

the Cosmic Microwave Background

angular power spectrum on the sphere: cl_1 .
observations of the CMB 2.

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<http://www.ias.u-psud.fr/dole/m2.php>

Jan-2012

Hervé Dole, IAS - M2 NPAC - Cosmological structure formation: theory and observations



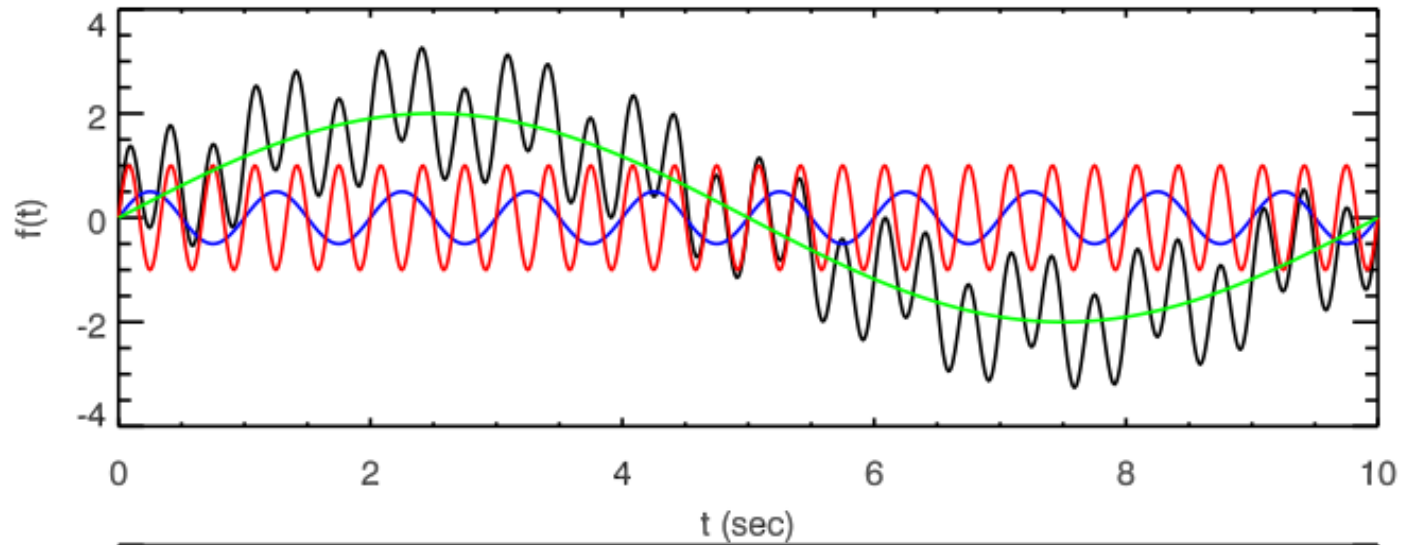
I. Angular Power Spectrum on the sphere: C_l

1. What is a power spectrum ?

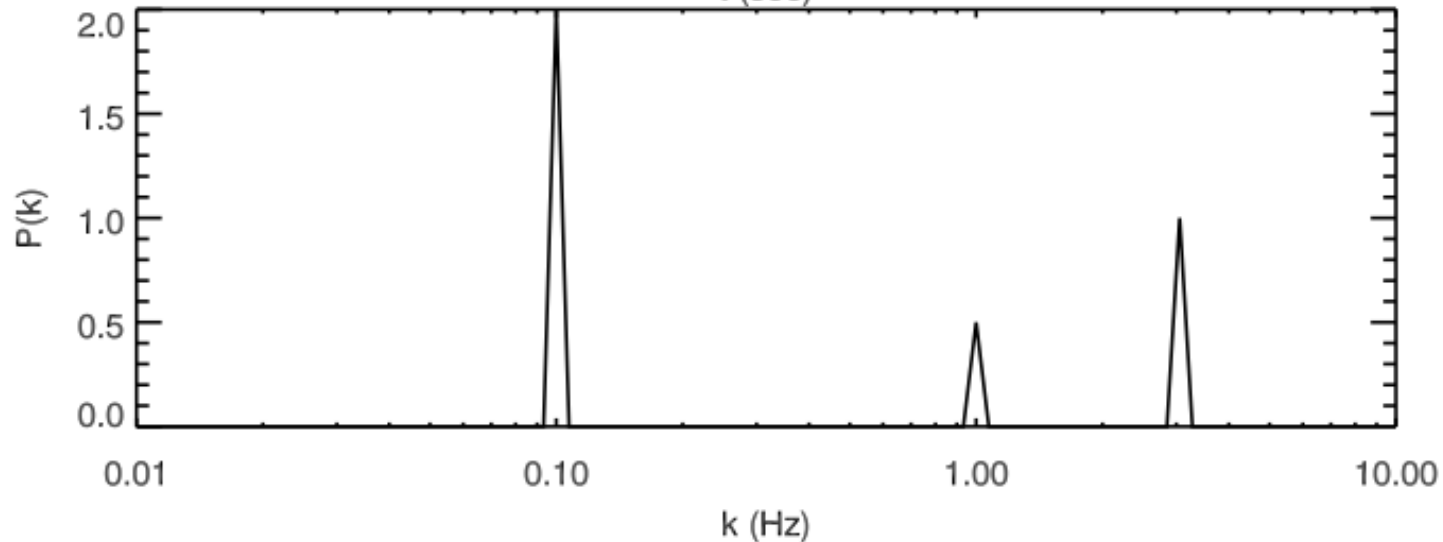
Fourier analysis

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

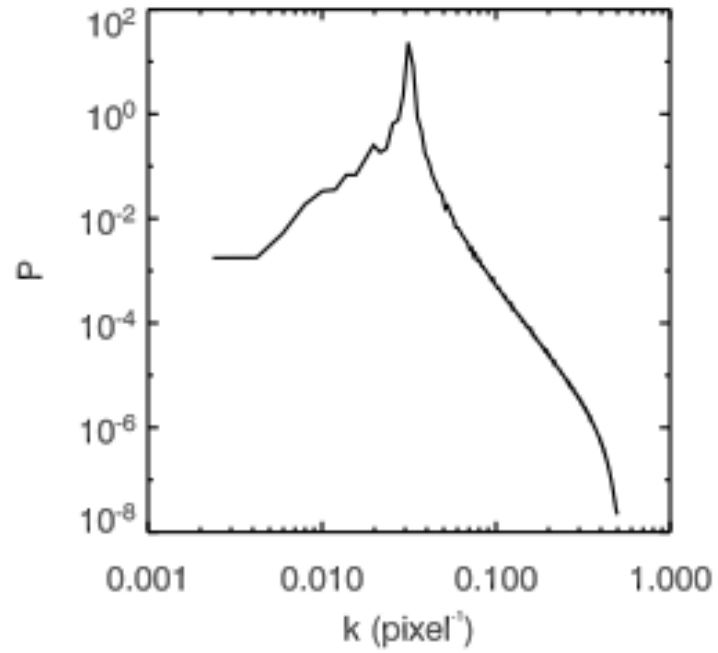
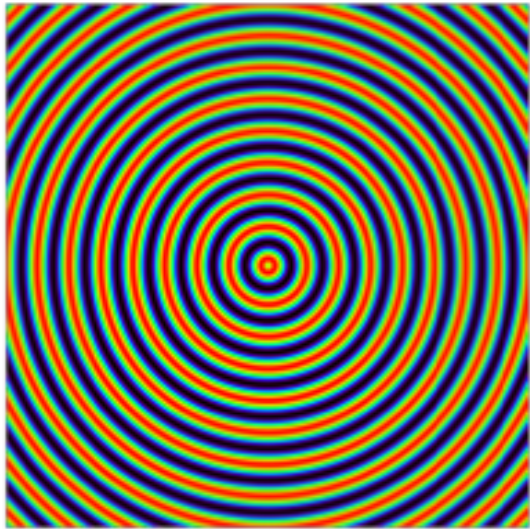
$$f(t) = \int_{-\infty}^{+\infty} \tilde{f}(\nu)e^{i2\pi\nu t} d\nu$$



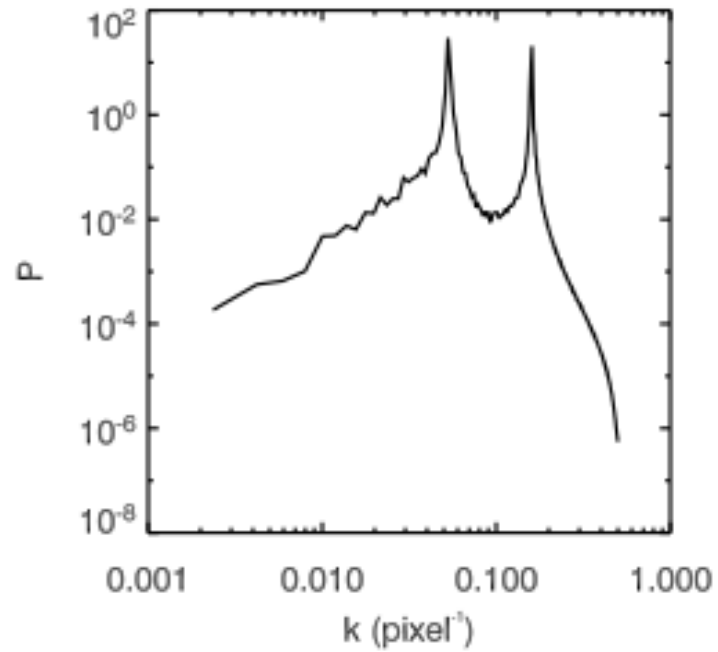
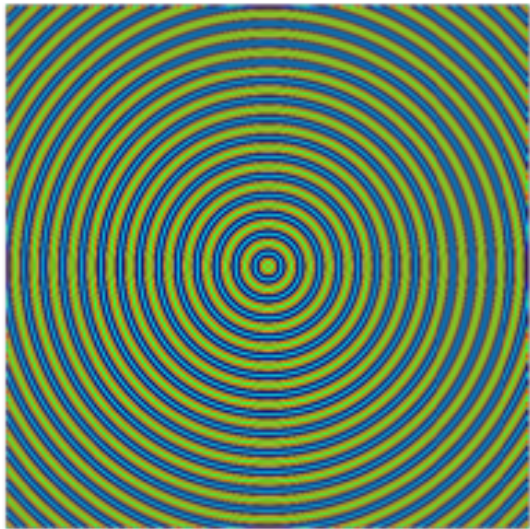
Espace direct:
time



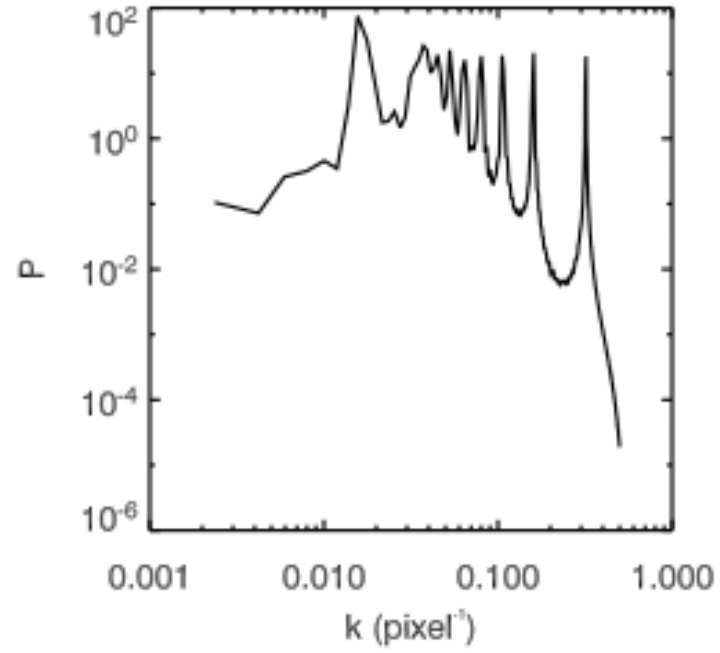
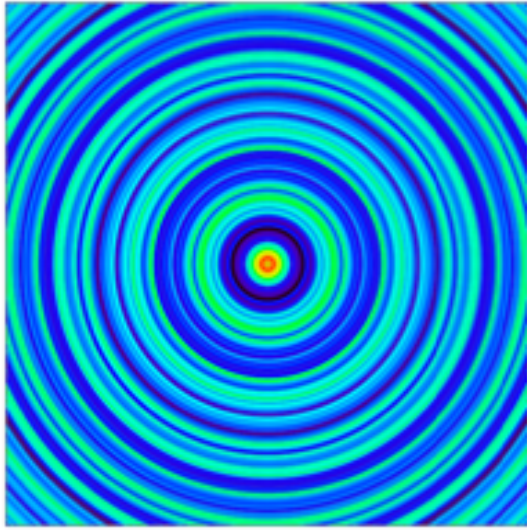
Espace
conjugué:
fréquence
temporelle



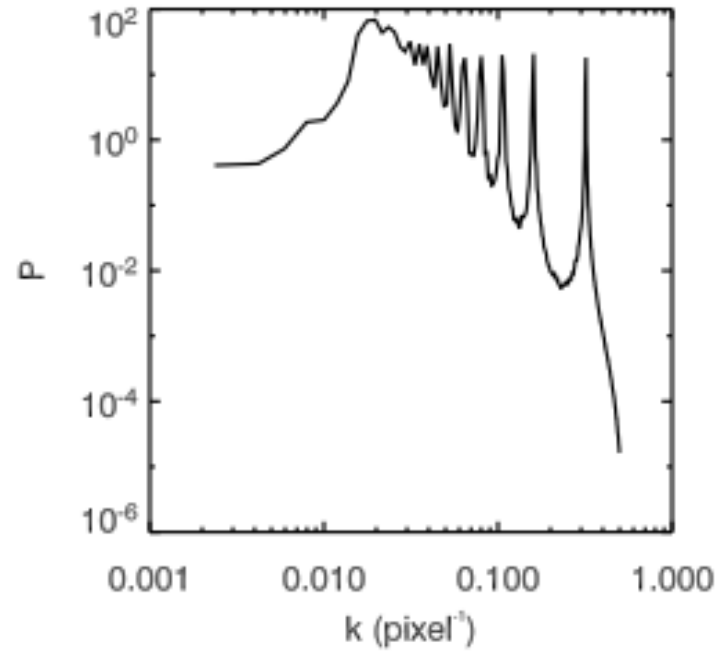
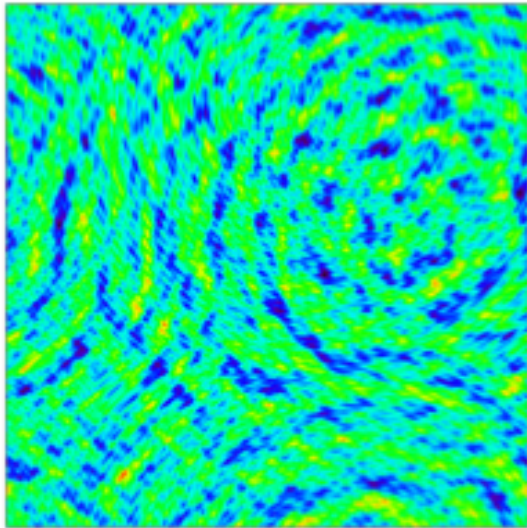
—
1 sine
centered



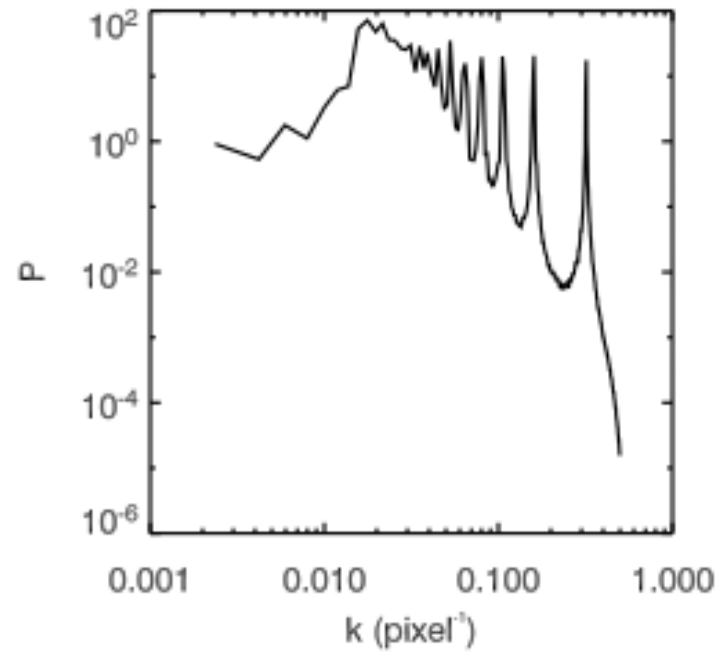
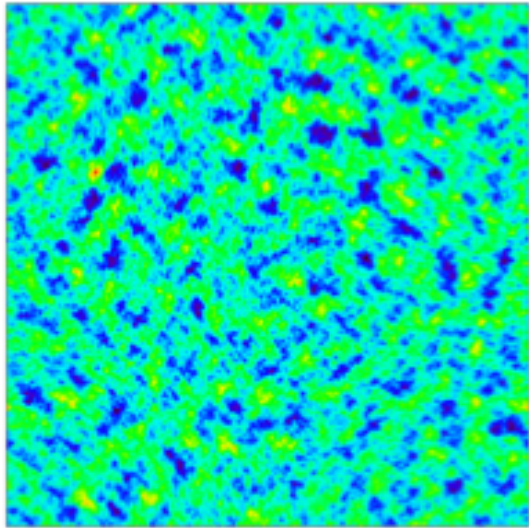
2 sine
centered



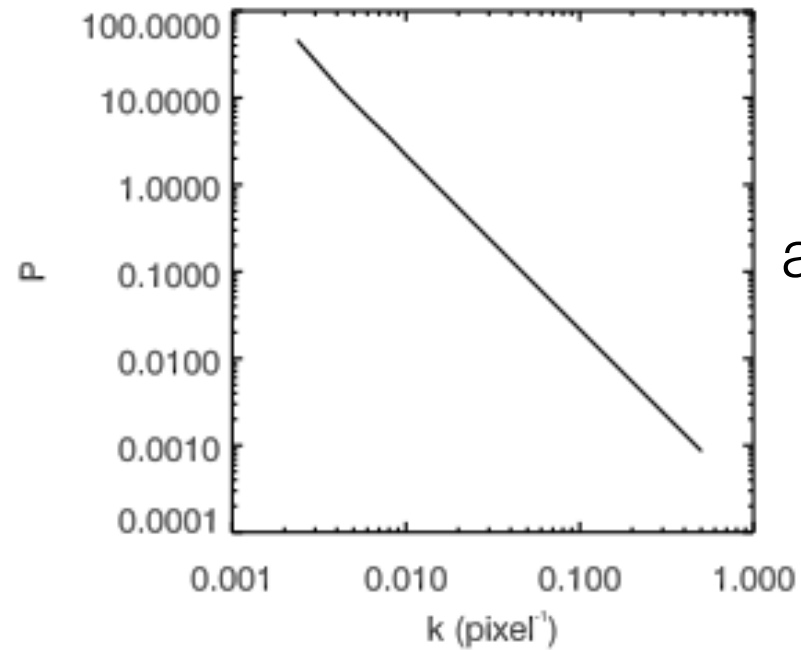
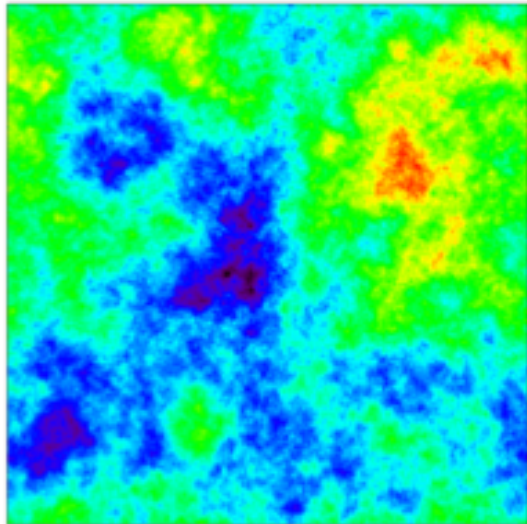
n sinus
centrés



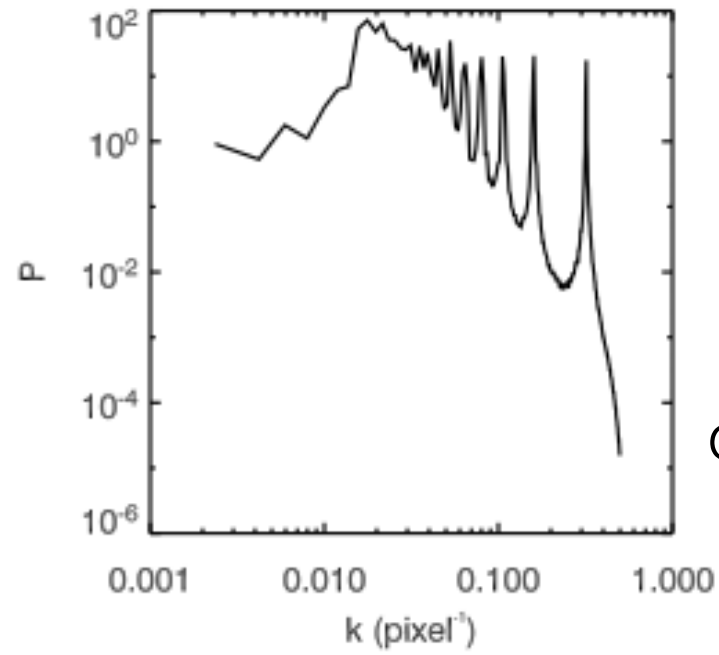
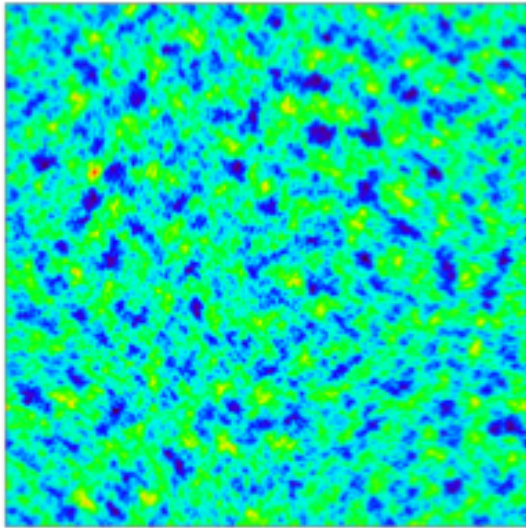
n sinus
décentrés



