

Comprendre l'infiniment grand

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L'infiniment grand...

- ~ La cosmologie :
 - Cosmologiste ?
 - Outils de recherche ?
 - Objet d'étude ?

À l'aube de la cosmologie moderne

Début du 20^e siècle

- L'Univers est considéré immuable et éternel
- Son étendue (univers visible) se résume à la Voie Lactée
- Possibilité envisagée d'autres « Univers – Îles » (cf. P.S. de Laplace, E. Kant)

Le Grand Débat : 1920



Shapley vs. Curtis

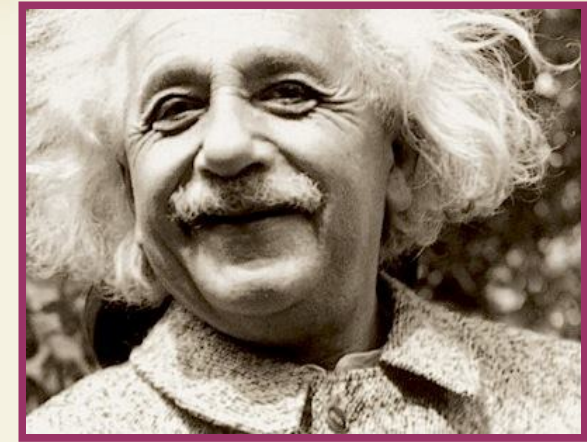
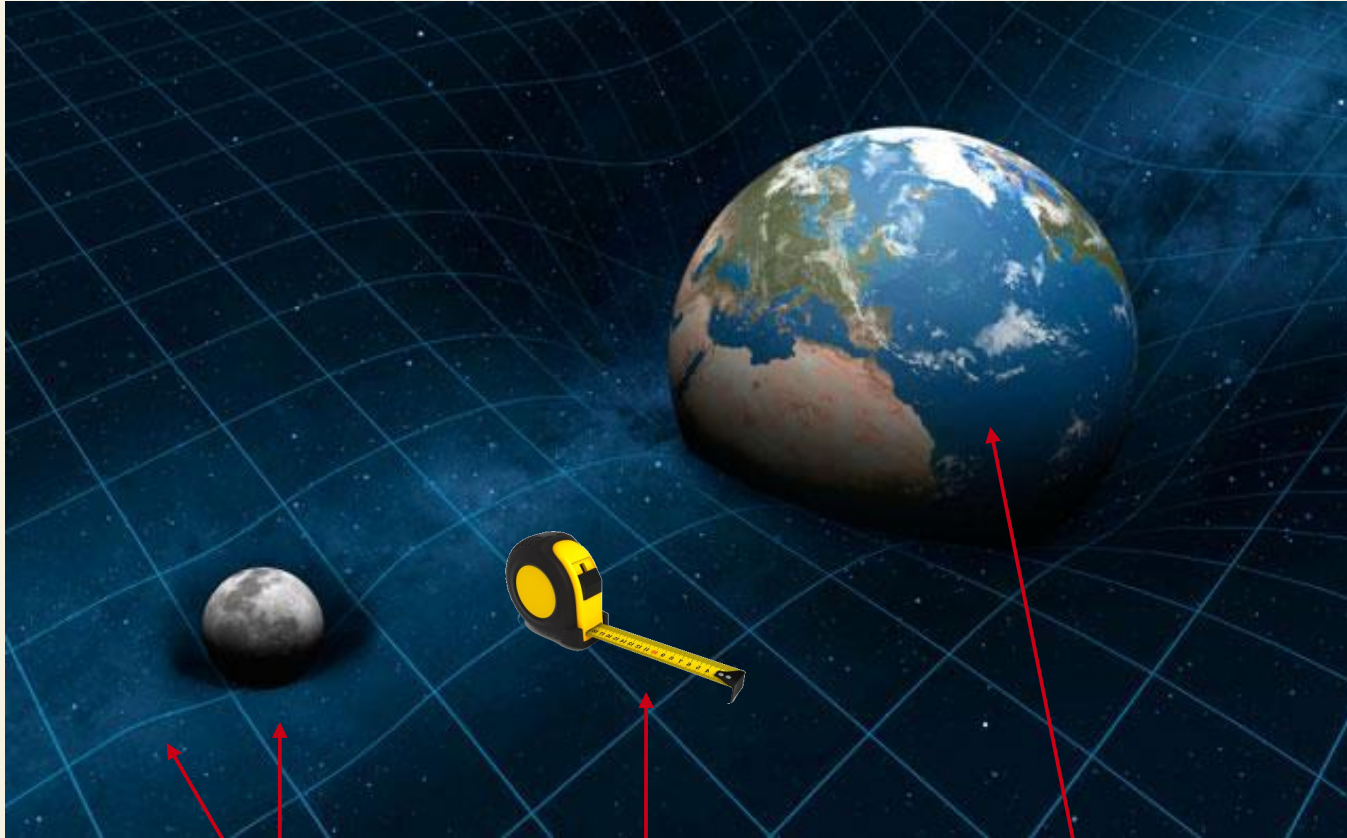


Citation de H. Shapley

« From the new point of view our galactic universe appears as a single, enormous, all-comprehending unit [...] The adoption of such an arrangement leaves us with no evidence of a plurality of stellar 'universes'. [...] The hypothesis that spiral nebulae are separate galactic systems now meets with further difficulties.» (1920)

Mais pendant ce temps, du côté de la théorie...

La Relativité Générale !



$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Variation de la
courbure
de place en place

Mesure des distances
étant donnée la courbure R
en chaque point

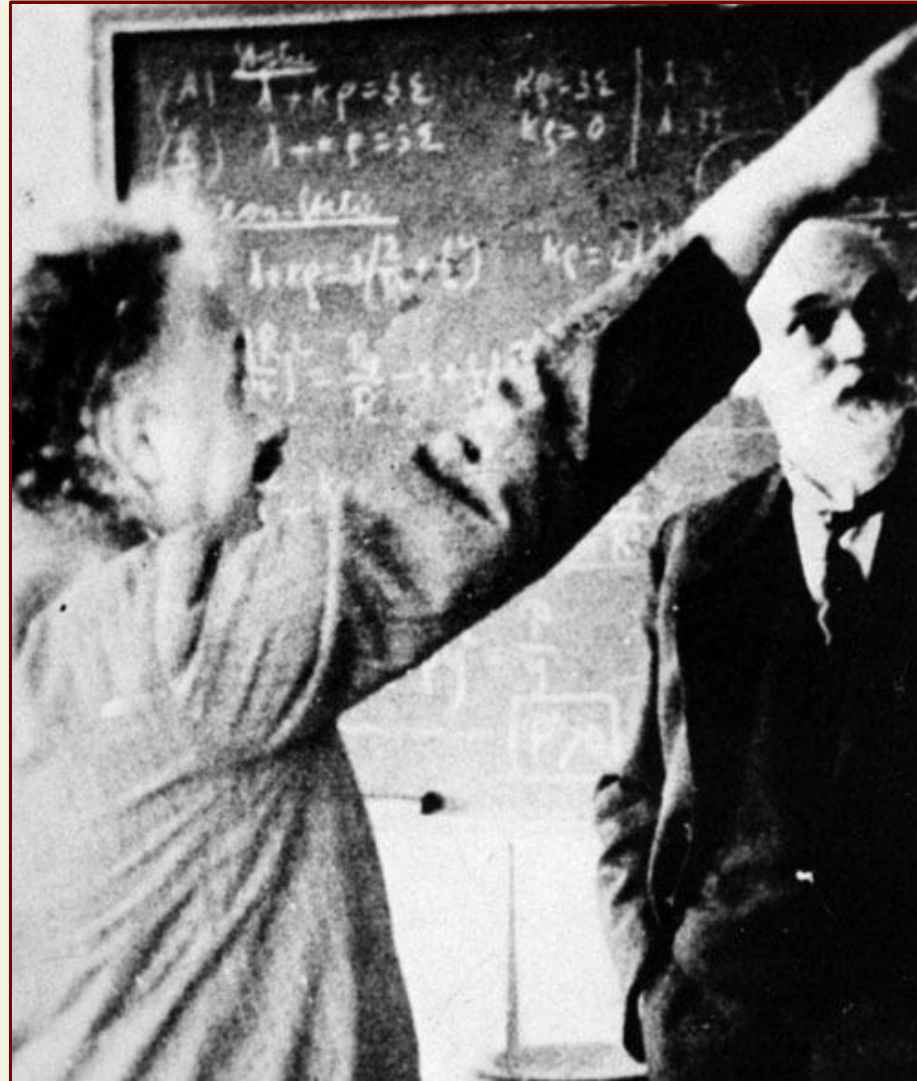
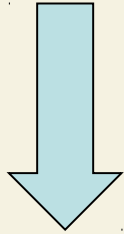
Matière et énergie
courbent l'espace

*Die Feldgleichungen
der Gravitation, 1915*

Application de la Relativité Générale à l'Univers entier : 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie

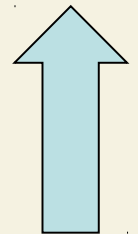
Albert Einstein



Univers vide,

courbure non-nulle,

solution : en expansion



Willem de Sitter

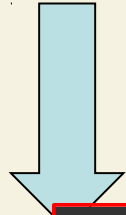
Univers plein de matière
courbure induite
par la masse,

**solution :
en expansion**

Application de la Relativité Générale à l'Univers entier : 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie

Albert Einstein



Univers vide,

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

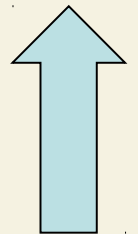
non-nulle,

Univers plat
courbure
par la masse,

solution :
en expansion



solution : en expansion



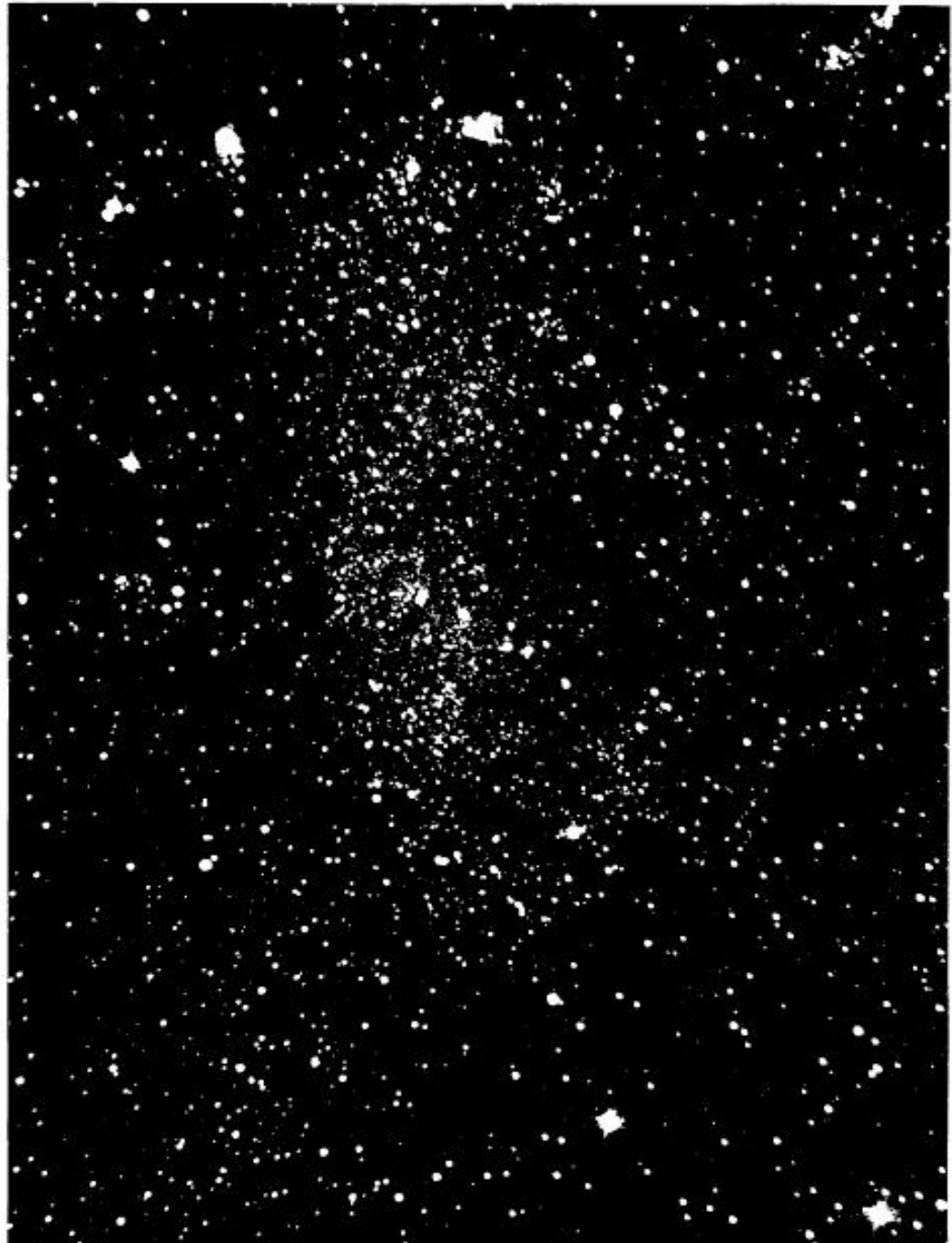
Willem de Sitter



Nébuleuses spirales
=
Galaxies, à l'extérieur!

