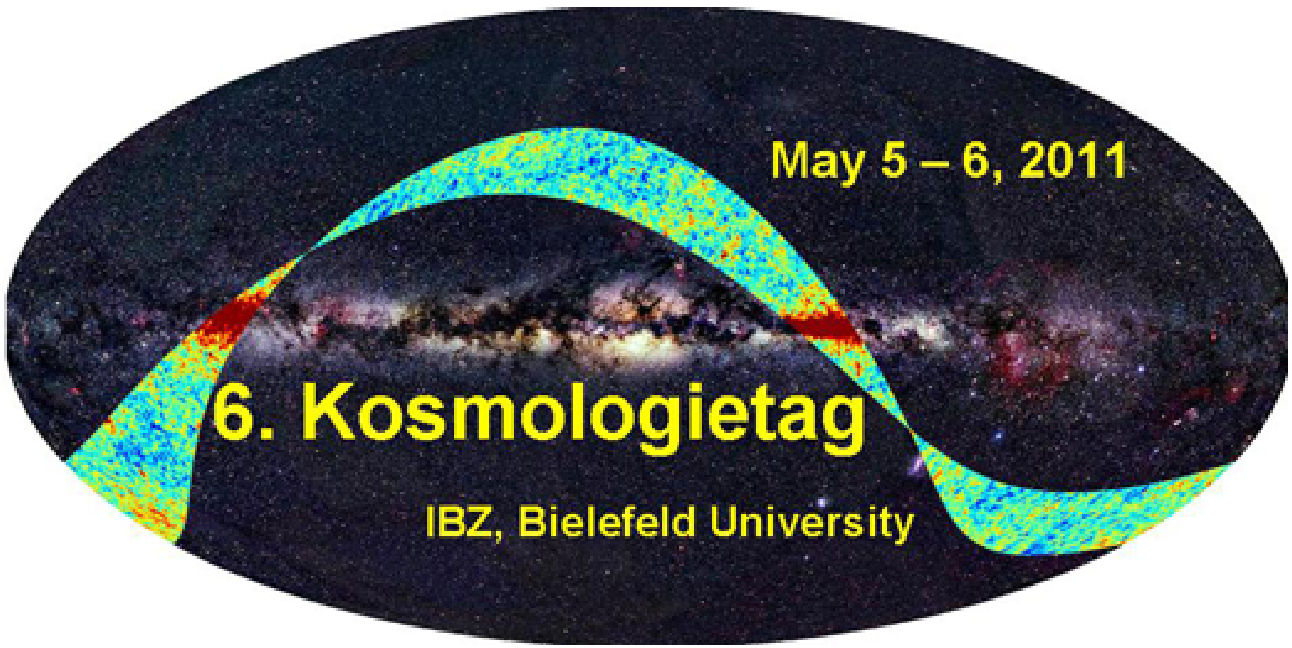
Planck: Status and Results

Sam Leach (SISSA)
On behalf of the Planck Collaboration



SCUOLA INTERNAZIONALE SUPERIORE di STUDI AVANZATI
International School for Advanced Studies

Aims of this talk

• To remind you about the basic experimental concept of Planck and show the first light images.

• To describe the performance of Planck and present some of the first astrophysical results.

• To remind you a bit about the forthcoming cosmological programme of Planck.

• To put Planck in the context of several other ongoing and planned CMB experiments.

Planck in a nutshell

- An ESA satellite mission to measure the cosmic microwave background. temperature and polarization anisotropies.
- Wide frequency coverage with nine channels covering 30 to 857 GHz.
- Angular resolution from 33' to 4.5'.
- Sensitivity!

Two instruments:

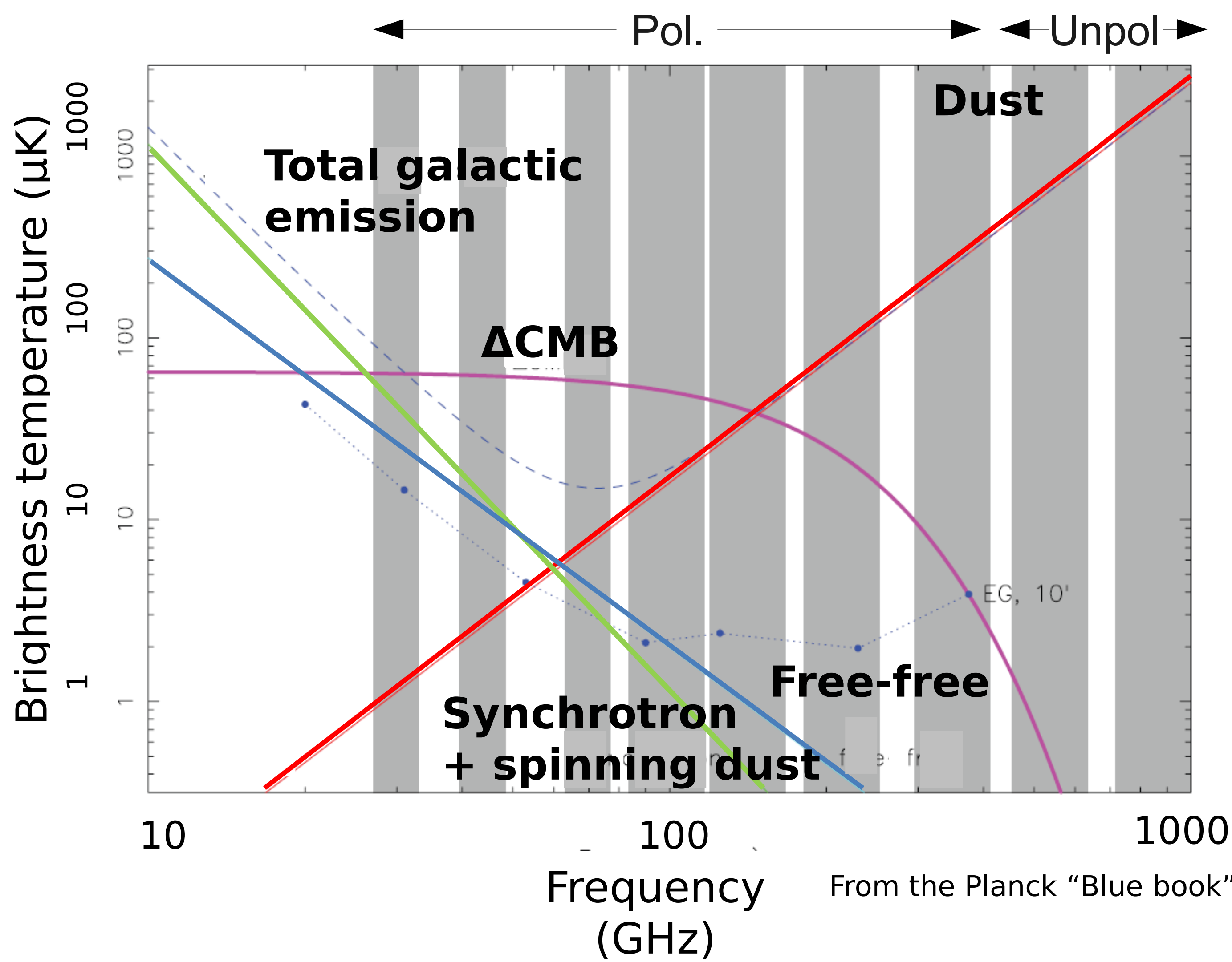
- "Low Frequency Instrument" (LFI) (HEMT low noise amplifiers).

    PI: Reno Mandolesi (IASF, Bologna)
- "High Frequency Instrument" (HFI) (spider web and polarization sensitive bolometers).

    PI: Jean Loup Puget (IAS, Paris)

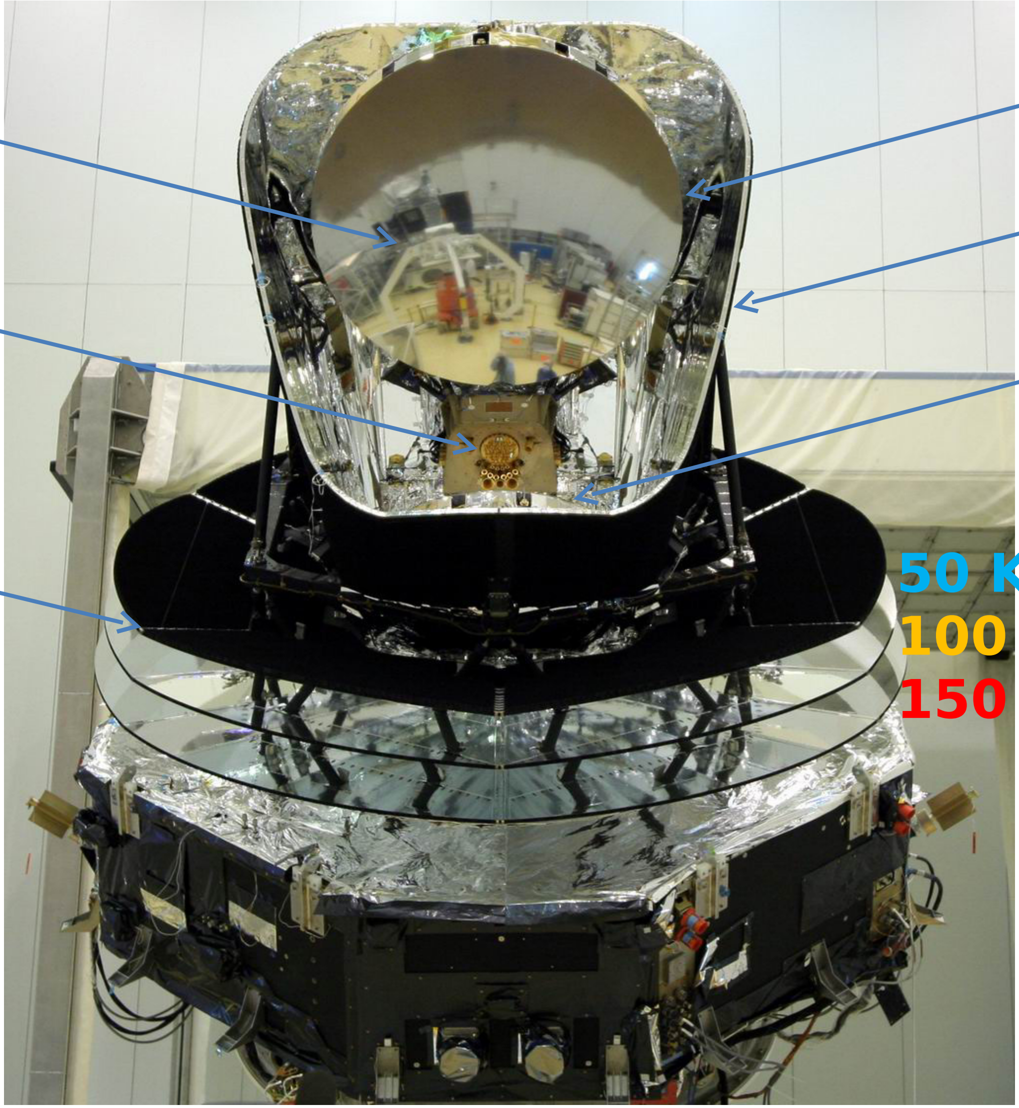
Wide frequency coverage

• Key advantage for cosmological foreground subtraction and astrophysics with Planck.



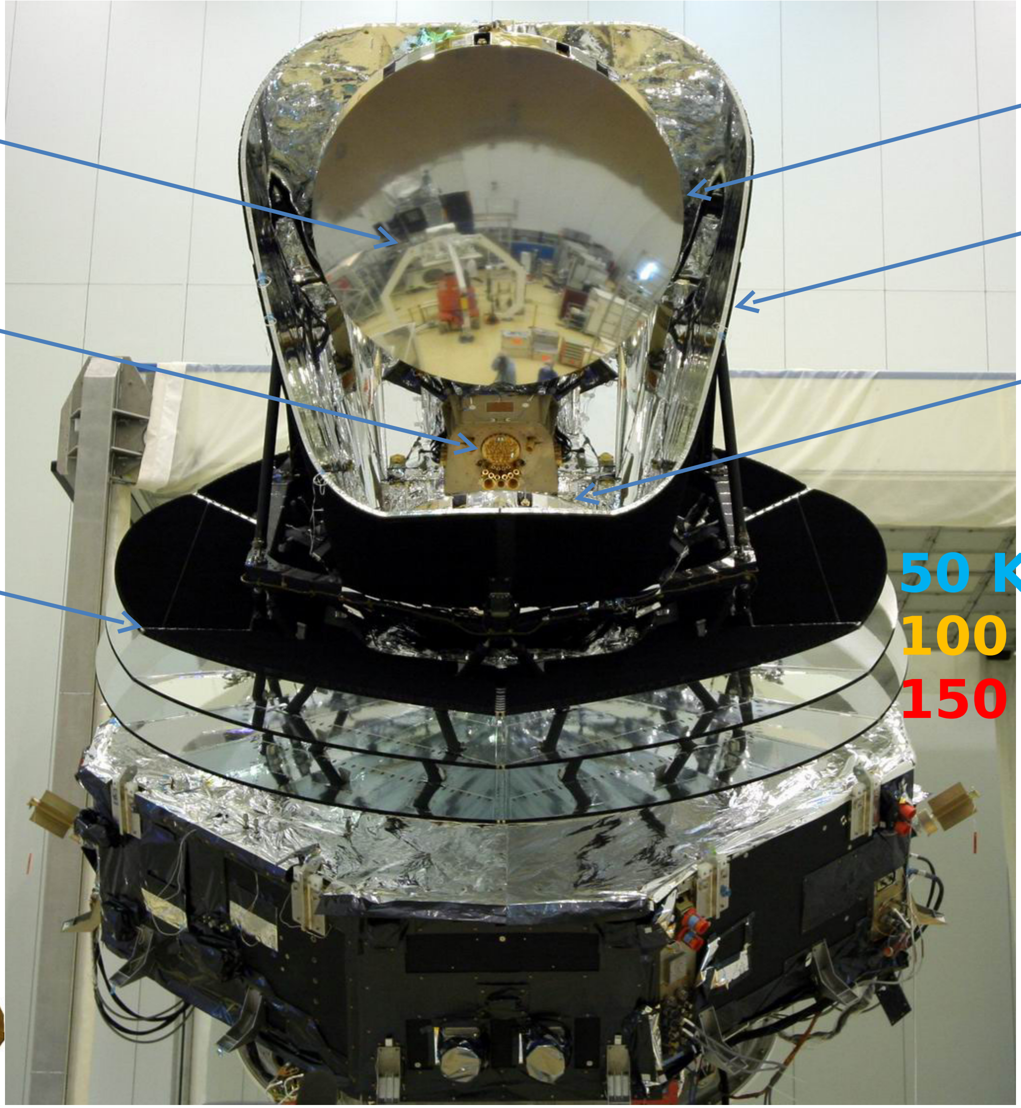
From the Planck "Blue book"

Planck



Herschel satellite
Focal plane unit
Heat shields
1.5m primary mirror
Telescope baffle
Secondary mirror
50 K
100 K
150 K

Planck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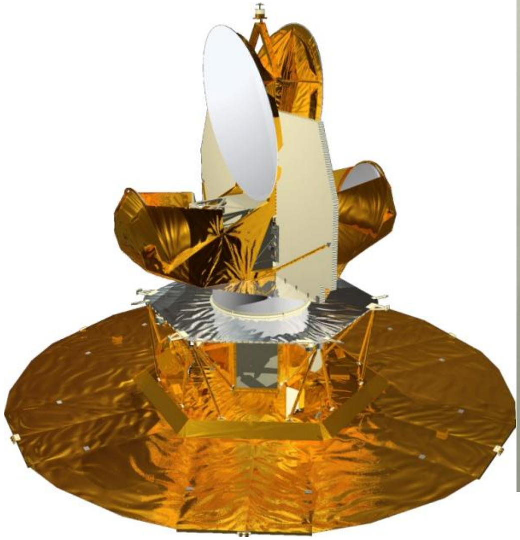


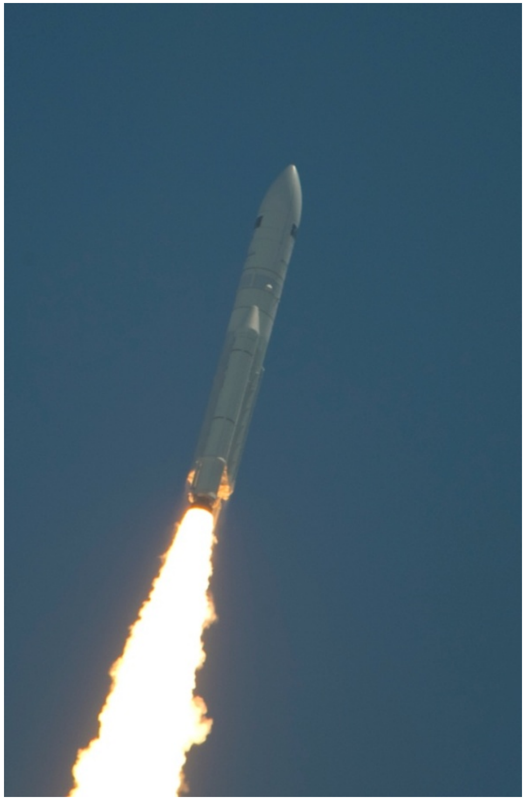
WMAP

Flight to Kourou

CSL (Liege) 18th February 2009

Launch day!

- Kourou, French Guiana, 14th May 2009.

