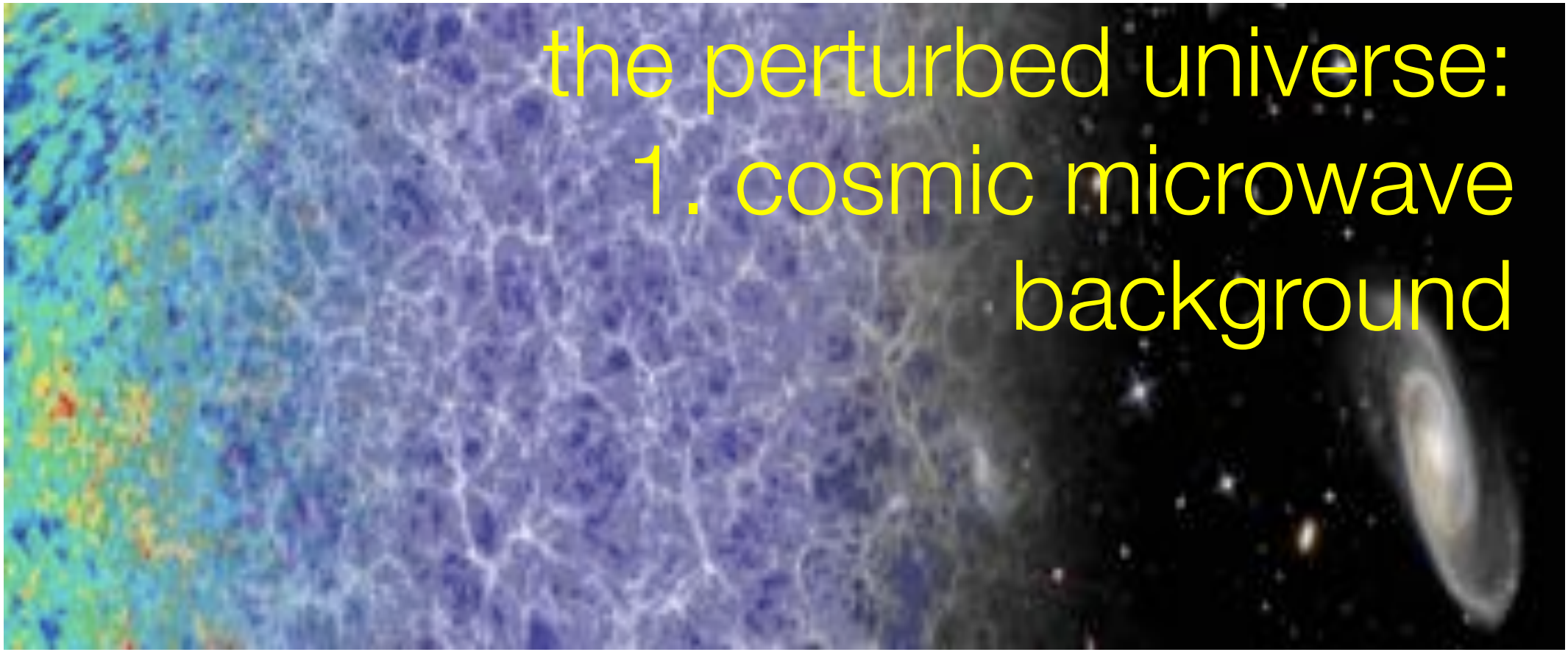


the perturbed universe: 1. cosmic microwave background

Hervé Dole

Institut d'Astrophysique Spatiale, Orsay
Université Paris Sud 11 & CNRS & IUF
http://www.ias.u-psud.fr/dole/m2.php

Montage: CMB, LSS, galaxies: SPACE

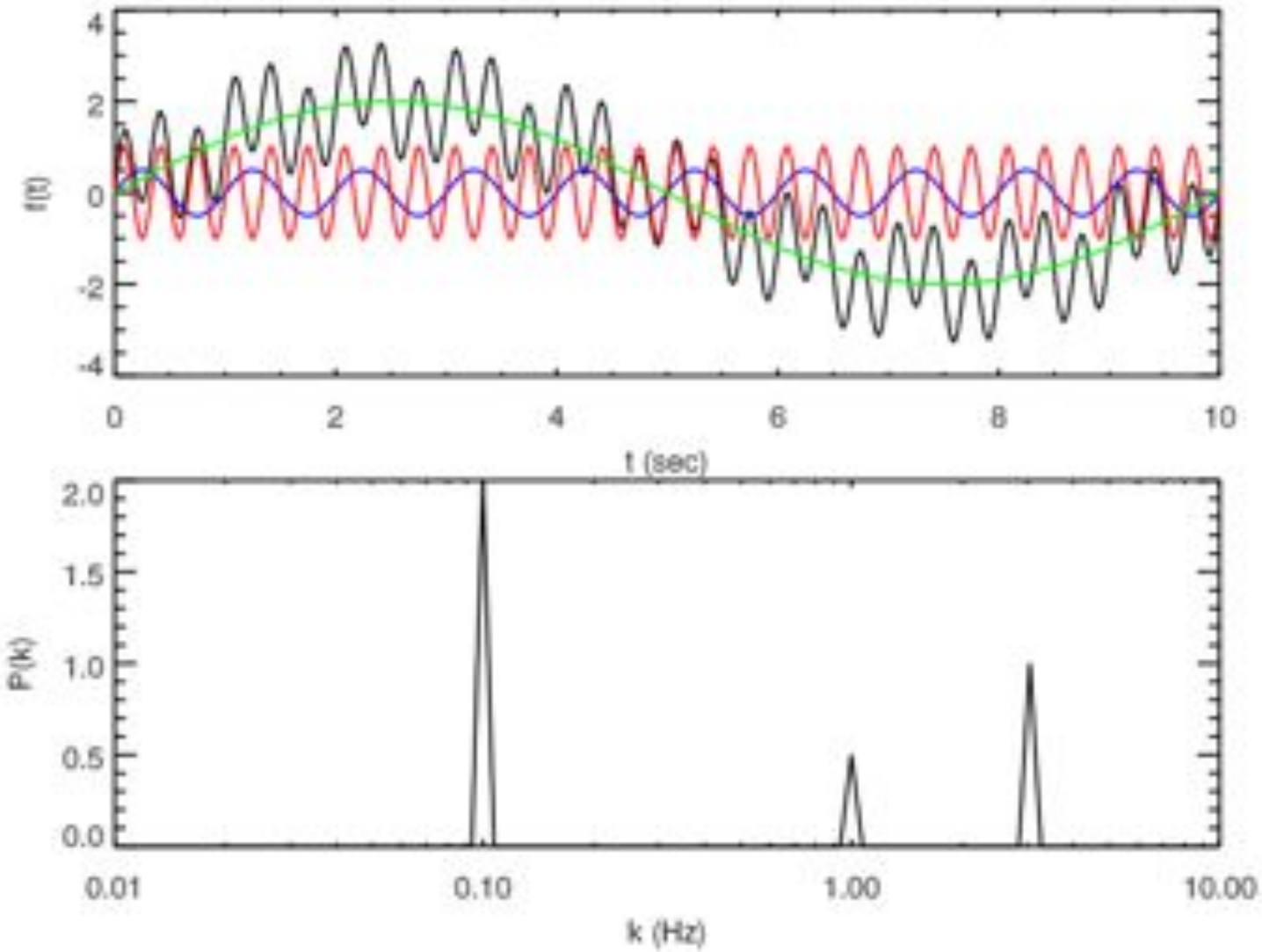
I. Angular Power Spectrum on the sphere: C_l

1. What is a power spectrum ?

Fourier analysis

$$\tilde{f}(\nu) = \int_{-\infty}^{+\infty} f(t) e^{-i2\pi\nu t}\, dt$$

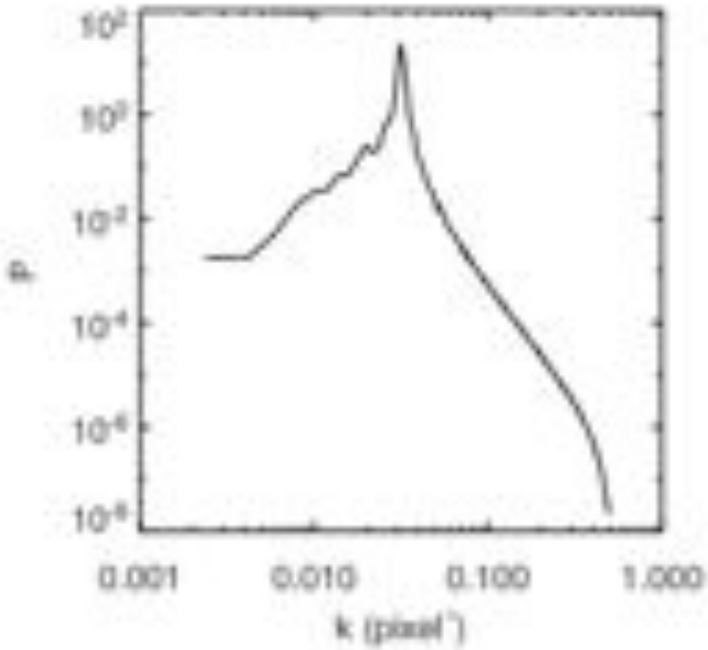
$$f(t) = \int_{-\infty}^{+\infty} \tilde{f}(\nu) e^{i2\pi\nu t}\, d\nu$$



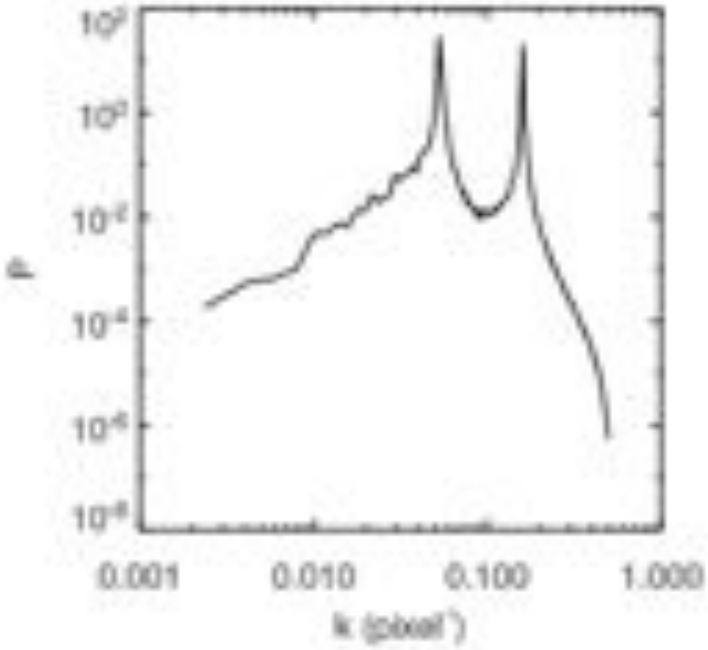
Espace direct: temps

Espace conjugué: fréquence temporelle

Courtesy Marc-Antoine Miville-Deschênes

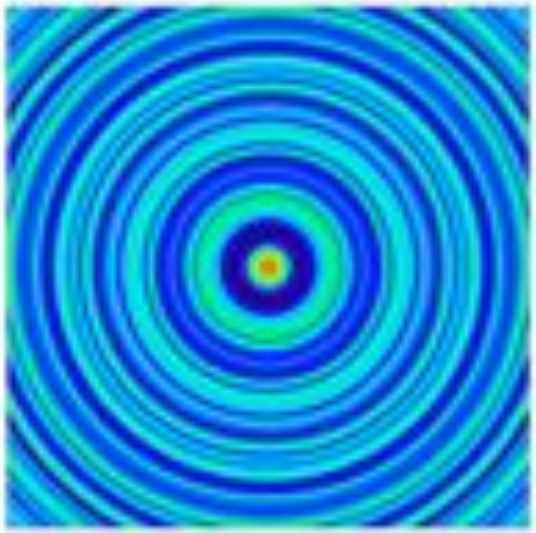


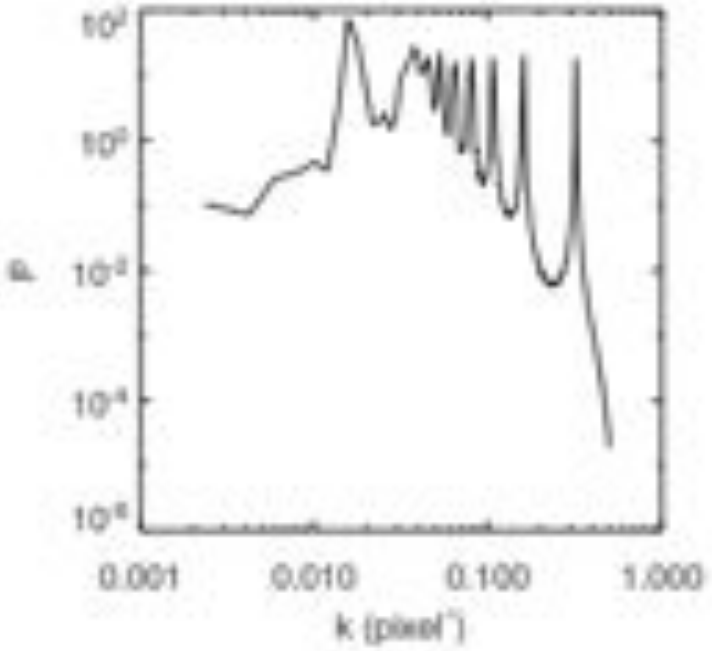
1 sinus centré



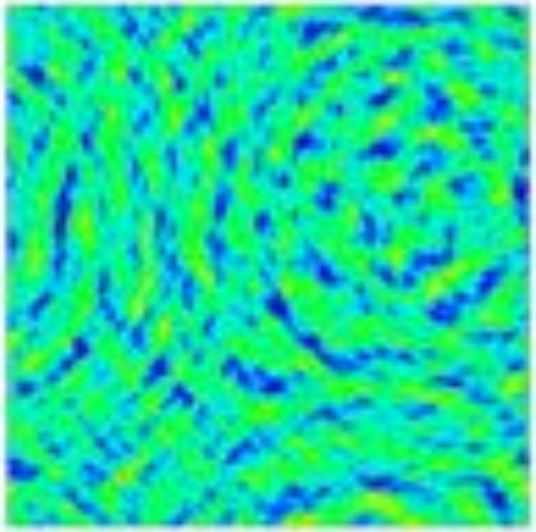
2 sinus centrés

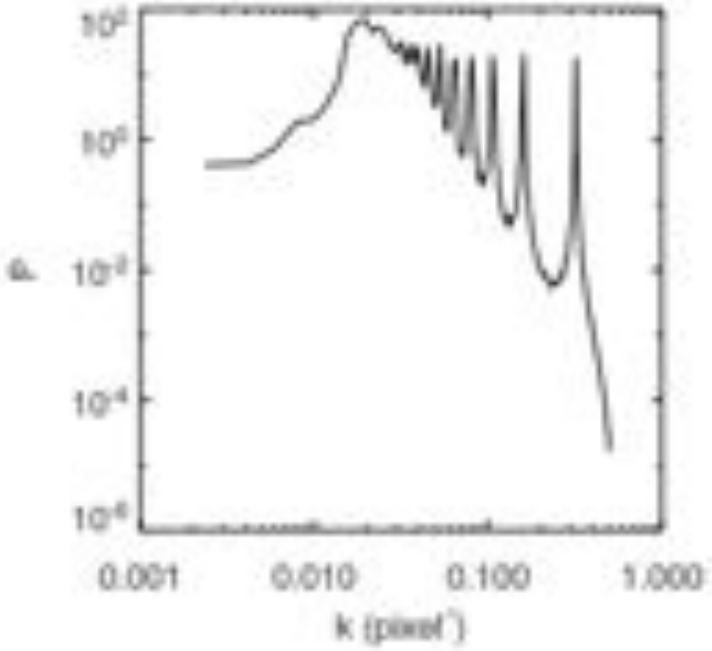
Courtesy Marc-Antoine Miville-Deschênes





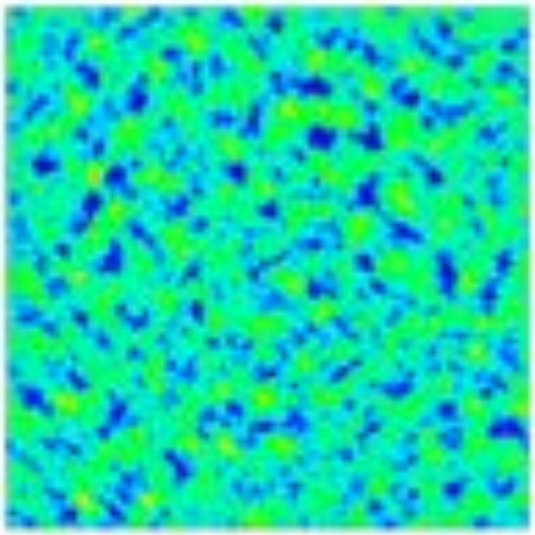
n sinus centrés

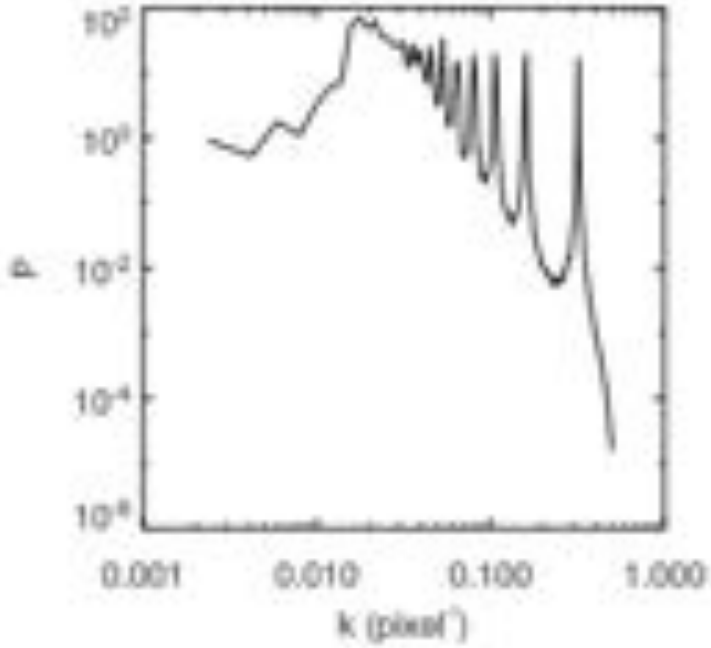




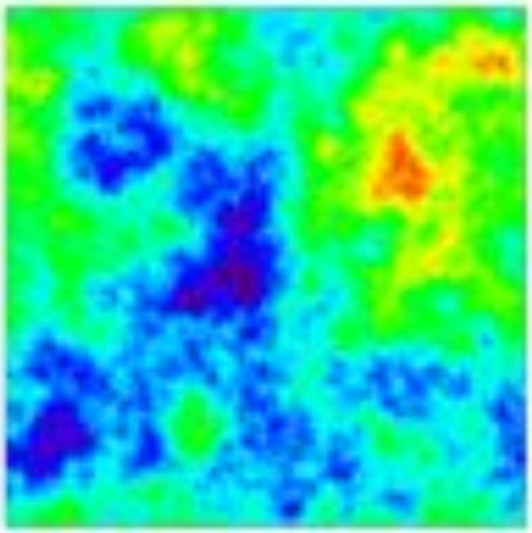
n sinus décentrés

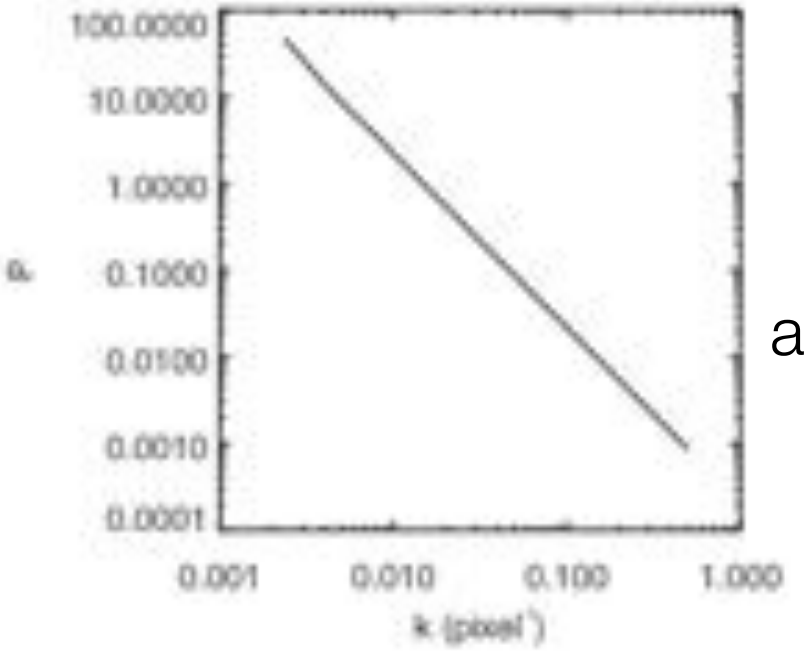
Courtesy Marc-Antoine Miville-Deschênes





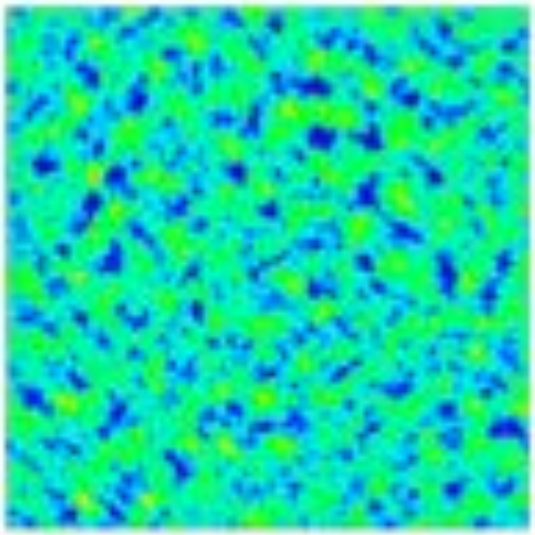
n sinus décentrés

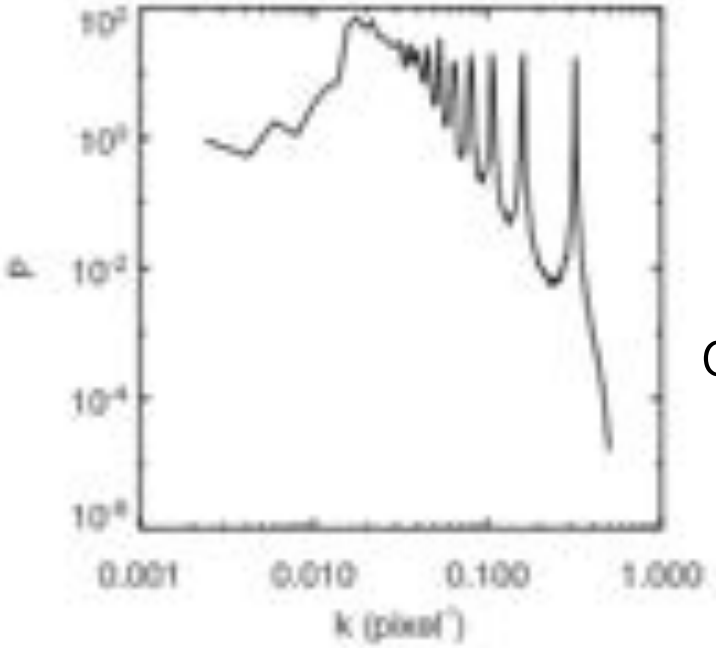




Forme autosimilaire (fractale)

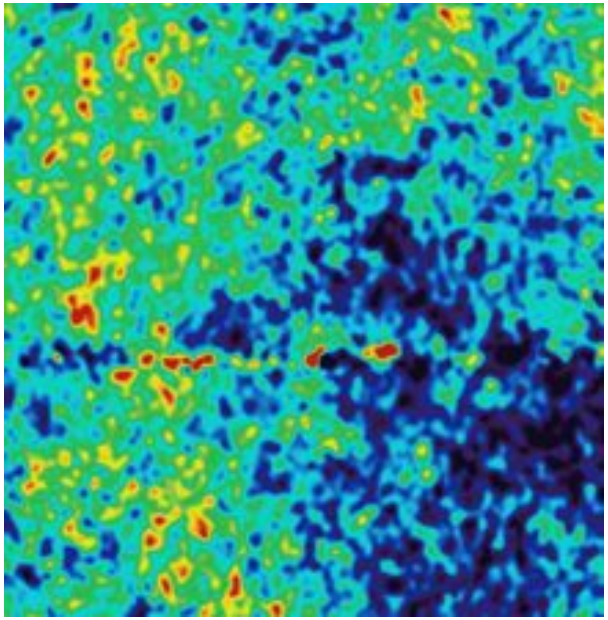
Courtesy Marc-Antoine Miville-Deschênes

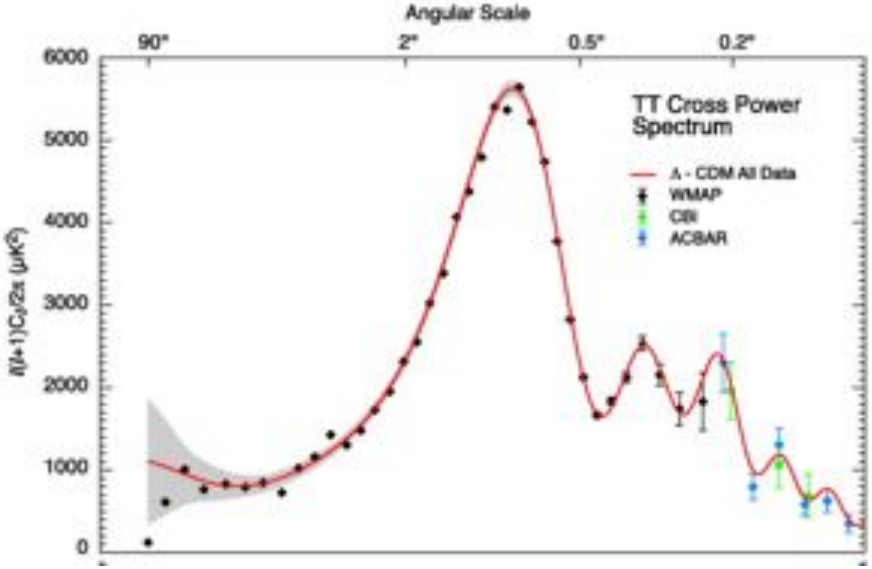




n sinus décentrés

Courtesy Marc-Antoine Miville-Deschênes



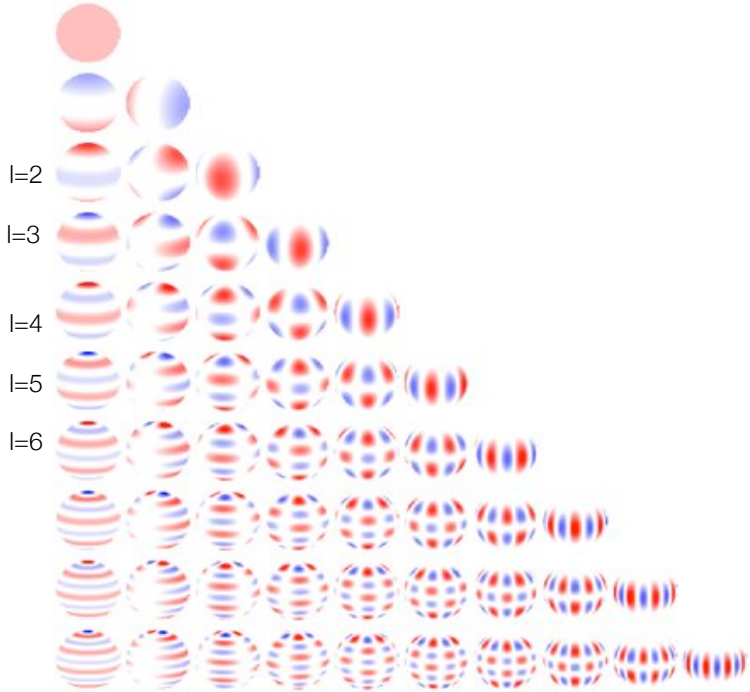


WMAP 1 yr

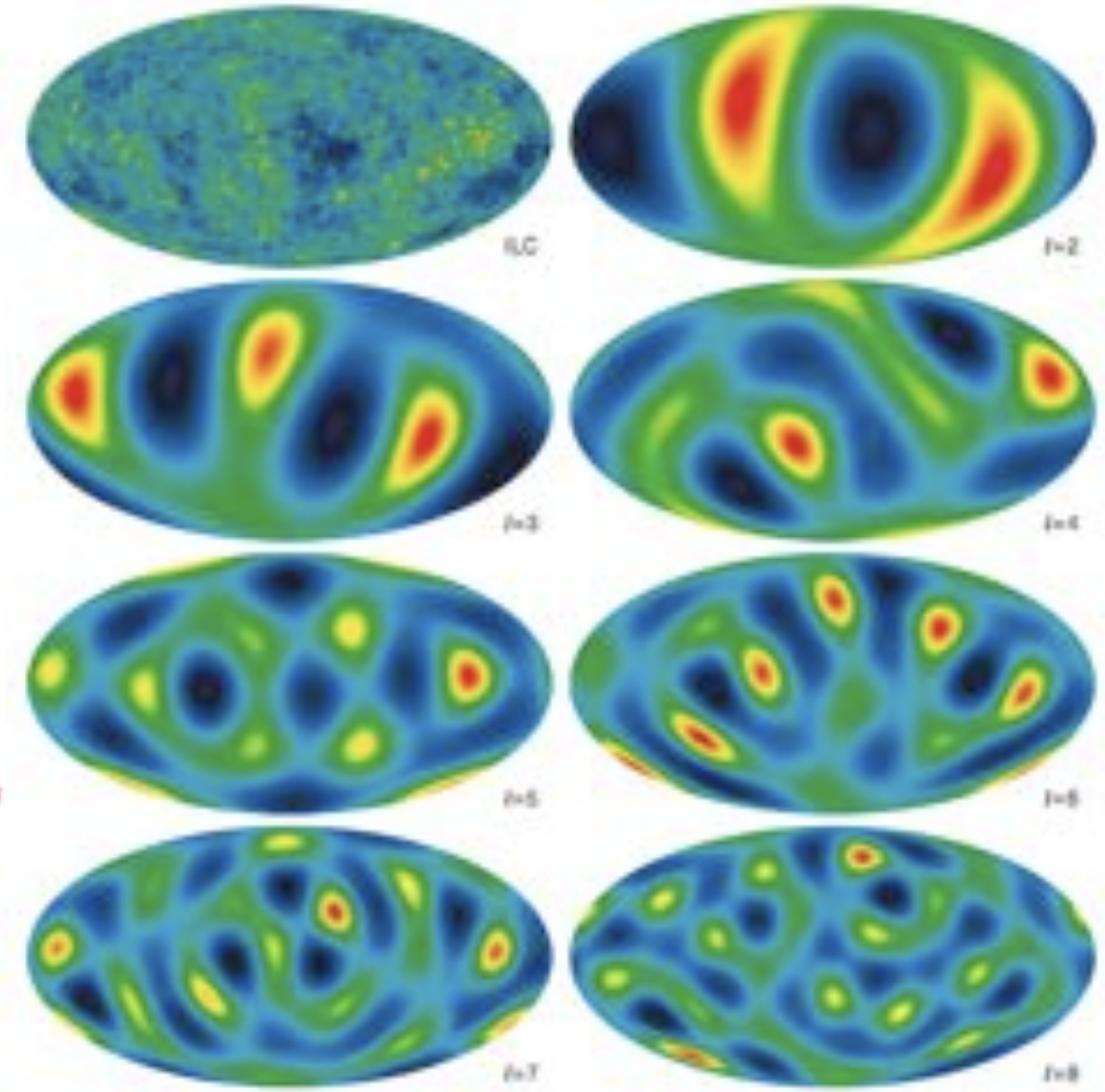
I. Angular Power Spectrum on the sphere: C_l

3. What is l (ell) ?

multipoles applied to the CMB



Ylm courtesy Benoit Mosser, LESIA



Hinshaw et al., 2007, WMAP3

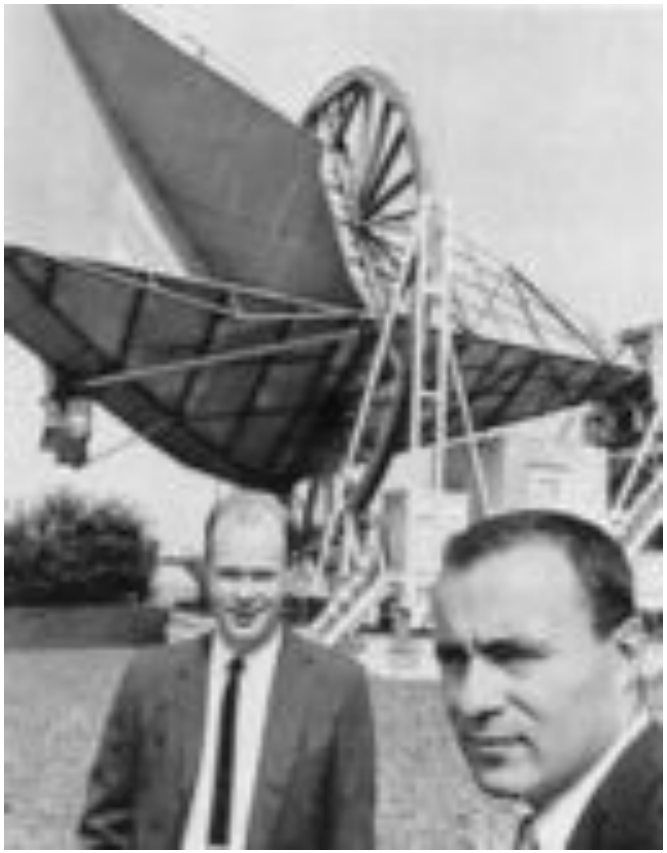
II. Observations of the Cosmic Microwave Background

1. Measurements

Cosmic Microwave Background

Découvert en 1965 par
Arno Penzias & Robert Wilson.

