

Le Big-Bang

Lemaître : modèle de l'atome primitif (1930), ancêtre du
Big-Bang, repris
en détail par **Gamow** à partir des années 40.

Rencontre cosmologie et physique nucléaire

The Origin of Elements and the Separation of Galaxies

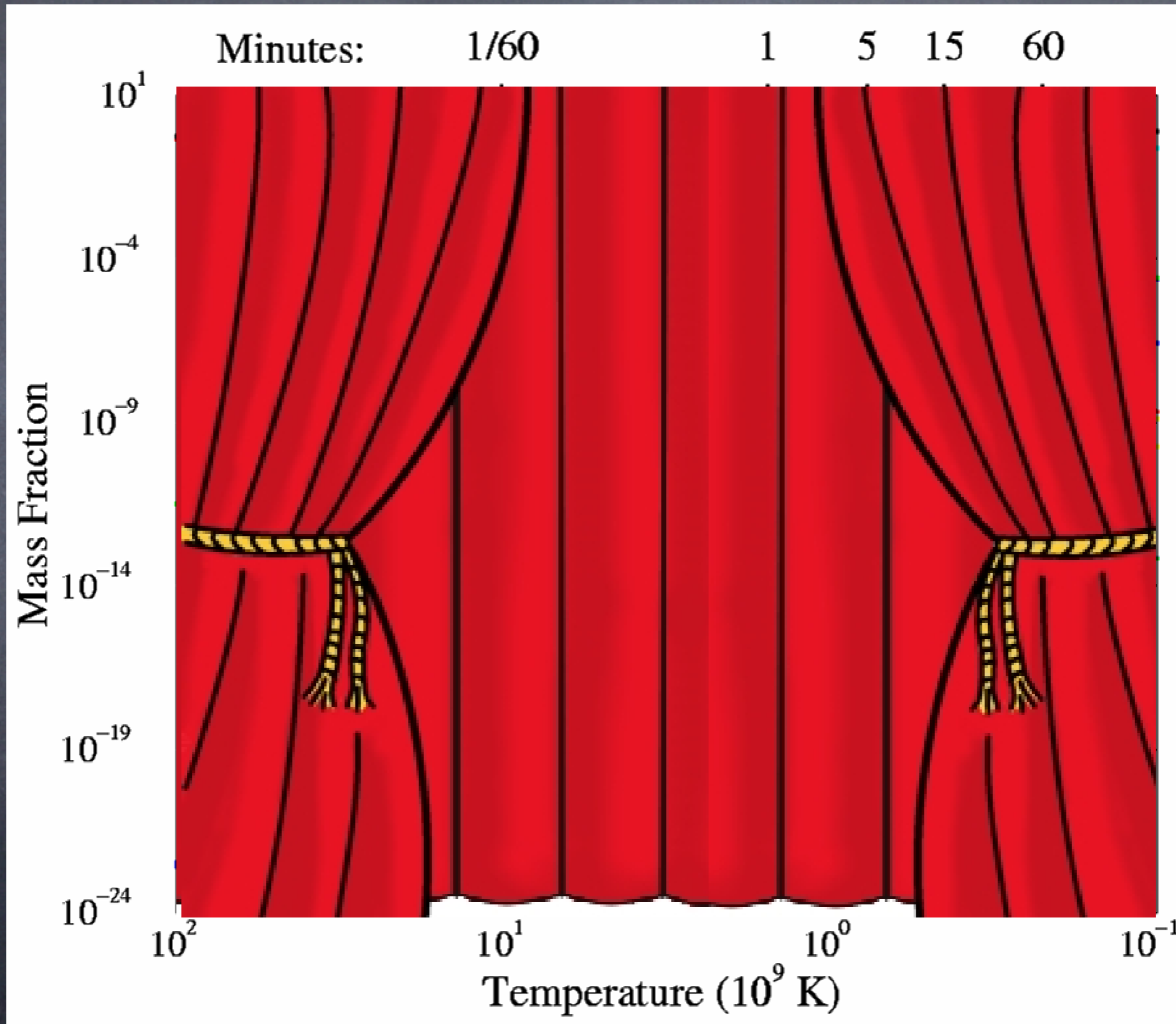
G. GAMOW

George Washington University, Washington, D. C.

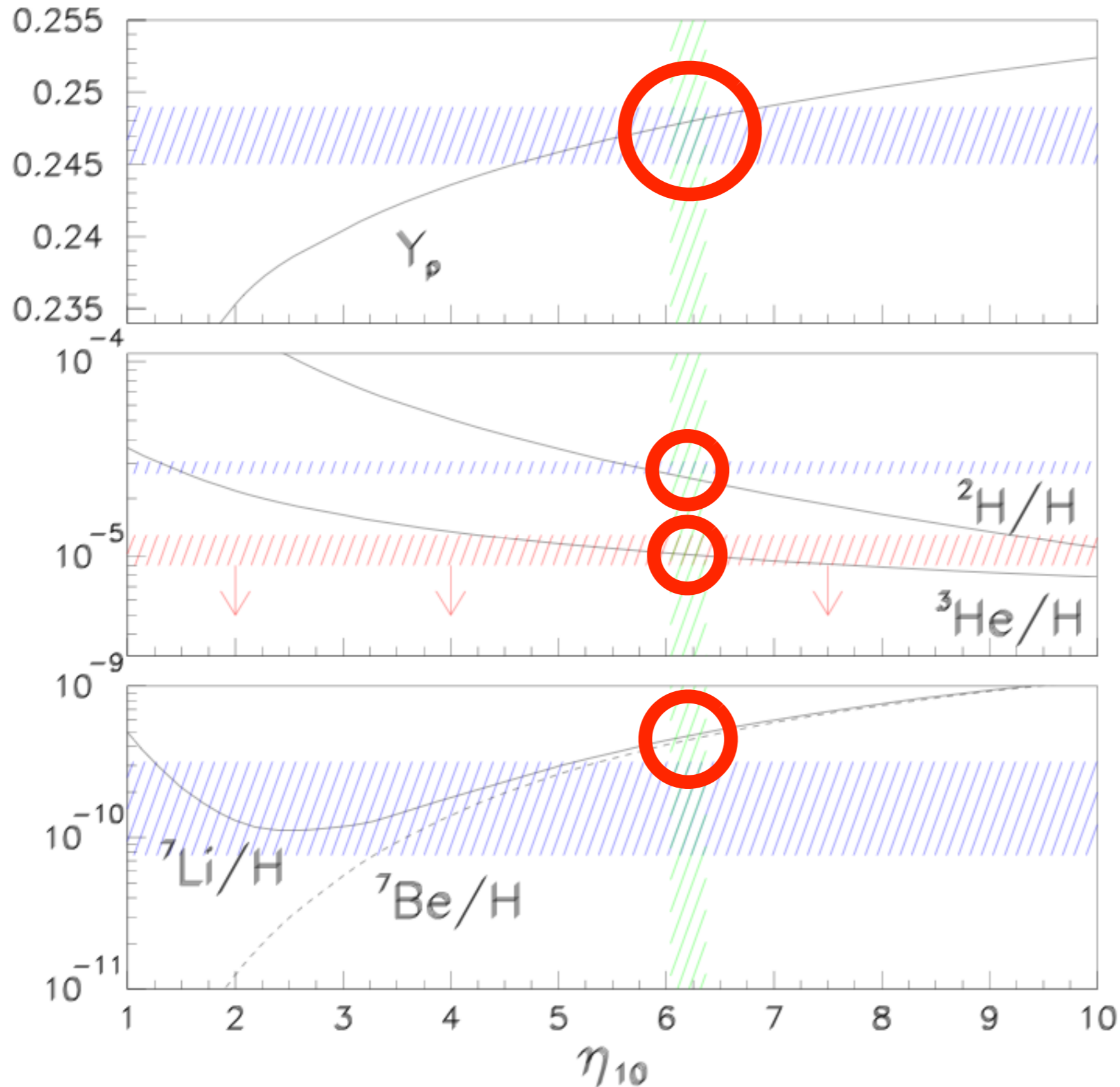
June 21, 1948

Gamow : Nucléosynthèse primordiale

Gamow : Nucléosynthèse primordiale



Gamow : Nucléosynthèse primordiale



extraordinaire
accord entre
théorie et
mesures !

Gamow : Nucléosynthèse primordiale

Cet excellent accord du modèle du avec les mesures font de la nucléosynthèse un des piliers du Big Bang.

Il existe un autre pilier, tout aussi important :
le rayonnement fossile.

Gamow : rayonnement fossile

PHYSICAL REVIEW

VOLUME 75, NUMBER 7

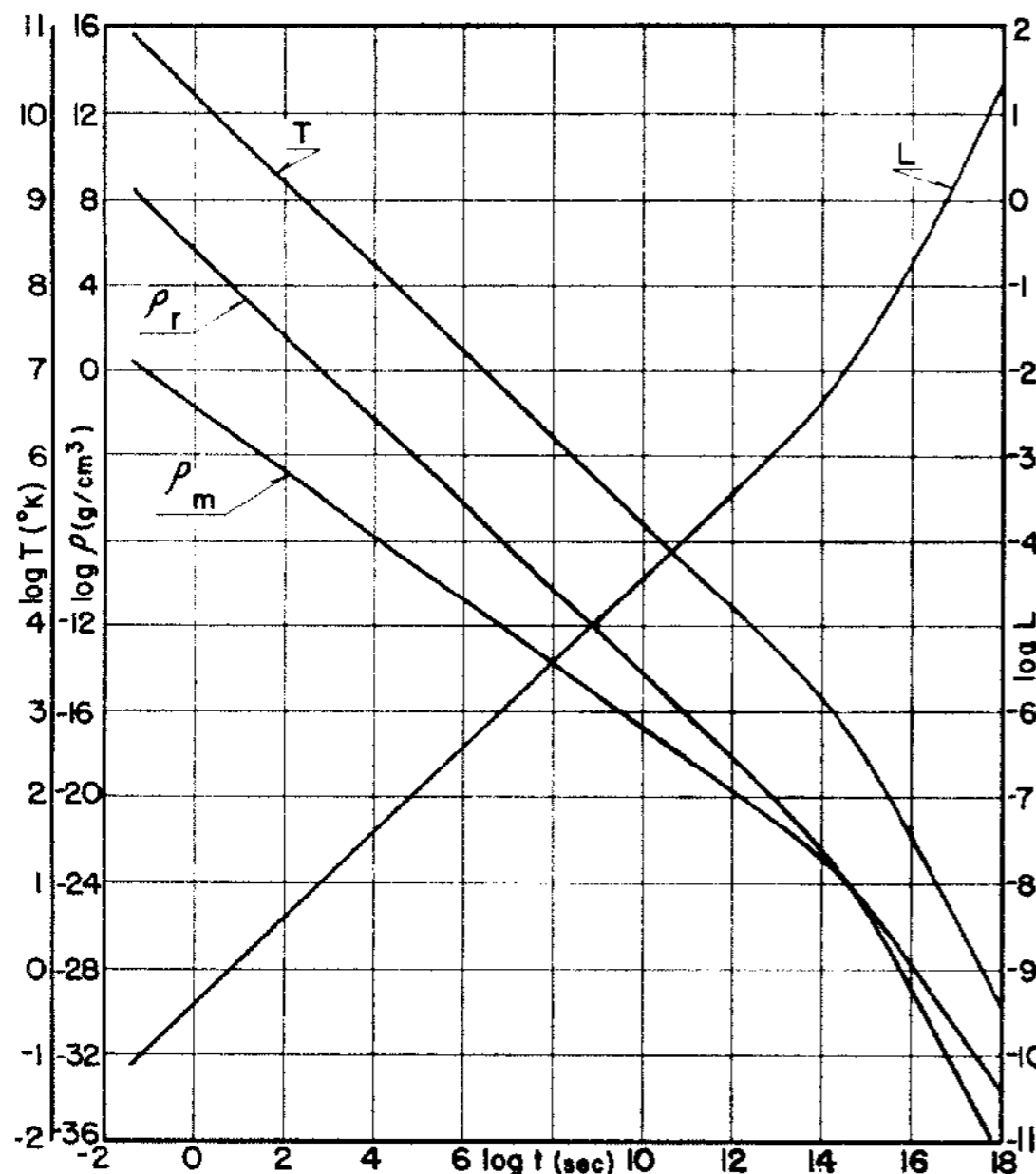
APRIL 1, 1949

Remarks on the Evolution of the Expanding Universe* †

RALPH A. ALPHER AND ROBERT C. HERMAN

Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

(Received December 27, 1948)



As discussed elsewhere,^{6,7} the temperature during the element-forming process must have been of the order of 10^8 – 10^{10} °K. This temperature is limited, on the one hand, by photo-disintegration and thermal dissociation of nuclei and, on the other hand, by the lack of evidence in the relative abundance data for resonance capture of neutrons. For purposes of simplicity we have chosen

$$\rho_r' \cong 1 \text{ g/cm}^3, \quad (12c)$$

which corresponds to $T \cong 0.6 \times 10^9$ °K at the time when the neutron capture process became important.

In accordance with Eq. (4), the specification of $\rho_{m''}$, $\rho_{m'}$, and ρ_r' fixes the present density of radiation, $\rho_{r''}$. In fact, we find that the value of $\rho_{r''}$ consistent with Eq. (4) is

$$\rho_{r''} \cong 10^{-32} \text{ g/cm}^3, \quad (12d)$$

which corresponds to a temperature now of the order of 5°K. This mean temperature for the universe is to be interpreted as the background temperature which would result from the universal

Gamow : rayonnement fossile

Origine du rayonnement fossile ?

il provient de la fin de la cuisson de la soupe cosmique !

la cuisson s'arrête car la soupe se dilue et que la
température diminue

Le rayonnement fossile

Interactions nombreuses entre photons d'une part et baryons d'autre part : **équilibre**, tant que les interactions ont lieu

l'Univers est alors **opaque** !

MAIS l'Univers est en expansion :

les interactions se font de plus en plus rares jusqu'à ce que les **atomes** puissent se former ce qui "libère les photons"

l'Univers devient **transparent** !

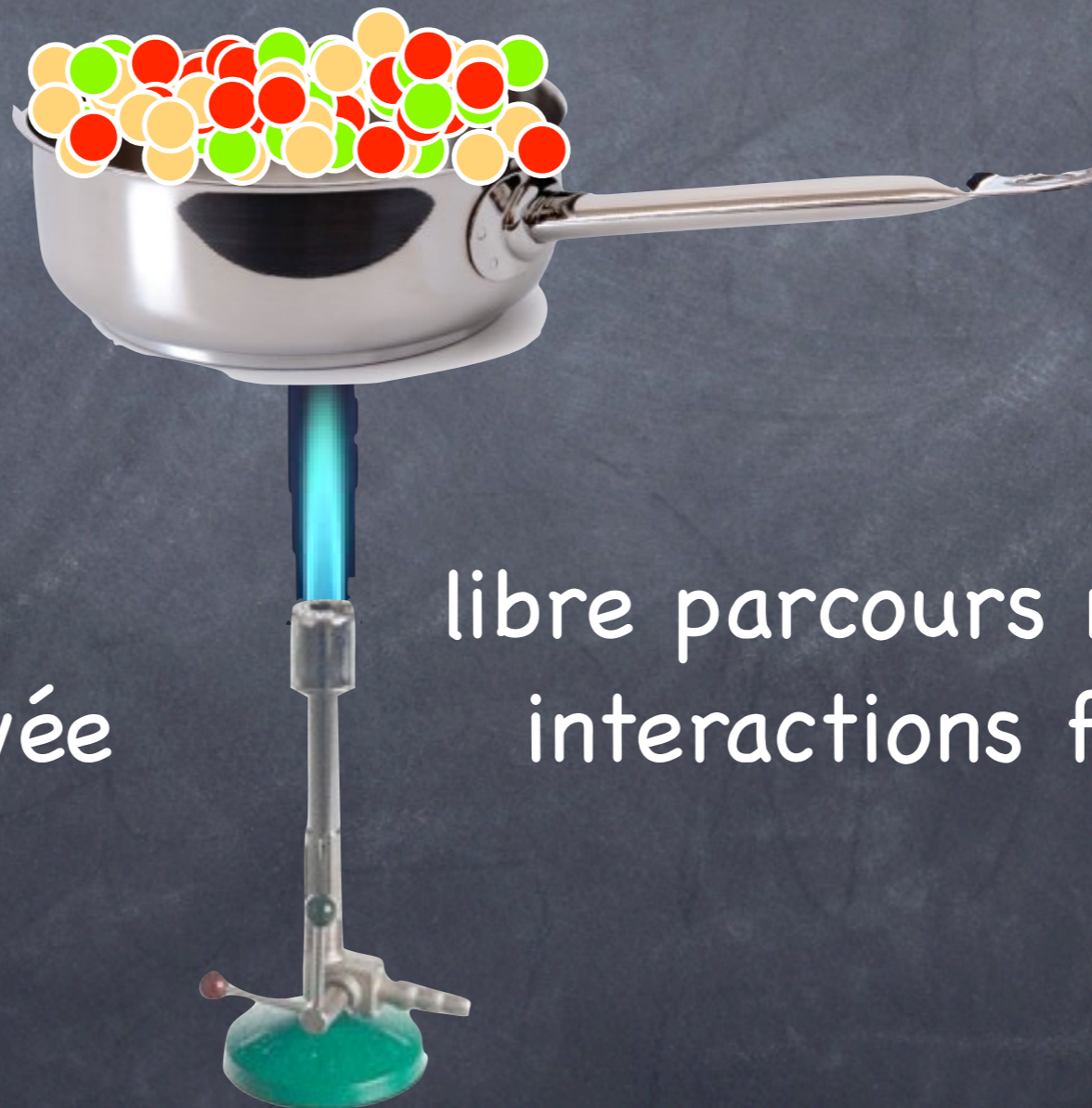
Le rayonnement fossile

2 critères :

proximité des ingrédients **taille de l'Univers**

température de la casserole **température de l'Univers**

- photons
- protons
- électrons



Univers petit
température élevée

libre parcours moyen petit,
interactions fréquentes

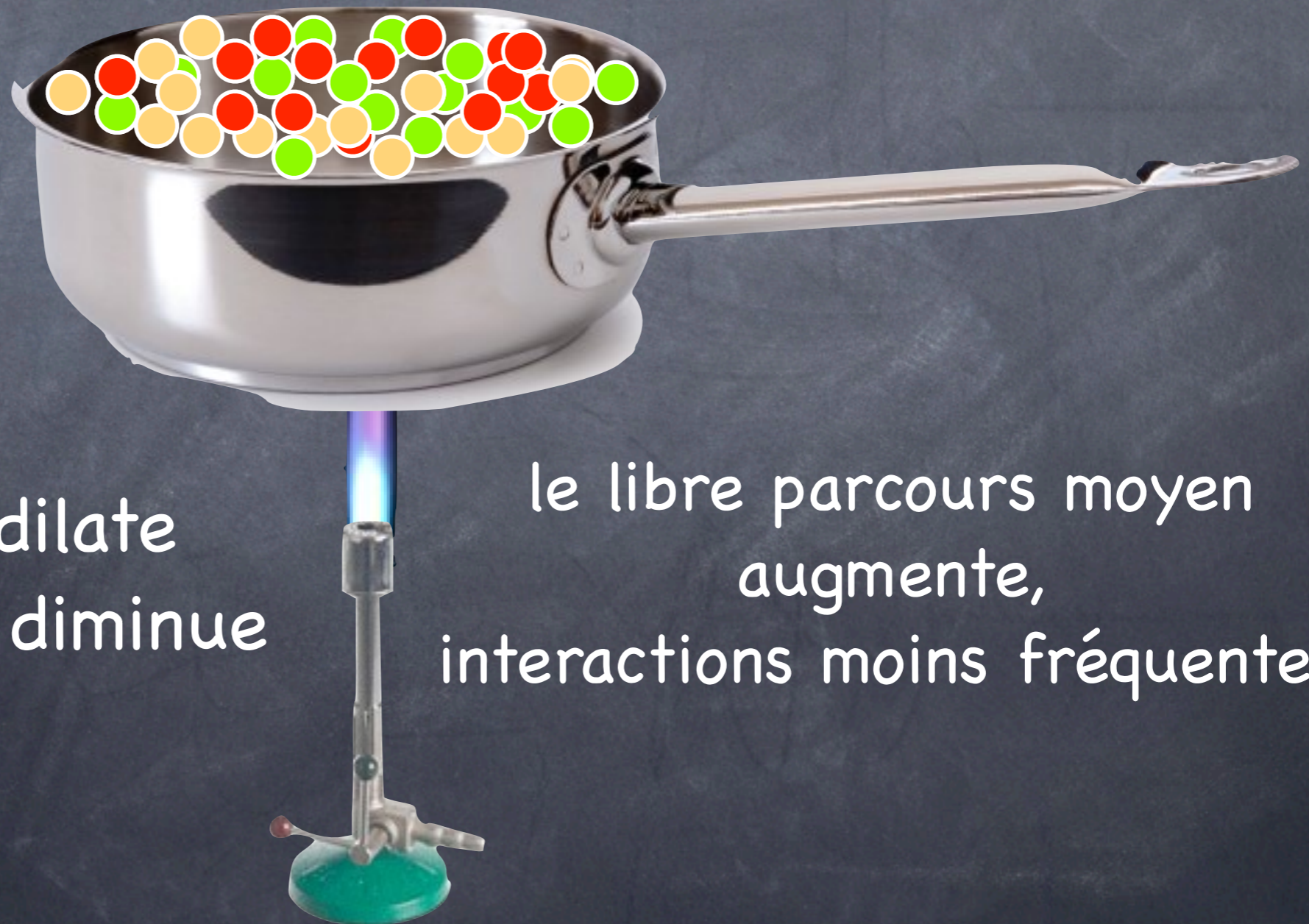
Le rayonnement fossile

2 critères :

proximité des ingrédients **taille de l'Univers**

température de la casserole **température de l'Univers**

- photons
- protons
- électrons



l'Univers se dilate
la température diminue

le libre parcours moyen
augmente,
interactions moins fréquentes

Le rayonnement fossile

2 critères :

proximité des ingrédients **taille de l'Univers**

température de la casserole **température de l'Univers**



- photons
- atomes neutres

sous une certaine température, les électrons forment des atomes d'hydrogène avec les protons : c'est la **recombinaison**, ou le **découplage**

Le rayonnement fossile

Le calcul montre que le découplage a eu lieu à

$$t_{\text{dec}} \sim 380\,000 \text{ ans}$$

$$z_{\text{dec}} \sim 1\,100$$

et que

$$T_{\text{dec}} \sim 3\,000 \text{ K}$$

or $T_0 = \frac{T}{1+z}$ donc

$$T_0 \sim 3 \text{ K}$$

Le rayonnement fossile

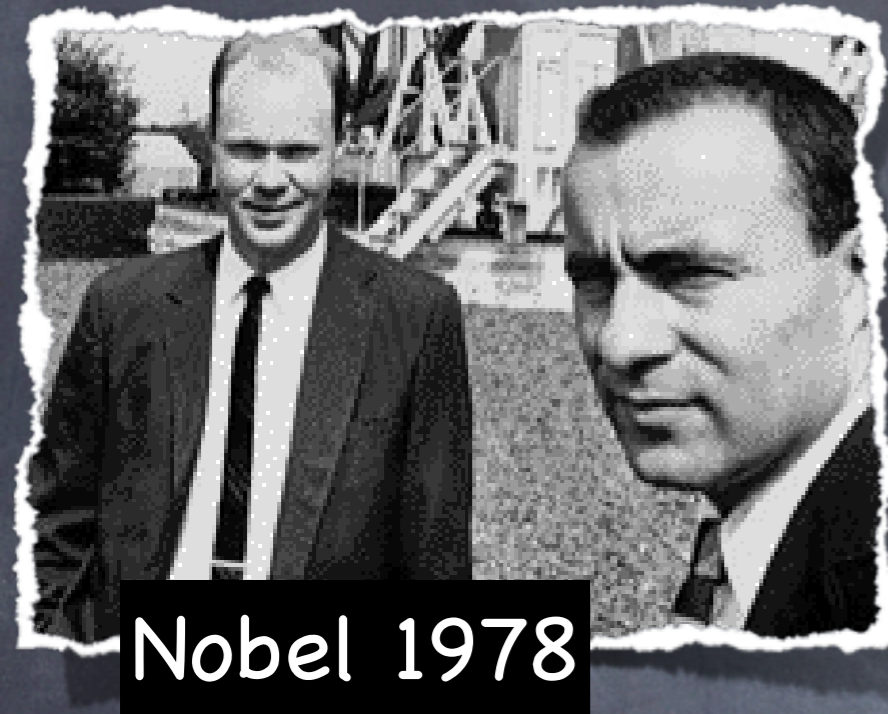
$$t_{\text{dec}} \sim 380\,000 \text{ ans}$$

si 14 milliards d'années = 80 ans
alors 380 000 ans = 19 heures
après la naissance !!!!

le rayonnement fossile nous donne
accès à la tendre enfance de l'Univers



Le rayonnement fossile : 1965



A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

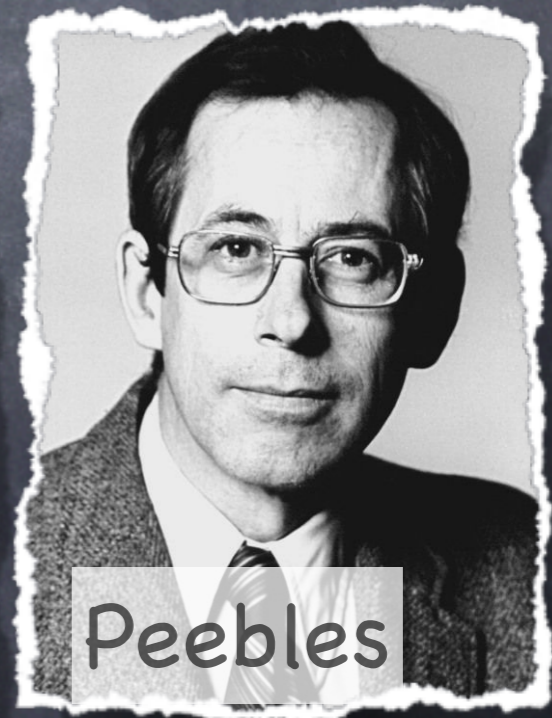
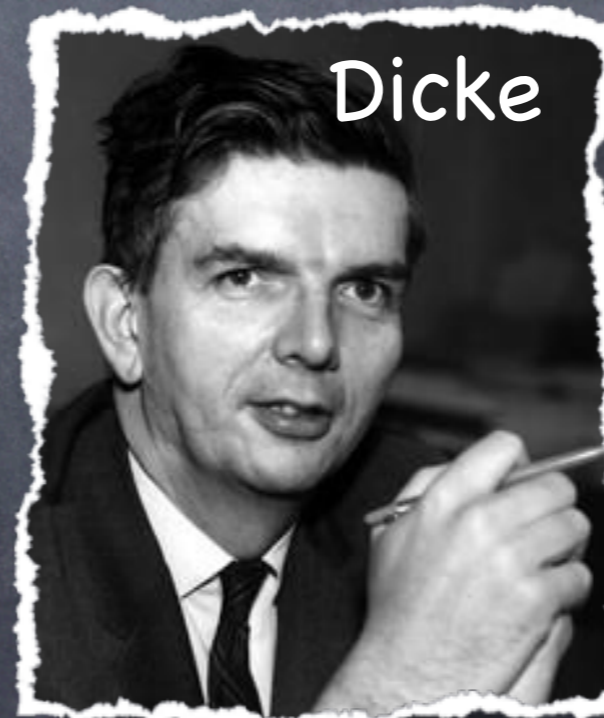
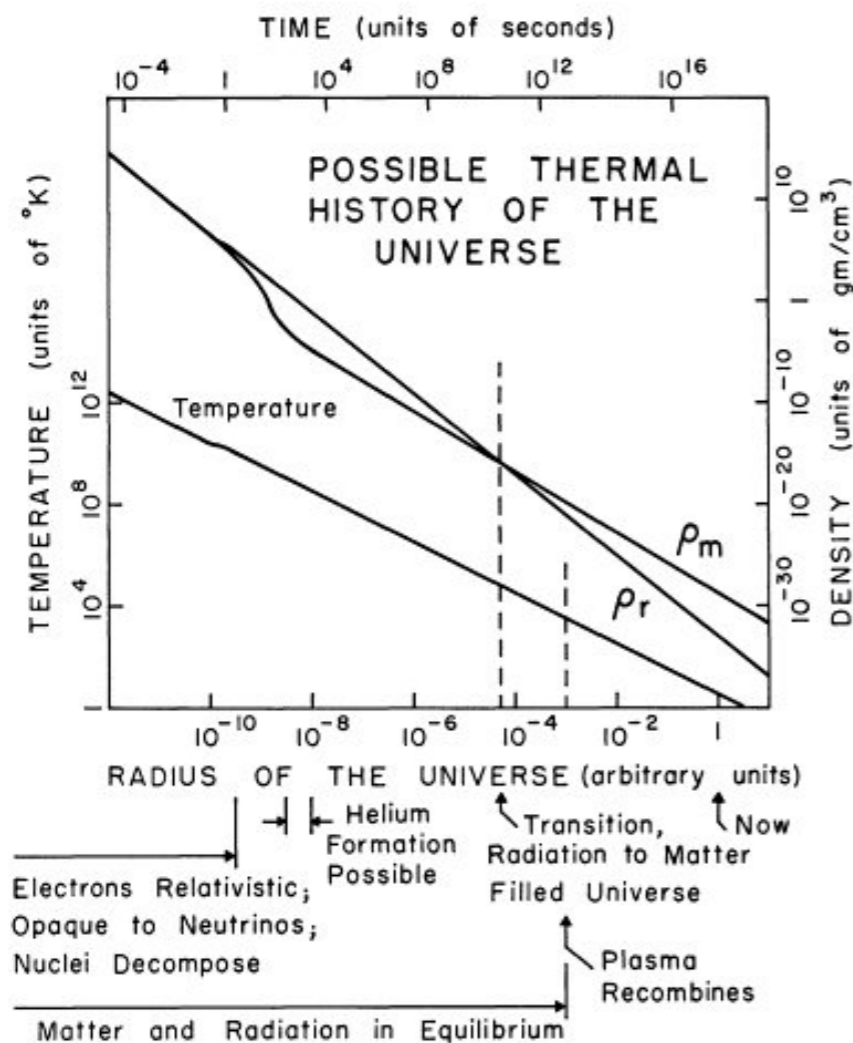
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5°K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

