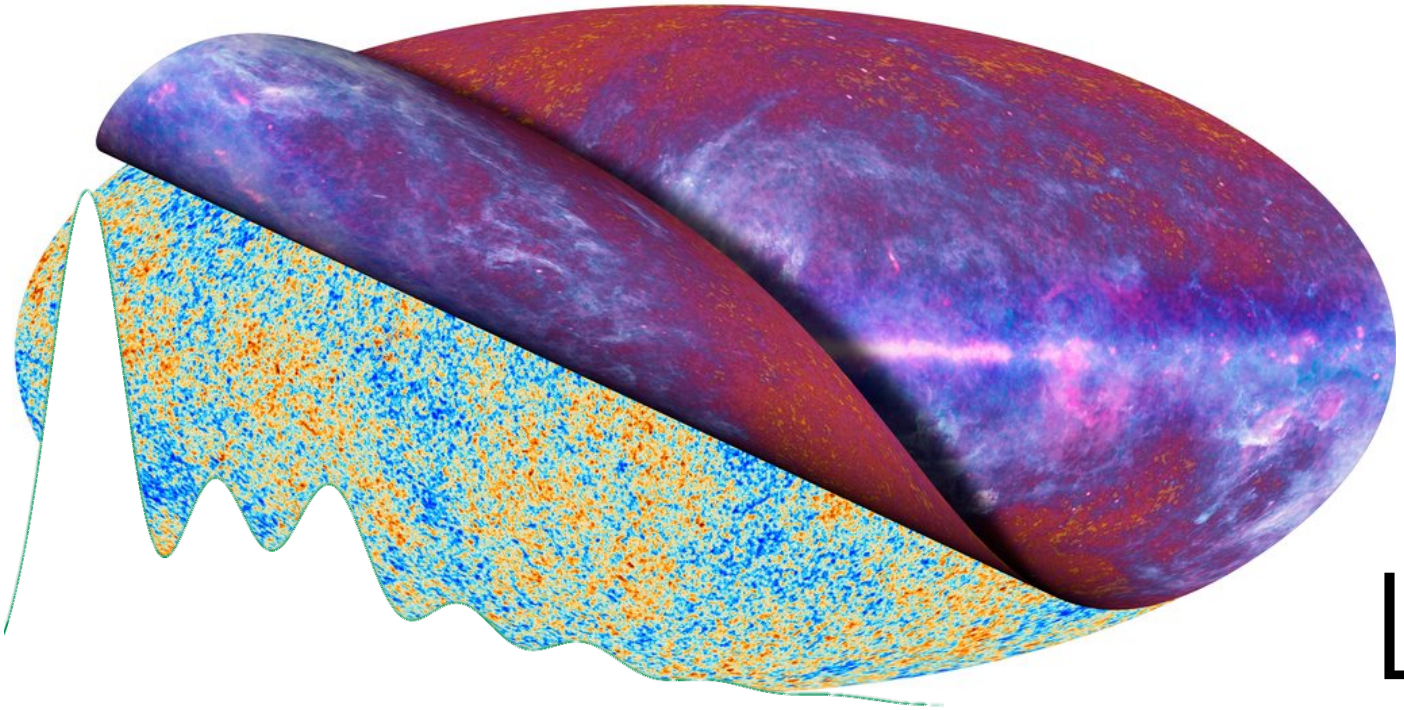


# L'Univers révélé par le satellite Planck

Hervé Dole

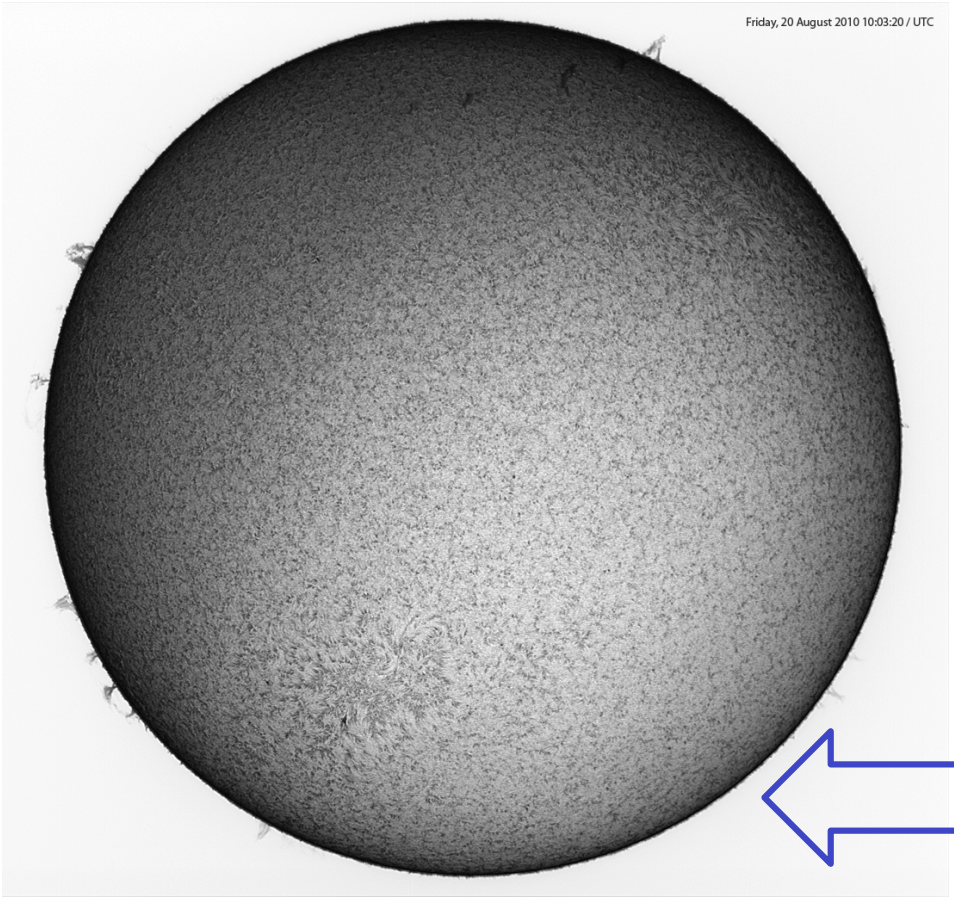
au nom de la collaboration Planck

Institut d'Astrophysique Spatiale, Orsay, France
Université Paris Sud & CNRS
Institut Universitaire de France
http://www.ias.u-psud.fr/dole/

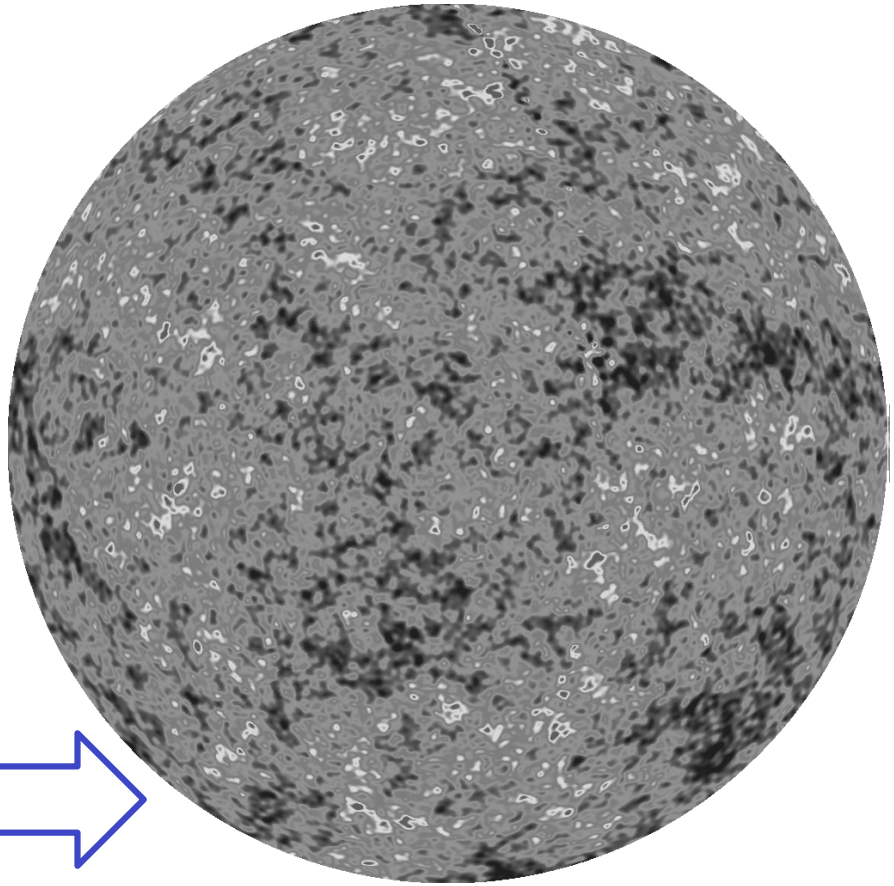
# notre ambition scientifique

comprendre la structure, l'évolution et les lois physiques fondamentales régissant l'univers et ses constituants.

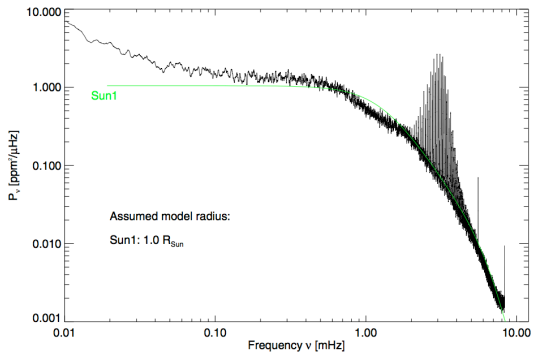
# un exemple



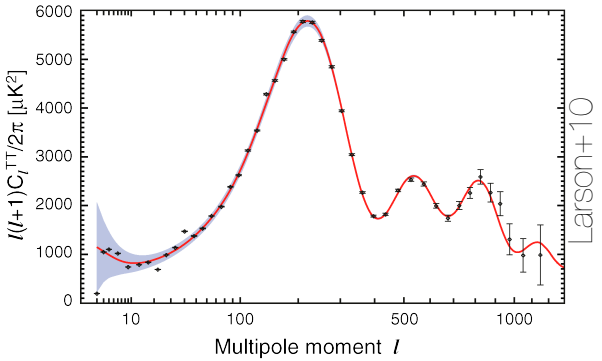

F. Noel – AAV 2010



WMAP




Ludwig+09




Larson+10

**Fig. 2.** Power spectra of disk-integrated photometric fluctuations for the Sun: the predicted background signal of model Sun1 (green/grey solid line) and observational data from SOHO/VIRGO (black solid line)

# notre ambition scientifique

comprendre la structure, l'évolution et les lois physiques fondamentales régissant l'univers et ses constituants.

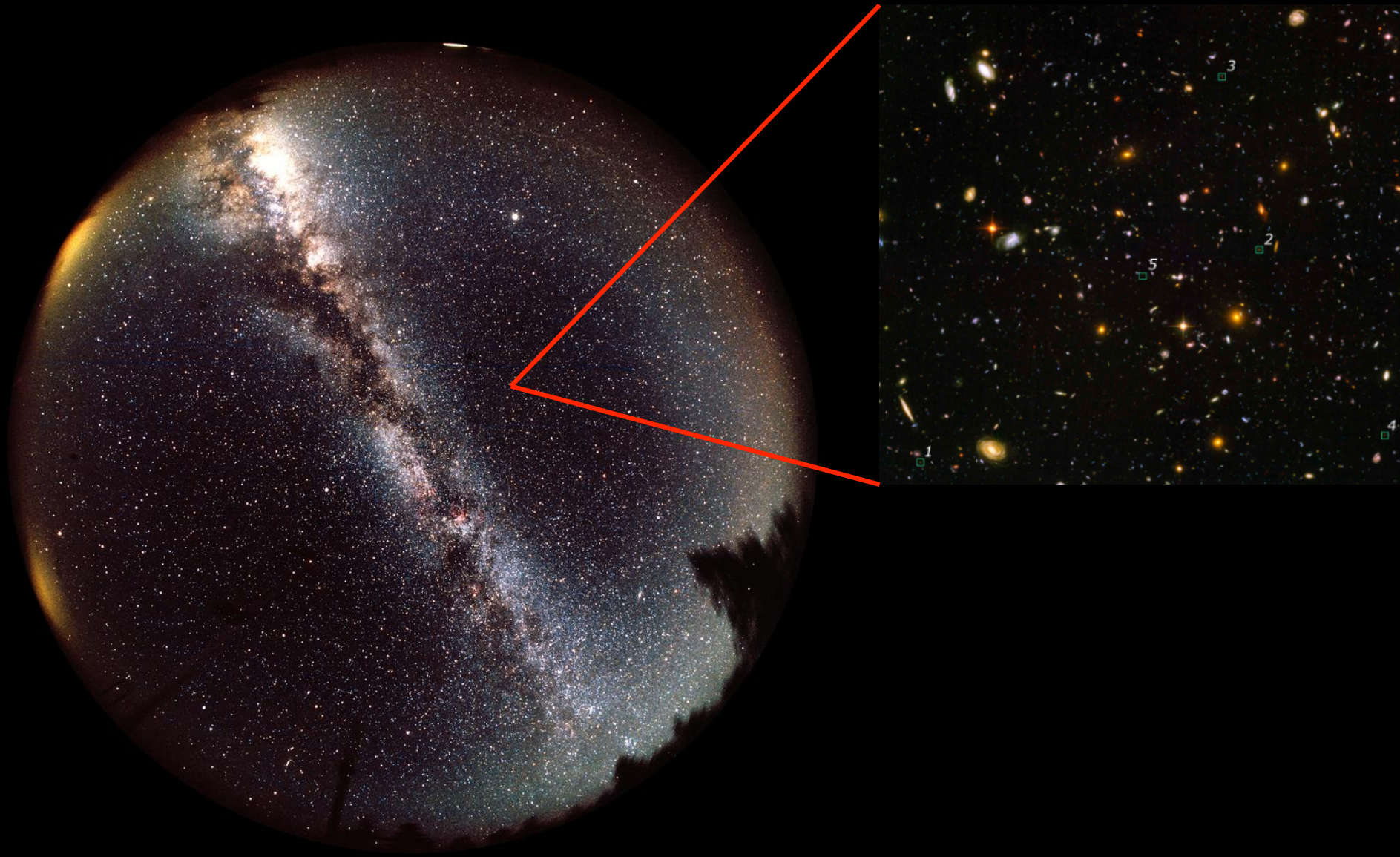
- conception, développement, réalisation, tests, étalonnage d'instruments
- opération des instruments
- analyse et interprétation des données
- archivage, diffusion de produits scientifiques à haute valeur ajoutée
- développement de modèles, simulations, avancées théoriques
- confrontation théorie+modèles vs données

- un des 5 grands laboratoires spatiaux en France
- specialisé dans l'instrumentation spatiale, analyse de données, modélisation/théorie

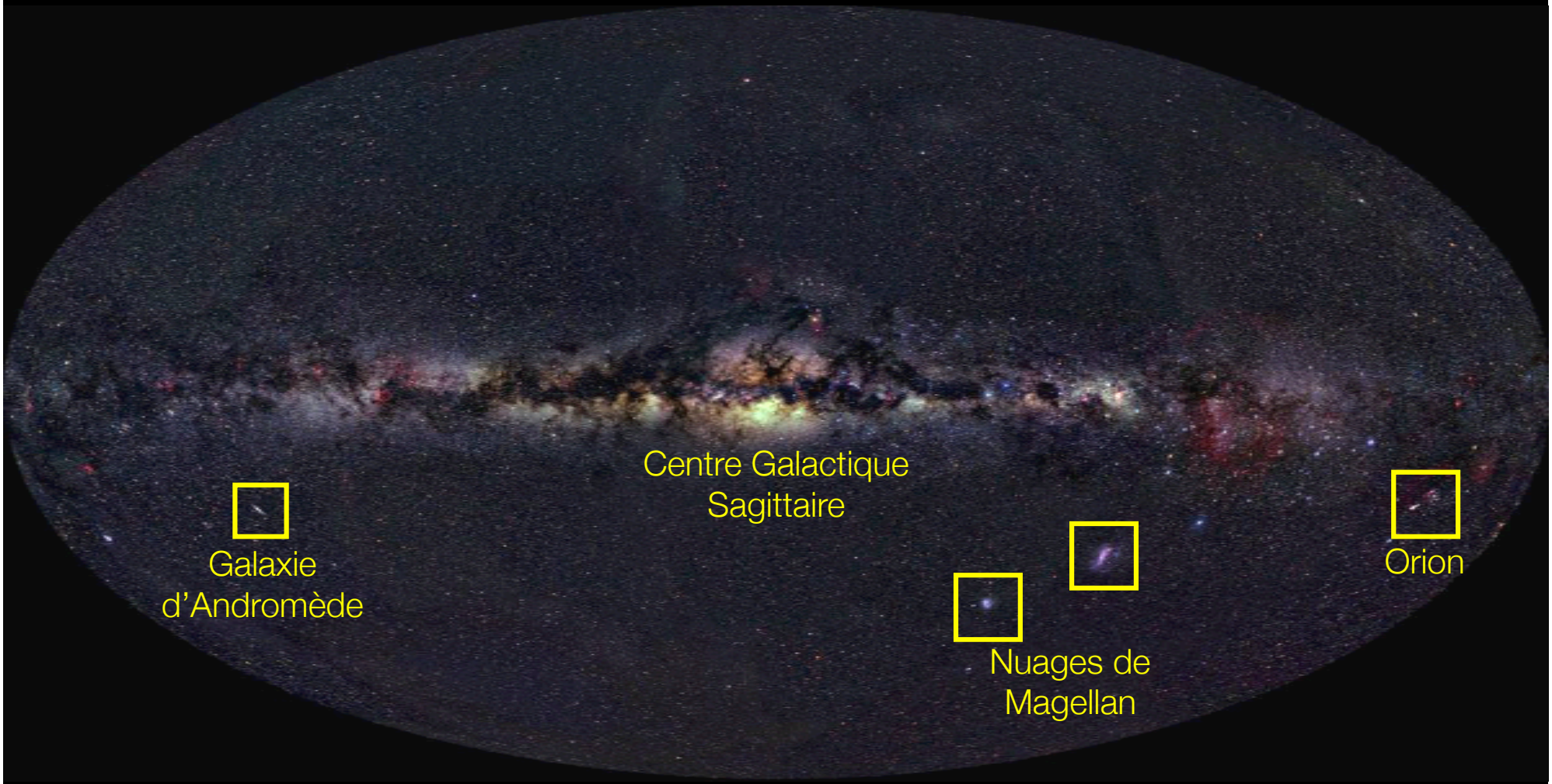
**The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada**


**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.**

# pourquoi la nuit est-elle noire ?



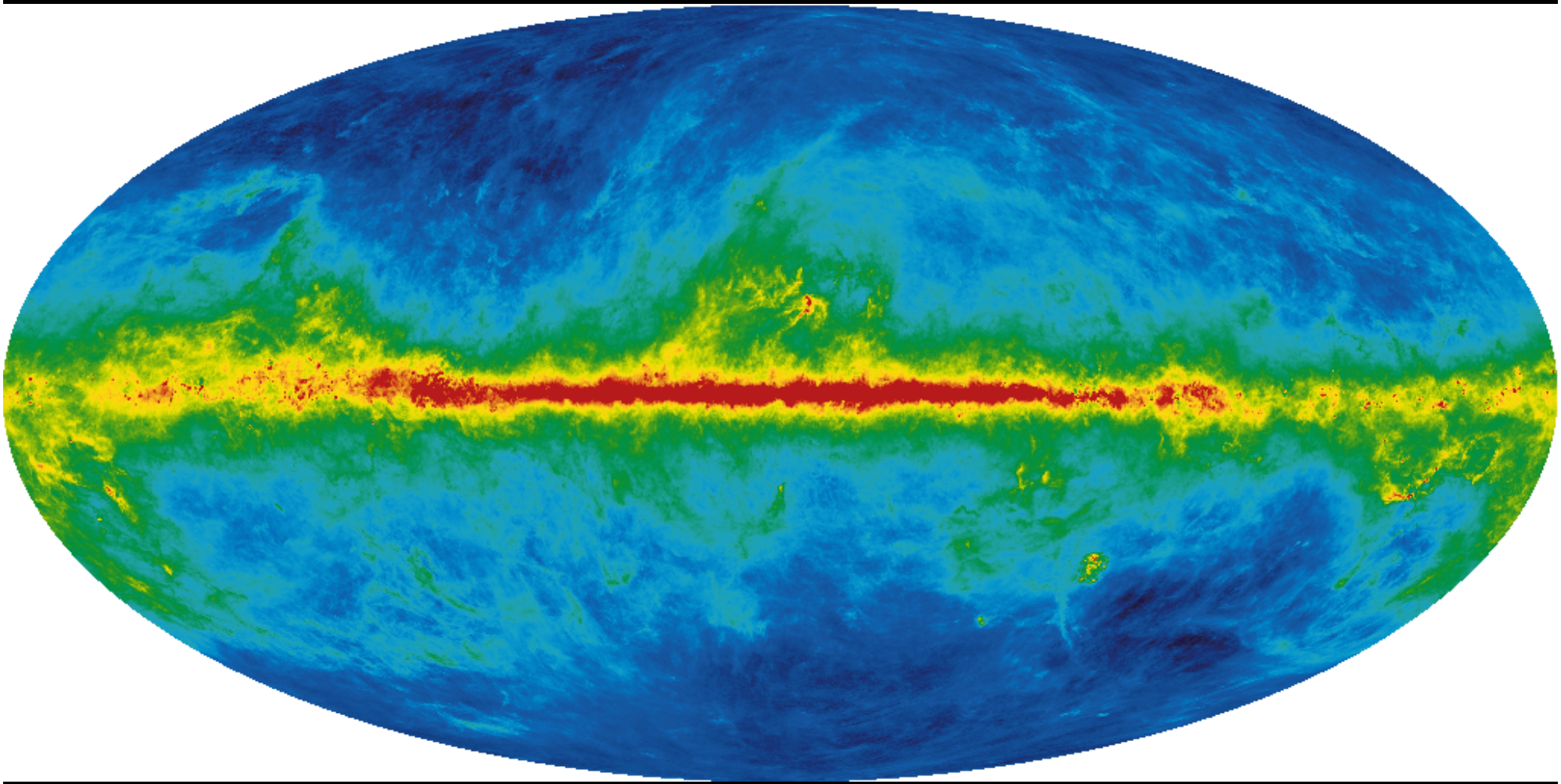
# the sky: visible wavelengths




Axel Mellinger

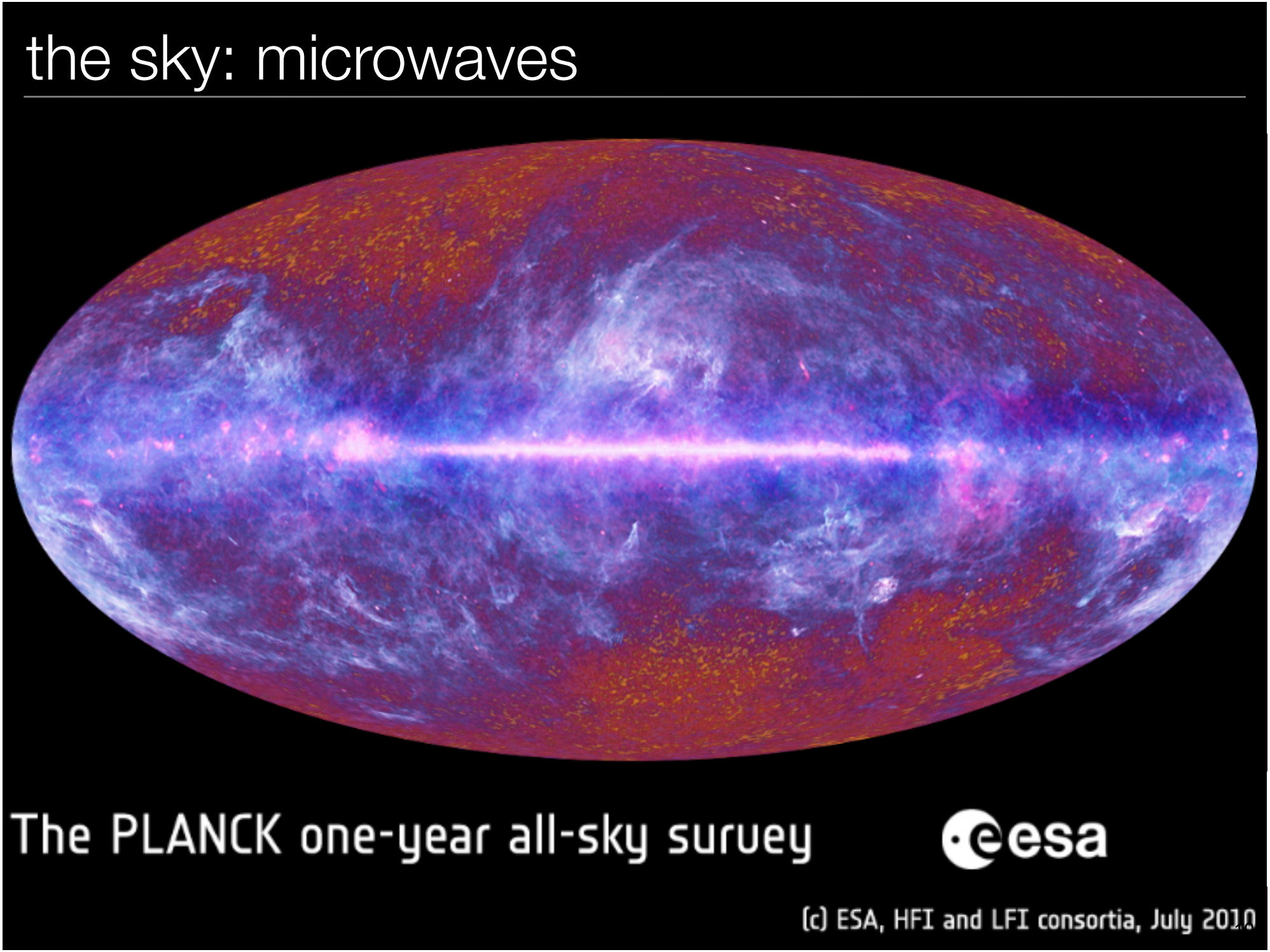
http://canopus.physik.uni-potsdam.de/~axm/mwpan/mwpan_web.html