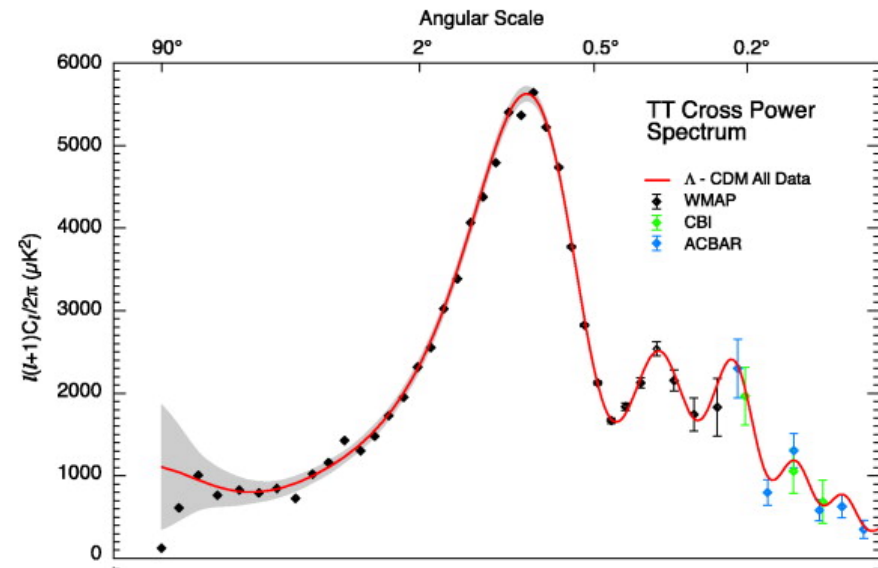
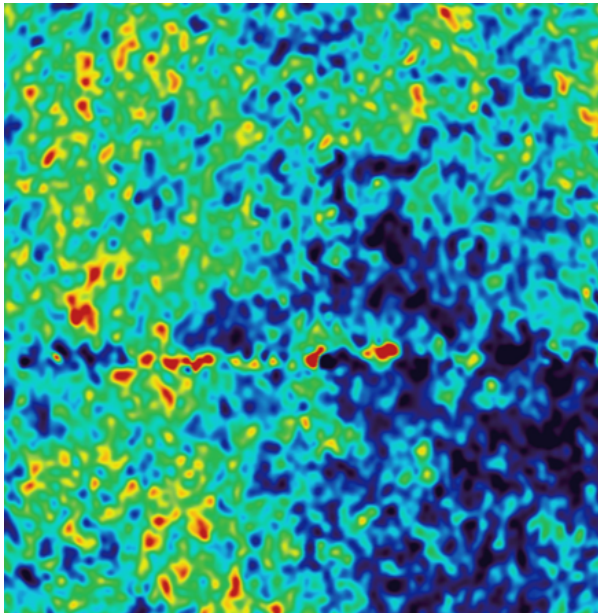
—
n sine
not
centred



autosimilar
form
(fractal)



n sine
not
centered

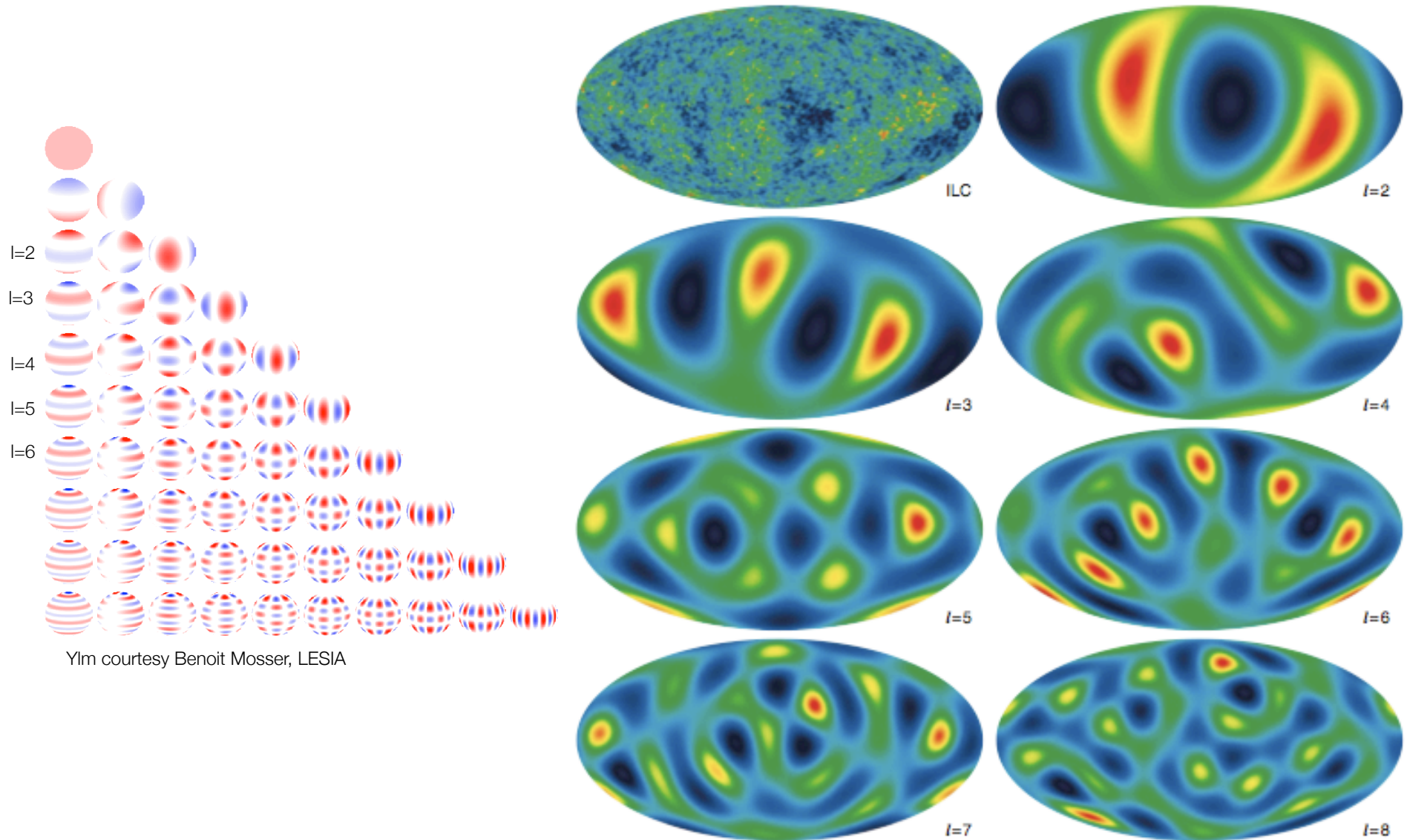


WMAP 1 yr

I. Angular Power Spectrum on the sphere: C_l

3. What is $l(l+1)$?

multipoles applied to the CMB



Hinshaw et al., 2007, WMAP3

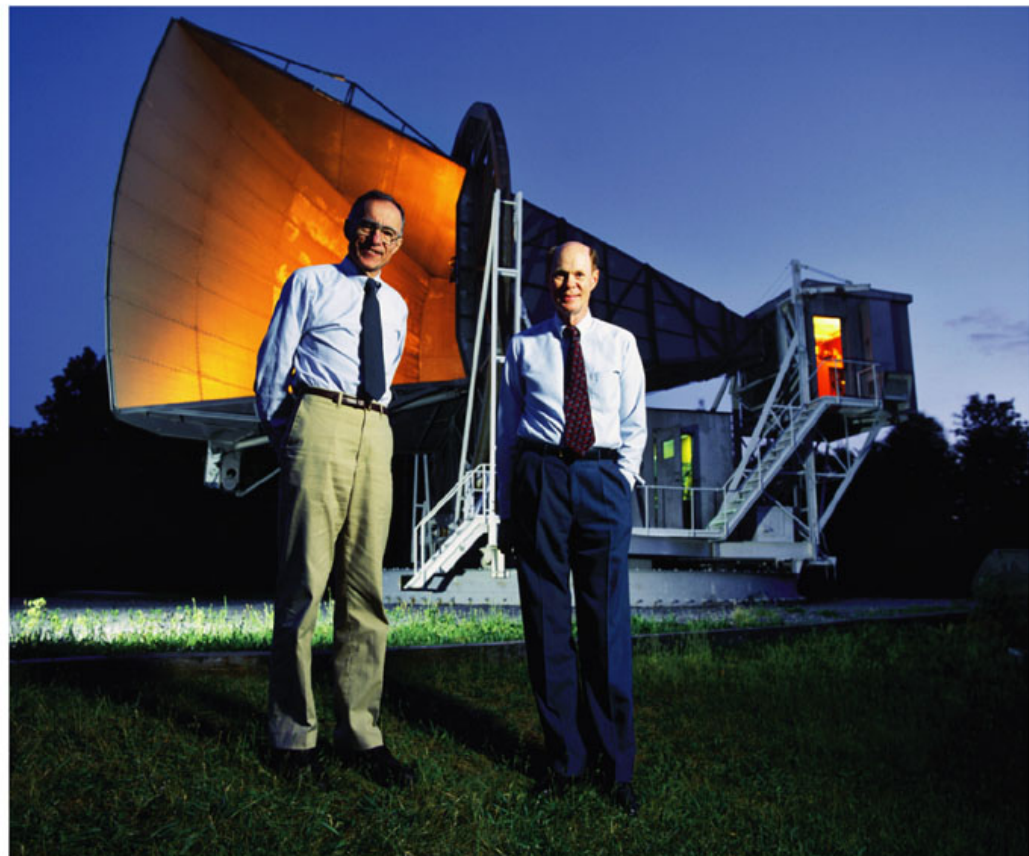
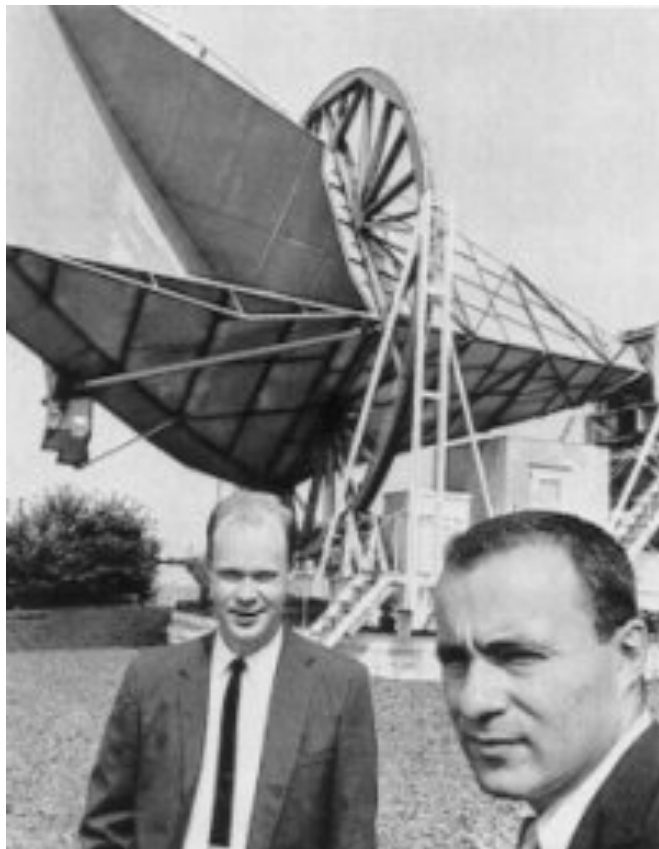
II. Observations of the Cosmic Microwave Background

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"

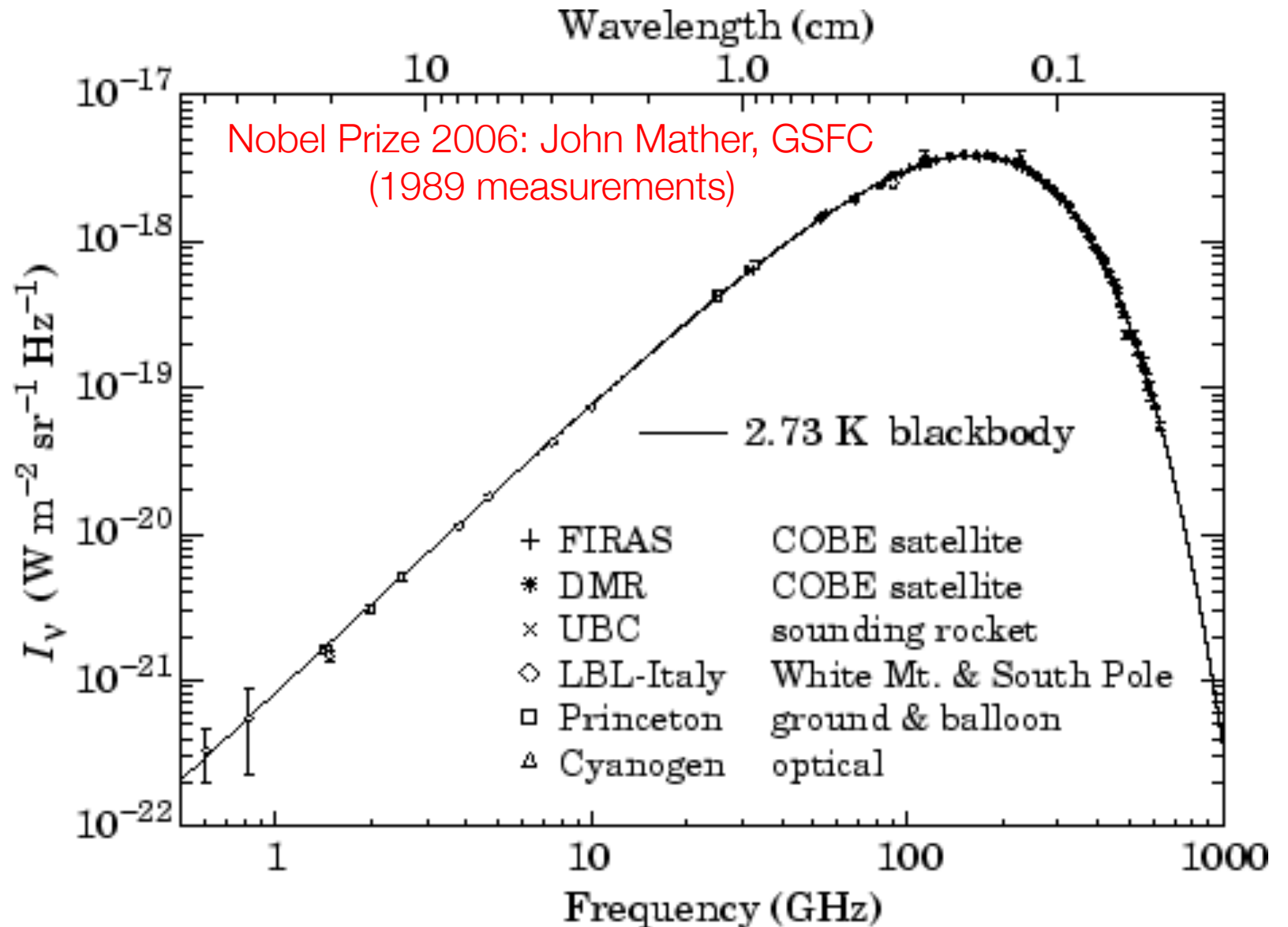


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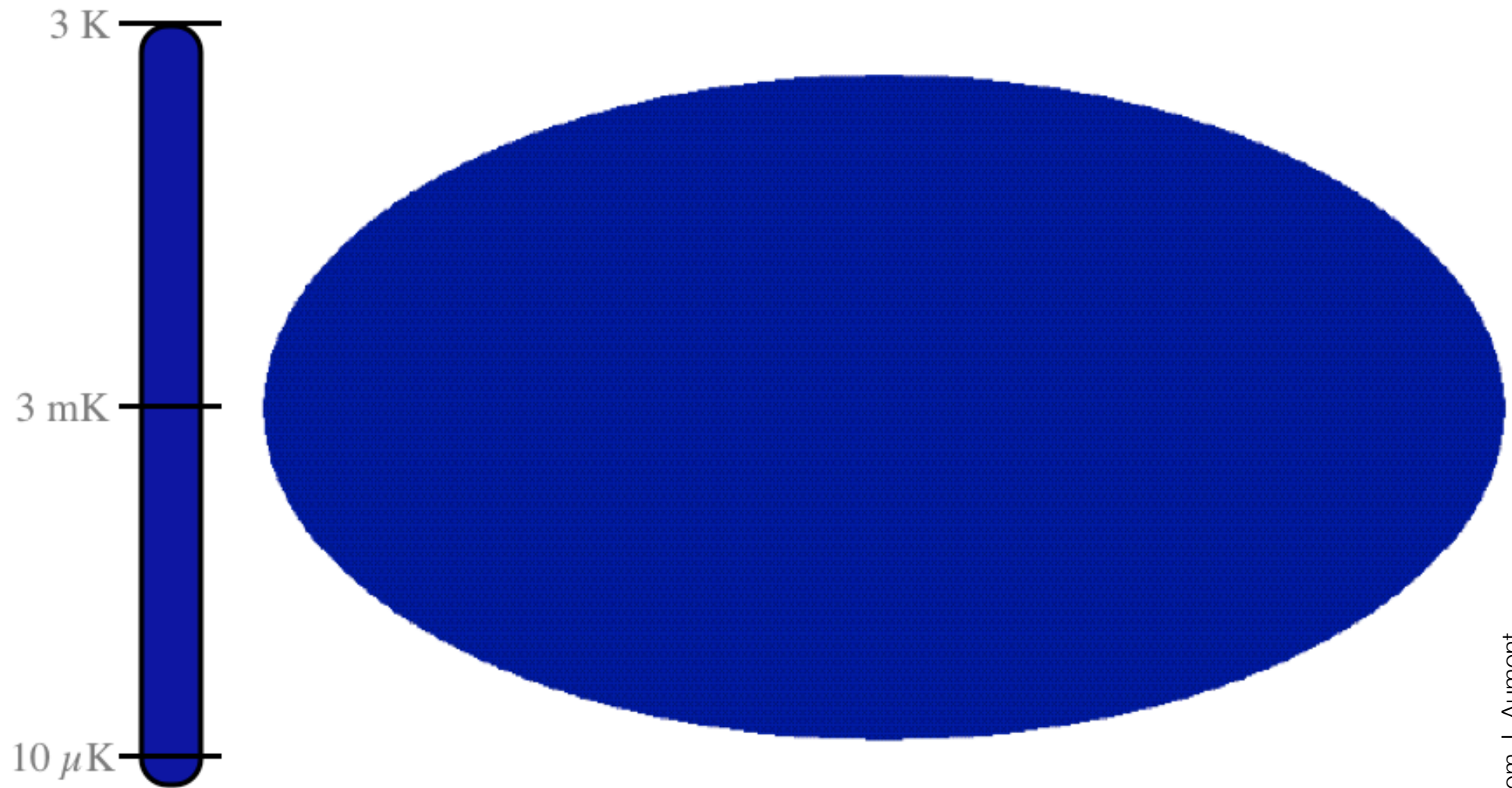
properties