420

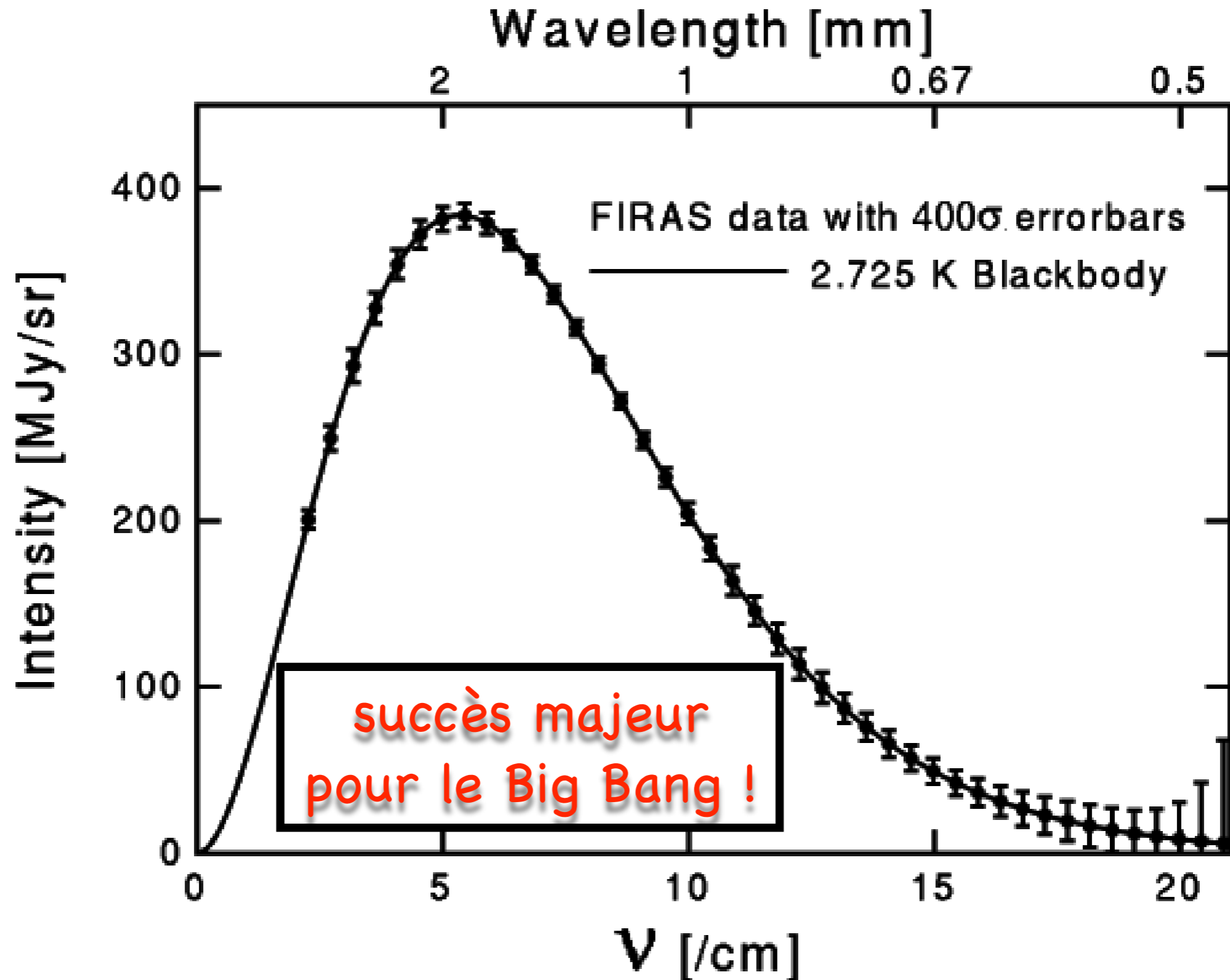
LETTERS TO THE EDITOR

Vol. 142

free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.



Le rayonnement fossile : COBE 1989-1992



1992

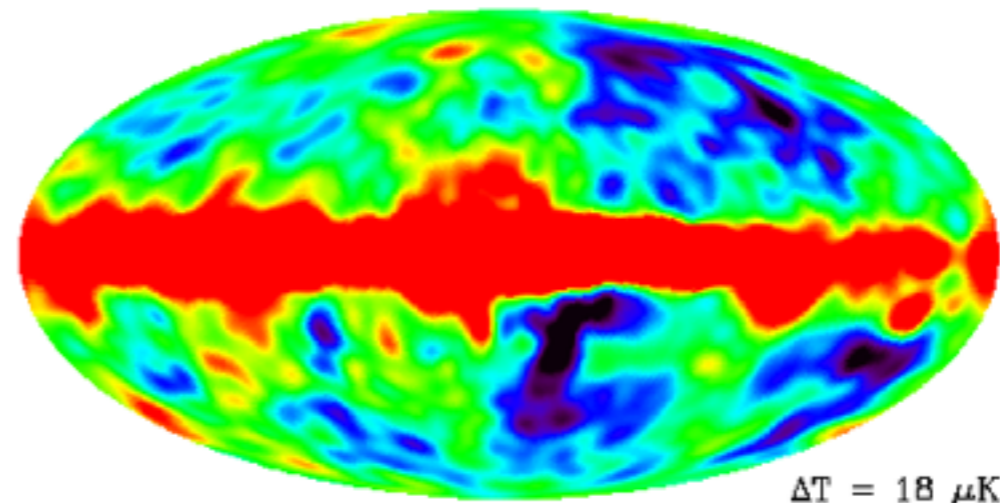
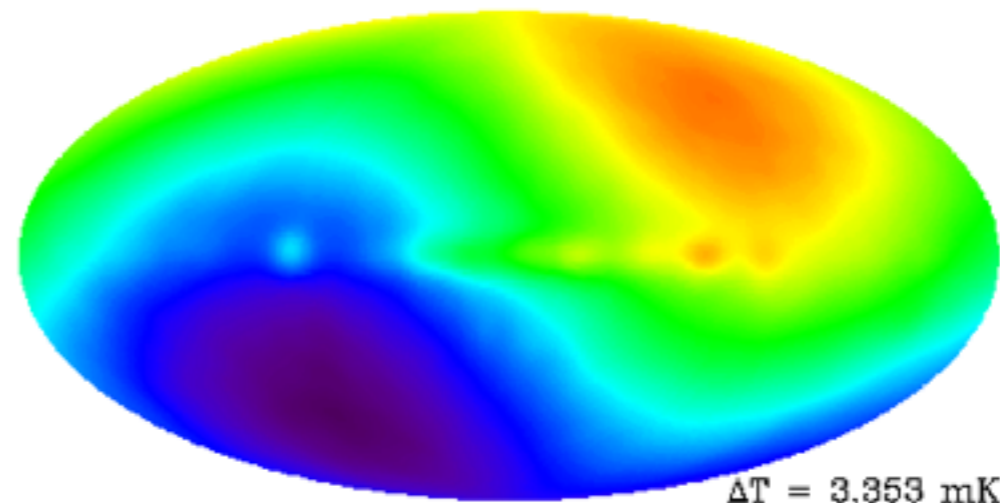
Le rayonnement fossile : COBE 1989-1992

principe
cosmologique
validé !

effet
Doppler

anisotropies ?

$$\frac{\Delta T}{T} \sim 1/100\,000$$



Les anisotropies du rayonnement fossile

fluctuations de température dans le rayonnement fossile dues à des fluctuations de densité qui formeront les amas, les galaxies, les étoiles...



Les anisotropies du rayonnement fossile

l'étude de la carte du ciel du rayonnement fossile nous renseignera sur les mécanismes qui en sont responsables

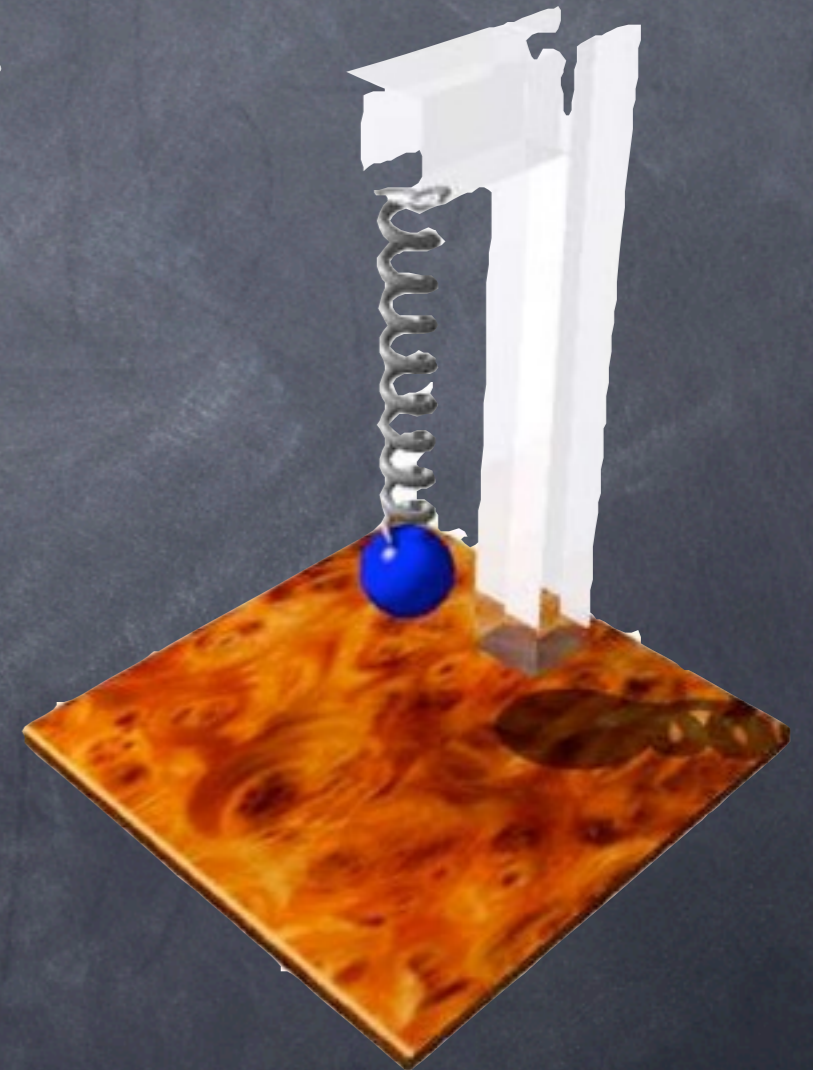


la lumière que nous recevons du soleil provient de sa **surface** exclusivement
l'étude de sa surface nous renseigne sur les mécanismes internes = **oscillations** dans notre cas !

Les anisotropies du rayonnement fossile

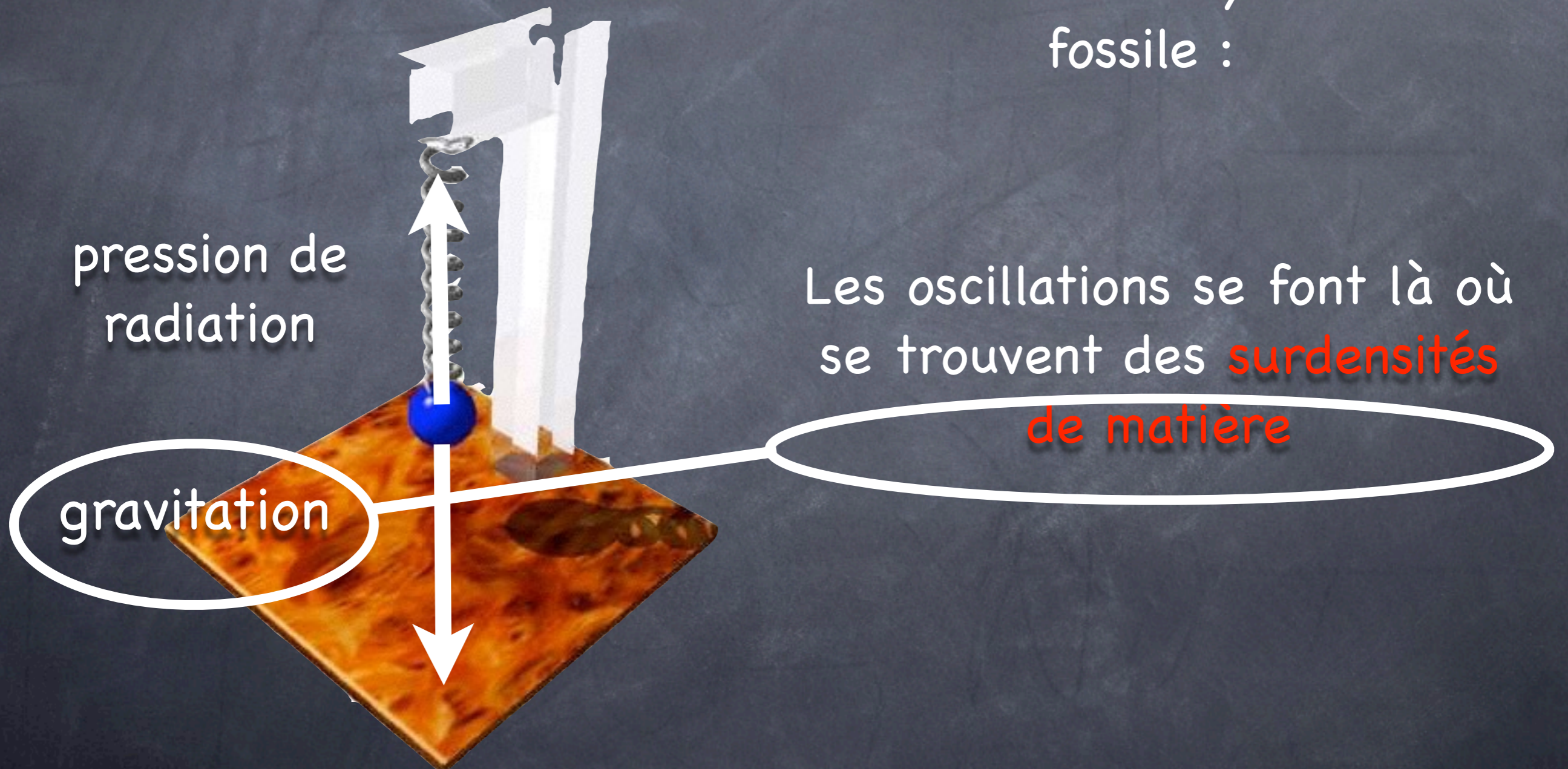
le fluide cosmique **oscille**

en physique du quotidien, une oscillation a lieu quand apparaissent deux forces opposées, par exemple :

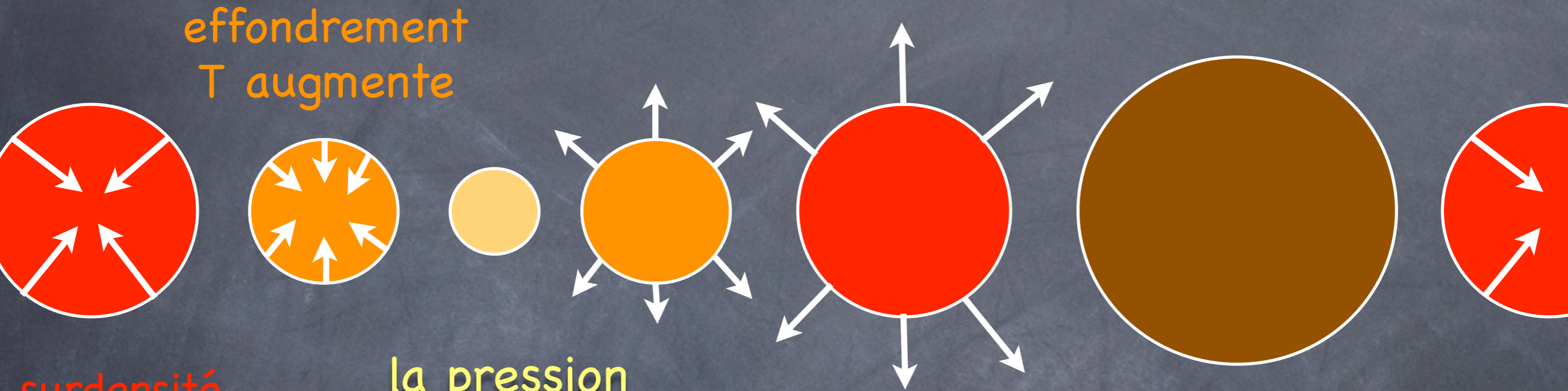


Les anisotropies du rayonnement fossile

dans le cas du rayonnement fossile :

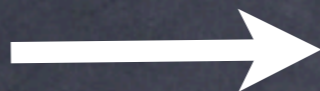


Les anisotropies du rayonnement fossile



T a suffisamment
diminué
pour que la gravitation
l'emporte à nouveau

mécanisme possible
jusqu'au découplage



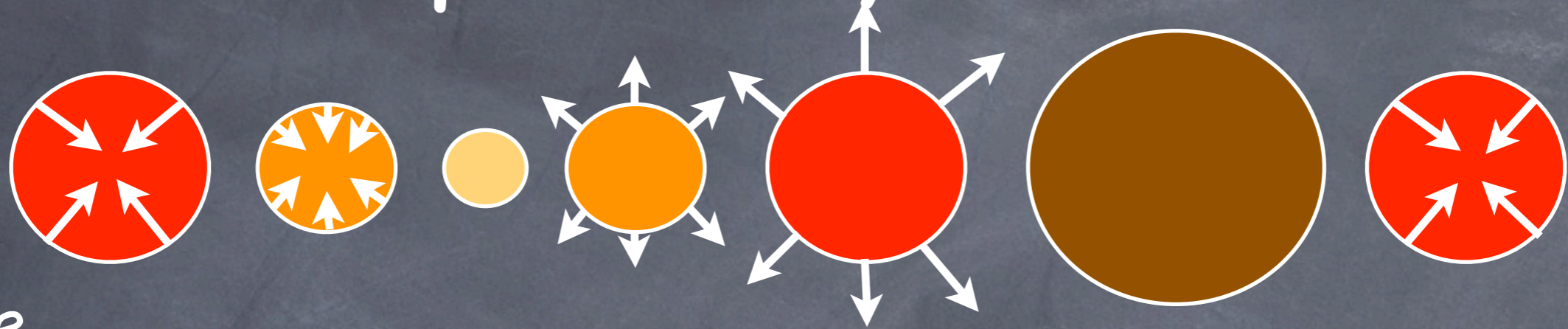
après le découplage, rien
n'empêche l'effondrement

Les anisotropies du rayonnement fossile

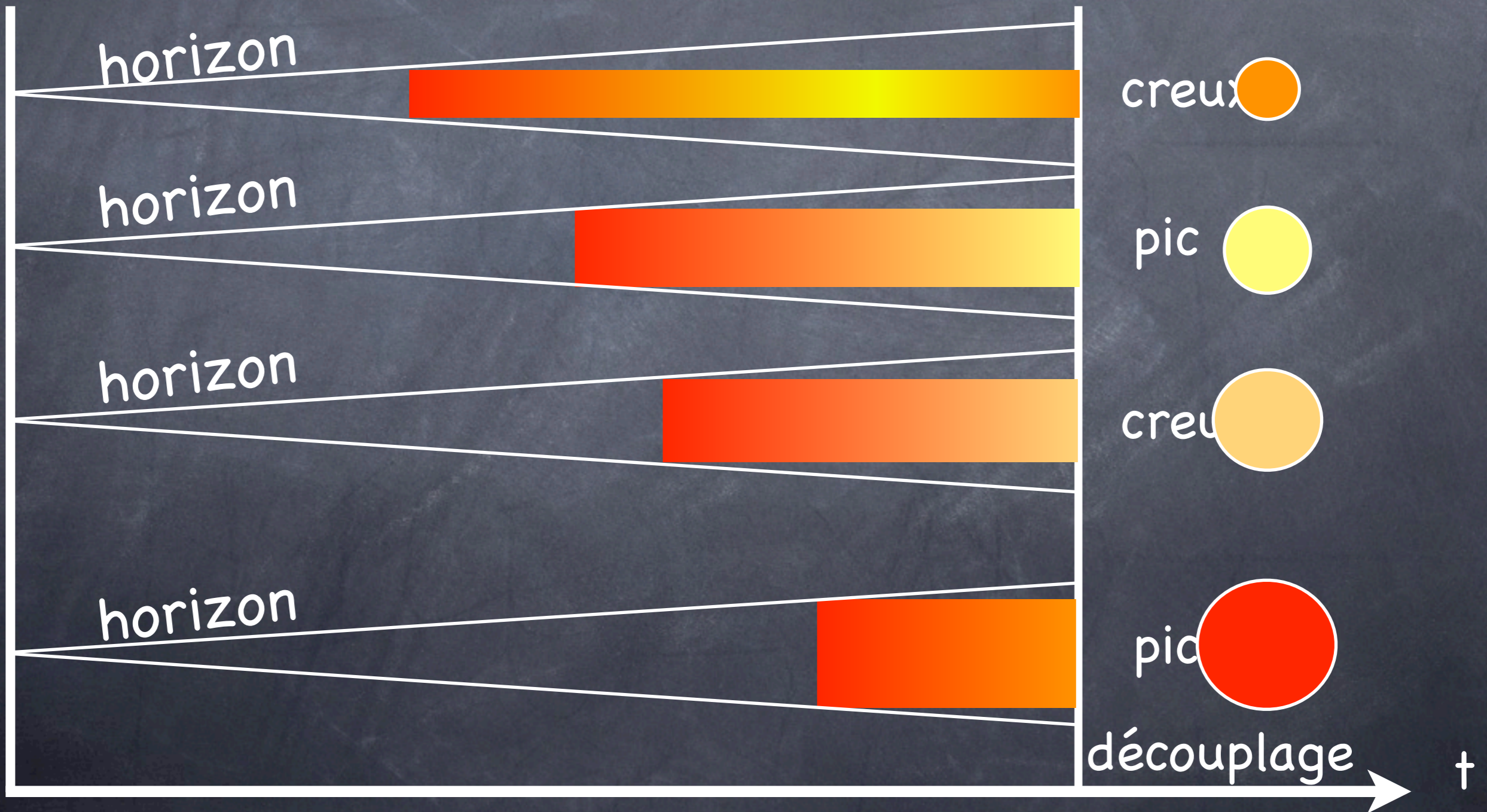
subtilités :

- ces oscillations se font **en phase** pour des oscillations de même taille
- les oscillations ne sont possibles que lorsque que la **taille de la perturbation est plus petite que l'horizon**

Les anisotropies du rayonnement fossile



espace



Bilan sur les anisotropies

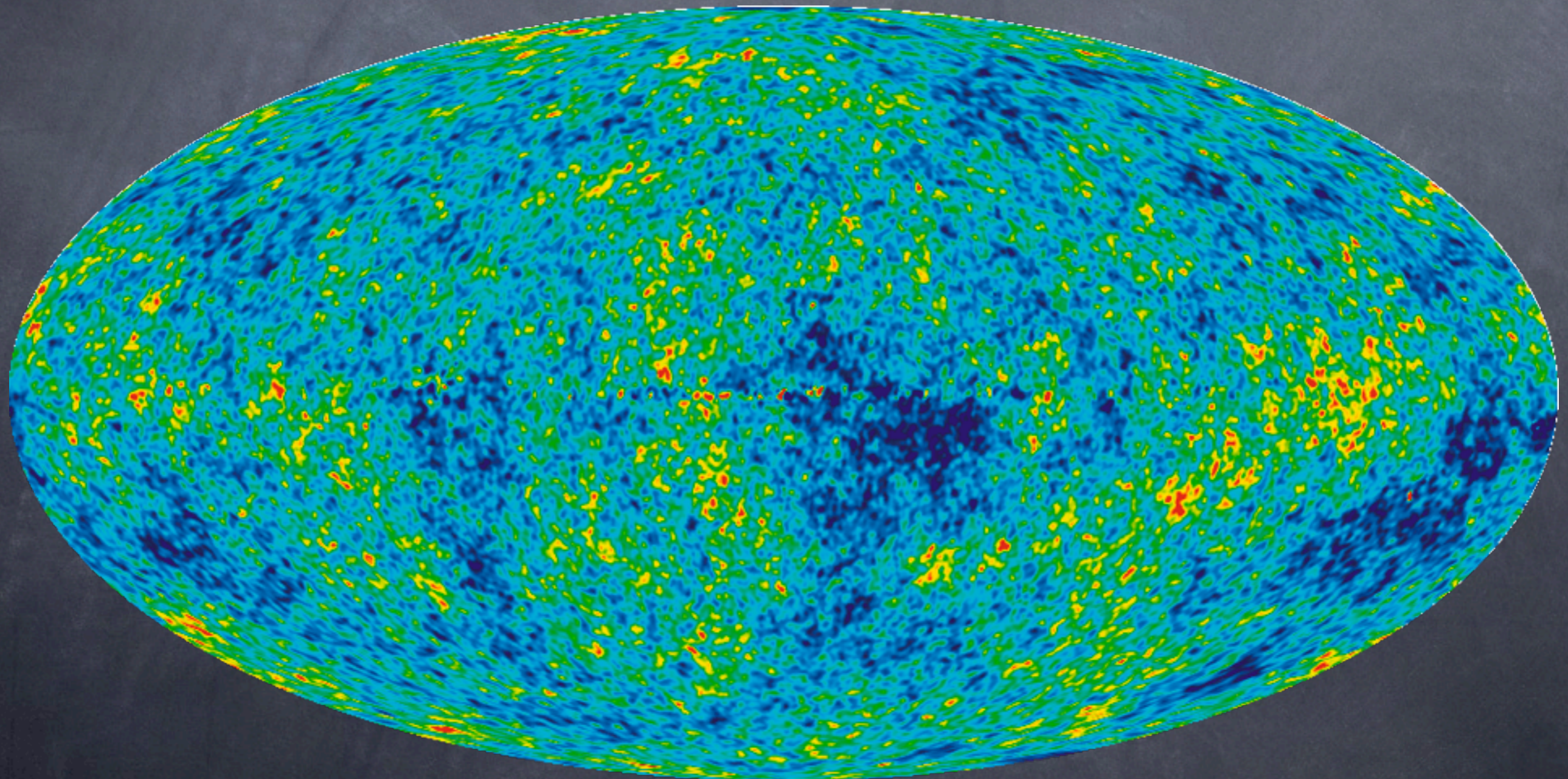
le fluide cosmique devient transparent à la lumière
380 000 ans après le Big-Bang

ce fluide n'est pas homogène, il contient des
grumeaux qui vont osciller sous l'effet de la
gravitation et de la pression

ces fluctuations de densité vont se voir dans des
fluctuations de température du rayonnement fossile
qui devront aussi présenter des pics et des creux