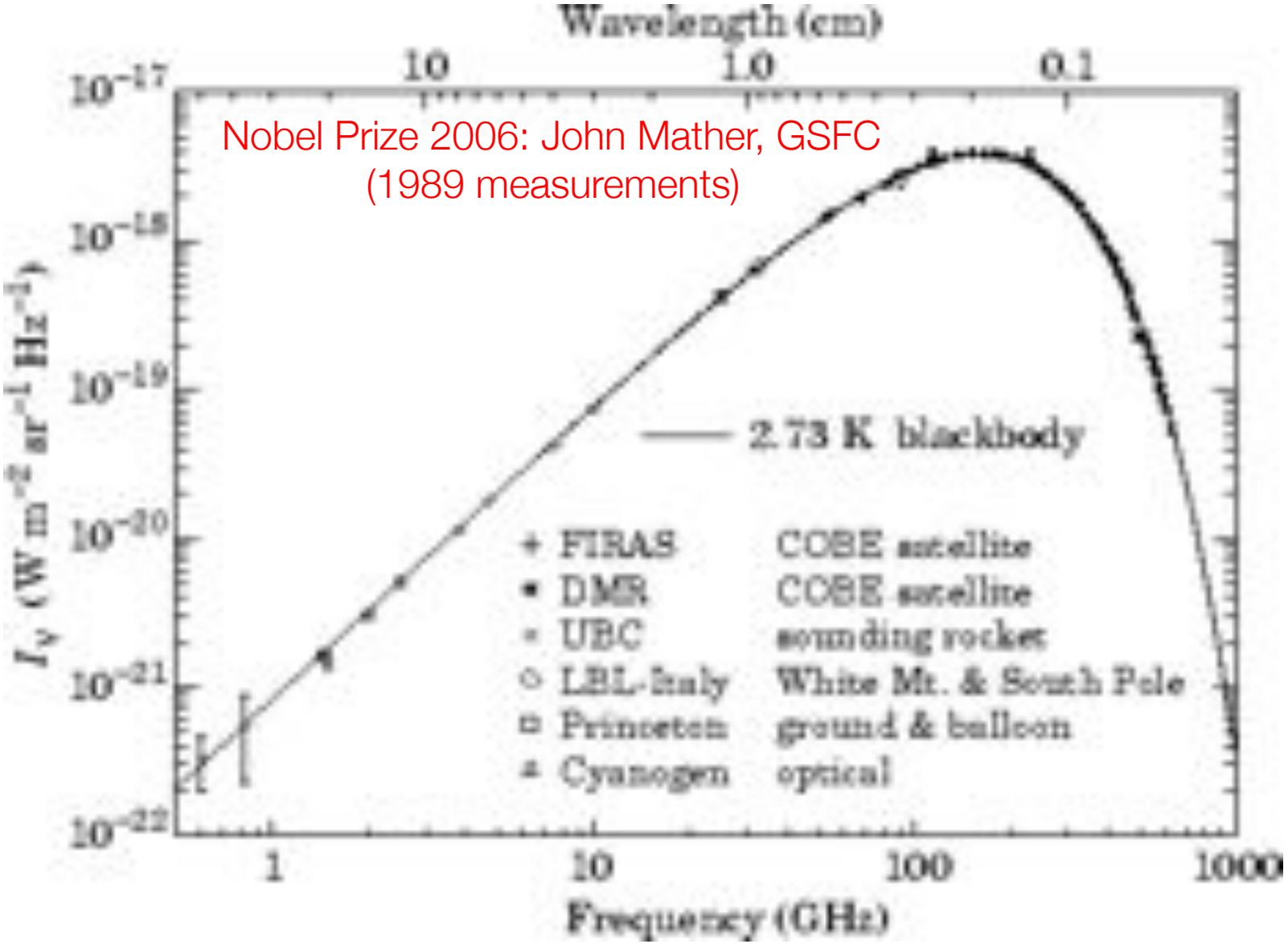
Nobel Prize 1978 "for their discovery of the cosmic microwave background radiation"



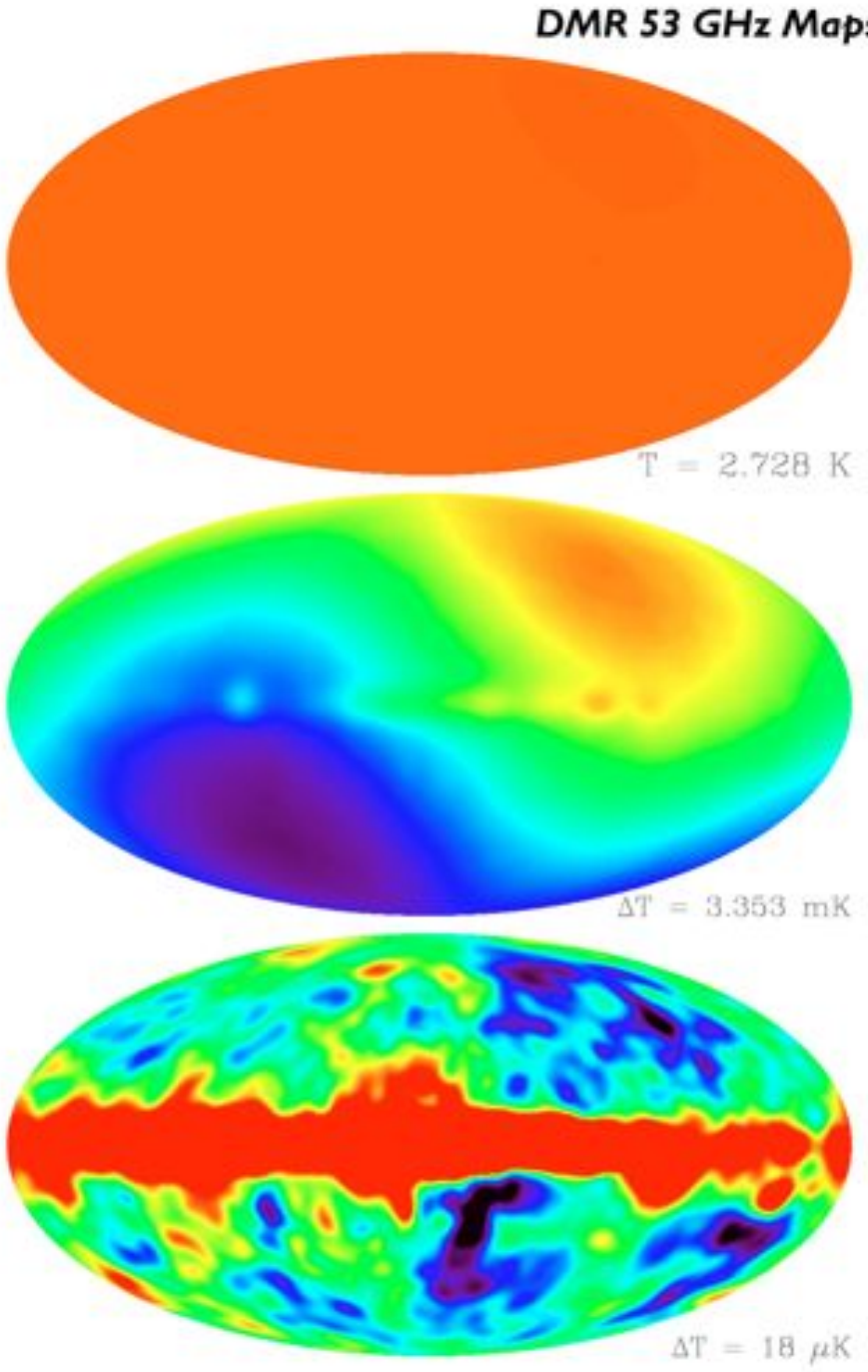
properties

Blackbody Radiation T=2.725 K

L'Univers est rempli de rayonnement: **la nuit n'est pas noire**, mais brillante en radio.



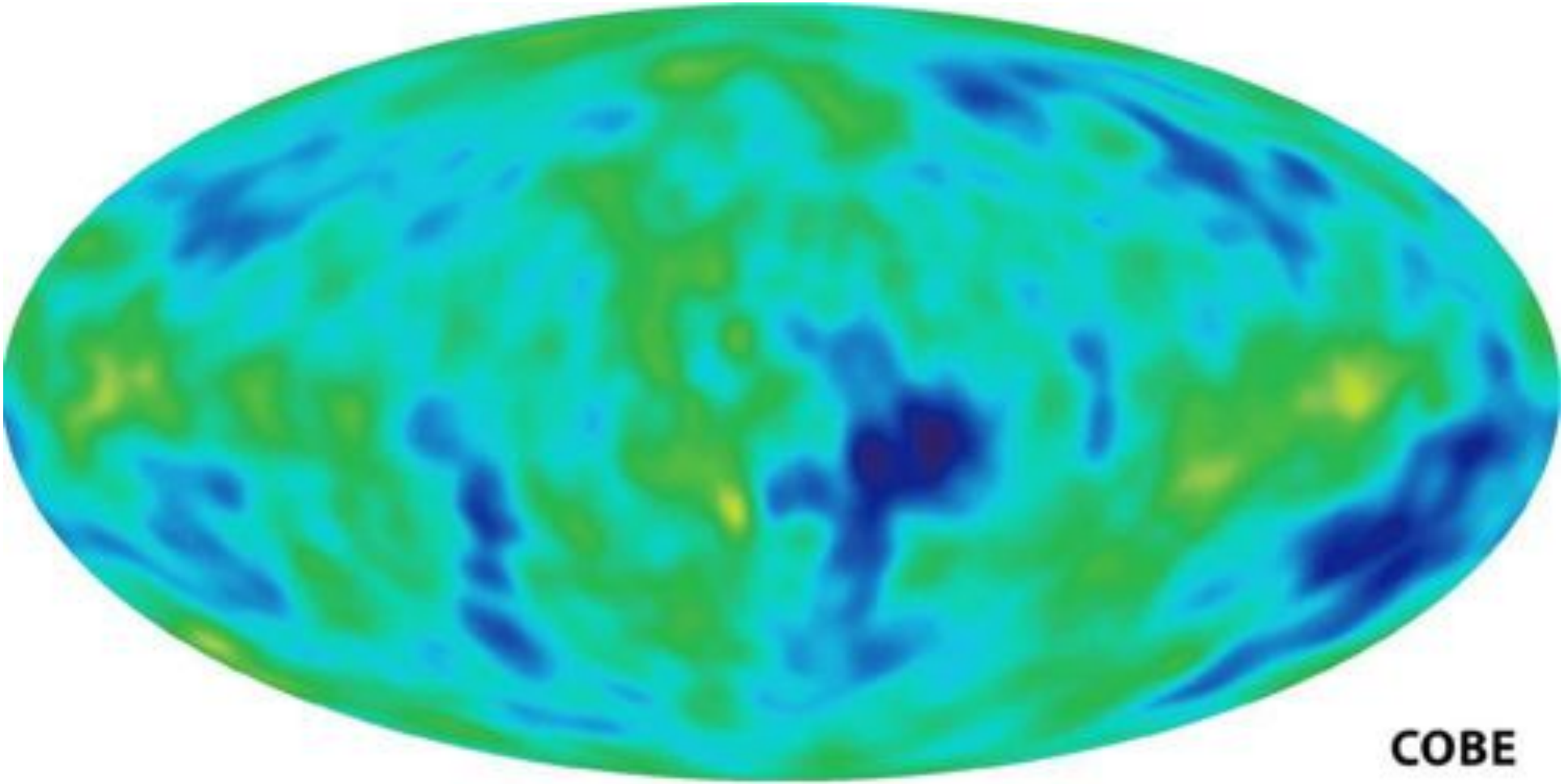
CMB by COBE in 1992



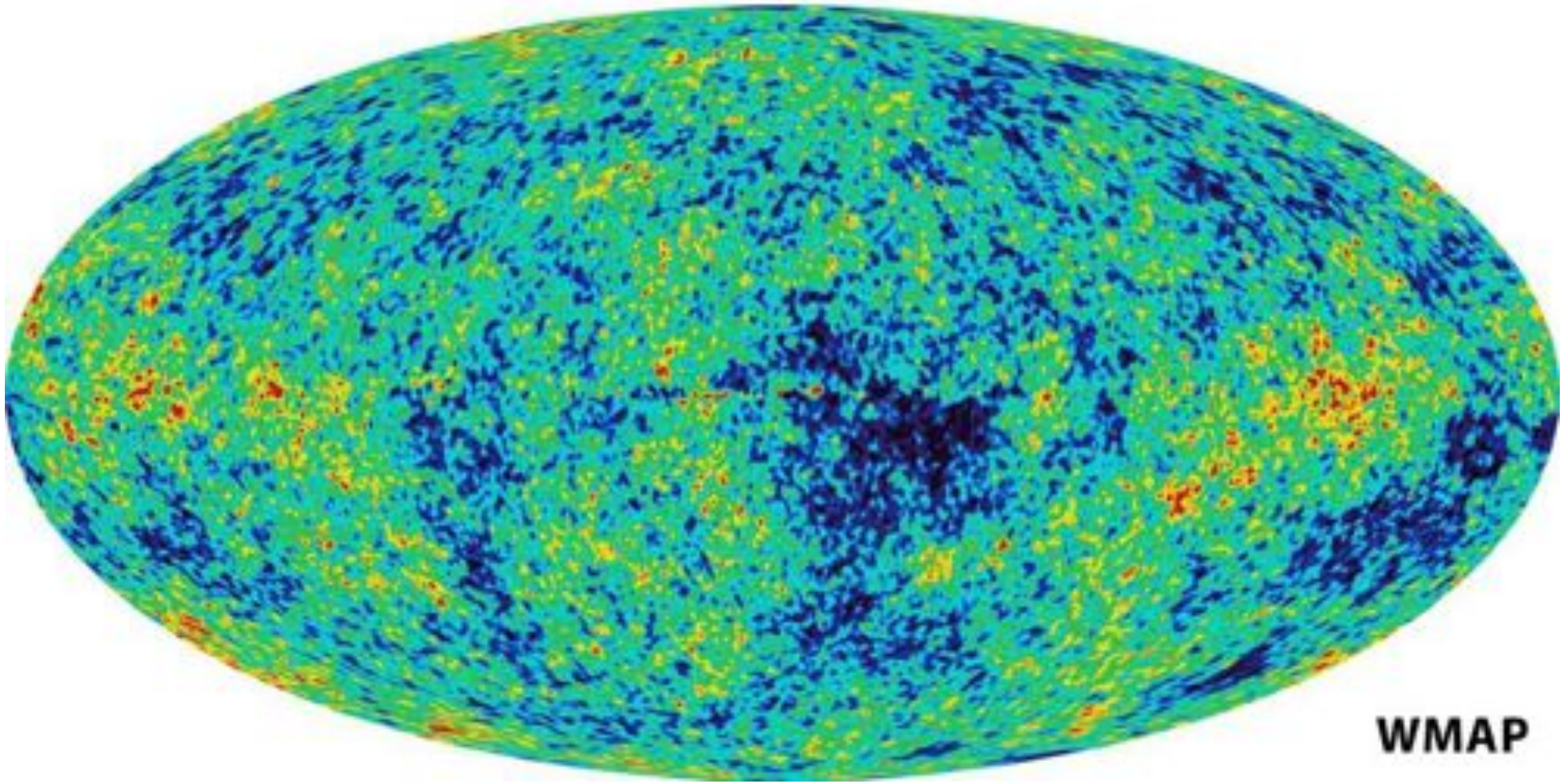
Nobel Prize 2006: G. Smoot, GSFC
(1992 measurements)
« for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation »

fluctuations de température

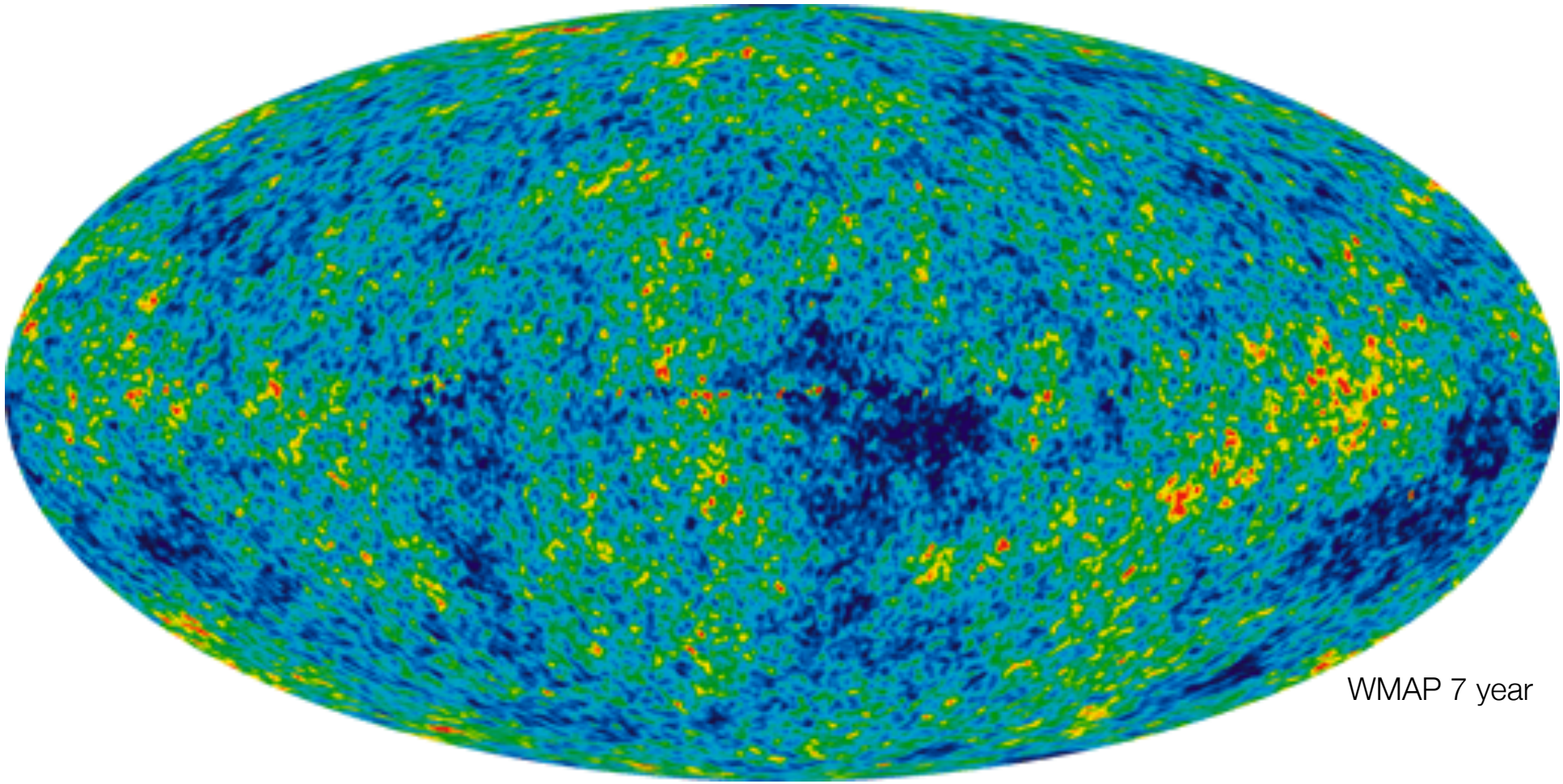
l'amplitude des fluctuations est de l'ordre de la dizaine de microKelvin !



fluctuations de température



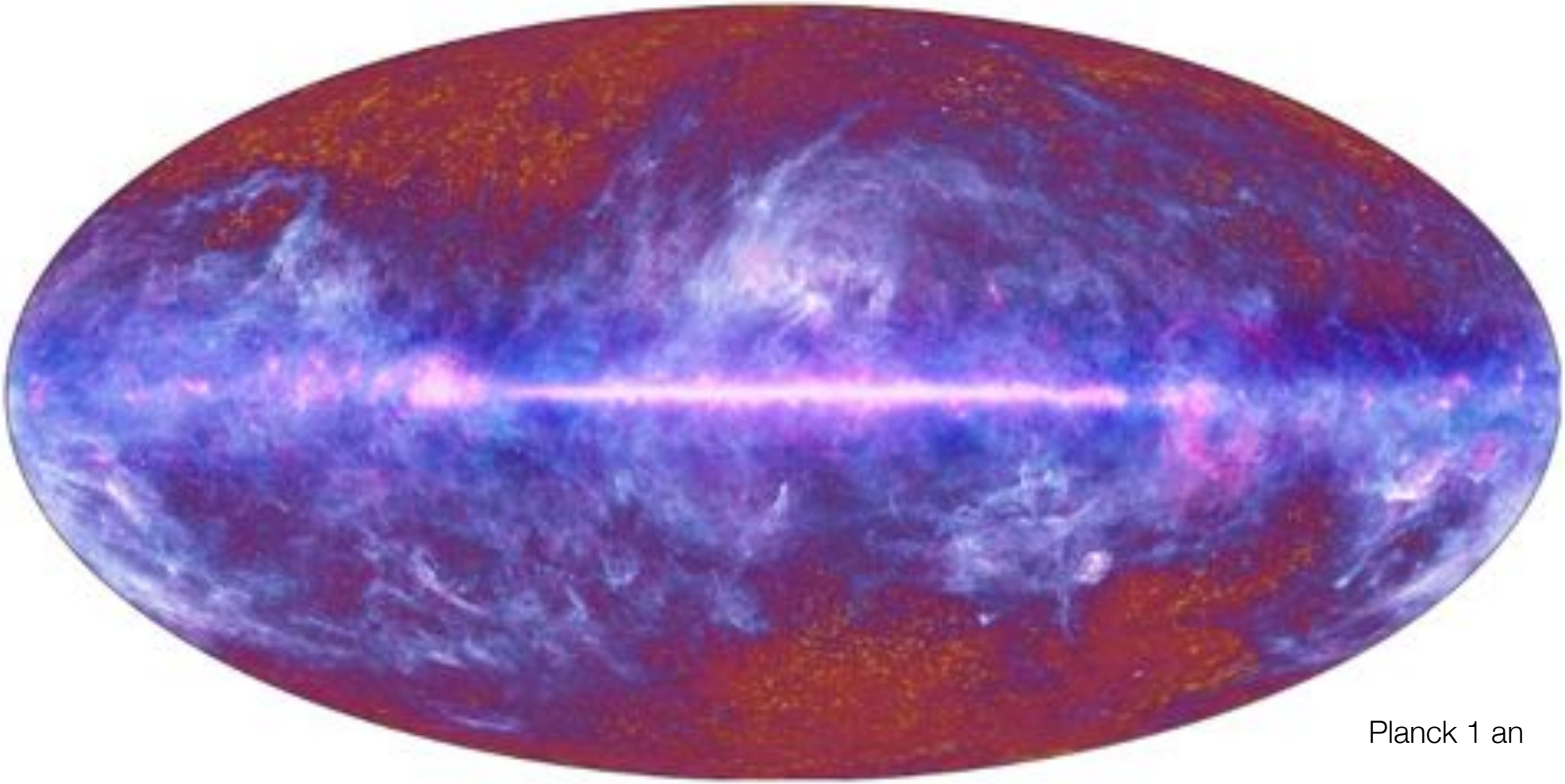
fluctuations de température



WMAP 7 year

fluctuations de température

+ Galaxie et galaxies, amas etc.



Planck 1 an

Planck ESA HFI LFI consortia

II. Observations of the Cosmic Microwave Background

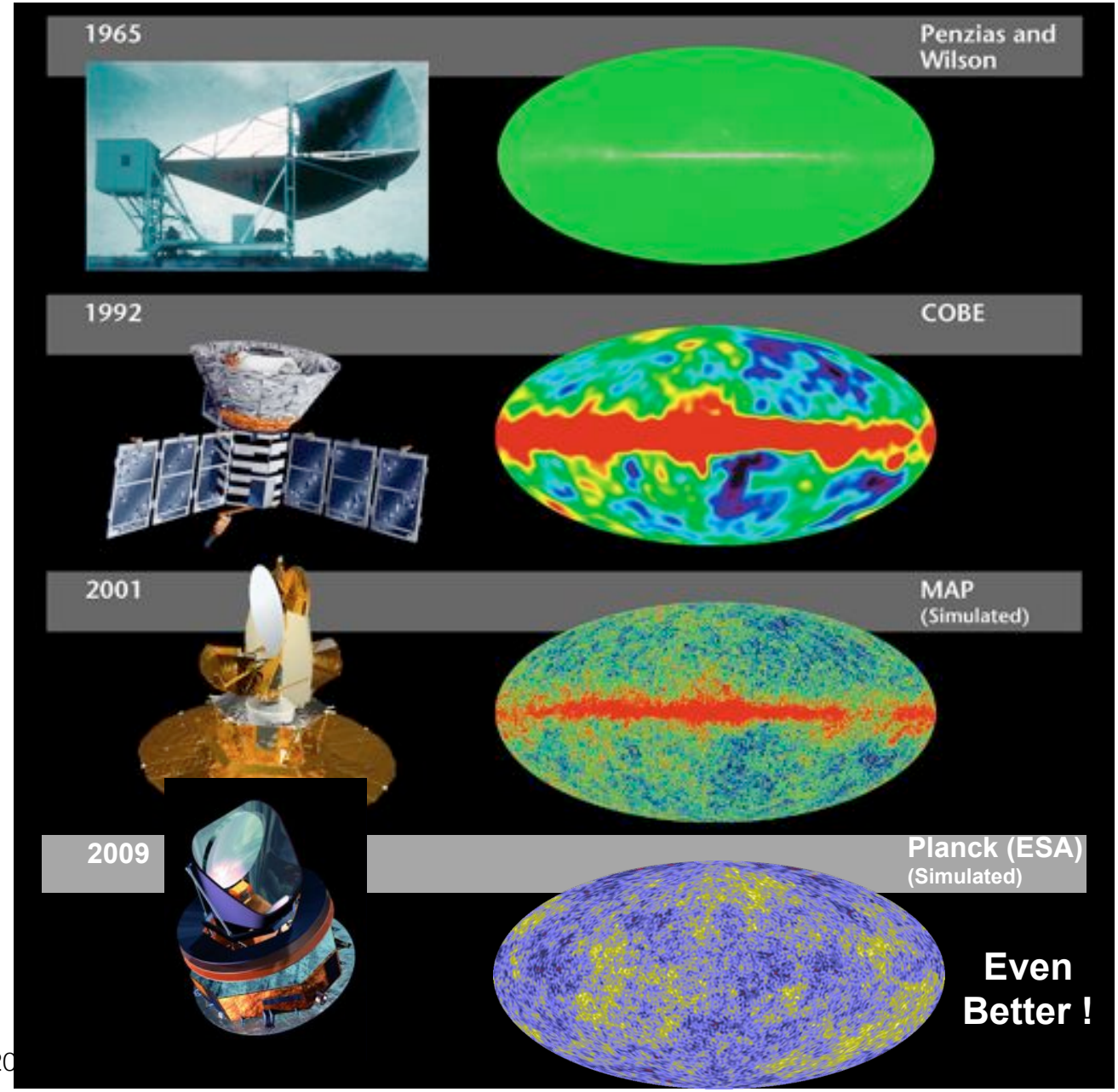
2. Strategy and Difficulties

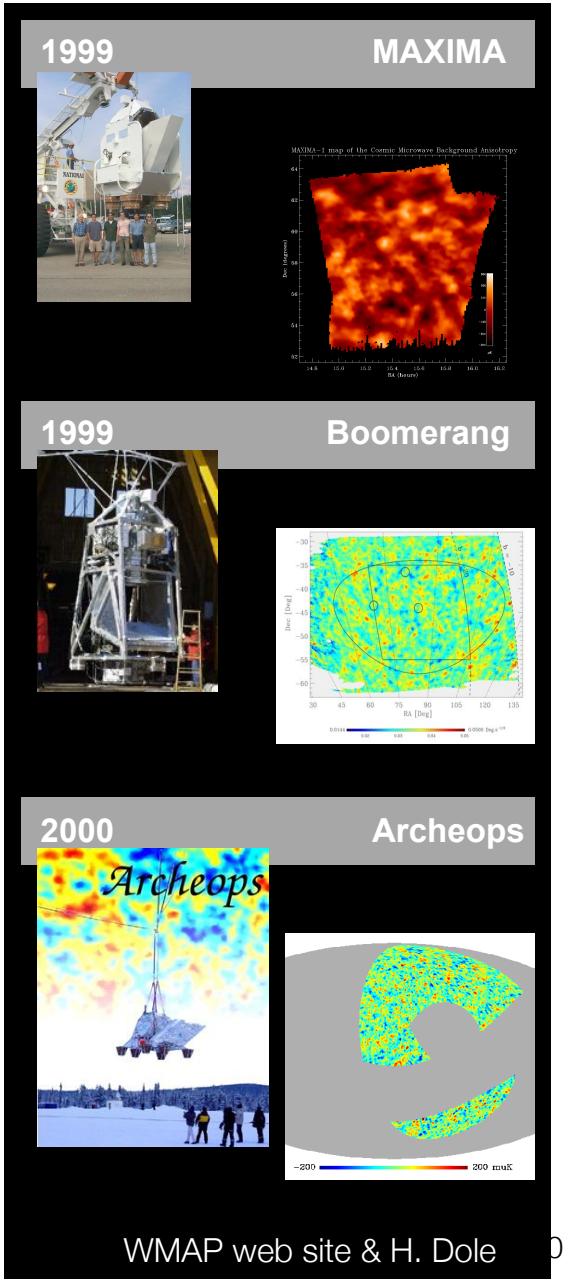
you play !

