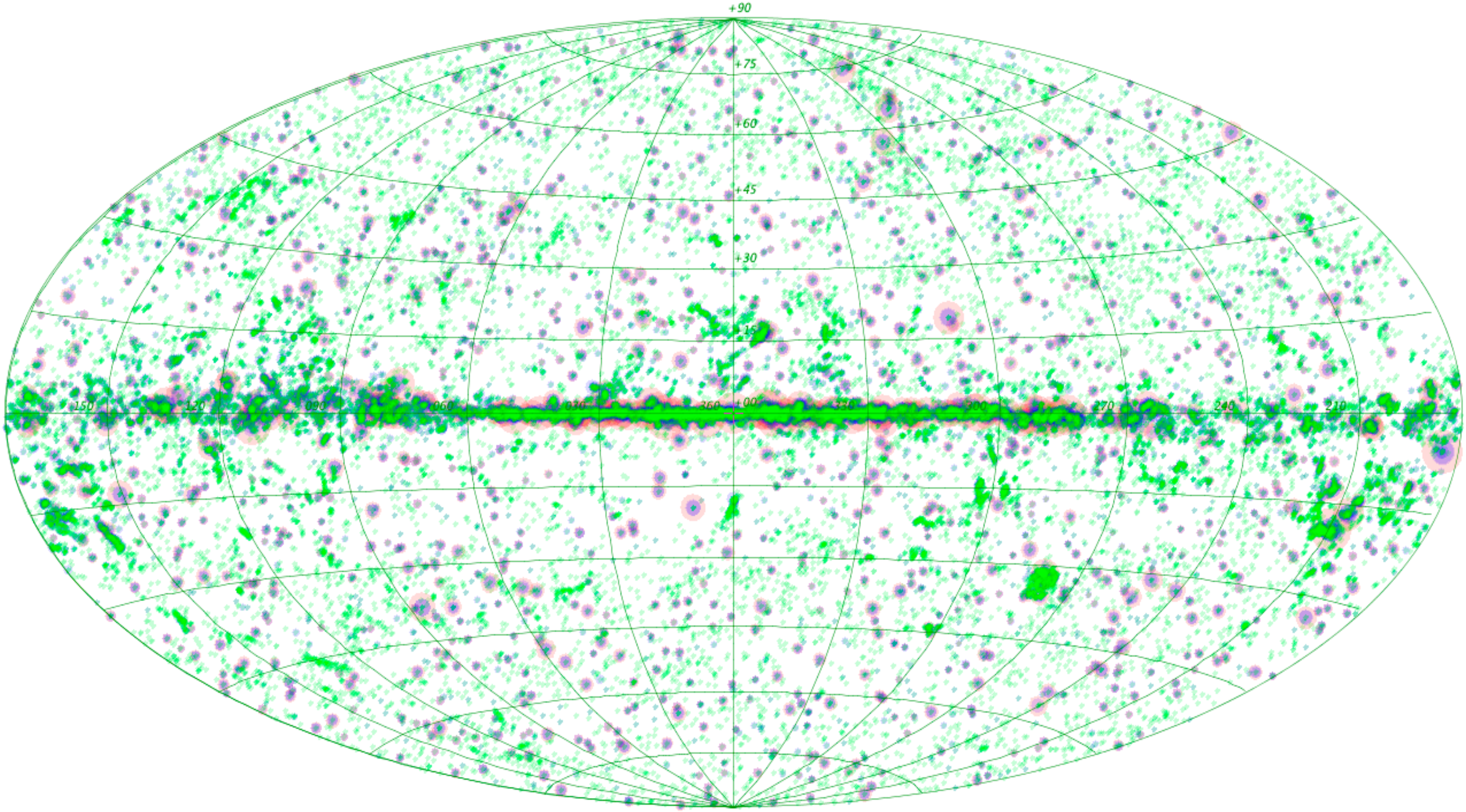
Thermal dust emission





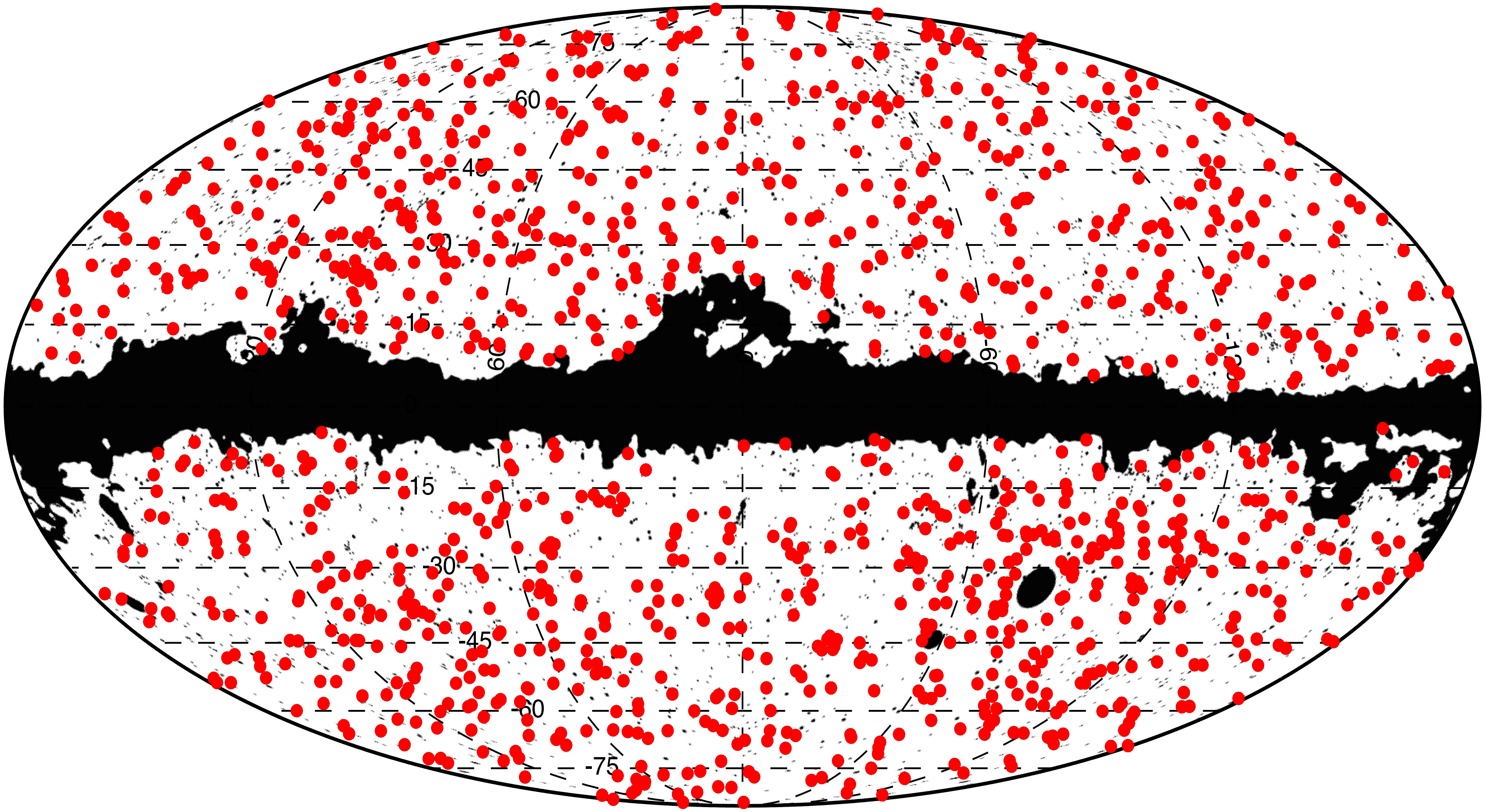
Carbon monoxide

Compact galactic and extragalactic sources

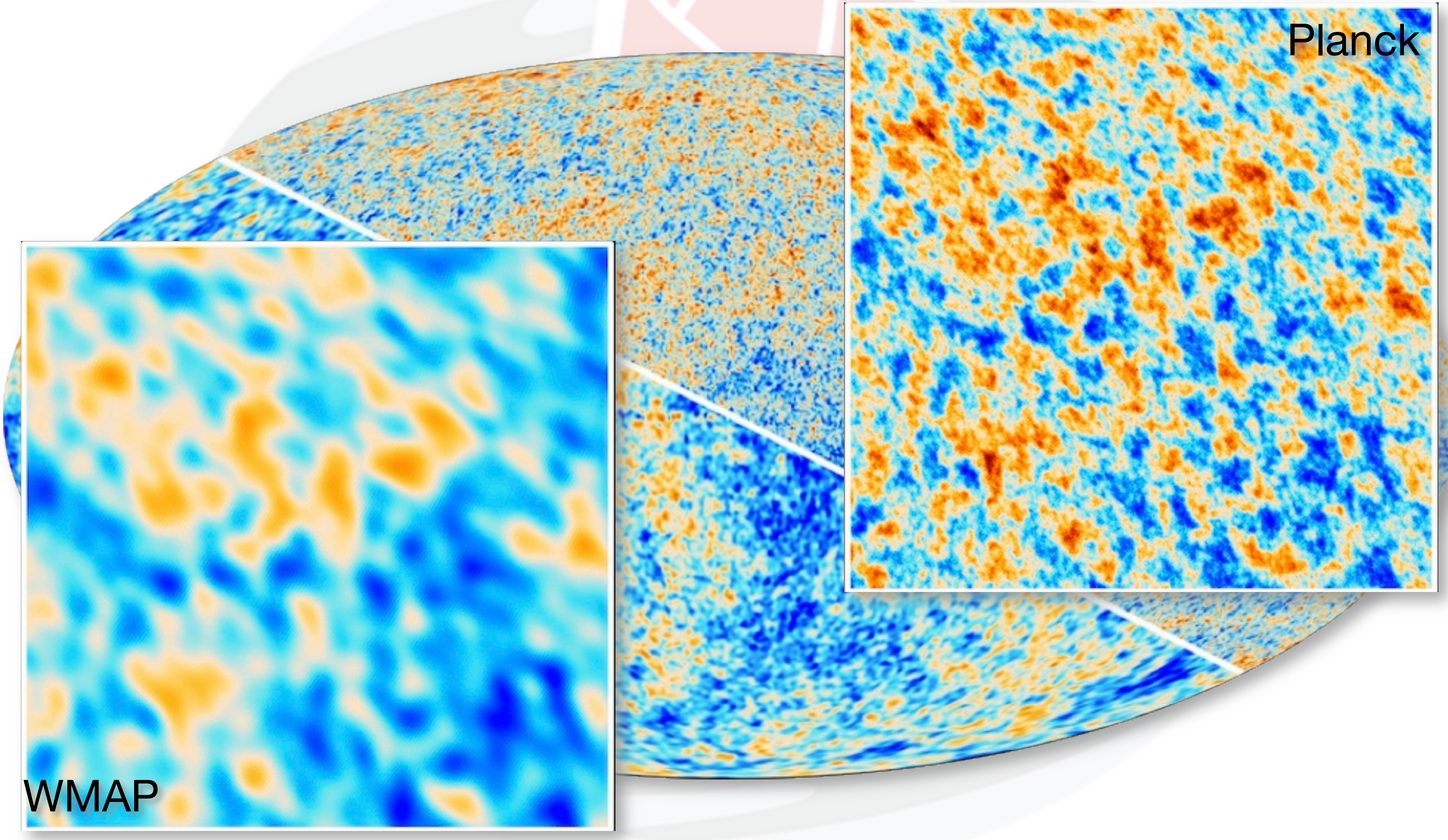


Clusters of galaxies

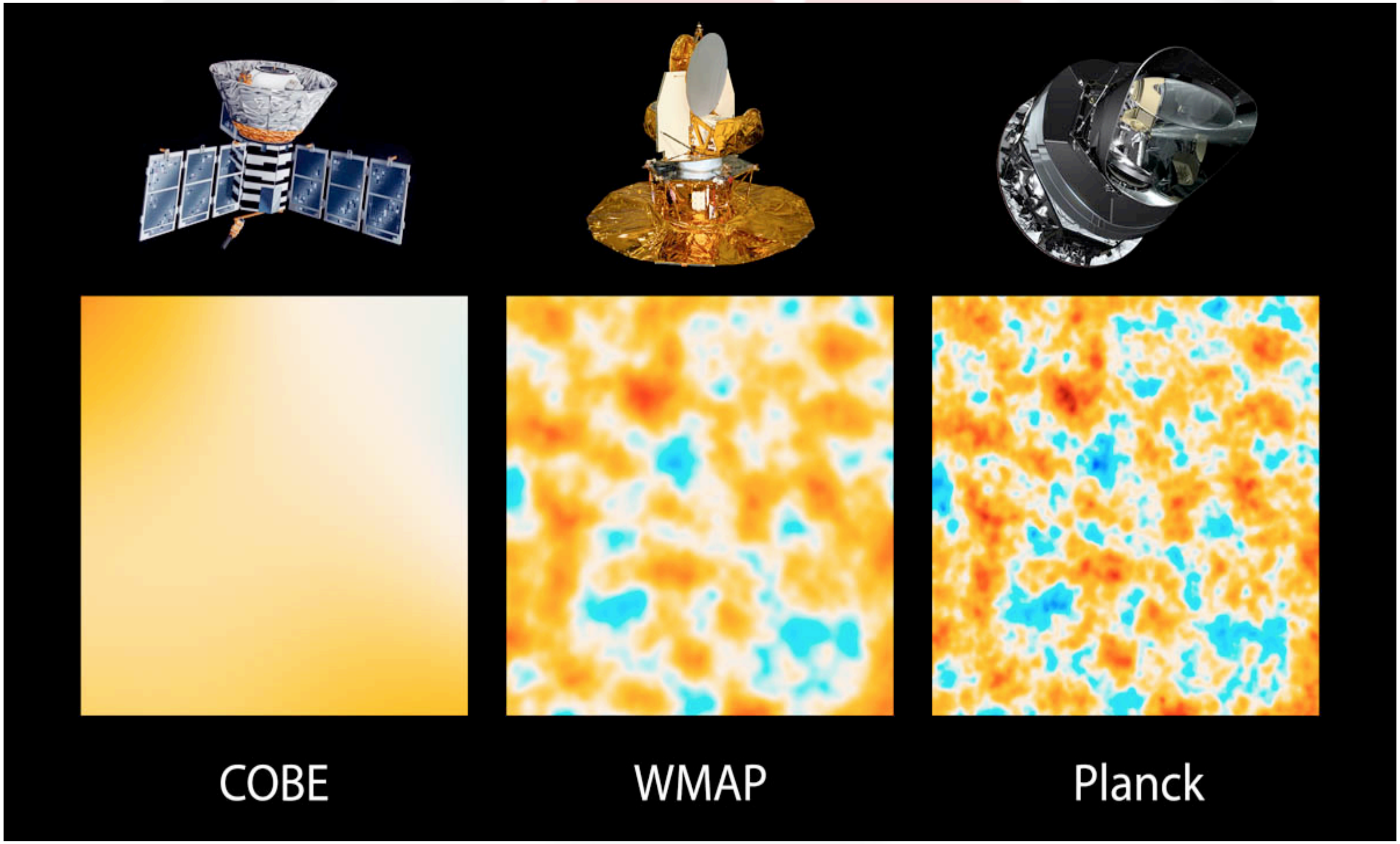
Planck SZ catalog



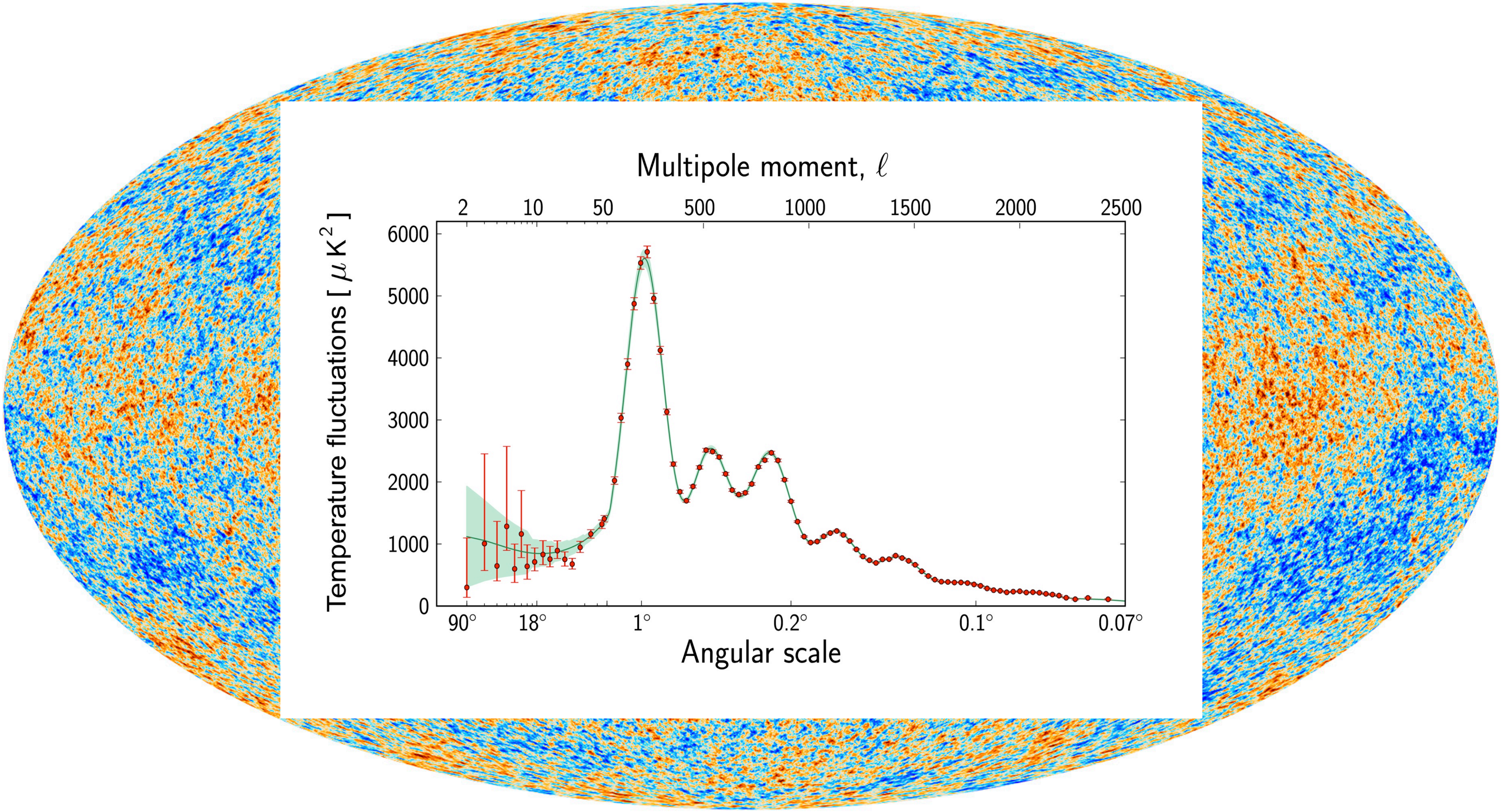
Planck versus WMAP

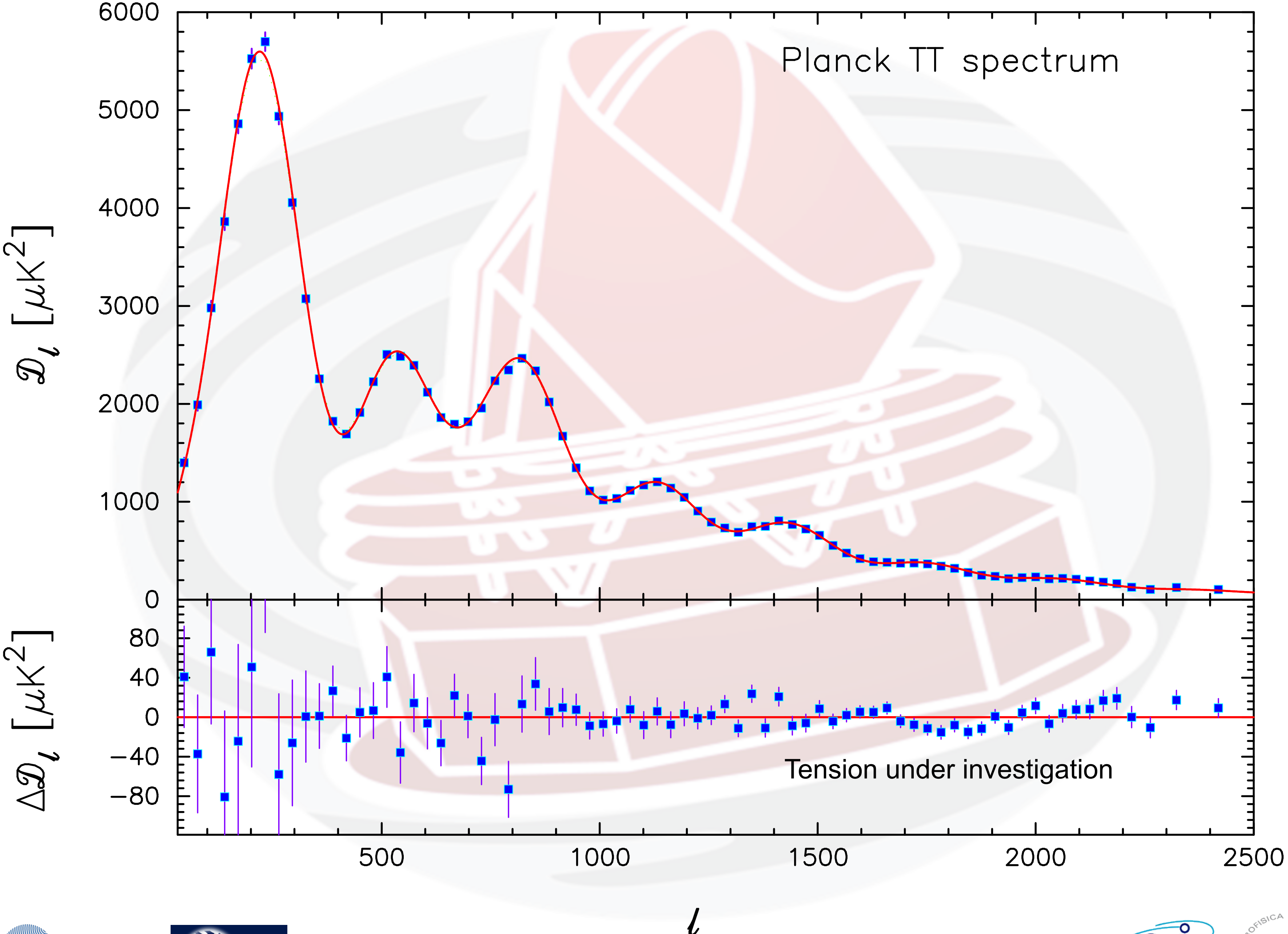


Comparison w/ forerunners

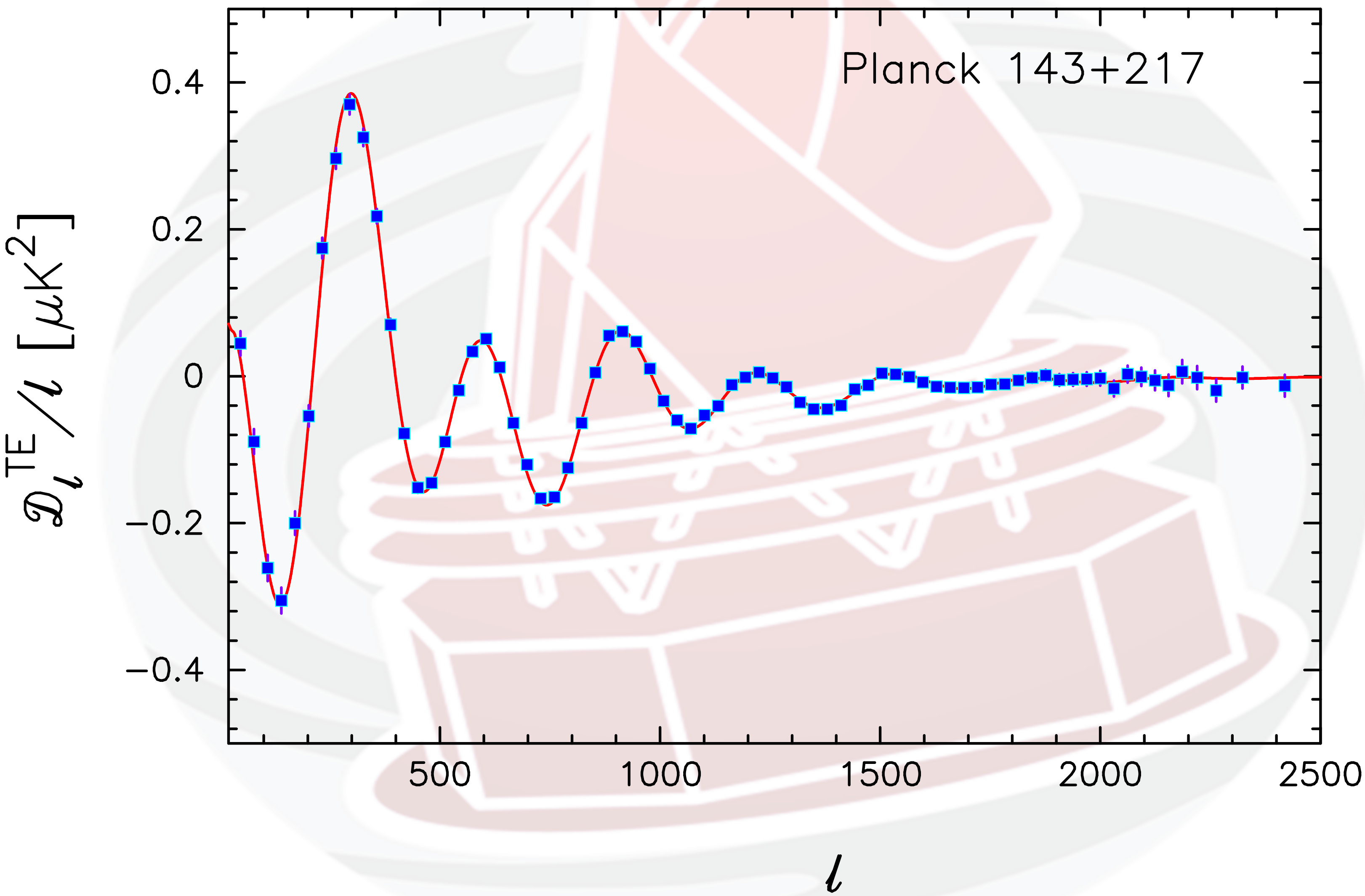


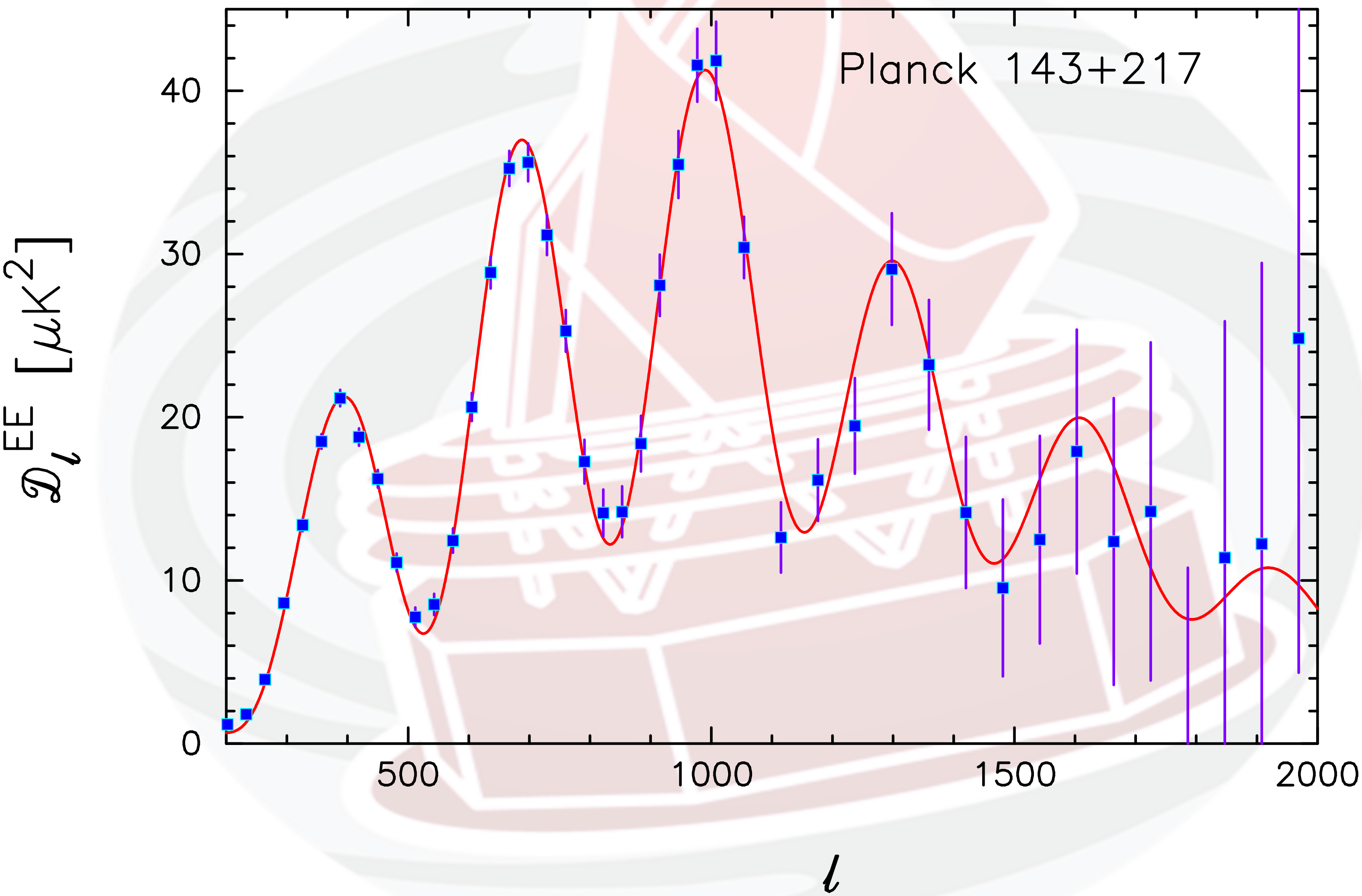
The anisotropies of the CMB





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


Planck 143+217
0.4
0.2
0
−0.2
−0.4
500
1000
1500
2000
2500
$\mathcal{D}_\ell^{TE}/\ell$ [μK^2]
ℓ

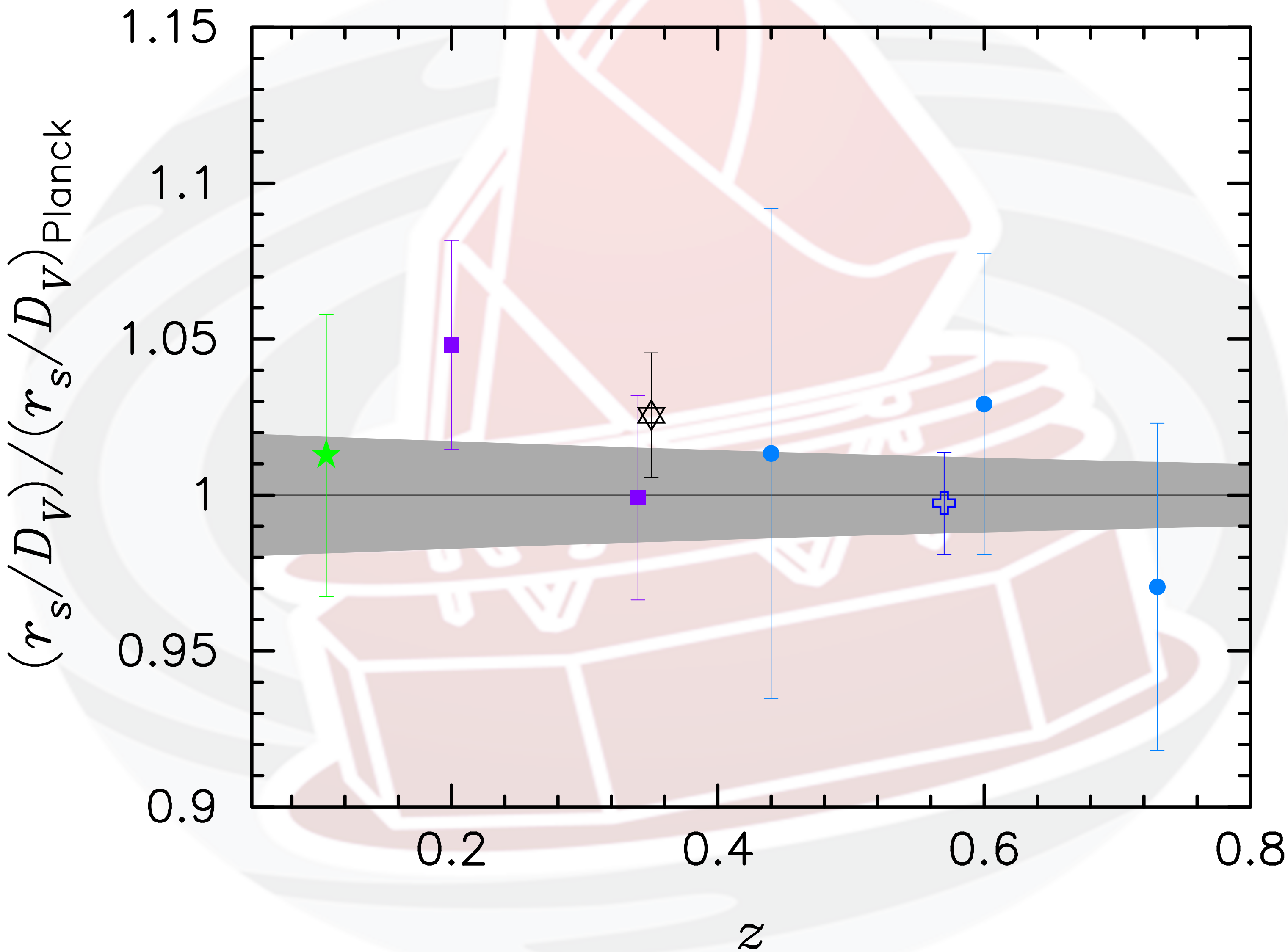


Planck 143+217
$\mathcal{D}_\ell^{EE}$ [μK^2]
