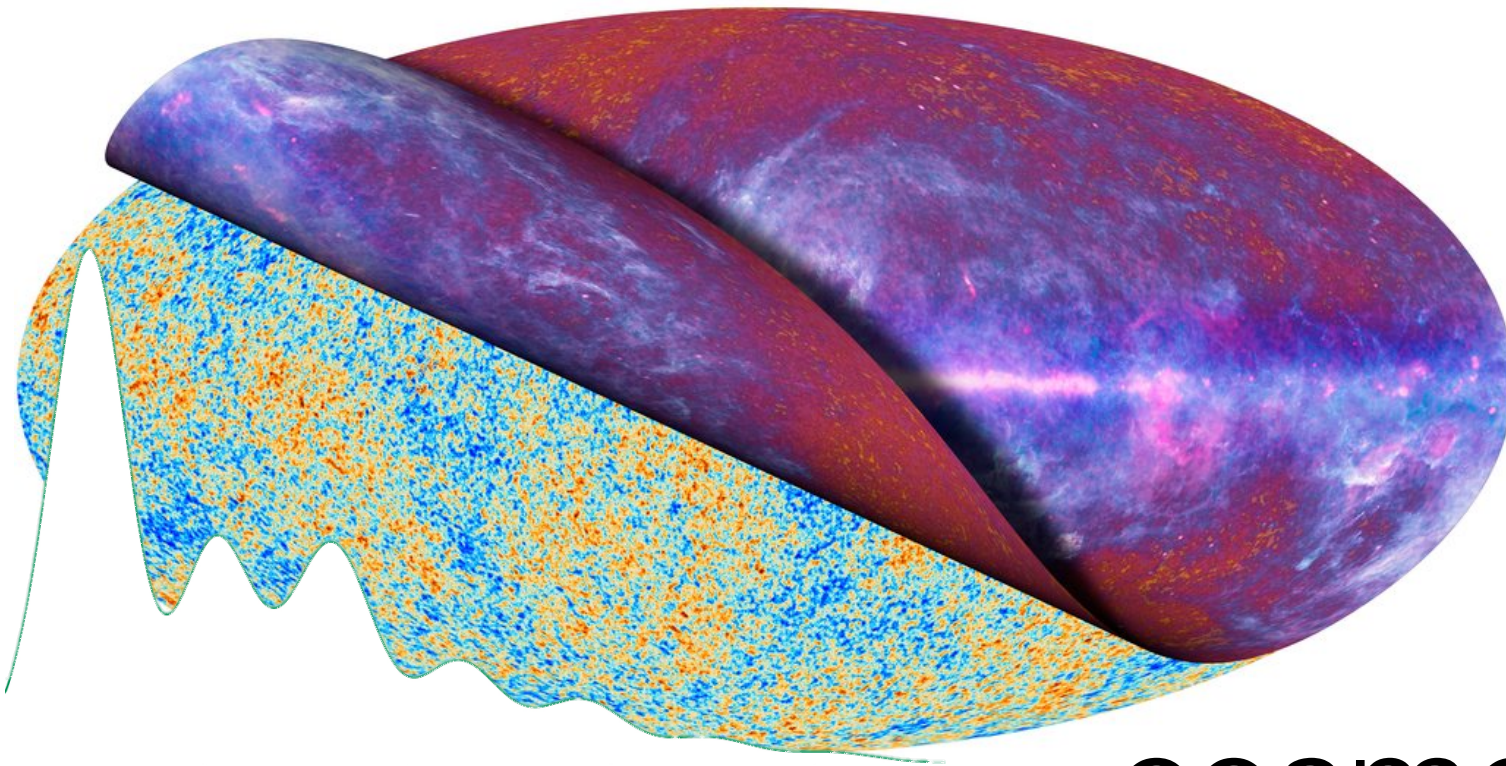




cosmological results from Planck

Hervé Dole

on behalf of the Planck collaboration

Institut d'Astrophysique Spatiale, Orsay, France

Université Paris Sud & CNRS

Institut Universitaire de France

<http://www.ias.u-psud.fr/dole/>



Comprendre le monde,
construire l'avenir®

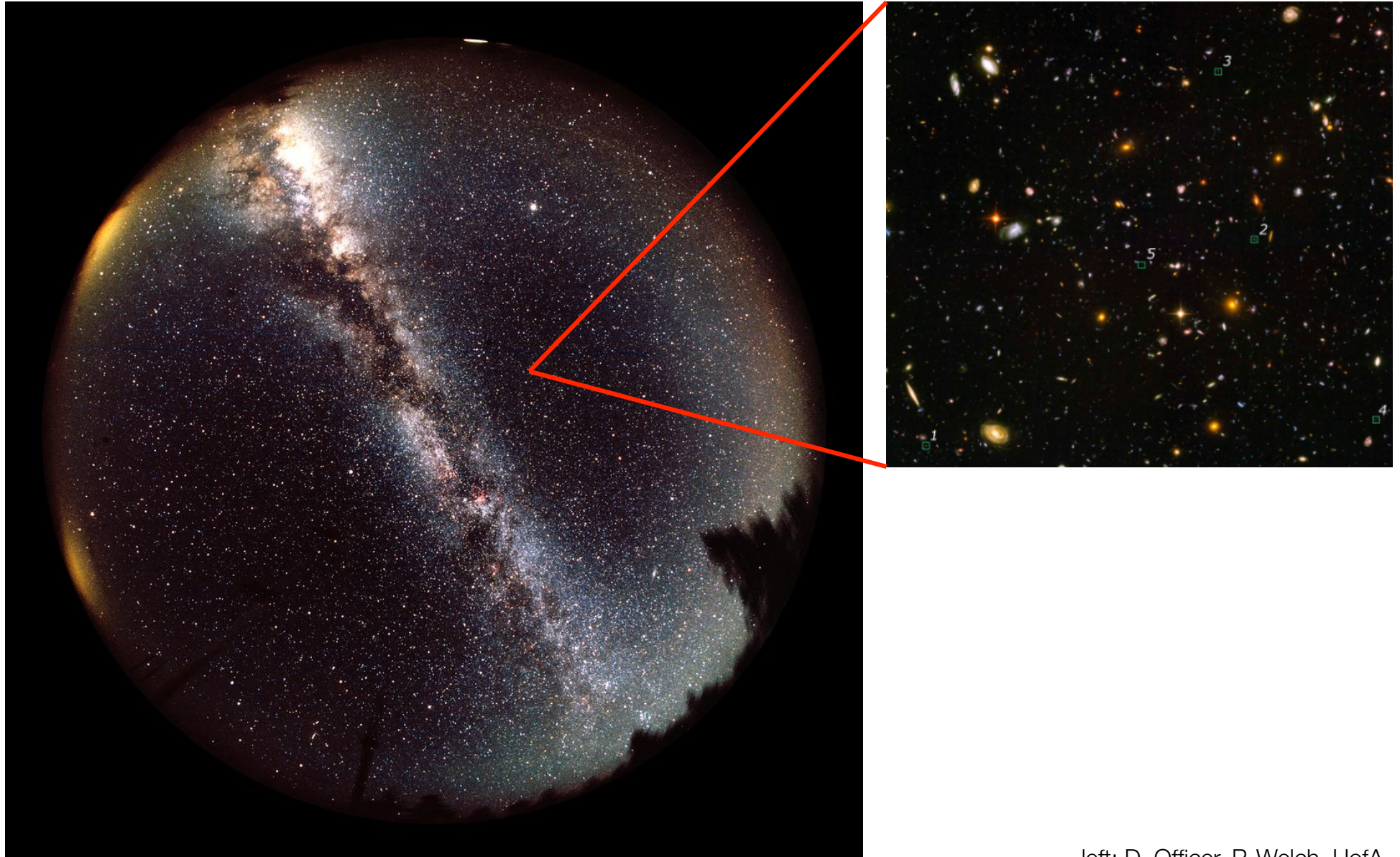


The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada



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.

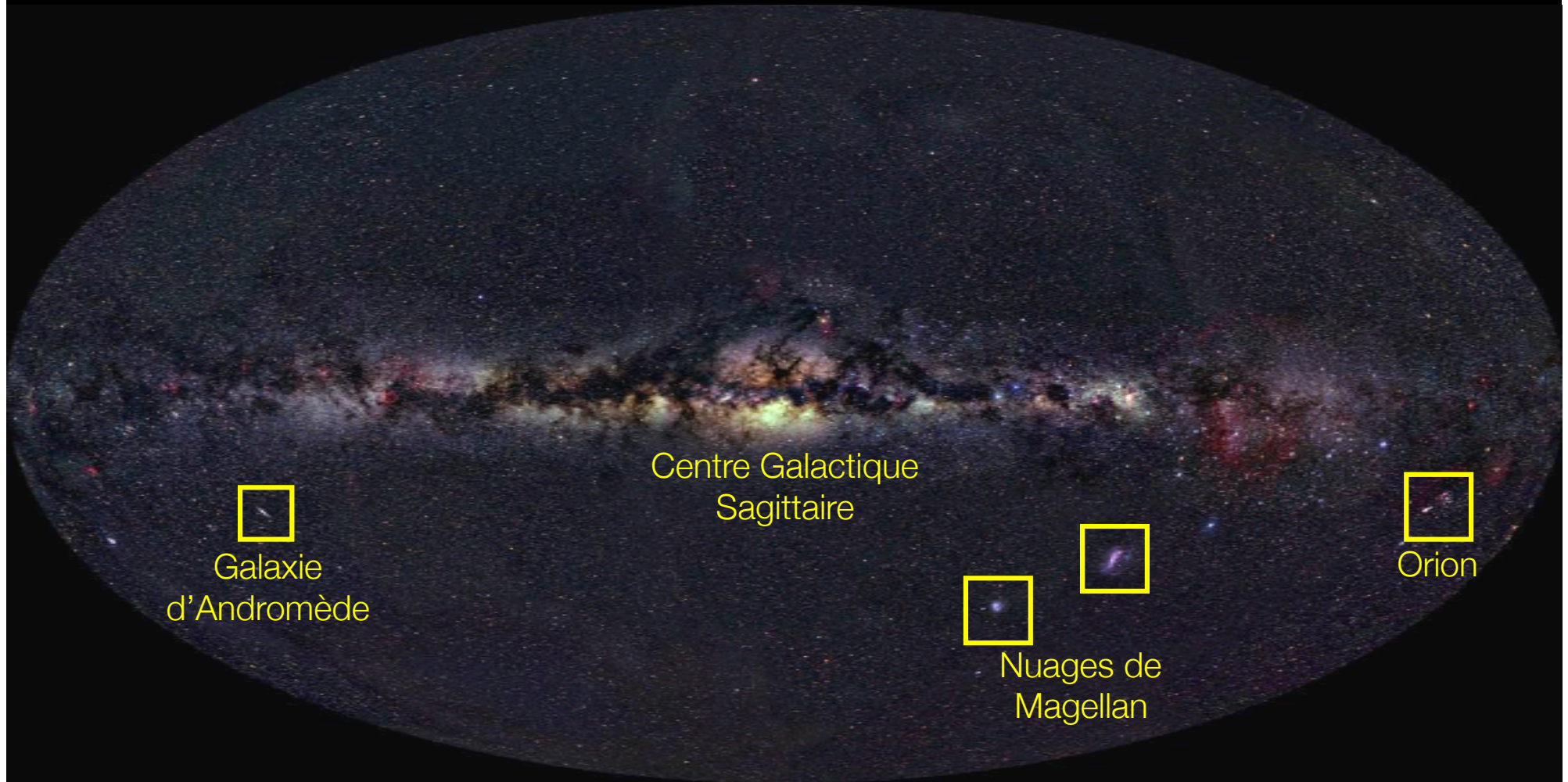
why is the night sky dark ?



Hervé Dole, IAS - Planck results - Strasbourg - Nov 8th 2013

left: D. Officer, P. Welch, UofA
right: NASA, HST 3

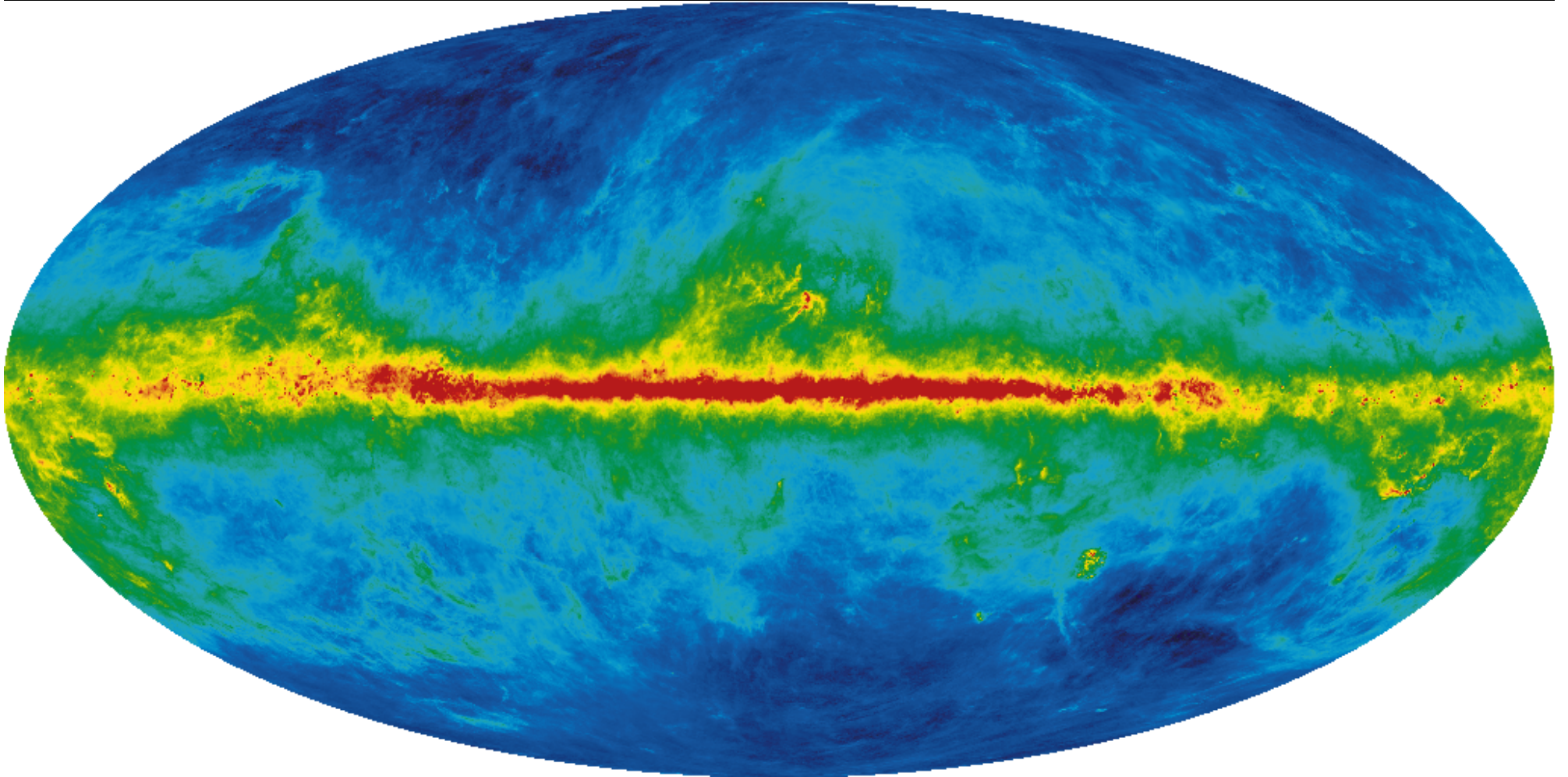
the sky: visible wavelengths



Axel Mellinger

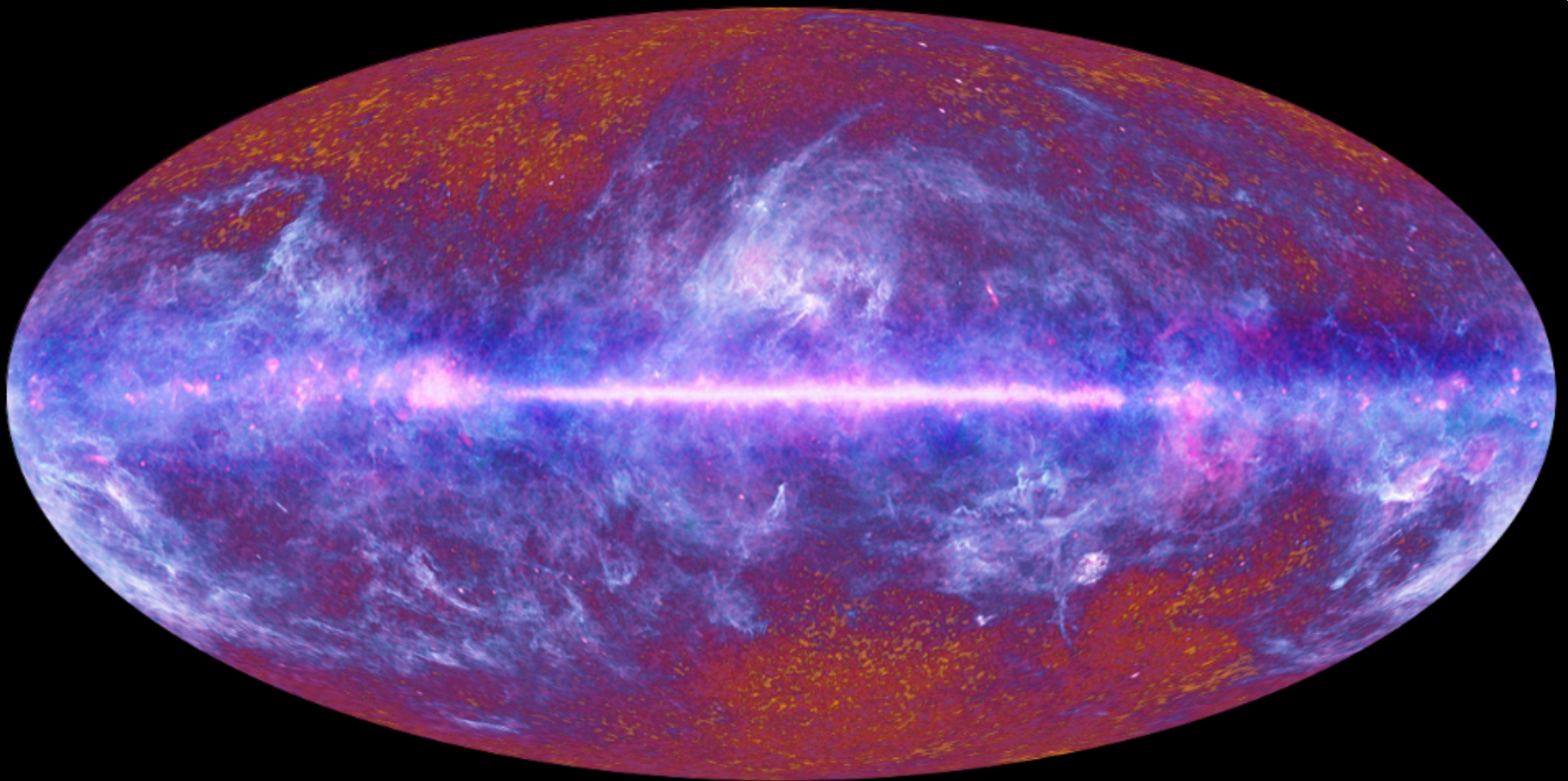
http://canopus.physik.uni-potsdam.de/~axm/mwpan/mwpan_web.html

the sky: far-infrared



IRAS 100um IRIS

the sky: microwaves

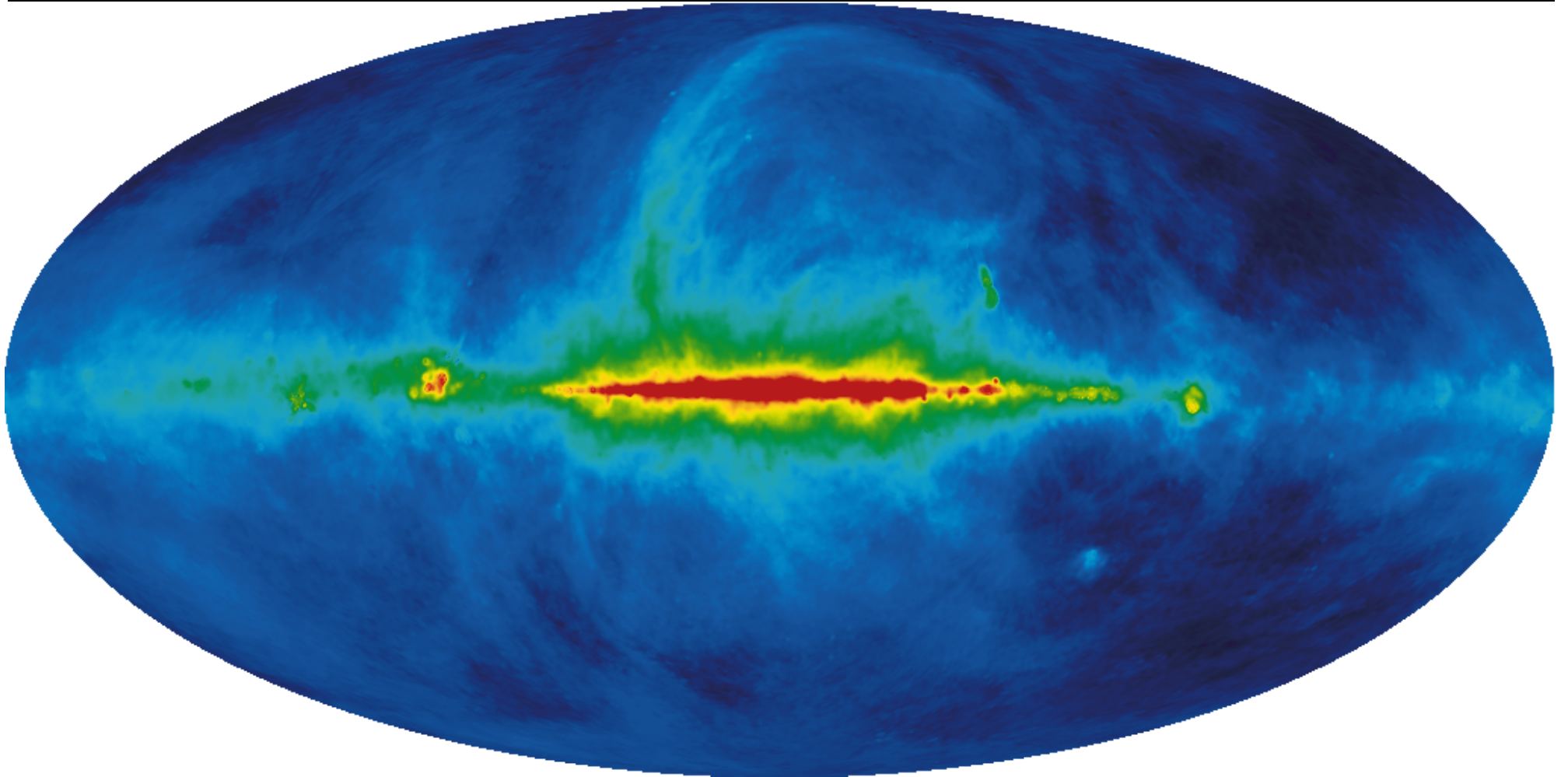


The PLANCK one-year all-sky survey



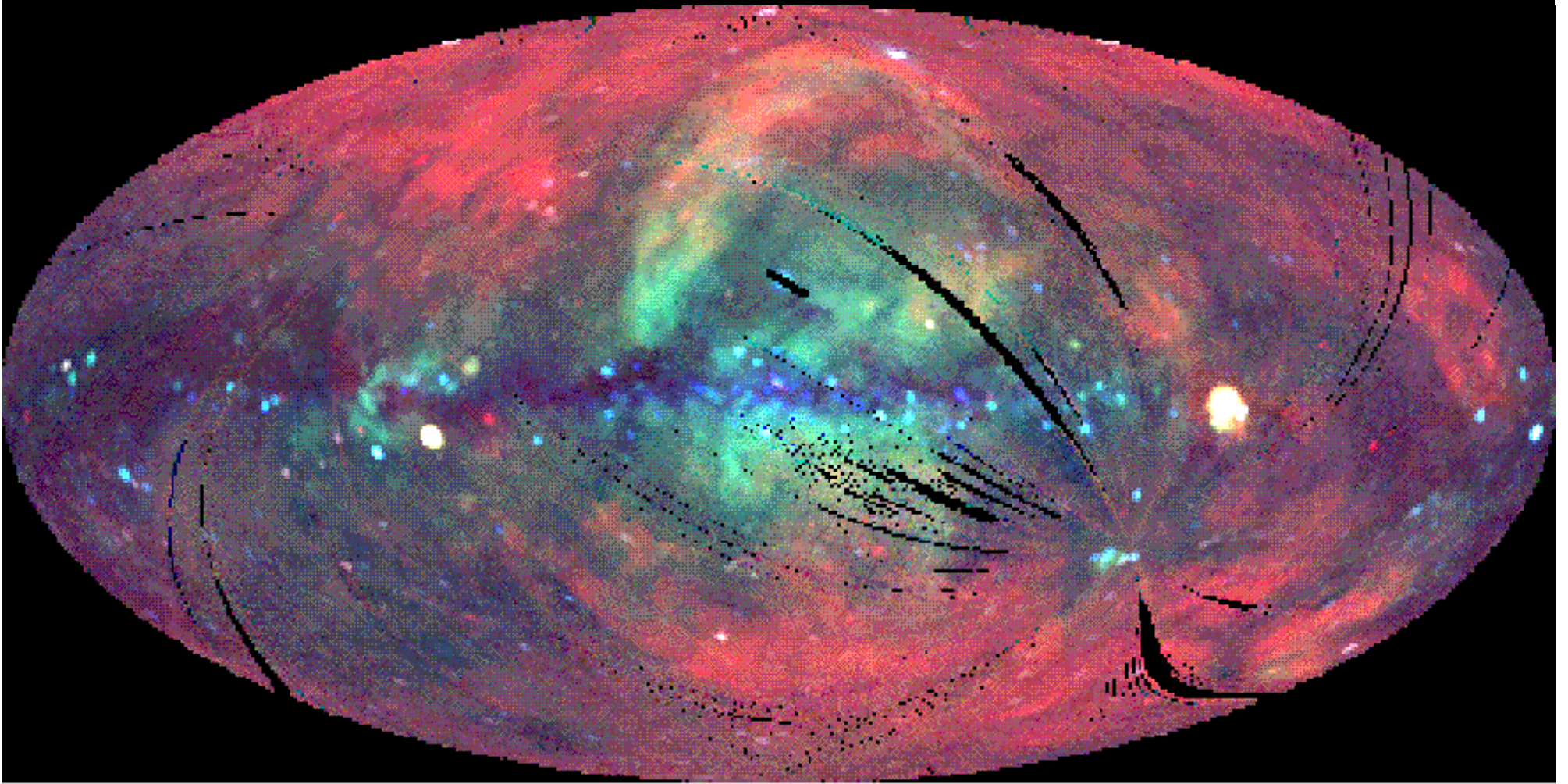
[c] ESA, HFI and LFI consortia, July 2010