(1925)

E



N.G.C. 6822

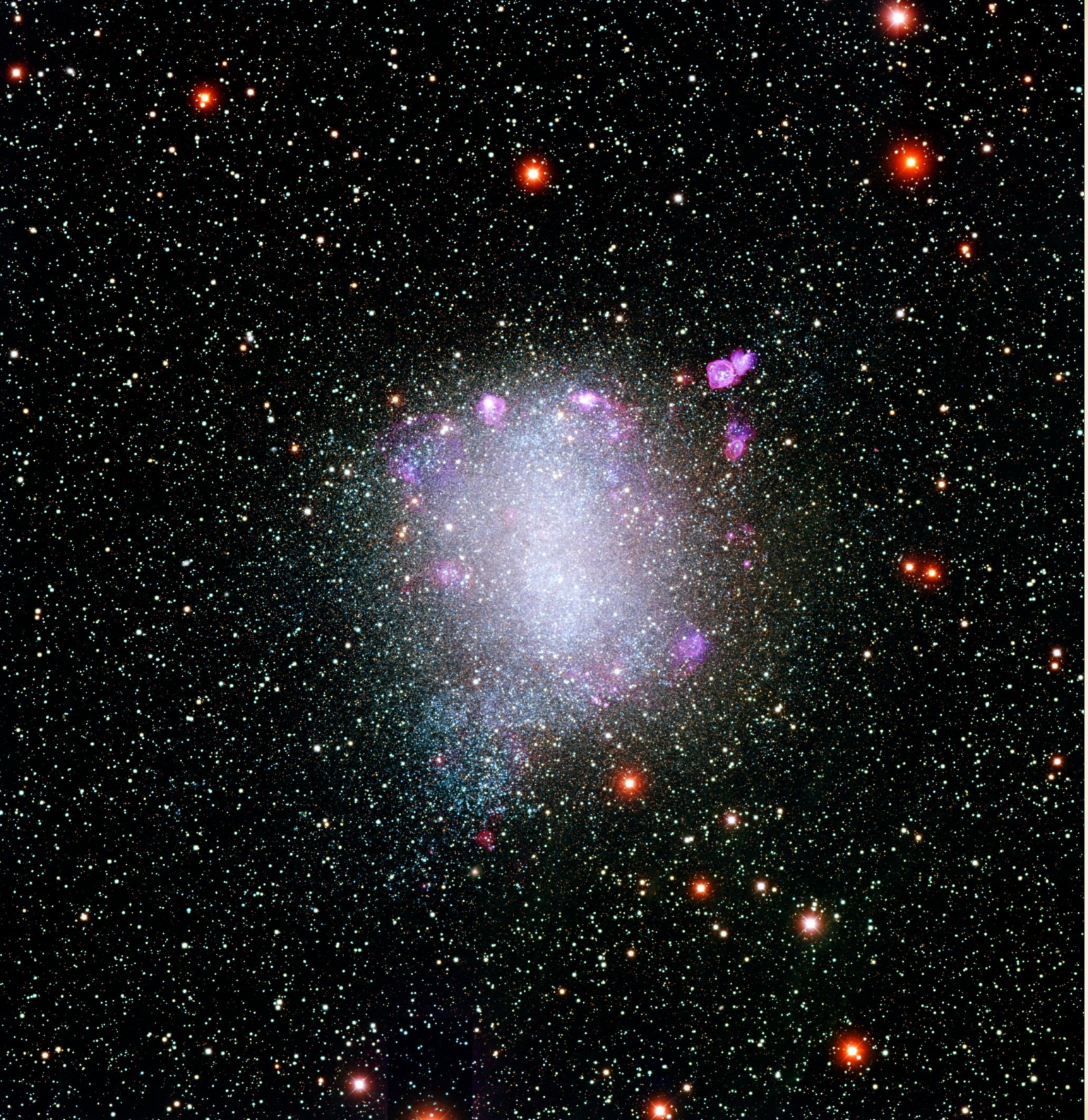
Photographed at the 42-foot focus of the 100-inch Hooker telescope on July 10, 1923. Exposure $3^{\text{h}}30^{\text{m}}$ on a Seed 30 plate. Enlargement 2.5 times original negative

N

W

E. P. Hubble, 1925, ApJ, 62 409
N.G.C. 6822, A Remote Stellar System

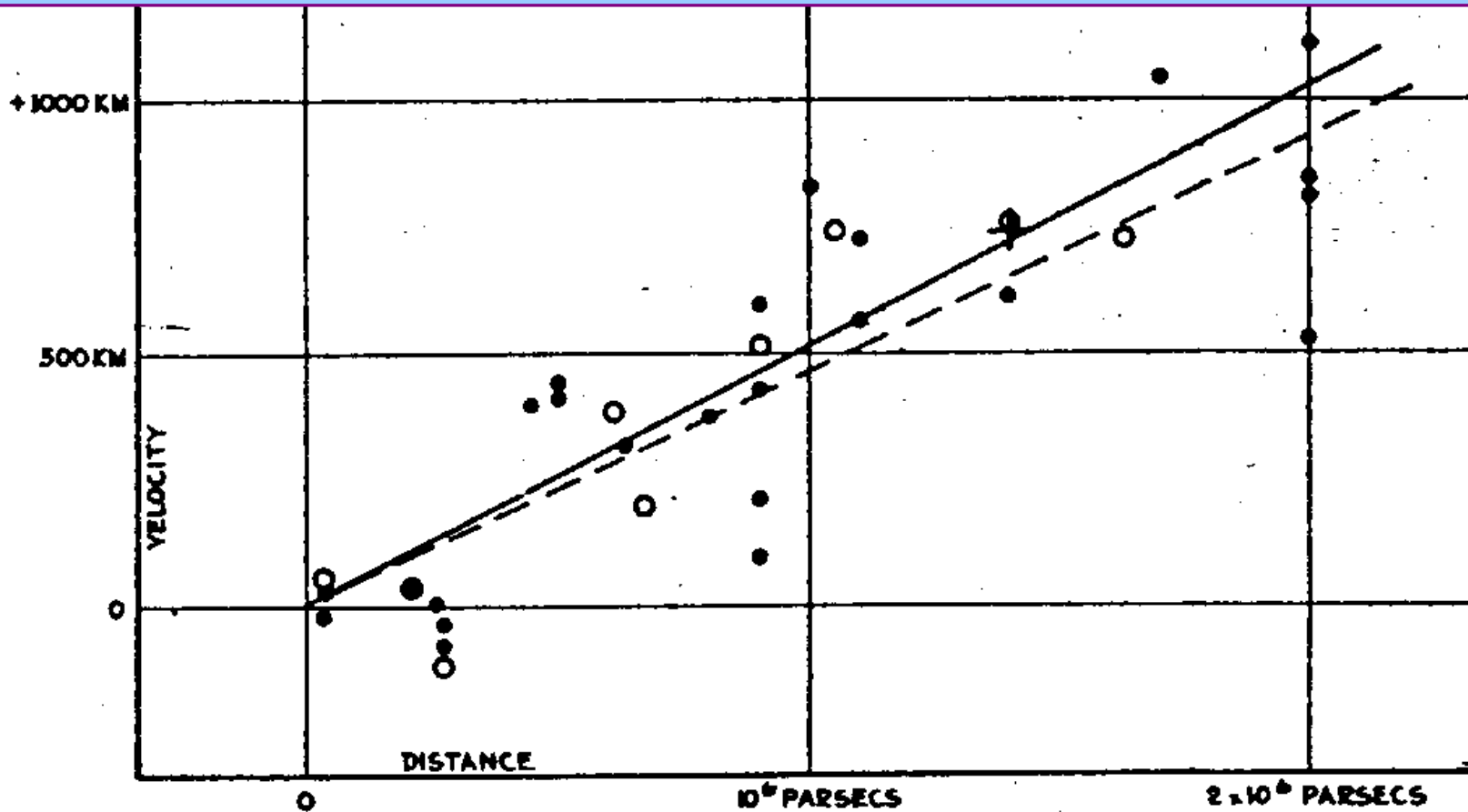
CERRO TOLOLO INTER-AMERICAN OBSERVATORY
P. Massey, G. Jacoby, K. Olsen, C. Smith & T.A. Rector, 2000



Récession des galaxies

E. P. Hubble, 1929, PNAS, **168**, 73

A relation between distance and radial velocity among extra-galactic nebulae



$$V = K \cdot D$$

avec

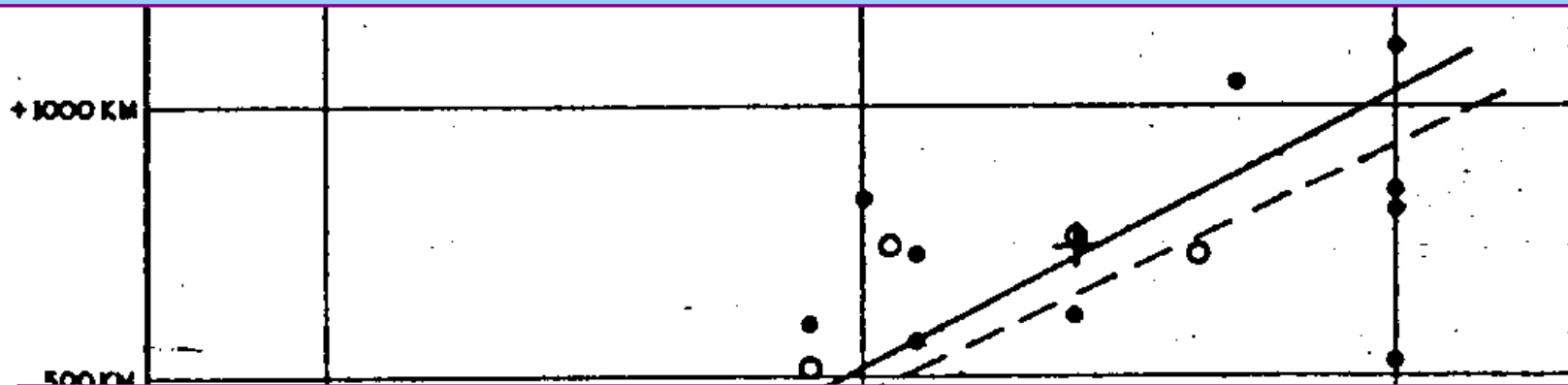
$$K = 500 \text{ km/s/Mpc}$$

1 parsec \sim 3.3 années lumière $\sim 3.1 \times 10^{13}$ km

Récession des galaxies

E. P. Hubble, 1929, PNAS, **168**, 73

A relation between distance and radial velocity among extra-galactic nebulae



Interprétation : **expansion de l'univers** lui-même !

Et donc, on abandonne Λ ...

(Einstein, de Sitter, Friedmann, Lemaître, Milne, Robertson, Walker)

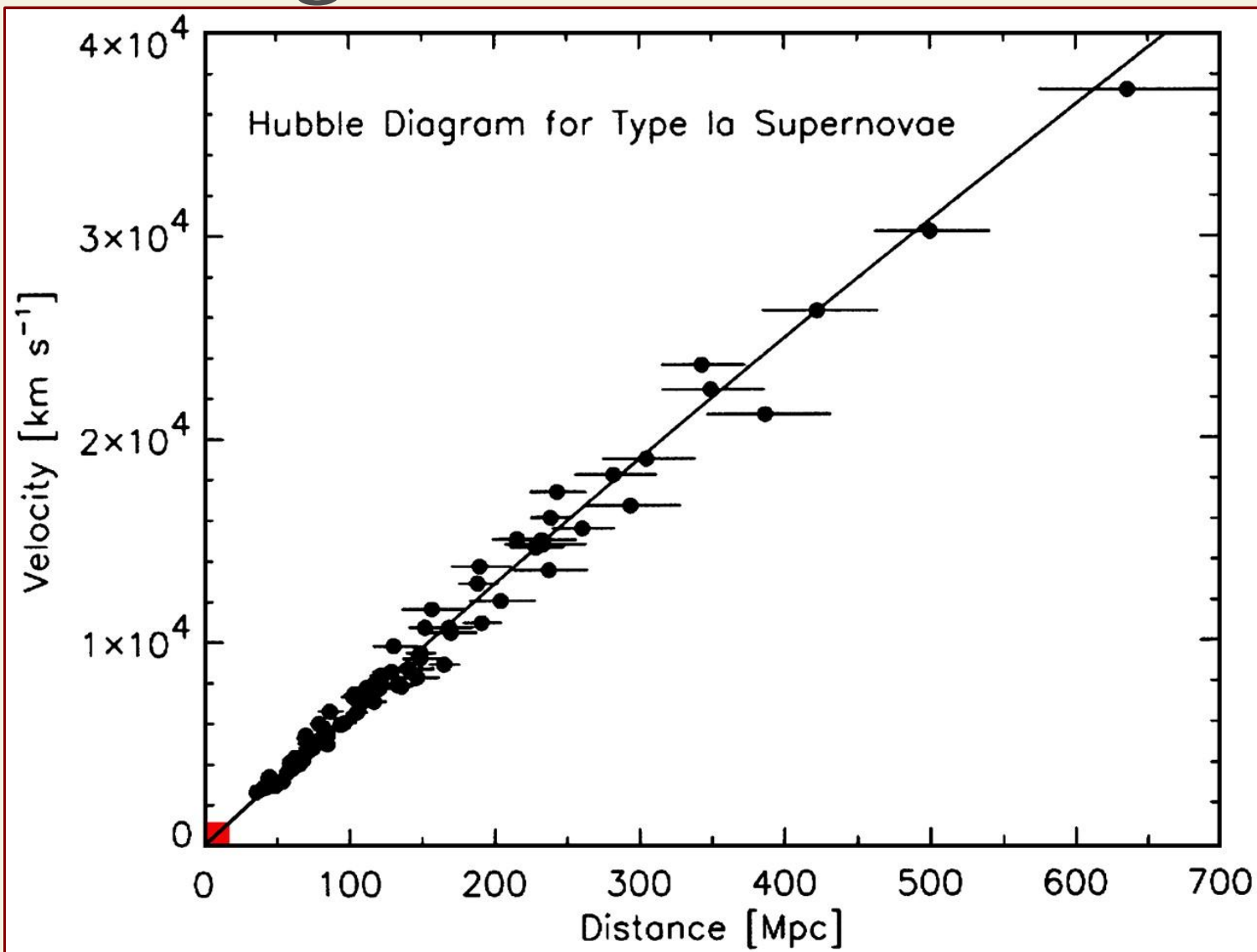
$$V = K \cdot D$$

avec

$$K = 500 \text{ km/s/Mpc}$$

1 parsec \sim 3.3 années lumière $\sim 3.1 \times 10^{13}$ km

Diagramme de Hubble

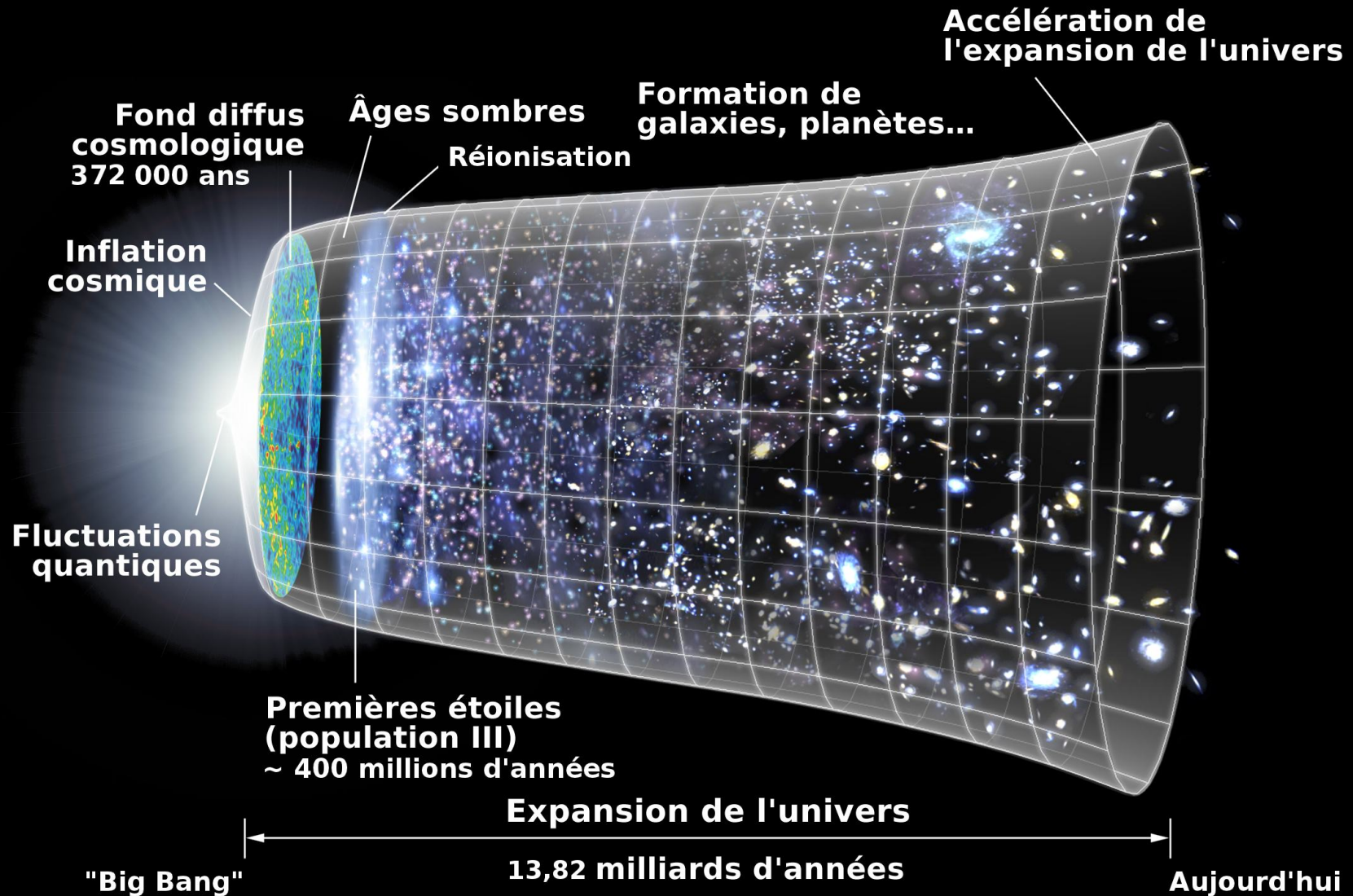


$$H_0 = 71 \pm 2.5 \text{ km/s/Mpc}$$

(WMAP-7,
mais voir
Planck...)