ℓ
0
10
20
30
40
500
1000
1500
2000

6 parameters of ΛCDM

- Baryon density
- Cold dark matter density
- Reionisation optical depth
- Peak scale
- Primordial spectral index
- Primordial amplitude

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		



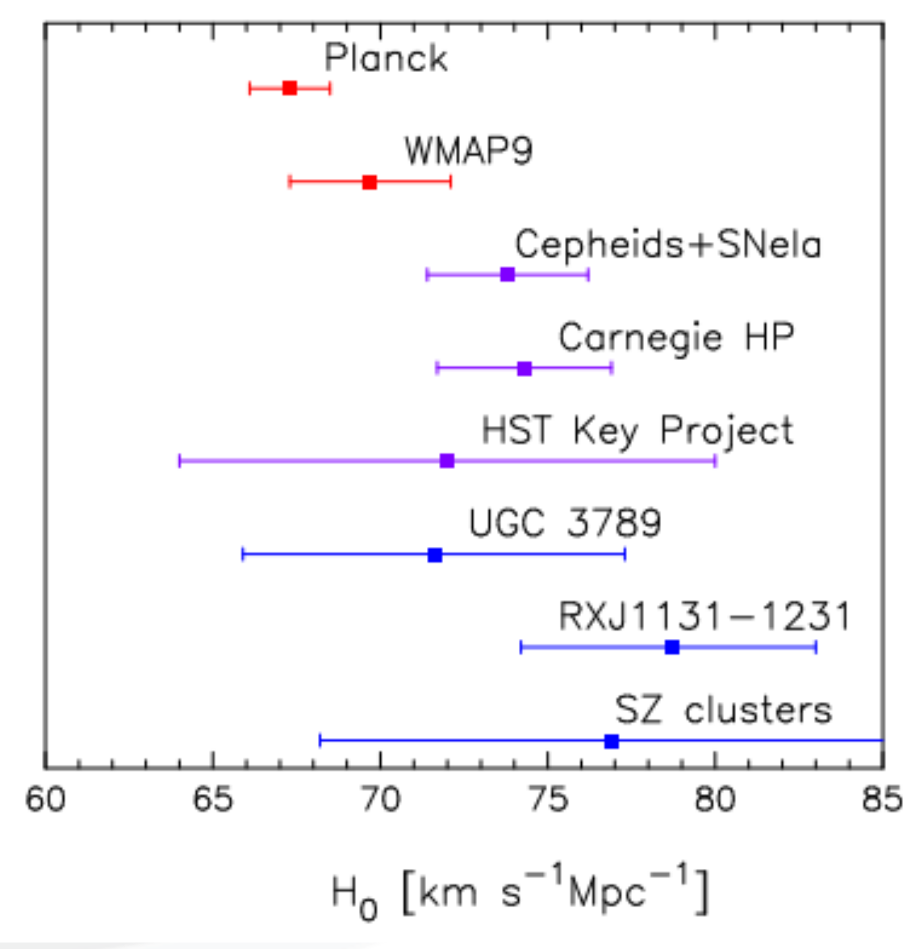
1.15
1.1
1.05
1
0.95
0.9
0.2
0.4
0.6
0.8
$(r_s/D_V)/(r_s/D_V)_{\mathrm{Planck}}$
z

Tension with Hubble Constant astrophysical measurements

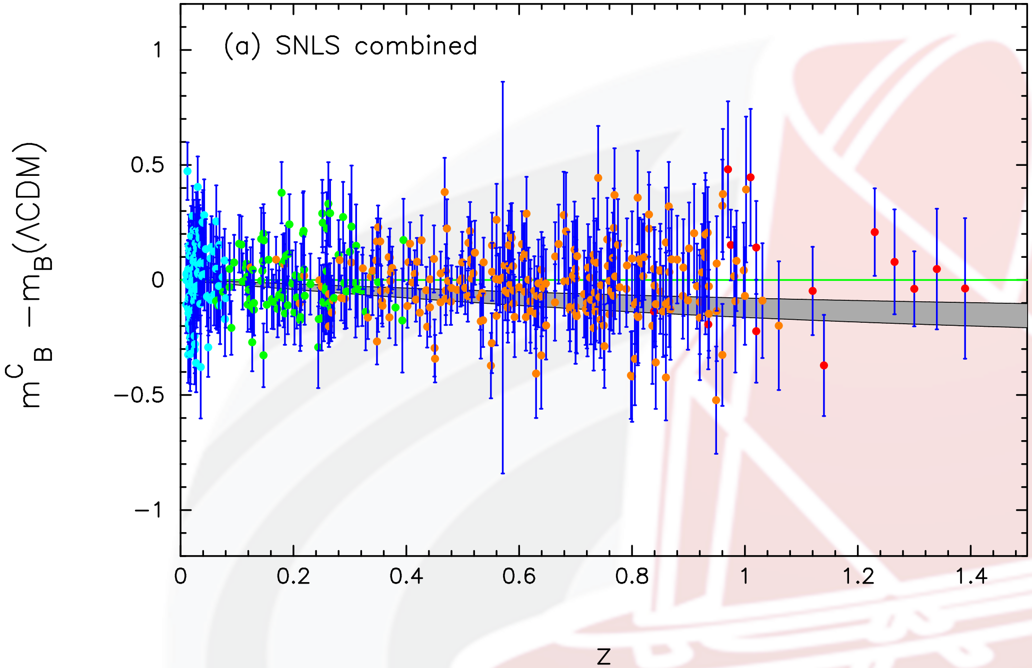
Planck value for the Hubble constant is in a tension with several other measurements (most notably the HST determination).

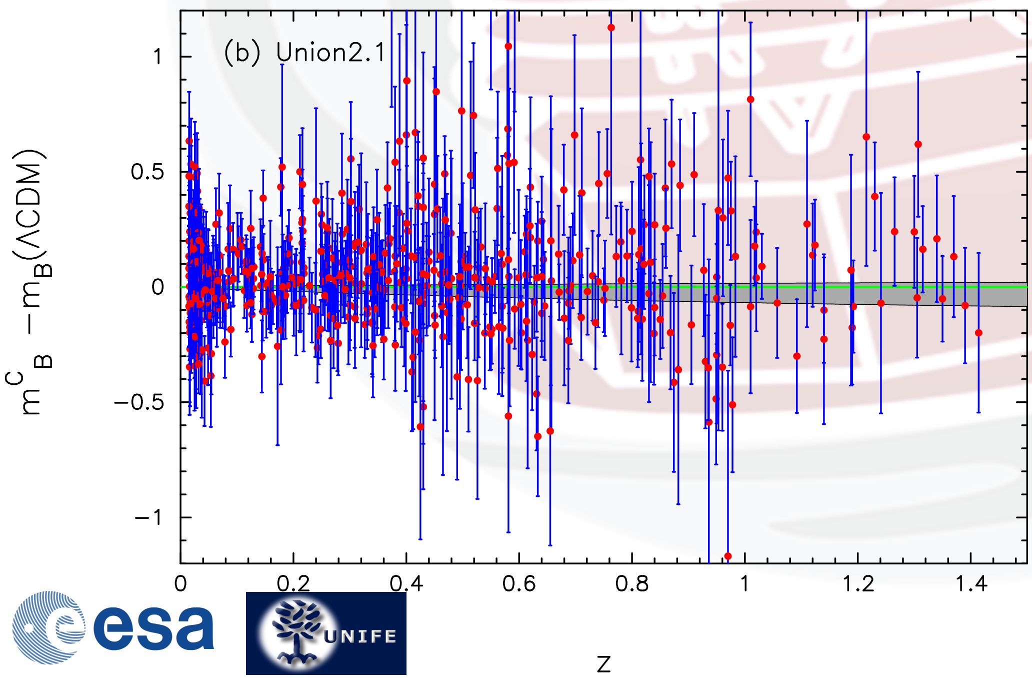
Systematics in luminosity distance measurements can be clearly there, however this tension could be also hinting towards new physics.

