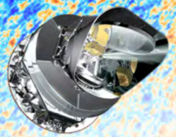


The Universe According to *Planck*
(or - Cosmology after *Planck*)

K. M. Górski

Jet Propulsion Laboratory, California Institute of Technology

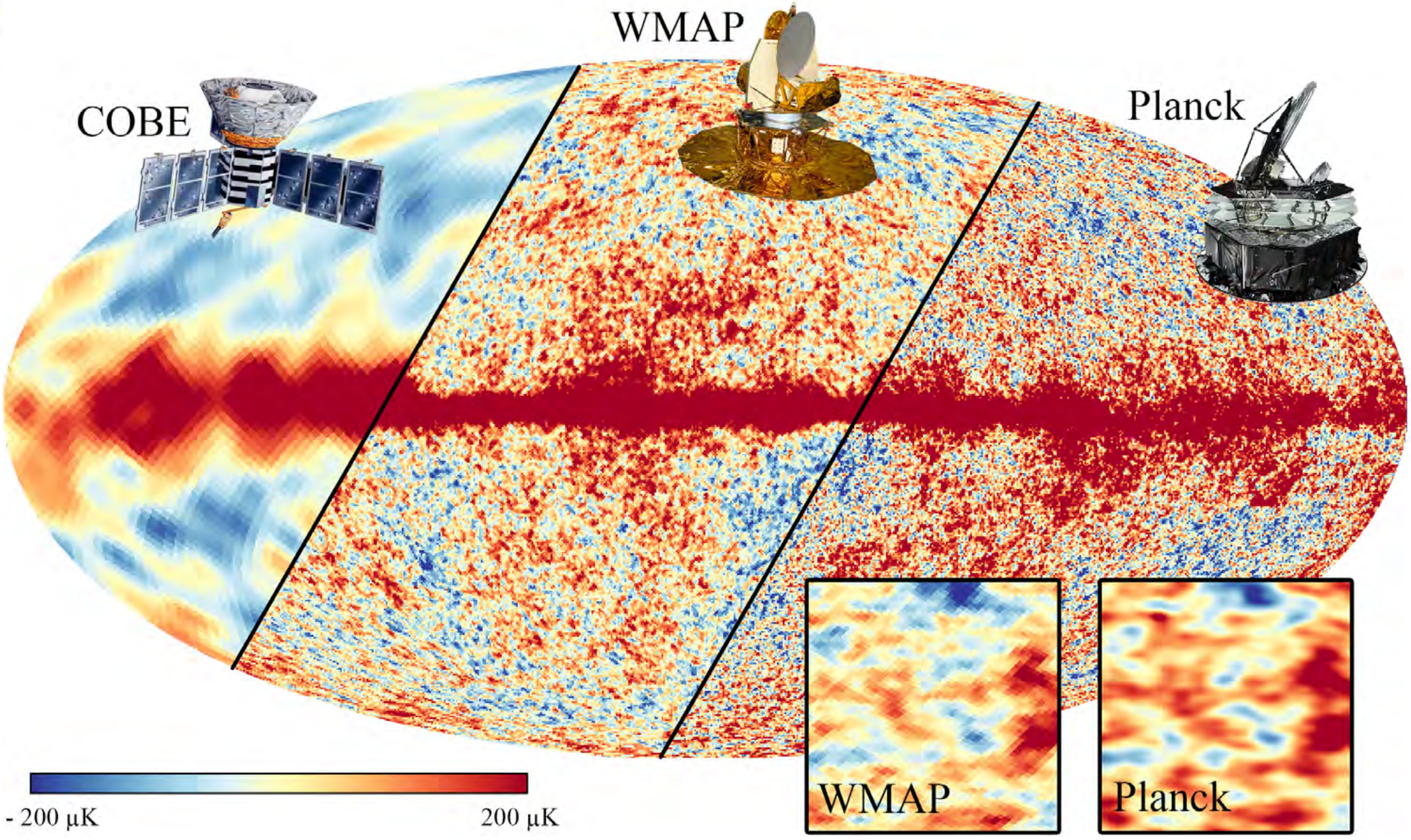
Warsaw University Observatory

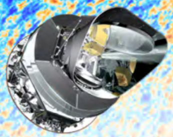
On behalf of the Planck collaboration

TAUP 2013

Asilomar, Sept. 9, 2013

Almost 50 years since the discovery of the CMB,
after scores of suborbital CMB experiments,
and two decades of 3 dedicated satellite missions –
we reached a REMARKABLE moment, but why are we doing this?





Why is the CMB important?
Simplicity and accessibility

- ❖ We see directly what the Universe was like 370,000 years after the Big Bang
- ❖ The Universe then was very simple
  - Basic constituents — no chemistry
    - Remember: p+, n, e−, D+, T+, 3He++, 4He++, Li+++, ν-s, plus "dark" matter. That's it!
  - Well-understood physical conditions
    - 3000 K
    - High vacuum (2.4×10^6 nuclei per m^3)
    - Extremely uniform (~ 1 part in 10^5)

=> Linear regime. "Straightforward" to calculate how matter and radiation behave as a function of many parameters that we would like to know.

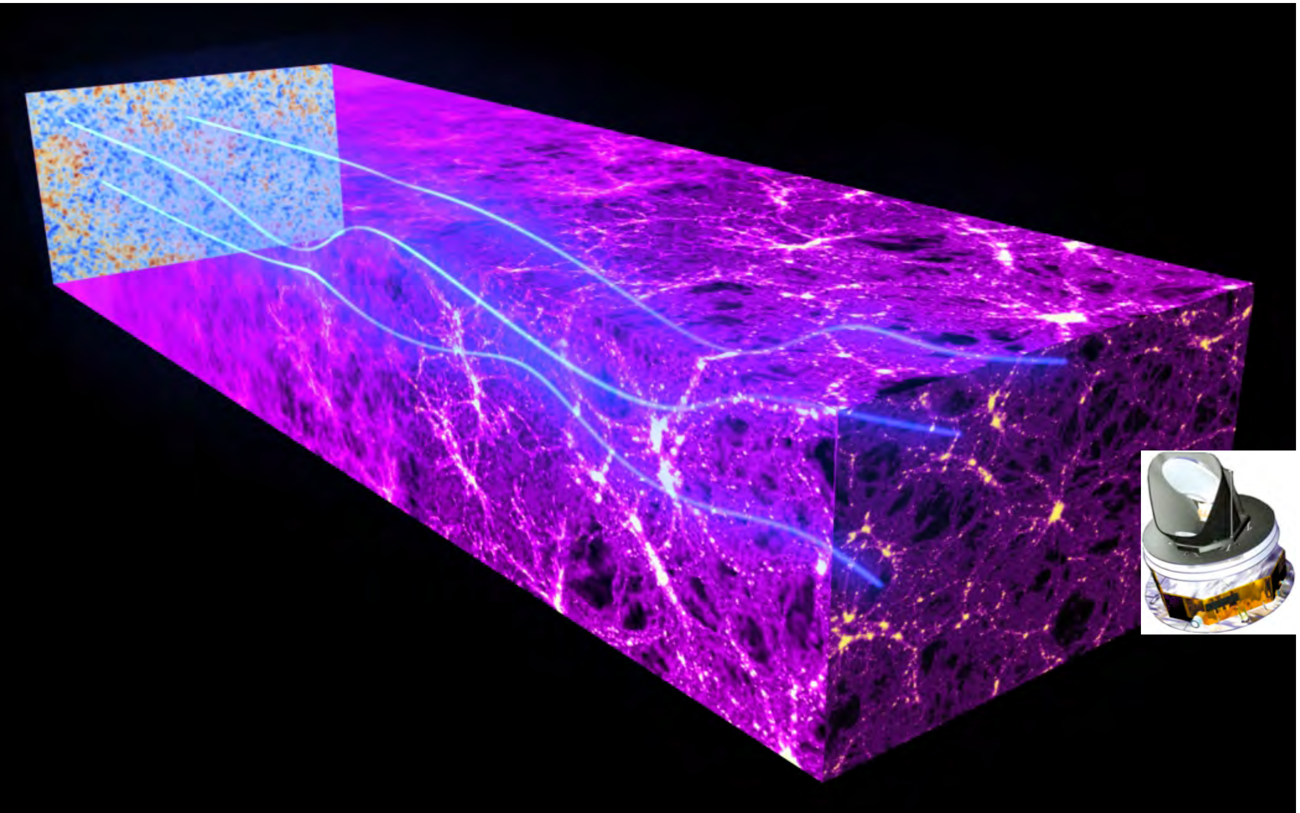
- ❖ We can calculate what the CMB would look like as a function of how much mass and what type of mass there is, what the overall geometry of the Universe is, how old and how big the Universe is, and so on - fundamental, basic things.

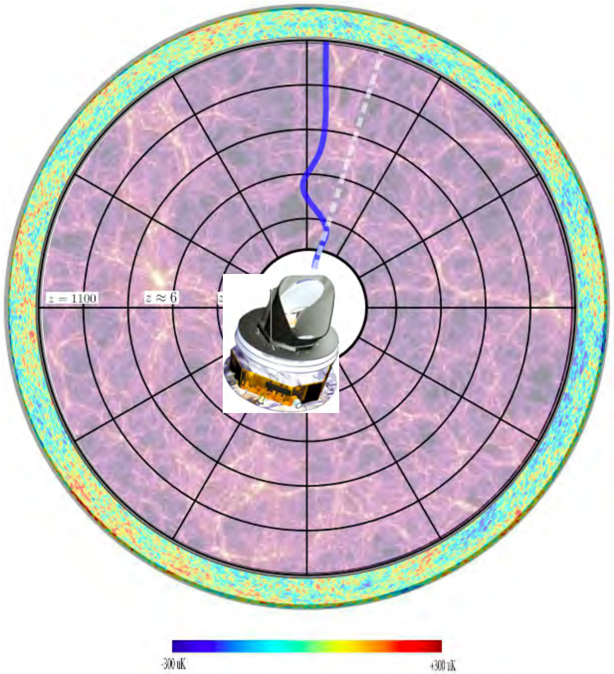
We compare with what we observe, and work out all those basic things.

K. M. Gorski

Why is the CMB important?

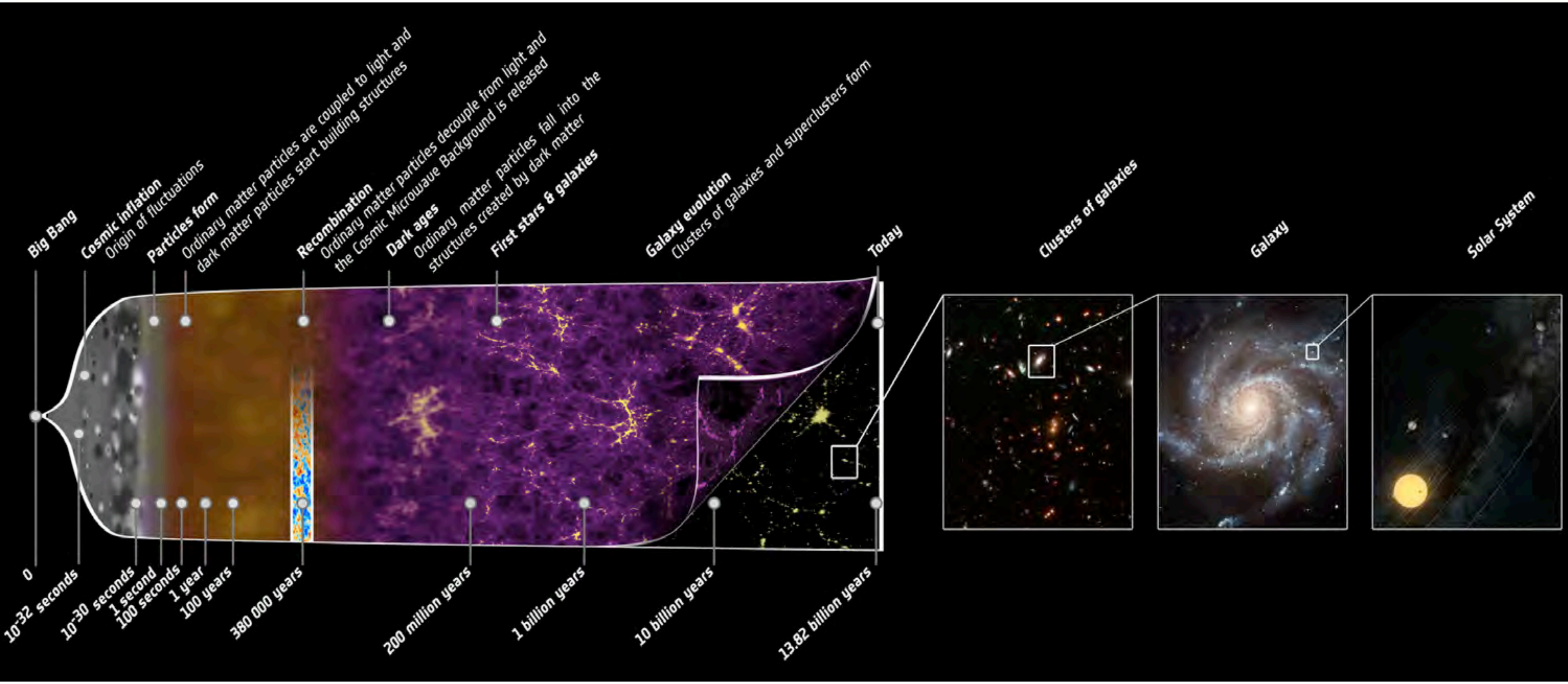
- It shows us directly the simple early Universe:
  - Determined by fundamental physical processes that happened 10^{-35} s after the Big Bang
  - Starting point for the further evolution of everything
- As this light travels to us on its 13.8 billion year journey it also brings us information about the intervening parts of the Universe



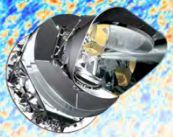


K. M. Gorski

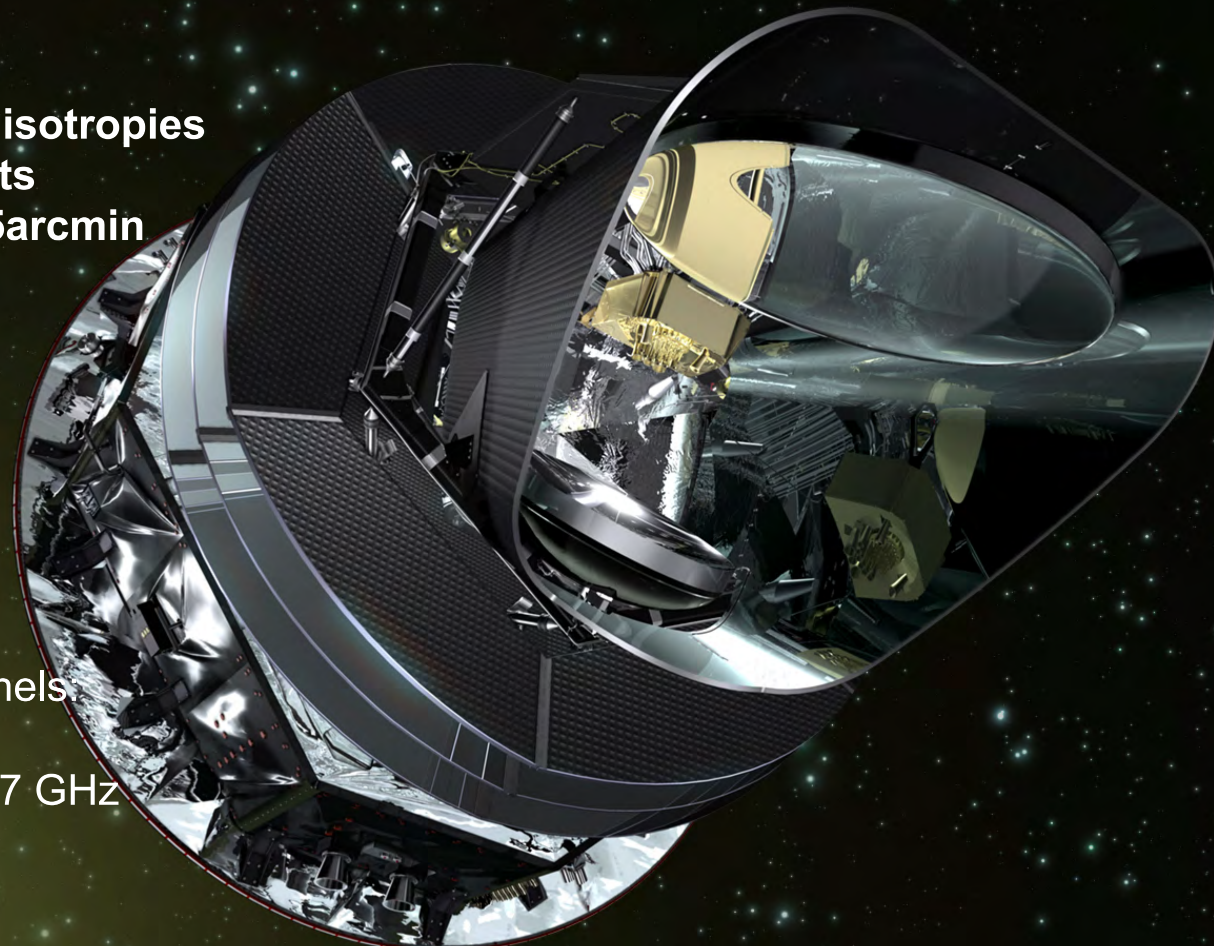
What does Planck see?



K. M. Gorski



Planck – some mission design specifications



✧ Primary scientific goal:
To measure the temperature anisotropies of the CMB to fundamental limits down to angular resolution of 5arcmin

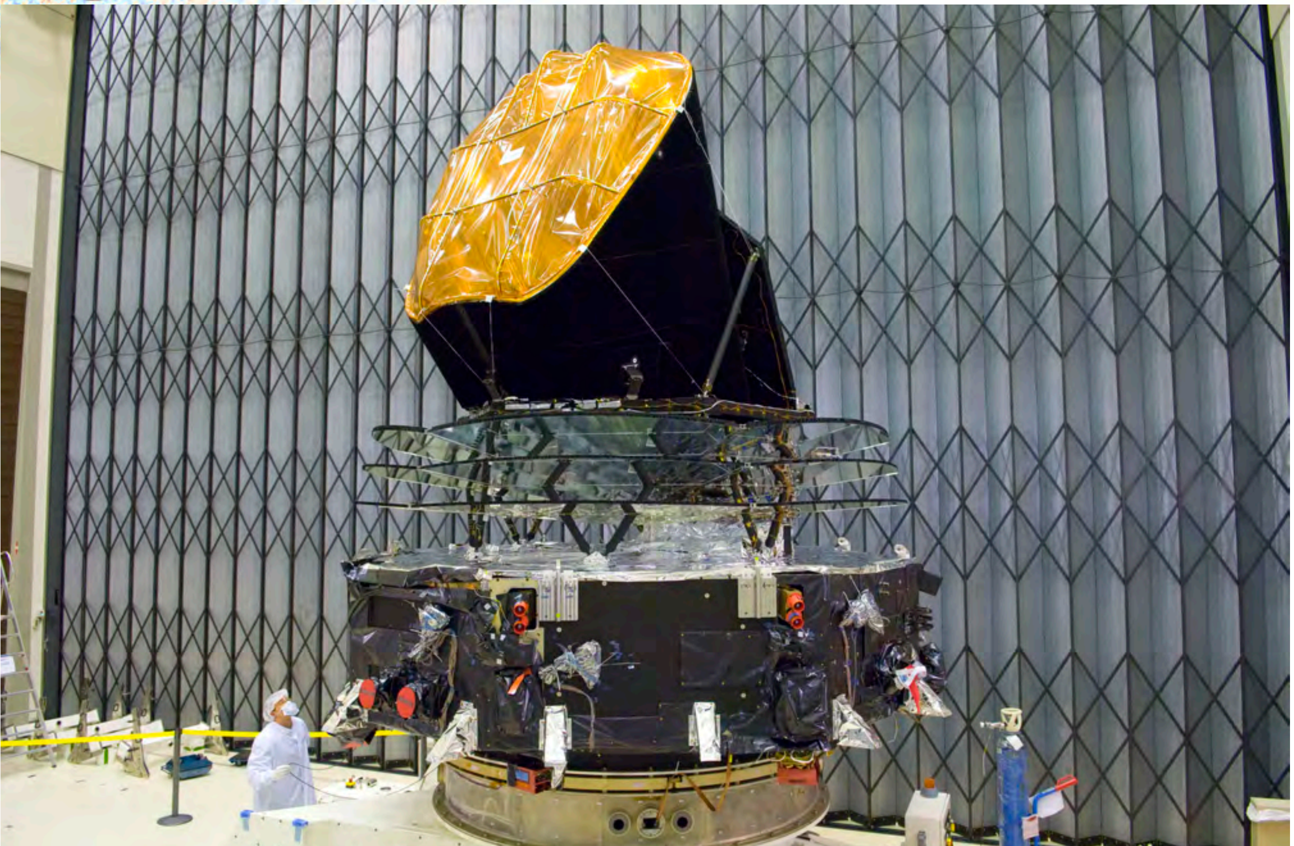
✧ Fly at Sun-Earth **L**2 point
✧ Use 4-stage cooling system
✧ Carry two instruments:
- Low Frequency Instrument (LFI), 20-K cryogenic amplifiers
- High Frequency Instrument (HFI), 0.1-K bolometers

✧ Observe at 9 frequency channels:
LFI - 30, 44, 70 GHz, and
HFI - 100, 143, 217, 353, 545, 857 GHz
to deal with foregrounds and render the best full sky CMB map

Planck is the third generation CMB space mission

- Formal description: “ESA mission with significant participation of NASA”
- Translation of “significant …”: thermal design, sorption coolers, all bolometers, and amplifiers, delivery of ERCSC, supercomputing support, expertise and participation in data analysis, and science

Ferrari of satellite CMB missions?



Planck
ready to go
in French Guyana

And off it went - Launch on May 14, 2009

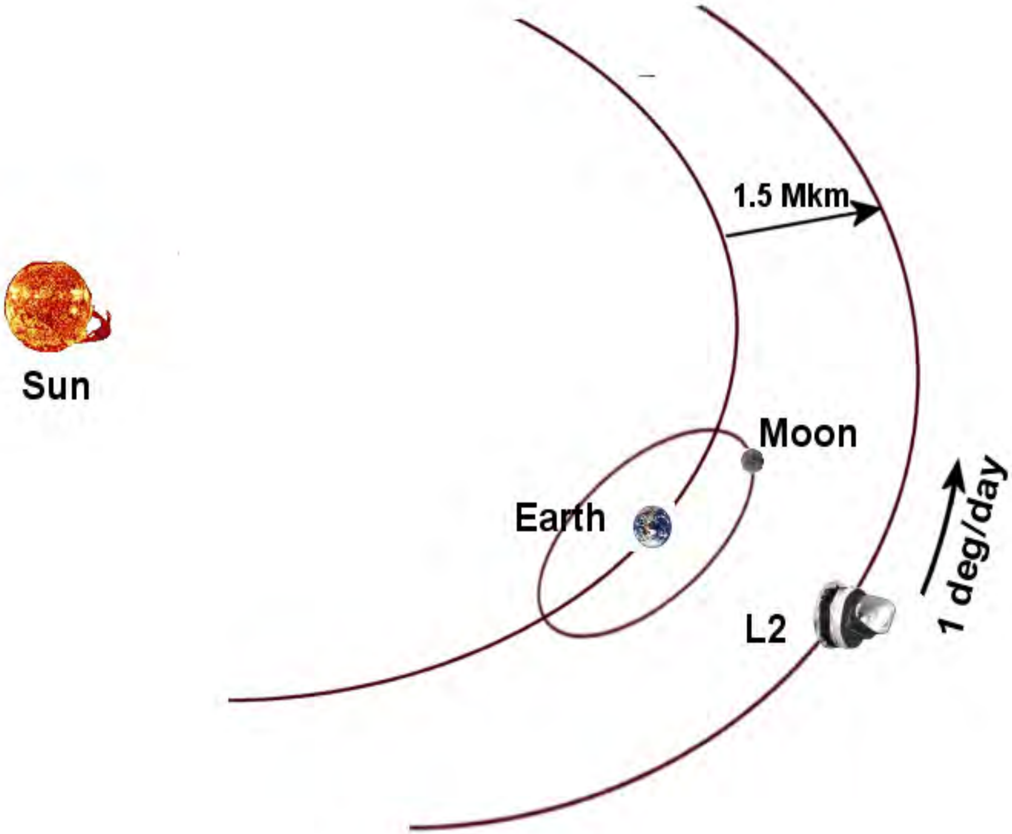
K. M. Gorski

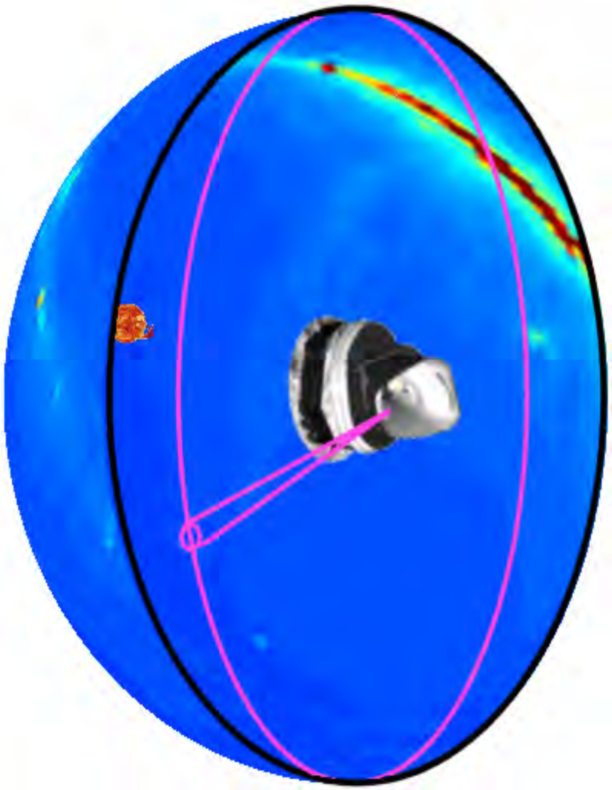
But the real deal is the people – at the joint meeting of the Core Teams of Planck

Let us remember those who we lost:
Richard Gispert
Jacques Charra
Andrew Lange

Planck Mission: observing the sky from L2 orbit

- Full sky observed every ~6 months

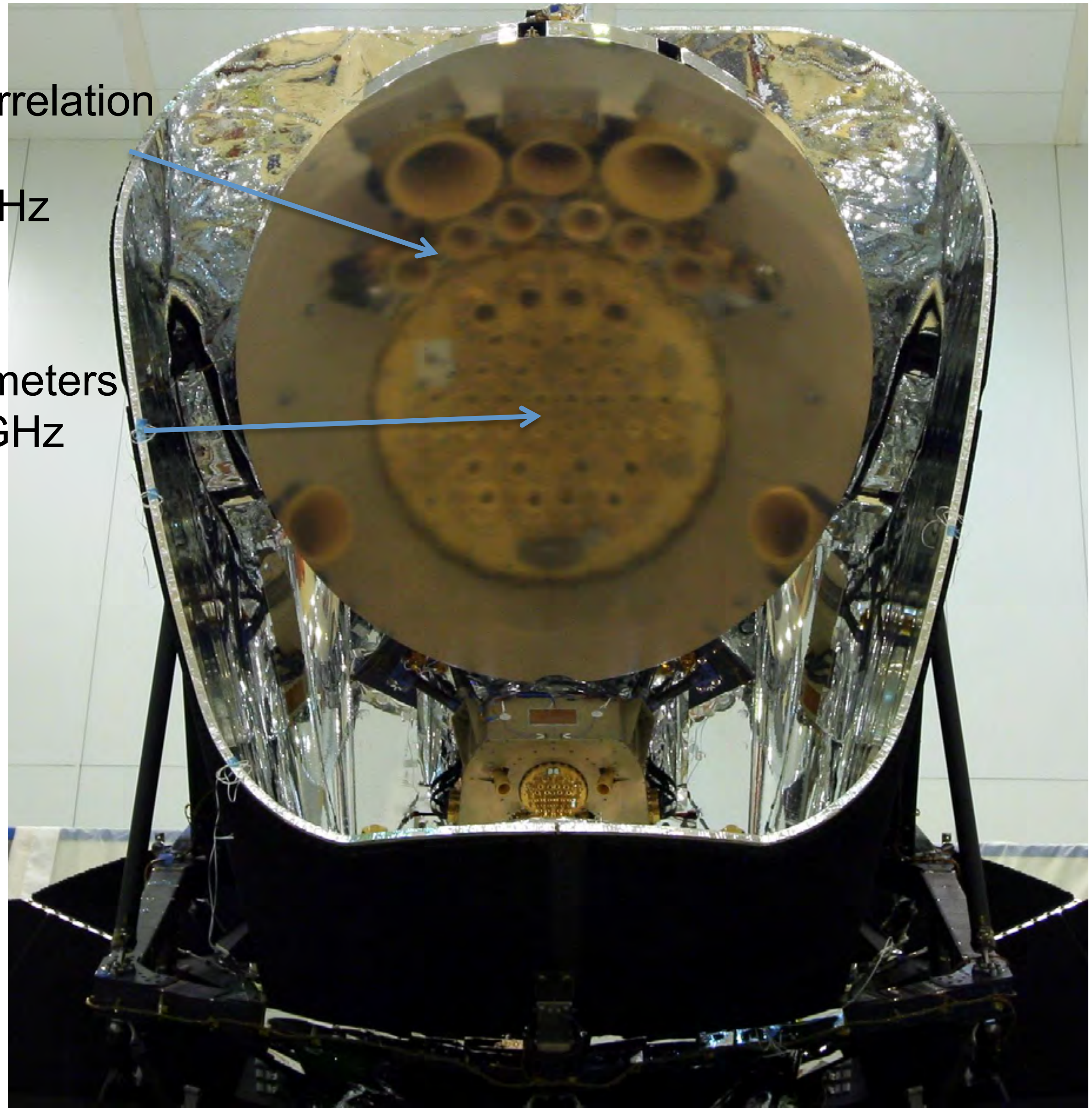




Two instruments onboard Planck – the focal plane reflection in the primary mirror