the sky: radio



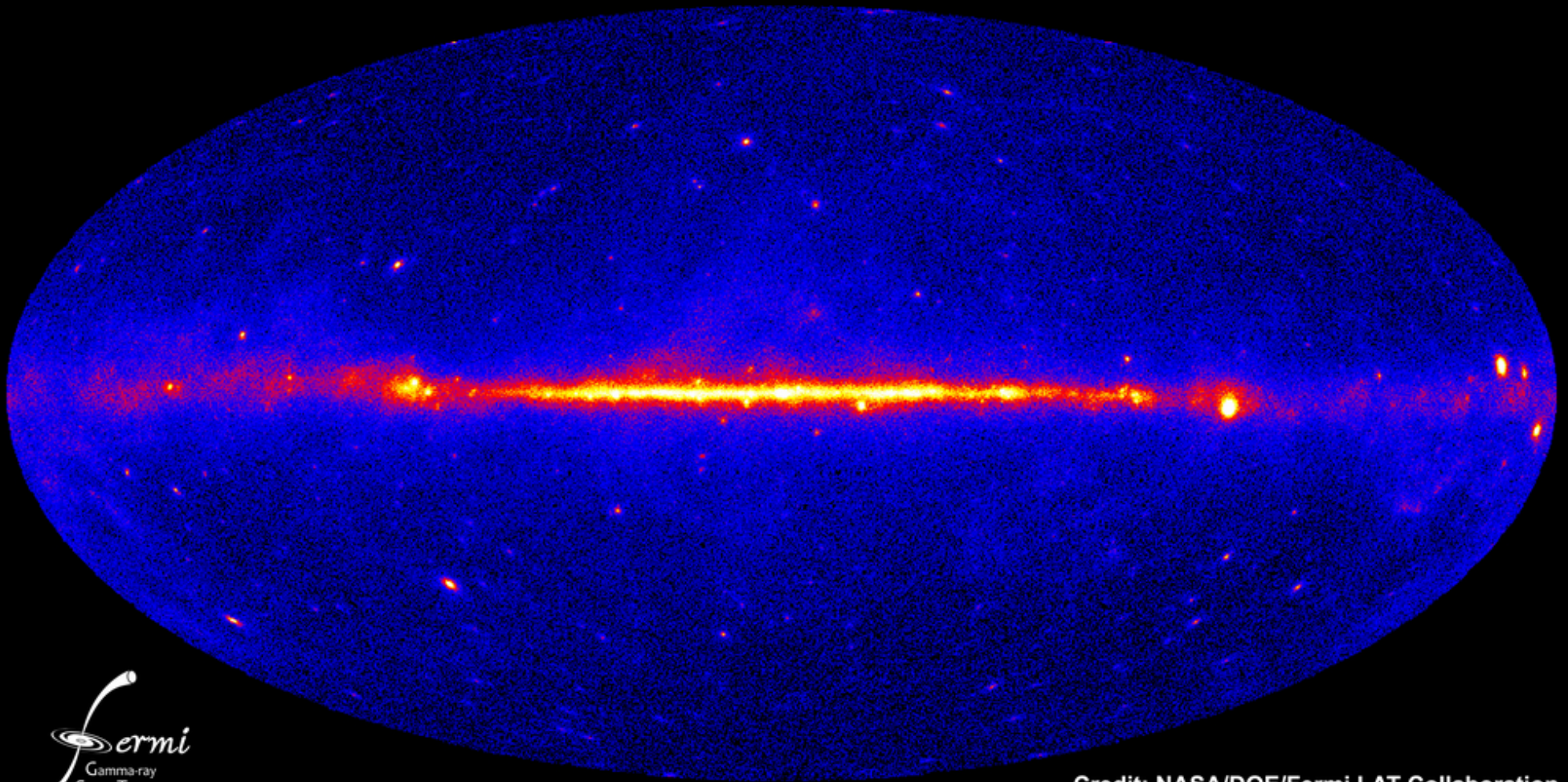
21 cm Leiden/Parkes

the sky: X-rays



ROSAT

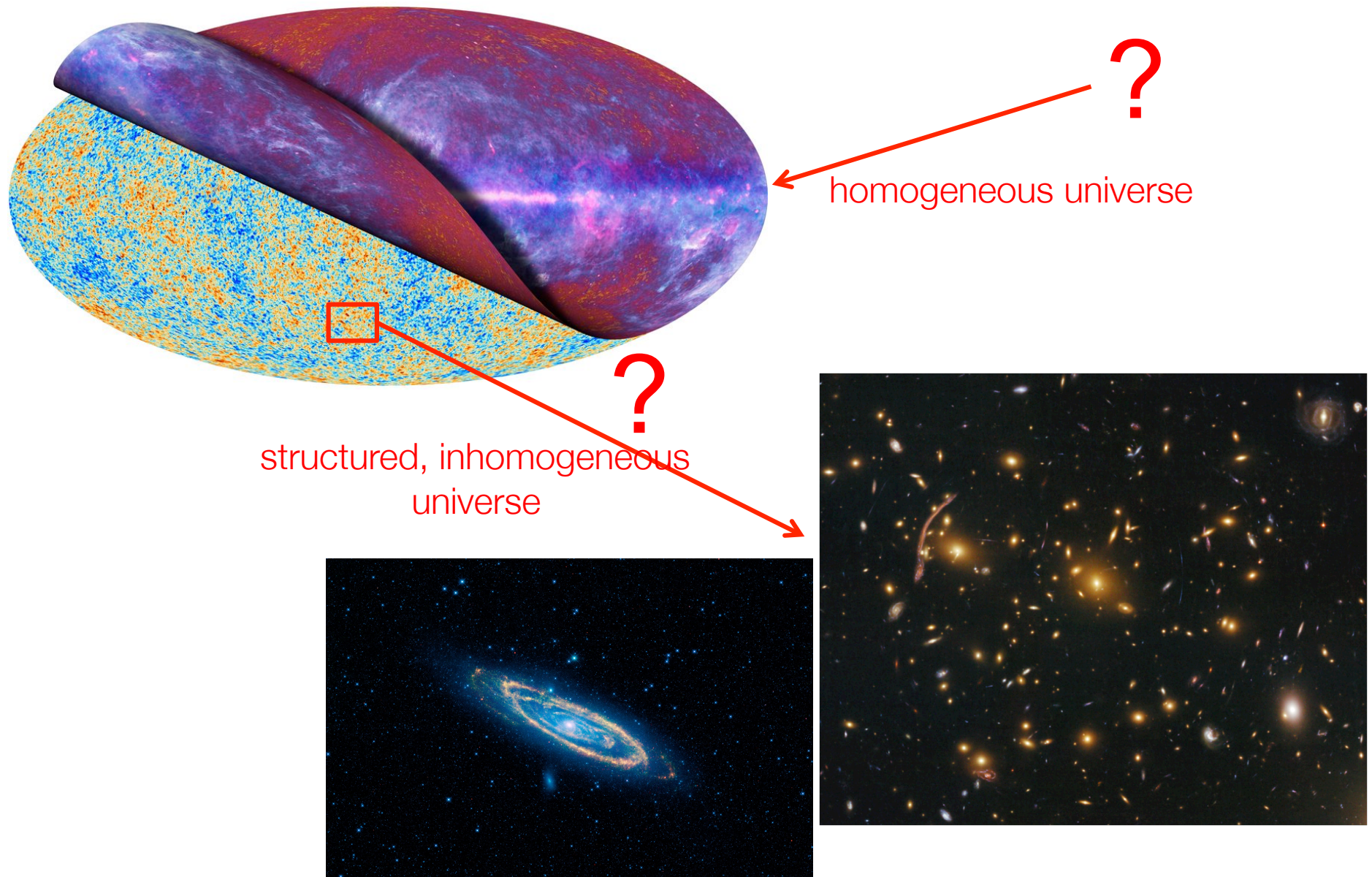
the sky: gamma-rays



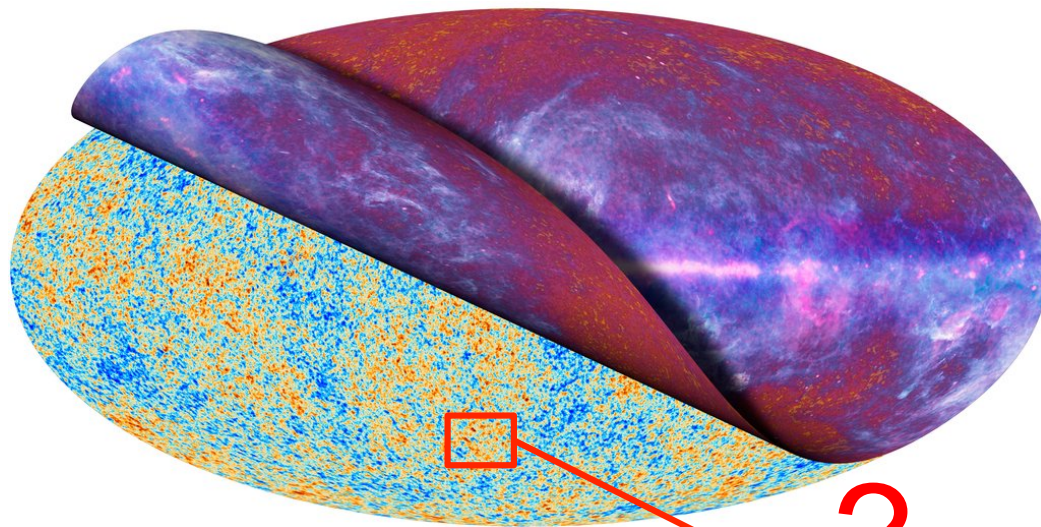
Credit: NASA/DOE/Fermi LAT Collaboration

FERMI LAT

the two outstanding questions



the two outstanding questions



?

homogeneous universe
inflation models ?

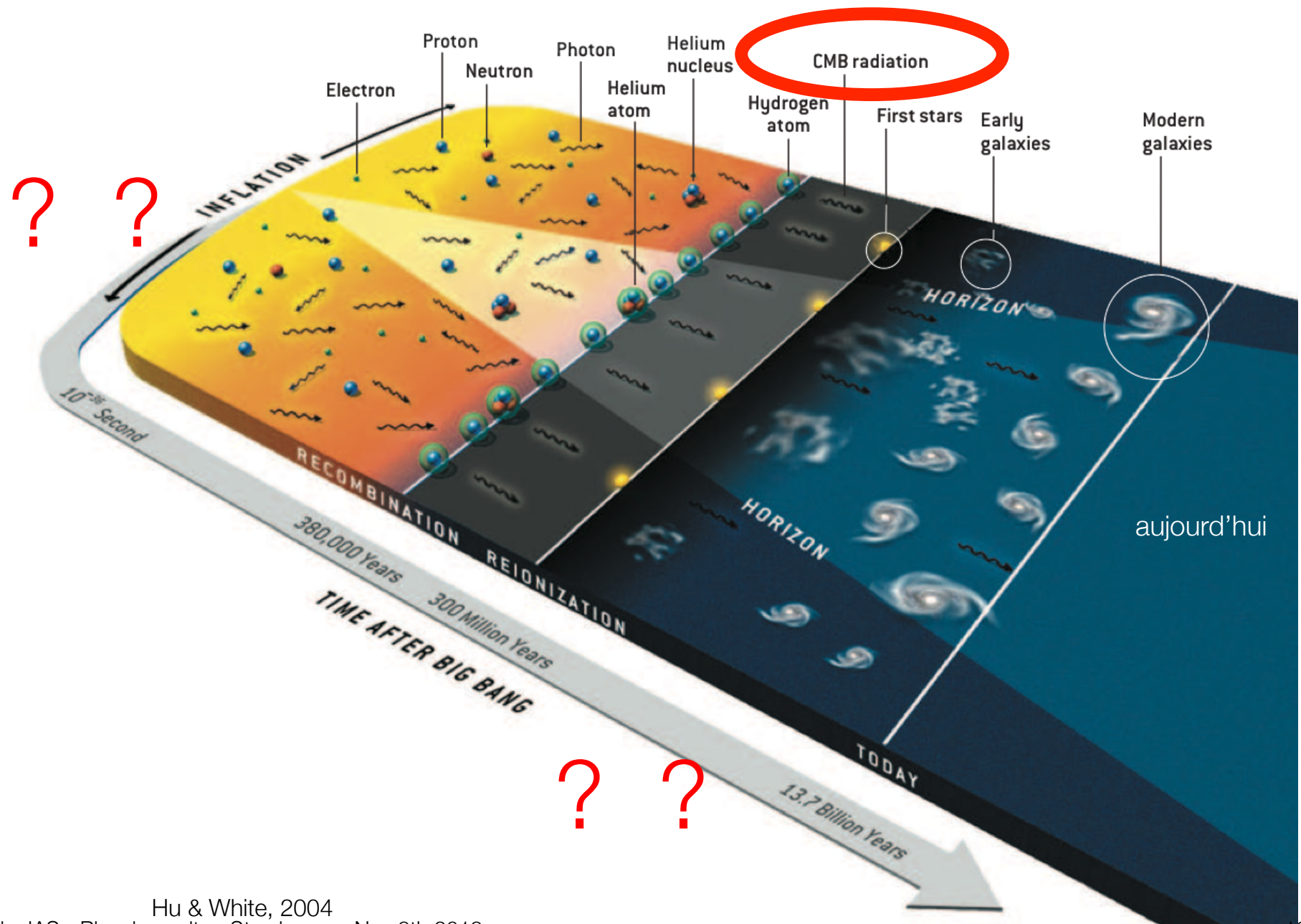
?

structured, inhomogeneous
universe

structure
formation,
 Λ CDM



how large scale structures form ?

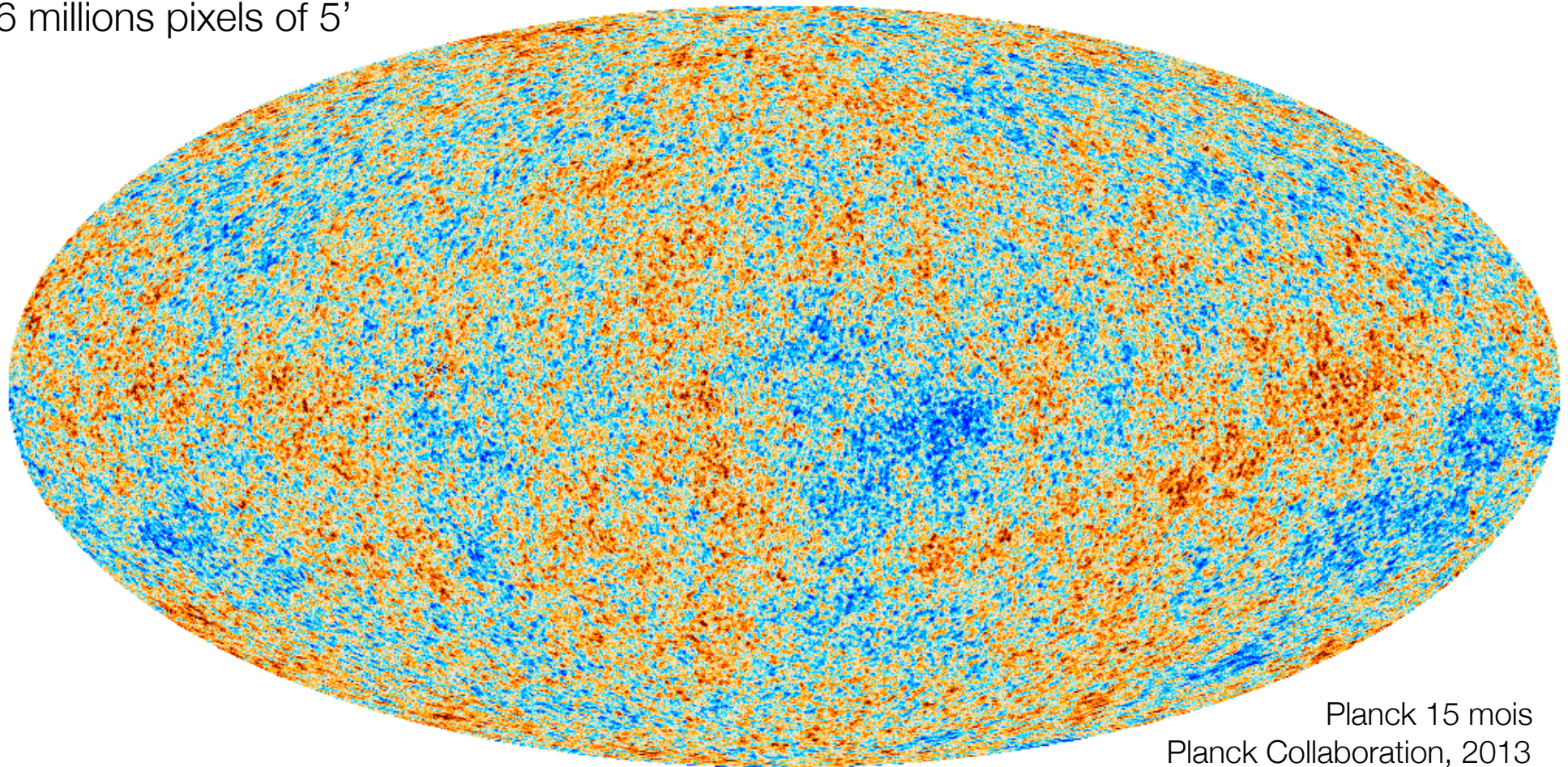


Hu & White, 2004

CMB temperature anisotropies

LE RAYONNEMENT FOSSILE par PLANCK

the universe at 2.10^{-5} of its present age
6 millions pixels of 5'



Planck 15 mois
Planck Collaboration, 2013



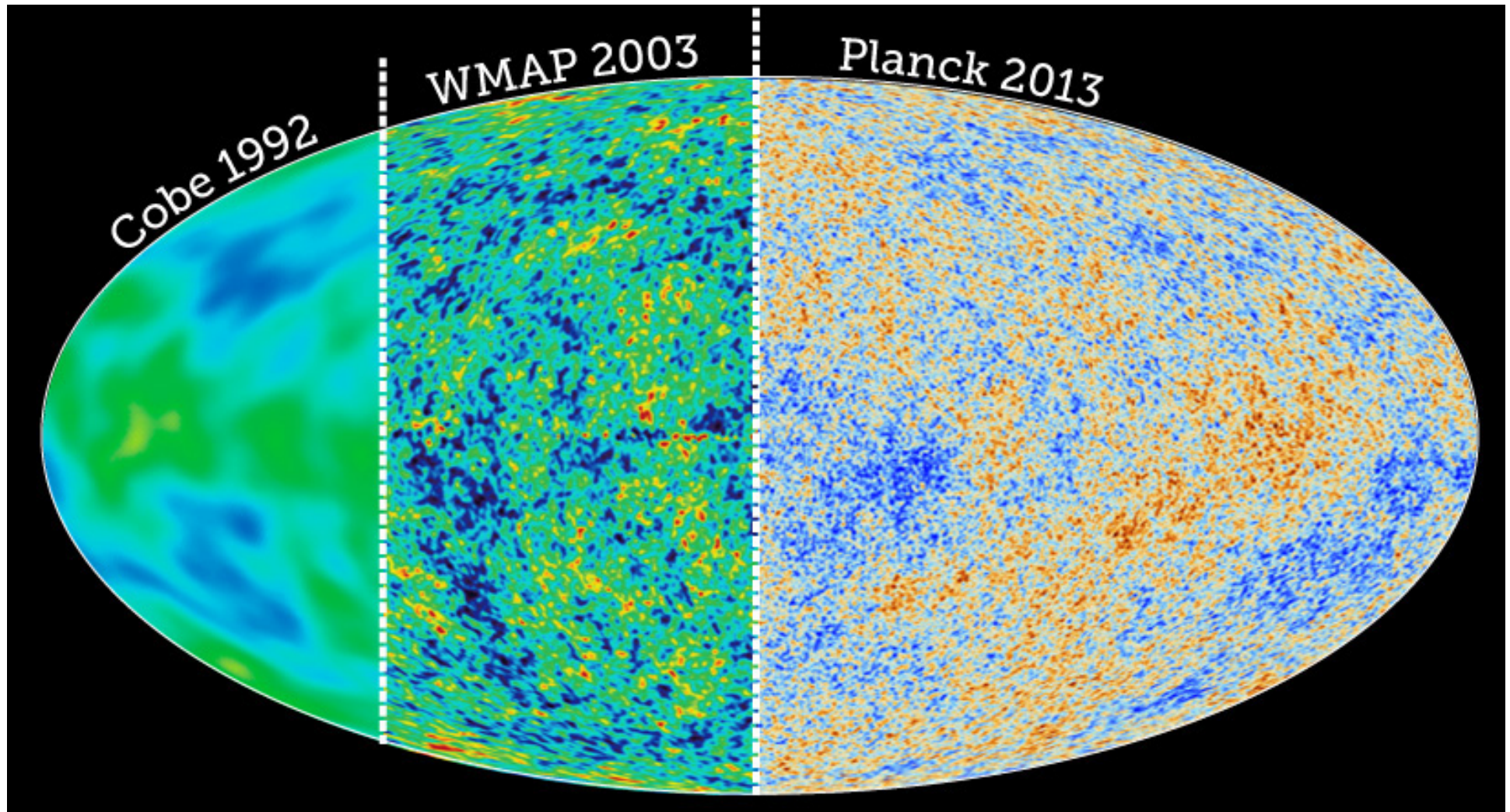
and a fairly wide coverage



March 21st or 22nd, 2013

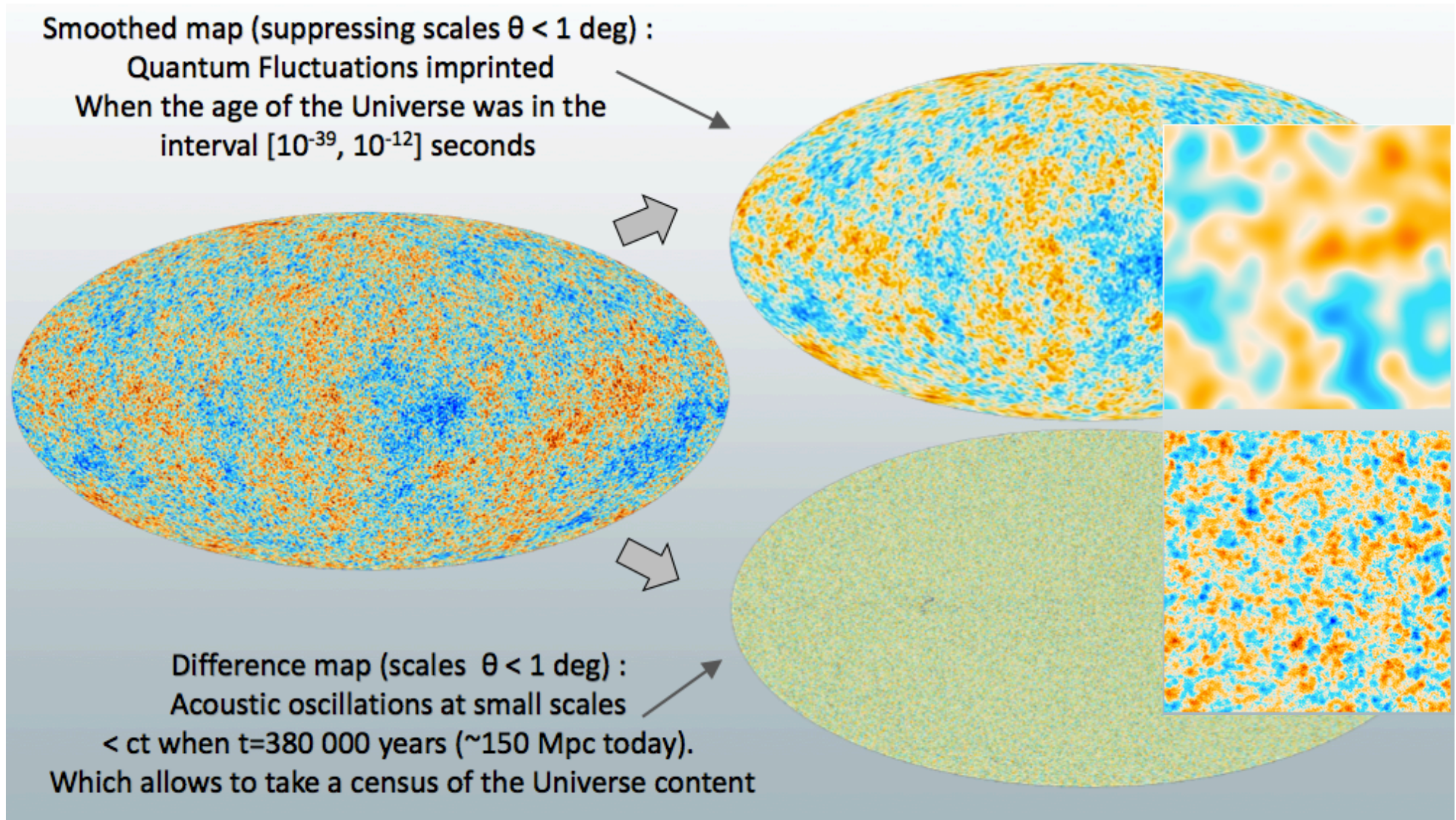
Hervé Dole, IAS - Planck results - Strasbourg - Nov 8th 2013

improvements with time & technology



Planck sensitivity in 1yr ~ 1000 years of WMAP

1. why Planck ?