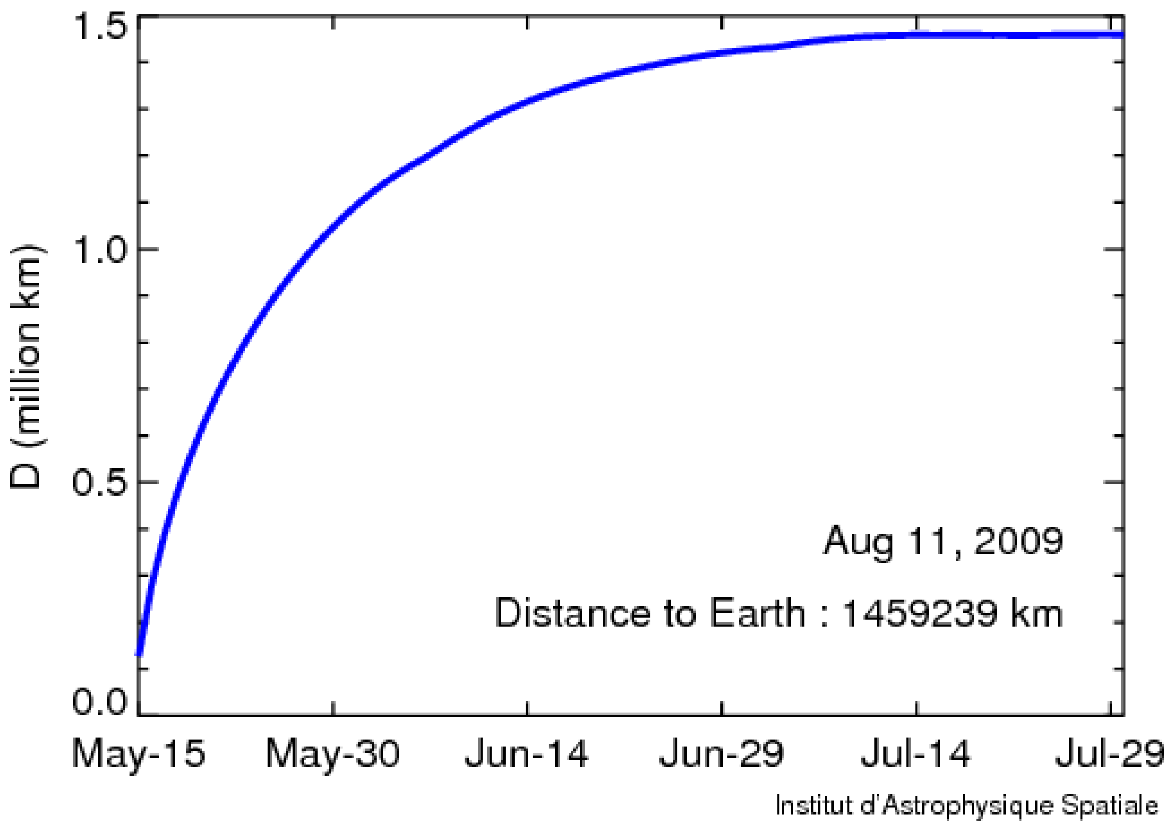


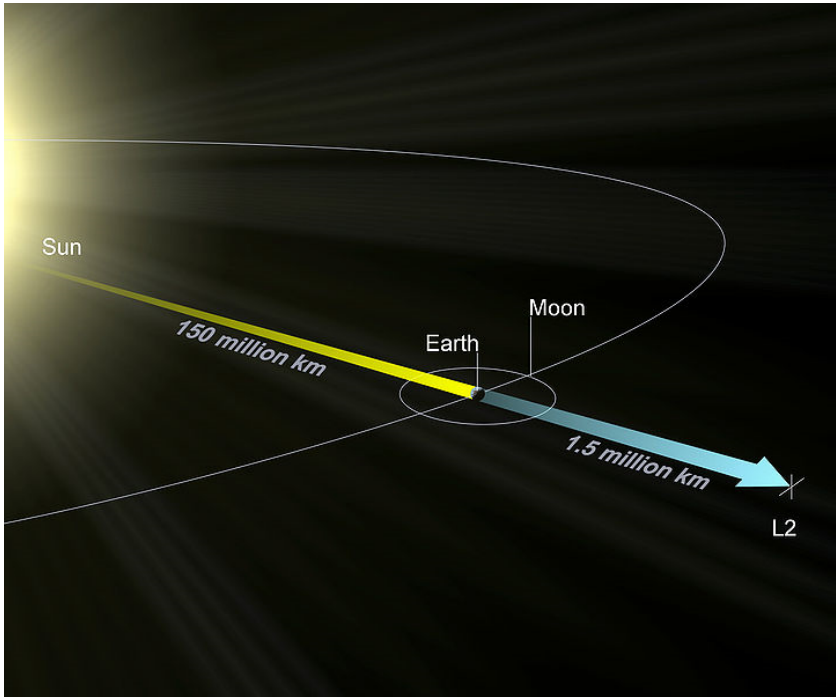
ESA - S. Corvaja

- Ariane 5 launcher, with the Herschel satellite.
- 175 tonnes of liquid propellant in 535s. 240 tonnes of solid propellant in 140s!

Journey to L2

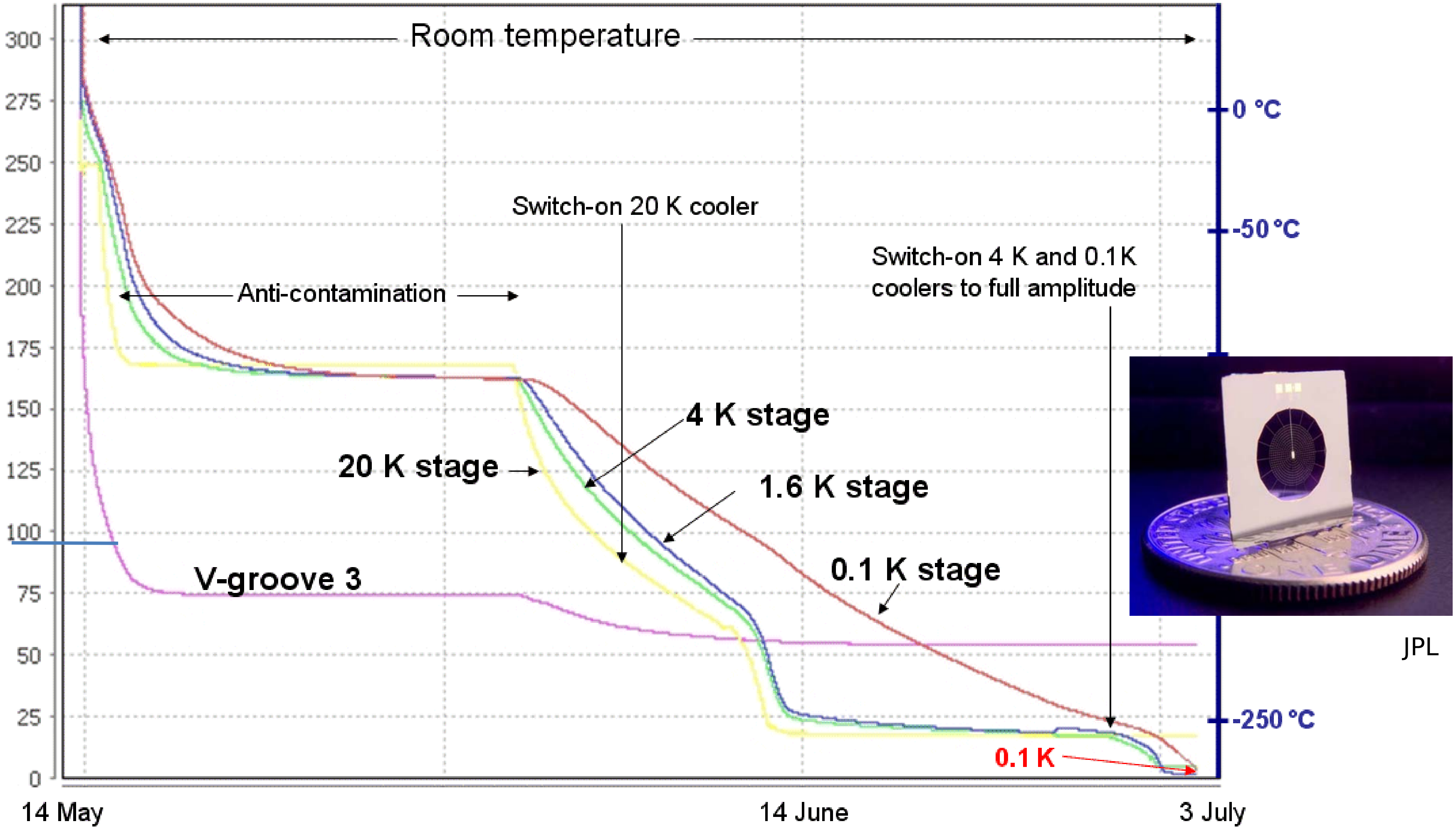
• Six week journey to observation point at Earth-Sun Lagrange point 2 for thermal stability and cool down to 100mK.





Cool down to 100mK

WMAP passive cooling ~95K



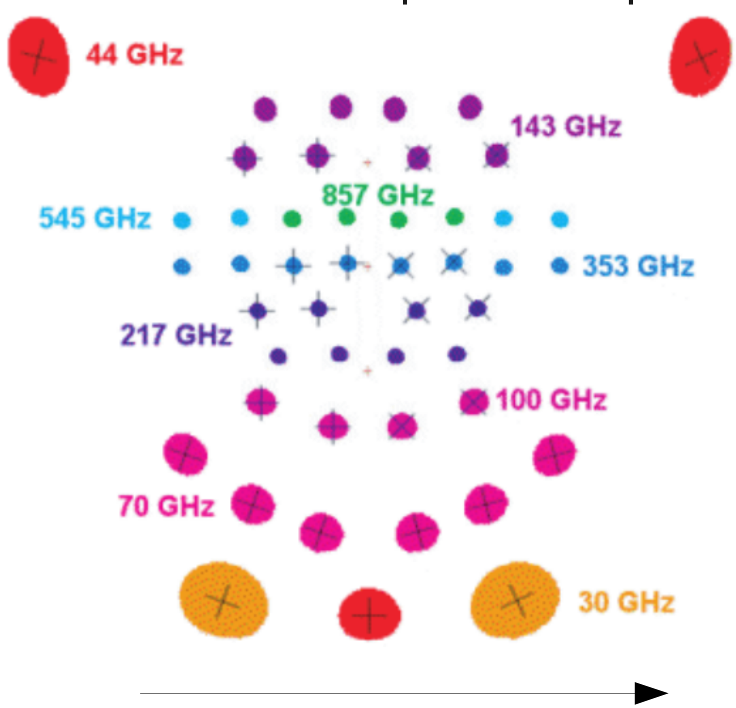
ESA and HFI Consortium

JPL

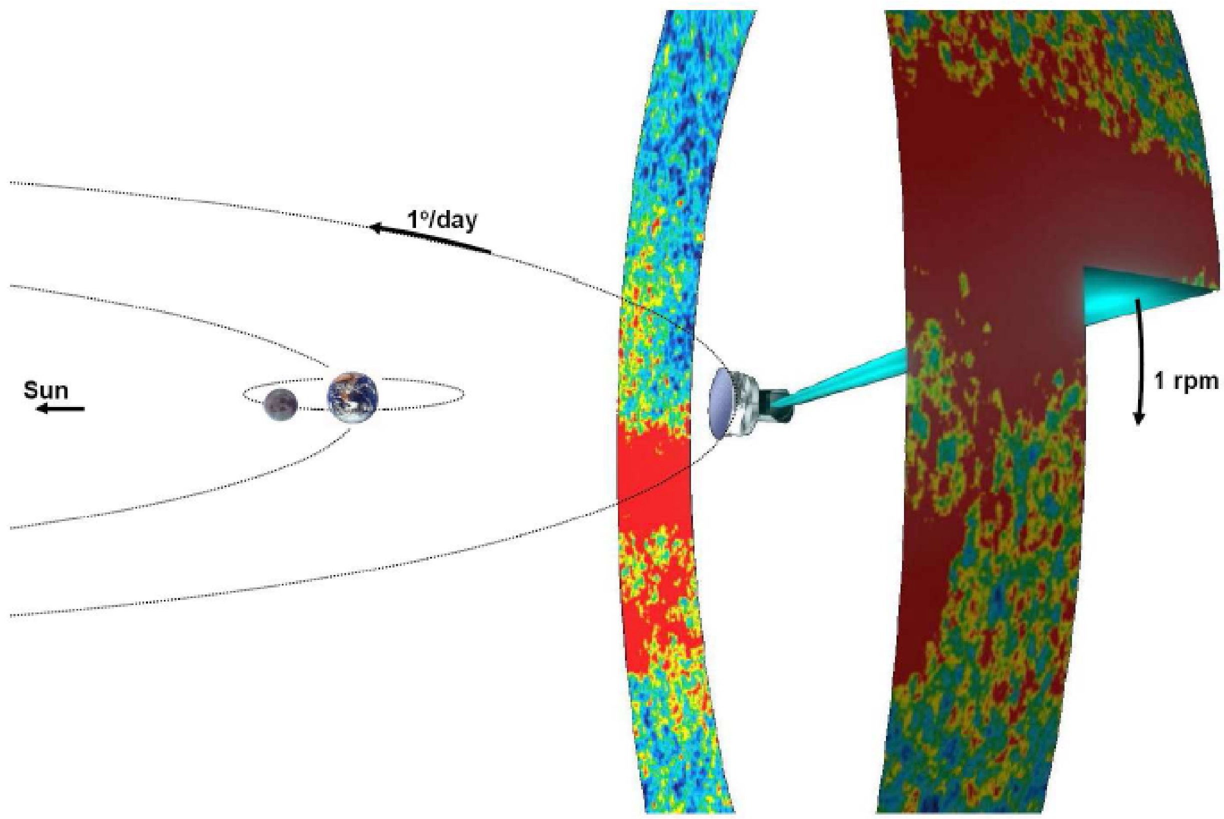
Scanning strategy

- Planck builds up a map from a series of "rings" – spinning at 1 rpm.
- Repointing of the telescope by 2' every ~ 40 minutes.
- Slow modulation of the spin axis for full sky coverage and polarimetry.
- One survey of the sky roughly every six months.

Planck focalplane "footprint"



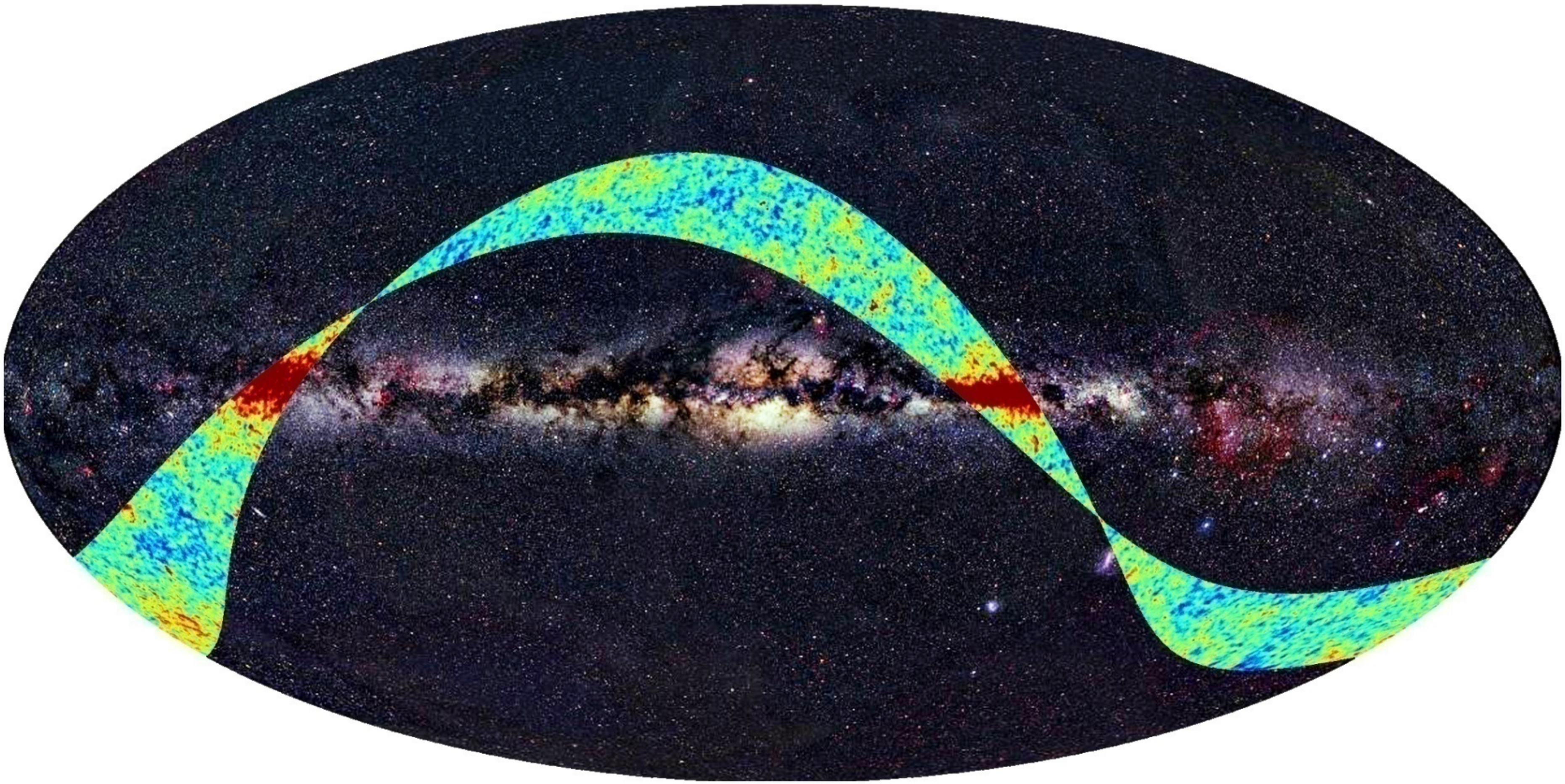
Scan direction



ESA

"First light survey"

- Two weeks of data from August 2009 covering ~10% of the sky.