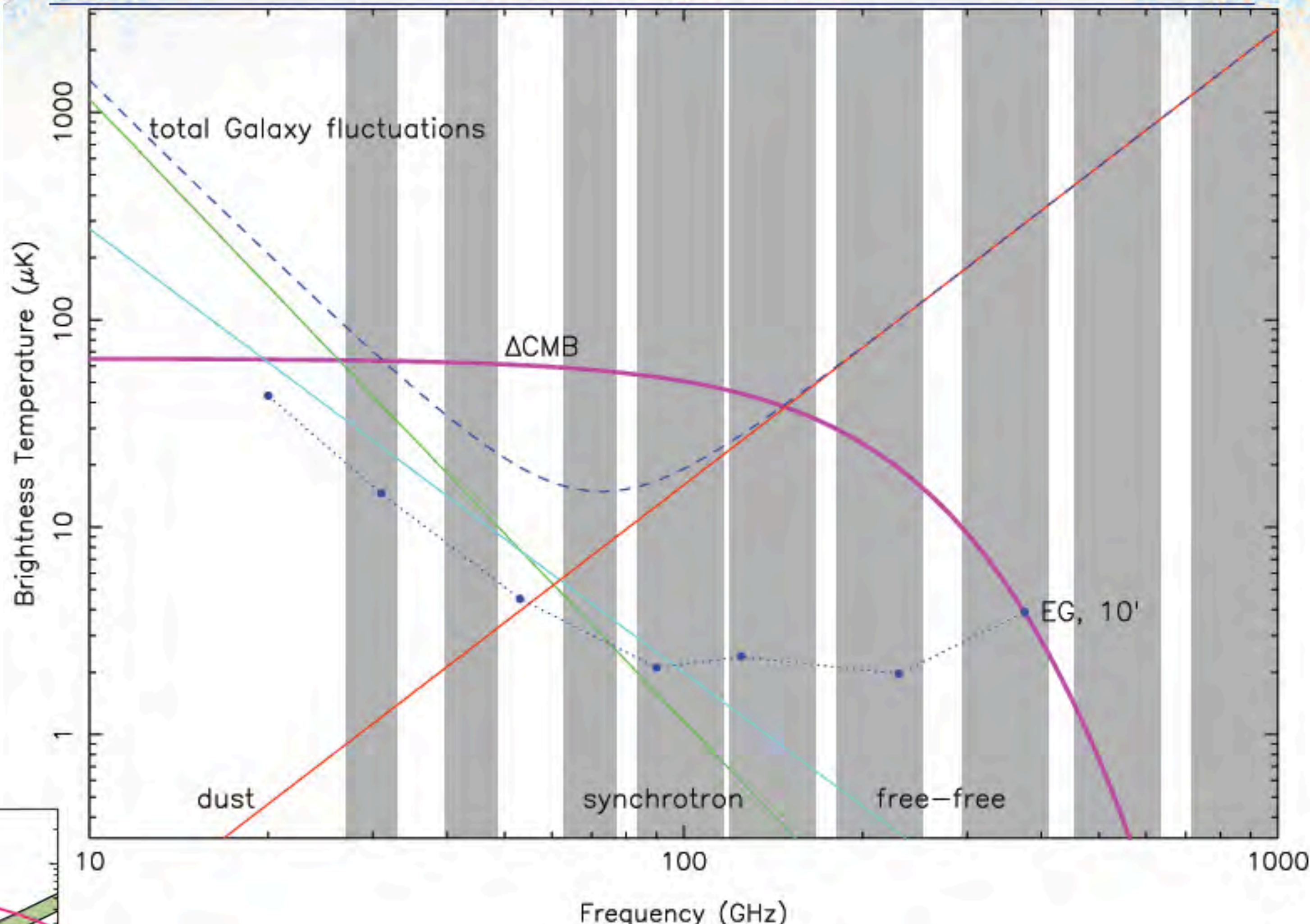
LFI: pseudo-correlation radiometers
30 GHz – 70 GHz

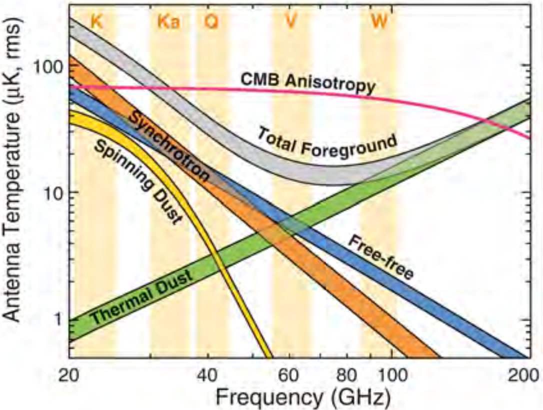
HFI: 0.1K bolometers
100 GHz-857 GHz



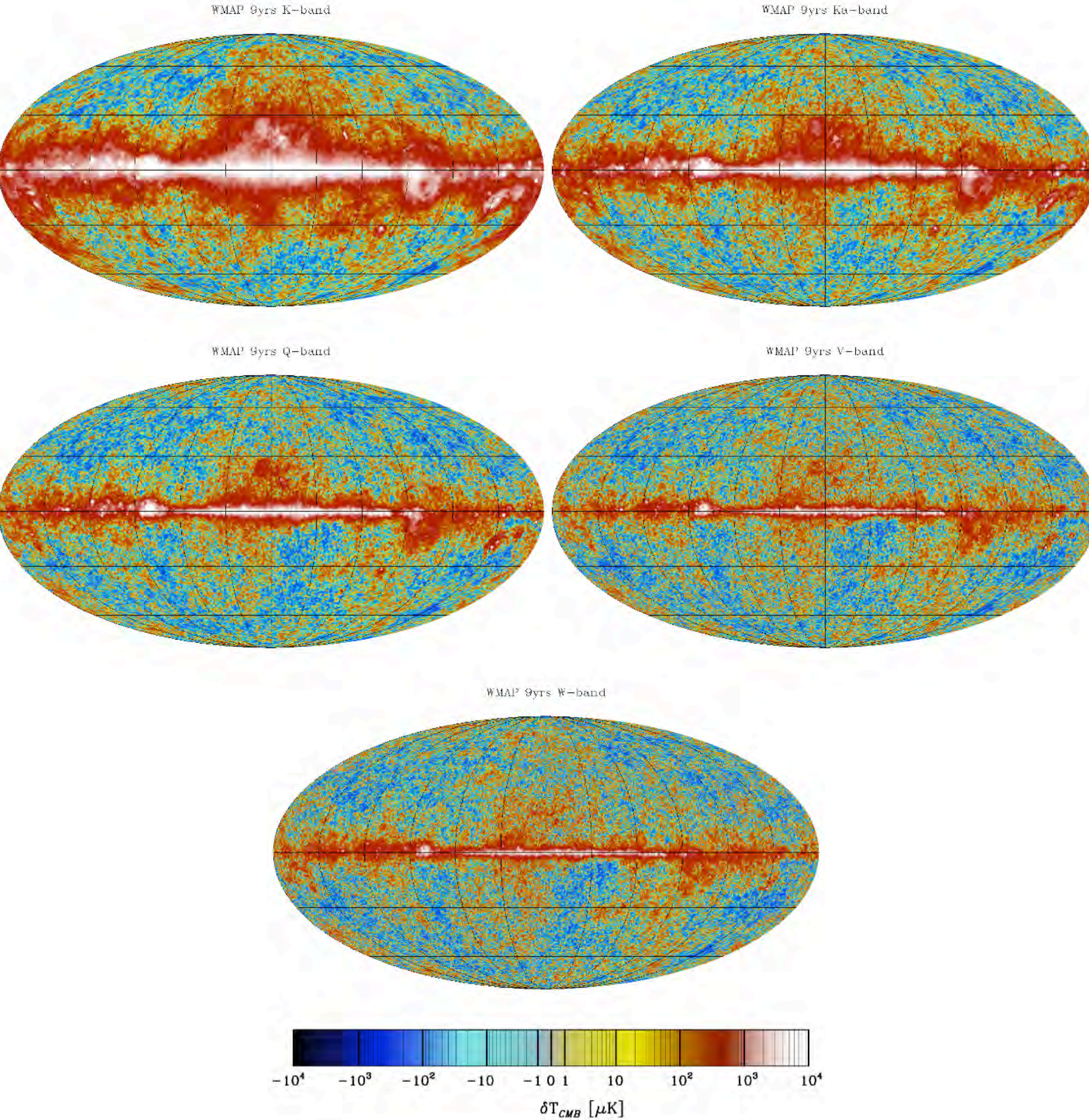
K. M. Gorski

Talking about the microwave sky before Planck …





K. M. Gorski

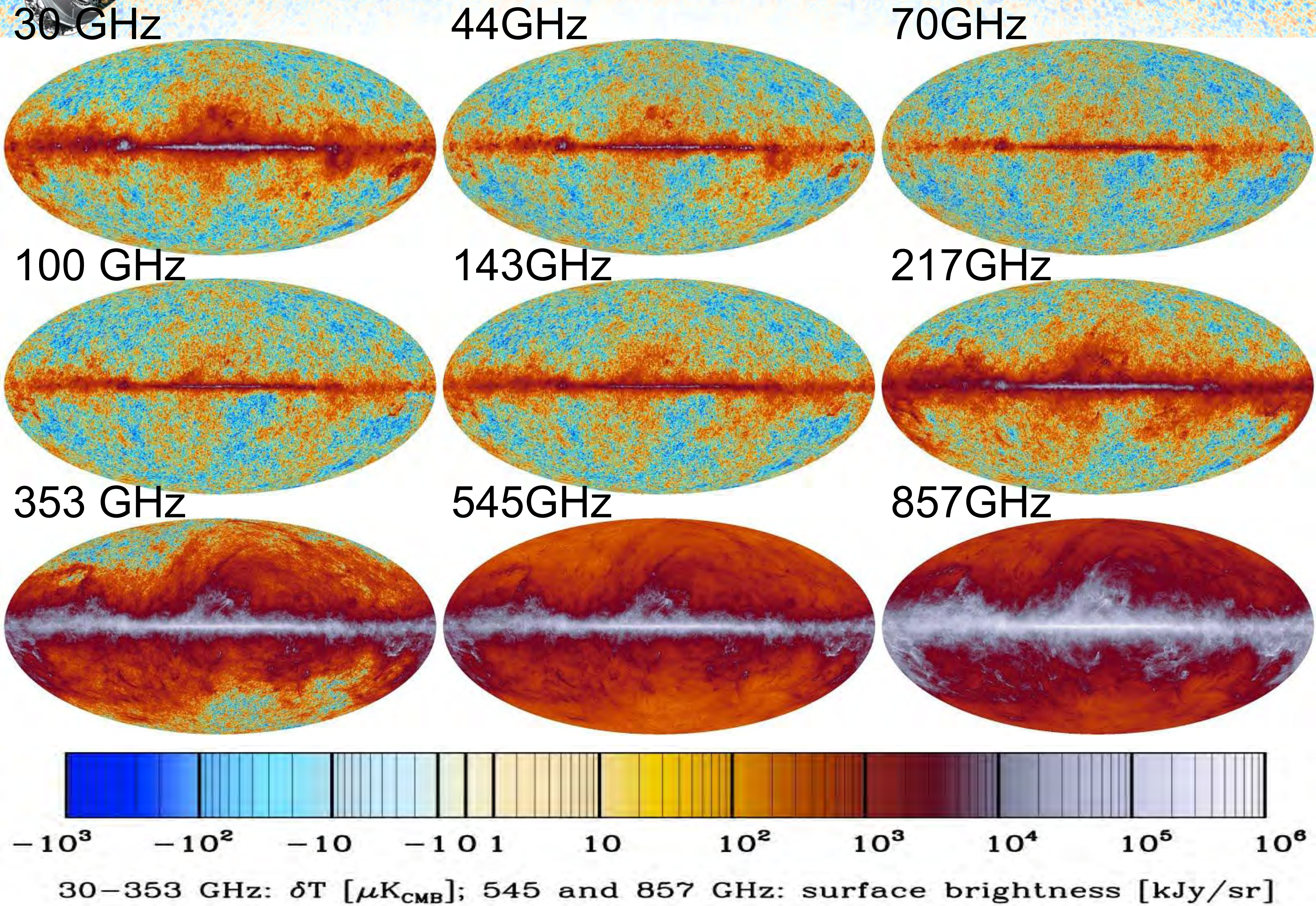


Pre-Planck microwave sky

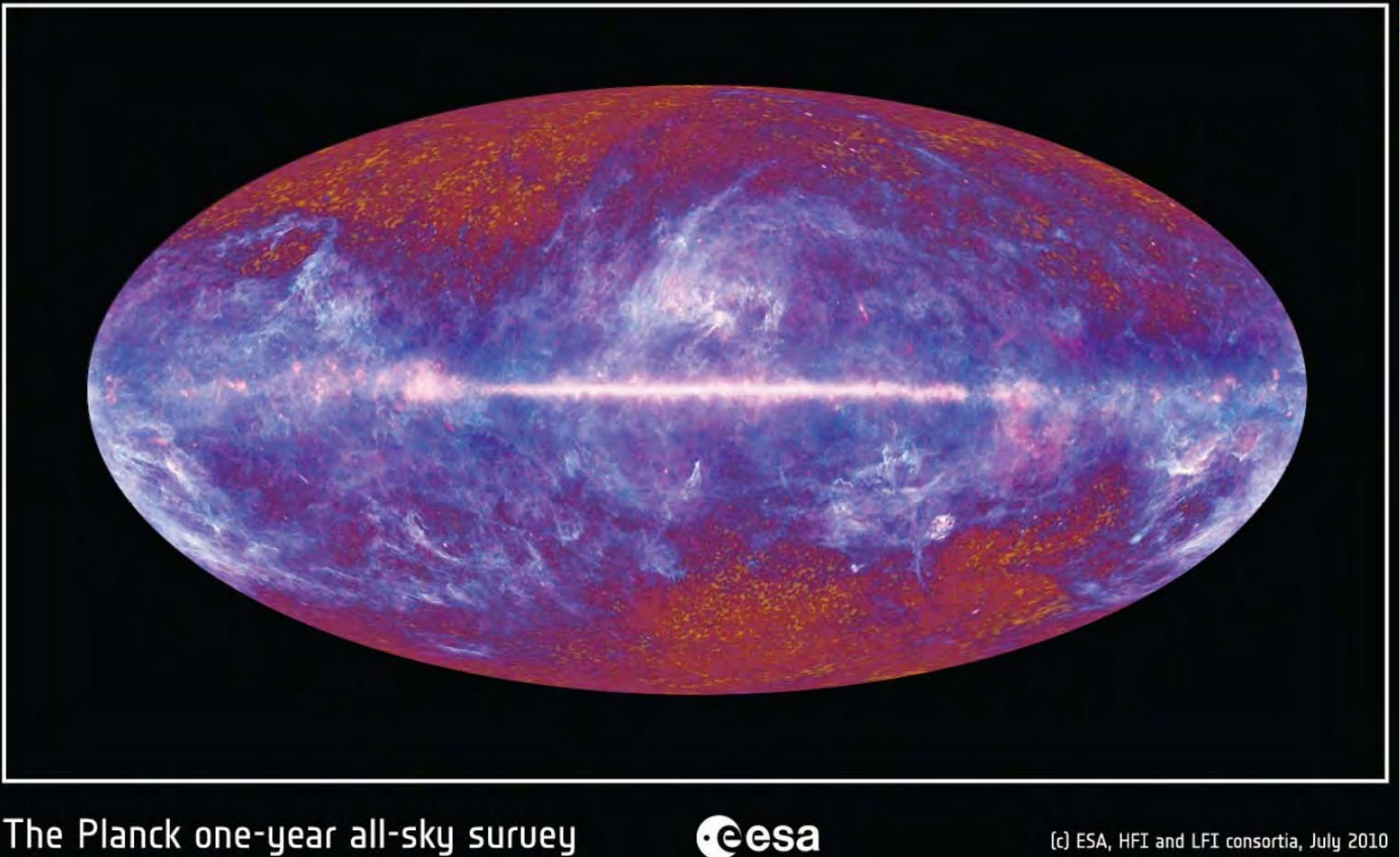
the great WMAP mission and its sky maps at 22-94 GHz

K. M. Gorski

Planck Maps of the microwave and sub-mm Sky



All these maps collapsed into a PR image of "Planck's Universe" – one of ESA's most beloved pictures

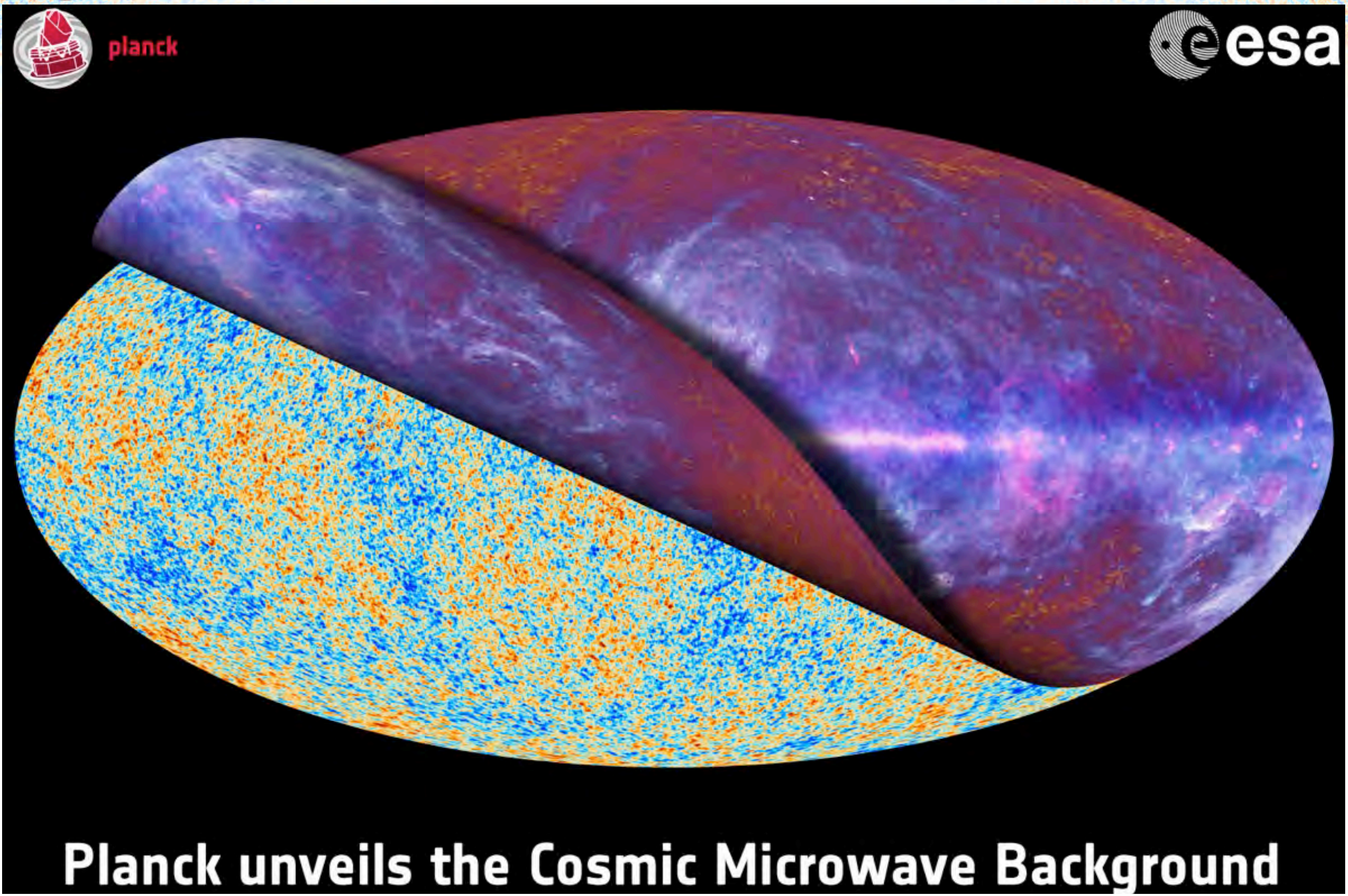


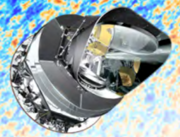
K. M. Gorski

This is when we come in – to pull the CMB anisotropy out of this … piece of cake ☺

And this is how you do it –
according to the new demonstration of the PR tour de force

PLANCK

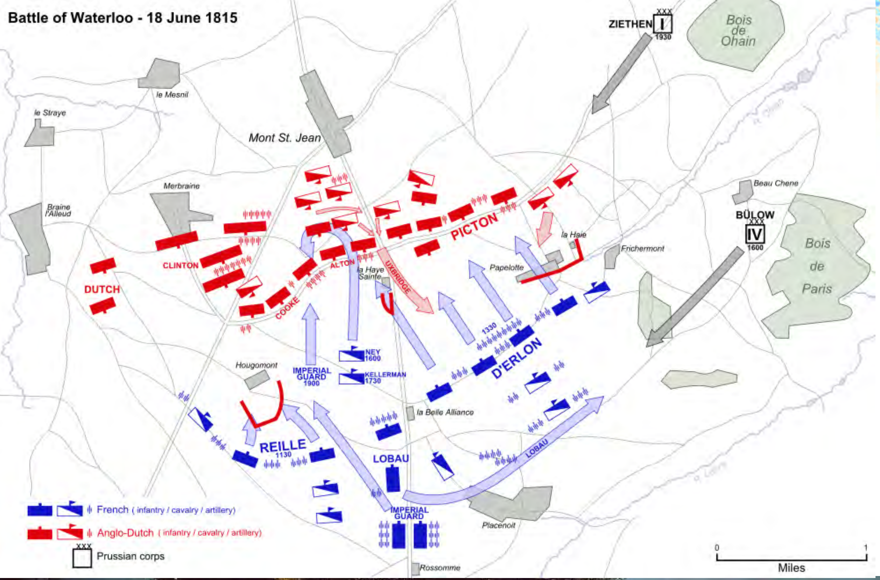




Our Order of Battle for the Planck 2013 Papers Crop

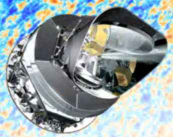
Almost 1000 pages already (!!!) but not yet done …

- I — Overview of products & results
  - Frequency Maps
  - Component Maps
  - Power Spectra
  - Parameters
- II — LFI Processing
  - III — LFI Systematics
  - IV — LFI Beams
  - V — LFI Calibration
- VI — HFI Processing
  - VII — HFI Time Response & Beams
  - VIII — HFI Calibration
  - IX — HFI Spectral Response
  - X — HFI Particle effects
- XI — Consistency of the Data
- XII — Component Separation
  - XIII — Galactic CO
  - XIV — Zodiacal Emission
- XV — Power Spectra & Likelihood
- XVI — Cosmological Parameters
- XVII — Lensing by LSS
- XVIII — Lensing by Star-forming Galaxies
- XIX — The Integrated Sachs-Wolfe Effect
- XX — Cosmology from SZ Counts
- XXI — Compton Parameter Map
- XXII — Inflation
- XXIII — Isotropy & Statistics
- XXIV — Primordial Non-Gaussianity
- XXV — Strings & Other Defects
- XXVI — Background Geometry & Topology
- XXVII — Special Relativistic Effects on the Dipole
- XXVIII — Catalogue of Compact Sources
- XXIX — Catalogue of SZ Sources

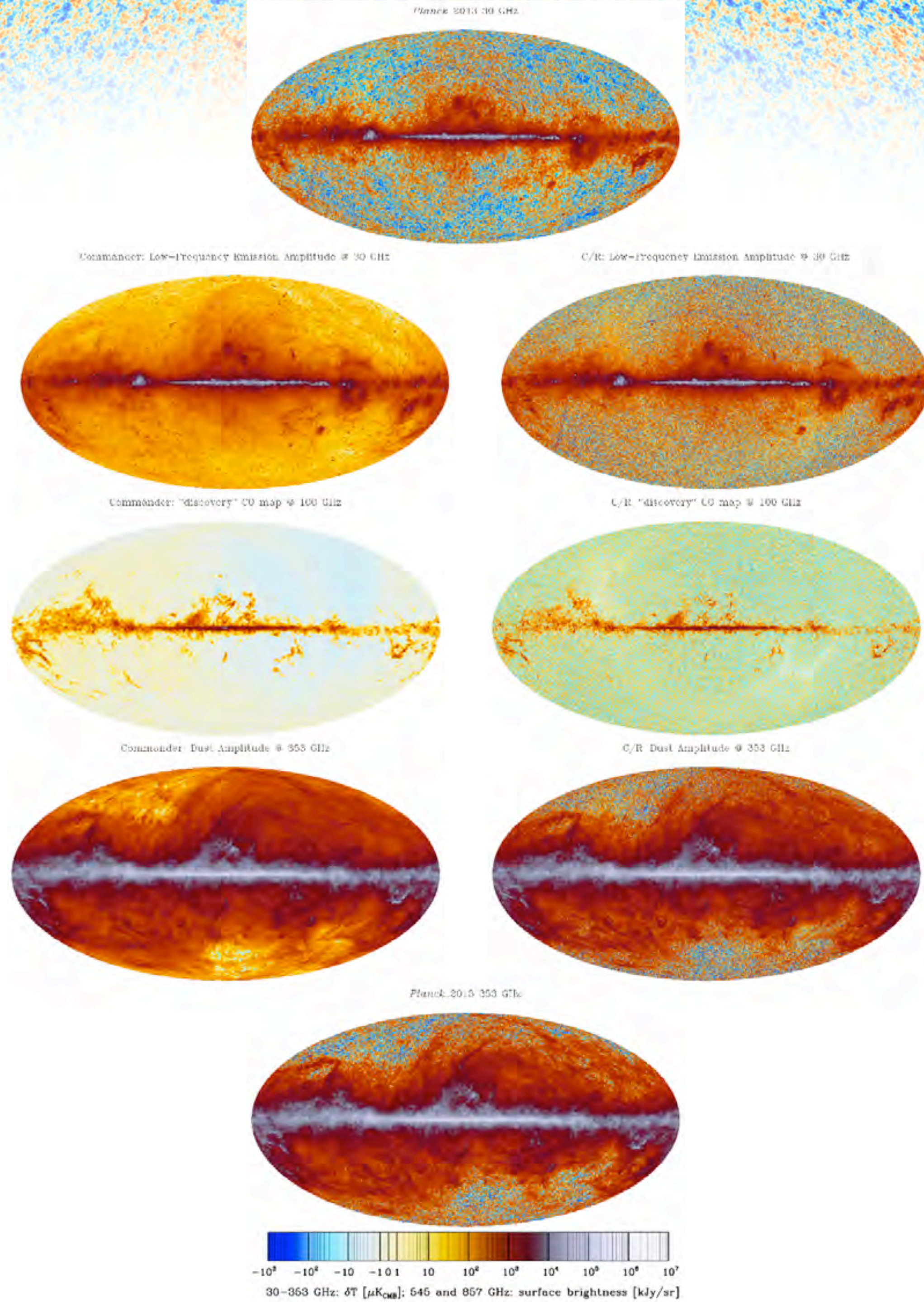


Somehow, despite resembling this at the outset …

what it felt like in the end was more like a real thing, however, …



Before we get to the CMB anisotropy here are the Physical Component Maps derived from Planck data



PLANCK

30 GHz

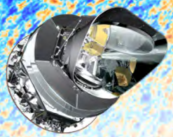
Synchrotron, AME, and free-free

^{12}CO "Aggregate of 1-0 and 2-1"