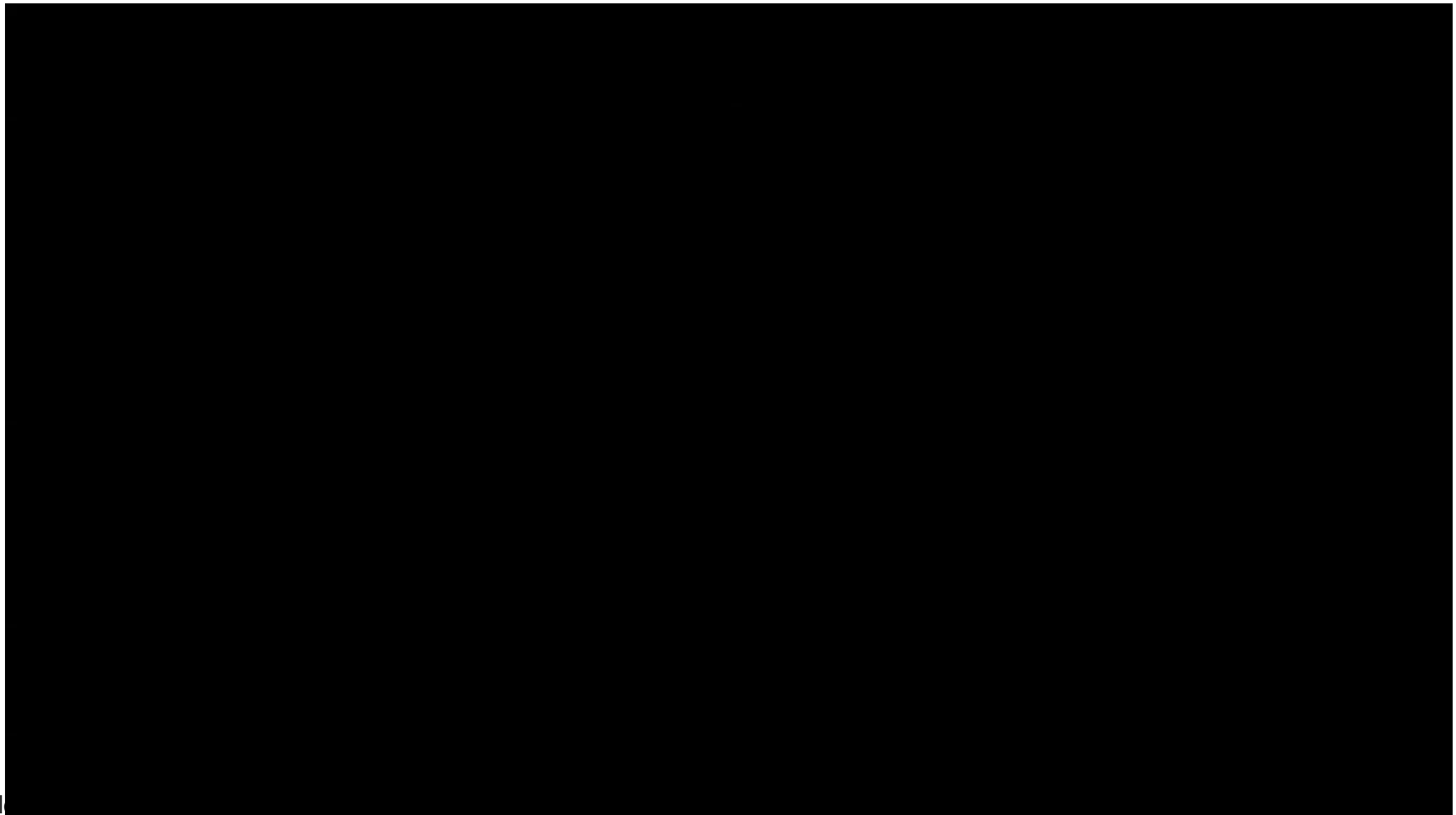
the key is to measure both large and small angular scales

outline

1. why Planck ?
2. the Cosmic Microwave Background (CMB) and the astrophysical components, incl galaxies
3. analysis of the CMB: angular power spectra
4. cosmological implications
5. a word about inflation
6. a clumpy Universe
7. digging into the Cosmic Infrared Background

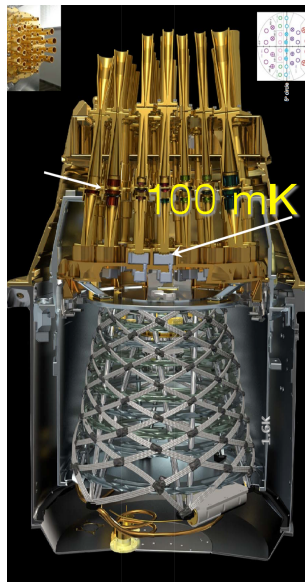
Planck goals and key facts

- selected in 1996 by ESA – launched in 2009
- HFI cooled at 100 mK -> bolometer technology
- 29 months of operation (goal was 12: nominal mission)
 - 5 all-sky surveys instead of 2 (nominal mission, this data release)



a technological success

stability: 0.1 mK !



Cryostat:
dilution He3/He4

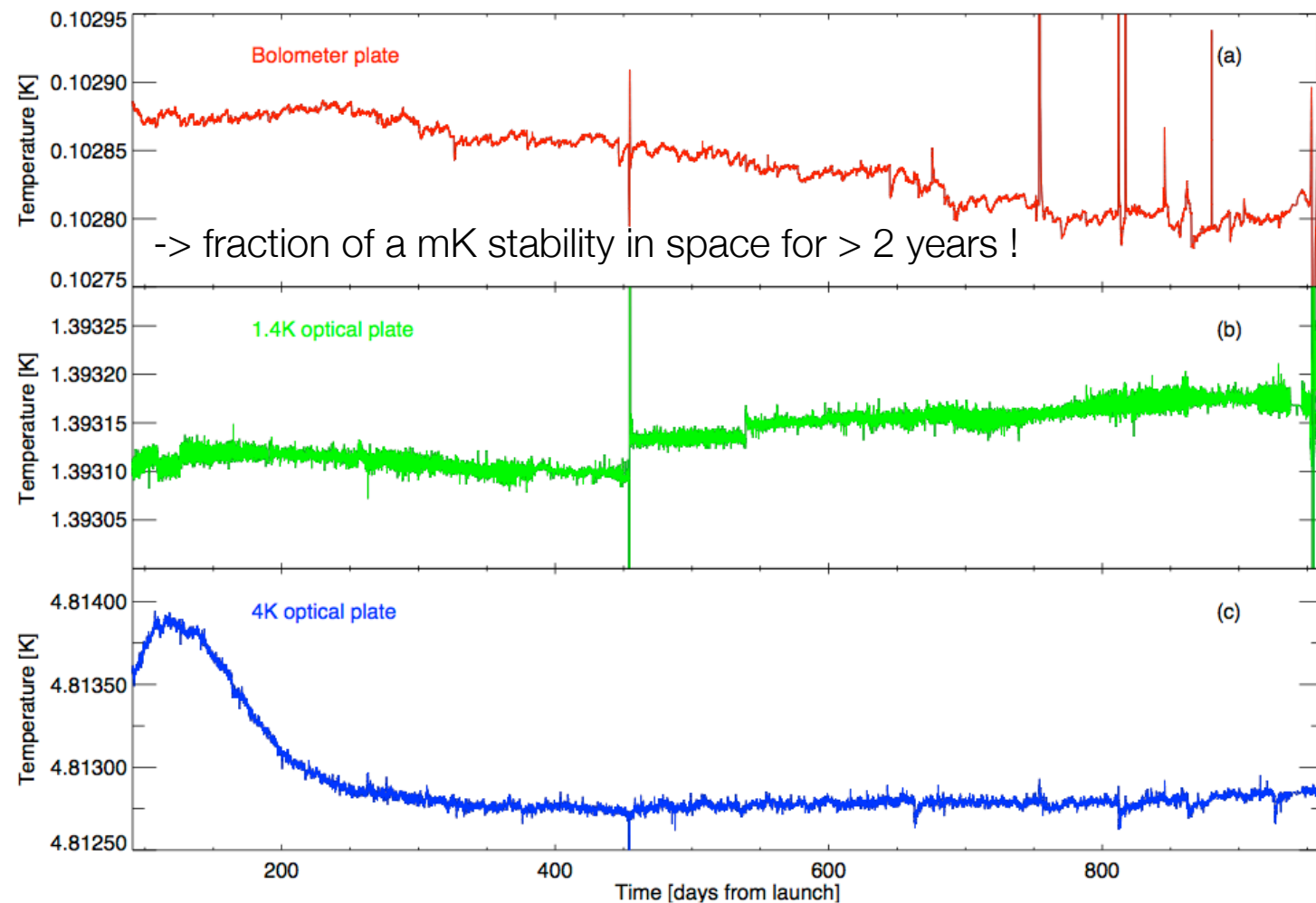
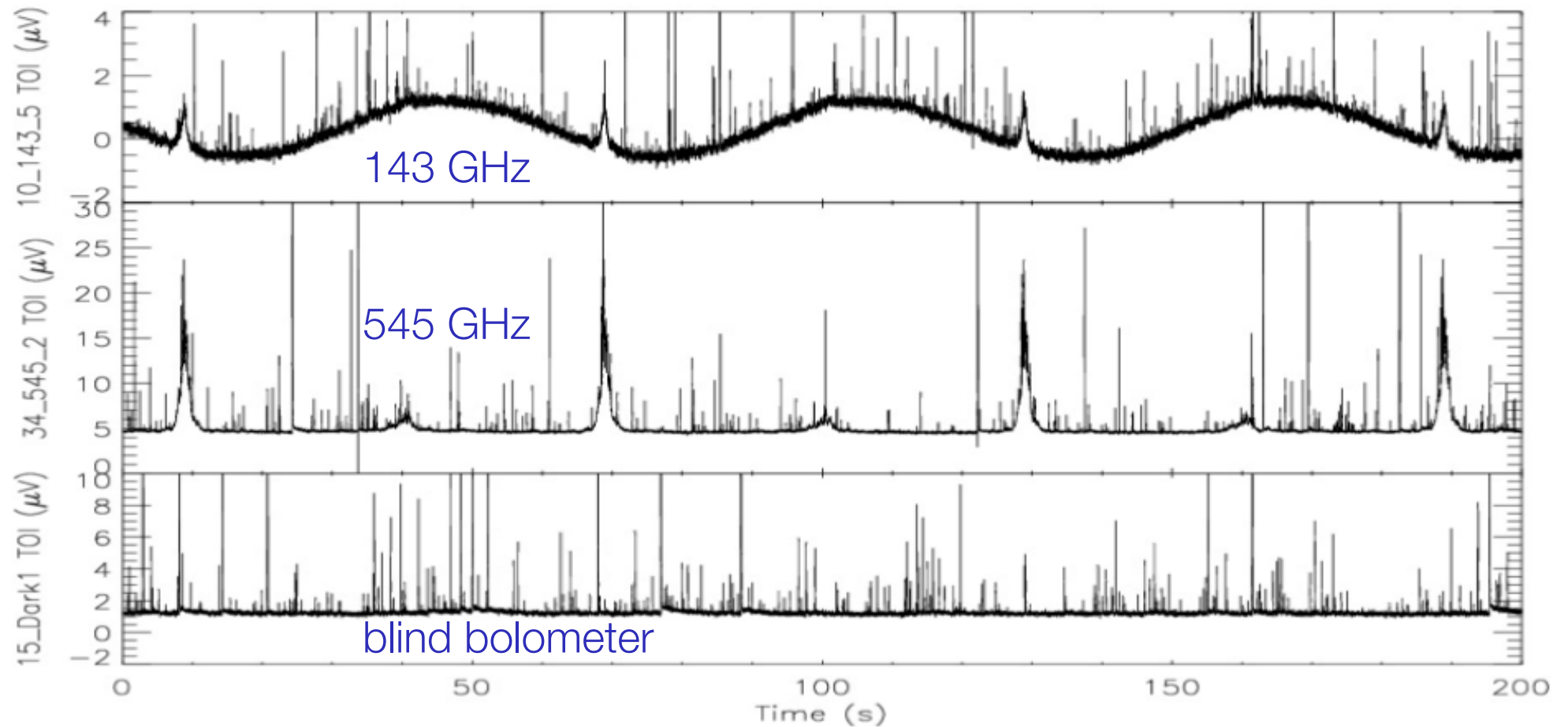


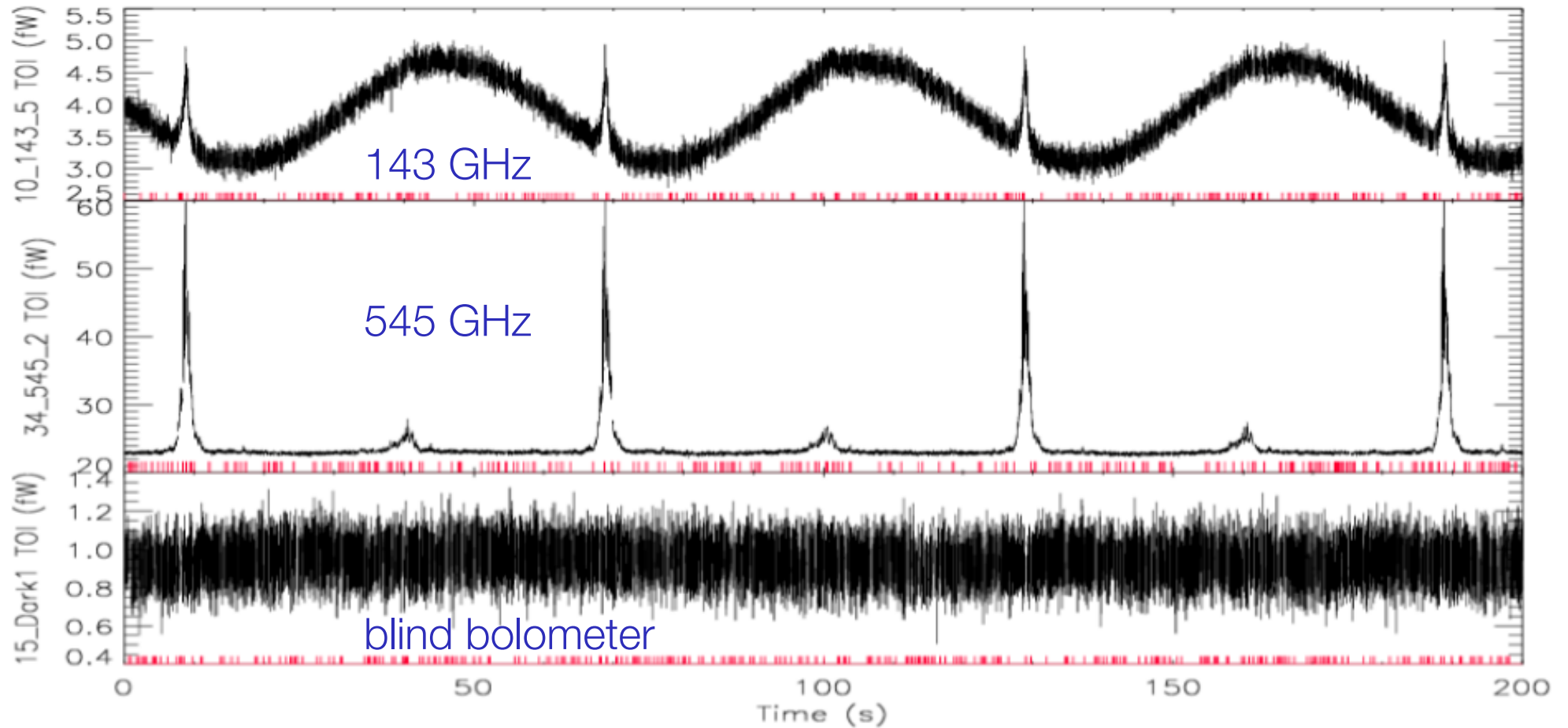
Fig. 7. The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the nominal mission.

a challenging analysis success



Planck-HFI Core Team, 2011

a challenging analysis success

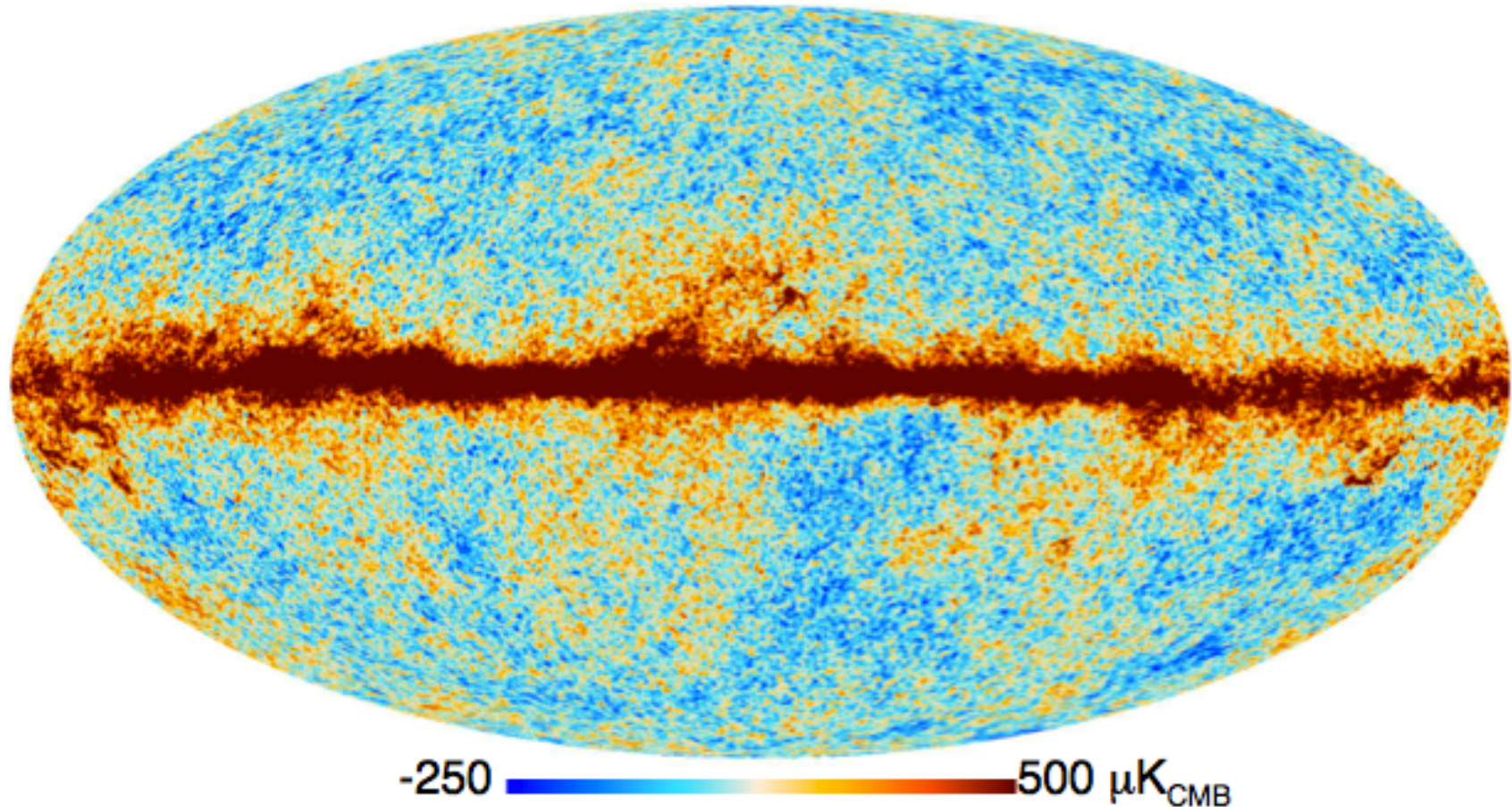


de <20% de données perdues à cause des glitches

Planck-HFI Core Team, 2011

many intermediate products for jackknives

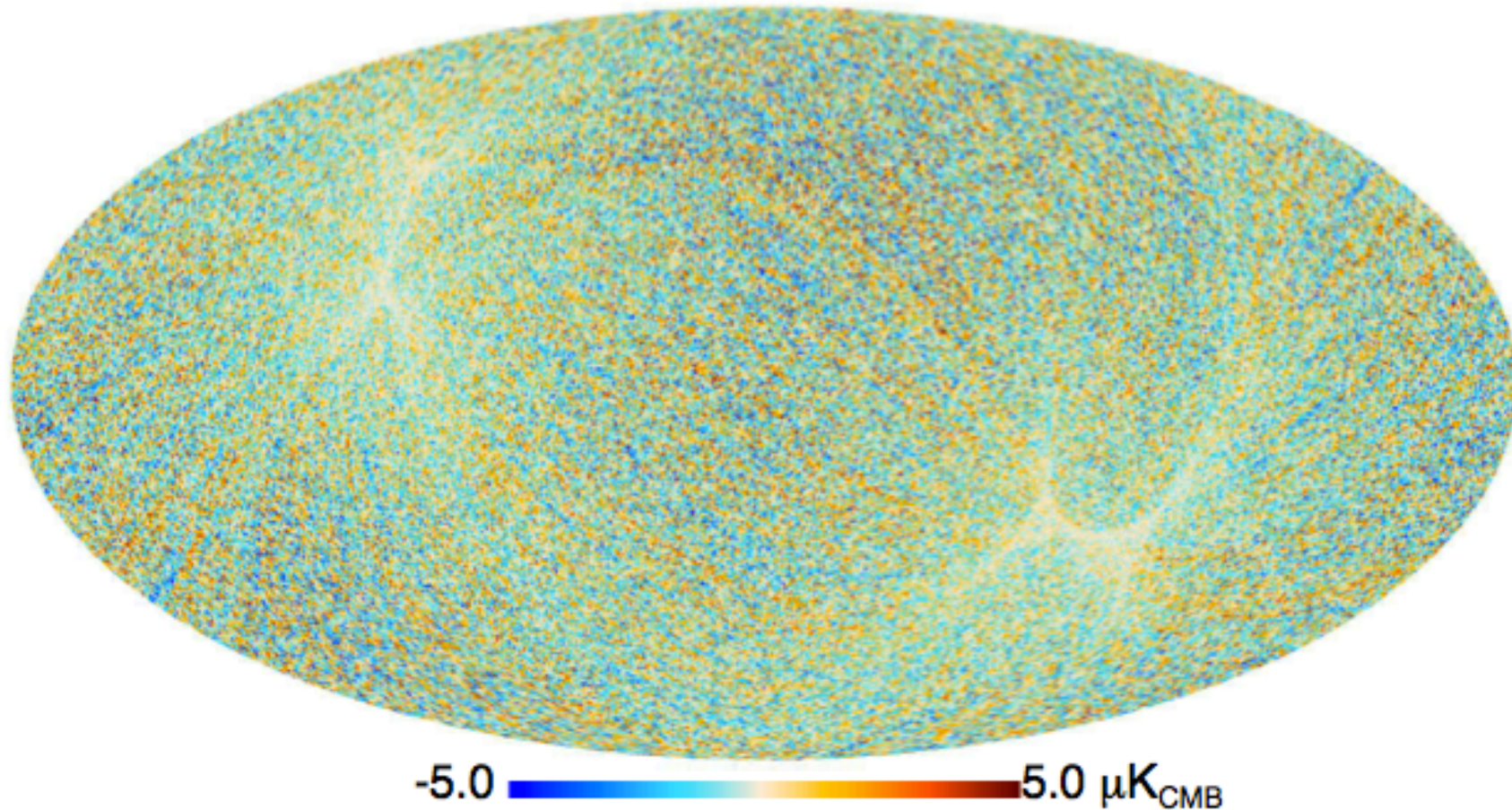
143 GHz map



Planck Collaboration, 2013, 6

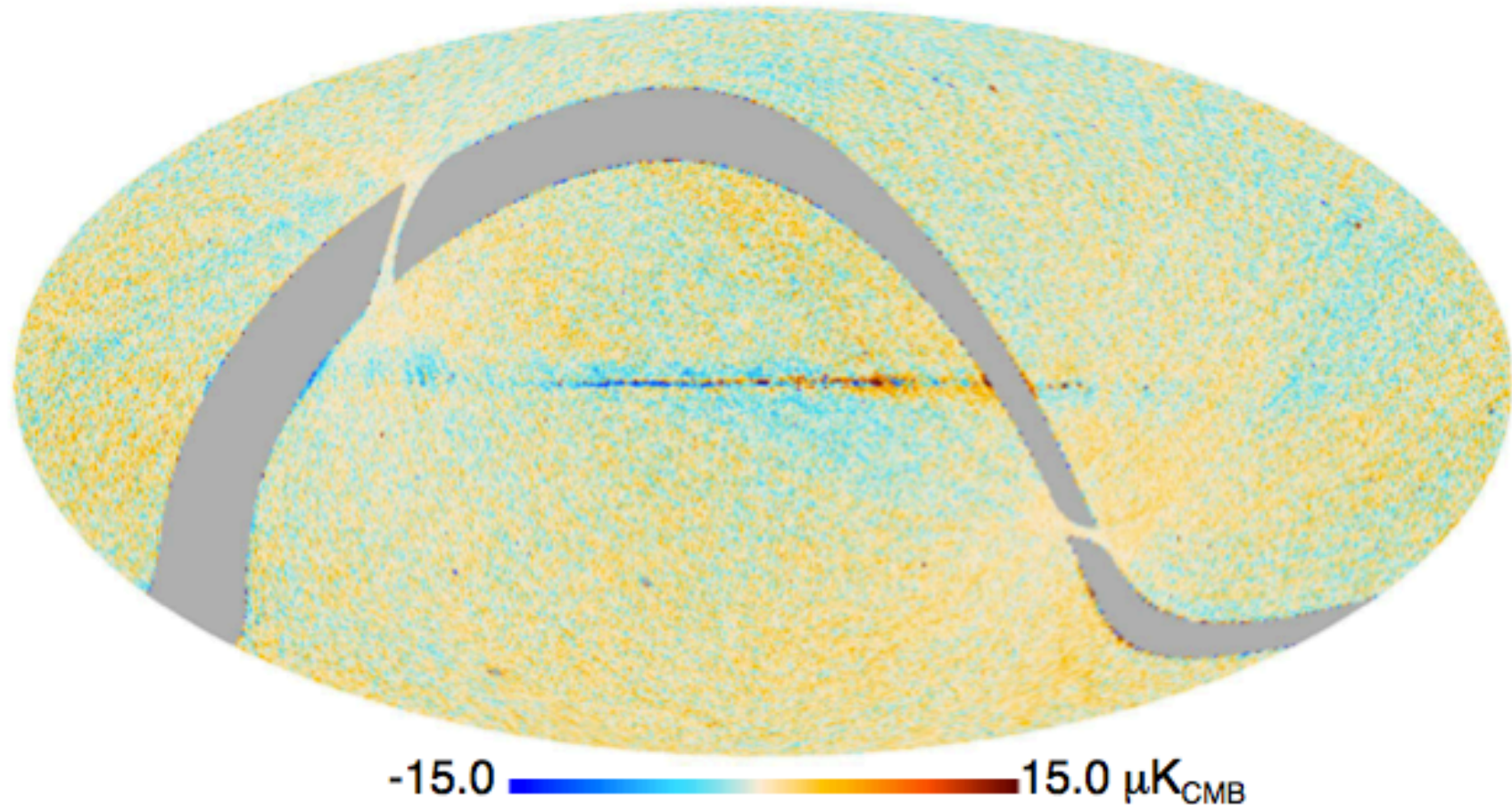
many intermediate products for jackknives