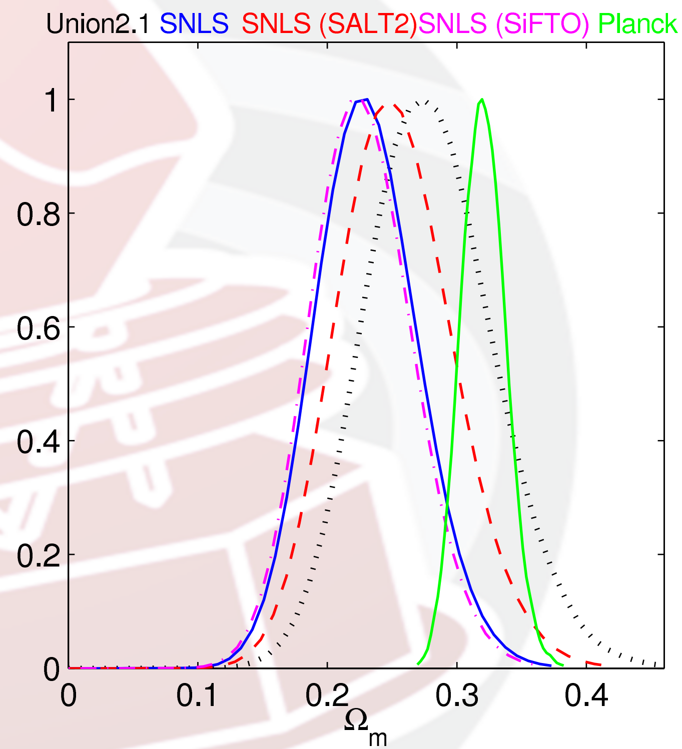
The determination of H_0 from Planck is indeed **model dependent**.



Tension under investigation


(a) SNLS combined
$m_B^C - m_B(\Lambda CDM)$
z

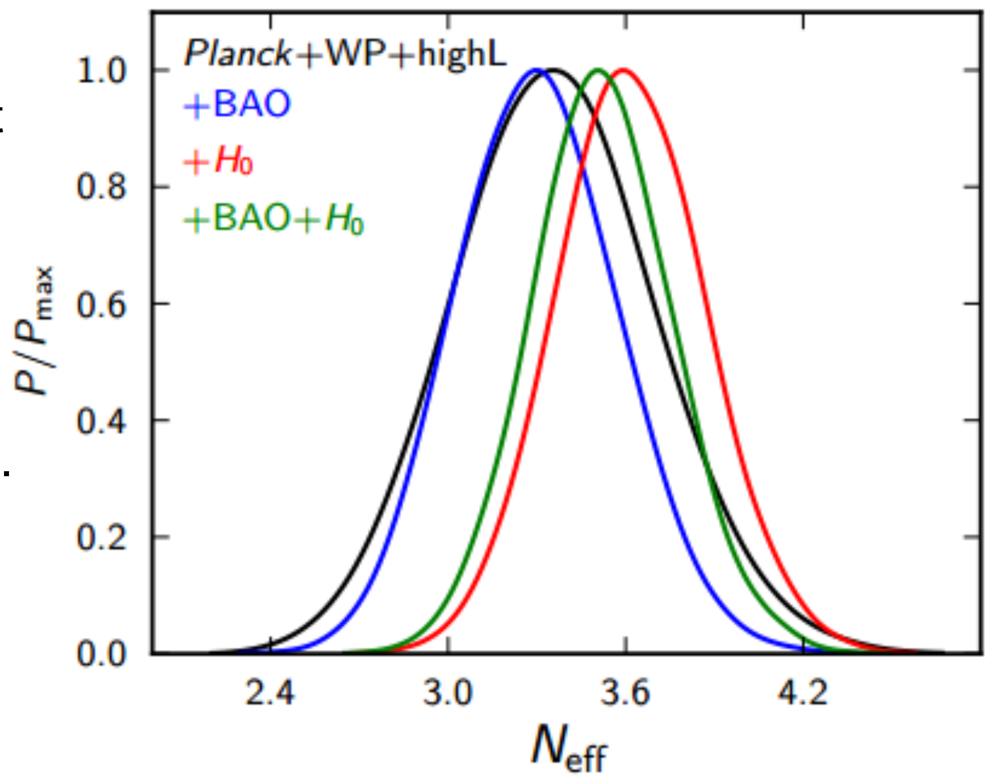

(b) Union2.1
$m_B^C - m_B(\Lambda CDM)$
z


Union2.1 SNLS SNLS (SALT2) SNLS (SiFTO) Planck
Ω_m

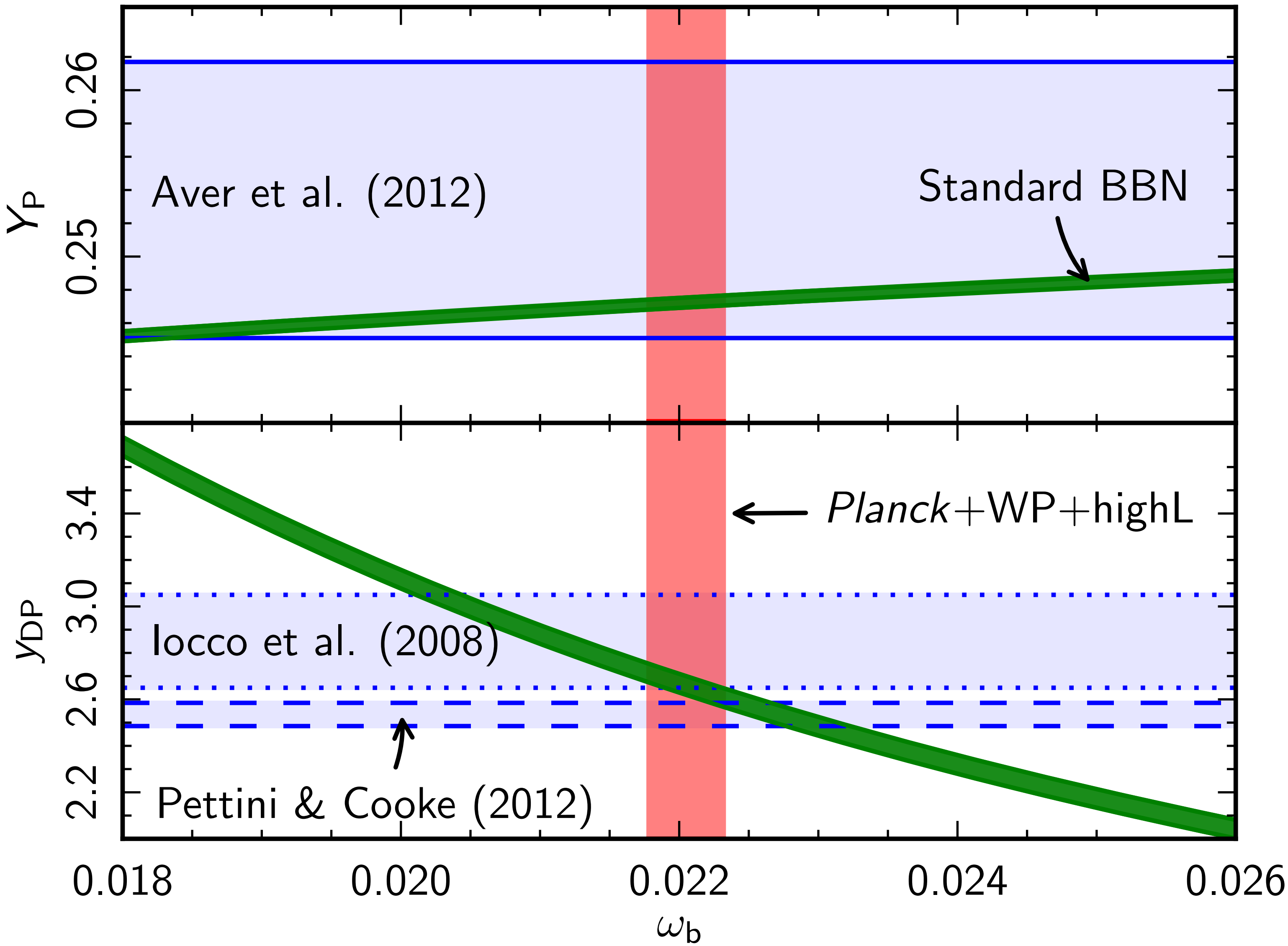
Example: extra degrees of freedom from Planck+HST ?

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.

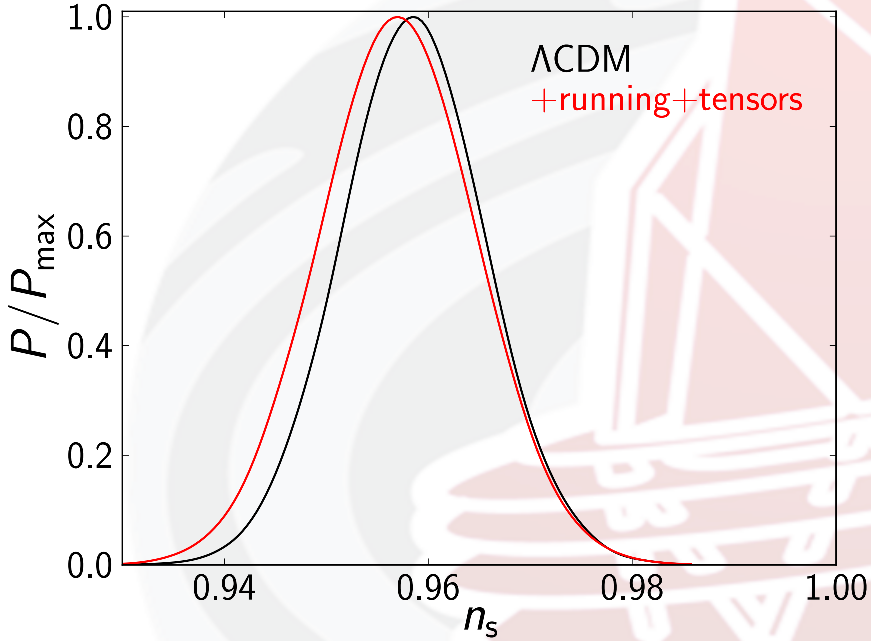
A sterile neutrino with non standard decoupling could explain this effect.



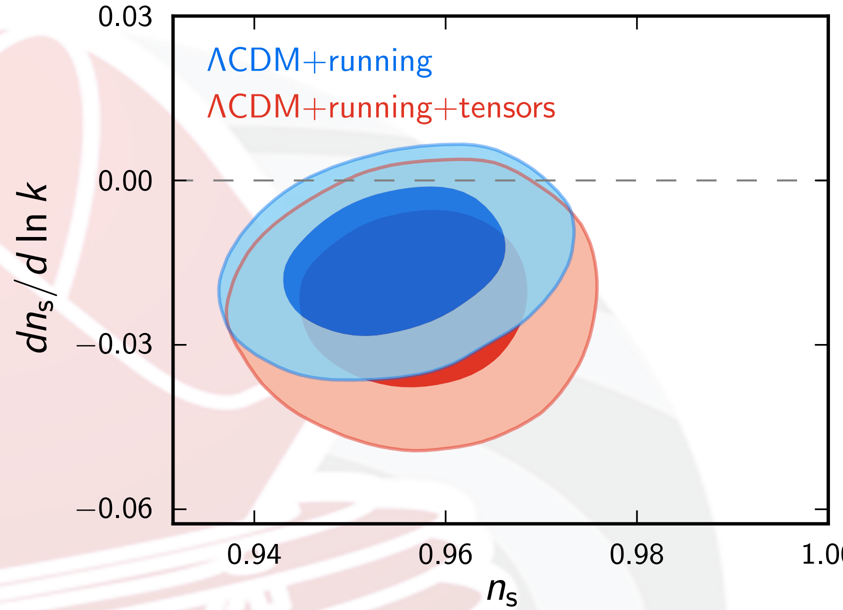
Other new physics mechanisms could explain this tension.



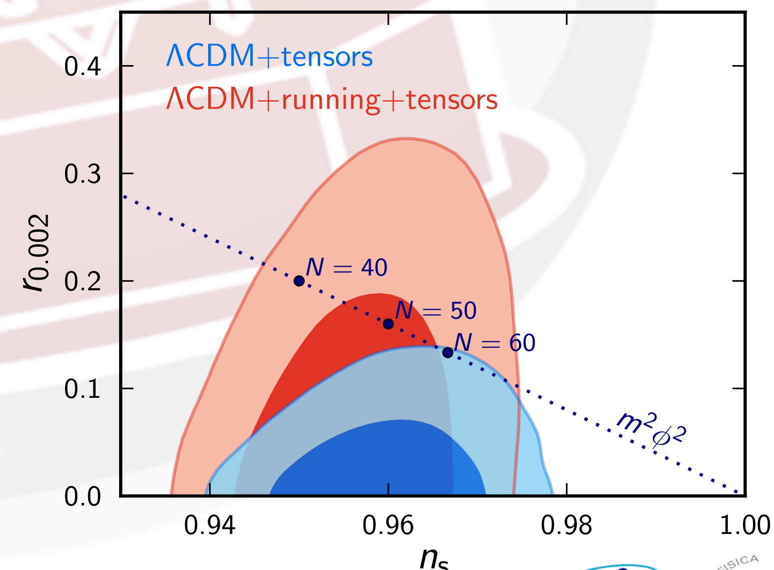
Aver et al. (2012)
Standard BBN
Y_P
0.26
0.25
y_{DP}
3.4
3.0
2.6
2.2
Planck+WP+highL
Iocco et al. (2008)
Pettini & Cooke (2012)
0.018
0.020
0.022
0.024
0.026
ω_b



ΛCDM
+running+tensors
P/P_{max}
1.0
0.8
0.6
0.4
0.2
0.0
0.94
0.96
0.98
1.00
n_s

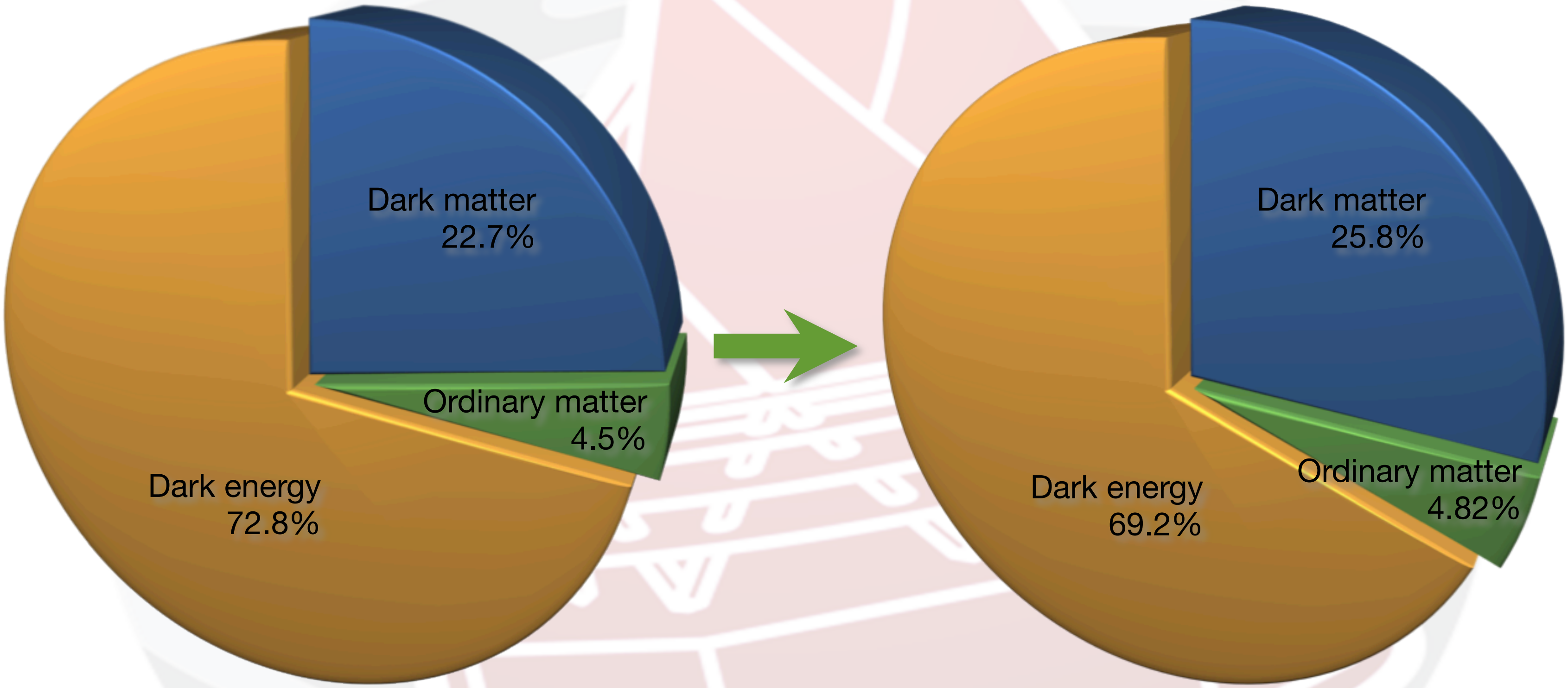


ΛCDM+running
ΛCDM+running+tensors
$dn_s/d\ln k$
0.03
0.00
−0.03
−0.06
0.94
0.96
0.98
1.00
n_s



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_s

A new cosmic recipe



Before March 21, 2013 | Today

Age of the Universe : 13.798 ± 0.037 Gyr
Hubble constant : 67.80 ± 0.77 km s^{-1} Mpc^{-1}
Parameters based on Planck + WMAP polarisation + highL + BAO

Baryonic matter : ± 0.05%
Dark matter : ± 0.4 %
Dark energy : ± 1.0 %

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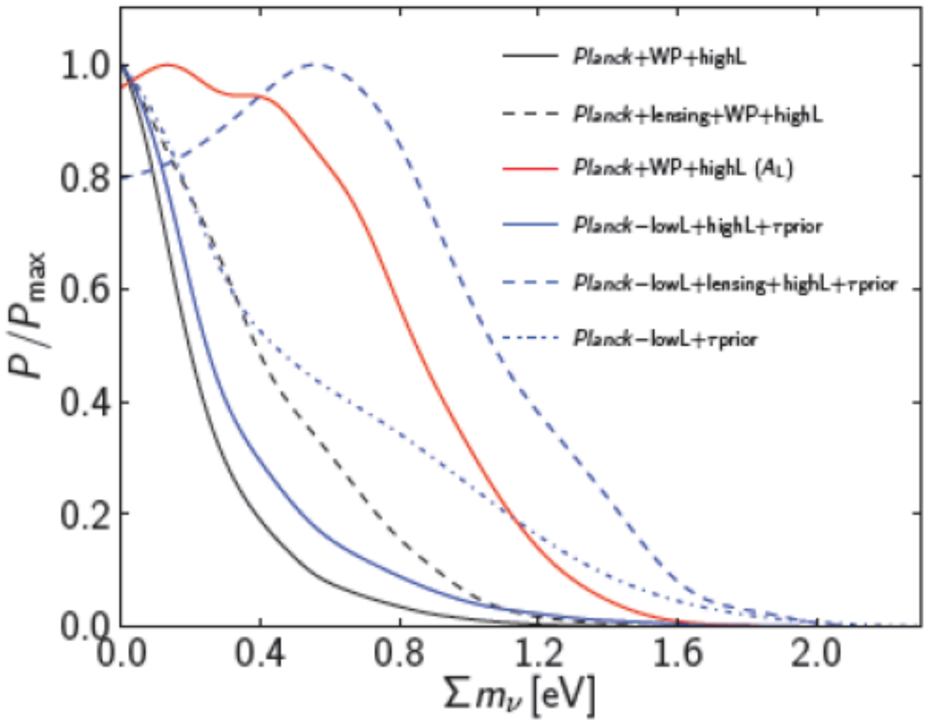
Constraints on Neutrino Mass (standard 3 neutrino framework)