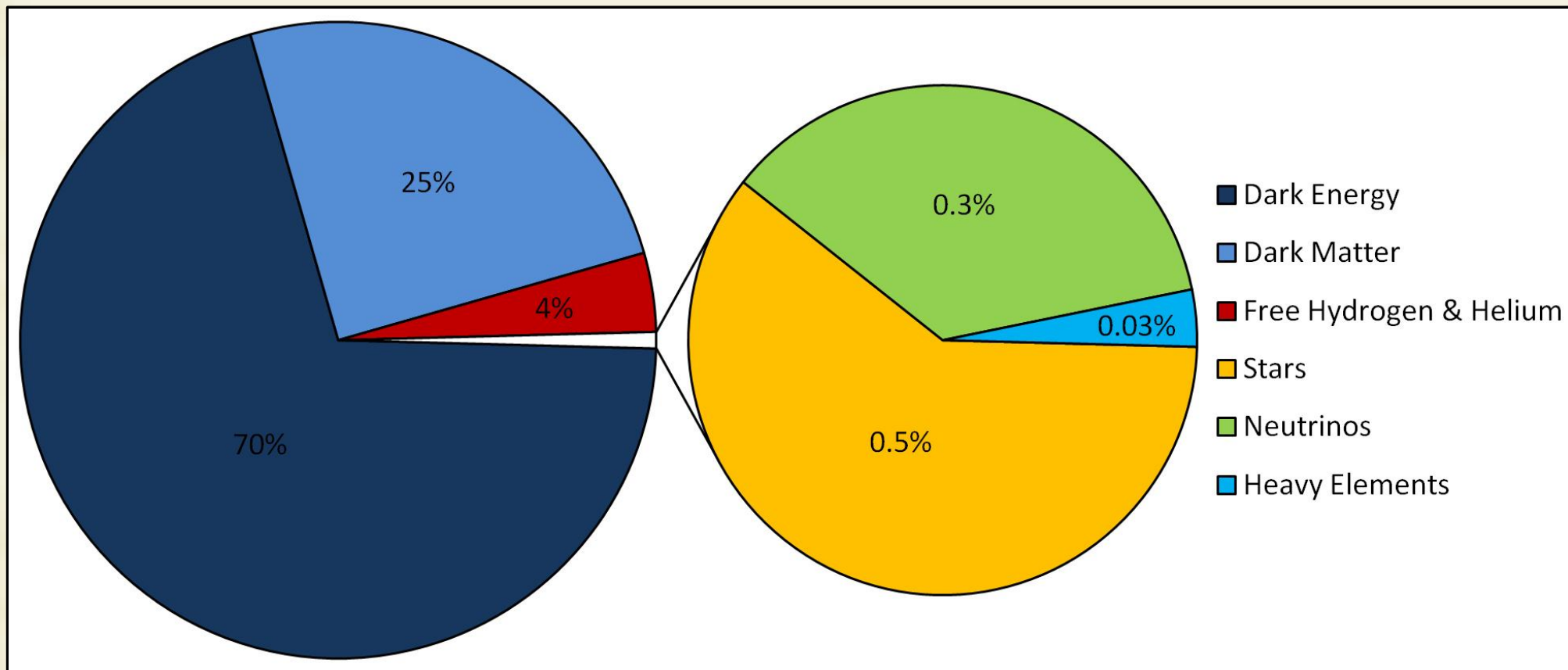
1 parsec \sim 3.3 années lumière $\sim 3.1 \times 10^{13}$ km

L'histoire de l'Univers, en une image...

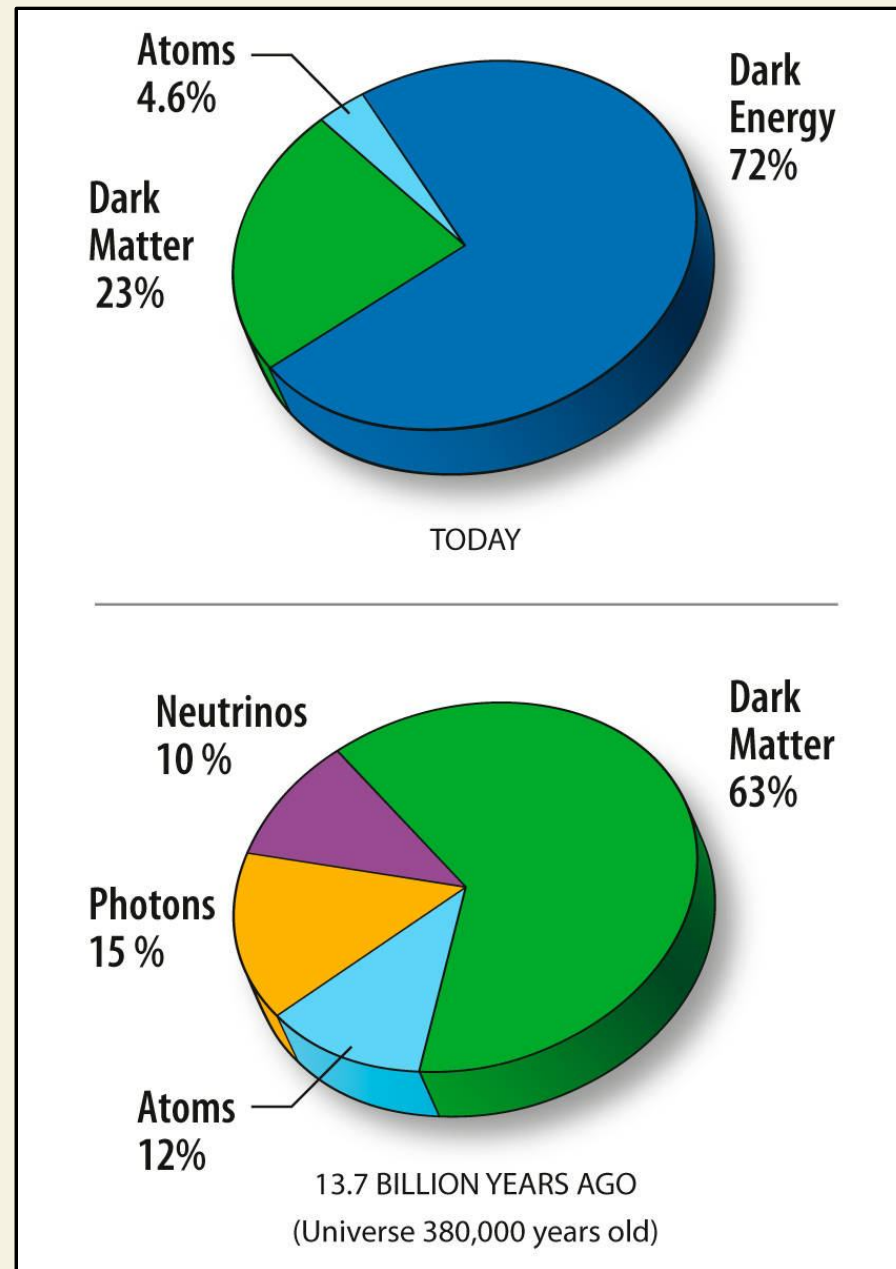


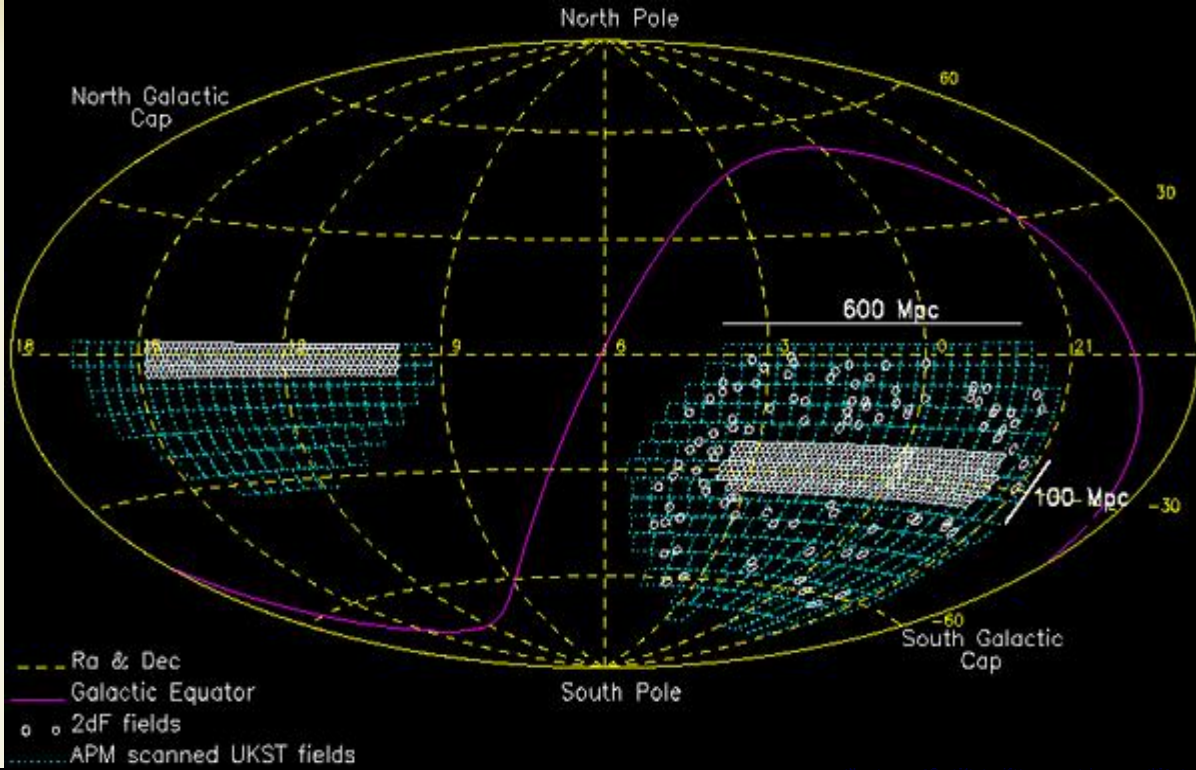
Le contenu actuel de l'Univers

(Rem : ici, chiffres à titre indicatif seulement...)