half ring difference



many intermediate products for jackknives

survey 1 – survey 2 difference

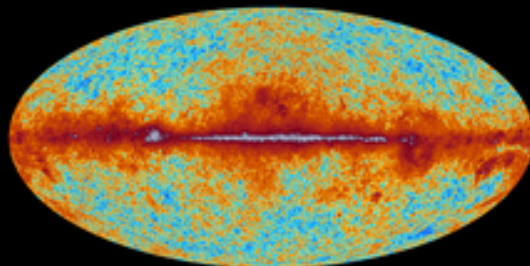


Planck all-sky maps

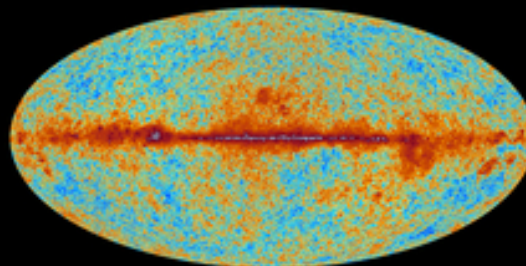


planck

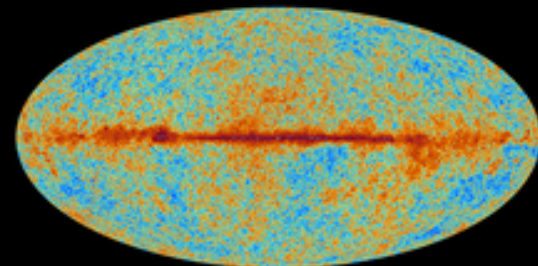
The sky as seen by Planck



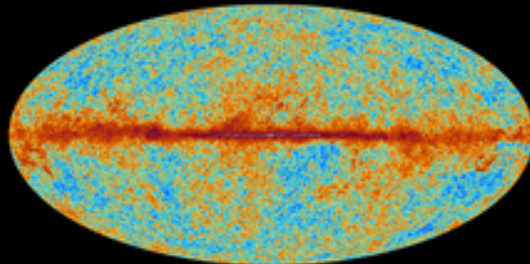
30 GHz



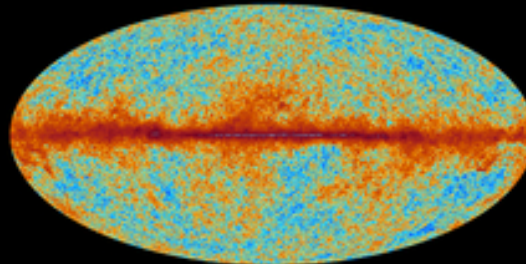
44 GHz



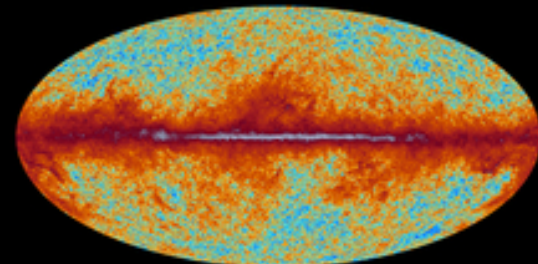
70 GHz



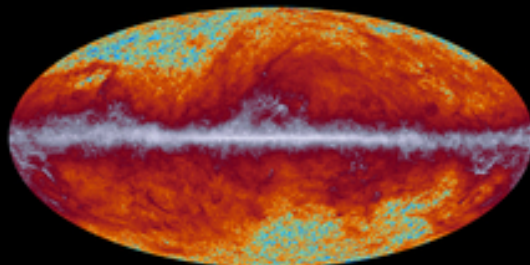
100 GHz



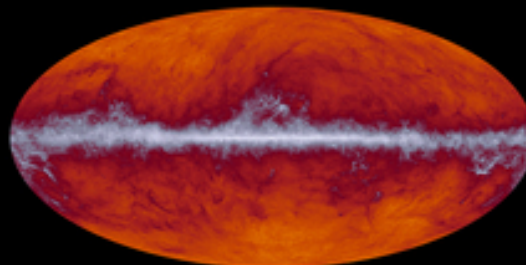
143 GHz



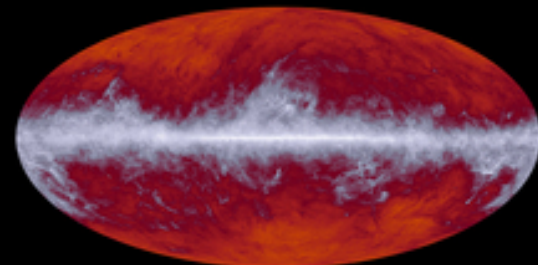
217 GHz



353 GHz

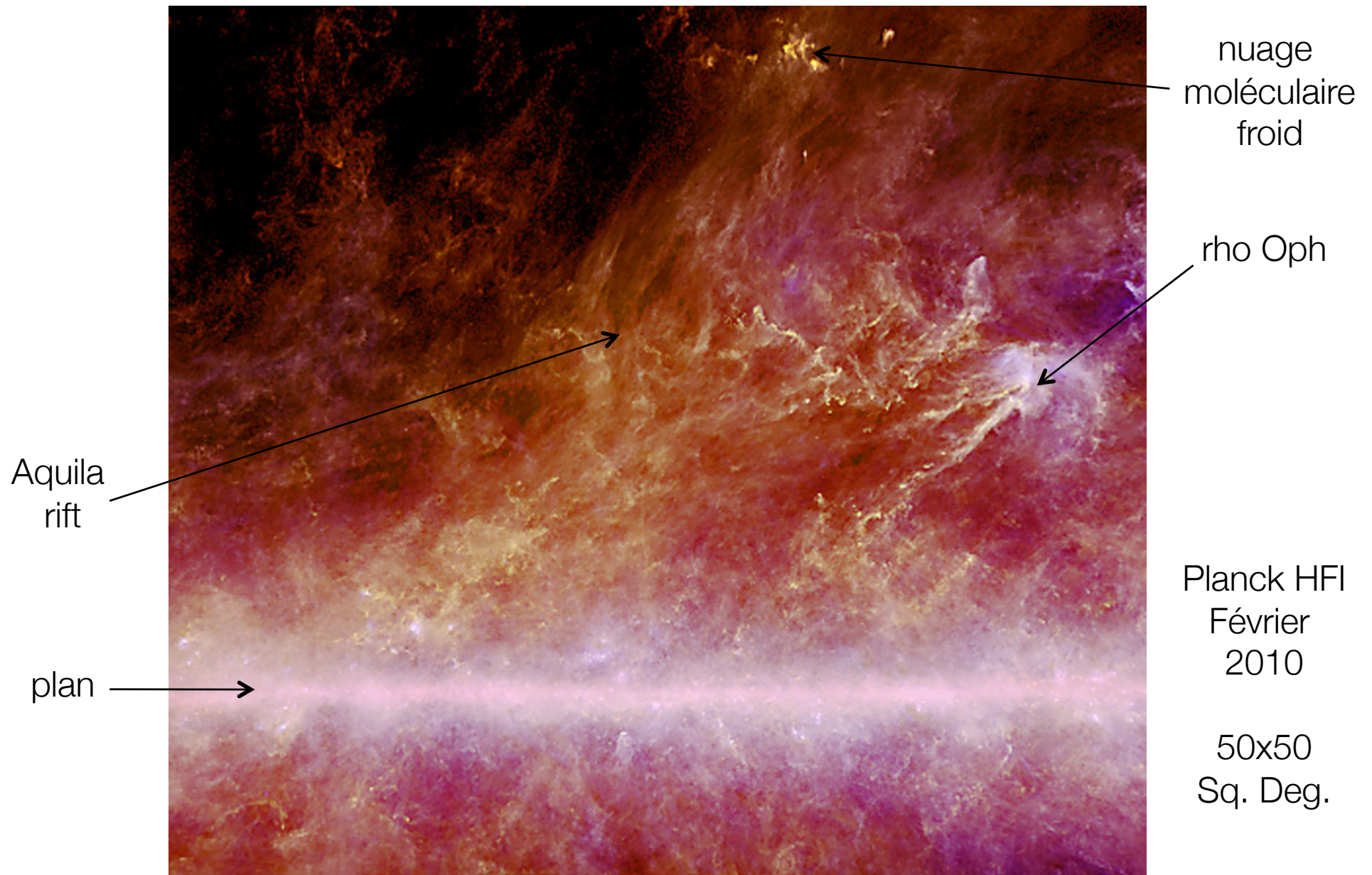


545 GHz



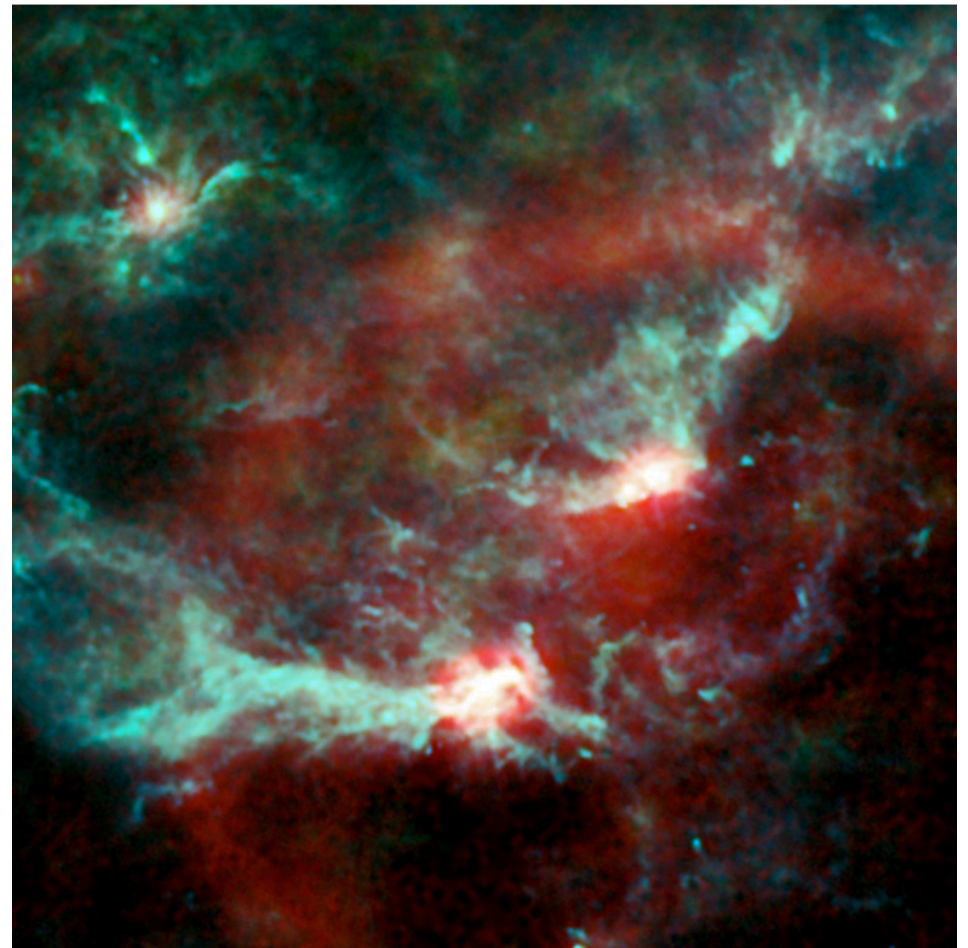
857 GHz

first Planck released images



first Planck released images

Planck HFI - Mars 2010 - Orion



Planck 2013 papers

- Planck 2013 results. I. Overview of products and results
- Planck 2013 results. II. Low Frequency Instrument data processing
- Planck 2013 results. III. LFI systematic uncertainties
- Planck 2013 results. IV. LFI beams
- Planck 2013 results. V. LFI calibration
- Planck 2013 results. VI. High Frequency Instrument data processing
- Planck 2013 results. VII. HFI time response and beams
- Planck 2013 results. VIII. HFI calibration and mapmaking
- Planck 2013 results. IX. HFI spectral response
- Planck 2013 results. X. HFI energetic particle effects
- Planck 2013 results. XI. Consistency of the data

- Planck 2013 results. XII. Component separation
- Planck 2013 results. XIII. Galactic CO emission
- Planck 2013 results. XIV. Zodiacal emission

Planck 2013 results. XV. Cosmological parameters, p. spectra, likelihood

- Planck 2013 results. XVII. Gravitational lensing by large-scale structure
- Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation
- Planck 2013 results. XIX. The integrated Sachs-Wolfe effect

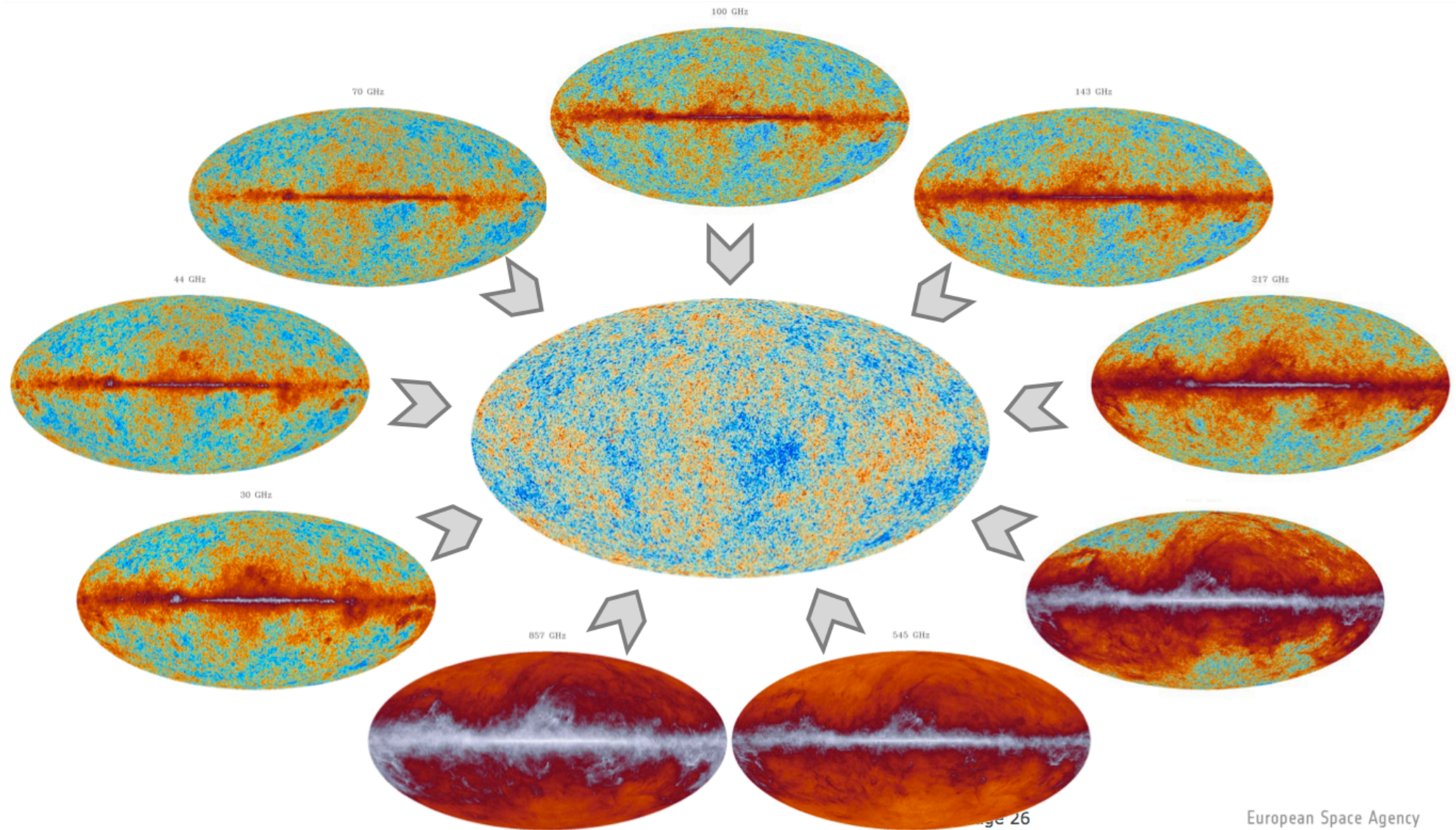
- Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts
- Planck 2013 results. XXI. All-sky Compton-parameter map and characterization

- Planck 2013 results. XXII. Constraints on inflation
- Planck 2013 results. XXIII. Isotropy and statistics of the CMB
- Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity
- Planck 2013 results. XXV. Searches for cosmic strings and other topological defects
- Planck 2013 results. XXVI. Background geometry and topology of the Universe
- Planck 2013 results. XXVII. Special relativistic effects on the CMB dipole

- Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources
- Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources
- Planck 2013 results. Explanatory supplement

29 papers (+1 to come on CIB) ; 800+ pages
1 Explanatory Supplement
all products available online