- we give you 600 ME to accurately measure the CMB
- its temperature and polarization anisotropies

- what telescope and instrument would you build ?

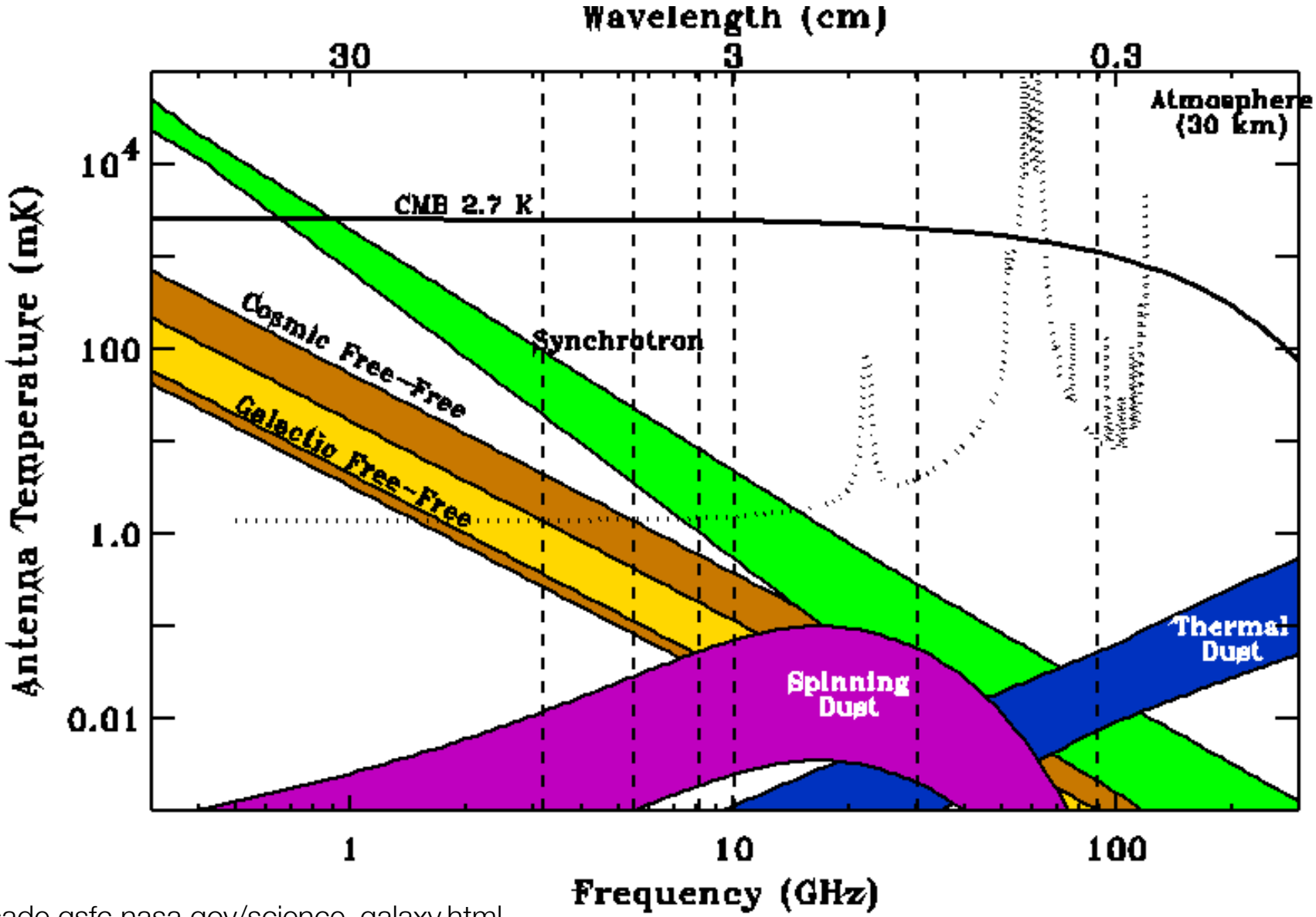
CMB observations





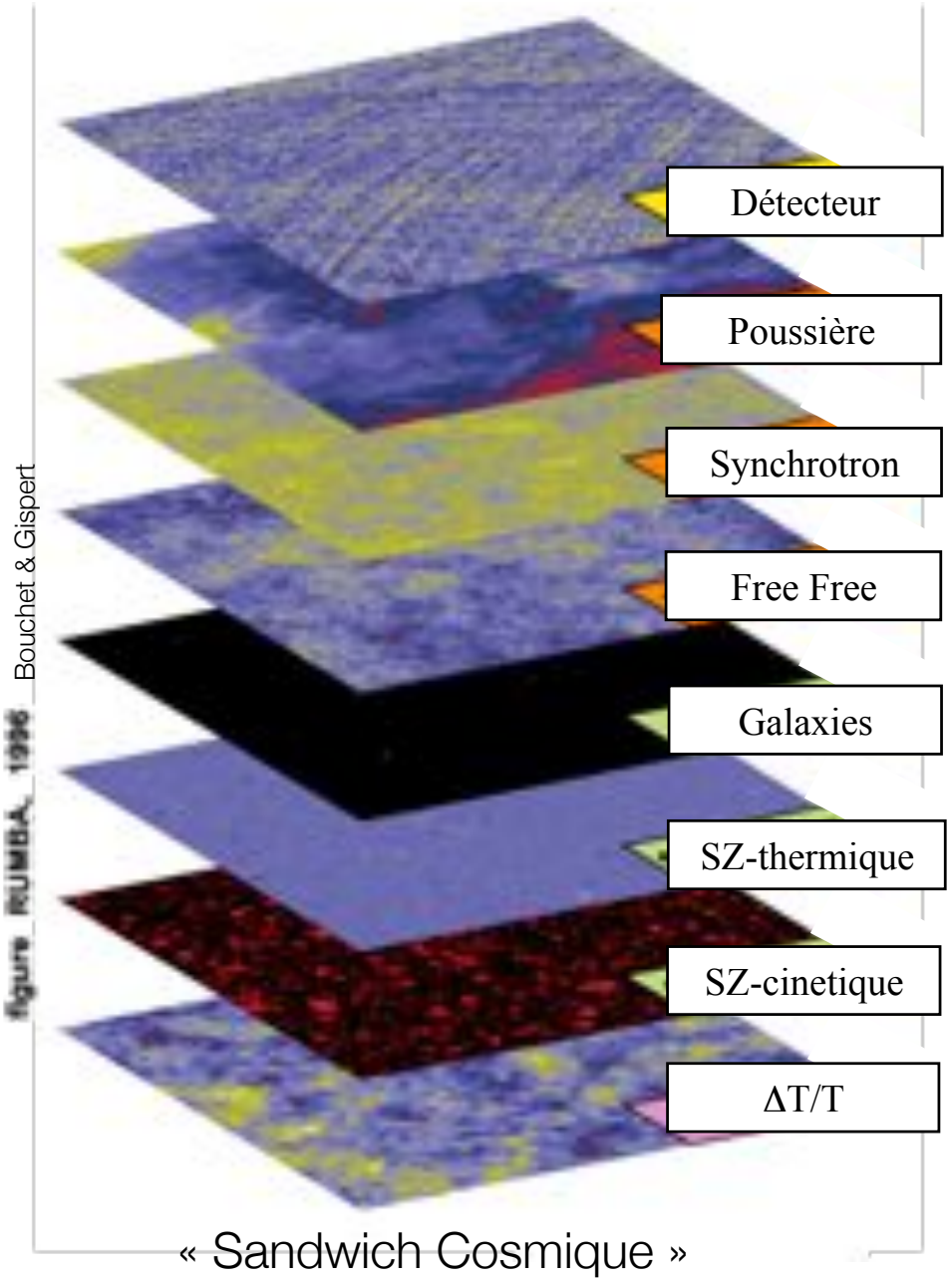
WMAP web site & H. Dole

difficulties

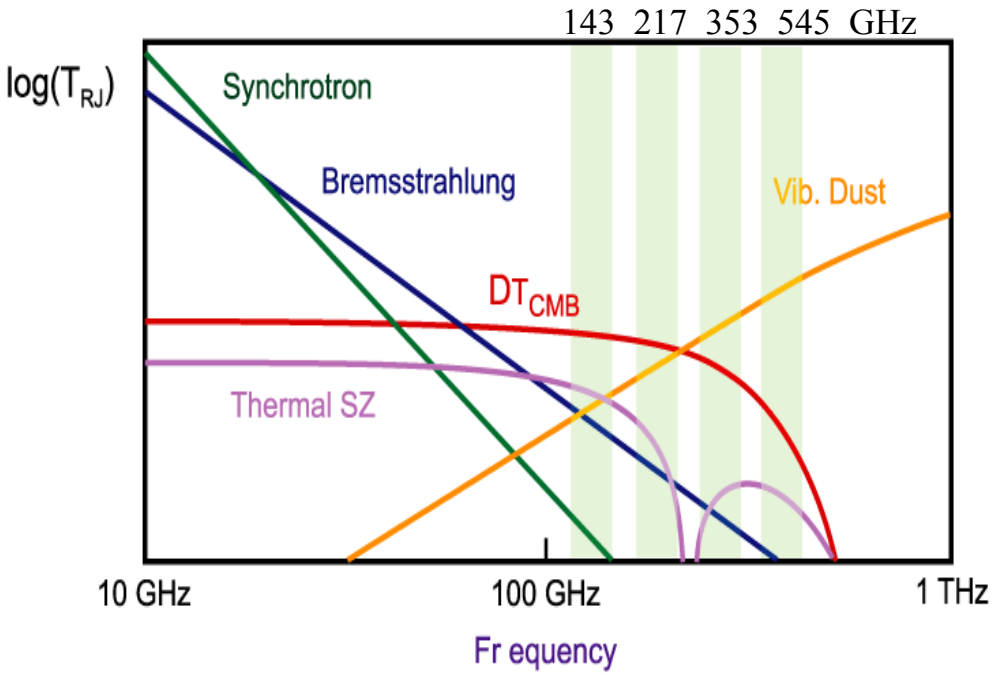


http://arcade.gsfc.nasa.gov/science_galaxy.html

foregrounds



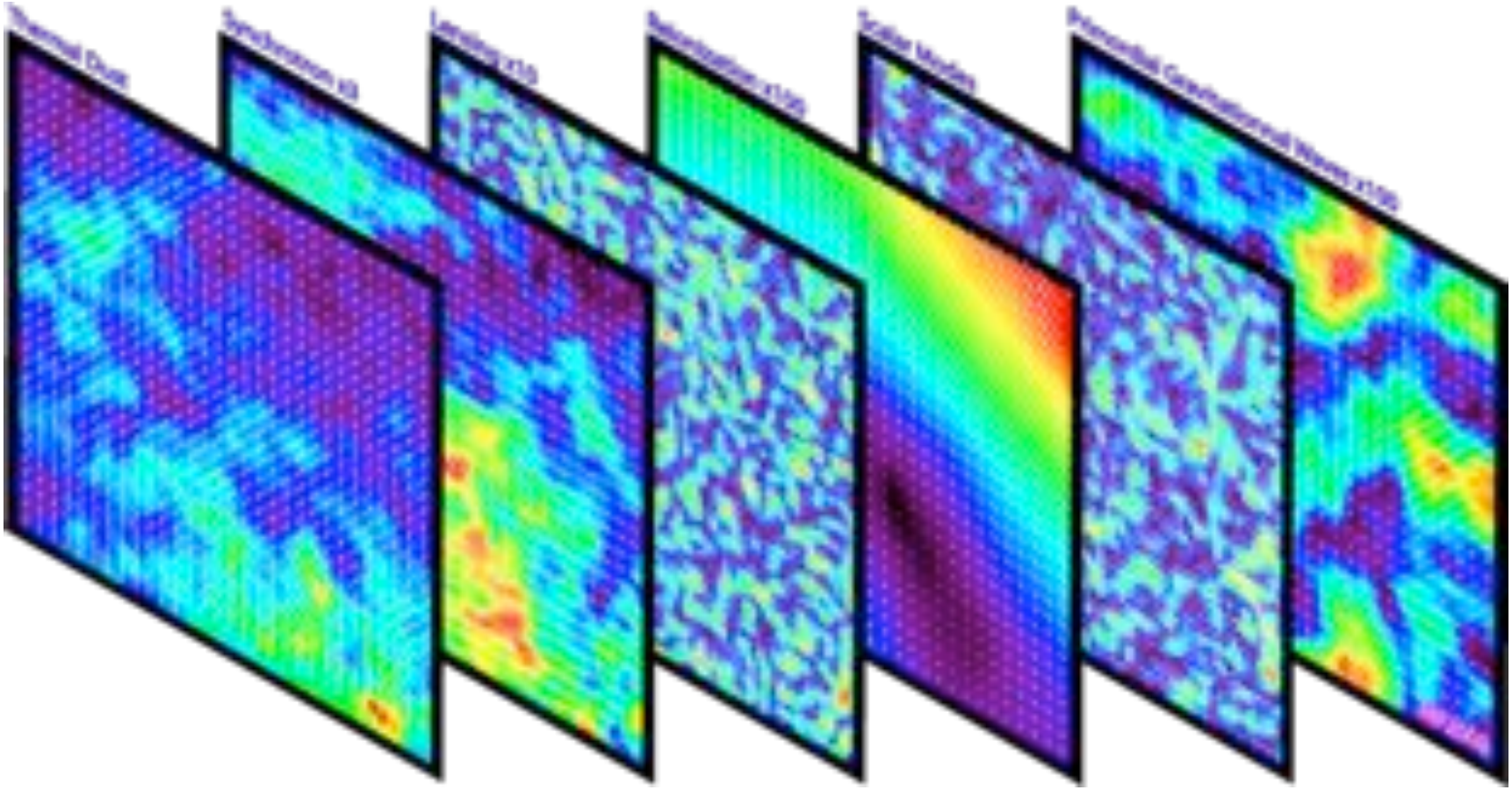
« Sandwich Cosmique »



La poussière domine à hautes fréquences et est donc un avant-plan important pour les observations bolométriques

Courtesy N. Ponthieu, IAS

foregrounds

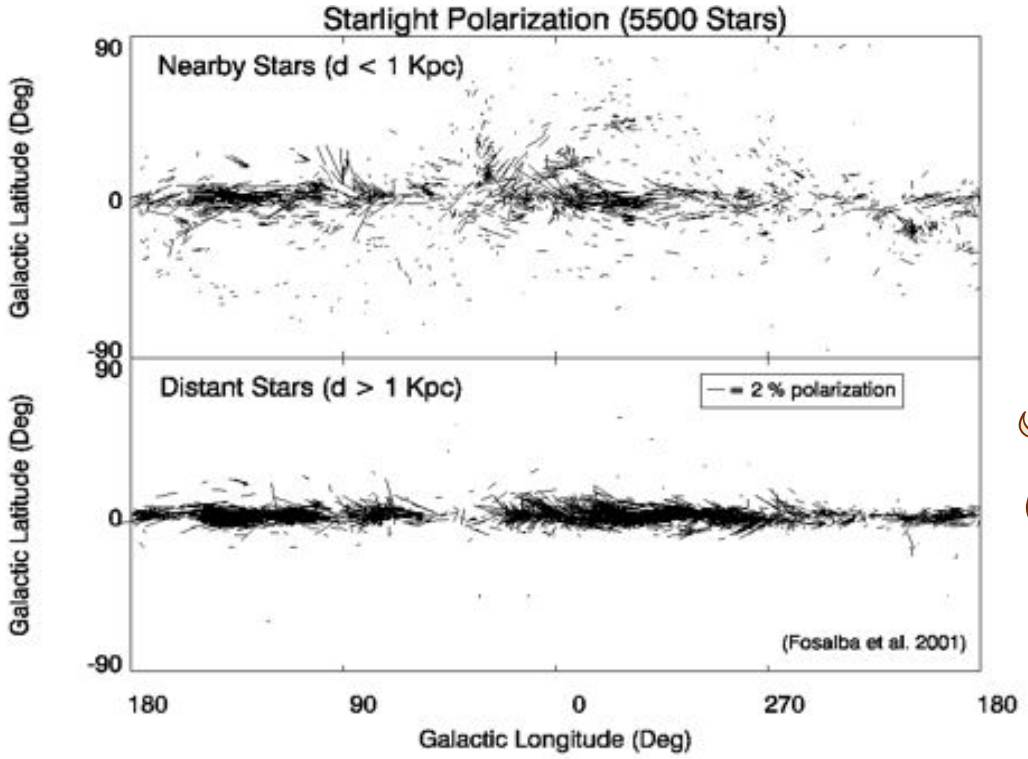


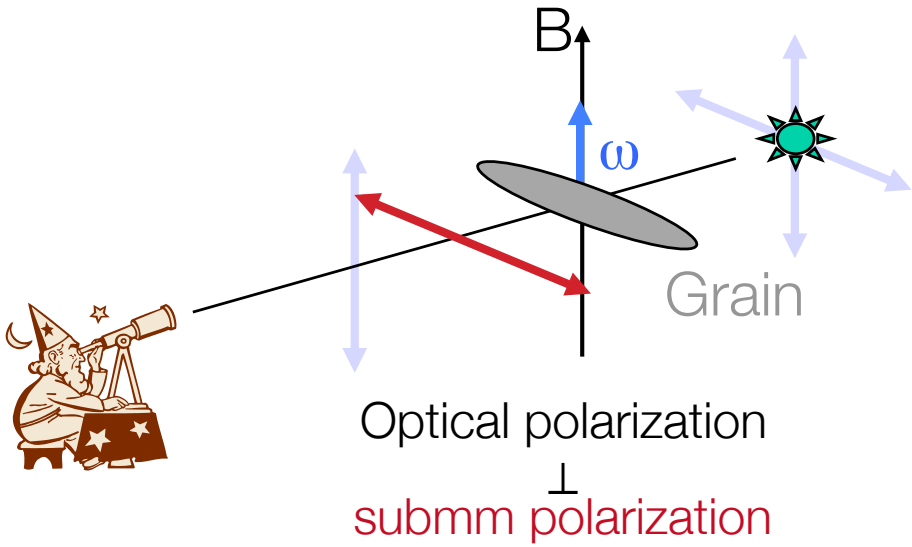
Courtesy N. Ponthieu, IAS

Polarisation de l'émission thermique de la poussière

- These grains align with the Galactic magnetic field and have selective absorption in the visible and UV…
- … which in turn leads to selective radiation in the submm

(Stein 66)





Serkowski et al 75
Heiles 01
Fosalba et al 02

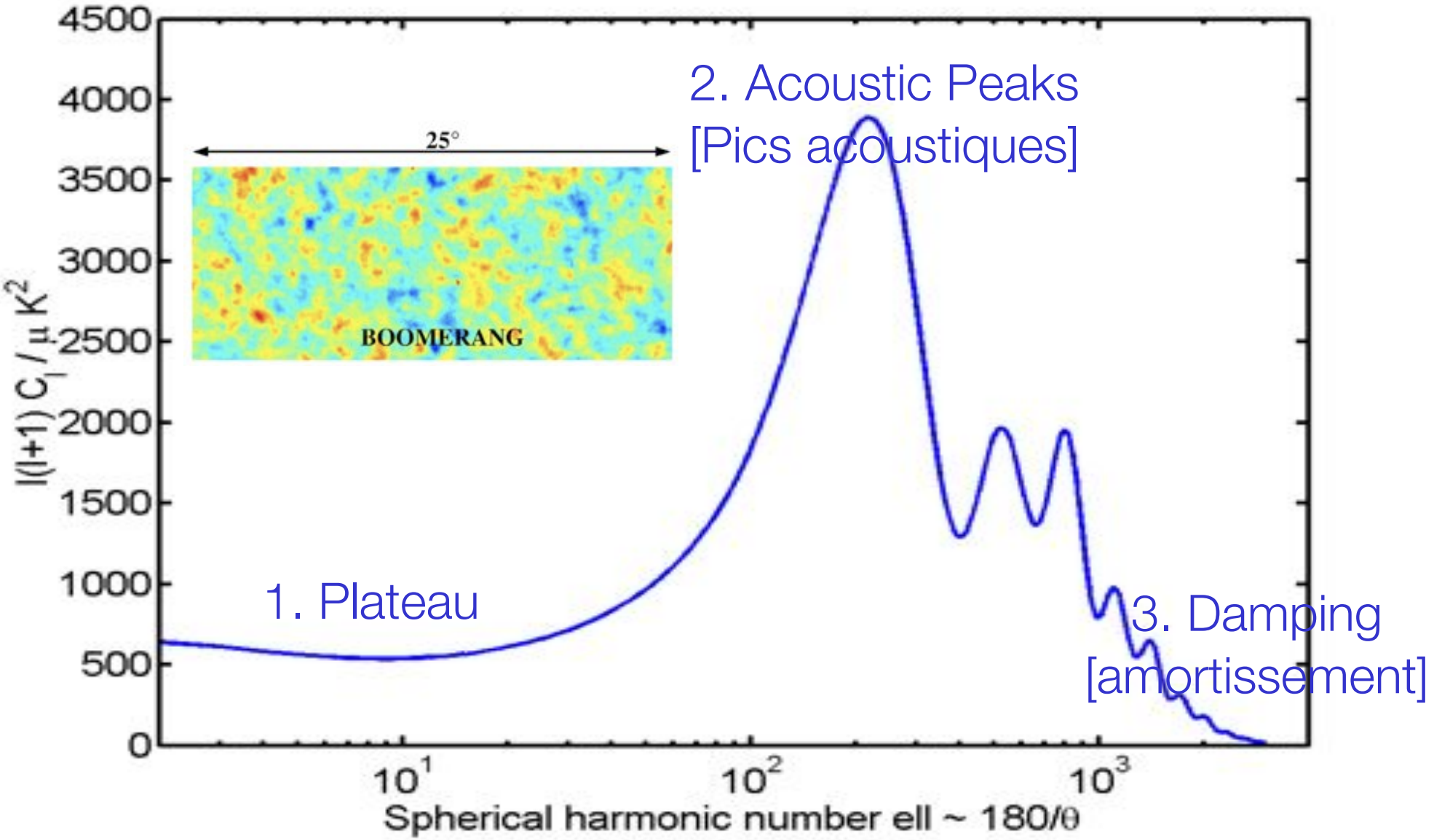
Courtesy N. Ponthieu, IAS

+ Manque de mesures à grandes échelles

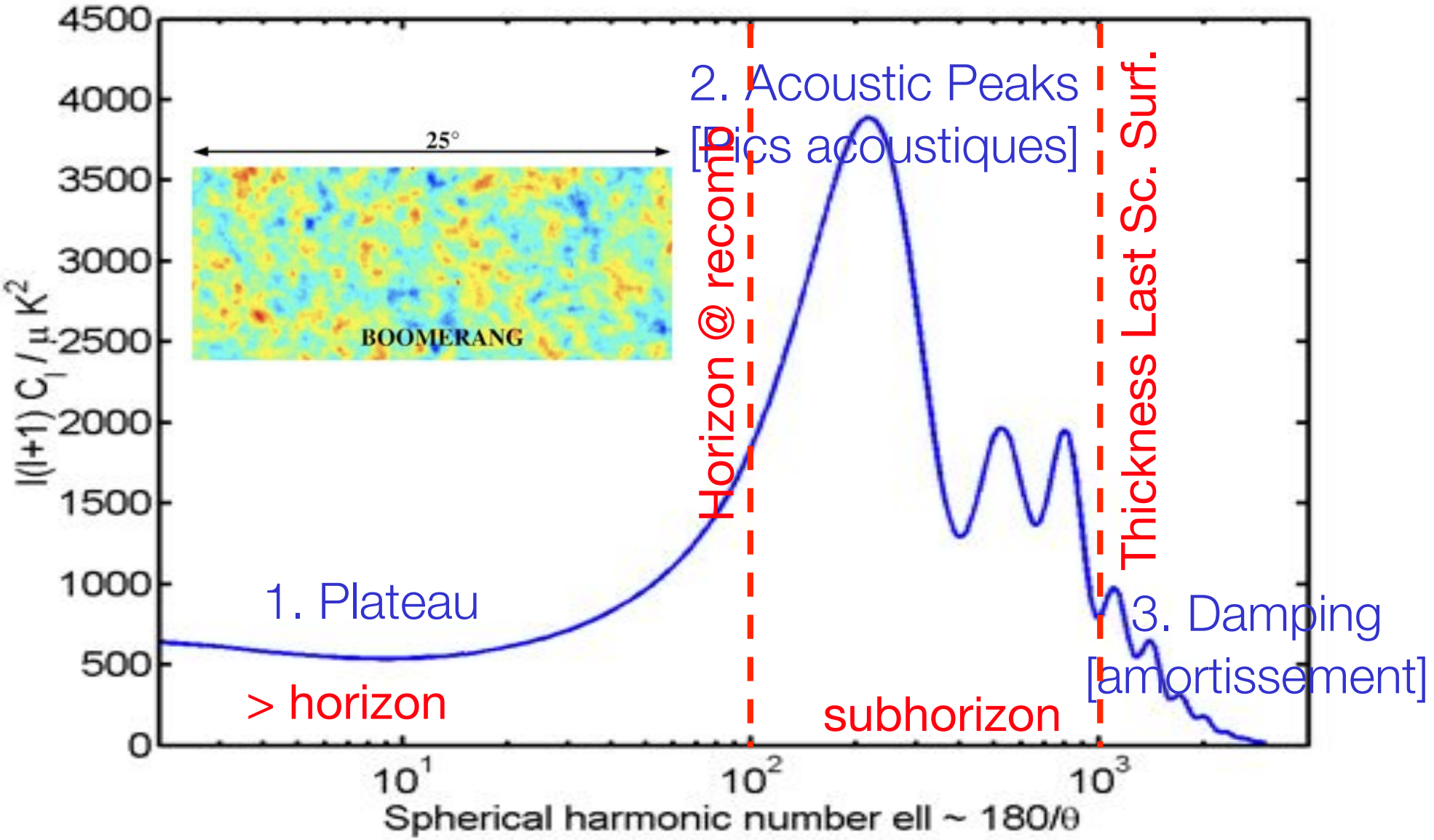
II. Observations of the Cosmic Microwave Background