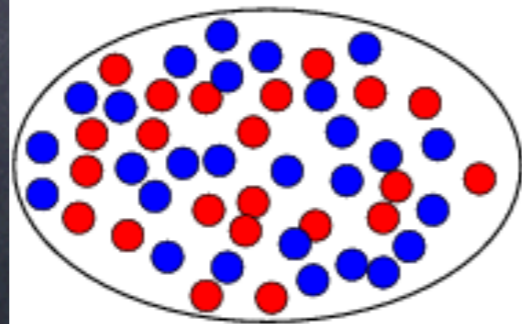
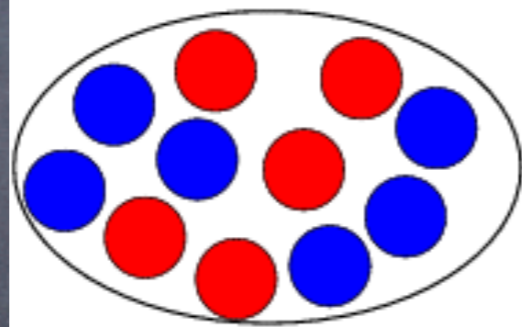
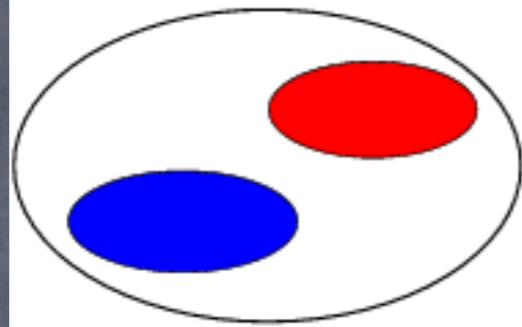
Les anisotropies du rayonnement fossile

Carte de WMAP en 2008 (45 ans de données)

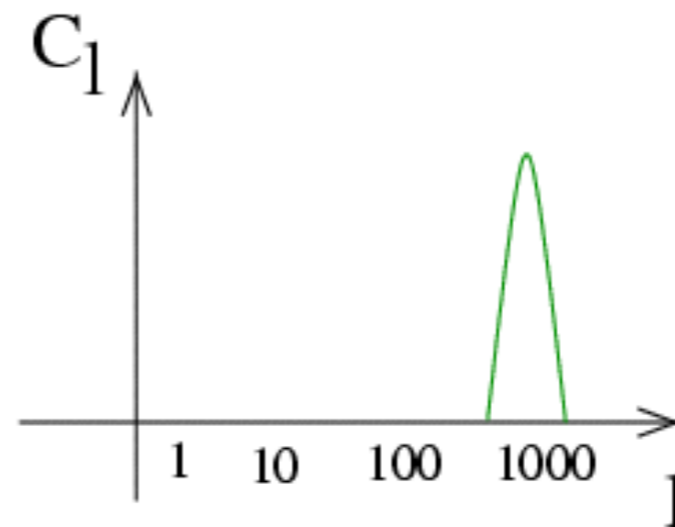
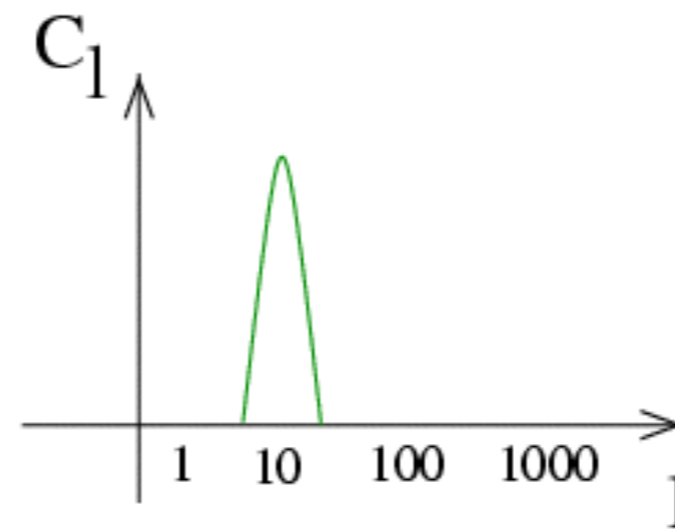
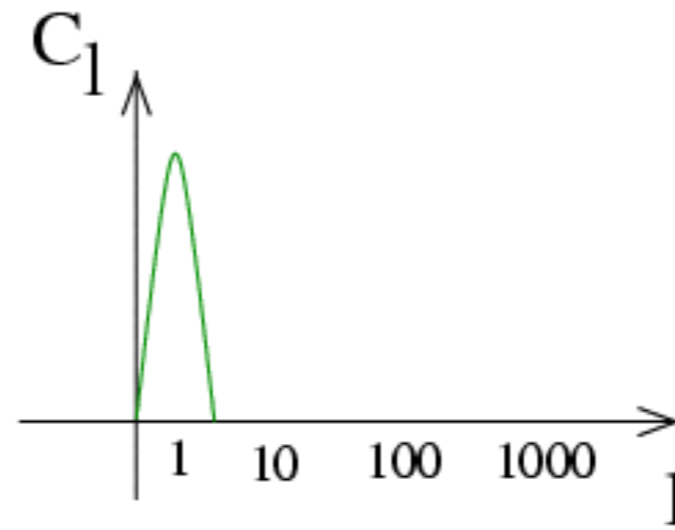


Les anisotropies du rayonnement fossile

Cartes

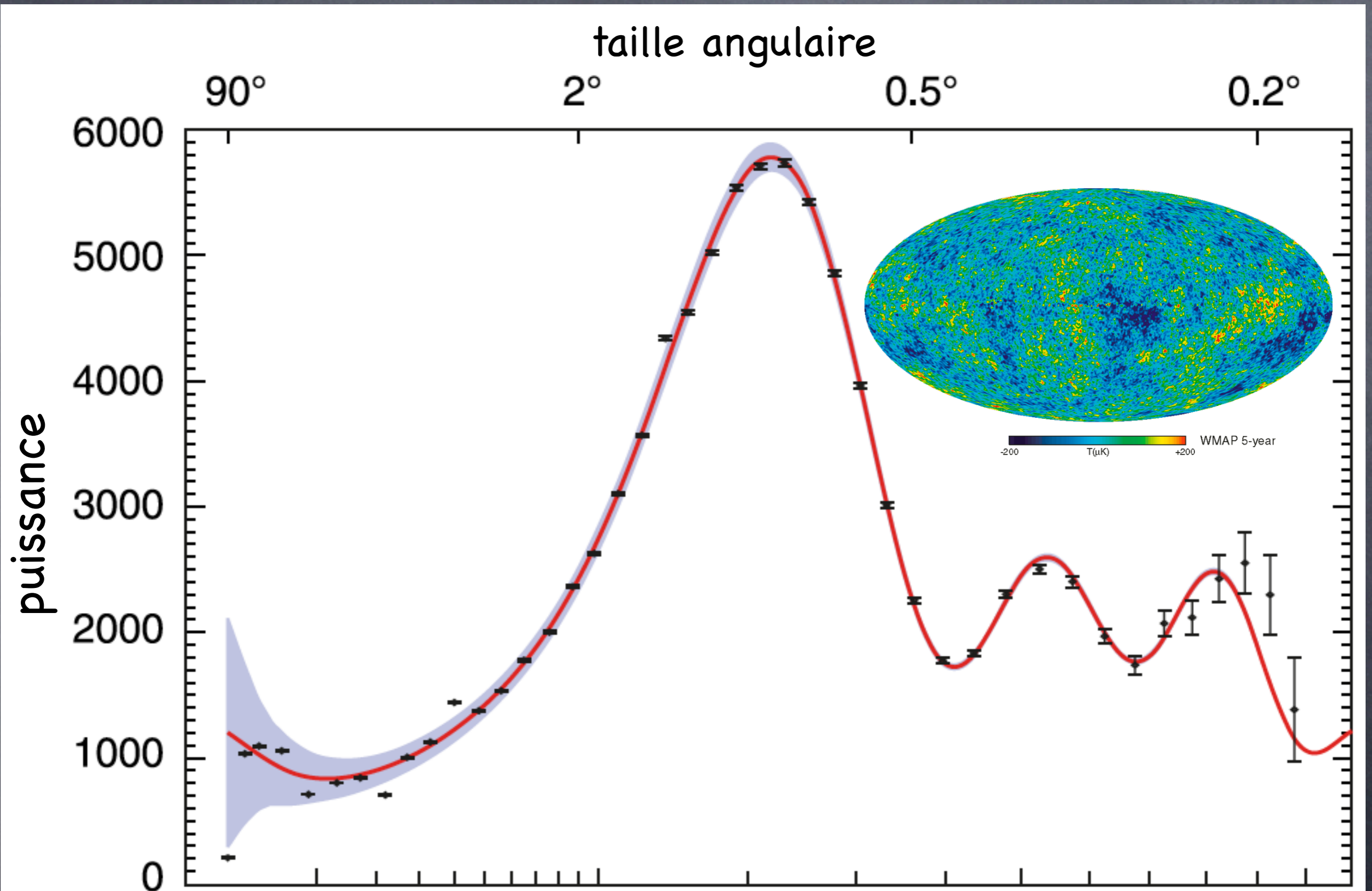


Spectres



comptage des
structures
selon leur
taille

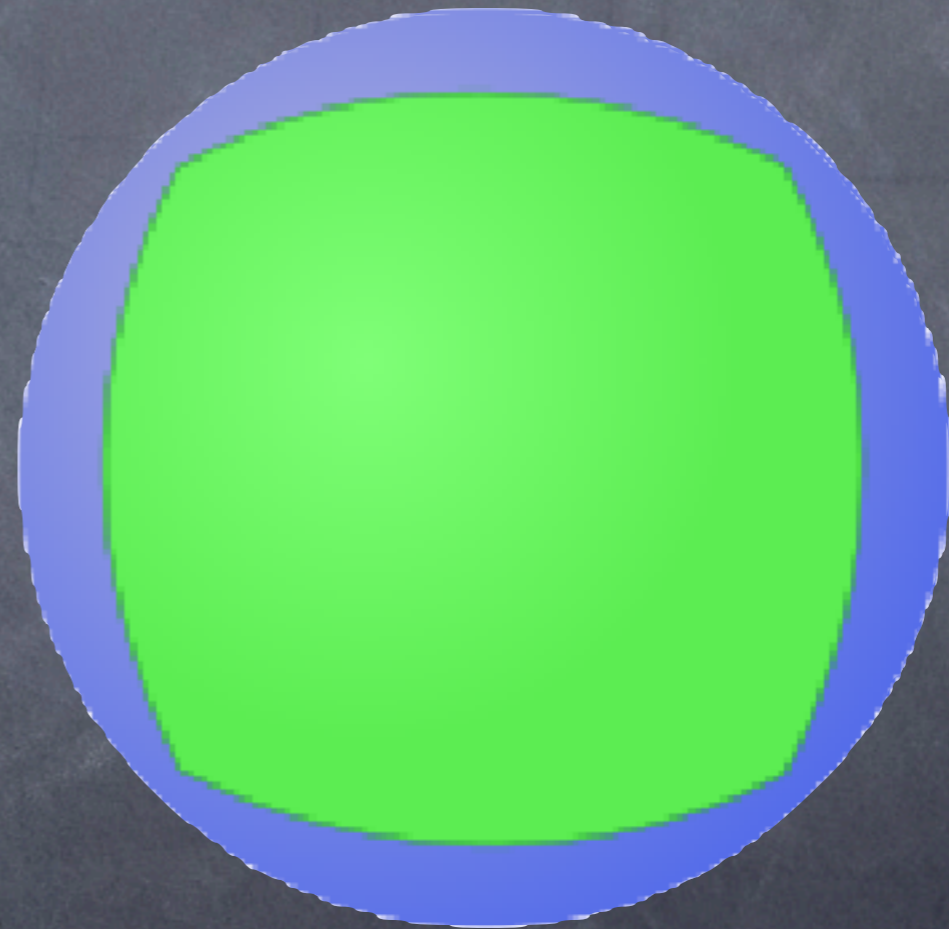
Les anisotropies du rayonnement fossile



Les anisotropies du rayonnement fossile

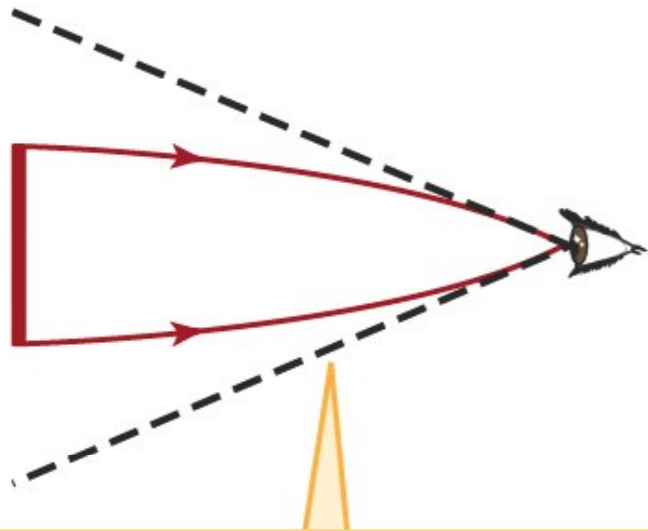
redshift de 1100 : très grande distance, possibilité de
sonder la courbure de l'Univers

on ne se rend pas
compte de la
courbure de la Terre
sur quelques mètres

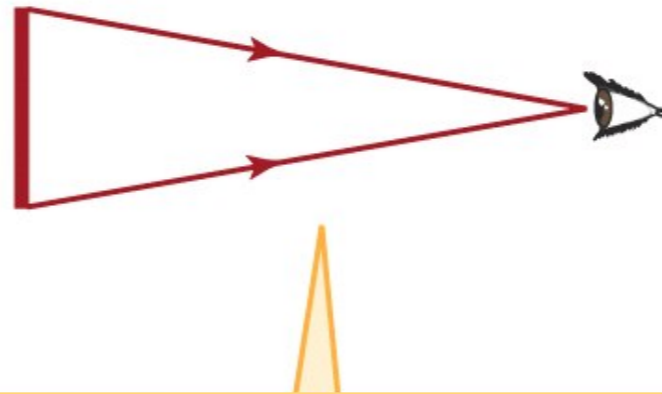


sonder la courbure : sensibilité à $\frac{\Omega_m + \Omega_\Lambda}{(\Omega_\kappa + 1)}$

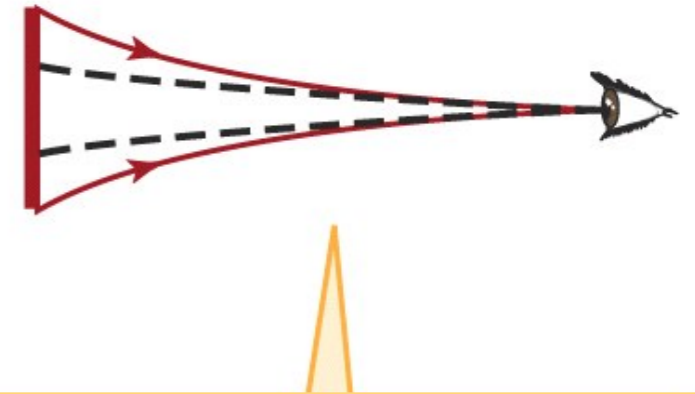
Les anisotropies du rayonnement fossile



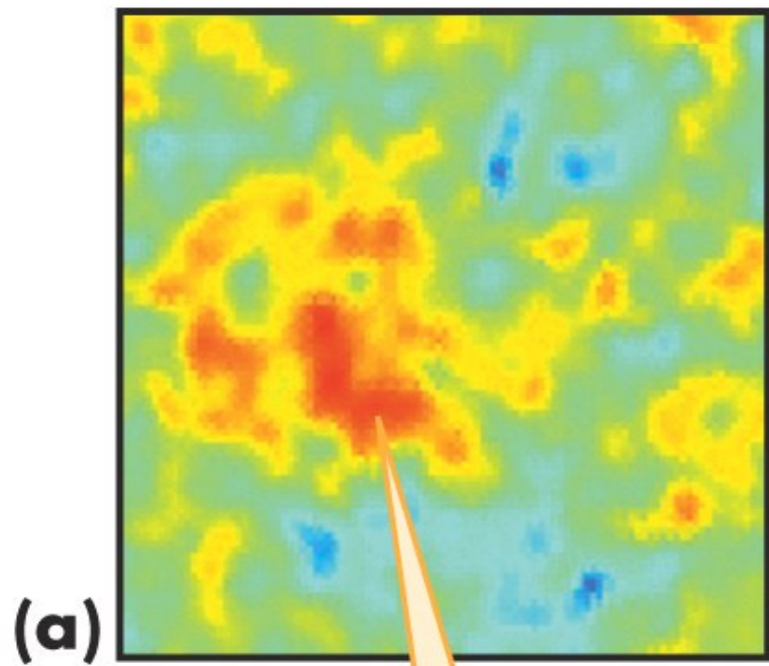
univers fermé : les rayons lumineux sont "bombés", élargis...



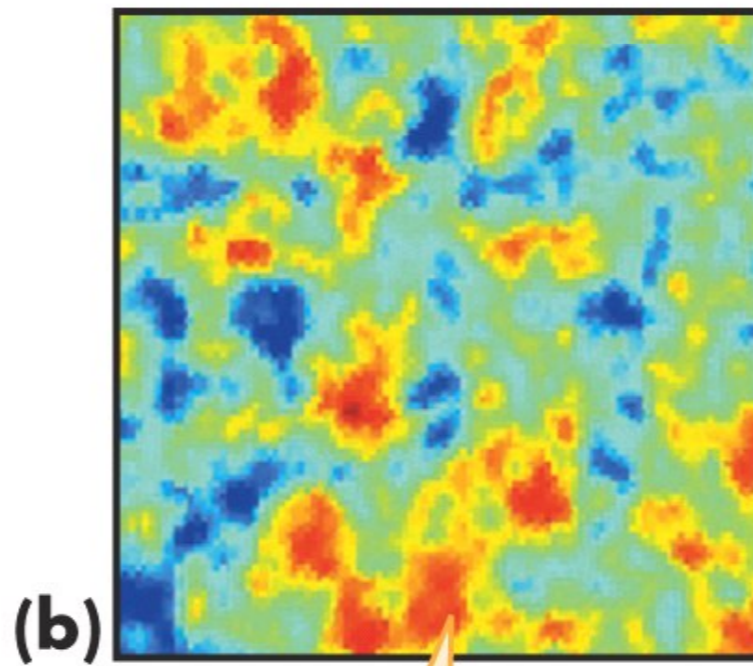
univers plat : les rayons lumineux ne sont pas déformés...



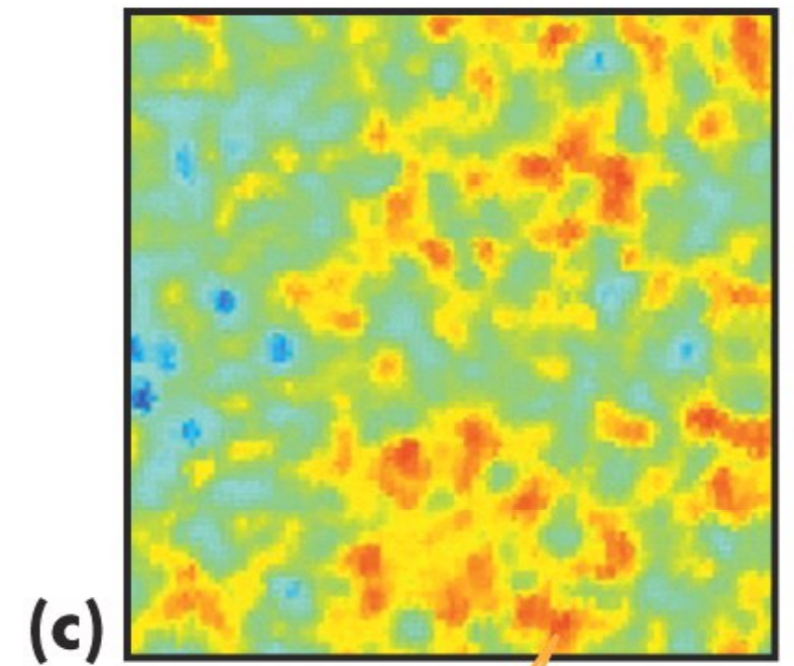
univers ouvert : les rayons lumineux sont amincis...



les structures paraissent plus grandes

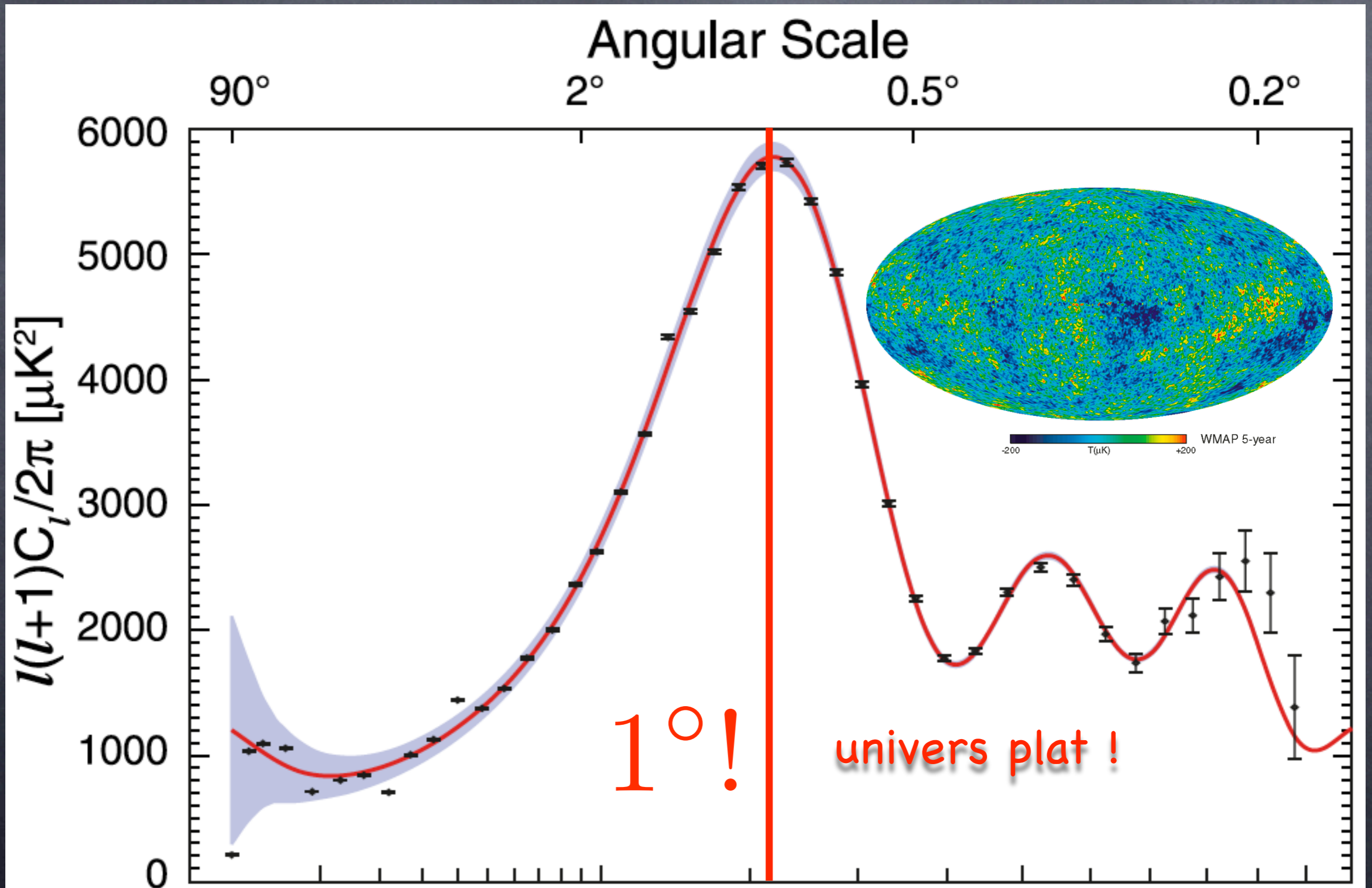


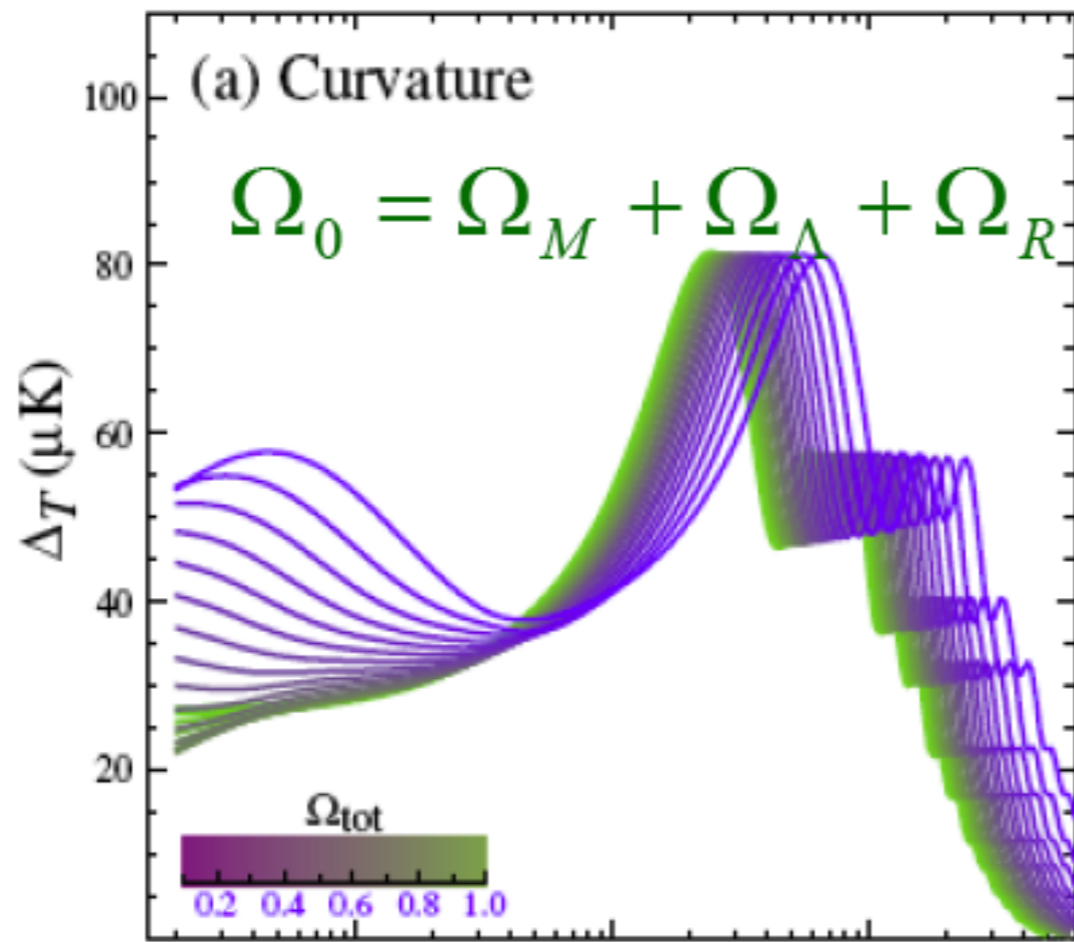
les structures sont vues avec leur taille réelle



les structures paraissent plus petites

Les anisotropies du rayonnement fossile





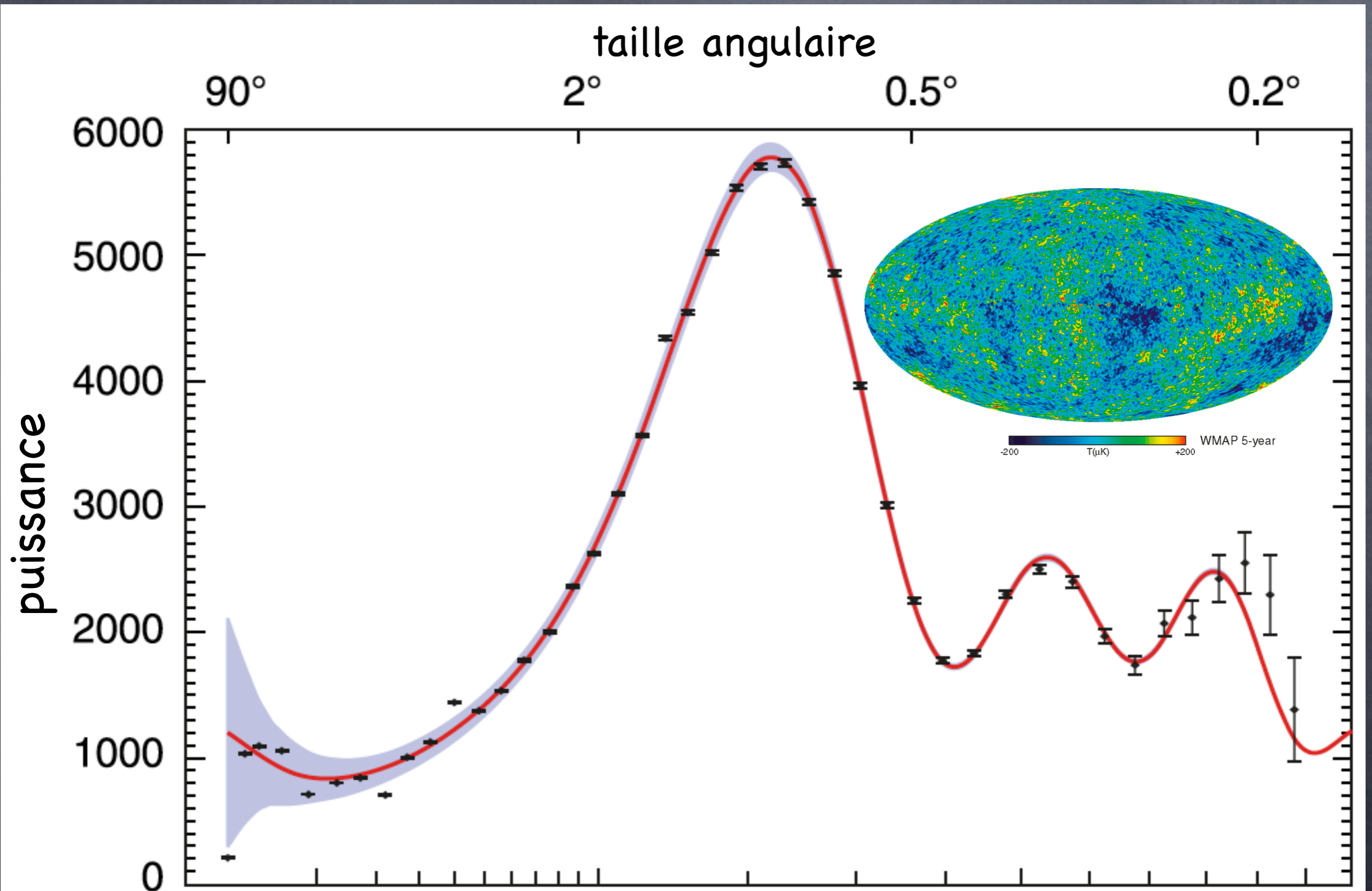
Les anisotropies du rayonnement fossile

Le spectre de puissance angulaire dépend fortement des paramètres cosmologiques !

idée : faire varier les paramètres de façon à être le plus proche possible des données, cela donne :

t_0	13.69 ± 0.13 Gyr	13.72 ± 0.12 Gyr
H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.5 ± 1.3 km/s/Mpc
Ω_b	0.0441 ± 0.0030	0.0456 ± 0.0015
$\Omega_b h^2$	0.02273 ± 0.00062	$0.02267^{+0.00058}_{-0.00059}$
Ω_c	0.214 ± 0.027	0.228 ± 0.013
$\Omega_c h^2$	0.1099 ± 0.0062	0.1131 ± 0.0034
Ω_Λ	0.742 ± 0.030	0.726 ± 0.015

Les anisotropies du rayonnement fossile



Les anisotropies du rayonnement fossile

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$$\Omega_{\text{matière}} = \Omega_c + \Omega_b \sim 0.25$$

Ω_Λ
matière noire!
86 % !!