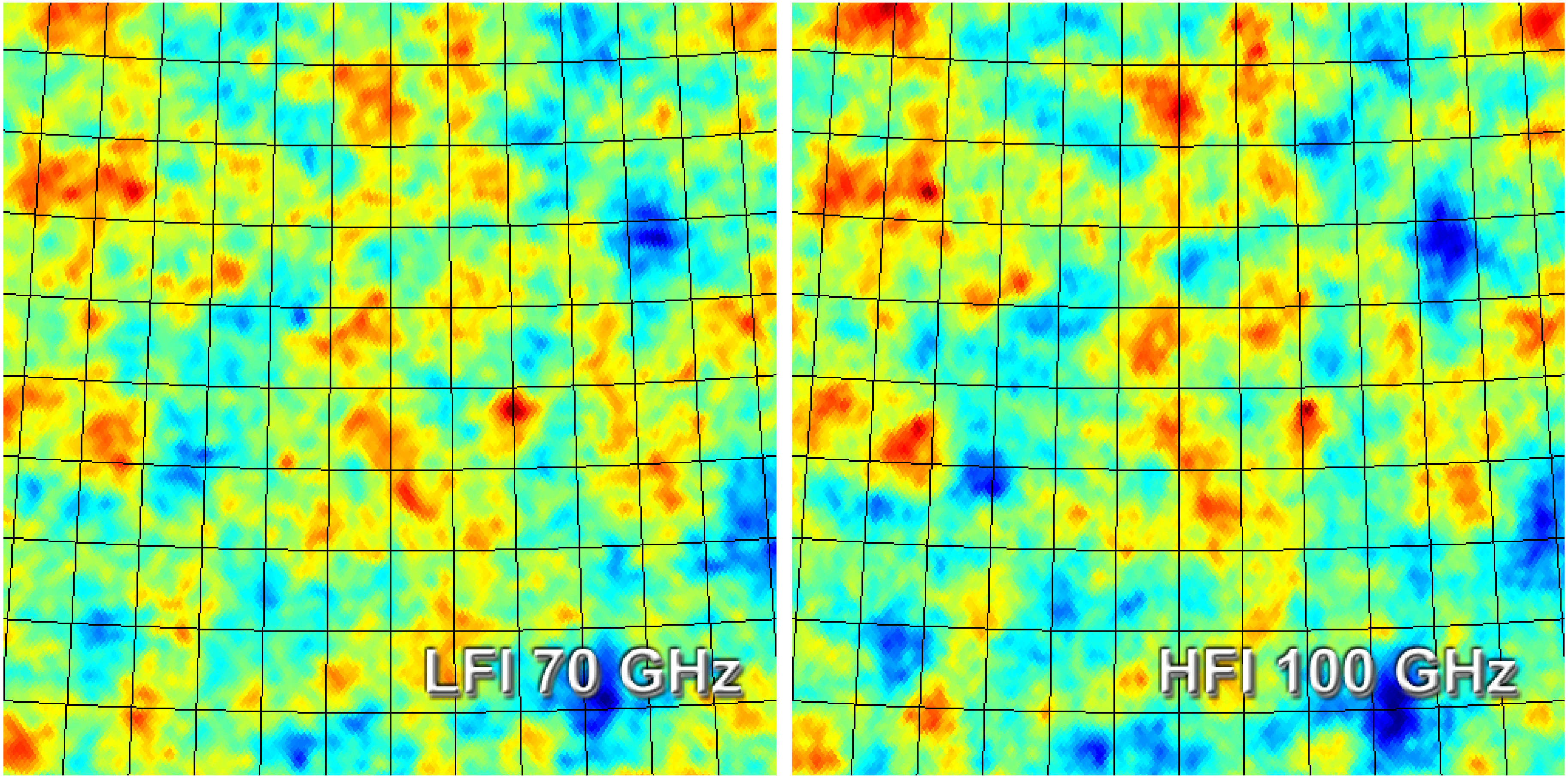


ESA, LFI & HFI Consortia (Planck), Background image: Axel Mellinger

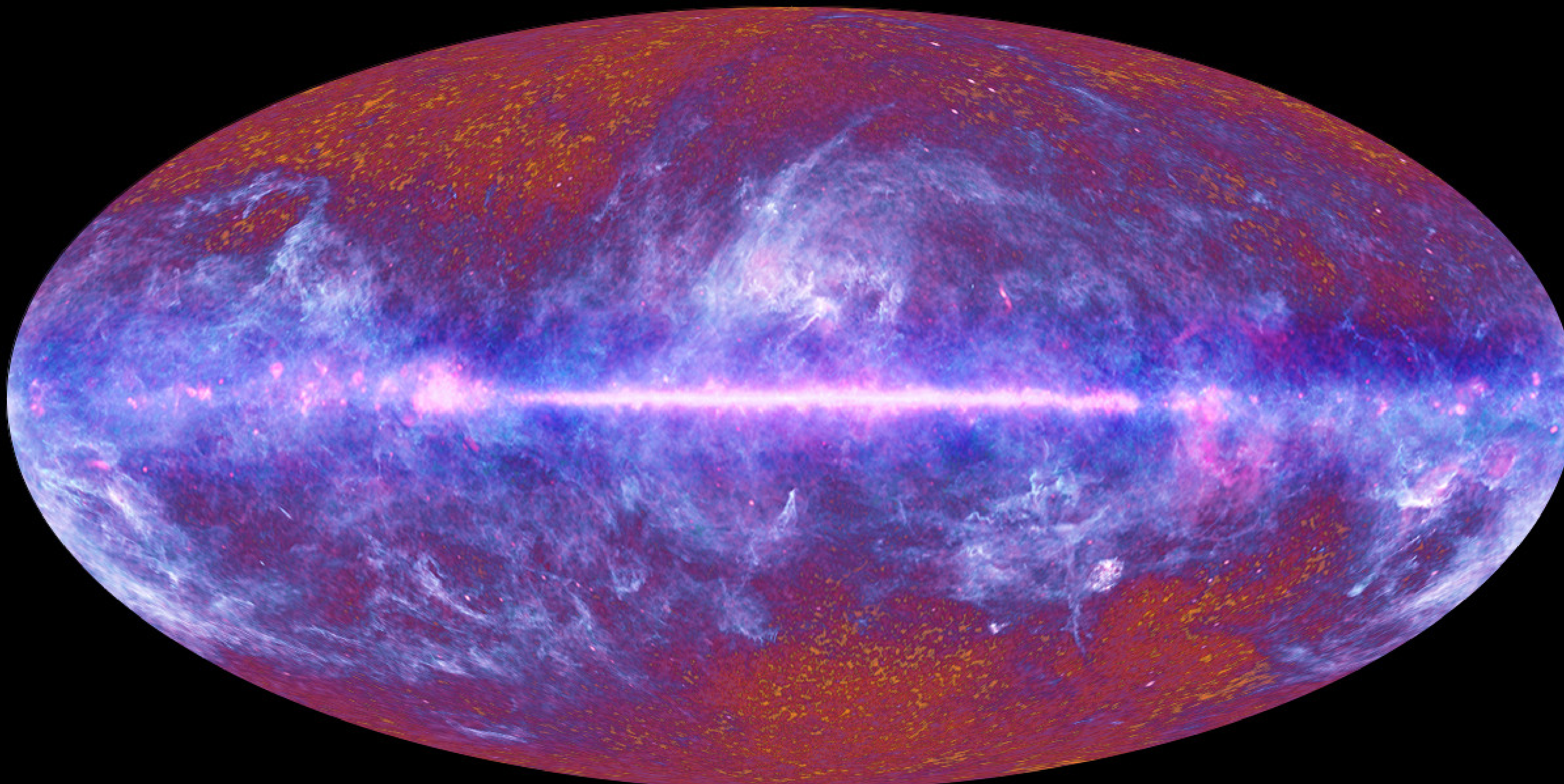
First light survey - CMB

- High latitude CMB anisotropies at 70 and 100 GHz.

$10^o \times 10^o$



ESA, LFI & HFI Consortia (Planck)



The Planck one-year all-sky survey

First results from Planck

- Broad science programme only sketched out here:

- Data processing.
- In flight performance.

- Planck (foreground) maps.
- SZ cluster candidates.
- Cosmic infrared background anisotropies.
- All-sky dust temperature.

Data processing

- **Calibration** off solar system CMB dipole (30 – 353 GHz) and off FIRAS data (545 – 857 GHz).

- **Beam measurement and focalplane reconstruction** off planets, each observed twice per year.

- **Map-making** with the destriping method, fitting for one offset per ring and then assuming white noise timestreams.

A worldwide simulation and analysis effort is in full swing.

In-flight performance

Table 3. *Planck* performance parameters determined from flight data.

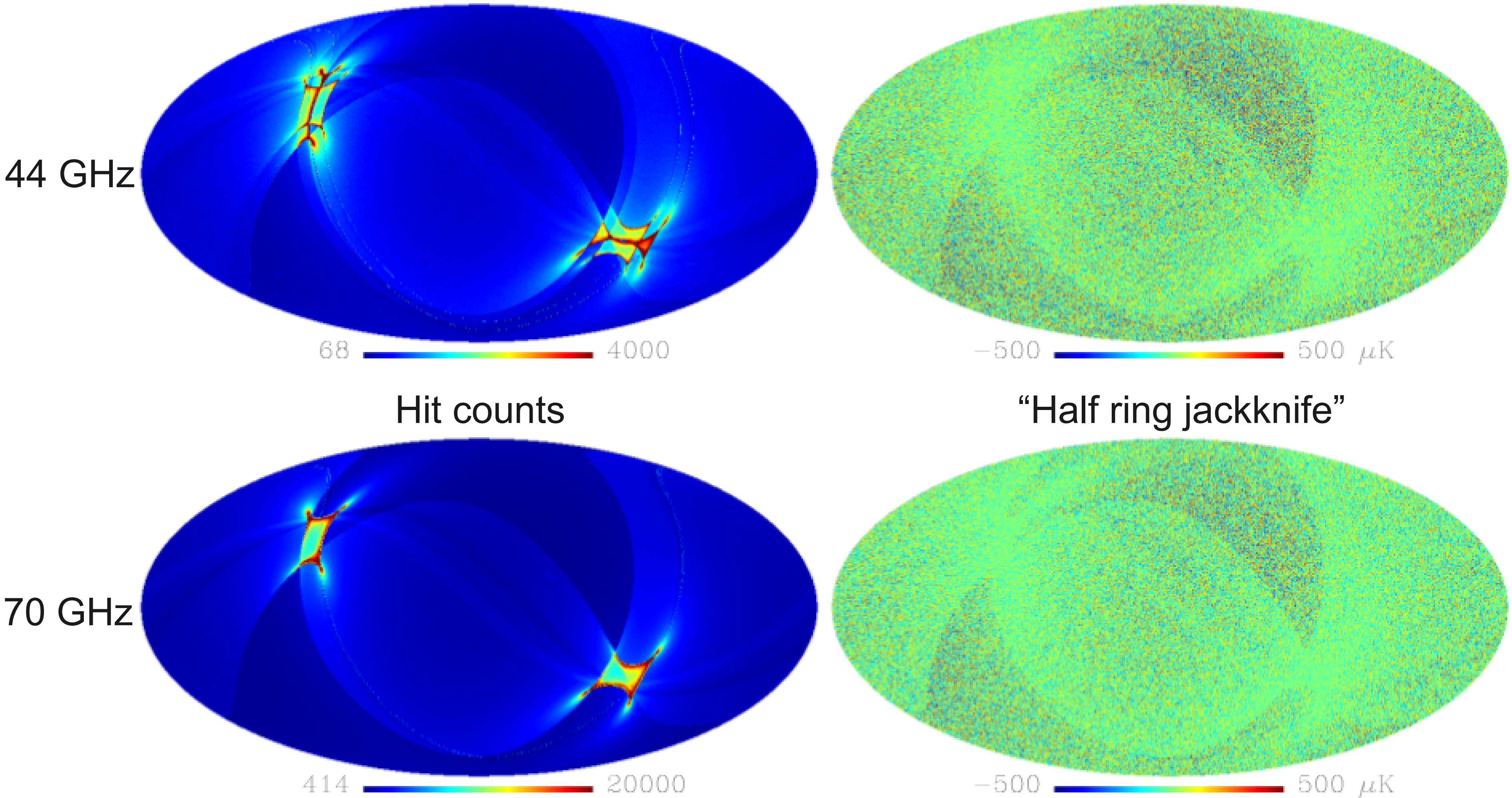
Channel	$N_{detectors}$ [a]	ν_{center} [b] [GHz]	Mean Beam[c] FWHM	Mean Beam[c] Ellipticity	White-noise[d] Sensitivity [$\mu K_{RJ}\, s^{1/2}$]	White-noise[d] Sensitivity [$\mu K_{CMB}\, s^{1/2}$]	Calibration[e] Uncertainty [%]	Faintest Source[f] in ERCSC $\lvert b \rvert > 30°$ [mJy]
30 GHz	4	28.5	32.65	1.38	143.4	146.8	1	480
44 GHz	6	44.1	27.92	1.26	164.7	173.1	1	585
70 GHz	12	70.3	13.01	1.27	134.7	152.6	1	481
100 GHz	8	100	9.37	1.18	17.3	22.6	2	344
143 GHz	11	143	7.04	1.03	8.6	14.5	2	206
217 GHz	12	217	4.68	1.14	6.8	20.6	2	183
353 GHz	12	353	4.43	1.09	5.5	77.3	2	198
545 GHz	3	545	3.80	1.25	4.9	. . .	7	381
857 GHz	3	857	3.67	1.03	2.1	. . .	7	655

From “Planck Early Results: The Planck Mission”: arXiv:1101.2022

- Based on a preliminary processing of the first 1.6 sky surveys.
- Very close to expectations in the Planck “Blue Book”.

Sky coverage

- **Inhomogeneous coverage** in I, Q and U. To be characterised with IQU covariance at each pixel, low resolution pixel-pixel covariance, “jackknife” maps and Monte Carlo simulations.



Systematics

Planck

- Interaction between calibration / low frequency noise / scanning strategy.

LFI

- Bandpass mismatch – Model foregrounds and subtract.
- Elliptical beams – Deconvolution or perturbative correction.

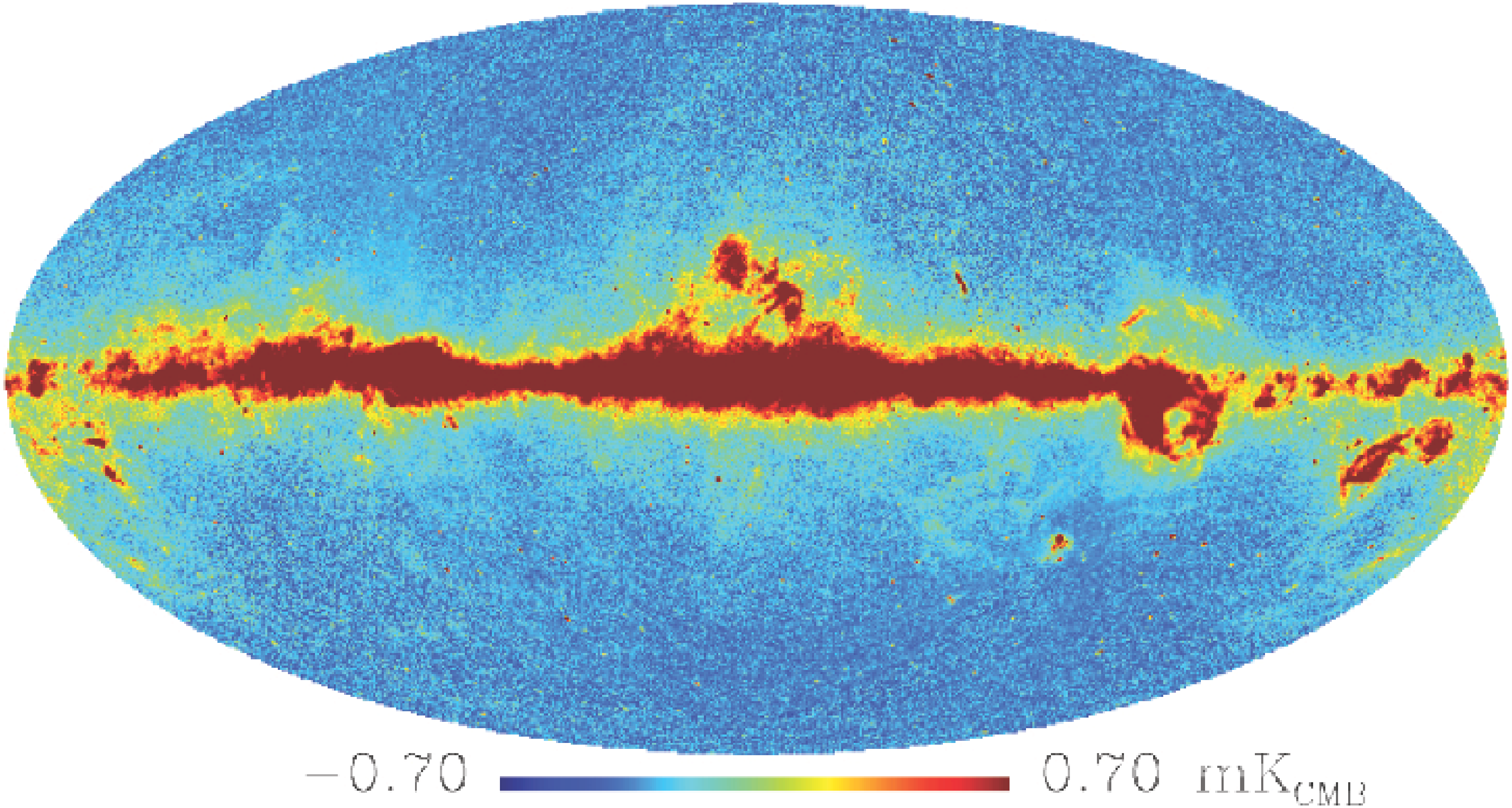
HFI

- Cosmic ray glitches – Higher rate than expected, manageable loss of data from glitch removal (~10-15%).
- CO line emission (115 and 230 GHz) – Mainly affecting 100 GHz and 217 GHz bands in regions of the sky near molecular clouds – Mitigation with external CO surveys.
- Non-gaussian beams at 545 and 857 GHz.

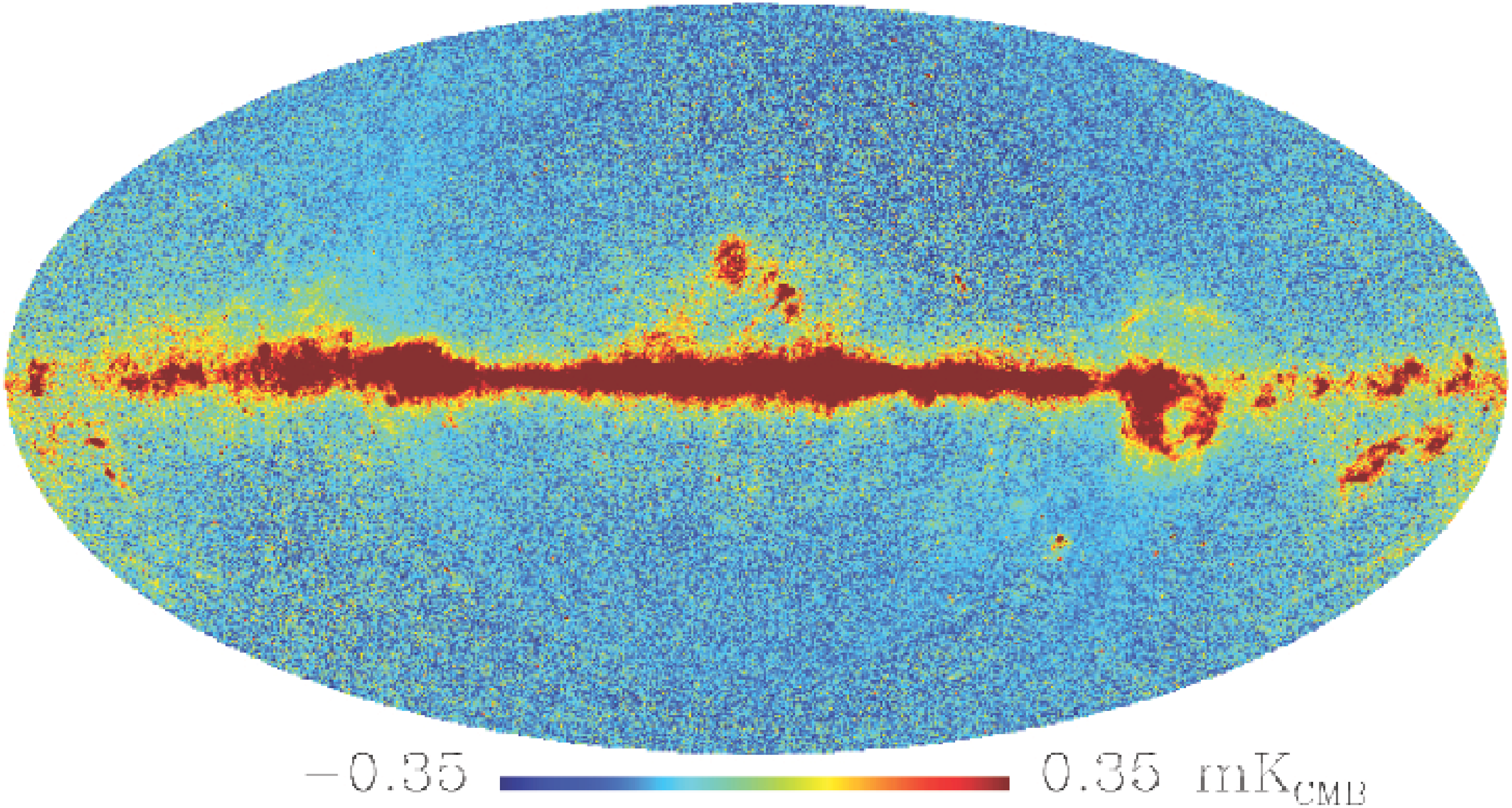
All the subject of a vigorous analysis and mitigation effort.