2. component separation

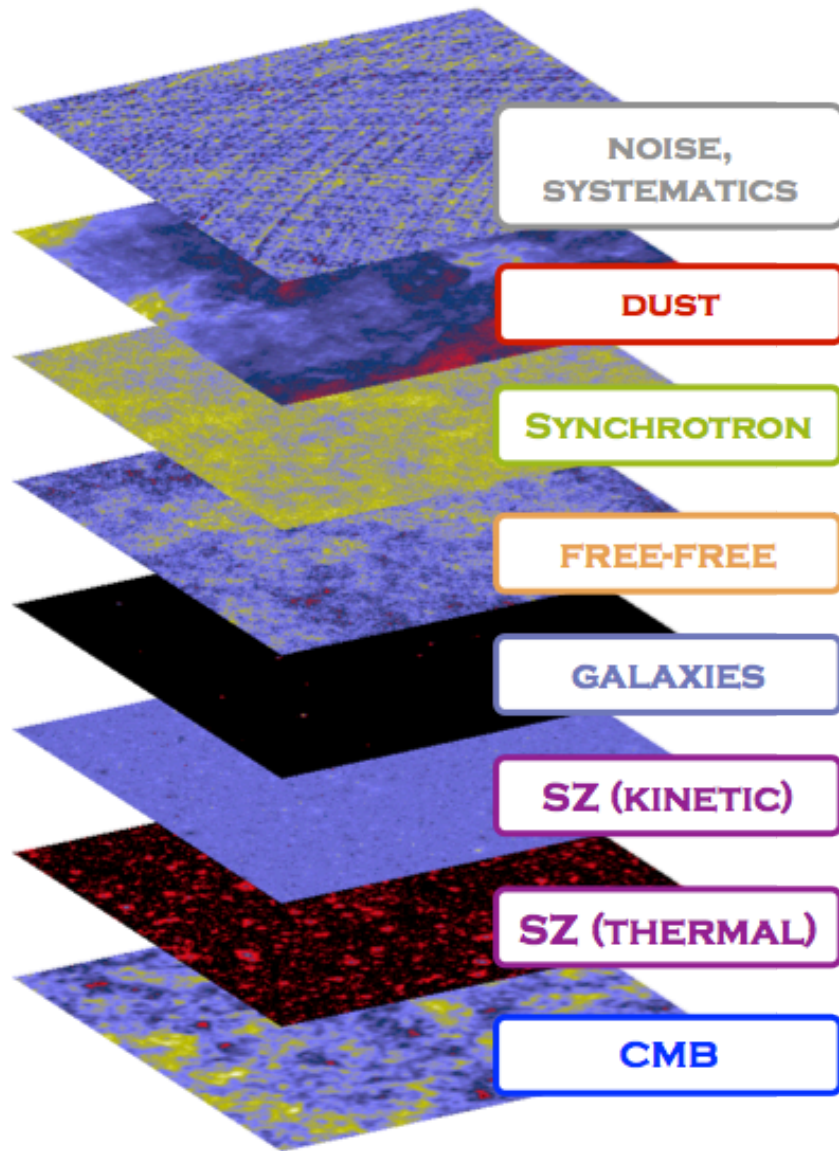


Page 26

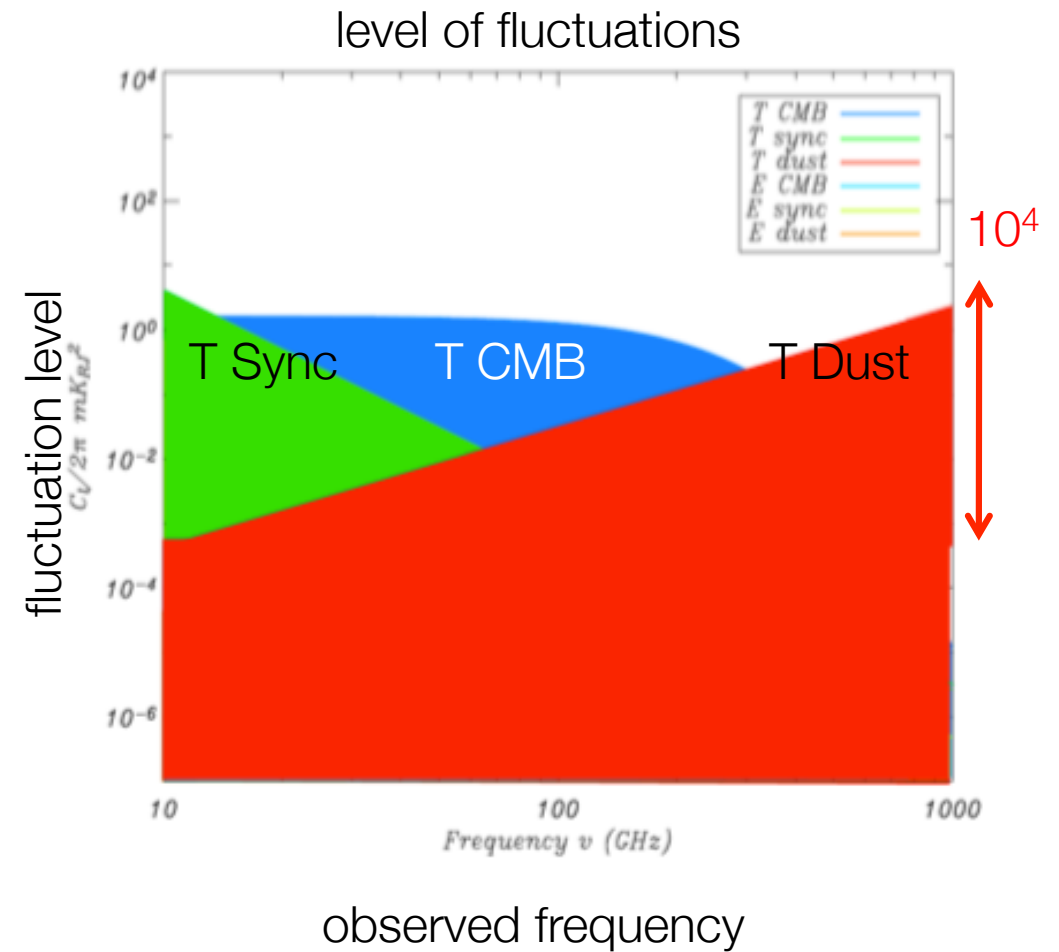
European Space Agency

various components

different spectral and spatial behavior

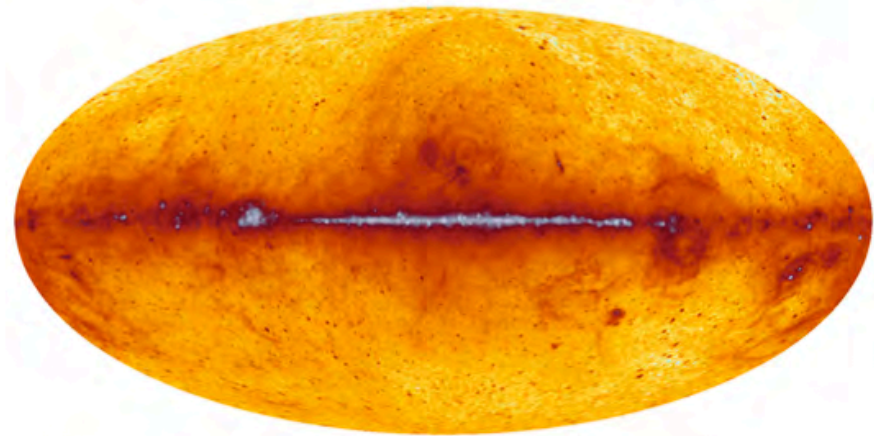


F.R. BOUCHET & R. GISPERT 1996

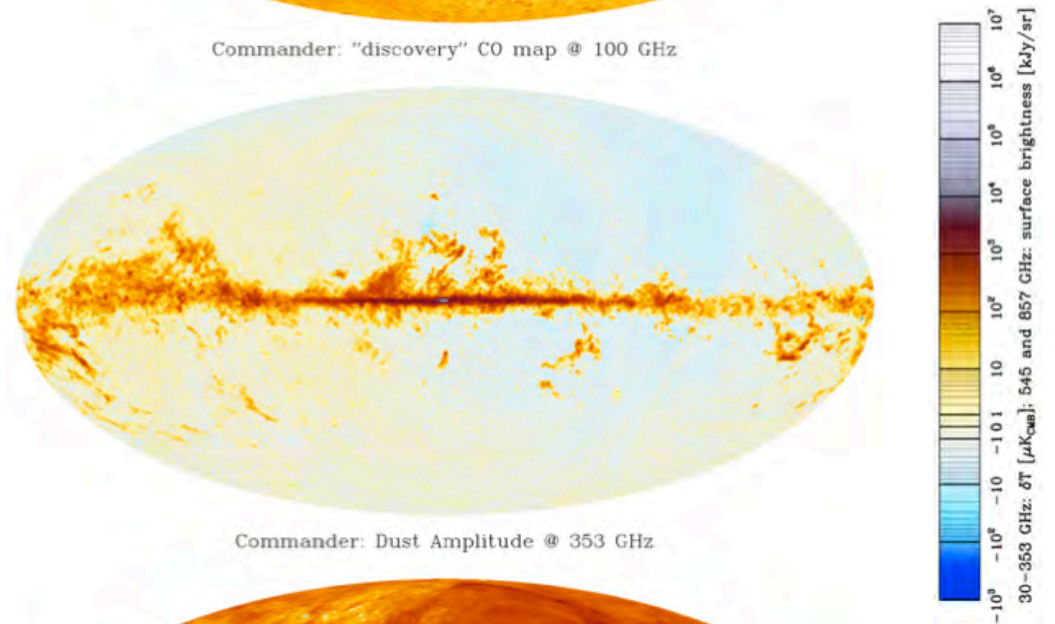


some components

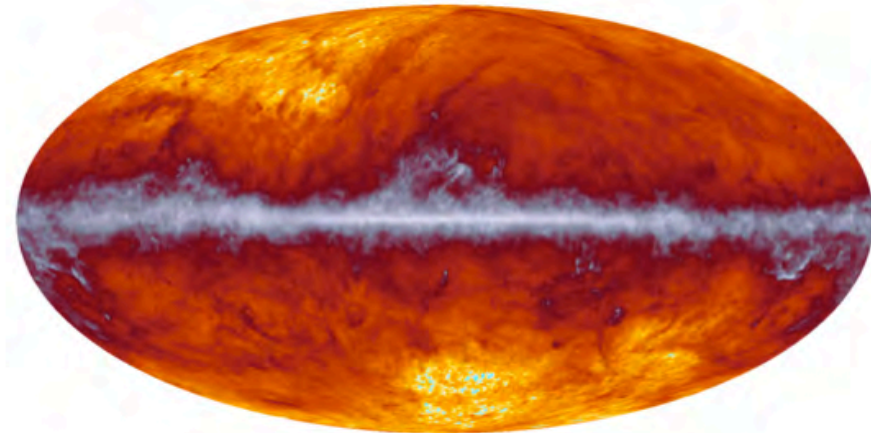
low frequency emission



CO map



dust at high frequency

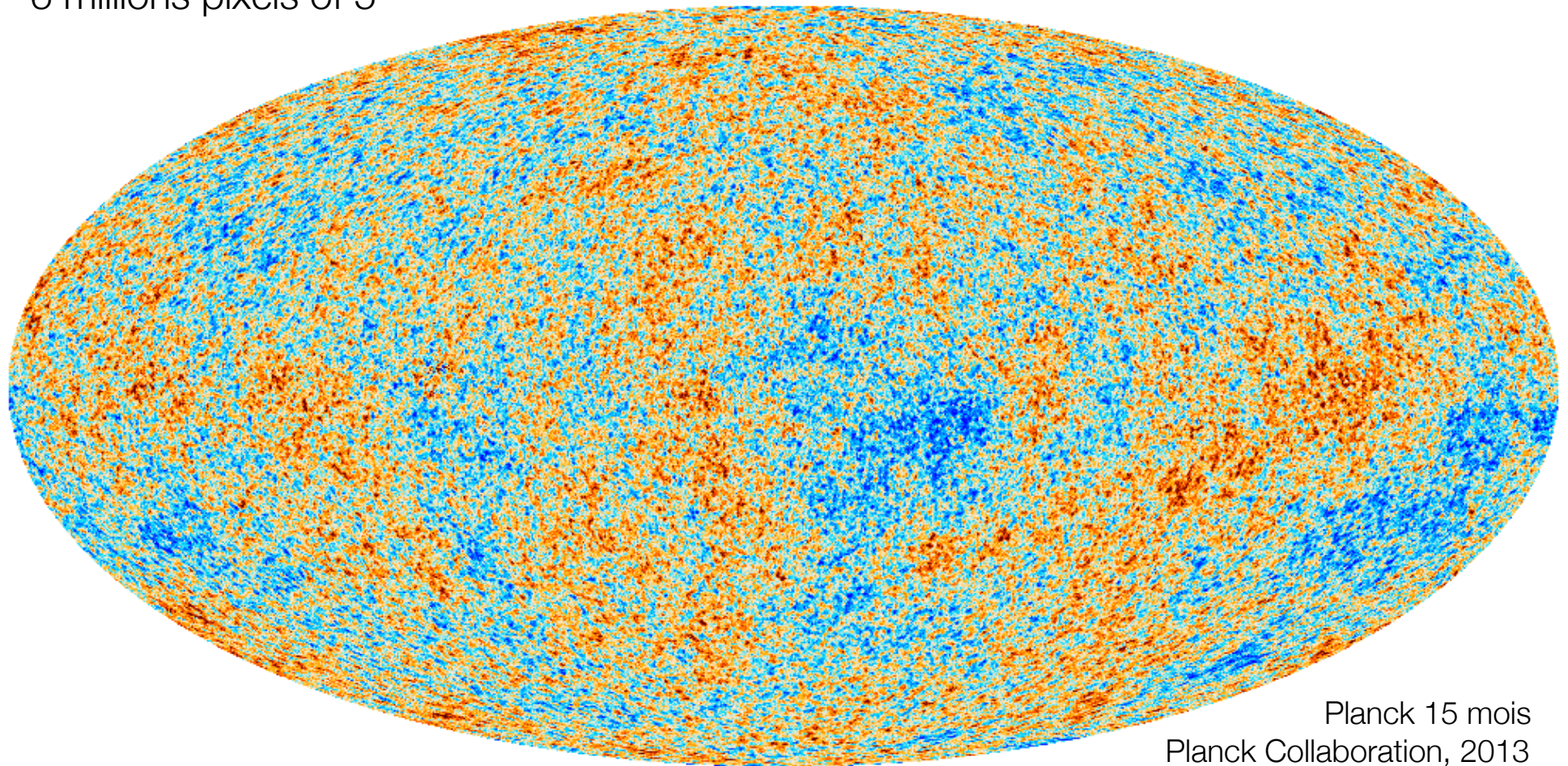


Planck Collab, 2013, 1, 12, 13, 14

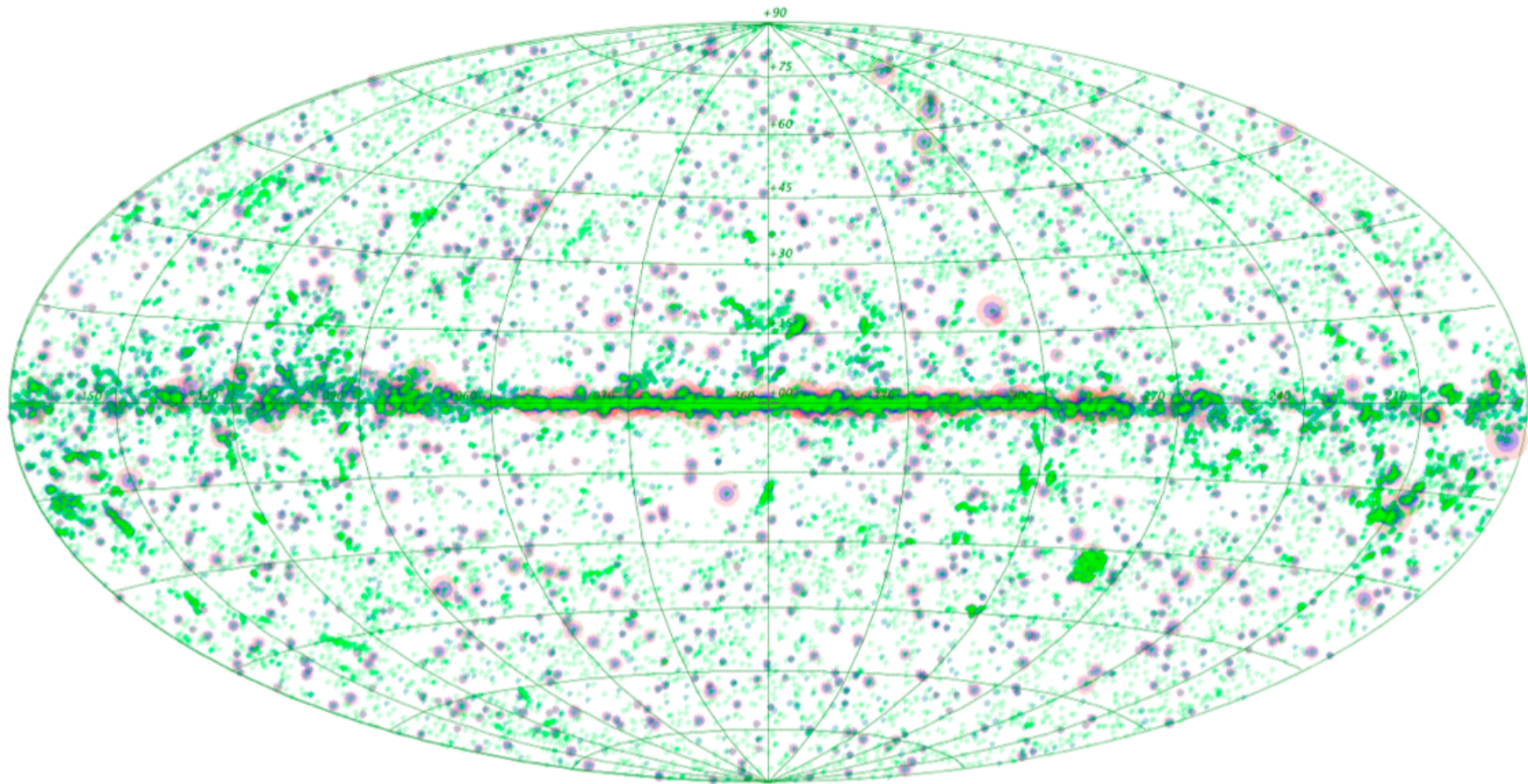
temperature anisotropies

LE RAYONNEMENT FOSSILE par PLANCK

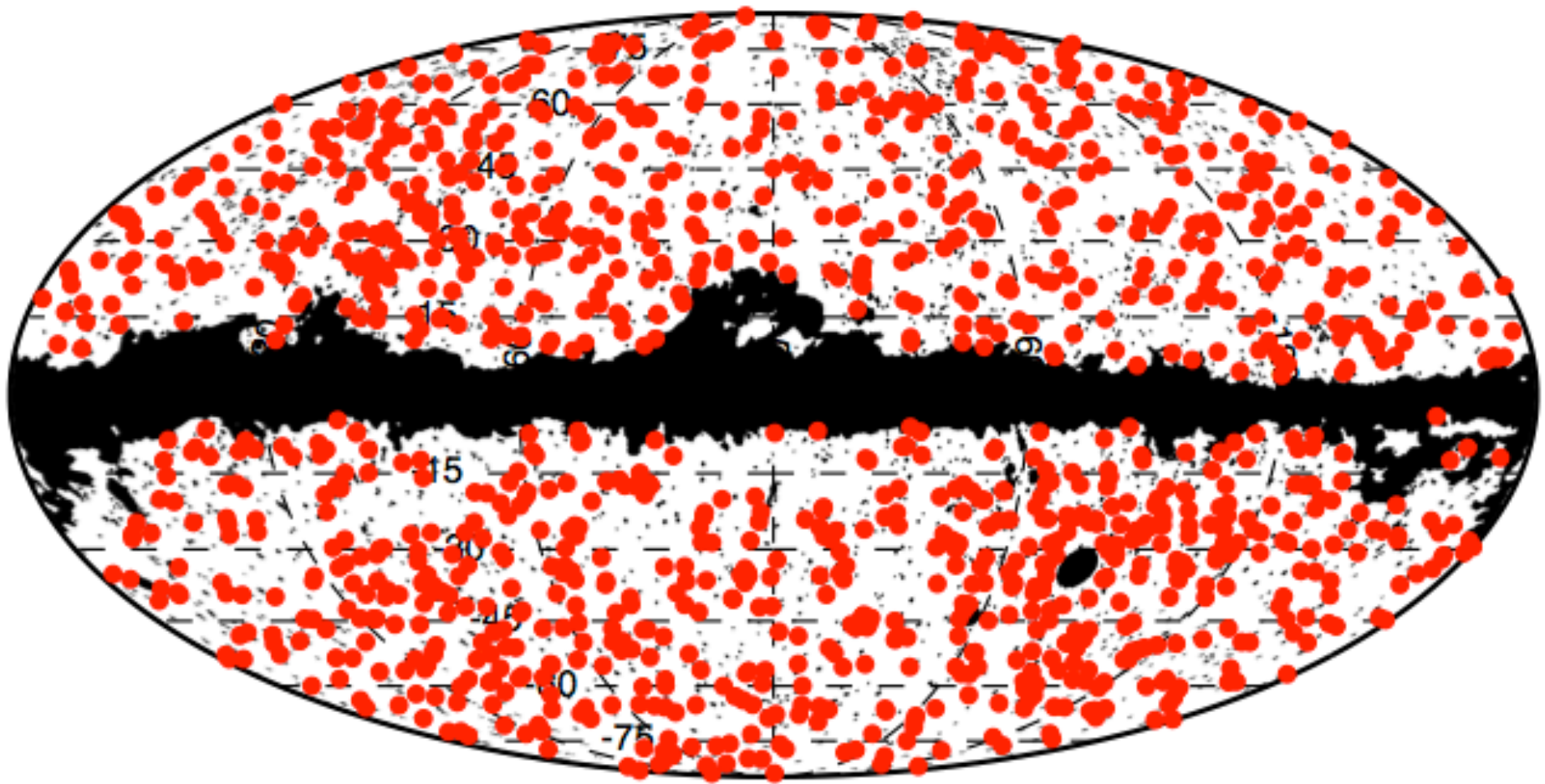
6 millions pixels of 5'



Planck Catalogue of Compact Sources [PCCS]