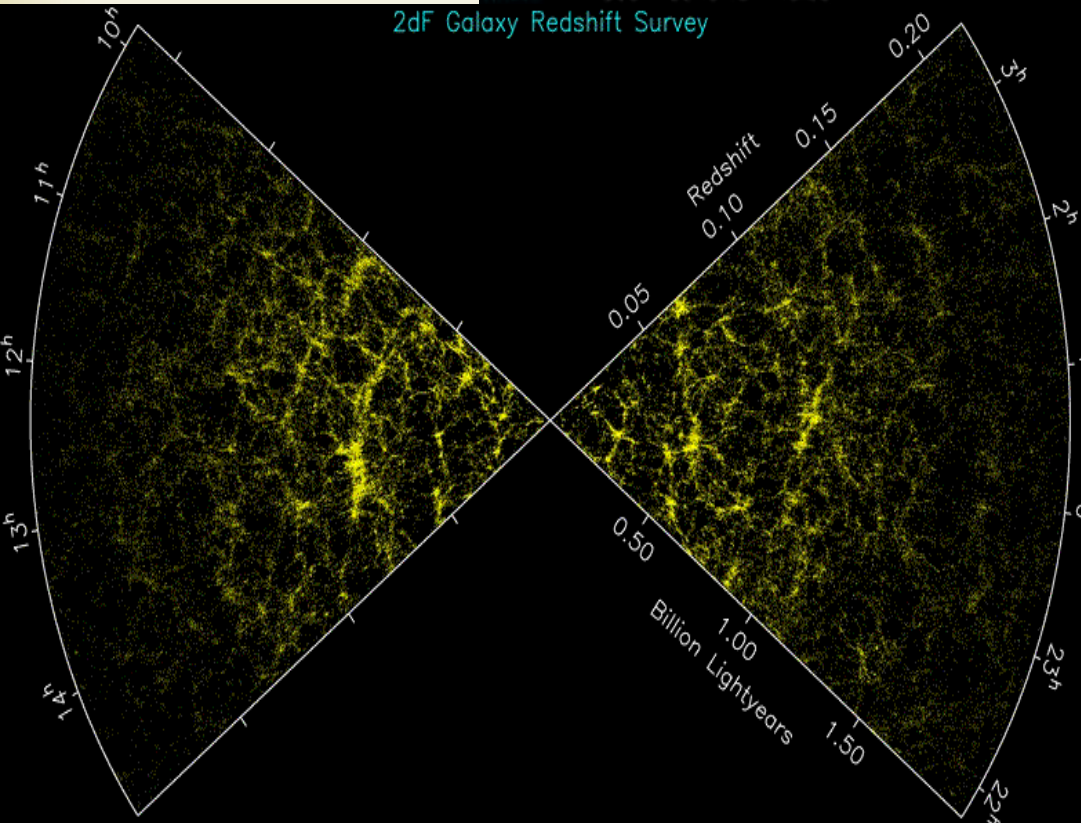


Évolution du contenu

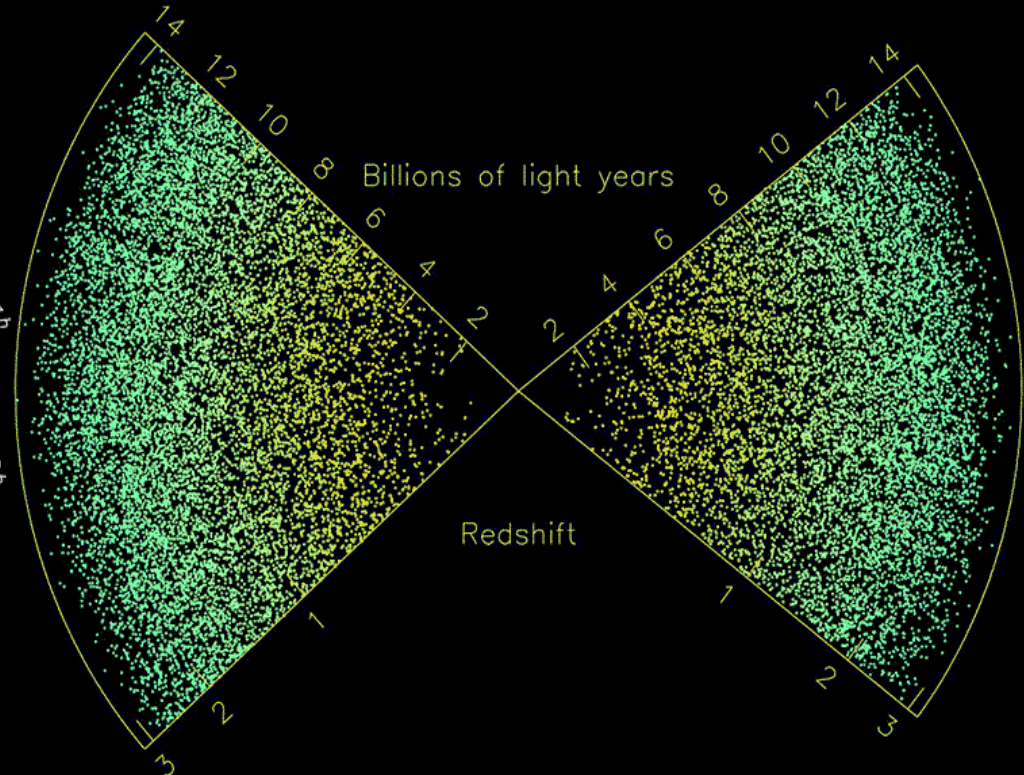




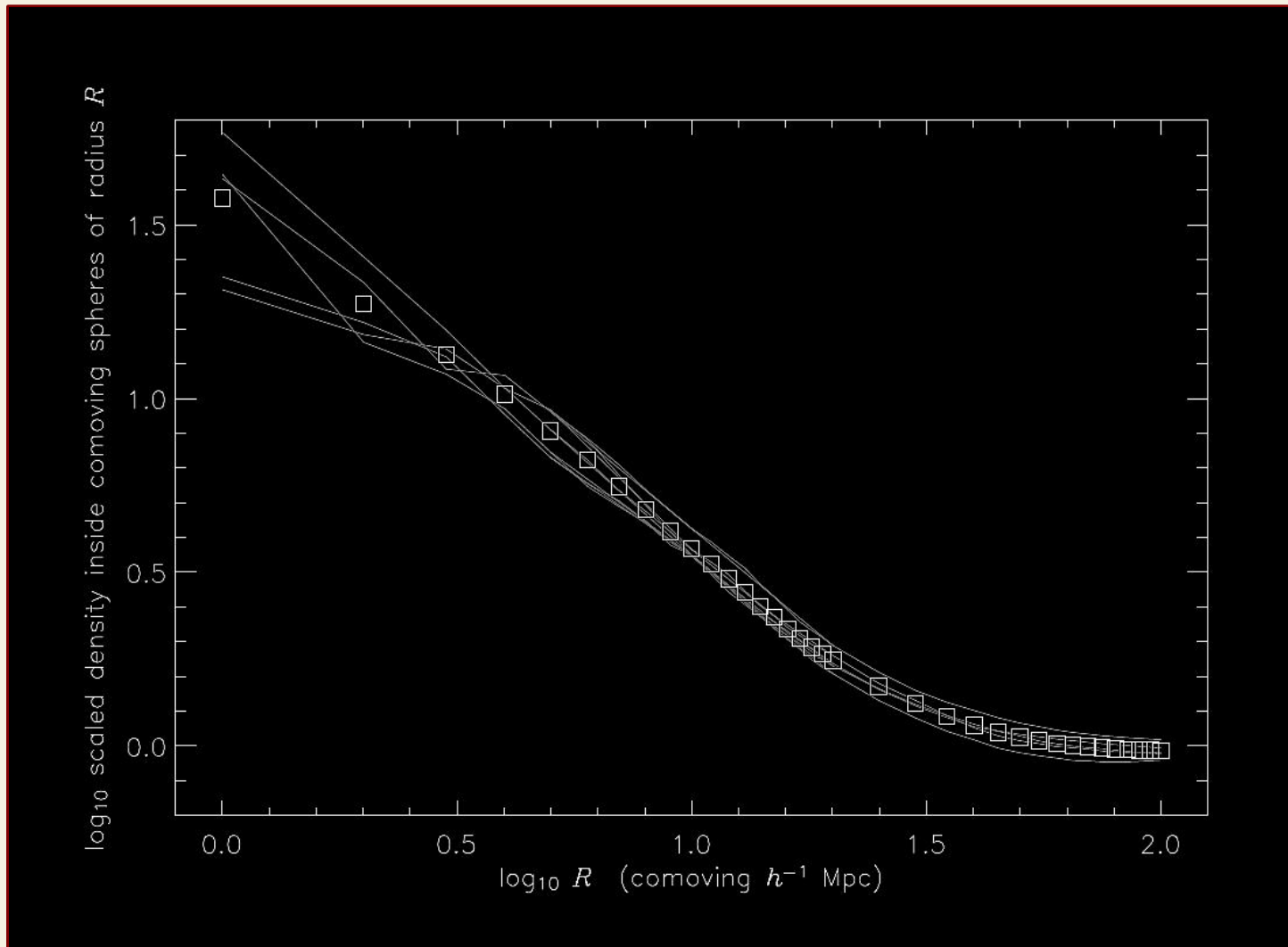
2dF Galaxy Redshift Survey



The 2dF Quasar Redshift Survey

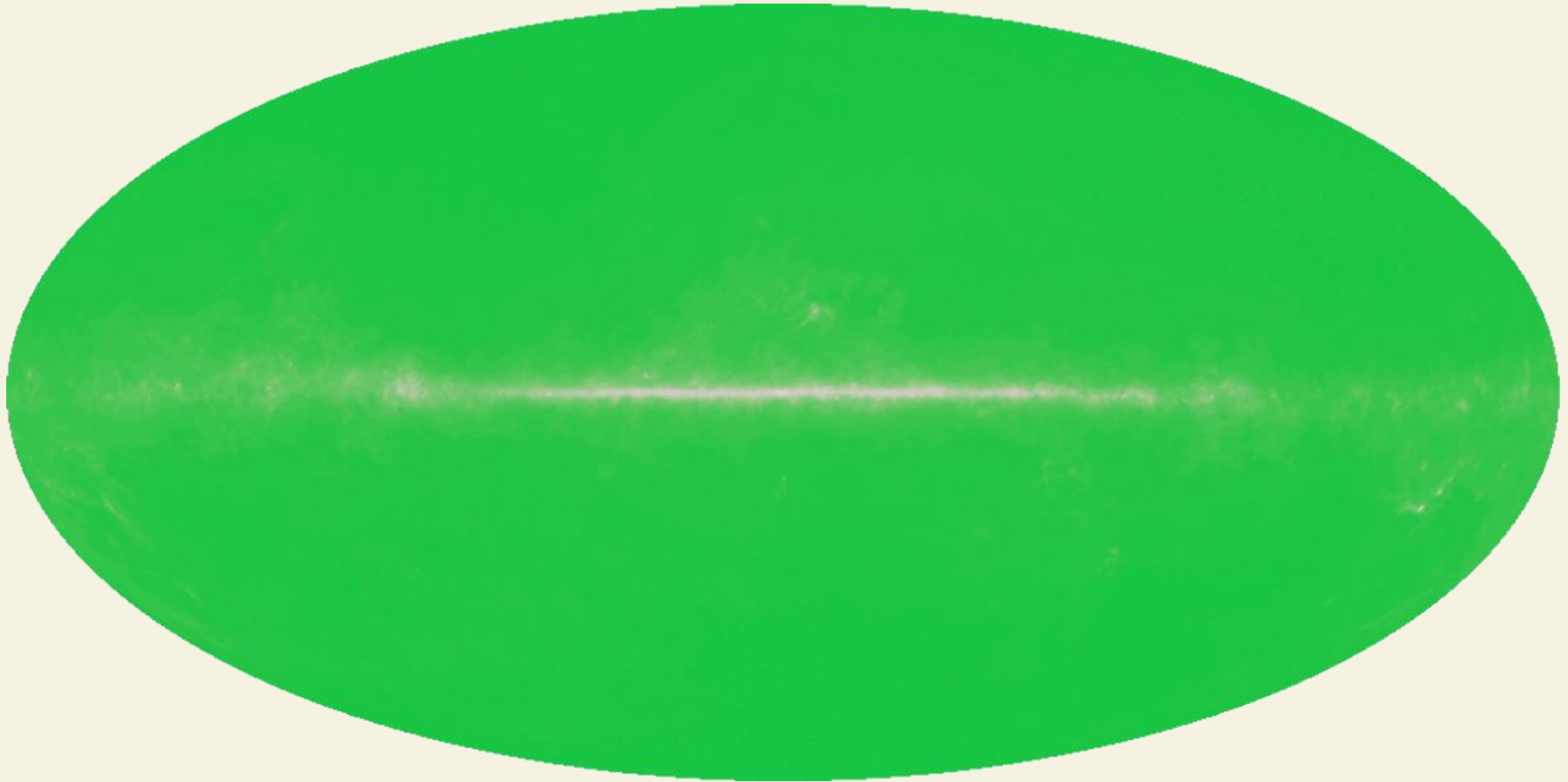


Homogénéité à grande échelle



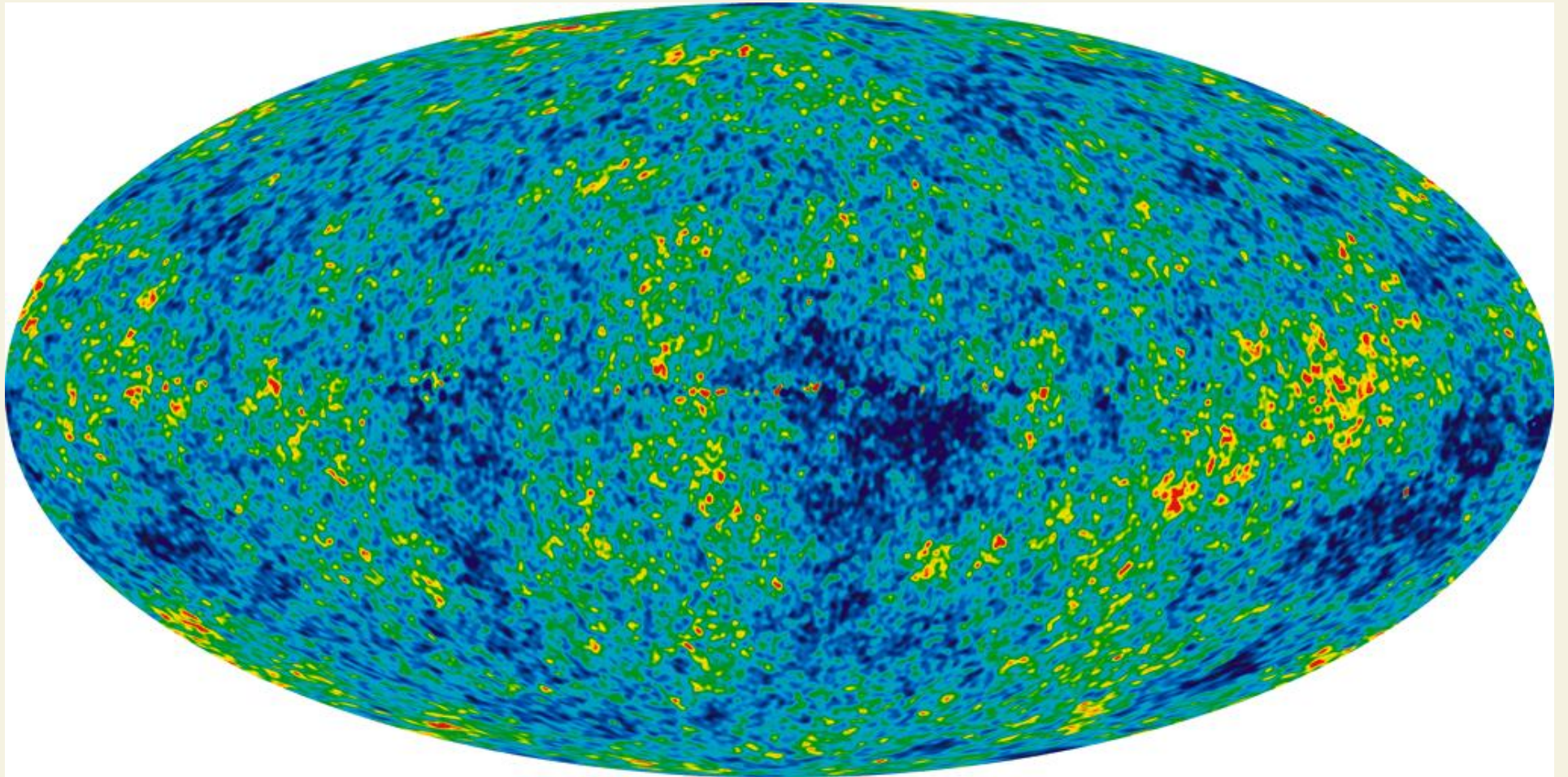
Densité normalisée de galaxies lumineuses rouges
contenues dans des sphères arbitraires de rayon R