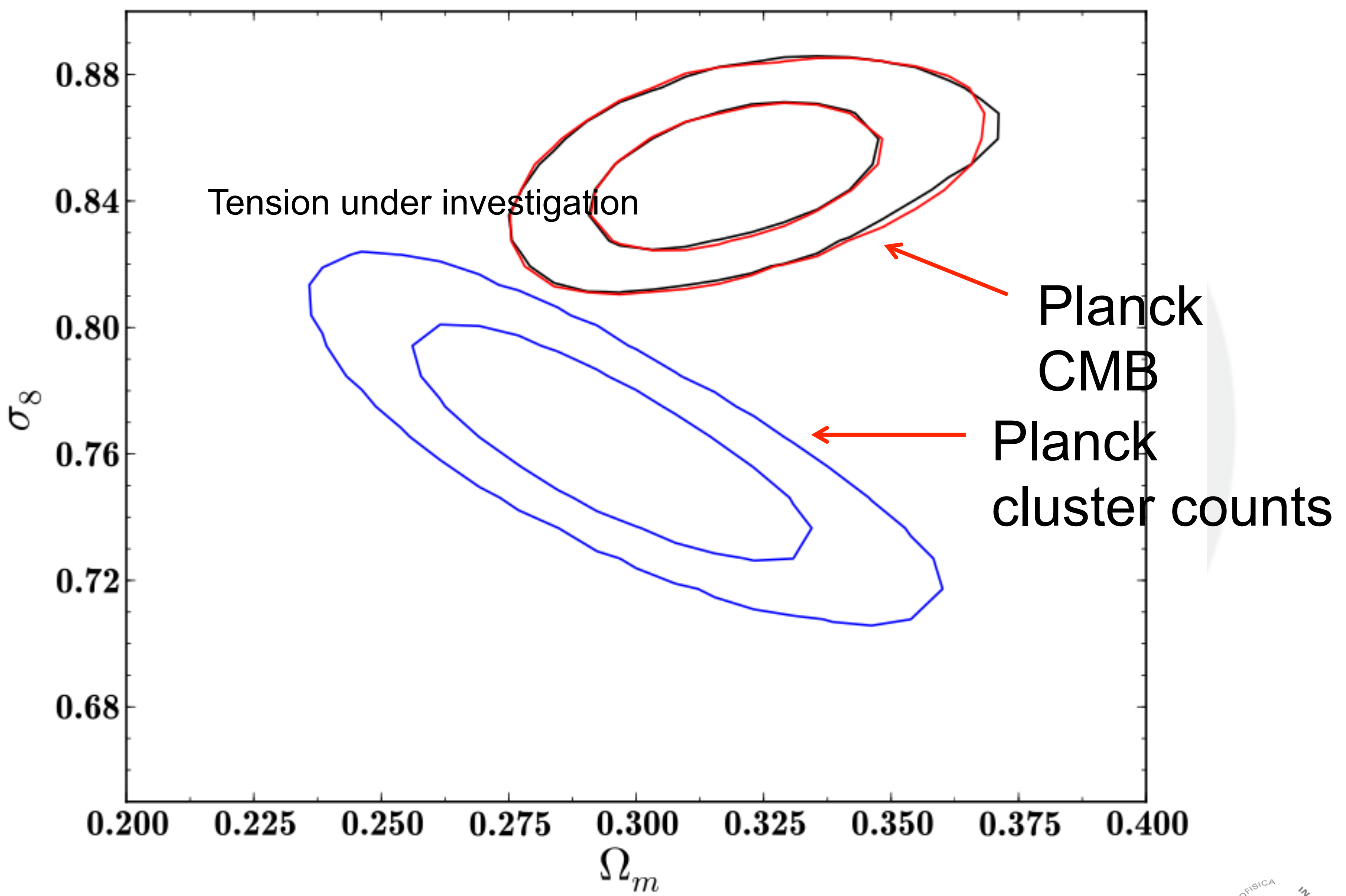
$$\sum m_\nu < 0.66\,\text{eV} \quad (95\%;\ \textit{Planck}\text{+WP+highL}).$$

$$\sum m_\nu < 1.08\,\text{eV} \quad [95\%;\ \textit{Planck}\text{+WP+highL}\ (A_\text{L})],$$

$$\sum m_\nu < 0.85\,\text{eV} \quad (95\%;\ \textit{Planck}\text{+lensing+WP+highL}),$$

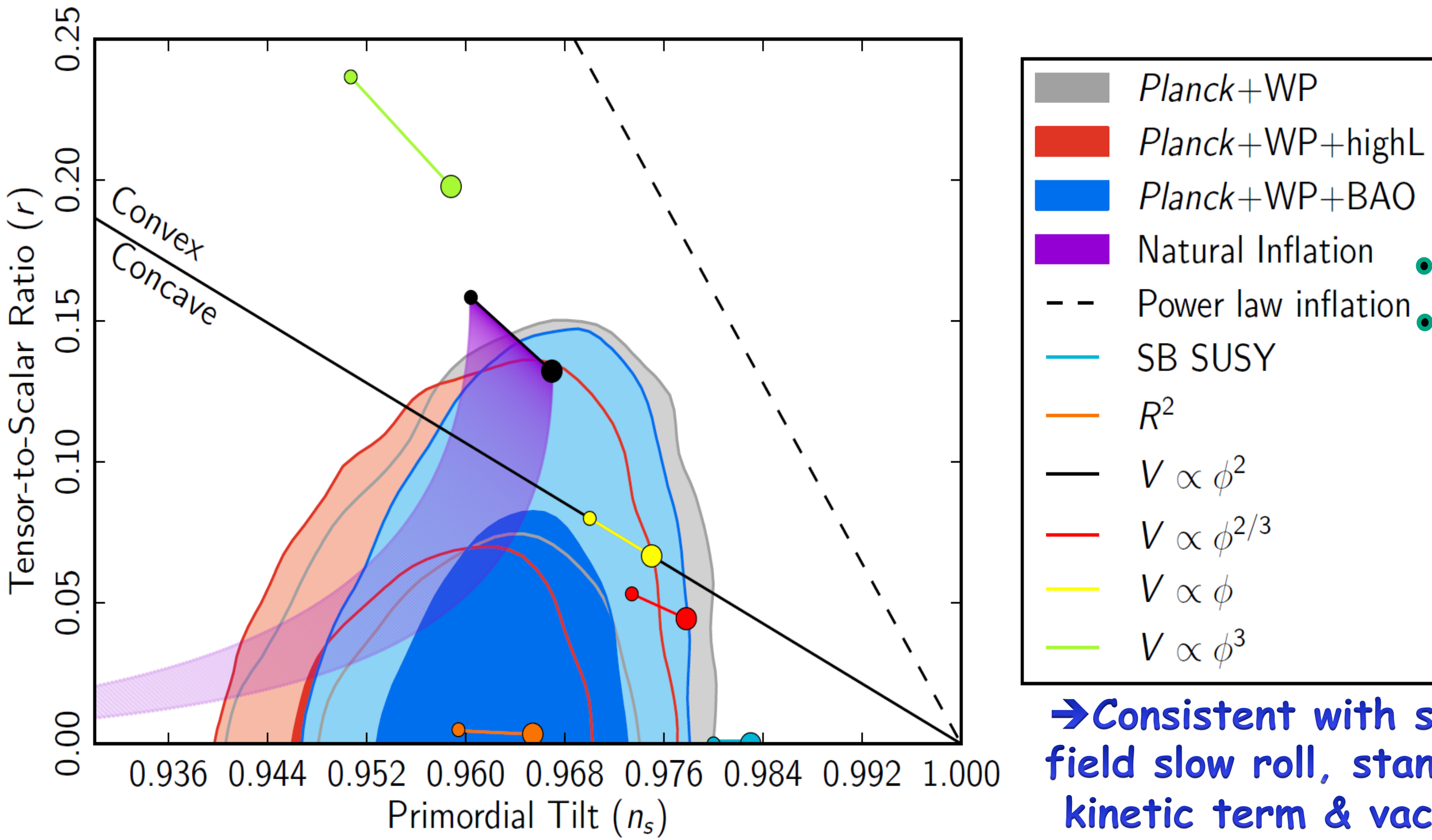
$$\sum m_\nu < 0.23\,\text{eV} \quad (95\%;\ \textit{Planck}\text{+WP+highL+BAO}).$$

- Planck strongly improves previous constraints on neutrino masses.
- Planck TT spectrum prefers a lensing amplitude higher than expected (A_{LENS}=1.2).
- Inclusion of lensing from TTTT weakens the Planck constraint by 20%
- Including BAO results in the best current constraint on neutrino masses of 0.23 eV



0.88
0.84
0.80
0.76
0.72
0.68
σ_8
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
Ω_m
Tension under investigation
Planck CMB
Planck cluster counts

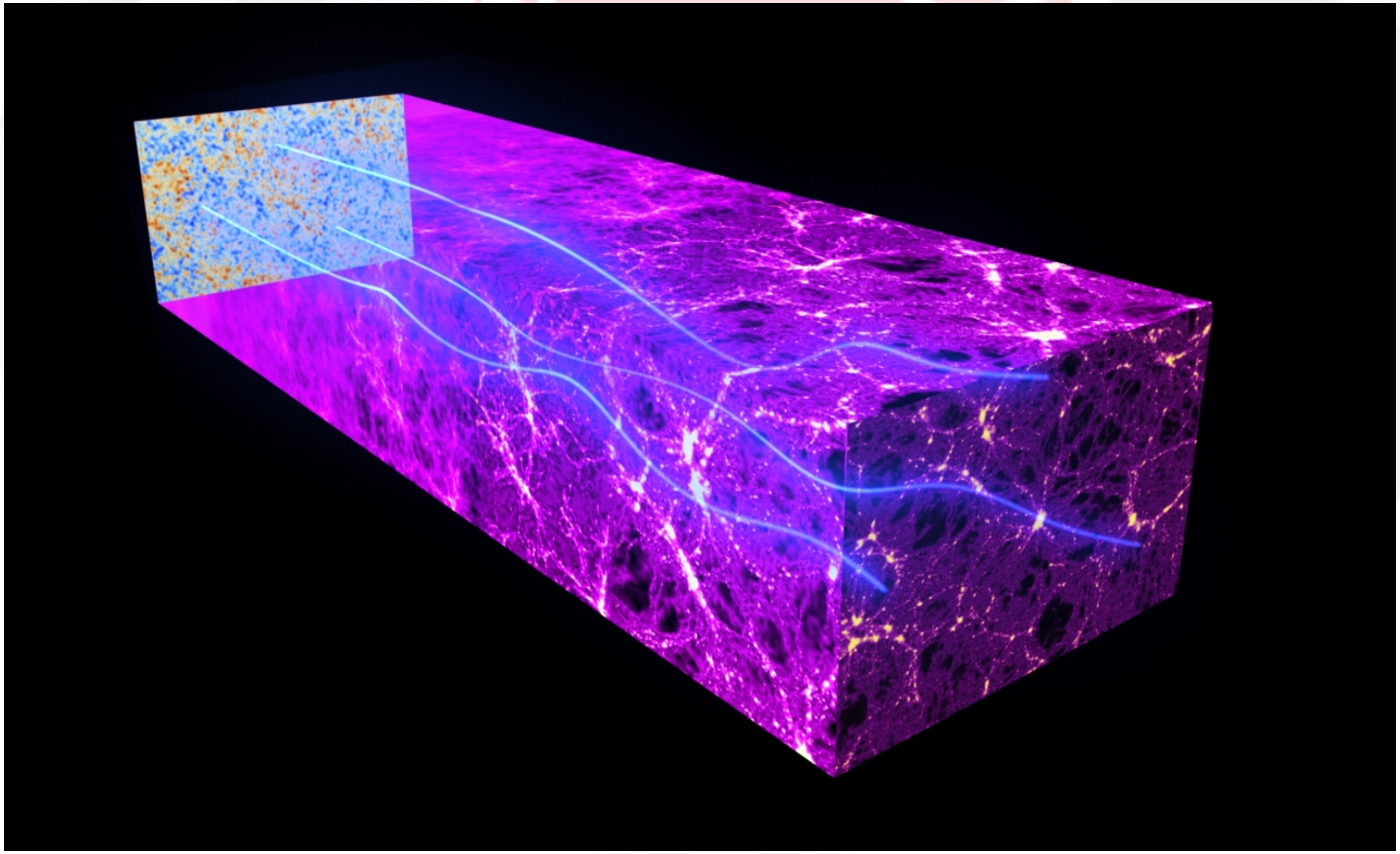
Main constraint on Inflation physics



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

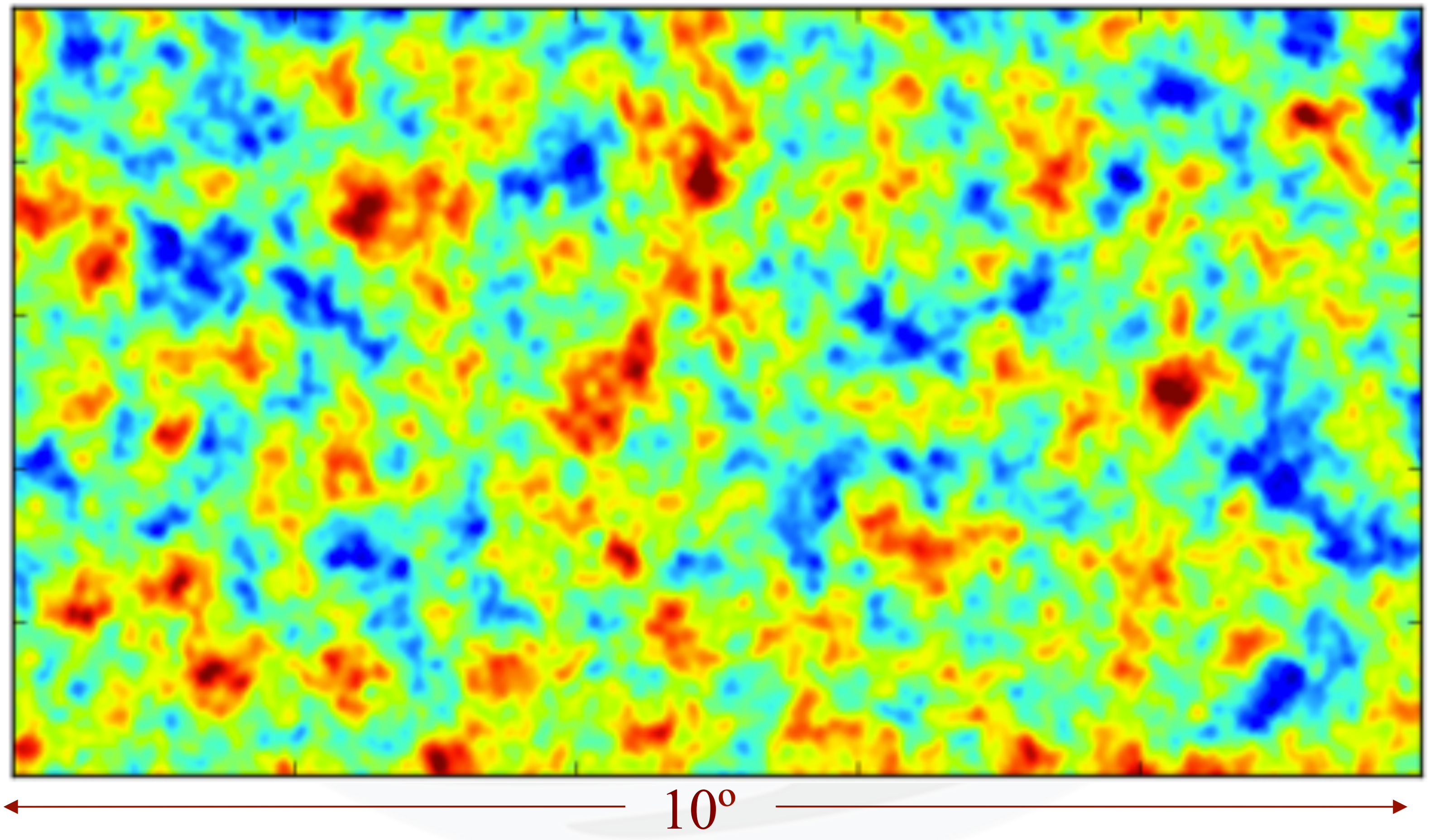
GRAVITATIONAL LENSING DISTORTS IMAGES

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



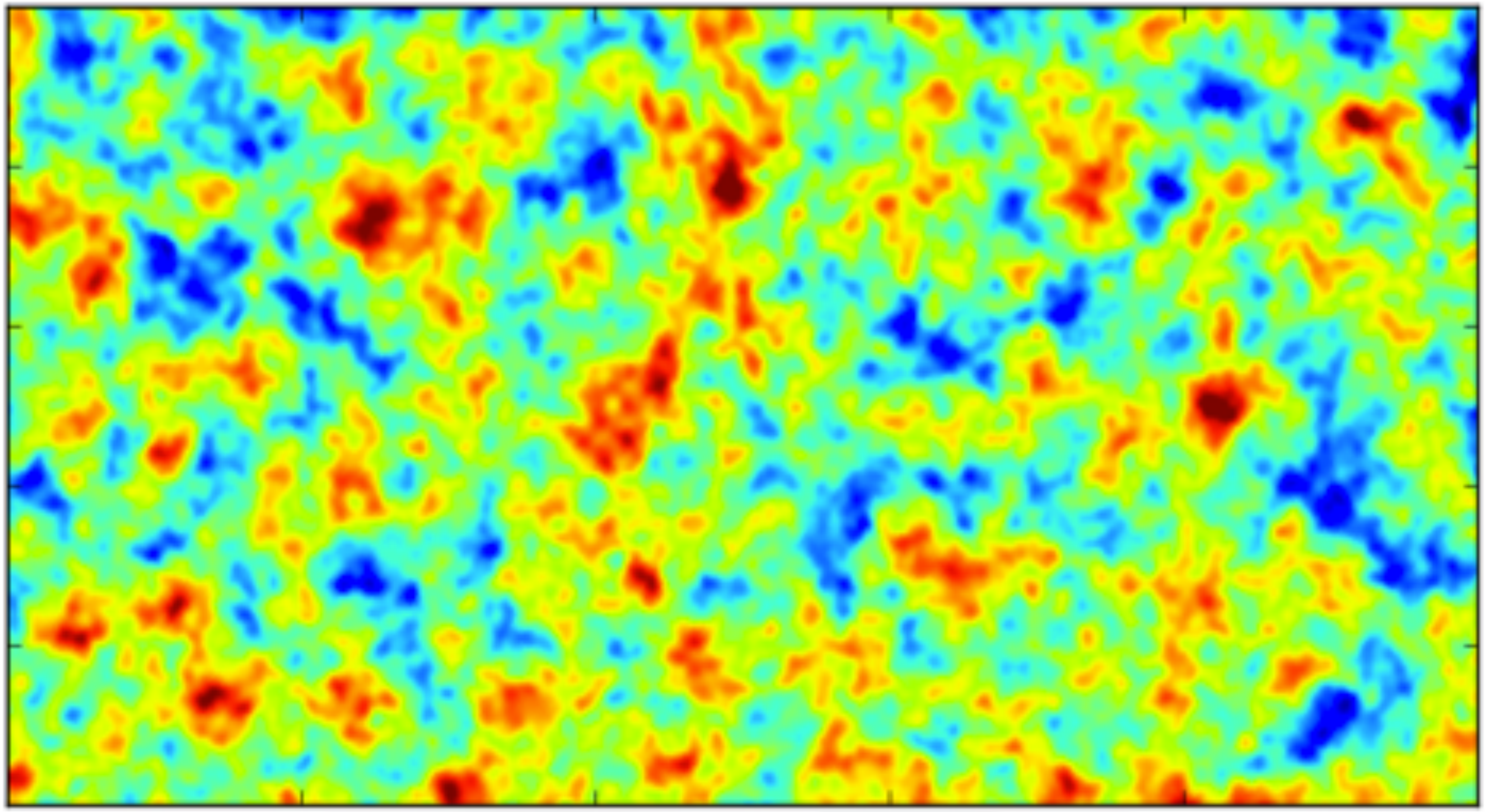
GRAVITATIONAL LENSING OF THE CMB

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



GRAVITATIONAL LENSING OF THE CMB

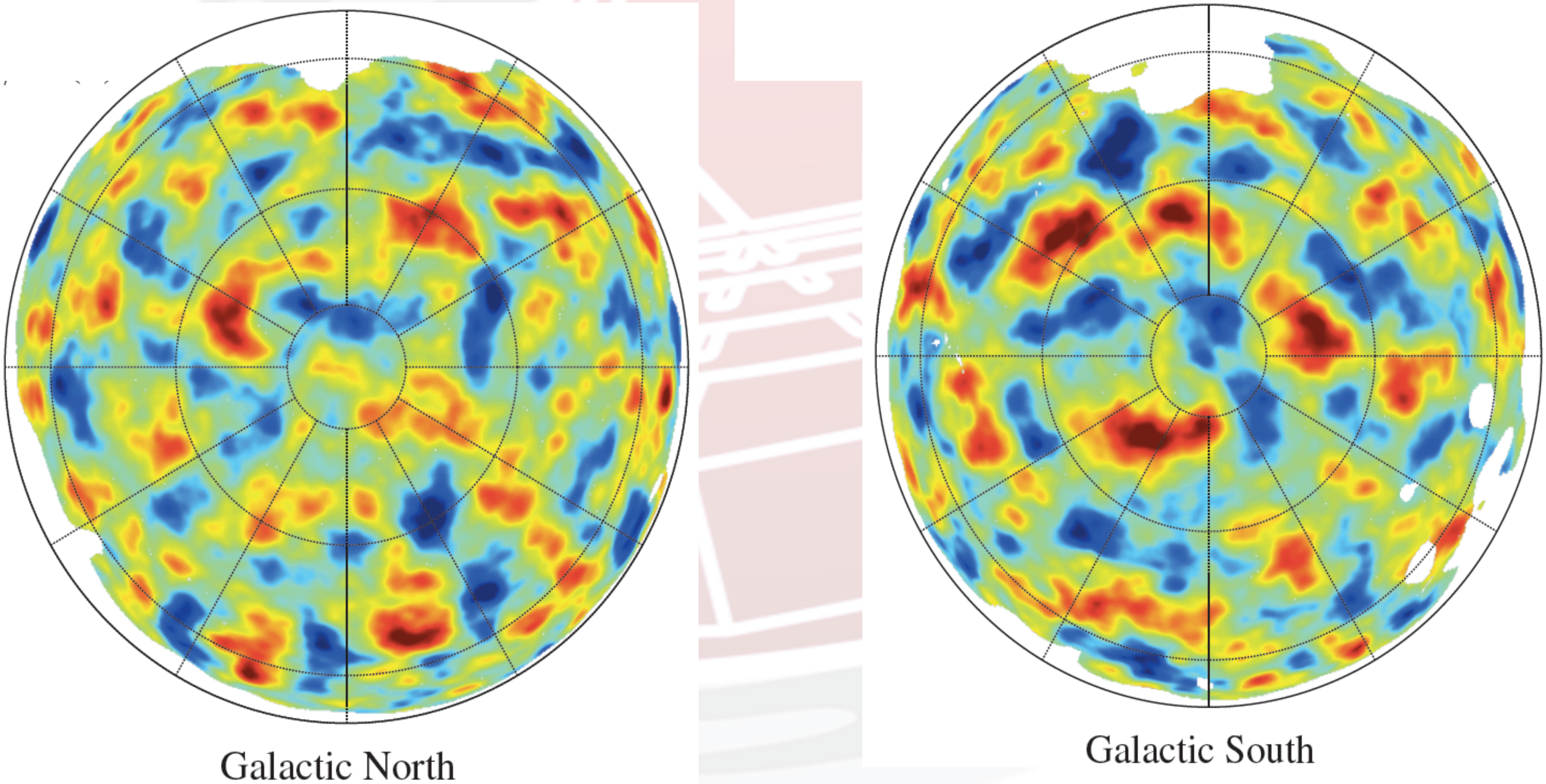
A simulated patch of CMB sky – **after lensing**