30 GHz

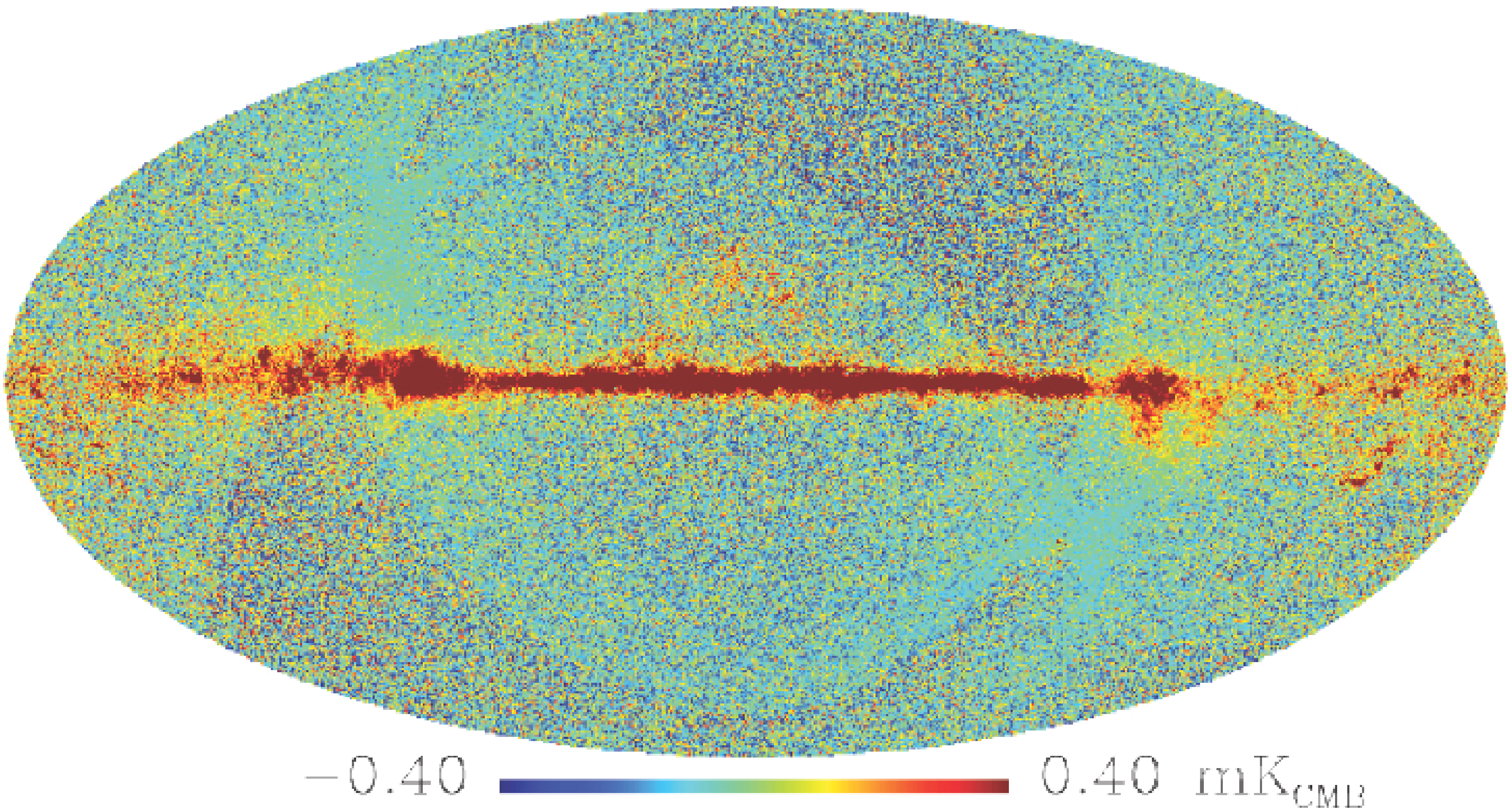
With CMB estimate subtracted



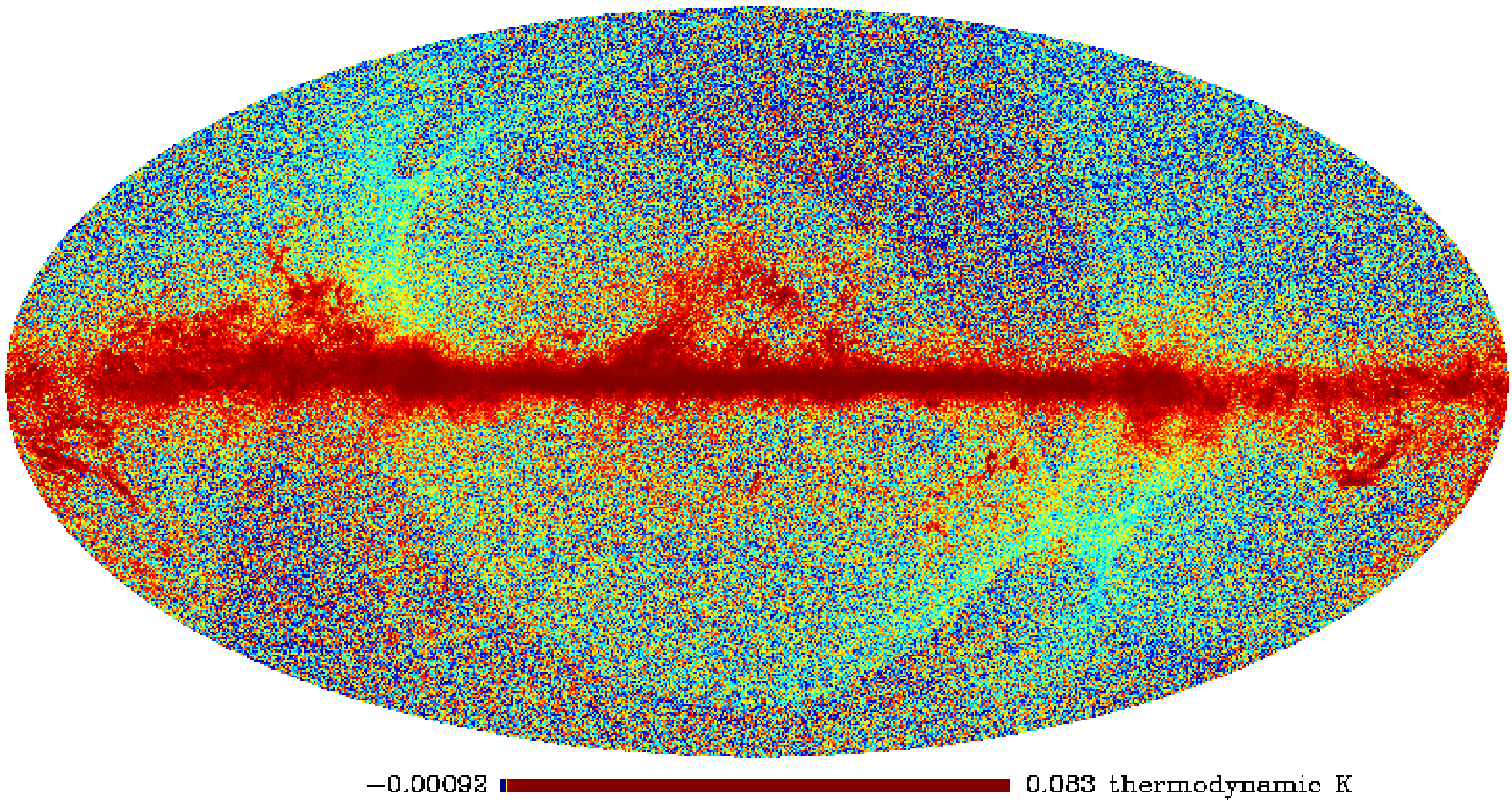
44 GHz



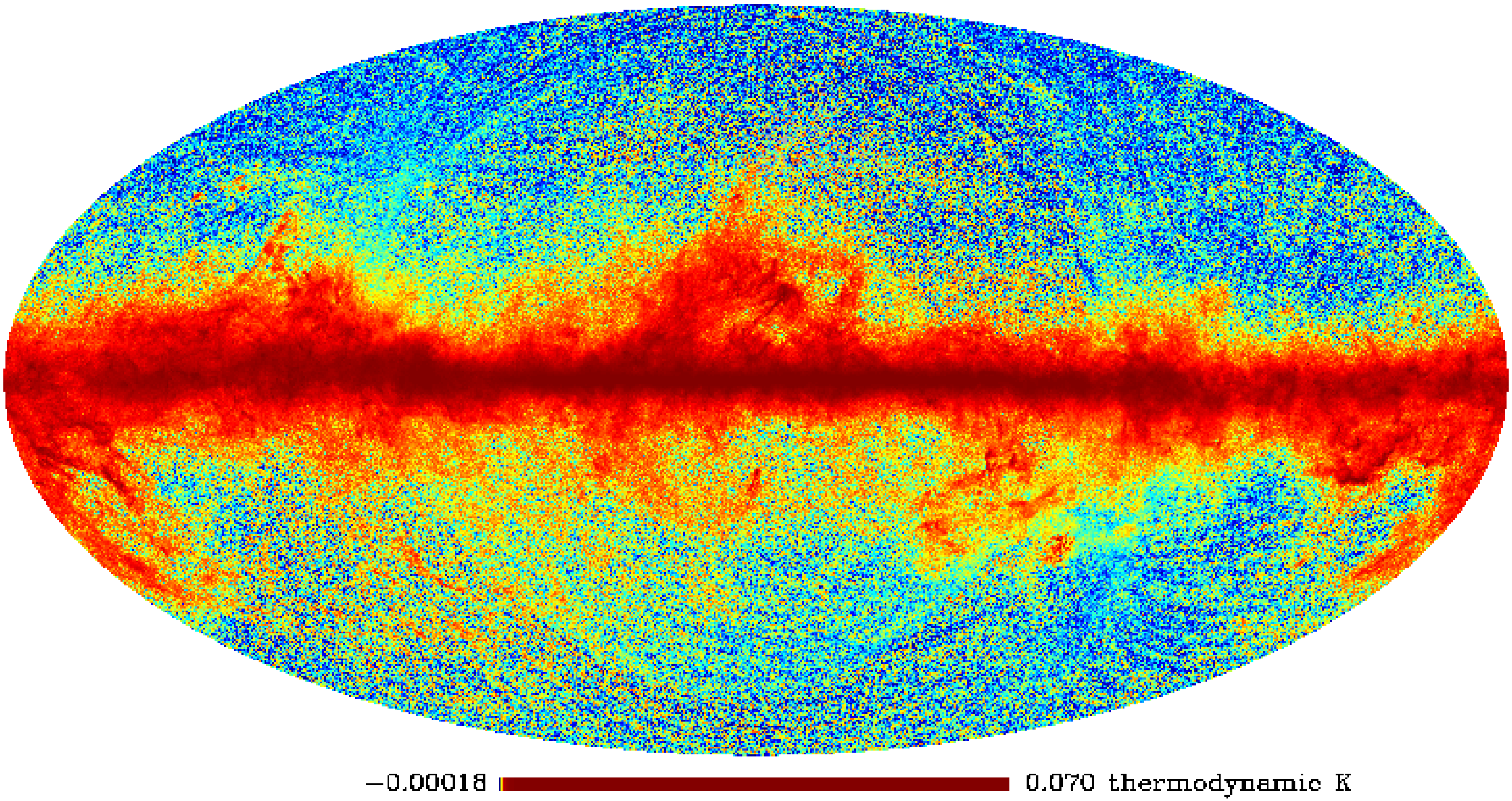
70 GHz



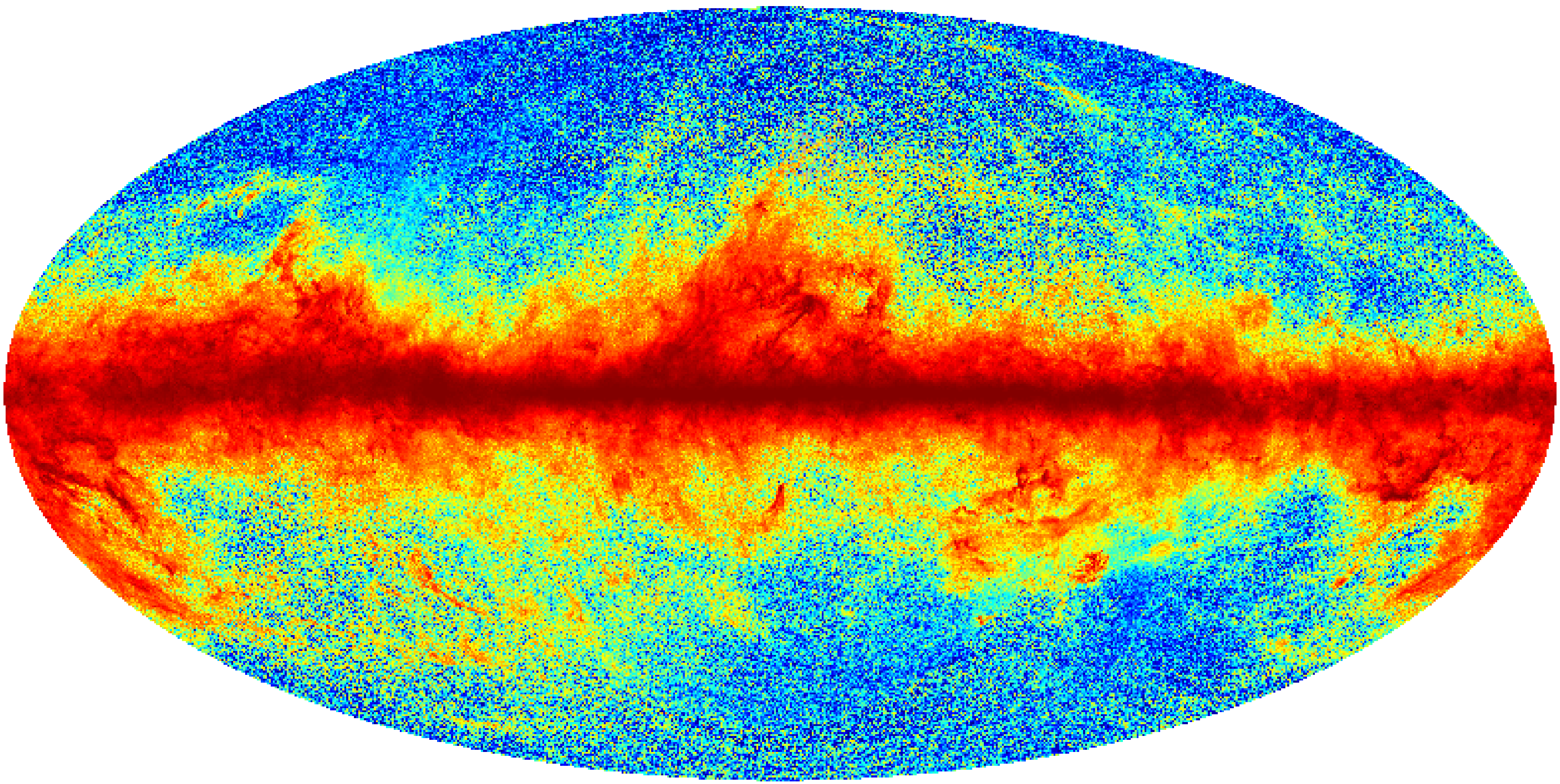
100 GHz



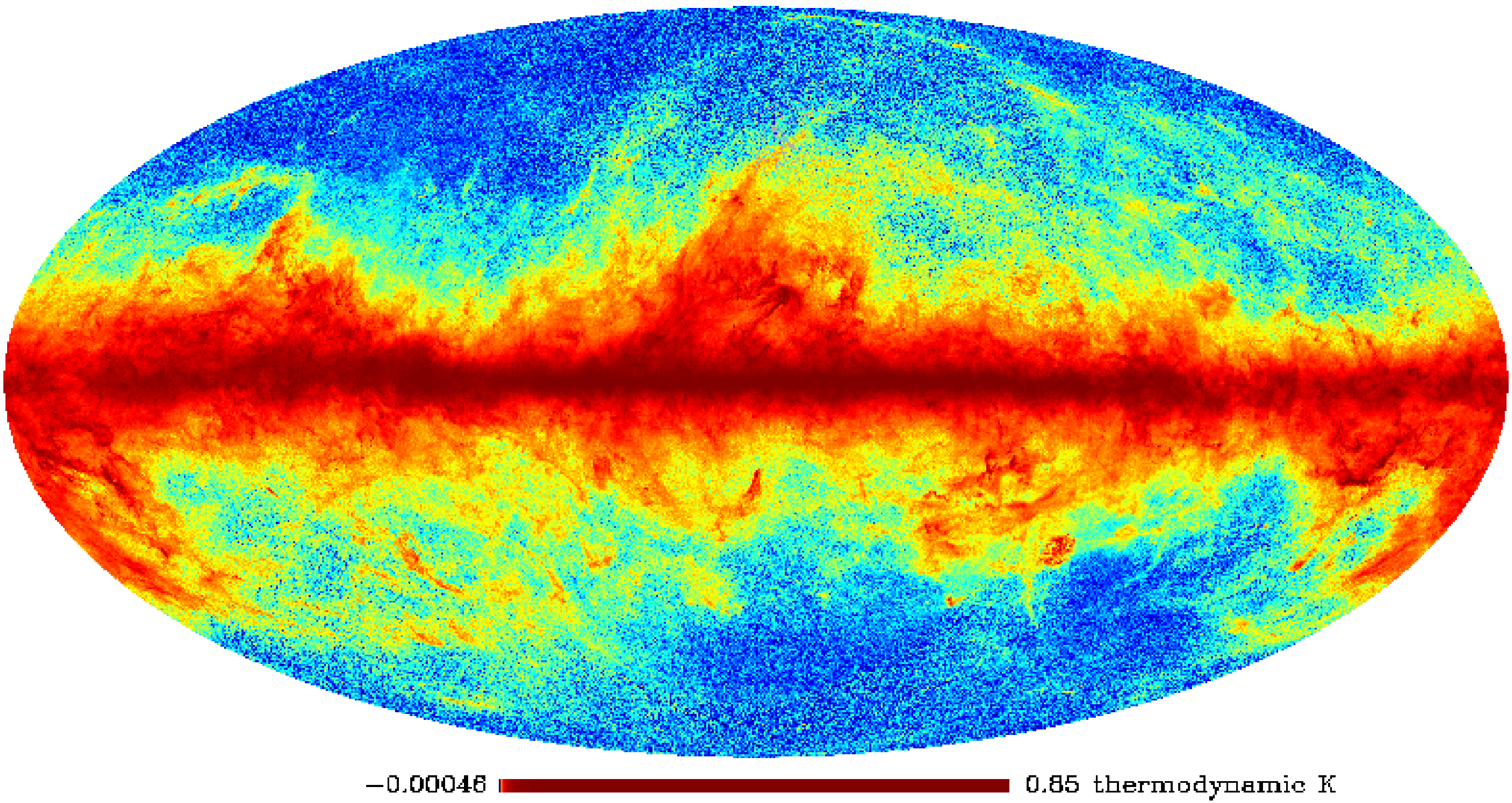
143 GHz



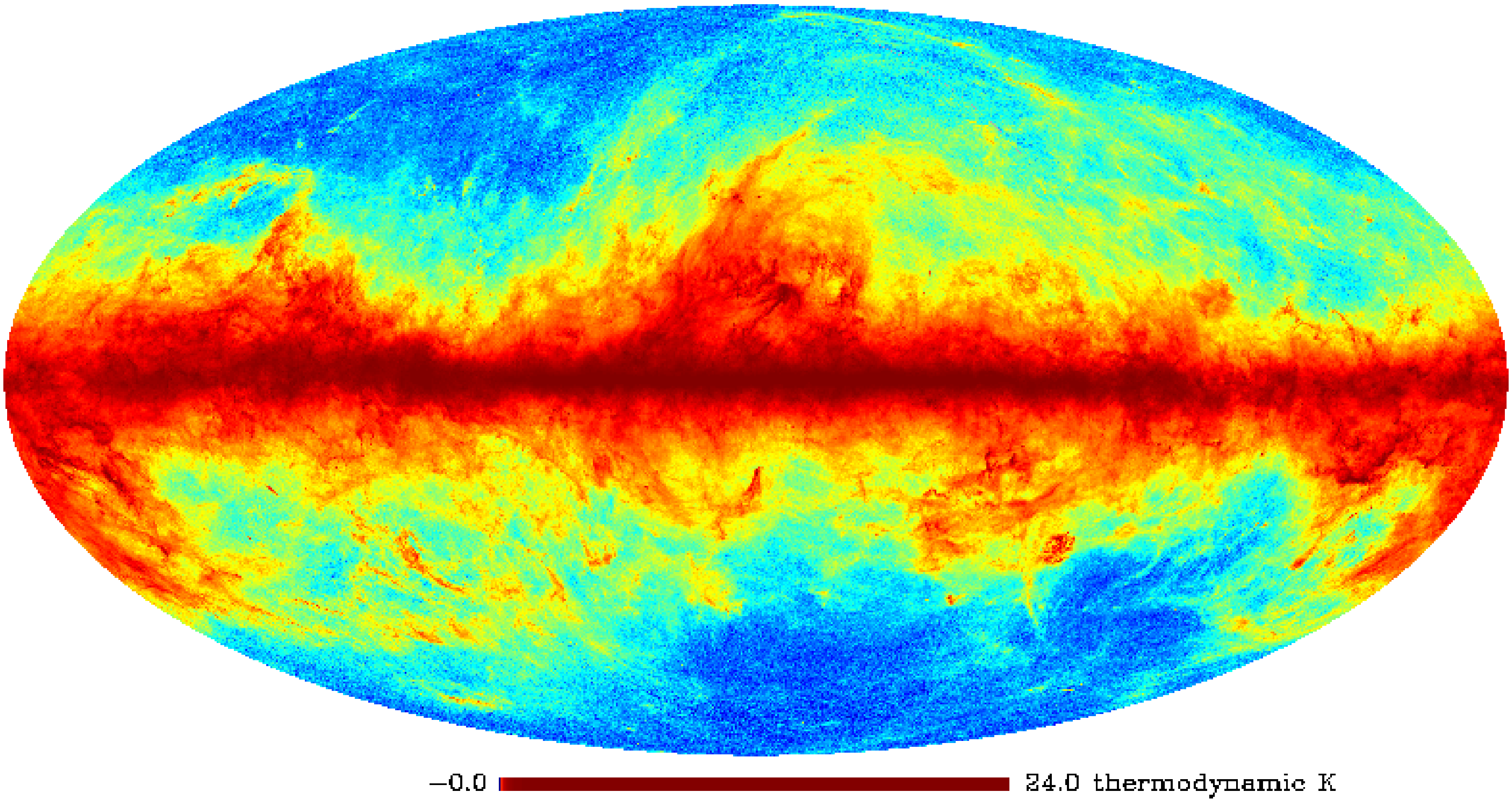
217 GHz



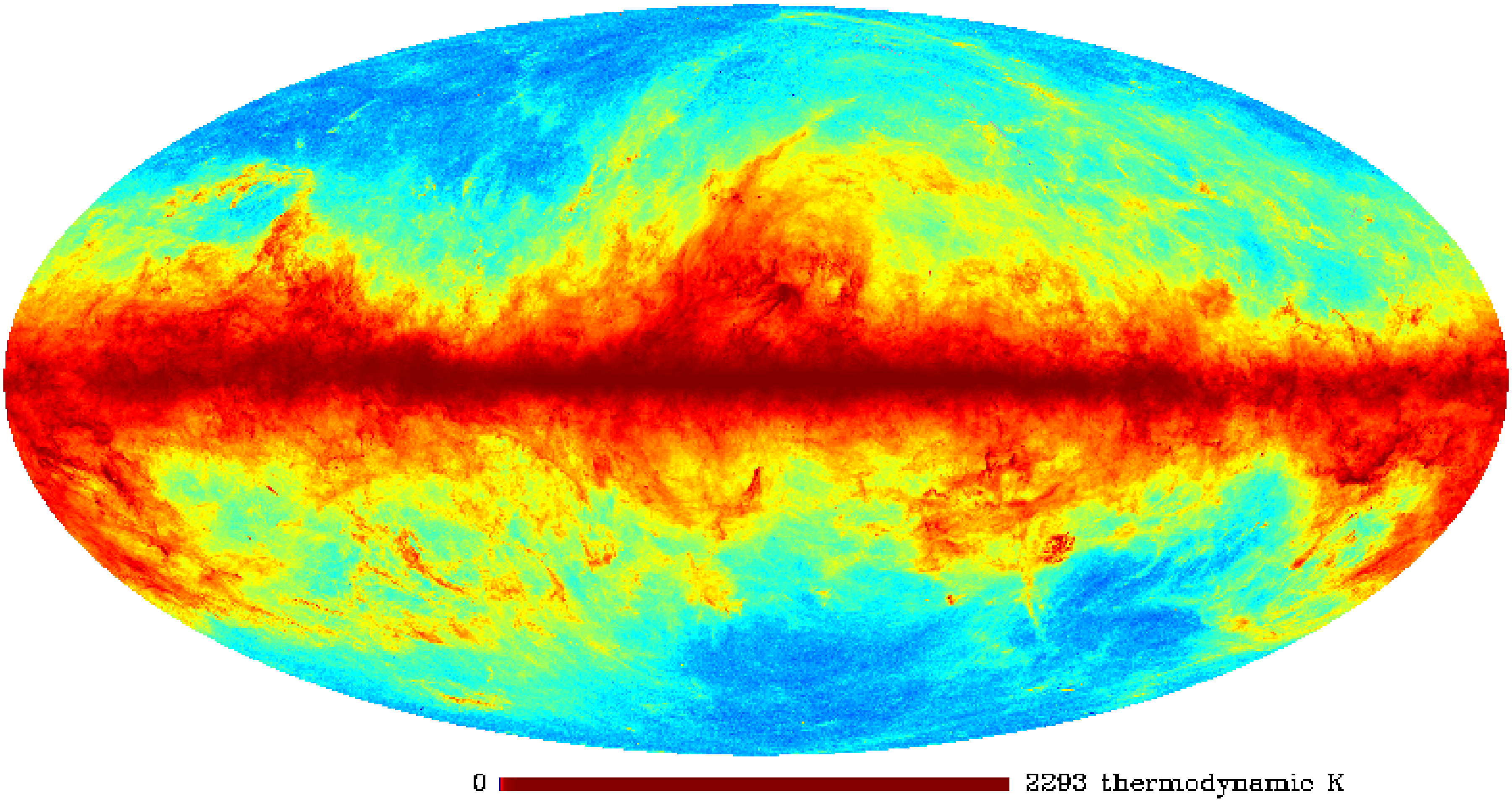
353 GHz



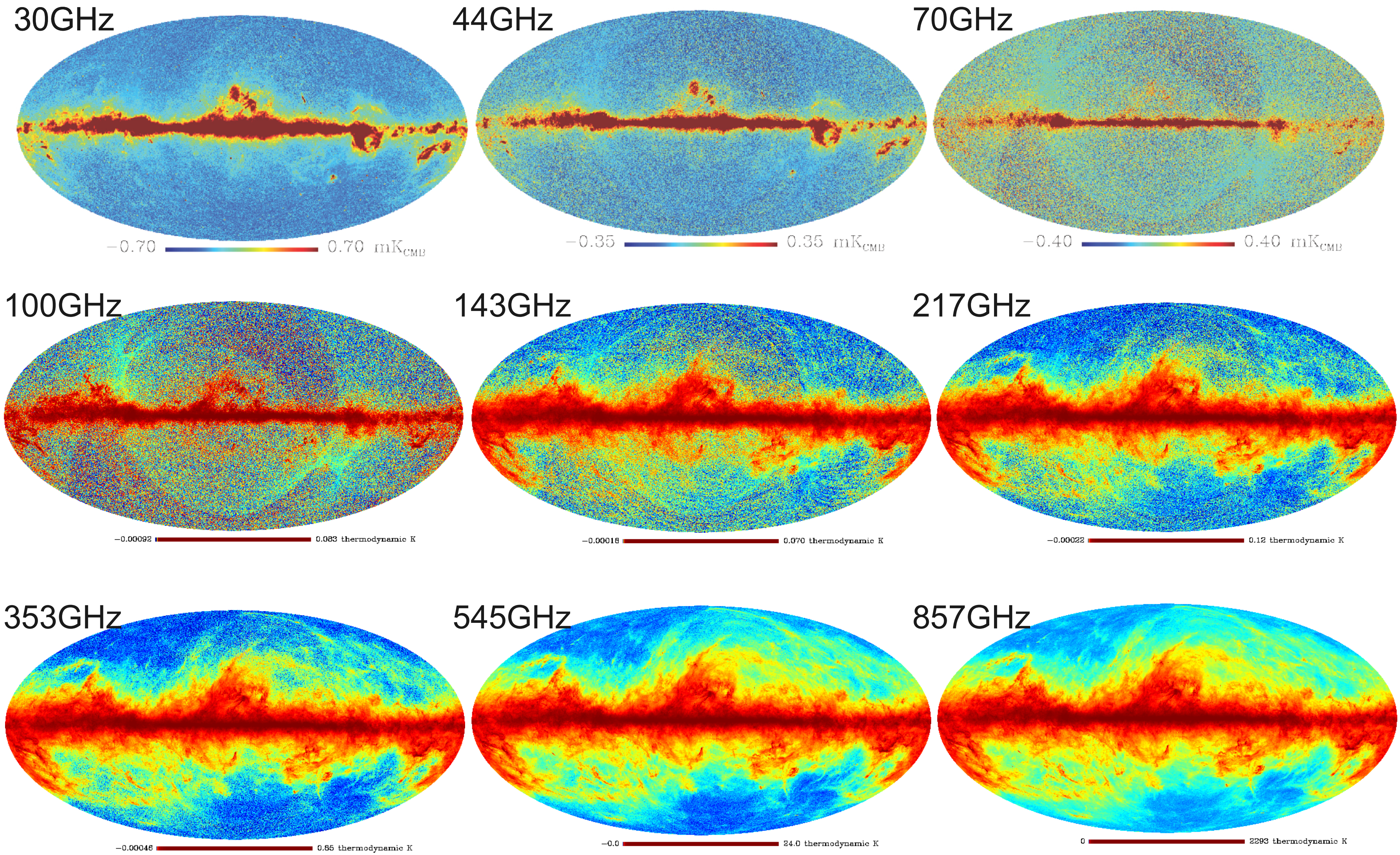
545 GHz



857 GHz



Planck foreground estimates



Sunyaev-Zel'dovich effect

- First all-sky SZ cluster catalogue.