galaxy clusters: Sunyaev-Zeldovich effect

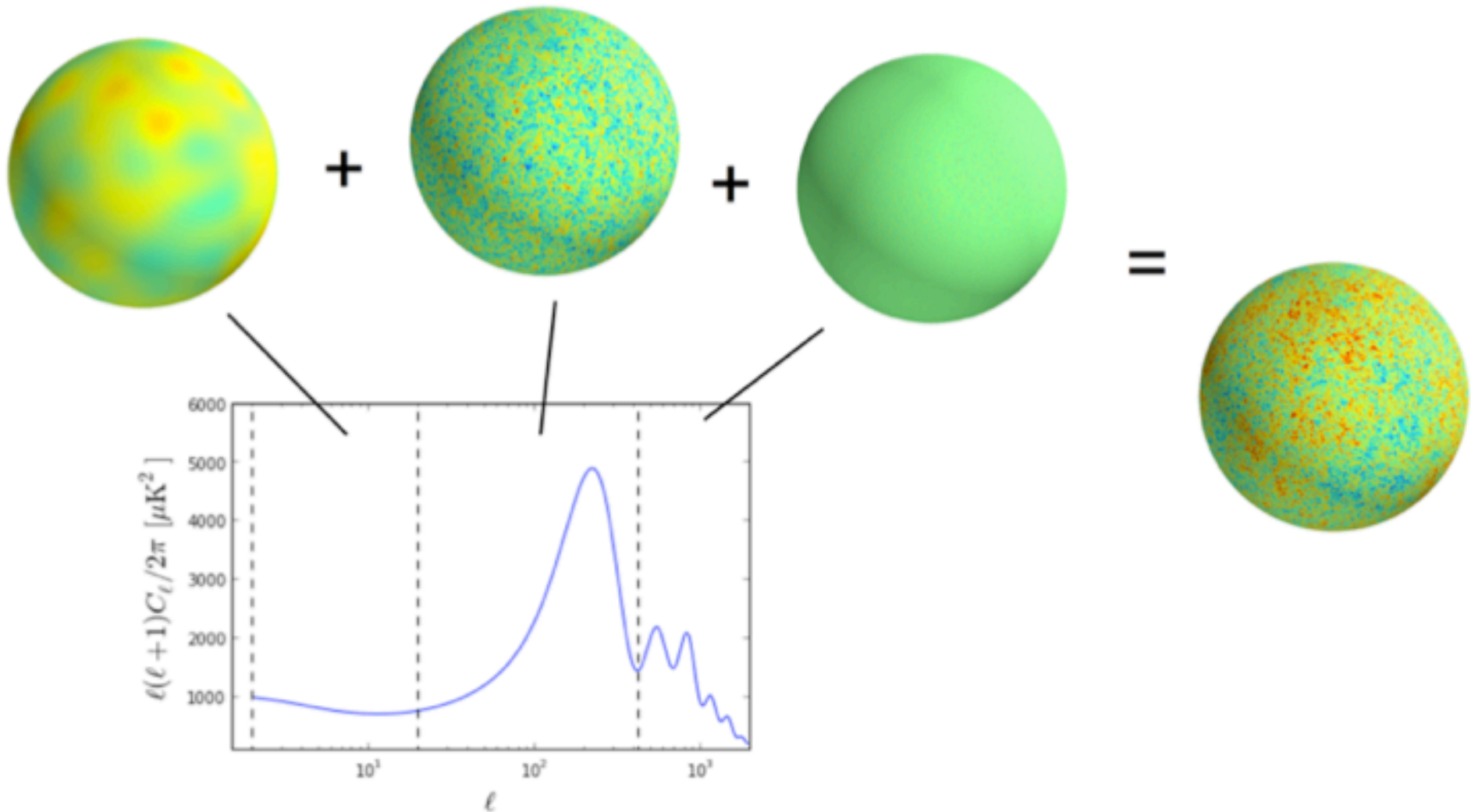


1227 SZ clusters -> including 366 brand new cluster candidates

Planck Collab, 2013, 29

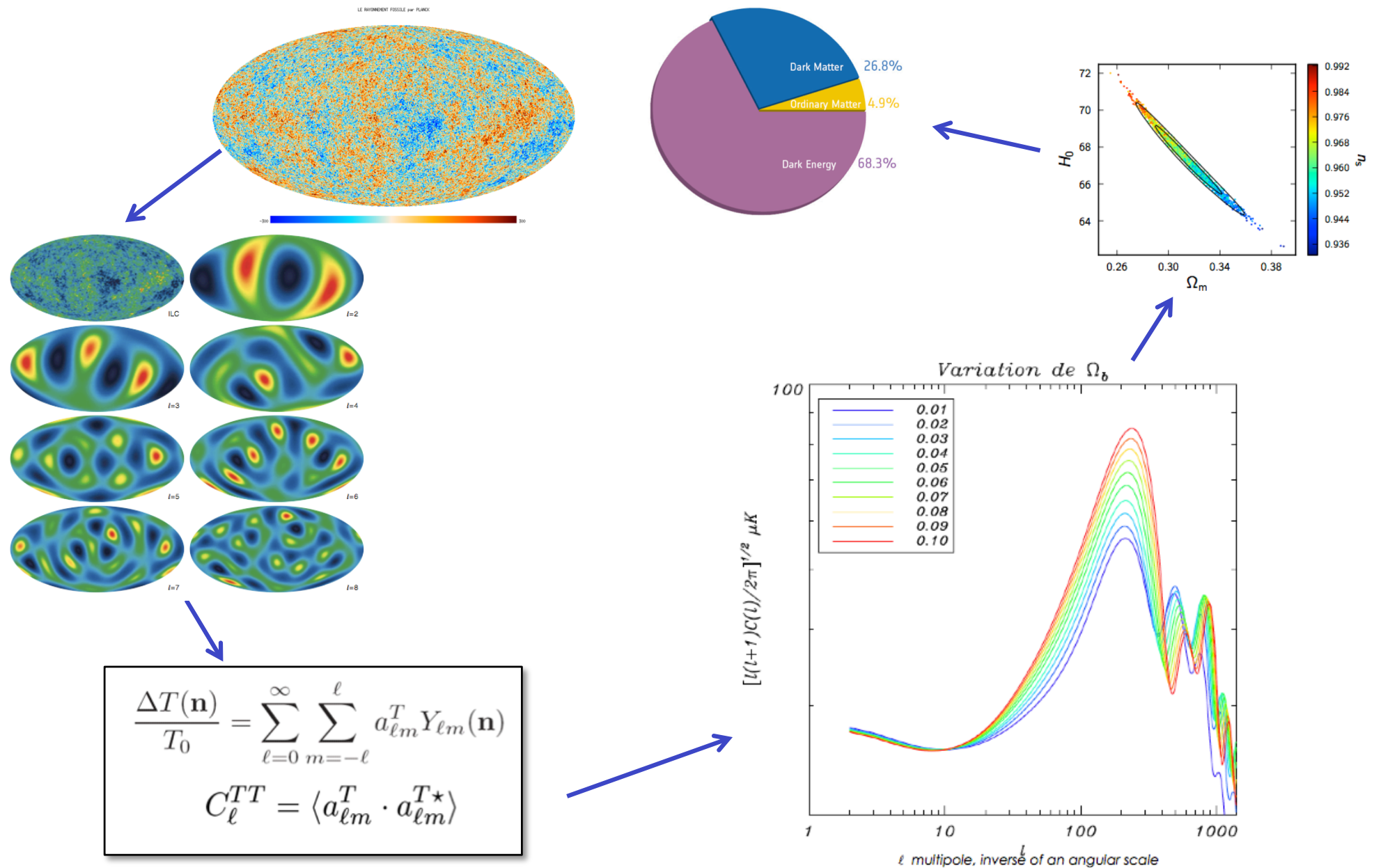
3. angular power spectra

$$\langle a_{lm}^* a_{lm} \rangle = C_l$$

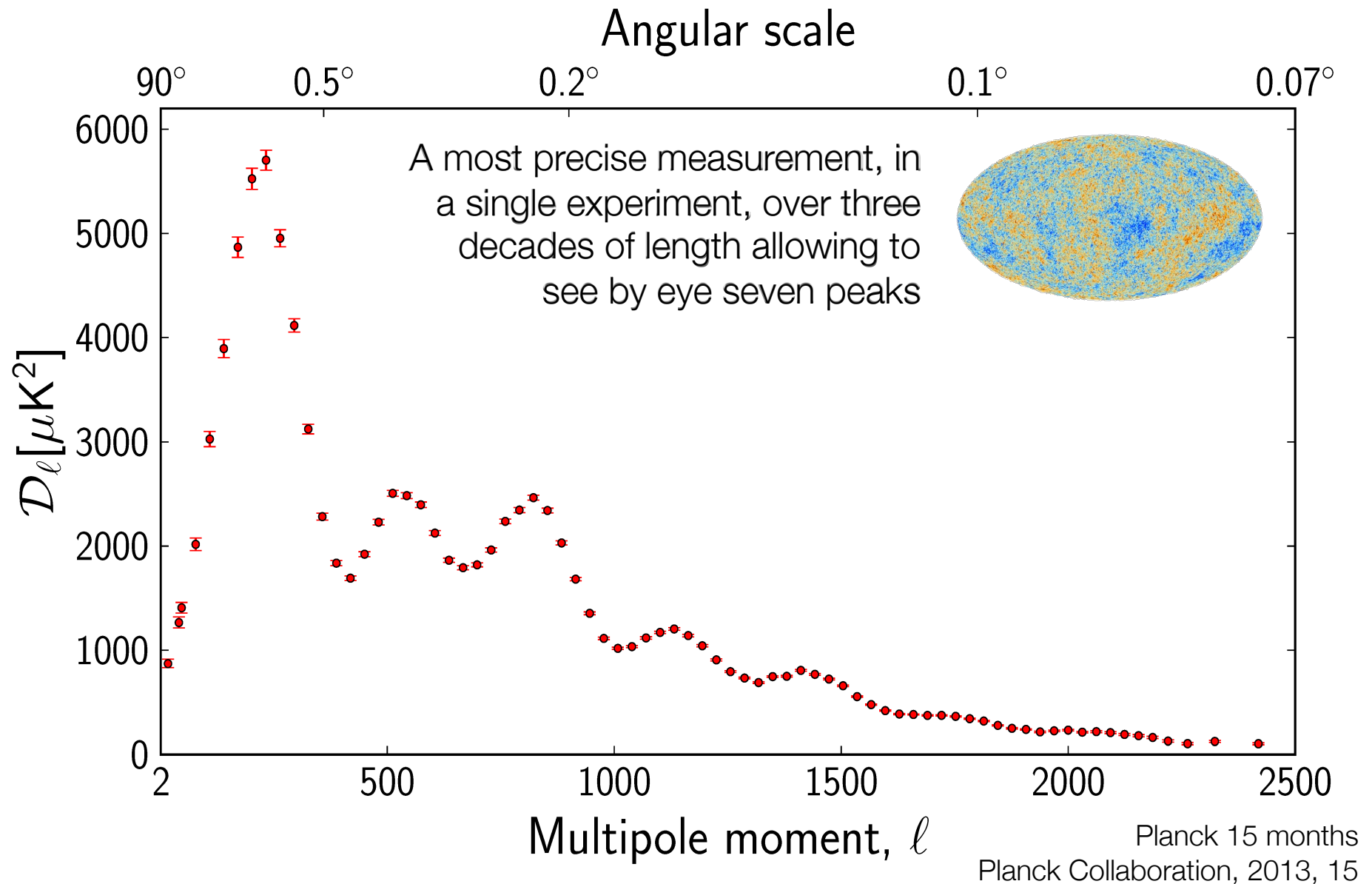


courtesy Olivier Doré

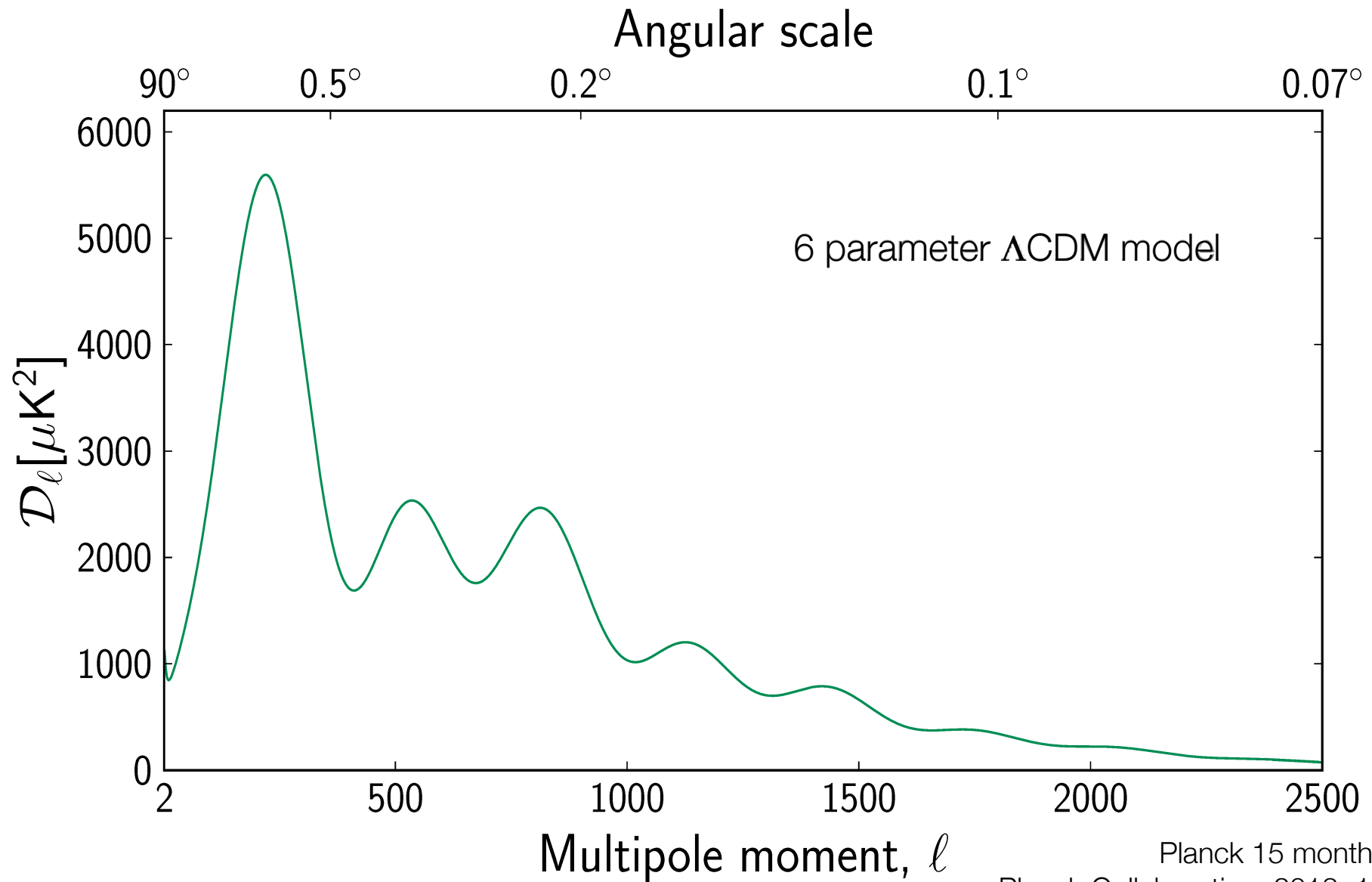
from maps to 6 cosmological parameters



the Planck spectrum of temperature anisotropies

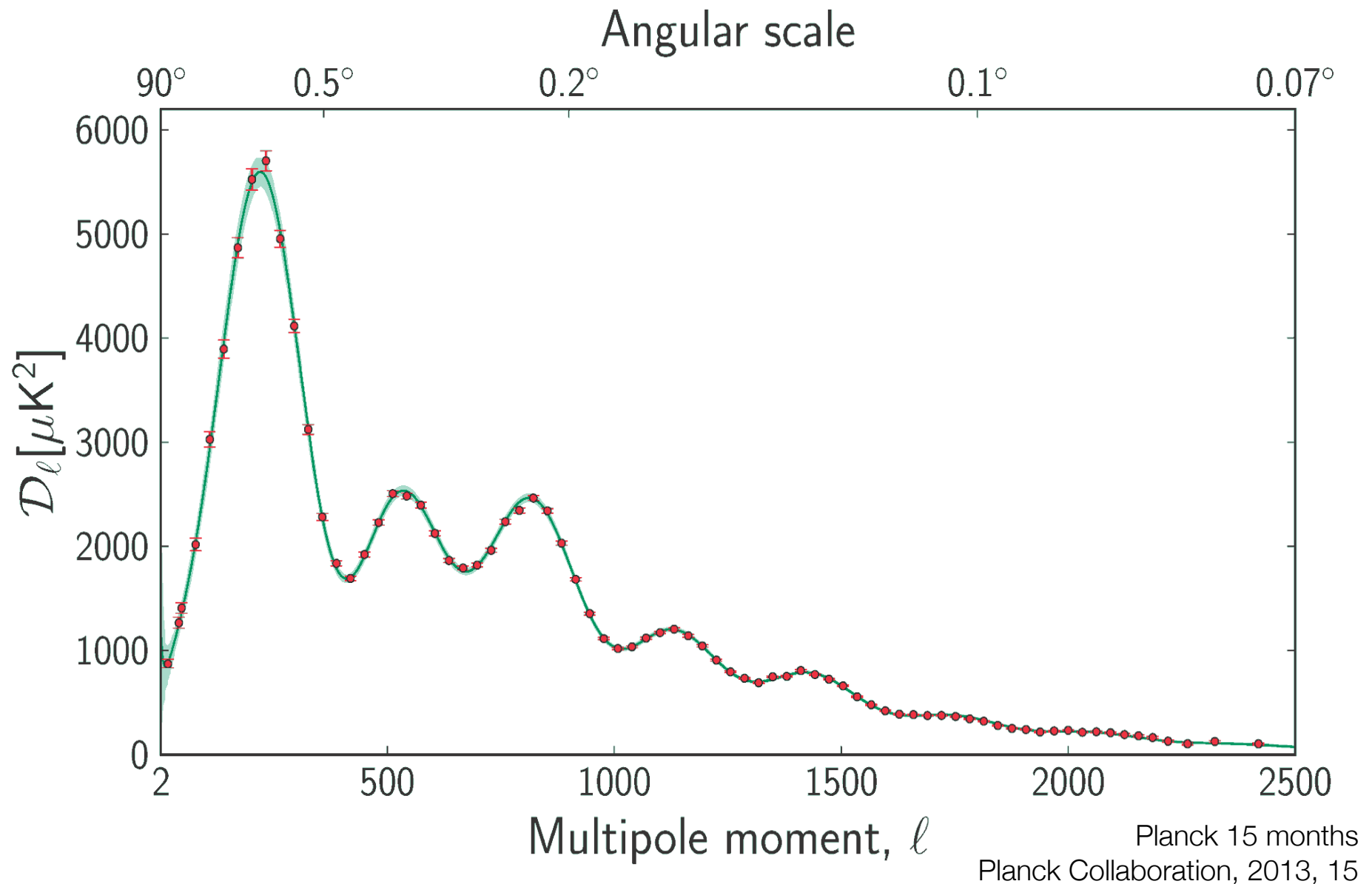


Planck best fitting theoretical model

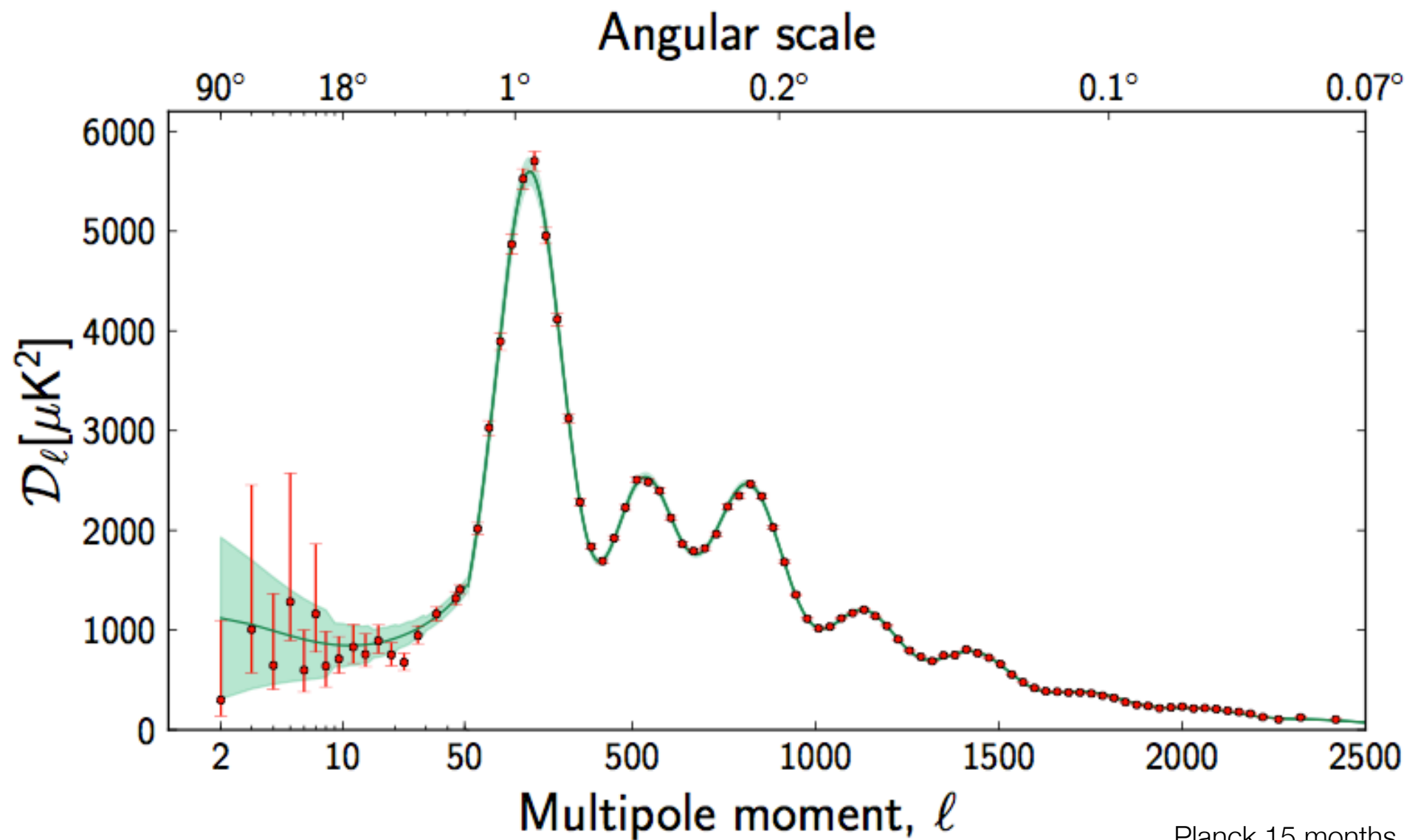


Planck 15 months
Planck Collaboration, 2013, 15

theory confronts data – 1



theory confronts data – 2



Planck 15 months
Planck Collaboration, 2013, 15

theory confronts data – 3 – polarization

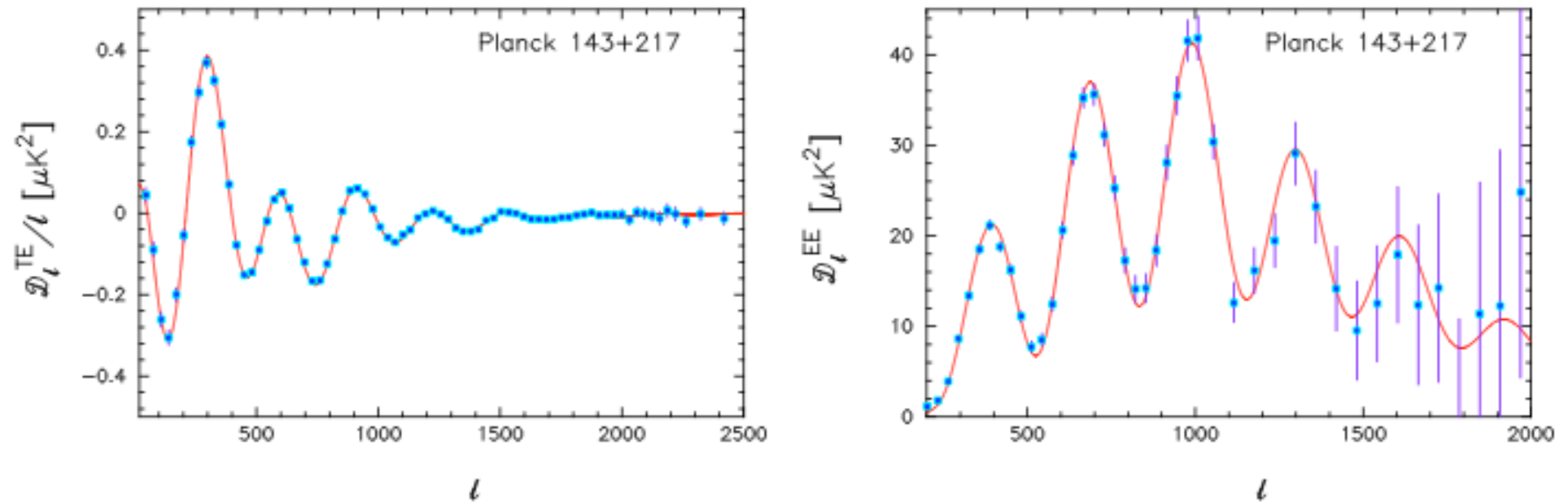
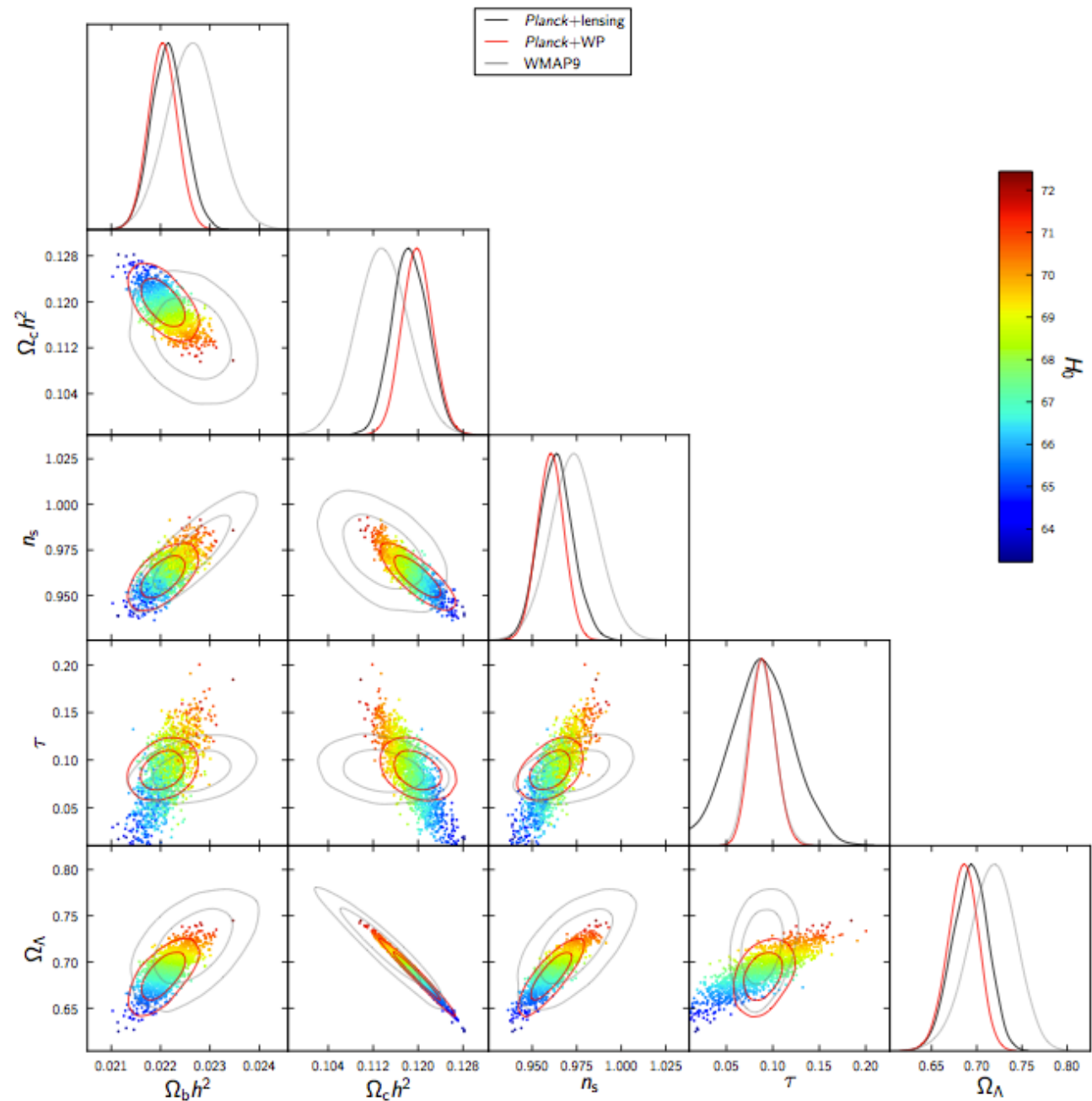


Fig. 11. *Planck TE (left) and EE spectra (right) computed as described in the text. The red lines show the polarization spectra from the base Λ CDM Planck+WP+highL model, which is fitted to the TT data only.*

-> NOT a fit to TE and EE, just an overplot at high- ℓ

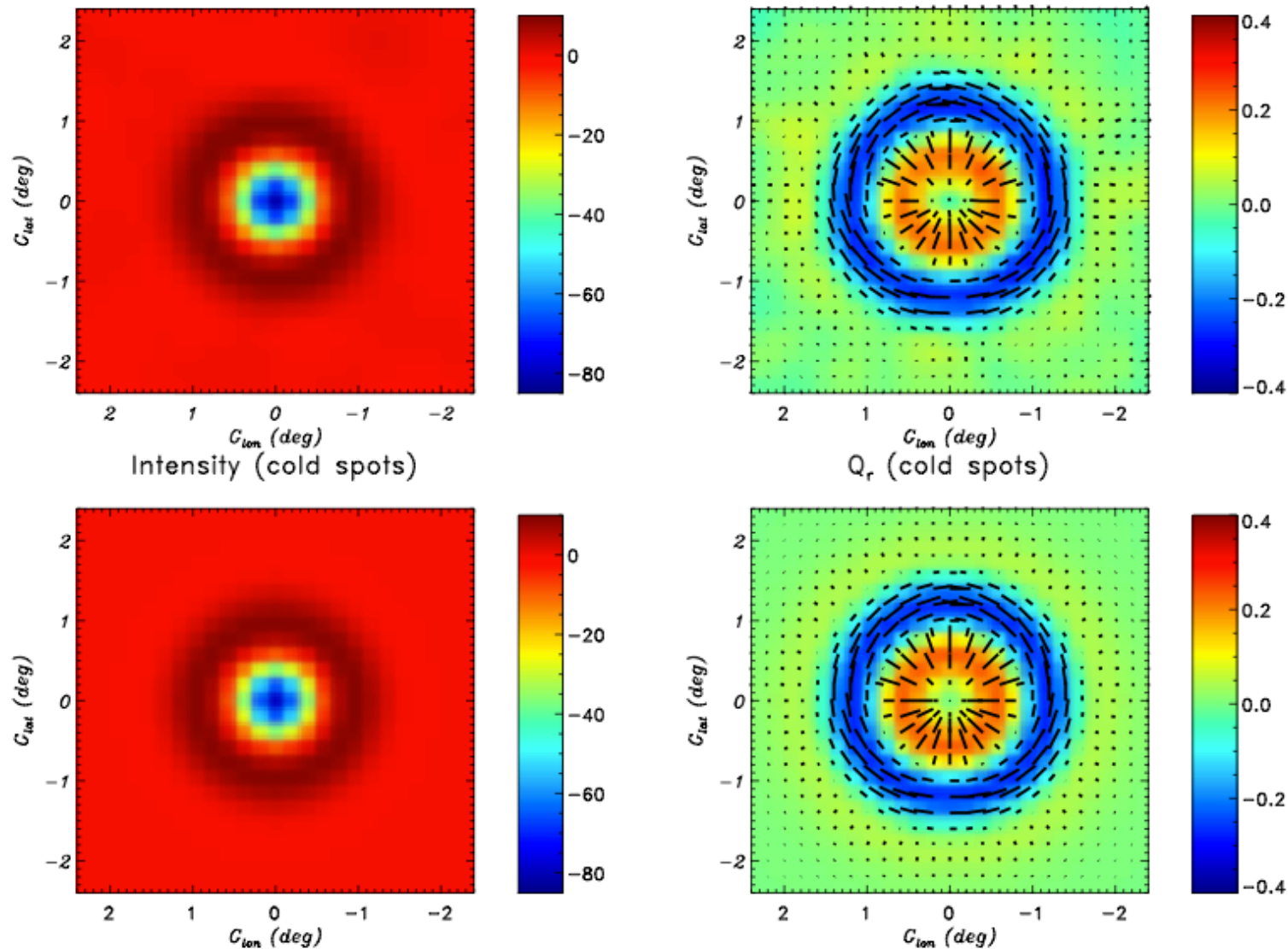
Planck 15 months
Planck Collaboration, 2013, 15

cosmological parameters estimates



Planck 15 months
Planck Collaboration, 2013, 16

matter density and velocity at recombination



Data (top) versus
expectation (bottom)
of stacked cold
spots

→ Planck “sees”
precisely the
dynamics of
fluctuations,
at ~380 000 years

Planck 15 months
Planck Collaboration, 2013, 1

4. standard Λ -CDM model

Unviers plat, avec constante cosmologique et matière noire froide

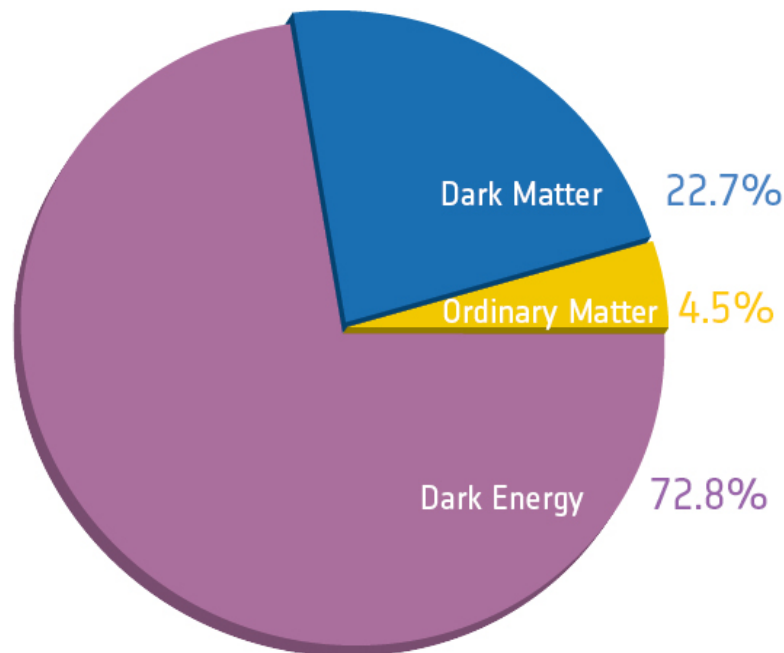
Seulement 6 paramètres.....