# the sky: far-infrared

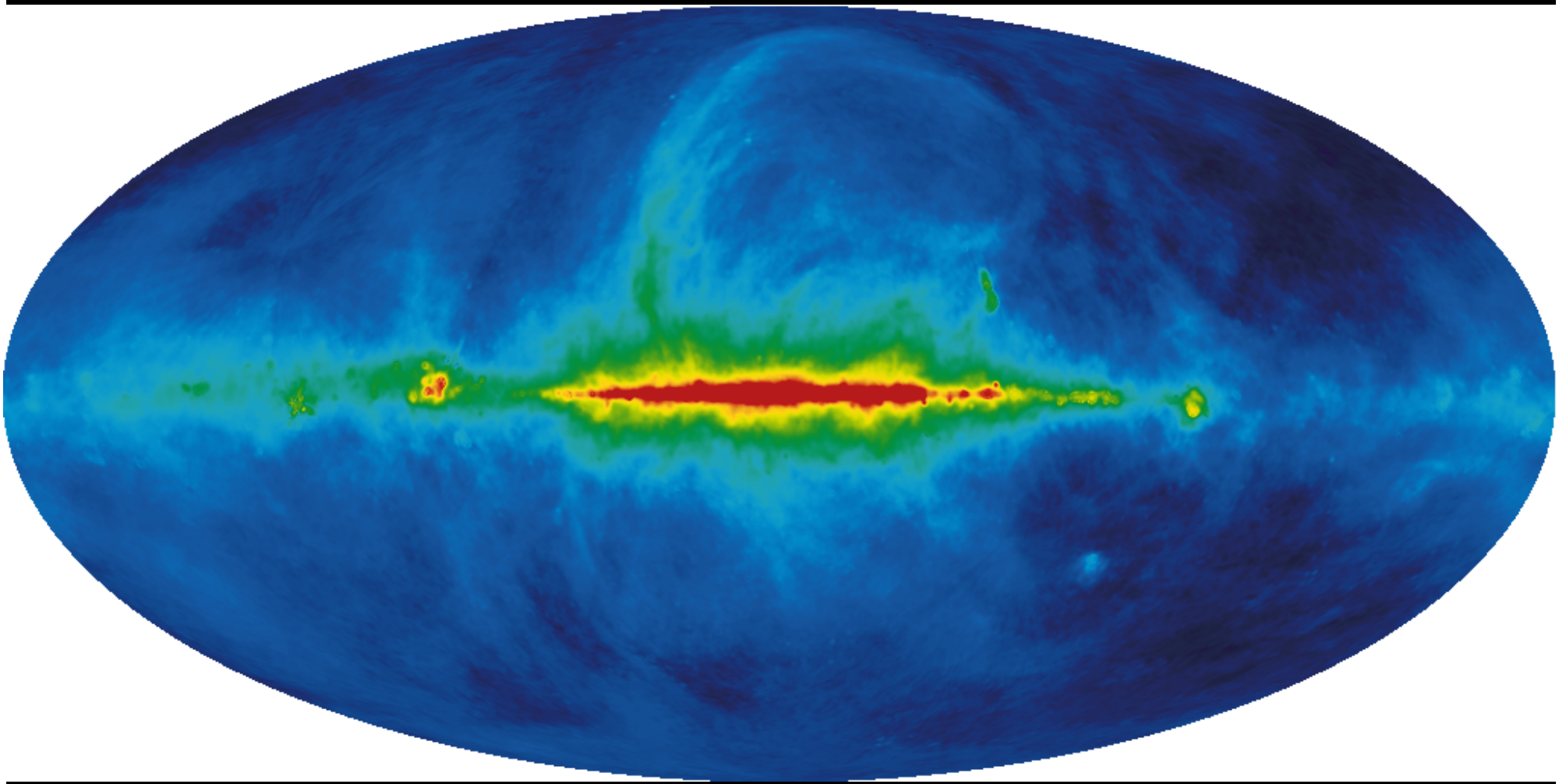


IRAS 100um IRIS

# the sky: microwaves

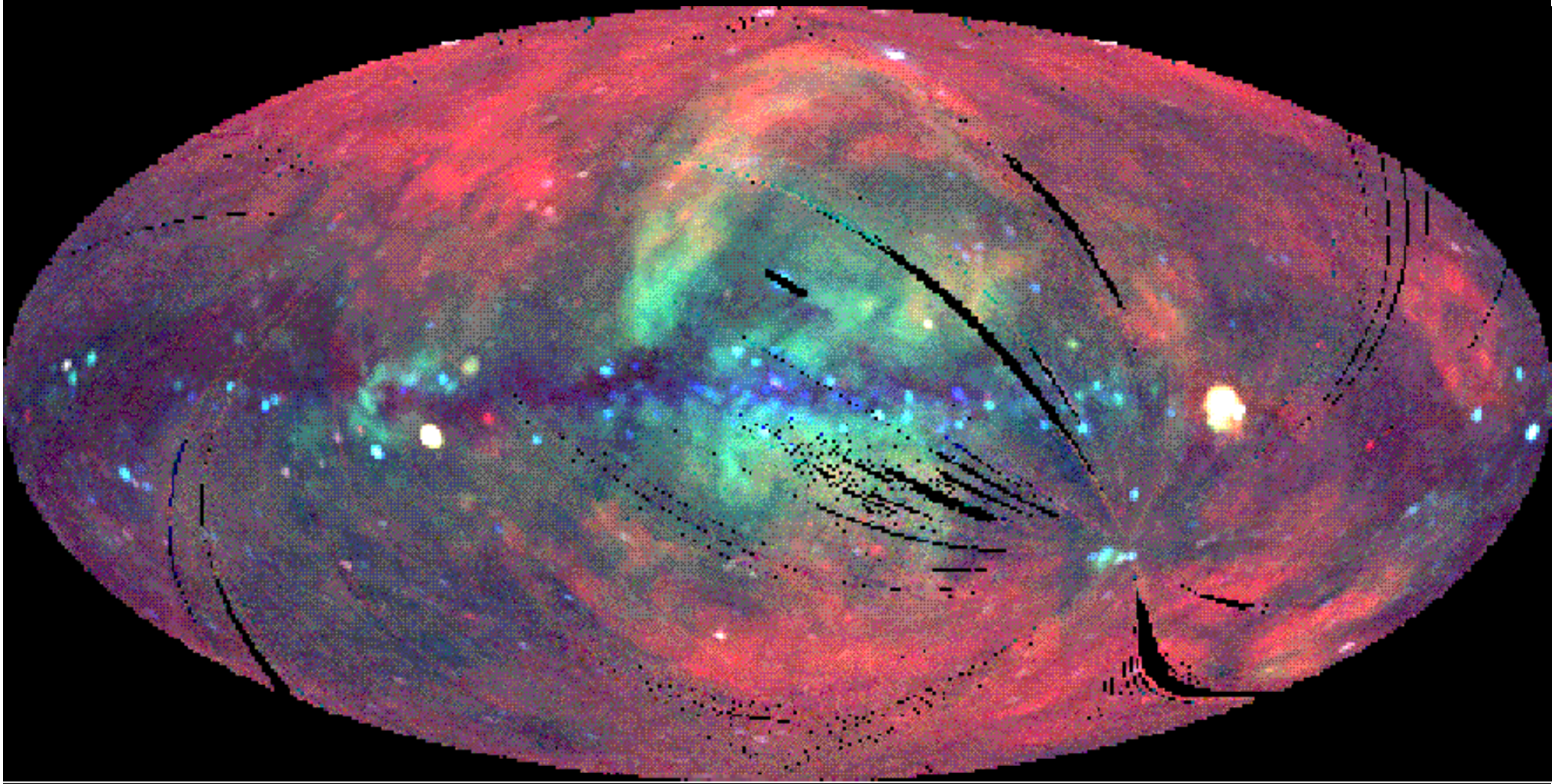


# the sky: radio



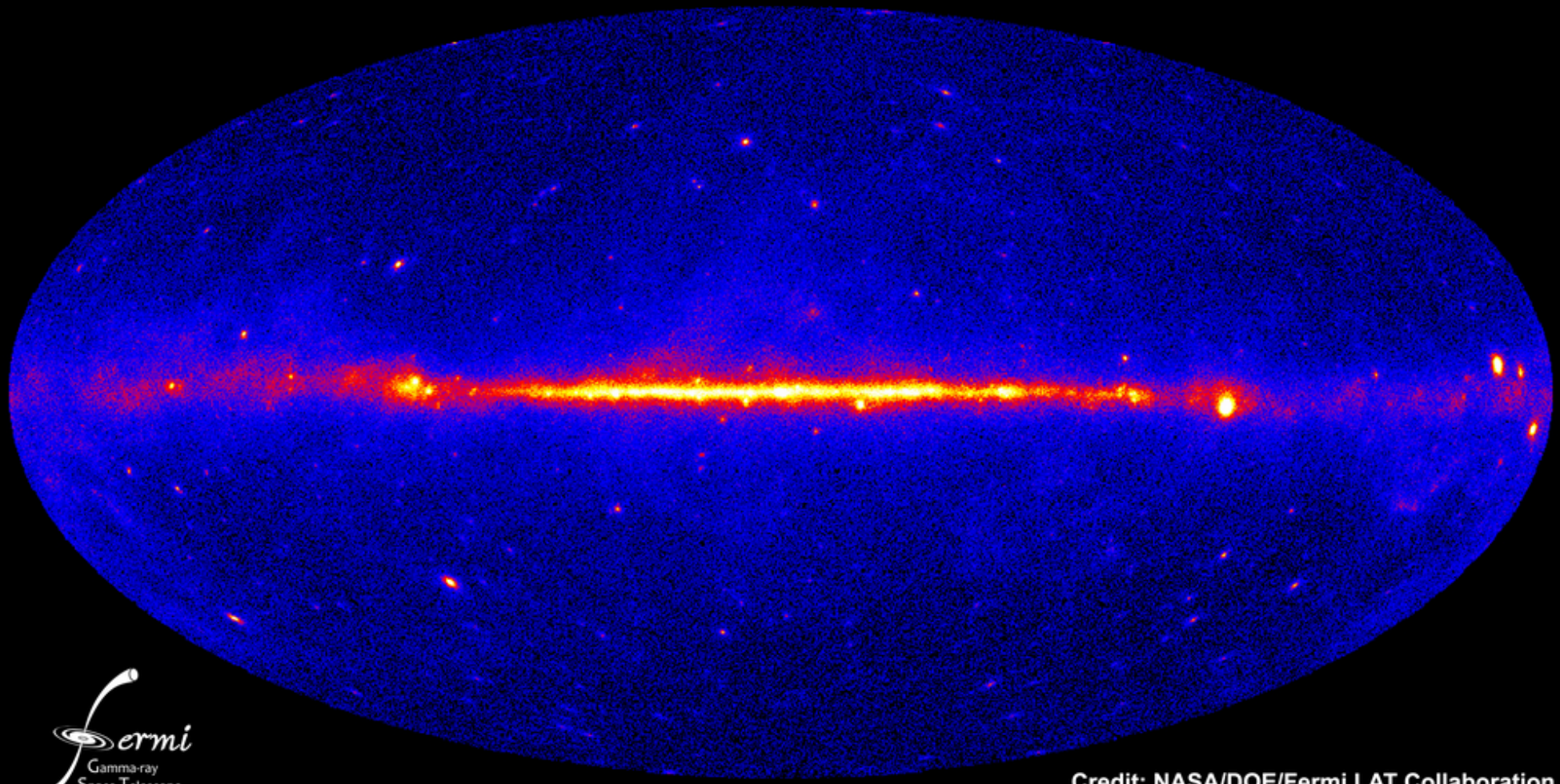
21 cm Leiden/Parkes

# the sky: X-rays



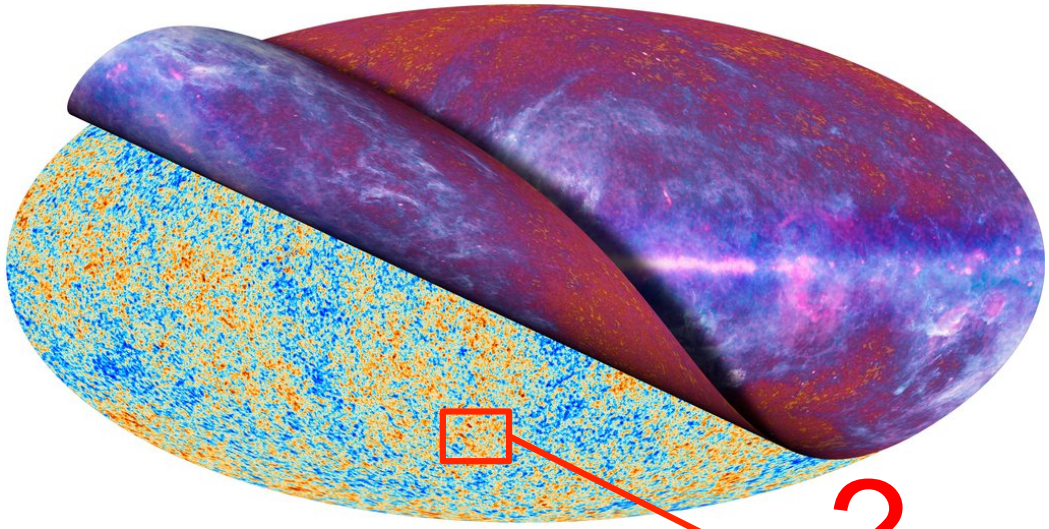
ROSAT

# the sky: gamma-rays




FERMI LAT

# les deux grandes questions



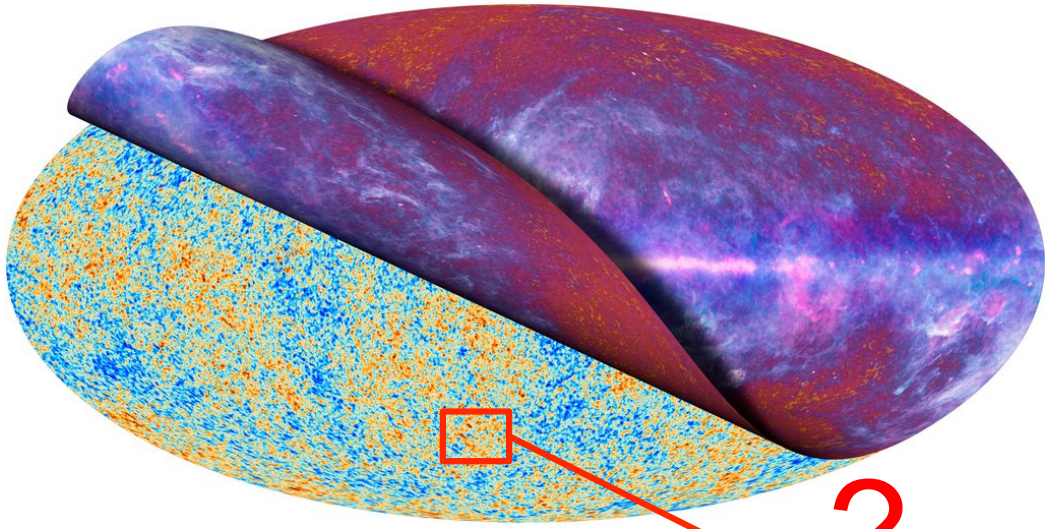
?

univers homogène

?

univers inhomogène,
structuré

# les deux grandes questions



?

univers homogène

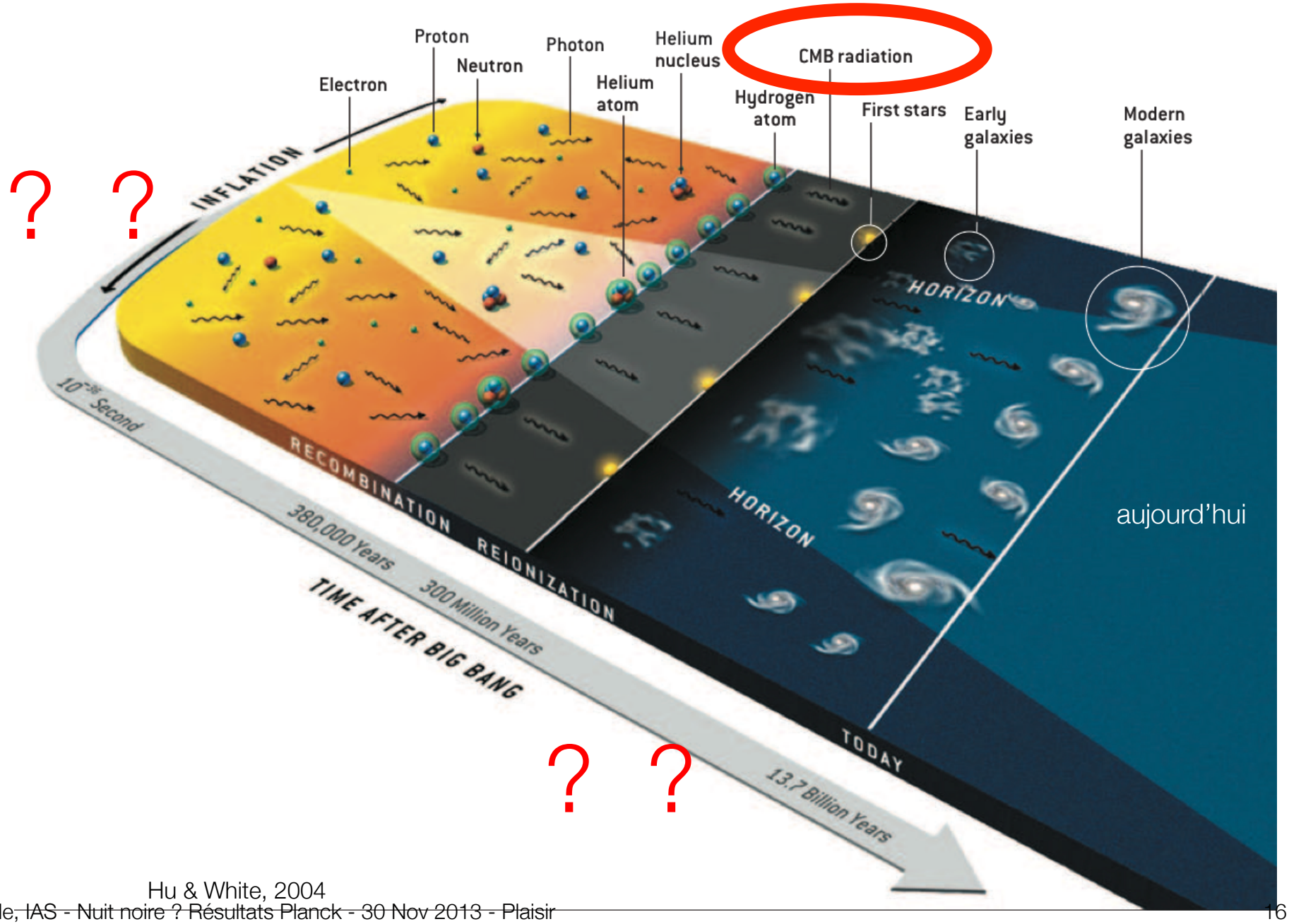
modèles d'inflation ?

?