- 189 SZ clusters, 20 new candidates, 11 confirmed by XMM, 4+1 confirmed by SPT, 1 confirmed by AMI.

"Planck Early Results: The all-sky early Sunyaev-Zel'dovich cluster sample"

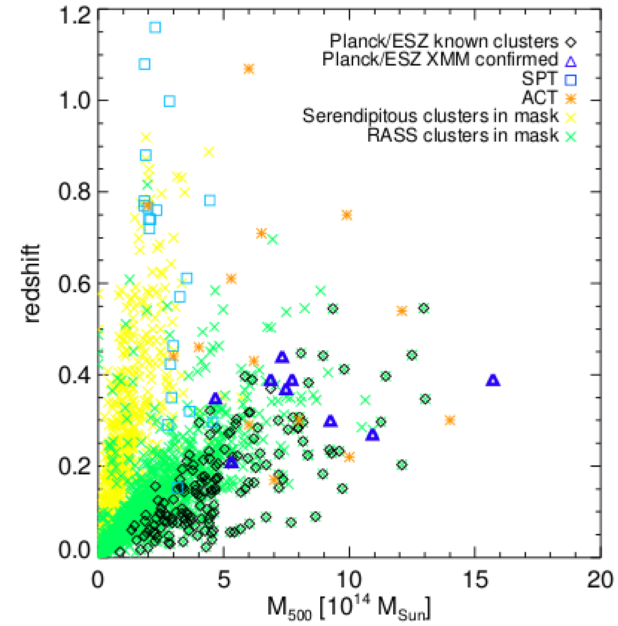
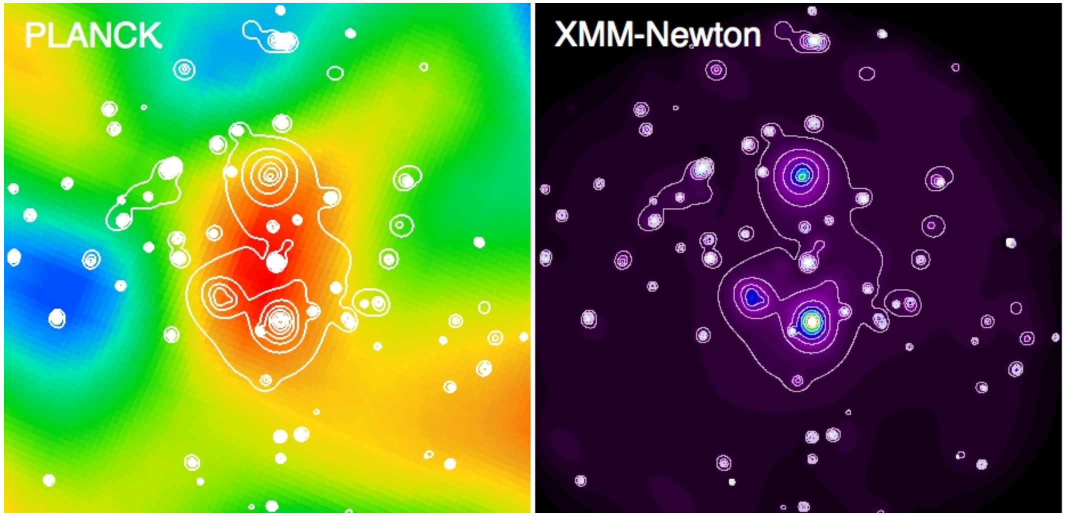
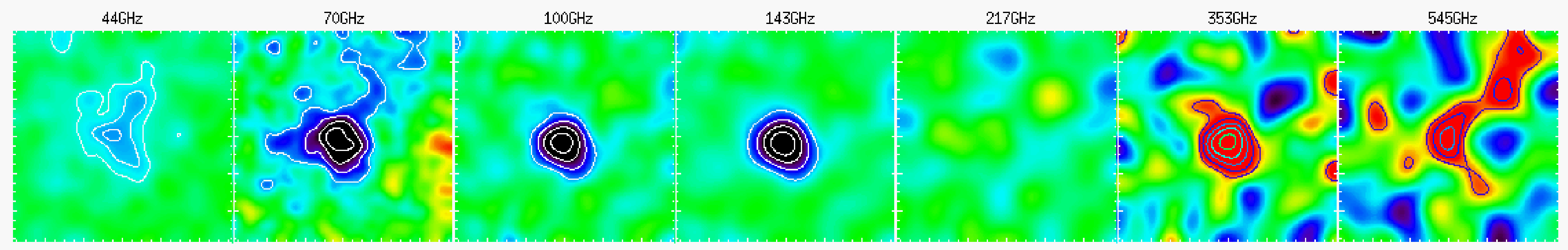


Fig. 20. The 158 clusters from the *Planck* ESZ sample identified with known X-ray clusters in redshift–mass space, compared with SPT and ACT samples from Menanteau et al. (2010); Vanderlinde et al. (2010), as well as serendipitous and RASS clusters