Température du Fond Diffus Cosmologique



$$T_{\text{cmb}} = 2.726 \pm 0.001 \text{ K}$$

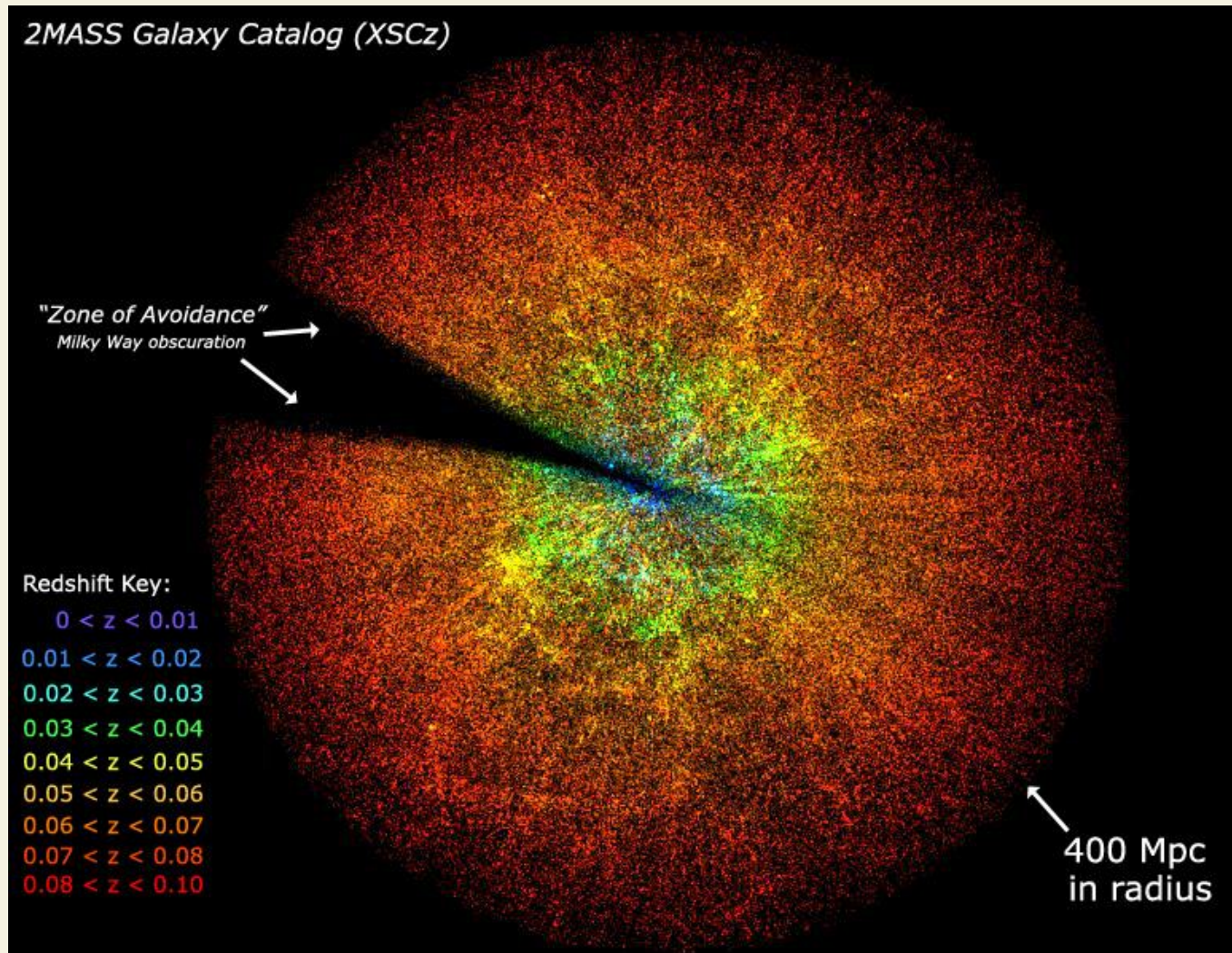
Fluctuations de température du FDC



WMAP-7, ILC map

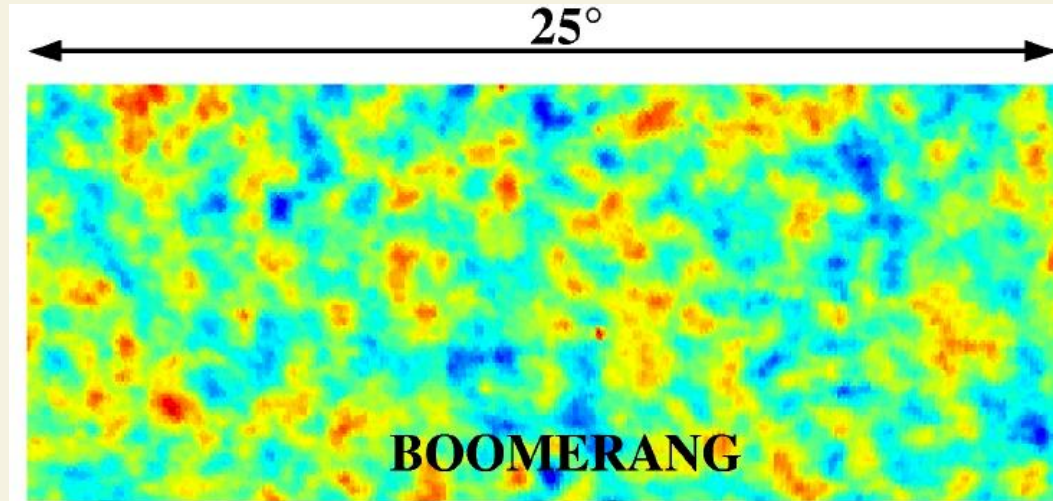
$$-200 \mu\text{K} \leq \Delta T \leq 200 \mu\text{K}$$

Distribution isotrope de galaxies



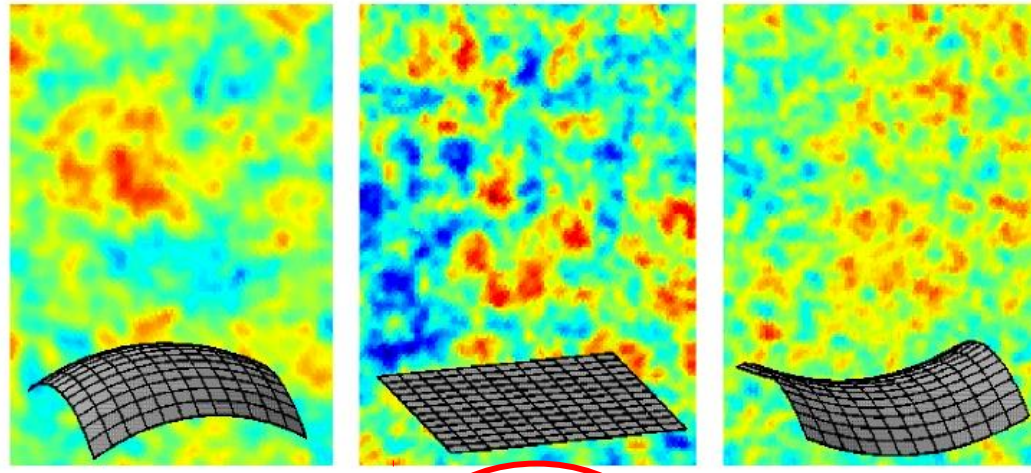
Le CMB et la géométrie de l'Univers

Données
(1998)



Taille angulaire
typique : 1°

Cartes
simulées



Sphérique

Euclidien
("plat")

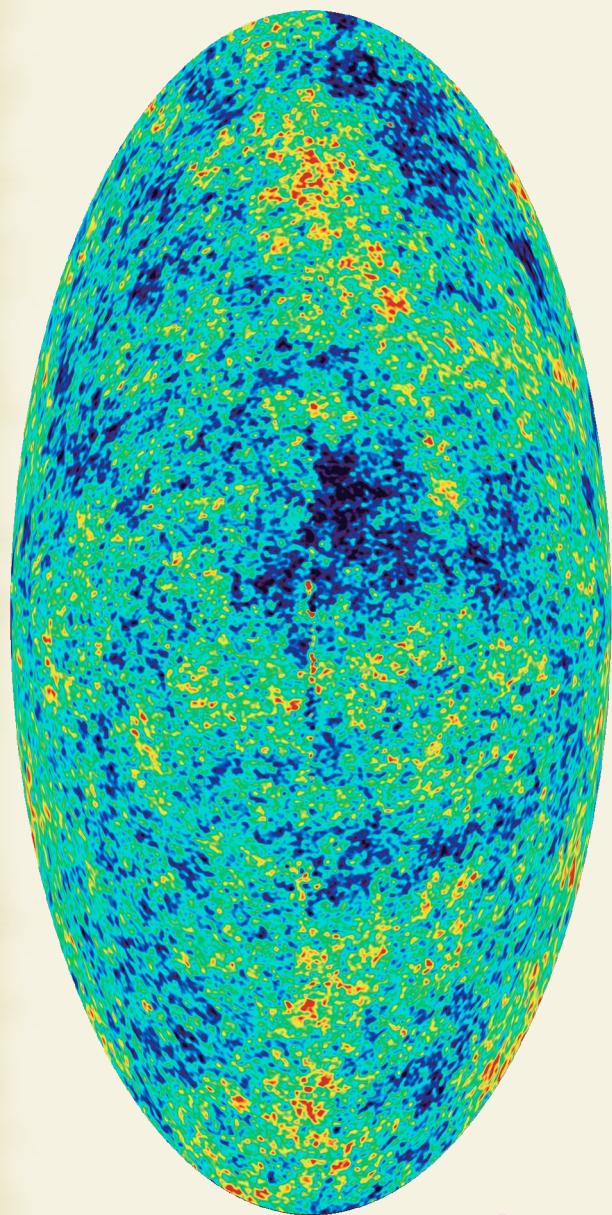
Hyperbolique

Analyse statistique

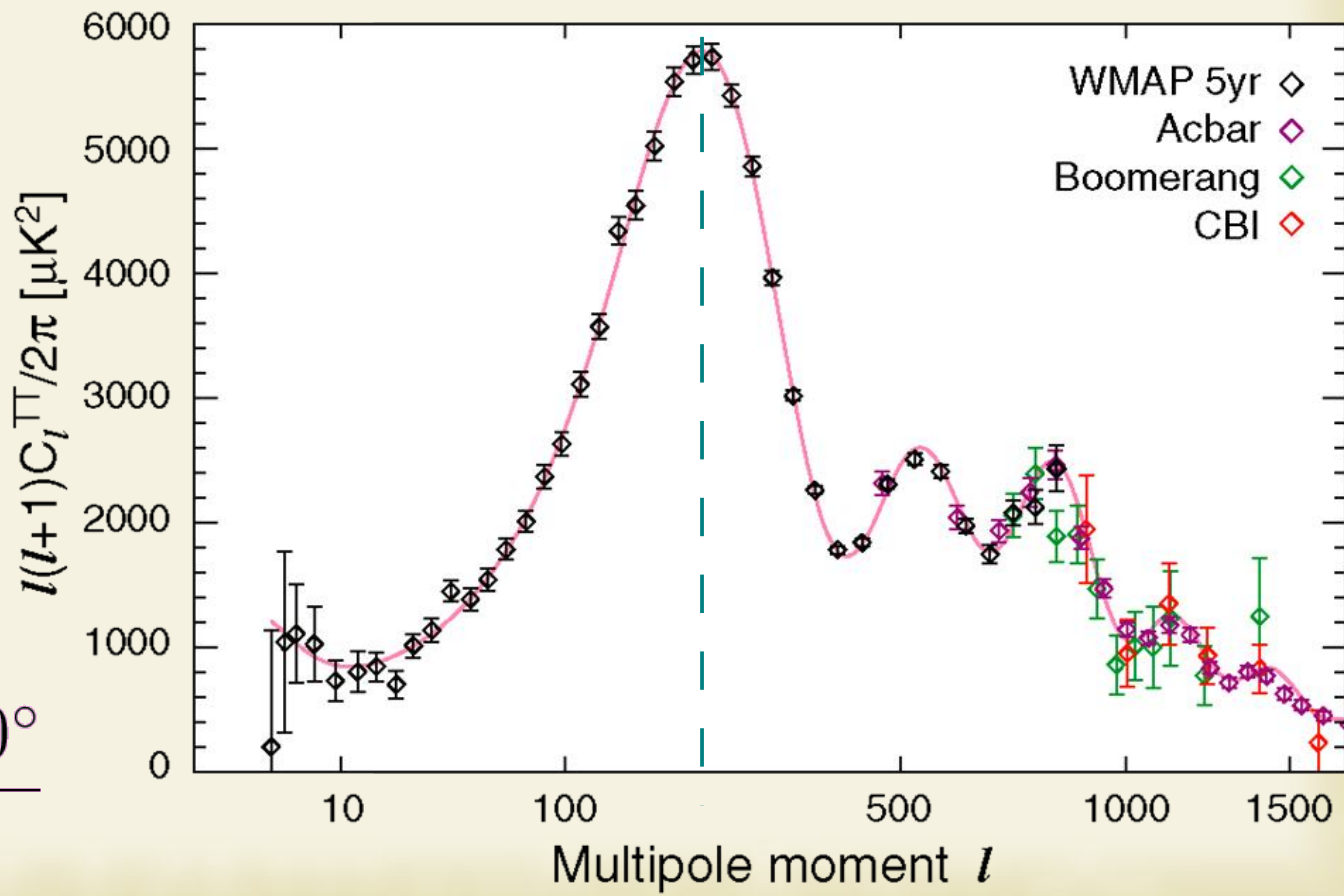
$$\frac{\Delta T}{\bar{T}}(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_l^m(\theta, \varphi)$$

$$C_l \sim \text{TF} \left[\left\langle \frac{\Delta T}{\bar{T}}(\vec{n}_1) \frac{\Delta T}{\bar{T}}(\vec{n}_2) \right\rangle \right]$$

$$\Rightarrow C_l = \langle |a_{lm}|^2 \rangle$$



$$l \simeq \frac{180^\circ}{\theta}$$



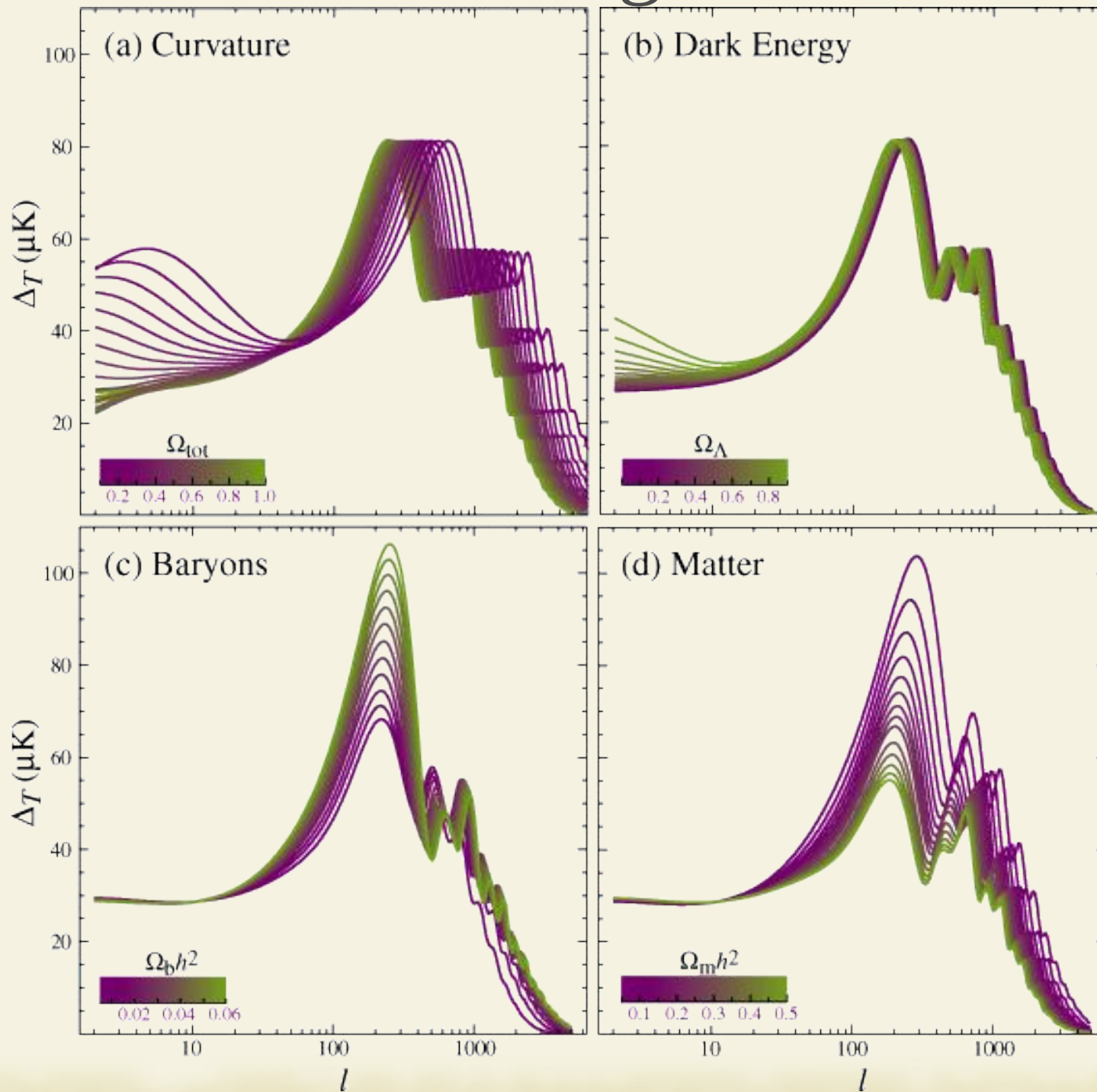
Simulation des anisotropies de température