	Parameter	Best fit	68% limits
Quantité d'atomes	$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
Quantité de matière noire	$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
Lié à la distance que parcourt le son	$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
Fraction de diffusion récente	τ	0.0925	0.097 ± 0.038
Variation d'échelles de la granulosité	n_s	0.9624	0.9616 ± 0.0094
Force de la granulosité	$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

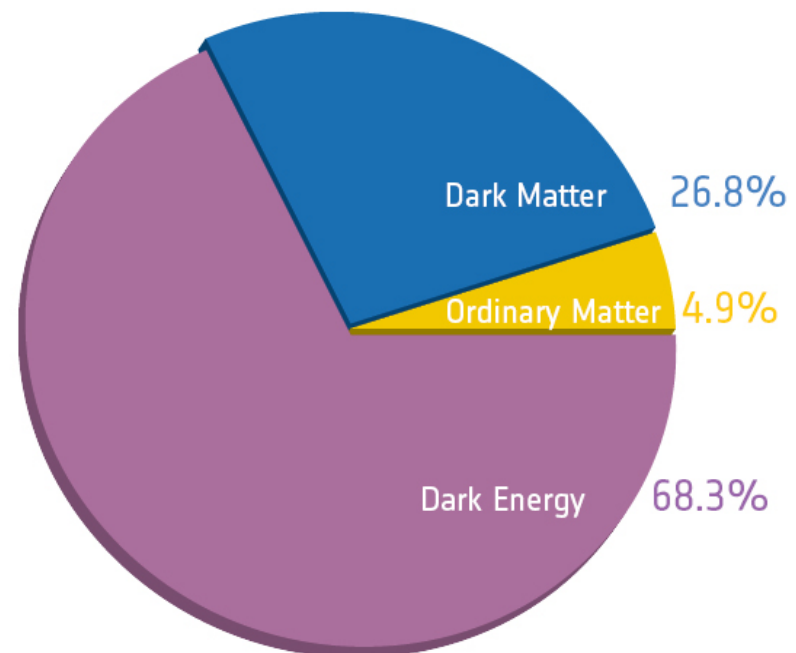
Et quelques paramètres dérivés

H_0	67.11	67.4 ± 1.4
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020

the Universe gets heavier...



Before Planck



After Planck

La quantité de matière ordinaire et de matière noire doit être augmentée de 10% par rapport aux estimations précédentes.

Planck 15 months

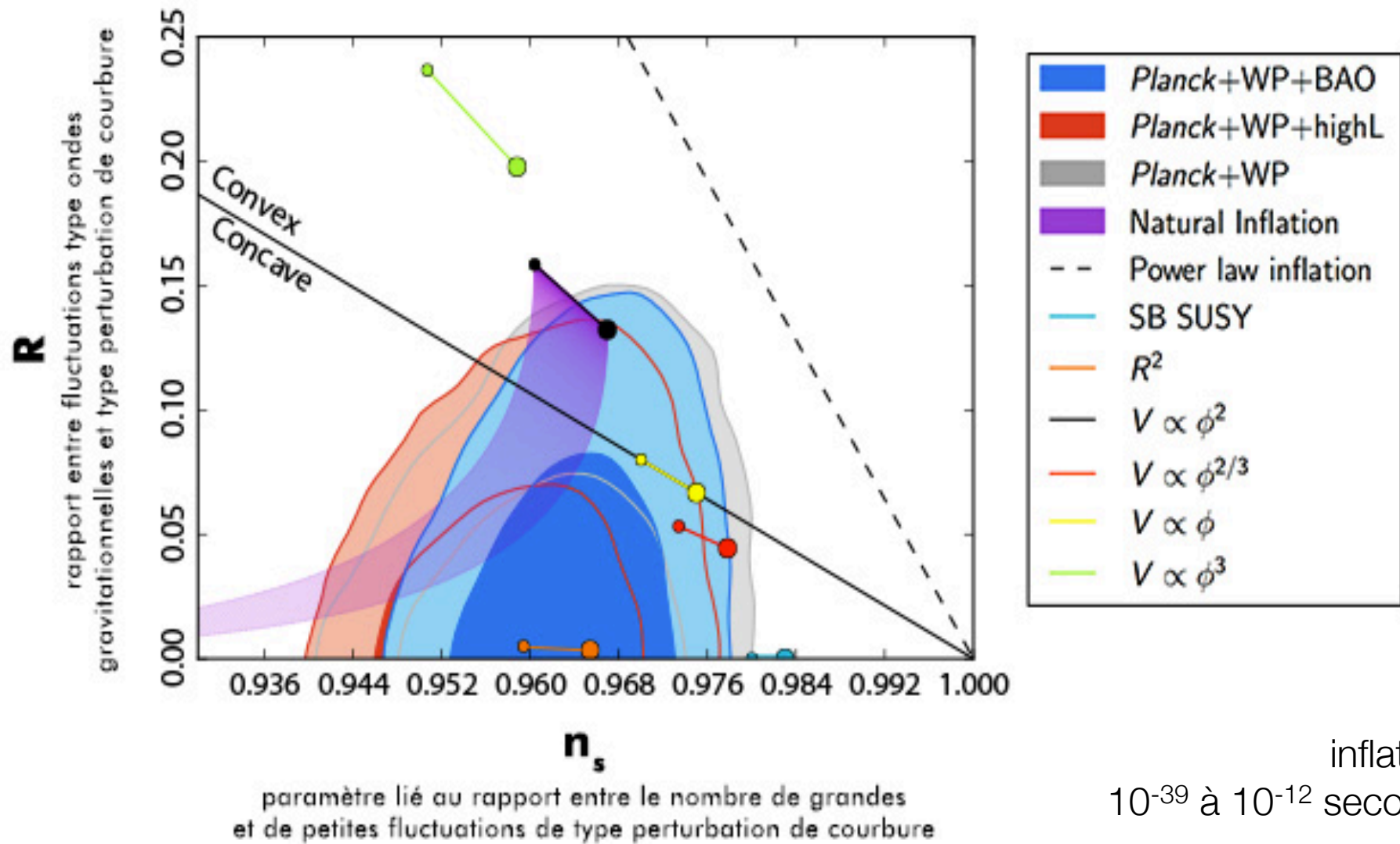
... and older

Parameter	Planck+WP		Planck+WP+highL		Planck+lensing+WP+highL		Planck+WP+highL+BAO	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A_{100}^{PS}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A_{143}^{PS}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	72.2	72 ± 8
A_{217}^{PS}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	60.2	58 ± 10
A_{143}^{CIB}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.25	3.24 ± 0.83
A_{217}^{CIB}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 5.0	52.3	50.0 ± 5.0
A_{143}^{tSZ}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.1}_{-1.9}$	4.64	$2.51^{+1.1}_{-1.9}$
$r_{143 \times 217}^{PS}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.069	0.814	0.825 ± 0.069
$r_{143 \times 217}^{CIB}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.930	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.081	0.656	0.643 ± 0.081
$\xi^{tSZ \times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{drp}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_s$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

km/s/Mpc
 67.80 ± 0.77
 Gyr
 13.798 ± 0.037

Planck 15 months

5. some inflation models excluded



inflation:
 10^{-39} à 10^{-12} seconde

more implications

- θ : sound horizon is determined by the position of the 7 peaks, and now measured at 0.05% precision
- n_s : exact scale invariance of the primordial fluctuations is ruled out, at more than 7σ (as predicted by base inflation models)
- upper limit on neutrino masses
- 3 neutrinos species favored by Planck
- no evidence for dynamical dark energy

Planck+WP+highL+BAO

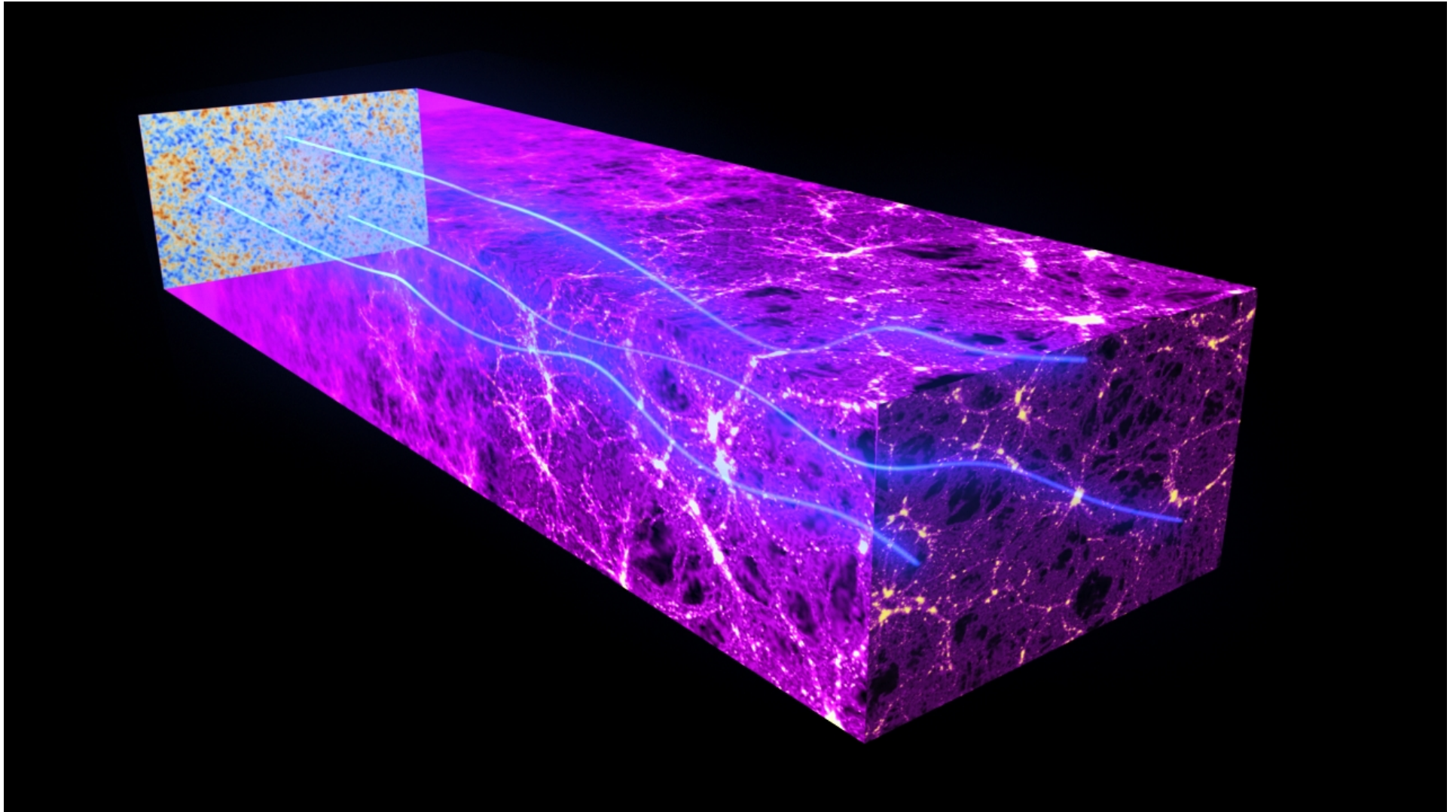
$$1.04147 \pm 0.00056$$

$$0.9608 \pm 0.0054$$

$$\sum m_\nu < 0.23 \text{ eV} \quad (95\%; \text{Planck+})$$

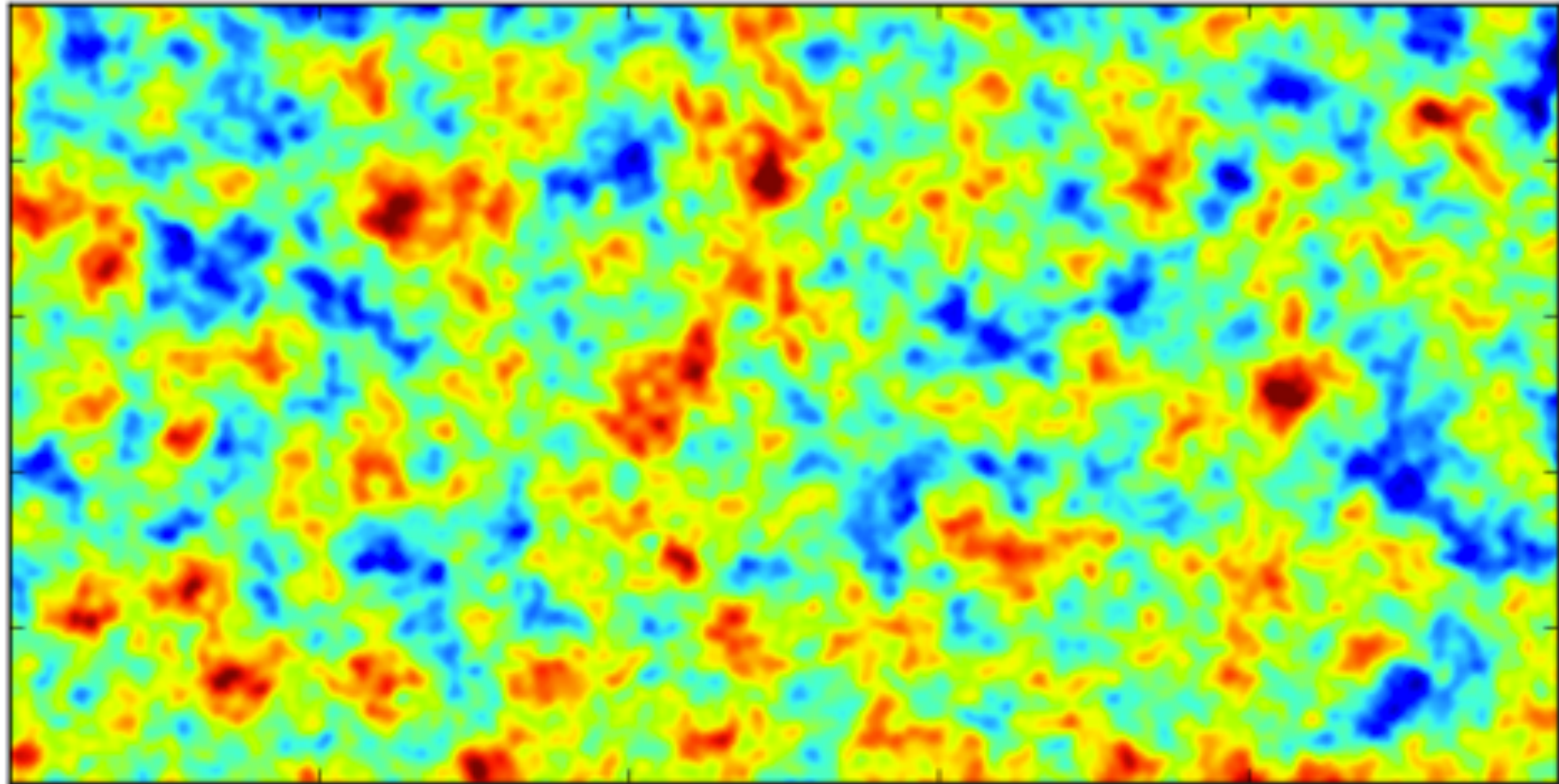
$$N_{\text{eff}} = 3.30^{+0.54}_{-0.51} \quad (95\%; \text{Pla})$$

6. between CMB and us: structures



gravitational lensing of the CMB

A simulated patch of CMB sky – before lensing

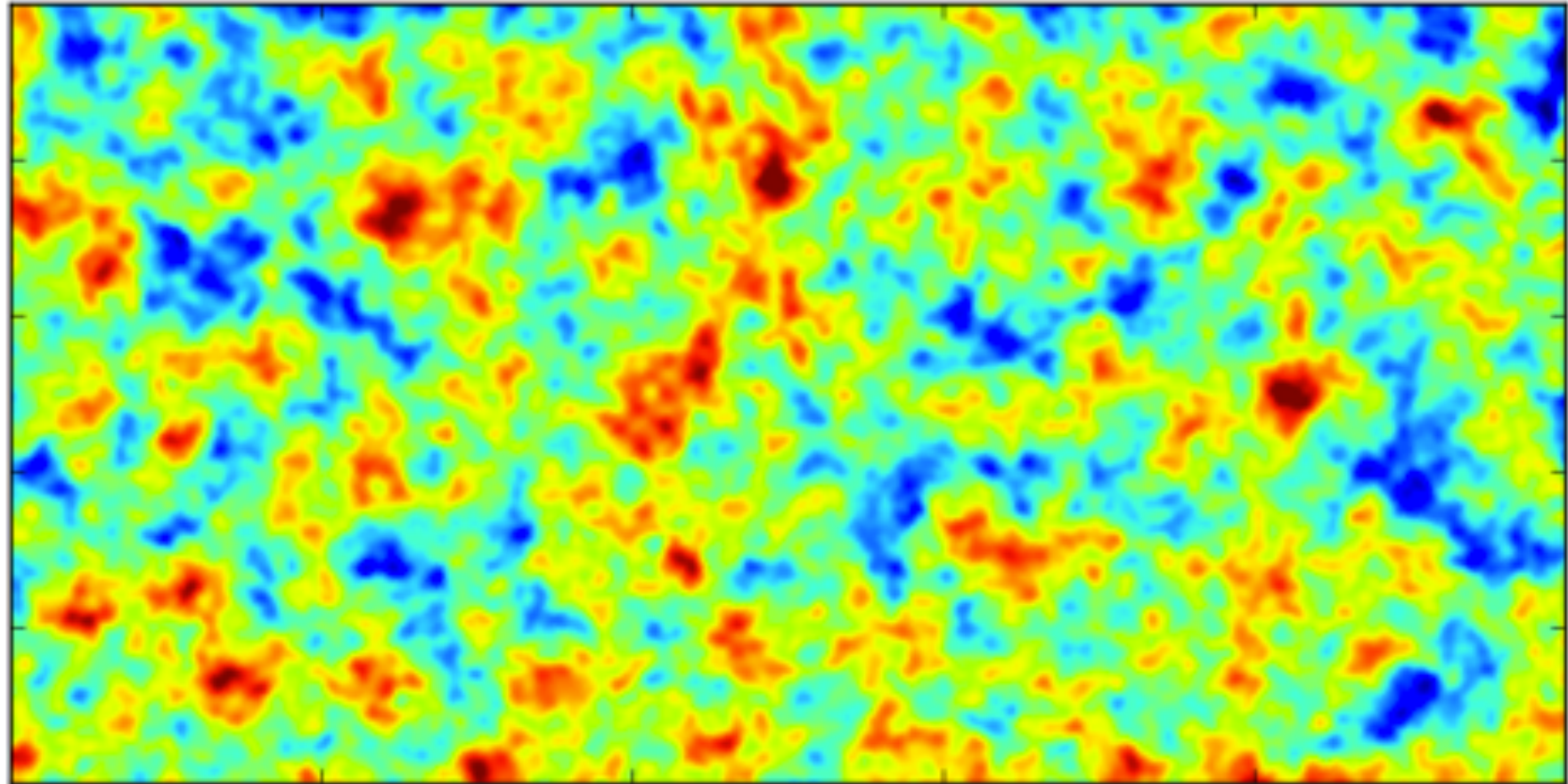


← 10° →

typical deflection: 2.4 arcmin

gravitational lensing of the CMB

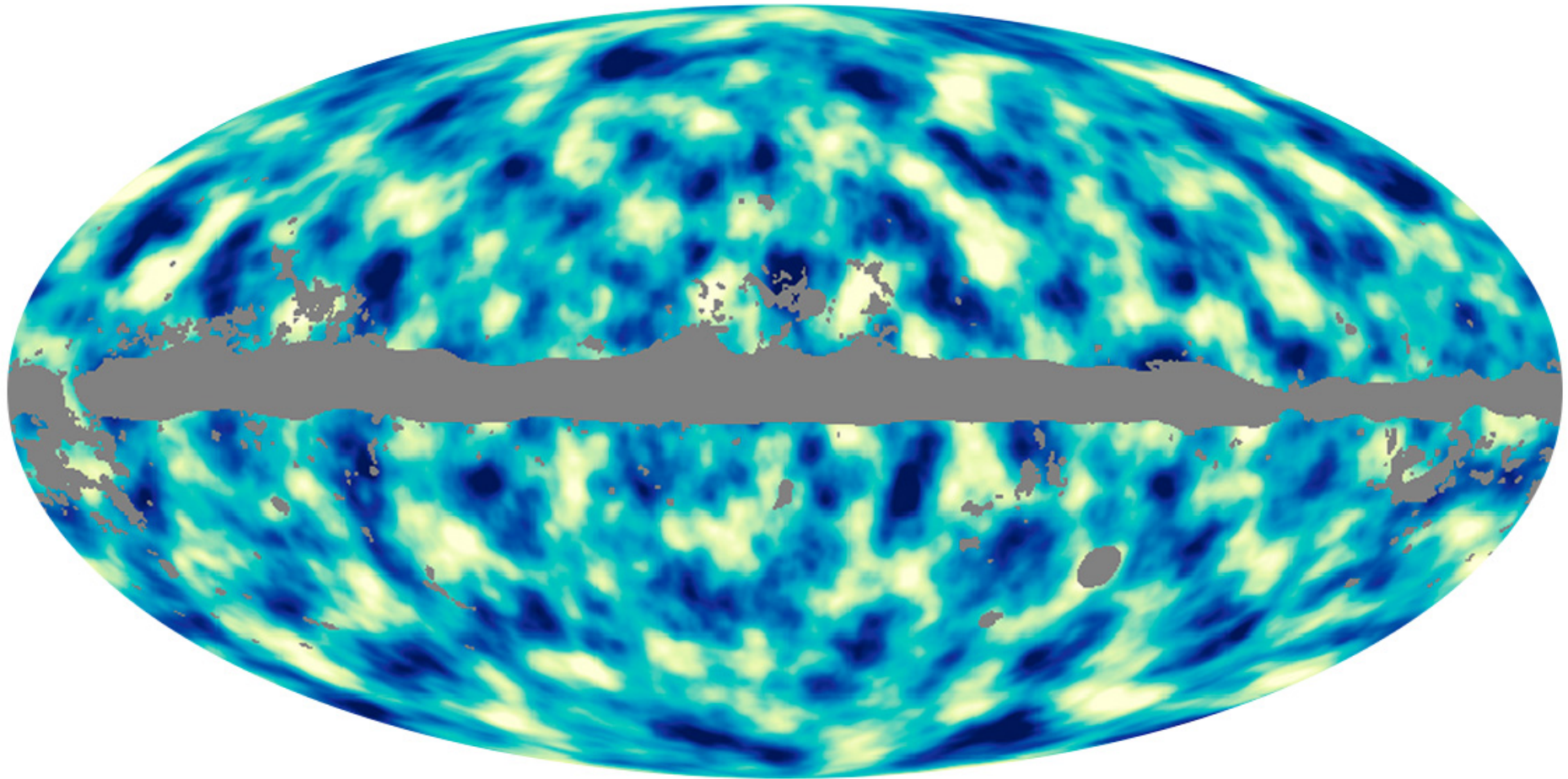
A simulated patch of CMB sky – after lensing