énergie noire ! (74 %)

matière usuelle (visible,
étoiles, galaxies, planètes...)

Les limites du Big Bang

Ω_{Λ} énergie noire ! (74 %)

expansion **accélérée** !

nature de la matière noire

platitude de l'Univers : **coïncidence extraordinaire** !

le rayonnement fossile est uniforme sur toute
la sphère céleste : **incompréhensible** !

Les limites du Big Bang

la platitude

$\Omega_m + \Omega_\Lambda > 1$	fermé	Big-Crunch !
$\Omega_m + \Omega_\Lambda < 1$	ouvert (exponentiel)	expansion éternelle
$\Omega_m + \Omega_\Lambda = 1$	ouvert (courbure nulle)	expansion éternelle

très instable !

mais c'est ce que nous observons !

Les limites du Big Bang

la platitude

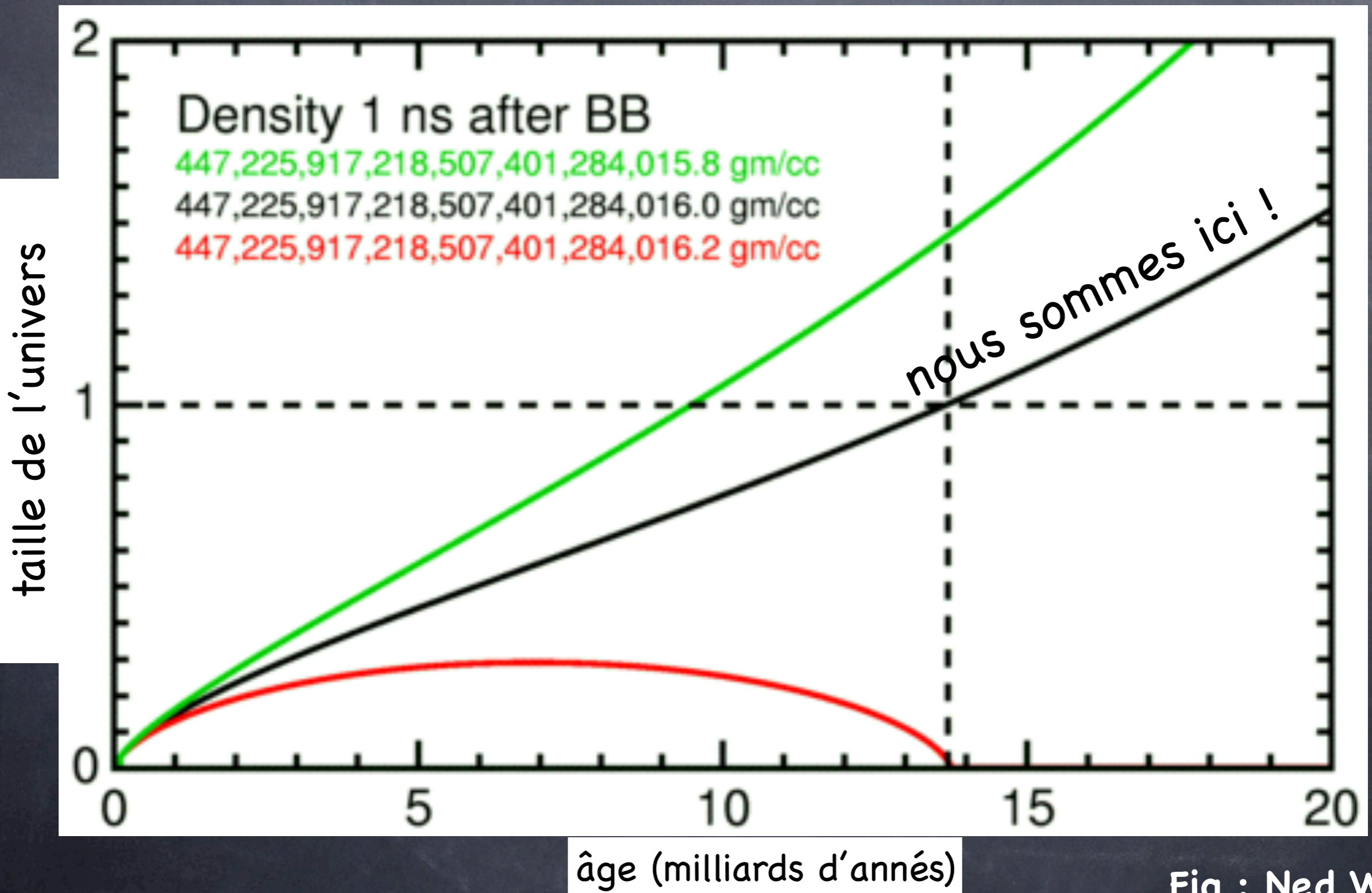
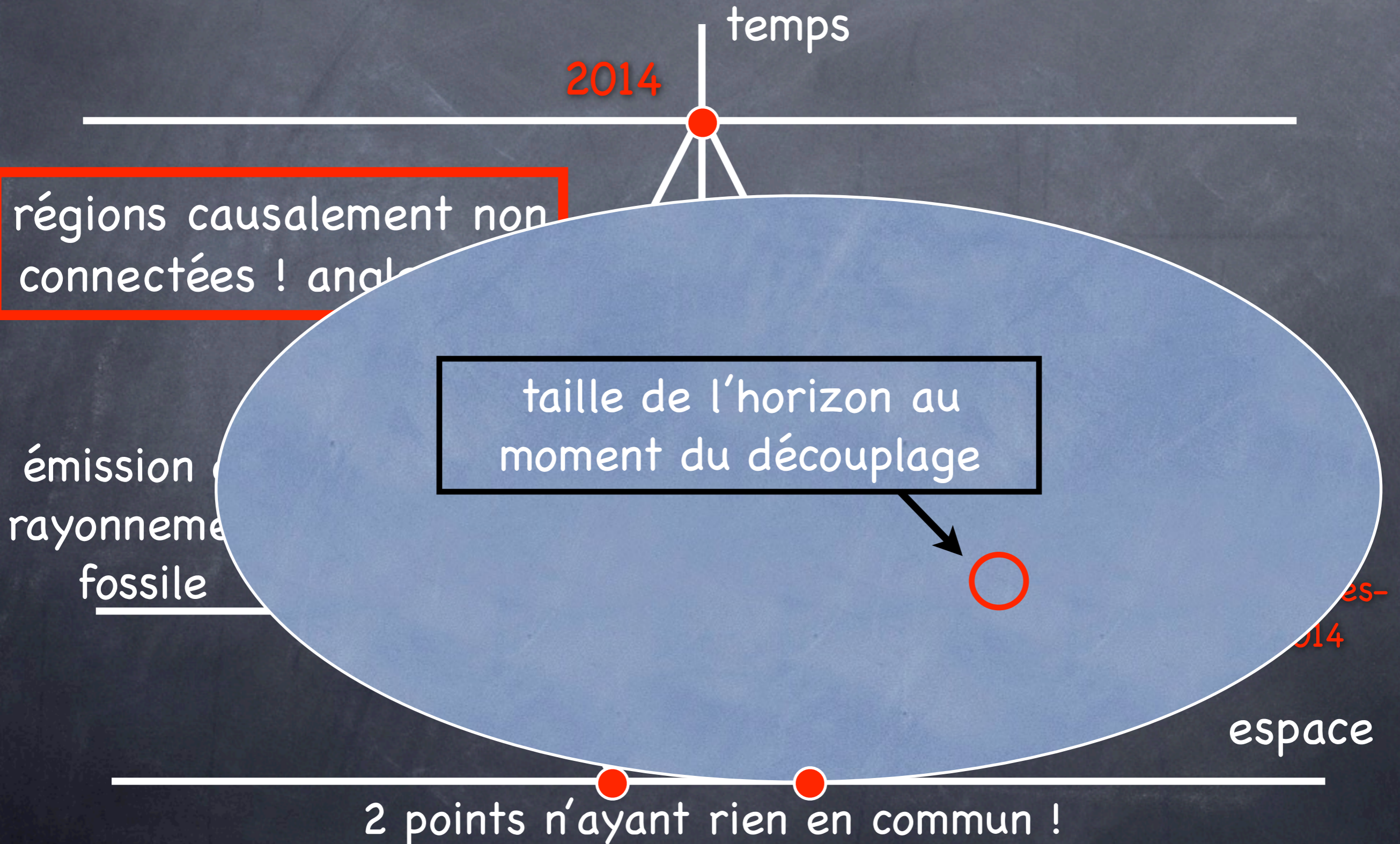


Fig : Ned Wright

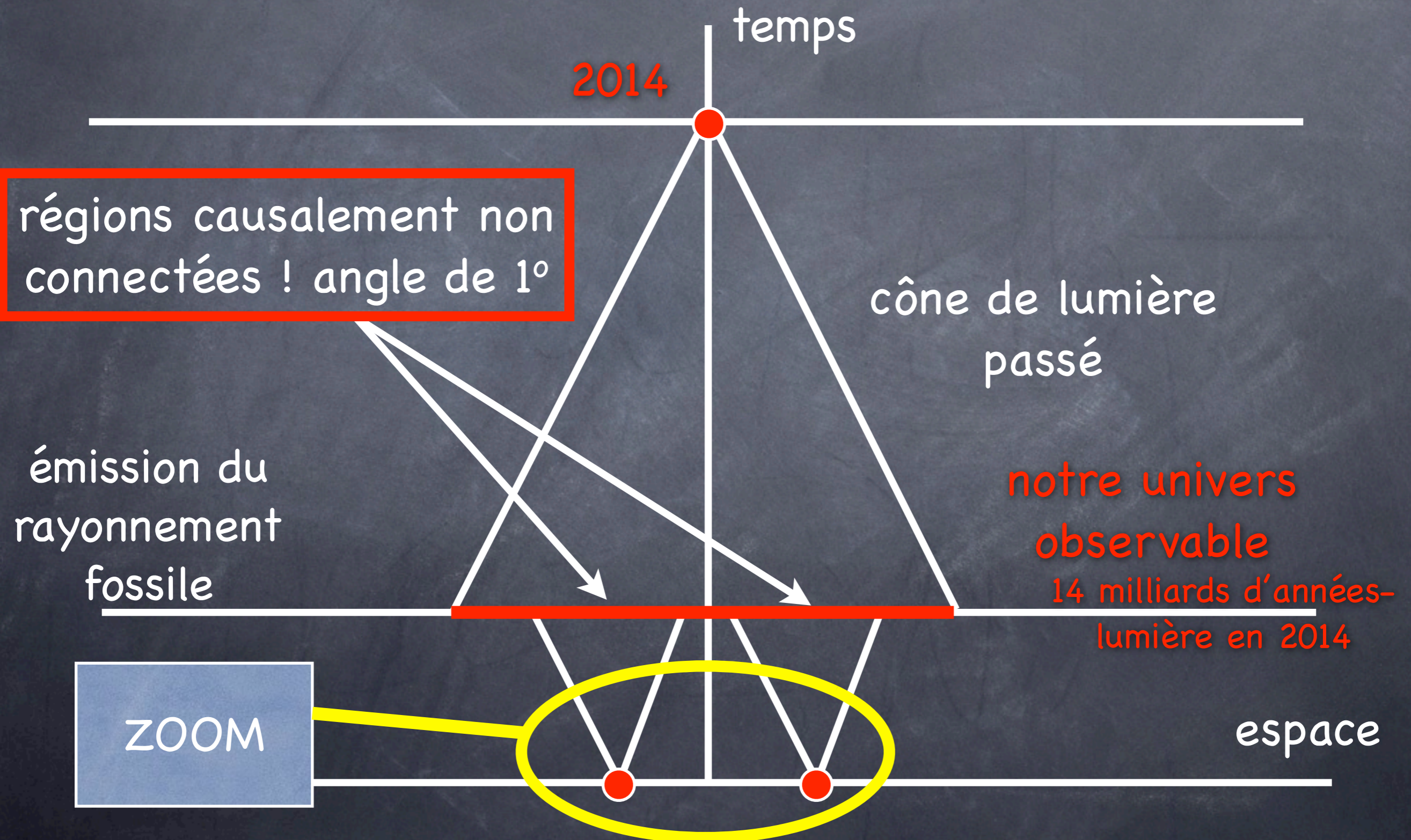
Les limites du Big Bang

uniformité du rayonnement fossile



Une solution élégante : l'inflation

uniformité du rayonnement fossile



Une solution élégante : l'inflation

uniformité du rayonnement fossile

émission du
rayonnement
fossile

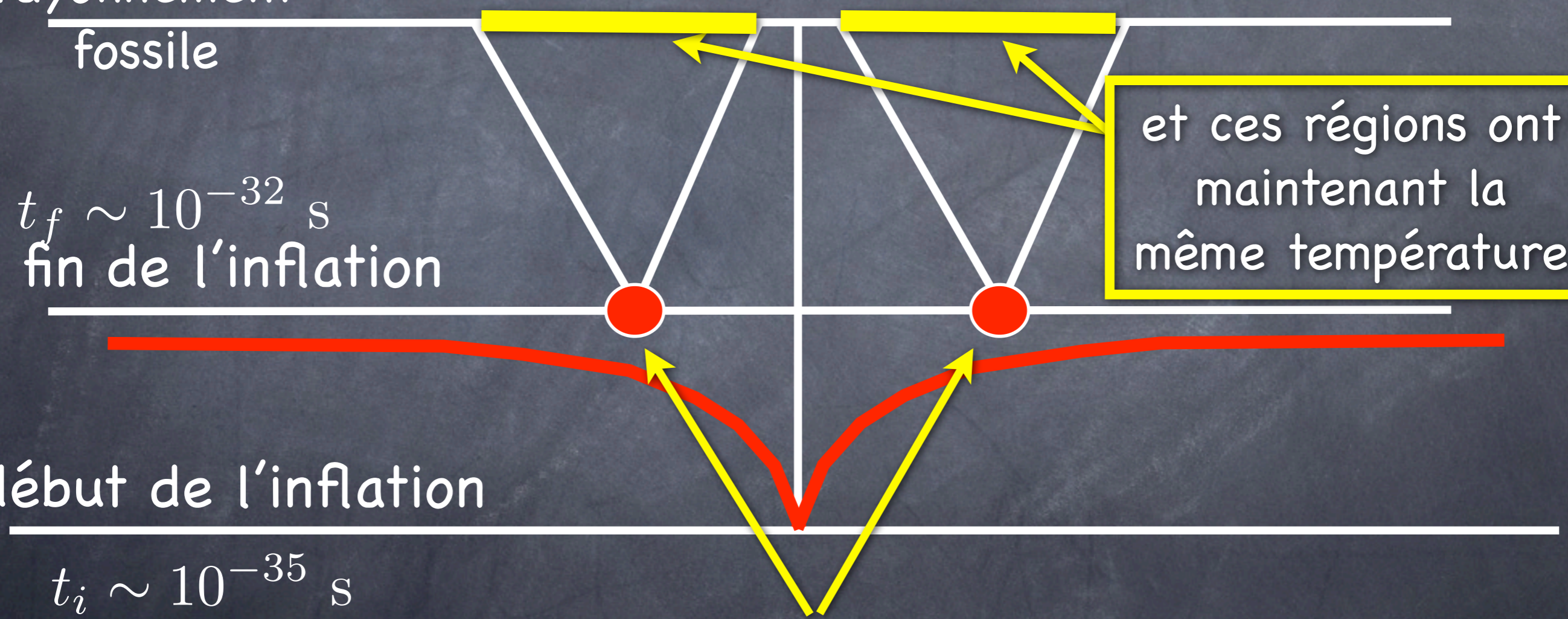
$t_f \sim 10^{-32}$ s
fin de l'inflation

début de l'inflation

$t_i \sim 10^{-35}$ s

et ces régions ont
maintenant la
même température

ces 2 événements sont maintenant
causalement connectés !



Une solution élégante : l'inflation

L'inflation fait maintenant partie intégrante du modèle standard de la cosmologie car :

- elle est **prédite** par la physique des particules
- elle **résoud les problèmes** de la platitude, de l'horizon et des fluctuations primordiales (non abordé ici)

mais.....

S-dimensional assisted inflation
assisted brane inflation
anomaly-induced inflation
assisted inflation
assisted chaotic 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
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
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
Hagedorn inflation
higher-curvature inflation
hybrid inflation
hyperextended inflation
induced gravity inflation
intermediate inflation
inverted hybrid inflation
isocurvature inflation.....

Une solution élégante : l'inflation

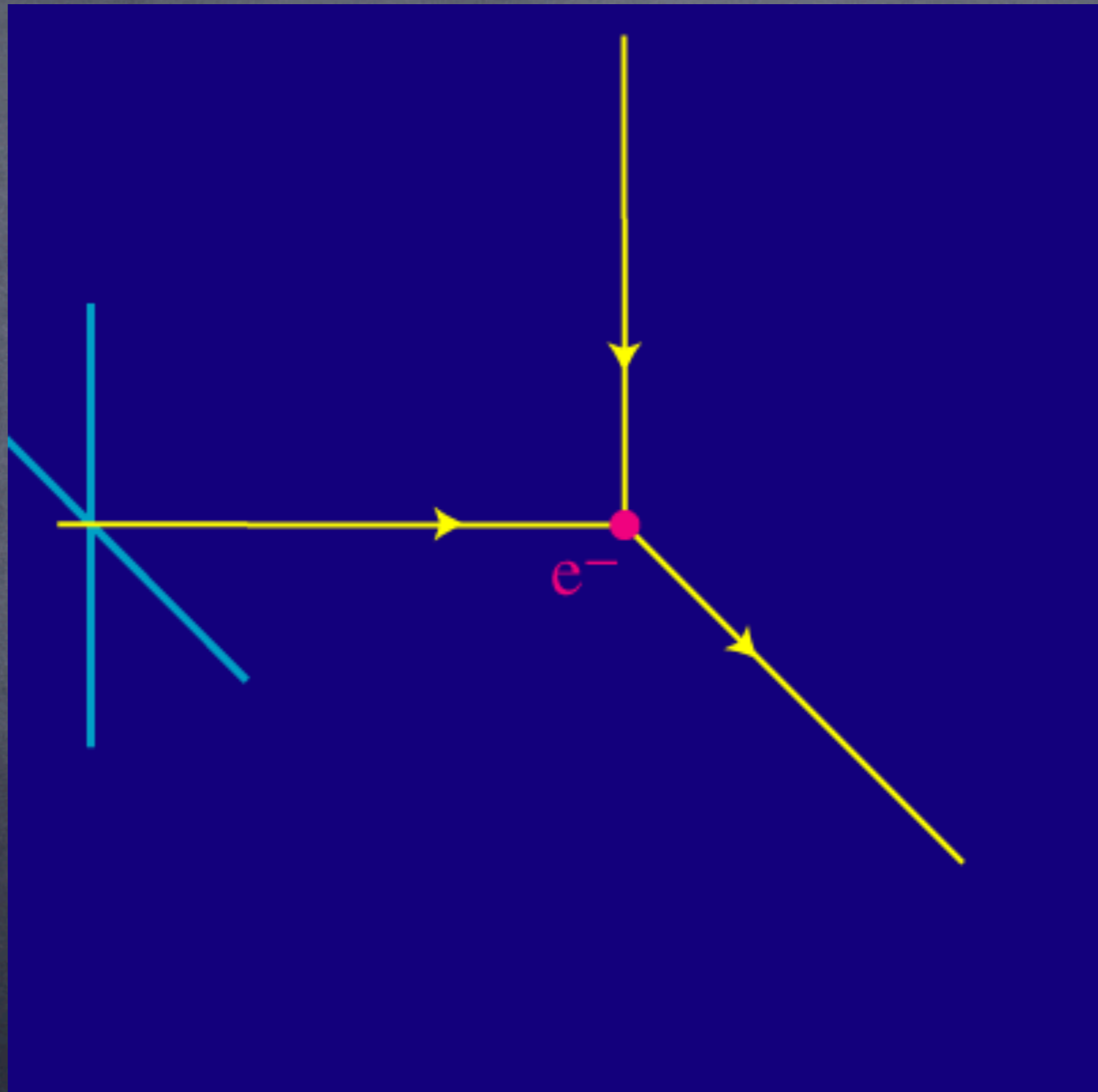
Pour bien contraindre l'inflation et déterminer la nature de l'énergie noire, il faudrait :

- des mesures plus **précises**,
- à des **échelles angulaires encore plus petites**

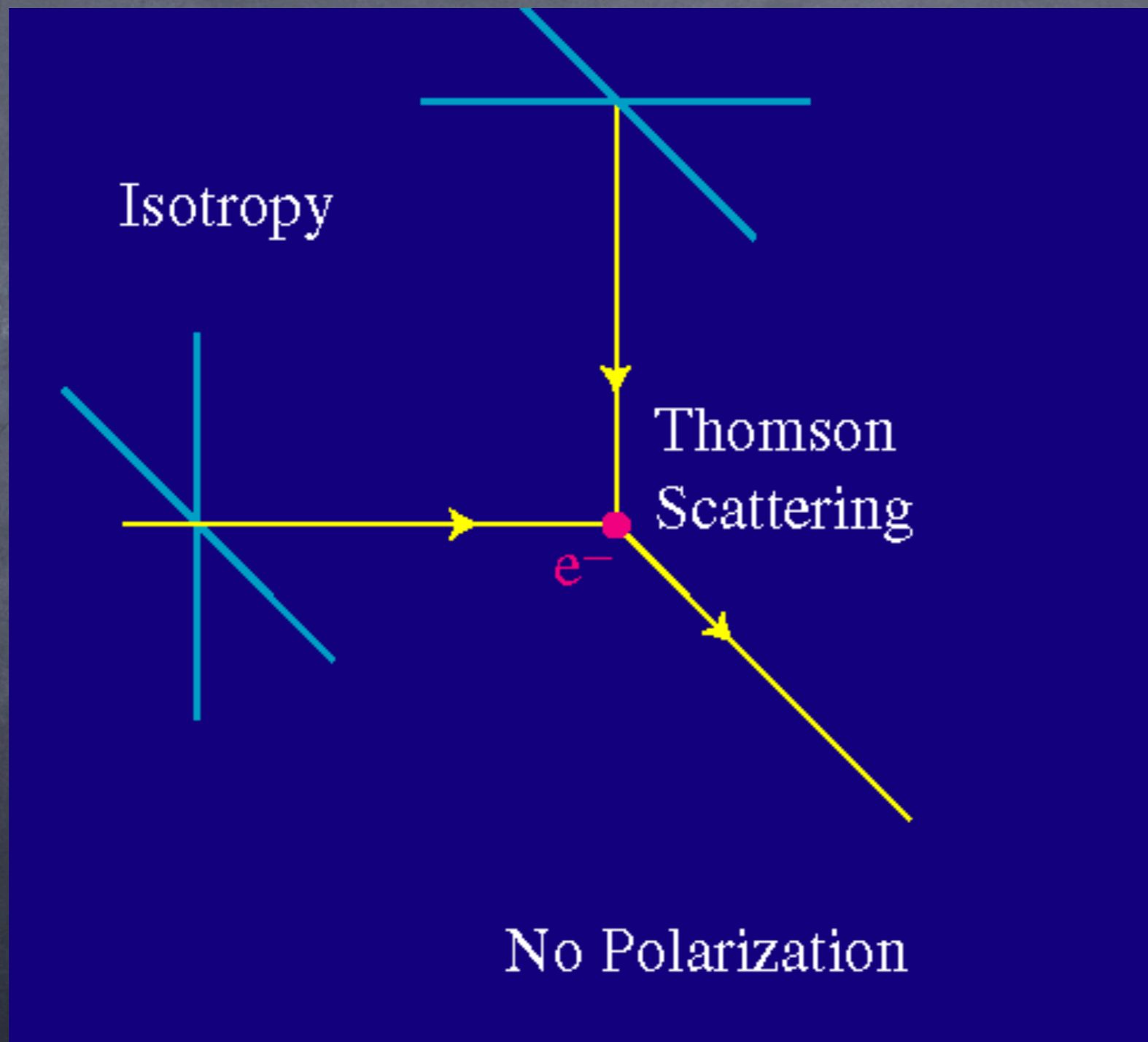
et mesurer la **polarisation** du rayonnement fossile