&

Paramètres cosmologiques :

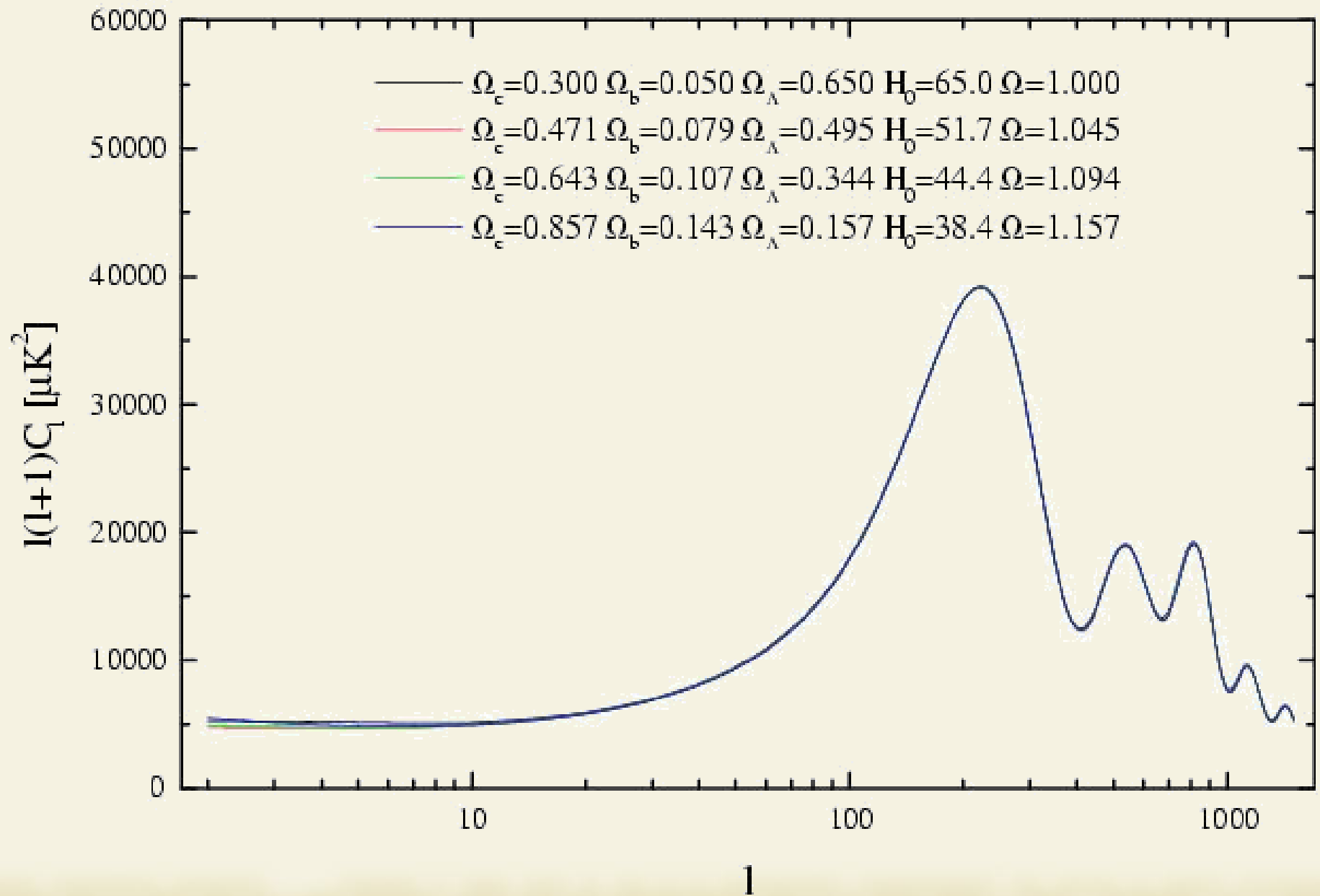
Planck simulator, <http://www.strudel.org.uk/planck/>

Le CMB et les dégénérescences



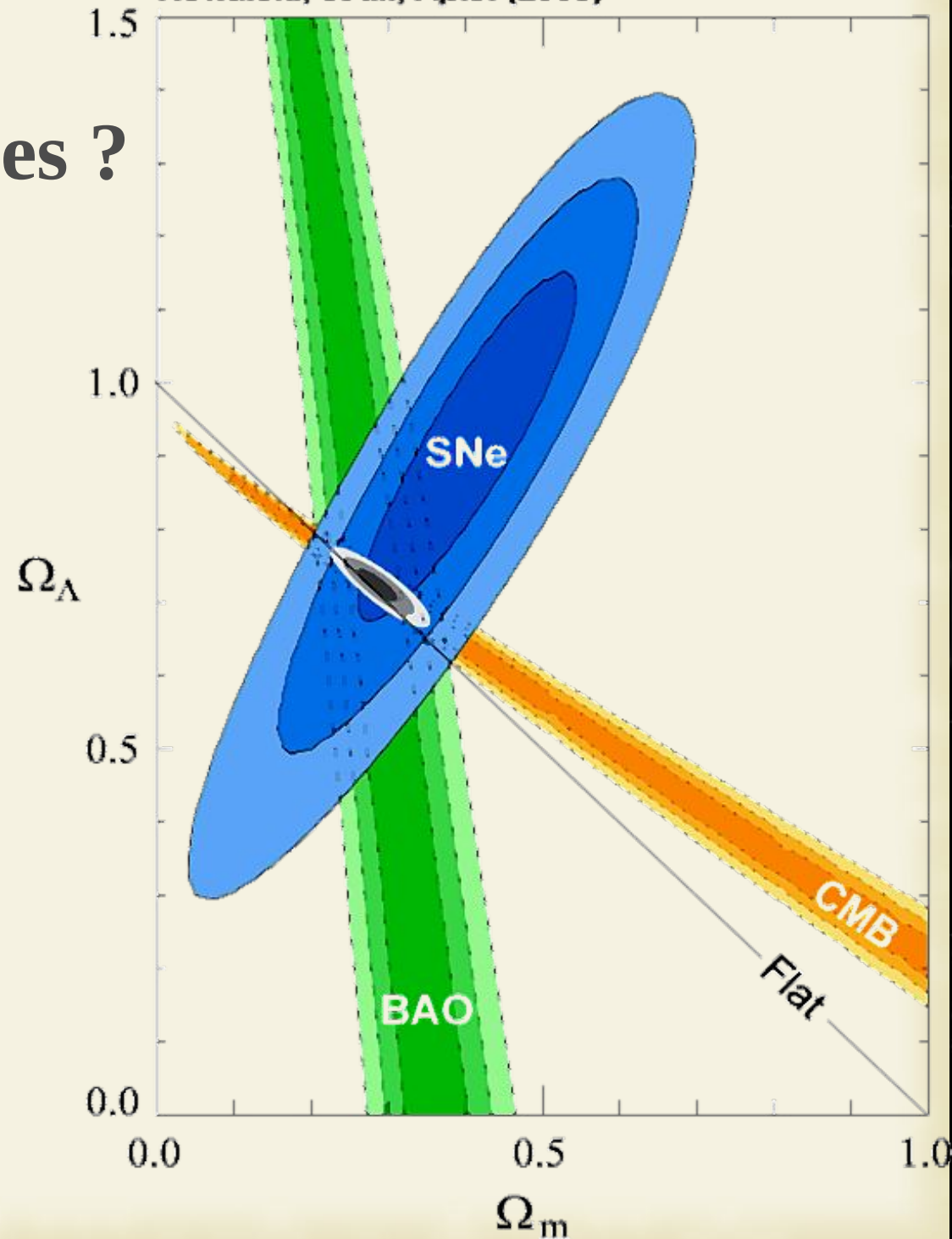
Hu & Dodelson, 2002

Le CMB et les dégénérescences



Lever les dégénérescences ?

Combinaison de
données
indépendantes !



Réduire les dégénérescences ?

→ Construire le télescope ultime : Planck

HFI : J.-L. Puget



LFI : N. Mandolesi

• Lancement le 14 mai 2009 de Kourou

• Orbite autour de L2

• Fin de la mission :