3. Description of the Angular Power Spectrum

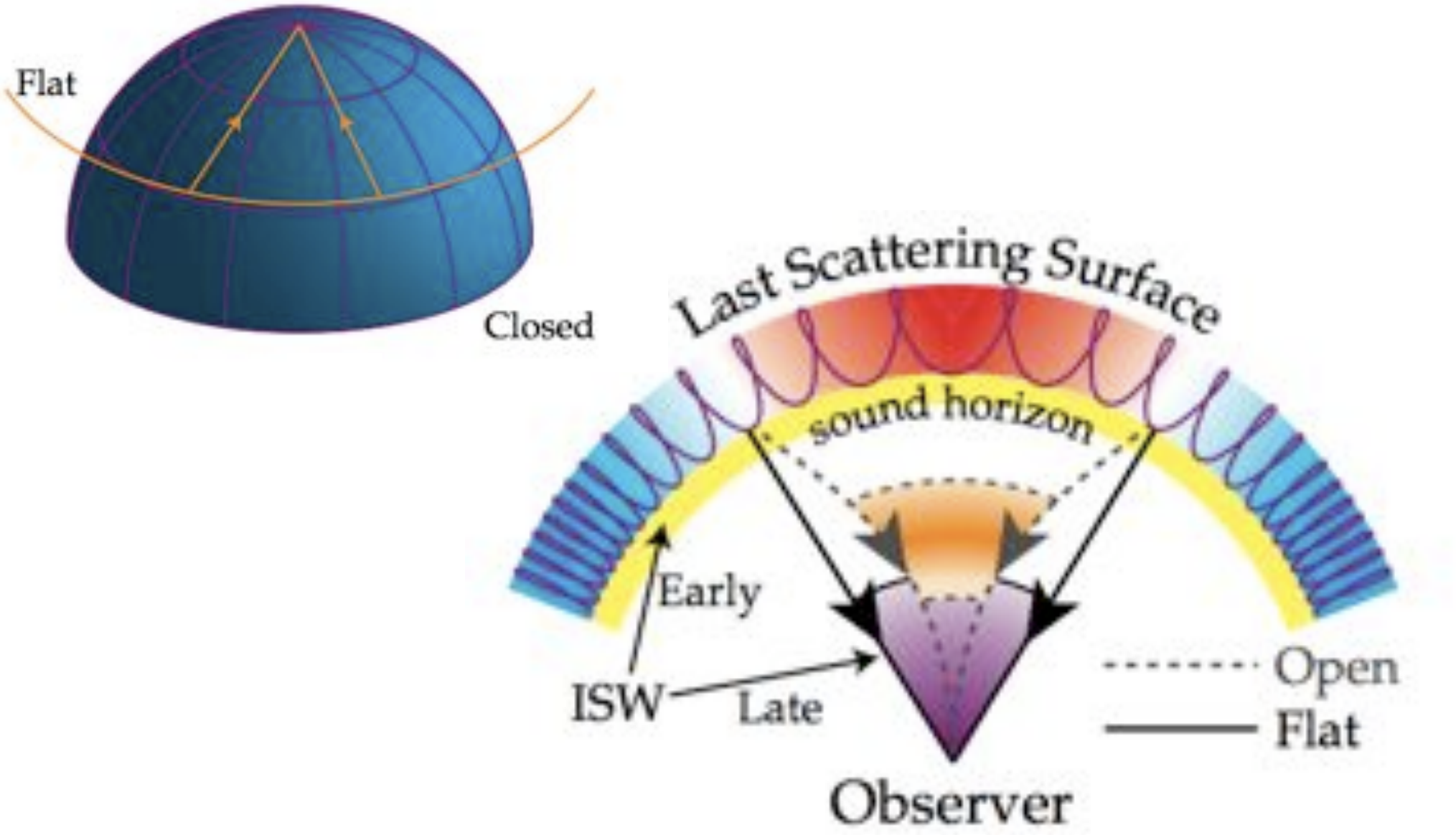
TT angular power spectrum: 3 regimes



TT angular power spectrum: 3 regimes

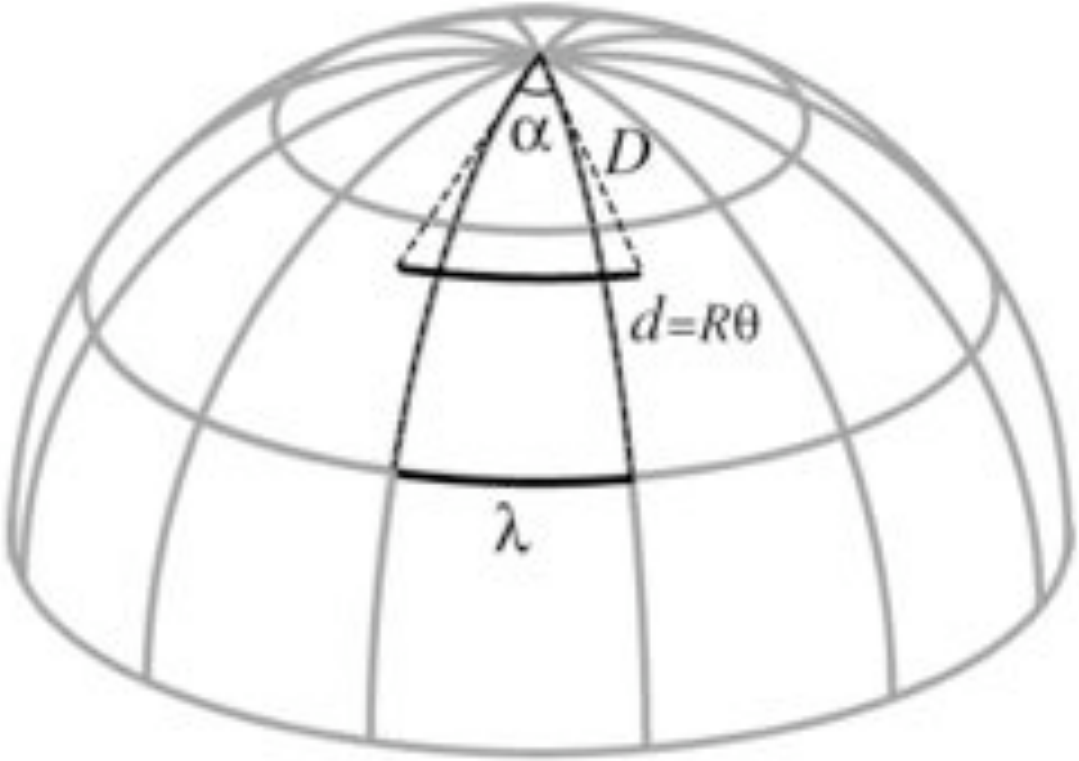


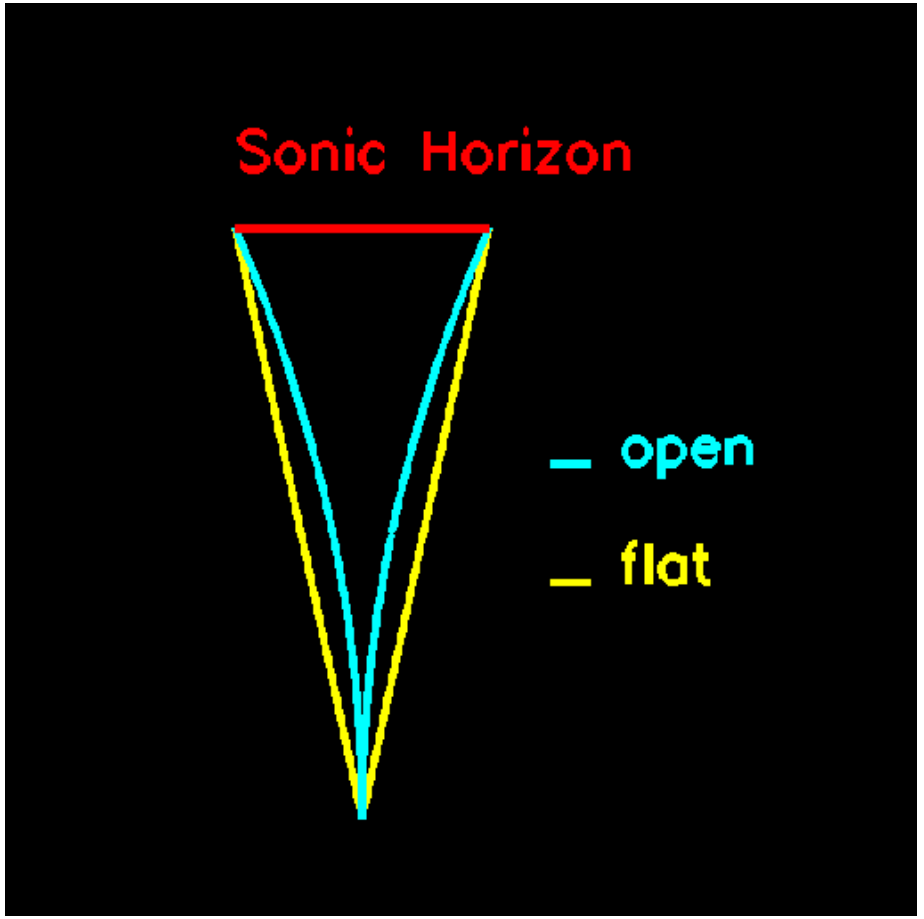
angle and geometrie



Hu, Sugiyama, Silk, 1999

angular distance



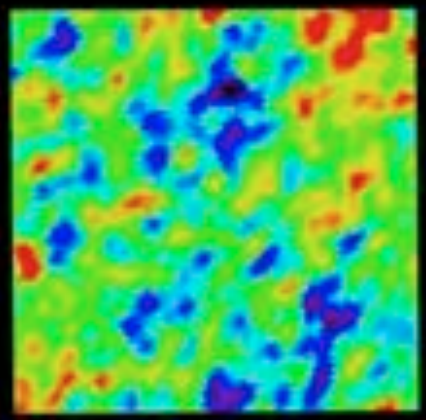
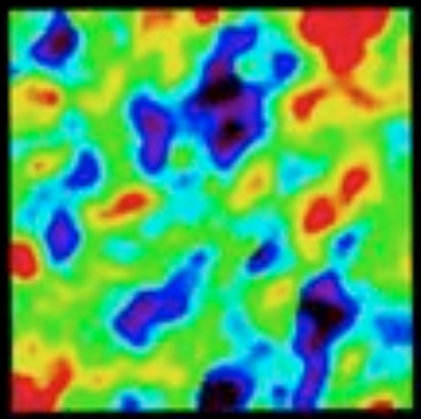
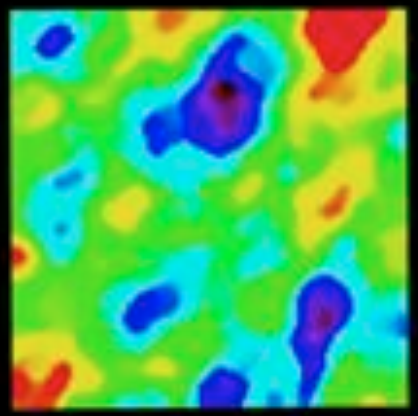


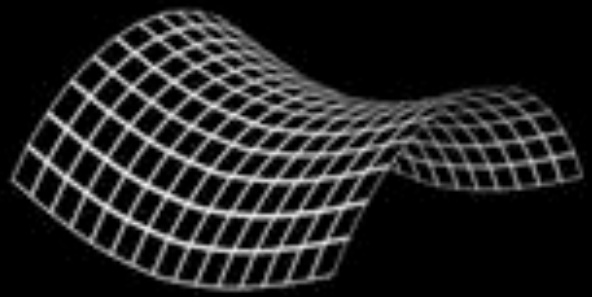
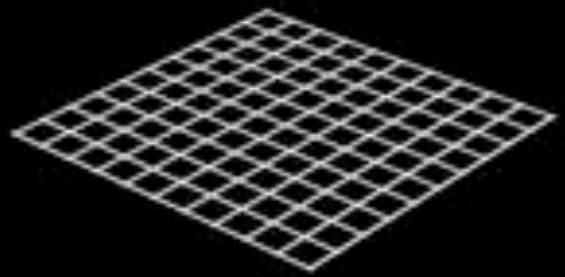
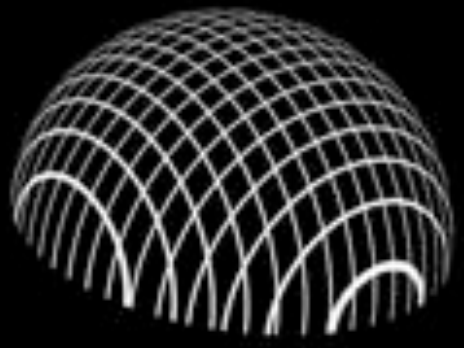
@z~1100

Hu & Dodelson, 2002, ARAA

WMAP

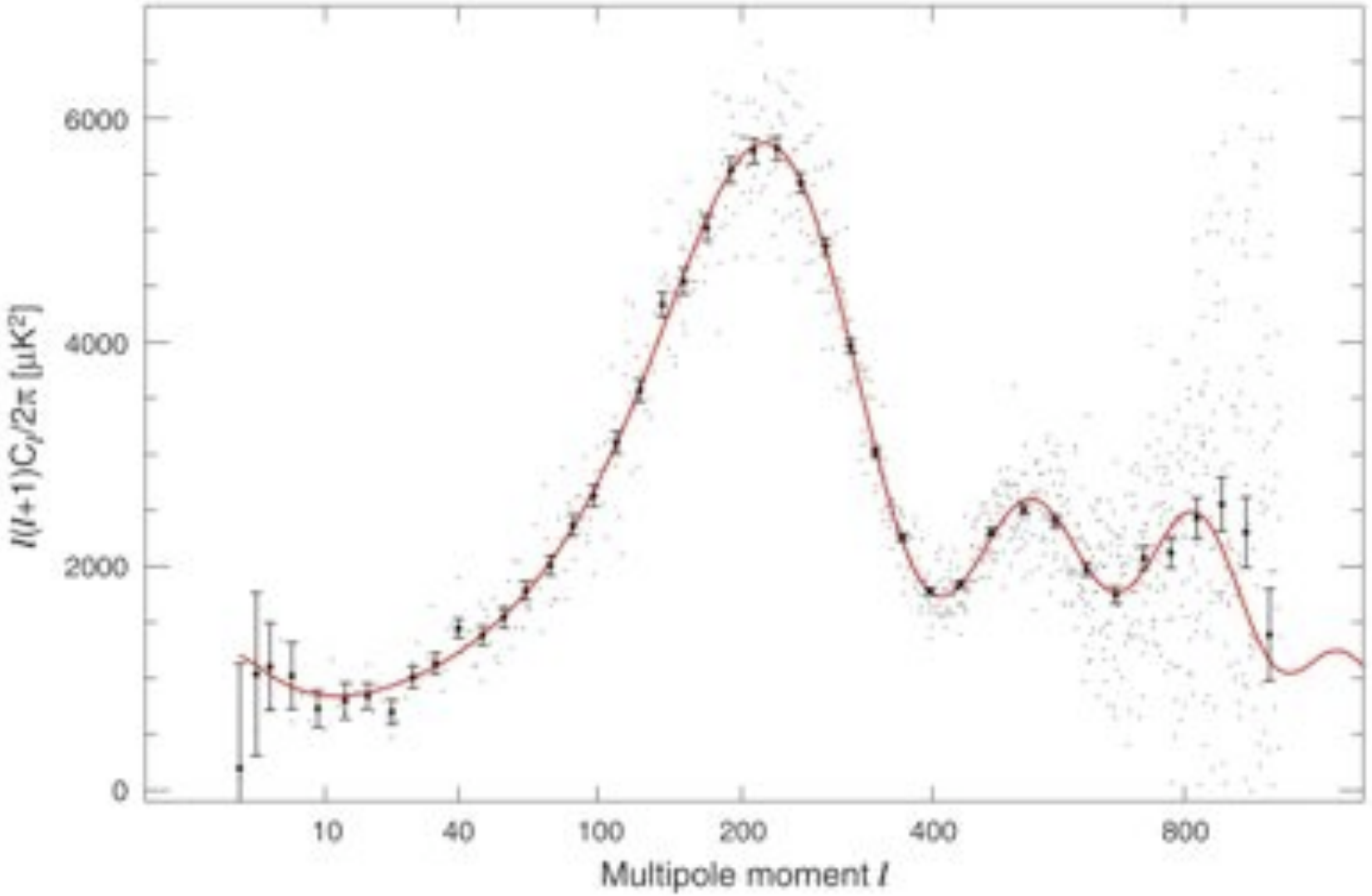
GEOMETRY OF THE UNIVERSE

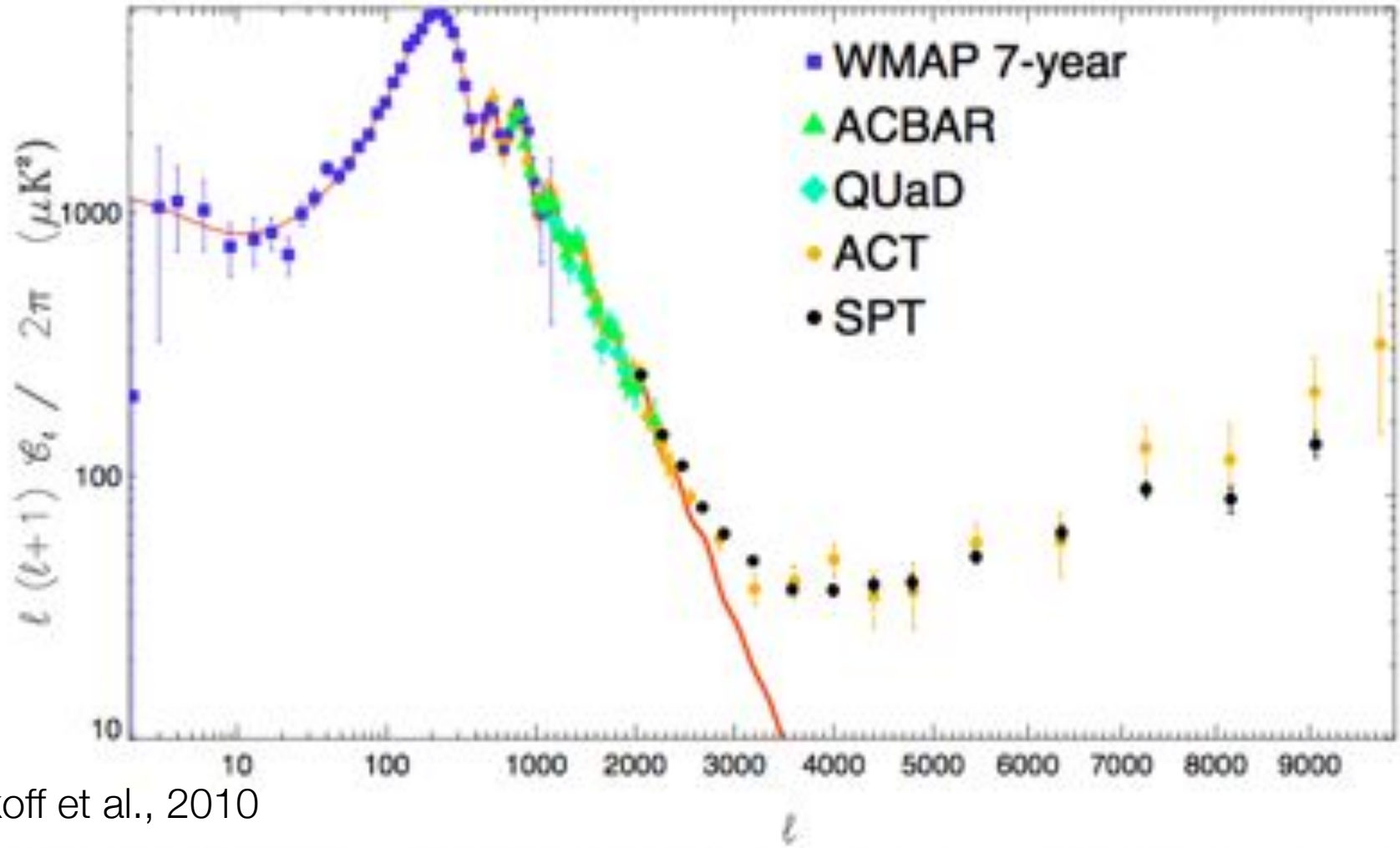
OPEN FLAT CLOSED

WMAP 5 TT



Dunkley et al., 2008, WMAP5

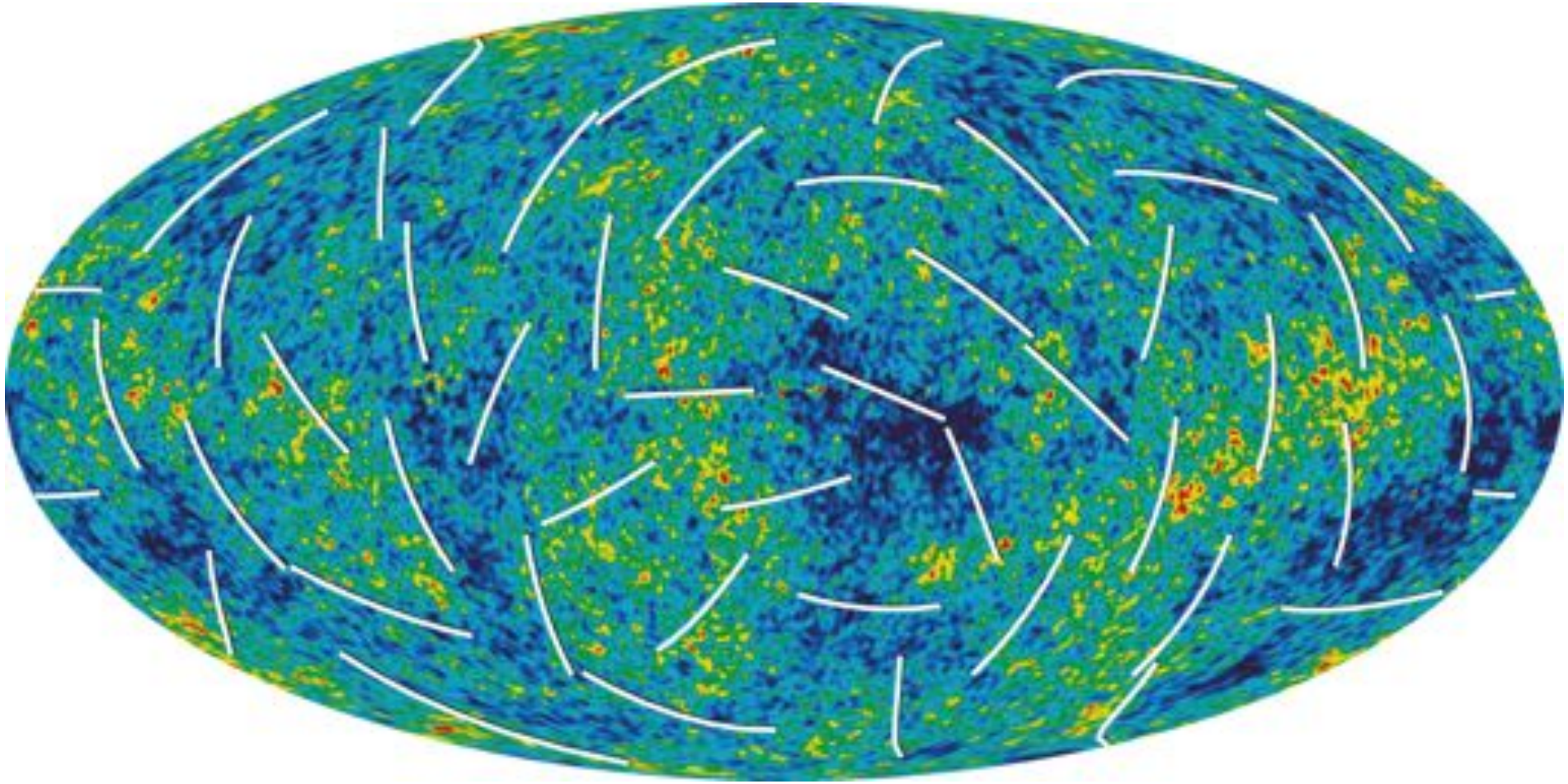
TT power spectrum at high ell



Shirokoff et al., 2010

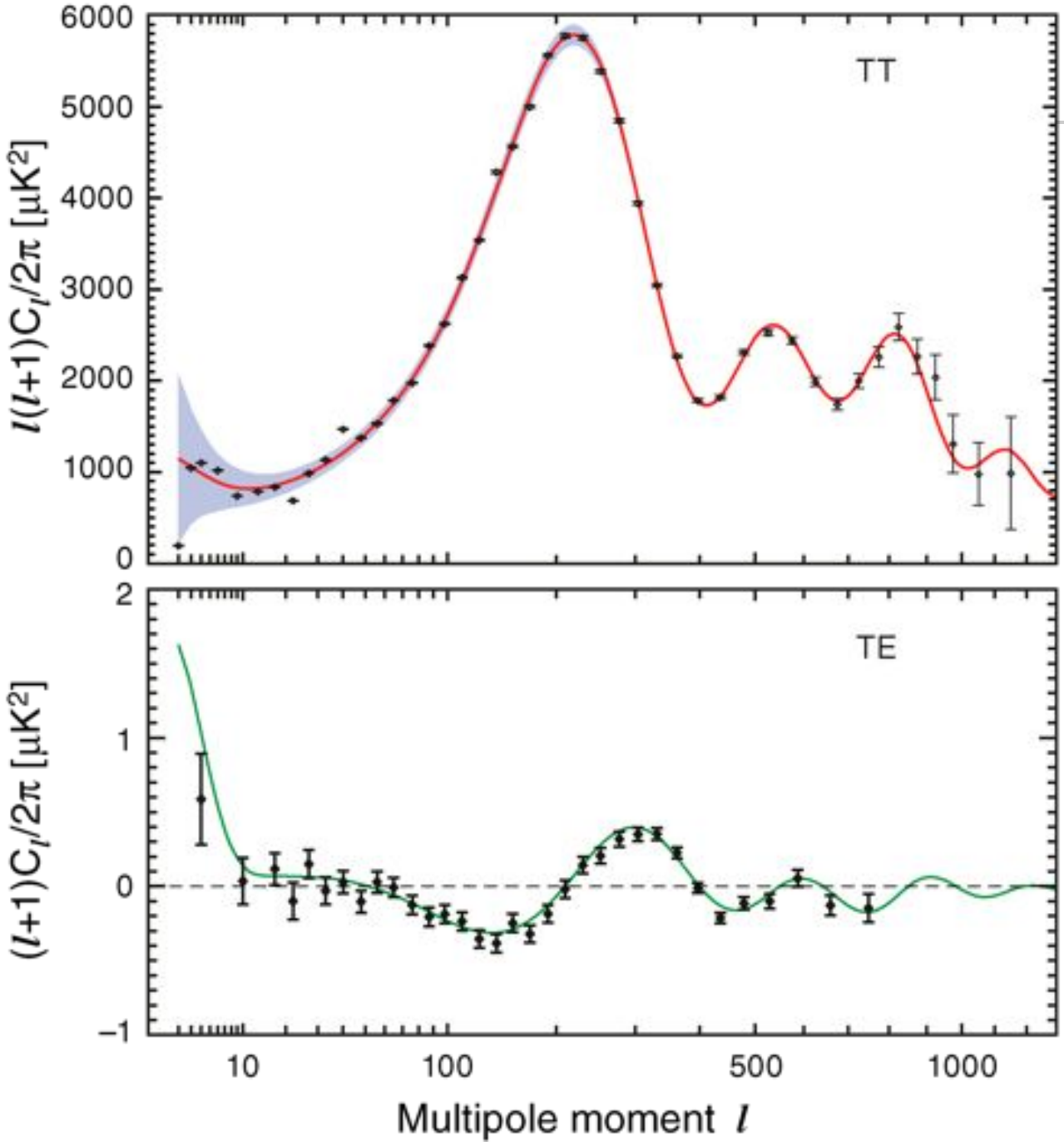
FIG. 4.— The SPT 150 GHz bandpowers (**black circles**), WMAP7 bandpowers (**purple squares**), ACBAR bandpowers (**green triangles**), QUaD bandpowers (**cyan diamonds**), and ACT 150 GHz bandpowers (**orange circles**) plotted against the best-fit lensed ΛCDM CMB spectrum. The damping tail of the primary CMB anisotropy is apparent below $\ell = 3000$. Above $\ell = 3000$, there is a clear excess due to secondary anisotropies and residual point sources that has now been measured by both SPT and ACT. Note that the source masking threshold in the SPT data (6.4 mJy) is lower than that in the ACT data, so we expect less radio source power at high ℓ. We have multiplied the SPT bandpowers by the best-fit calibration of 0.92 as determined in parameter fits.