univers inhomogène,
structuré

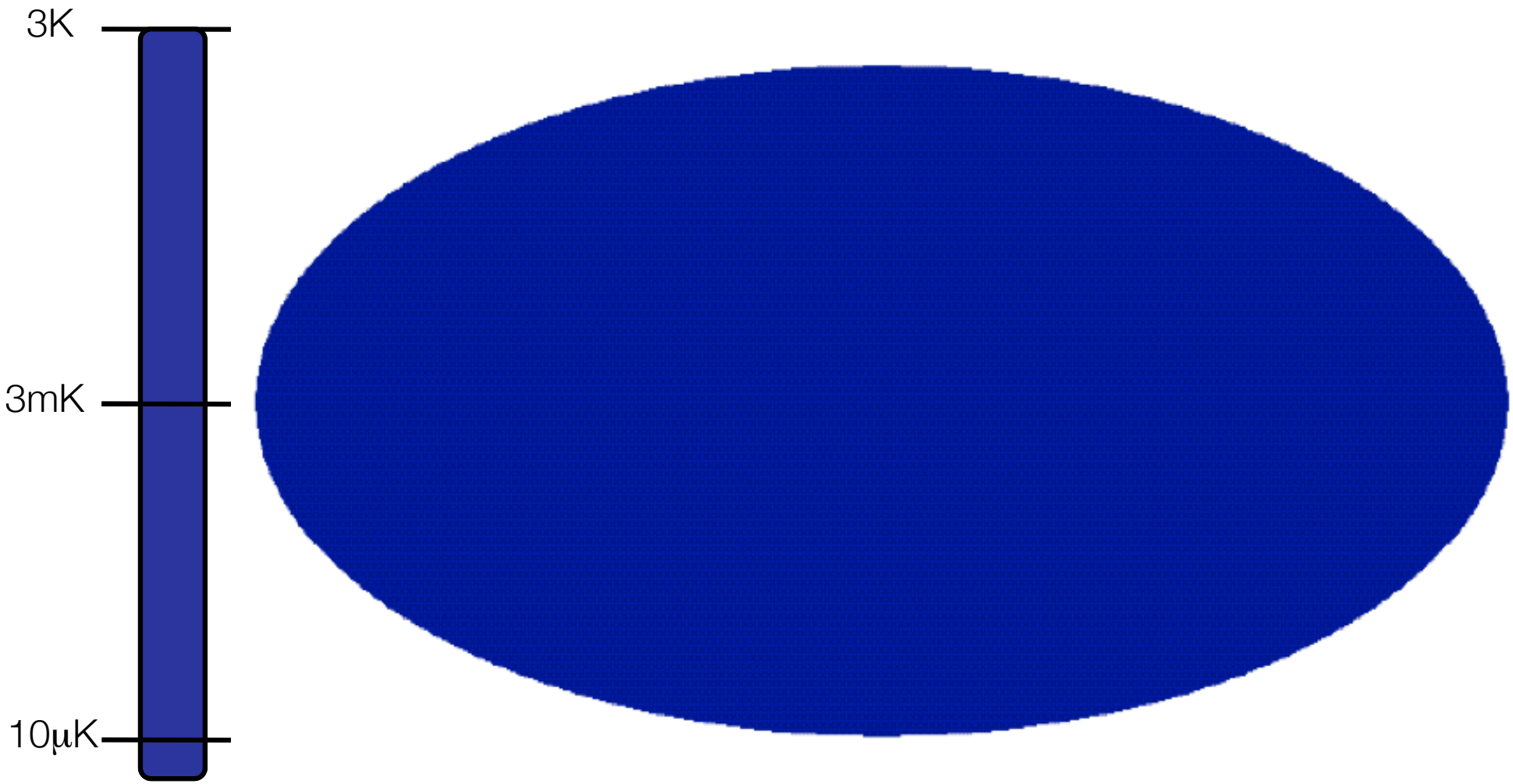
formation
des structures

# comment se forment les structures ?

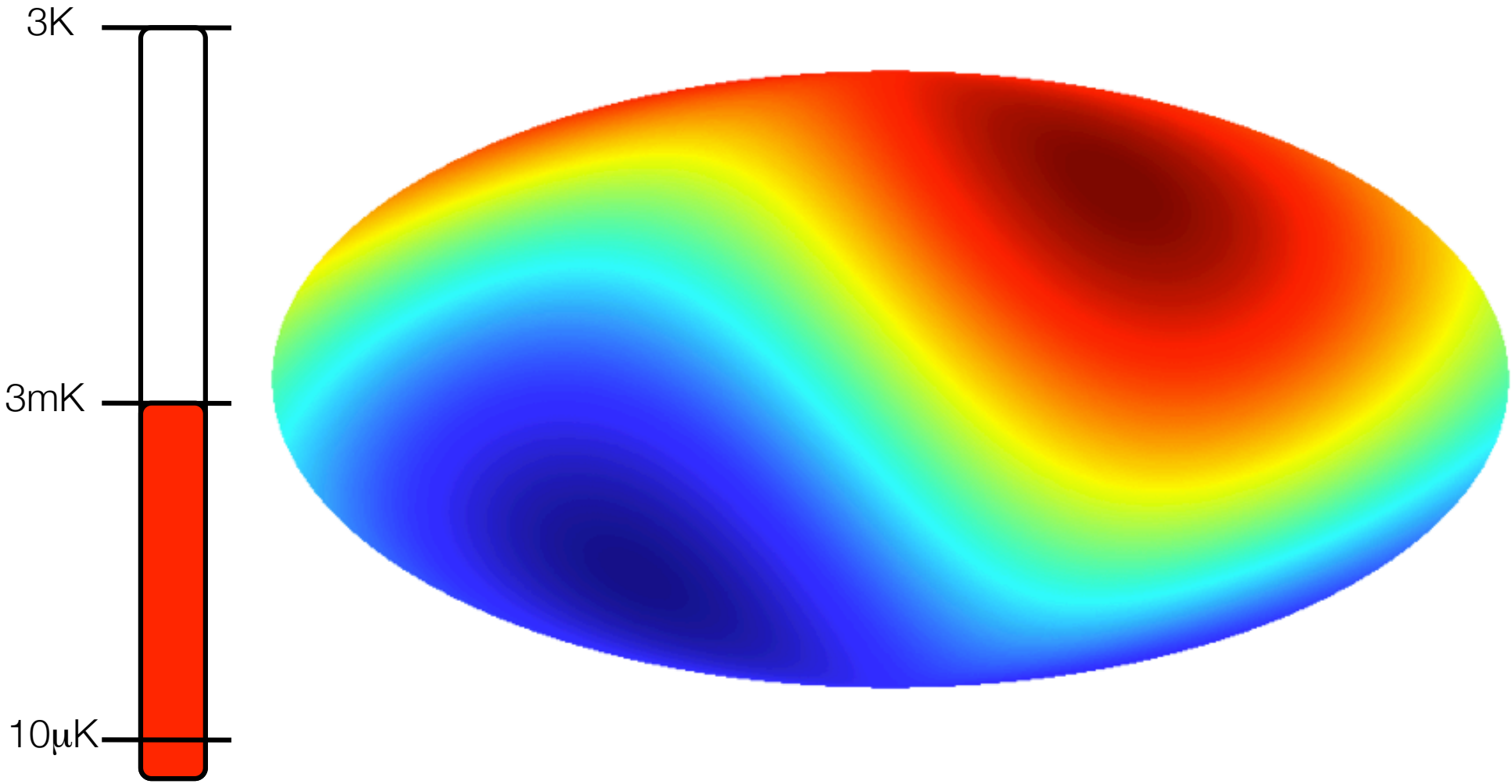



Hu & White, 2004

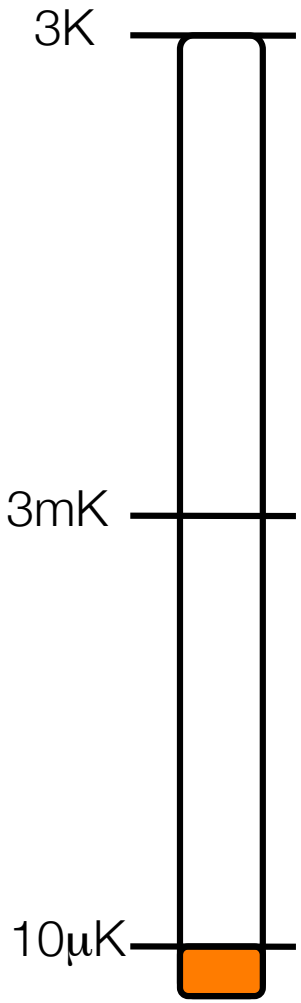
# fond diffus cosmologique: monopôle

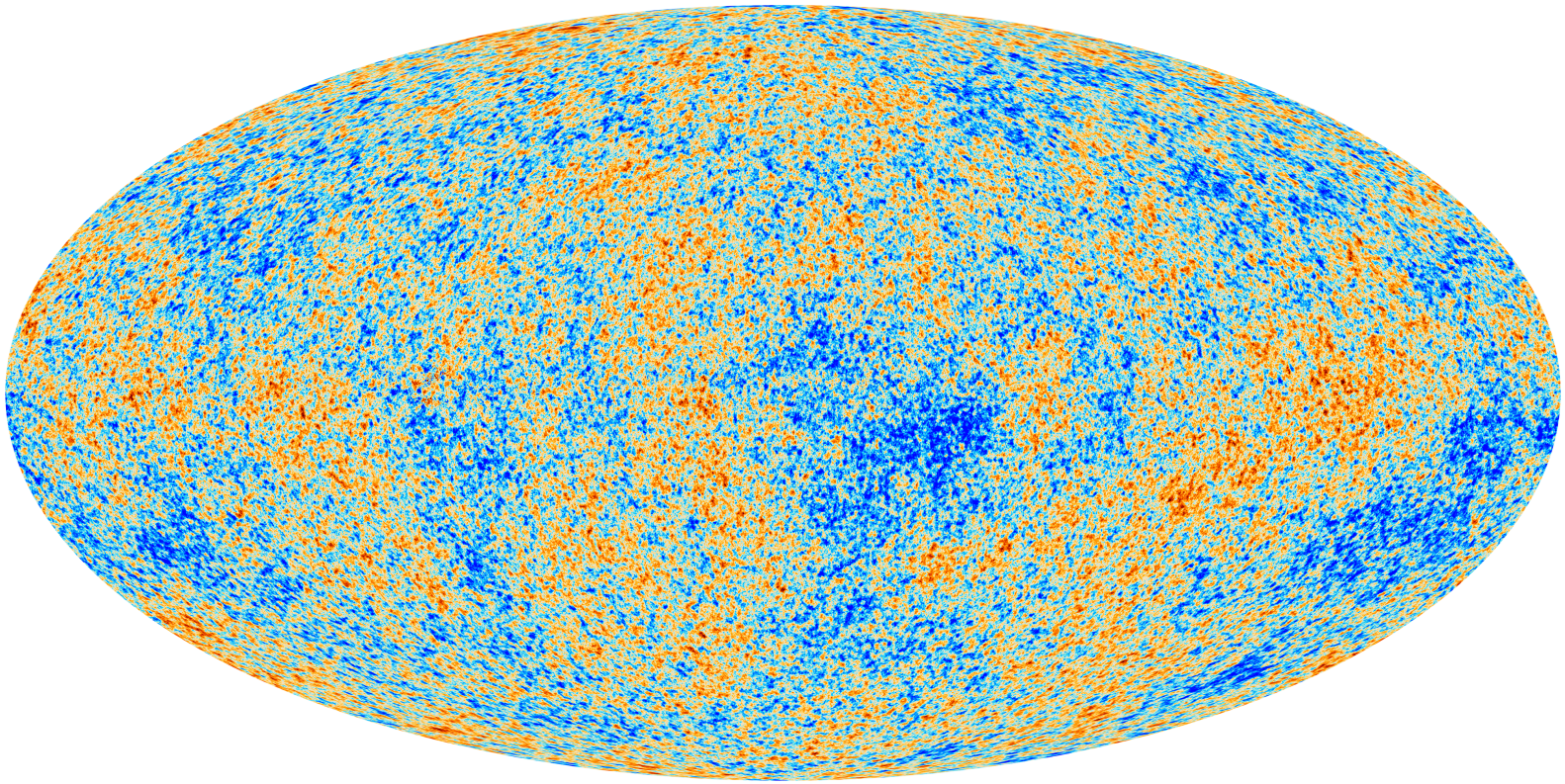


# fond diffus cosmologique: dipôle



# fond diffus cosmologique: fluctuations



# plan

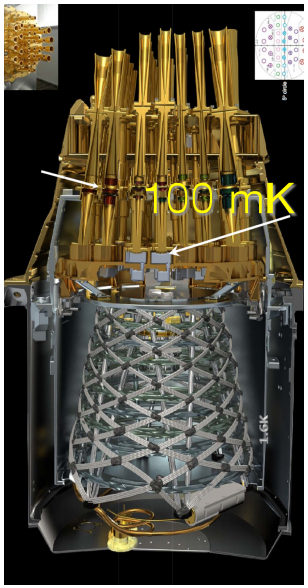
1. pourquoi Planck ?
2. le fond diffus cosmologique (CMB) et les composantes astrophysiques
3. analyses du CMB: spectre de puissance angulaire
4. implications cosmologiques
5. un mot d'inflation
6. un univers structuré: matière noire
7. en grattant de le rayonnement de fond infrarouge

# 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: 0.1mK !




Cryostat:
dilution He3/He4

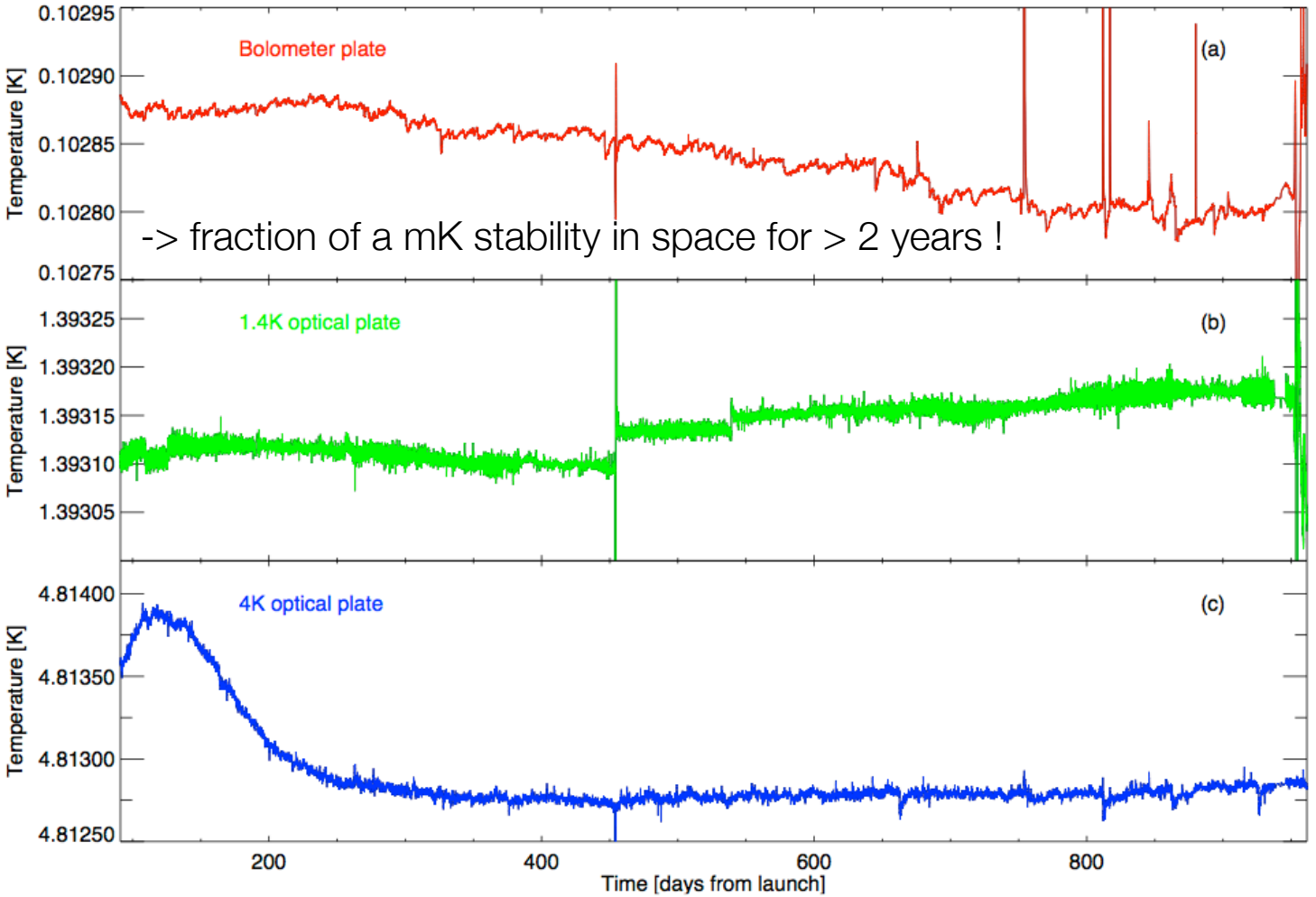
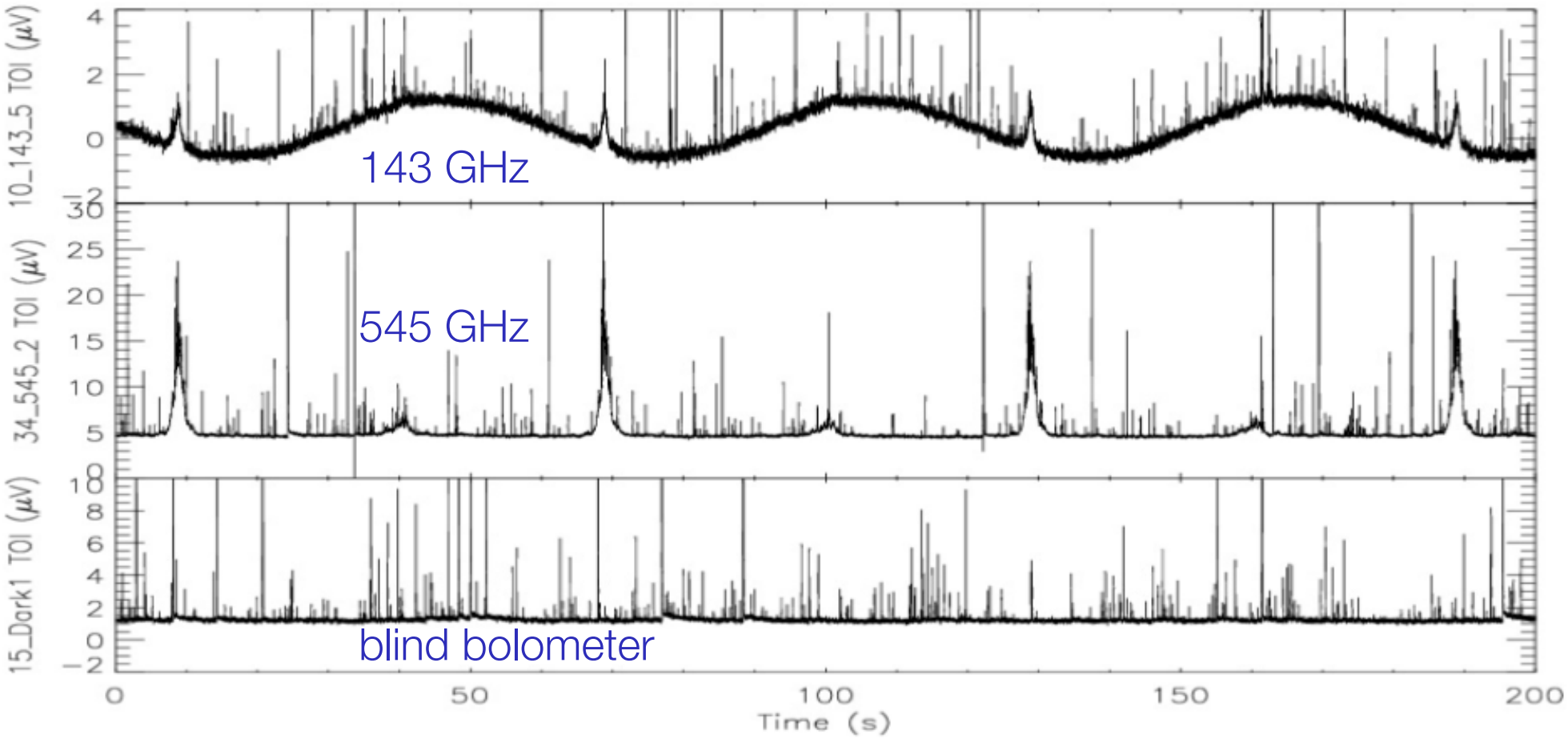



**Fig. 7.** The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the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