Blackbody
Radiation
 $T=2.725$ K

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

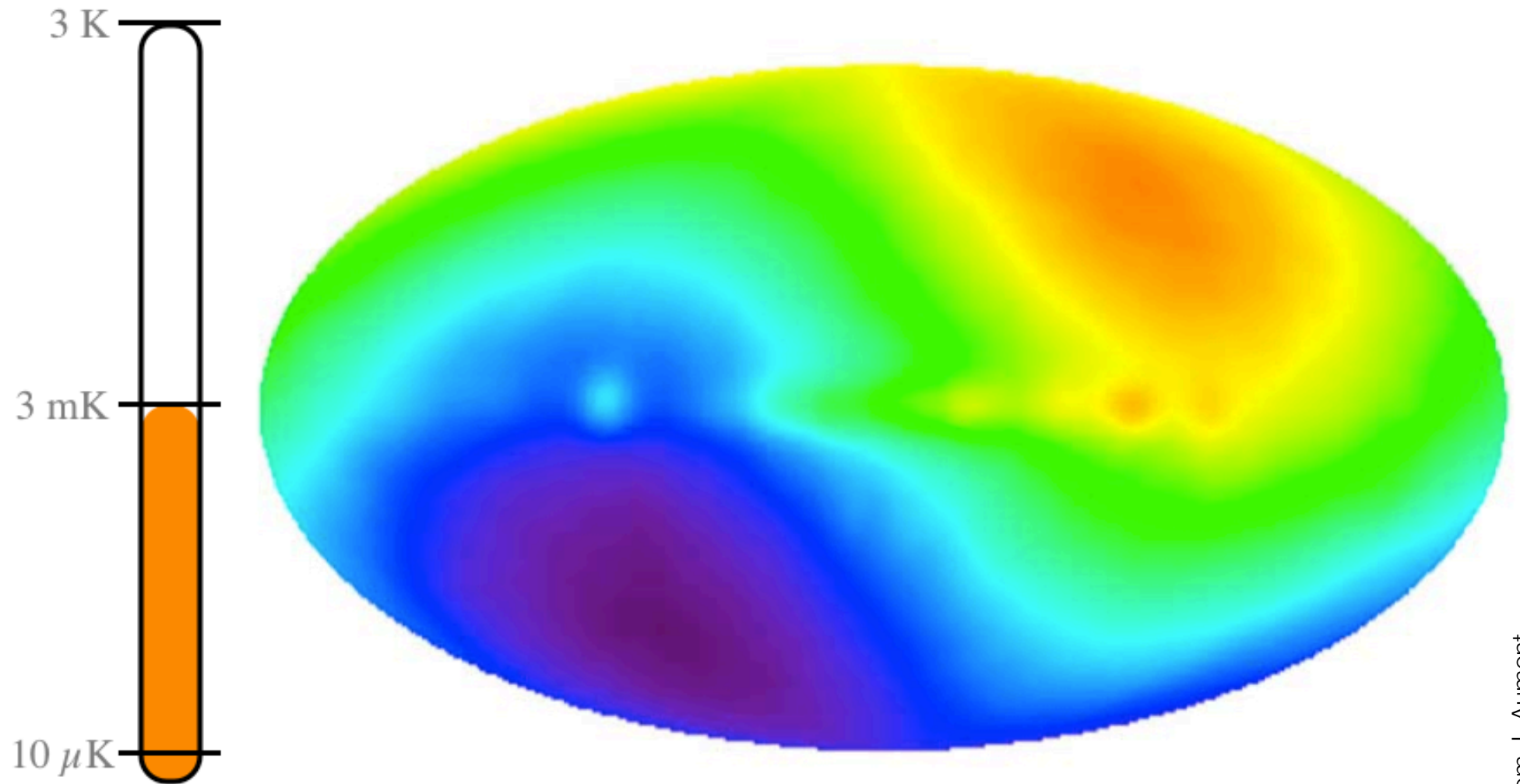


fond cosmologique CMB



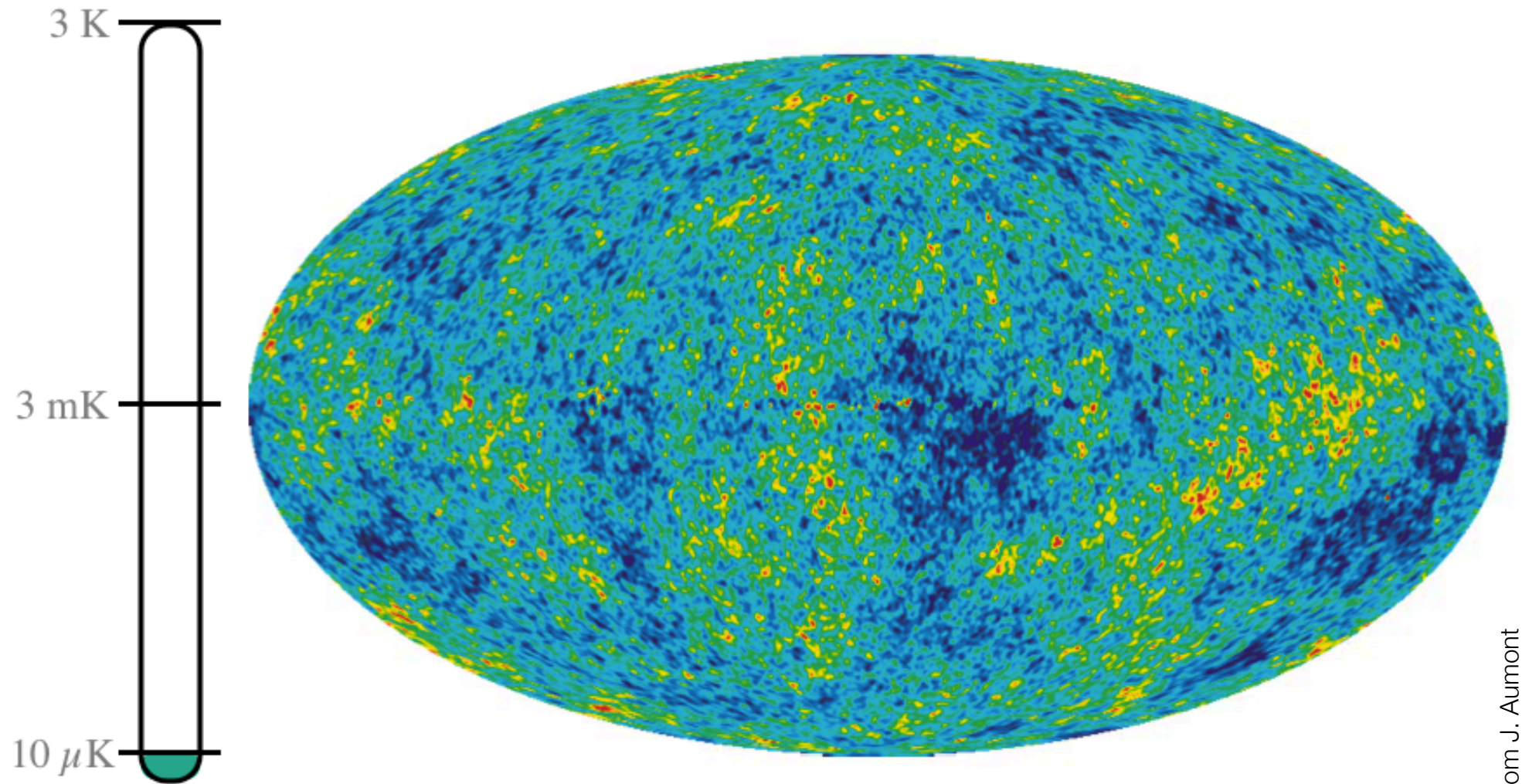
from J. Aumont

fond cosmologique CMB



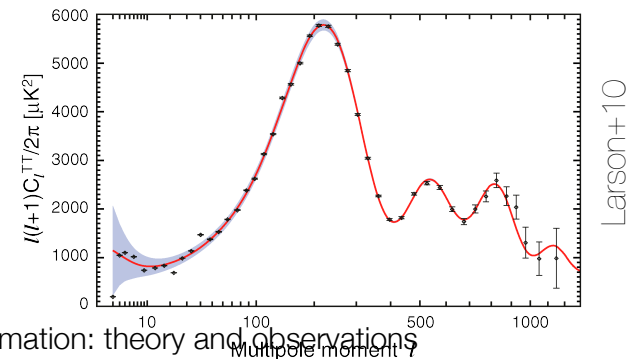
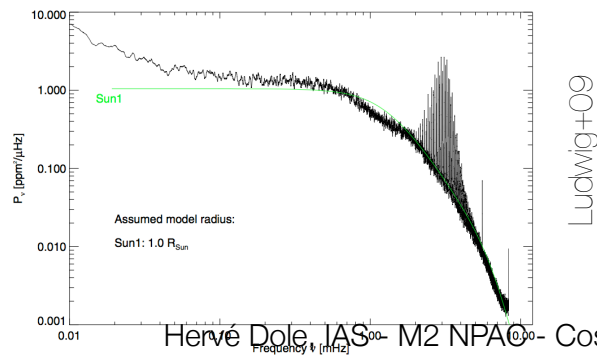
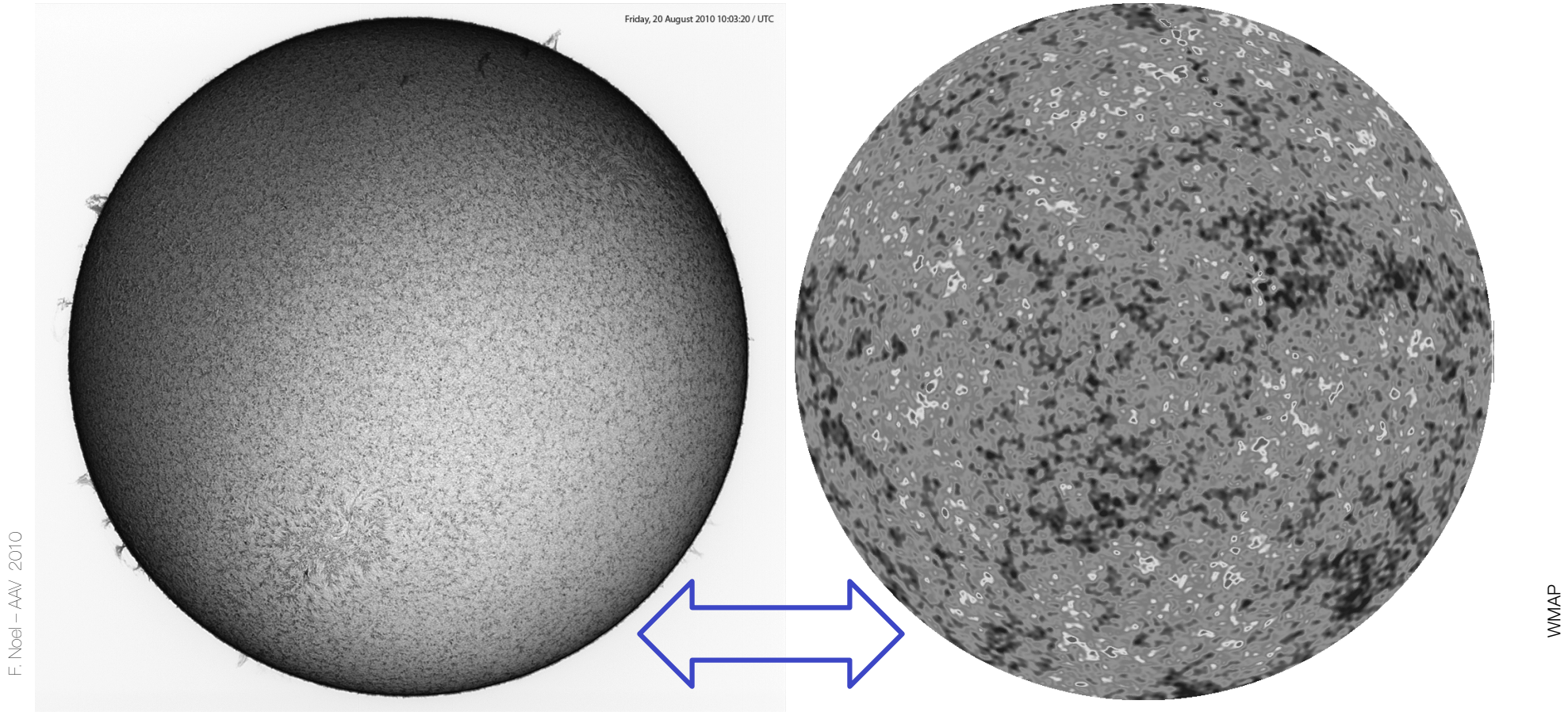
from J. Aumont

fond cosmologique CMB



from J. Aumont

last scattering surface

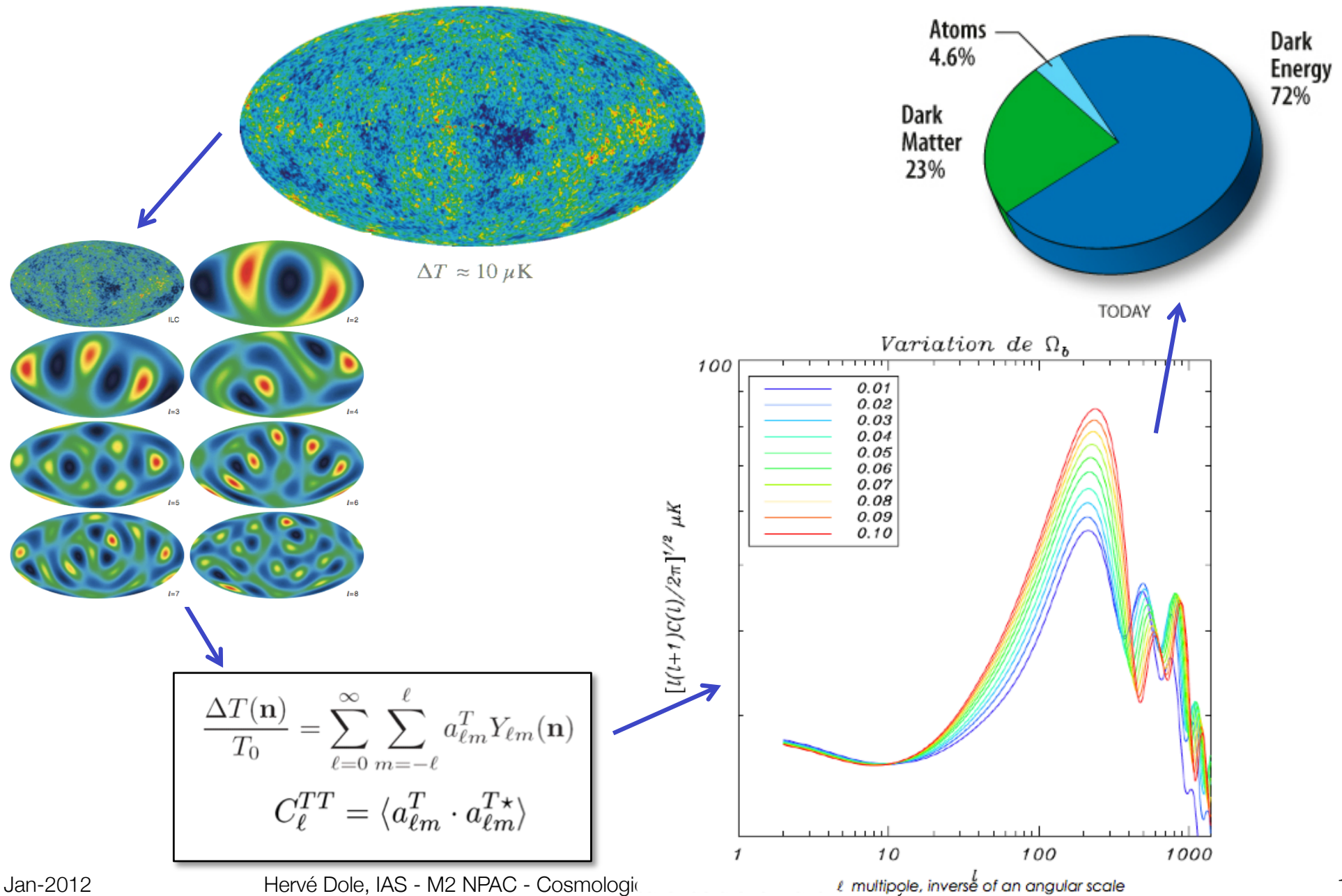


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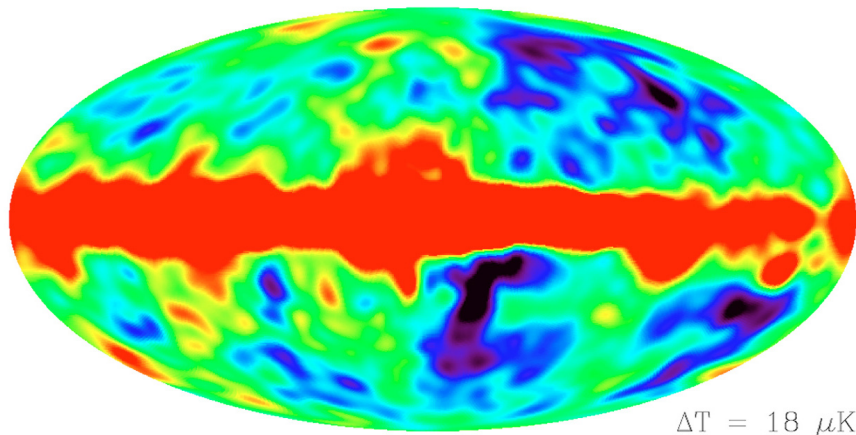
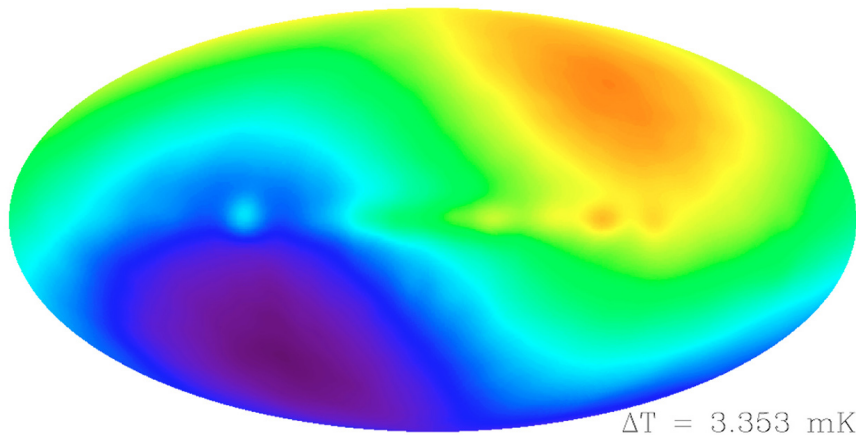
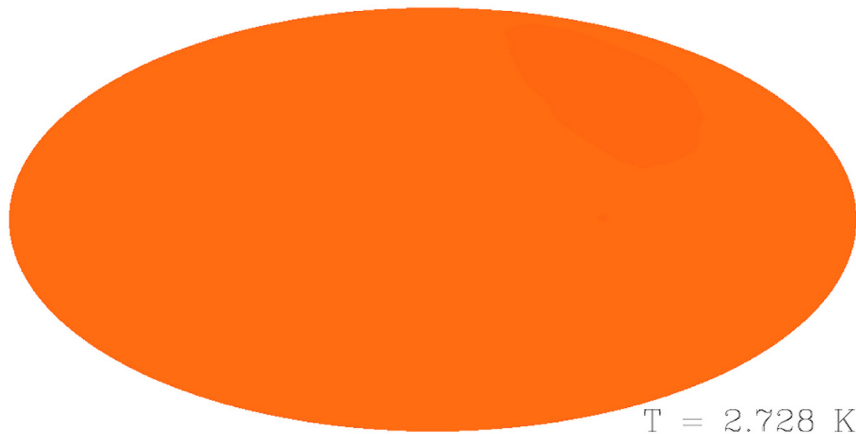
Herve Dole, IAS⁰⁰- M2 NPAC - Cosmological structure formation: theory and observations

Fig. 2. Power spectra of disk-integrated photometric fluctuations for the Sun: the predicted background signal of model Sun1 (green/grey solid

statistics of anisotropies



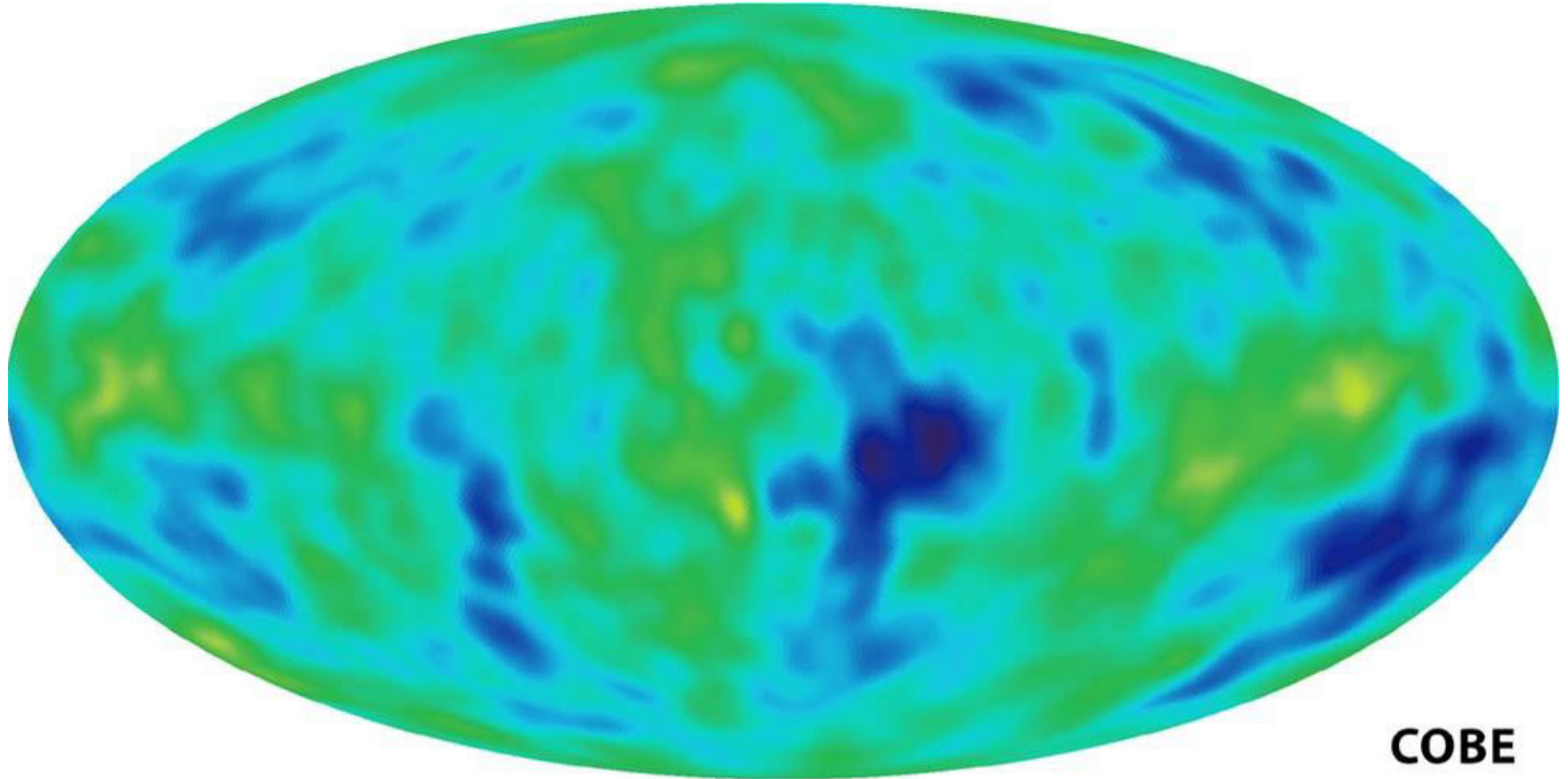
CMB by COBE in 1992



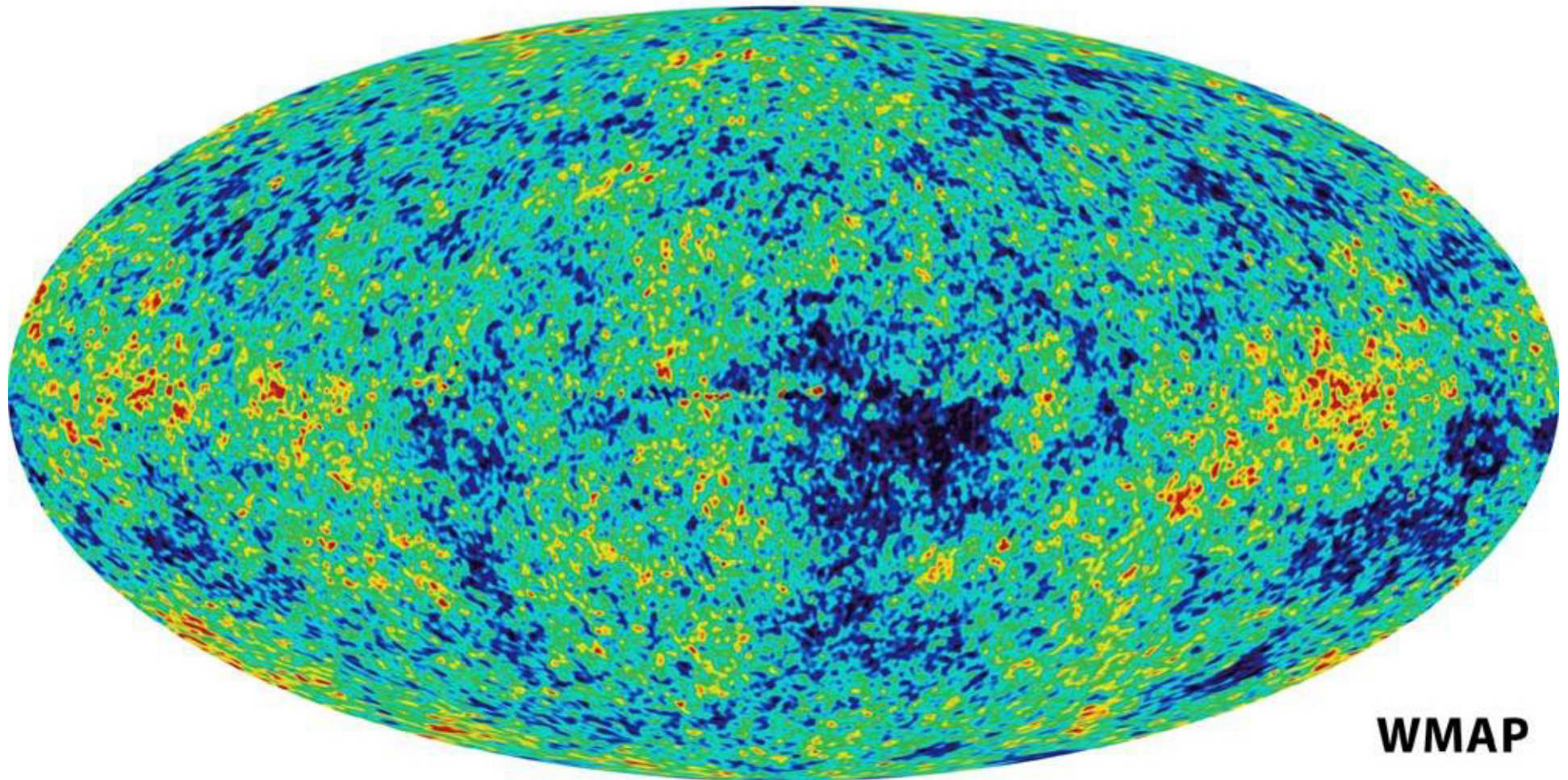
Nobel Prize 2006: G. Smoot, GSFC
(1992 measurements)
« for their discovery of the blackbody
form and anisotropy of the cosmic
microwave background radiation »

fluctuations de température

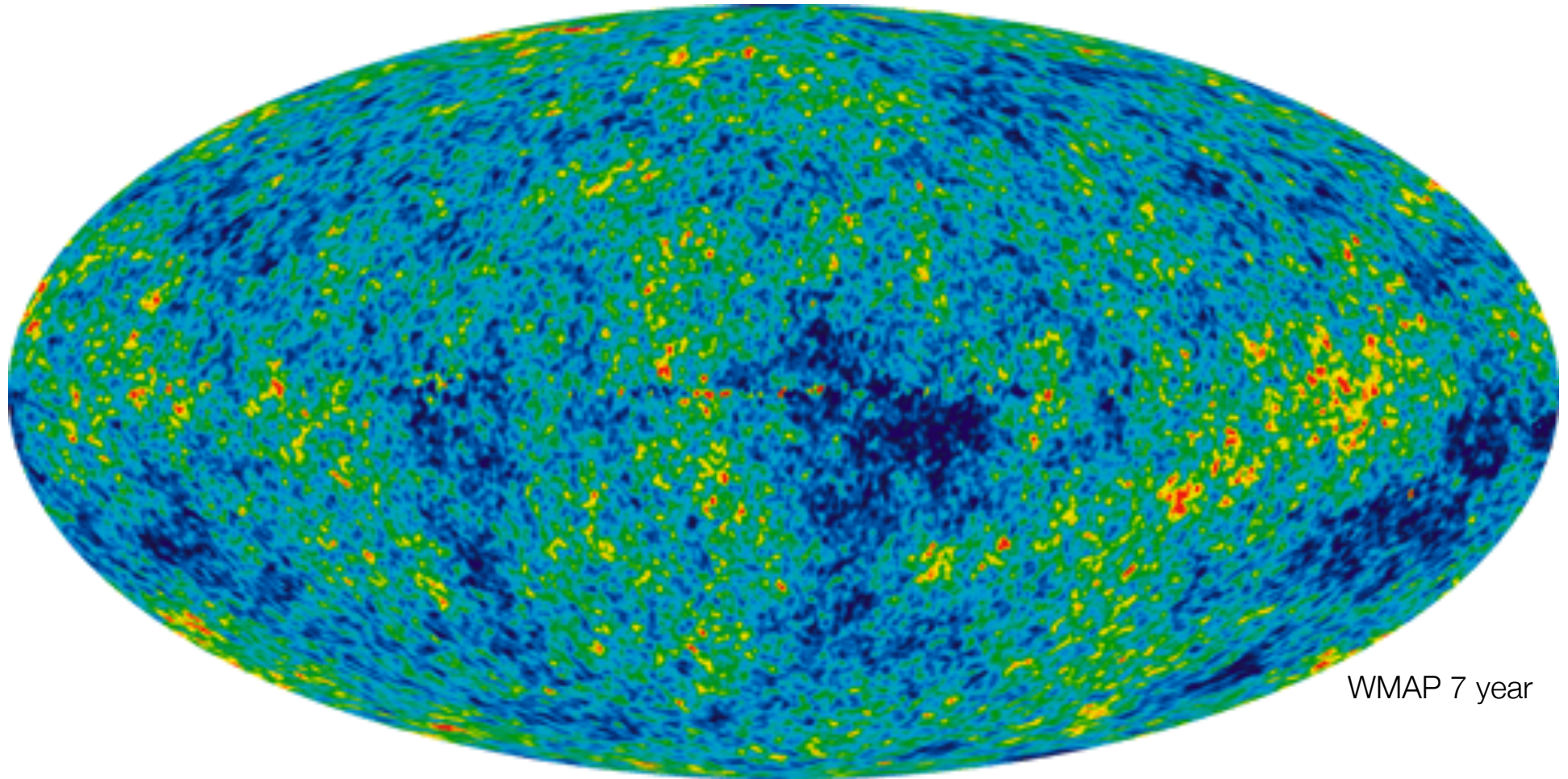
l'amplitude des fluctuations est de l'ordre de la dizaine de microKelvin !