polarized microwave sky

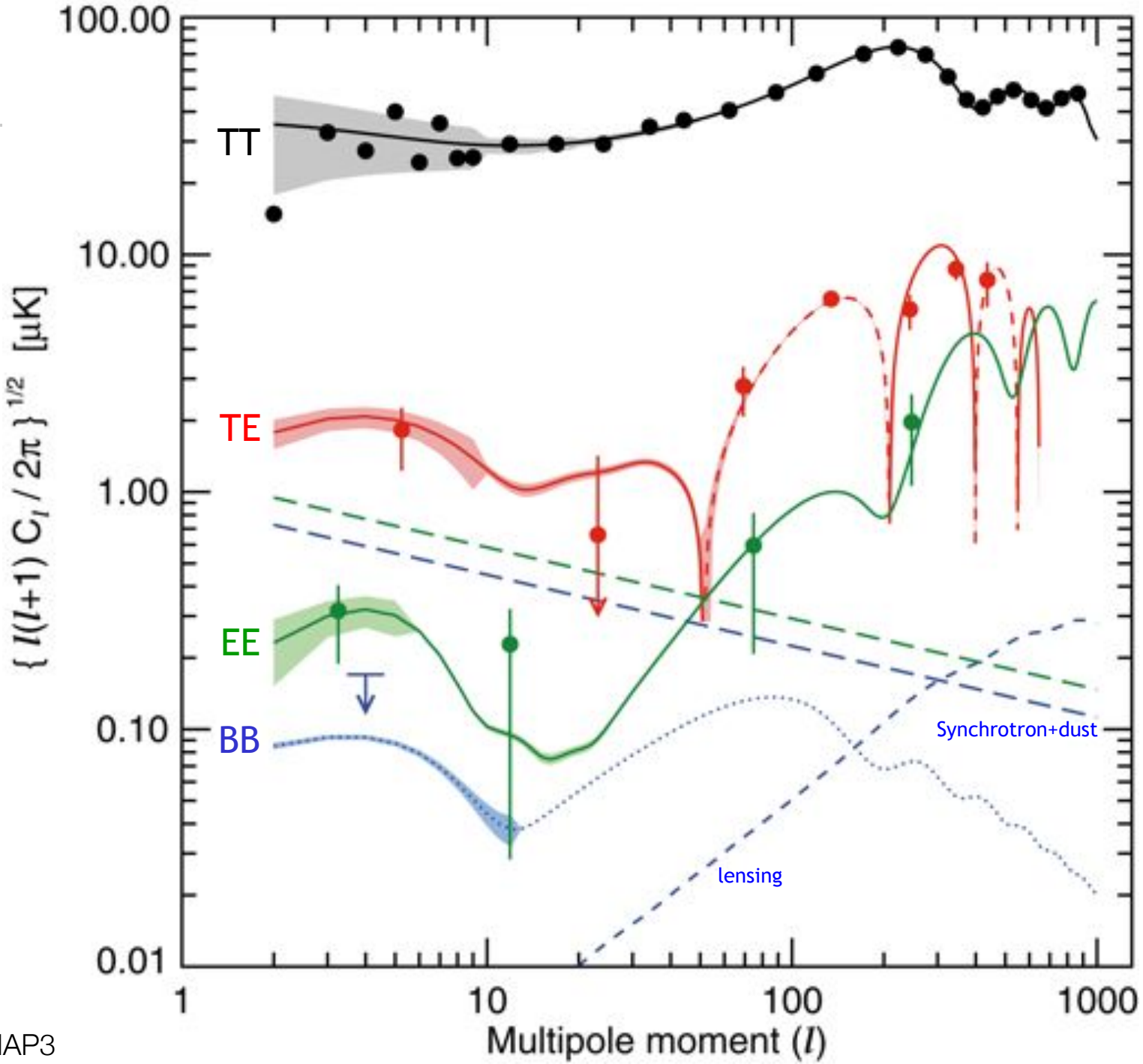


WMAP 3

TT & TE



Jarosik et al., 2009, WMAP7

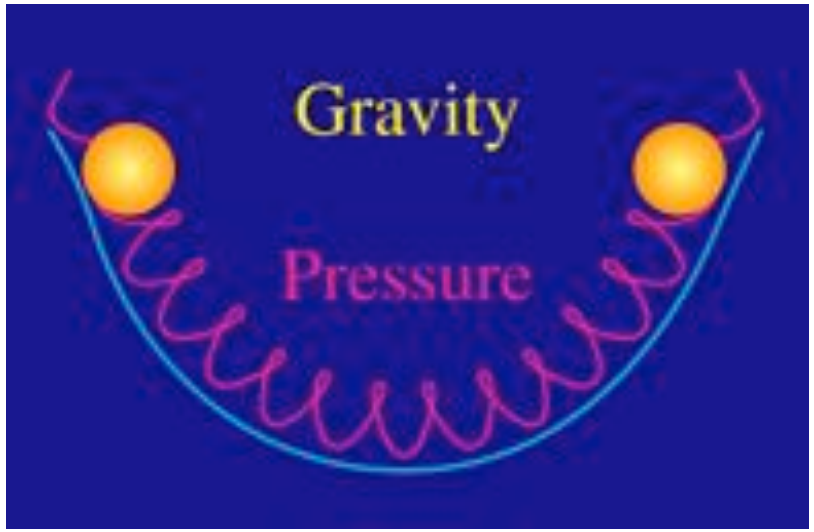


Page et al., 2007, WMAP3

II. Observations of the Cosmic Microwave Background

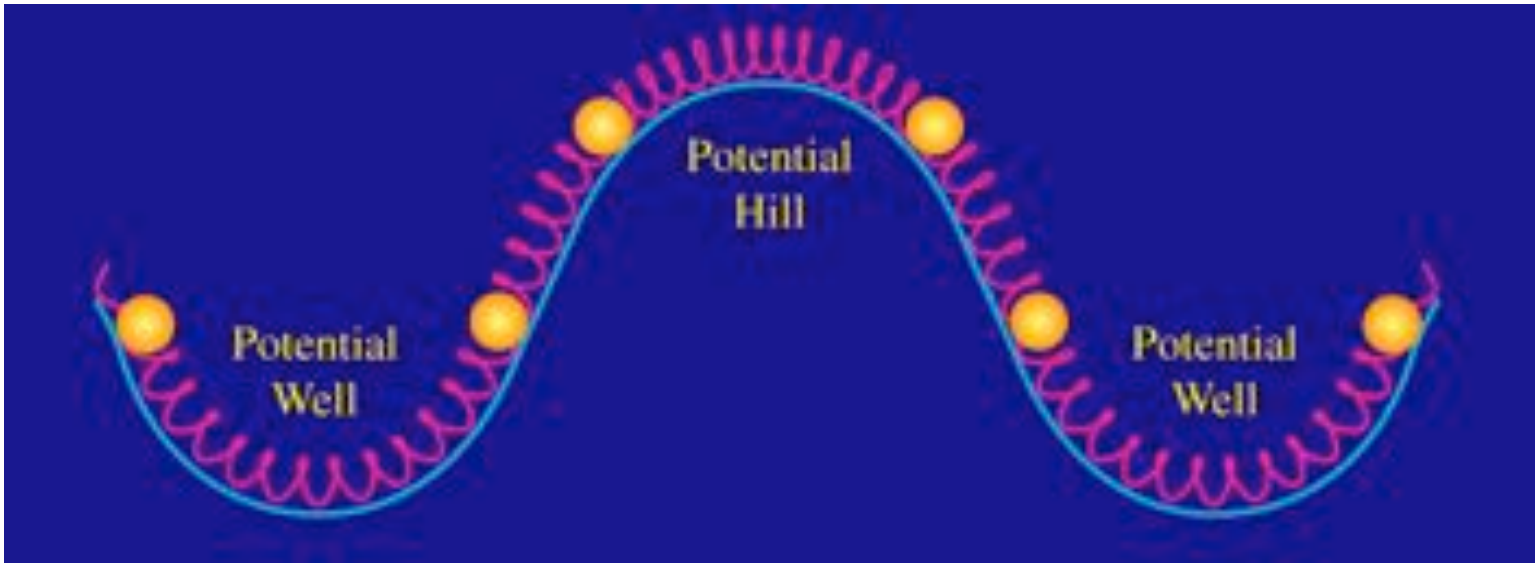
4. C_l and Cosmological Parameters

origine of fluctuations

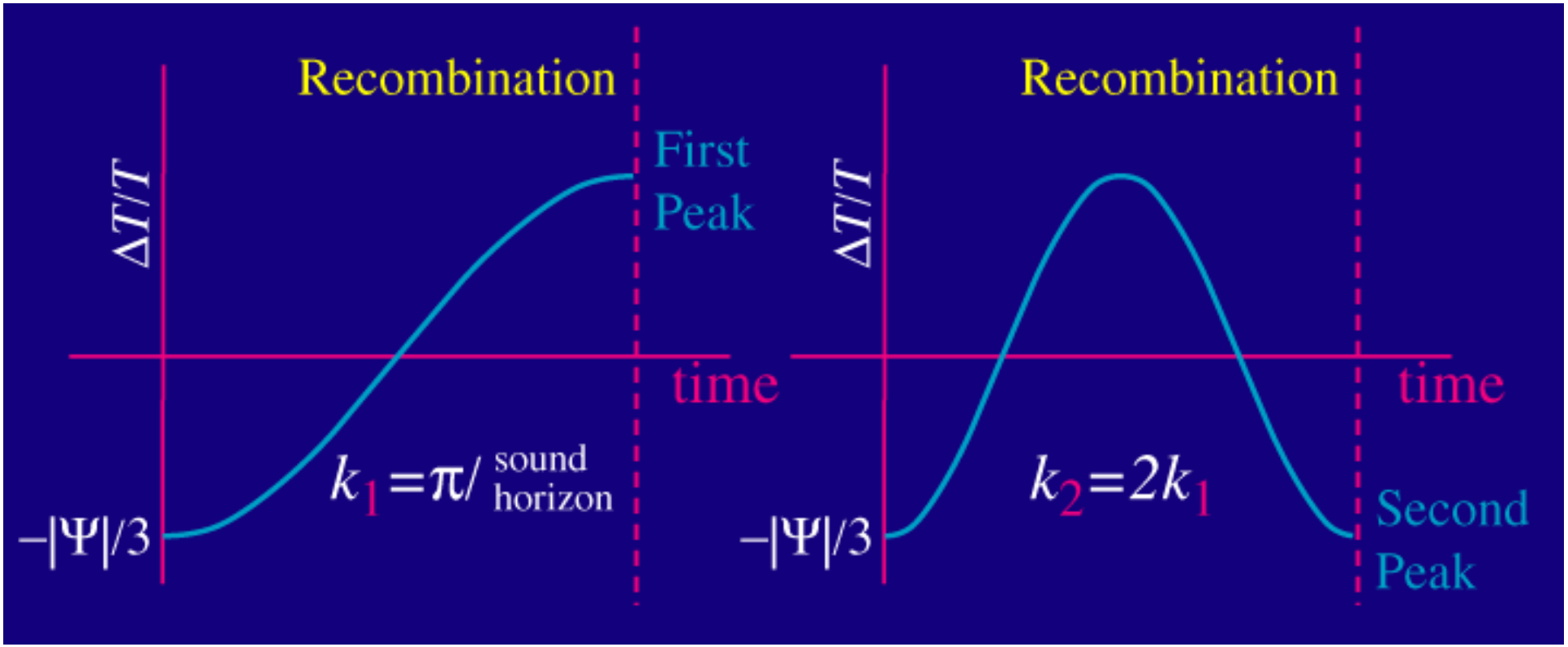


Matière => puits de potentiel

Puits de potentiel
- les photons qui tombent se réchauffent (compression)
- les photons qui en sortent sont refroidis (détente)

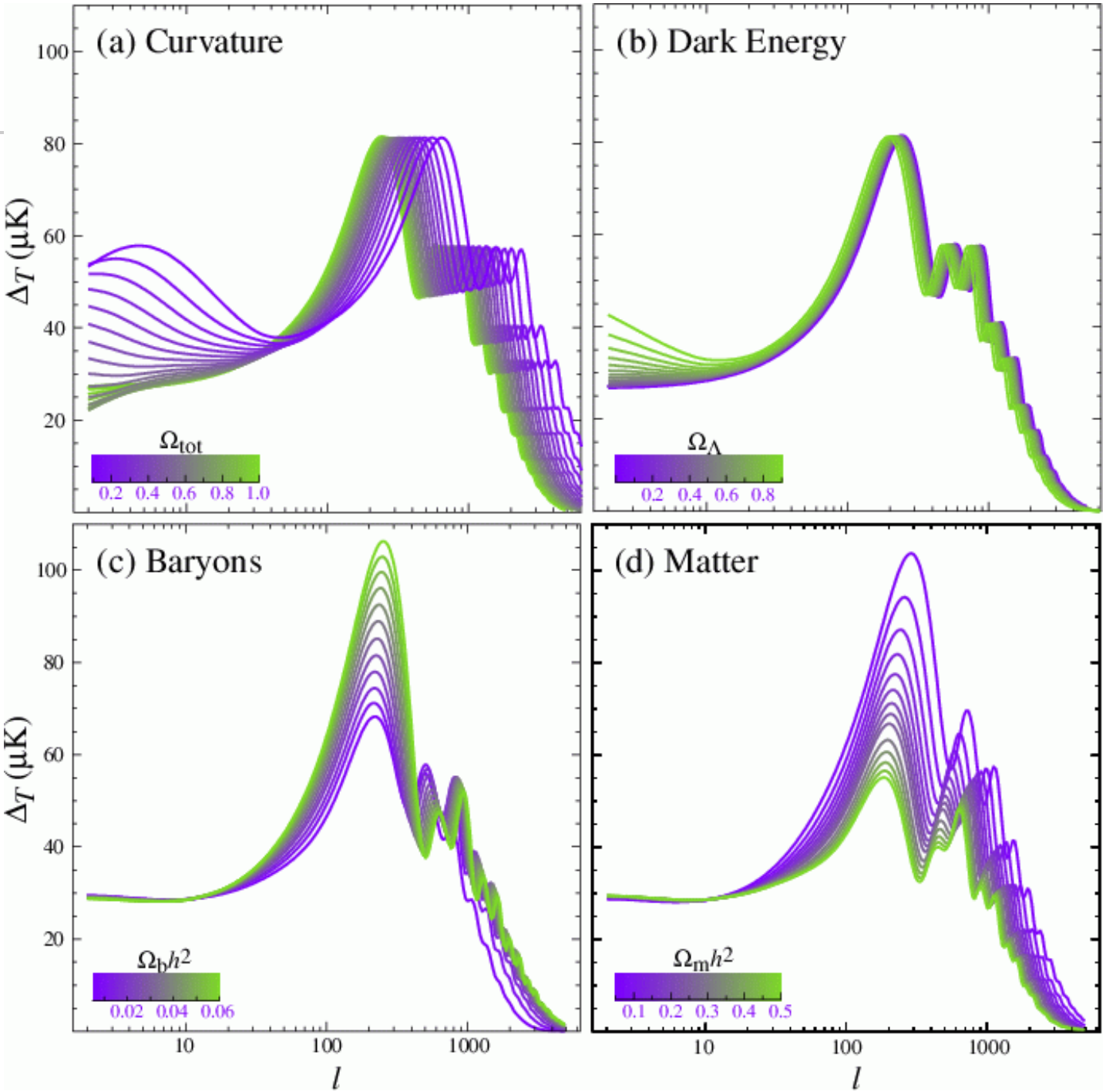


acoustic waves at recombination



La physique de ces ondes dépend des paramètres cosmologiques

C_l

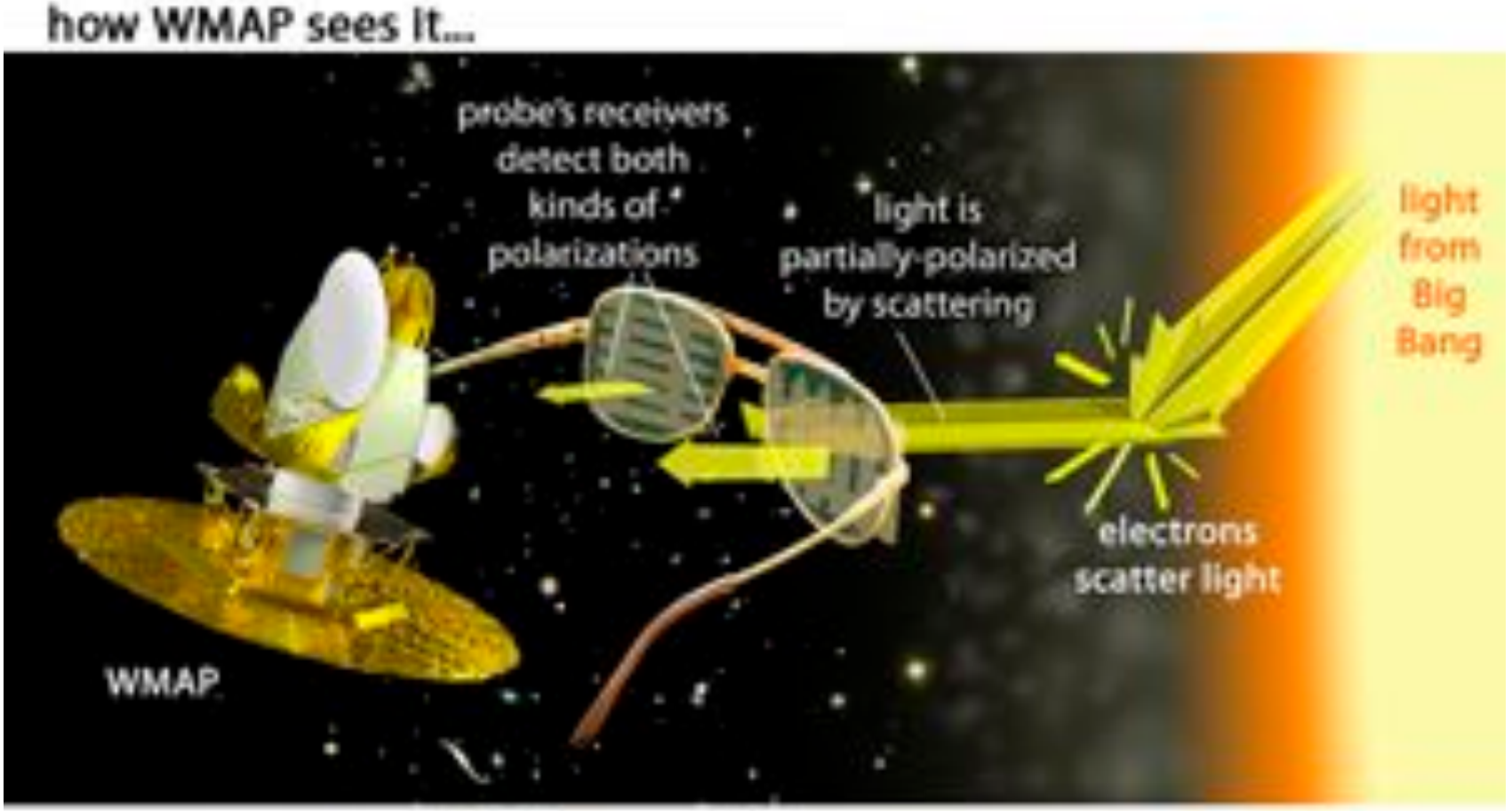


Hu & Dodelson, ARAA, 2002

II. Observations of the Cosmic Microwave Background

5. Polarization

CMB polarization for dummies

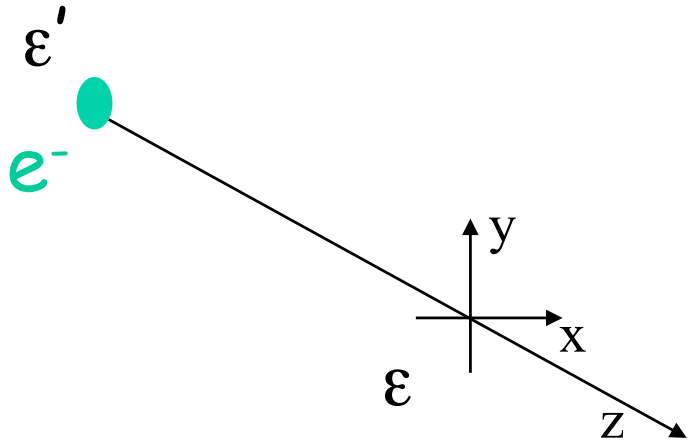


Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$

avec $\sigma_T \sim 1/m^2$ -> e-
et $d\Omega$: angle solide

Rayonnement isotrope
(monopole)

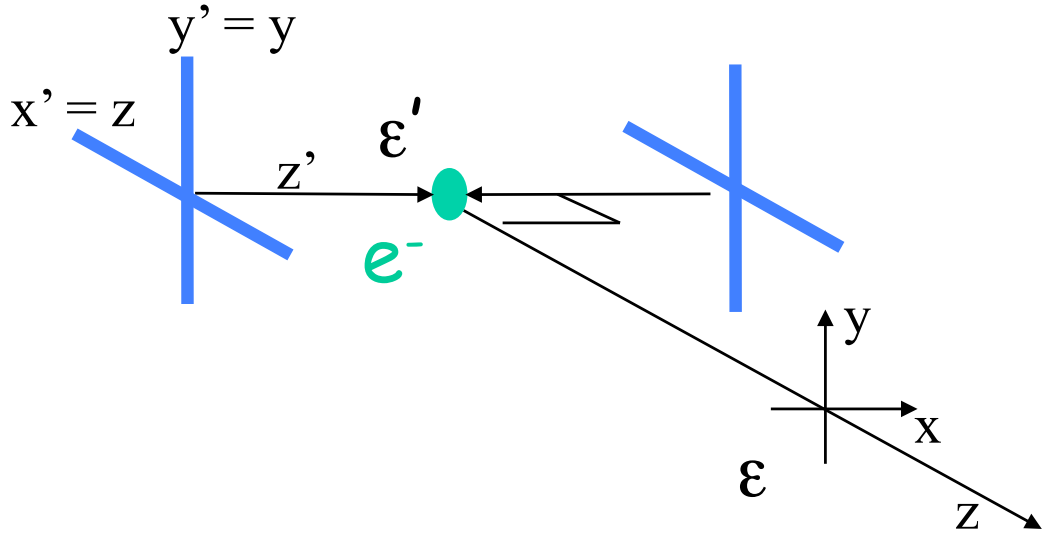


Courtesy N. Ponthieu, IAS

Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$

Rayonnement isotrope
(monopole)

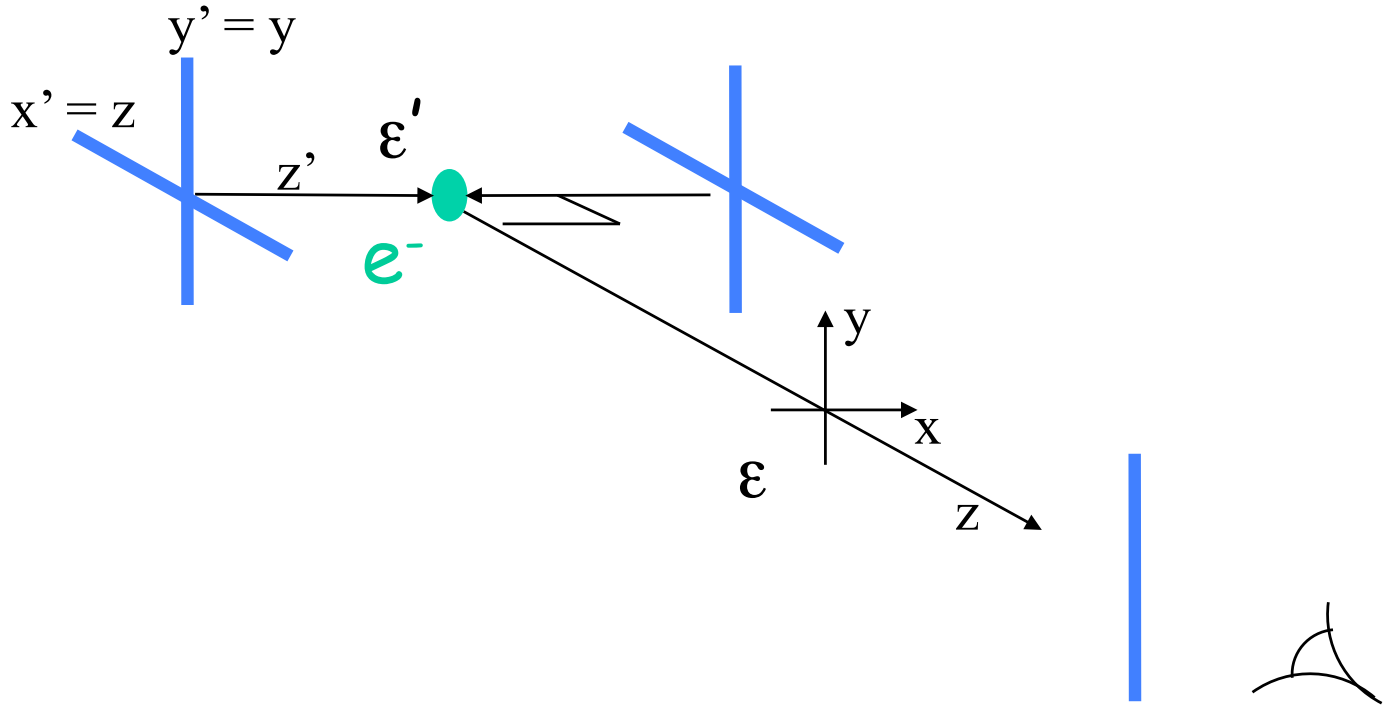


Courtesy N. Ponthieu, IAS

Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$

Rayonnement isotrope
(monopole)

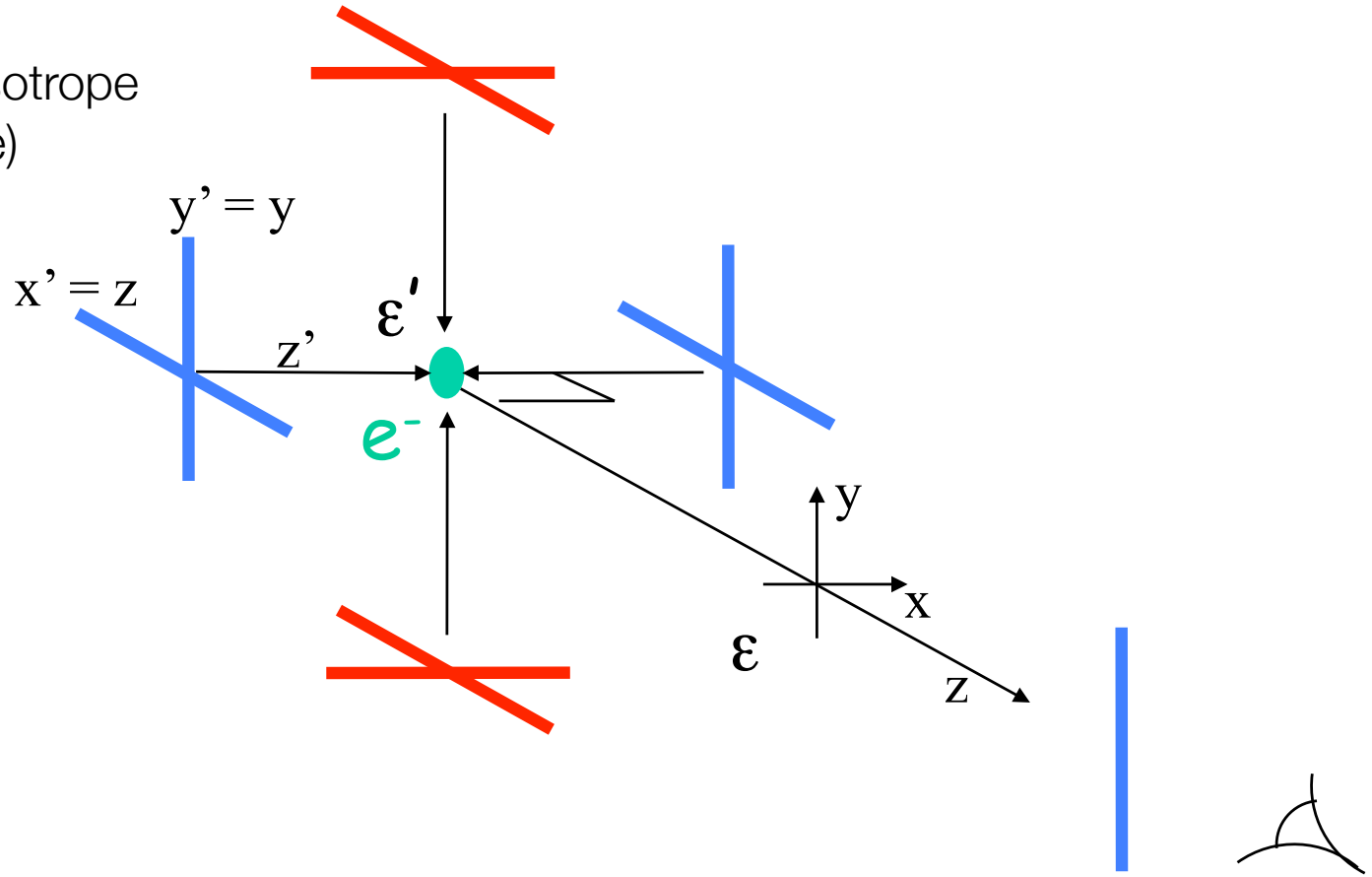


Courtesy N. Ponthieu, IAS

Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$

Rayonnement isotrope
(monopole)

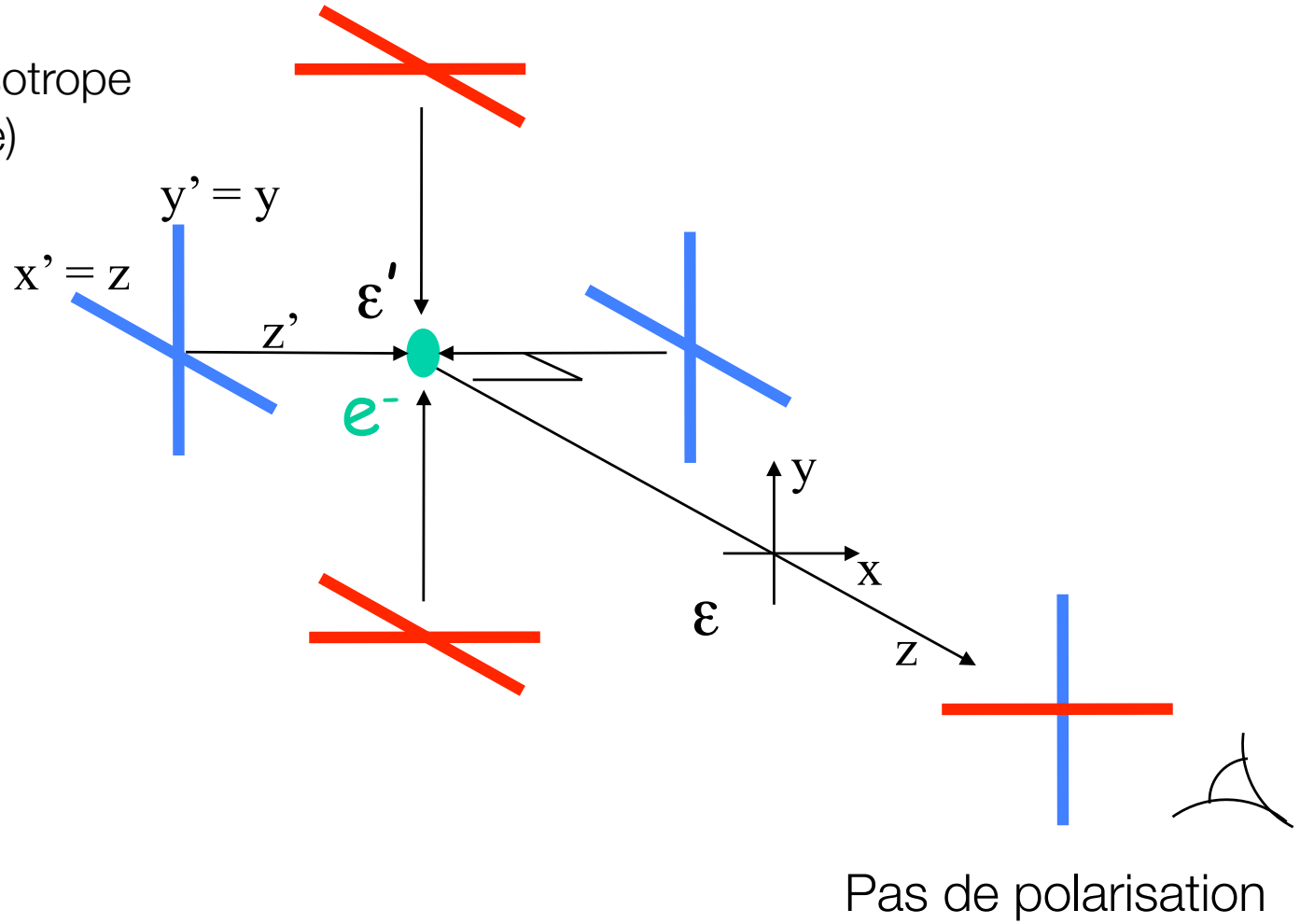


Courtesy N. Ponthieu, IAS

Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$

Rayonnement isotrope
(monopole)