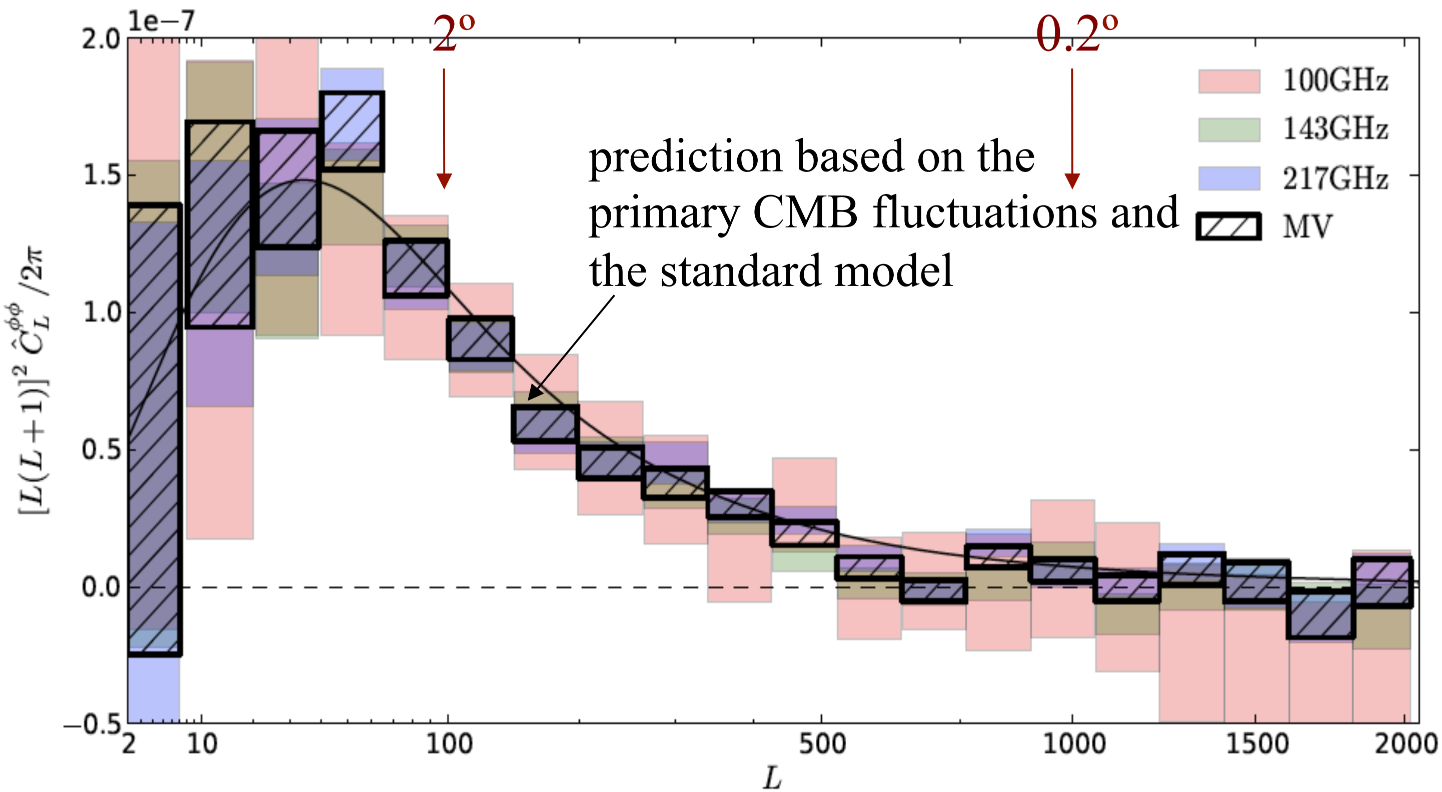
10°

Planck dark matter distribution

Planck images of the mass distribution throughout (almost) the entire visible Universe. This is 85% Dark Matter, 15% ordinary matter....



PLANCK LENSING POTENTIAL POWER SPECTRUM



It is a 25 sigma effect!!

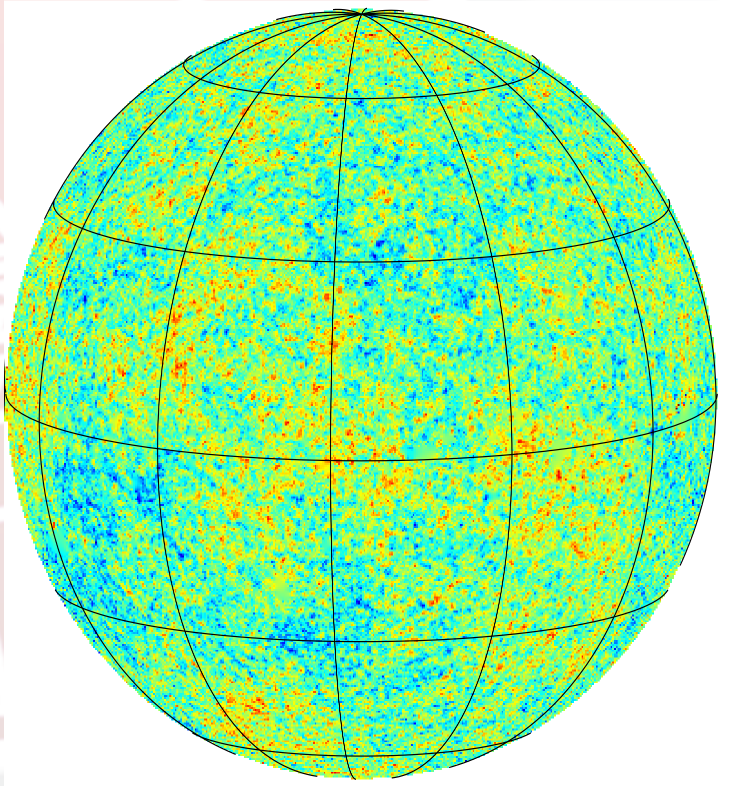
Non Gaussianity in the CMB

Nearly perfectly Gaussian fluctuation are a prediction of the inflation.

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

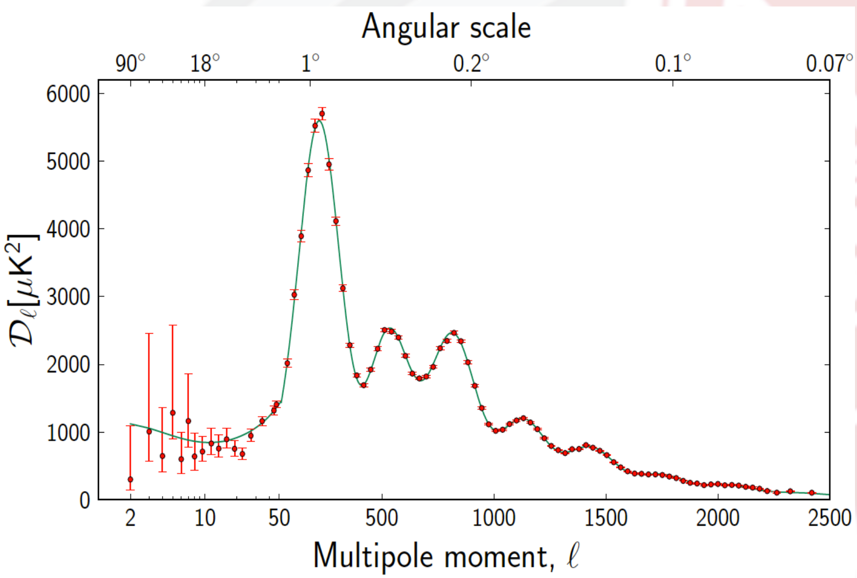
$$\frac{\Delta T}{T} + f_{NL}\left(\frac{\Delta T}{T}\right)^2$$

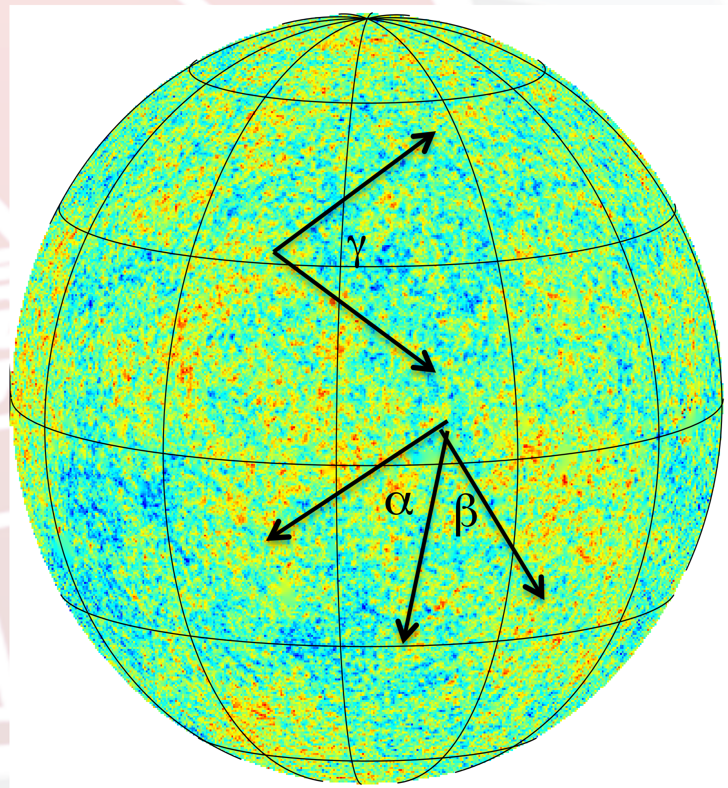
$$\left(\frac{\Delta T}{T}\right)^2 \approx 10^{-10}$$



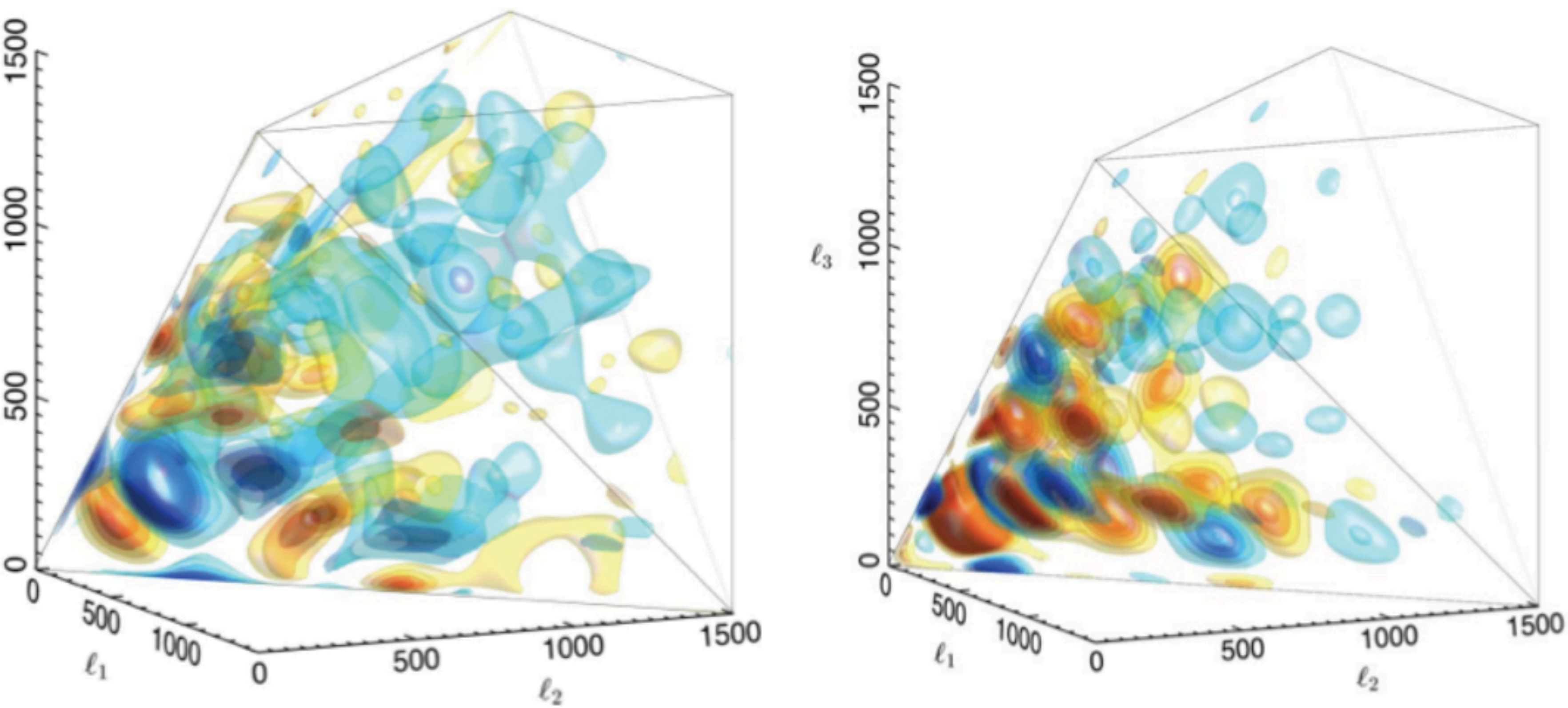
How test for Gaussianity? And how?

The power spectrum compares two points separated by one angle:

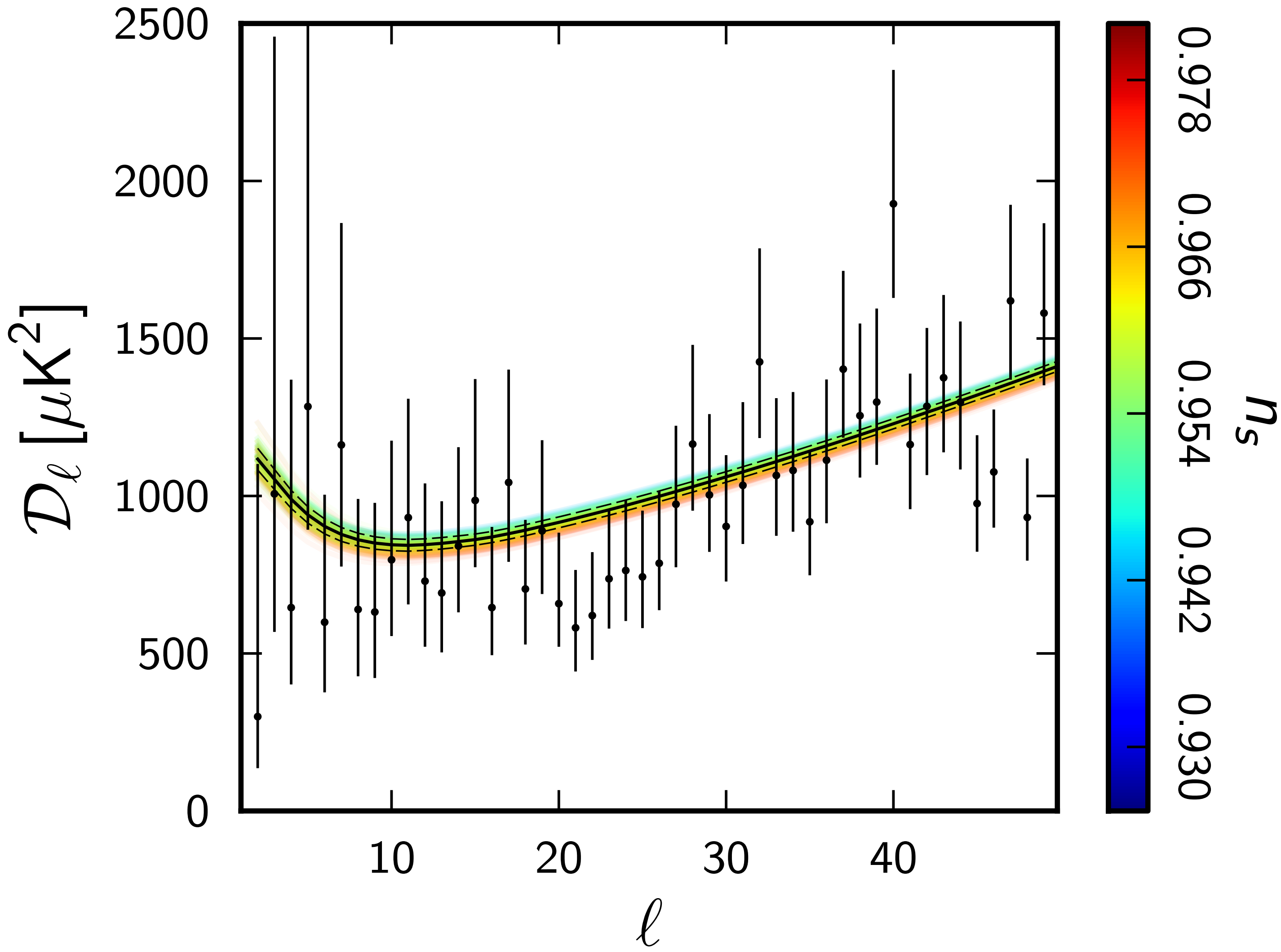




To check for non Gaussianity you can compare three points at two angles: the “power” bispectrum.