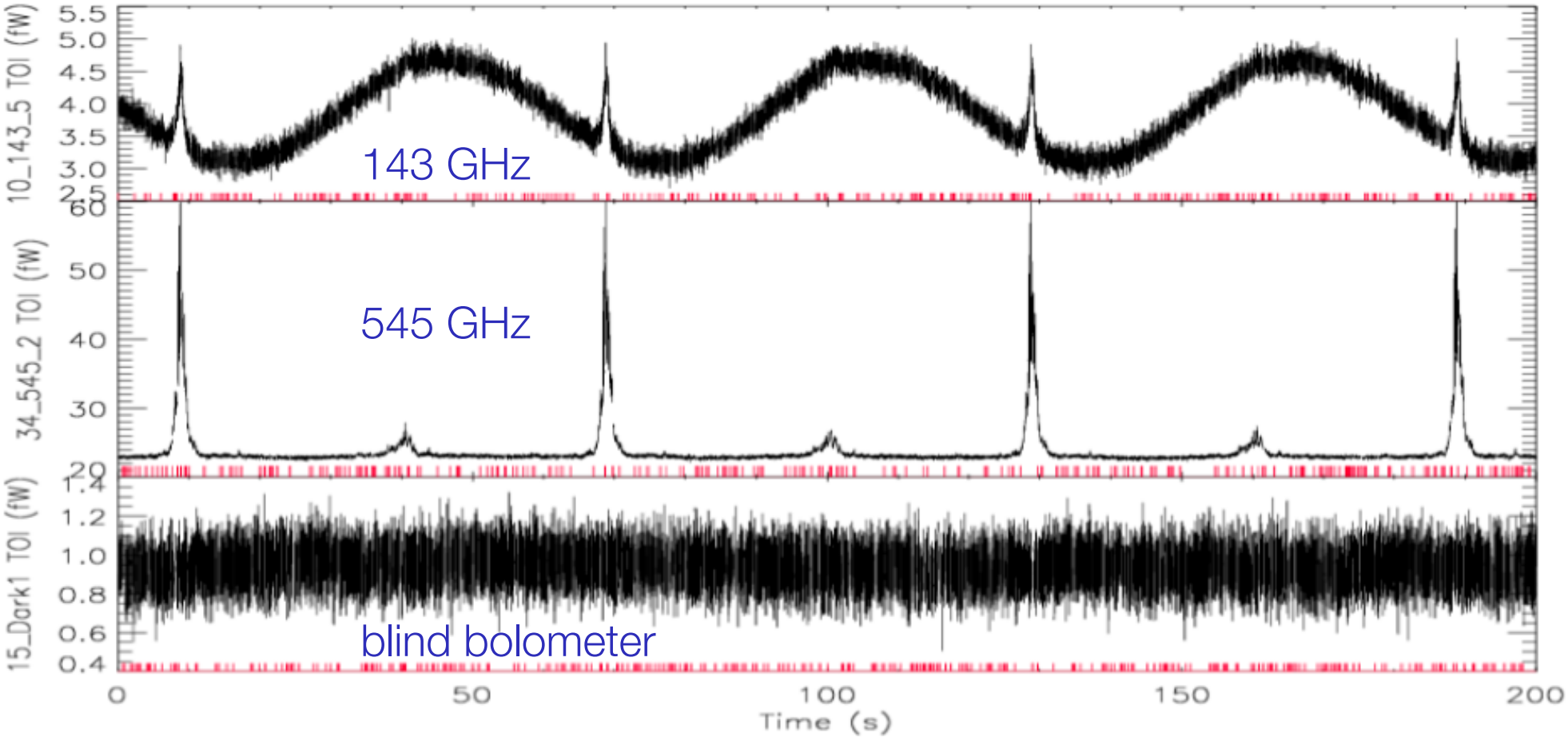
Planck Collab, 2013, 1

# a challenging analysis success




Planck-HFI Core Team, 2011

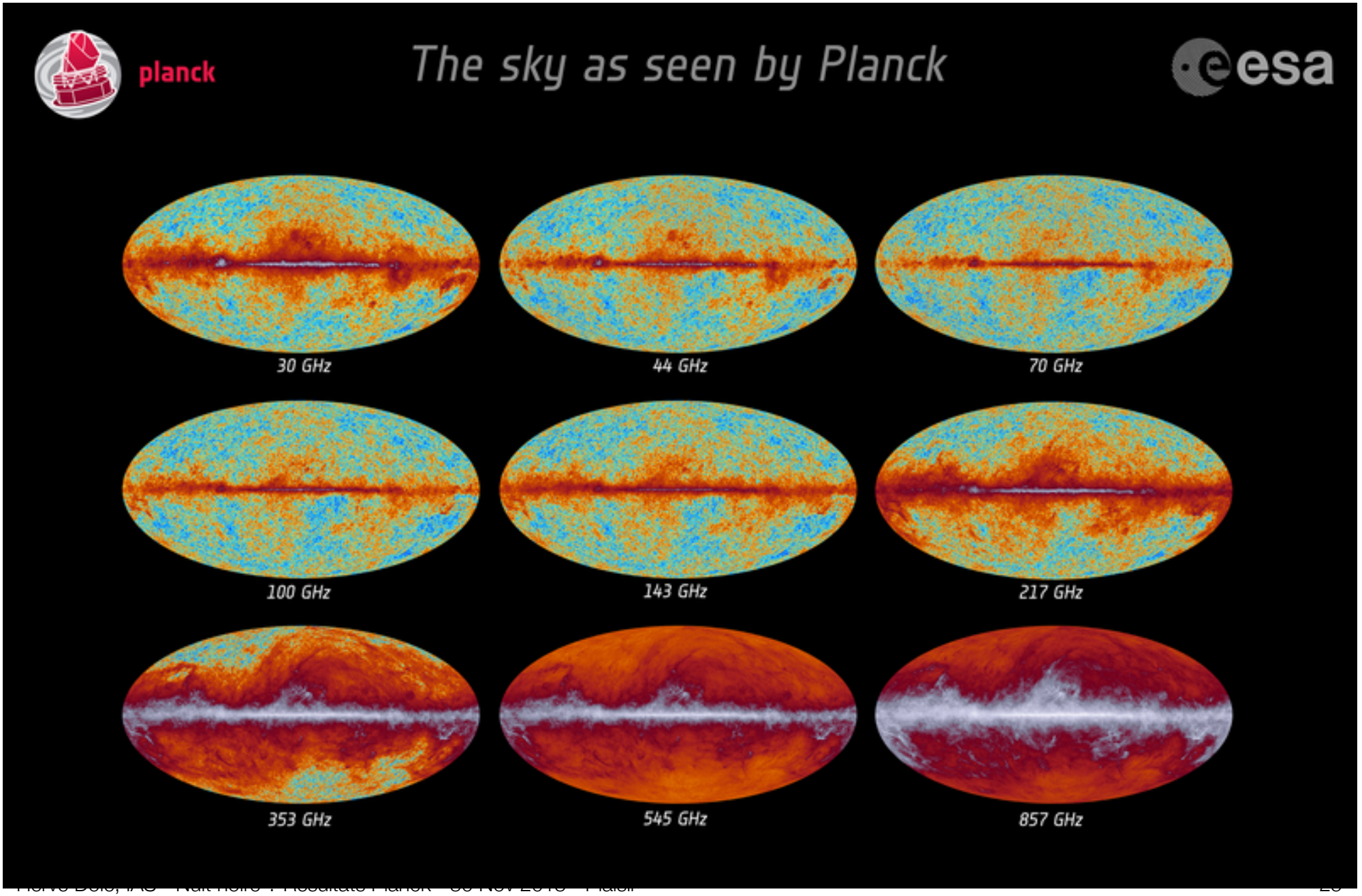
# a challenging analysis success



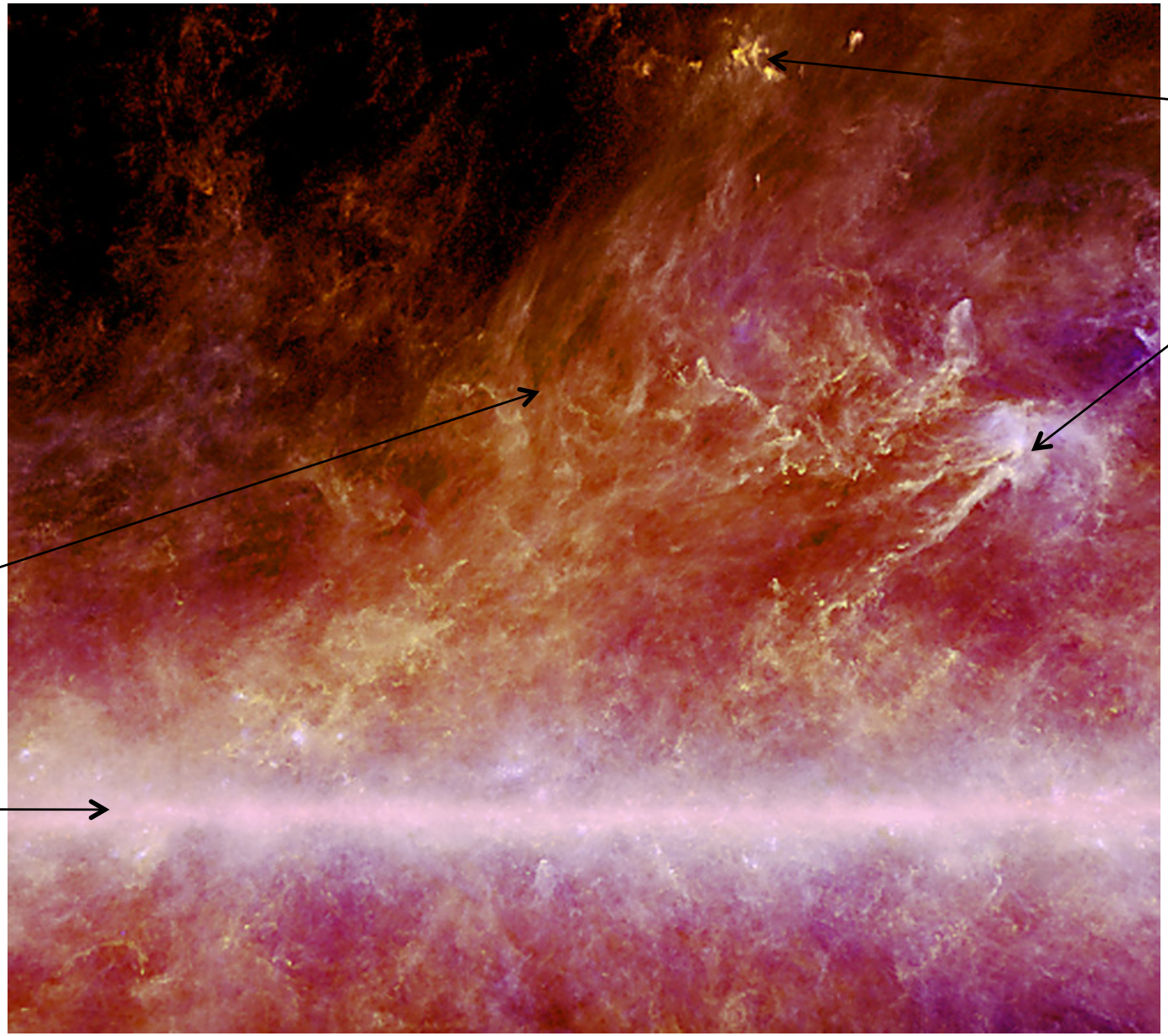

de <20% de données perdues à cause des glitches

Planck-HFI Core Team, 2011

# Planck all-sky maps

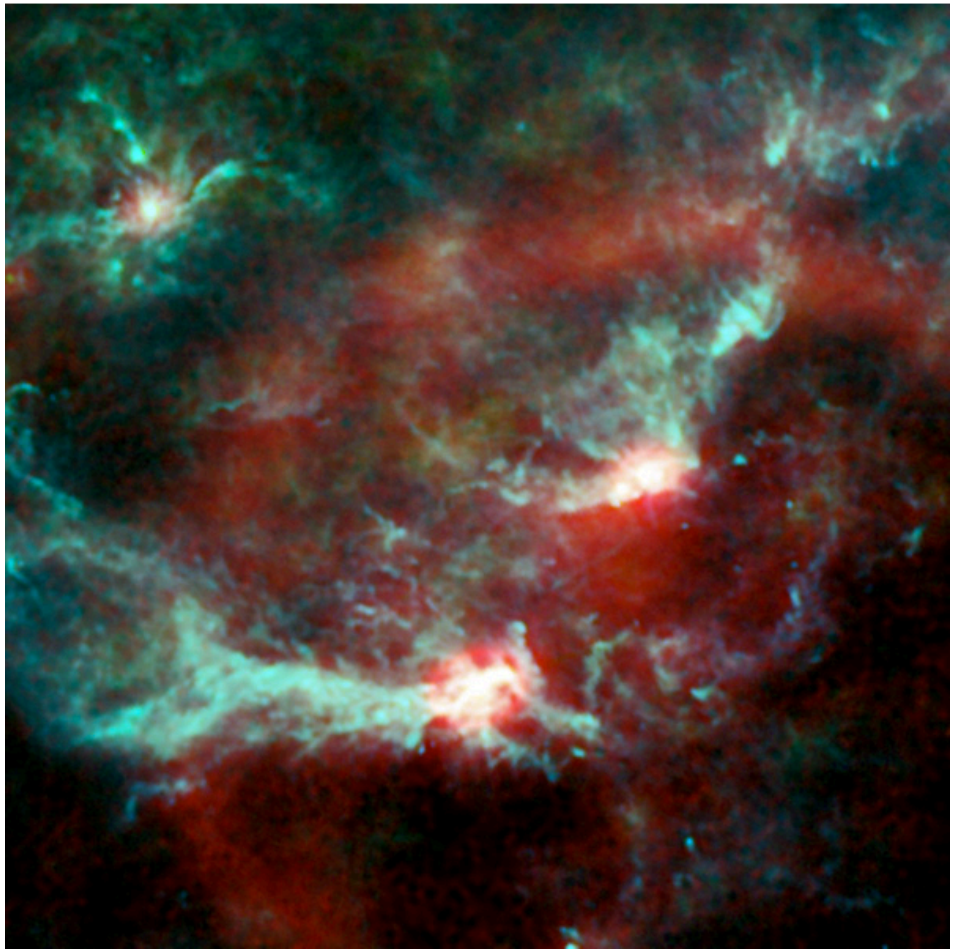


# first Planck released images



# 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

11 papers: instrument: calibration, processing, systematics

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

3 papers: component separation

- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters

2 papers: 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

3 papers: line of sight effects: lensing, CIB, ISW

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

2 papers: SZ clusters and map

- 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

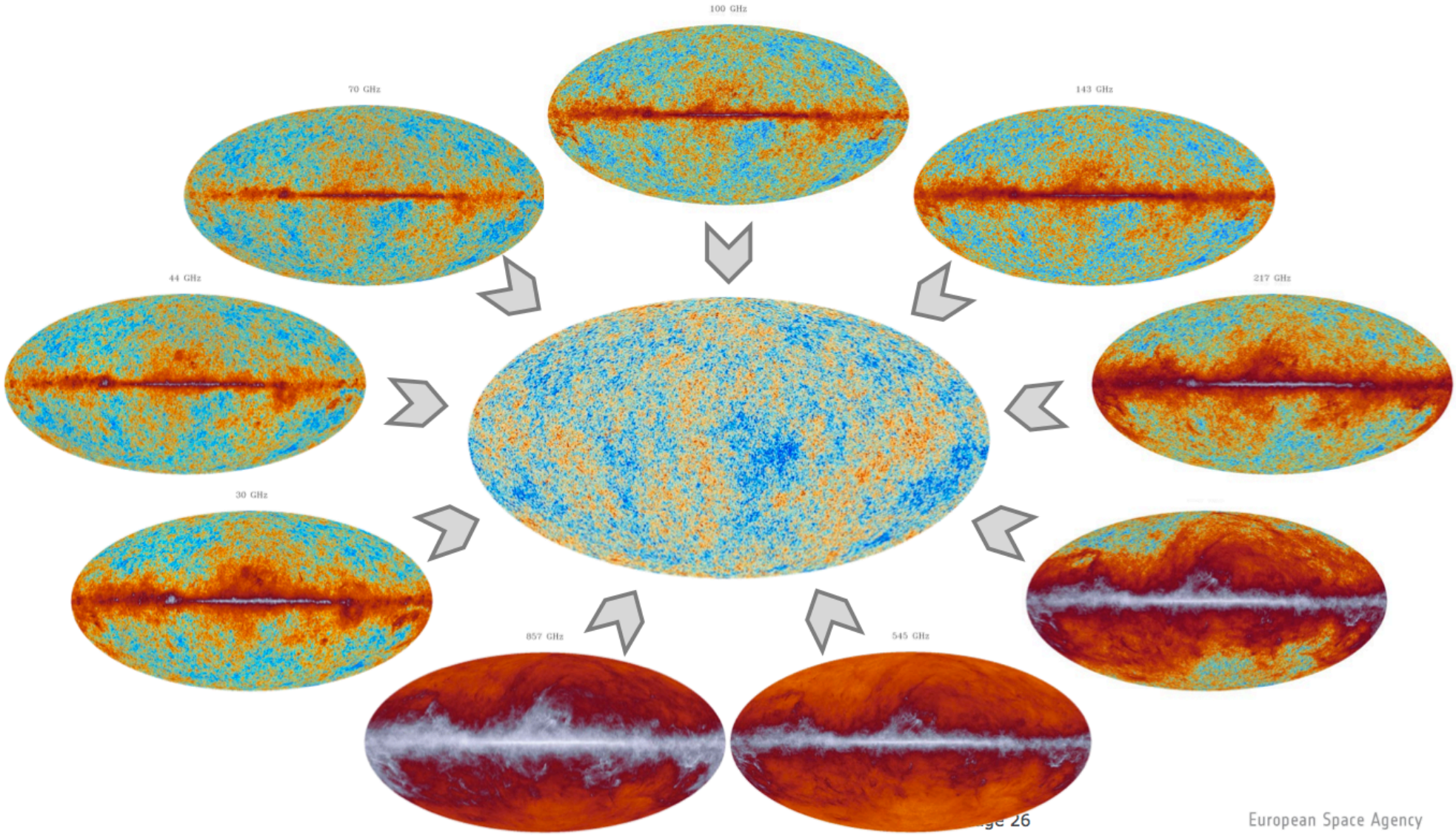
6 papers: cosmology, constraints

- 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

3 papers: products (catalog), XS

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

# 2. component separation

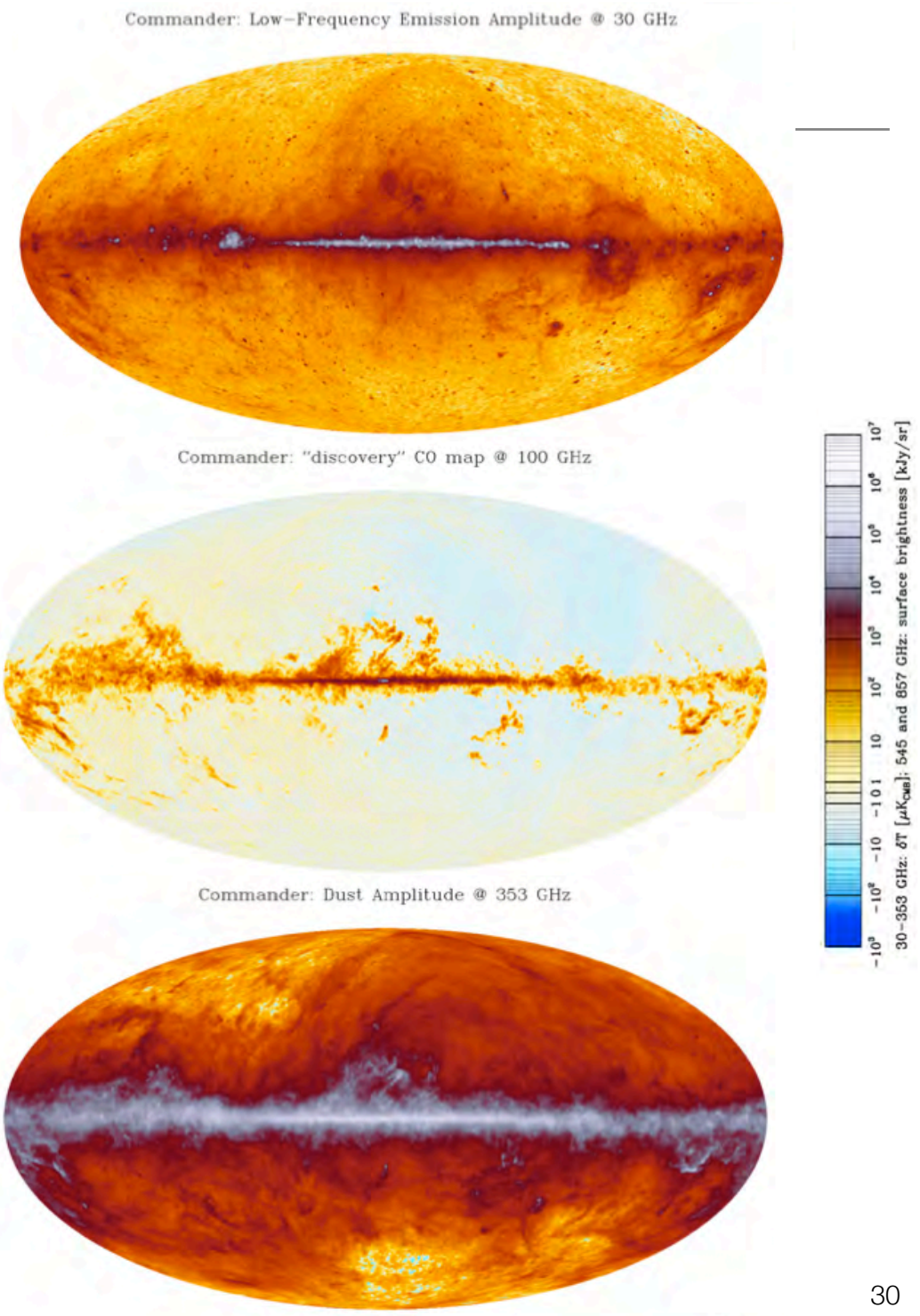


# some components

low frequency emission

CO map

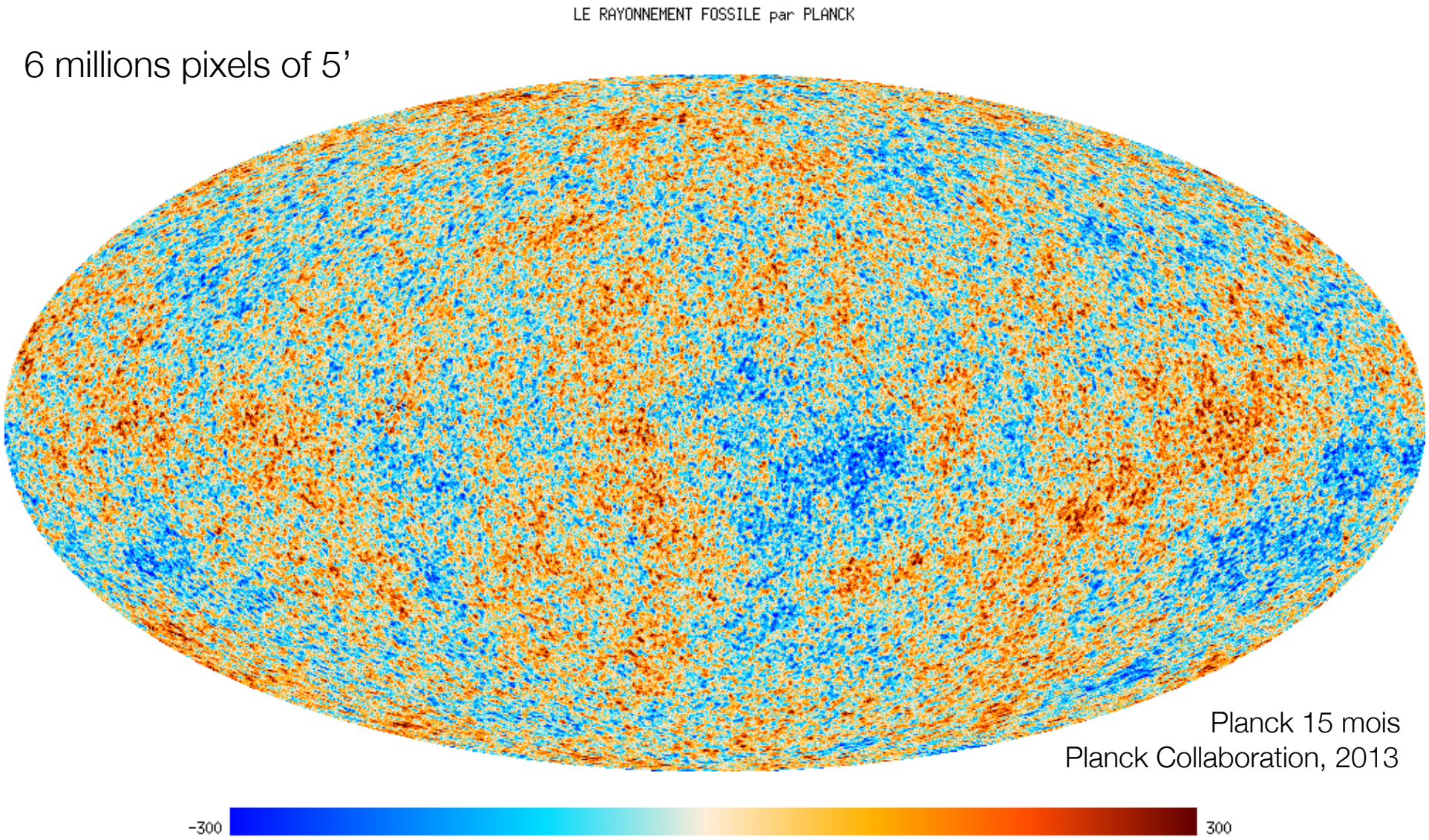
dust at high frequency




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

# temperature anisotropies

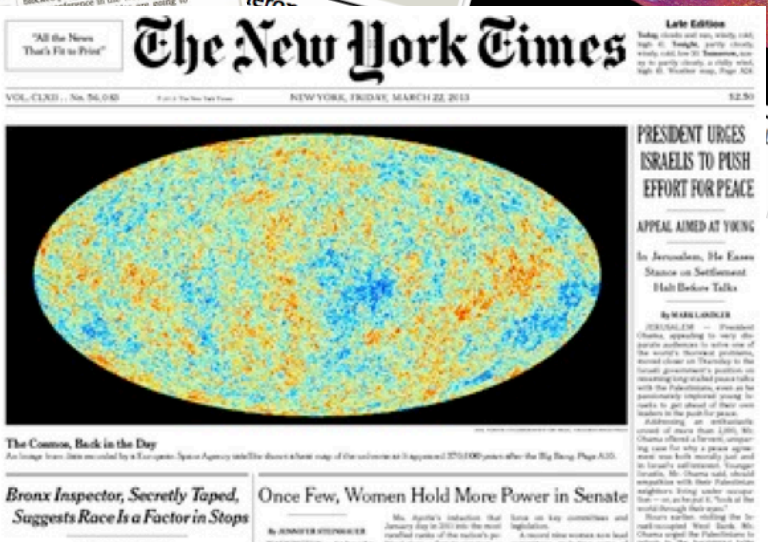
6 millions pixels of 5’