← 10° →

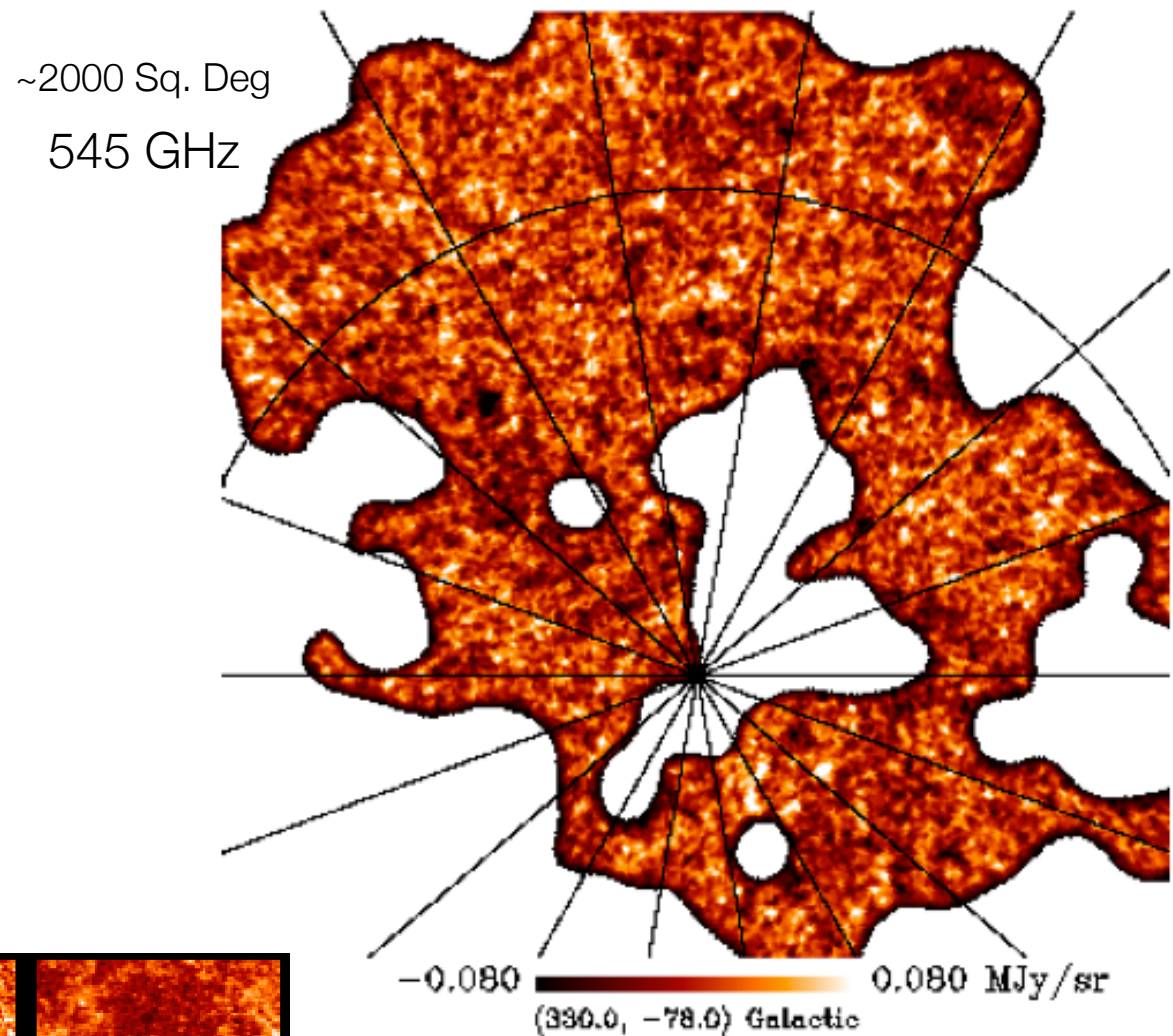
typical deflection: 2.4 arcmin

Planck all-sky map of the dark matter

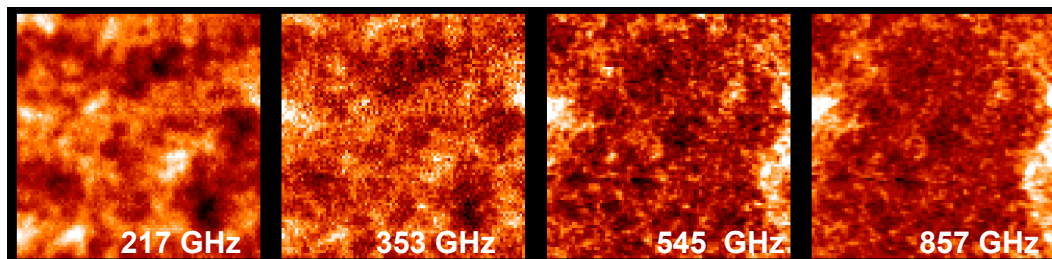


= Carte de la masse projetée sur la ligne de visée

Cosmic IR Background maps probe high-z SFR



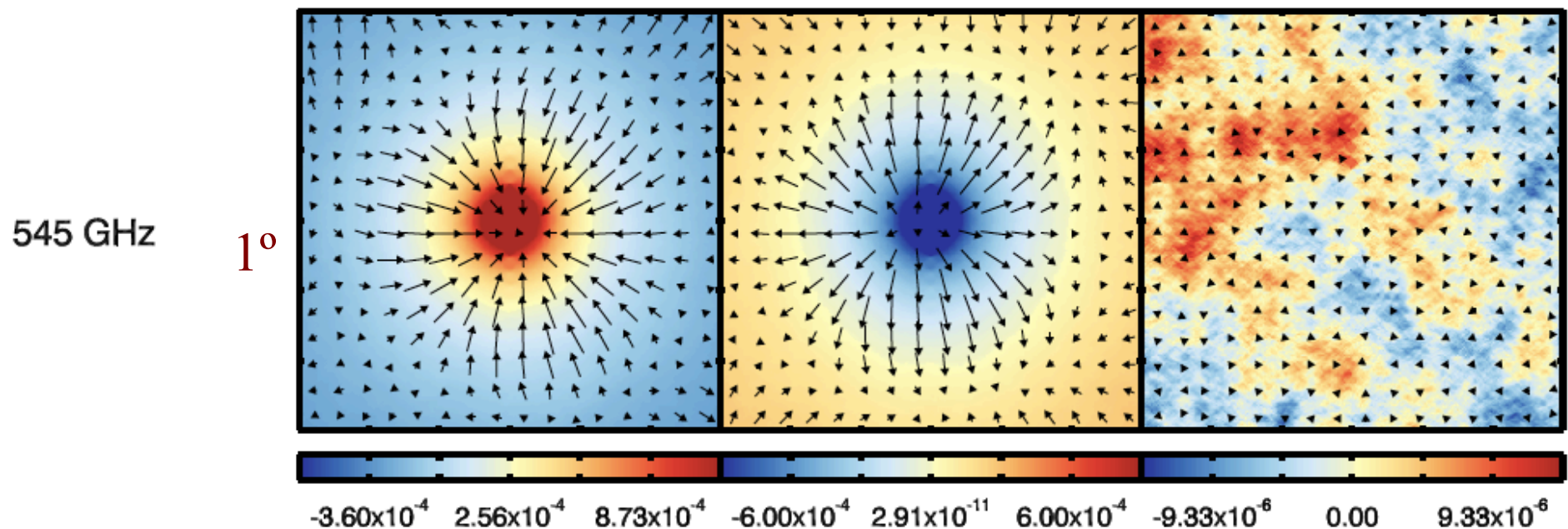
Planck Collab., 2013, 30



few 10 Sq Deg fields in 2011

CIB peaks correspond to mass peaks

Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies. This is mostly Dark Matter.



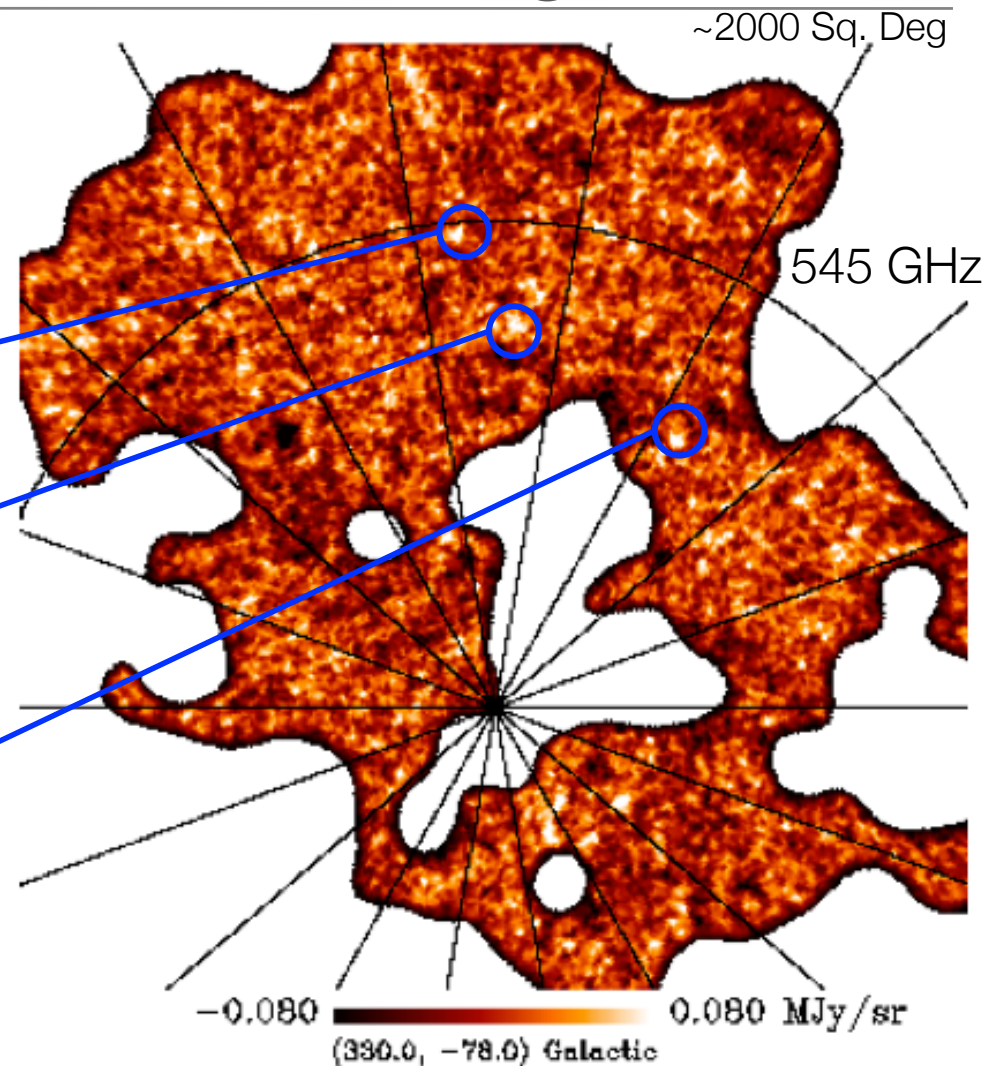
see also Hanson et al., 2013 about
lensing induced B-modes
(NOT primordial B-modes !)

Planck 15 months
Planck Collaboration, 2013, 18

7. digging into the Cosmic IR Background

« cold sources » of the CIB
in Planck data (4.5' beam)

- $z > 1.5$ overdensities of intensely star forming galaxies ?
- $z > 1.5$ extremely bright lensed sources ?
- large scale structure alignments ?
- residual cirrus ?

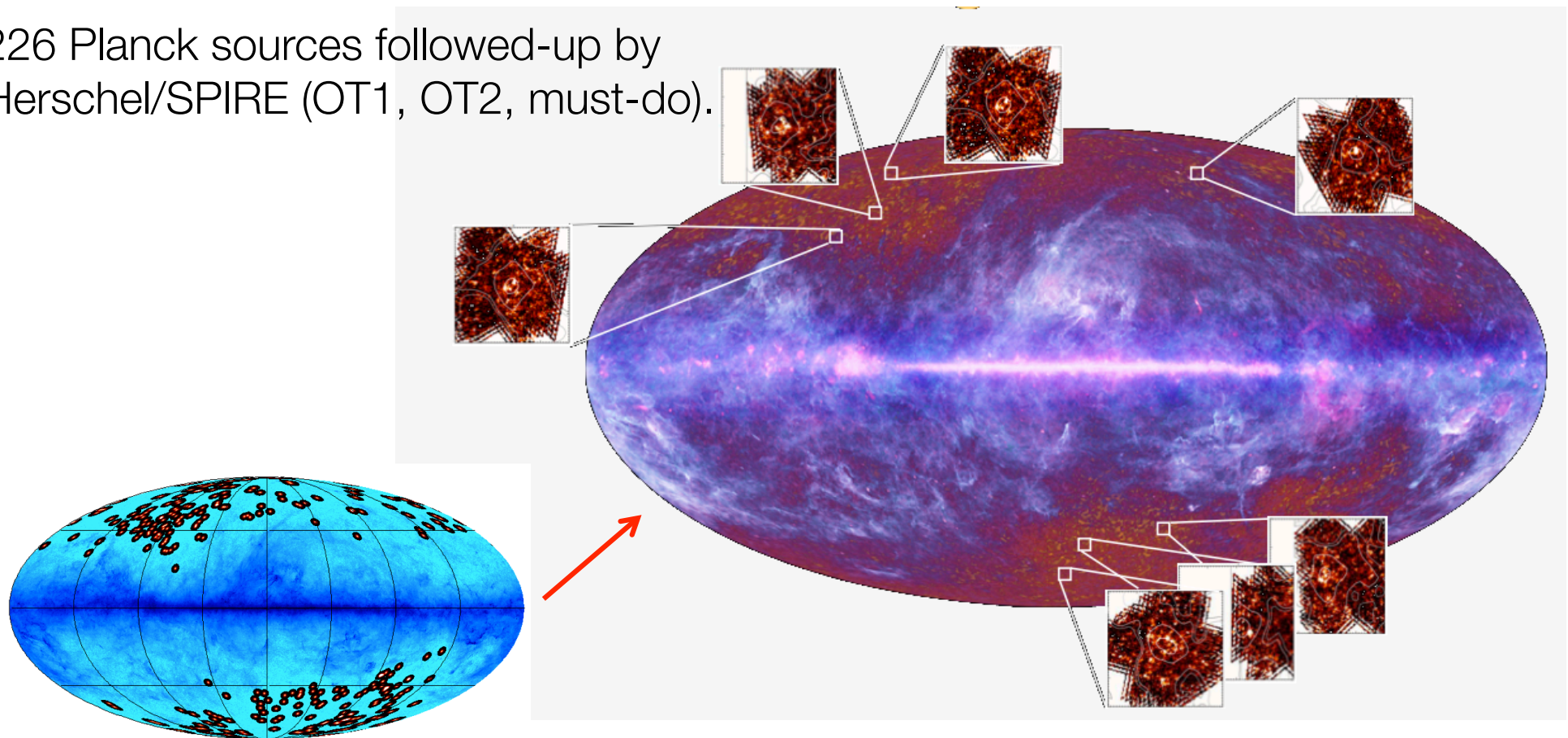


Planck Collab., 2013, 30

predicted number of extragalactic objects :
100 – 1000 (Negrello+2005)

several hundred Planck high-z candidates

226 Planck sources followed-up by
Herschel/SPIRE (OT1, OT2, must-do).

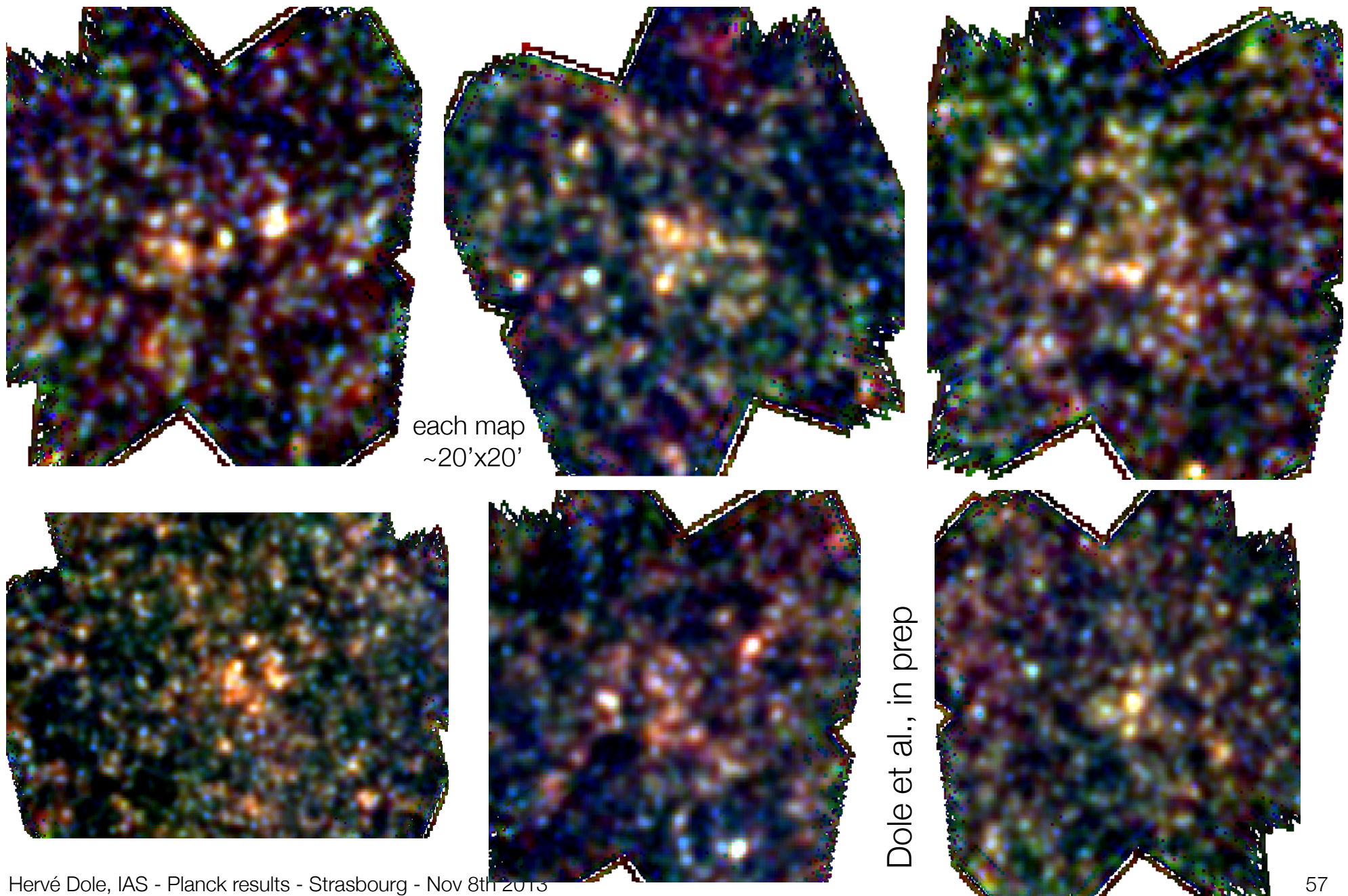


98% success

- either bright lensed candidates
- or overdensities of red galaxies
- 1.4% of the fields were cirrus

Dole et al., in prep

a remarkable dataset



more identifications to go

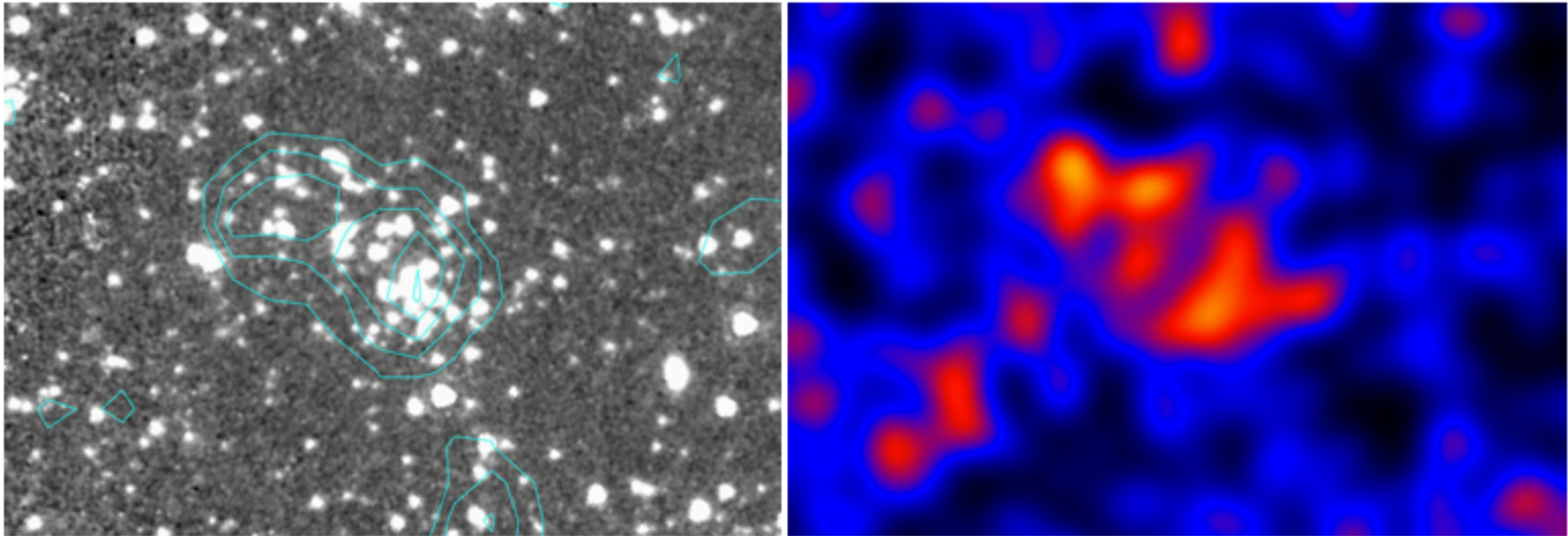


Figure 10. A high- z cluster candidate observed by *Planck*, *Herschel*, and here *Spitzer*-IRAC ($3.5' \times 2.3'$). Left: IRAC channel 2 ($4.5 \mu\text{m}$) with SPIRE $350 \mu\text{m}$ contour. Right: color image of the 4.5/3.6 color ratio, showing the red color of the sources within the cluster candidate.

more identifications to go

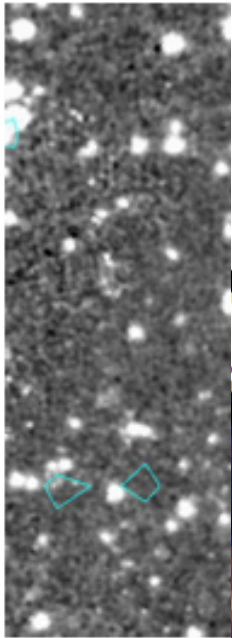
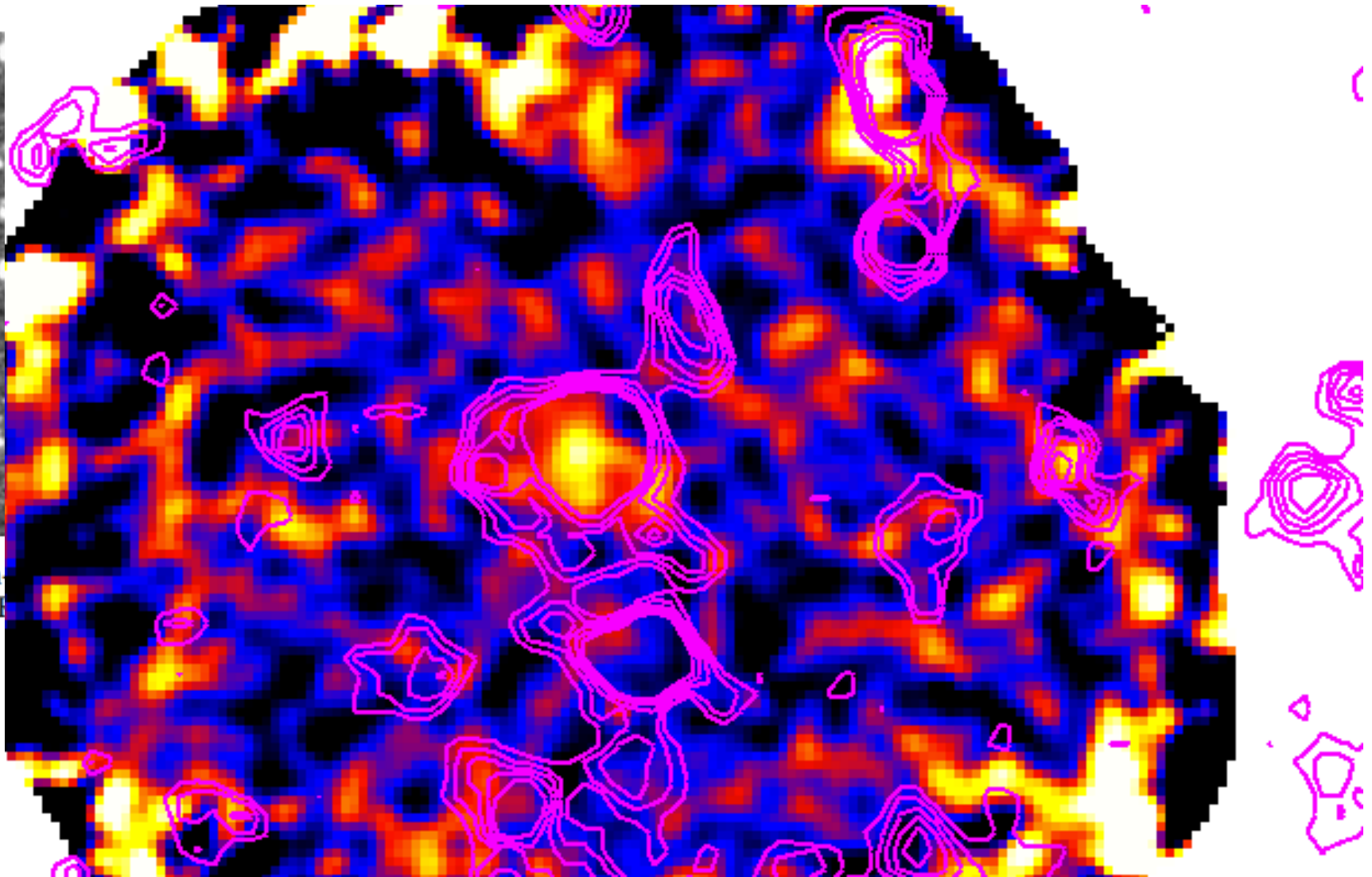


Figure 10. A high-resolution image (4.5 μm) with SPIRE cluster candidate.



NEW! IRAM 30m GISMO image at 2mm + SPIRE 350um contour

Dole et al., in prep

finally

- one sky round per minute (repeated 50 times at the same place)
- 200 measurements/second per detector, during 30 months at temperature 0.1K at 1.5M km from Earth
- ~1000 billion samples (72 ch., 30 months) and few billion telemetry packets to downlink
- raw data for one detector (Time Ordered Information, TOI)
 - 50 Gb (multiply by 52 detectors, and many versions)
- 1 release: 1 month of processing, 2200 maps generated
- sky maps : 50 millions pixels (6 freq for HFI + 3 LFI)
- Cosmic Microwave Background angular power spectrum: 1000 values
- **only 6 cosmological parameters** perfectly fitting the data
- and next year: POLARIZATION !!!

finally

- un tour sur l-
- 200

LE RAYONNEMENT FOSSILE par PLANCK

to get the best-ever map of the early Universe
(~380 000yr or $z=1090$)

... all that for only
7 cents/european/year over 20 years
under European lead

stant parfaitement