• HFI : fin 2011

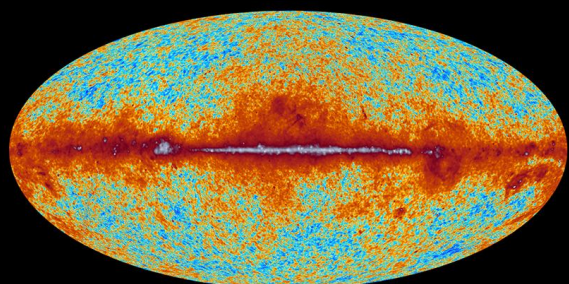
• LFI : mi-2013



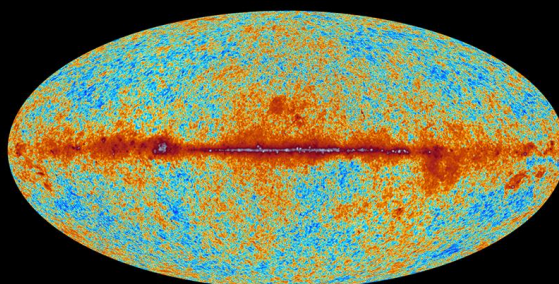


planck

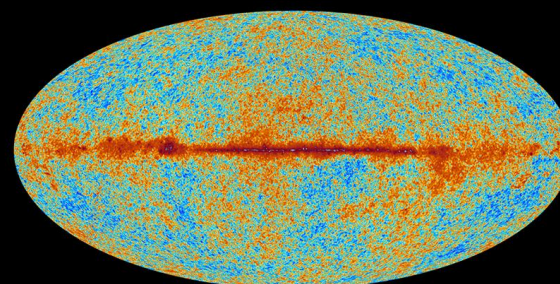
The sky as seen by Planck



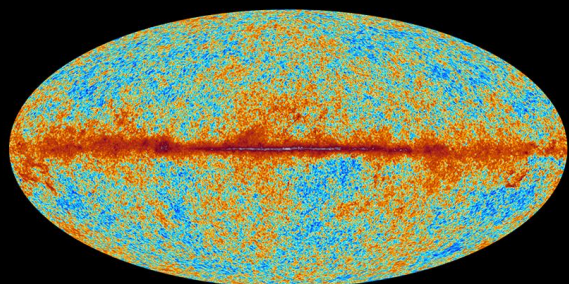
30 GHz



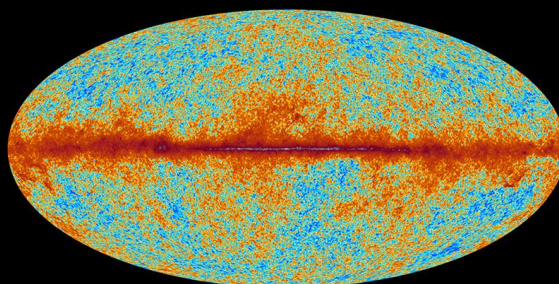
44 GHz



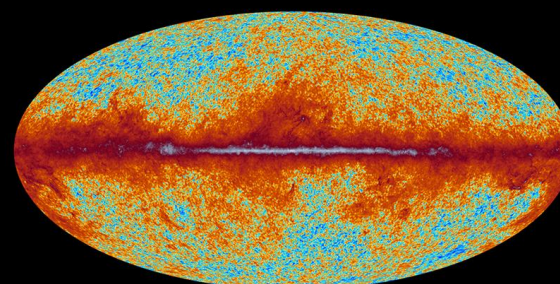
70 GHz



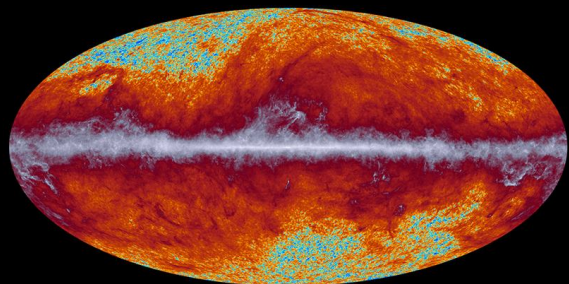
100 GHz



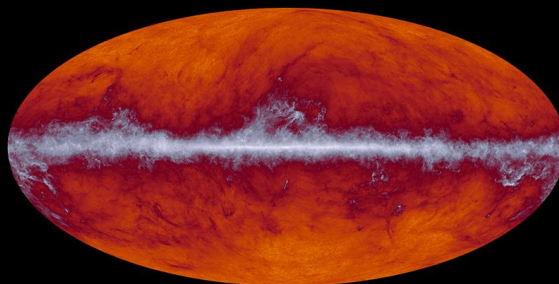
143 GHz



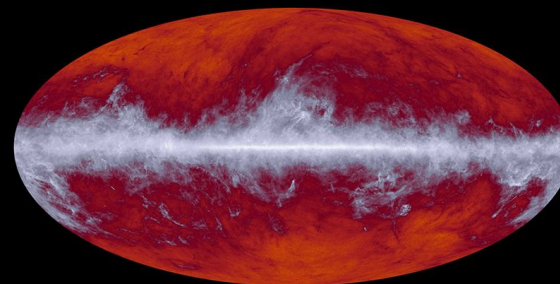
217 GHz



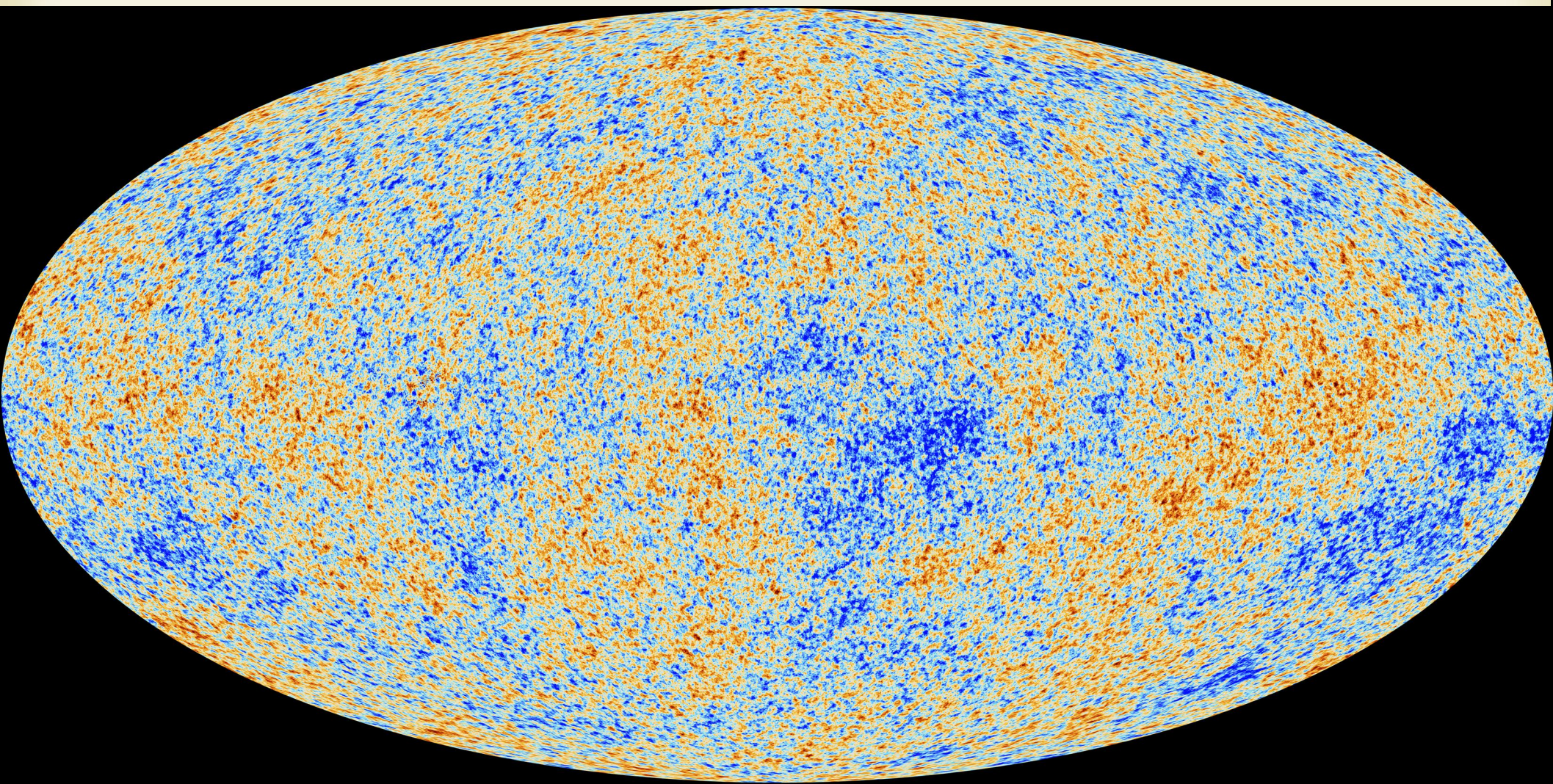
353 GHz



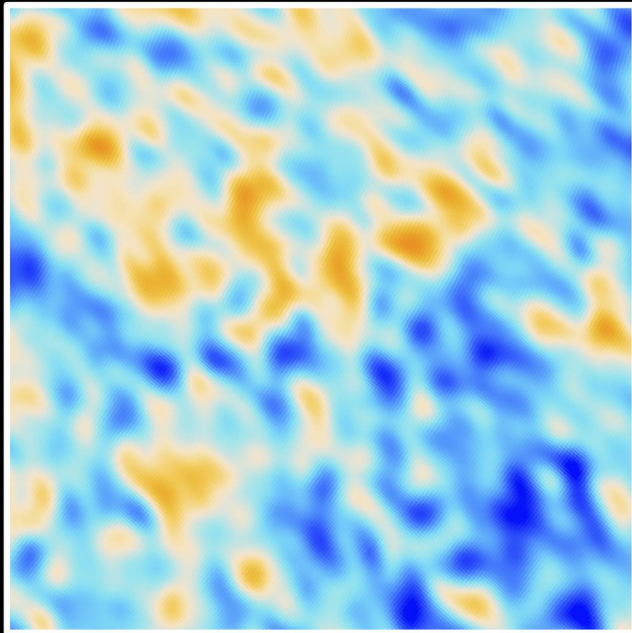
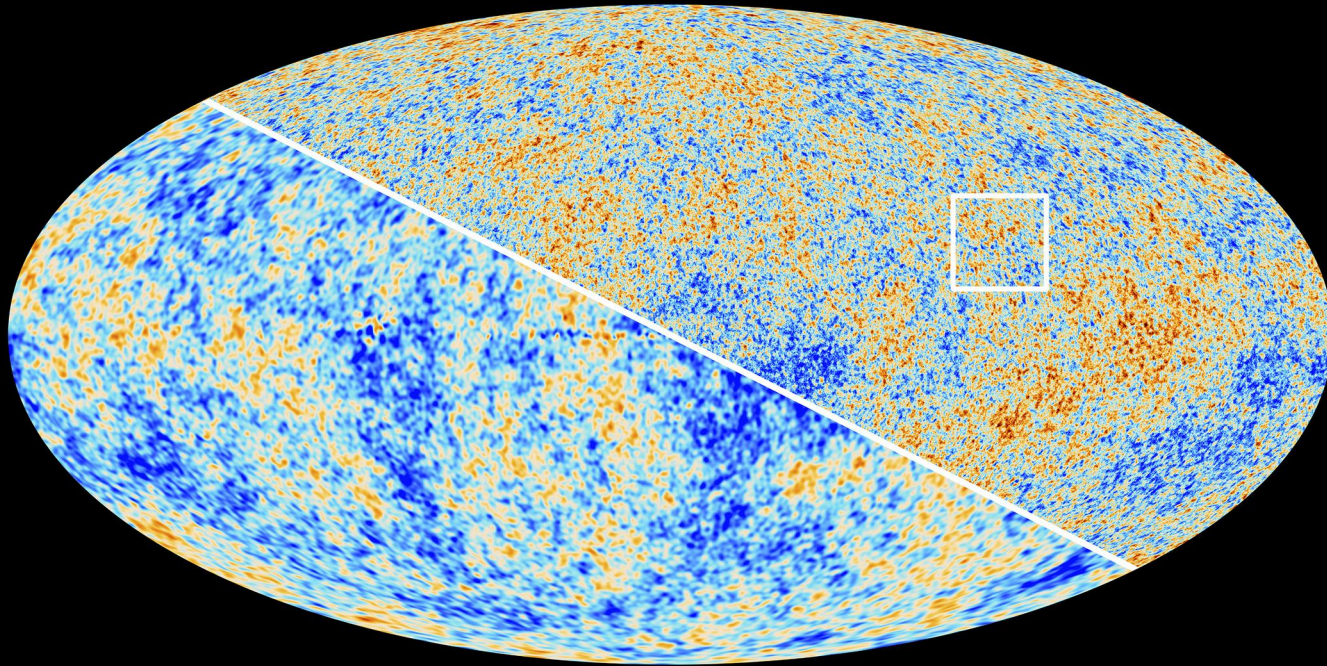
545 GHz



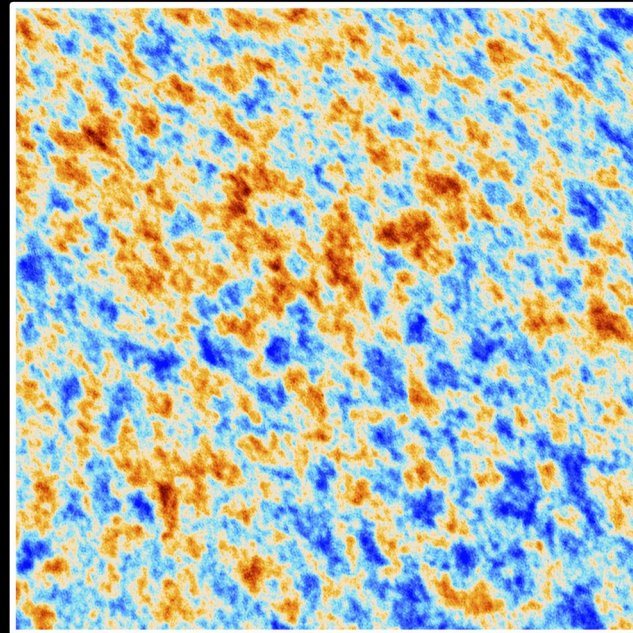
857 GHz



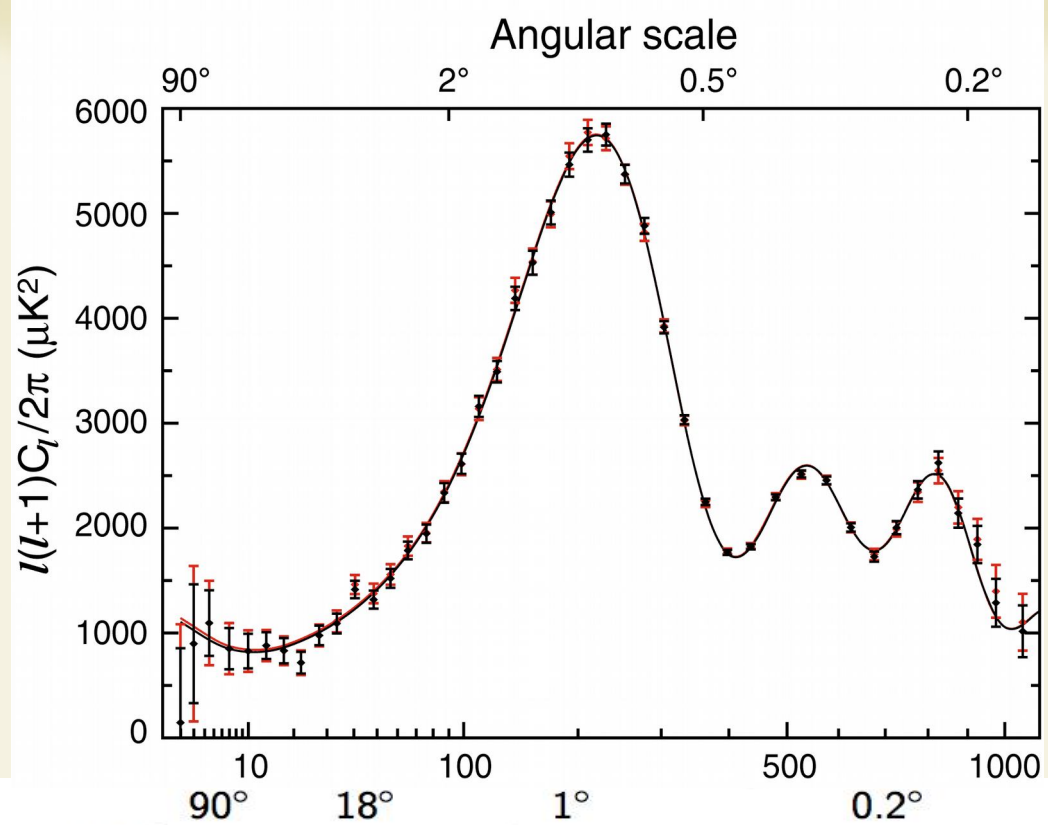
The Cosmic Microwave Background as seen by Planck and WMAP