Phase Wavenumber	$\phi = 0$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\phi = \pi/4$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\phi = \pi/2$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\phi = 3\pi/4$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)
$k_c = 0.01000$	−110 ± 159 (−0.7)	−98 ± 167 (−0.6)	−17 ± 147 (−0.1)	56 ± 142 (0.4)
$k_c = 0.01125$	434 ± 170 (2.6)	363 ± 185 (2.0)	57 ± 183 (0.3)	−262 ± 168 (−1.6)
$k_c = 0.01250$	−70 ± 158 (−0.4)	130 ± 166 (0.8)	261 ± 167 (1.6)	233 ± 159 (1.5)
$k_c = 0.01375$	35 ± 162 (0.2)	291 ± 145 (2.0)	345 ± 147 (2.3)	235 ± 162 (1.5)
$k_c = 0.01500$	−313 ± 144 (−2.2)	−270 ± 137 (−2.0)	−95 ± 145 (−0.7)	179 ± 154 (1.2)
$k_c = 0.01625$	81 ± 126 (0.6)	177 ± 141 (1.2)	165 ± 144 (1.1)	51 ± 129 (0.4)
$k_c = 0.01750$	−335 ± 137 (−2.4)	−104 ± 128 (−0.8)	181 ± 117 (1.5)	366 ± 126 (2.9)
$k_c = 0.01875$	−348 ± 118 (−3.0)	−323 ± 120 (−2.7)	−126 ± 119 (−1.1)	137 ± 117 (1.2)
$k_c = 0.02000$	−155 ± 110 (−1.4)	−298 ± 119 (−2.5)	−241 ± 113 (−2.1)	−44 ± 105 (−0.4)
$k_c = 0.02125$	−43 ± 96 (−0.4)	−186 ± 107 (−1.7)	−229 ± 115 (−2.0)	−125 ± 104 (−1.2)
$k_c = 0.02250$	22 ± 95 (0.2)	−115 ± 92 (−1.2)	−194 ± 105 (−1.8)	−148 ± 107 (−1.4)
$k_c = 0.02375$	70 ± 100 (0.7)	−56 ± 94 (−0.6)	−159 ± 93 (−1.7)	−164 ± 101 (−1.6)
$k_c = 0.02500$	106 ± 93 (1.1)	6 ± 97 (0.1)	−103 ± 98 (−1.1)	−153 ± 94 (−1.6)



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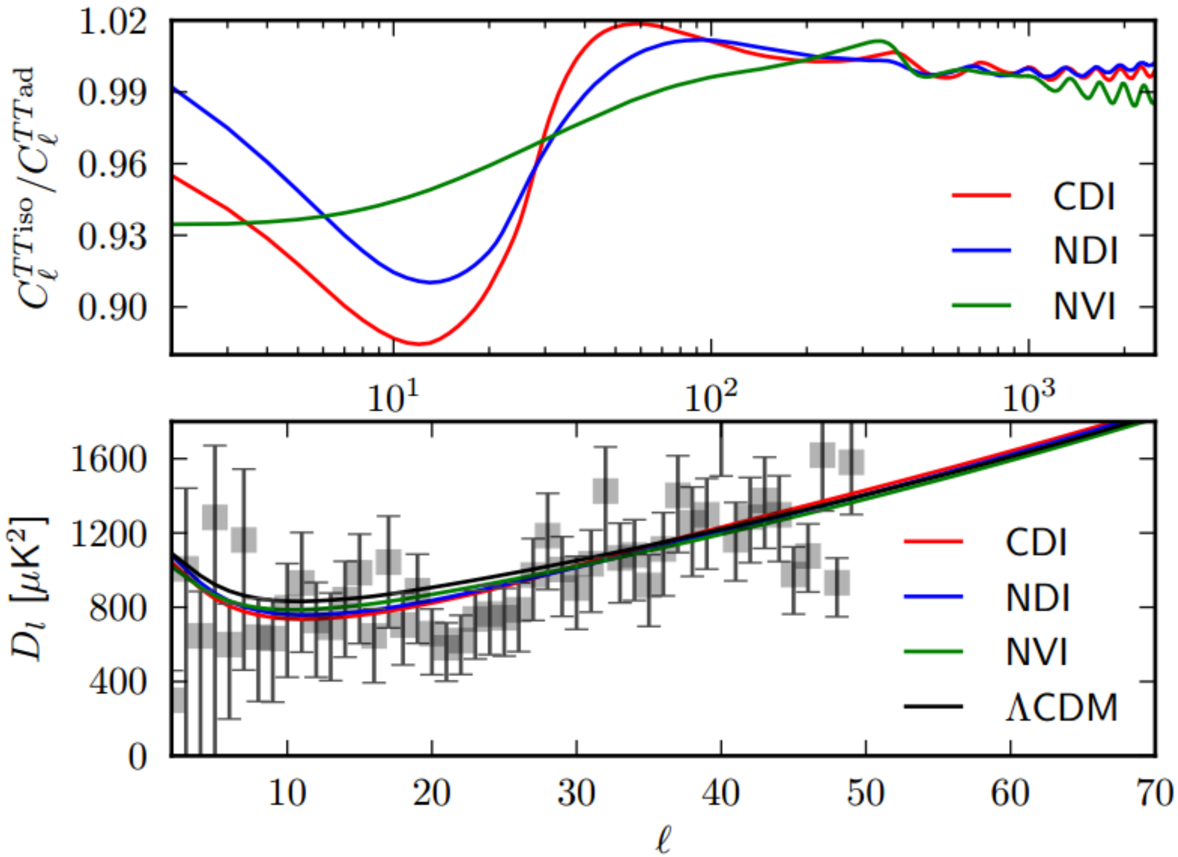
Isocurvature modes ?

A mixed adiabatic-isocurvature model can provide a better Fit to the low-l region.

In the Figure we see 3 models:

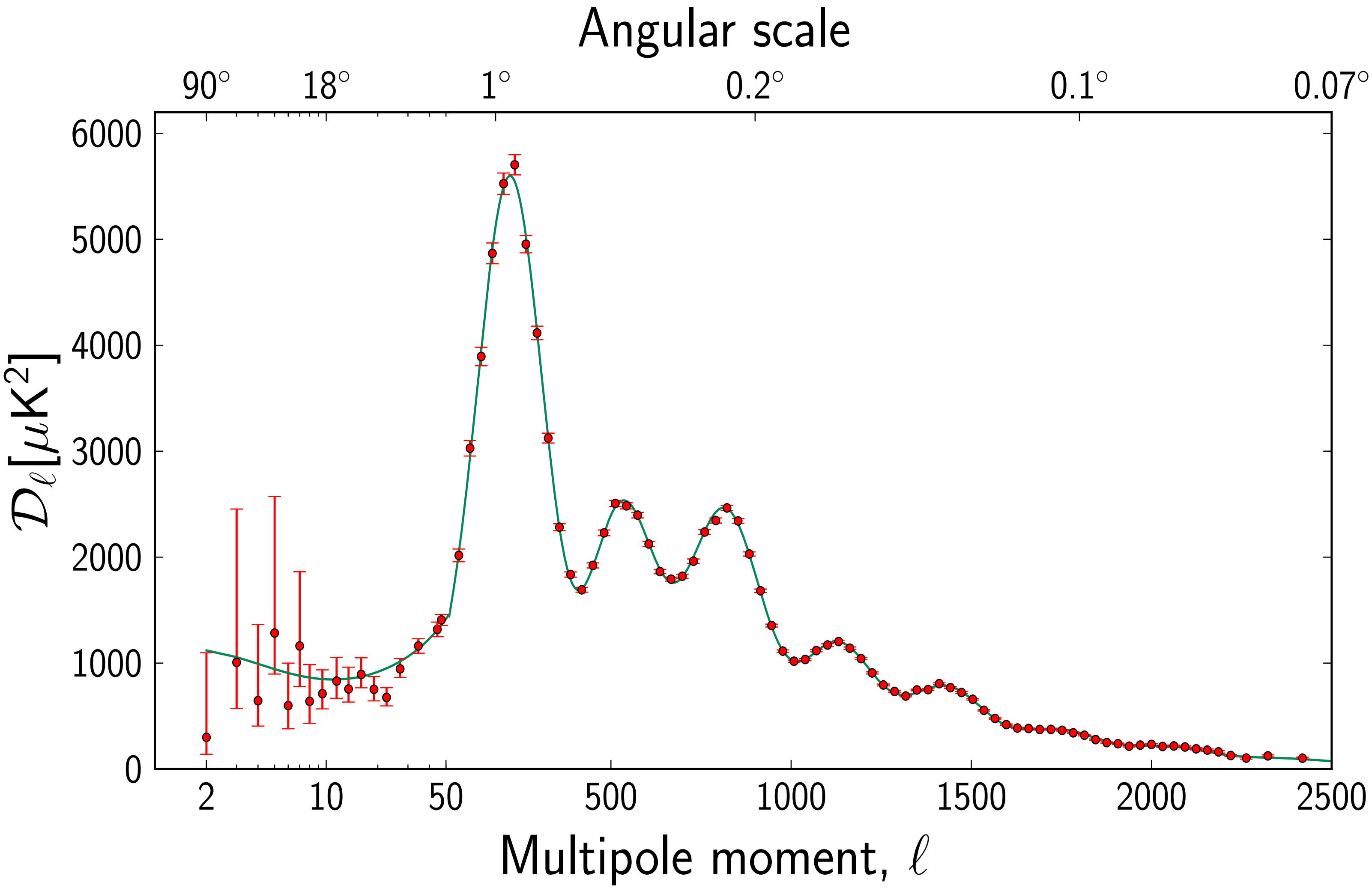
CDI: Cold Dark Matter Density Isocurvature Mode
NDI: Neutrino Density Isocurvature Mode
NVI: Neutrino Velocity Isocurvature Mode



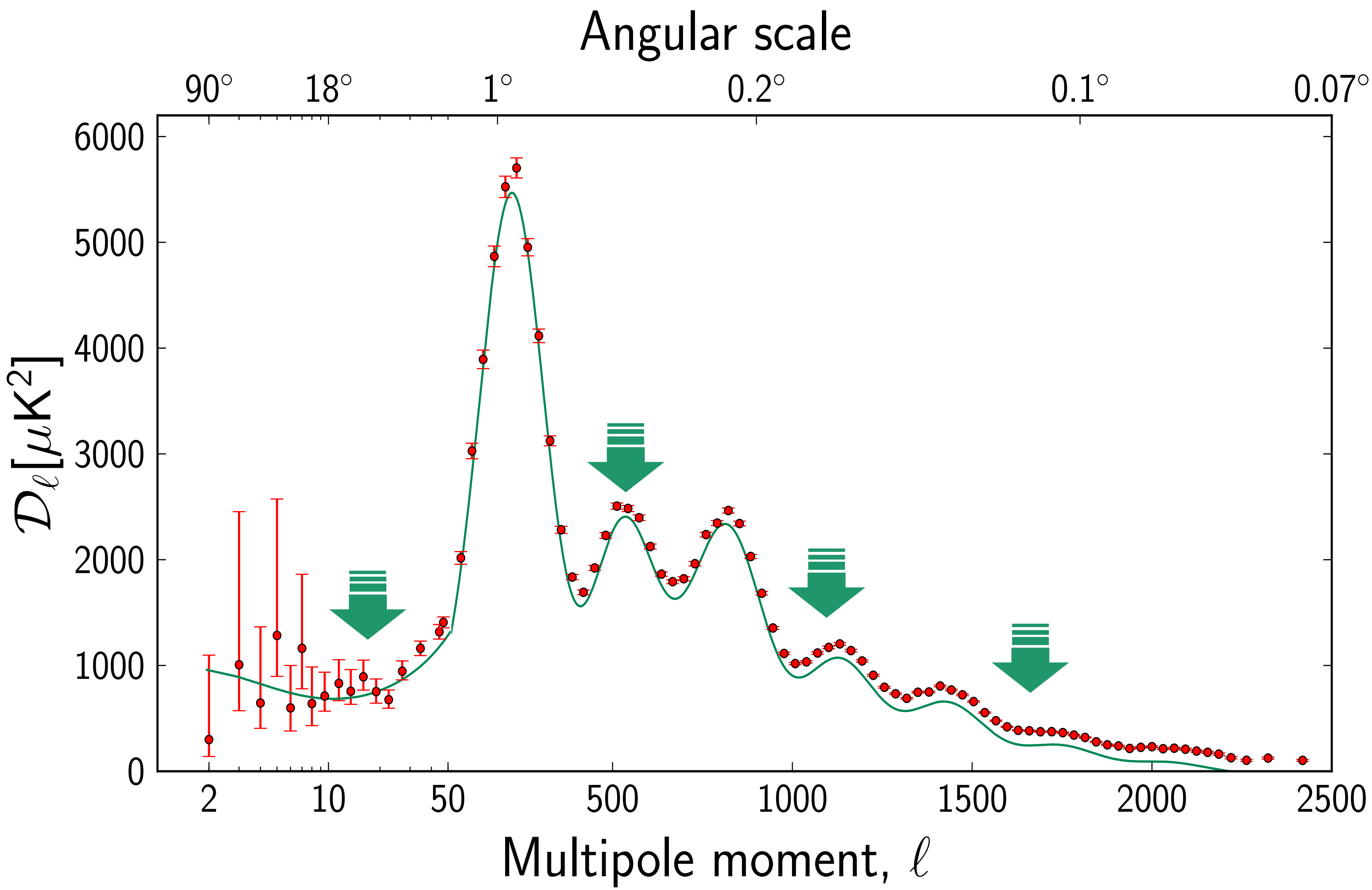
The isocurvature mode is favoured at the level of 2 sigmas.
This kind of model is compatible with multi-field inflation.

But as we can see from the data, isocurvature modes are not enough to compensate the low-low-l signal !