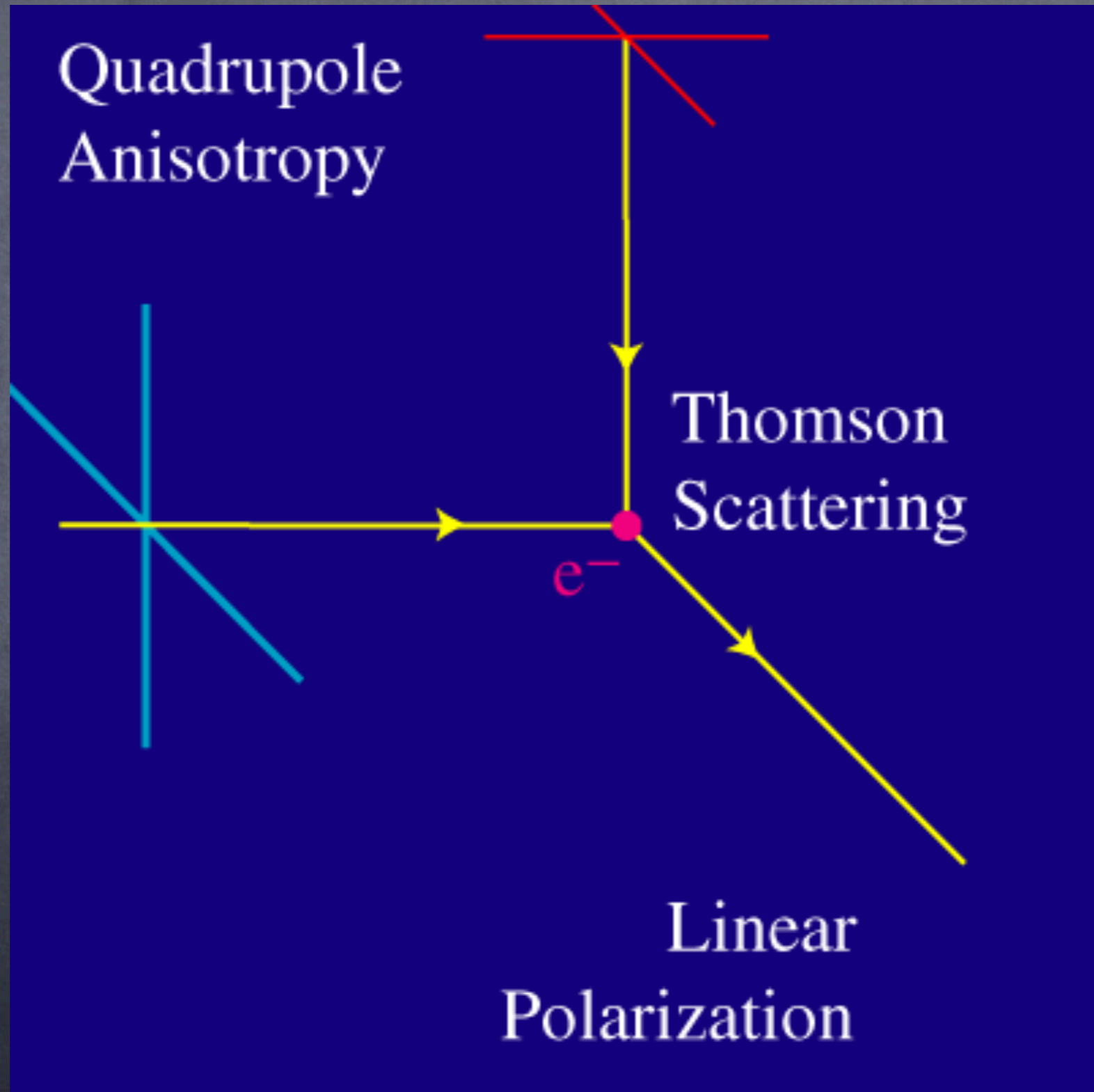
La polarisation



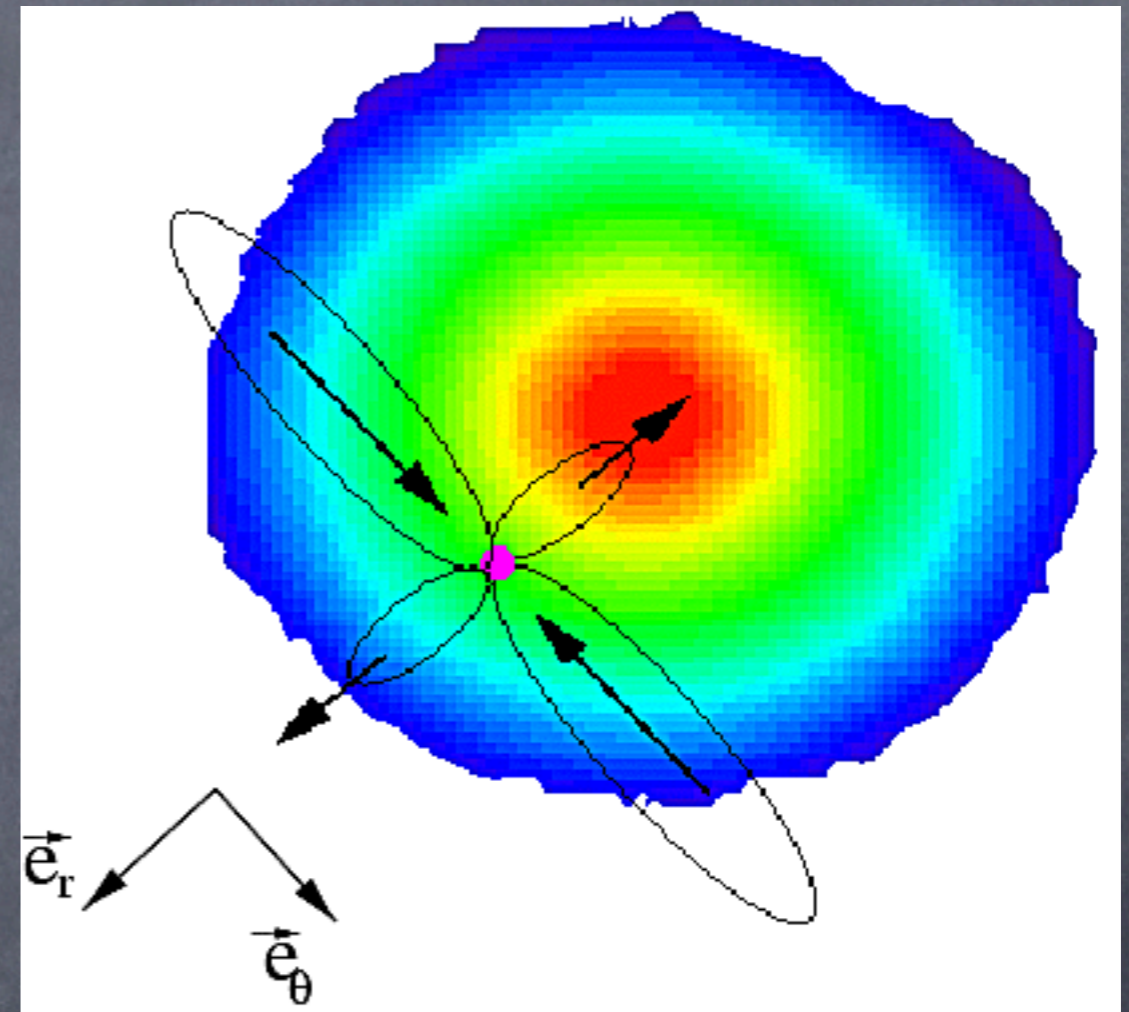
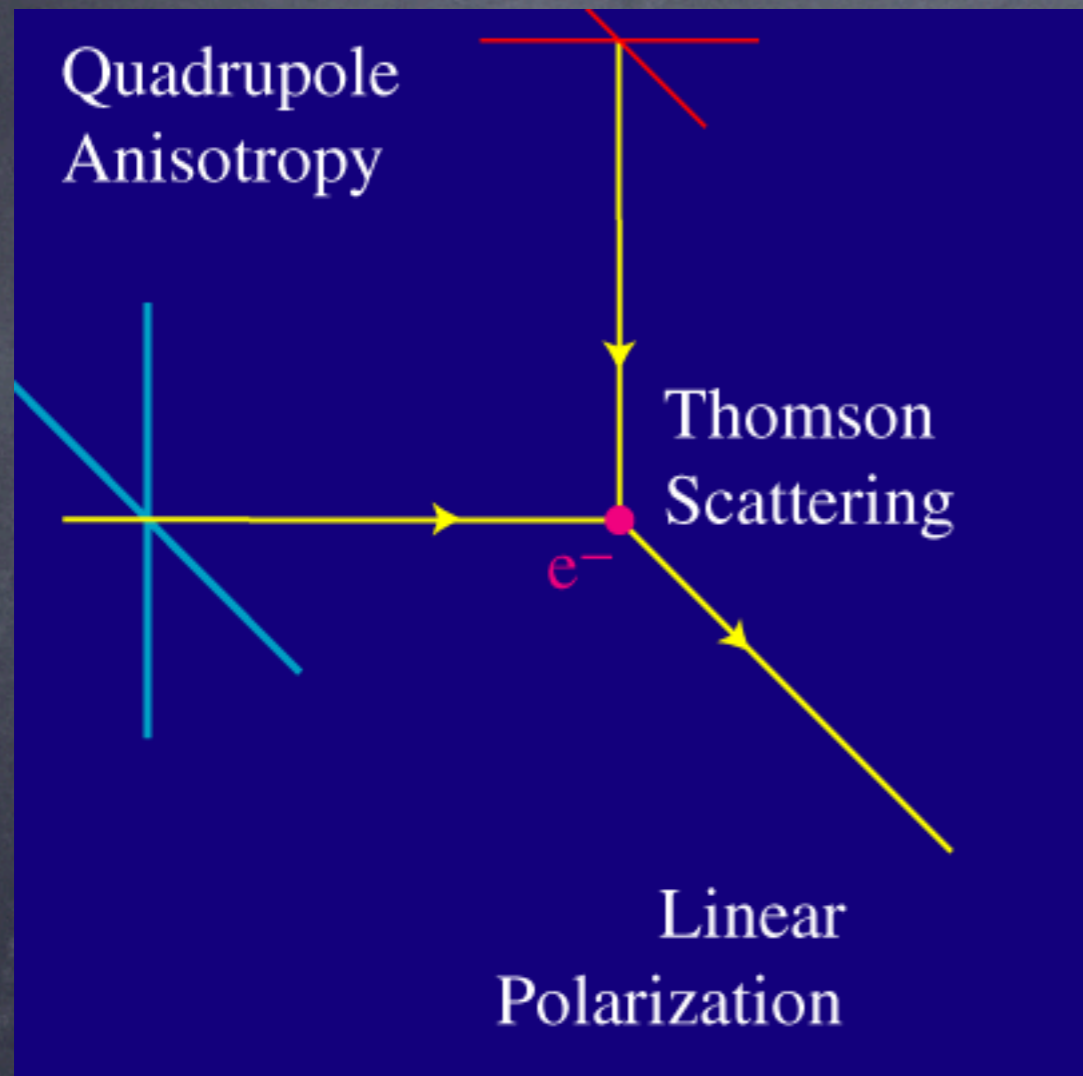
La polarisation



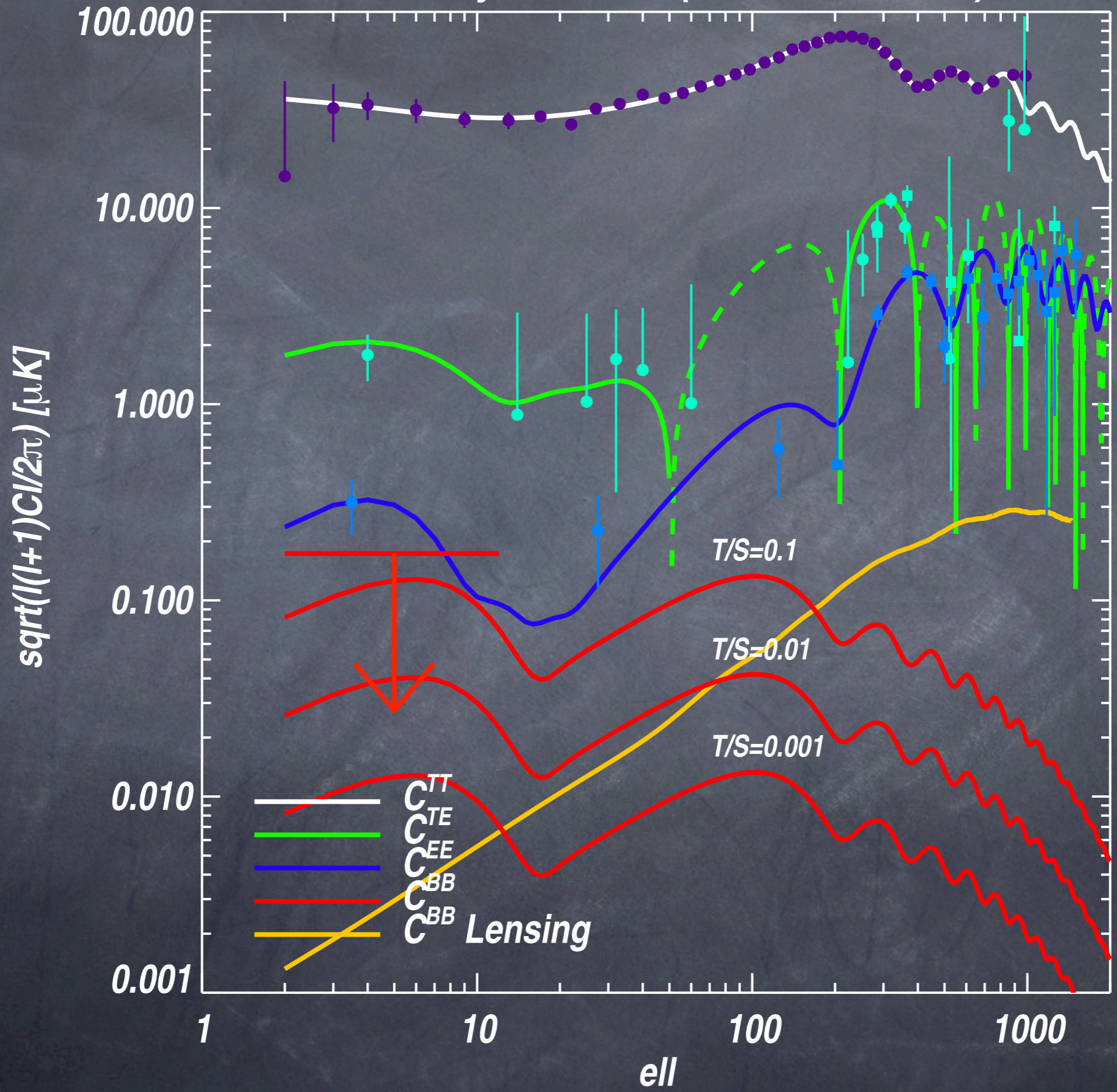
La polarisation



La polarisation

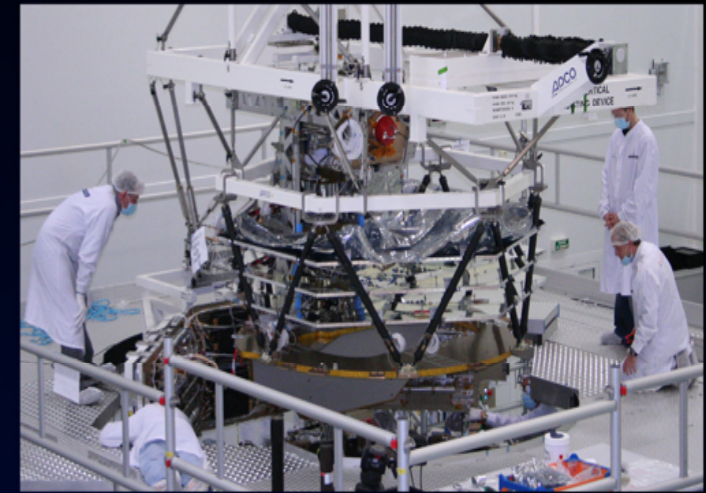
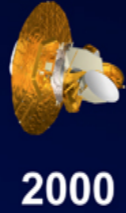


WMAP3y + QUAD (Ade et al. 2007)

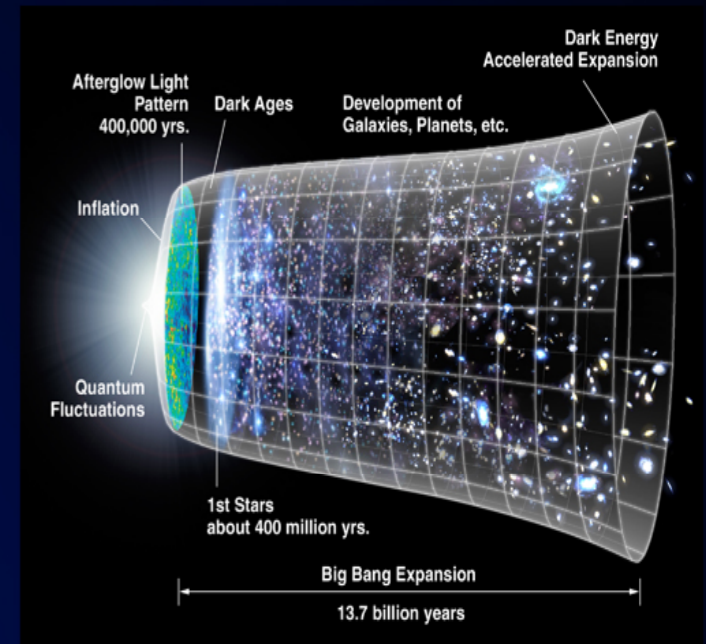
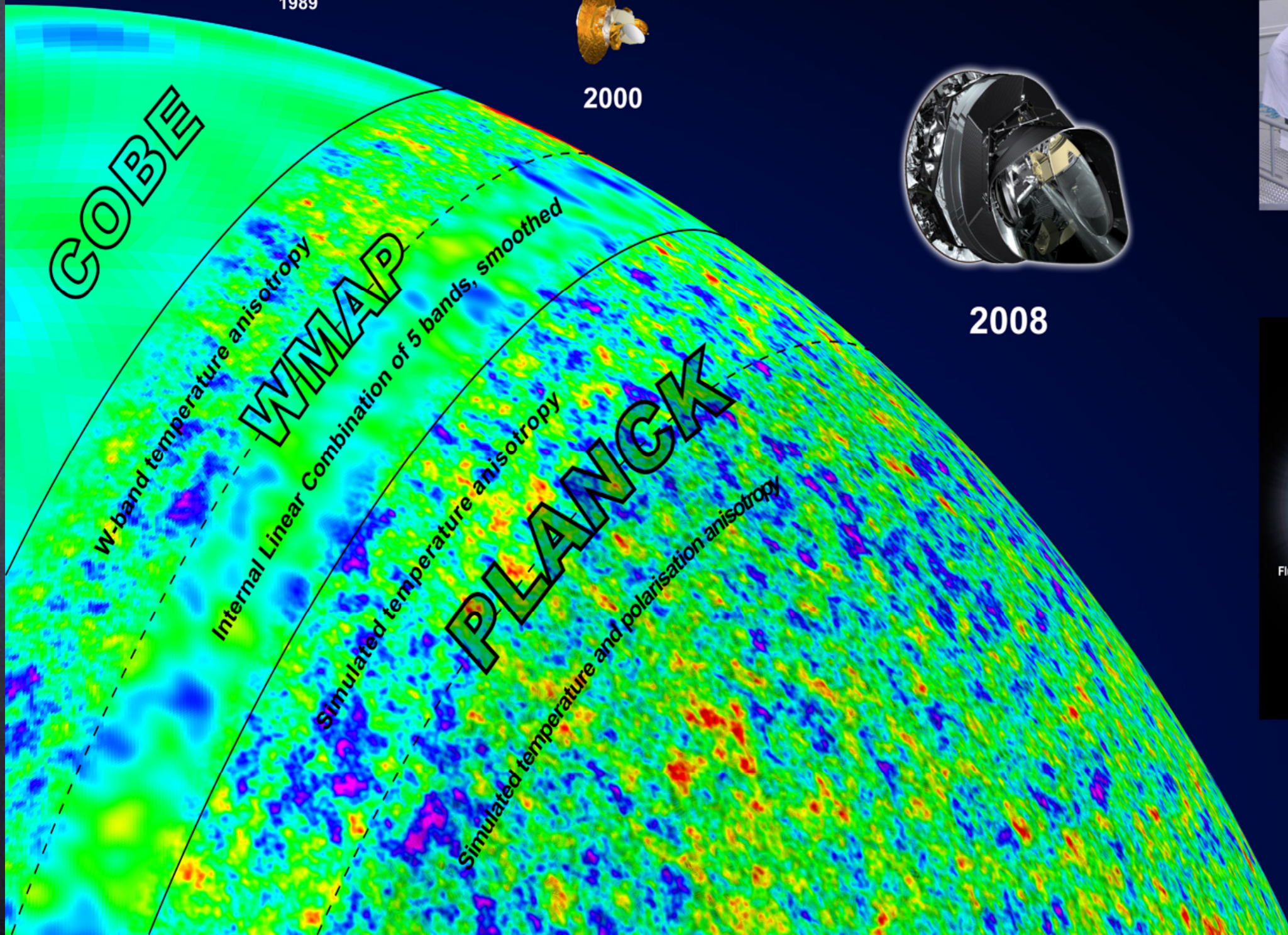


CMB Missions Revolutionise Our Understanding of the Universe

PLANCK



Planck spacecraft in clean assembly at Alcatel Alenia Space in January 2007



Planck

Télescope : miroir primaire
de 1,5 m de diamètre

Plan Focal
contenant les instruments
scientifiques refroidis

Plate-forme :

- Avionique (Contrôle d'attitude,
gestion des données)
- Puissance électrique
- Télécommunications
et instruments électroniques

Panneau solaire
et module de service



4,2 m



4,2 m



Poids : 2 000 kg
Puissance électrique : 1 600 W
Durée de vie : 21 mois

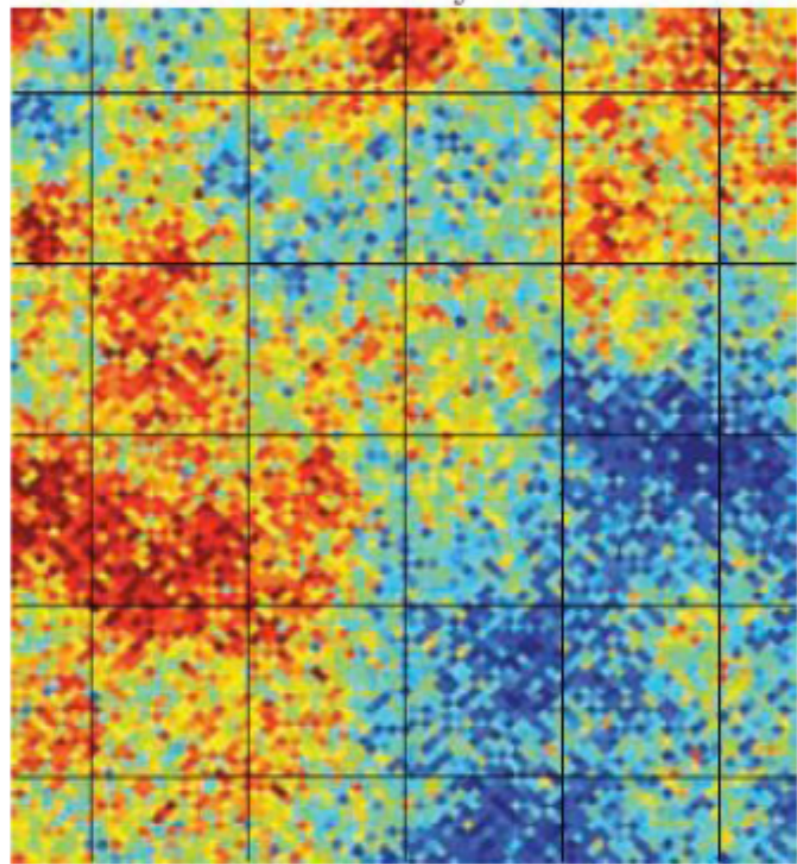
Planck HFI, c'est aussi :

- 50 000 composants électroniques,
- 36 000 litres d'Hélium 4,
- 12 000 litres d'Hélium 3,
- 11 400 documents.

Planck - performances

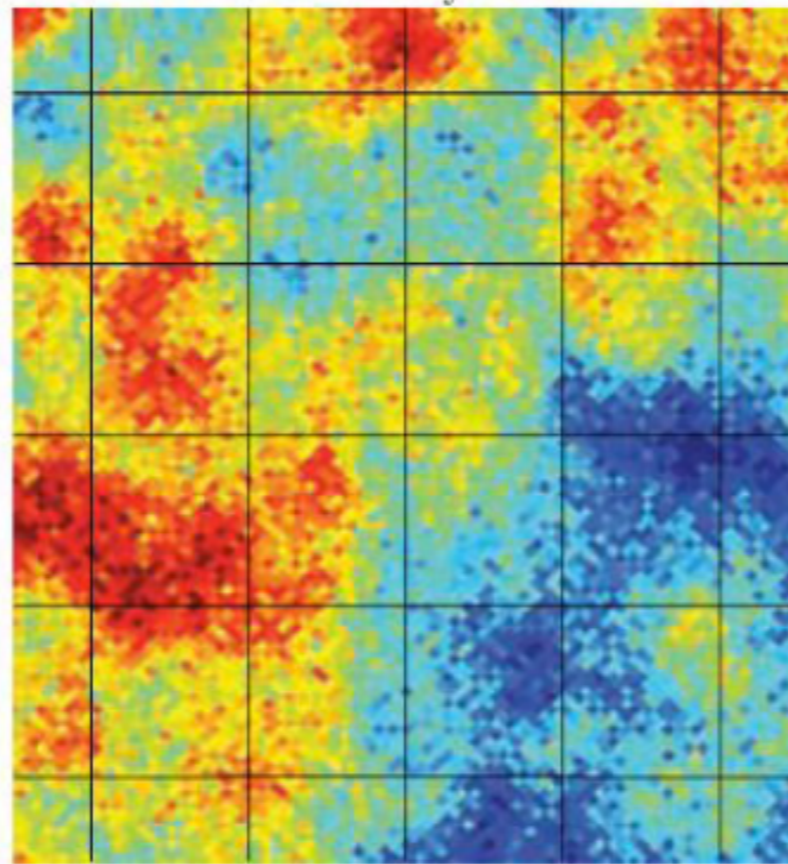
10 fois plus sensible que WMAP, une
résolution angulaire 3 fois meilleure et
sensible à la polarisation