fluctuations de température



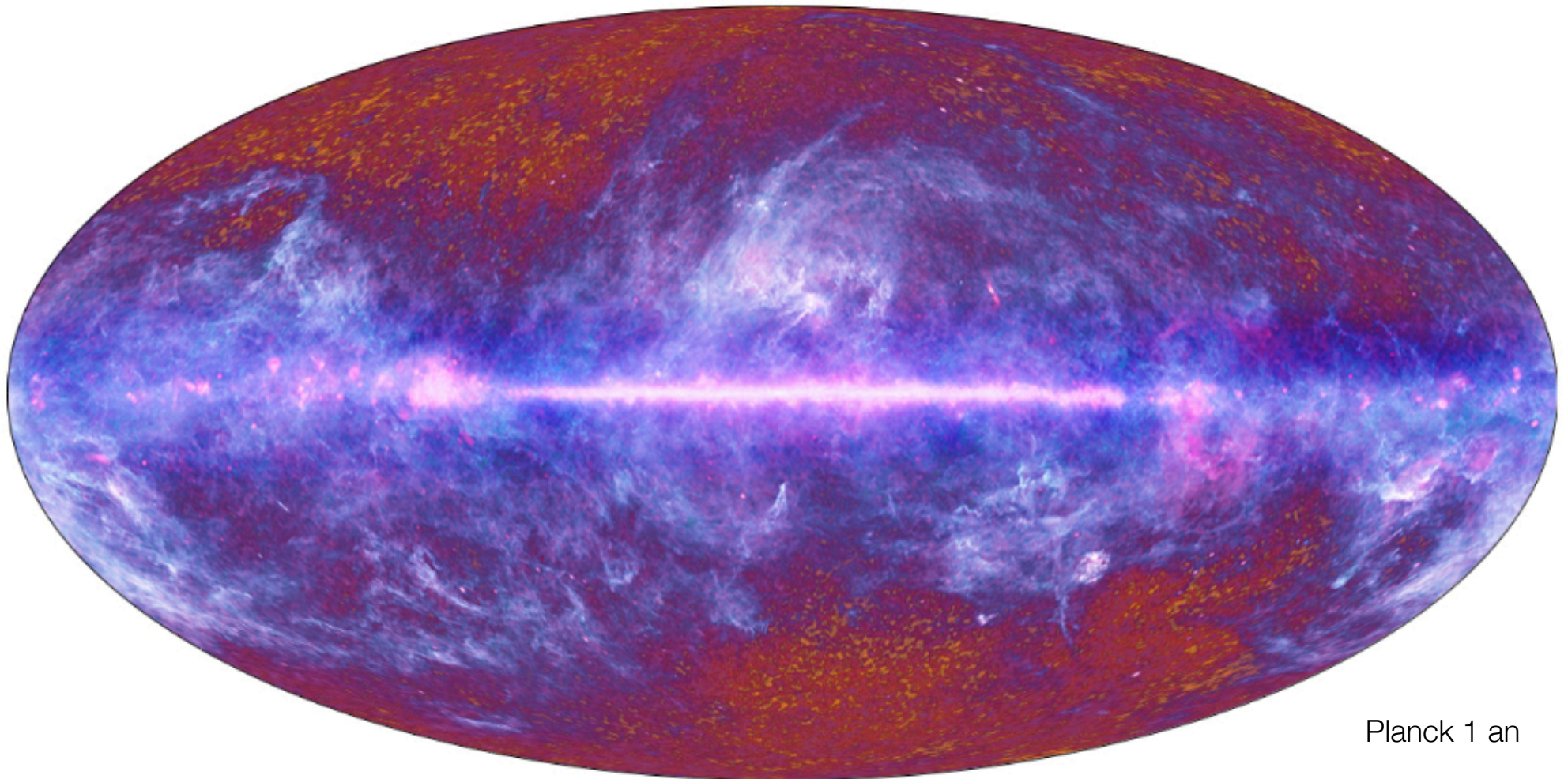
fluctuations de température



WMAP 7 year

fluctuations de température

+ Galaxie et galaxies, amas etc.



Planck 1 an

II. Observations of the Cosmic Microwave Background

2. Strategy and Difficulties

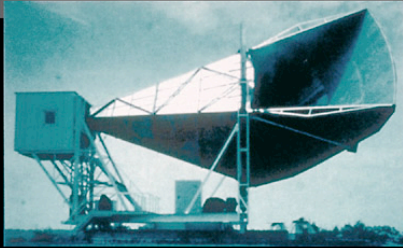
you play !

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

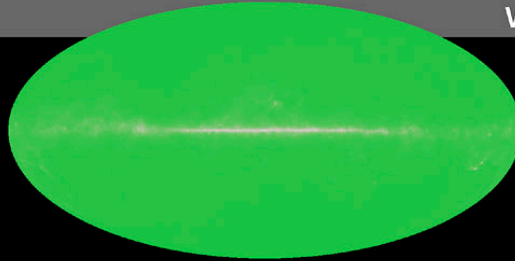
- what telescope and instrument would you build ?

CMB observations

1965



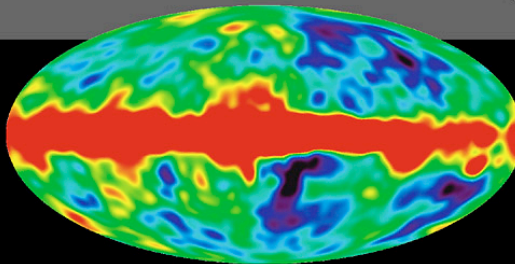
Penzias and Wilson



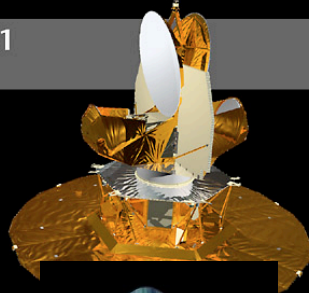
1992



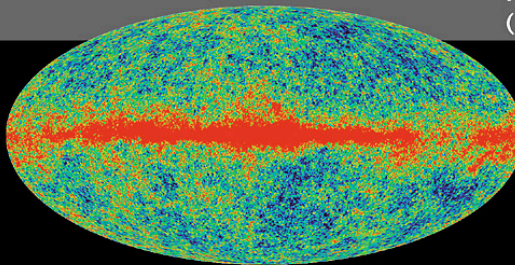
COBE



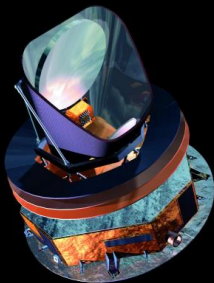
2001



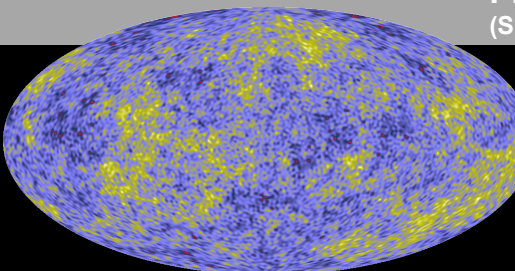
MAP
(Simulated)



2009



Planck (ESA)
(Simulated)

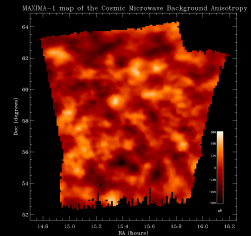


Even
Better !

1999



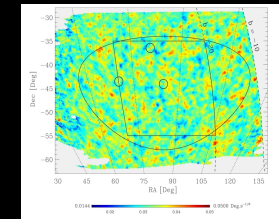
MAXIMA



1999



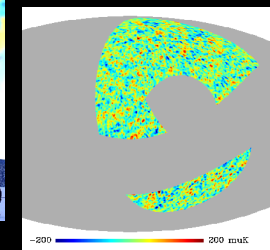
Boomerang



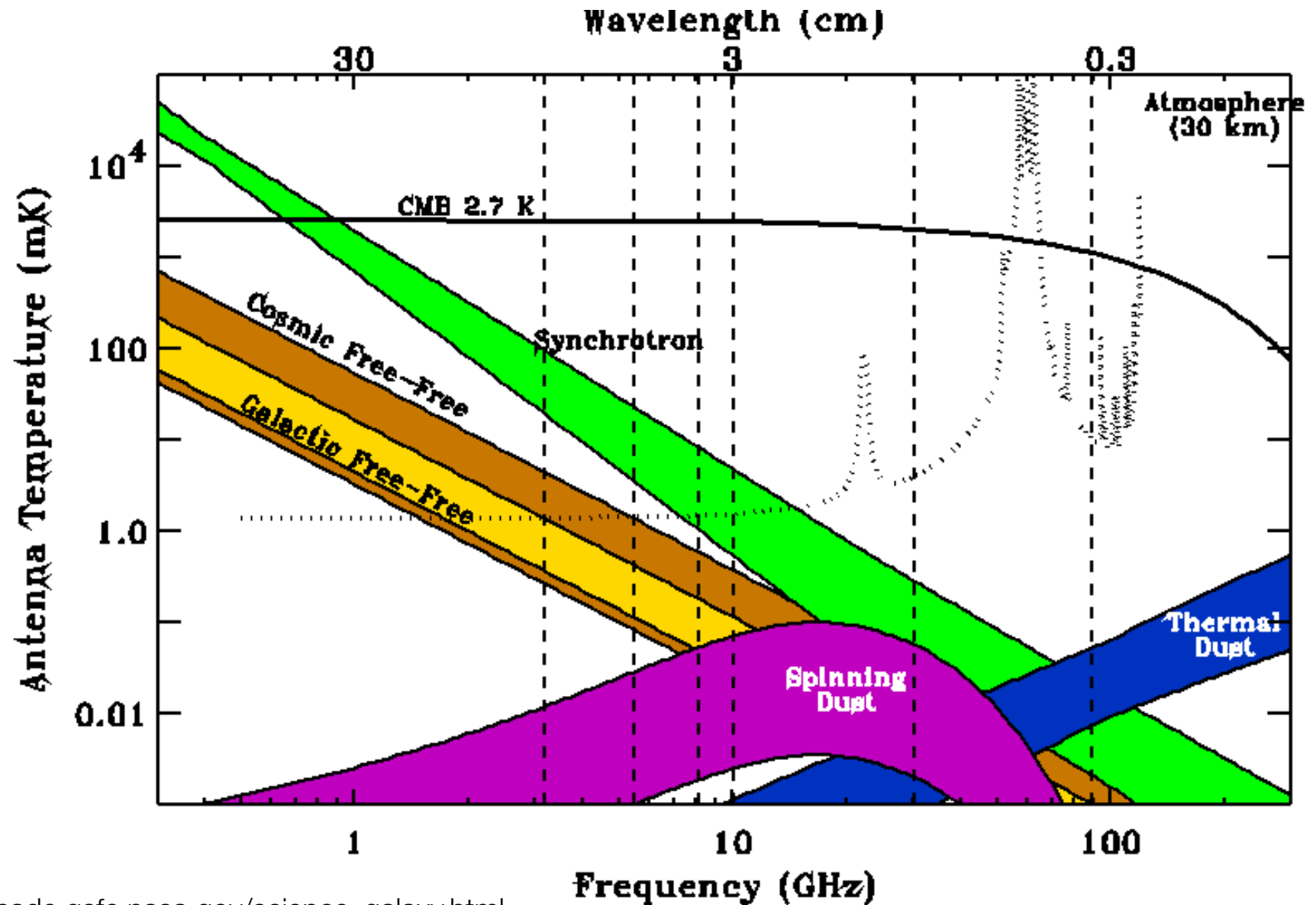
2000



Archeops



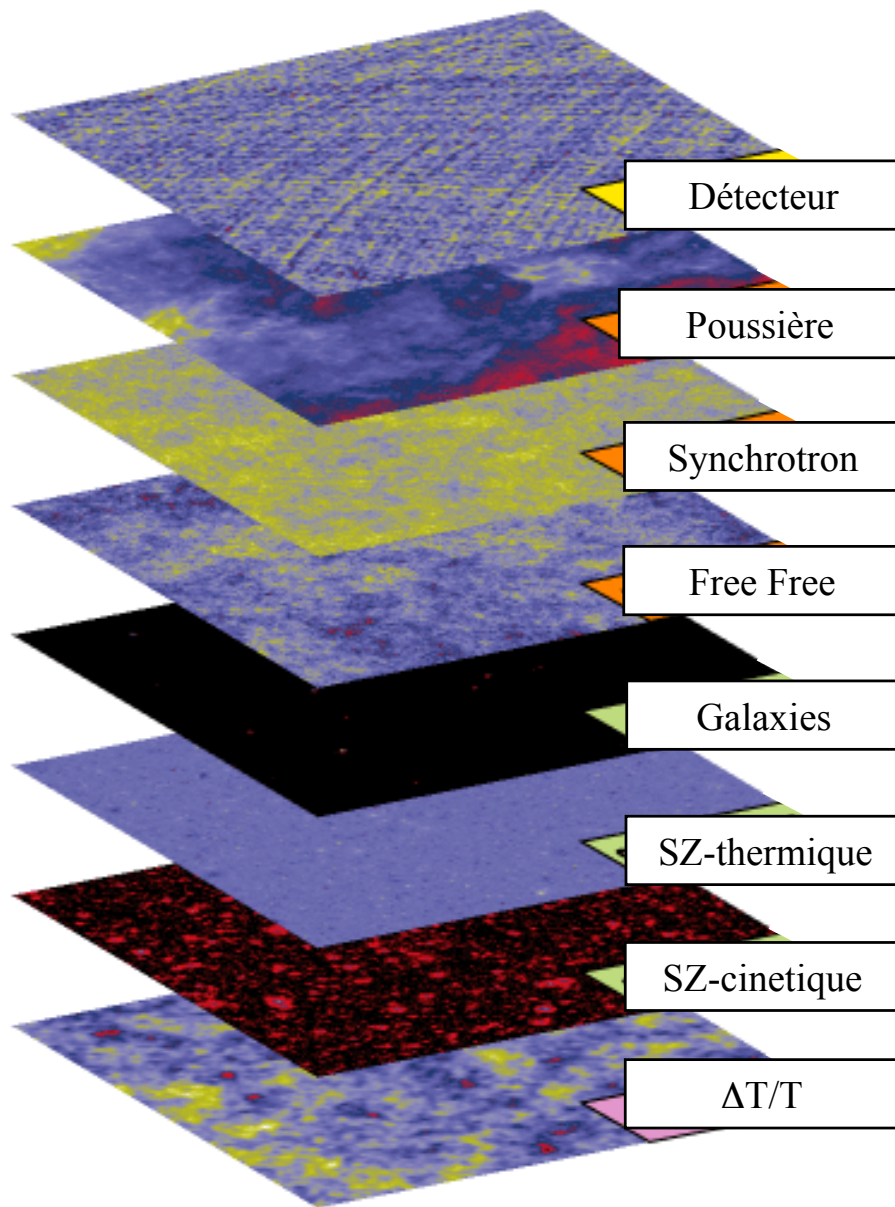
difficulties



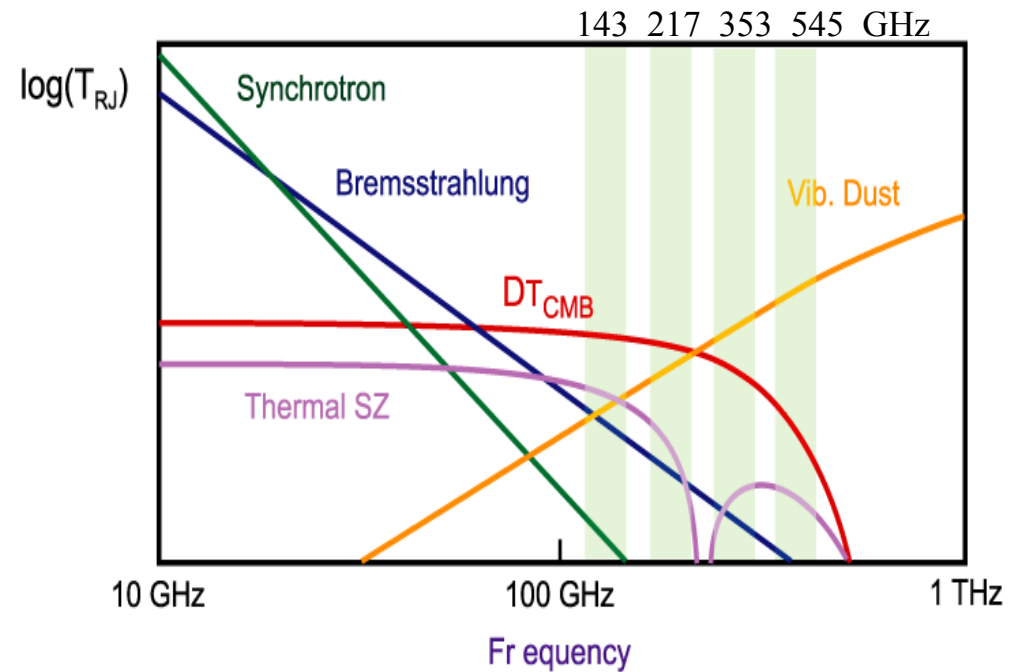
http://arcade.gsfc.nasa.gov/science_galaxy.html

foregrounds

figure RUMBA, 1996 Bouchet & Gispert

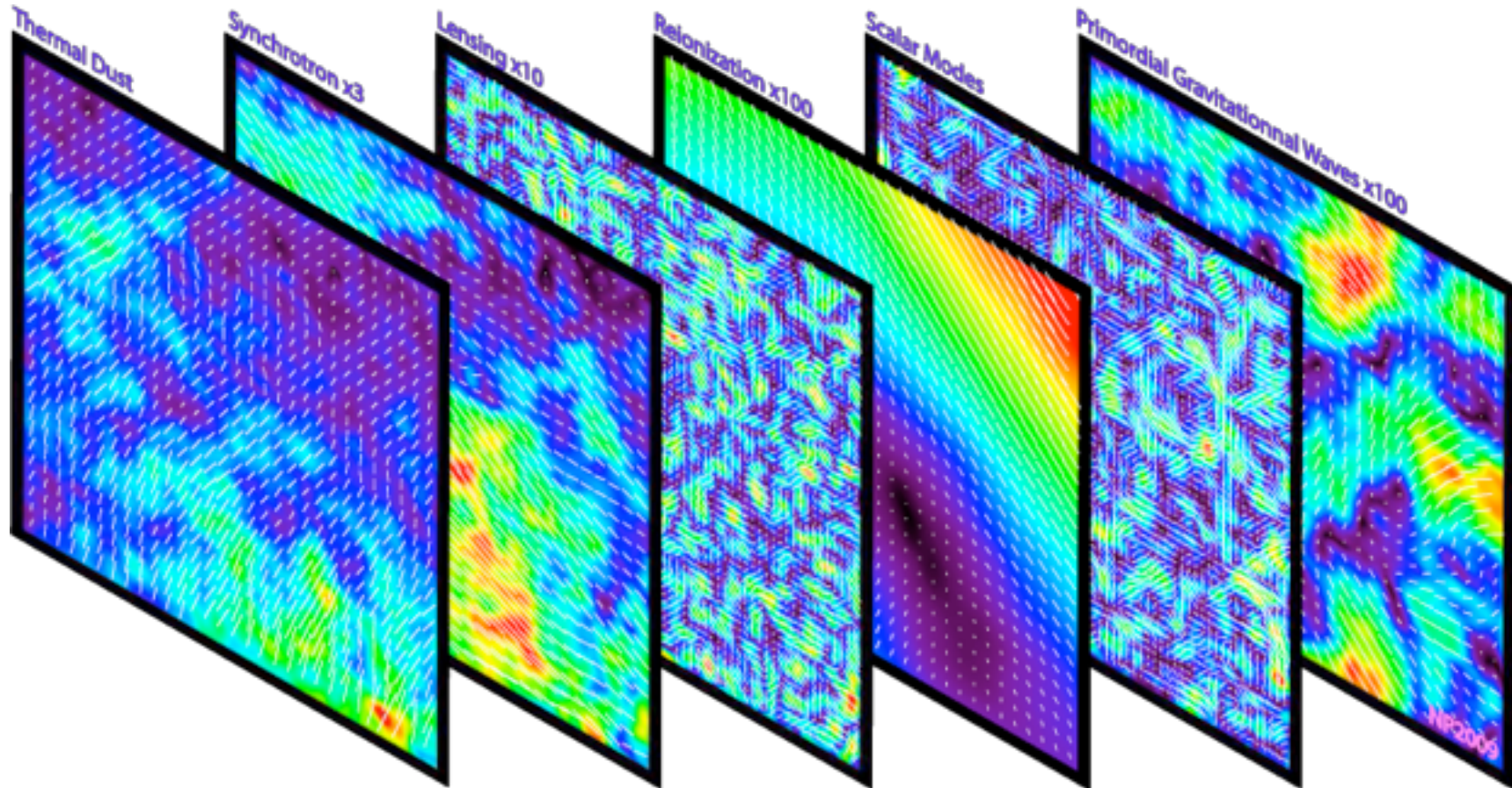


« Sandwich Cosmique »