Dust emission at 353 GHz

353 GHz

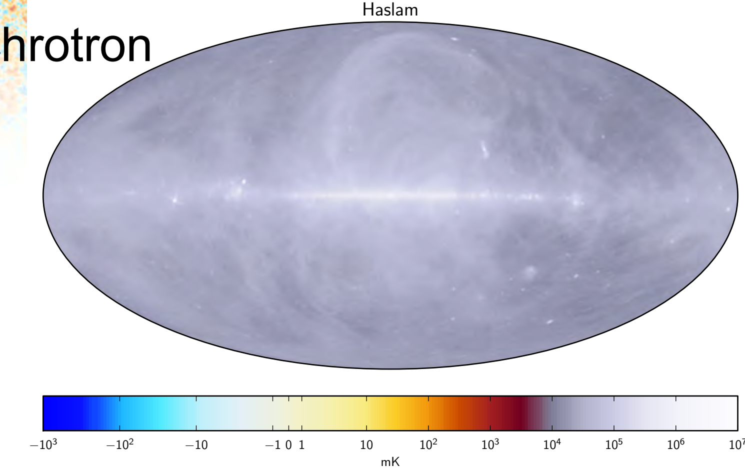
K. M. Gorski

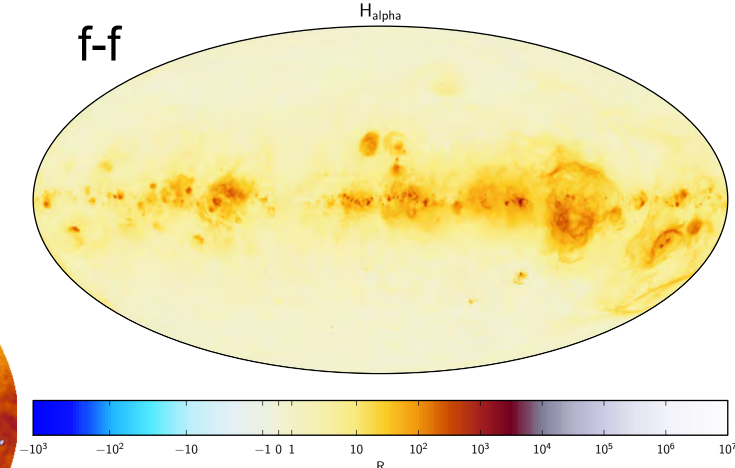


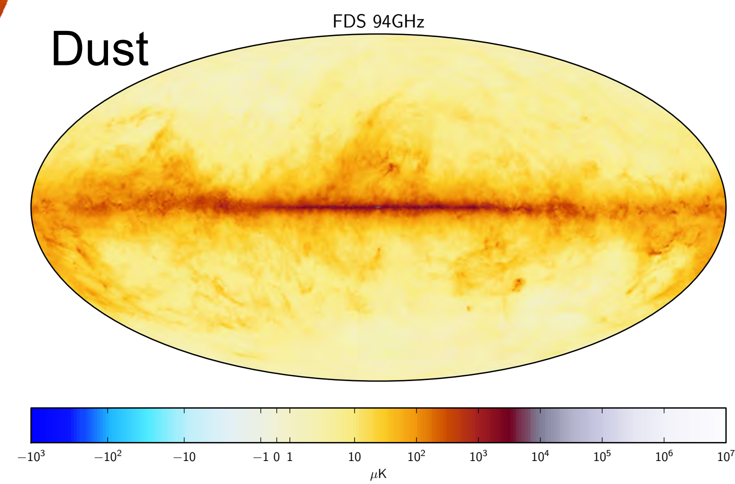
Understanding the Galaxy at low frequencies

Analysis of the actual Planck component separation low-frequency solution

Commander: Low−Frequency Emission Amplitude @ 30 GHz

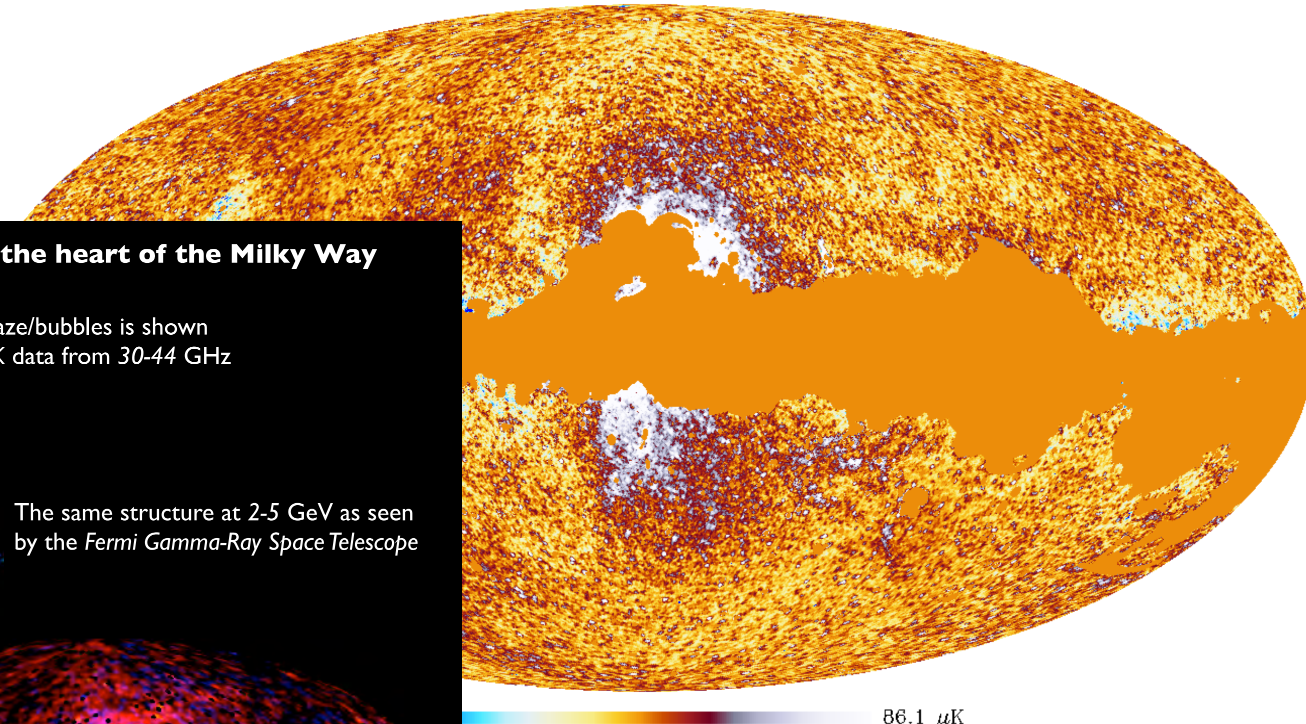


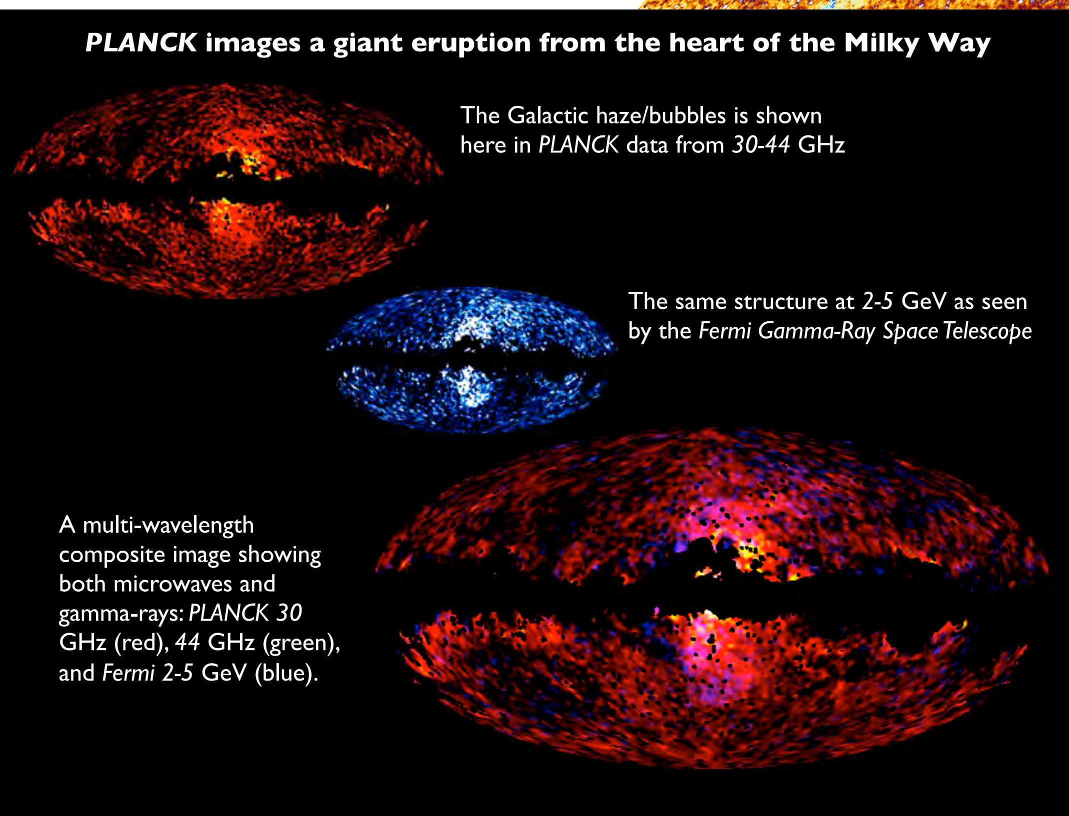




via regression against the 3 classic foreground emission templates results in revealing the galactic haze emission …

Haze rederived from component separation solutions involving the publicly released Planck data (update on the content of the forthcoming A&A paper on the haze)





K. M. Gorski

CO line response in HFI spectral bands – averaged over individual detectors

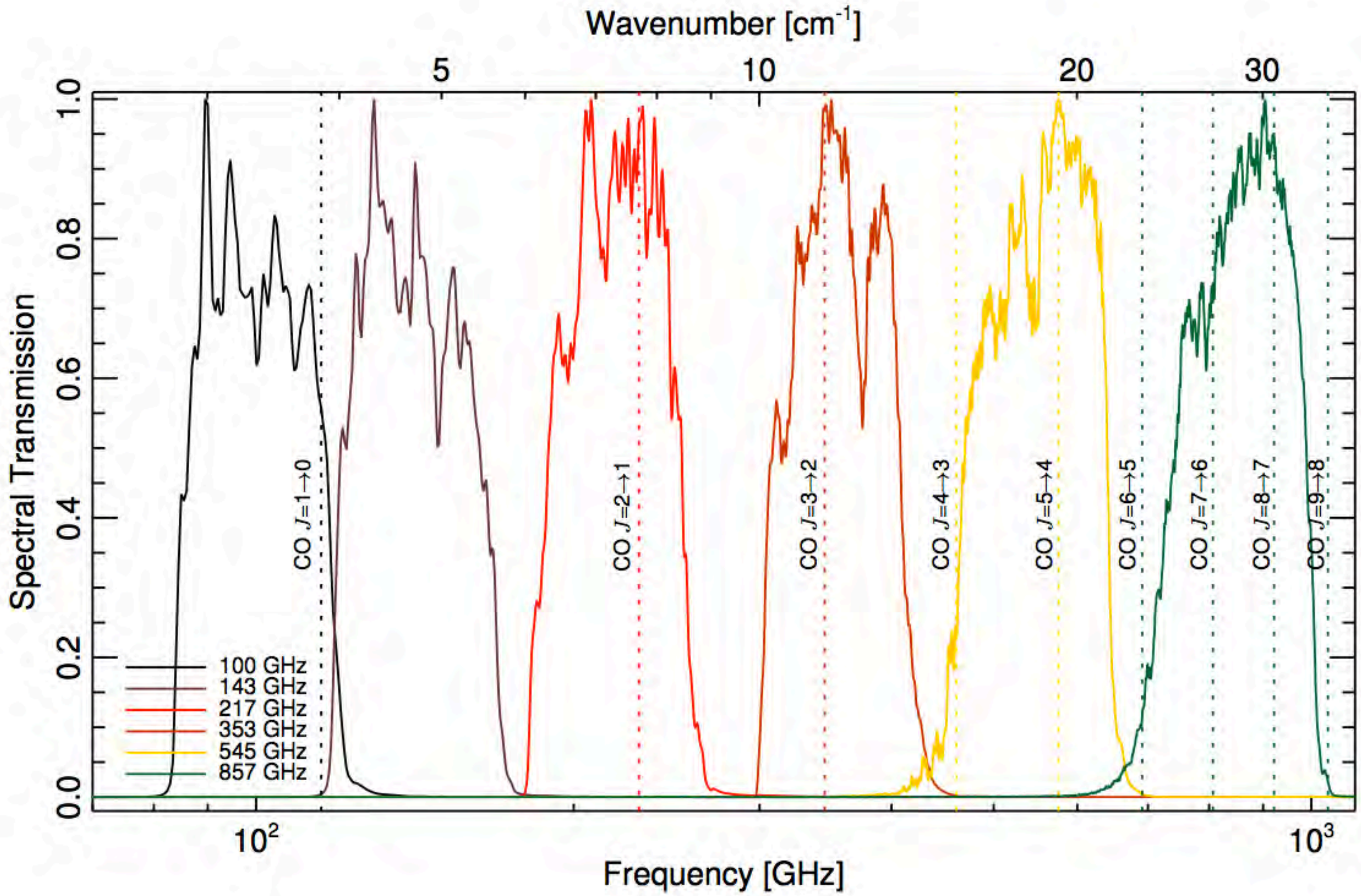
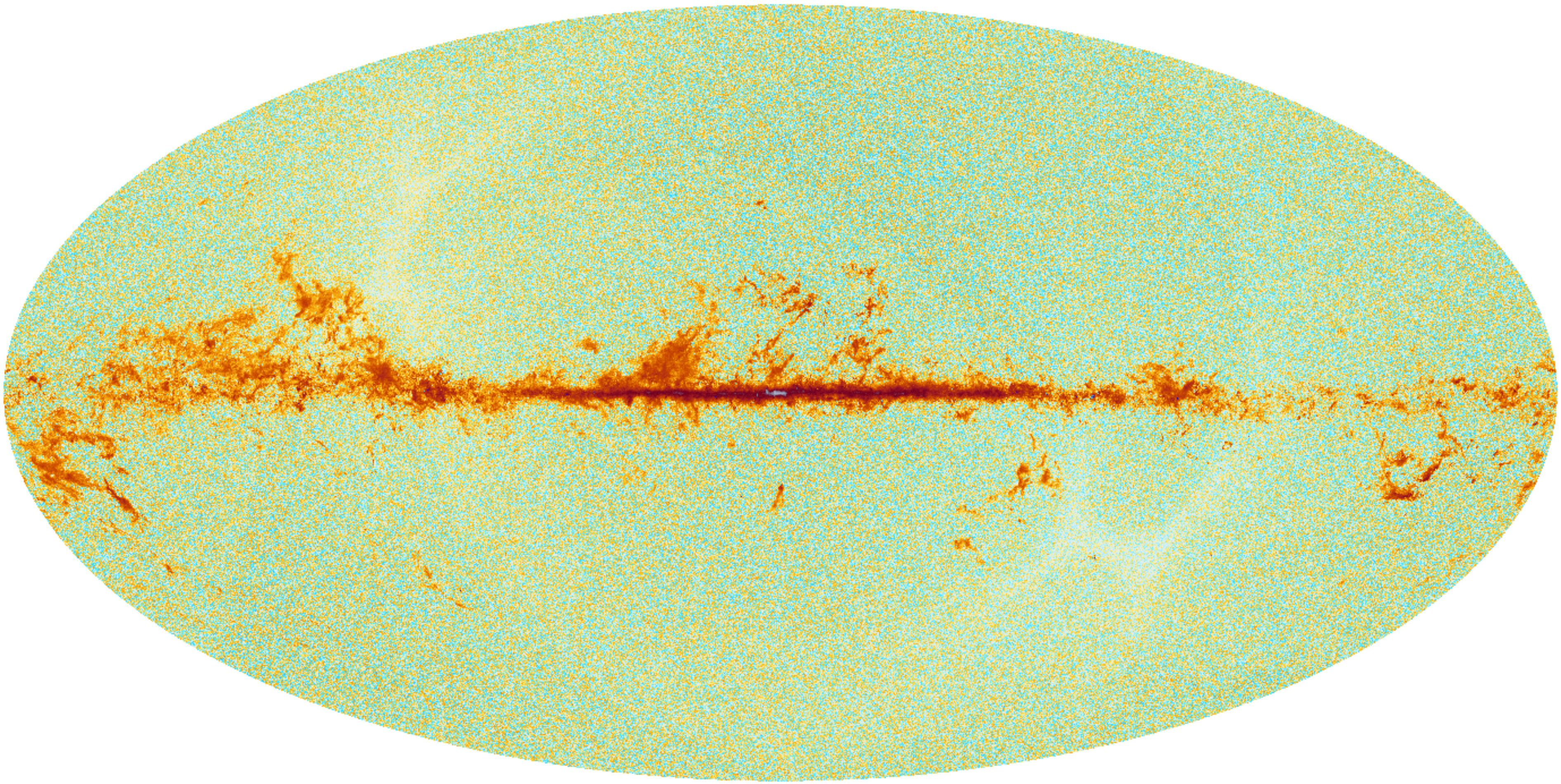


Fig. 1. The average spectral response for each of the HFI frequency bands. The vertical bars represent the CO rotational transitions.

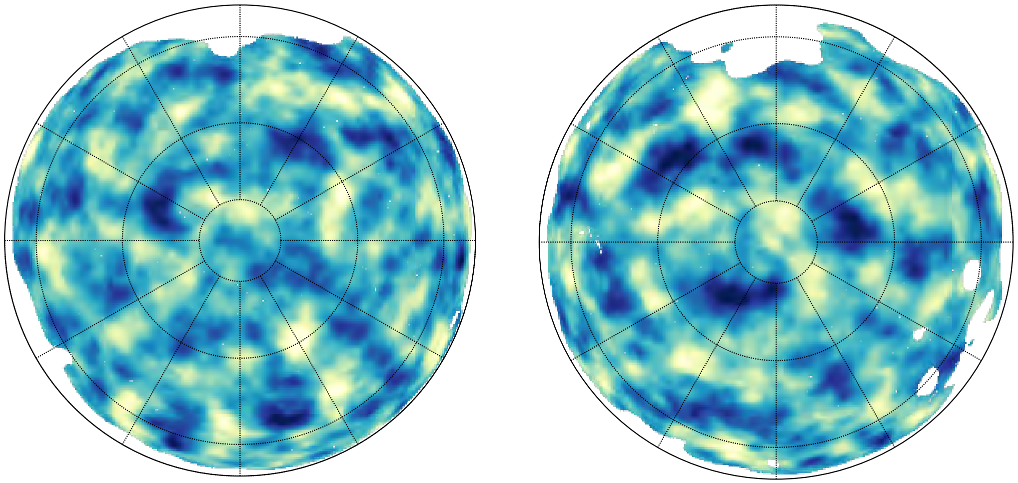
M. Gorski

Planck delivers unprecedented full sky CO emission maps

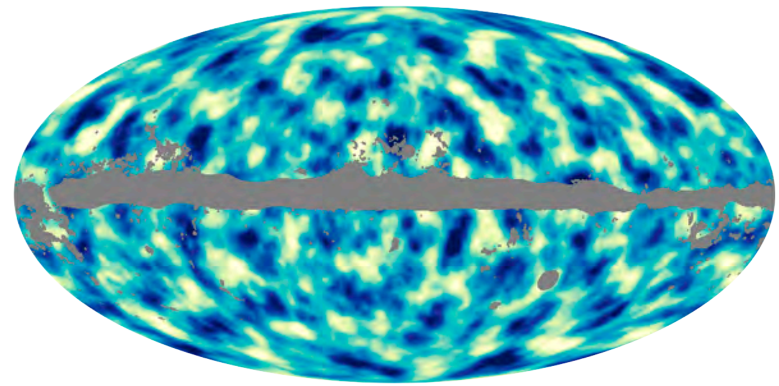
C/R: "discovery" CO map @ 100 GHz

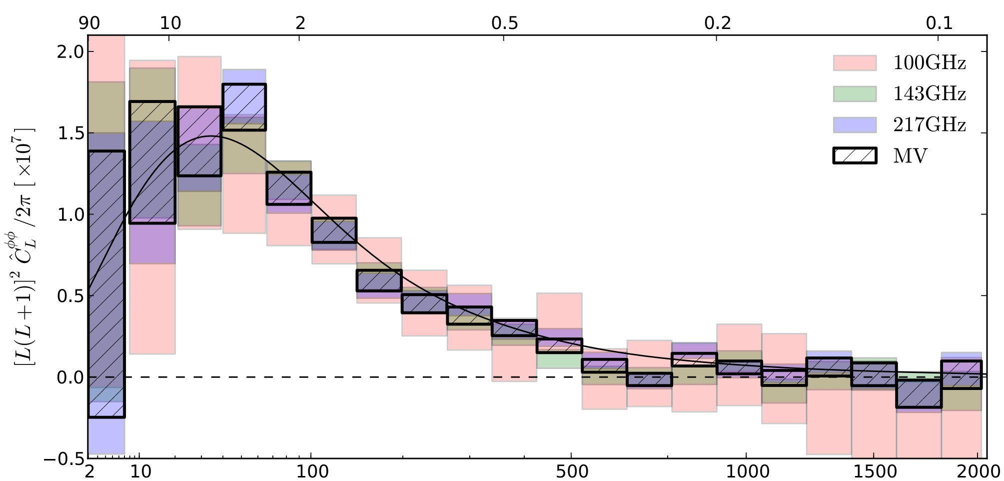


Lensing by large scale structure



Wiener-filtered lensing potential estimate reconstruction, in Galactic coordinates using orthographic projection





~25σ-detection

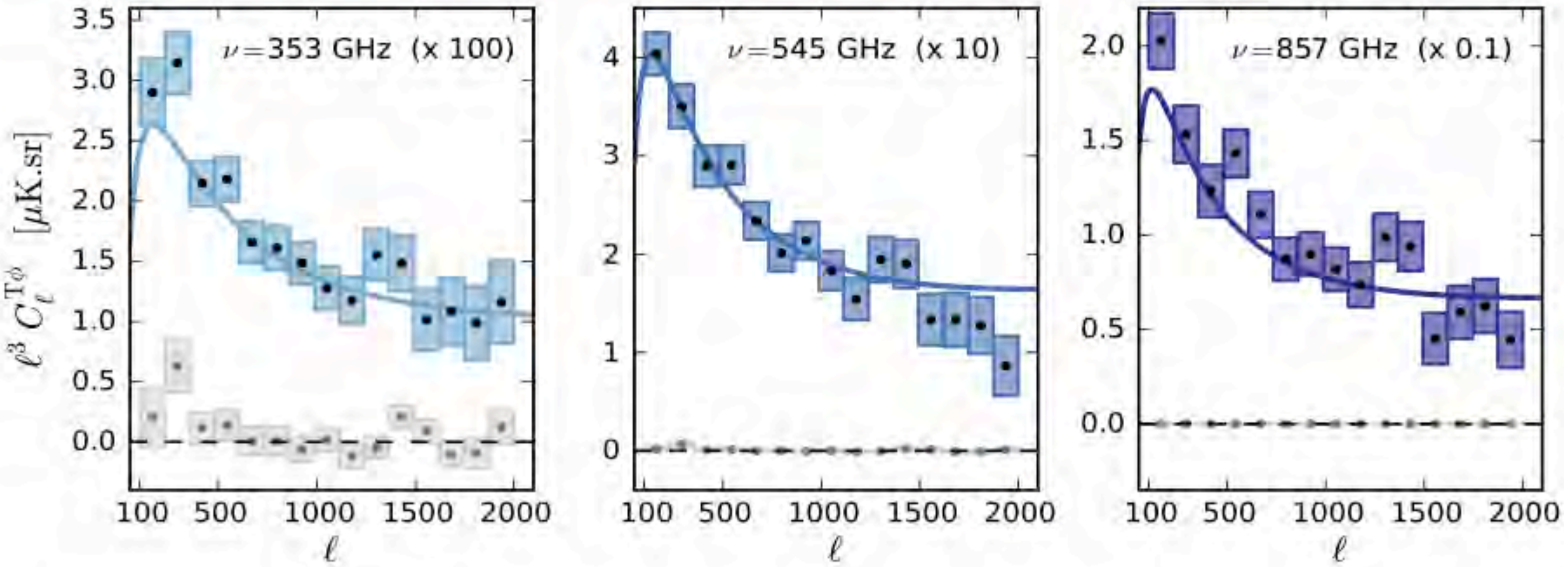
Lensing potential power spectrum

Best fit model ΛCDM model from CMB Temperature power spectrum (black line)

$C_\ell^{\phi\phi}$ Derived from the measured trispectrum (4-point function)

K. M. Gorski

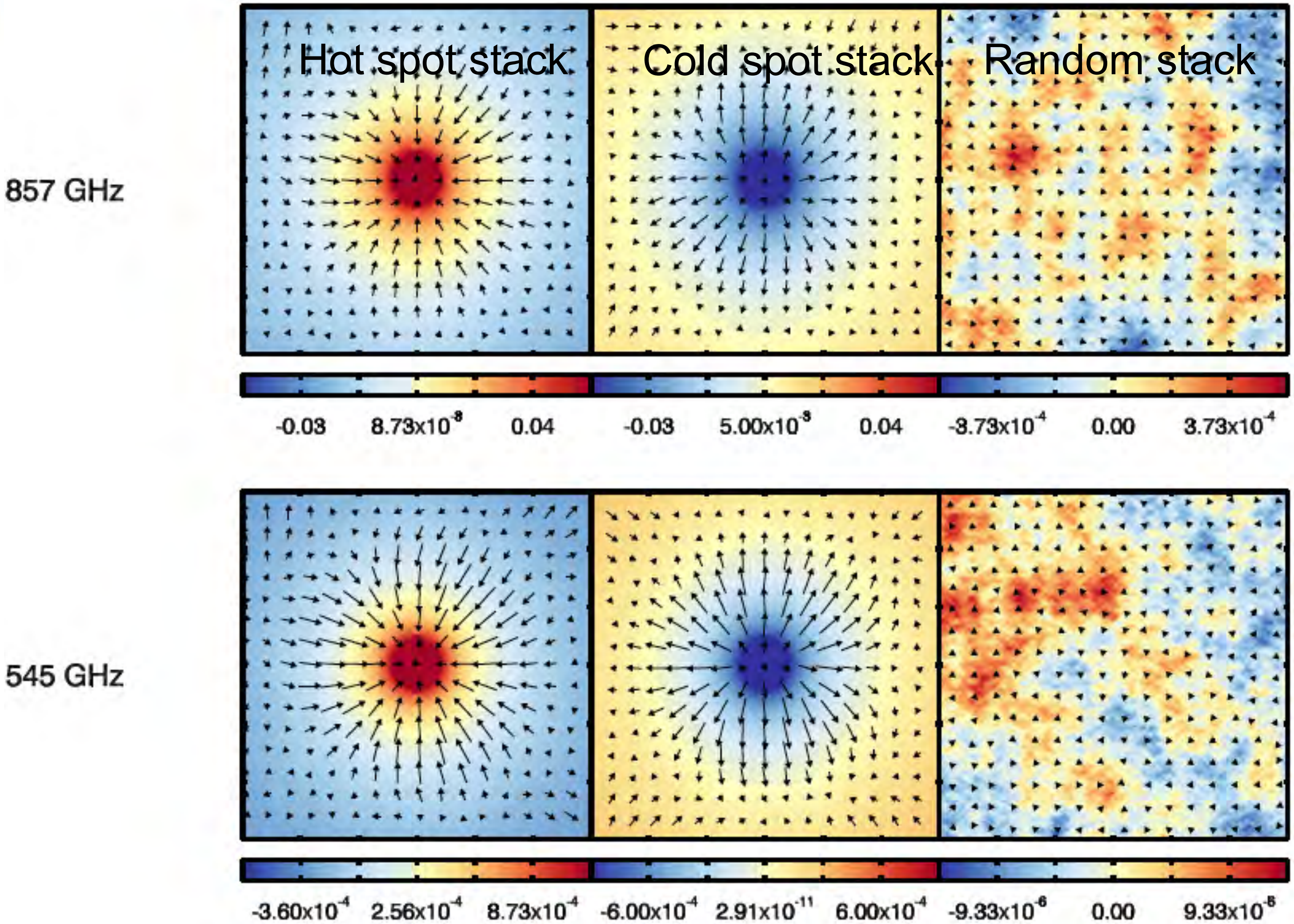
CMB Lensing - Infrared Background Correlation



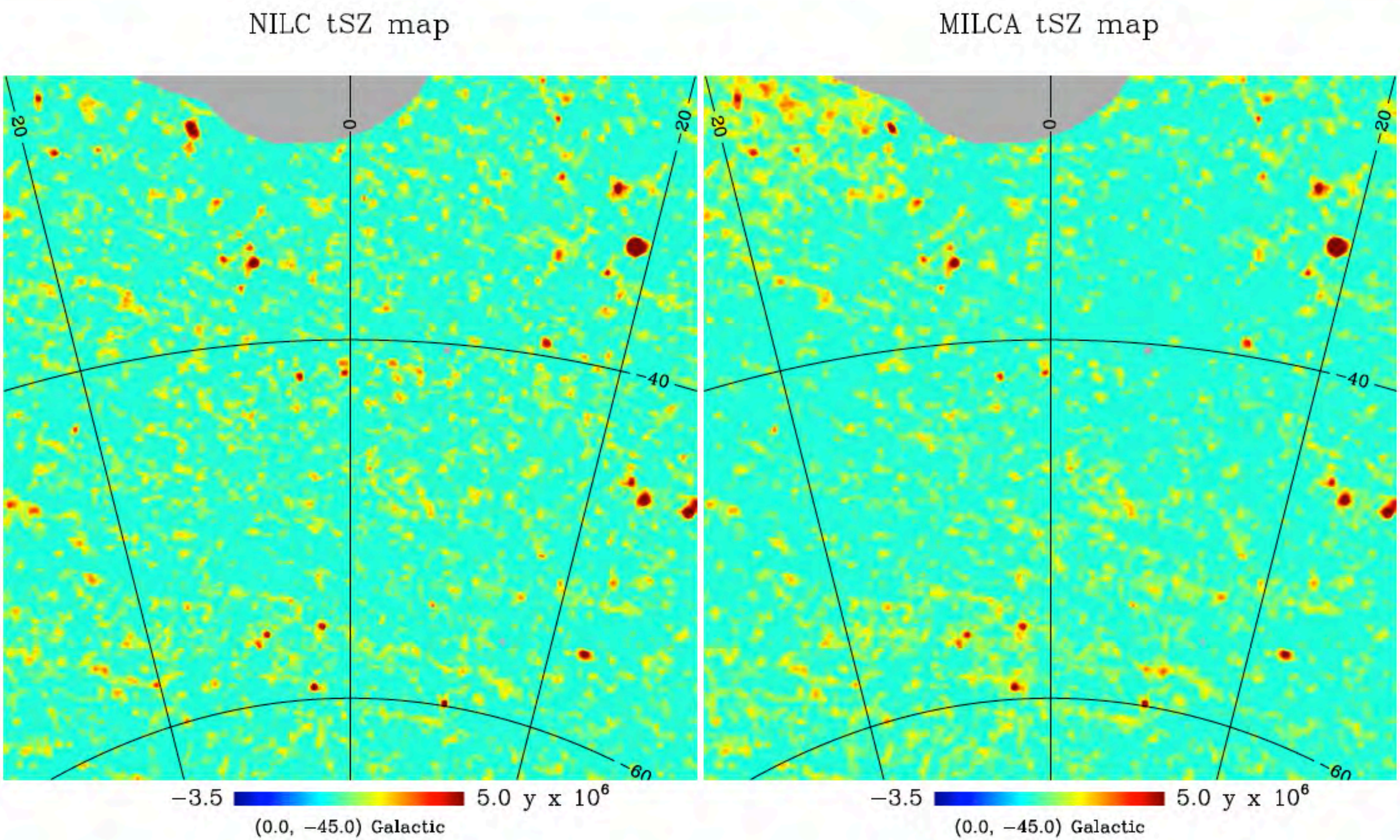
- Using Planck data alone, we report a strong correlation between the CMB lensing gravitational potential and all temperature maps at frequencies above 217 GHz.
- The detection levels reach 42σ statistical 545 GHz.
- We interpret this measurement as the correlation between the CMB lensing and the CIB.
- This is a direct detection of the total mass associated with galaxies at the time they were making most of their stars.
- Using this correlation we can thus constrain the star formation rate at high redshift.