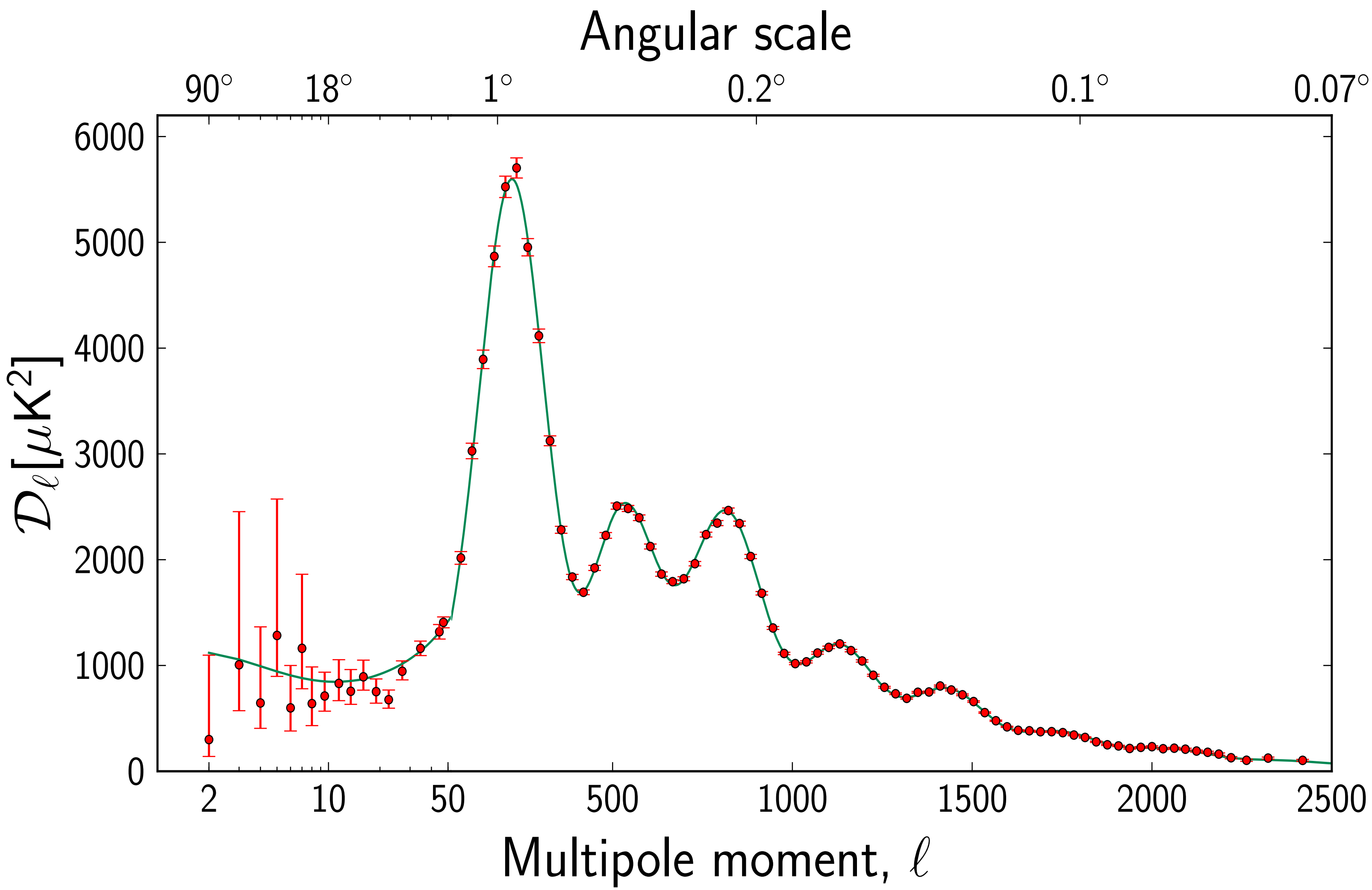
The low-l anomaly



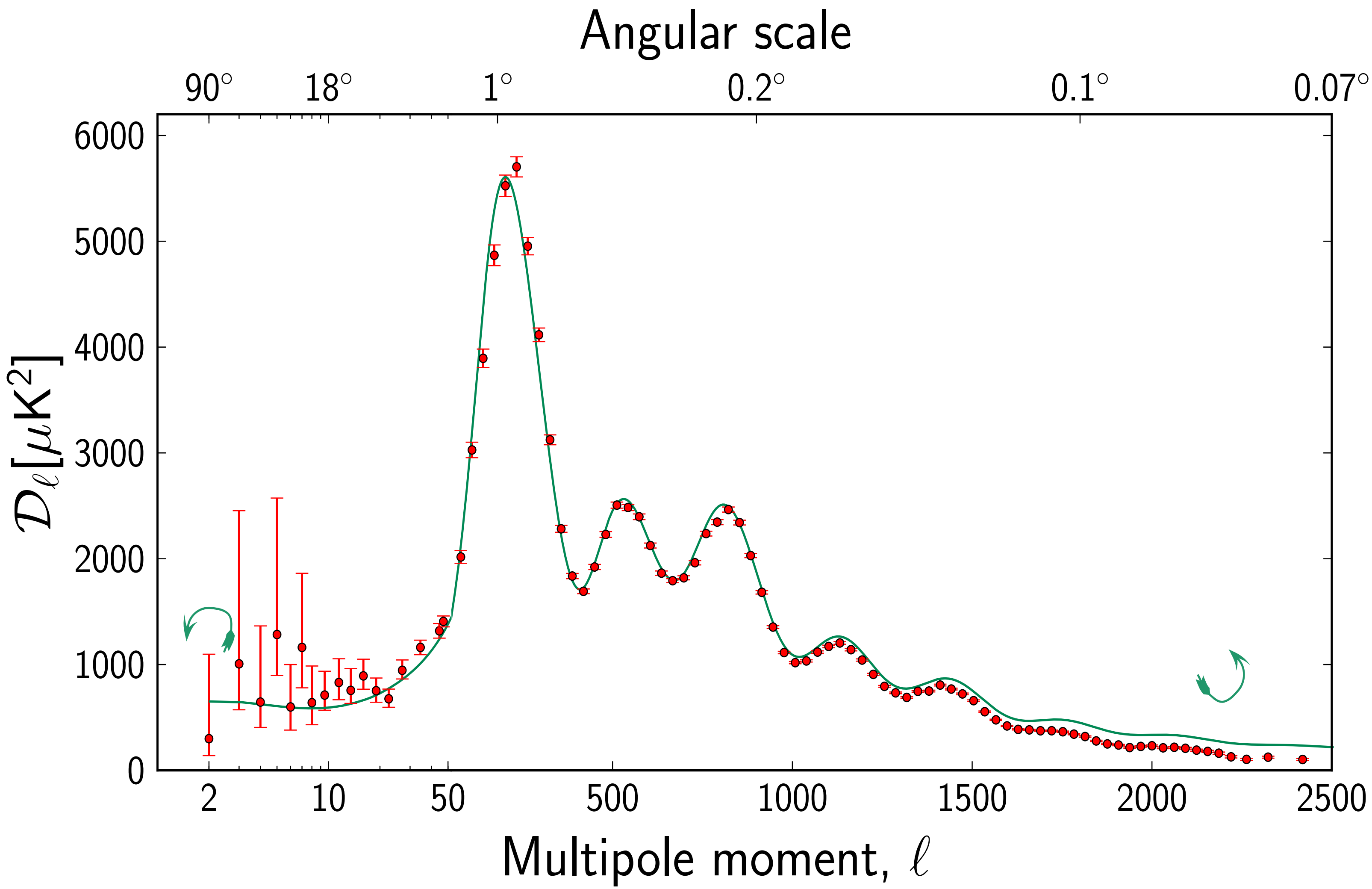
The low-l anomaly



The low-l anomaly



The low-l anomaly



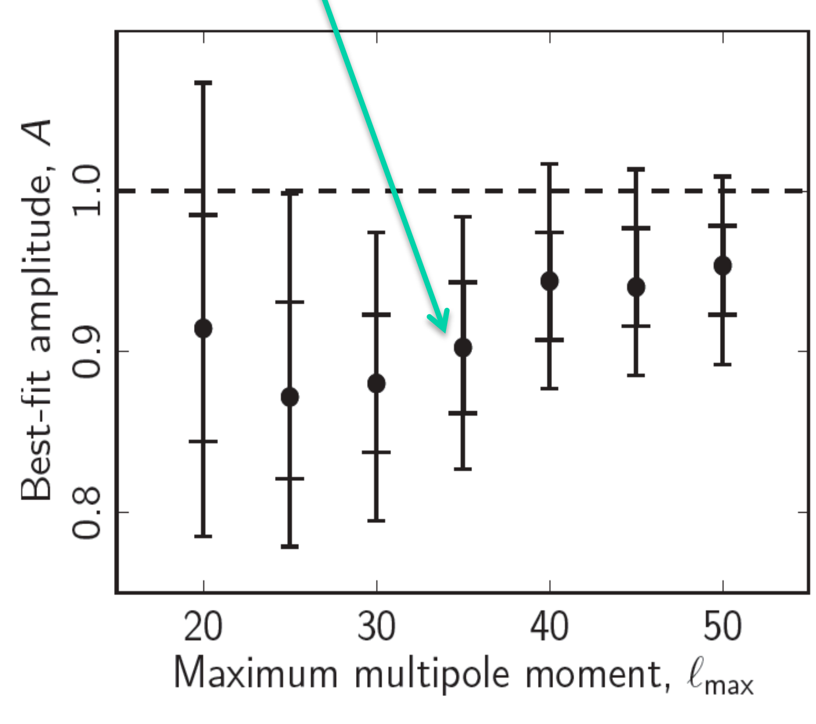
A simple amplitude test

- 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

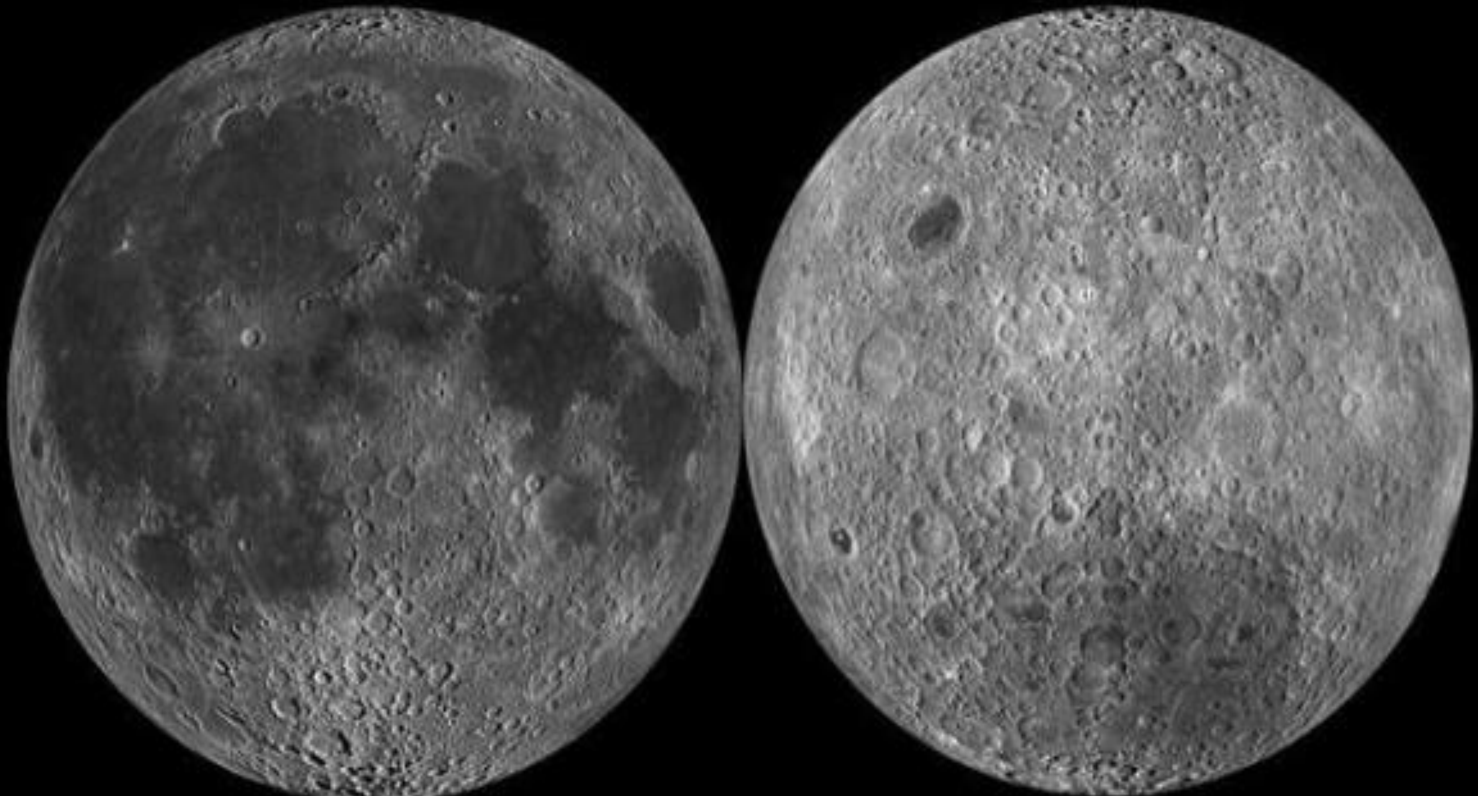


The low-l anomaly

- Theory (the ΛCDM model) fits the Planck data remarkably well at small and intermediate angular scale
- Planck shows that, at very large scales, the fit is not good → there is an “anomaly”?
- This may suggest that the standard accepted model is incomplete.

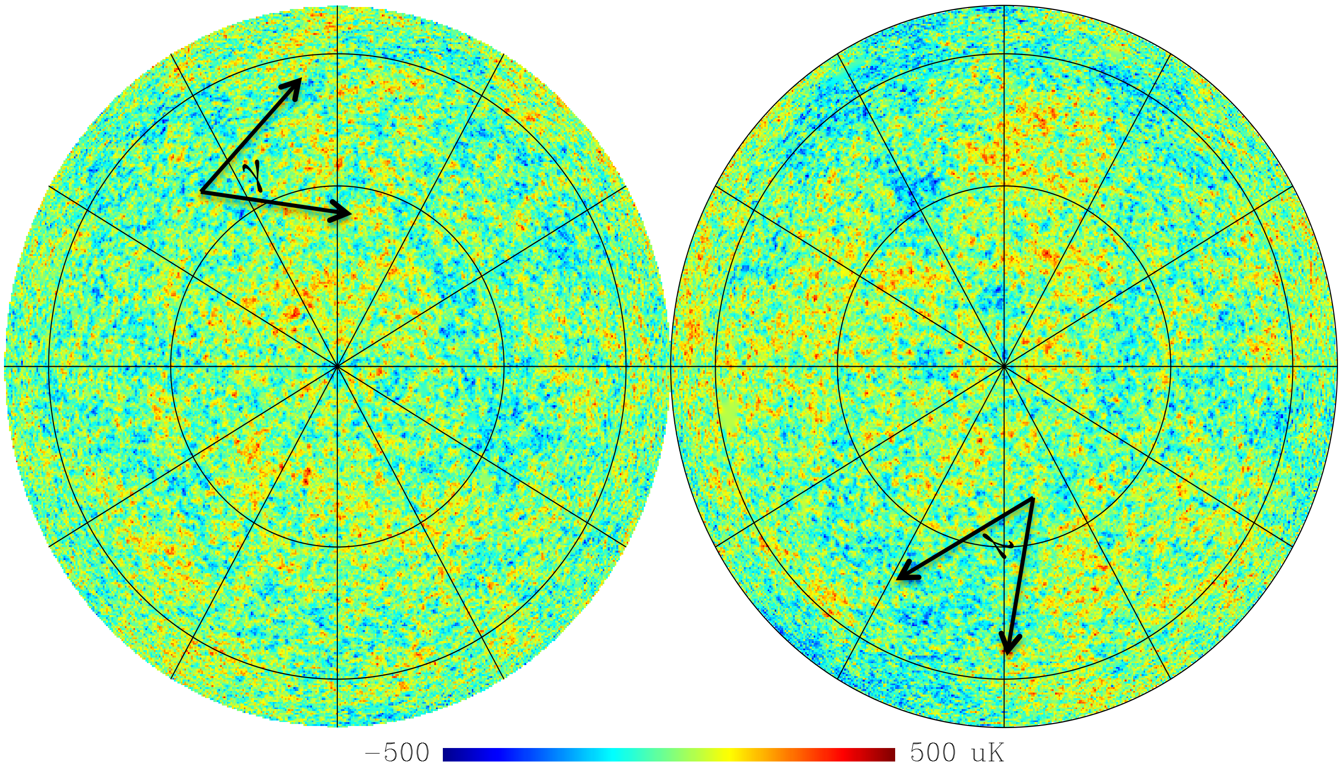
A known celestial source

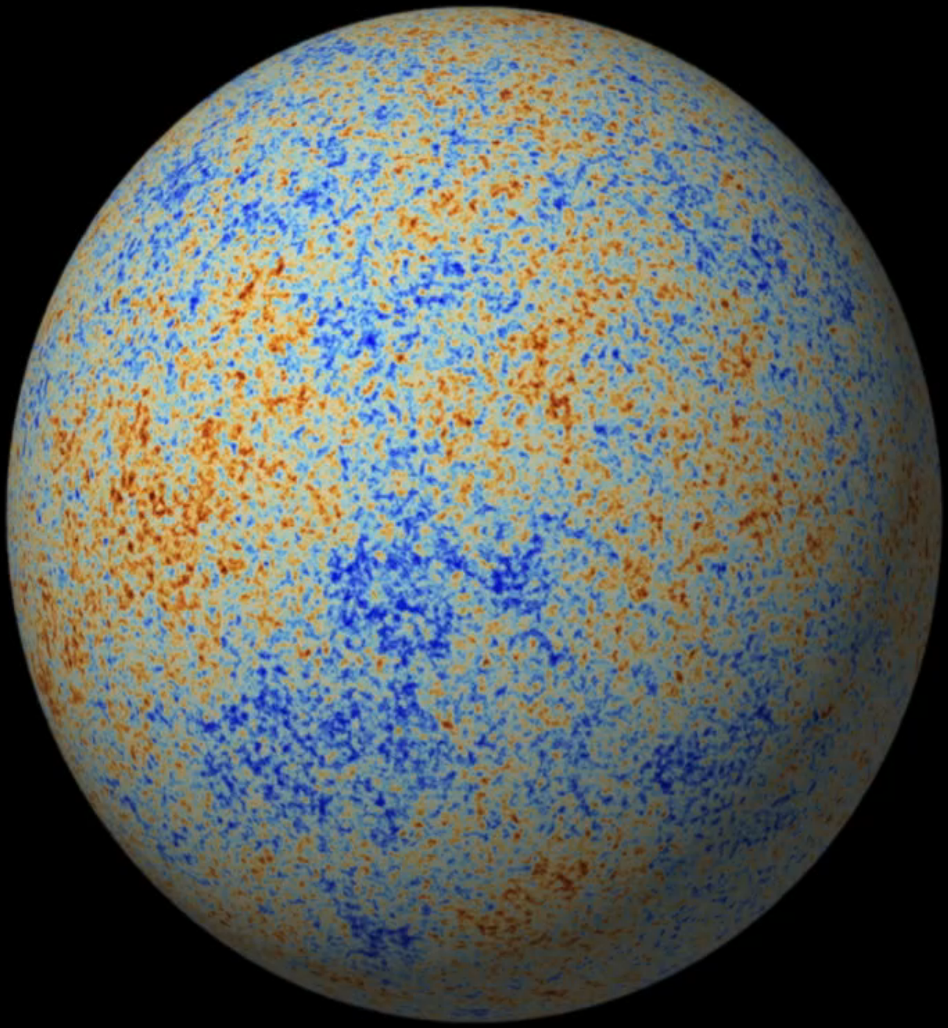
Does the other side of the Moon look alike?



Is the Universe statistically isotropic?

Isotropy is a fundamental assumption of the LCDM model
It must be tested.

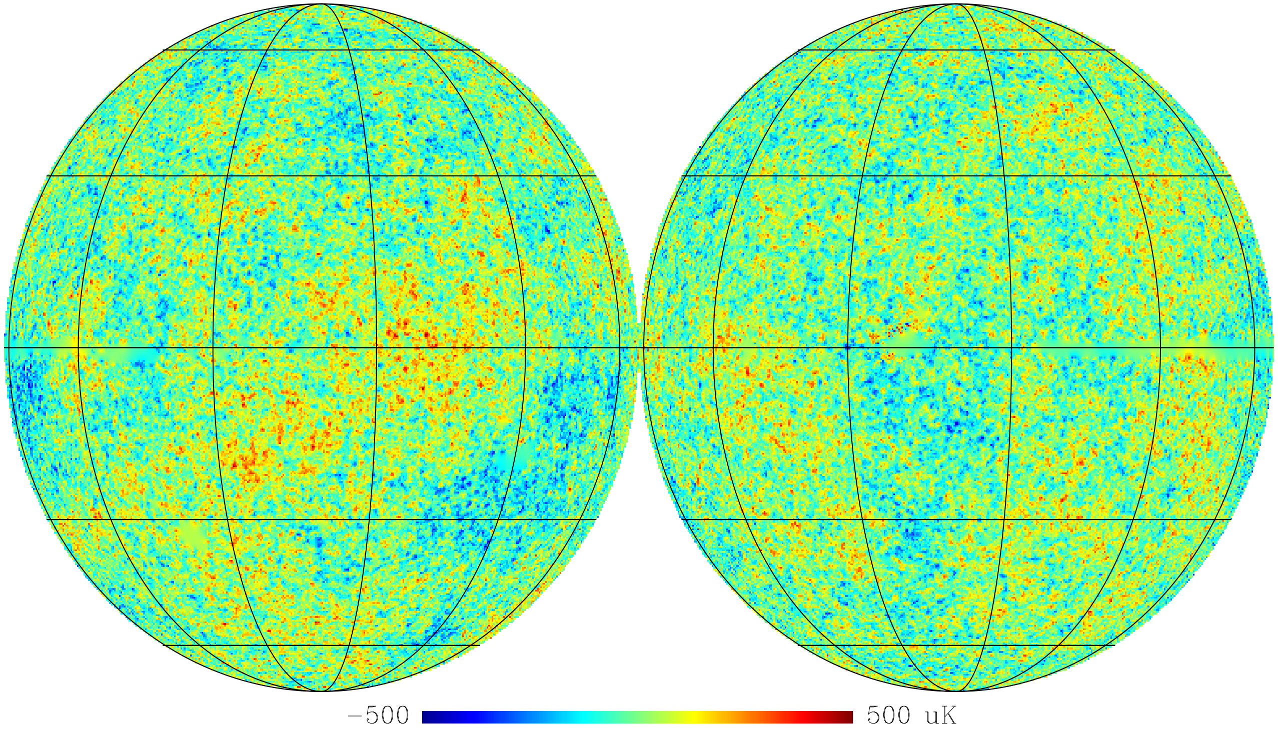




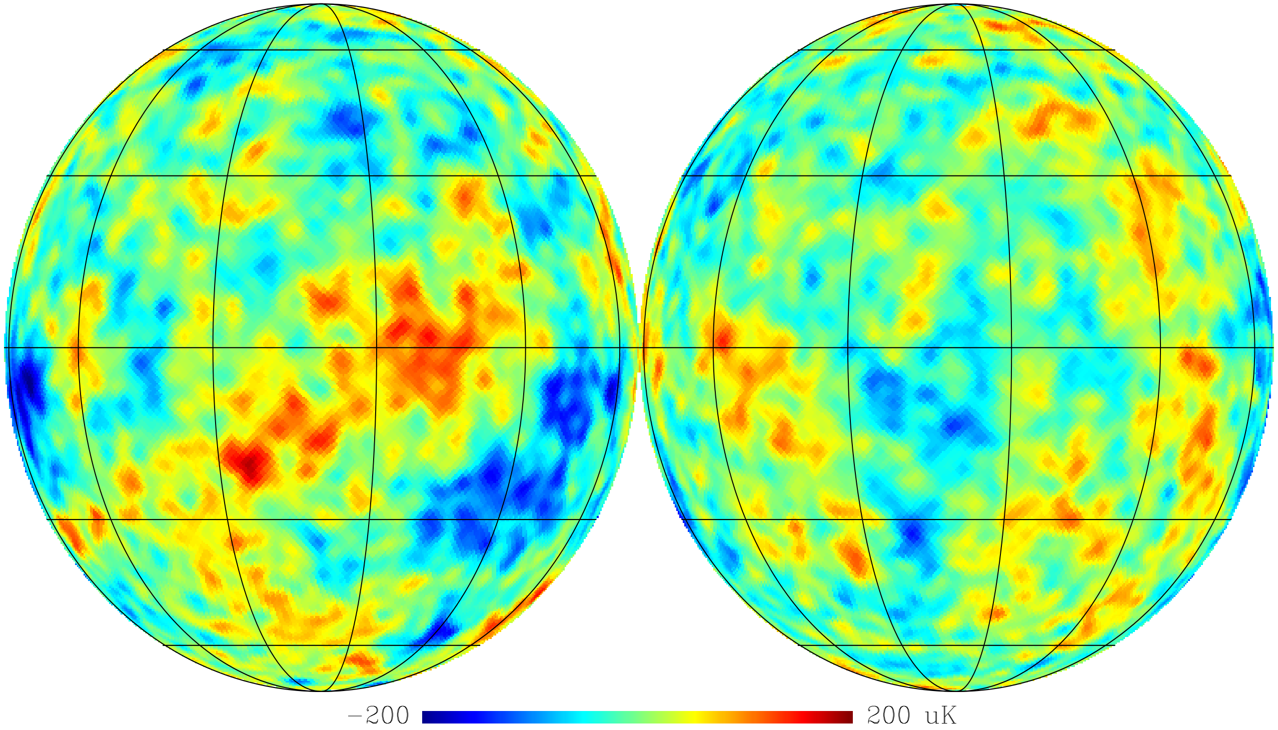
European Space Agency

Is the Universe isotropic?

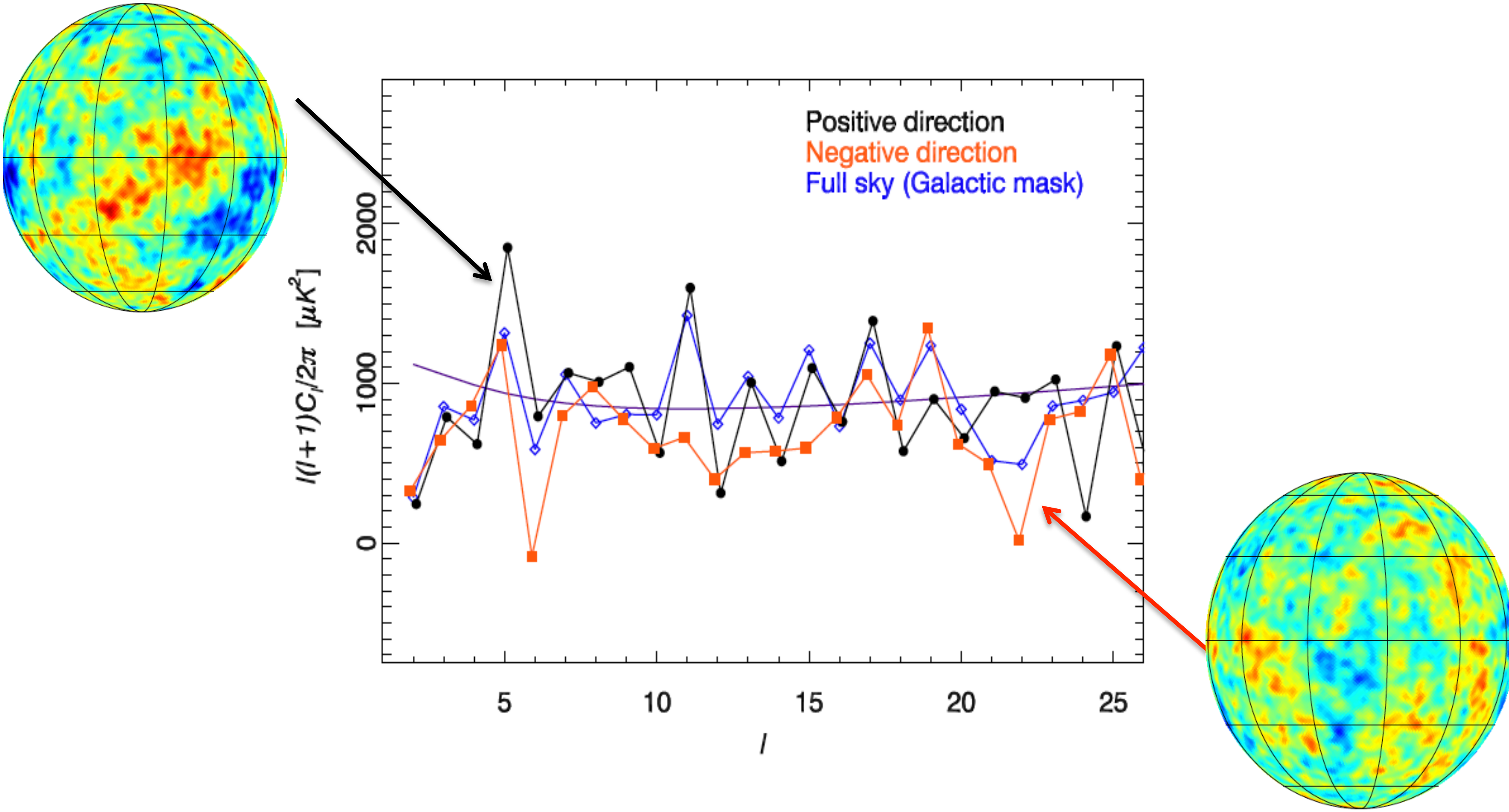
Two sides of the same (celestial) sphere



Take the high resolution stuff out



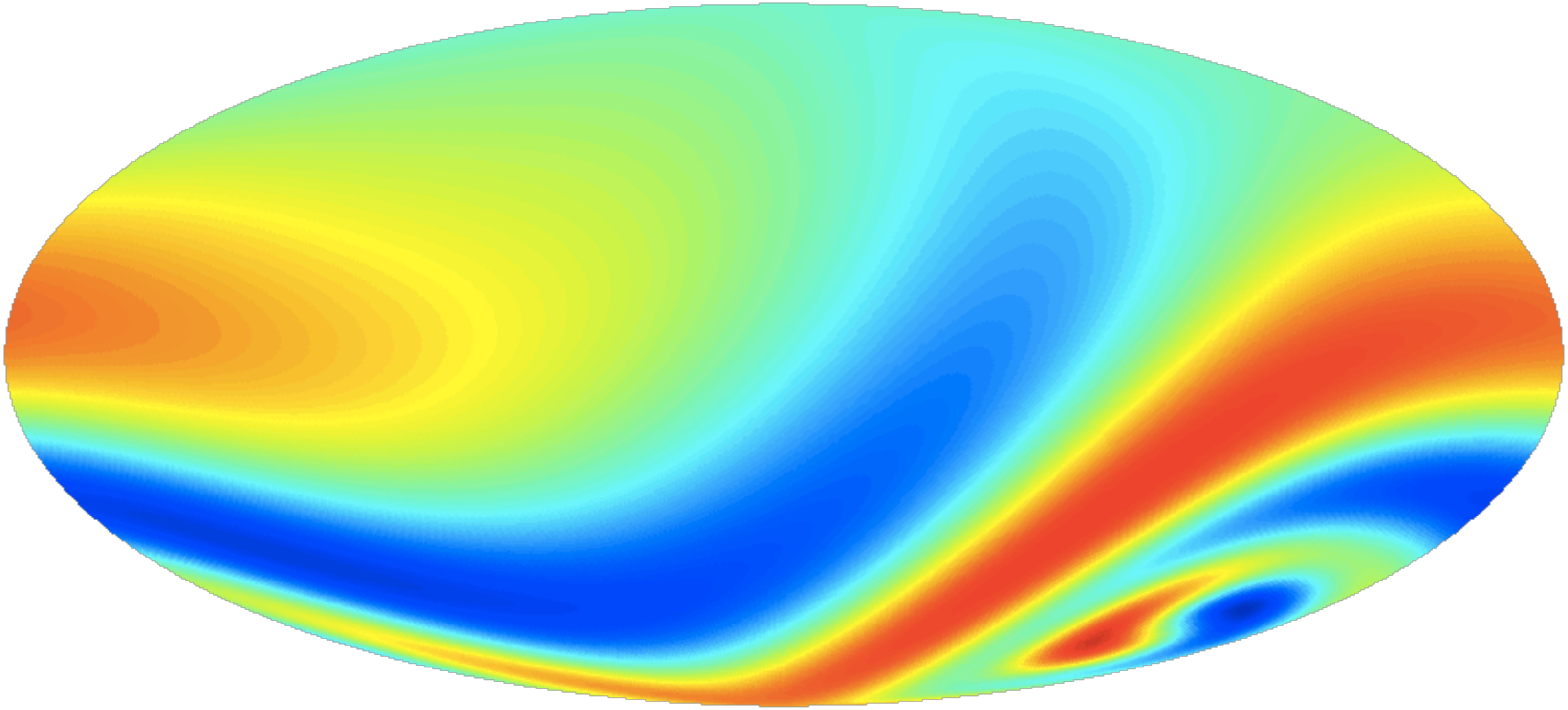
Are the two hemispheres compatible?