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

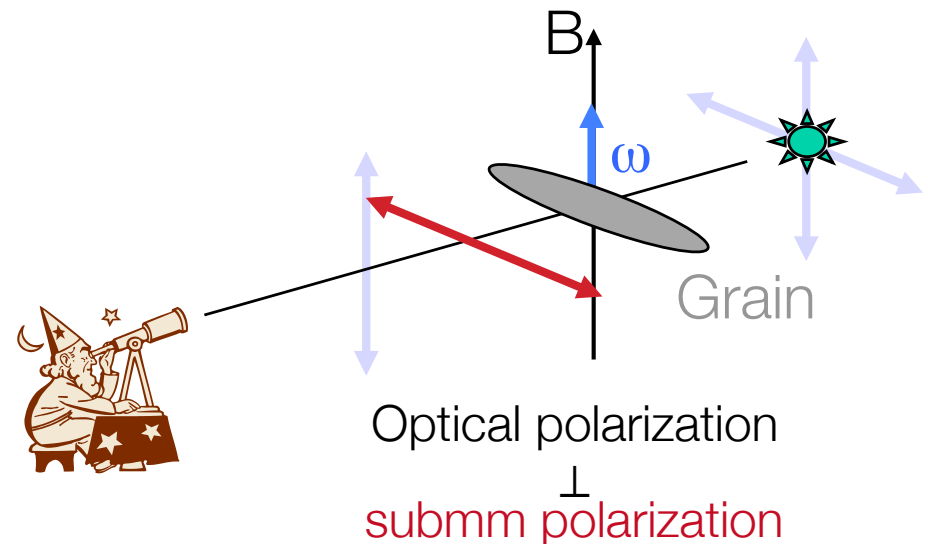
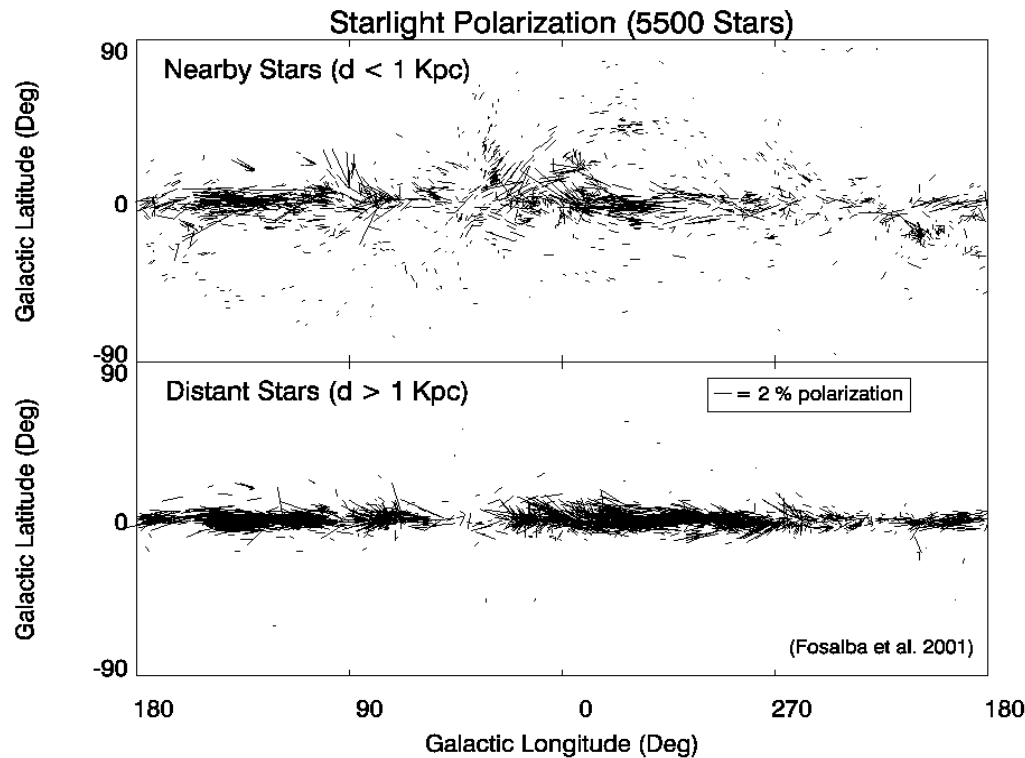
foregrounds



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

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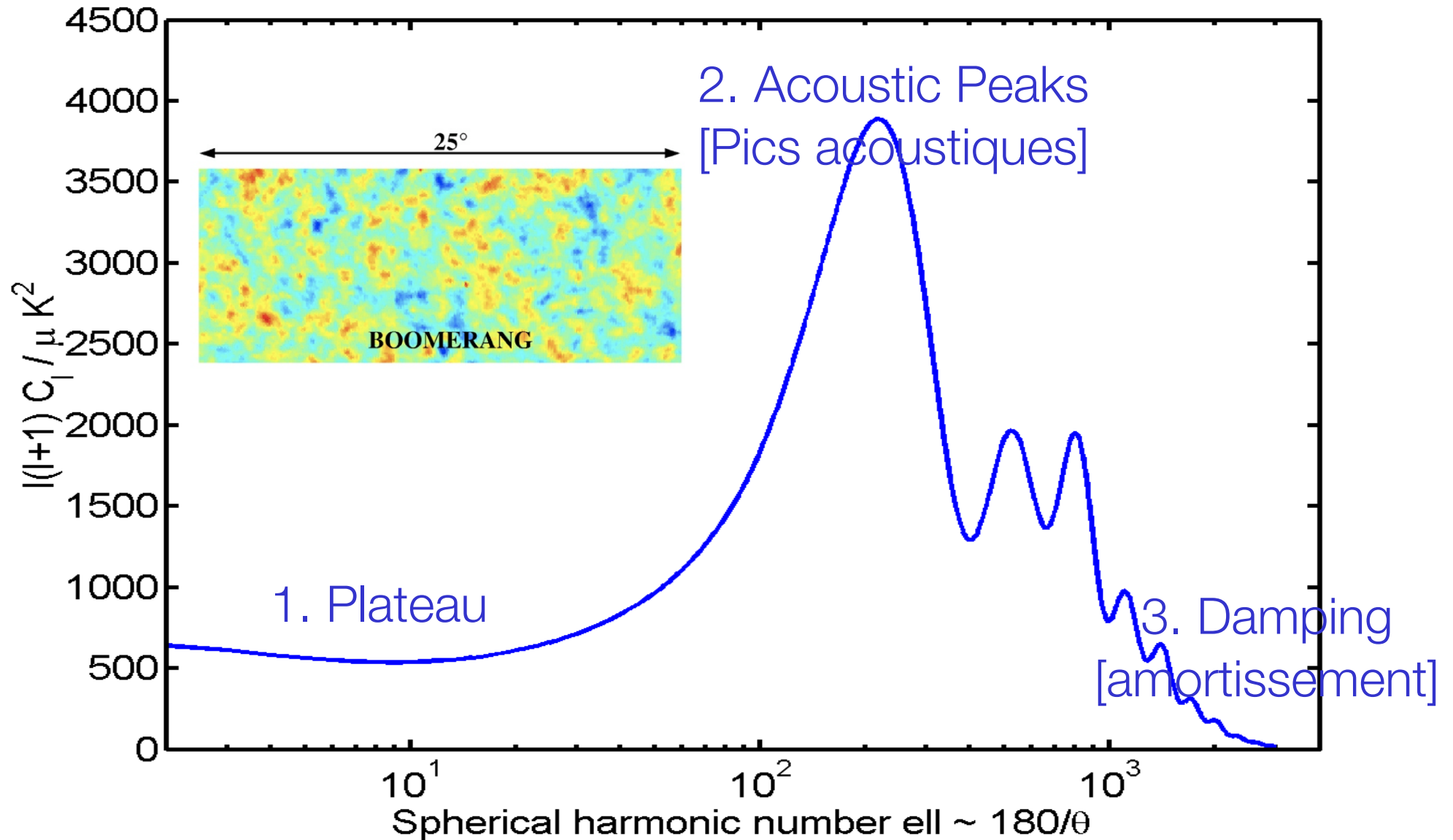
+ Manque de mesures à grandes échelles

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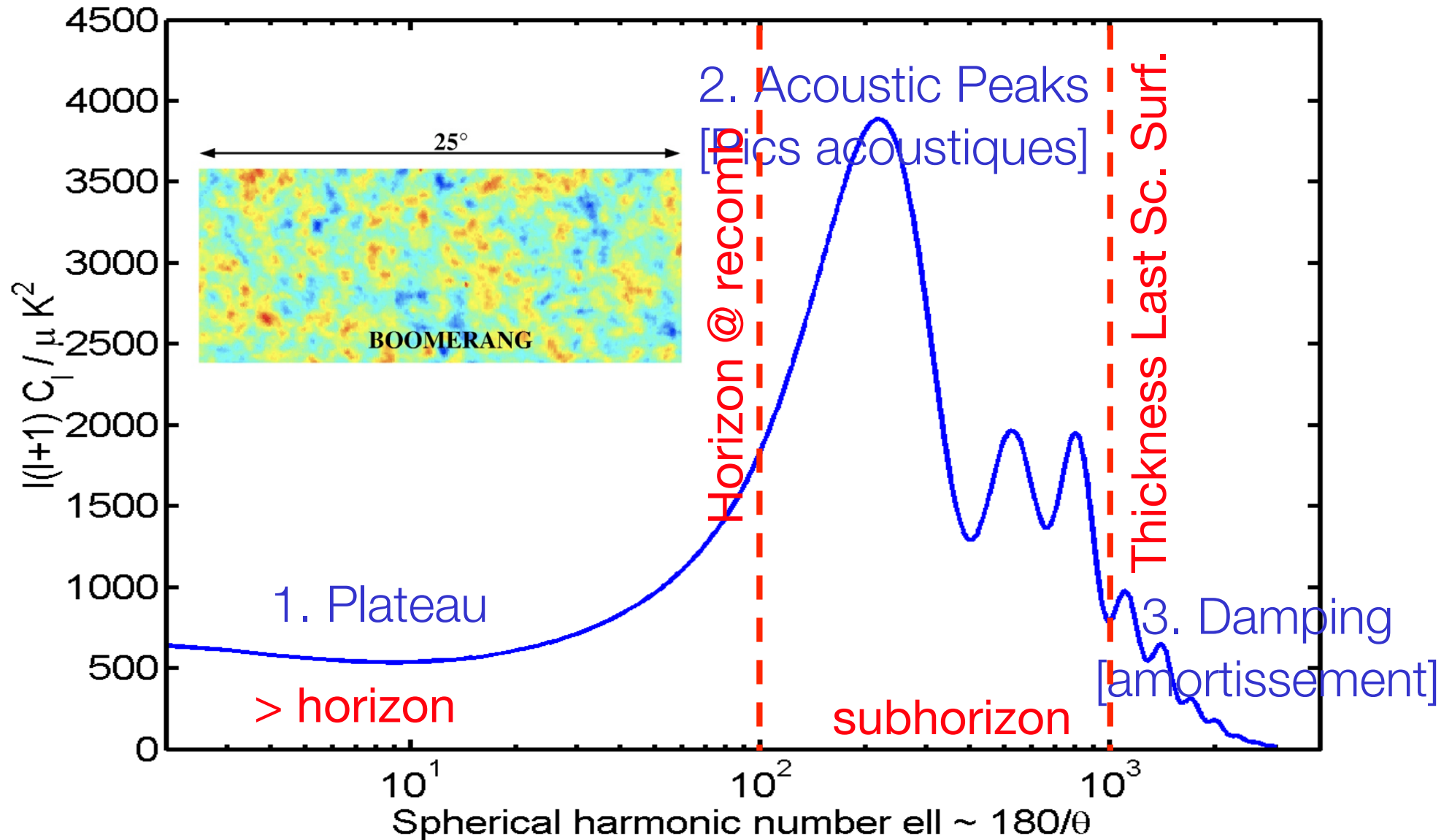
II. Observations of the Cosmic Microwave Background

3. Description of the Angular Power Spectrum

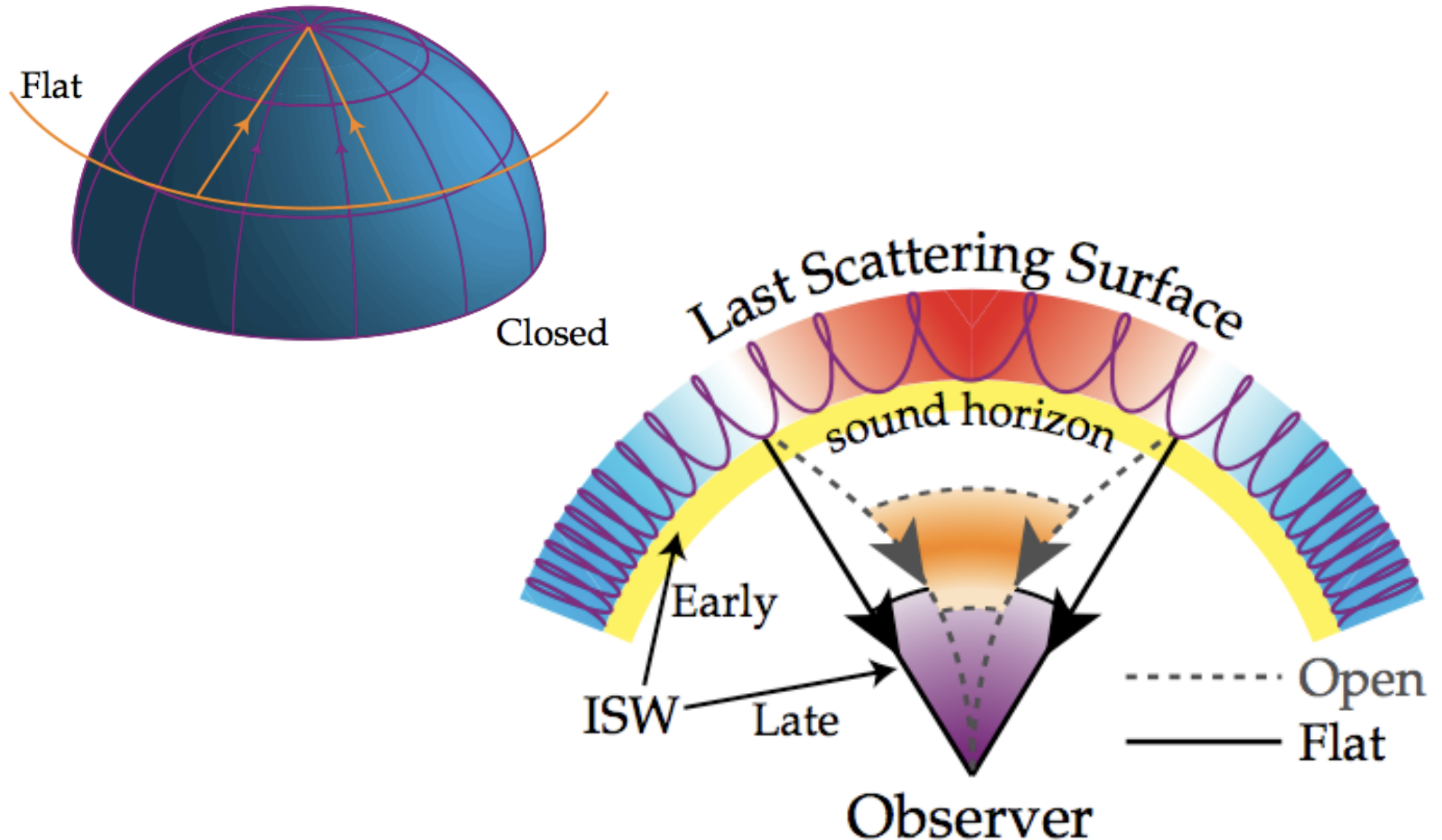
TT angular power spectrum: 3 regimes



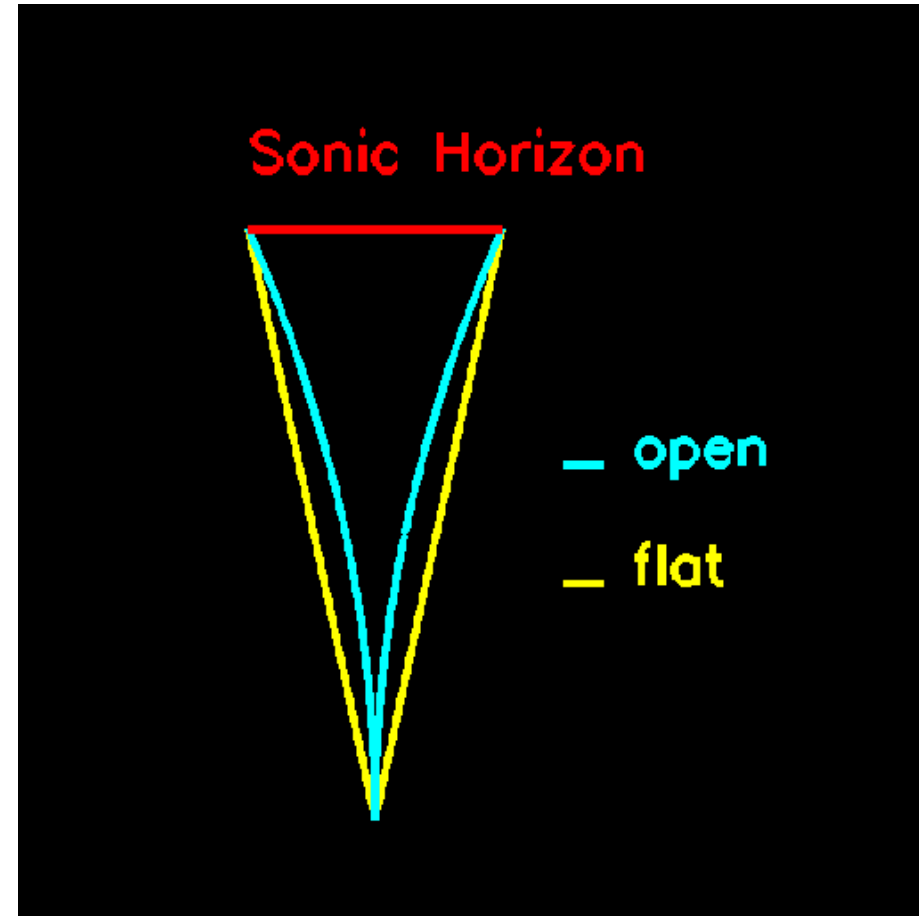
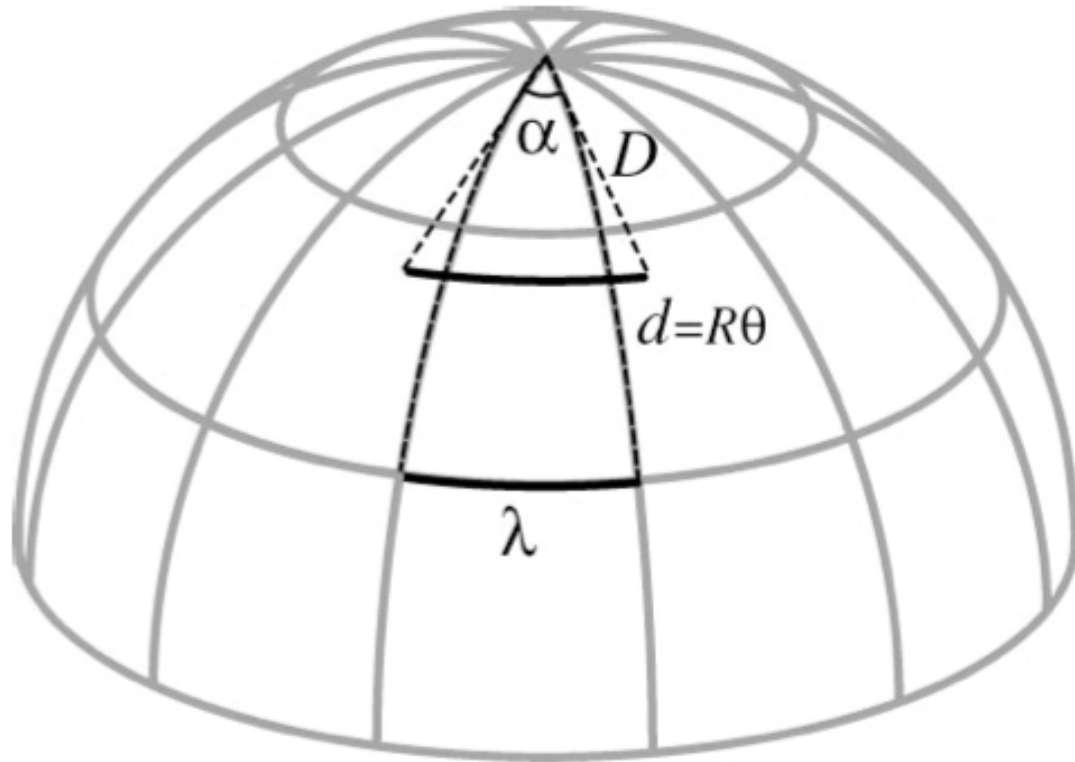
TT angular power spectrum: 3 regimes



angle and geometrie



angular distance

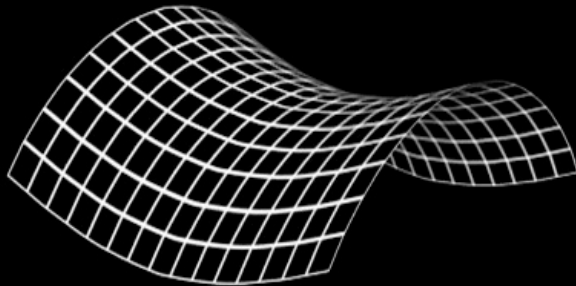
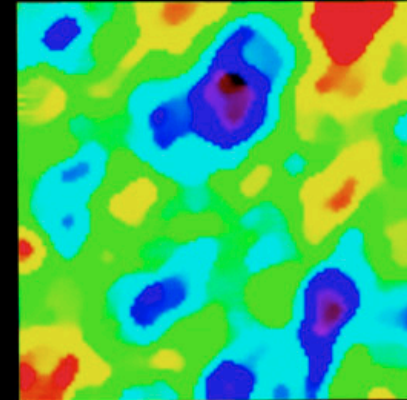
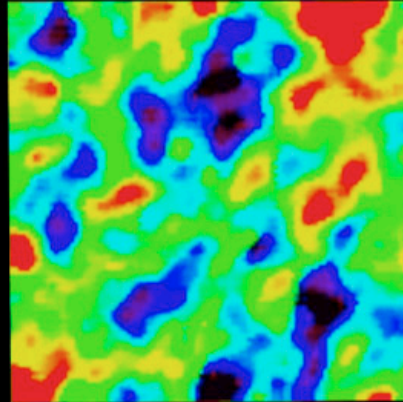
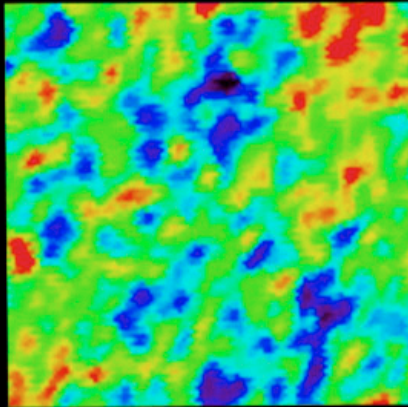