Gorski

Lensing deflection correlates with CIB



Full Sky Thermal SZ Maps – amazing stuff



and its spectrum

Planck Collaboration: Cosmology with the all-sky *Planck* Compton parameter *y*-map

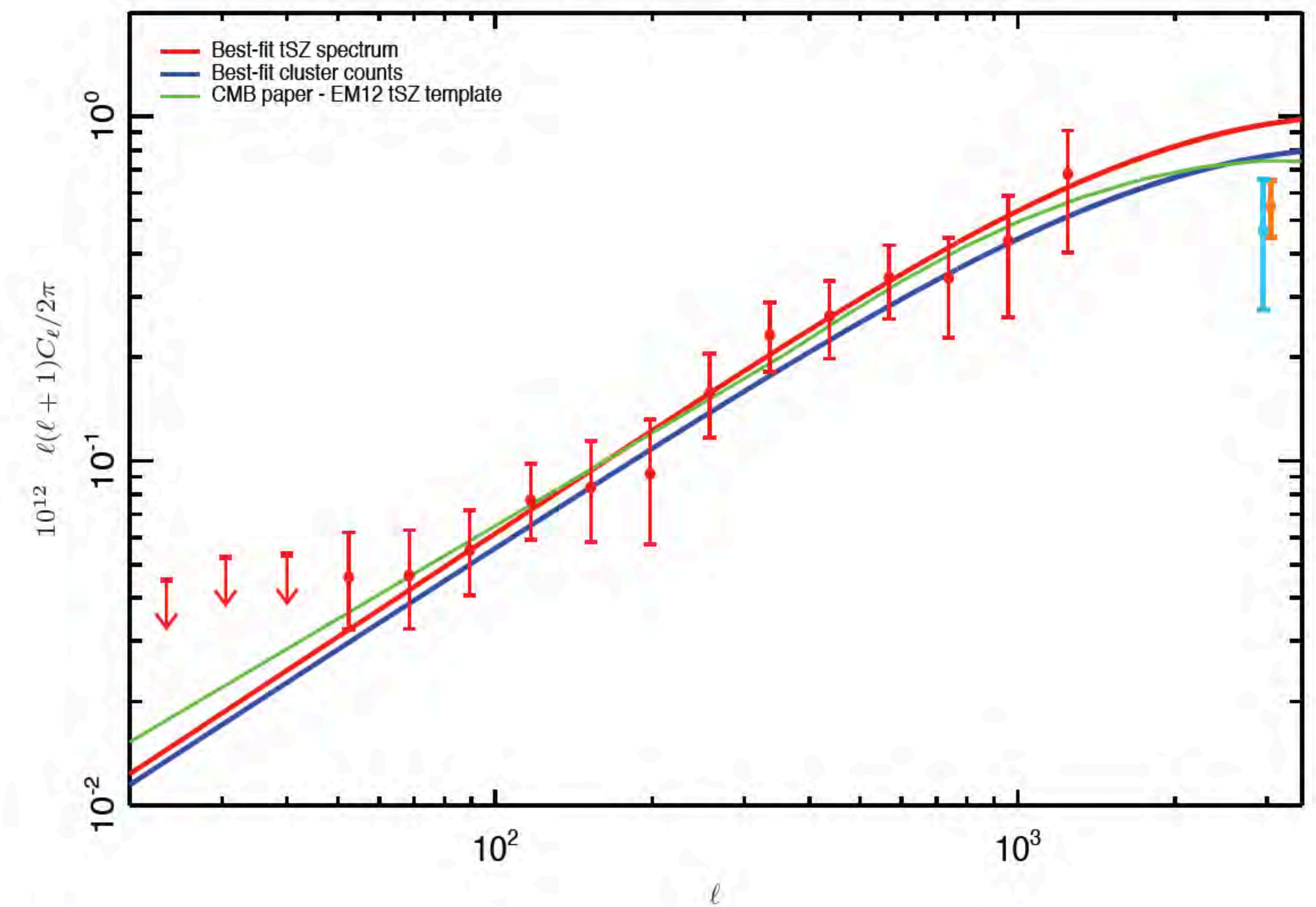
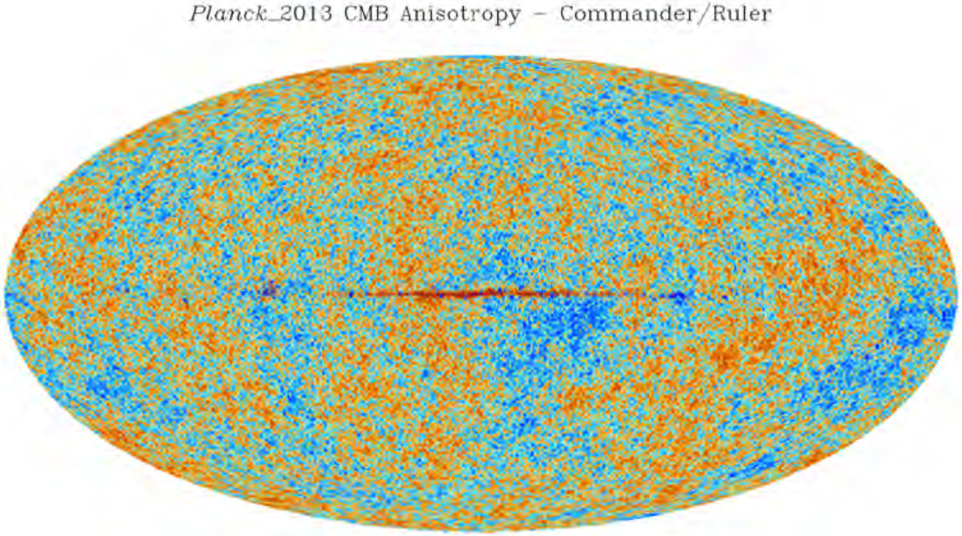
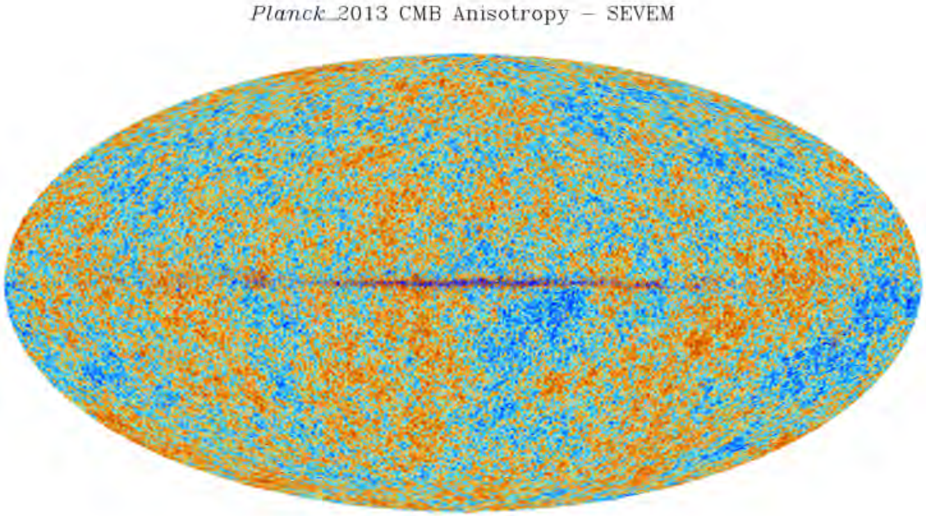


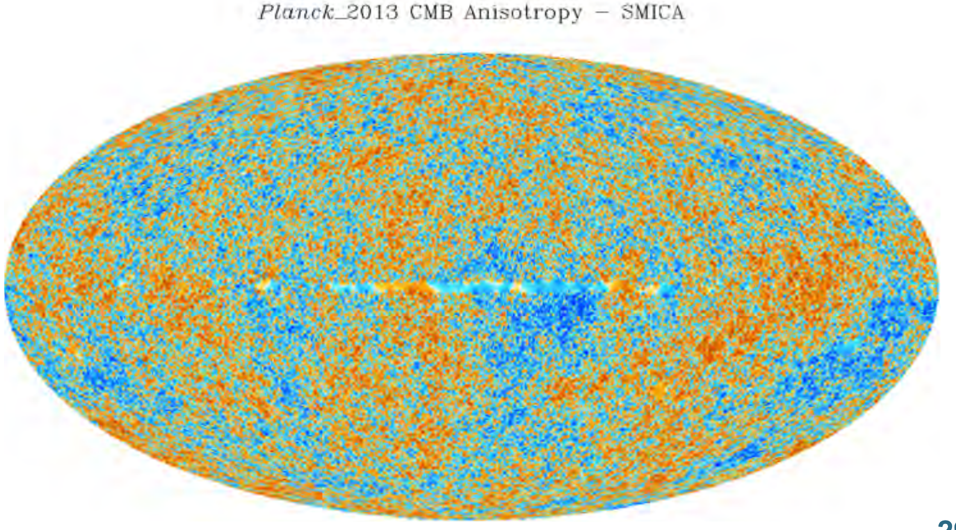
Fig. 15. Marginalized bandpowers of the *Planck* tSZ power spectrum with total (statistical plus foreground) uncertainties (red points). The red solid line represents the best-fit tSZ power spectrum model. We also show as a blue solid line the best-ft tSZ power-spectrum obtained from the analysis of cluster number counts (Planck Collaboration XX 2013). The tSZ power spectrum template used in the CMB cosmological analysis (Planck Collaboration XV 2013; Planck Collaboration XVI 2013) is presented as a green solid line.

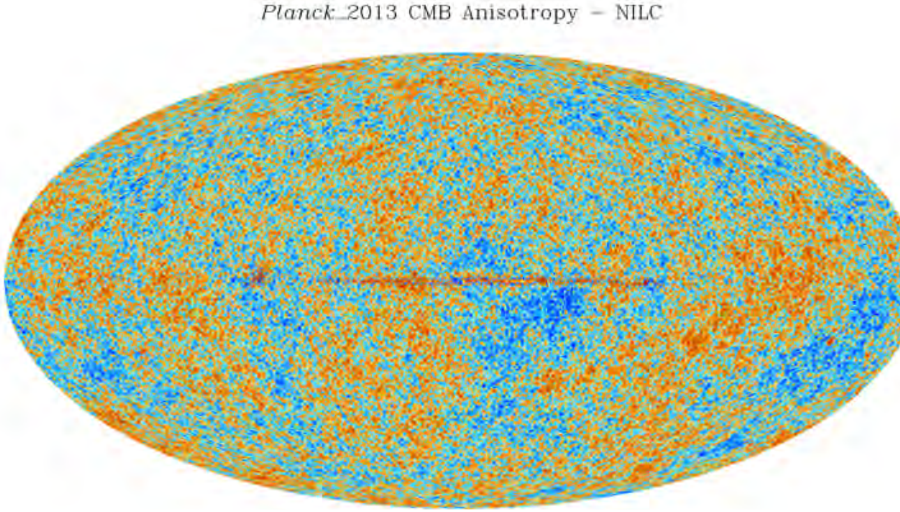
K. M. Gorski

After these two examples of Planck's power to engage in galactic astronomy let us move on to CMB anisotropy: 4 component-separation CMB solutions

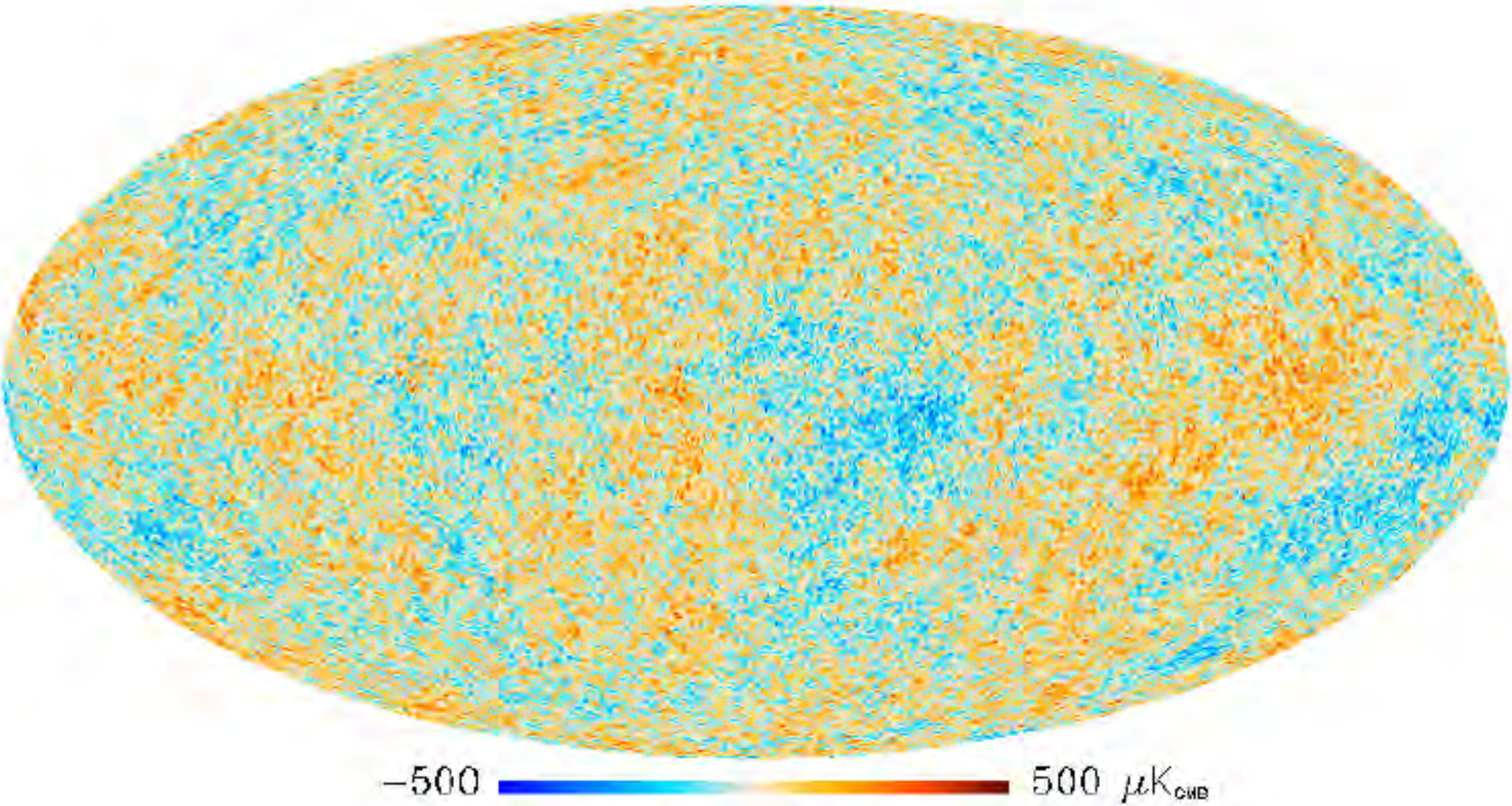






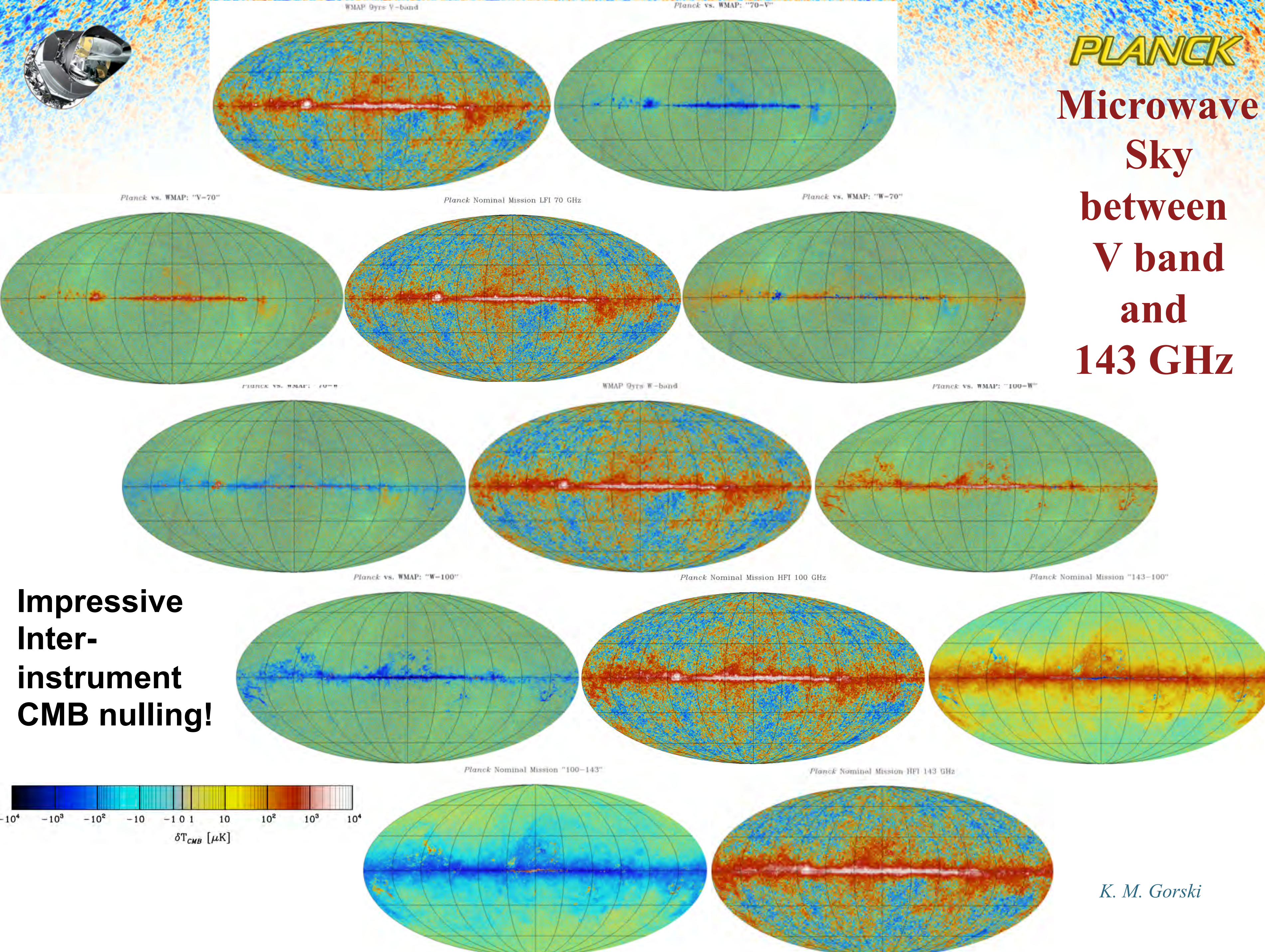


The Cosmic Microwave Background from Planck



PLANCK

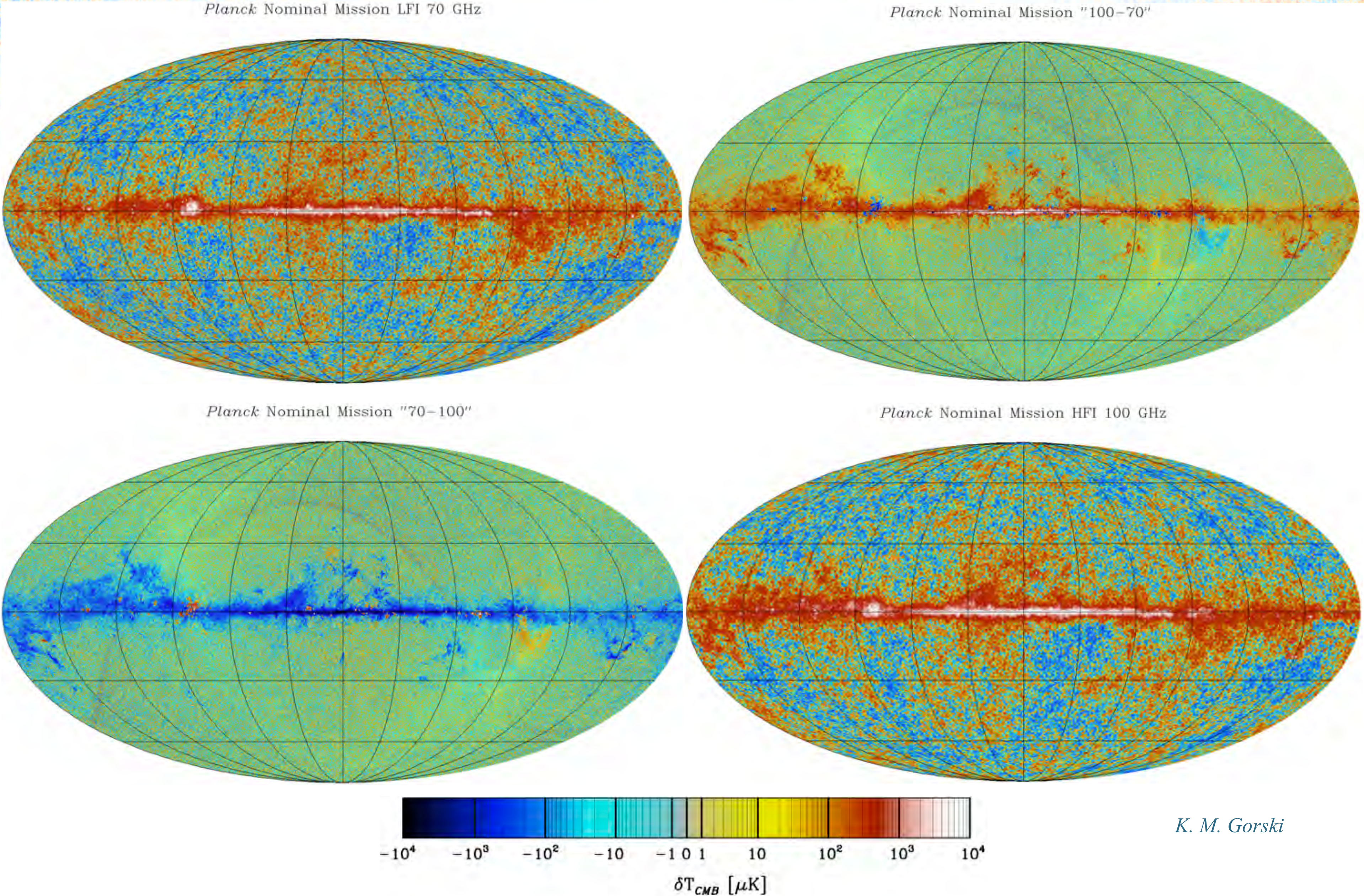
Microwave Sky between V band and 143 GHz



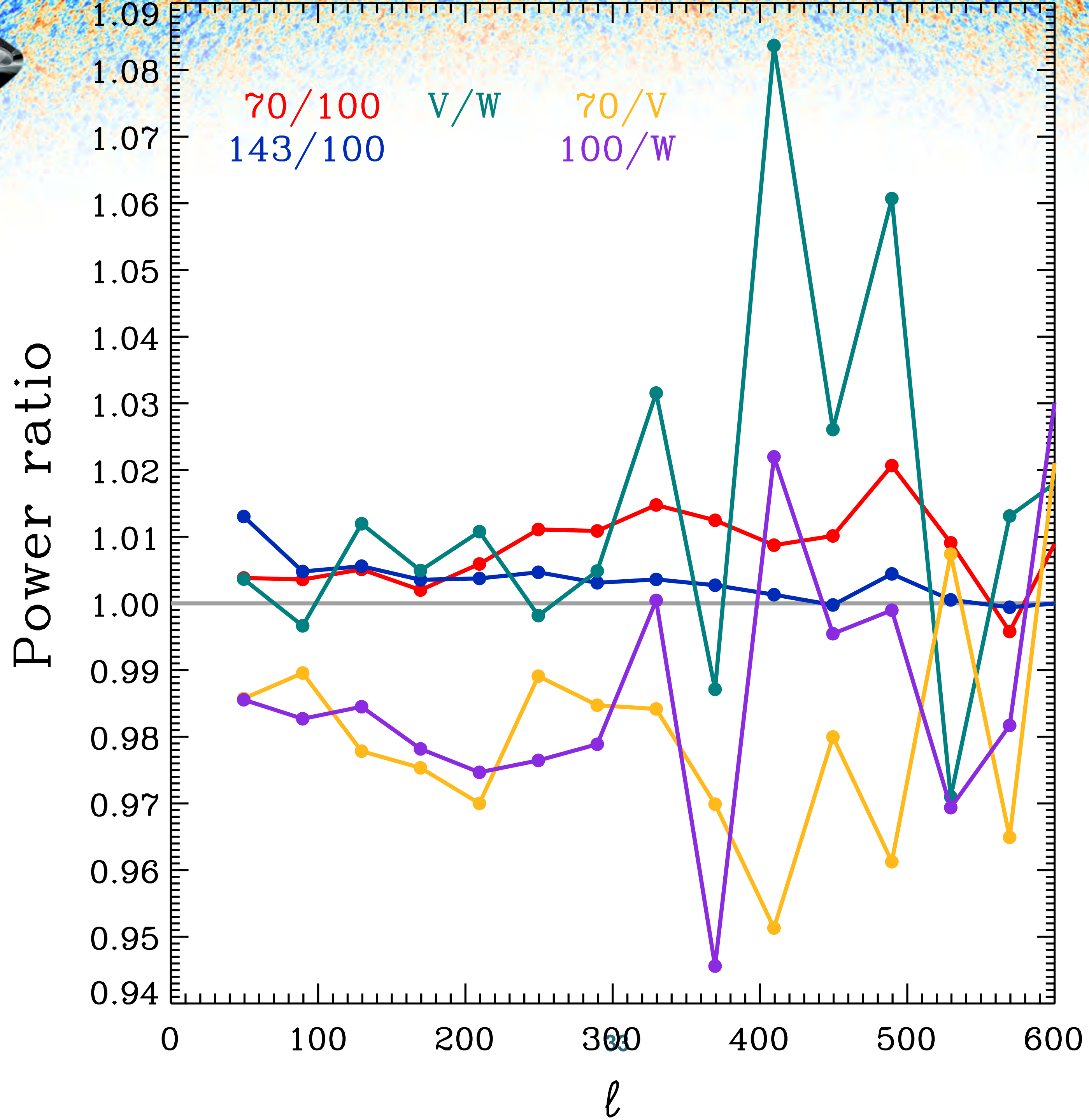
Impressive Inter-instrument CMB nulling!