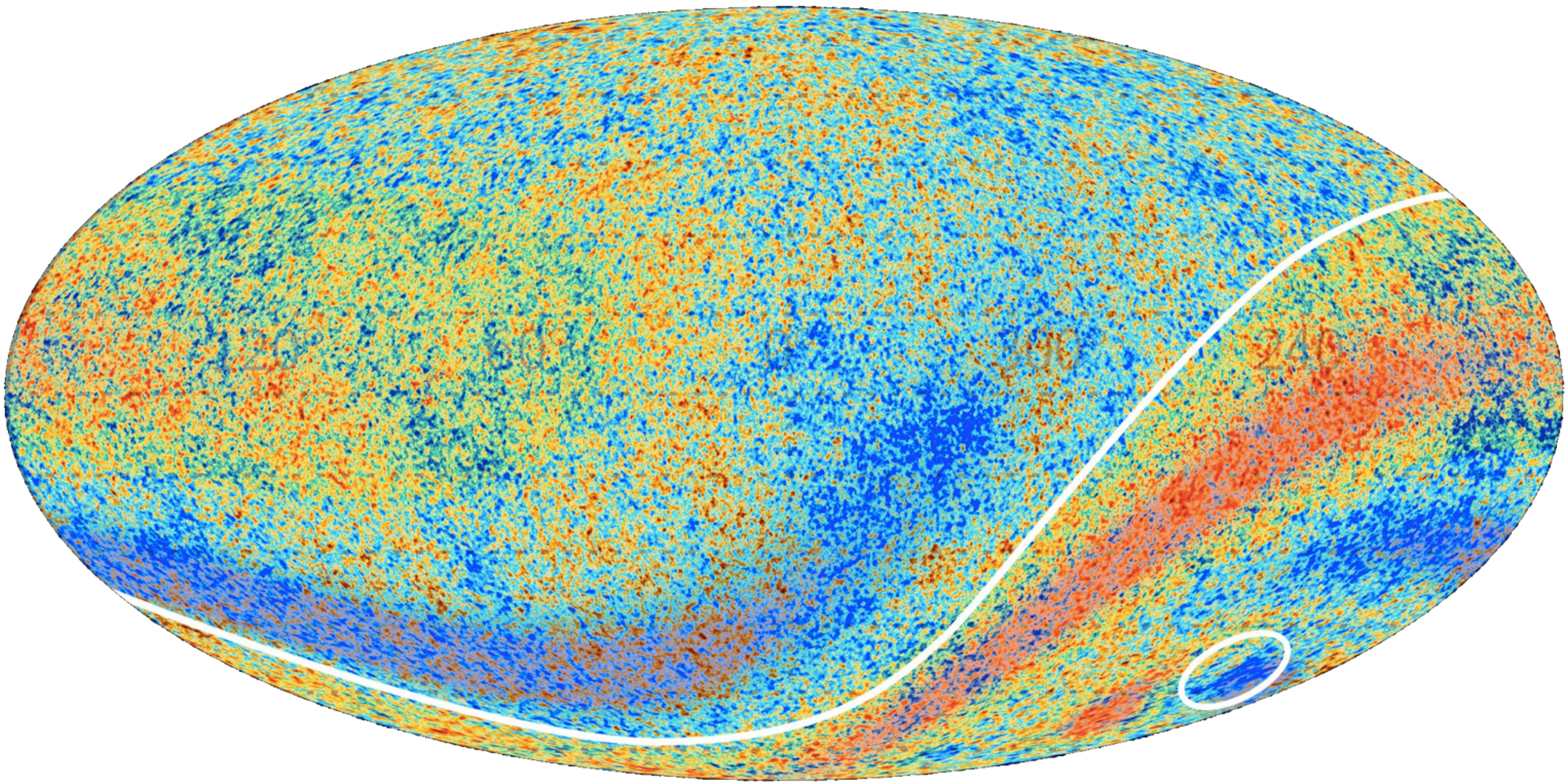
So, what are we seeing?

- Are these anomalies a manifestation of some yet unknown physics? Perhaps. Are there interpretations?
  - Phenomenological, e.g. dipole modulation. Is the dipole influencing the higher multipoles for some reason?
  - Physical, e.g. Bianchi models (cosmologies of a non isotropic universe, Bianchi VII looks appealing.)
- But no really convincing explanation exists yet.
- The large scale modes in the CMB are very primordial. They can be traced back directly to the inflation. If there is really physics behind the anomalies, rest assured it is exiting.
- How do we move further?
- New theories → new models to test
- Better observations by Planck → polarization

Bianchi model VII



Does Mr Bianchi get along with Mr Planck?

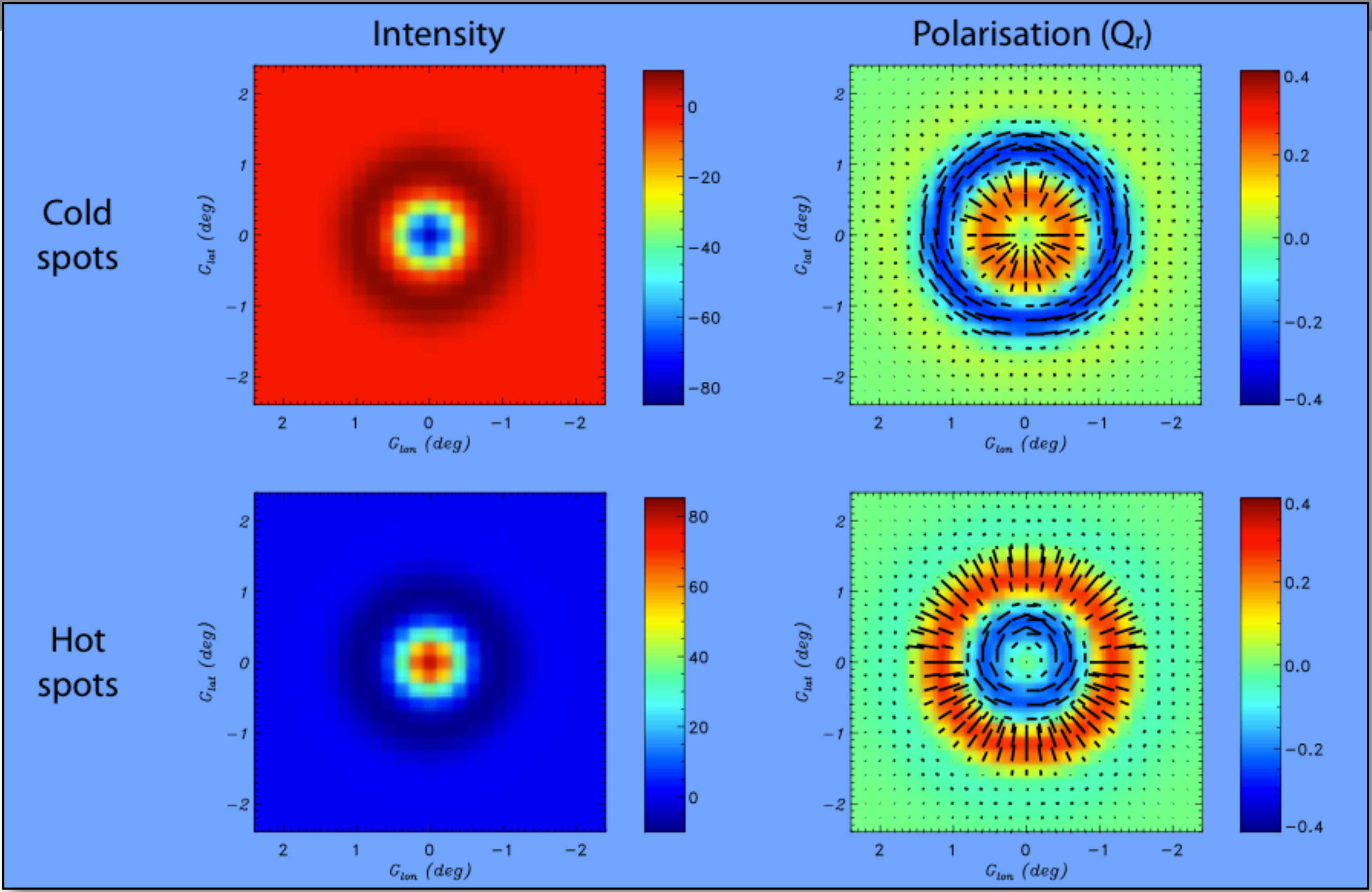


Large scale isotropy is challenged by Planck data.

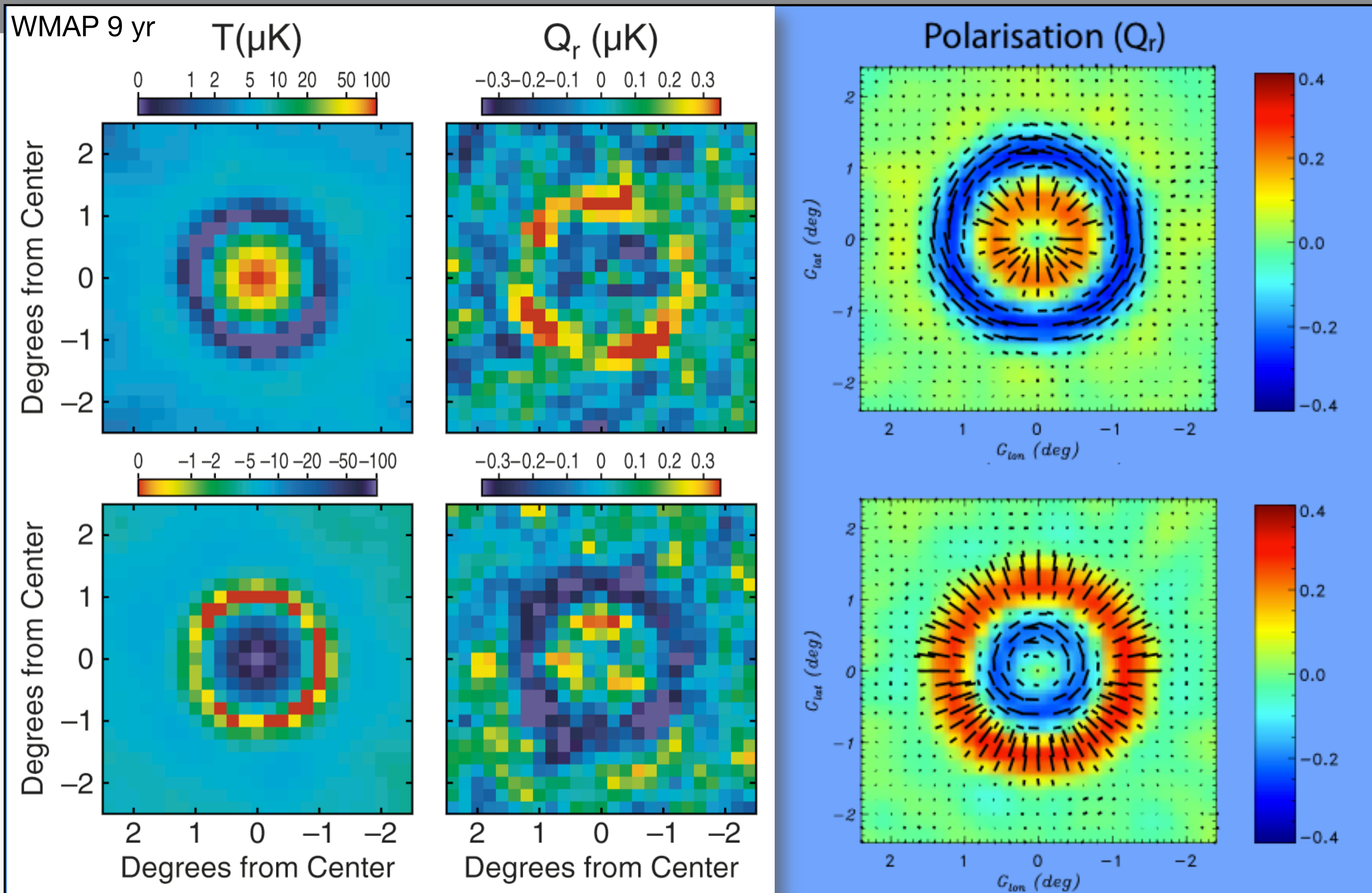
Several effects at 99% statistical significance or more:

- ΛCDM in tension with large scale anisotropy
- Hemispherical asymmetry in power spectrum
- And there are other, possibly related anomalies. Read Planck Collaboration XIII today.
  - Multipole alignment
  - A very "cold" spot
  - Phase correlations
  - Even-odd parity power asymmetry
  - And others further.
- Thanks to Planck, we are certain that they are genuine features of the CMB.
- Are they related? Is there a fundamental reason?

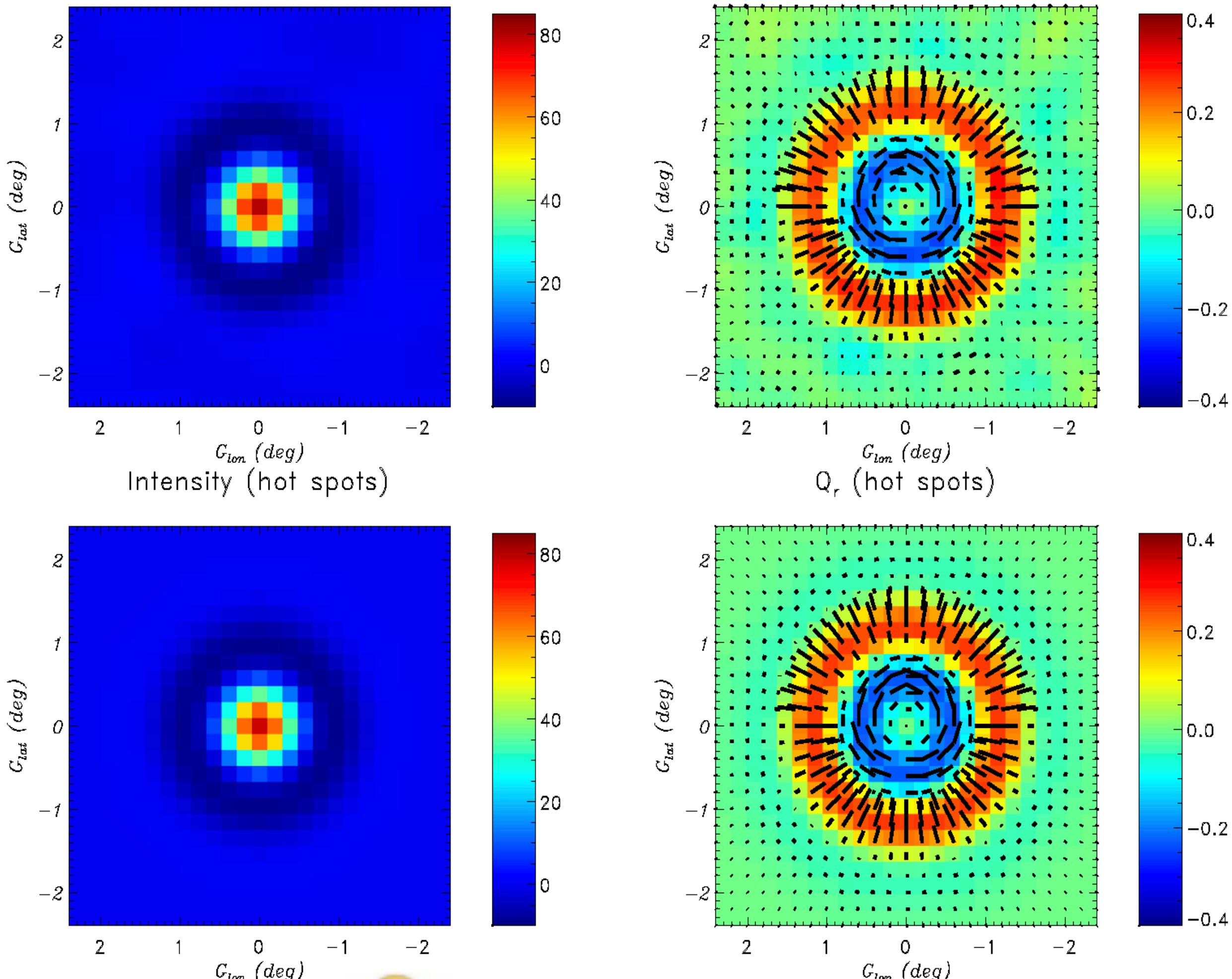
Testing polarisation via stacking



Testing polarisation via stacking



Polarisation around hot spots



Data (top) versus expectation (bottom)

➔ Planck "sees" precisely the dynamics of fluctuations, at ~380 000 years

Summary of Planck results

- 6-parameter "vanilla" ΛCDM model fits data very well
  - No need for additional physics
- Estimated parameters are different from previous best results
  - More matter, less dark energy
  - Hubble constant smaller than commonly-held
  - Curvature very tightly constrained
- No evidence for >3 types of neutrinos
- No evidence for non-gaussianity
- New constraints on inflationary models
  - Single field slow-roll inflation is preferred (n_s clearly just less than 1)
- Confirmation of WMAP anomalies
  - Deficit of power at large angular scales
- High significance of CMB lensing and CMB-CIB cross-correlation

The future for Planck

- Planck has already been a huge success
  - Has worked near-flawlessly since launch and well beyond baseline
  - Has met all performance requirements
  - With March 2013 release, has met most of its science goals already
- But Planck is not done: much more to come, including polarisation

- August 2013:
  - End of second LFI-only extension (total 8 sky surveys)
- October 2013:
  - Decommissioning / injection into “museum orbit”
- February 2014:
  - Delivery of full cryo- and first LFI-only extension data to ESA; release March 2014
- August 2014:
  - Delivery of new generation of products, including second LFI-only extension data to ESA; release September 2014

Conclusions

- The 2013 Planck T map anisotropy leaves behind it a legacy which will stay for many years (…before next Planck release) and will not be replaced easily.
- Excellent agreement between the Planck temperature spectrum at high l and the predictions of the ΛCDM model.
- But…anomalies are also seen and will be investigated

Next release

- 2014: Twice as much data (LFI is still in operation and in August 2013 it will reach 8 sky observed surveys)
- Expected results:
  - By measuring polarisation B modes Planck may detect primordial gravitational waves
  - From B modes we can measure the energy scale of inflation and constrain the nature of the "inflaton"
  - Next release wil be the input to understand if the "deviations" are fundamental and if we need a "new physics"

Cosmological parameters

6-parameters model

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Baryon density today	$\Omega_b h^2$	0.00028	0.00013
Cold dark matter density today	$\Omega_c h^2$	0.0027	0.0010
Thomson scattering optical depth	τ	0.013	0.0042
Hubble constant [km/s/Mpc]	H_0	1.2	0.53
Scalar spectrum power-law index	n_S	0.007	0.0031

Constraints on other parameters

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Effective number of neutrino species	N_{eff}	0.42	0.18
Fraction of baryonic mass in helium	Y_p	0.035	0.010
Dark energy equation of state	w	0.32	0.20
Varying fine-structure constant	α/α_0	0.0043	0.0018

→ Expected reduction in error bars by factors of 2 or more

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