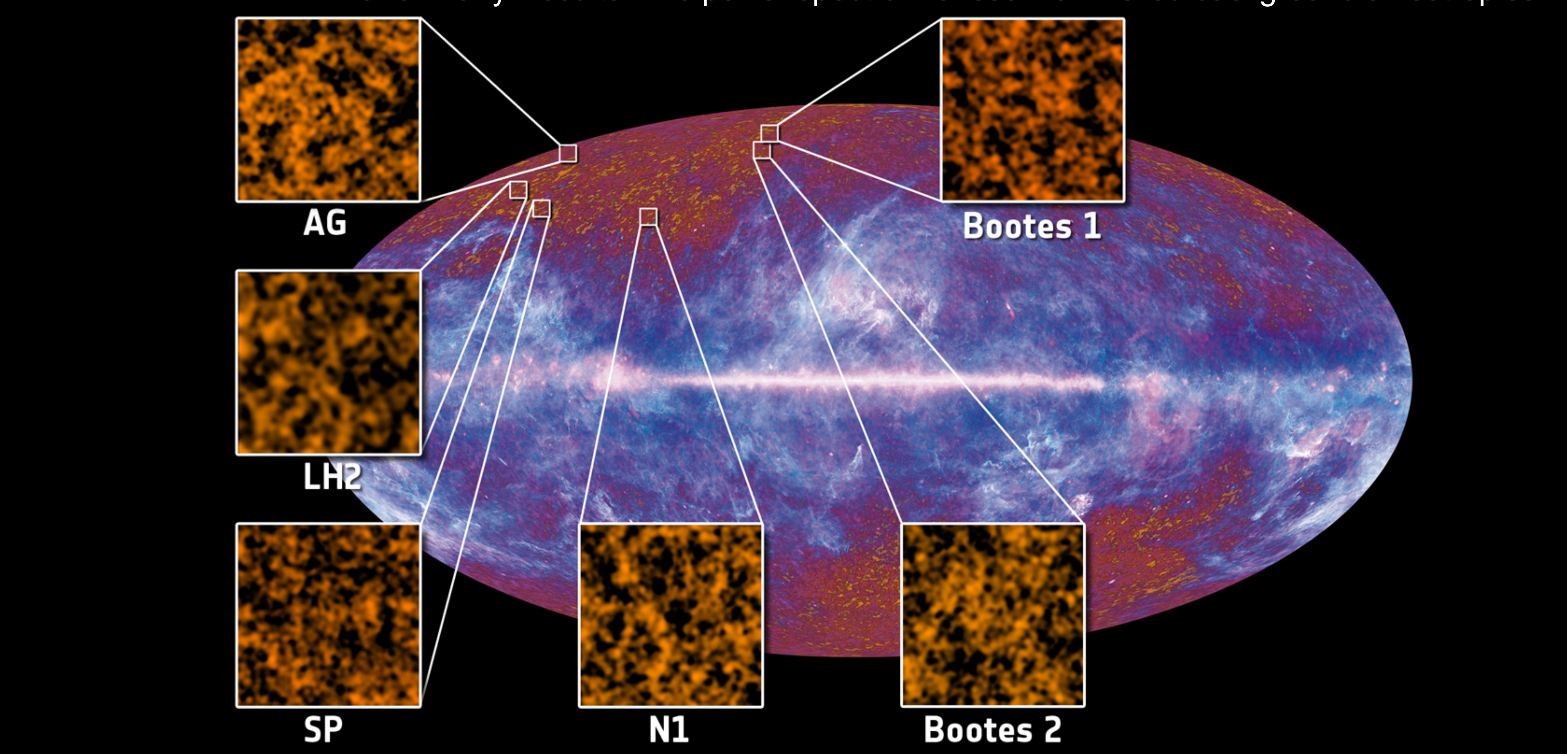
Planck SZ detection around Abel 2319



Cosmic infrared background

- Unresolved high redshift dusty galaxies in the 217 – 857 GHz bands.
- Demonstrating Planck's ability to perform component separation, and to measure and characterise temperature anisotropies.
- Contaminant to the CMB power spectrum at high multipoles.

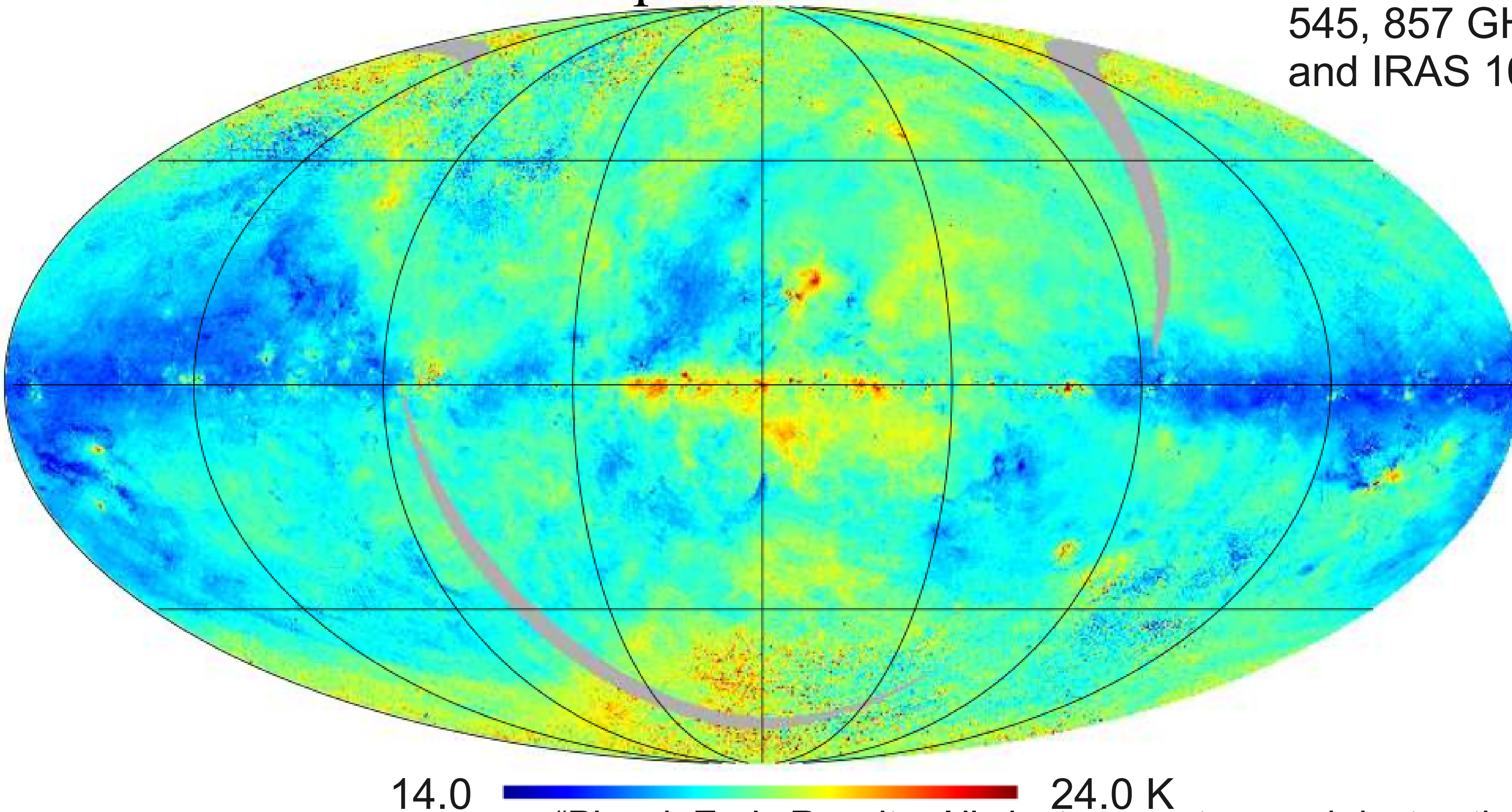
“Planck Early Results: The power spectrum of cosmic infrared background anisotropies”



All-sky dust temperature

- Planck bands well suited for finding cold dust in the ISM.
- How do these measured dust temperature variations extrapolate across the CMB channels ?
- What does this look like in polarization ?

545, 857 GHz
and IRAS 100um

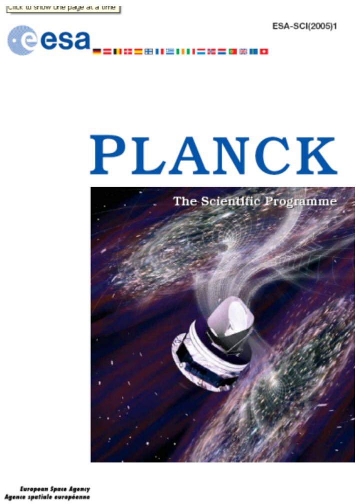


"Planck Early Results: All sky temperature and dust optical depth from Planck and IRAS: Constraints on the "dark gas" in our Galaxy"

Planck cosmology programme

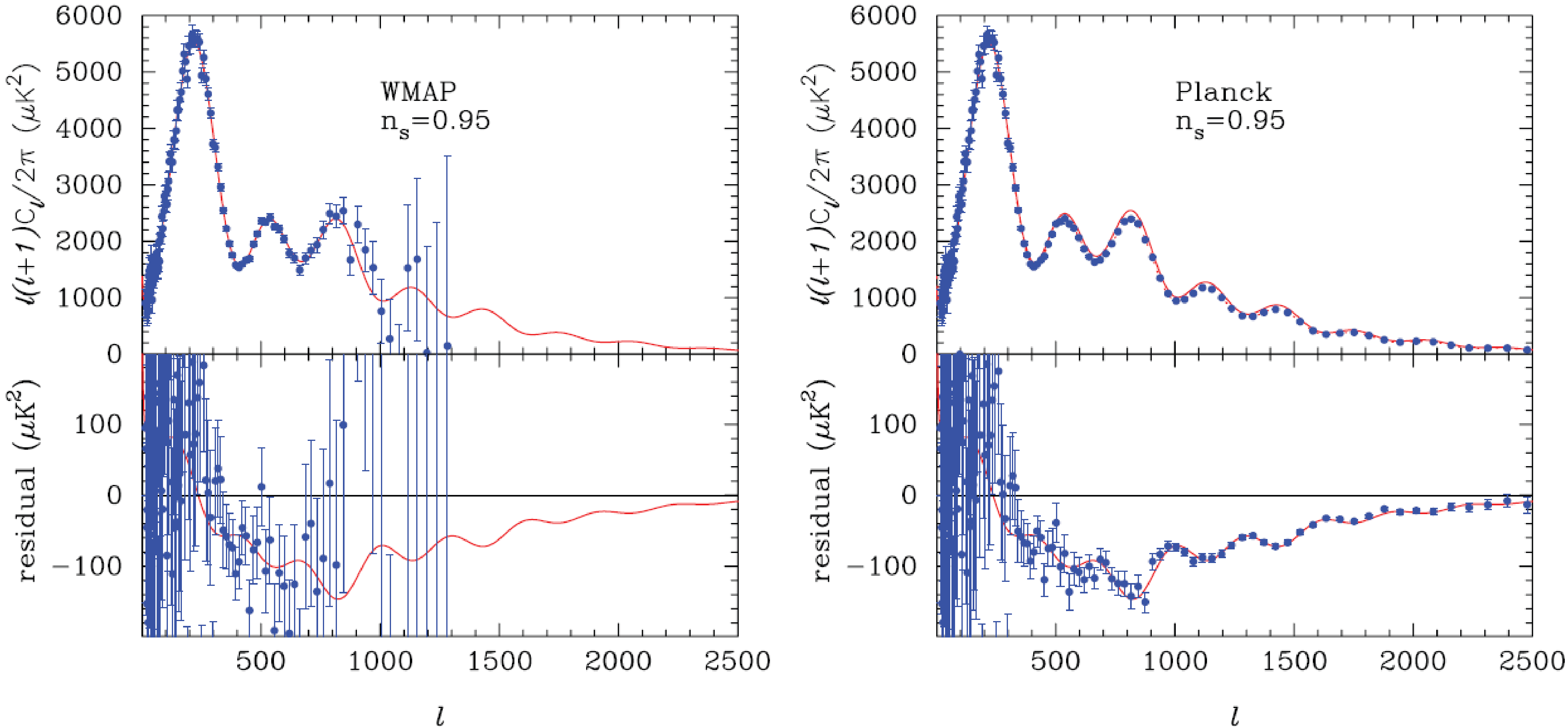
- Sketched out in the Planck “Blue Book” (astro-ph/0604069). Includes,

  - Inflation parameters and primordial power spectrum reconstruction.
  - CMB statistics and isotropy.
  - Characterisation of CMB non-gaussianity.
  - CMB weak lensing.
  - Topology.



Angular power spectra - temperature

- Forecasts from the Blue Book:



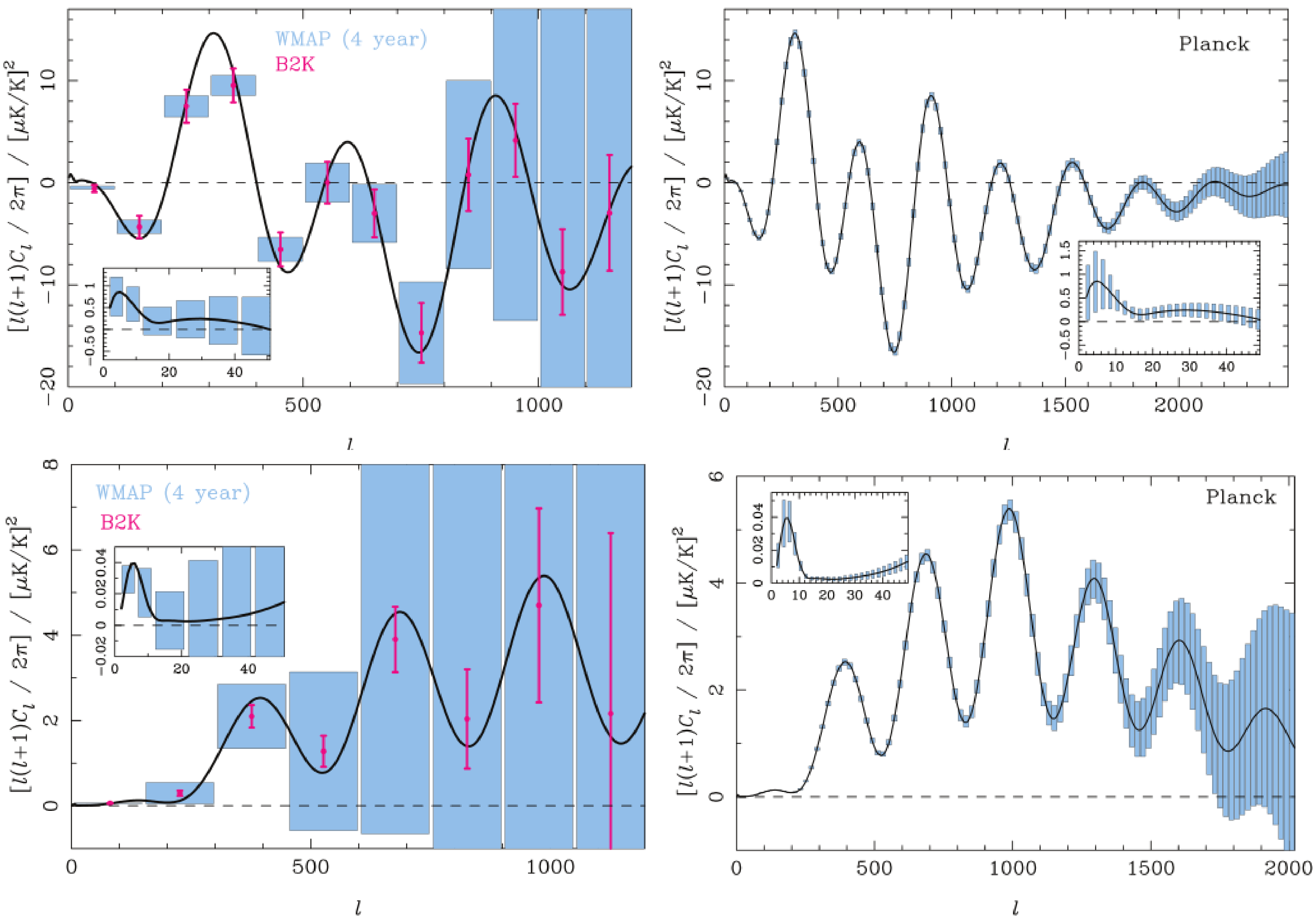
- Science to be enabled by Planck's angular resolution and sensitivity.