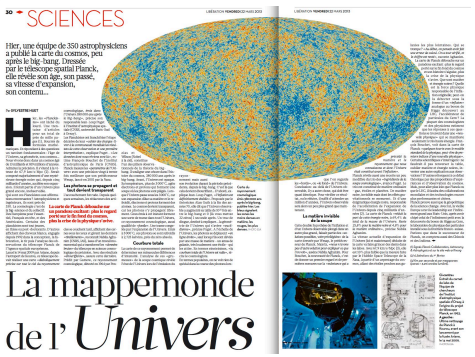



Planck 15 mois
Planck Collaboration, 2013

# and a fairly wide coverage

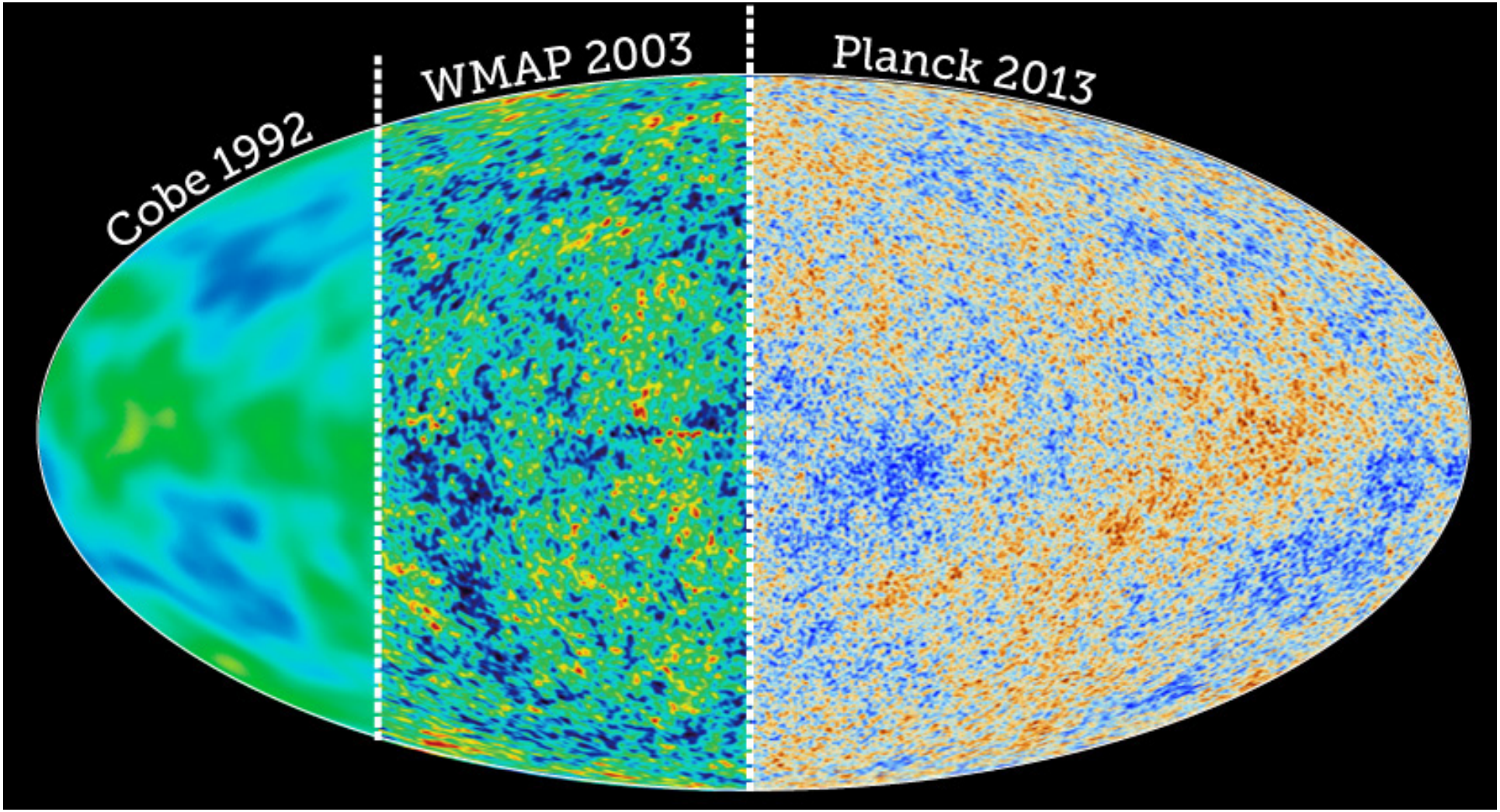




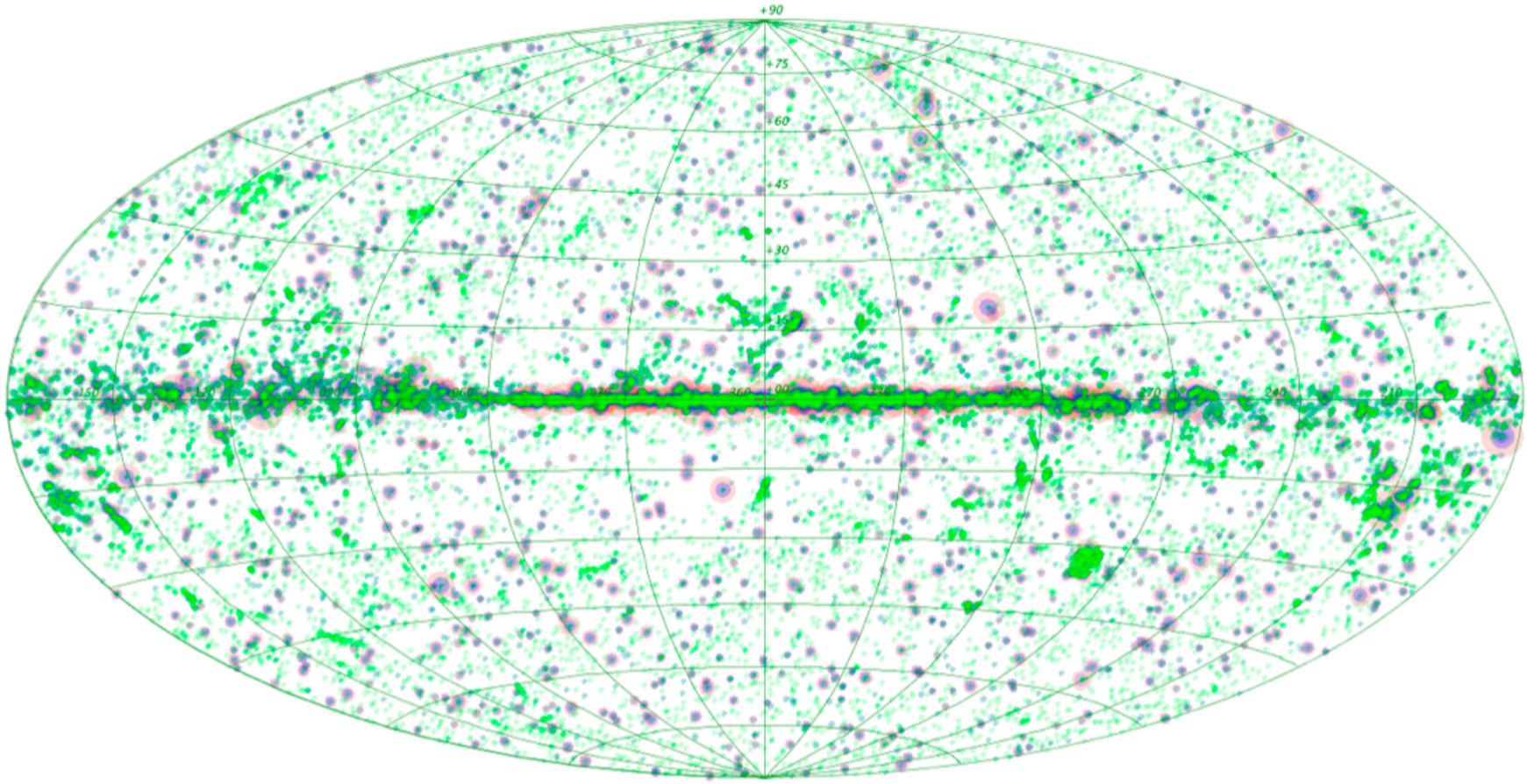




March 21st or 22nd, 2013

# improvements with time & technology

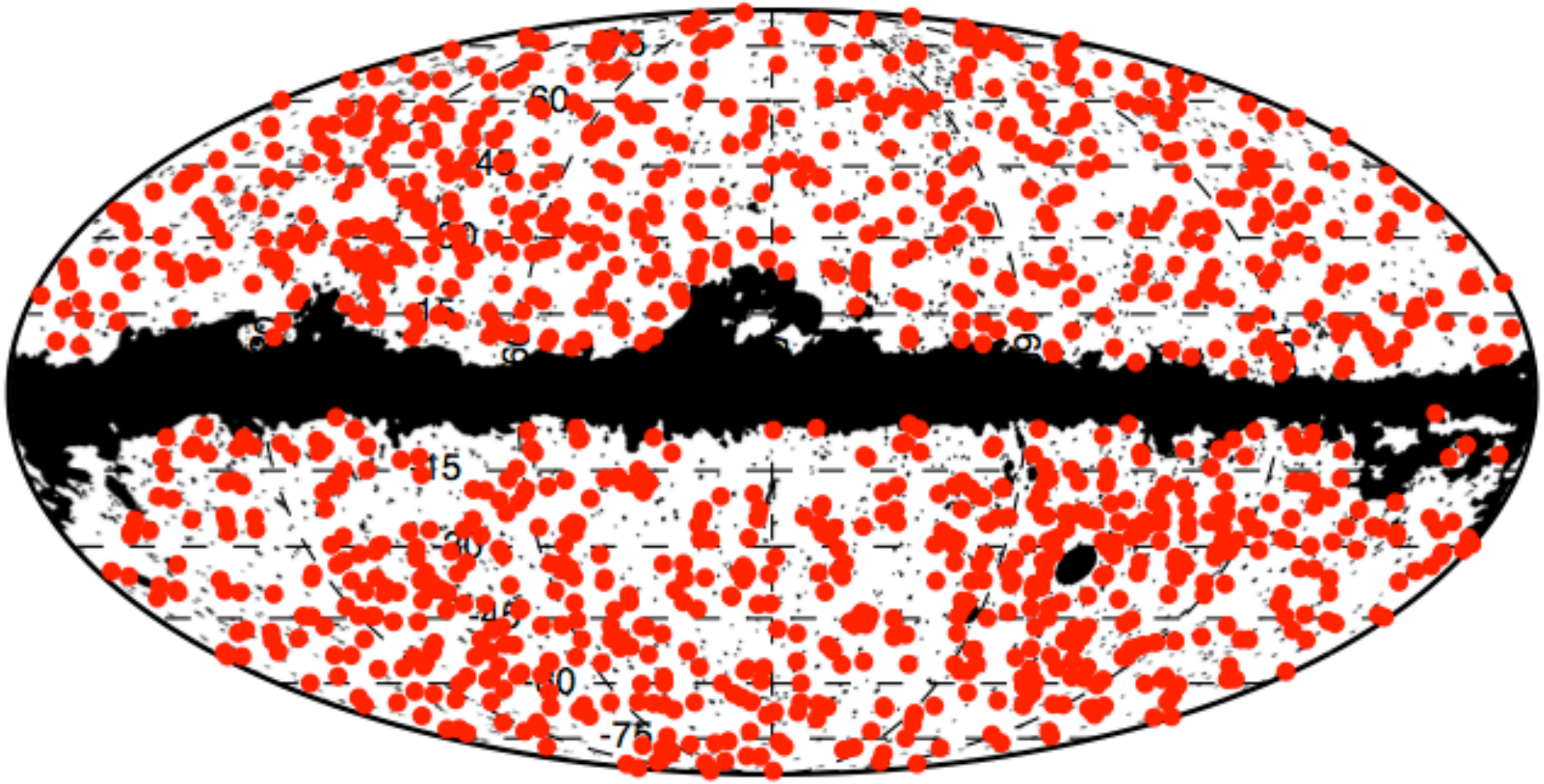


# Planck Catalogue of Compact Sources [PCCS]




Planck Collab, 2013, 28

# galaxy clusters: Sunyaev-Zeldovich effect

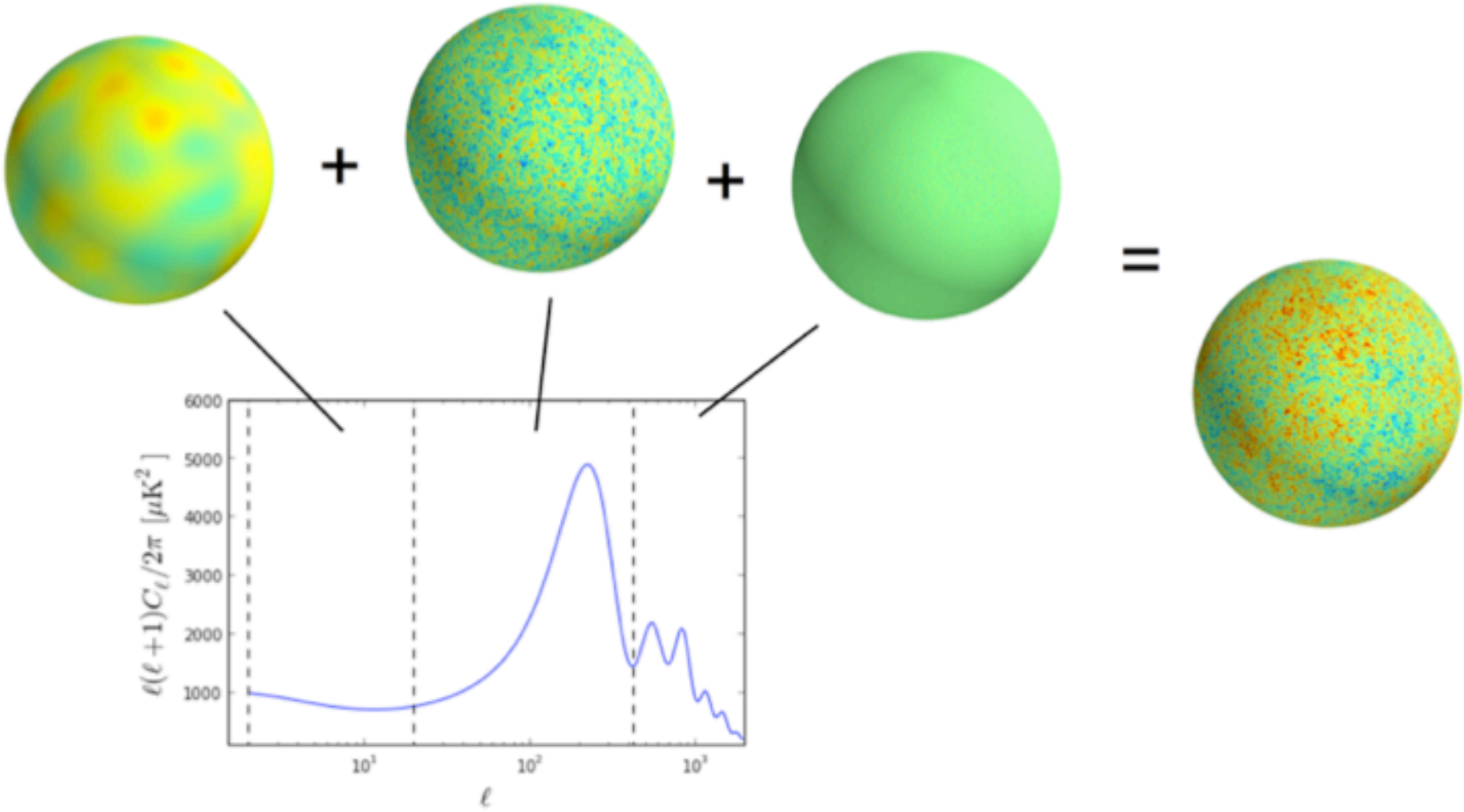



1227 SZ clusters -> including 366 brand new cluster candidates

Planck Collab, 2013, 29

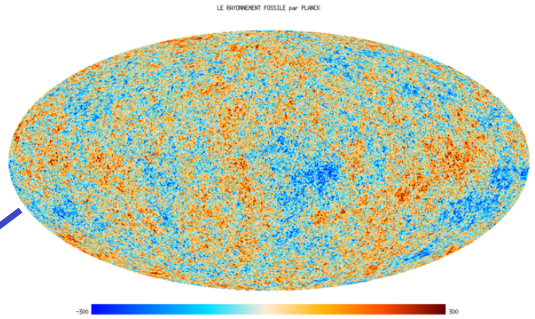
# 3. angular power spectra

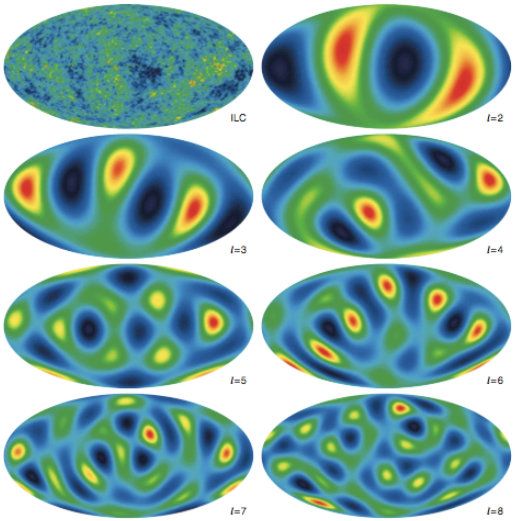
$$\langle a^*_{lm} a_{lm} \rangle = C_l$$




courtesy Olivier Doré

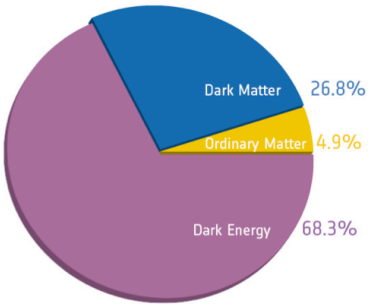
# from maps to 6 cosmological parameters

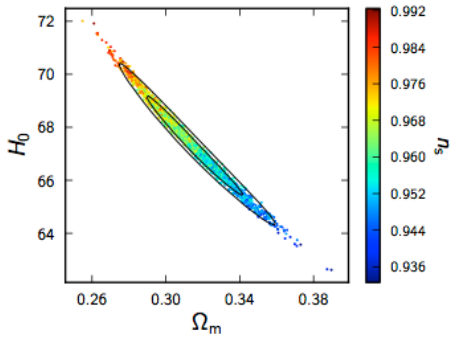


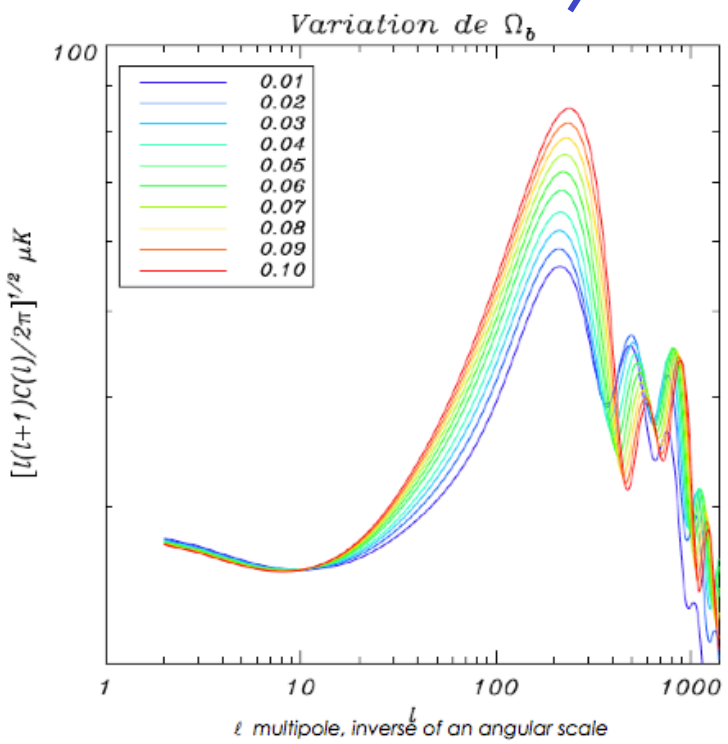



$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell m}(\mathbf{n})$$

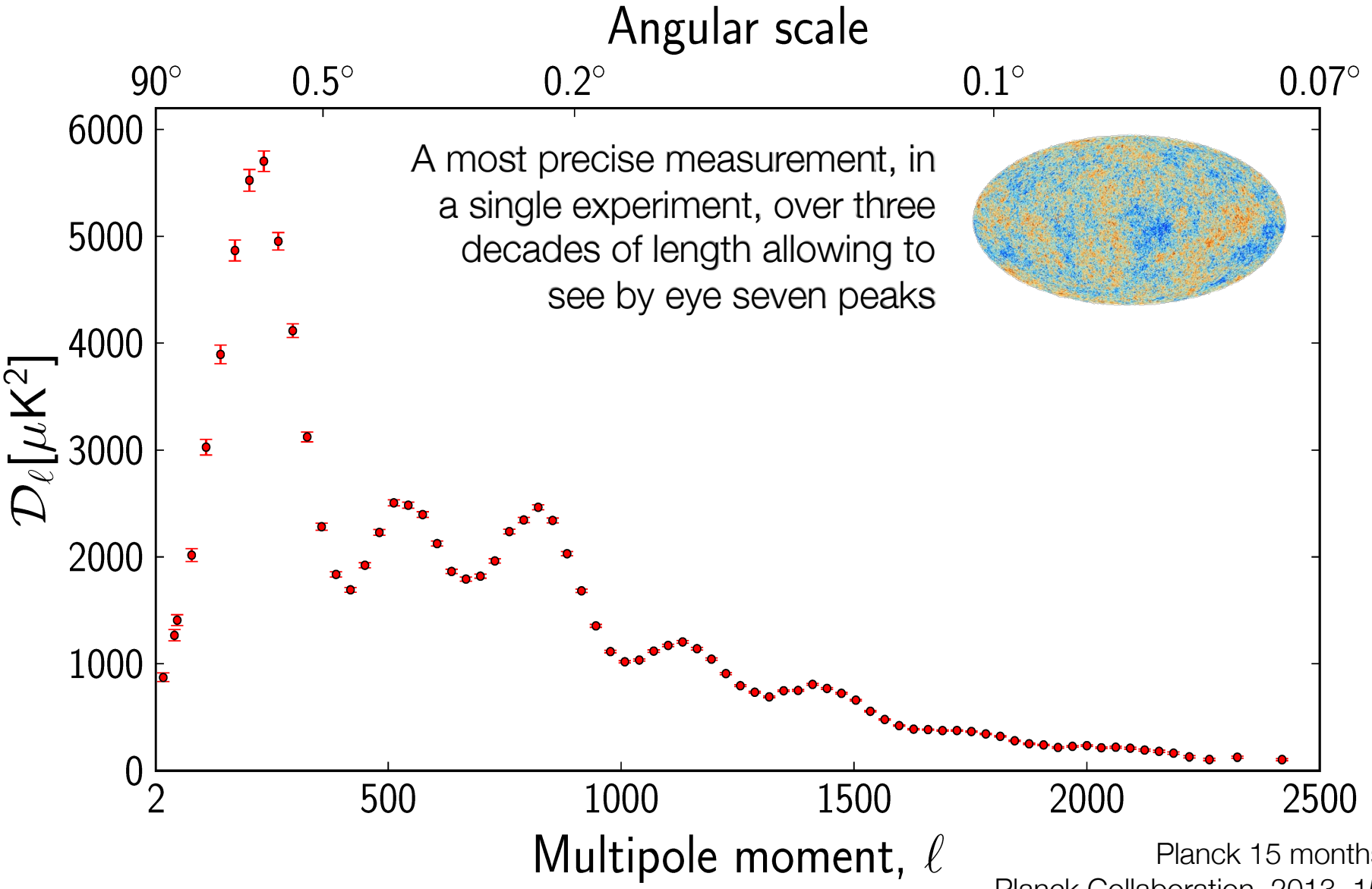
$$C_\ell^{TT} = \langle a_{\ell m}^T \cdot a_{\ell m}^{T\star} \rangle$$



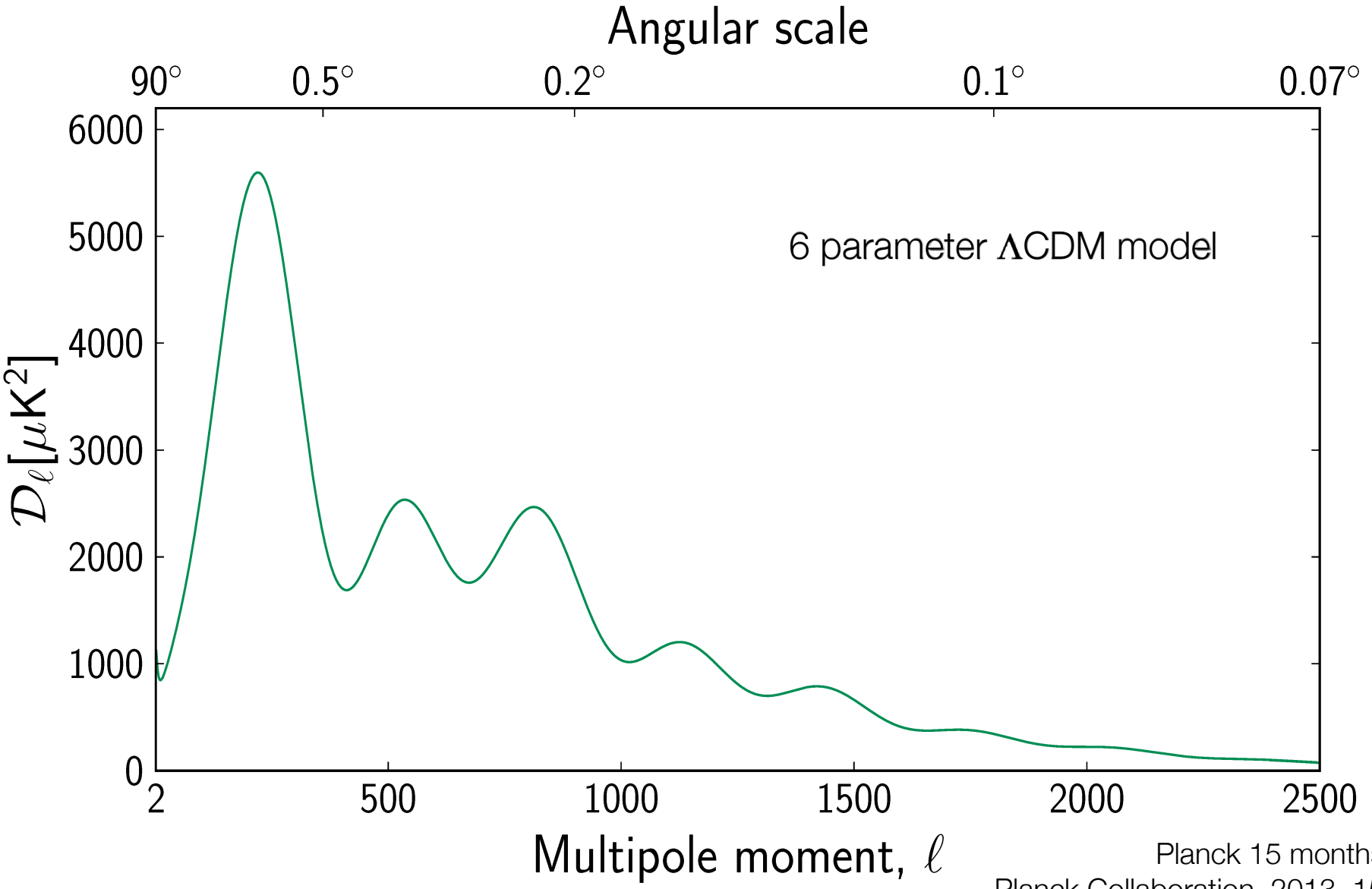
# the Planck spectrum of temperature anisotropies