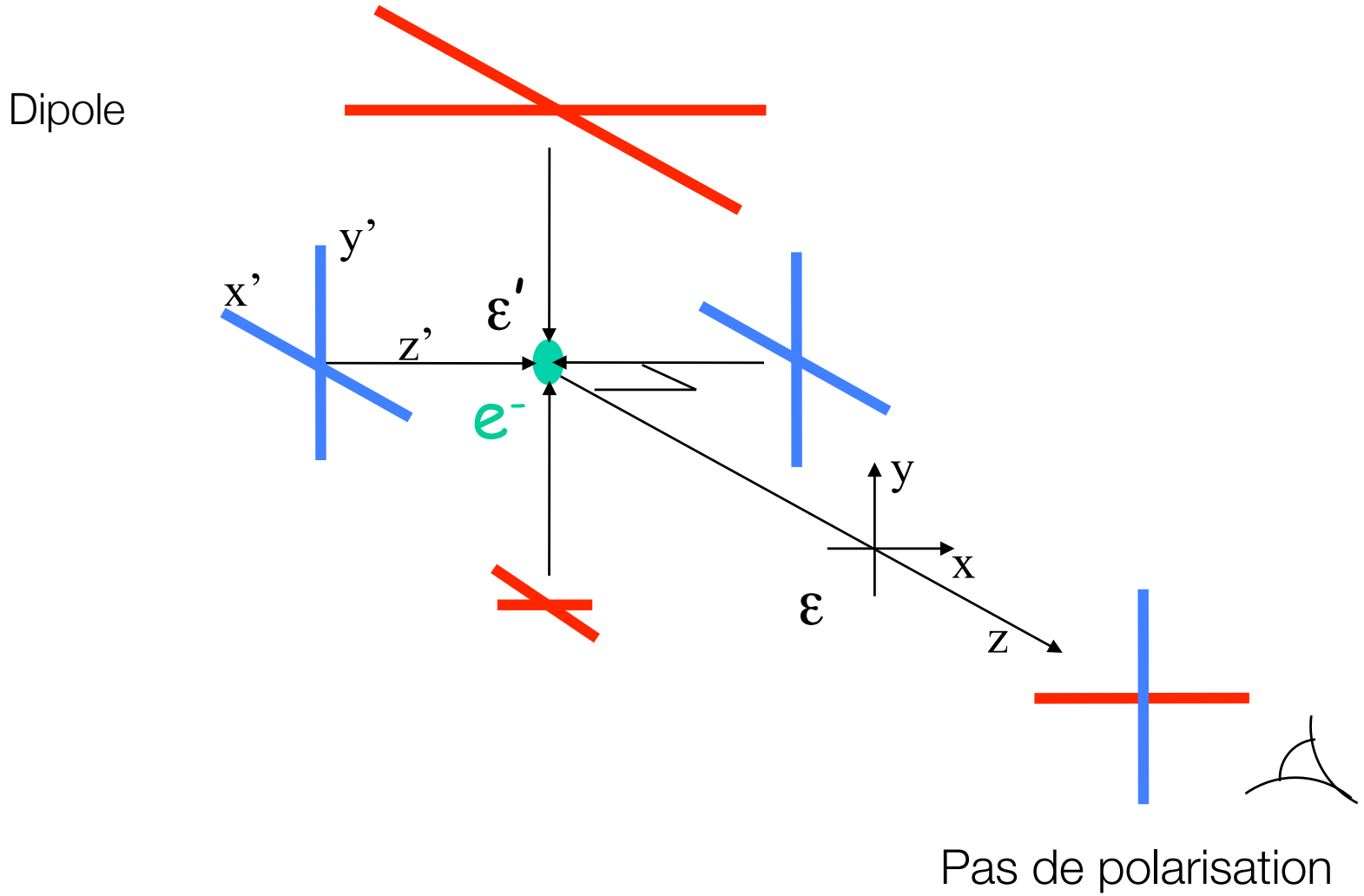


Pas de polarisation

Courtesy N. Ponthieu, IAS

Recombination

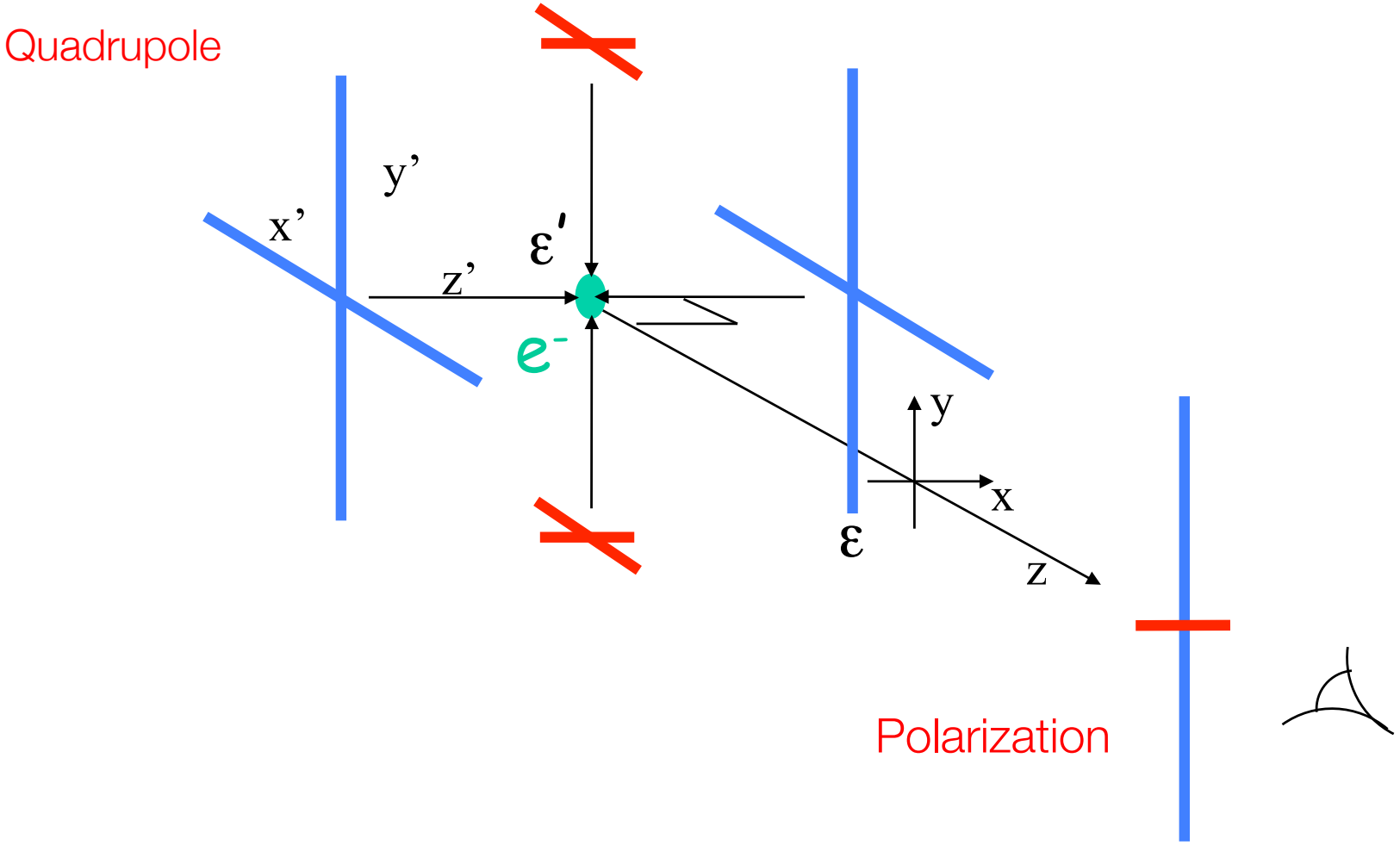
Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$



Courtesy N. Ponthieu, IAS

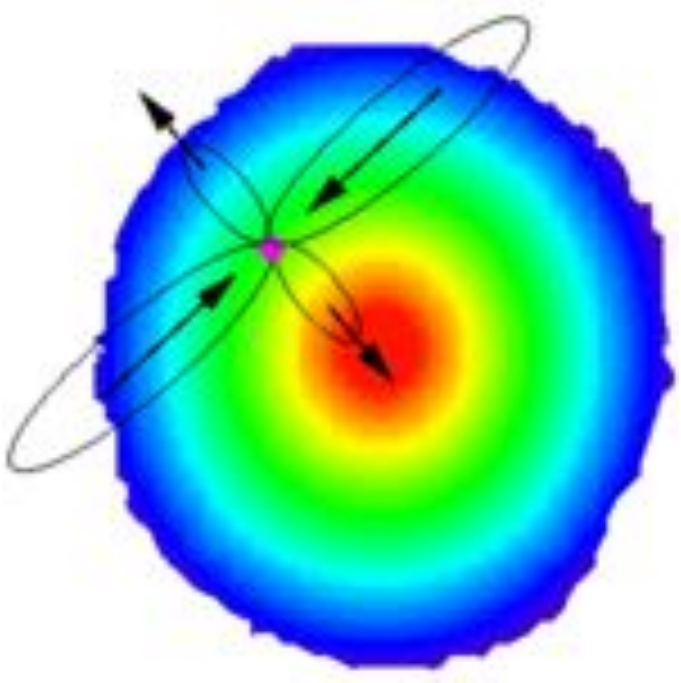
Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$



Courtesy N. Ponthieu, IAS

quadrupoles at recombination



Les sur (sous) densités génèrent de la polarisation (vitesse)

On sonde directement la recombinaison

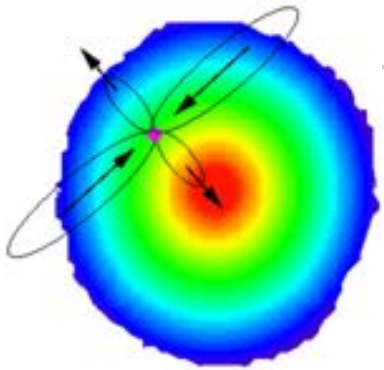
Over (under) densities generate polarization (speed)

Polarization: a direct probe of recombination processes

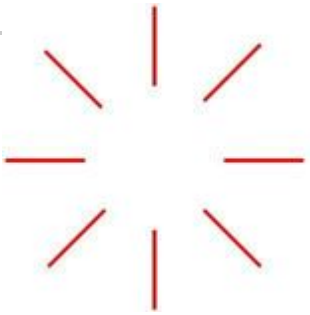
Rees, 1968

Courtesy N. Ponthieu, IAS

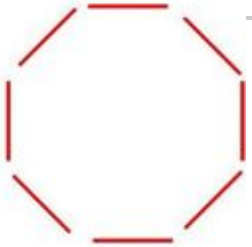
Perturbations scalaires



surdensité



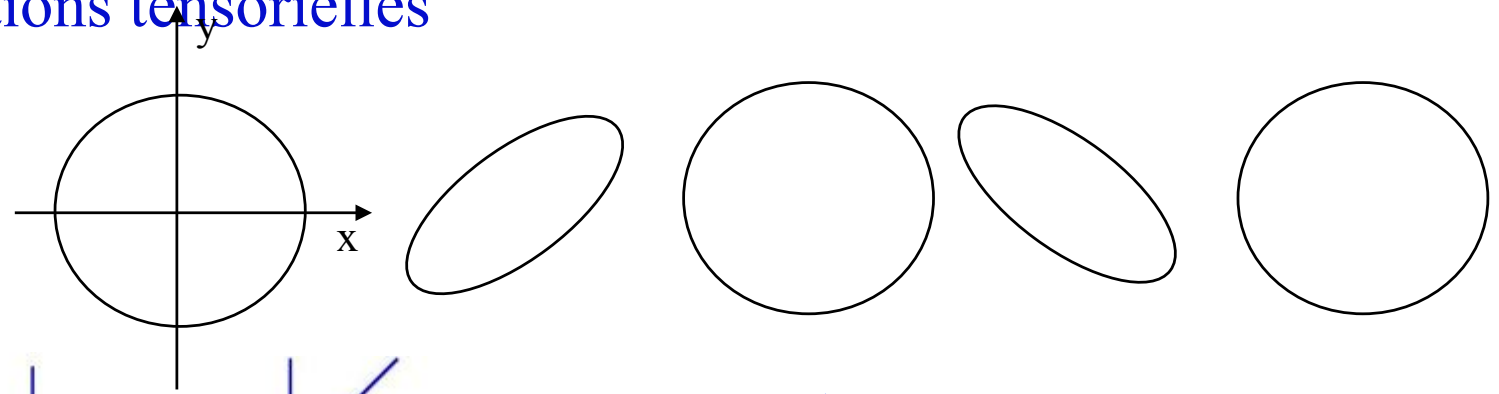
sousdensité

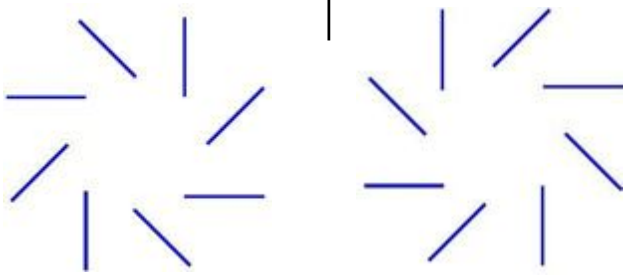


Parité

« modes E »

Perturbations tensorielles





~~Parité~~

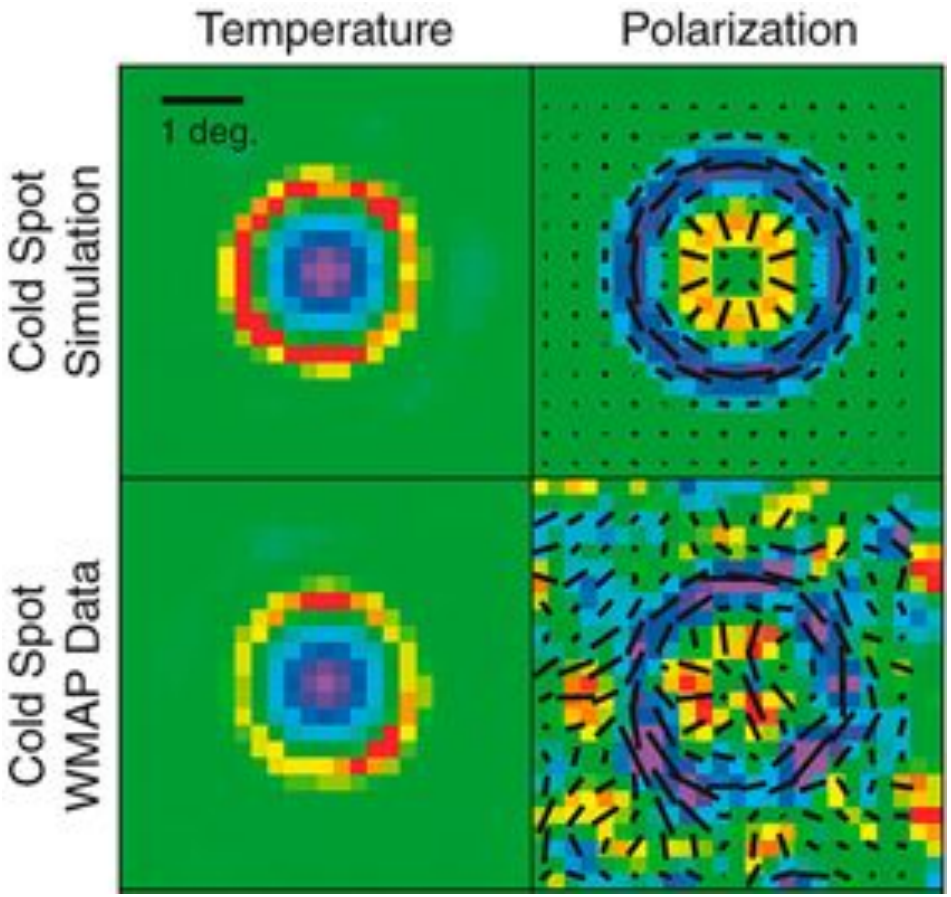
« modes B »

La polarisation permet de distinguer les différents types de perturbation

Première possibilité de détection des ondes gravitationnelles primordiales générées pendant la phase d'inflation

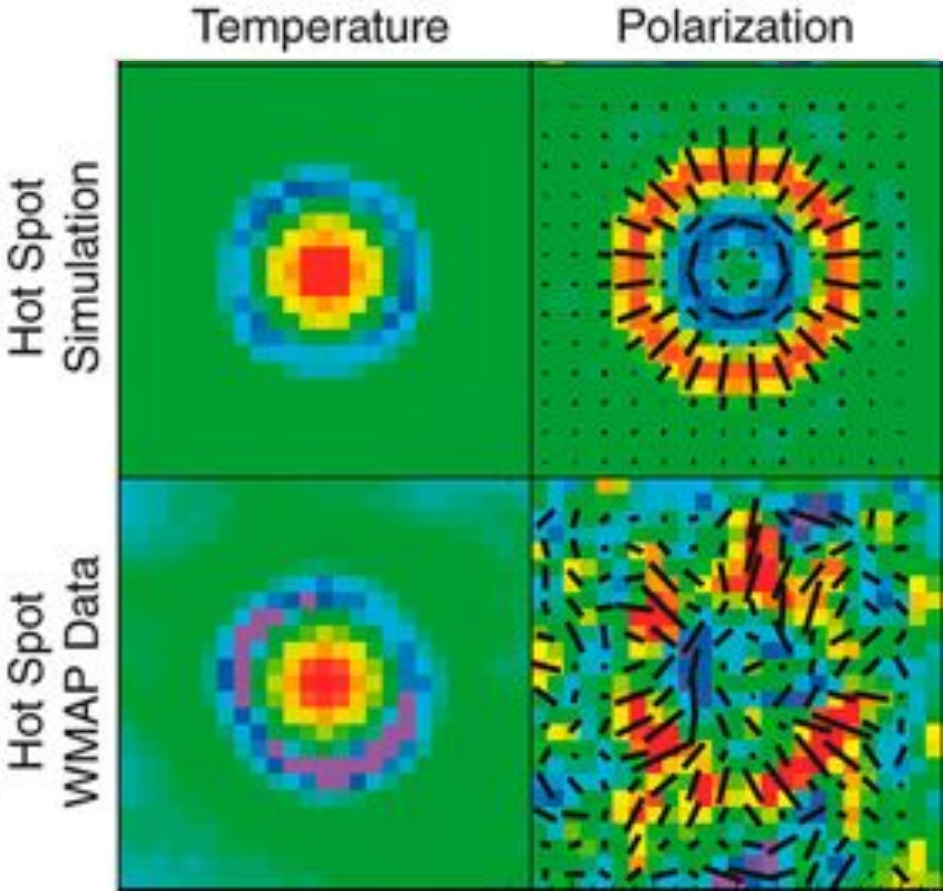
Courtesy N. Ponthieu, IAS

polarization data !



WMAP7 Komatsu et al., 2009

Planck data (embargoed) really look like the simulations !

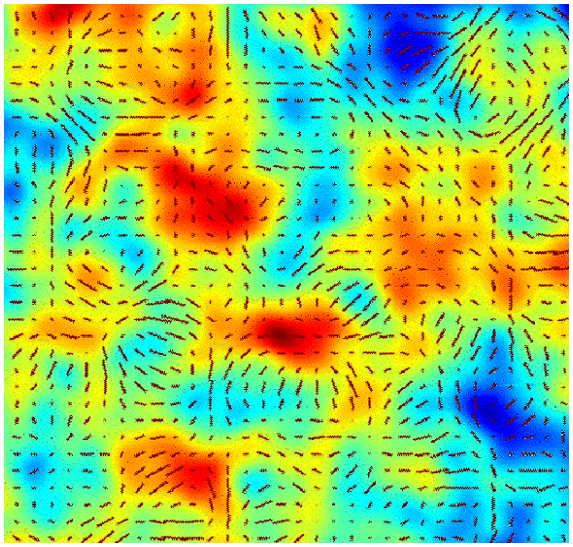


polarisation: bilan

✓ Il faut une anisotropie quadrupolaire pour générer de la polarisation

✓ Les fluctuations de densité (scalaires) et les ondes gravitationnelles (tensorielles) créent des quadrupoles

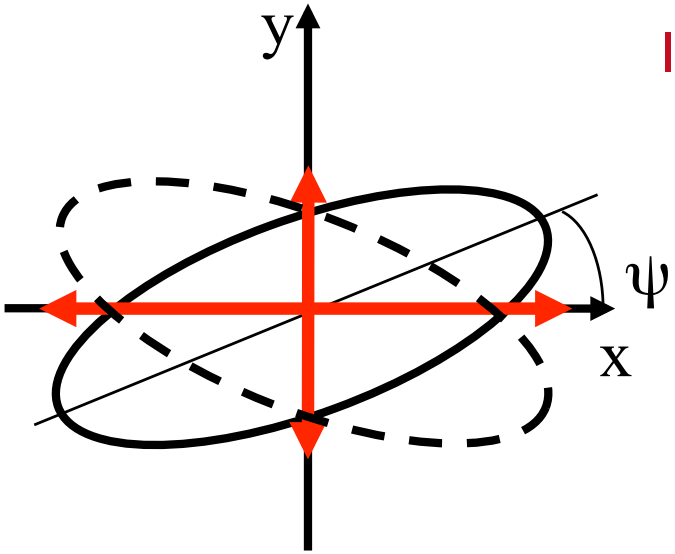
✓ Les figures de polarisation sont différentes



Spectre de puissance et physique…

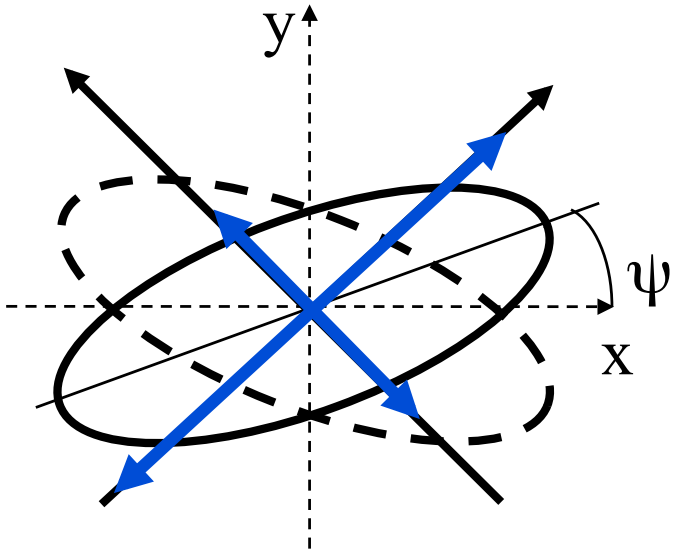
Courtesy N. Ponthieu, IAS

les paramètres de Stokes



$I = I_x + I_y$

$Q = I_x - I_y$



$U = I_x^{45} - I_y^{45}$

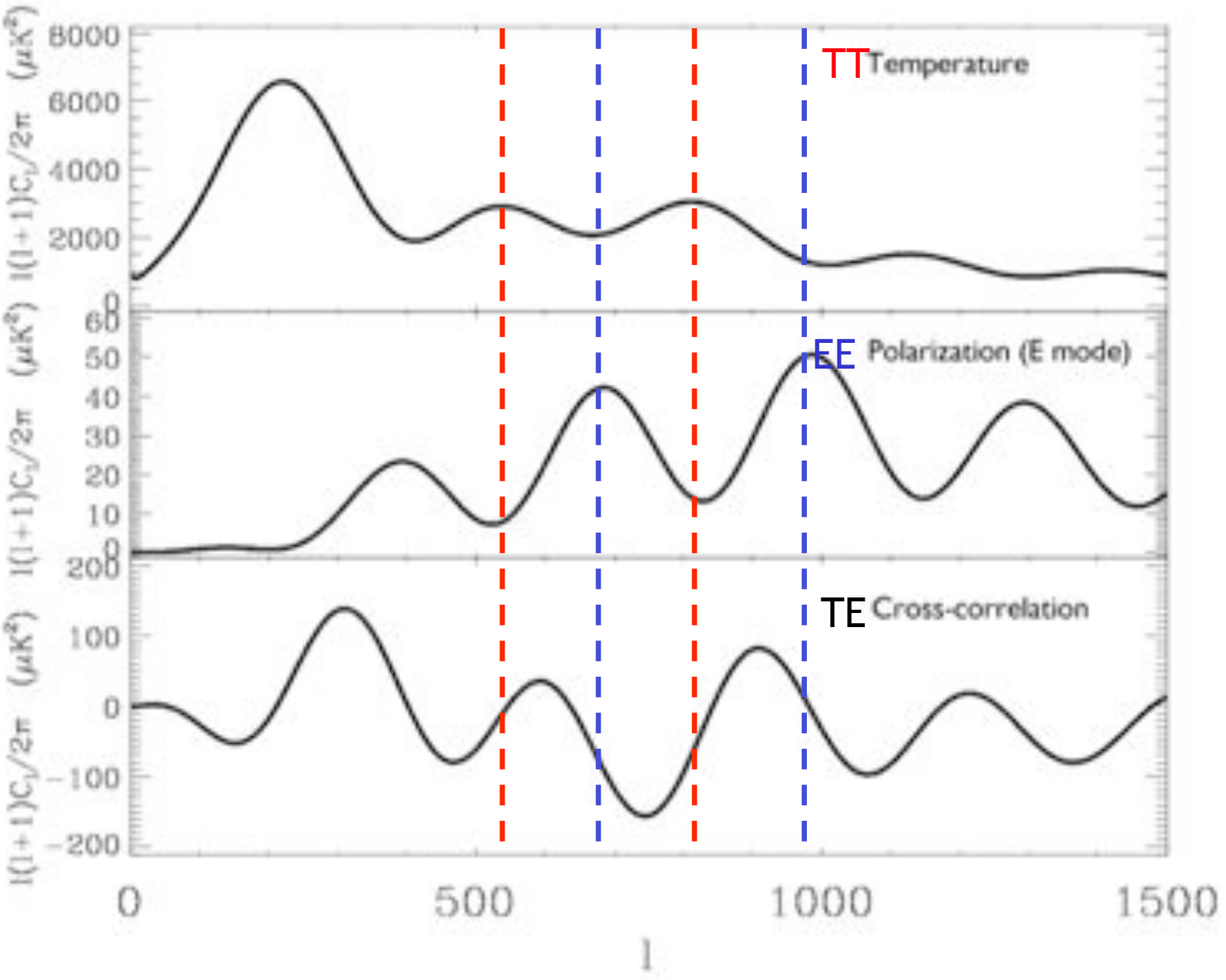
I, Q, U donnent une description complète de l'etat de polarisation

Courtesy N. Ponthieu, IAS

TT, EE, TE: behaviour

phase shift: opposition
[déphasage: opposition de phase]

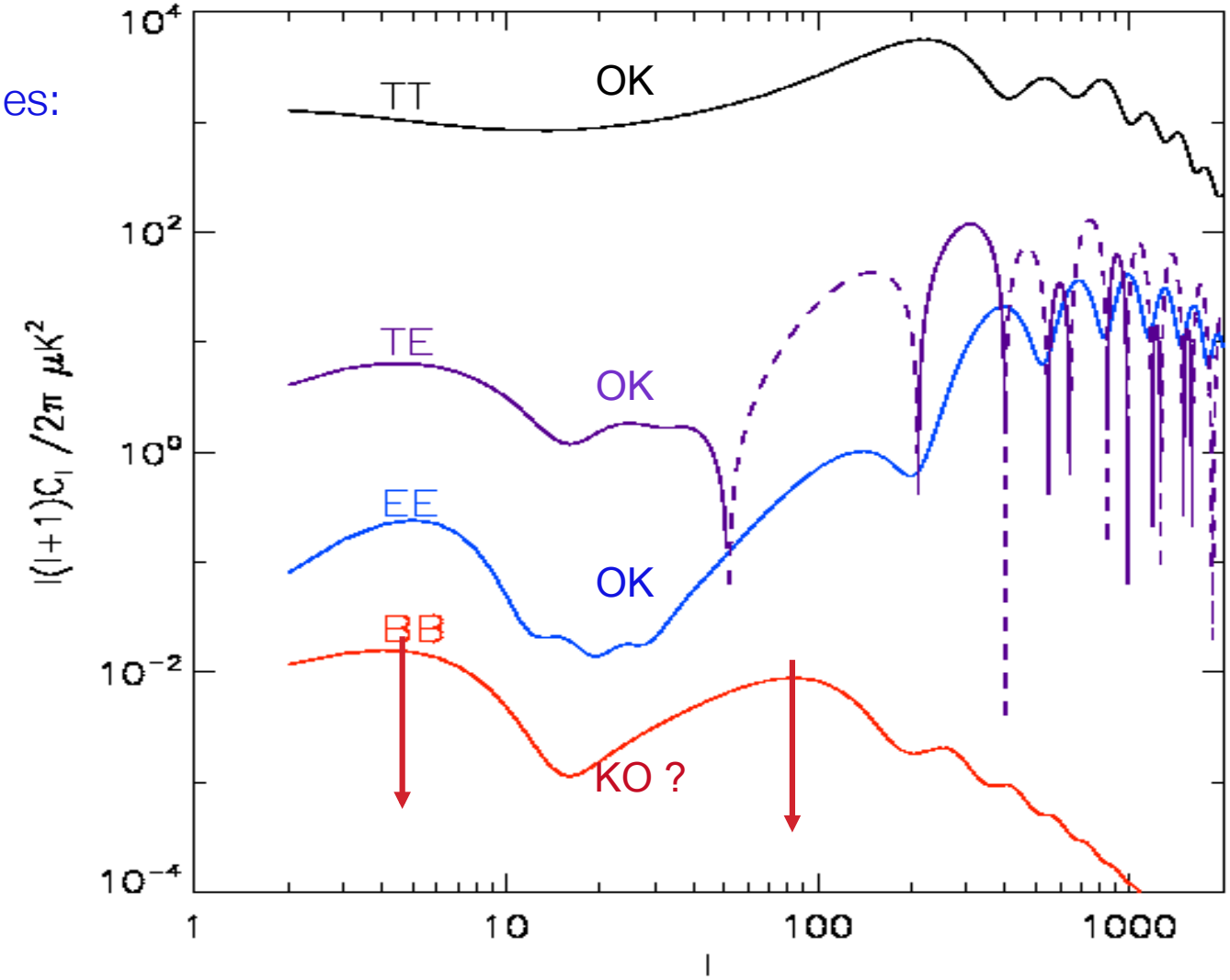
phase shift: half
[déphasage de pi/2]