@z~1100

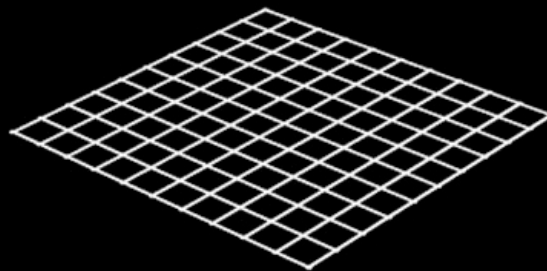
Hu & Dodelson, 2002, ARAA

WMAP

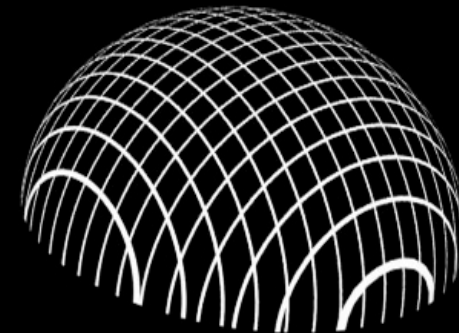
GEOMETRY OF THE UNIVERSE



OPEN

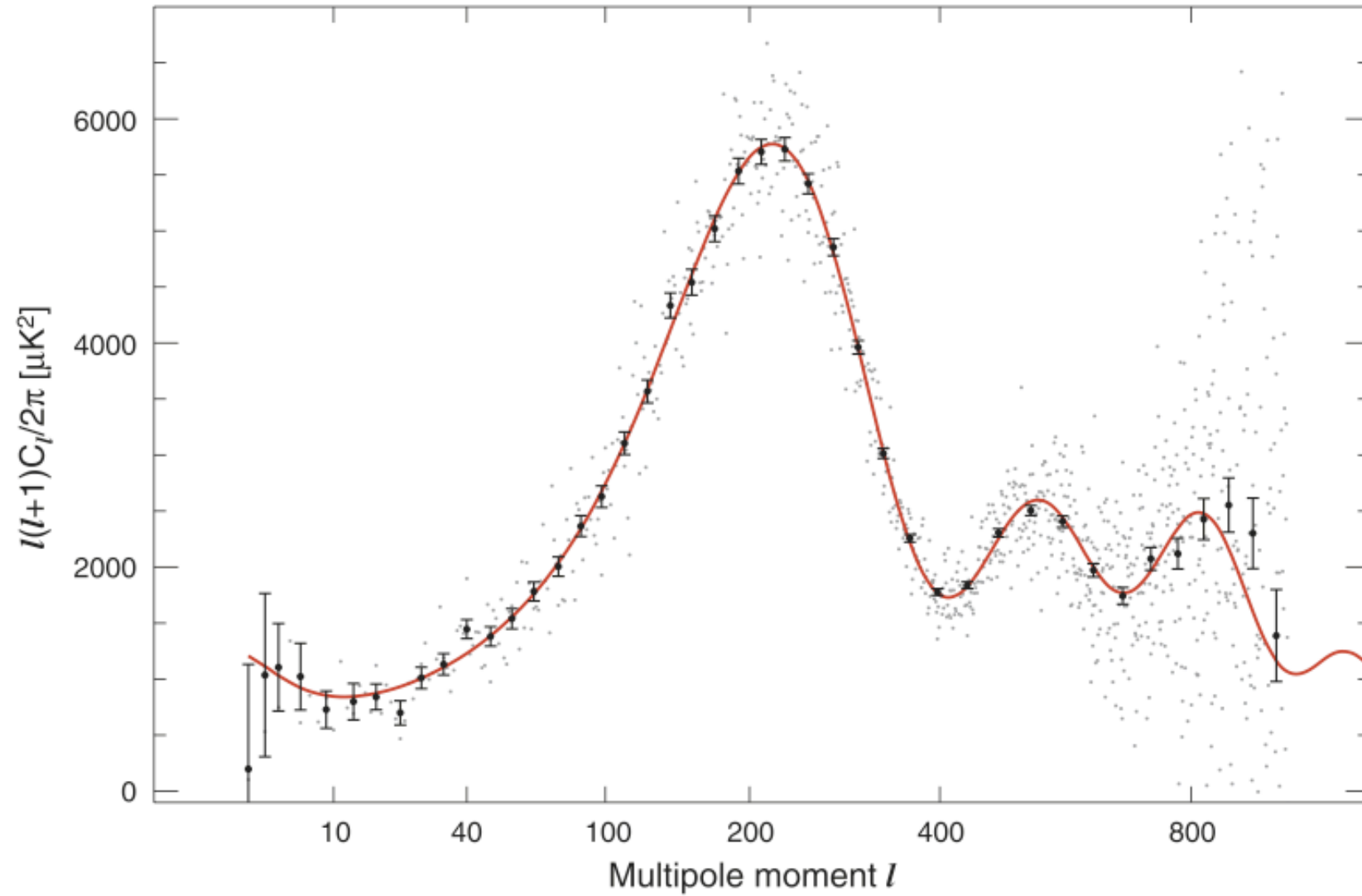


FLAT



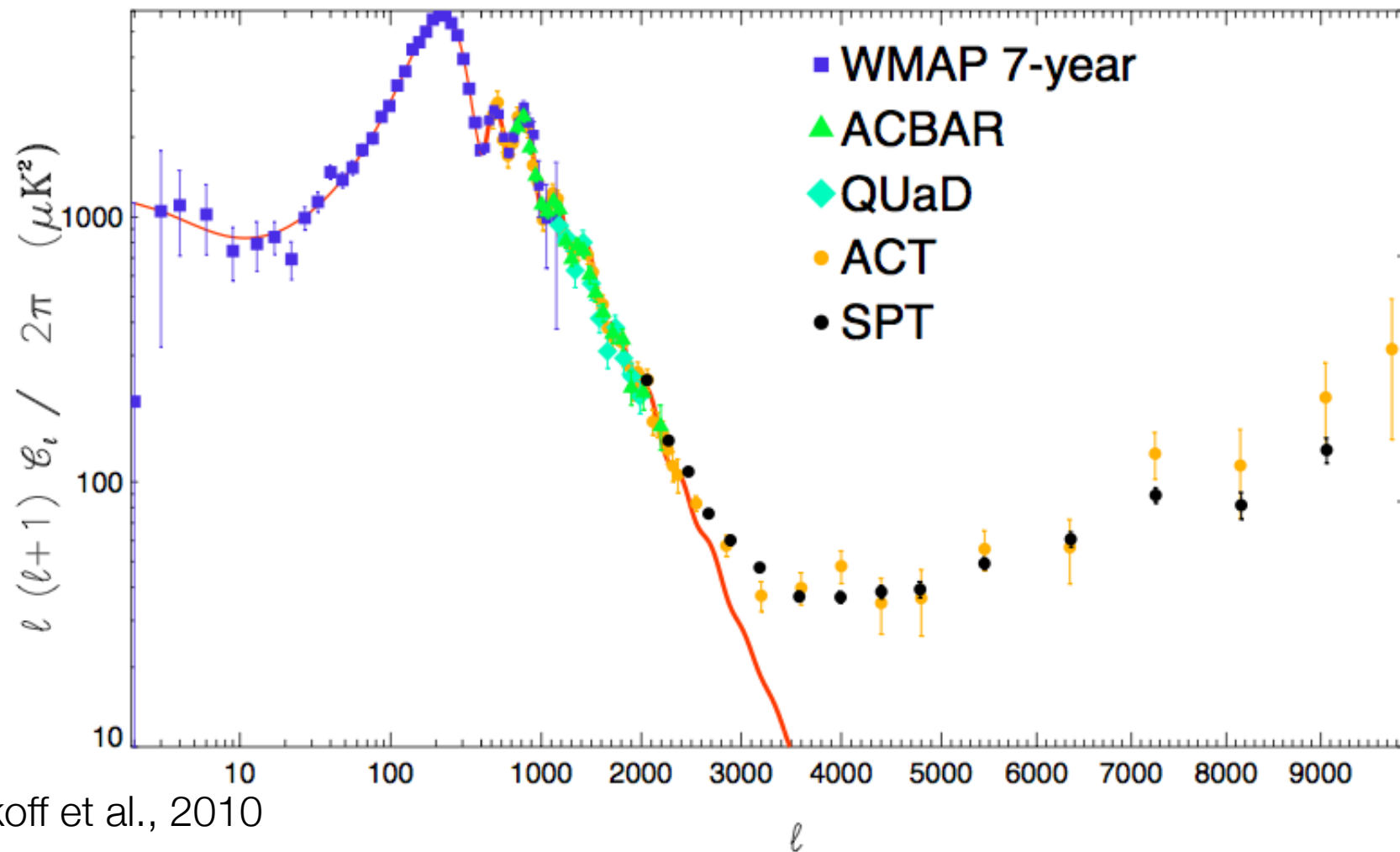
CLOSED

WMAP 5 TT



Dunkley et al., 2008, WMAP5

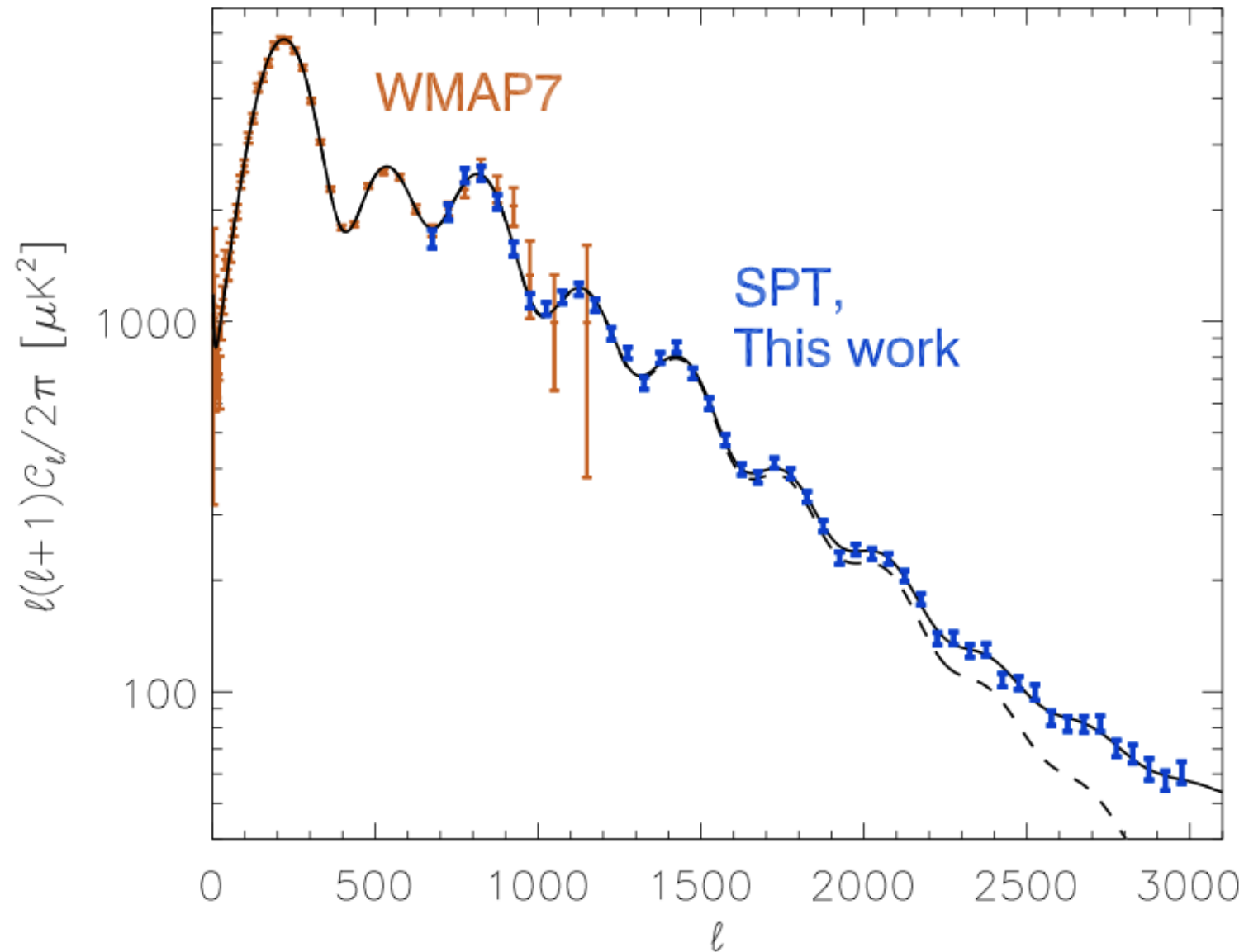
TT power spectrum at high ℓ



Shirokoff et al., 2010

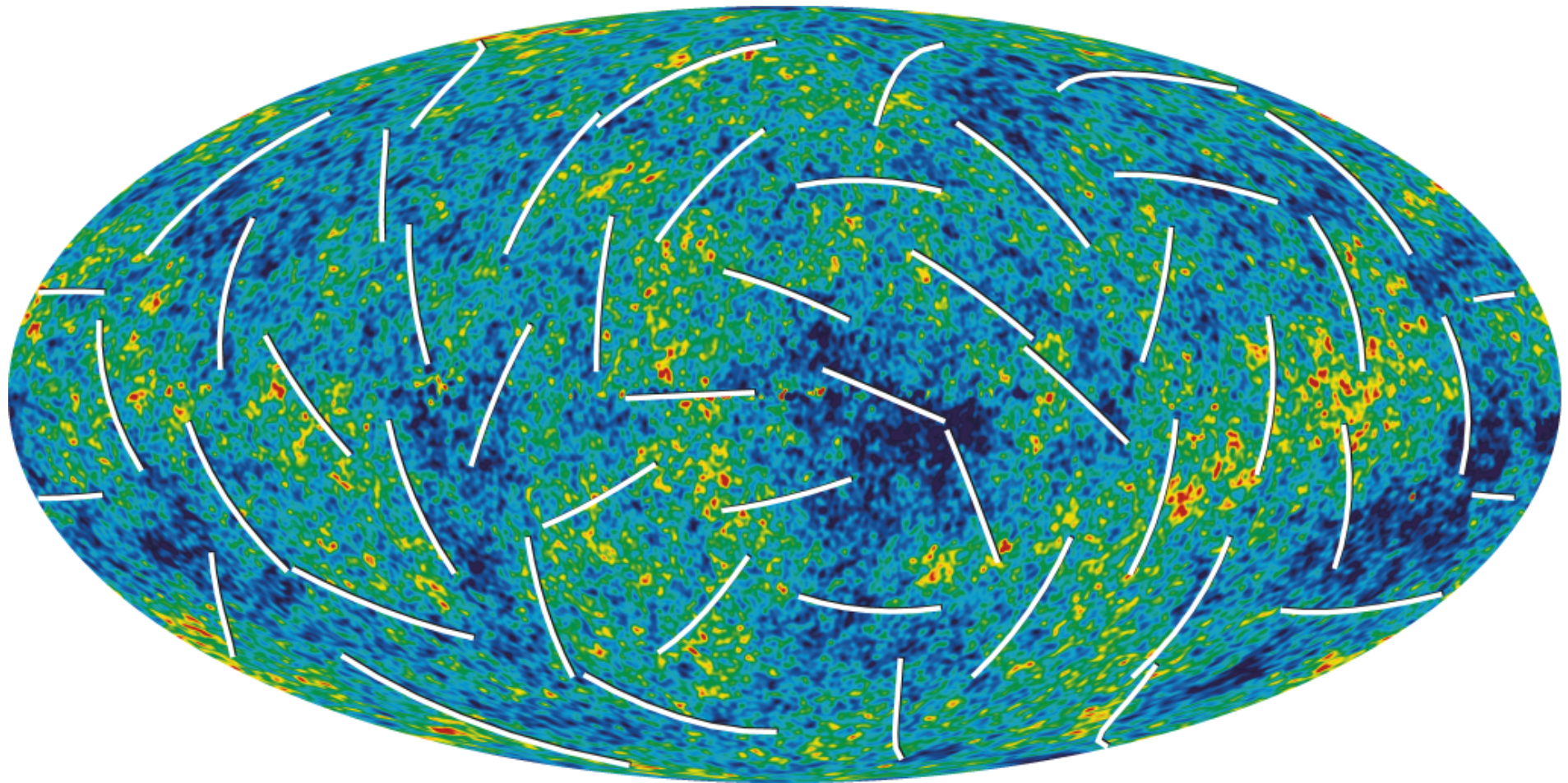
FIG. 4.— The SPT 150 GHz bandpowers (black circles), WMAP7 bandpowers (purple squares), ACBAR bandpowers (green triangles), QUaD bandpowers (cyan diamonds), and ACT 150 GHz bandpowers (orange circles) plotted against the best-fit lensed Λ CDM CMB spectrum. The damping tail of the primary CMB anisotropy 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.