Planck 15 months
Planck Collaboration, 2013, 15

courtesy François Bouchet

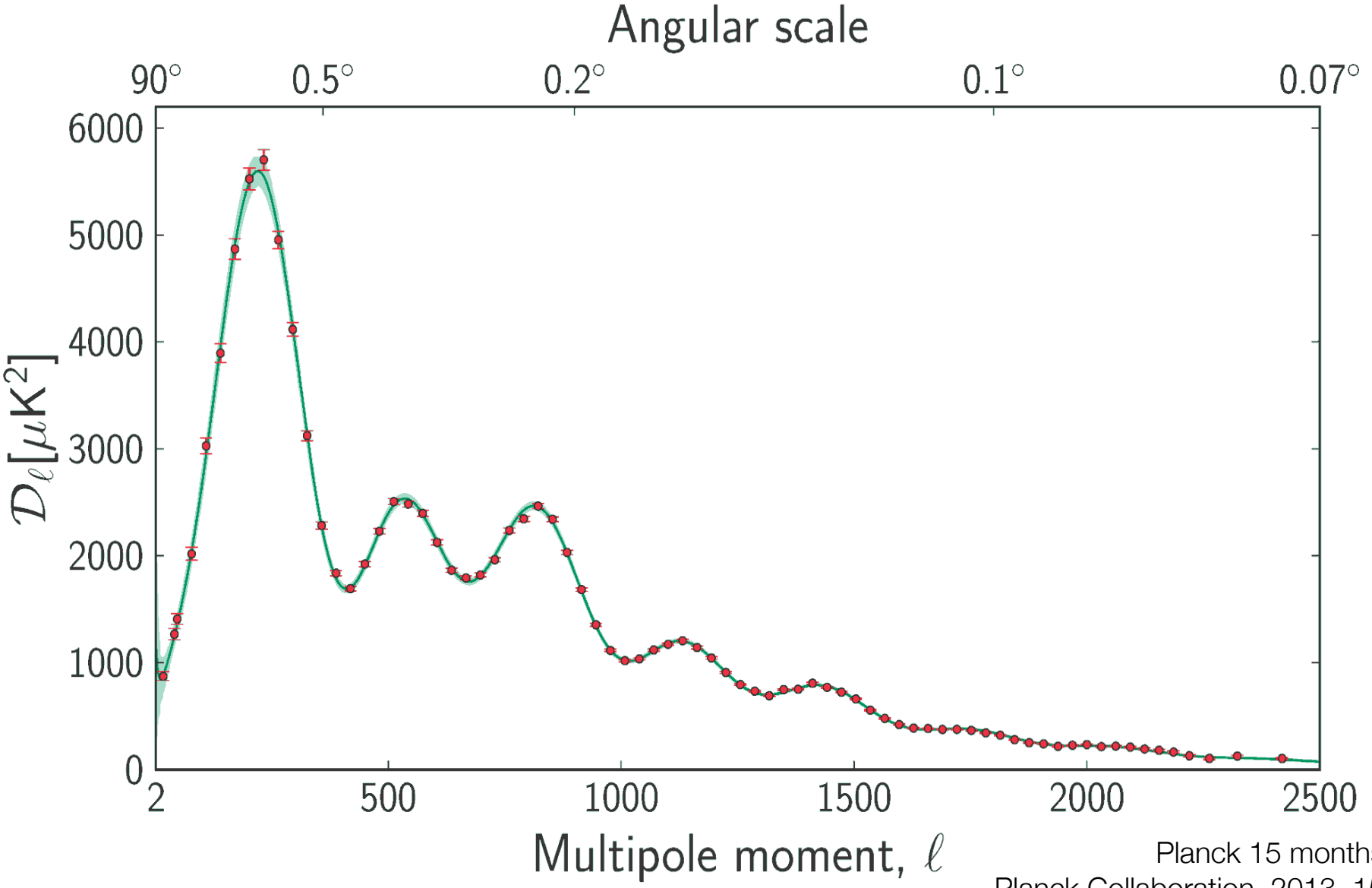
# Planck best fitting theoretical model




Planck 15 months
Planck Collaboration, 2013, 15

courtesy François Bouchet

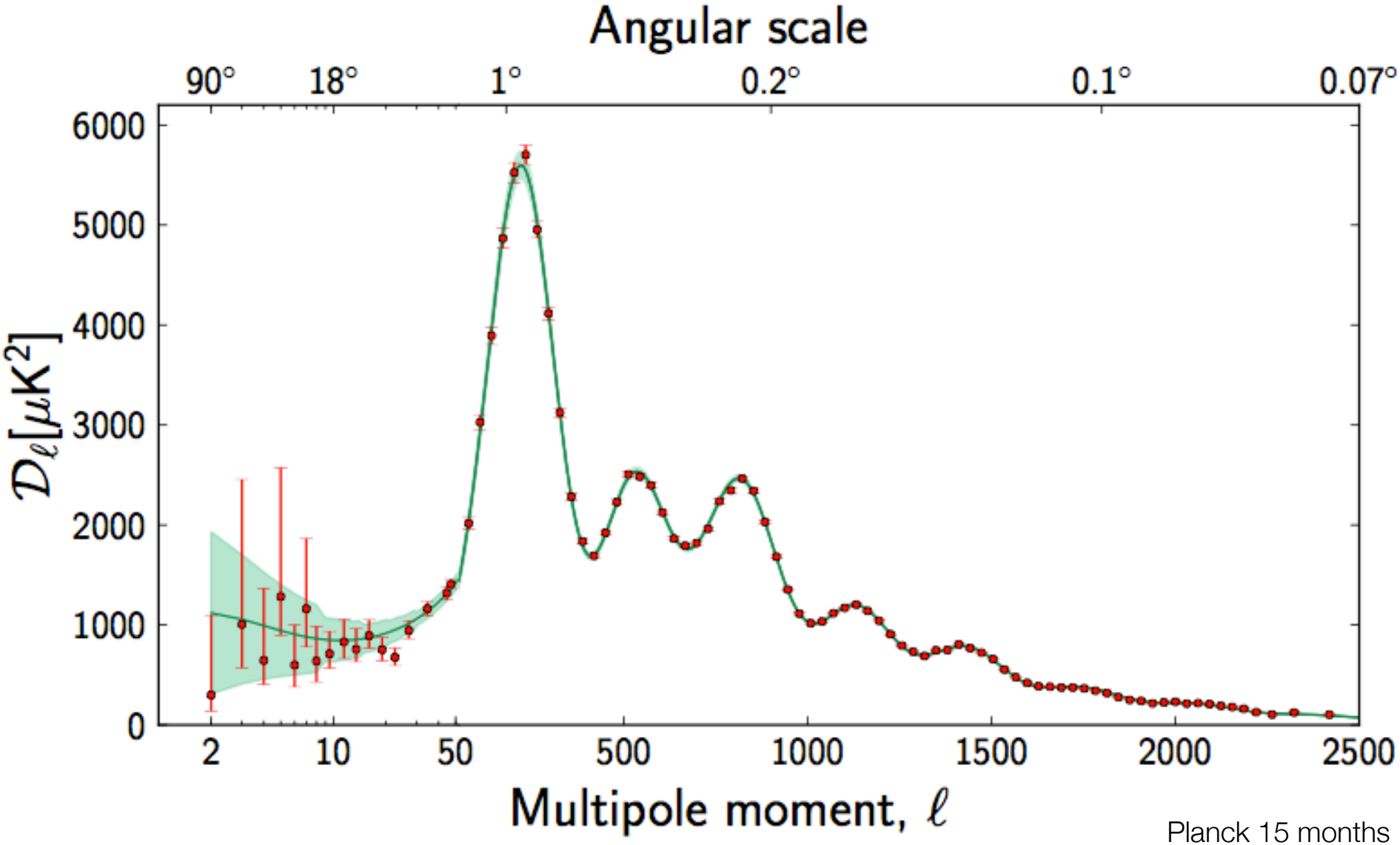
# theory confronts data – 1




Planck 15 months
Planck Collaboration, 2013, 15

courtesy François Bouchet

# theory confronts data – 2




Planck 15 months
Planck Collaboration, 2013, 15

# theory confronts data – 3 – polarization

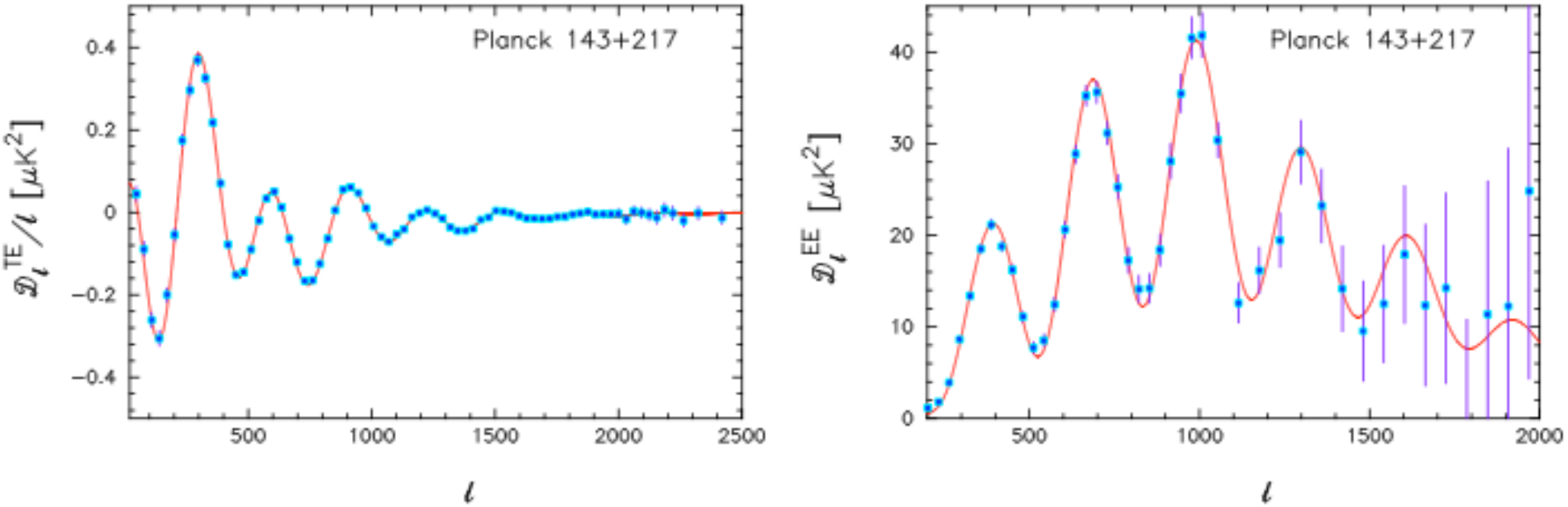
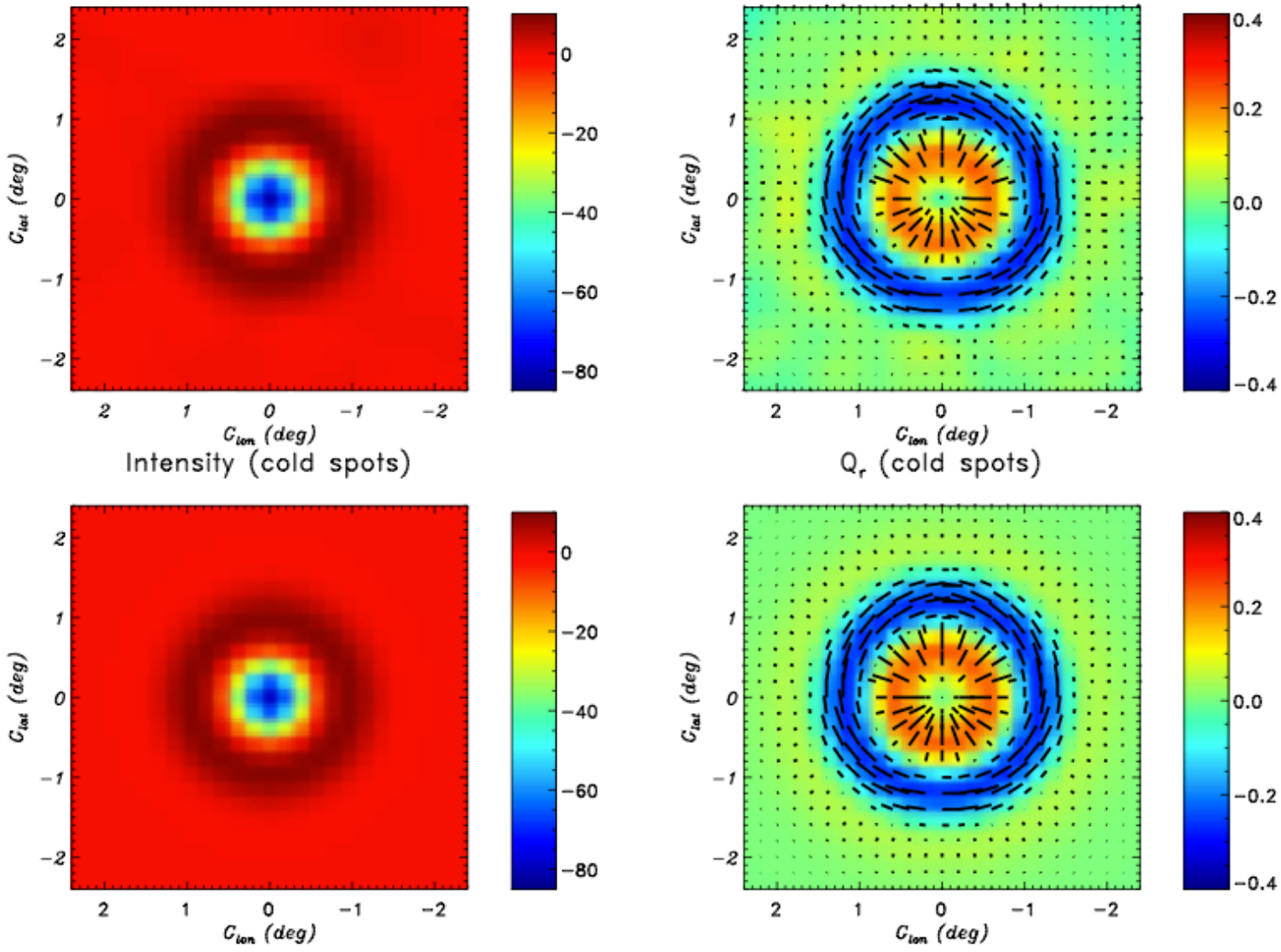



**Fig. 11.** *Planck TE* (left) and *EE* spectra (right) computed as described in the text. The red lines show the polarization spectra from the base ΛCDM *Planck*+WP+highL model, *which is fitted to the TT data only*.

-> NOT a fit to TE and EE, just an overplot at higl-ell

Planck 15 months
Planck Collaboration, 2013, 15

# 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. le modèle standard Λ-CDM

Unviers plat, avec constante cosmologique et matière noire froide

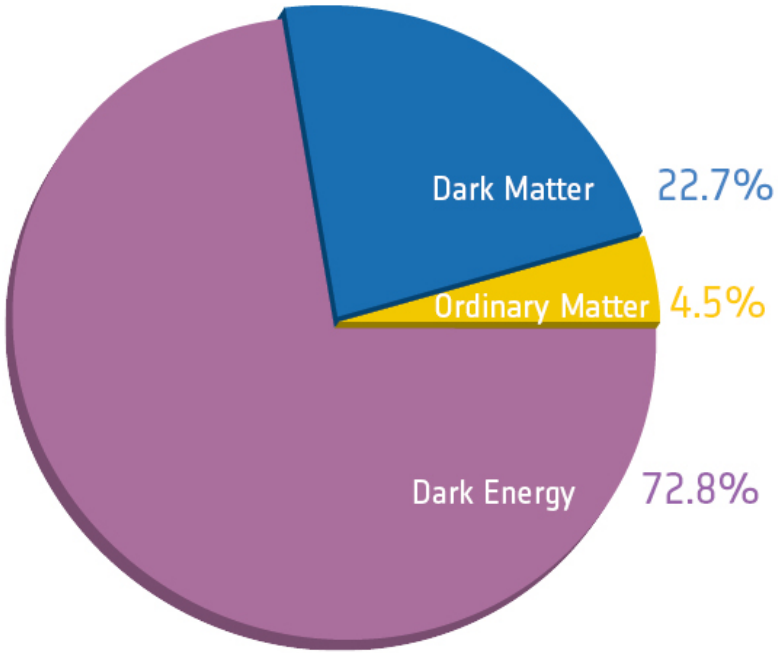
Seulement 6 paramètres…..

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

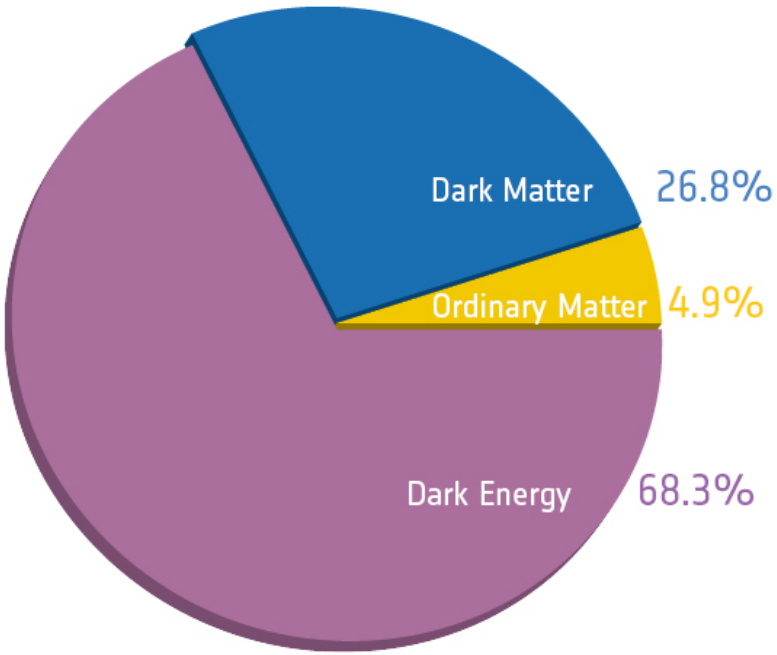
Et quelques paramètres dérivés

| | | |
|---|---|---|
| $H_0$ | 67.11 | $67.4 \pm 1.4$ |
| $\Omega_\Lambda$ | 0.6825 | $0.686 \pm 0.020$ |
| $\Omega_m$ | 0.3175 | $0.314 \pm 0.020$ |

# 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
Planck Collaboration, 2013, 16

# ... and older

| Parameter | *Planck*+WP Best fit | *Planck*+WP 68% limits | *Planck*+WP+highL Best fit | *Planck*+WP+highL 68% limits | *Planck*+lensing+WP+highL Best fit | *Planck*+lensing+WP+highL 68% limits | *Planck*+WP+highL+BAO Best fit | *Planck*+WP+highL+BAO 68% limits |
|---|---|---|---|---|---|---|---|---|
| $\Omega_b h^2$ | 0.022032 | $0.02205 \pm 0.00028$ | 0.022069 | $0.02207 \pm 0.00027$ | 0.022199 | $0.02218 \pm 0.00026$ | 0.022161 | $0.02214 \pm 0.00024$ |
| $\Omega_c h^2$ | 0.12038 | $0.1199 \pm 0.0027$ | 0.12025 | $0.1198 \pm 0.0026$ | 0.11847 | $0.1186 \pm 0.0022$ | 0.11889 | $0.1187 \pm 0.0017$ |
| $100\theta_{MC}$ | 1.04119 | $1.04131 \pm 0.00063$ | 1.04130 | $1.04132 \pm 0.00063$ | 1.04146 | $1.04144 \pm 0.00061$ | 1.04148 | $1.04147 \pm 0.00056$ |
| $\tau$ | 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 | $0.092 \pm 0.013$ |
| $n_s$ | 0.9619 | $0.9603 \pm 0.0073$ | 0.9582 | $0.9585 \pm 0.0070$ | 0.9624 | $0.9614 \pm 0.0063$ | 0.9611 | $0.9608 \pm 0.0054$ |
| $\ln(10^{10} A_s)$ | 3.0980 | $3.089^{+0.024}_{-0.027}$ | 3.0959 | $3.090 \pm 0.025$ | 3.0947 | $3.087 \pm 0.024$ | 3.0973 | $3.091 \pm 0.025$ |
| $A^{PS}_{100}$ | 152 | $171 \pm 60$ | 209 | $212 \pm 50$ | 204 | $213 \pm 50$ | 204 | $212 \pm 50$ |
| $A^{PS}_{143}$ | 63.3 | $54 \pm 10$ | 72.6 | $73 \pm 8$ | 72.2 | $72 \pm$ | | |
| $A^{PS}_{217}$ | 117.0 | $107^{+20}_{-10}$ | 59.5 | $59 \pm 10$ | 60.2 | $58 \pm$ | | |
| $A^{CIB}_{143}$ | 0.0 | $< 10.7$ | 3.57 | $3.24 \pm 0.83$ | 3.25 | $3.24 \pm$ | | |
| $A^{CIB}_{217}$ | 27.2 | $29^{+6}_{-9}$ | 53.9 | $49.6 \pm 5.0$ | 52.3 | $50.0 \pm$ | | |
| $A^{tSZ}_{143}$ | 6.80 | ... | 5.17 | $2.54^{+1.1}_{-1.9}$ | 4.64 | $2.51^{+}$ | | |
| $r^{PS}_{143\times217}$ | 0.916 | $> 0.850$ | 0.825 | $0.823^{+0.069}_{-0.077}$ | 0.814 | $0.825 \pm$ | | |
| $r^{CIB}_{143\times217}$ | 0.406 | $0.42 \pm 0.22$ | 1.0000 | $> 0.930$ | 1.0000 | $> 0.9$ | | |
| $\gamma^{CIB}$ | 0.601 | $0.53^{+0.13}_{-0.12}$ | 0.674 | $0.638 \pm 0.081$ | 0.656 | $0.643 \pm$ | | |
| $\xi^{tSZ\times CIB}$ | 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 | $5.34^{+2.8}_{-2.0}$ |
| $\Omega_\Lambda$ | 0.6817 | $0.685^{+0.018}_{-0.016}$ | 0.6830 | $0.685^{+0.017}_{-0.016}$ | 0.6939 | $0.693 \pm 0.013$ | 0.6914 | $0.692 \pm 0.010$ |
| $\sigma_8$ | 0.8347 | $0.829 \pm 0.012$ | 0.8322 | $0.828 \pm 0.012$ | 0.8271 | $0.8233 \pm 0.0097$ | 0.8288 | $0.826 \pm 0.012$ |
| $z_{re}$ | 11.37 | $11.1 \pm 1.1$ | 11.38 | $11.1 \pm 1.1$ | 11.42 | $11.1 \pm 1.1$ | 11.52 | $11.3 \pm 1.1$ |
| $H_0$ | 67.04 | $67.3 \pm 1.2$ | 67.15 | $67.3 \pm 1.2$ | 67.94 | $67.9 \pm 1.0$ | 67.77 | $67.80 \pm 0.77$ |
| Age/Gyr | 13.8242 | $13.817 \pm 0.048$ | 13.8170 | $13.813 \pm 0.047$ | 13.7914 | $13.794 \pm 0.044$ | 13.7965 | $13.798 \pm 0.037$ |
| $100\theta_*$ | 1.04136 | $1.04147 \pm 0.00062$ | 1.04146 | $1.04148 \pm 0.00062$ | 1.04161 | $1.04159 \pm 0.00060$ | 1.04163 | $1.04162 \pm 0.00056$ |
| $r_{drag}$ | 147.36 | $147.49 \pm 0.59$ | 147.35 | $147.47 \pm 0.59$ | 147.68 | $147.67 \pm 0.50$ | 147.611 | $147.68 \pm 0.45$ |