K. M. Gorski

Quick look at large and intermediate angular scales: 70 vs. 100 GHz



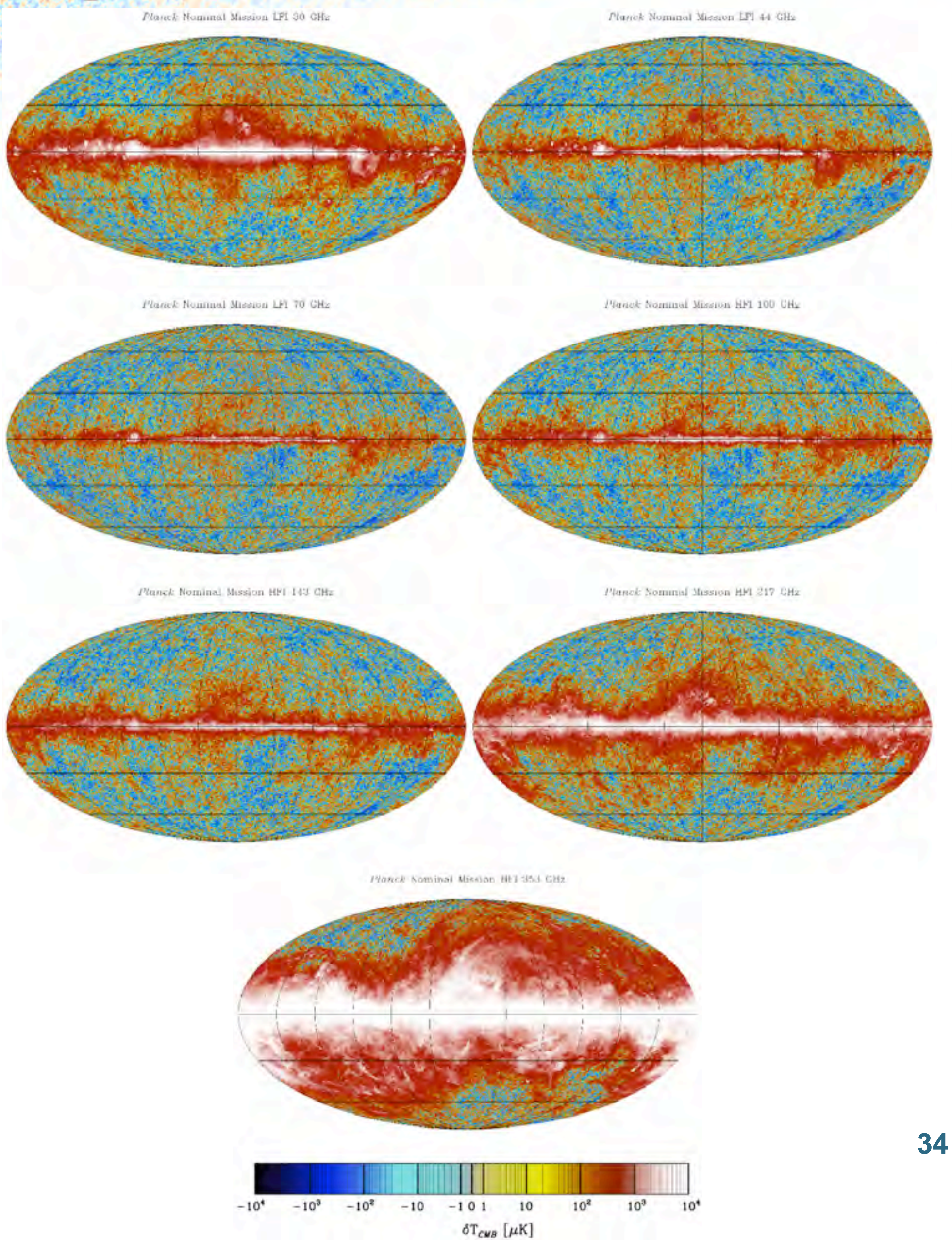
K. M. Gorski

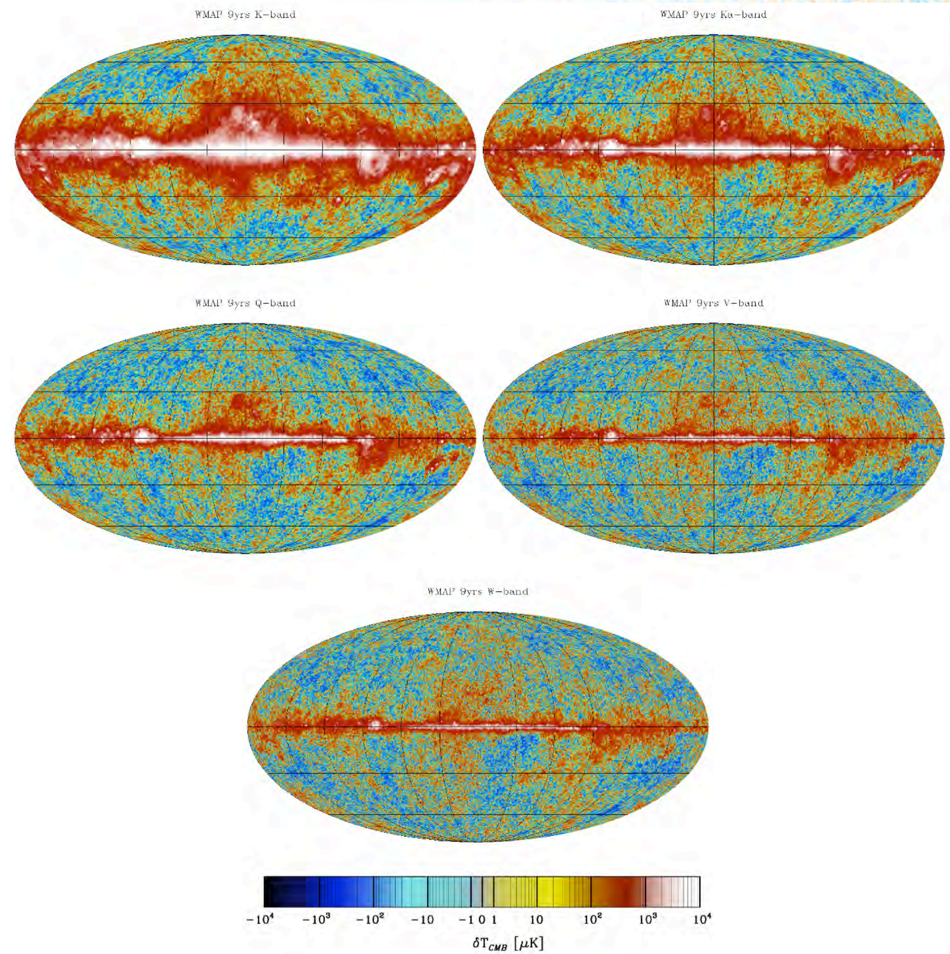


70/100
V/W
70/V
143/100
100/W
Power ratio
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0
100
200
300
400
500
600
ℓ
PLANCK

K. M. Gorski

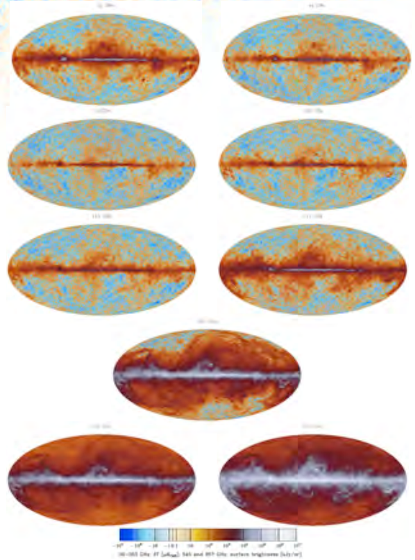
Still, eventually, the joint Planck and WMAP data set will prove indispensable, especially for improved foreground studies





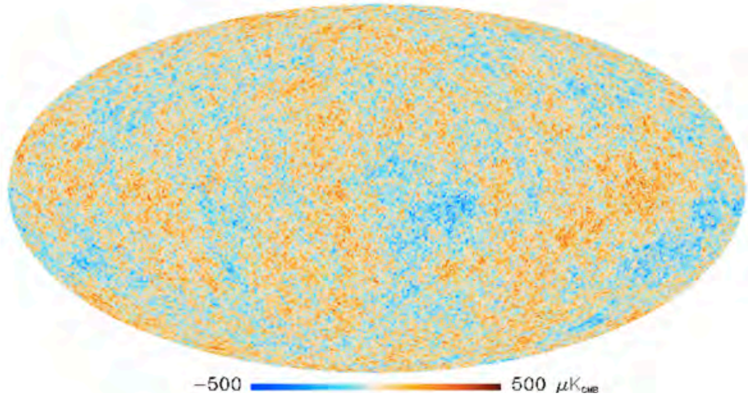
Science Extraction from the Multi-frequency CMB Sky Maps (in a Nutshell)

PLANCK



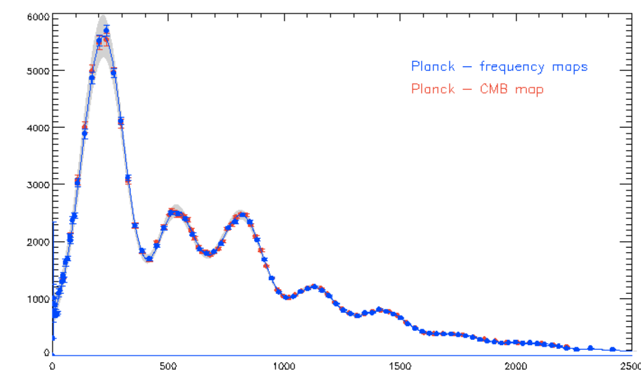
Frequency maps

Component Separation

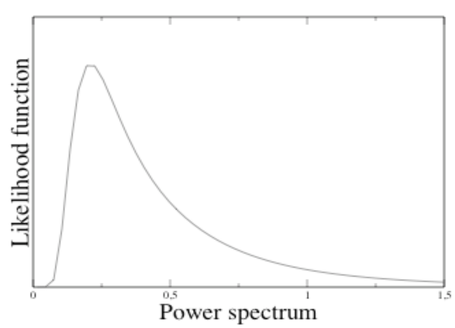


Cleaned CMB map

directly from sky maps
to the likelihood



Angular Power spectrum



Likelihood

MCMC

n_s Ω_b σ_8 Ω_0 H_0 τ

Cosmological parameters

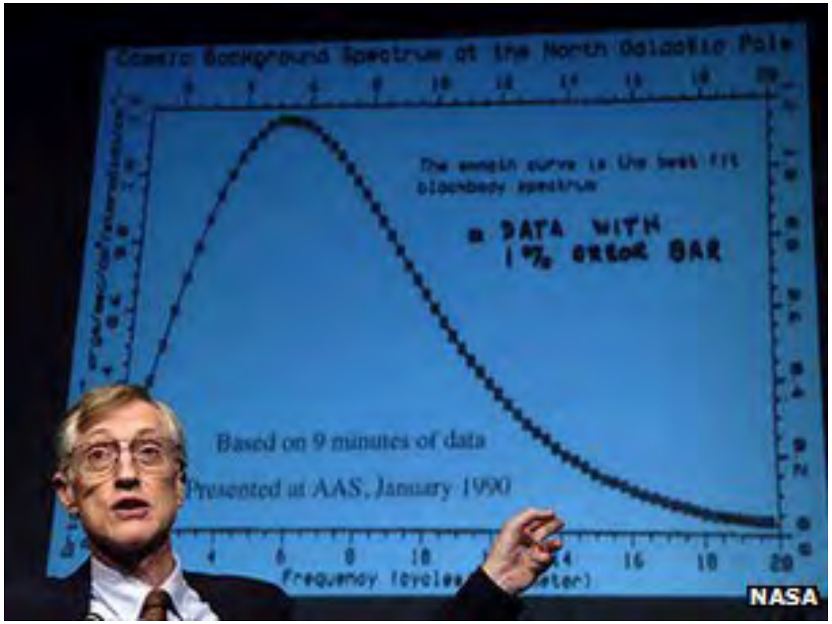
K. M. Gorski

To get us inspired ... How high is the bar?

"I'm hoping there's something surprising there for them. If they just say, 'well, other people were right' - that's not exciting; the last decimal places are never very interesting. What we want is some new phenomenon."

American **Nobel Laureate John Mather** believes the bar has been set very high for the **European Space Agency's (Esa) Planck surveyor**.

From
“The first fractions of a second after the Big Bang”
by Jonathan Amos
on
BBC NEWS Science & Environment;
March 18, 2013



"Planck has the extra sensitivity and resolution to retrieve yet more information," the Nasa scientist told BBC News. "The question then is: have they done the right things with the data?"

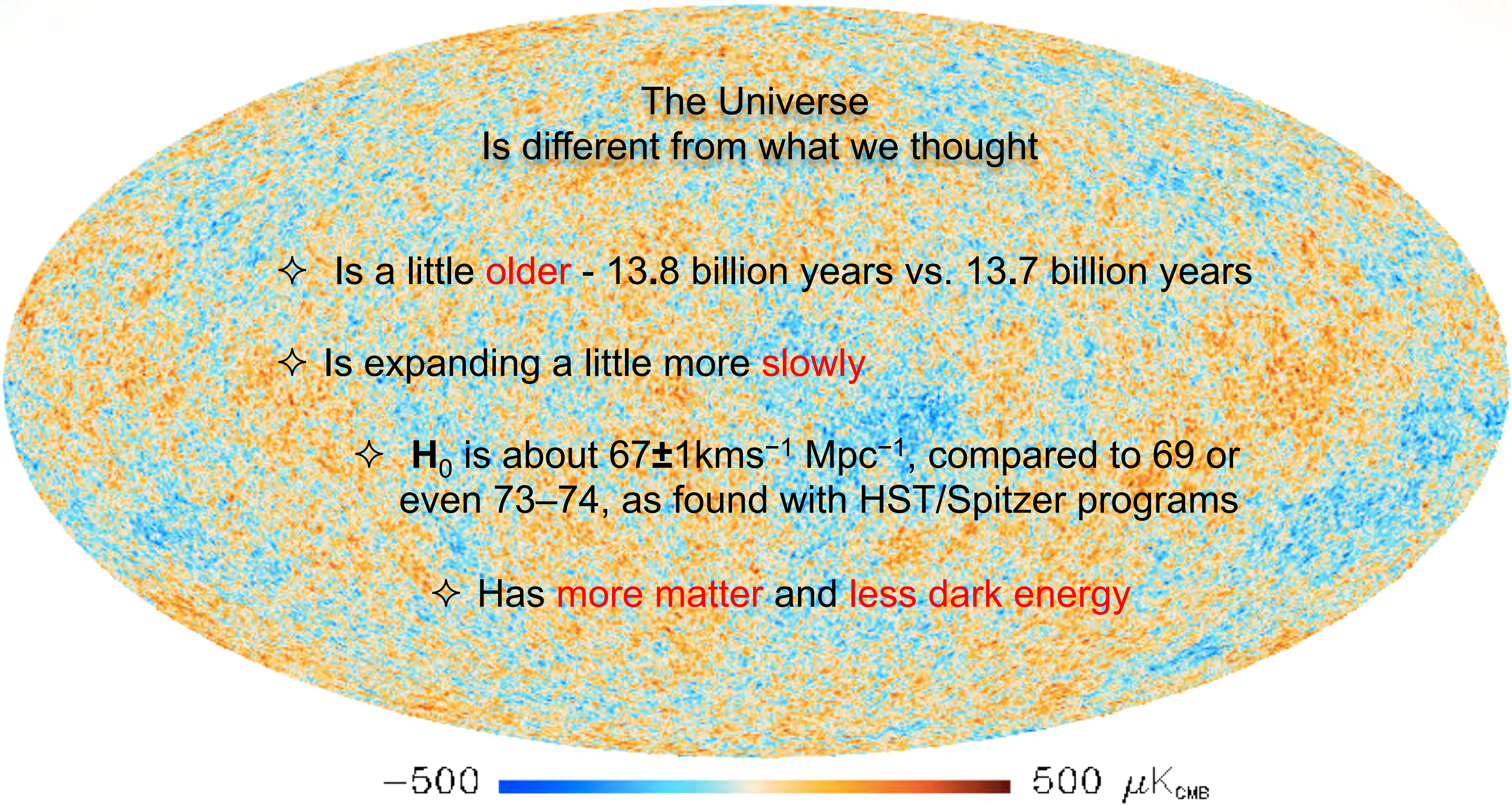
The European team behind Planck will present maps of the sky in nine frequencies - six more than COBE, and three more than its **US successor, WMAP, which flew in 2001**.

What Have We Learned from Planck in a Few Words?

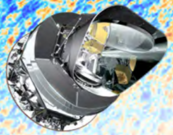
PLANCK

The Universe
Is different from what we thought

- ✧ Is a little older - 13.8 billion years vs. 13.7 billion years
- ✧ Is expanding a little more slowly
  - ✧ $\mathbf{H_0}$ is about 67±1kms^{-1} Mpc^{-1}, compared to 69 or even 73–74, as found with HST/Spitzer programs
- ✧ Has more matter and less dark energy



K. M. Gorski



But then we knew we really made it (forget NYT) when …

PLANCK

97°

Winter blahs transitioning into spring blahs

the ONION®
America's Finest News Source

VIDEO · POLITICS · SPORTS · BUSINESS · SCIENCE/TECH · ENTERTAINMENT

Universe Older, Wider Than Previously Thought

AMERICAN VOICES · **Opinion** · **ISSUE 49•12** · Mar 22, 2013

171 86 4

Astronomers determined that the universe is actually 13.8 billion years old, about 80 to 100 million years older than previously believed, and that it is also a bit wider than once thought. What do *you* think?

"How embarrassing."

Victoria Rosegard –
Street Cleaner

"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

Francois Jenevein –
Hide Trimmer

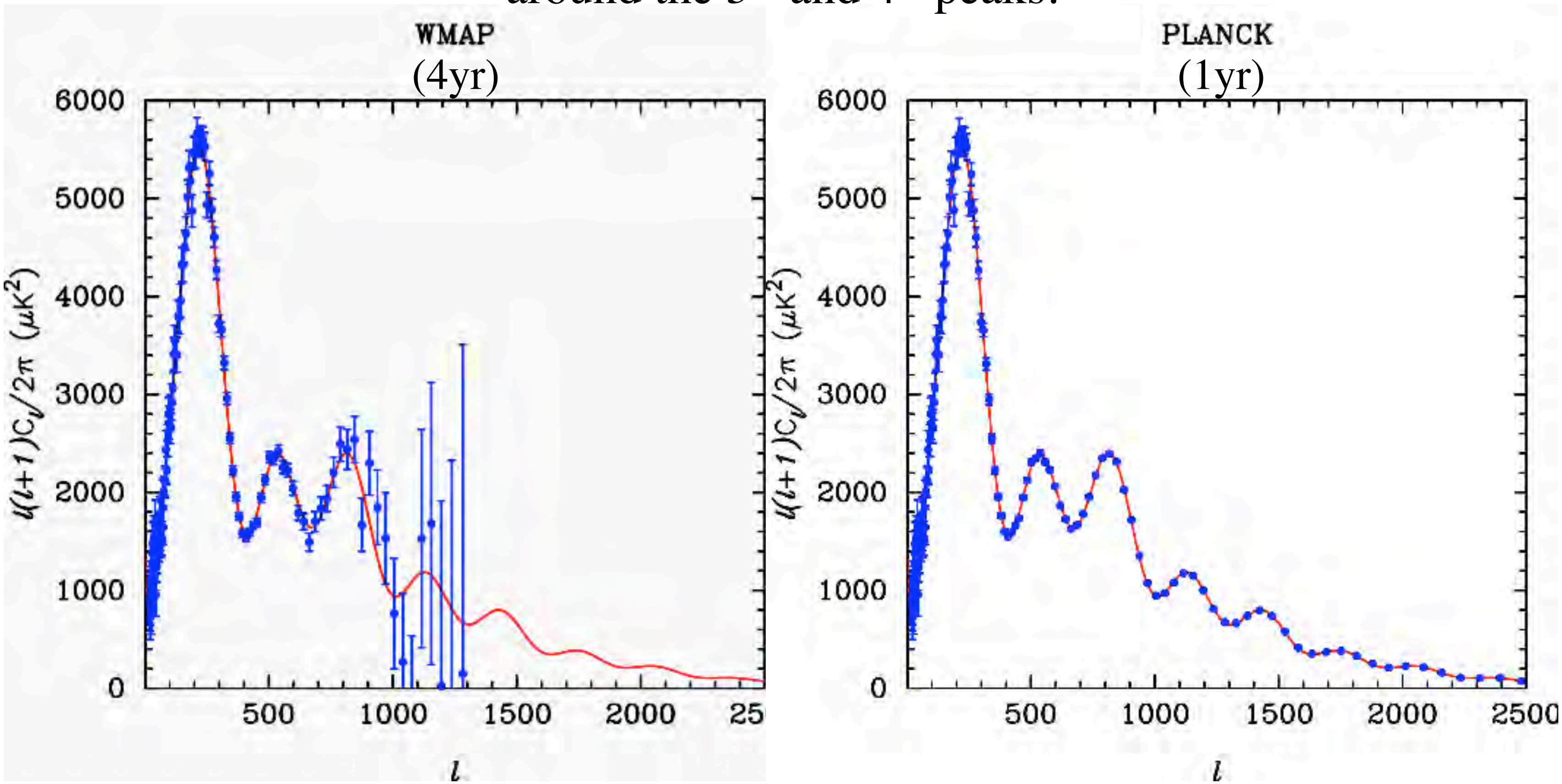
"Just like it says in Leviticus."

Chris Vanderhorst –
Systems Analyst

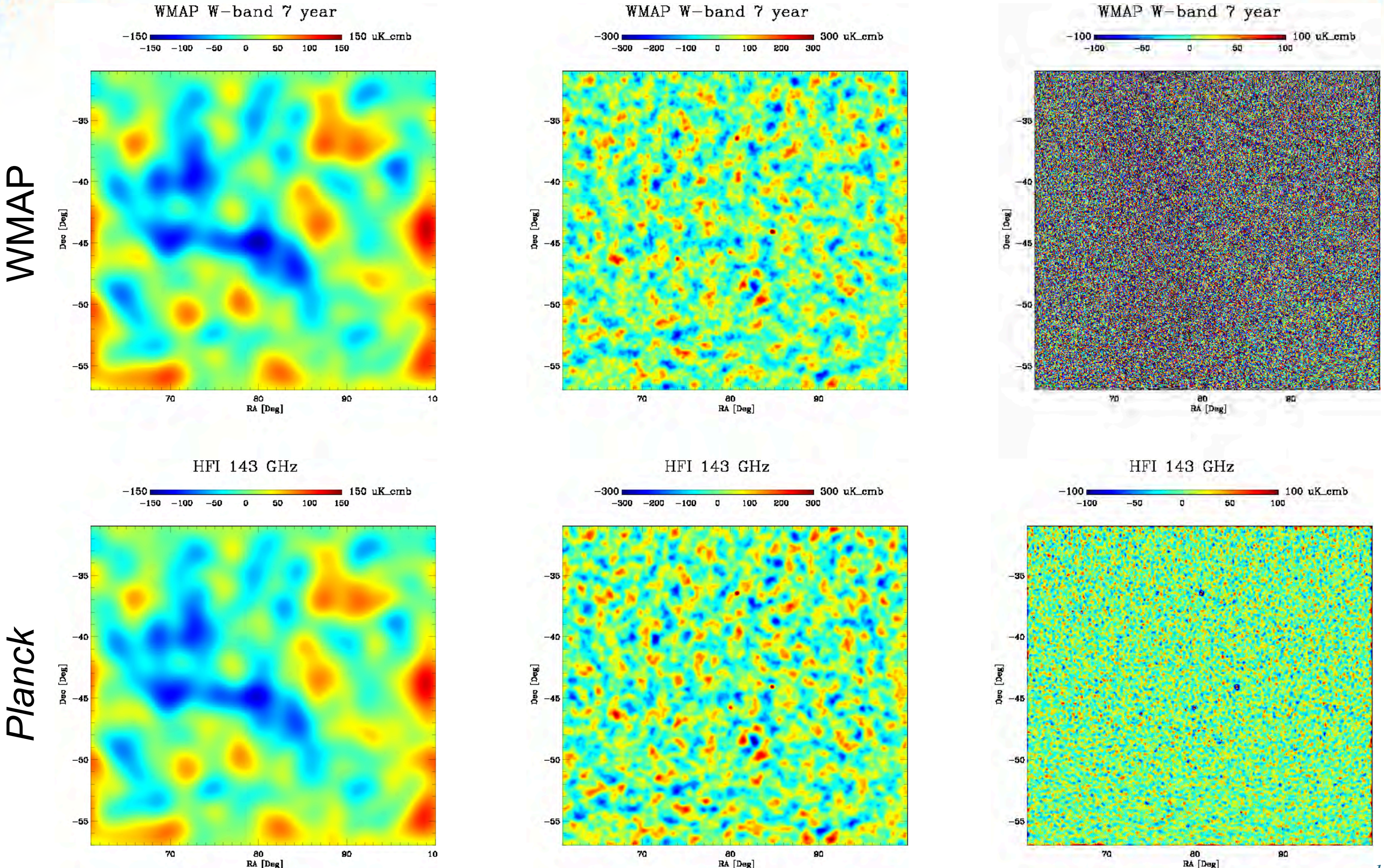
K. M. Gorski

What (we expectED) Planck will add: Primary CMB

In addition to wider frequency coverage and better sensitivity than WMAP, Planck has the resolution needed to see into the damping tail. It will be the first experiment to make a cosmic variance limited measurement of the scales around the 3rd and 4th peaks.