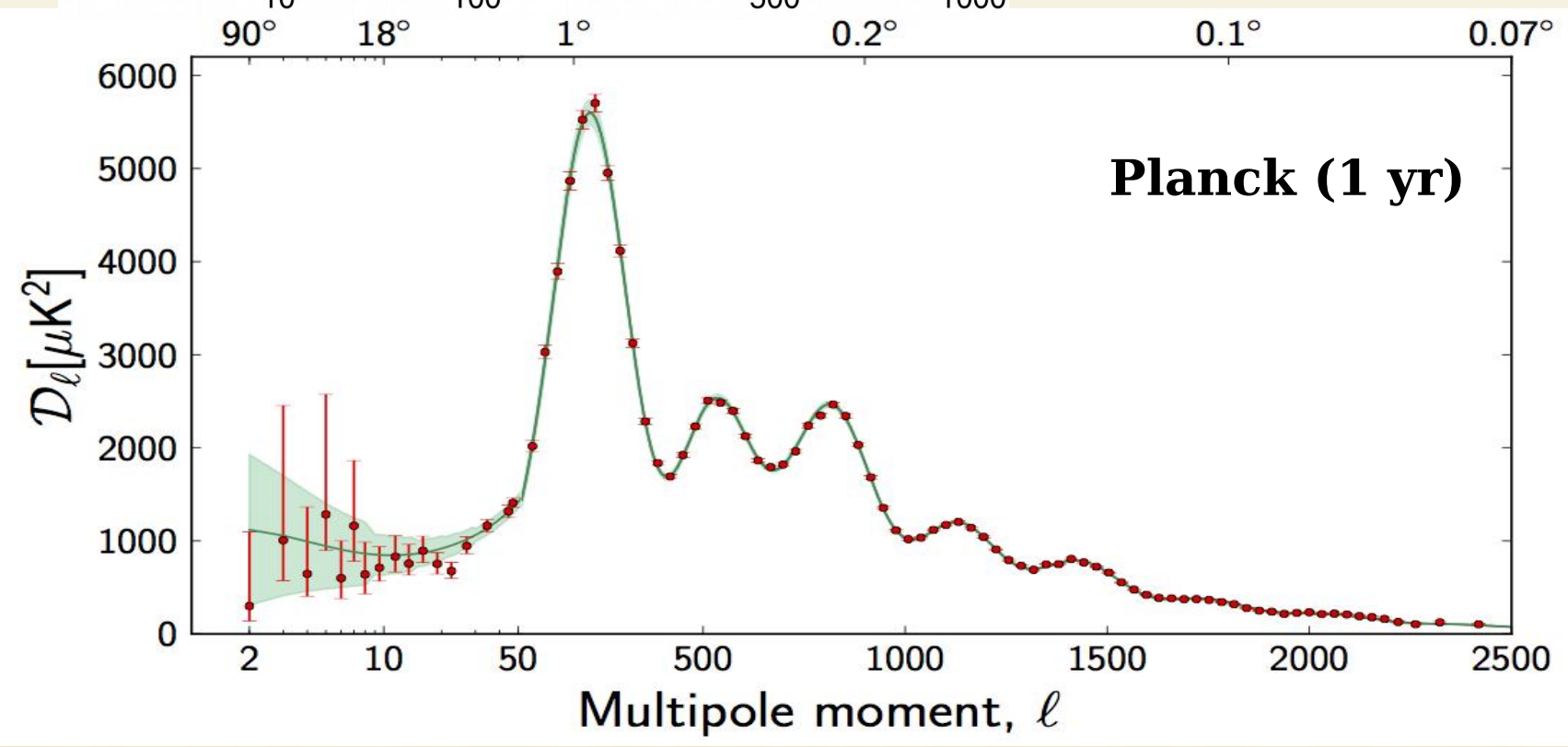
WMAP

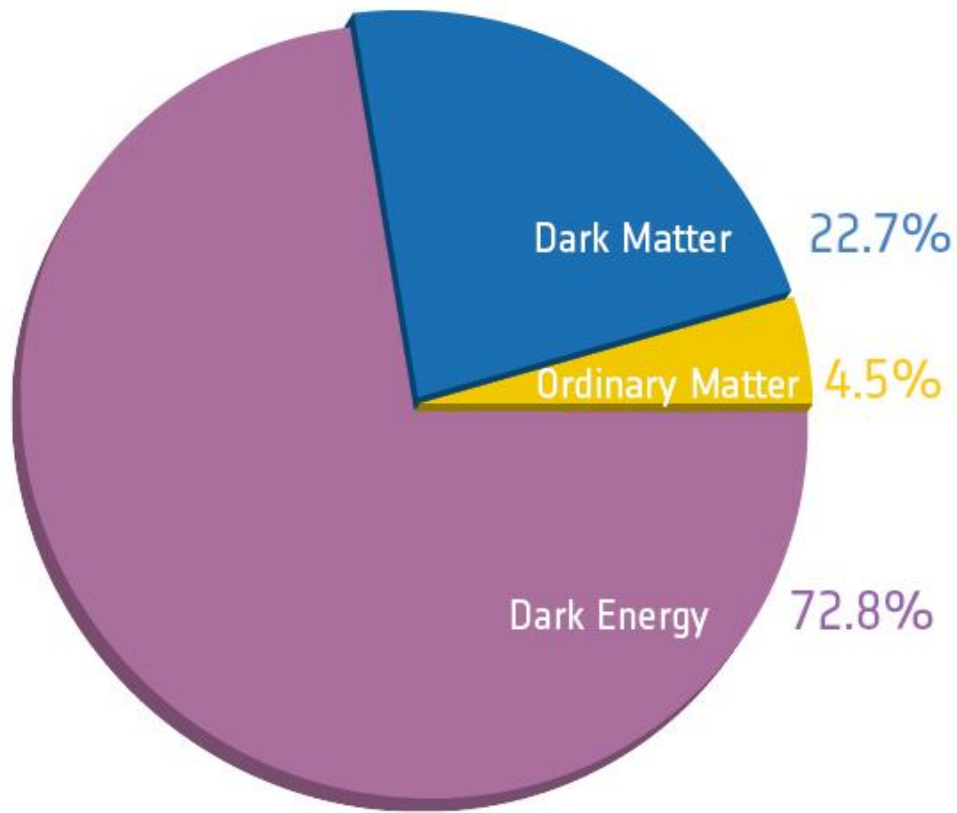


Planck

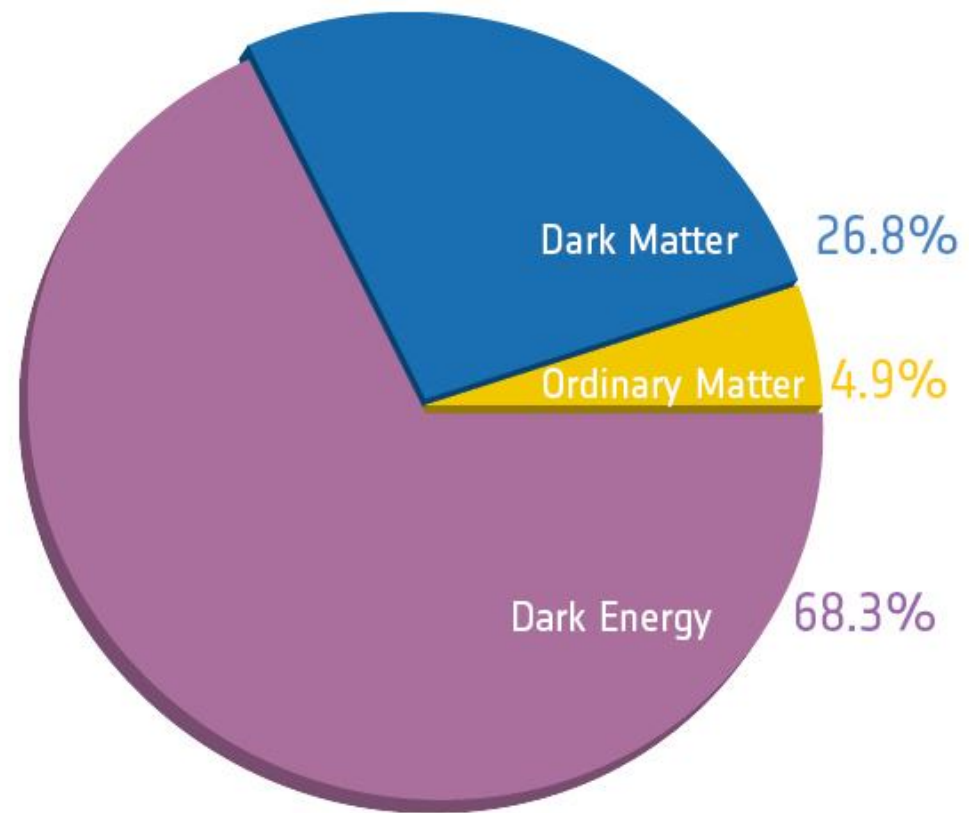


WMAP-9





Before Planck



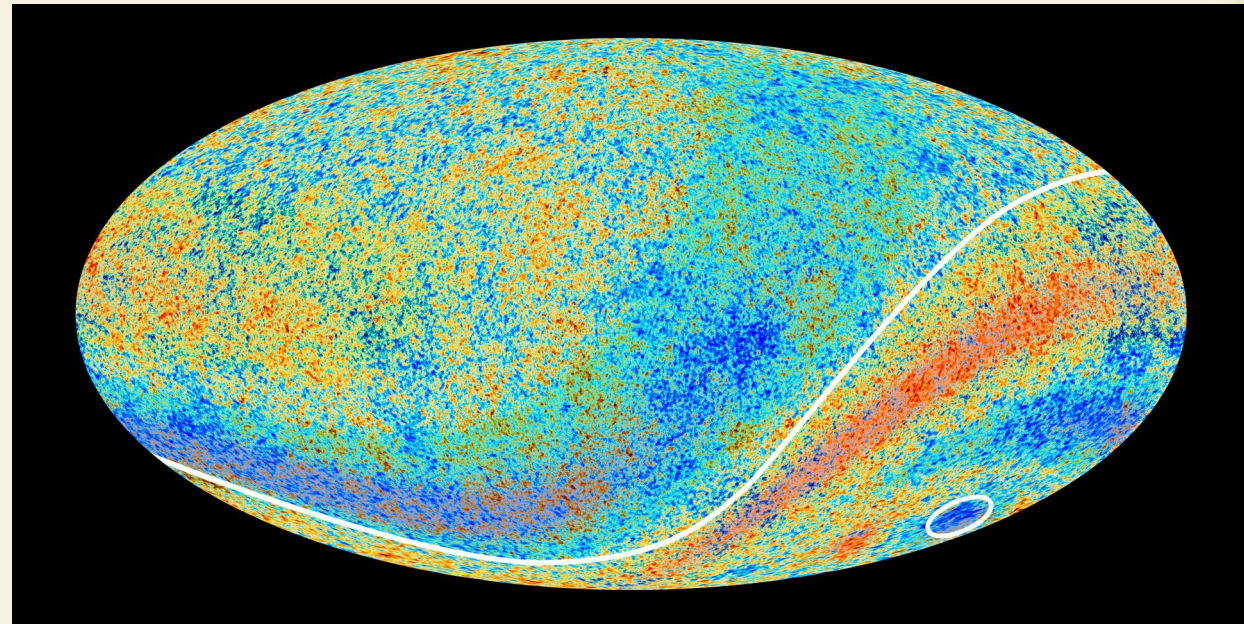
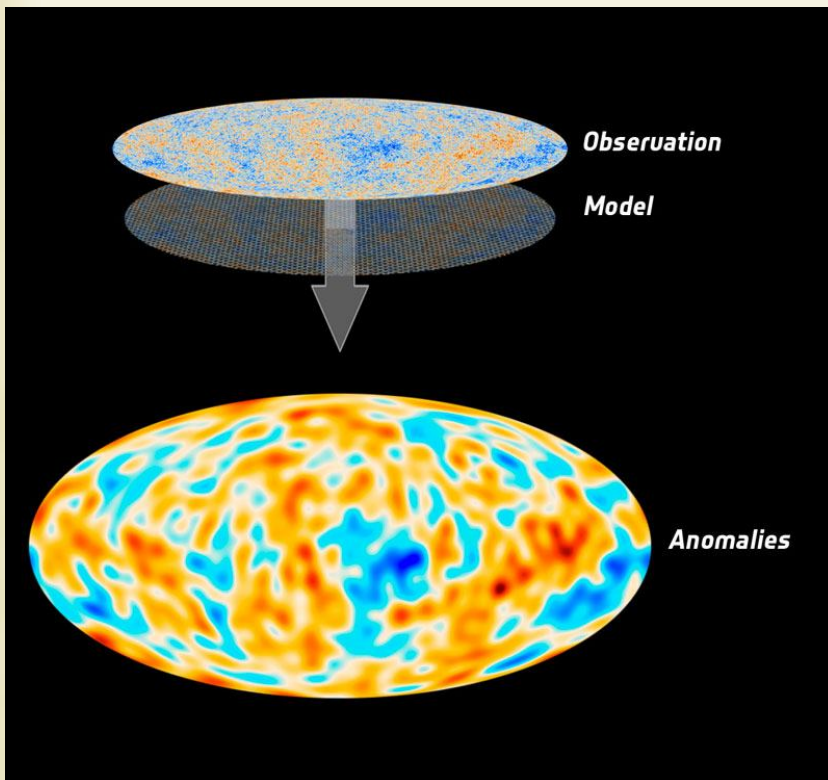
After Planck

Parameter	<i>Planck</i>		<i>Planck+lensing</i>		<i>Planck+WP</i>	
	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

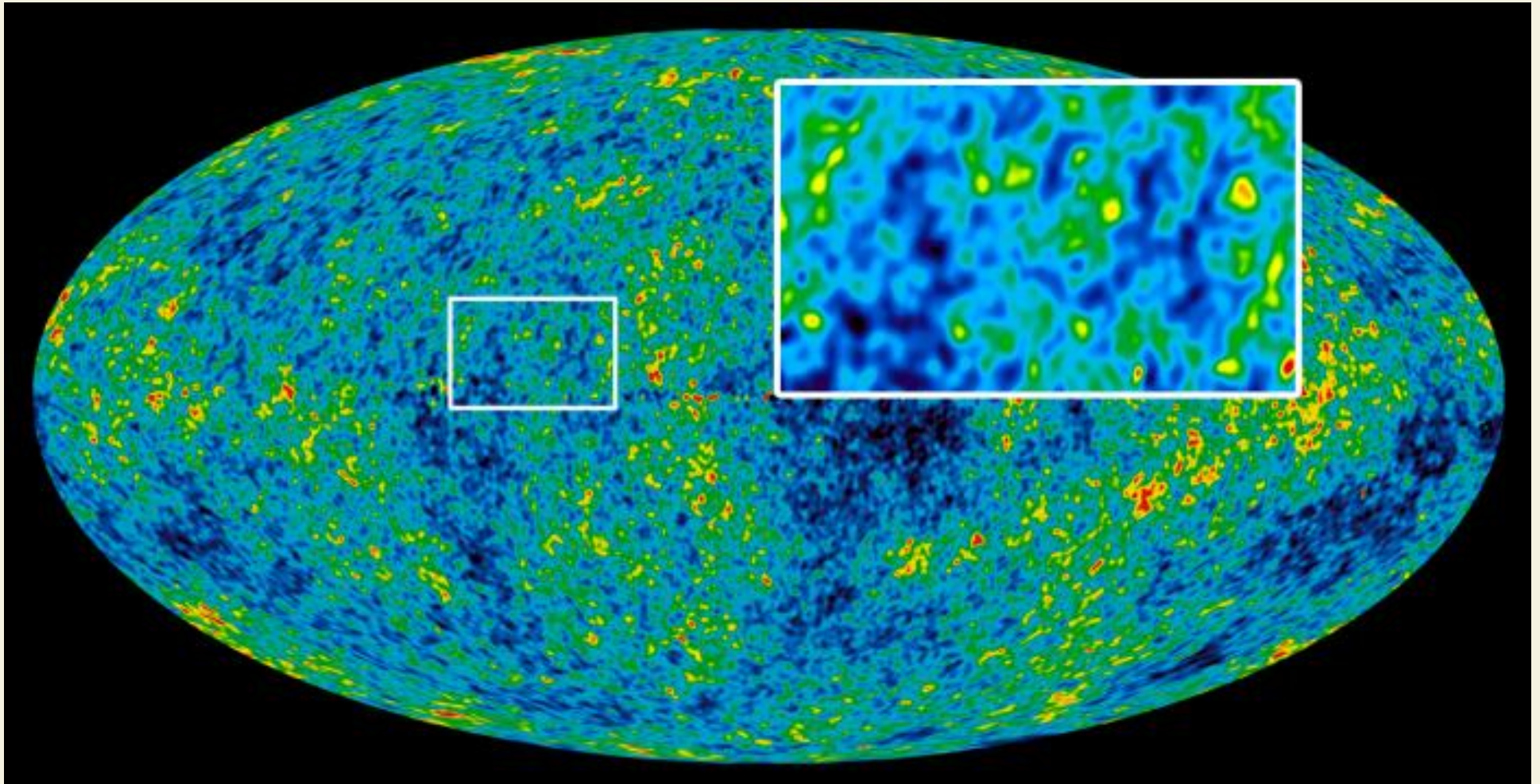
Table 2. Cosmological parameter values for the six-parameter base Λ CDM model. Columns 2 and 3 give results for the *Planck* temperature power spectrum data alone. Columns 4 and 5 combine the *Planck* temperature data with *Planck* lensing, and columns 6 and 7 include *WMAP* polarization at low multipoles. 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.

Exploration des paramètres au-delà de l'ensemble de base

- Nombre effectif d'espèces de neutrinos relativistes : 3 (précisément 3.30 ± 0.27)
- Somme des masses des neutrinos ≤ 0.23 eV
- Espace-temps euclidien à 0.1 % près
- Pas d'indices de variations de la constante de structure fine, ni de la Constante Cosmologique
- Signes d' « anomalies » aux très grandes échelles



Méfions-nous tout de même..



signifiante statistique ?