Balbi et al., 2006

4 CMB anisotropies power spectra

3 observables:
T, E, B

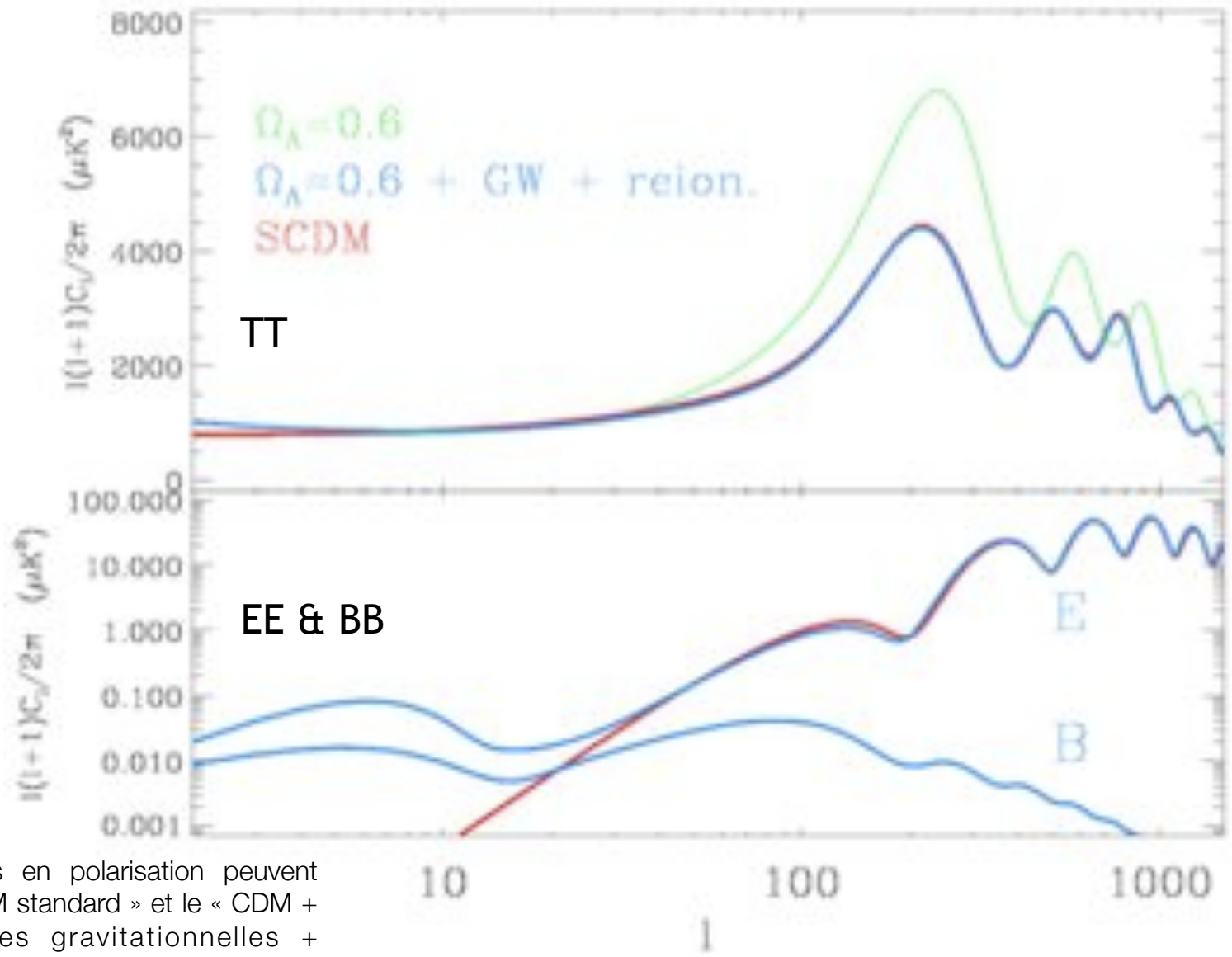


T, E : scalaire
B : pseudo-scalaire

TB, EB = 0

Courtesy N. Ponthieu, IAS
feb 2011

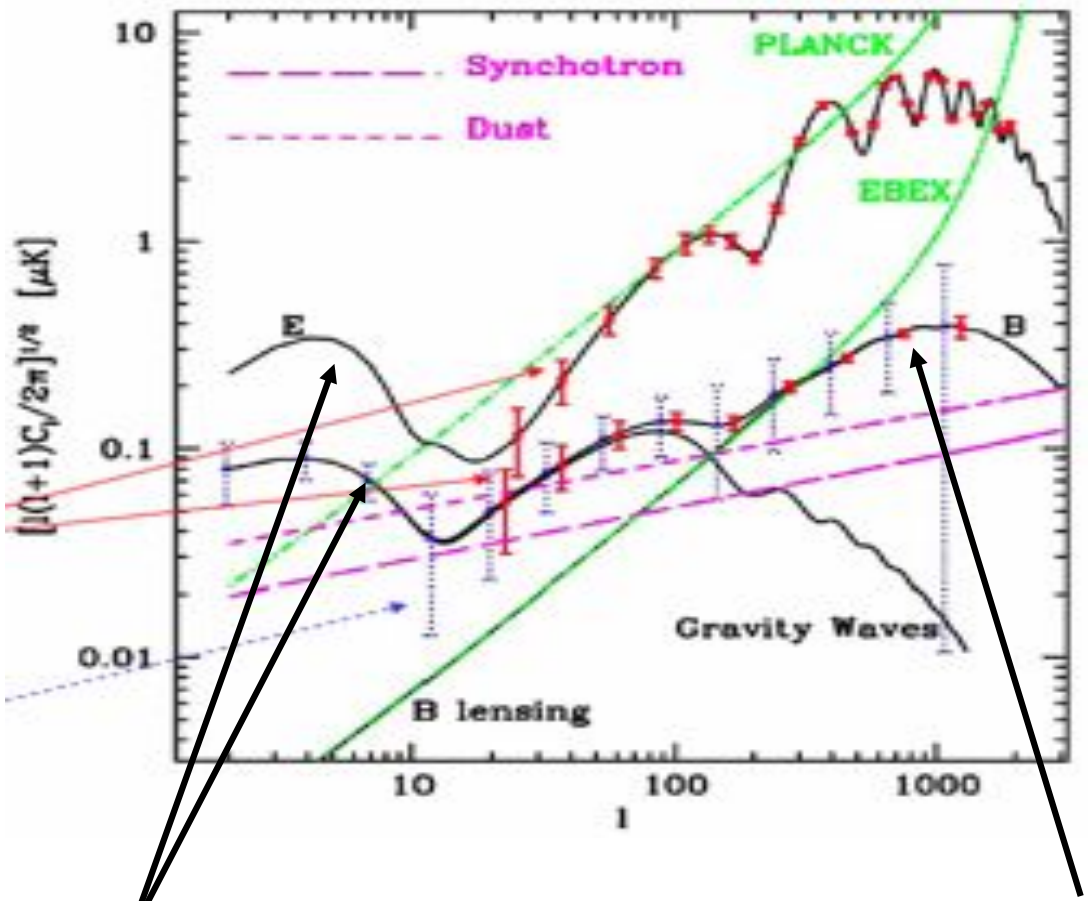
why polarization helps



Balbi et al., 2006

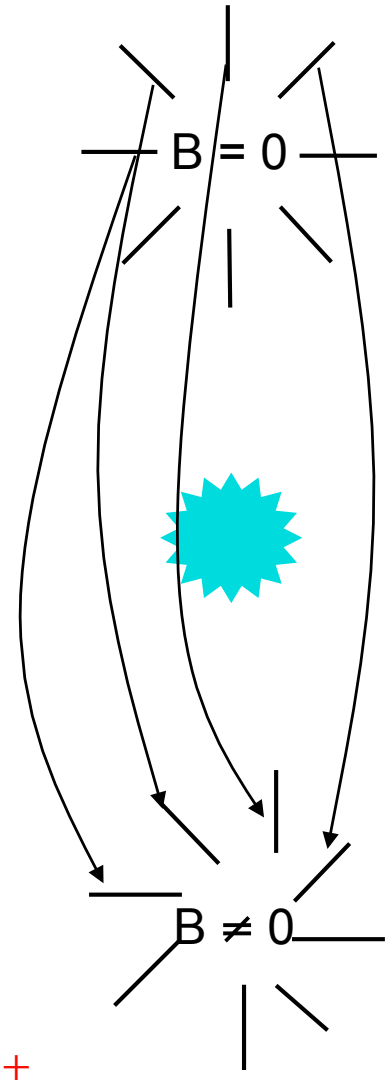
Seules des observations en polarisation peuvent discriminer entre le « CDM standard » et le « CDM + energie noire + ondes gravitationnelles + reionisation »

anisotropies secondaires



2ème diffusion Thomson lors de la Réionisation

Distorsion par effet de lentilles faibles



Dark Energy + Neutrinos + Large Scale Structures

Courtesy N. Ponthieu, IAS feb 2011

qques résultats WMAP5

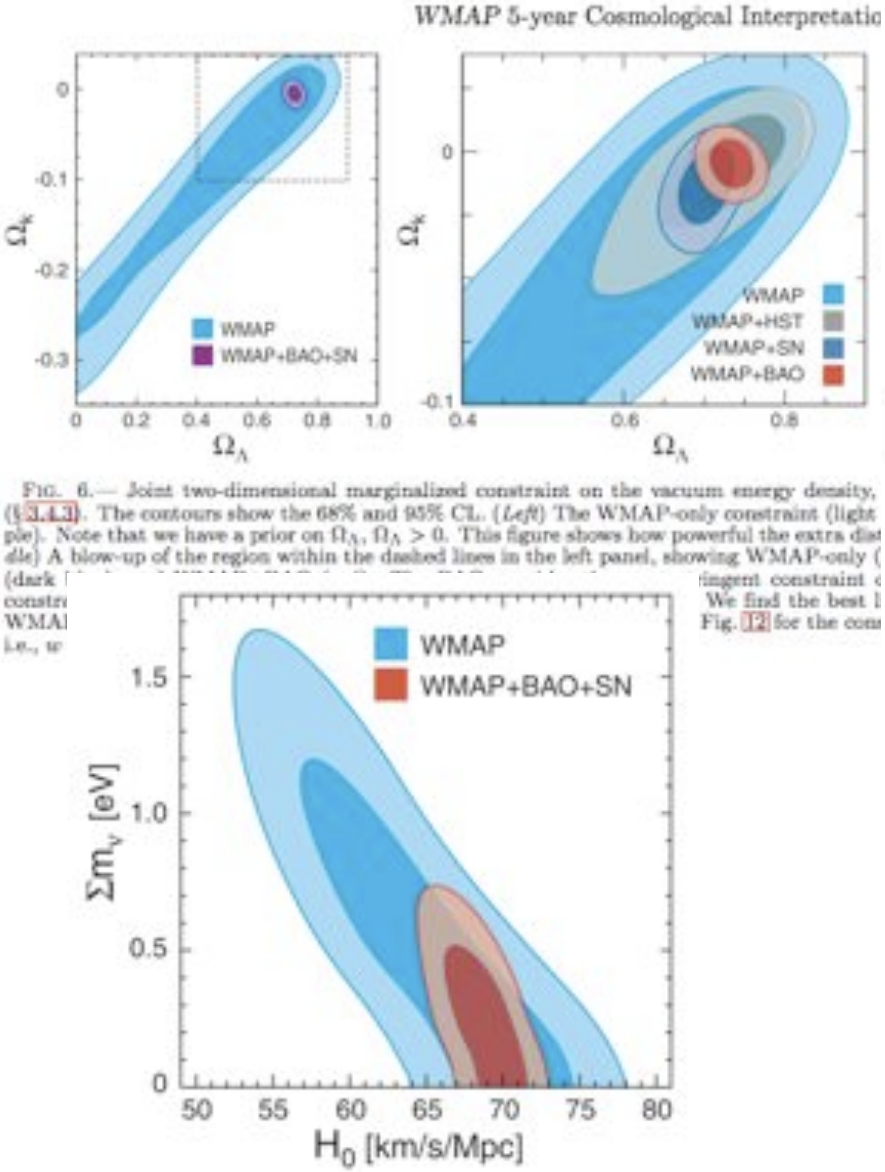
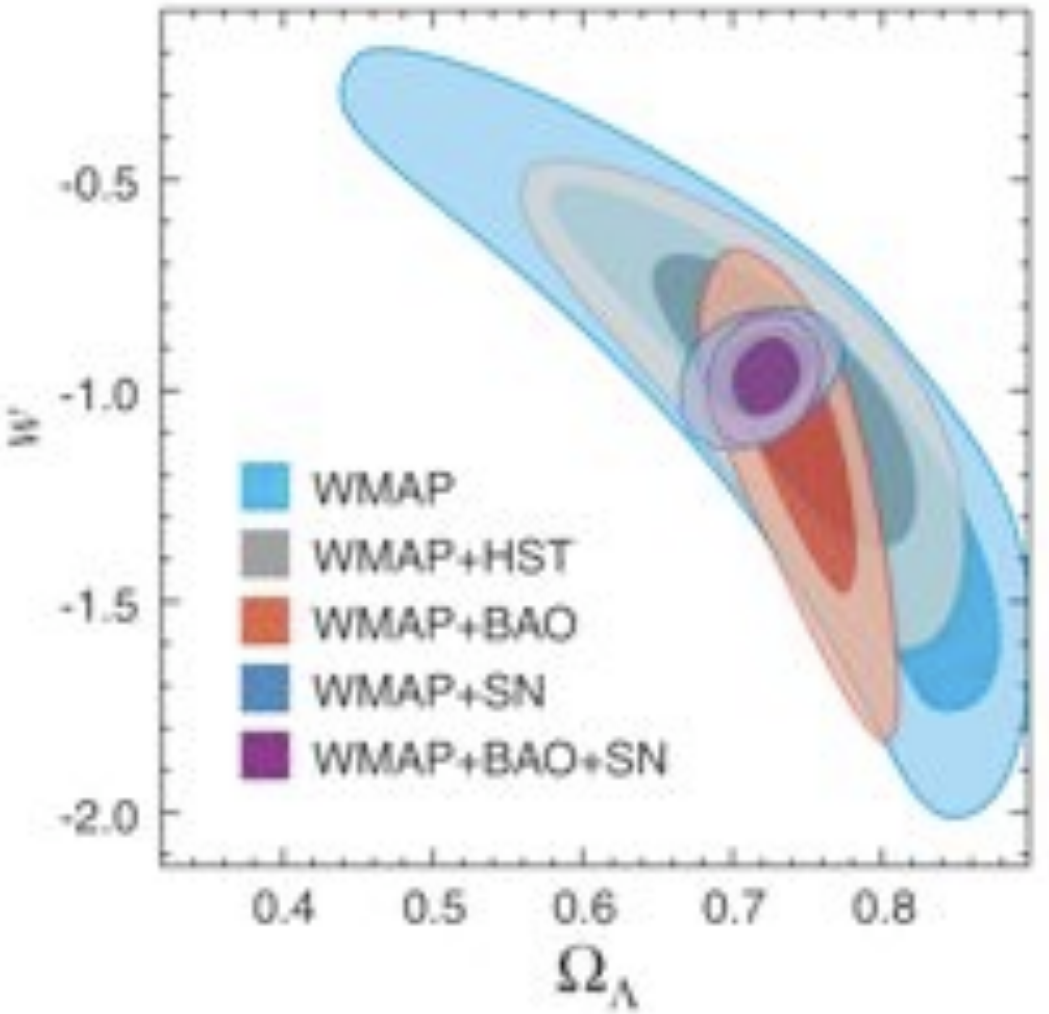


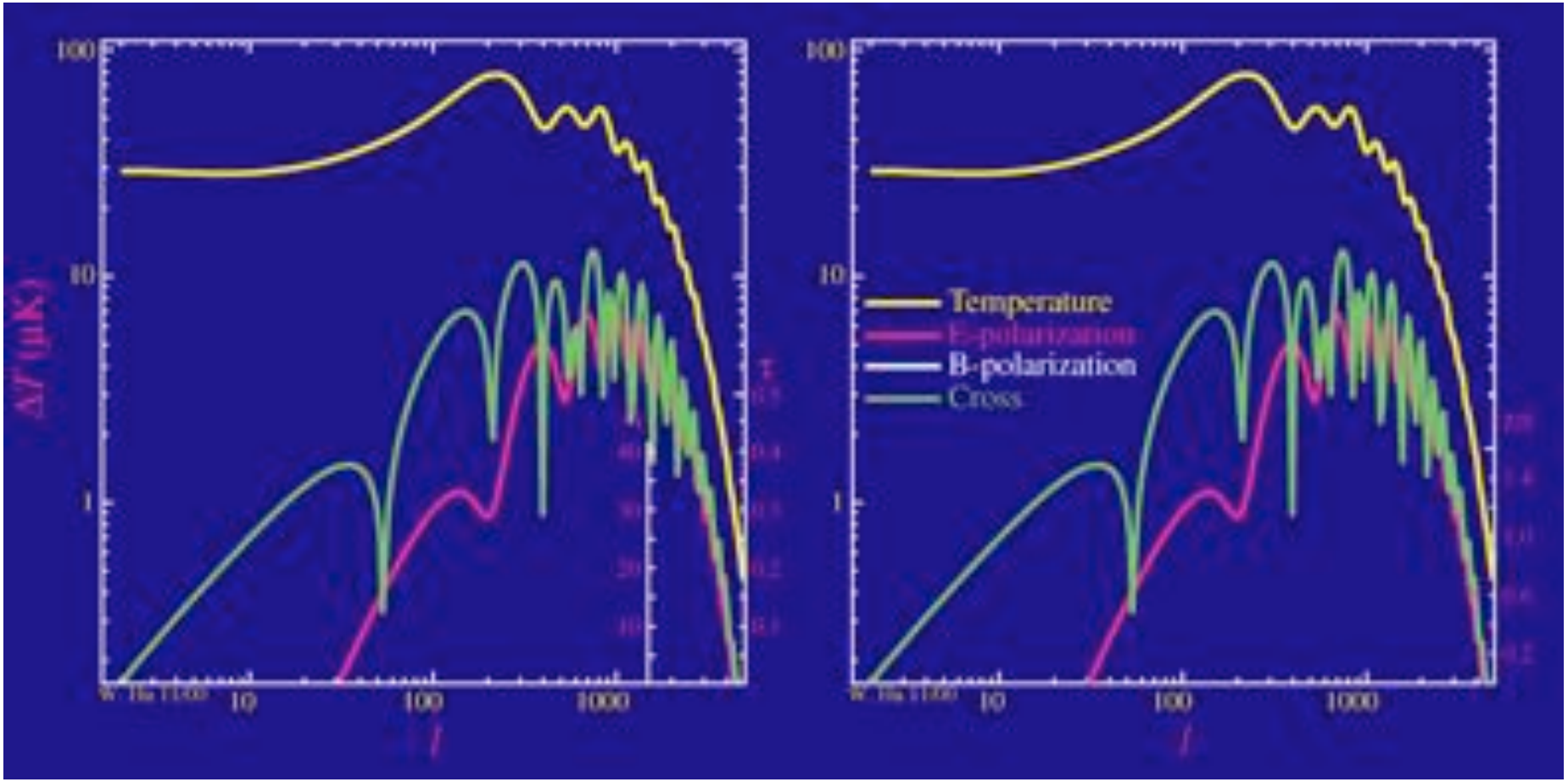
FIG. 6.— Joint two-dimensional marginalized constraint on the vacuum energy density, (§ 3.4.3). The contours show the 68% and 95% CL. (*Left*) The WMAP-only constraint (light gle). Note that we have a prior on Ω_Λ, $\Omega_\Lambda > 0$. This figure shows how powerful the extra dist *dle*) A blow-up of the region within the dashed lines in the left panel, showing WMAP-only ((dark ingent constraint constr We find the best l WMAl Fig. 12 for the con i.e., w



Komatsu et al., 2008, WMAP5

polarisation et spectre de puissance

Wayne Hu, Chicago: http://background.uchicago.edu/~whu/intermediate/intermediate.html



create your own CMB !

- with CMBeasy: http://www.cmbeasy.org
- based on CMBfast

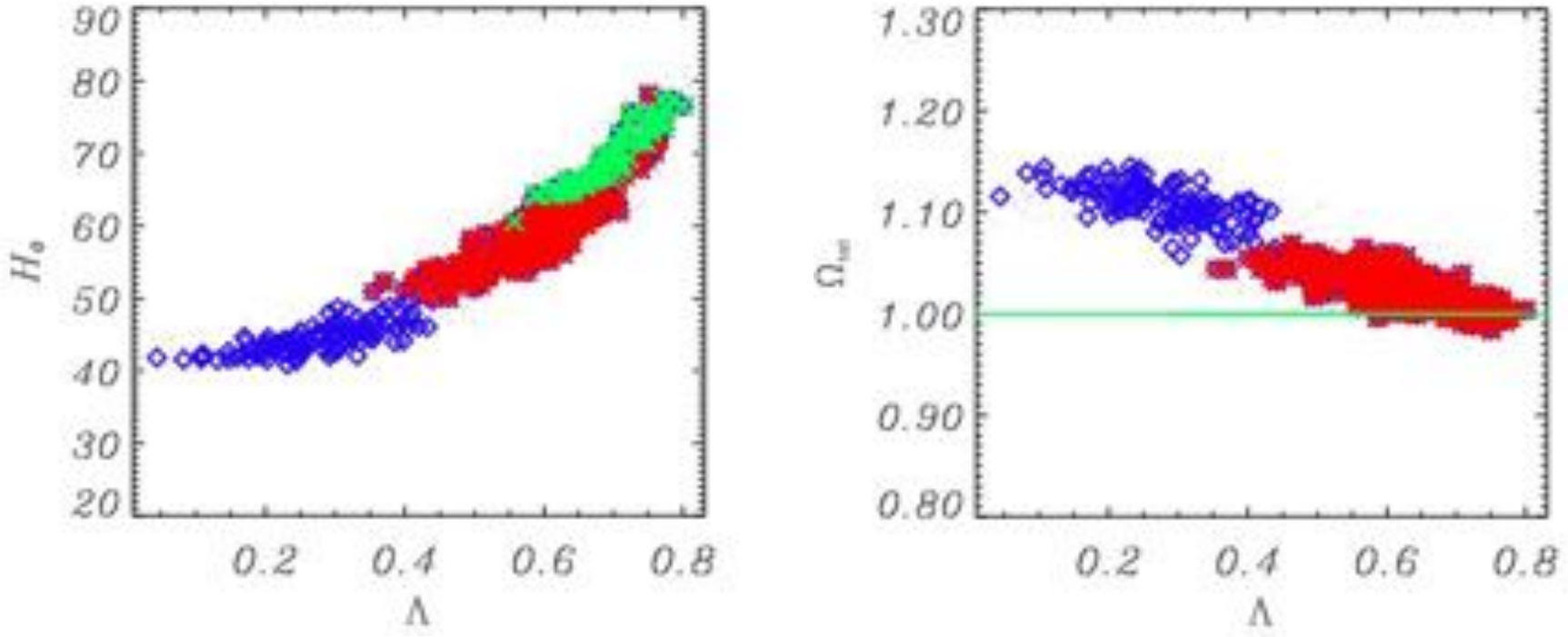
II. Observations of the Cosmic Microwave Background

6. Degeneracies

1. Dégénérescence « essentielle »

From CMB physics

Ωh^2, H_0, Λ



$\Omega_{tot} = 1$ "fixes" H_o and Λ (cf. WMAP)

(MCMC with WMAP)

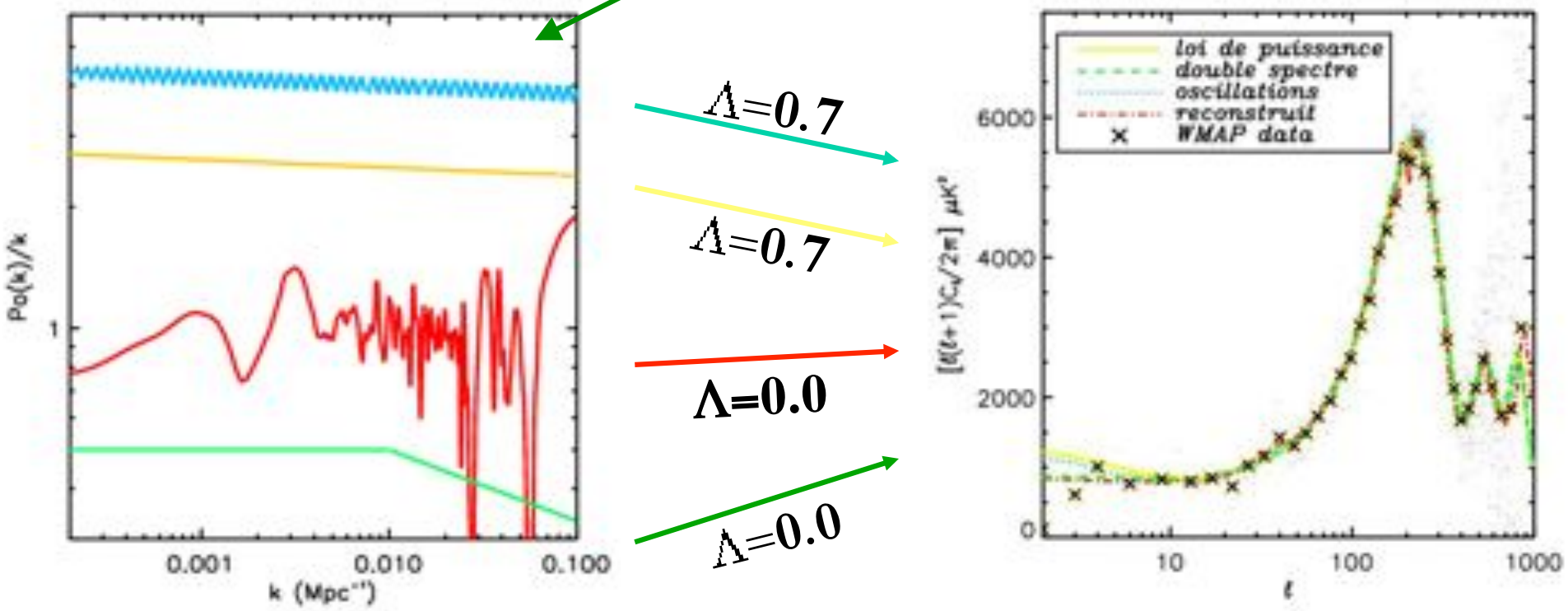
Courtesy M. Douspis, IAS

1. Dégénérescence « essentielle »

From CMB physics

Initial conditions versus Evolution

$$C_l \propto \int P_o(k)\Delta^2(k,l)dk$$



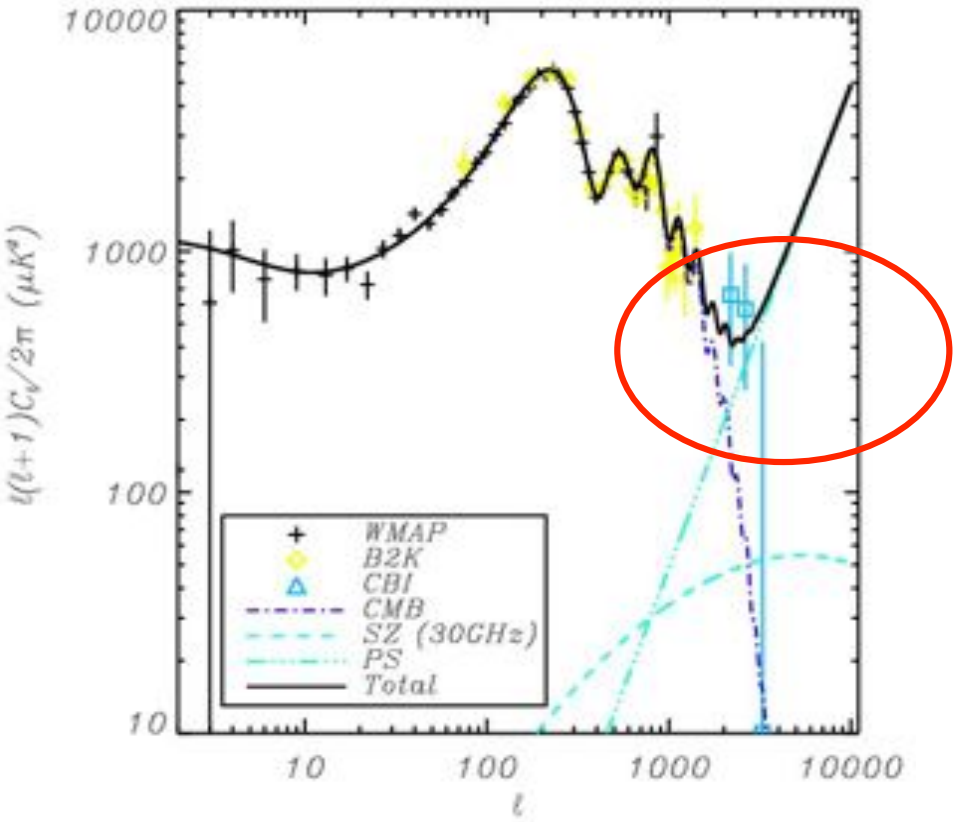
Courtesy M. Douspis, IAS

Blanchard, Douspis et al. 03,05
Tocchini, Douspis, Silk 04

2. Dégénérescence « intégrale »

From additional physics

Secondaries and Foregrounds



Courtesy M. Douspis, IAS

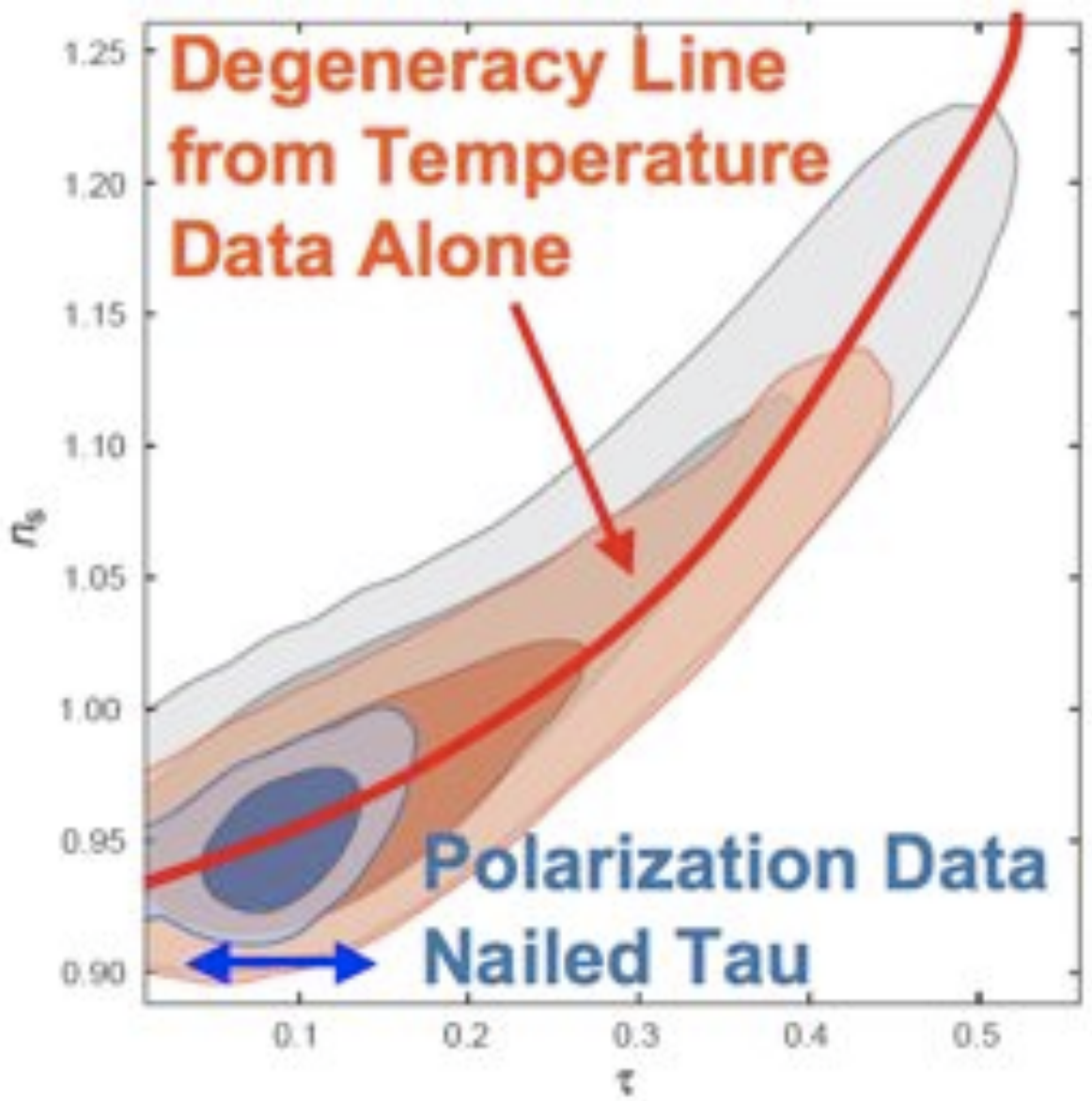
Power excess @ small scales compared to primary CMB