TT power spectrum at high ℓ



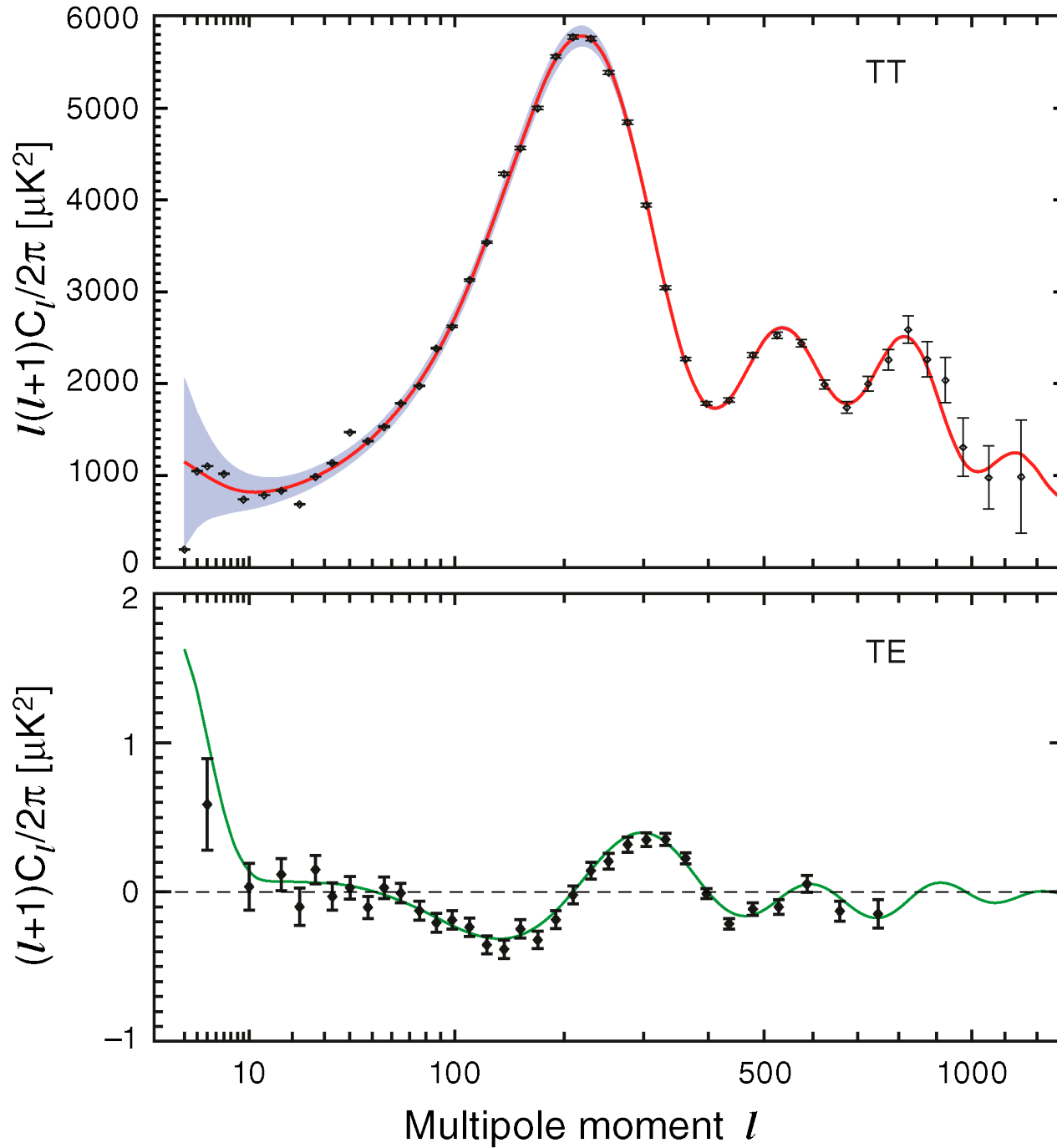
Keisler et al., 2011

polarized microwave sky

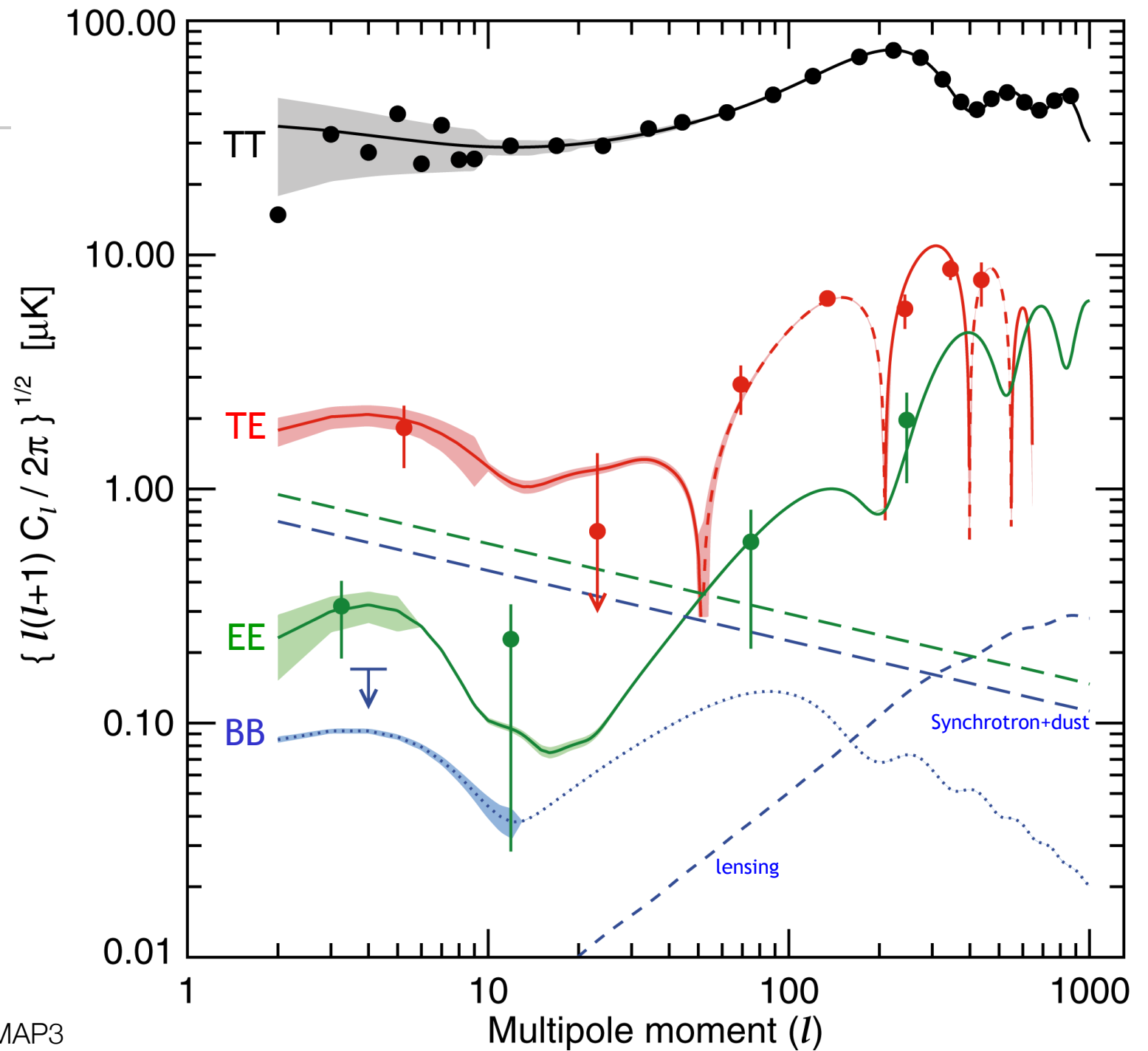


WMAP 3

TT & TE



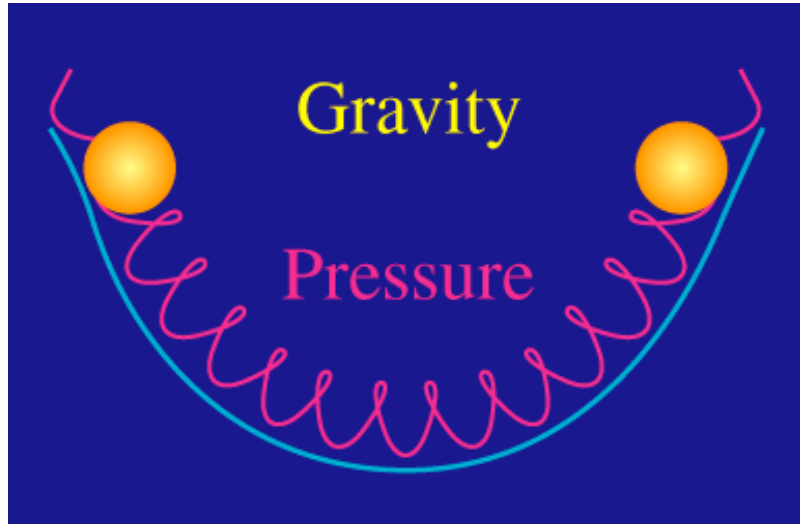
Jarosik et al., 2009, WMAP7



II. Observations of the Cosmic Microwave Background

4. C_l and Cosmological Parameters

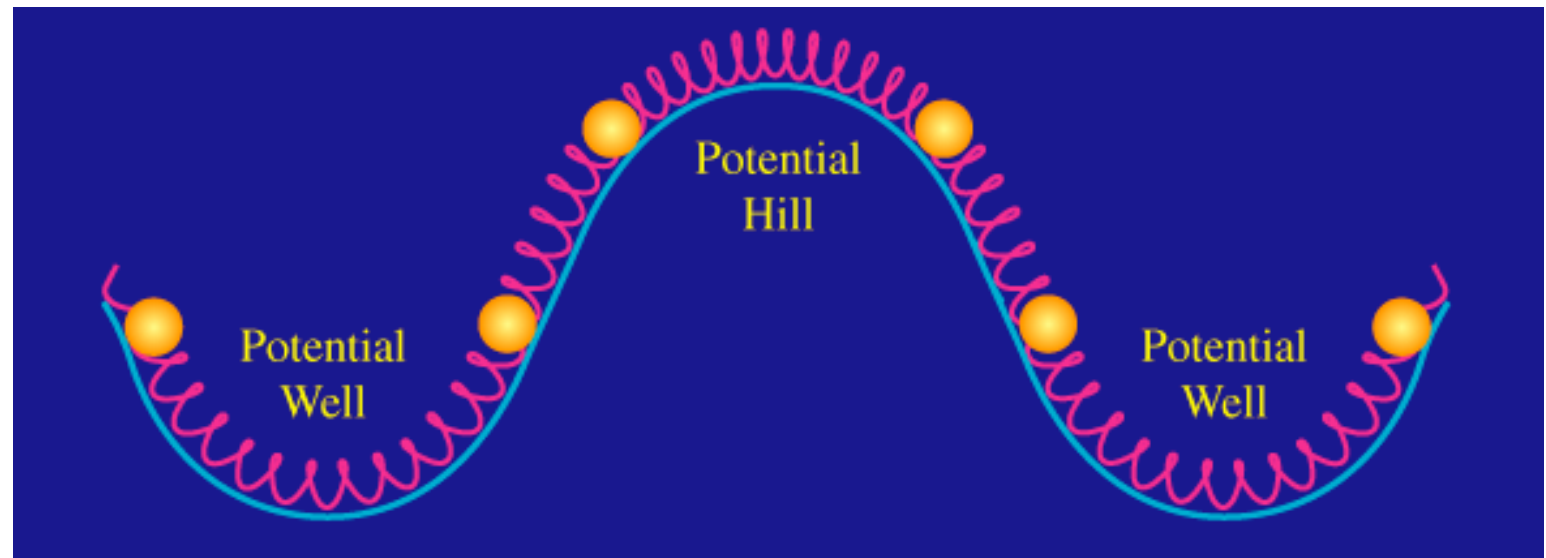
origine of fluctuations



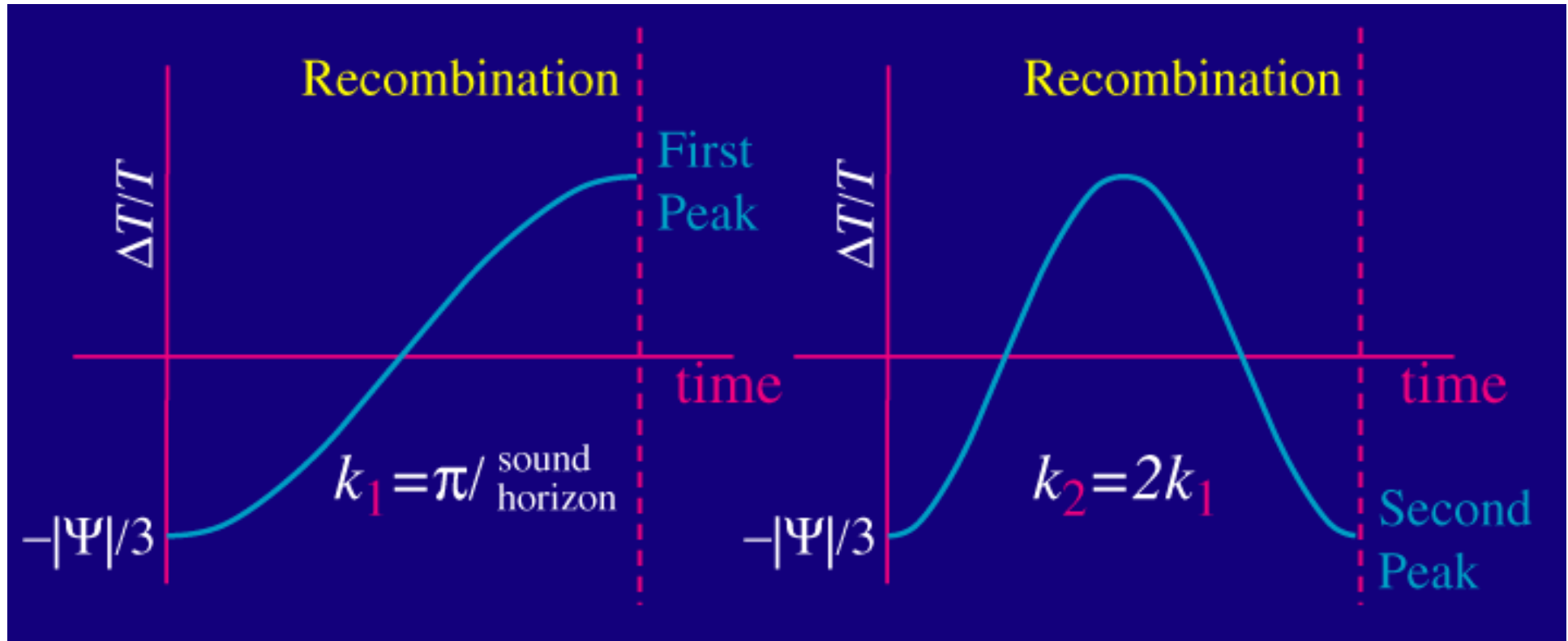
Matière => puits de potentiel

Puits de potentiel

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

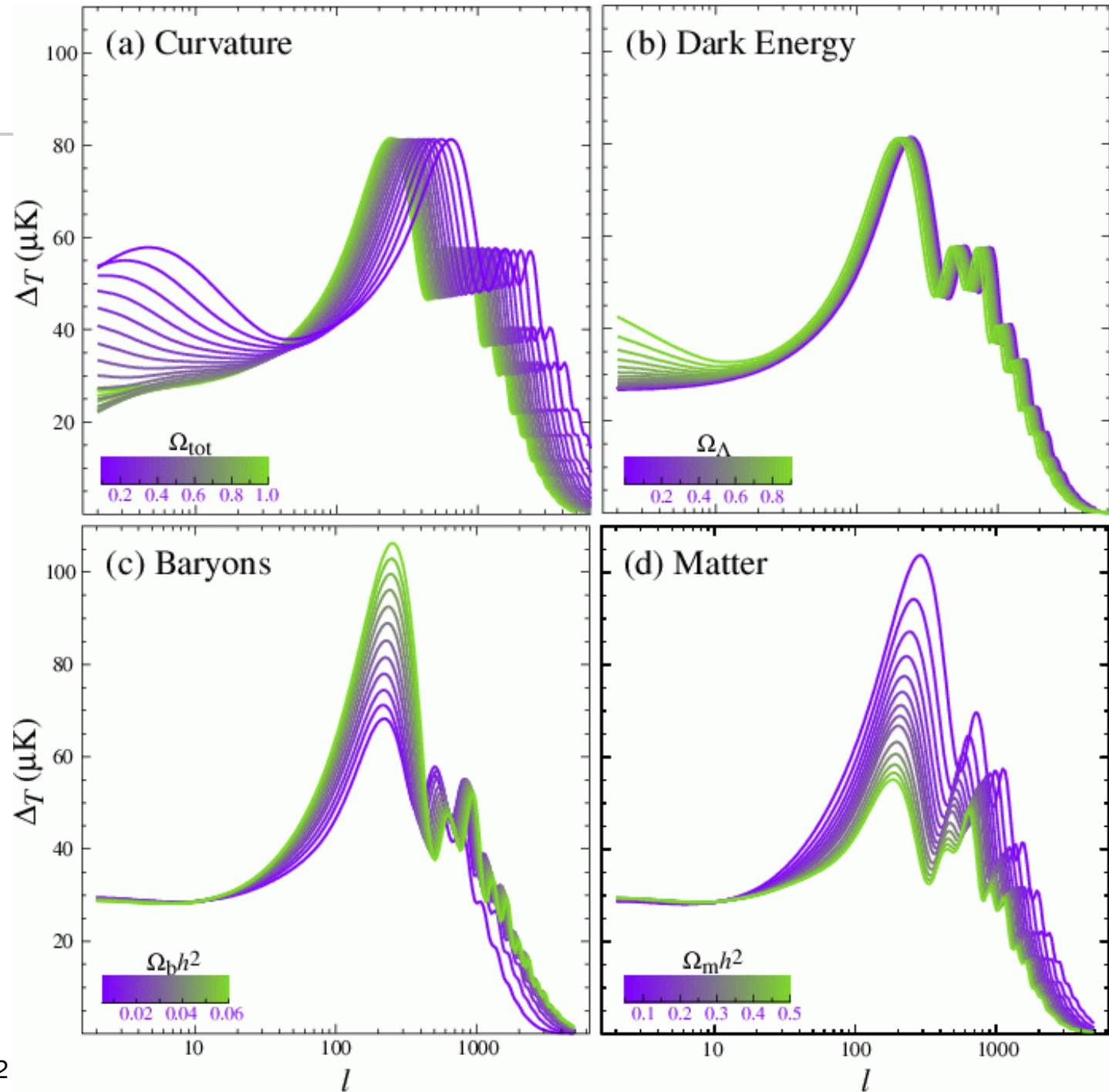


acoustic waves at recombination



La physique de ces ondes dépend des paramètres cosmologiques

C_l



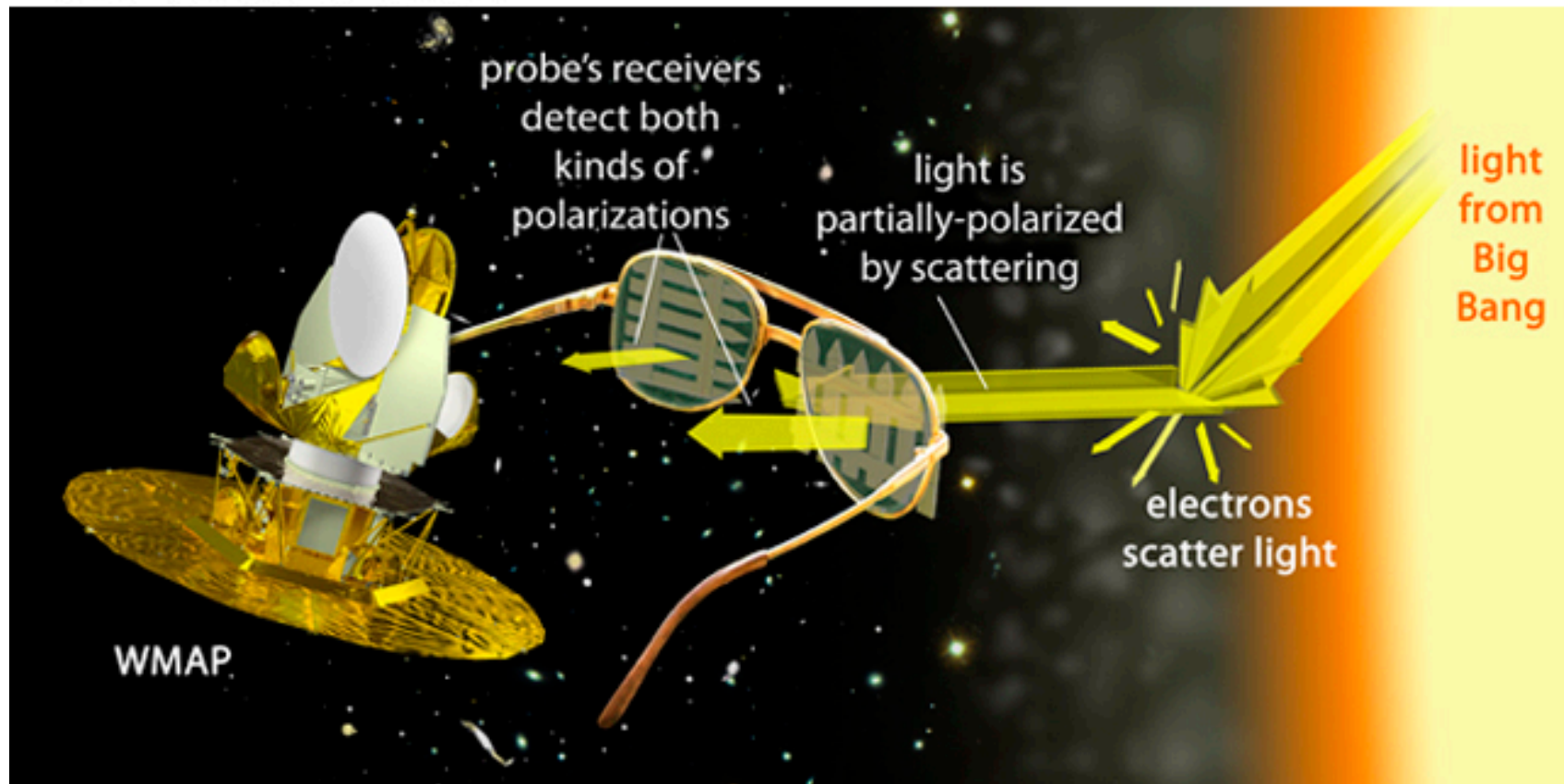
Hu & Dodelson, ARAA, 2002

II. Observations of the Cosmic Microwave Background

5. Polarization

CMB polarization for dummies

how WMAP sees it...

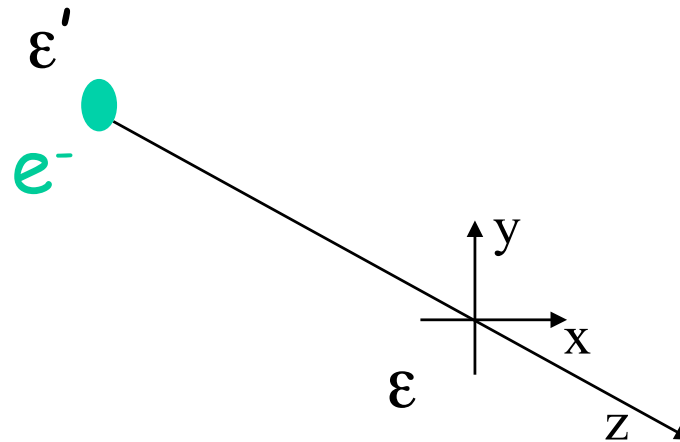


Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}'|^2$

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

Rayonnement isotrope
(monopole)

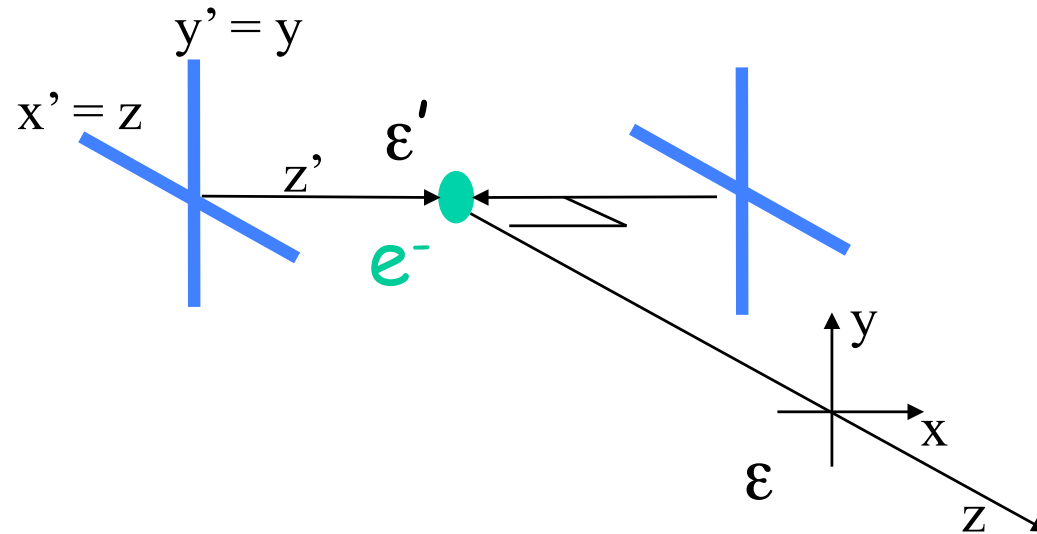


Courtesy N. Ponthieu, IAS

Recombination

$$\text{Diffusion Thomson : } d\sigma/d\Omega \sim |\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}'|^2$$

Rayonnement isotrope
(monopole)

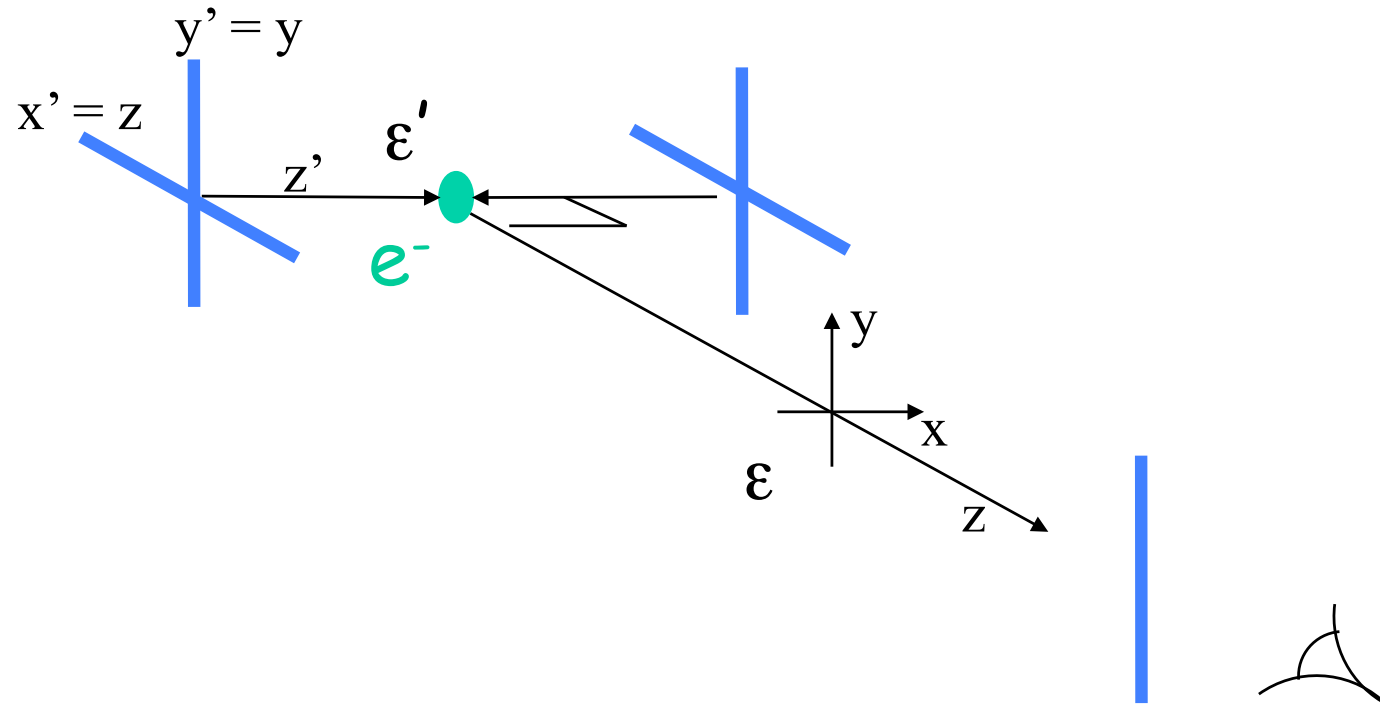


Courtesy N. Ponthieu, IAS

Recombination

$$\text{Diffusion Thomson : } d\sigma/d\Omega \sim |\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}'|^2$$