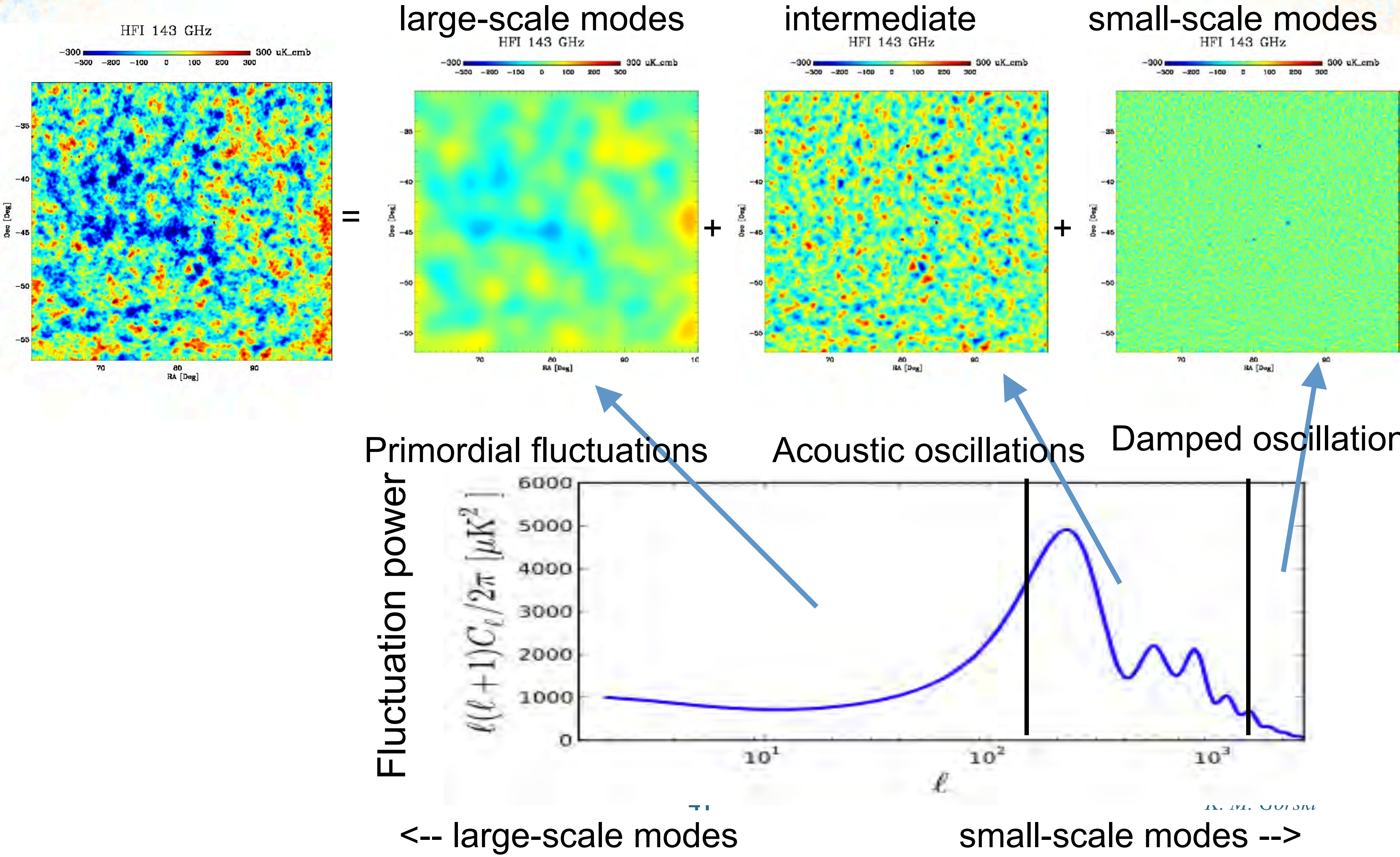


Even if it (the damping tail) shows modestly on the large scale maps …

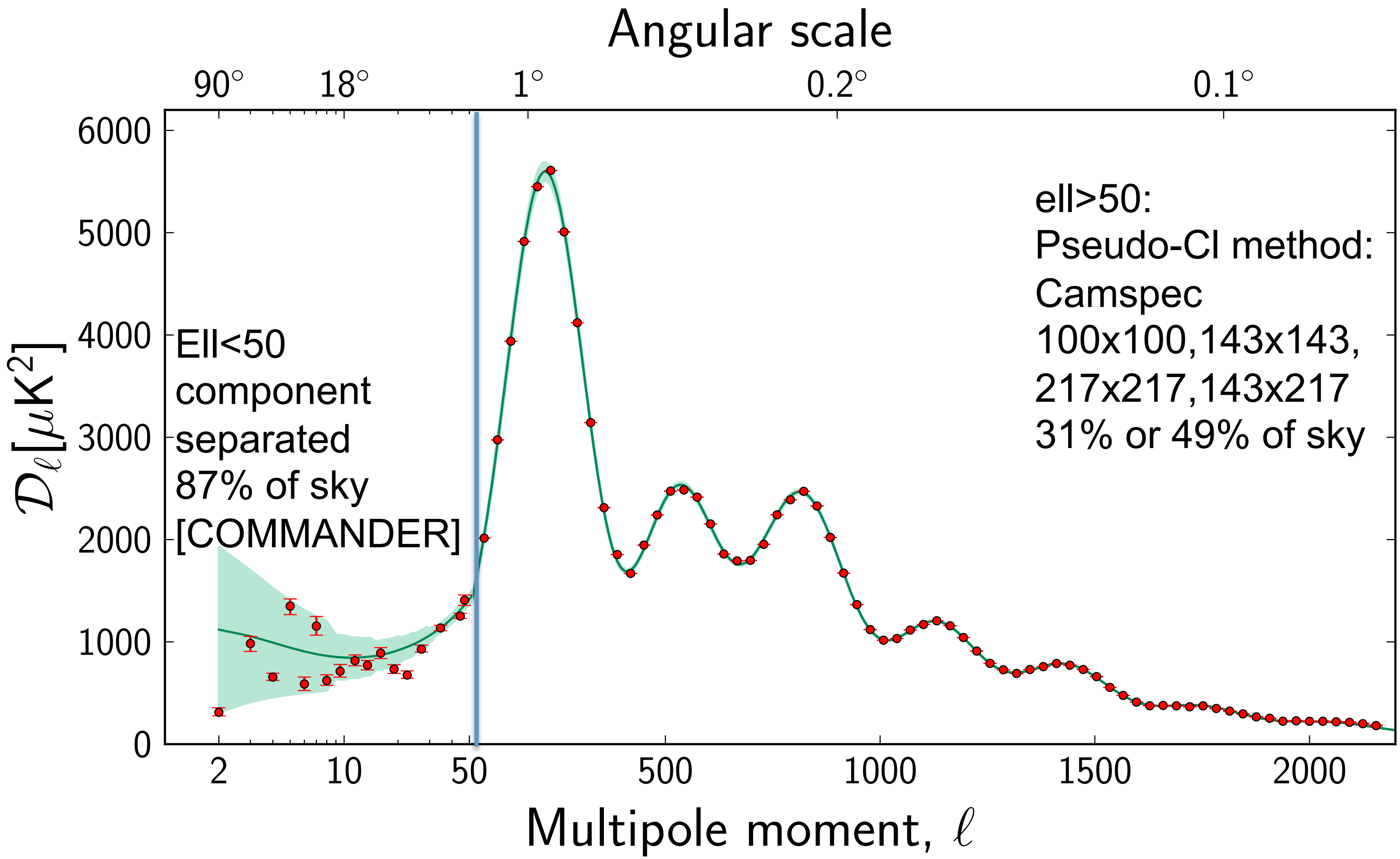


ki

It is there, and the angular power spectrum is, of course, the tool to use in this regime

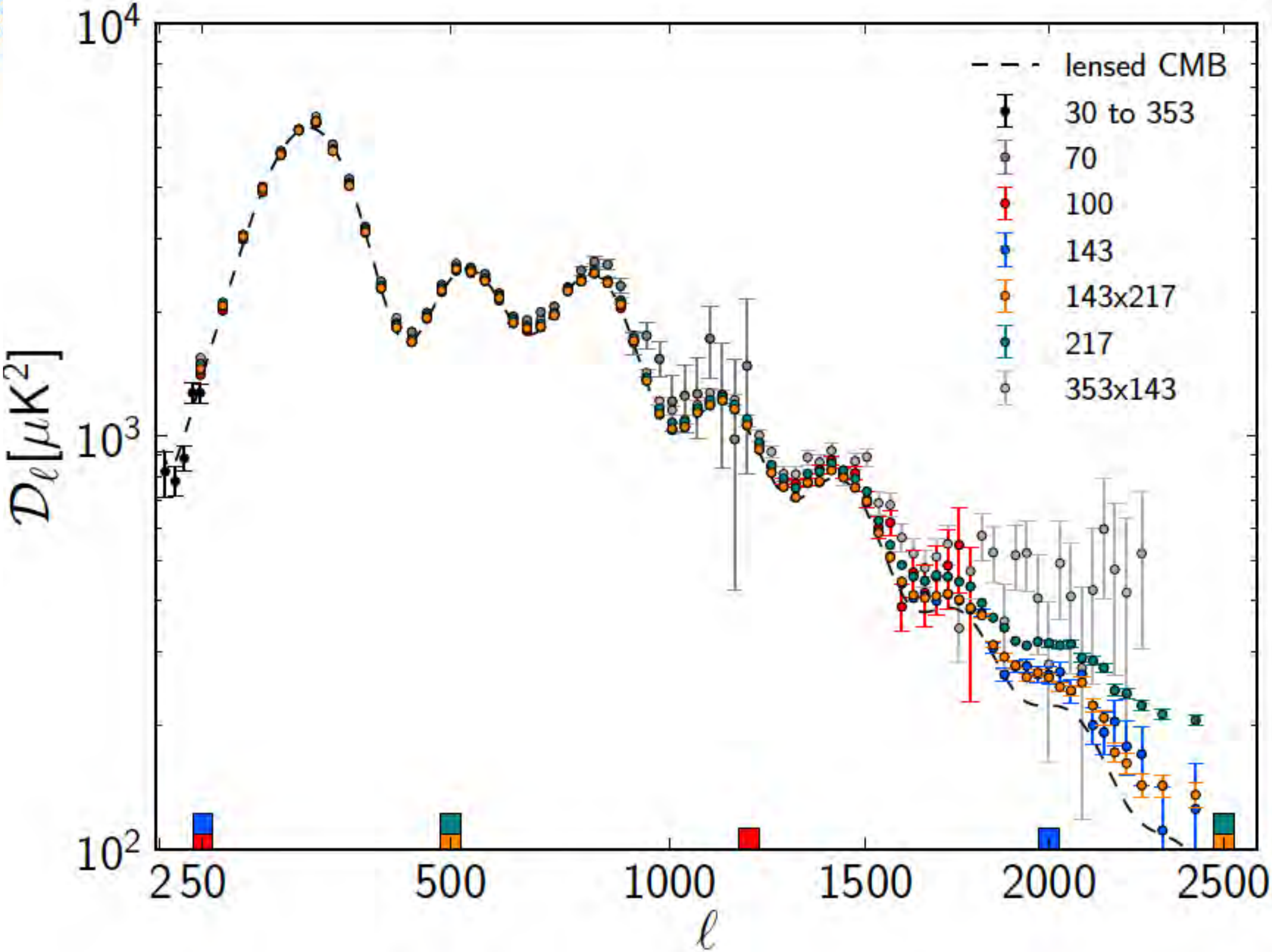


Planck's CMB angular power spectrum

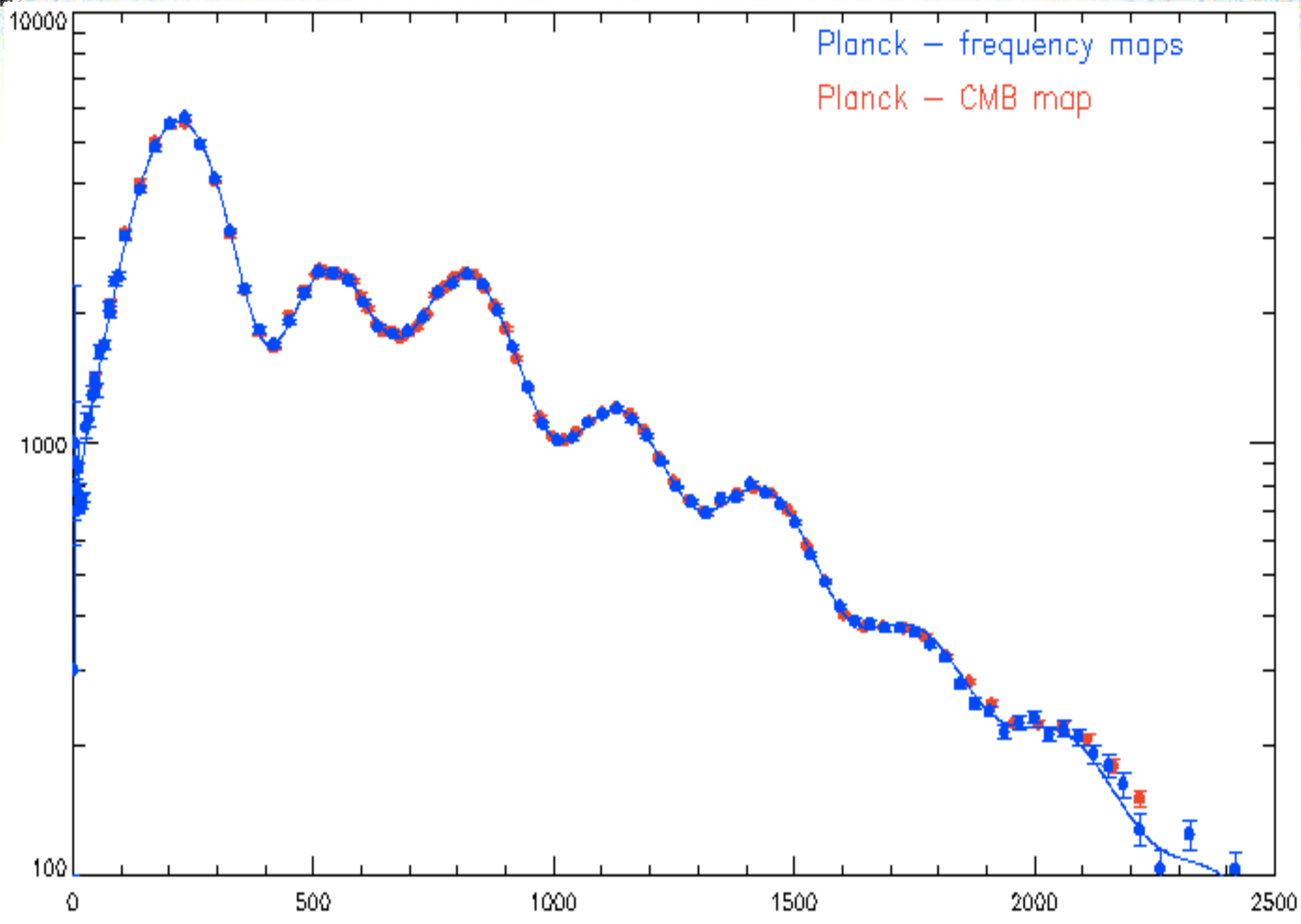


K. M. Gorski

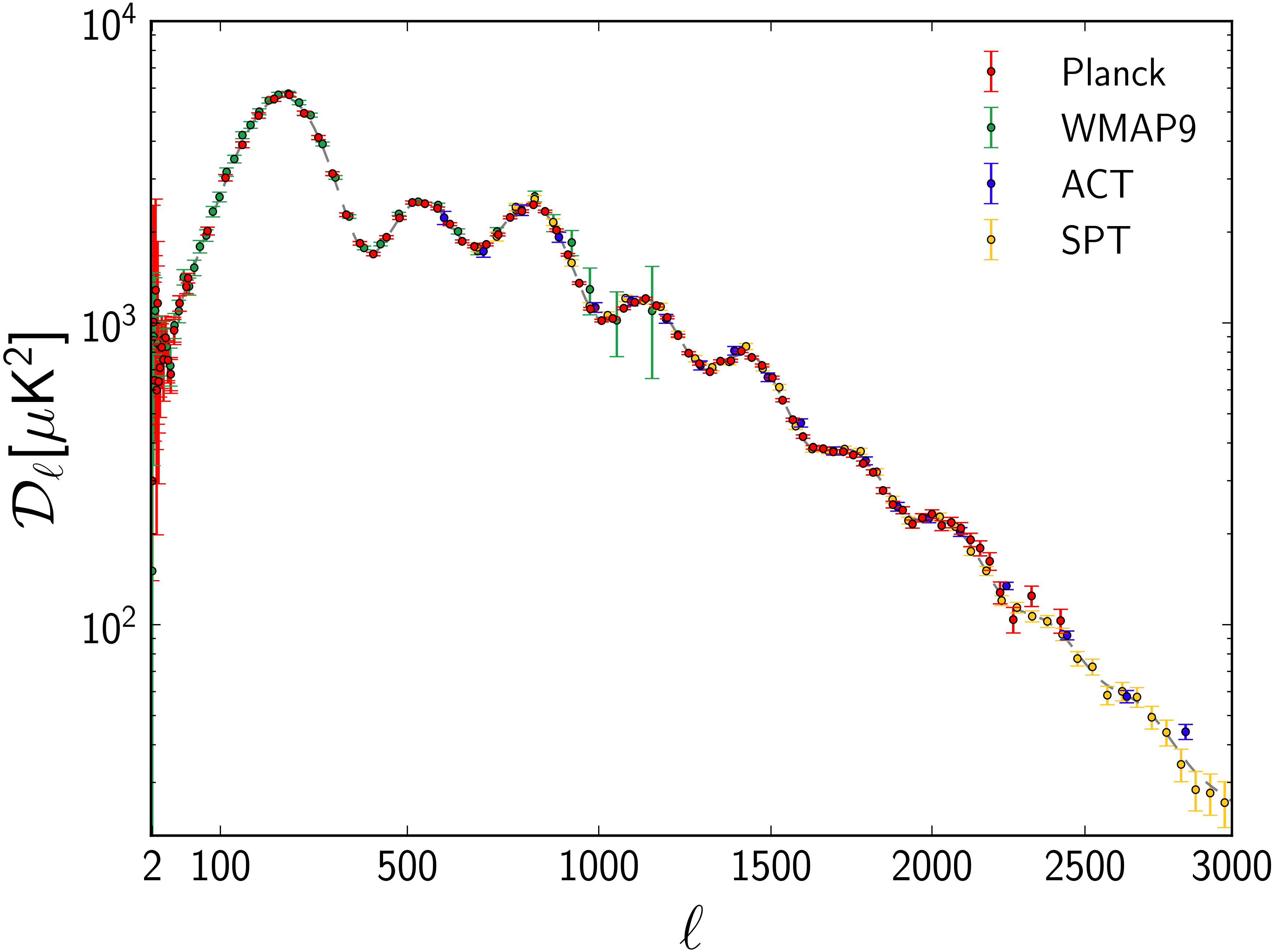
Spectral consistency frequency to frequency



Planck dT/T spectrum derived via VERY different methods

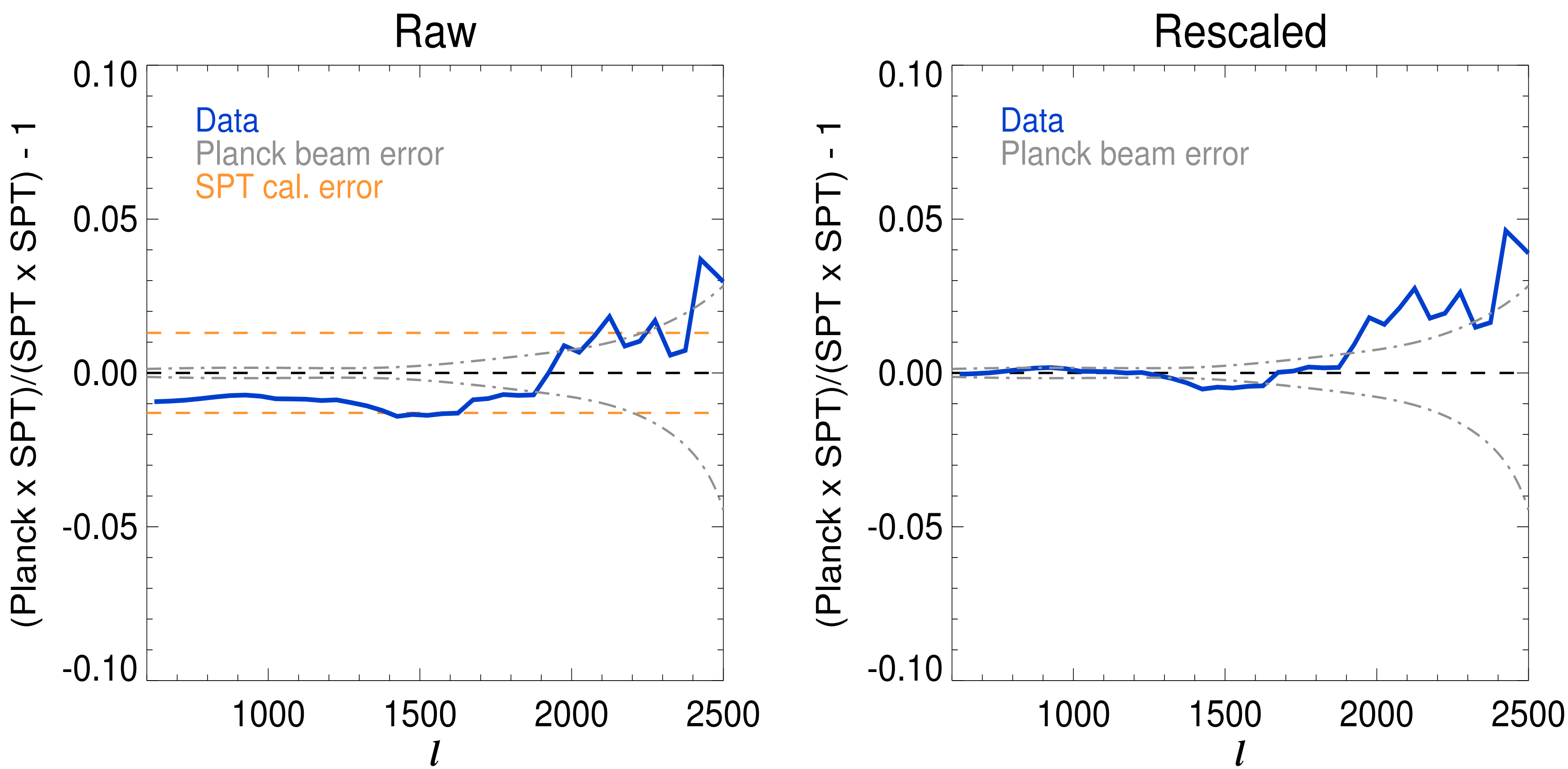


dT/T spectra measured by different experiments



Planck vs. SPT

When SPT is calibrated to Planck the agreement is excellent



K. M. Gorski

6 parameters + inflation + general relativity + E&M : all you need to describe the Universe (ΛCDM)

A_s, n_s

Governs Spectrum of primordial fluctuations from inflation

$\rho_b = \Omega_b h^2$

$\rho_\Lambda = \Omega_\Lambda h^2$

$\rho_c = \Omega_c h^2$

Content of the universe:

Baryons, dark energy, dark matter

(total density = critical density)

a_{reion}

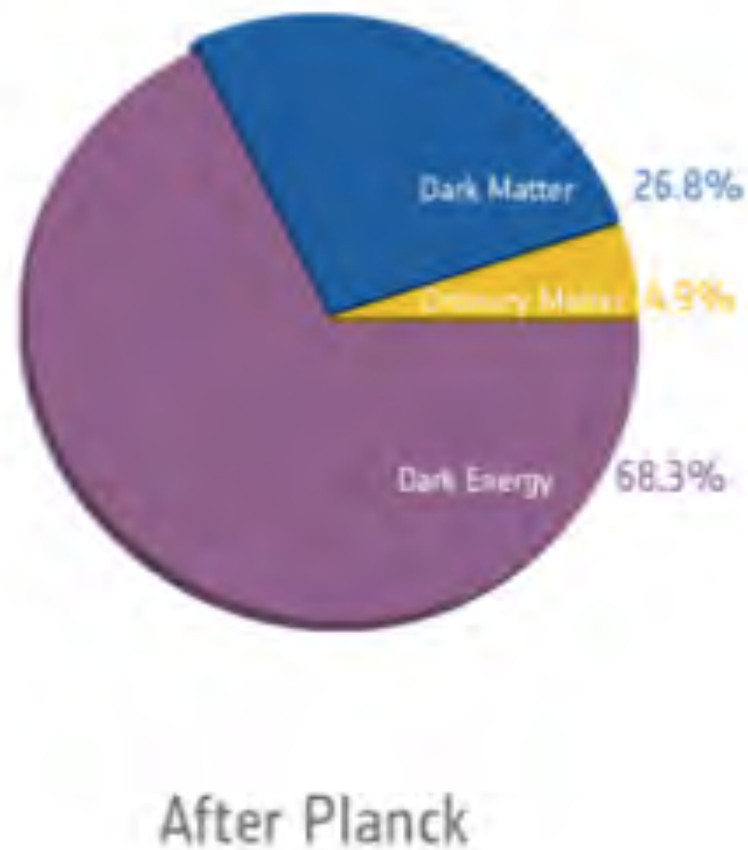
Scale factor at reionization:

(when star formation started)

ΛCDM model parameters from Planck

The Universe

Has more matter and less dark energy



$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

$$\Omega_c h^2 = 0.1199 \pm 0.0027$$

$$n_s = 0.9603 \pm 0.0073$$

$$\ln(10^{10} A_s) = 3.089 \pm 0.025$$

$$100\theta = 1.04131 \pm 0.00063$$

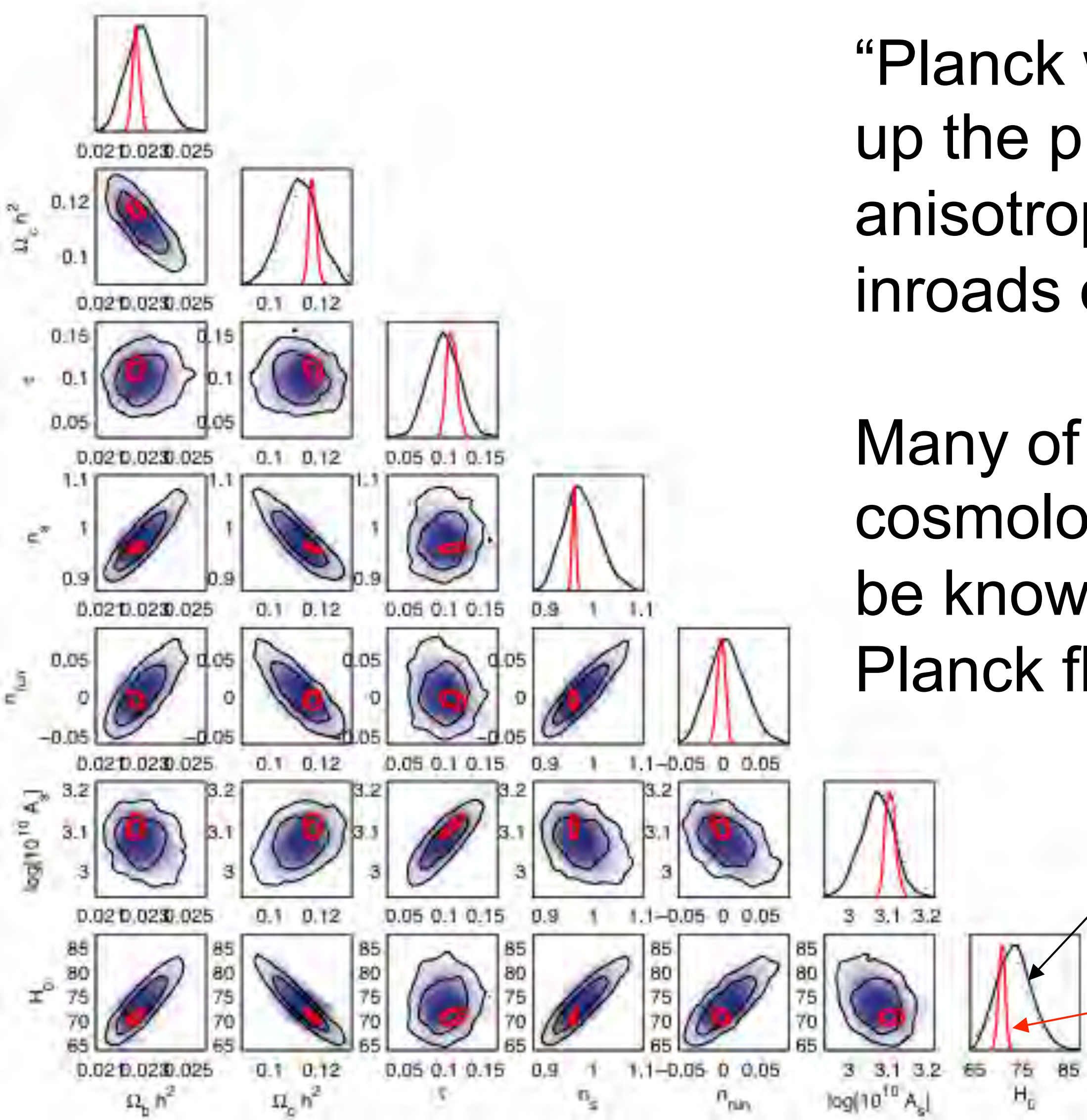
$$H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Age = 13.81± 0.05 billion years

Consistent with spatial flatness to % level

A dramatic advance
(again, a quote from the Blue Book forecast)

Planck blue book



"Planck will essentially clean up the primary temperature anisotropies and make great inroads on polarization.