WMAP 2 years



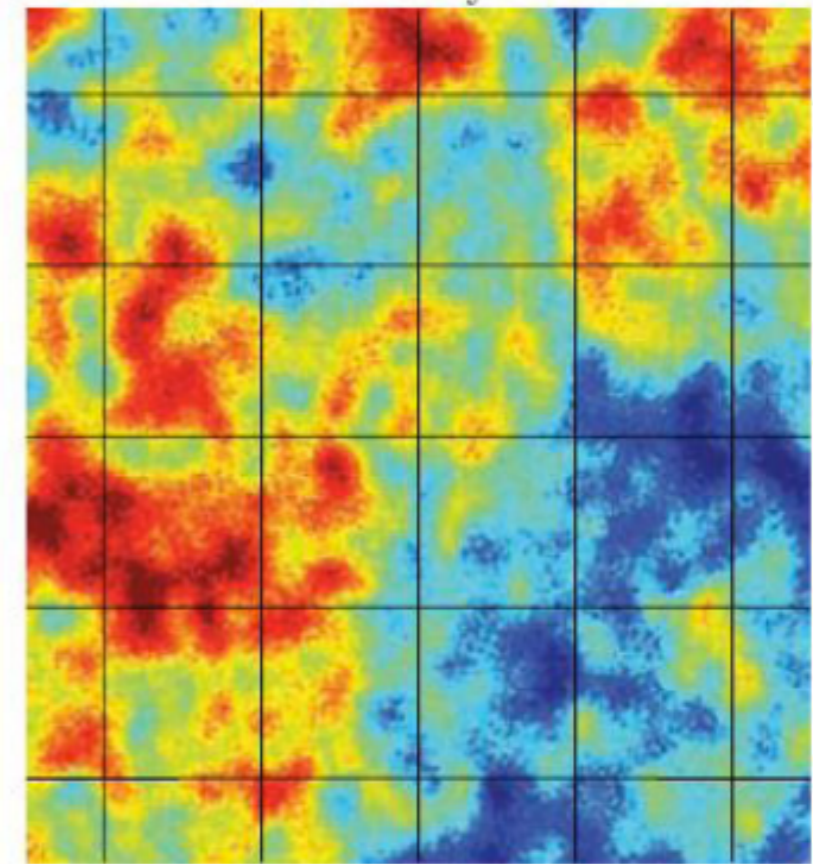
-300 300 μK

WMAP 8 years



-300 300 μK

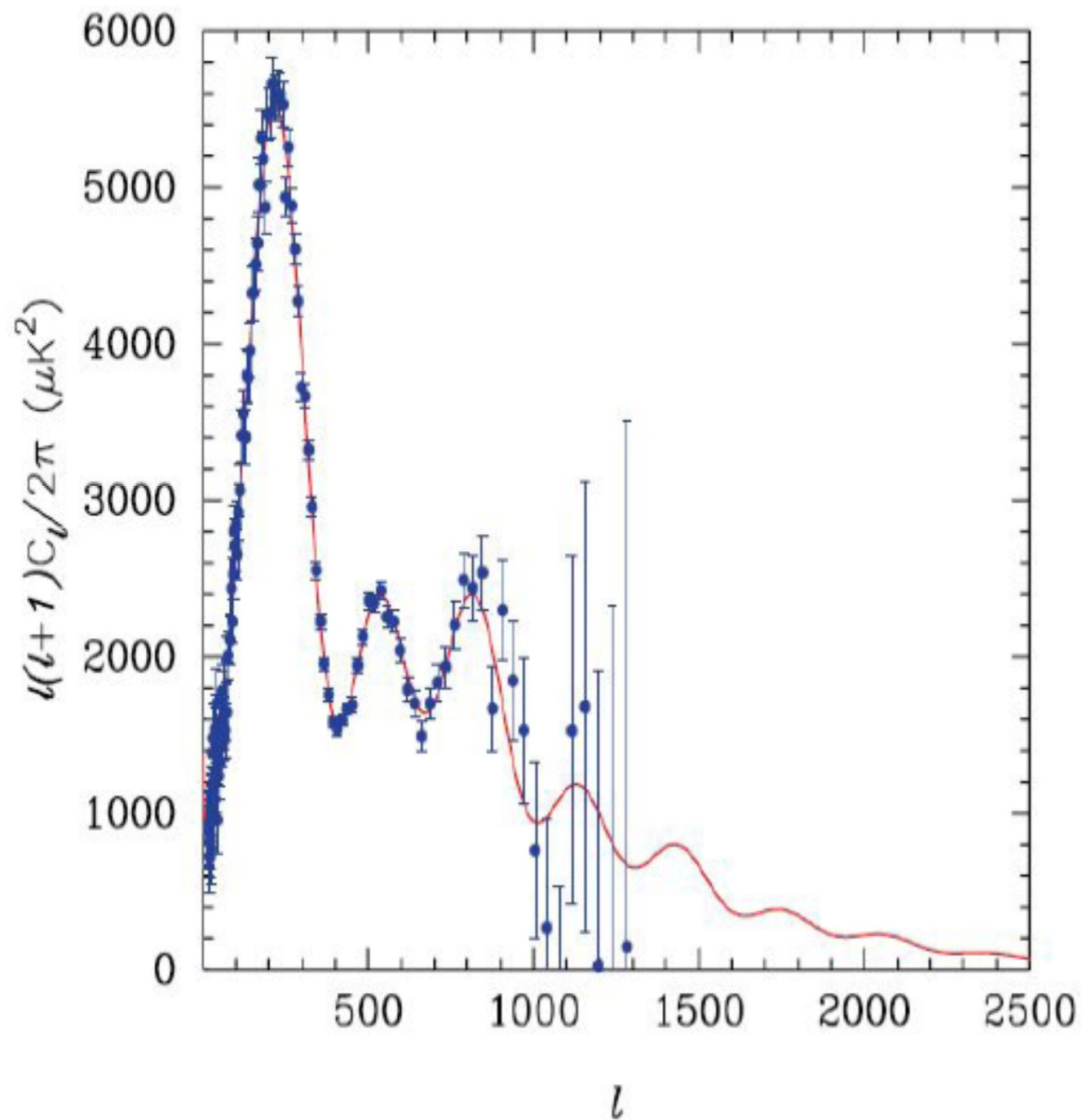
Planck 1 year



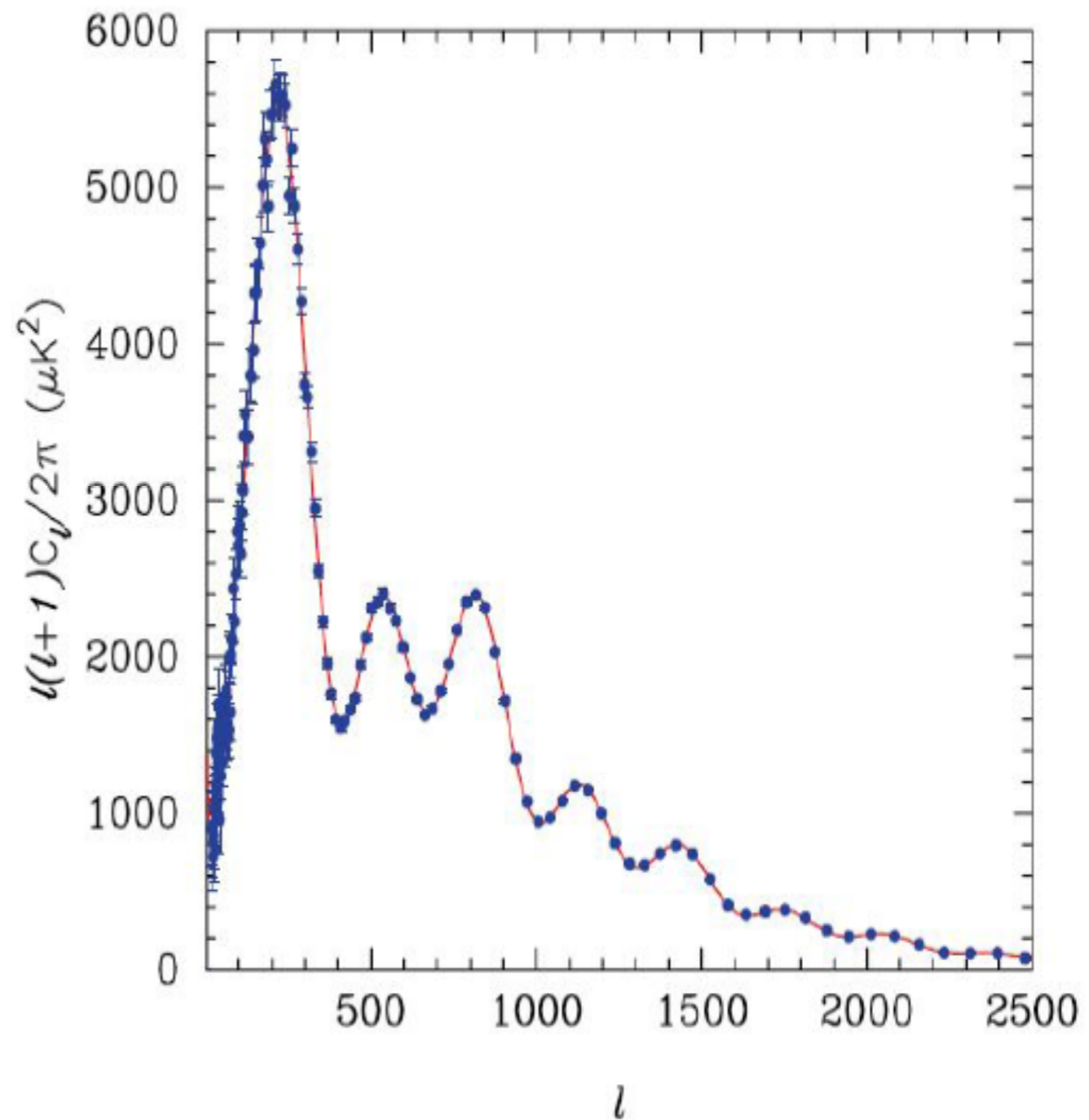
-300 300 μK

Planck

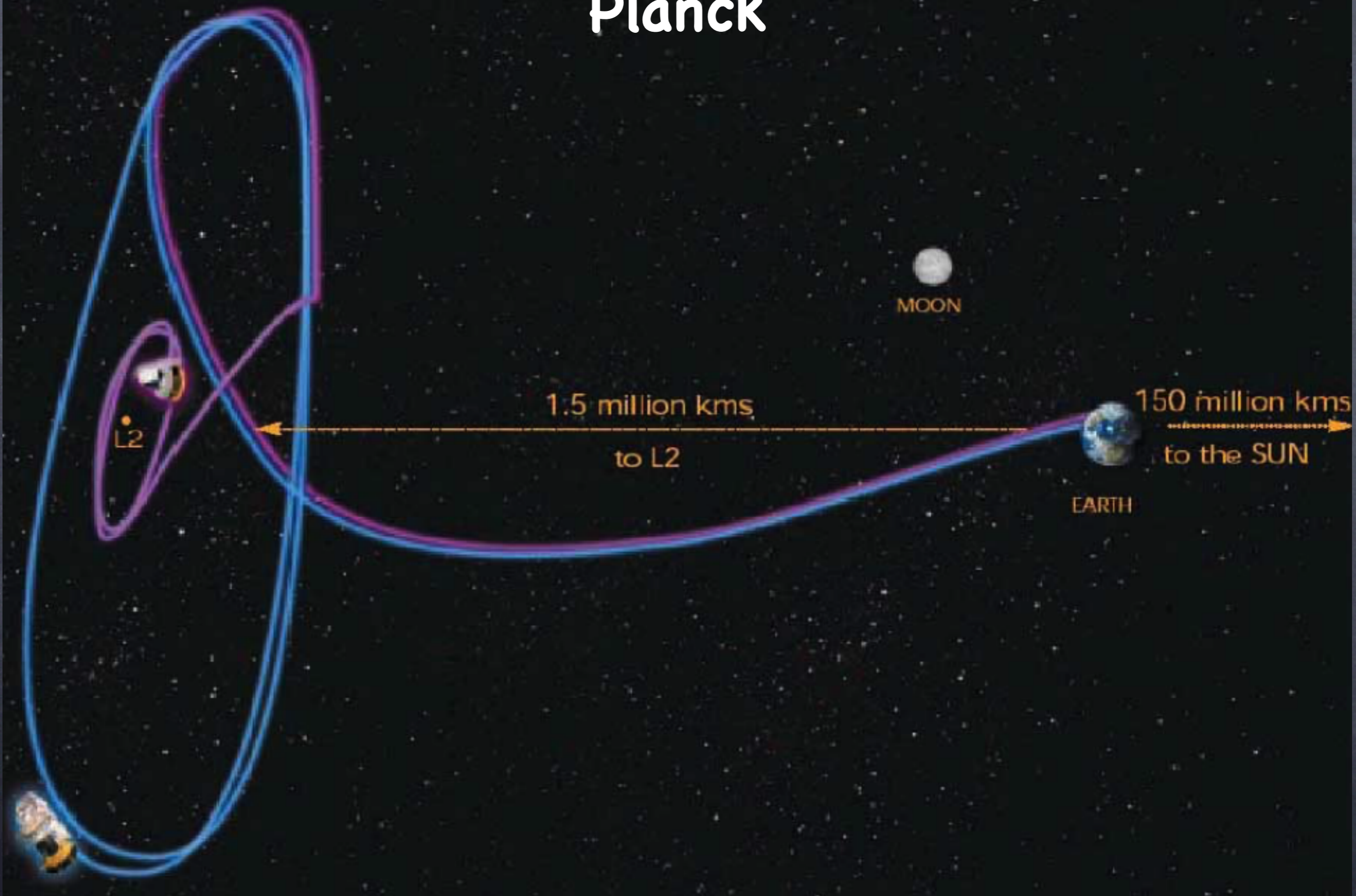
WMAP



PLANCK



Planck



Planck

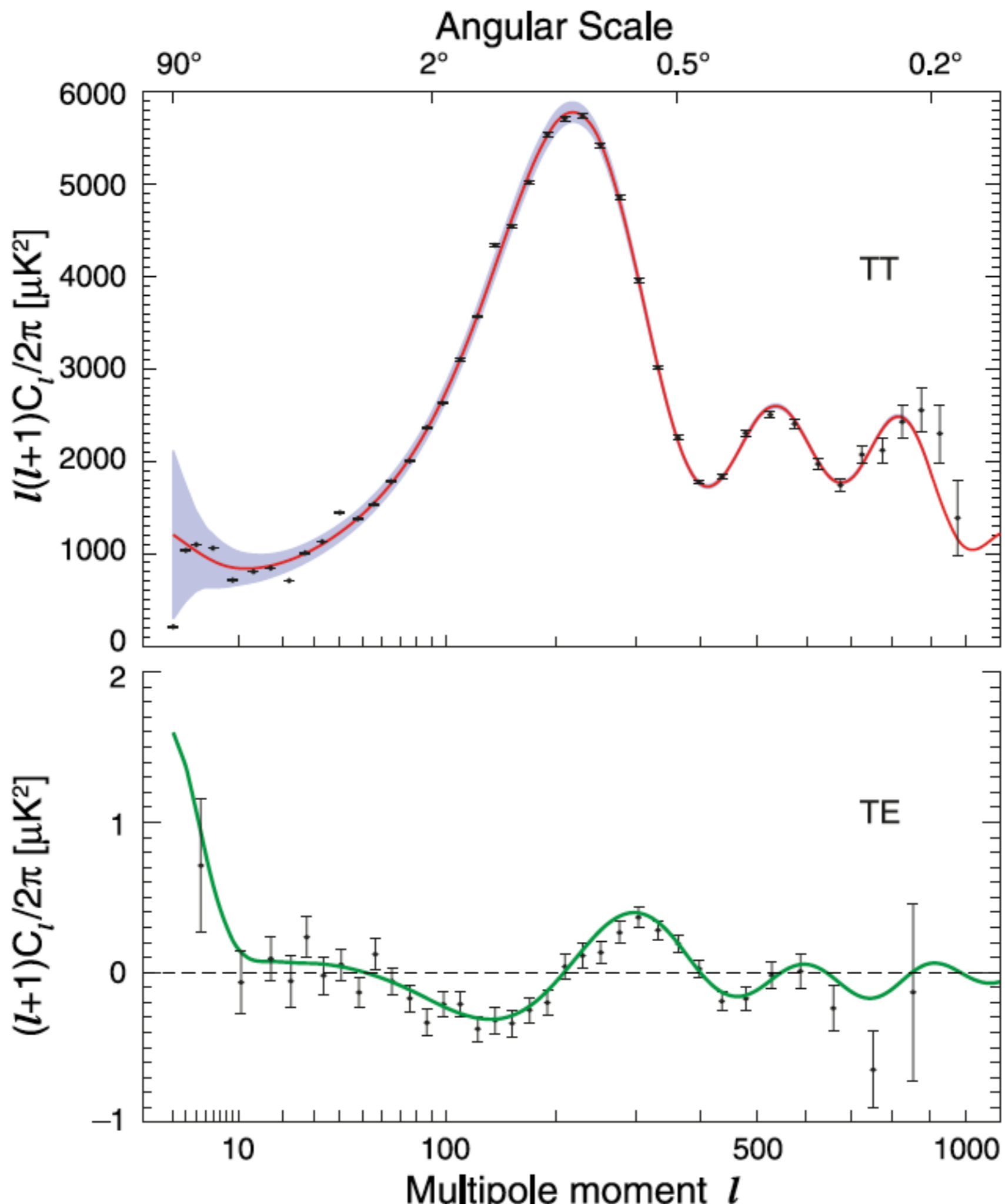
Lancé en mai 2009 !

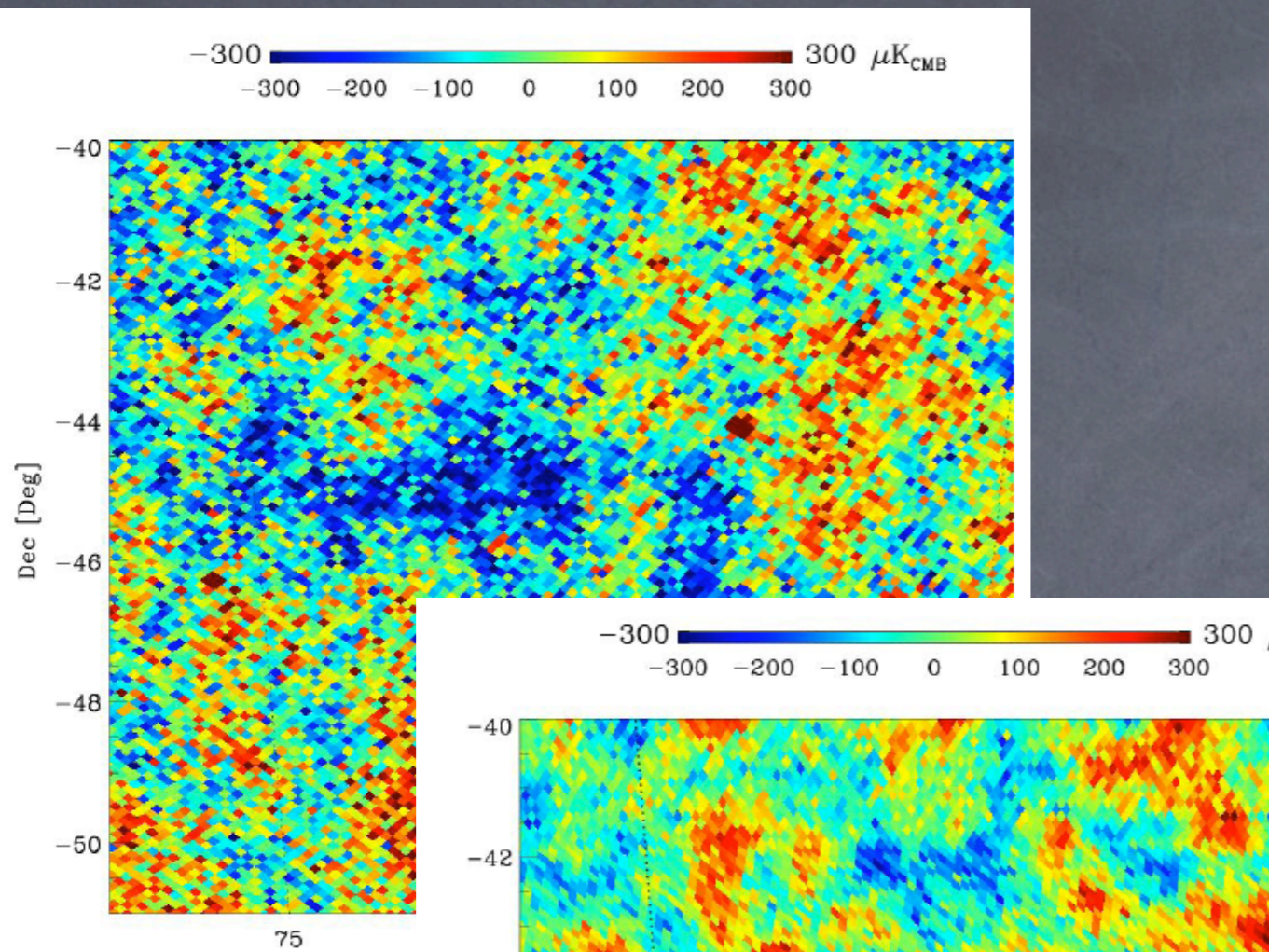


Herschel

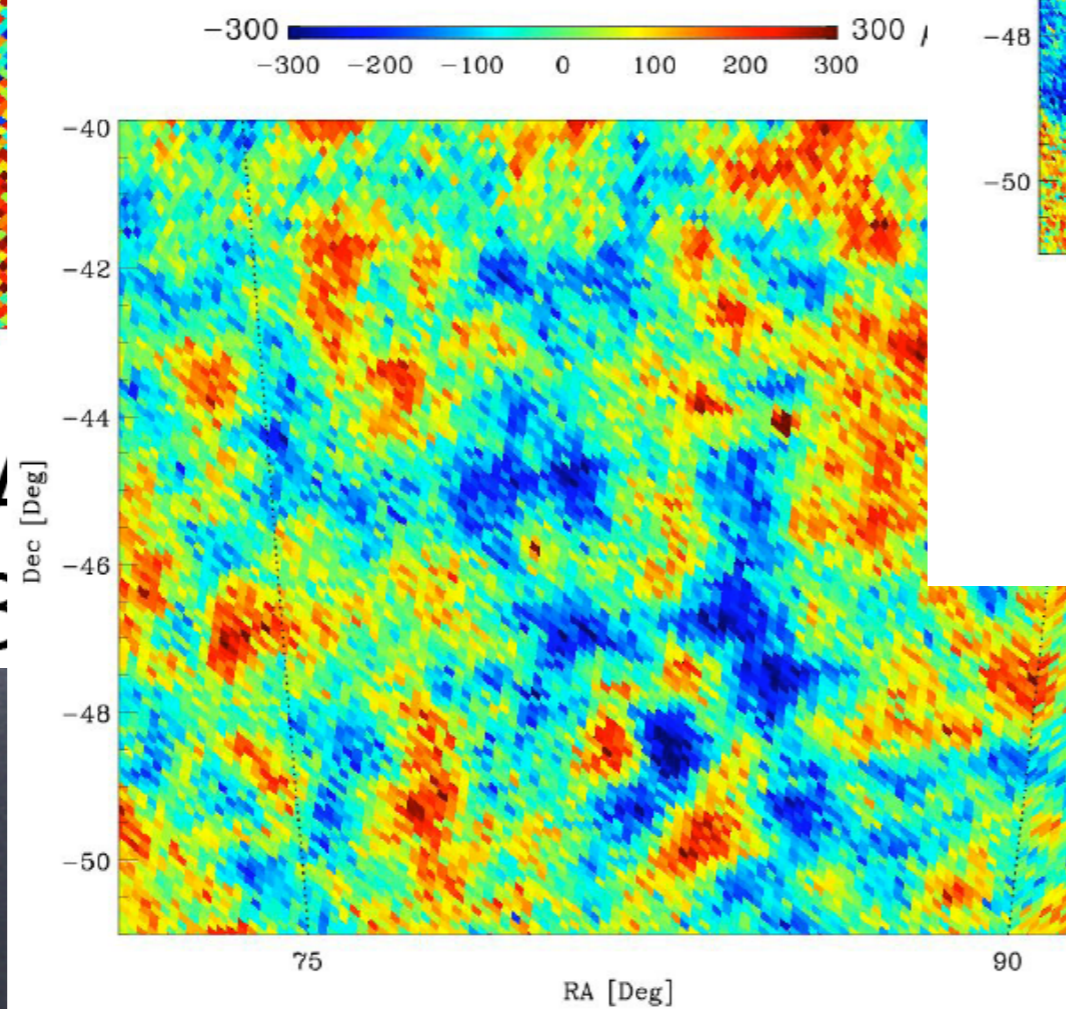
Planck



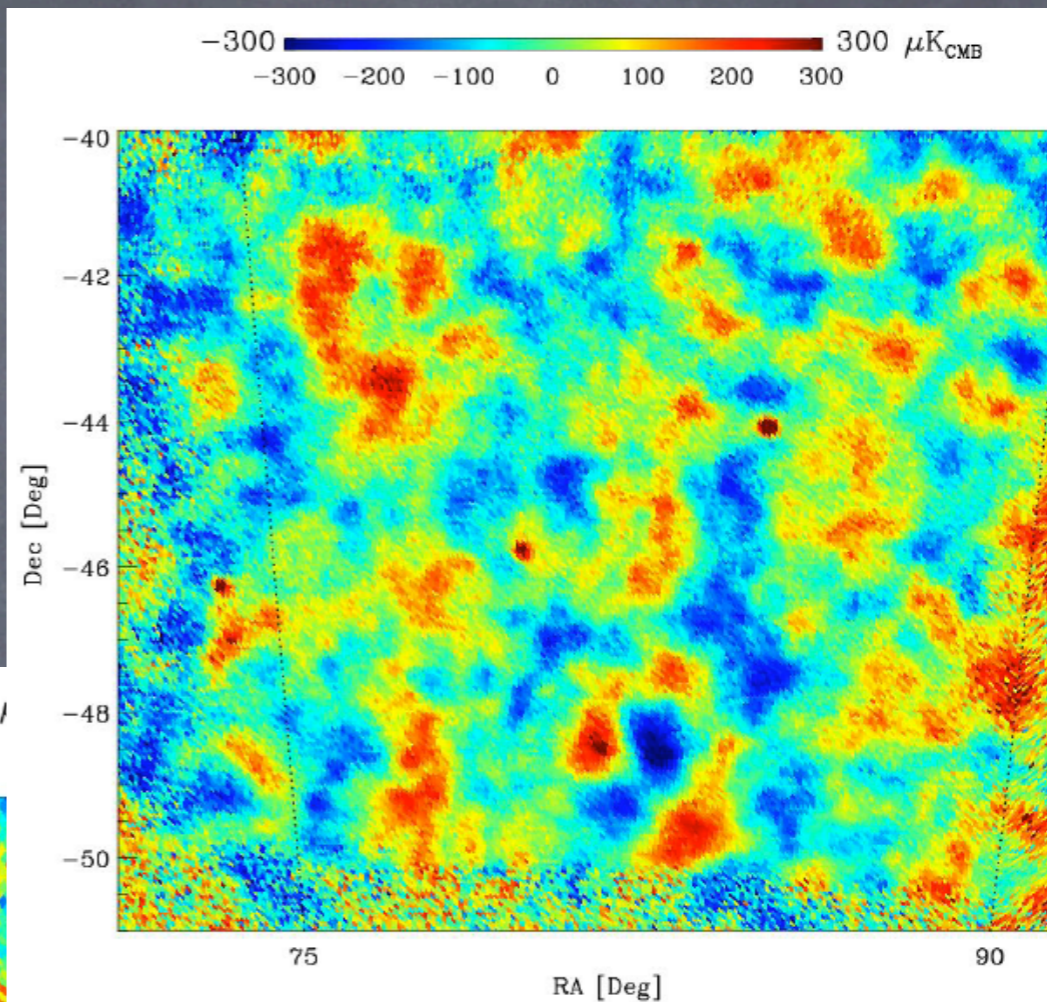




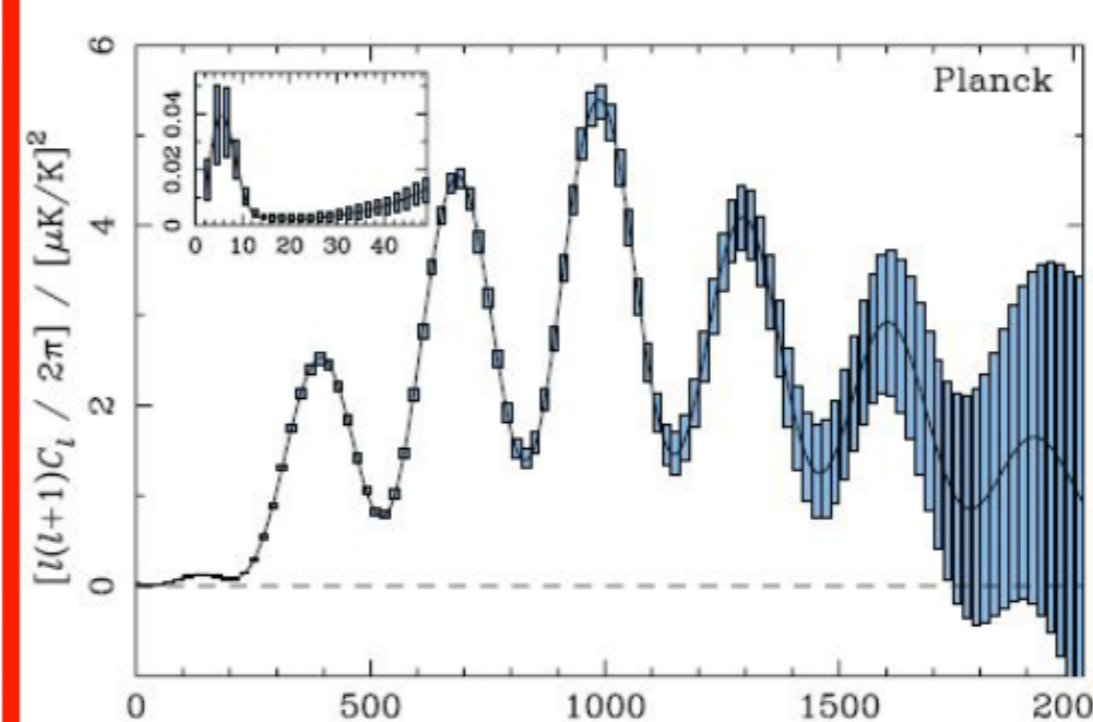
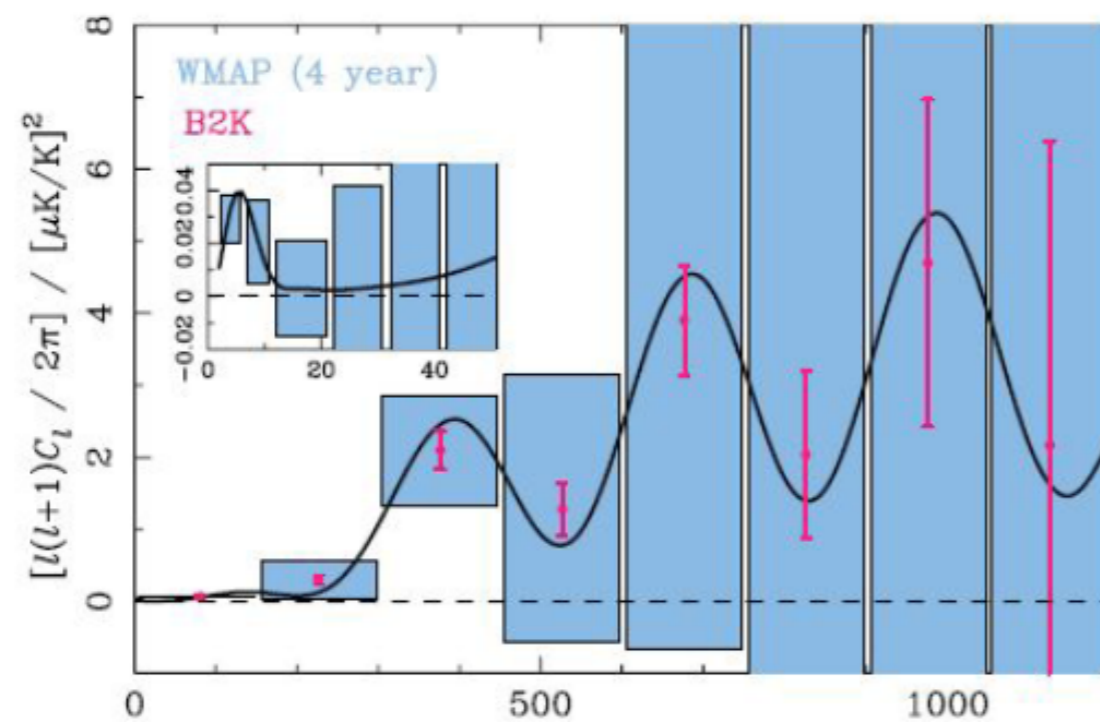
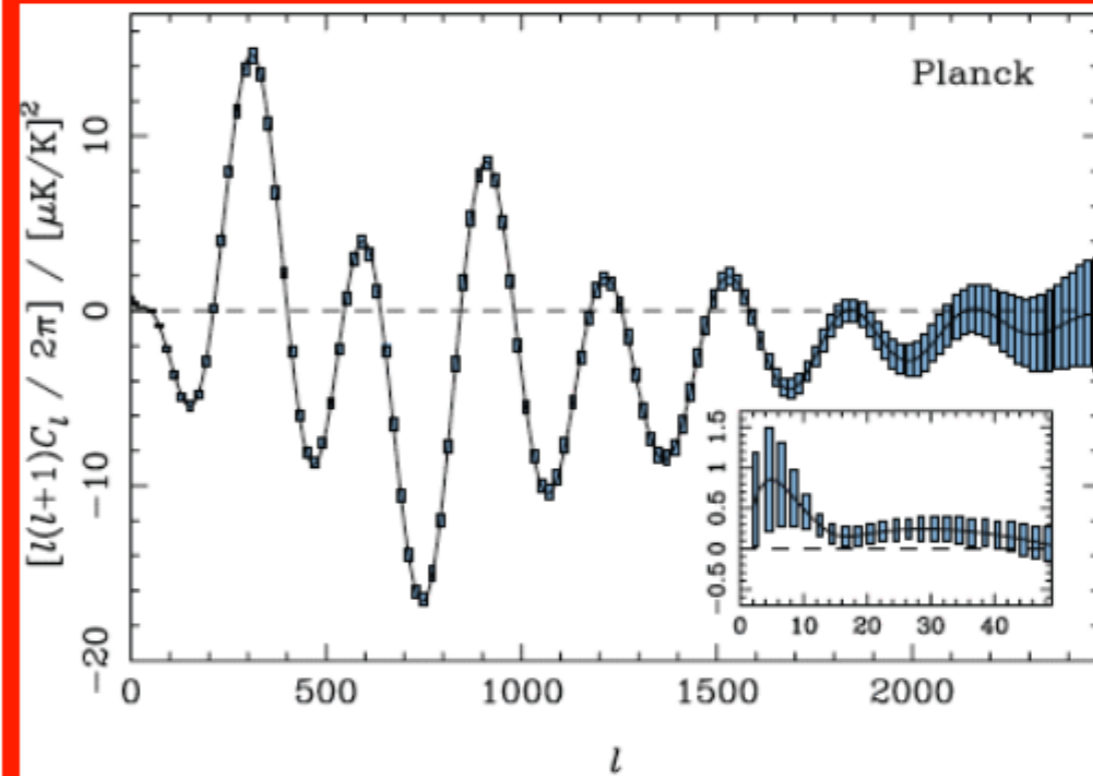
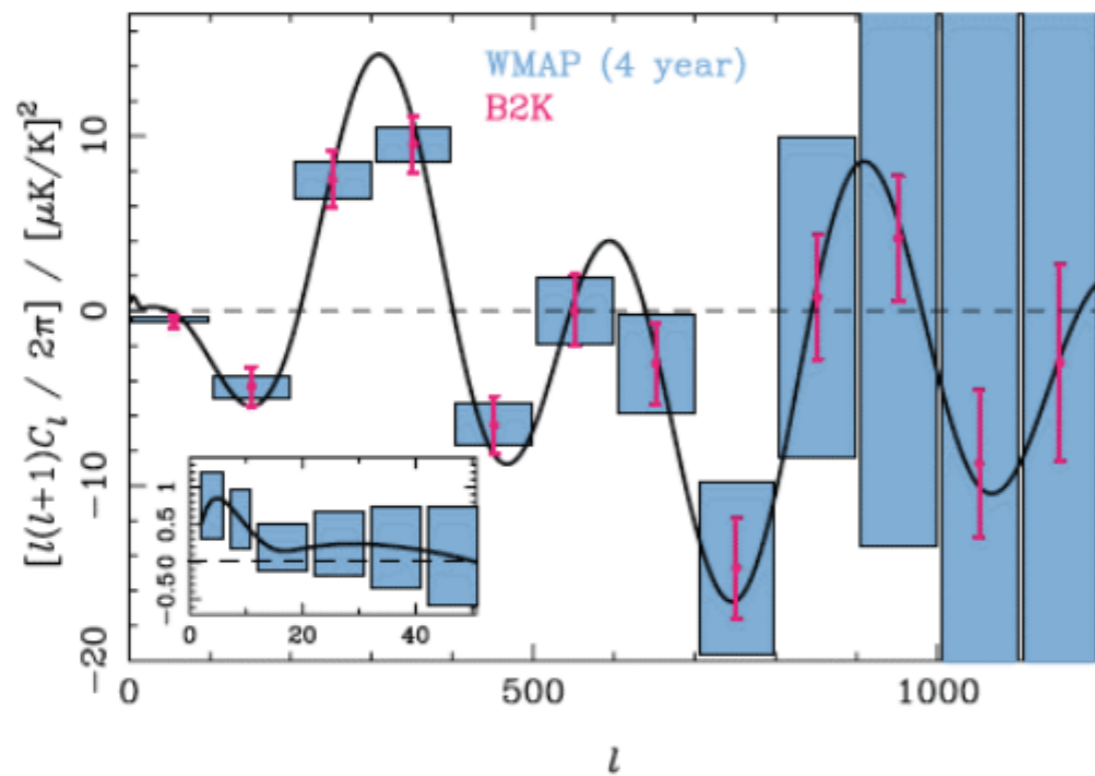
WMA
23