Planck forecast:

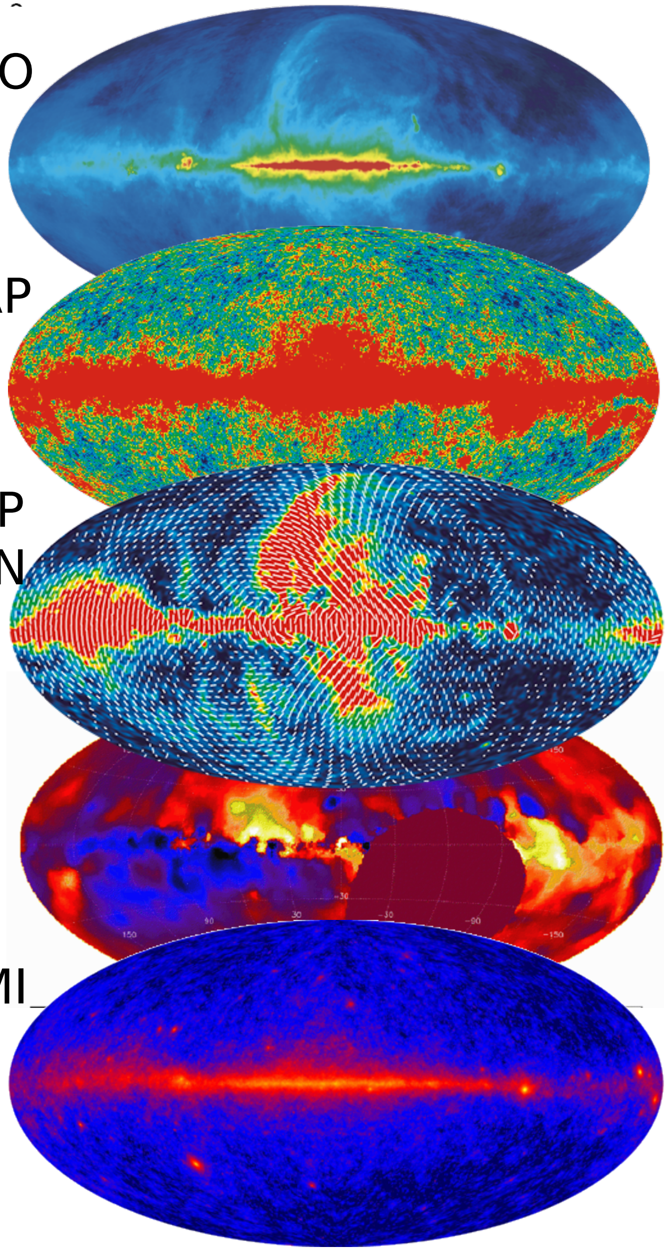
$$\Delta n_S \simeq 0.005$$

Angular power spectra – TE and E-modes

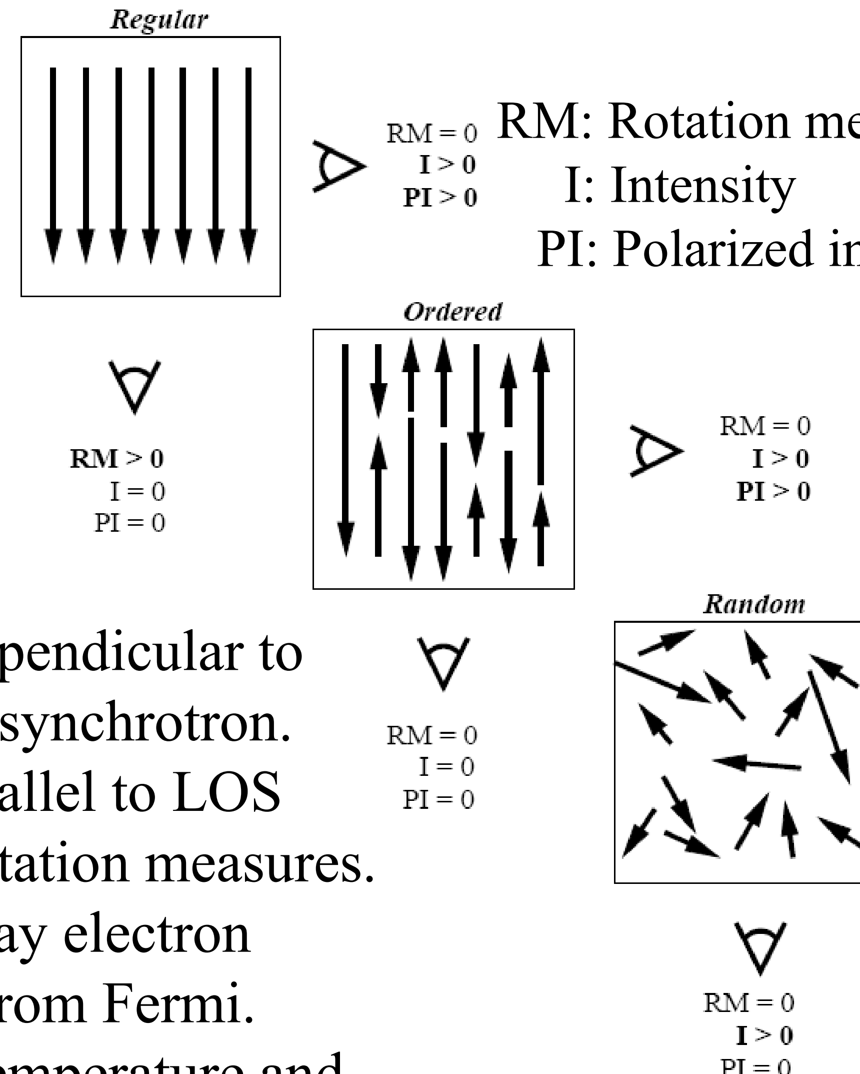
- Forecasts from the Blue Book:



Galactic magnetic field – B-mode foreground?



RM: Rotation measure
I: Intensity
PI: Polarized intensity



From T.R.Jaffe et al 2009

- GMF perpendicular to LOS from synchrotron.
- GMF parallel to LOS Faraday rotation measures.
- Cosmic ray electron spectrum from Fermi.
- Dust in temperature and polarization as new tracer of GMF from Planck.

Inflation constraints

Back to cosmology, Basic idea in place for some time now:

$$C_\ell^{XX'} = \frac{2\pi}{\ell(\ell+1)} \int d\ln k\, \mathcal{P}(k)\, T_\ell^{X}(k;\{\omega_i\})\, T_\ell^{X'}(k;\{\omega_i\})$$

- Phenomenological constraints on $n_\mathrm{S}, \dfrac{dn_\mathrm{S}}{d\ln k}, r$

  CosmoMC: Lewis and Bridle 2001

- Analytic slow-roll expansion of P(*k*) – Direct constraints on the Hubble expansion rate and its derivatives during inflation.

  Leach, Liddle, Martin, Schwarz 2002

- Exact numerical integration of inflationary mode equations – Departures from slow-roll, features in the potential.

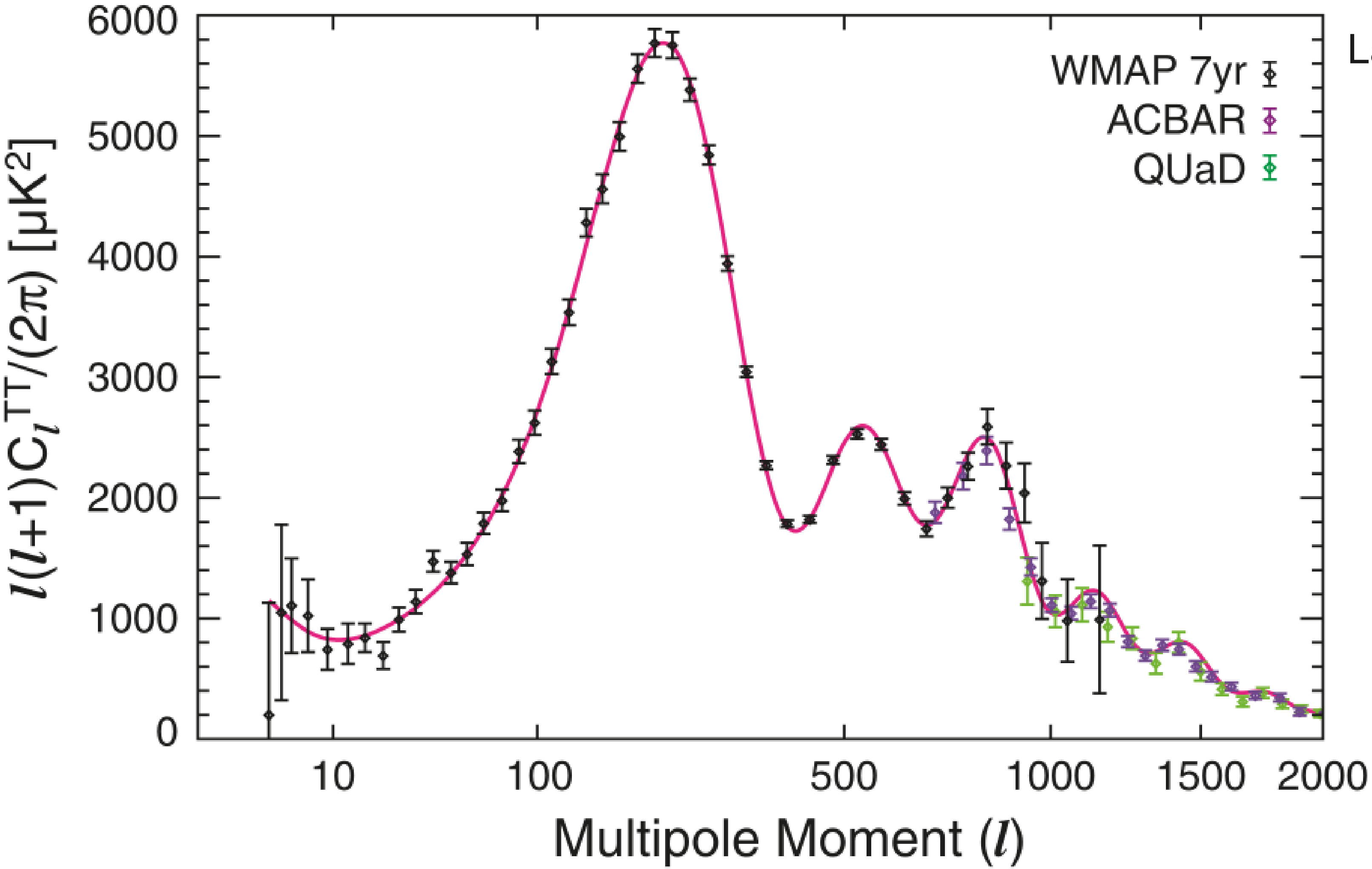
  Lesgourgues, Starobinsky, Valkenburg 2008, Mortonson, Peiris, Easther 2010

- Primordial power spectrum and inflation potential reconstruction.

  Hu and Okamato 2004, Hamann, Shafieloo, Souradeep 2010, Dvorkin and Hu 2010

Implement and apply these analysis methods, and figure out the implications

Current measurements - WMAP



Larson et al 2011

- Cosmic variance limited up to l = 550
- WMAP team adamant that their maps are gaussian. Bennett et al 2011

Current inflation constraints

Komatsu et al 2010

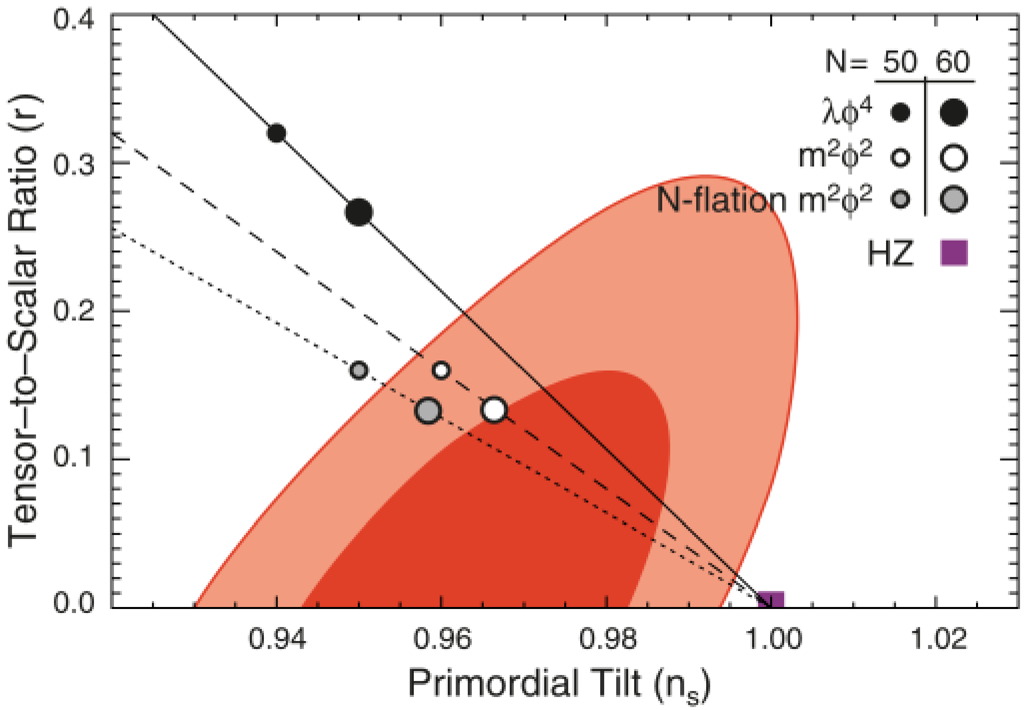
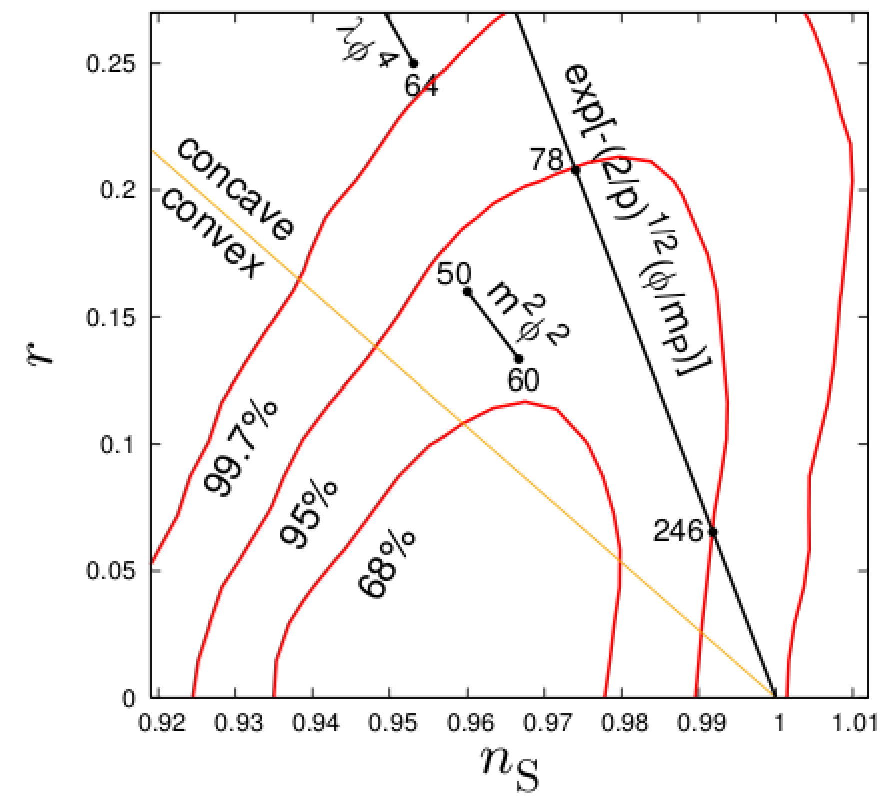


FIG. 20.— Two-dimensional joint marginalized constraint (68% and 95% CL) on the primordial tilt, n_s, and the tensor-to-scalar ratio, r, derived from the data combination of $WMAP$+BAO+H_0. The symbols show the predictions from "chaotic" inflation models whose potential is given by $V(\phi) \propto \phi^\alpha$ (Linde 1983), with $\alpha = 4$ (solid) and $\alpha = 2$ (dashed) for single-field models, and $\alpha = 2$ for multi-axion field models with $\beta = 1/2$ (dotted; Easther & McAllister 2006).

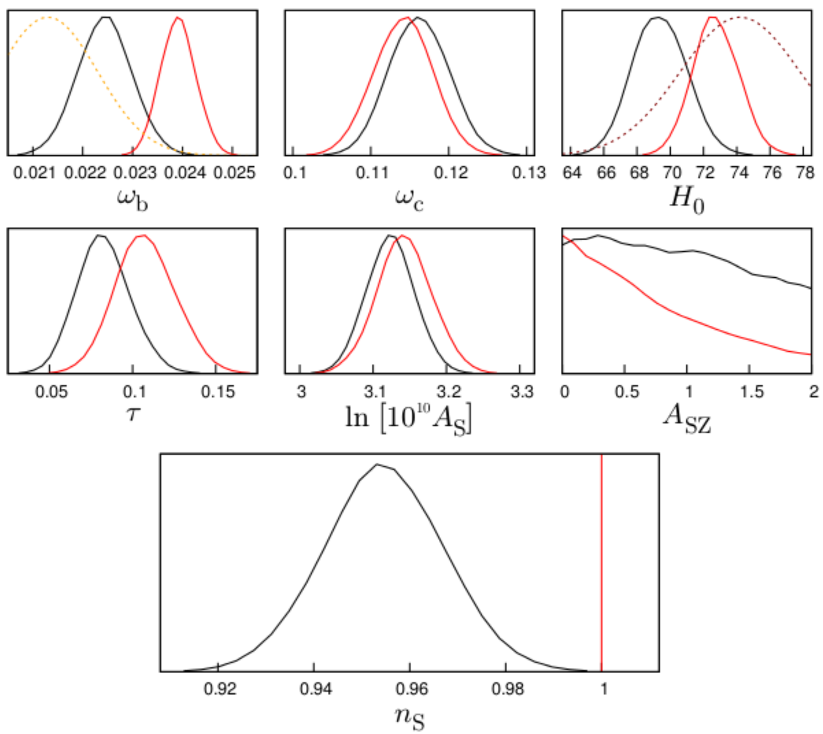
Finelli, Leach, Hamann, Lesgourgues 2010

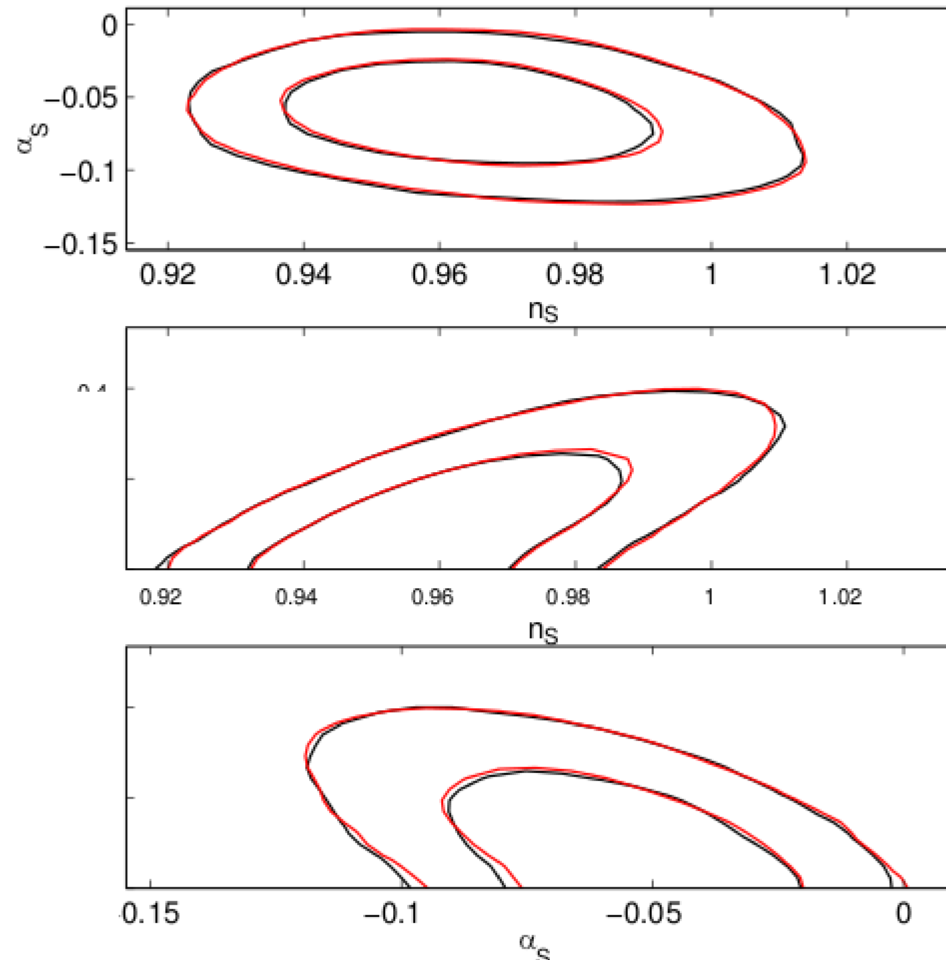


WMAP5+QUAD+ACBAR+SDSS LRG7

Scale invariant spectrum?