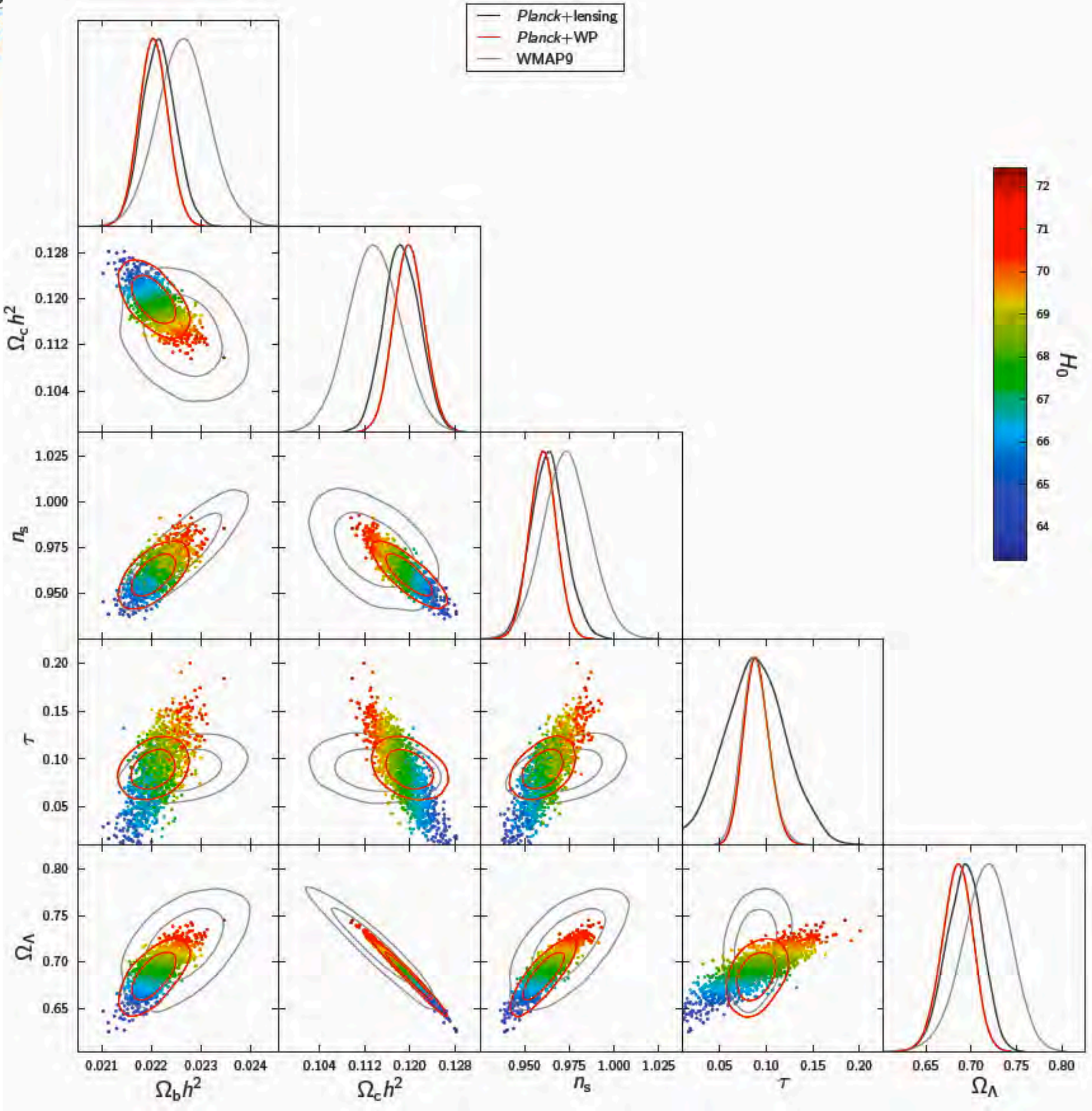
Many of the most important cosmological parameters will be known *much* better after Planck flies."

Projected WMAP likelihood on Hubble constant

Projected Planck likelihood

K. M. Gorski

ΛCDM model parameters from Planck - 2d and 1d marginal distributions



Spatially flat 6-parameter ΛCDM Cosmology with a power law spectrum of adiabatic scalar primordial perturbations

$$P_R(k) = A_s \left(\frac{k}{k_0} \right)^{n_s}$$

(or with spectral running:

$$P_R(k) = A_s \left(\frac{k}{k_0} \right)^{n_s - 1 + (1/2 (dn_s/d\ln k) \ln(k/k_0))}$$

if supported by data …)

K. M. Gorski

Extensions to ΛCDM model

PLANCK

Potential new physics ?

The Universe

- ✧ No evidence *so far* for a time-varying dark energy

$$w = -1.13 \pm 0.24 \qquad 95\%$$

- ✧ No evidence for new types of ultralight particles such as neutrinos

$$N_{eff} = 3.3 \pm 0.27 \qquad \sum m_\nu < 0.23 eV$$

- ✧ No evidence for variations of the fundamental constants of nature, e.g.

$$\alpha / \alpha_0 = 0.9936 \pm 0.0043 \qquad 68\%$$

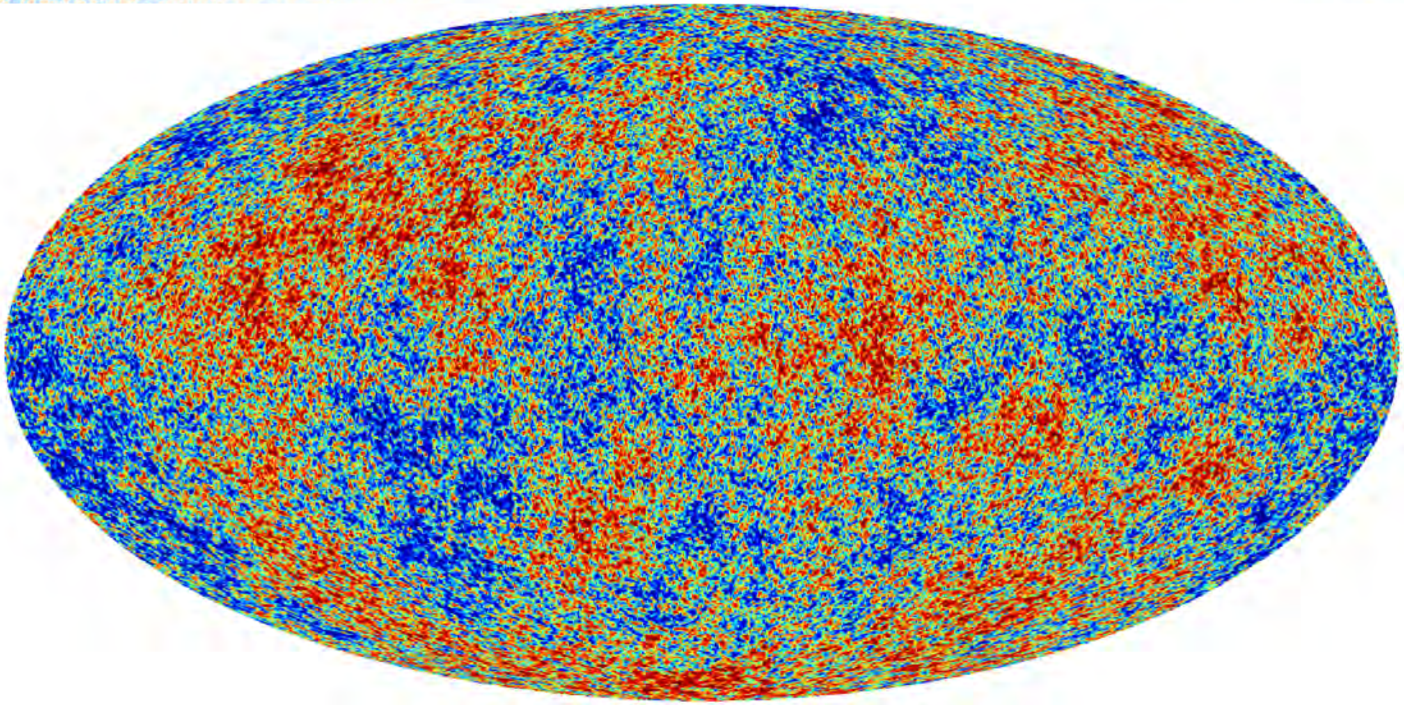
- ✧ No evidence *yet* for primordial gravitational waves $r < 0.11$

- ✧ Fluctuations are random (Gaussian)

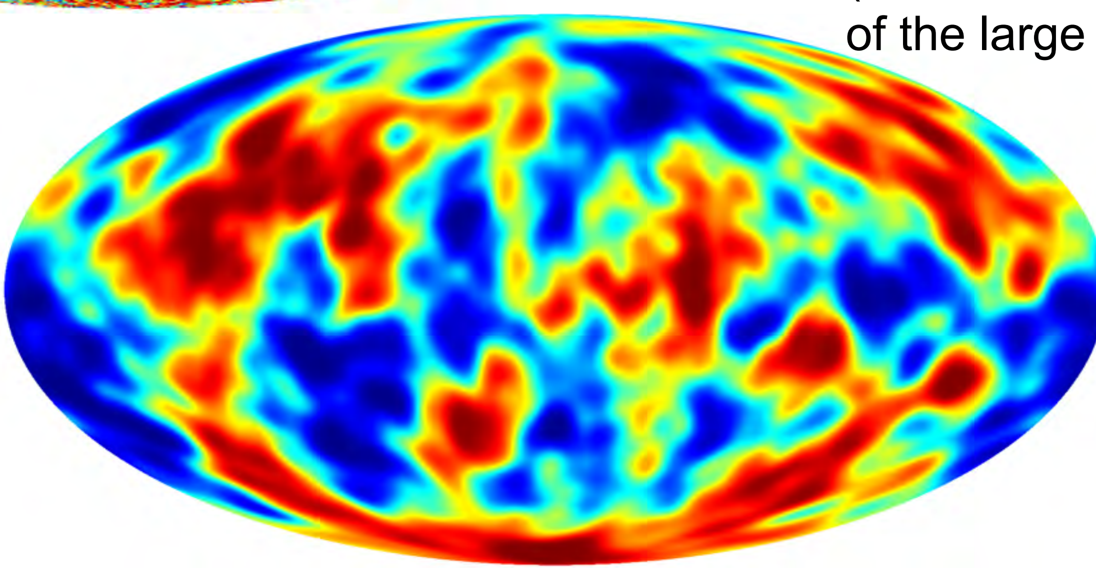
−500 500 μK_{CMB}

K. M. Gorski

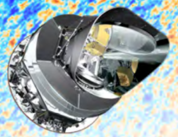
Where are those primordial fluctuations in the CMB anisotropy maps that we are looking at …



For this “Planck-like” CMB anisotropy map the primordial content of only the ~scale-invariant, Gaussian distributed, curvature perturbations would lead to a dT/T imprint shown below (note the same phases of the large angle dT/T)



I. Gorski



Inflation has a few variants …

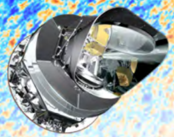
PLANCK

- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- B-inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke inflation
- bulky brane inflation
- chaotic inflation
- chaotic hybrid inflation
- chaotic new inflation
- Chromo-Natural Inflation
- D-brane inflation
- D-term inflation
- dilaton-driven inflation
- dilaton-driven brane inflation
- double inflation
- double D-term inflation
- dual inflation
- dynamical inflation
- dynamical SUSY inflation
- S-dimensional assisted inflation
- eternal inflation
- extended inflation
- extended open inflation
- extended warm inflation
- extra dimensional inflation

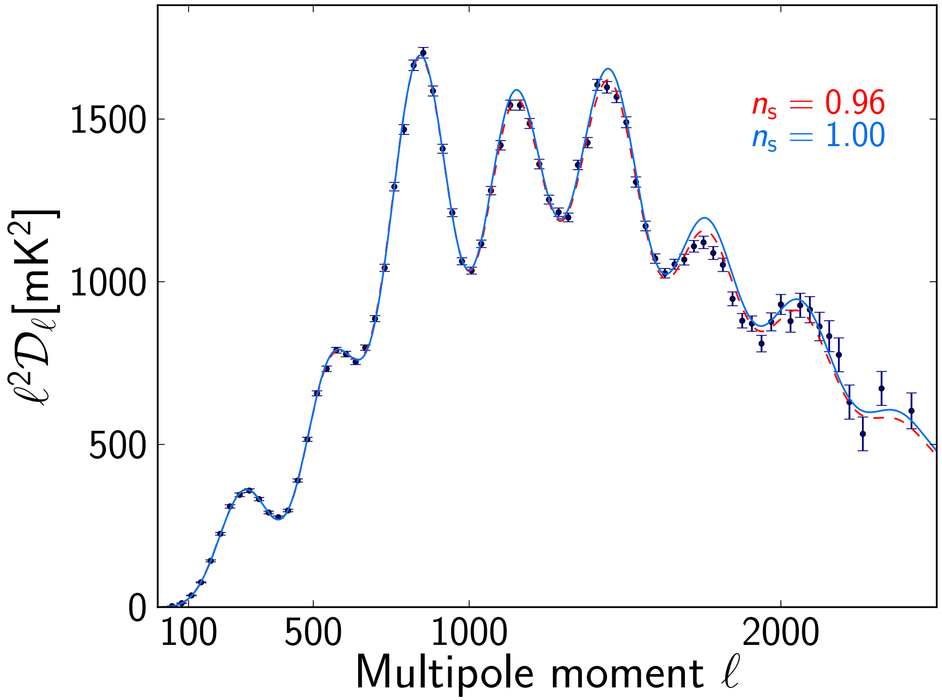
- F-term inflation
- F-term hybrid inflation
- false-vacuum inflation
- false-vacuum chaotic inflation
- fast-roll inflation
- first-order inflation
- gauged inflation
- Ghost inflation
- Hagedorn inflation

- higher-curvature inflation
- hybrid inflation
- Hyper-extended inflation
- induced gravity inflation
- intermediate inflation
- inverted hybrid inflation
- Power-law inflation
- K-inflation
- Super symmetric inflation

- Quintessential inflation
- Roulette inflation
- curvature inflation
- Natural inflation
- Warm natural inflation
- Super inflation
- Super natural inflation
- Thermal inflation
- Discrete inflation
- Polarcap inflation
- Open inflation
- Topological inflation
- Multiple inflation
- Warm inflation
- Stochastic inflation
- Generalised assisted inflation
- Self-sustained inflation
- Graduated inflation
- Local inflation
- Singular inflation
- Slinky inflation
- Locked inflation
- Elastic inflation
- Mixed inflation
- Phantom inflation
- Non-commutative inflation
- Tachyonic inflation
- Tsunami inflation
- Lambda inflation
- Steep inflation
- Oscillating inflation
- Mutated hybrid inflation
- Inhomogeneous inflation

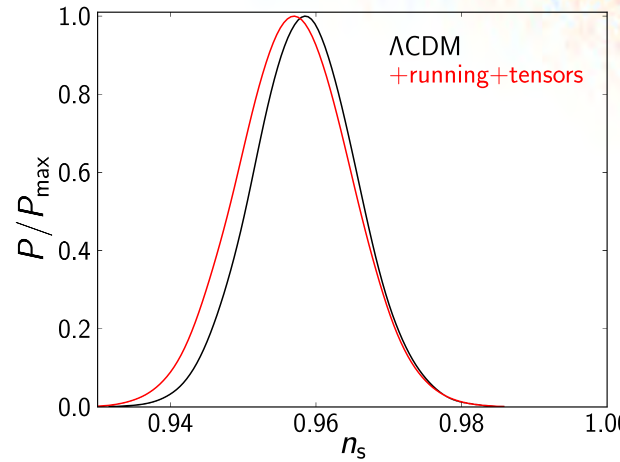


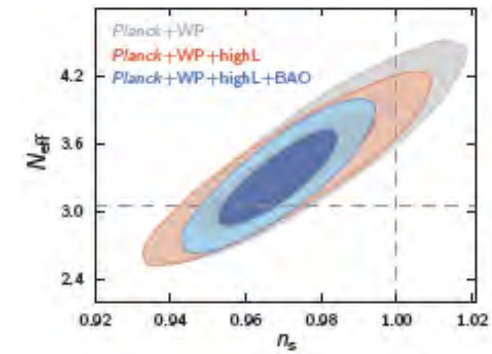
Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk, and r



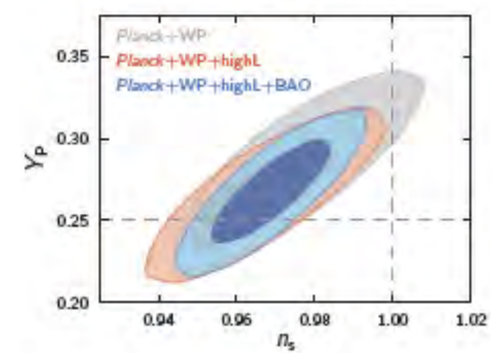
6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$





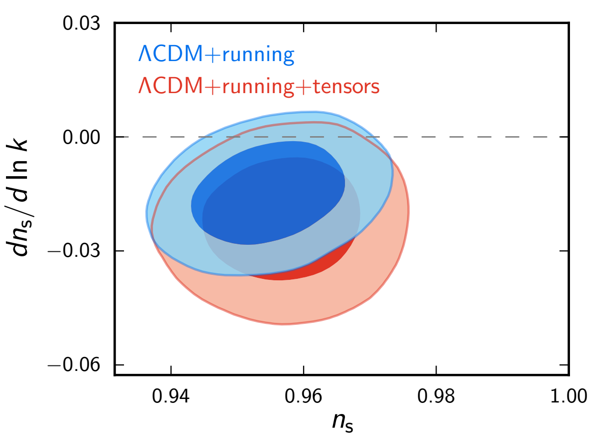
3σ

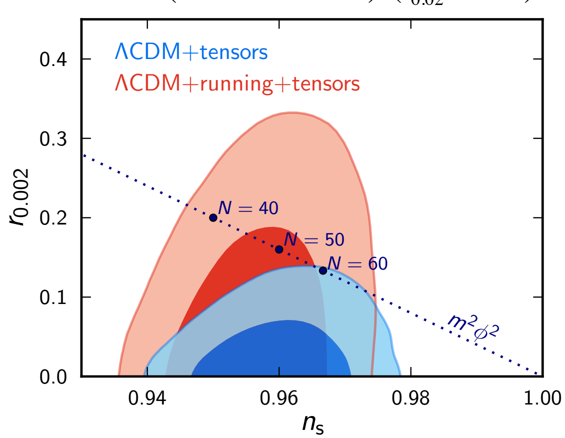


$$r < 0.11$$

(l<50) $dn_s / d\ln k = -0.0134 \pm 0.0090$

$$V = (1.94 \times 10^{16} GeV)^4 (r_{0.02} / 0.12)$$





Synopsis for Gaussianity and Isotropy

- Isotropy and Statistics project, leading to the paper, was undertaken to support the sufficiency, or otherwise, of the use of the two-point statistic (i.e. the power spectrum) for the extraction of the principal science results of the mission

- Regarding Statistics, a non-parametric data interrogation leads to the conclusion that Gaussian statistics are sufficient to describe the primordial CMB fluctuation, although a small number of exceptions remain

- The Isotropy part targeted WMAP anomalies for scrutiny in confrontation with the new, independent data set

  - since the original claims were met with noticeable skepticism

  - because *Planck* data offers significant advantages due to frequency coverage and foreground mitigation potential, and provides complete systematic redundancy

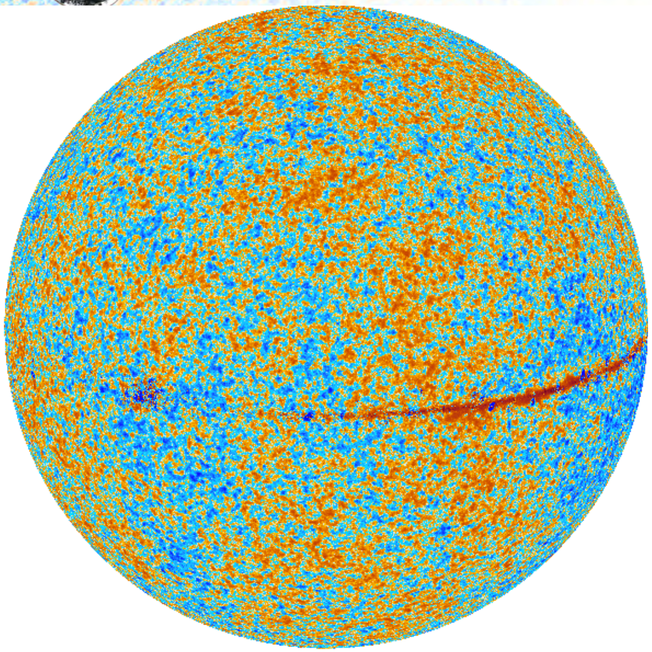
- Yet the anomalies proved resilient – not surprisingly given the very good overall Planck/WMAP consistency on large and intermediate angular scales

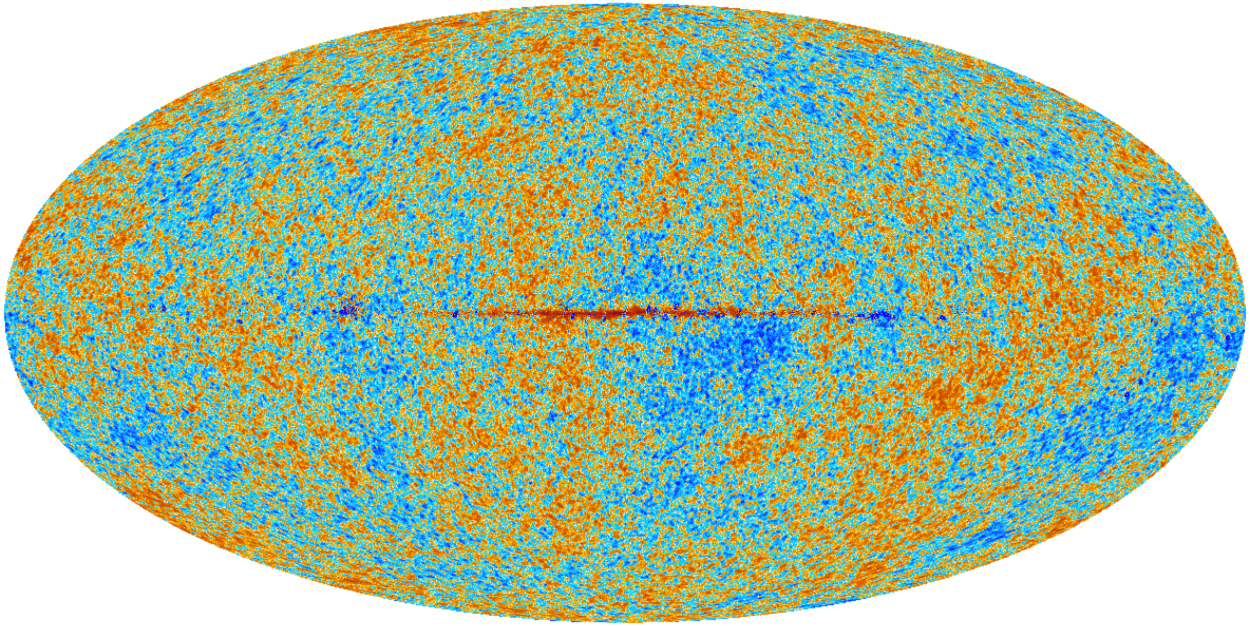
- **Are these anomalies of the observed CMB sky a figment of the imagination, or messengers from the universe on super-horizon scales indicating**

  - **Possible new physics of generation of primordial perturbations, or**

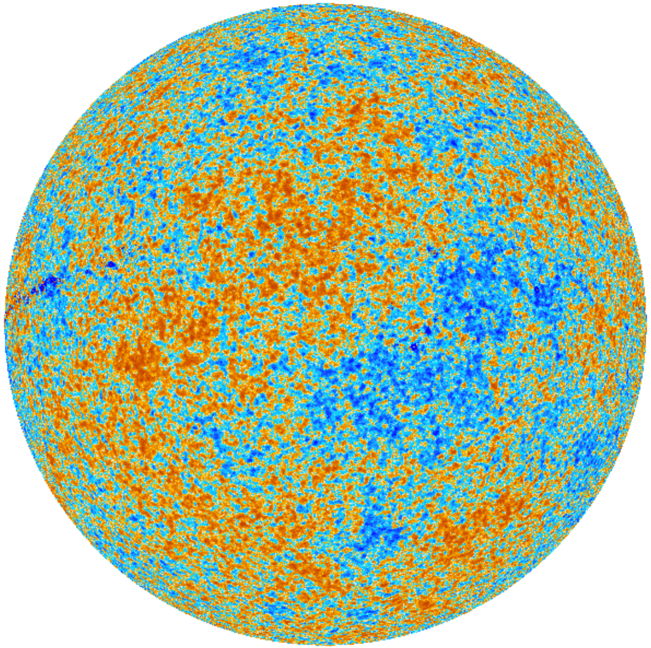
  - **Breakdown of global isotropy**

post component separation CMB map, and “the” Hemispheres





Amongst the various strange features of the observed CMB sky, one of the more persistent ones (w.r.t. the data set and/or the analysis methodology applied) is the hemispherical asymmetry of the distribution of CMB anisotropies



Is this a mere fluke, or is it telling us something interesting about the universe?
The big, fundamental question is whether the universe is indeed isotropic …

A “mother” of WMAP anomalies – the quadrupole-octopole alignment

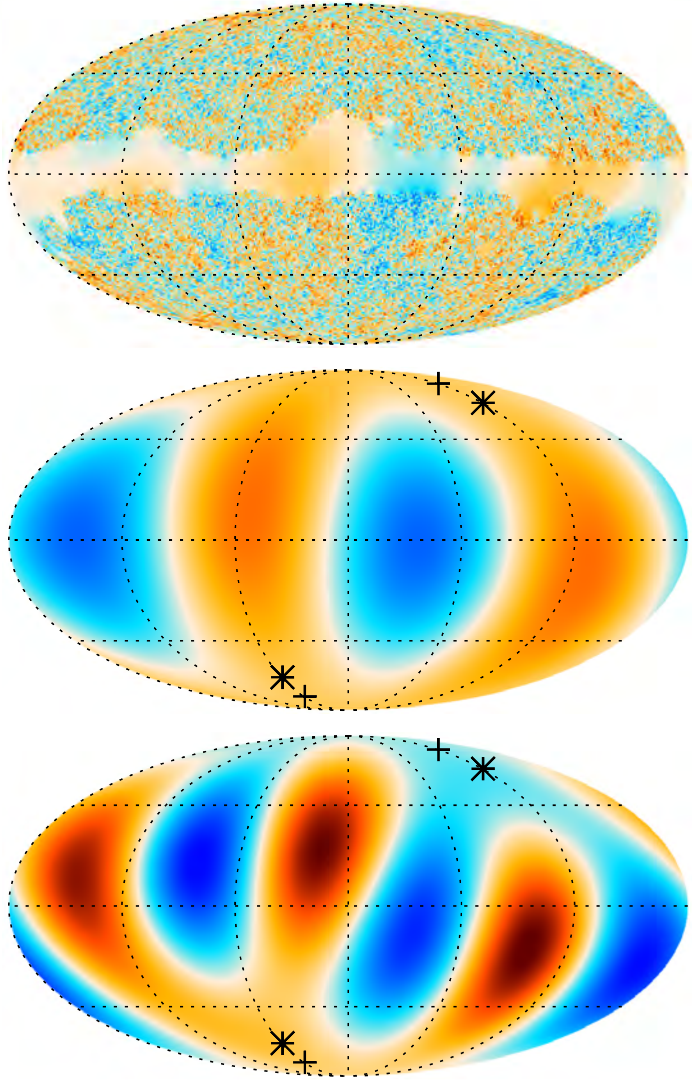


Fig. 20. Upper: The Wiener filtered SMICA CMB sky (temperature range $\pm$ 400 μK). Middle: the derived quadrupole (temperature range $\pm$ 35 μK). Lower: the derived octopole (temperature range $\pm$ 35 μK). Cross and star signs indicate axes of the quadrupole and octopole, respectively, around which the angular momentum dispersion is maximized.