Douspis, Aghanim & Langer 06

2. Dégénérescence « intégrale »

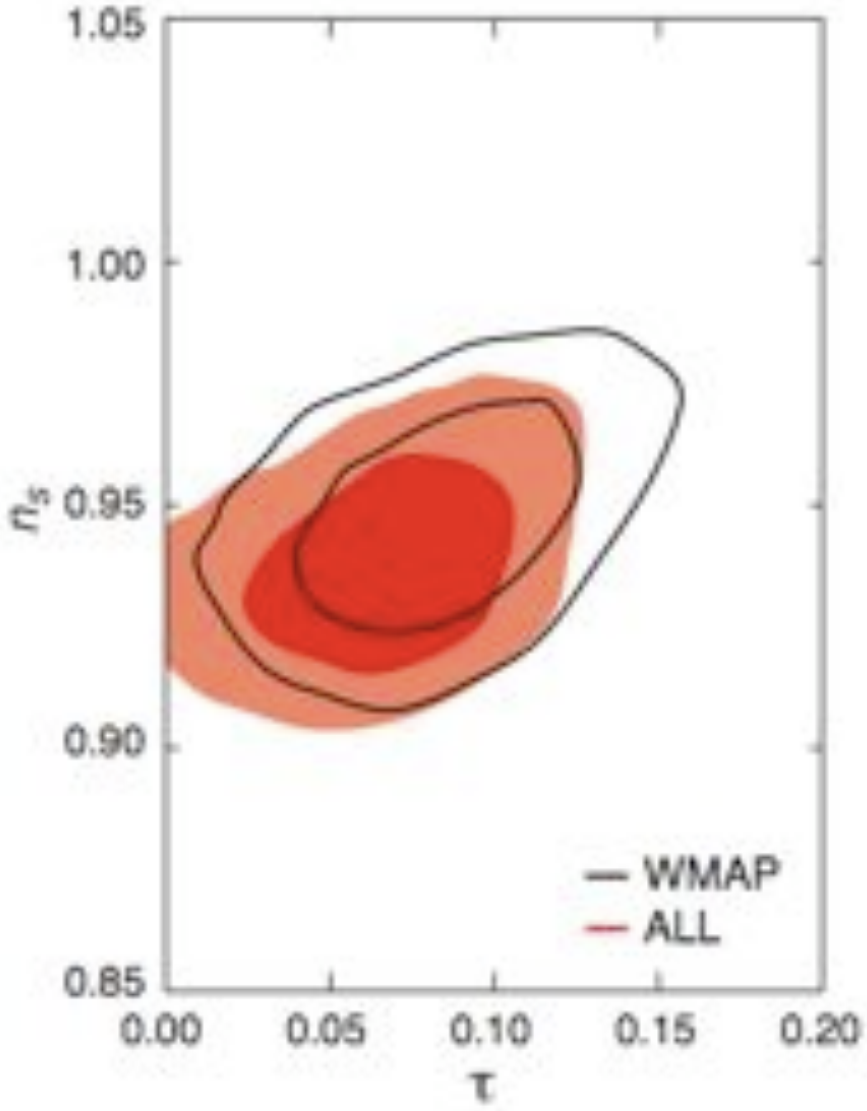
τ: Profondeur optique

$$\tau = \int_0^{z_i} \sigma_T n_e(z) \frac{dt}{dz} dz$$



Spergel et al., 2007, WMAP3

2. Dégénérescence « intégrale »



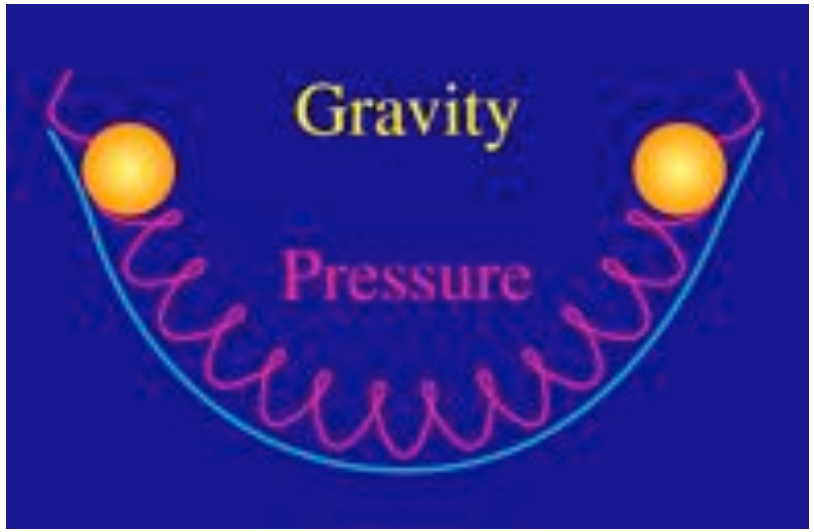
Spergel et al., 2007, in press WMAP3

3. Dégénérescence «instrumentale»

II. Observations of the Cosmic Microwave Background

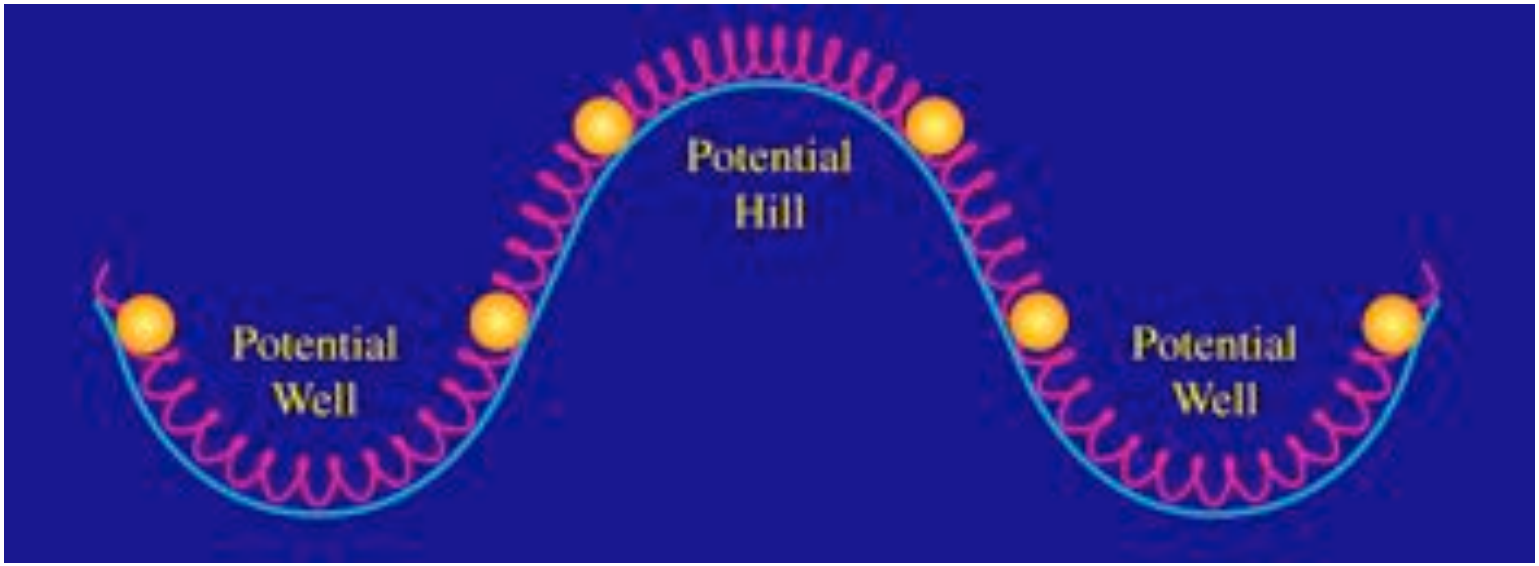
7. Origin of fluctuations

origine des fluctuations

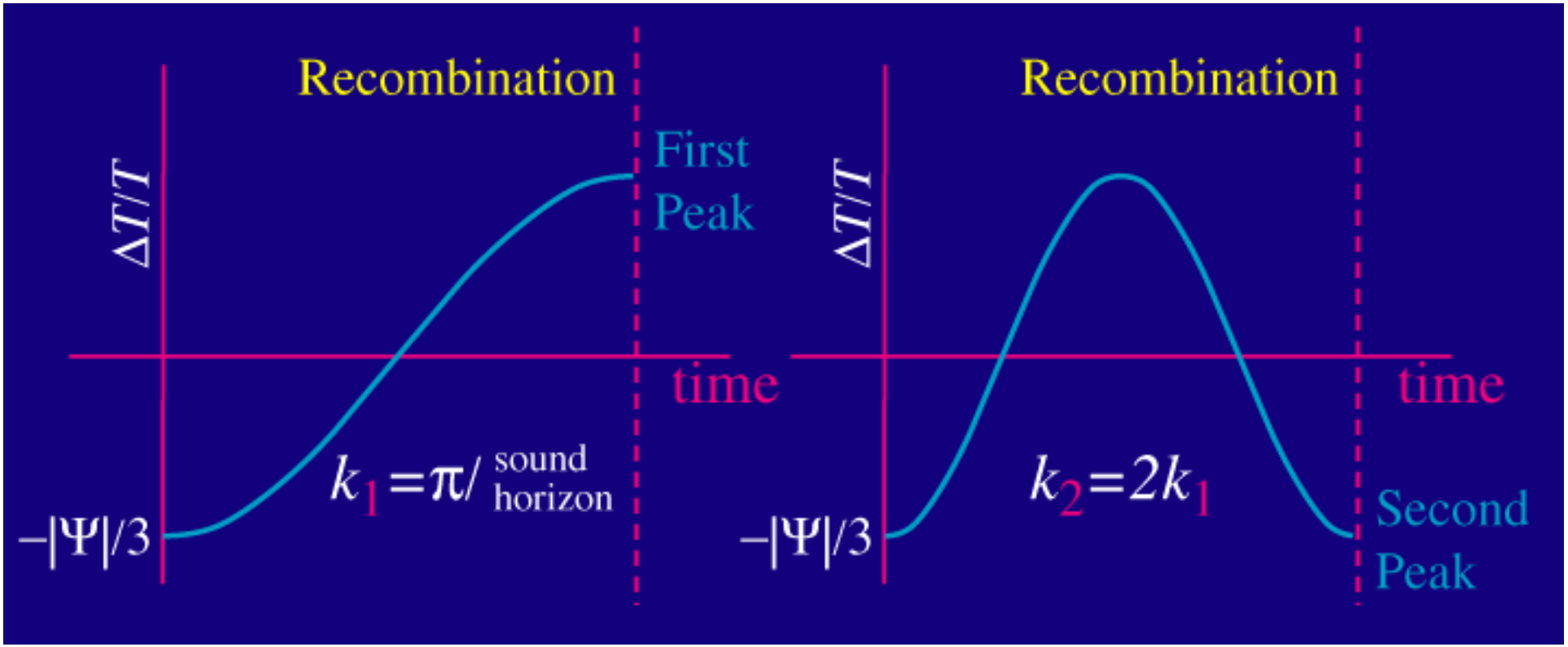


Matière => puits de potentiel

Puits de potentiel
- les photons qui tombent se réchauffent (compression)
- les photons qui en sortent sont refroidis (détente)

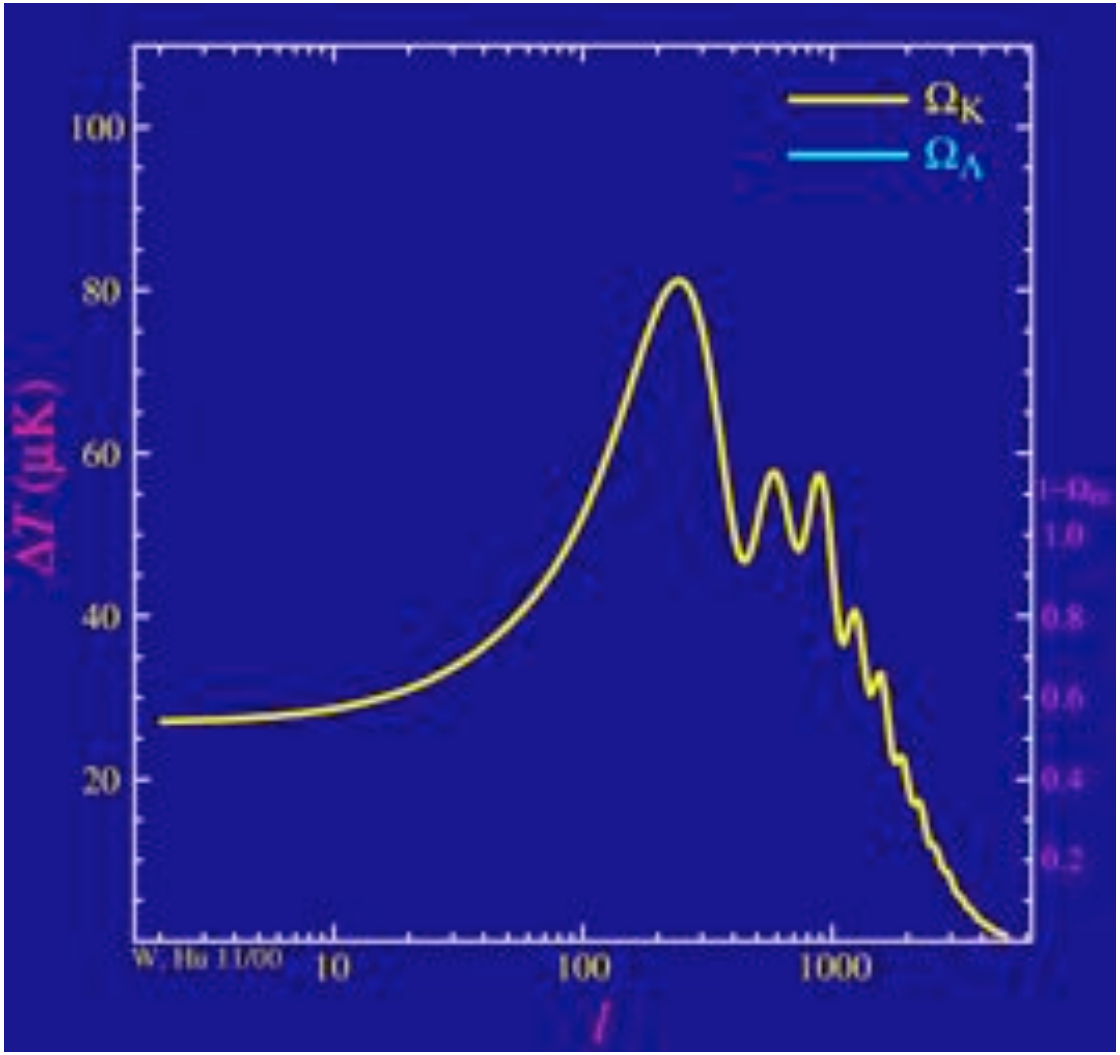


Ondes Acoustiques à la Recomb.



La physique de ces ondes dépend des paramètres cosmologiques

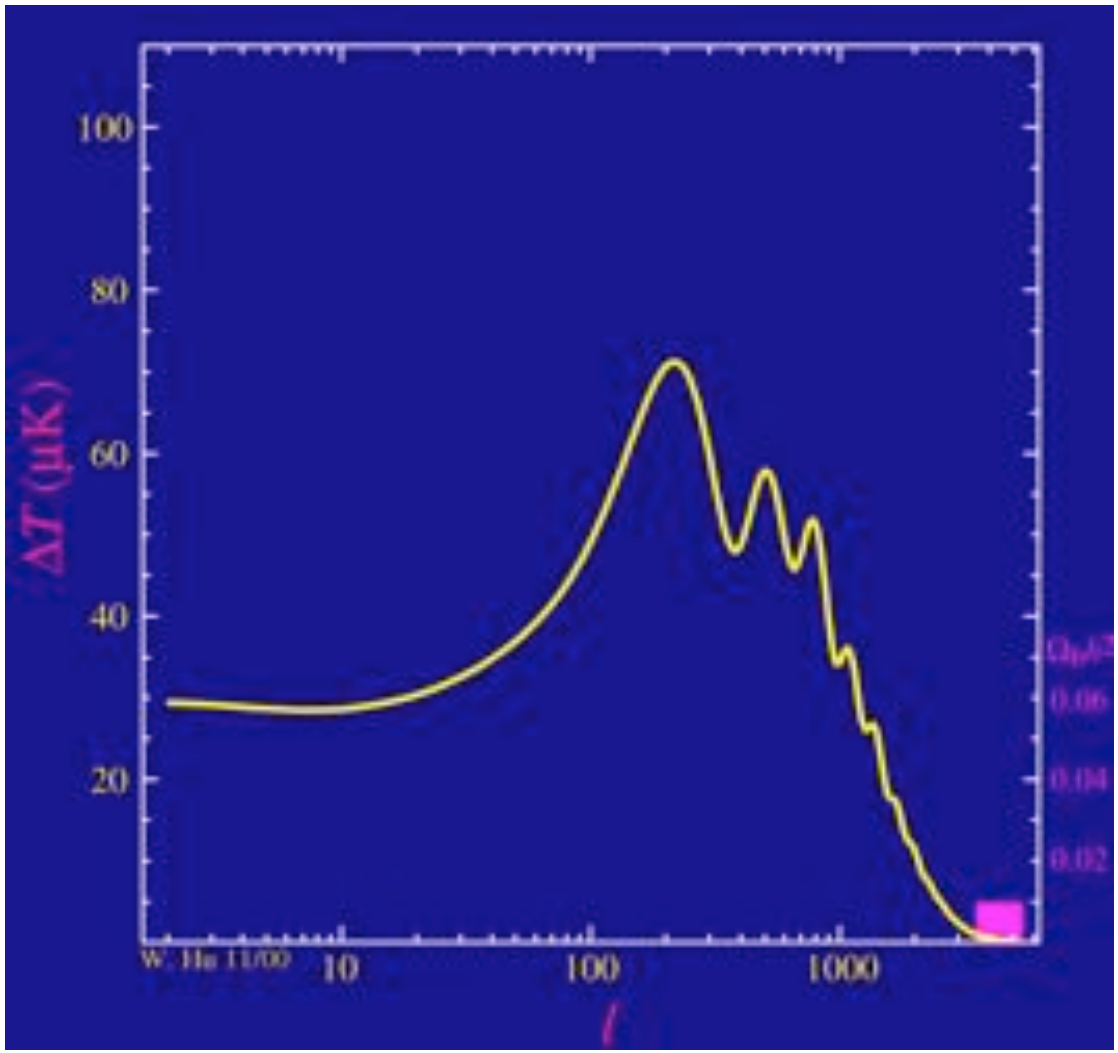
Courbure



Position du 1er pic acoustique <=> courbure de l'Univers

Wayne Hu, Chicago: http://background.uchicago.edu/~whu/intermediate/intermediate.html

Contenu en Baryons

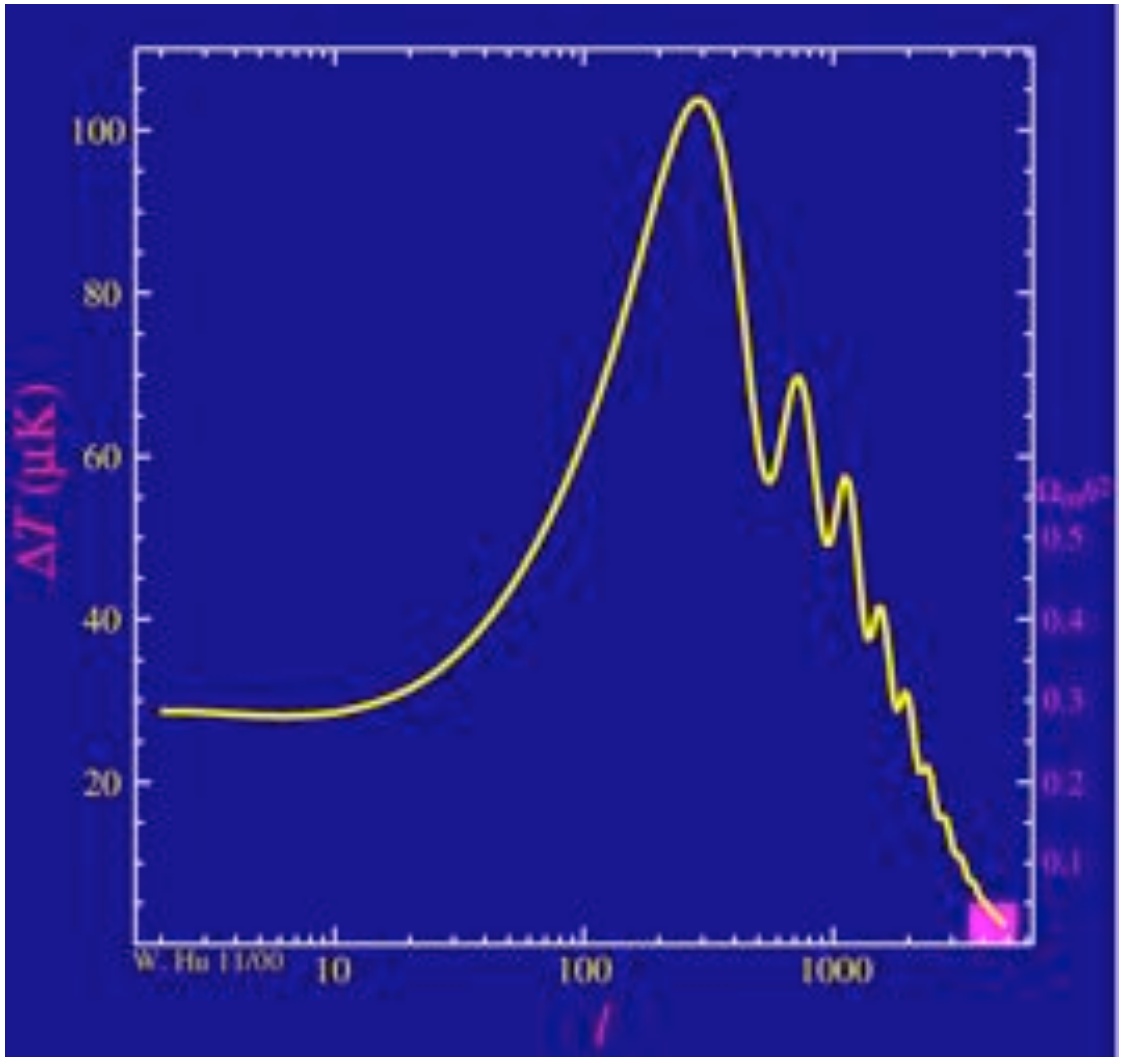


Position du 2nd pic acoustique <=> contenu en baryons

Wayne Hu, Chicago: http://background.uchicago.edu/~whu/intermediate/intermediate.html

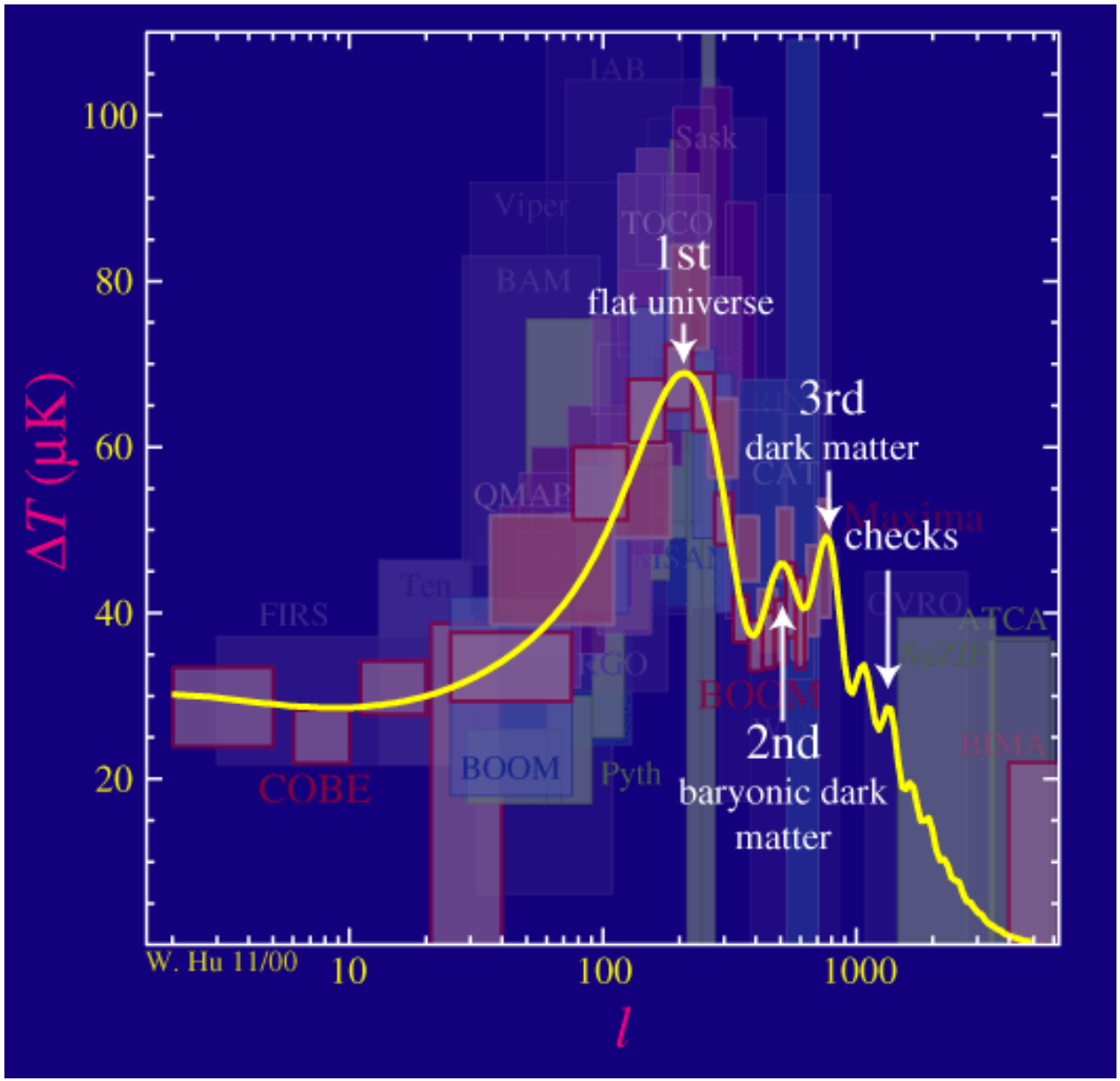
Matière Noire

Wayne Hu, Chicago: http://background.uchicago.edu/~whu/intermediate/intermediate.html

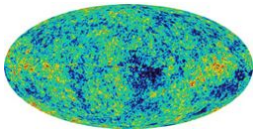


Position du 3ème pic acoustique <=> contenu en matière noire

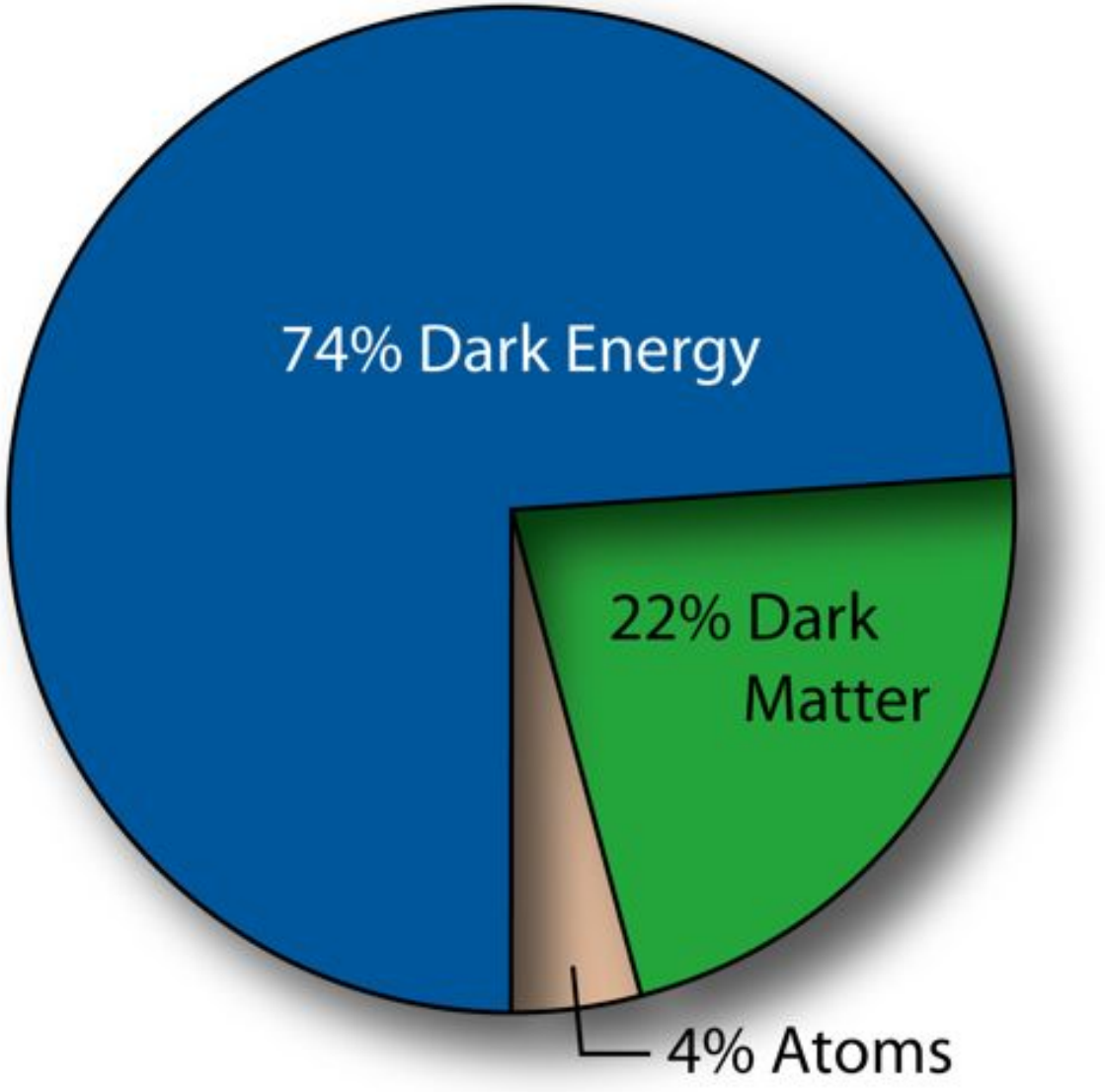
Pics Acoustiques dans le Sp. P.



Wayne Hu, Chicago: http://background.uchicago.edu/~whu/intermediate/intermediate.html



Cosmic Microwave Background



WMAP 3 yr