	HZ	tilted
ω_b	0.0239 ± 0.0007	0.0224 ± 0.001
ω_c	0.114 ± 0.007	0.116 ± 0.007
h	$0.728^{+0.027}_{-0.026}$	$0.694^{+0.032}_{-0.030}$
τ	$0.108^{+0.036}_{-0.034}$	$0.083^{+0.032}_{-0.029}$
$\log[10^{10} A_S]$	3.14 ± 0.07	3.12 ± 0.06
n_S	–	$0.955^{+0.024}_{-0.026}$
σ_8	0.853 ± 0.048	$0.822^{+0.047}_{-0.045}$





Finelli, Leach, Hamann, Lesgourgues 2010

$$\frac{dn_S}{d\ln k} = -0.046 \pm 0.039, \quad 95\%\mathrm{CL}$$

$$\epsilon_1 < 0.021\ , \quad \epsilon_2 + 2.7\epsilon_1 = 0.085^{+0.038}_{-0.039}\ , \quad \epsilon_2\epsilon_3 = 0.061^{+0.046}_{-0.042} \quad (95\%\ \mathrm{c.l.}).$$

Planck forecast:

$$\Delta \frac{dn_S}{d\ln k} \simeq 0.005$$

Sub-orbital CMB experiments

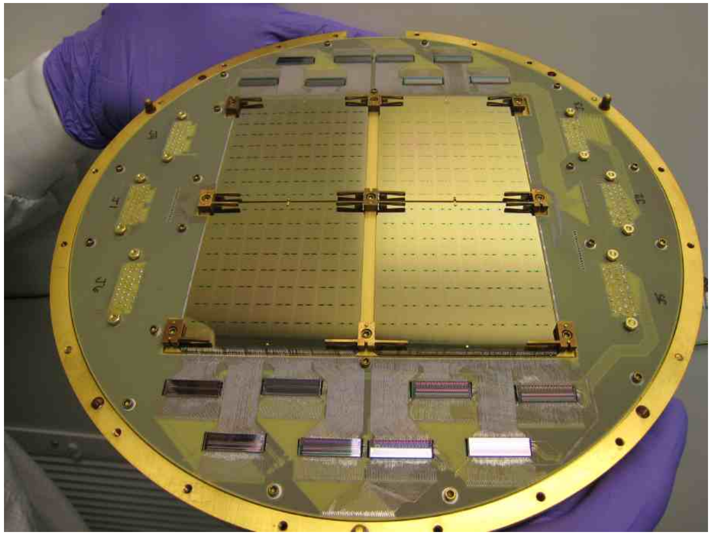
Ground-based:
- SPT(pol)
- ACT(pol)
- BICEP2/Keck
- PolarBear
- C-BASS
- QUIET

Balloon-borne:
- EBEX
- SPIDER
- PIPER

- Chasing a lot of the same science as Planck!
- Developing near term B-mode technology.

SPT

ACT

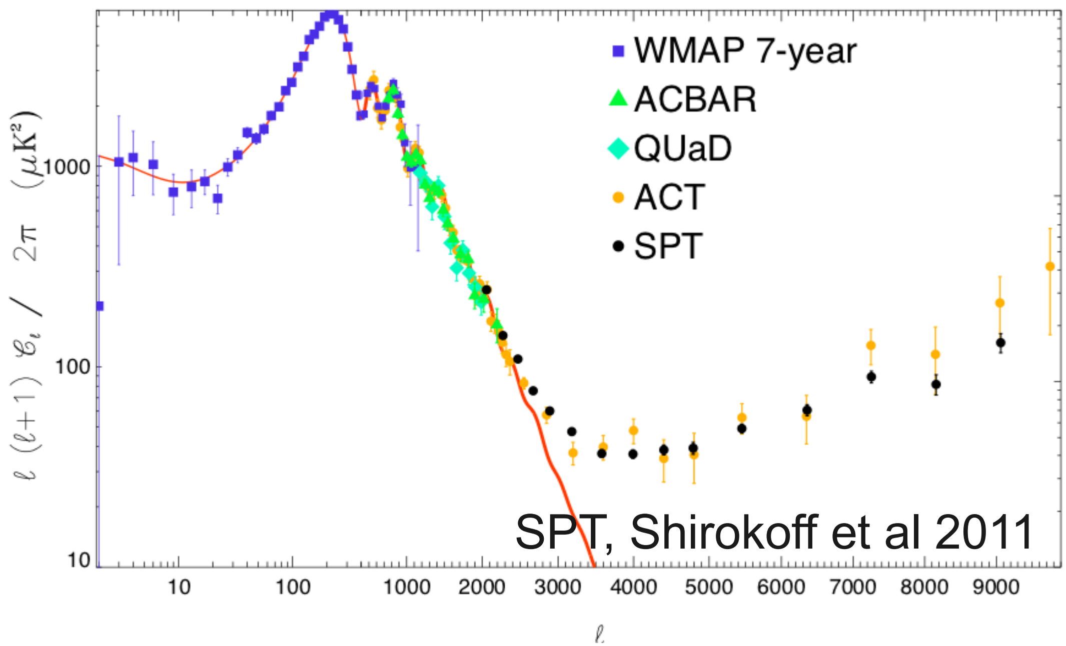


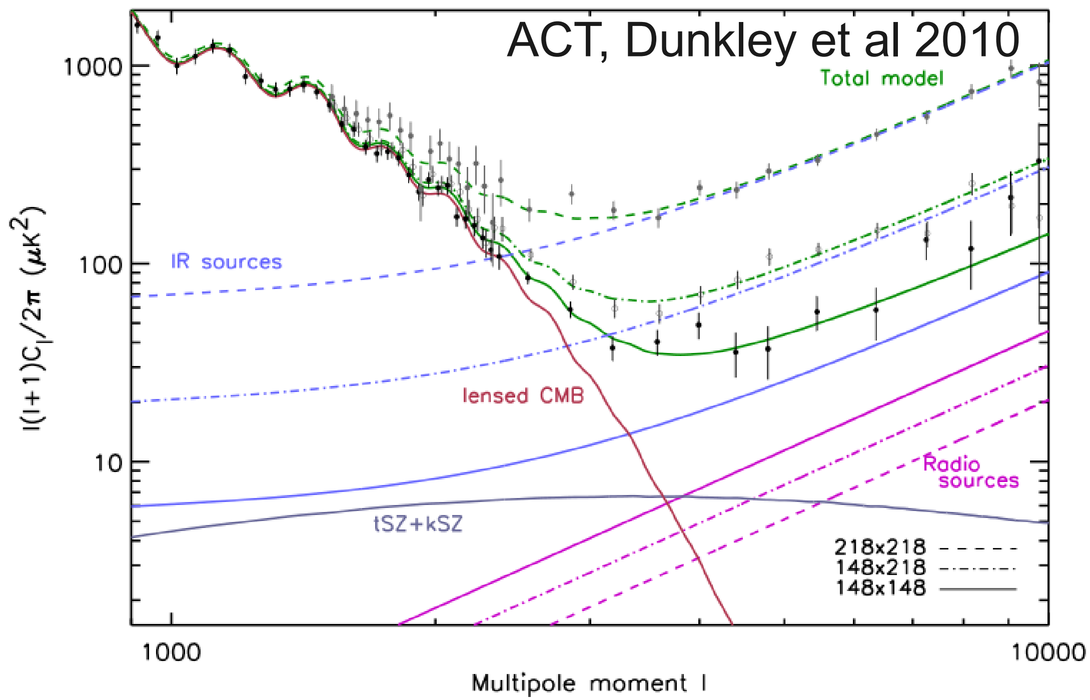
SPIDER

EBEX

Current measurements - secondaries

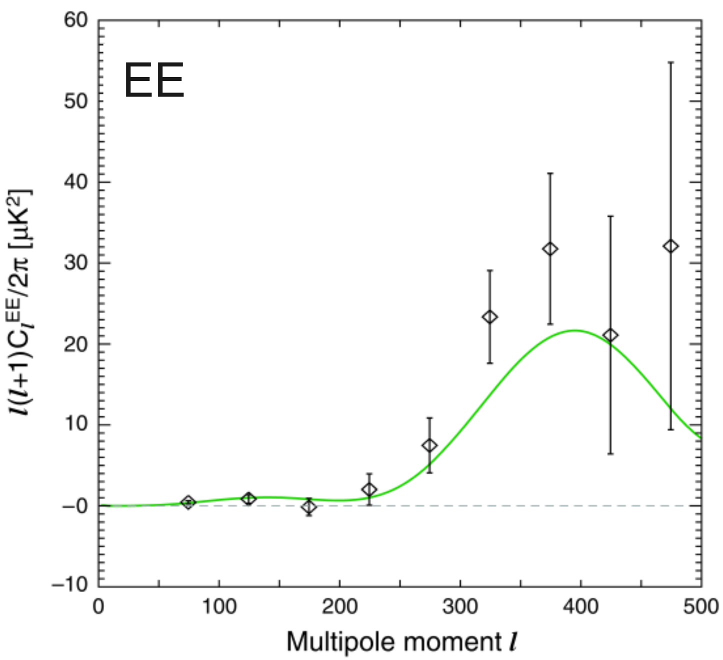
- New data flooding in from ground-based surveys.
- Helping Planck build up a model for high-l residual foreground uncertainties.



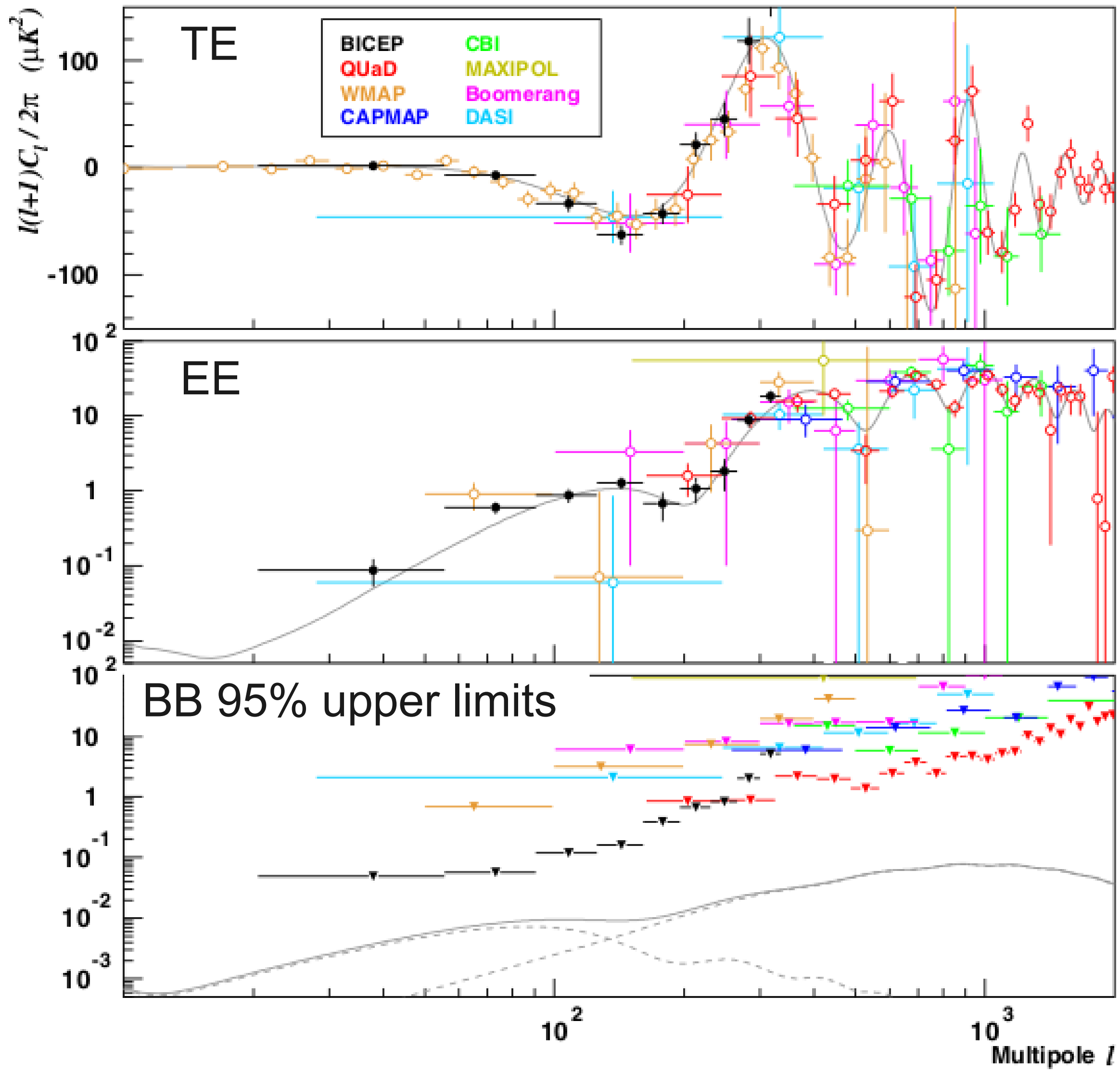


Current measurements - polarization

- Beginning to ramp up in sensitivity using 100s/1000s of detectors (cf Planck's 74 detectors).



Larson et al 2011



Chiang et al 2010

Path towards CMB cosmology

• August 2009:	Beginning of first survey.
• March 2010:	Beginning of second survey.
• October 2010:	End of nominal 14 month mission. Start of 1+1 years of data reduction and proprietary period. Start of 12+ month extended mission.
• ~January 2012:	HFI will stop working (five surveys). LFI (30 – 70 GHz) will operate beyond this date. WMAP9?
• **January 2013:**	**First cosmological results from Planck** (based on two sky surveys).

Planck - First data release

- Planned for January 2013.

- Cleaned, calibrated, time-ordered data.
- Frequency maps.
- Component maps and sky model.
- Source catalogues.
- Likelihood function.

Conclusions

- Planck is performing very well.
- Early astrophysical results demonstrate Planck's unique combination of frequency coverage, angular resolution and sensitivity.
- Now on the path towards CMB cosmology in January 2013.
- Get ready for Planck!

esa

planck

cnes

asi
agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

Gobierno de España
Ministerio de Ciencia e Innovación

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

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A" Aalto University

APC

California Institute of Technology

ioa

KICC
Kavli Institute for Cosmology Cambridge

Cavendish Astrophysics

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CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

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CESR

CITA–ICAT

CNRS IN2P3
Les deux infinis

ipac
Infrared Processing and Analysis Center

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Instituto de Astrofísica de Canarias

IFCA
Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
DATA CENTRE FOR ASTROPHYSICS

JPL

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LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

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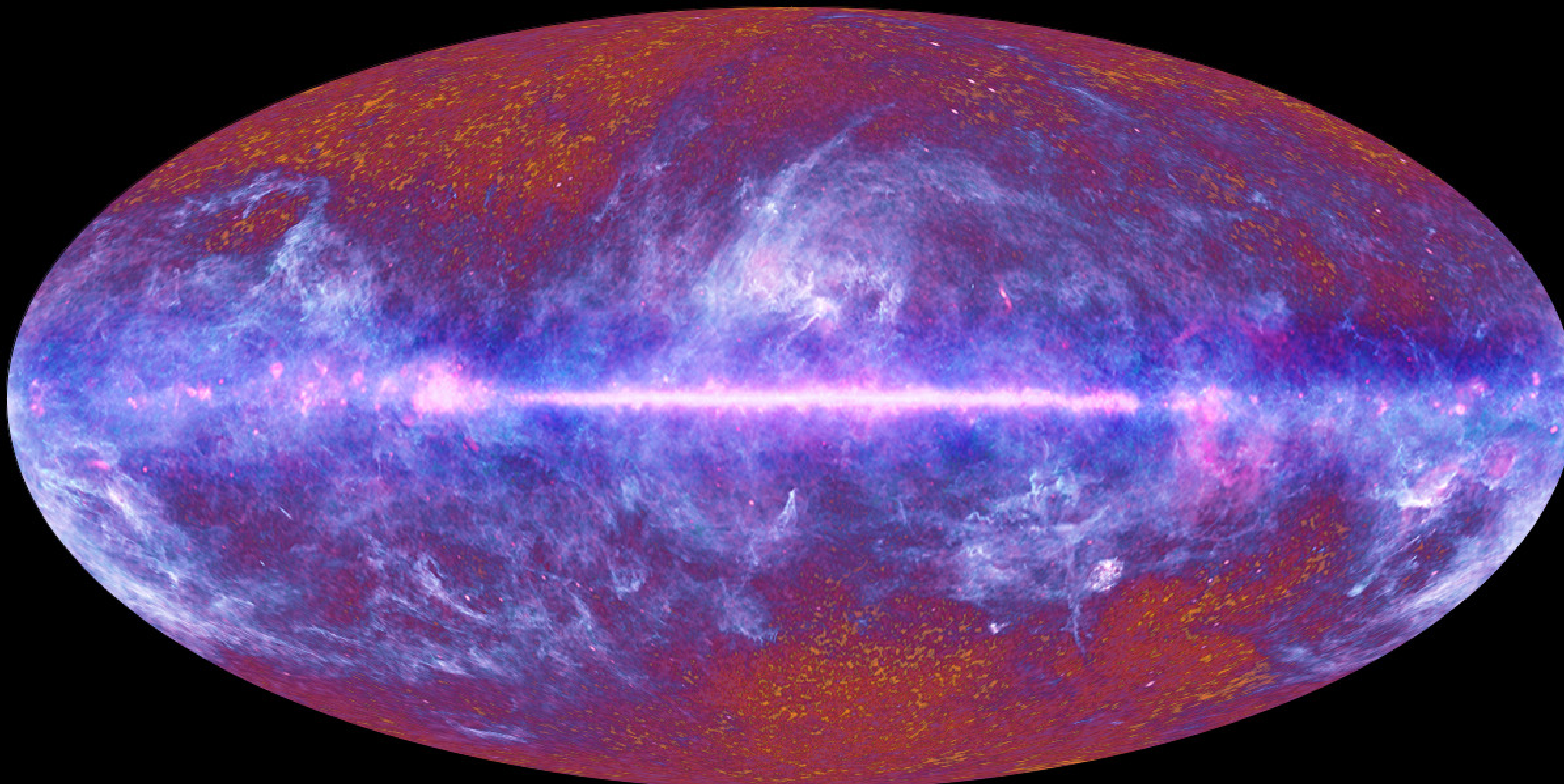
asdc
ASI Science Data Center



The Planck one-year all-sky survey

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