BOOMERanG-98
145 GHz

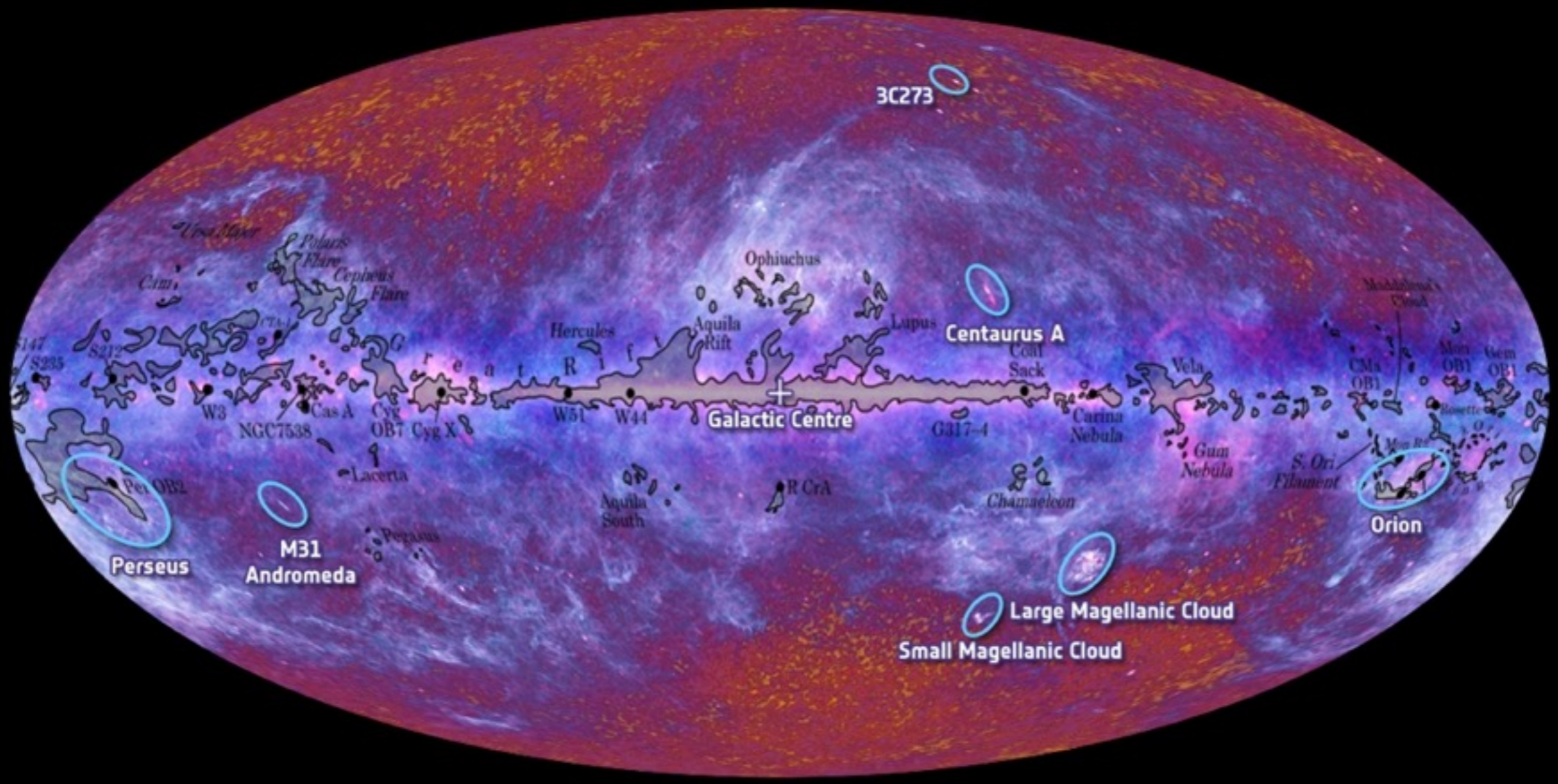


BOOMERanG-03
145 GHz



E-modes, as will be observed by Planck

Couverture totale du ciel



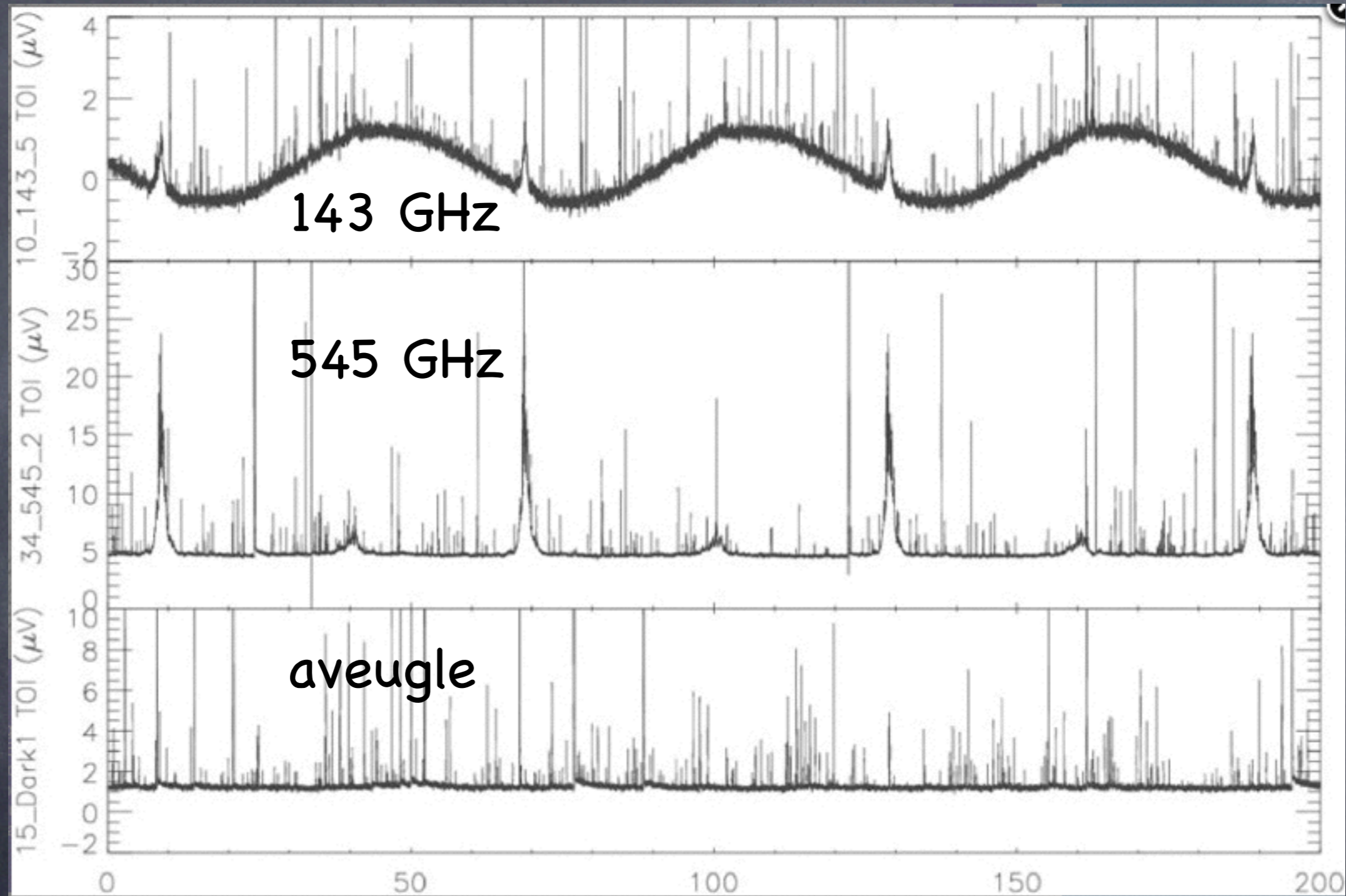
Premières 26 publications de Planck (1 an)

- I. The Planck mission
- II. The thermal performance of Planck
- III. First assessment of the Low Frequency Instrument in-flight performance
- IV. First assessment of the High Frequency Instrument in-flight performance
- V. The Low Frequency Instrument data processing
- VI. The High Frequency Instrument data processing
- VII. The Early Release Compact Source Catalogue
- VIII. The all-sky early Sunyaev-Zeldovich cluster sample
- IX. XMM-Newton follow-up for validation of Planck cluster candidates
- X. Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters
- XI. Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations
- XII. Cluster Sunyaev-Zeldovich optical scaling relations
- XIII. Statistical properties of extragalactic radio sources in the Planck Early Release Compact Source Catalogue
- XIV. Early Release Compact Source Catalogue validation and extreme radio sources
- XV. Spectral energy distributions and radio continuum spectra of northern extragalactic radio sources
- XVI. The Planck view of nearby galaxies
- XVII. Origin of the submillimetre excess dust emission in the Magellanic Clouds
- XVIII. The power spectrum of cosmic infrared background anisotropies
- XIX. All-sky temperature and dust optical depth from Planck and IRAS – constraints on the "dark gas" in our Galaxy
- XX. New light on anomalous microwave emission from spinning dust grains
- XXI. Properties of the interstellar medium in the Galactic plane
- XXII. The submillimetre properties of a sample of Galactic cold clumps
- XXIII. The Galactic cold core population revealed by the first all-sky survey
- XXIV. Dust in the diffuse interstellar medium and the Galactic halo
- XXV. Thermal dust in nearby molecular clouds
- XXVI. Detection with Planck and confirmation by XMM-Newton of PLCK G266.6-27.3, an exceptionally X-ray luminous and massive galaxy cluster at $z \sim 1$

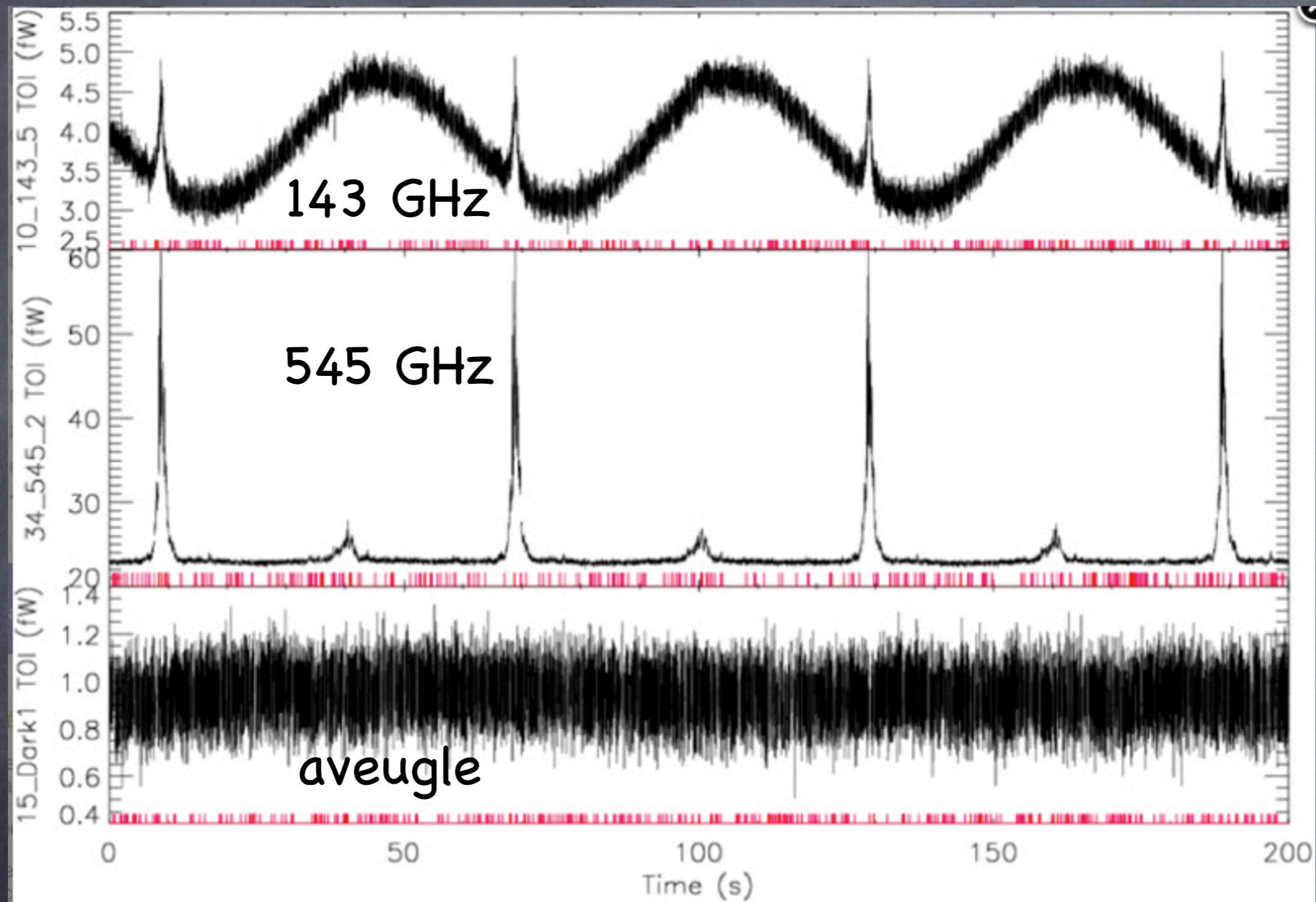
Planck

27 novembre 2011 : quatrième cartographie complète du ciel
fin 2012 : résultats cosmologiques de la mission Planck

Planck



Planck



Dans la presse grand public

Mise à jour 05:24
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LE FLASH ACTU 14h19 Mort d'un scénariste des Simpsons

L'enfance de l'Univers vue par le satellite européen Planck

ACTUALITE > SCIENCES Par Tristan Vey | Mis à jour le 28/03/2013 à 05:23 | Publié le 21/03/2013 à 12:24

< PRÉC | SURV >
L'AUTEUR ↘

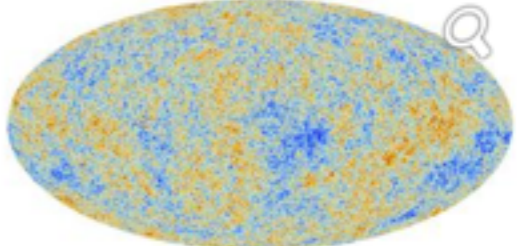
Le rayonnement fossile, sorte de lumière originelle émise 380.000 ans seulement après le big bang, a été isolé puis cartographié par l'Agence spatiale européenne avec une précision inégalée.

Liberation
{SCIENCES²}
Par Sylvestre Huet
Journaliste à Libération

rechercher 🔍

À LIRE AUSSI

PLANCK RÉVÈLE LA CARTE DE L'UNIVERS



Nous vivons...
13 milliards e...
la précision...
67,9 km/s...
majoritairement...
qui, depuis cir...
expansion. Il...
grand encore...
Ces chiffres s...

Carte sur tout le ciel du rayonnement cosmologique dressée par Planck.

Le Monde.fr
Dernière mise à jour à 16h14

"All the News That's Fit to Print"
The New York Times
VOL. CLXII - No. 56,083
FRIDAY, MARCH 22, 2013

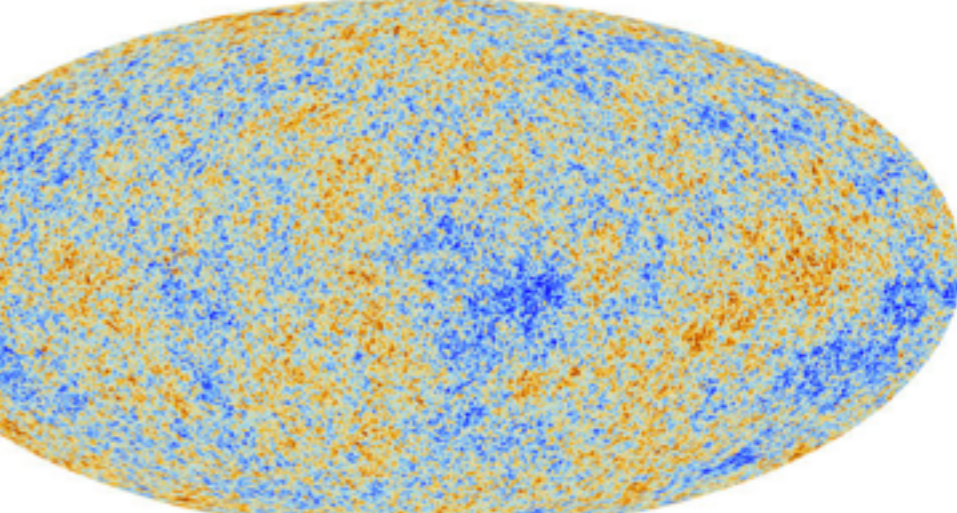


The Cosmos, Back in the Day
An image from data recorded by a European Space Agency satellite shows a heat map of the universe as it appeared 370,000 years after the Big Bang. Page A10.

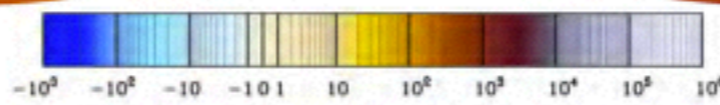
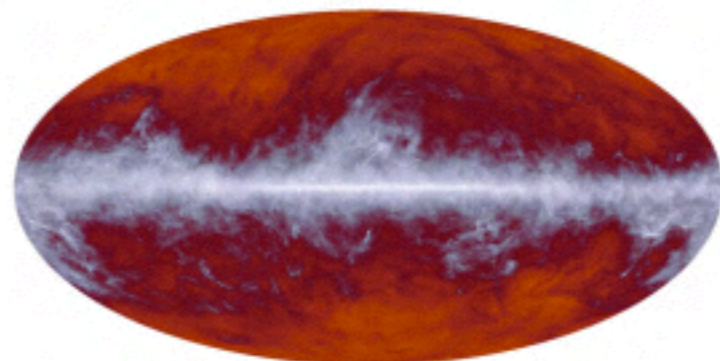
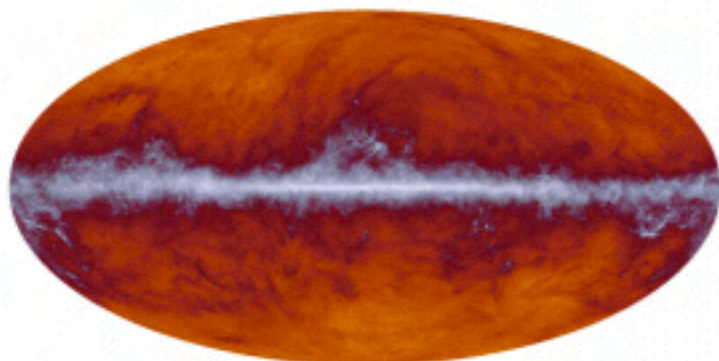
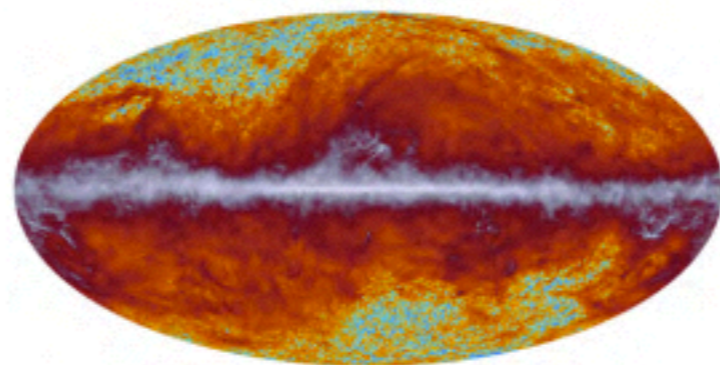
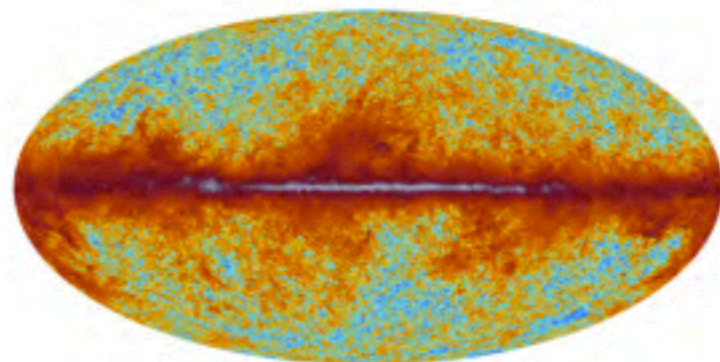
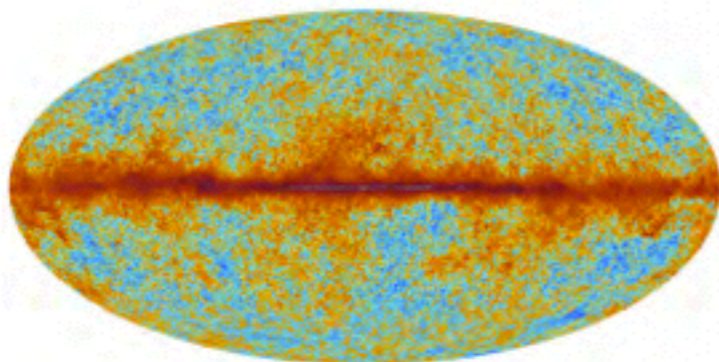
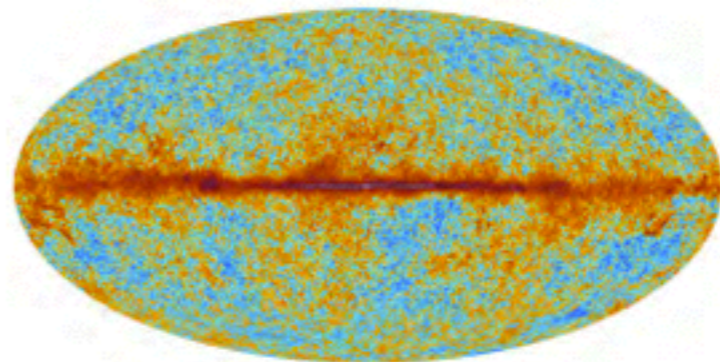
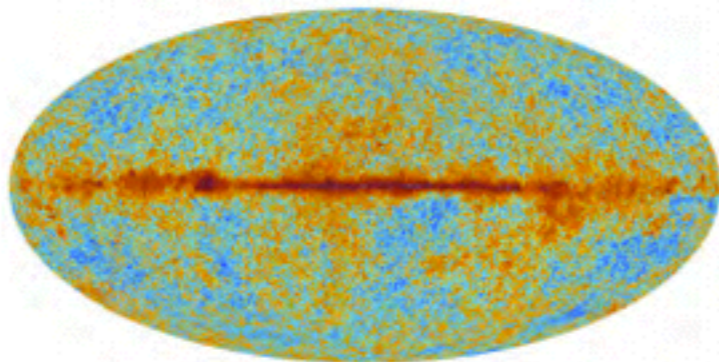
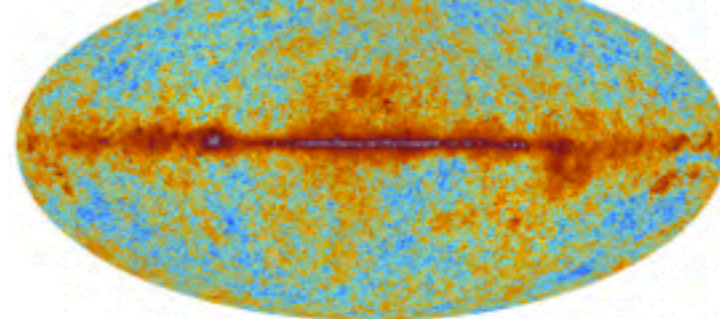
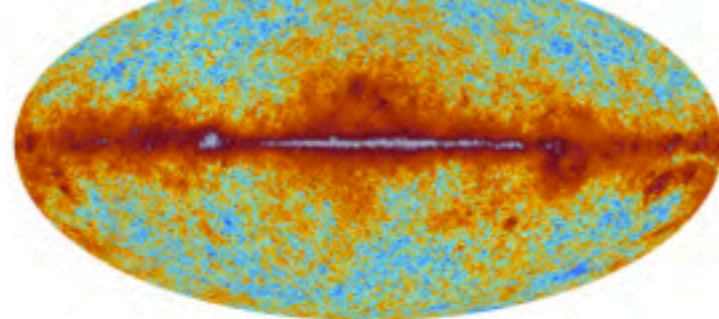
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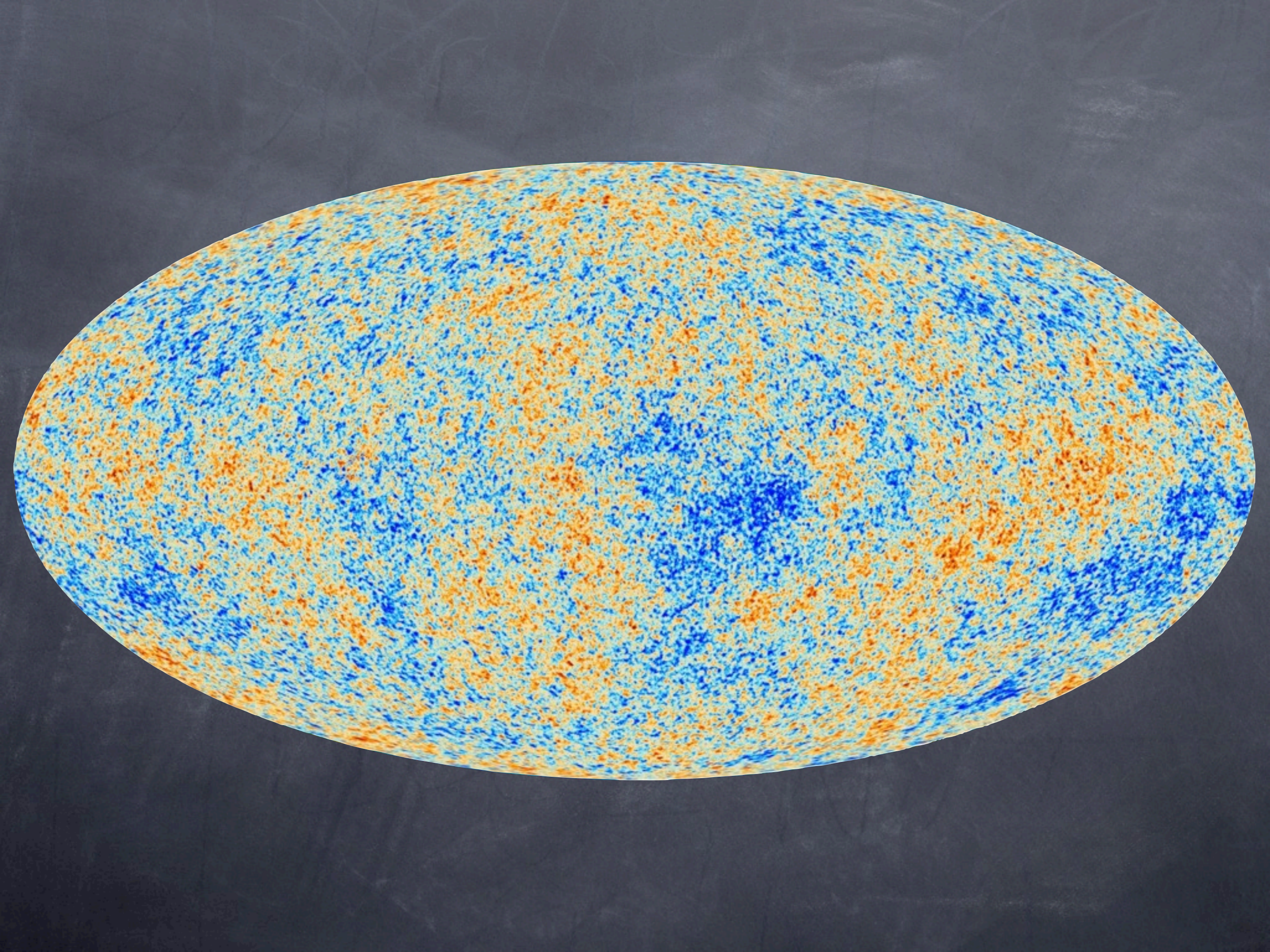
Jérôme Cahuzac | Chypre | Irak | Mali | Syrie | Pape | Monde Académie