km/s/Mpc

$67.80 \pm 0.77$

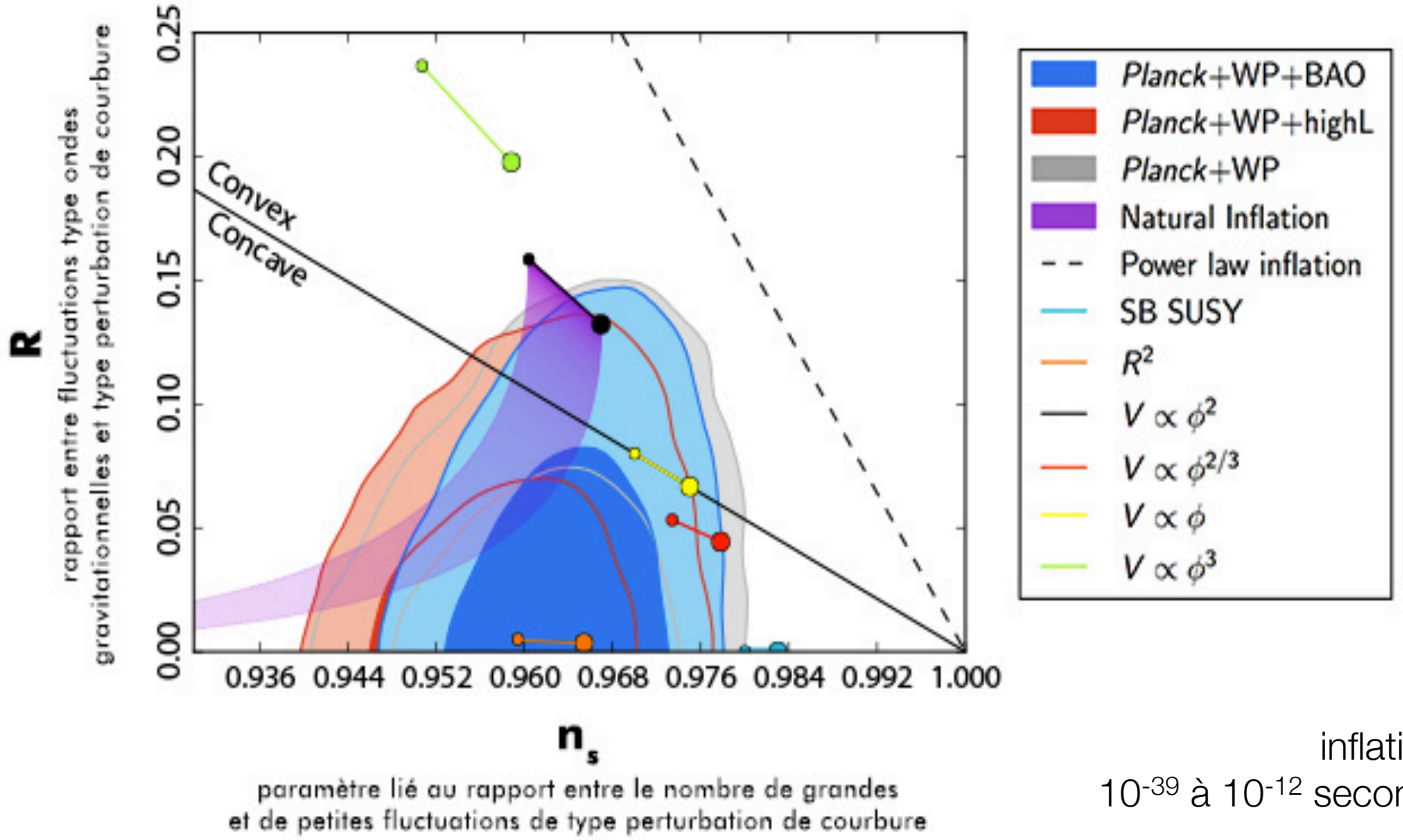
Gyr

$13.798 \pm 0.037$

Planck 15 months

Planck Collaboration, 2013, 16

# 5. some inflation models excluded




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

Planck 15 months
Planck Collaboration, 2013, 22

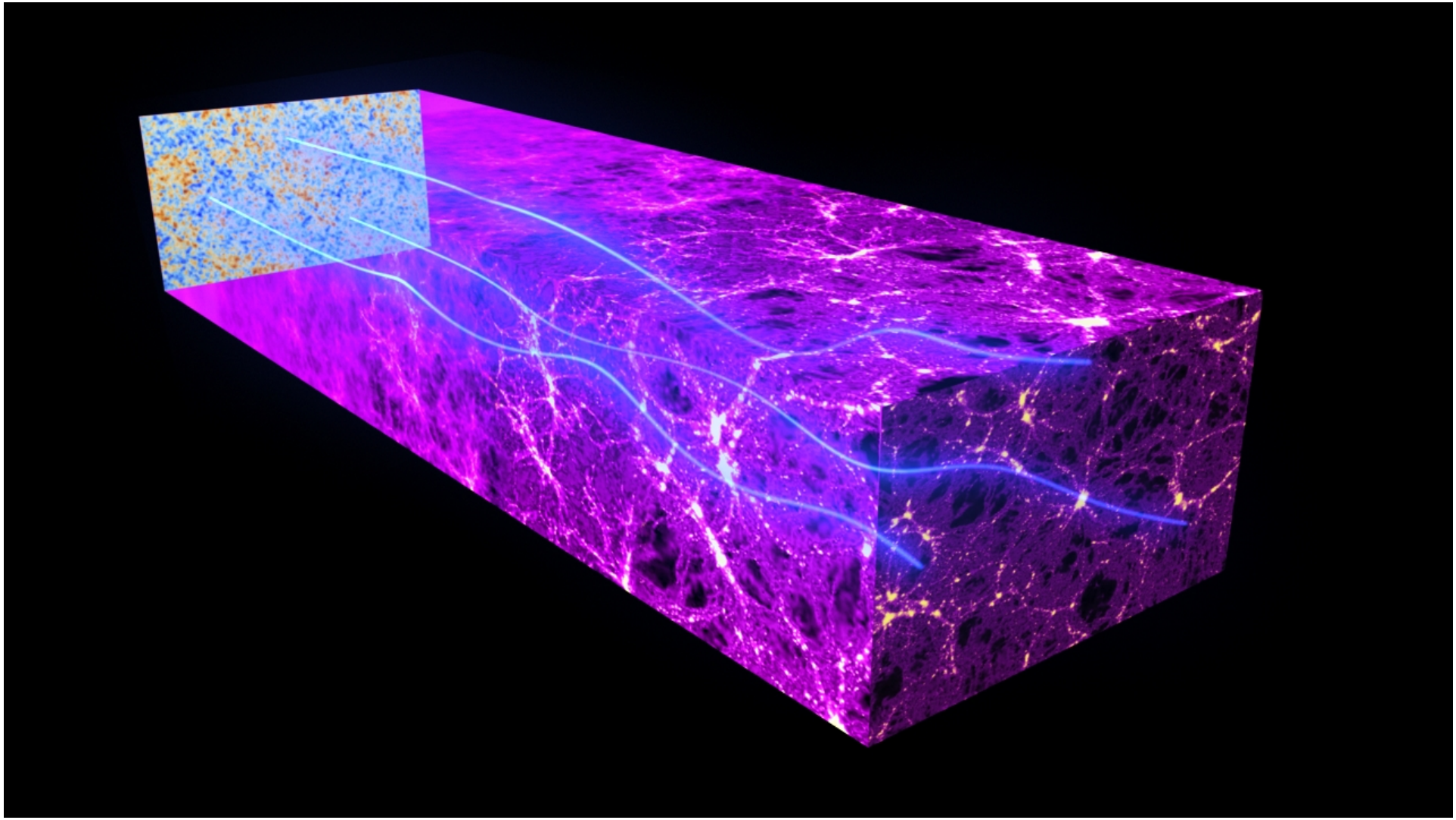
# more implications

- $\theta$: 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 $7\sigma$ (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 |
|---|
| $1.04147 \pm 0.00056$ |
| $0.9608 \pm 0.0054$ |
| $\sum m_\nu < 0.23\,\mathrm{eV}$ (95%; *Planck*+ |
| $N_{\mathrm{eff}} = 3.30^{+0.54}_{-0.51}$ (95%; *Pla* |

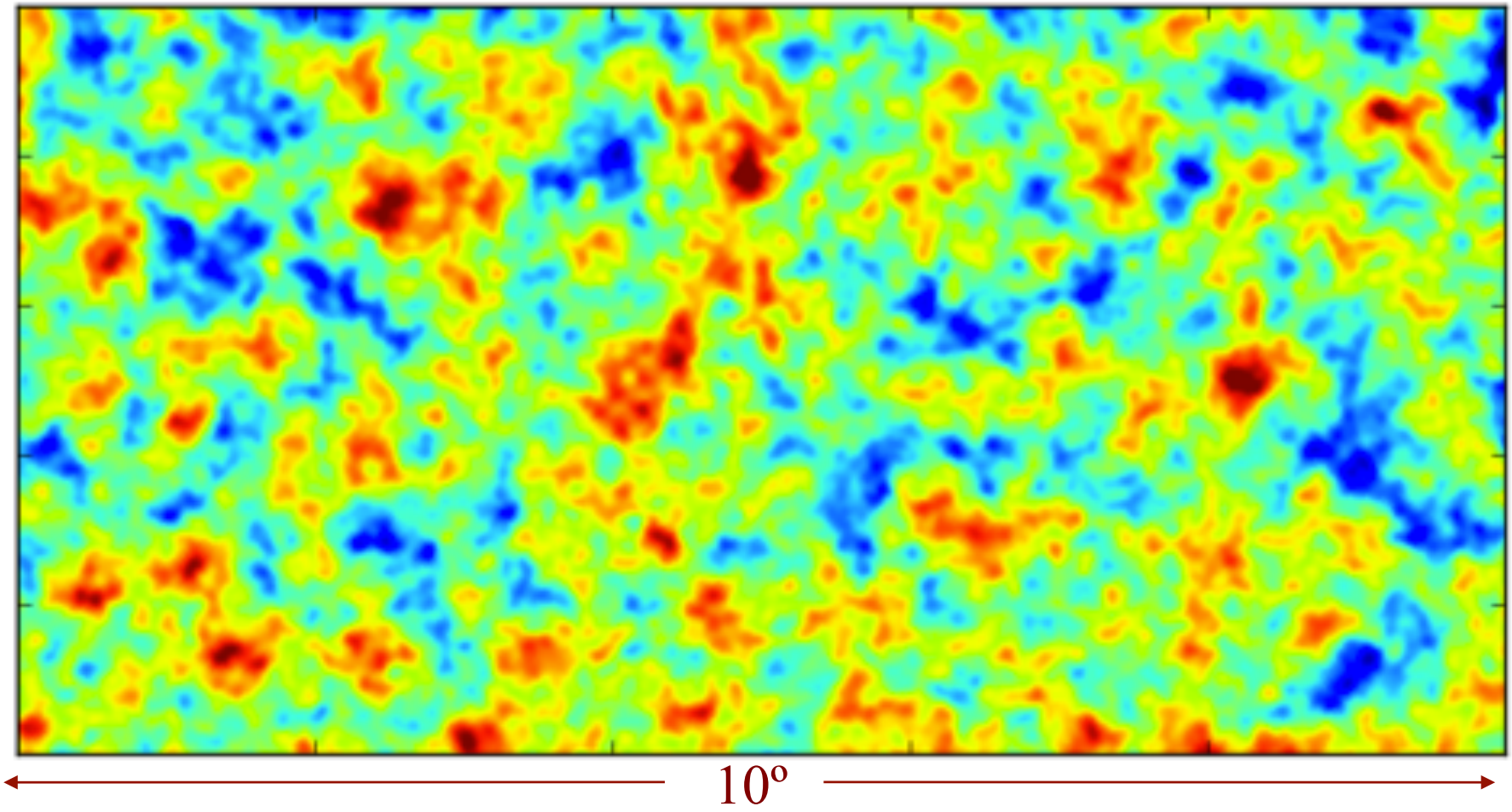
Planck 15 months
Planck Collaboration, 2013, 16

# 6. between CMB and us: structures



# gravitational lensing of the CMB

A simulated patch of CMB sky – before lensing

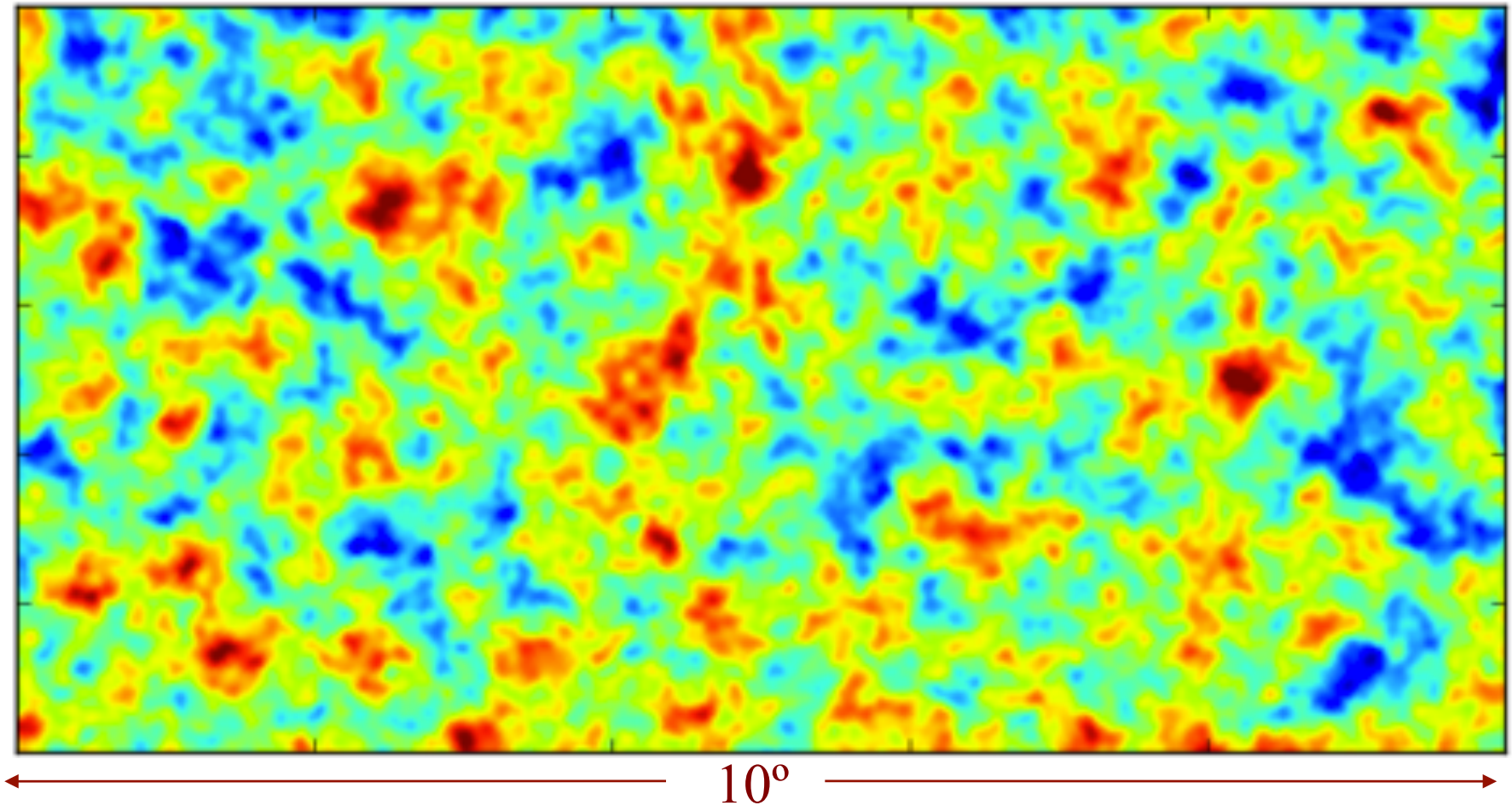



typical deflection: 2.4 arcmin

Planck 15 months
Planck Collaboration, 2013, 17

# gravitational lensing of the CMB

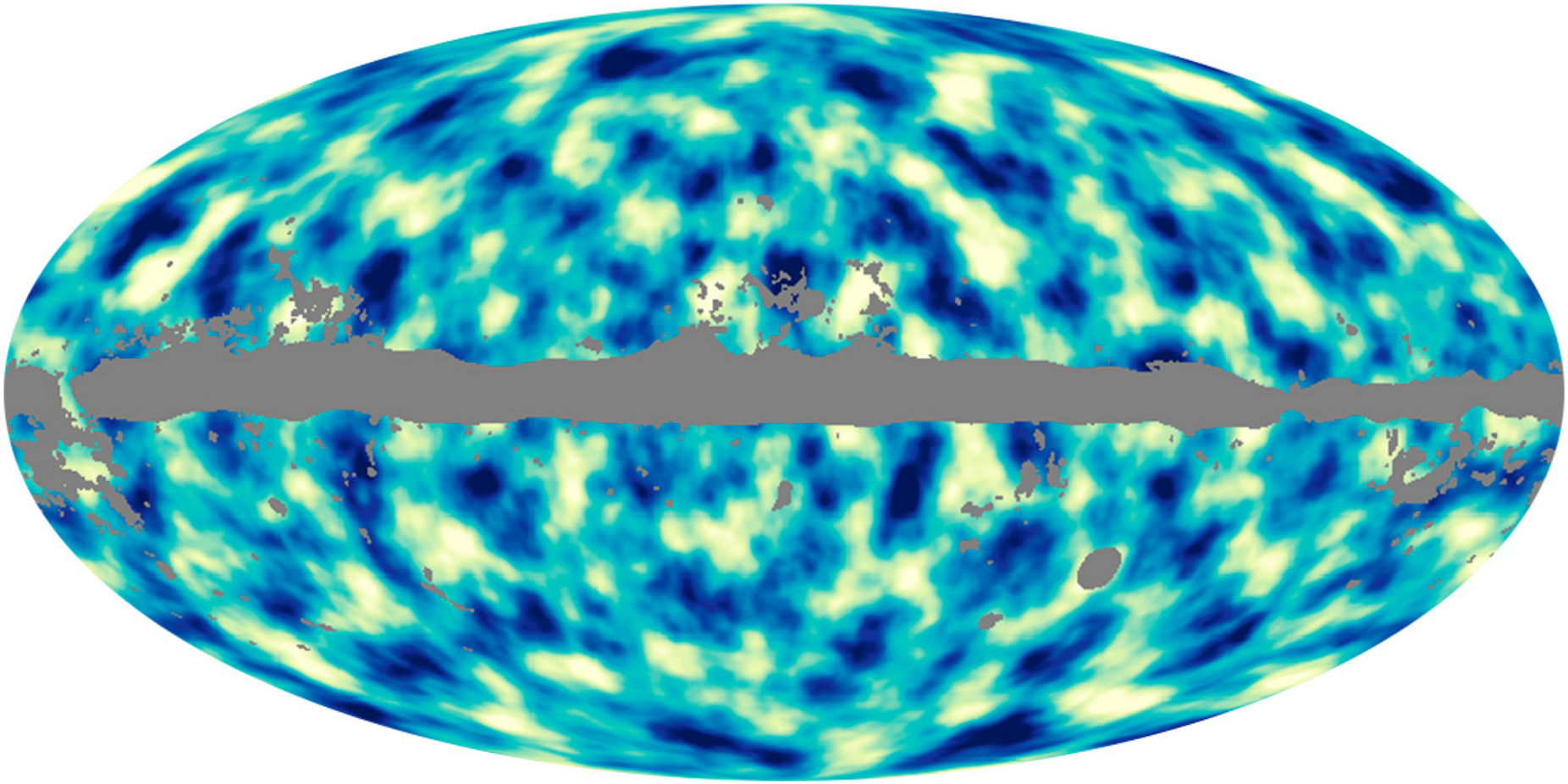
A simulated patch of CMB sky – after lensing




typical deflection: 2.4 arcmin

Planck 15 months
Planck Collaboration, 2013, 17

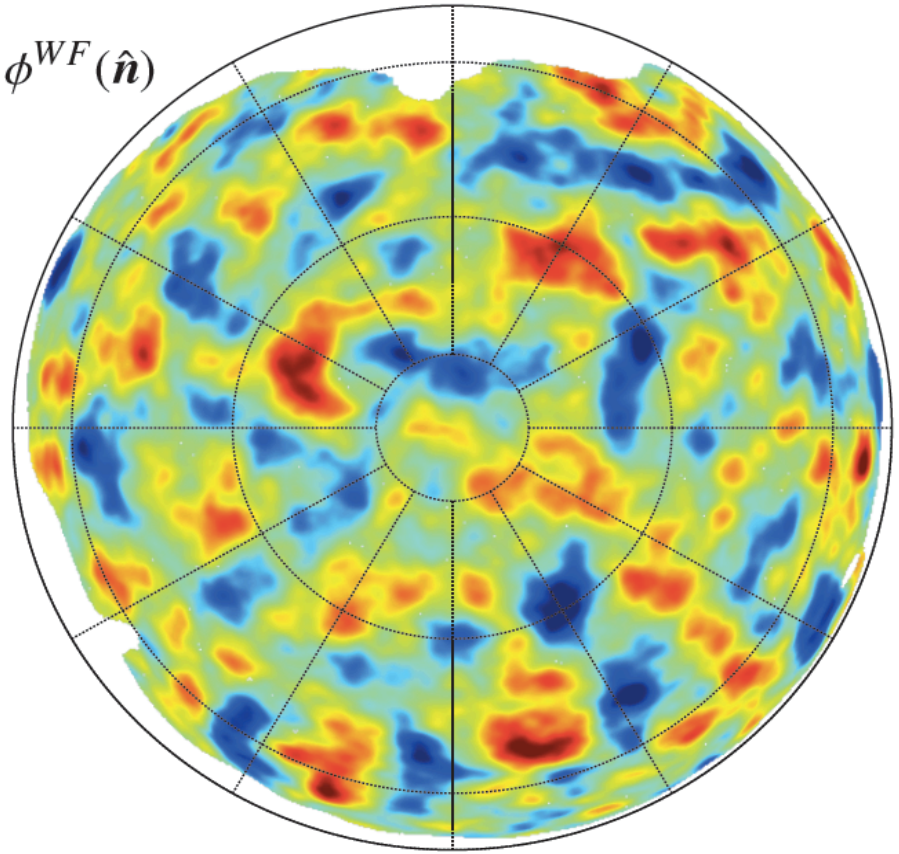
# Planck all-sky map of the dark matter



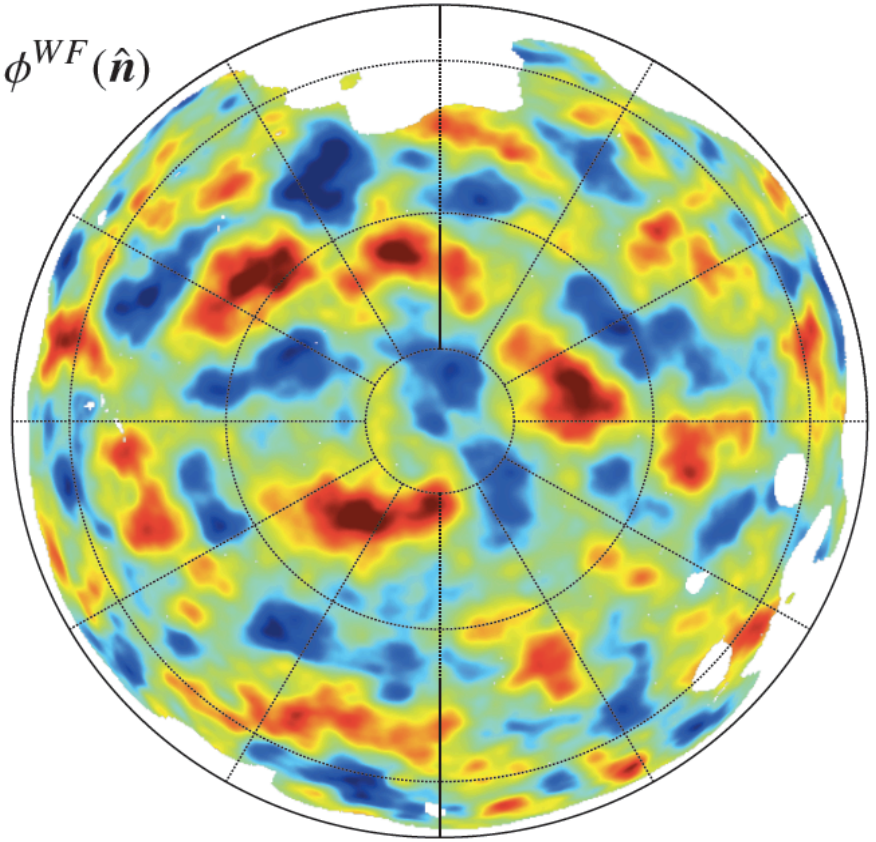
= Carte de la masse projetée sur la ligne de visée

Planck 15 months
Planck Collaboration, 2013, 17

# Planck all-sky map of the dark matter




Galactic North

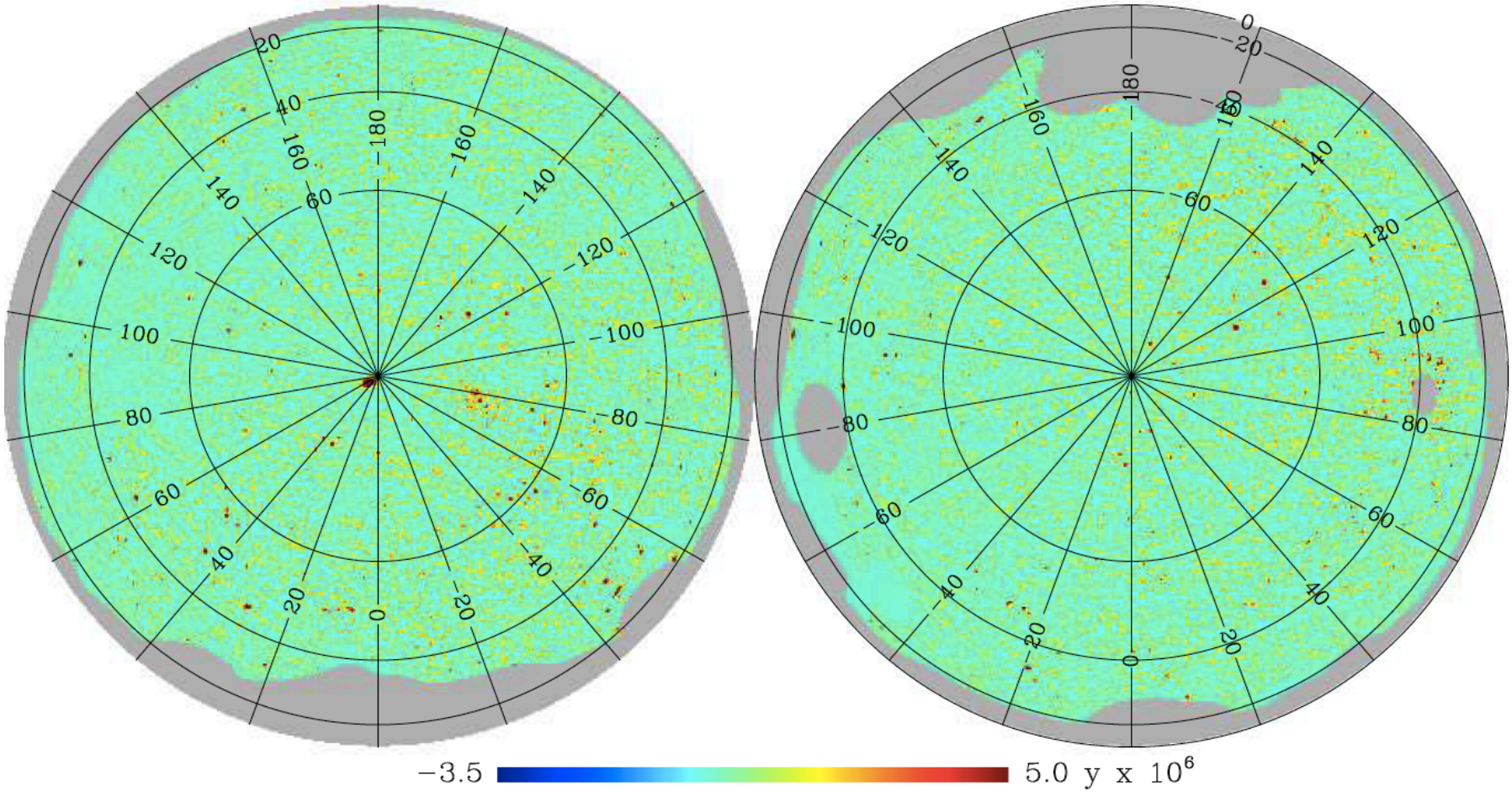



Galactic South

Planck 15 months
Planck Collaboration, 2013, 17

# Planck map of the baryon distribution

Planck can also image the gas (baryon) distribution in the low-redshift Universe using scattering of CMB photons off the electrons. This SZ (Sunyaev-Zeldovich) effect causes a change in the shape of the CMB spectrum