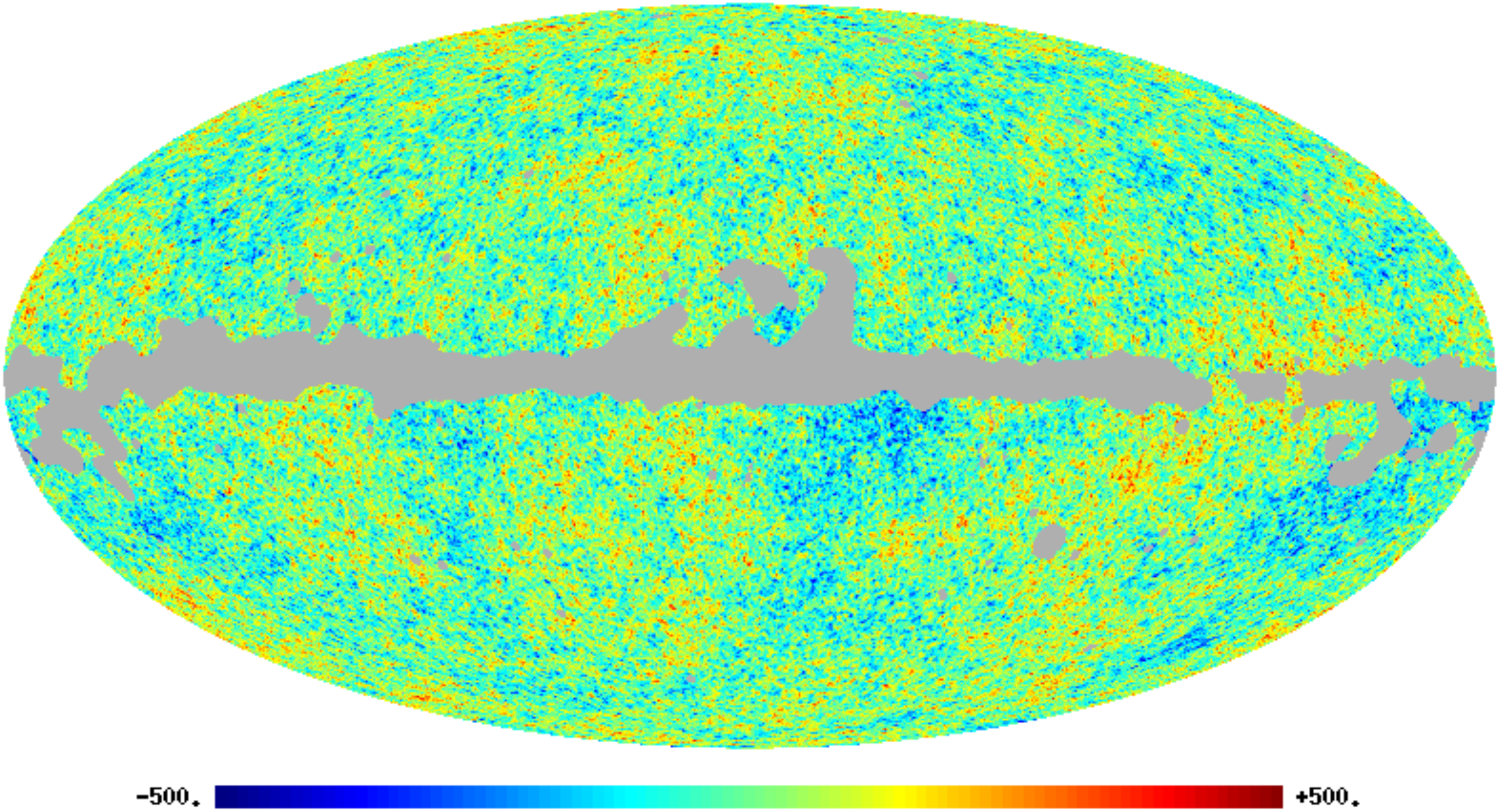
Less remarkable in *Planck* than in WMAP

Hint:
This is the time to ask about the “axis of evil”

K. M. Gorski

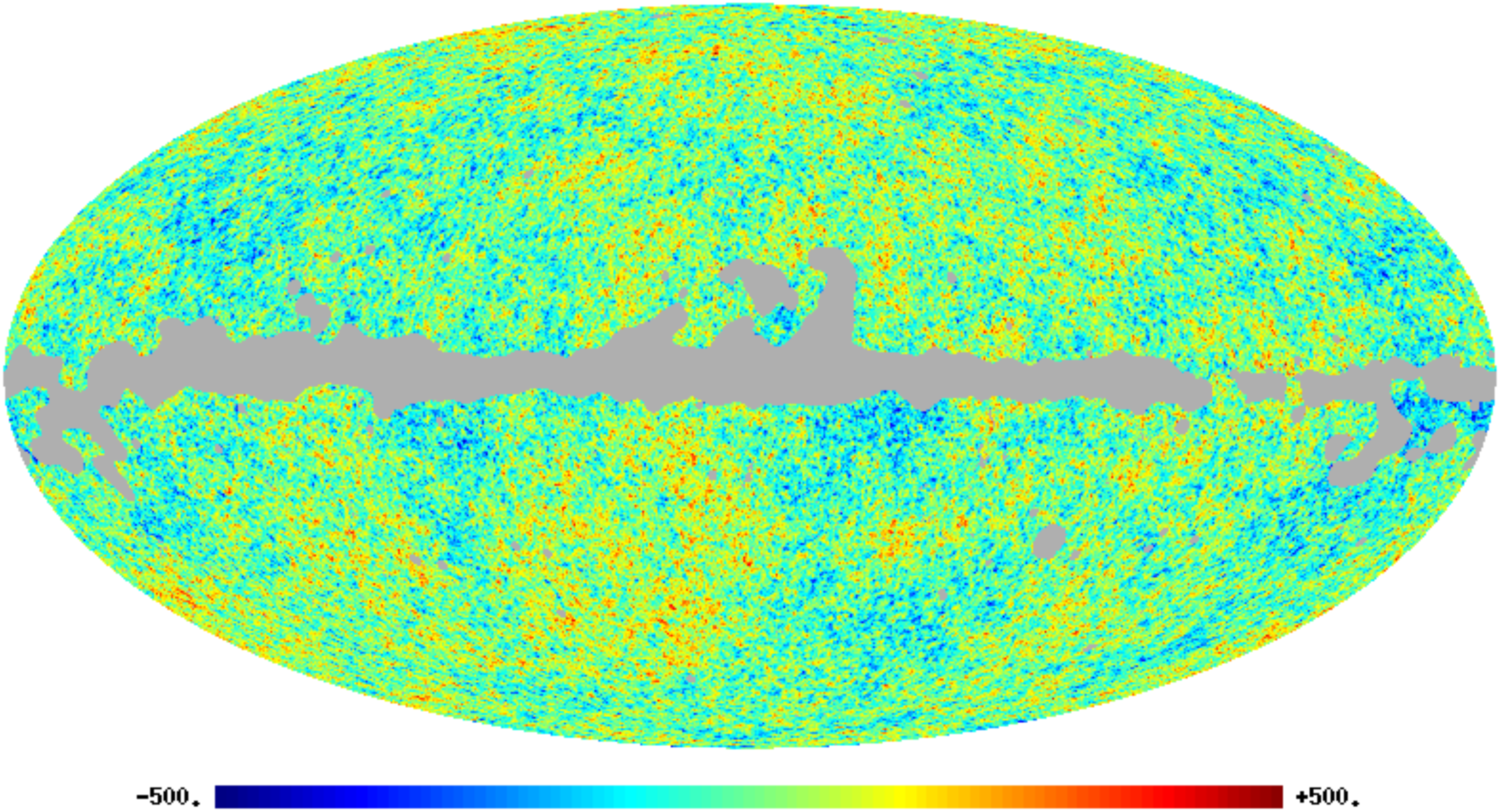
The Bianchi Conundrum …

The Observed CMB Sky



K. M. Gorski

The Corrected, More Manifestly Isotropic CMB Sky

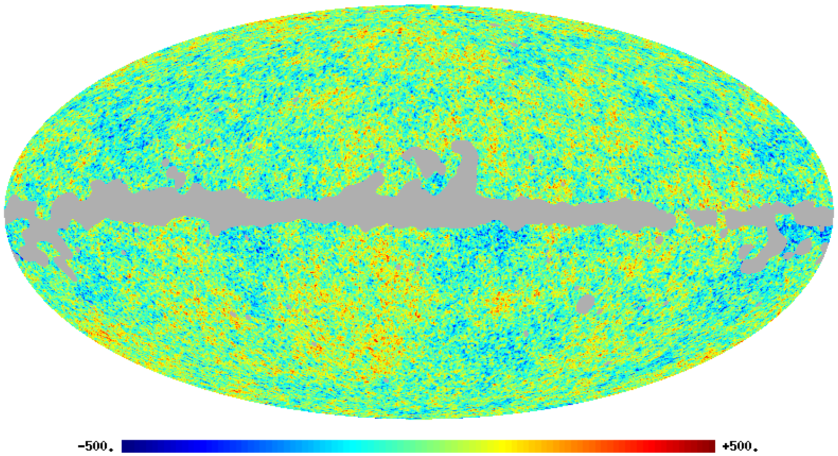


K. M. Gorski

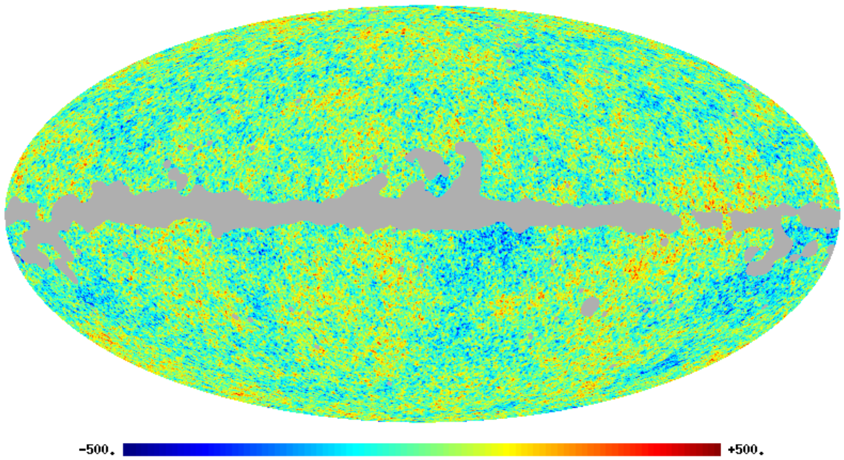
A Paradoxical "Solution" to the Idiosyncratic Appearance of our CMB Sky

The Bianchi model **must be open** to fit the data, and cannot be merged with the overall flat cosmology that describes the observed universe

Corrected CMB Sky

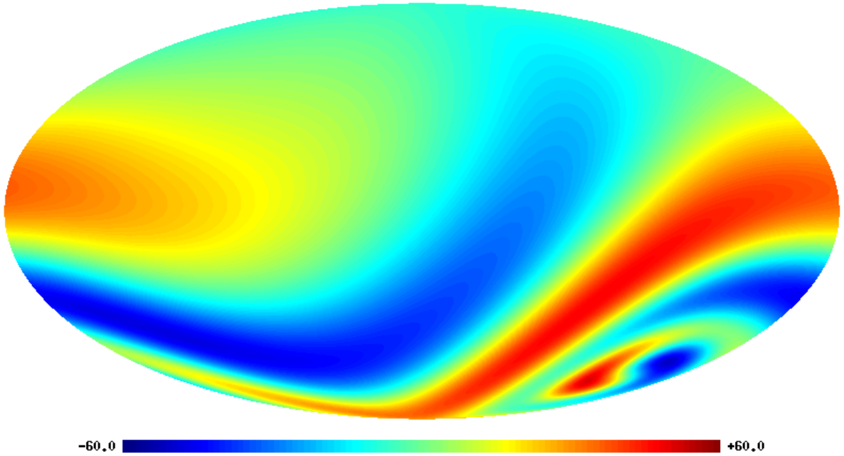


Real CMB Sky



=

+



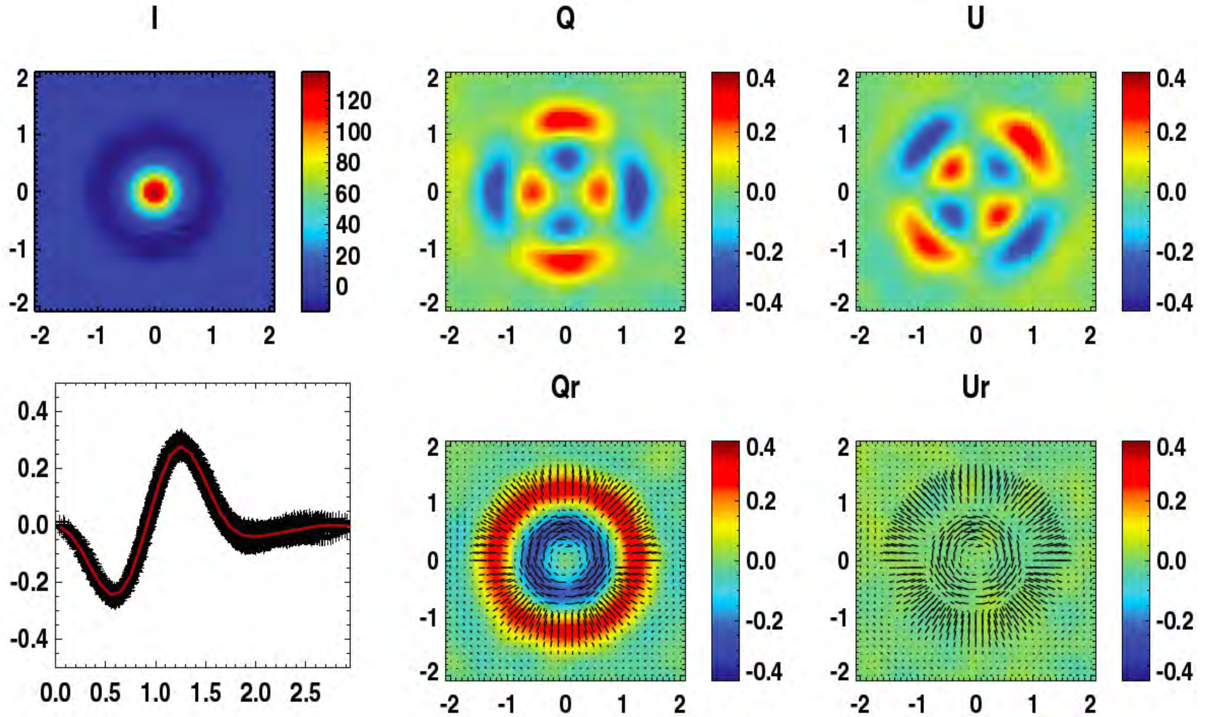
Correction that fits the sky:
a homogeneous, anisotropic Bianchi VII_h model

A summary in a nut-shell

- No compelling evidence found for non-Gaussianity of primordial fluctuations
- This is a noteworthy conclusion regarding the future of inflationary models
  - Possible non-Gaussianity of primordial fluctuations, themselves a manifestation of quantum nature of the generation mechanism during inflation, became of interest as an alternative candidate for "smoking gun" of inflation w.r.t. the polarization B-modes (as imprints of inflation generated gravitational wave background)
  - *Planck* via a combination of constraints on primordial perturbations involving their very Gaussian statistics, the overall shape of their spectrum, and its lack of discernible features, brings forth increasingly severe limitations on the liberties that can be taken in modeling inflation
- Simplest models of inflation fare the best, complicated ones end up in trouble
- Quantitatively, a 4-5* better significance than WMAP9, and no near hints of detection (for the same parametric models of non-G)

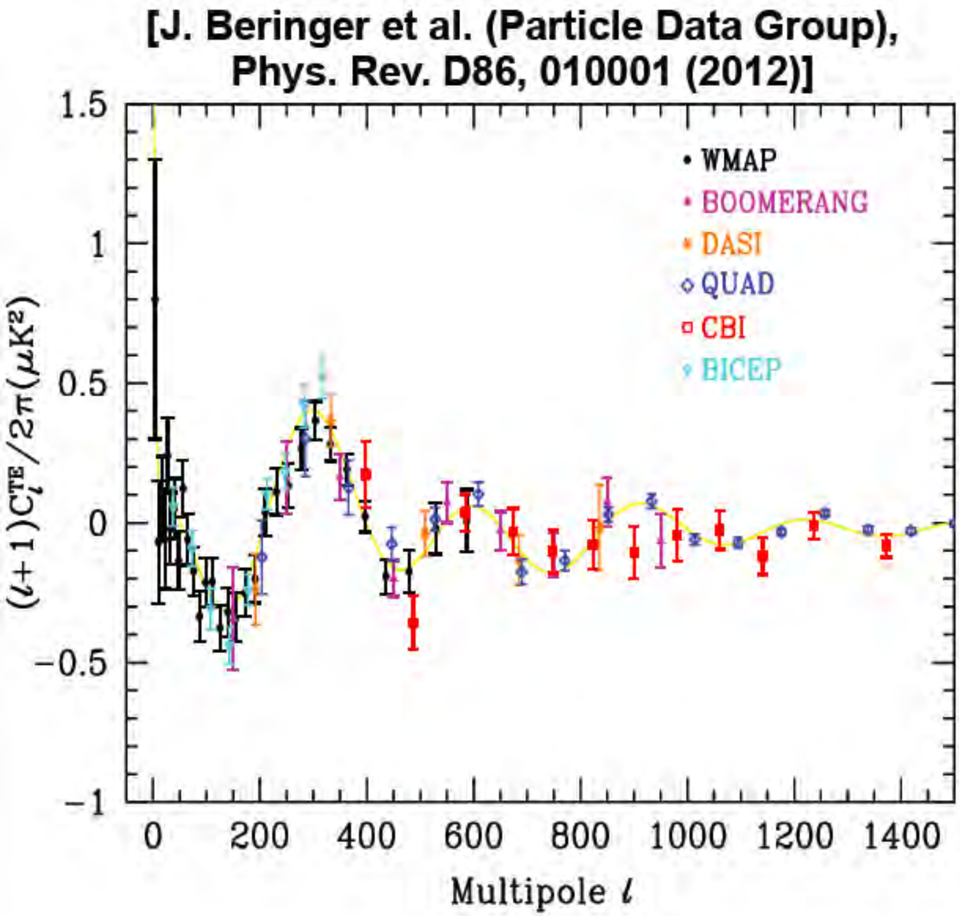
Polarization from Planck

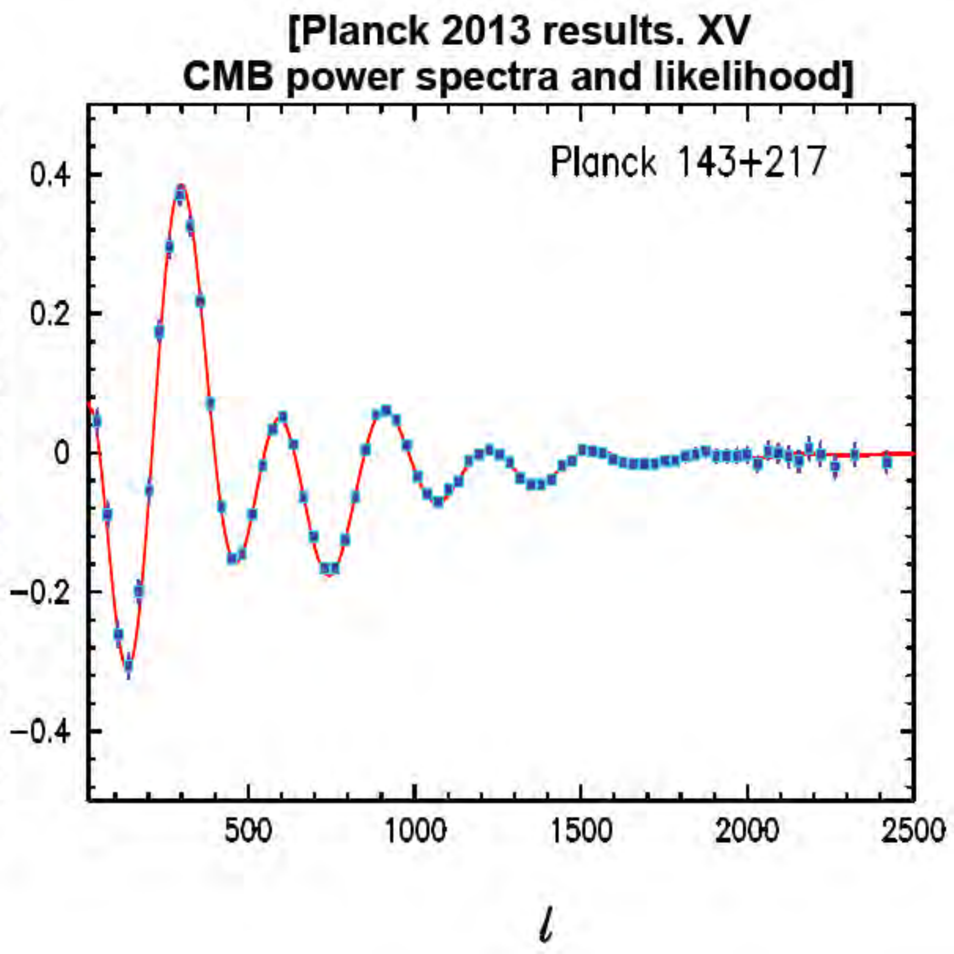
- Yet another handle on LCDM: in particular, constrain reionization
- Stronger constraints on lensing (mixes E->B)
- Tensor mode signatures: B modes on large scales



K. M. Gorski

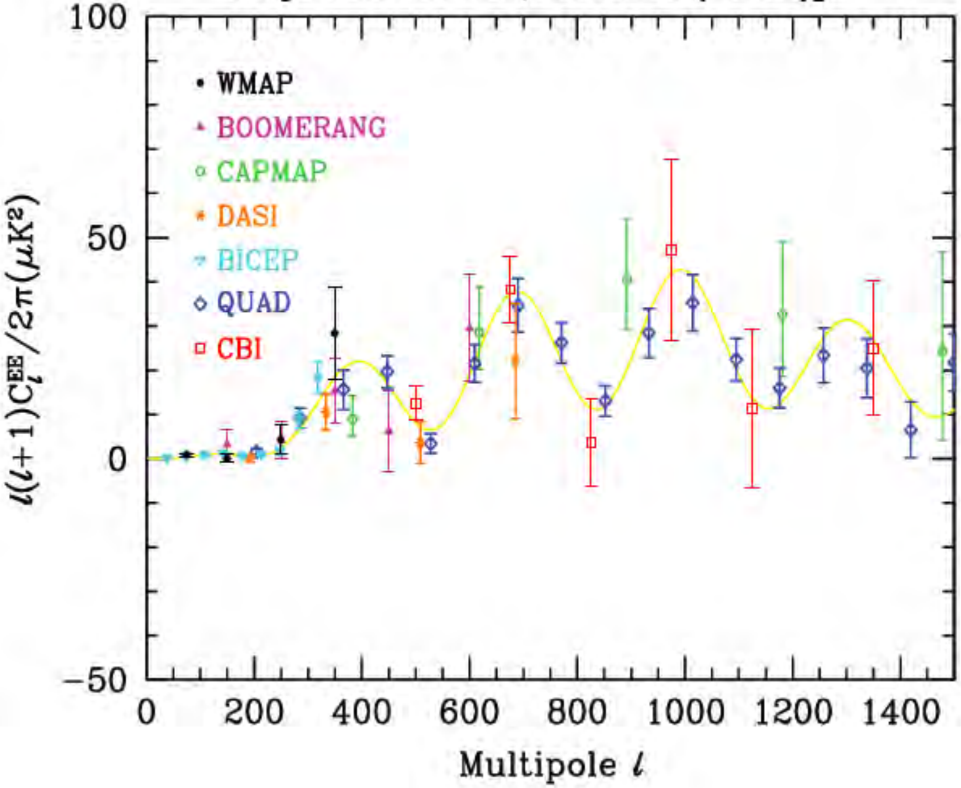
E-mode Polarization – temperature correlation (TE)



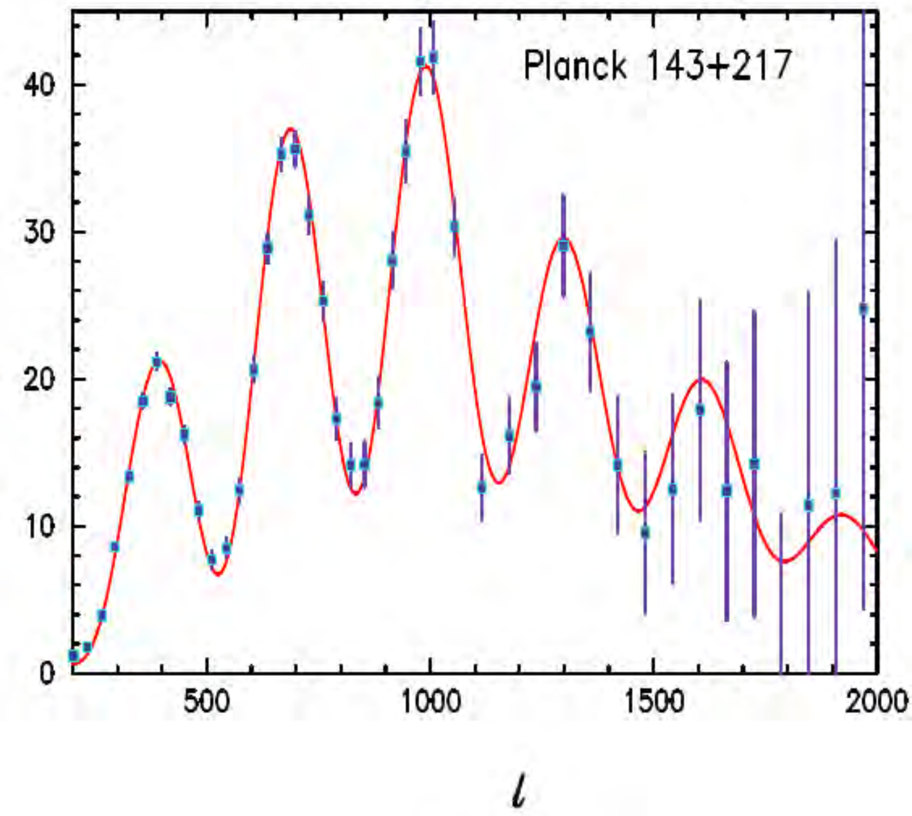


E-mode polarization (EE)

[J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)]

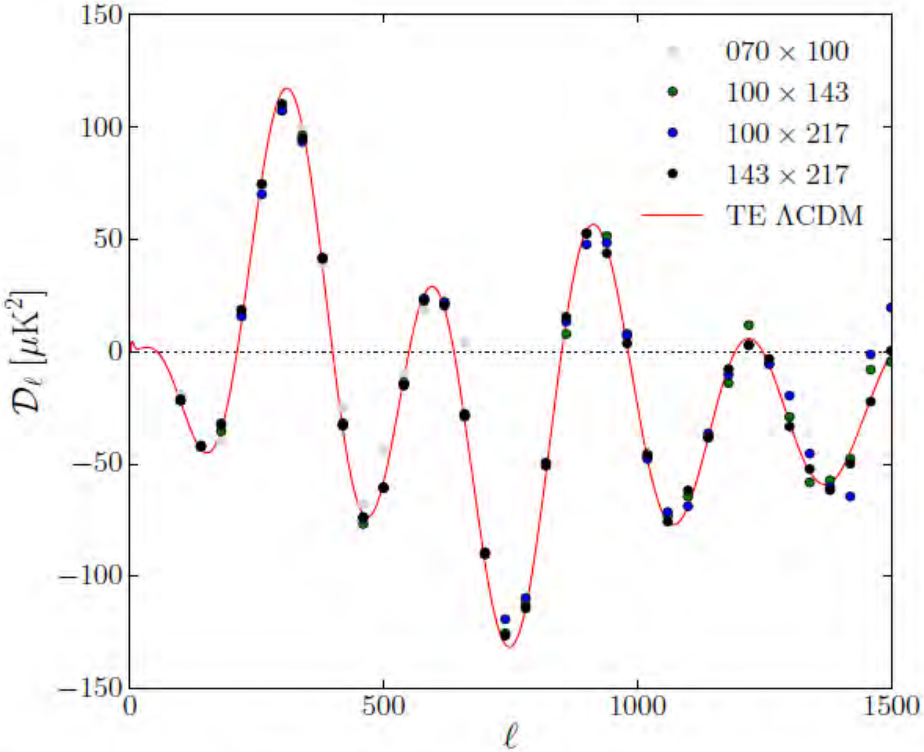


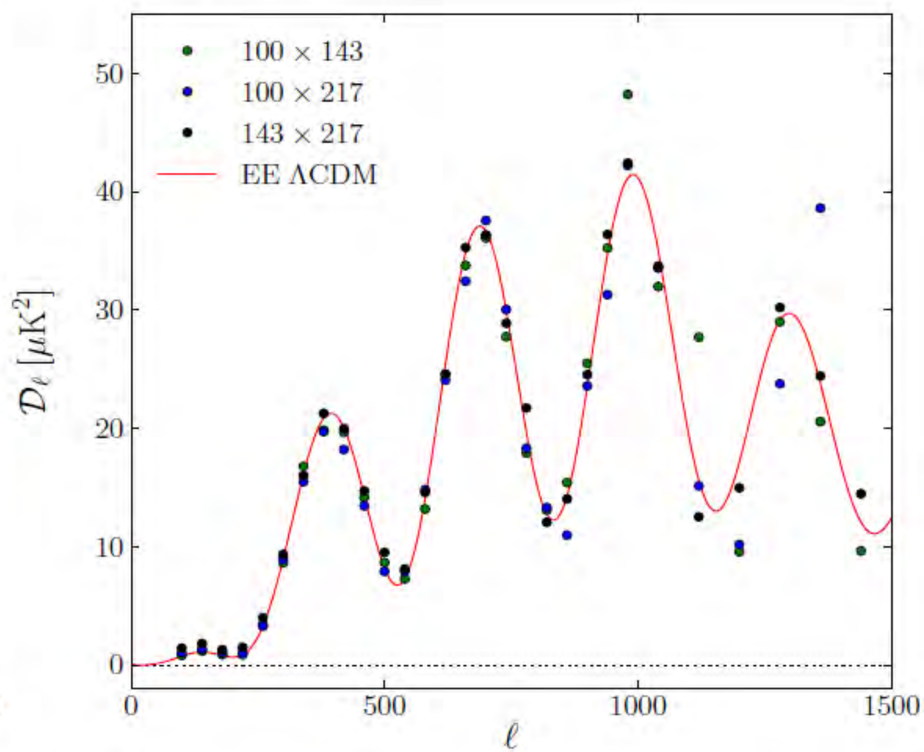
[Planck 2013 results. XVI. Cosmological parameters]



Polarization

TE and EE Power Spectra (preliminary!) - red line is not a fit to the polarized spectra – it is the TT best fit model





Excellent quality of the data
Foregrounds and systematics are not dominant at those high-l

K. M. Gorski

What next?

- Recently released Planck data set is a treasure-box; it will take a long time to exploit it fully.

- We have learnt a great deal about the Universe, and made a step forward toward precision cosmology

- There is still a huge amount to learn and do. Full mission Planck data are being analyzed; special care is being extended to the polarization measurements; next science release is expected around mid-2014

- It has taken us 20 years to get to this point. Remarkable measurements of the various properties of the universe abound, but **a truly fundamental explanation for the properties of the universe is still wanting.**

The scientific results presented 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.

K. M. Gorski