L'enfance de l'Univers dévoilée

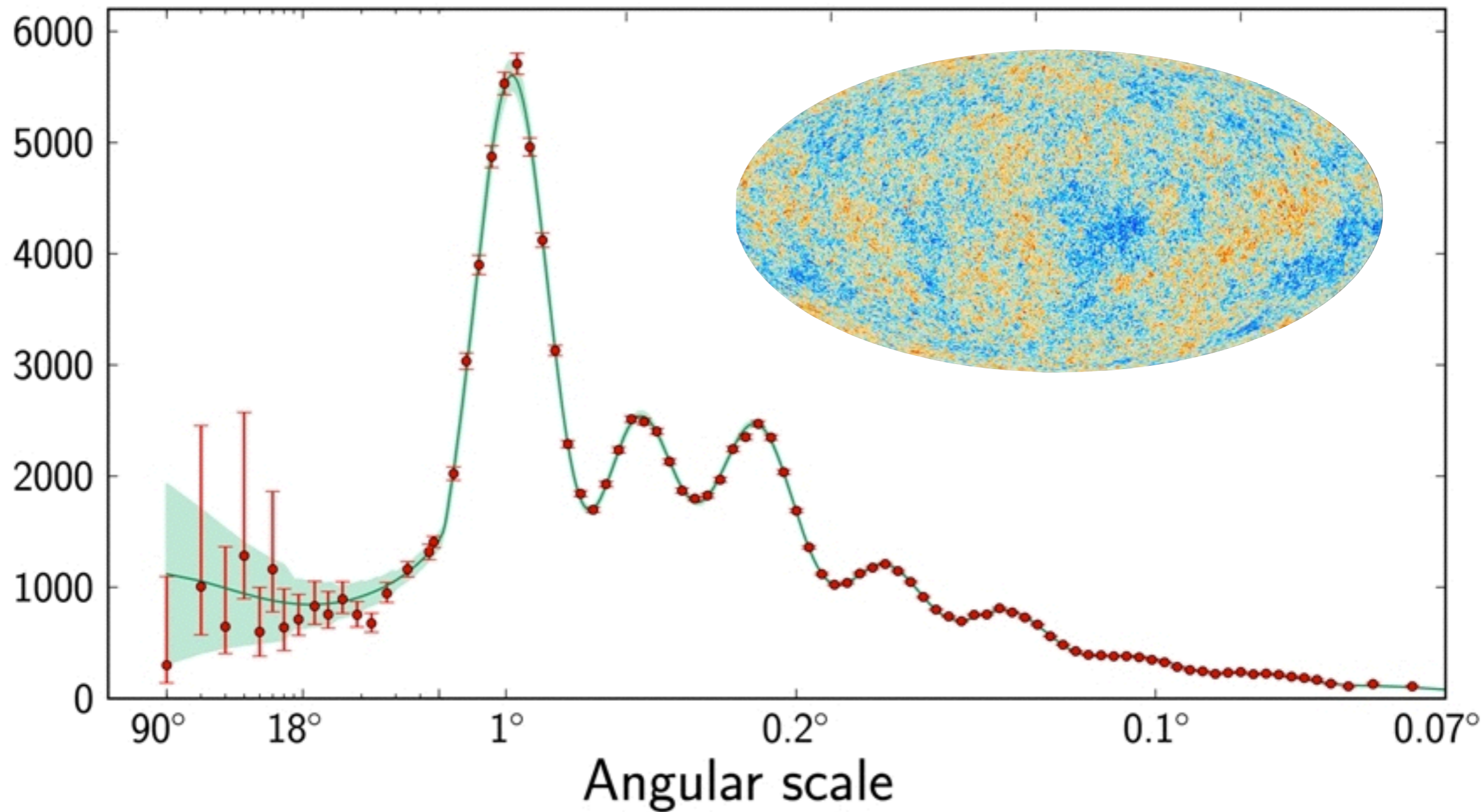


européen Planck livre des images inédites du cosmos. 380 000 ans après le Big Bang.





Temperature fluctuations [μK^2]



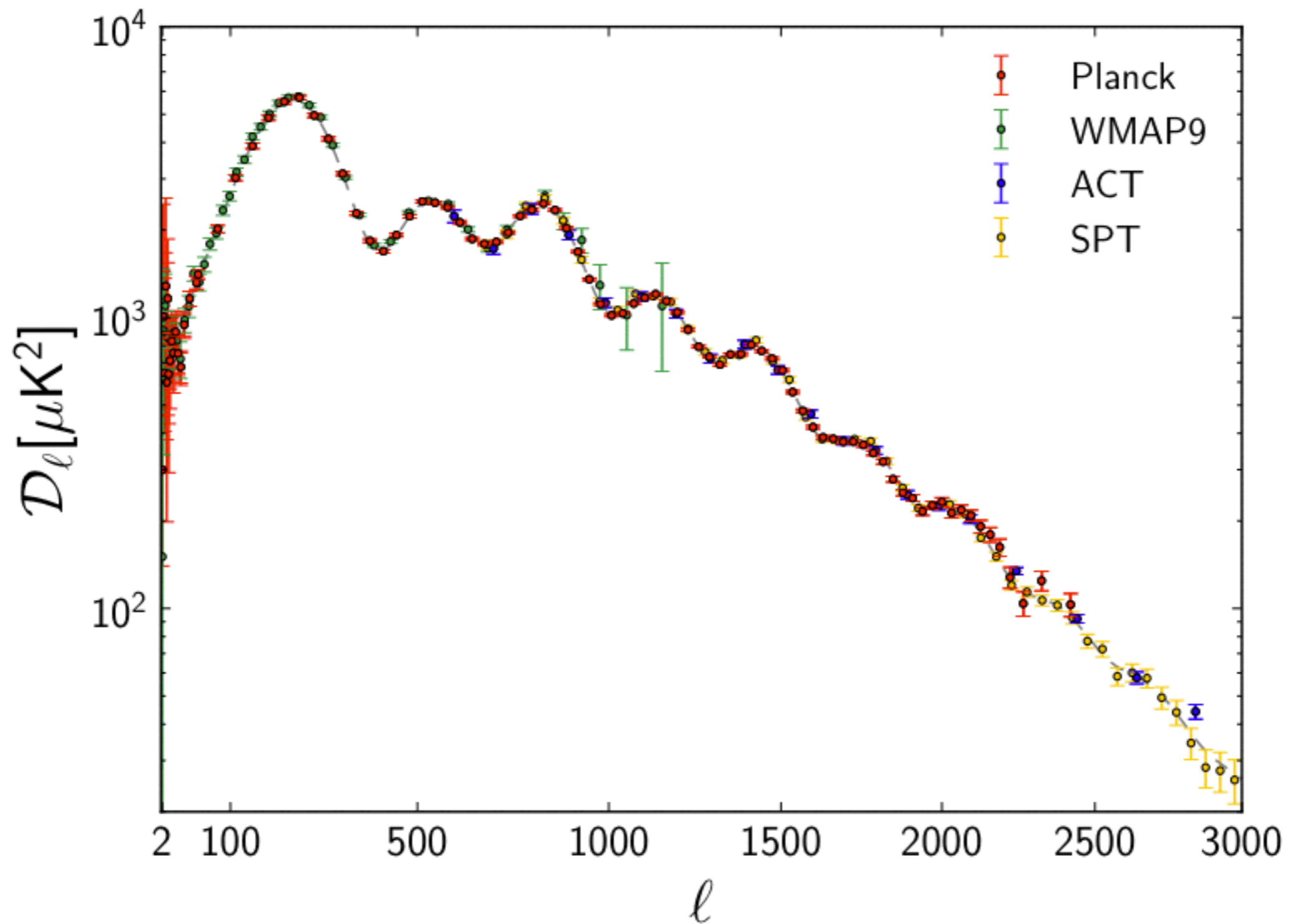
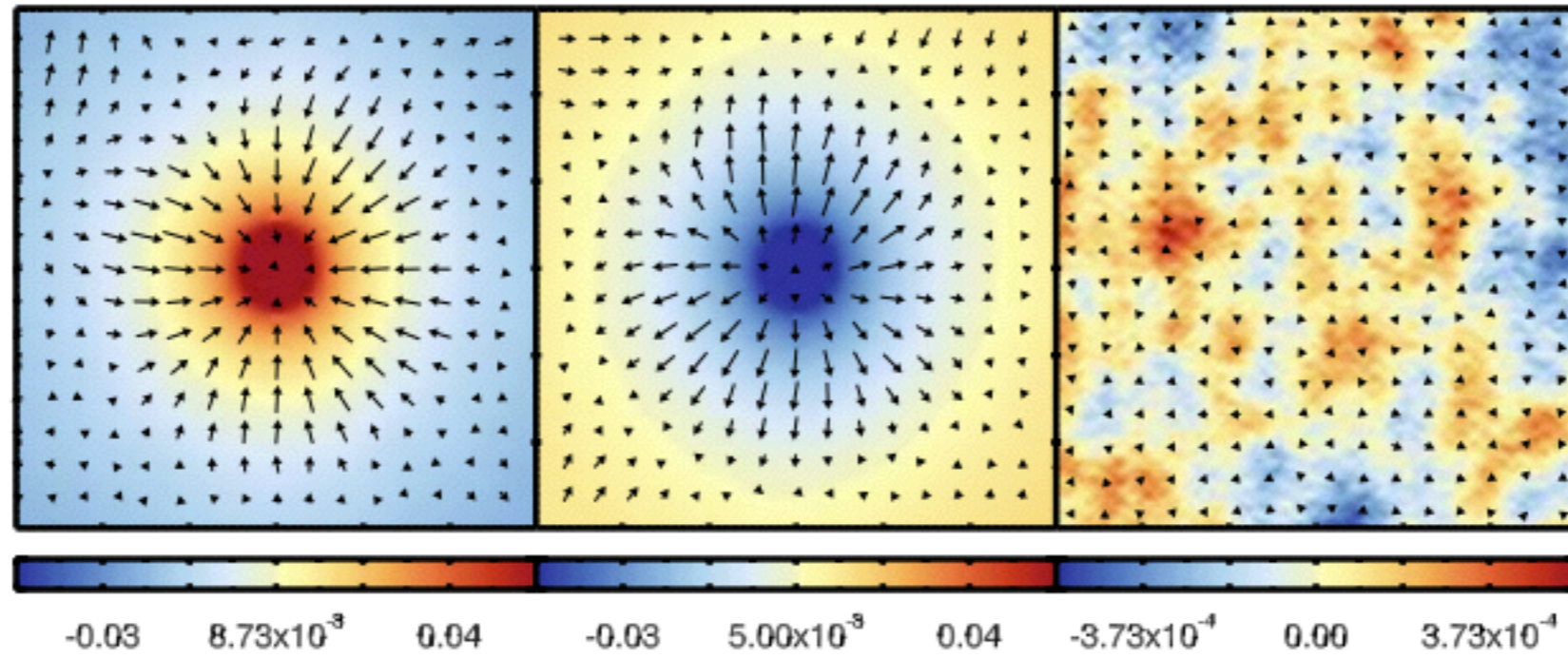


Fig. 25. Measured angular power spectra of *Planck*, WMAP9, ACT, and SPT. The model plotted is *Planck*'s best-fit model including *Planck* temperature, WMAP polarization, ACT, and SPT (the model is labelled [Planck+WP+HighL] in *Planck* Collaboration XVI (2013)). Error bars include cosmic variance. The horizontal axis is $\ell^{0.8}$.

857 GHz



545 GHz

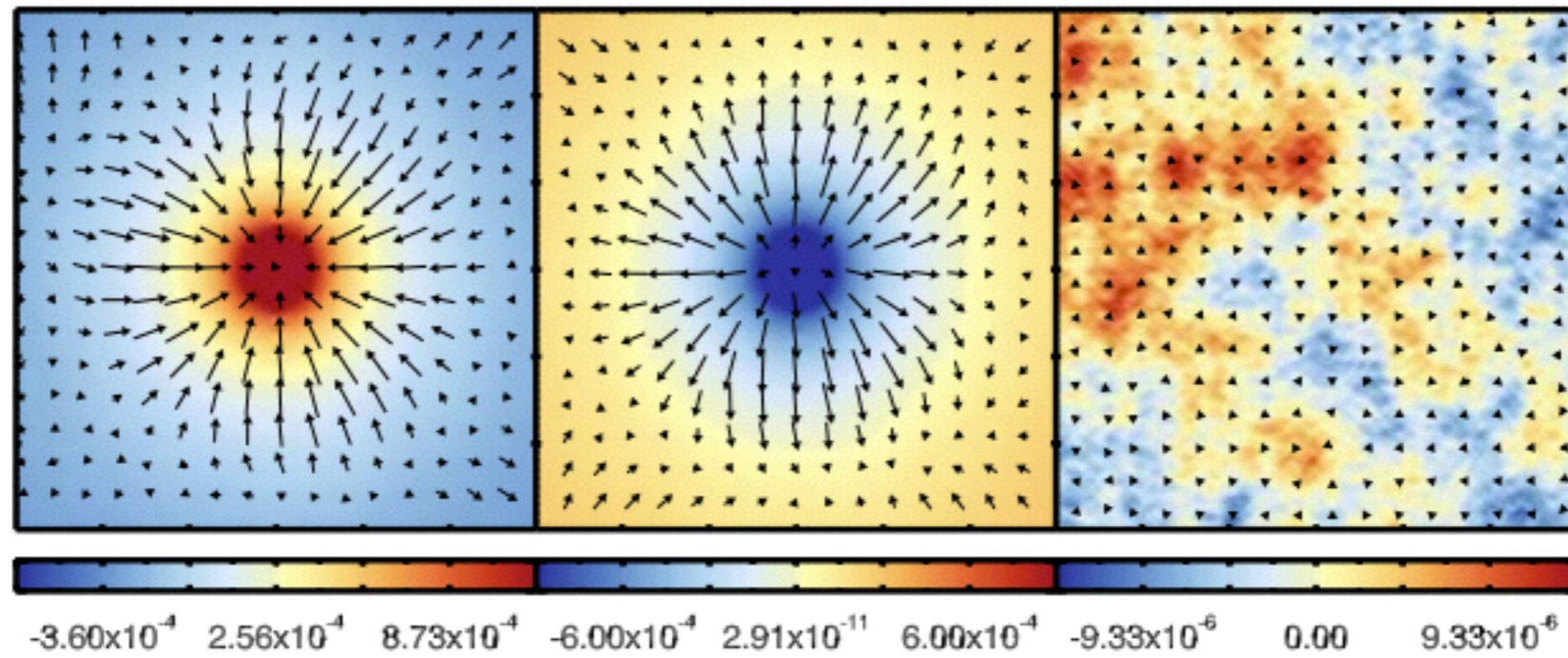


Fig. 28. Temperature maps of size 1 deg^2 at 545 and 857 GHz stacked on the 20,000 brightest peaks (left column), troughs (centre column) and random map locations (right column). The stacked (averaged) temperature maps is in K. The arrows indicate the lensing deflection angle deduced from the gradient of the band-pass filtered lensing potential map stacked on the same peaks. The longest arrow corresponds to a deflection of $6.3''$, which is only a fraction of the total deflection angle because of our filtering. This stacking allows us to visualize in real space the lensing of the CMB by the galaxies that generate the CIB. The small offset between the peak of the lensing potential and the CIB is due to noise in the stacked lensing potential map. We choose the same random locations for both frequencies, hence the similar pattern seen in the top and bottom right panels.

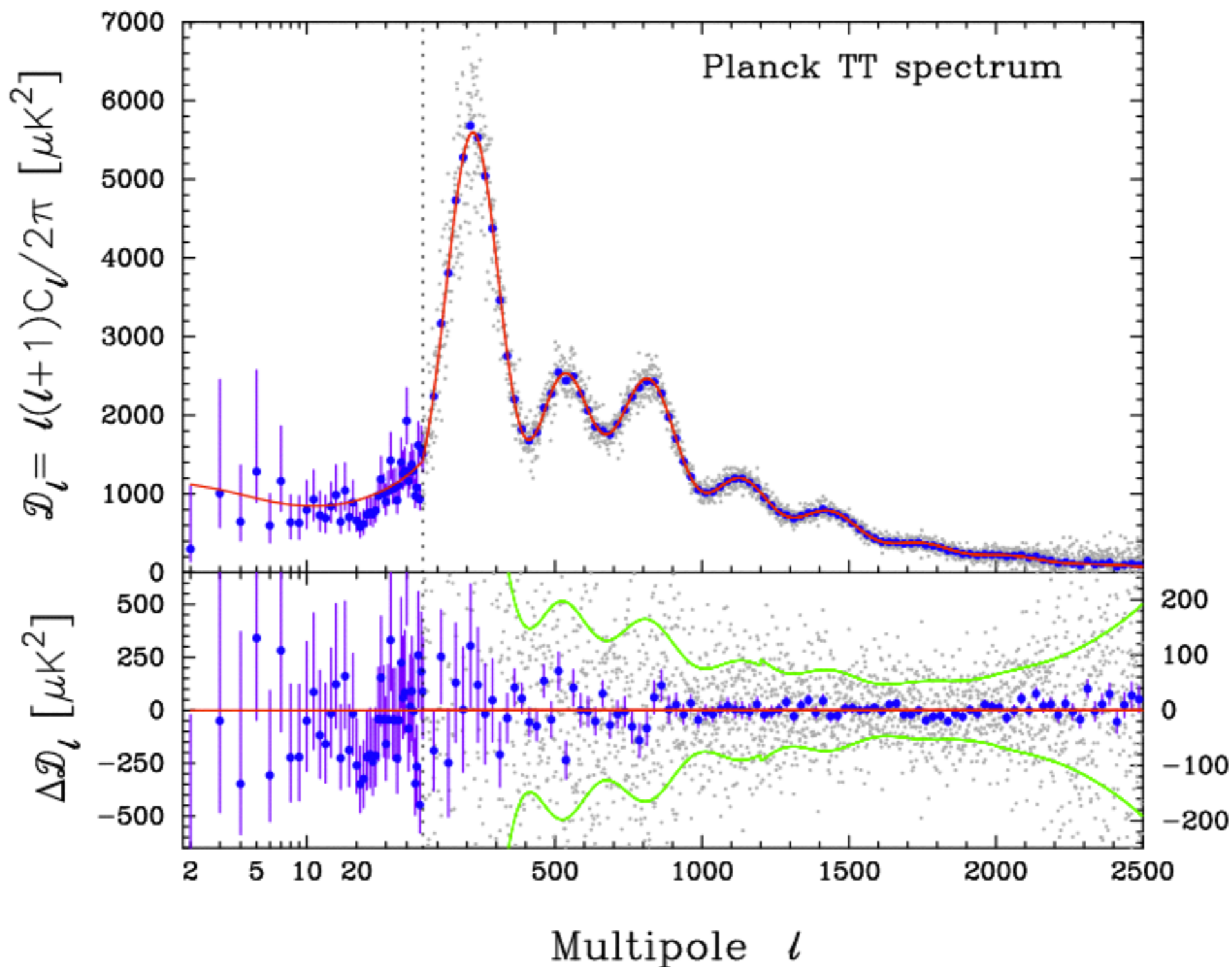


Fig. 1. *Planck* foreground-subtracted temperature power spectrum (with foreground and other “nuisance” parameters fixed to their best-fit values for the base Λ CDM model). The power spectrum at low multipoles ($l = 2$ –49, plotted on a logarithmic multipole scale) is determined by the Commander algorithm applied to the *Planck* maps in the frequency range 30–353 GHz over 91% of the sky. This is used to construct a low-multipole temperature likelihood using a Blackwell-Rao estimator, as described in [Planck Collaboration XV \(2013\)](#). The asymmetric error bars show 68% confidence limits and include the contribution from uncertainties in foreground subtraction. At multipoles $50 \leq l \leq 2500$ (plotted on a linear multipole scale) we show the best-fit CMB spectrum computed from the CamSpec likelihood (see [Planck Collaboration XV 2013](#)) after removal of unresolved foreground components. The light grey points show the power spectrum multipole-by-multipole. The blue points show averages in bands of width $\Delta l \approx 31$ together with 1σ errors computed from the diagonal components of the band-averaged covariance matrix (which includes contributions from beam and foreground uncertainties). The red line shows the temperature spectrum for the best-fit base Λ CDM cosmology. The lower panel shows the power spectrum residuals with respect to this theoretical model. The green lines show the $\pm 1\sigma$ errors on the individual power spectrum estimates at high multipoles computed from the CamSpec covariance matrix. Note the change in vertical scale in the lower panel at $l = 50$.

Table 2. Cosmological parameter values for the six-parameter base Λ CDM model. Columns 2 and 3 give results for the *Planck* temperature power spectrum data alone. Columns 4 and 5 combine the *Planck* temperature data with *Planck* lensing, and columns 6 and 7 include *WMAP* polarization at low multipoles. We give best fit parameters as well as 68% confidence limits for constrained parameters. The first six parameters have flat priors. The remainder are derived parameters as discussed in Sect. 2. Beam, calibration parameters, and foreground parameters (see Sect. 4) are not listed for brevity. Constraints on foreground parameters for *Planck*+WP are given later in Table 5.

Parameter	<i>Planck</i>		<i>Planck</i> +lensing		<i>Planck</i> +WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_p	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

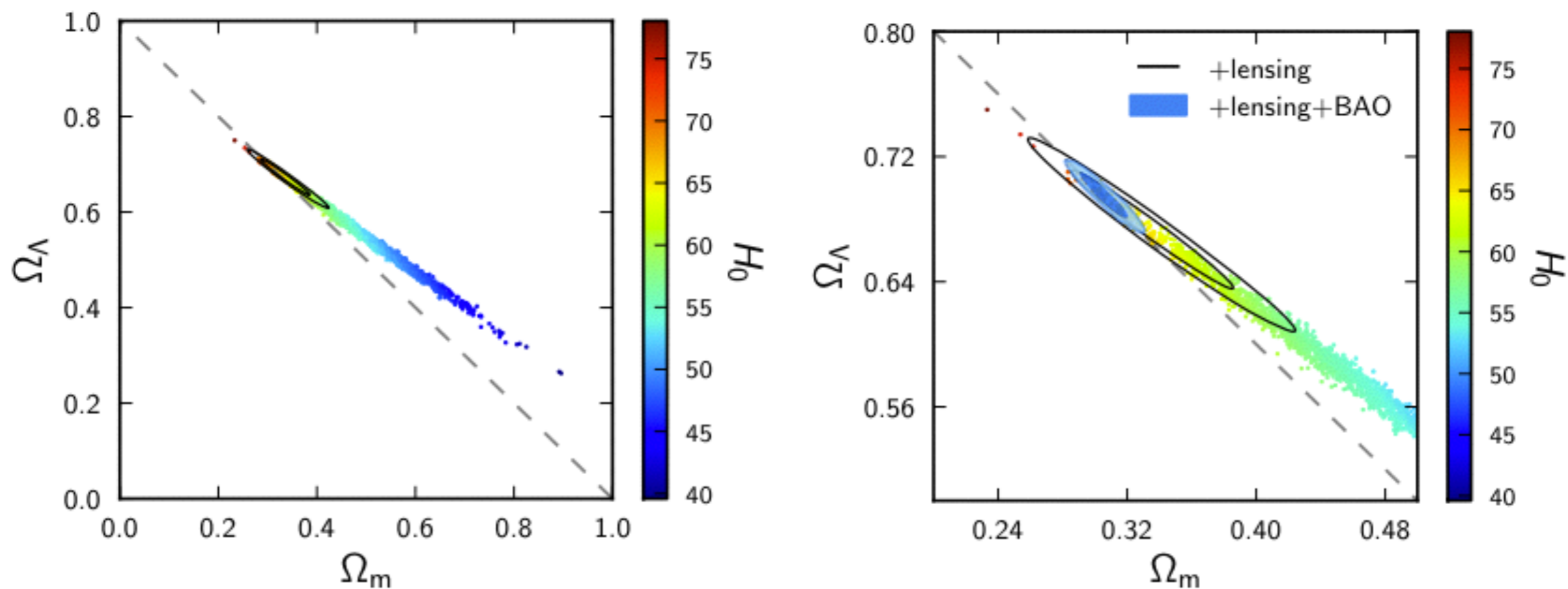


Fig. 25. The *Planck*+WP+highL data combination (samples; colour-coded by the value of H_0) partially breaks the geometric degeneracy between Ω_m and Ω_Λ due to the effect of lensing in the temperature power spectrum. These limits are significantly improved by the inclusion of the *Planck* lensing reconstruction (black contours). Combining also with BAO (right; solid blue contours) tightly constrains the geometry to be nearly flat.