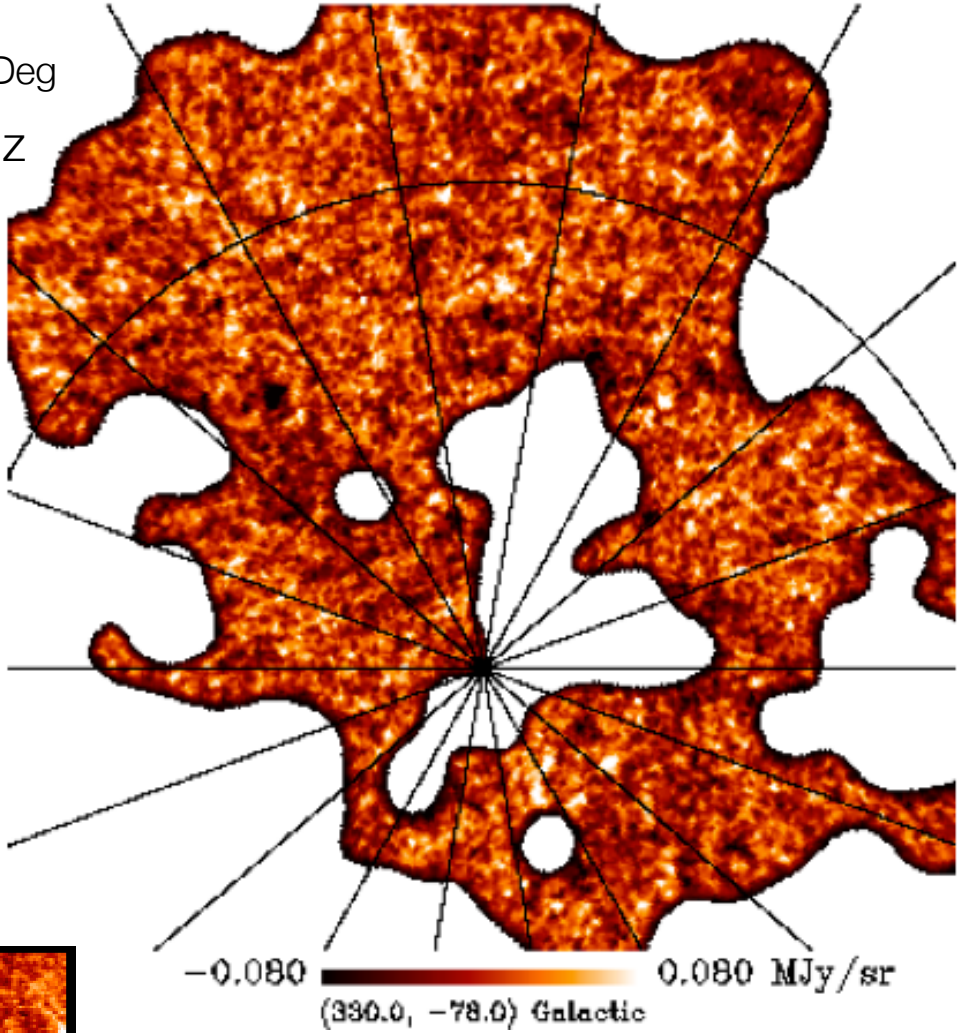



Planck 15 months
Planck Collaboration, 2013, 21

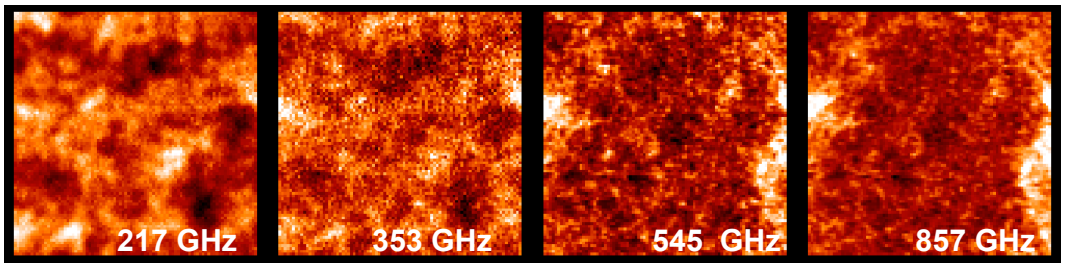
# Cosmic IR Background maps probe high-z SFR

~2000 Sq. Deg

545 GHz



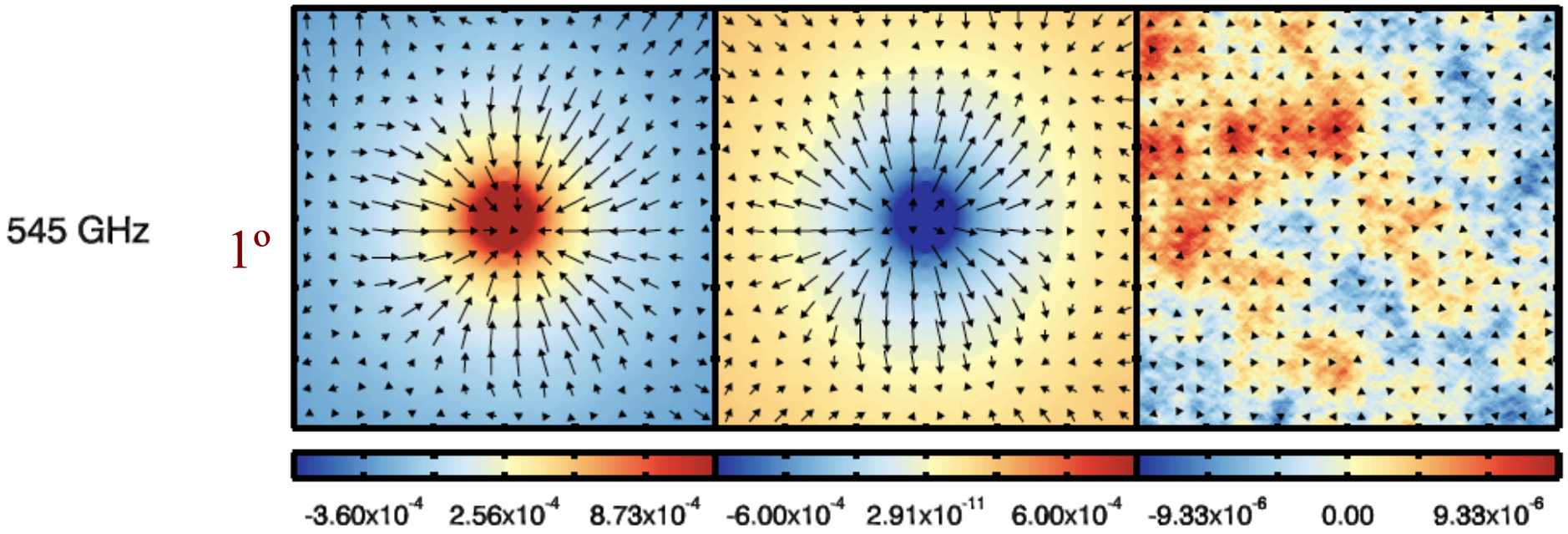

Planck Collab., 2013, 30




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.



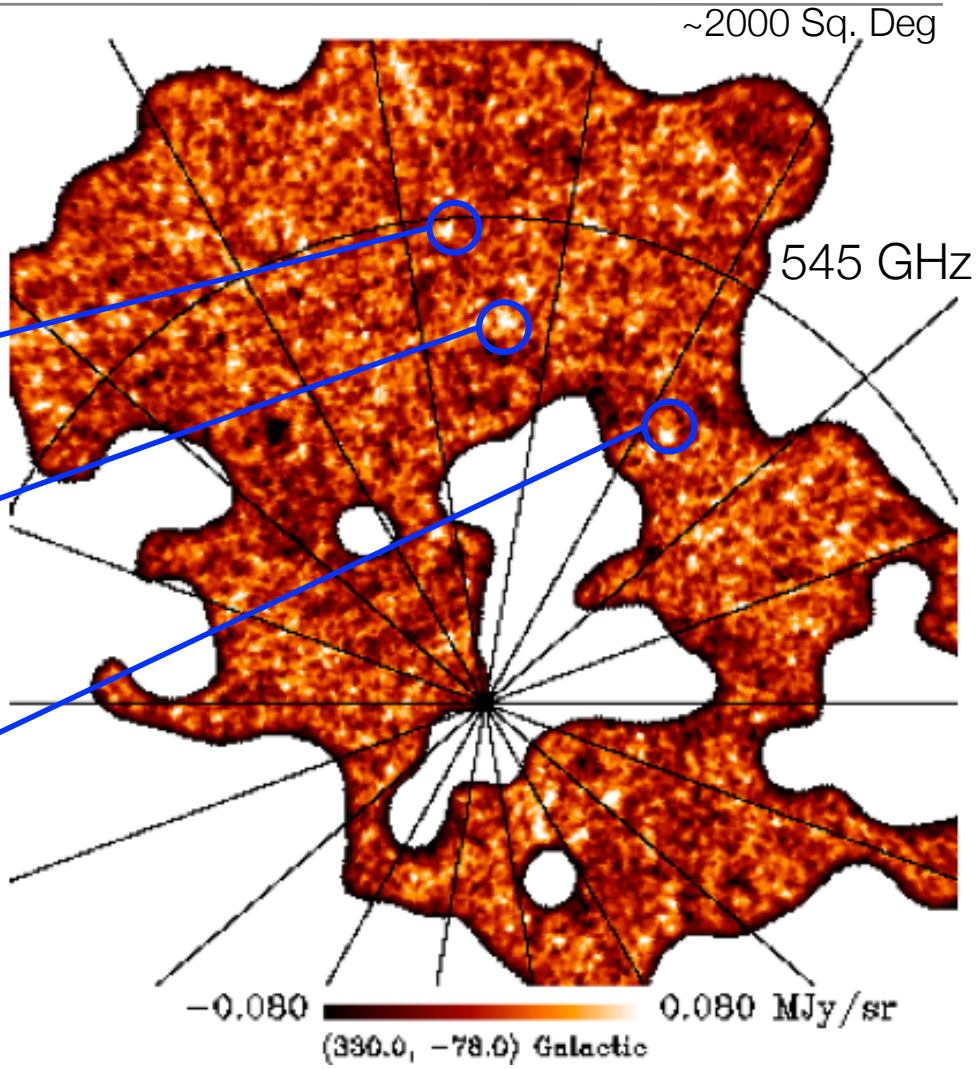

see also Hanson et al., 2013 about lensing induced B-modes (NOT primordial B-modes !)

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 ?

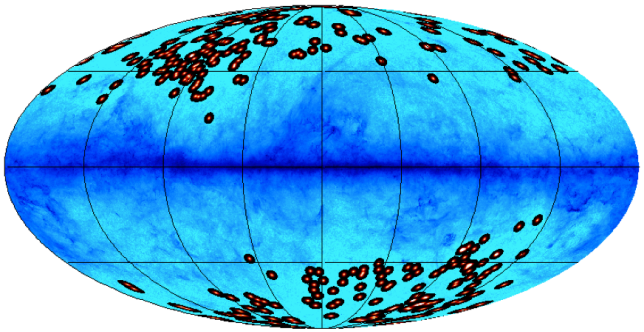


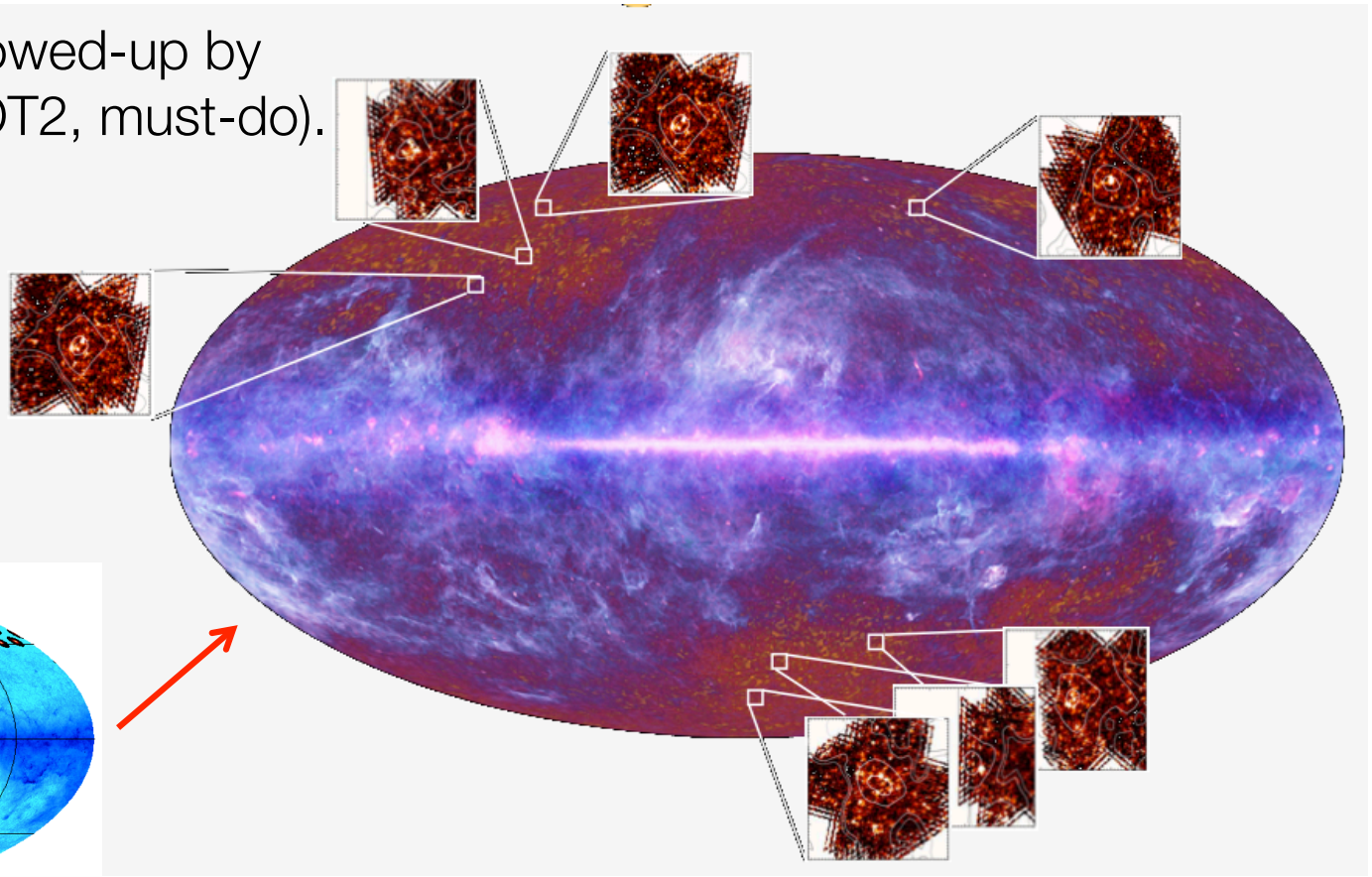

Planck Collab., 2013, 30

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).

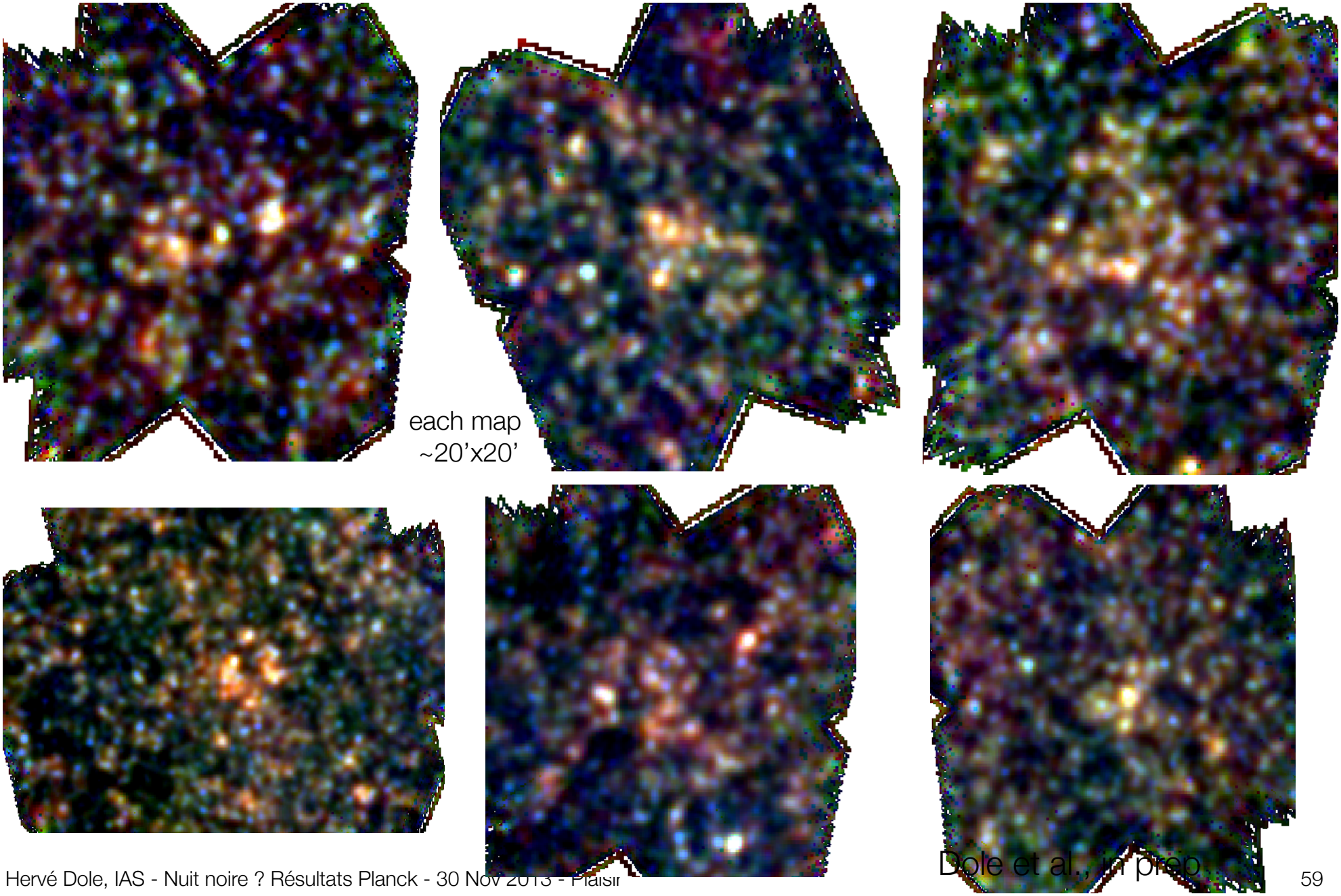




98% success
- either bright lensed candidates
- or overdensities of red galaxies
- 1.4% of the fields were cirrus

Dole et al., in prep

# a remarkable dataset




Dole et al., in prep.

# more identifications to go

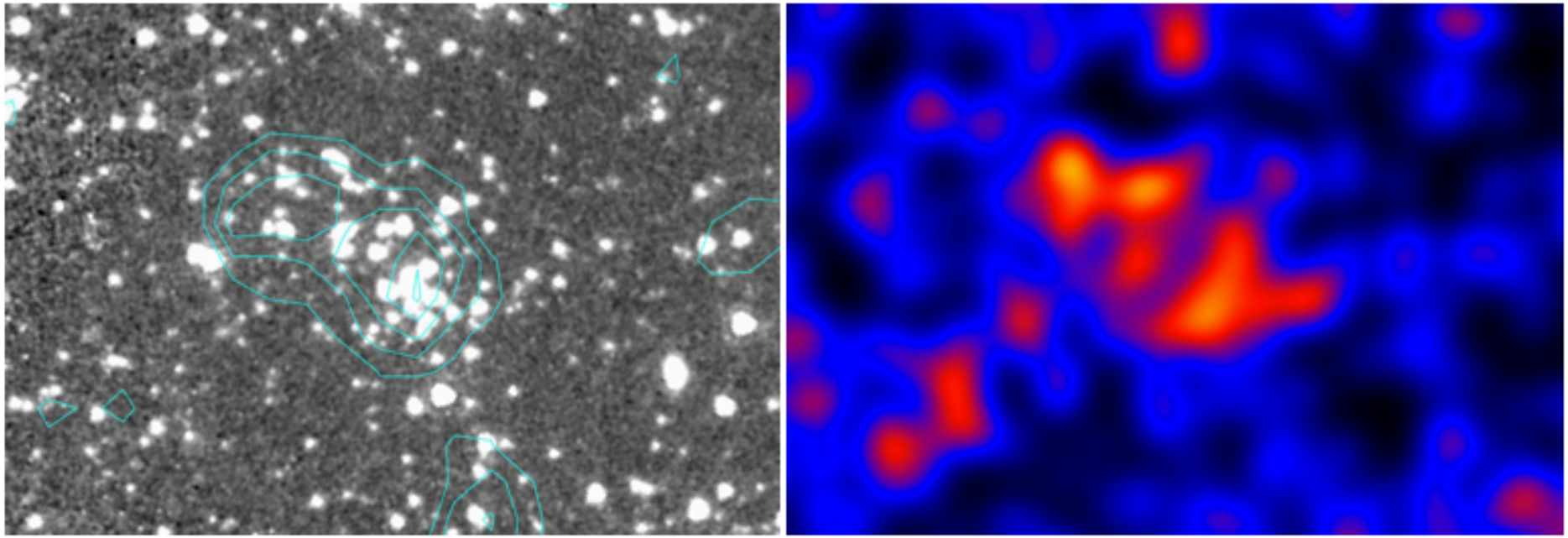


**Figure 10.** A high-z cluster candidate observed by *Planck*, Herschel, and here Spitzer-IRAC (3.5′ × 2.3′). Left: IRAC channel 2 (4.5 $\mu$m) with SPIRE 350 $\mu$m contour. Right: color image of the 4.5/3.6 color ratio, showing the red color of the sources within the cluster candidate.

Dole et al., in prep

# au final

- un tour sur le ciel par minute (répété 50 fois au même endroit)
- 200 mesures du ciel par seconde et par détecteur, en continu pendant 30 mois à 0.1K
- ~1000 milliards d'échantillons (72 voies, 30 mois) et quelques milliards de paquets de télémétrie à « descendre »
- données brutes d'un détecteur (TOI)
  - 50 Go (et on a 52 détecteurs, et plusieurs versions)
- 1 release: 1 mois de processing, 2200 cartes
- cartes du ciel: 50 millions de pixels (6 fréquences HFI + 3 LFI)
- spectres de puissance du fond diffus cosmologique: 1000 valeurs
- seulement 6 paramètres cosmologiques ajustant parfaitement les données
- année prochaine: données de POLARISATION !

# au final

- un tour sur l
- 20
- pour obtenir la meilleure image de l'univers jeune (~380 000 ans ou z=1090)
- ... et tout cela pour 7 centimes/européen/an sur 20 ans
- stant parfaitement