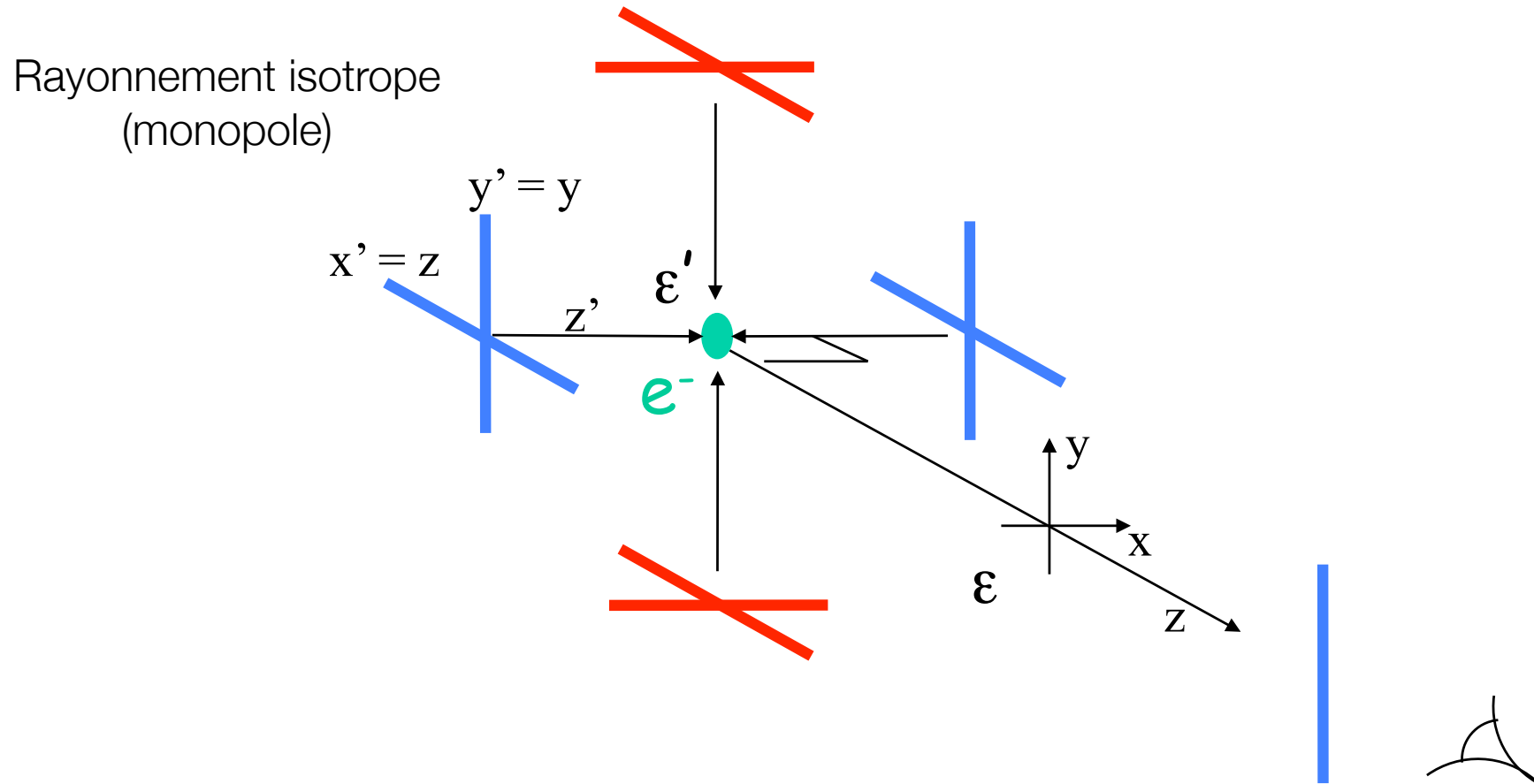
Rayonnement isotrope
(monopole)



Courtesy N. Ponthieu, IAS

Recombination

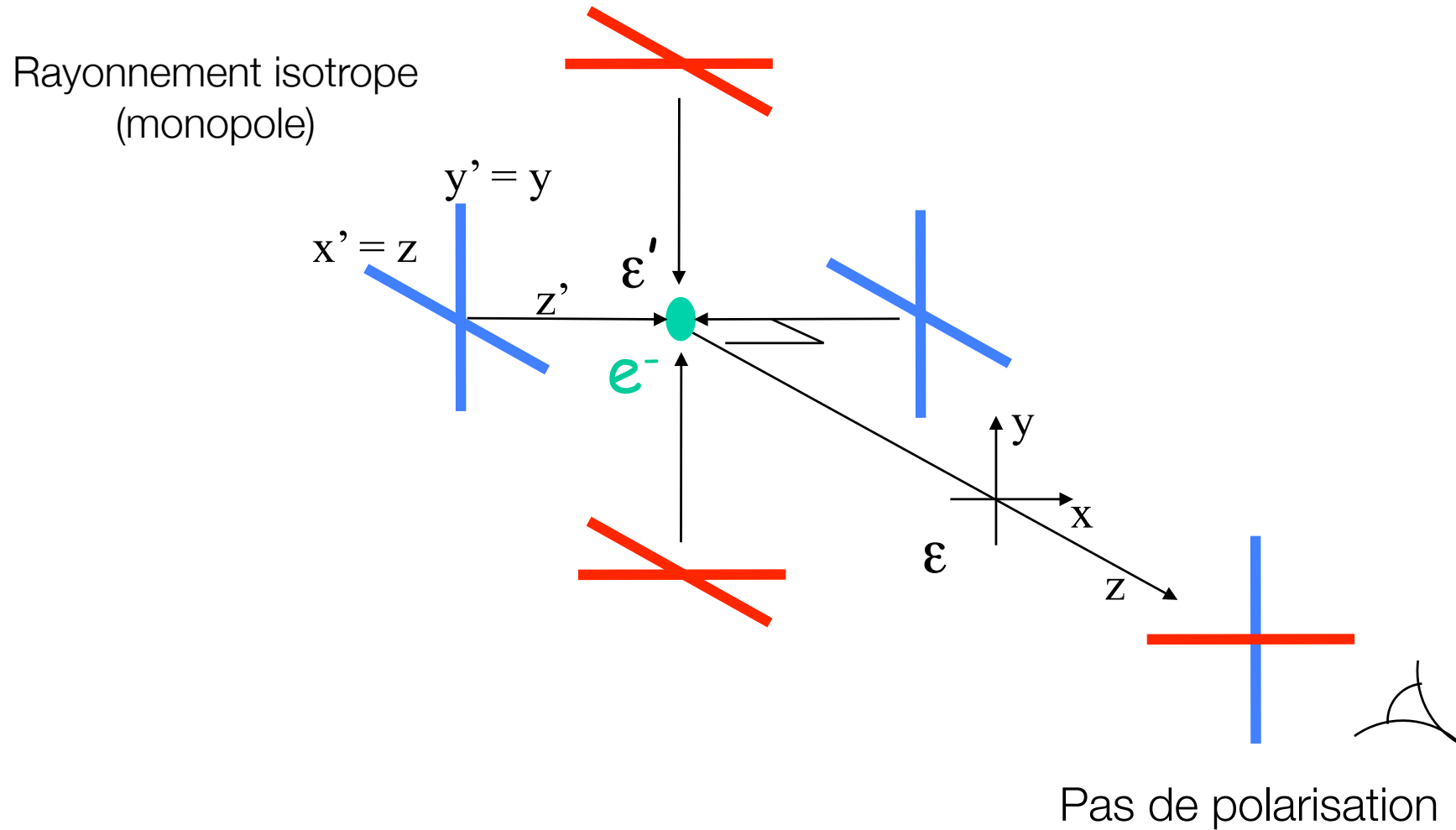
Diffusion Thomson : $d\sigma/d\Omega \sim |\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}'|^2$



Courtesy N. Ponthieu, IAS

Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\epsilon \cdot \epsilon'|^2$

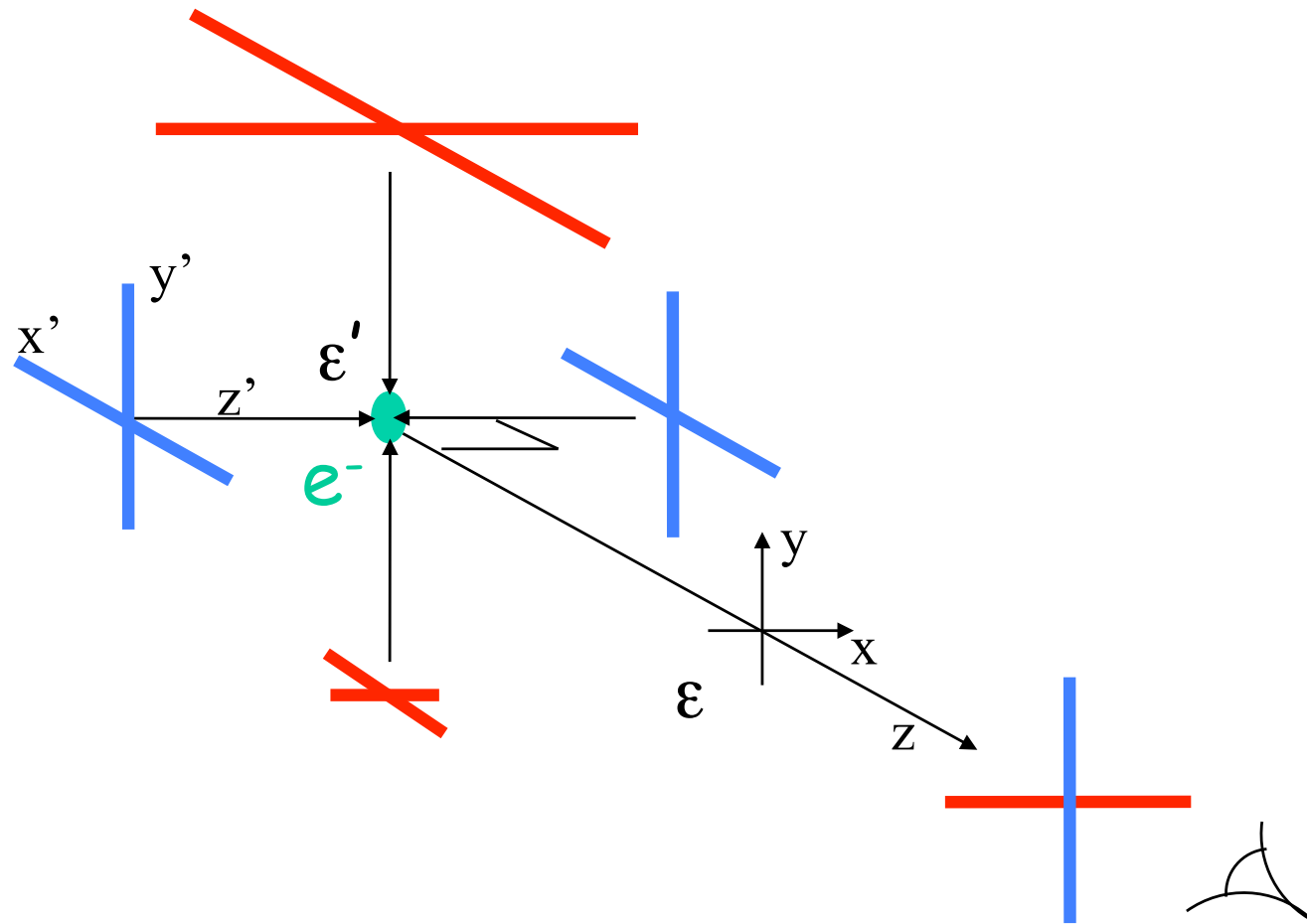


Courtesy N. Ponthieu, IAS

Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\epsilon \cdot \epsilon'|^2$

Dipole

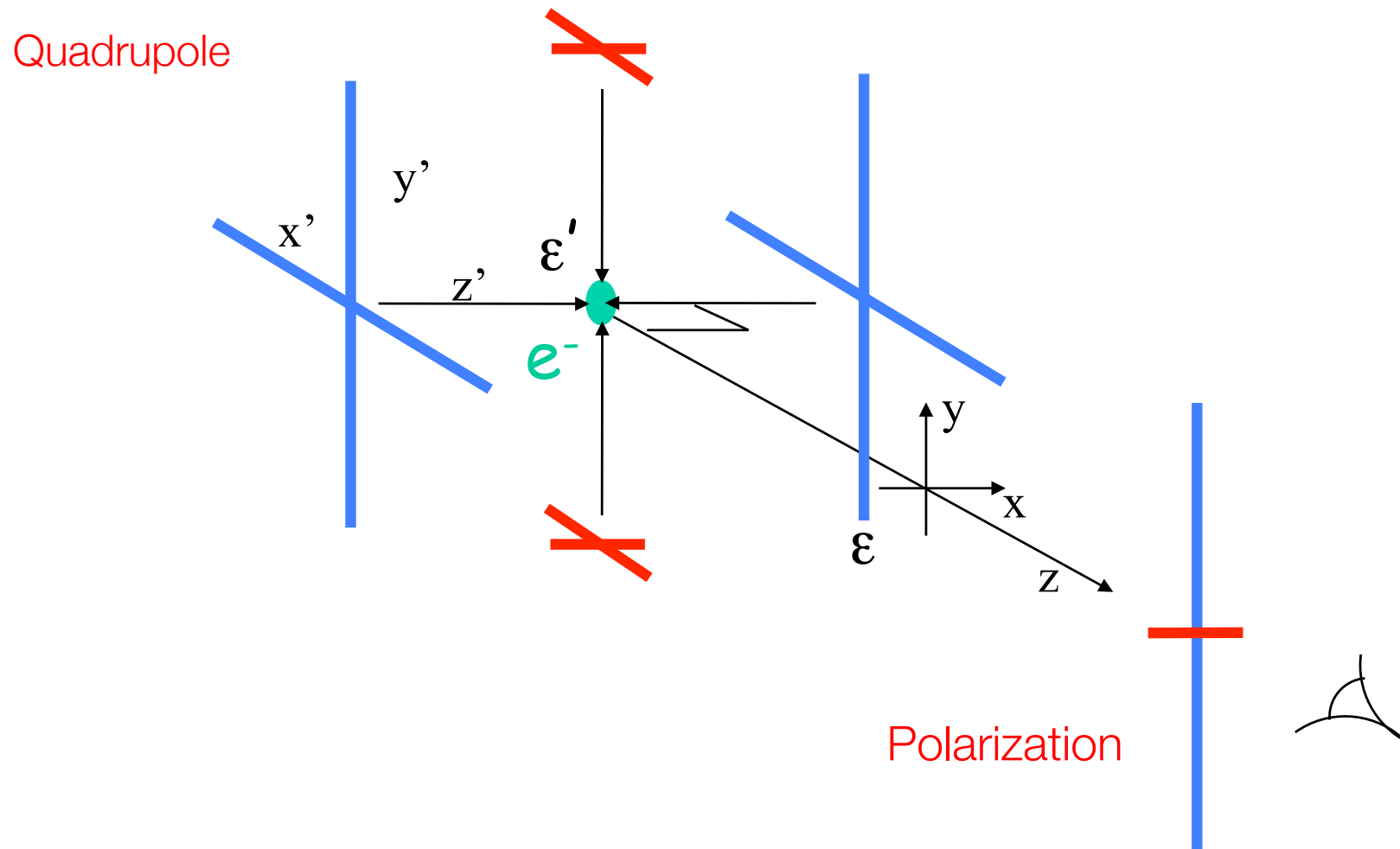


Pas de polarisation

Courtesy N. Ponthieu, IAS

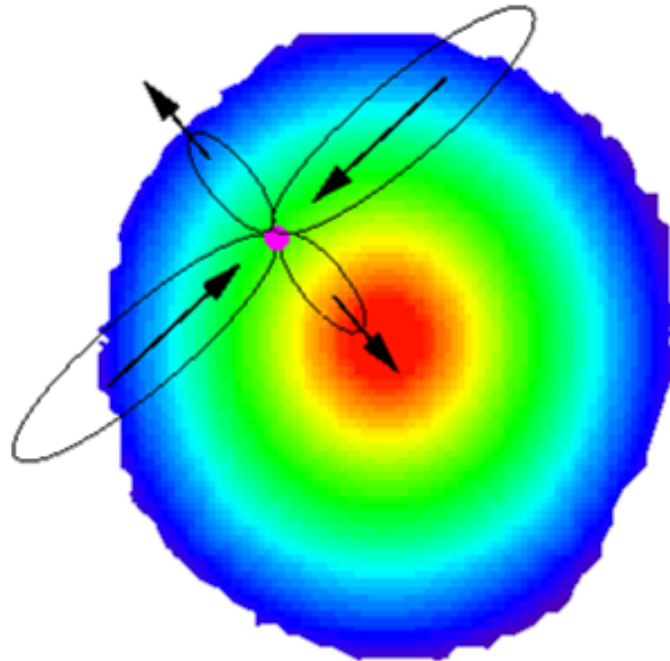
Recombination

Diffusion Thomson : $d\sigma/d\Omega \sim |\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}'|^2$



Courtesy N. Ponthieu, IAS

quadrupoles at recombination



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

On sonde directement la recombinaison

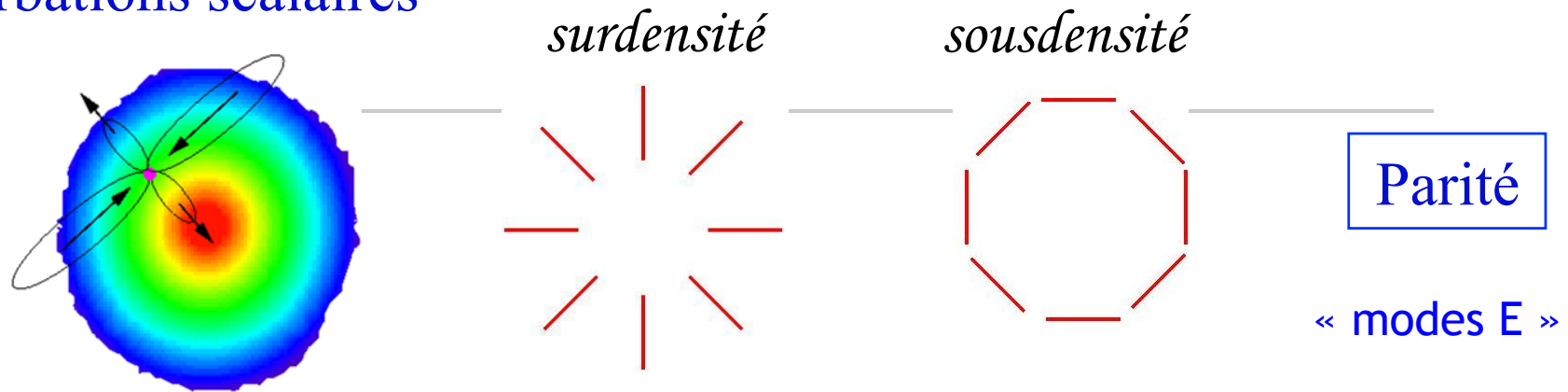
Over (under) densities generate polarization (speed)

Polarization: a direct probe of recombination processes

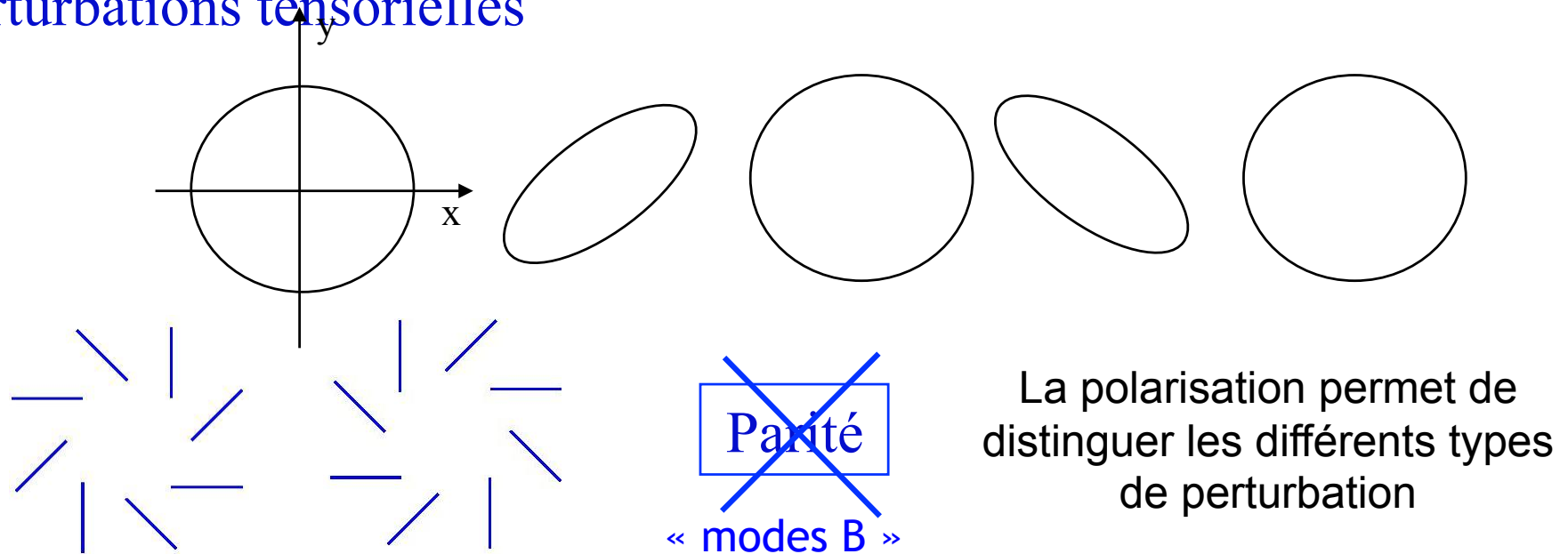
Rees, 1968

Courtesy N. Ponthieu, IAS

Perturbations scalaires

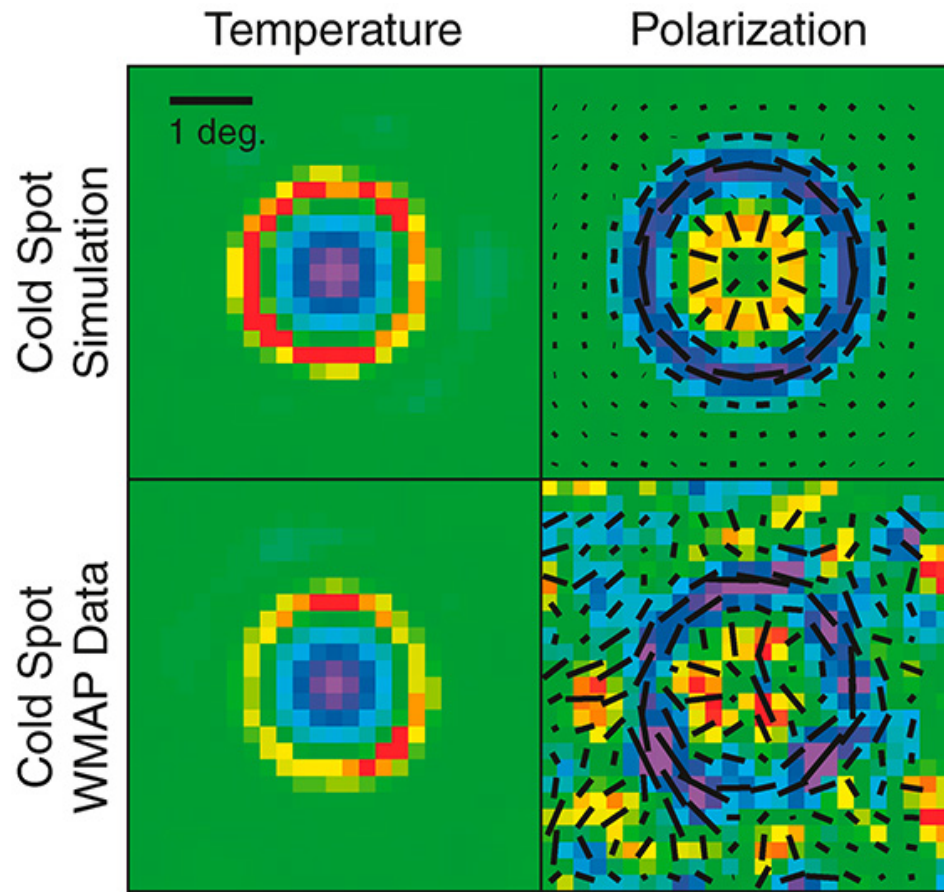


Perturbations tensorielles

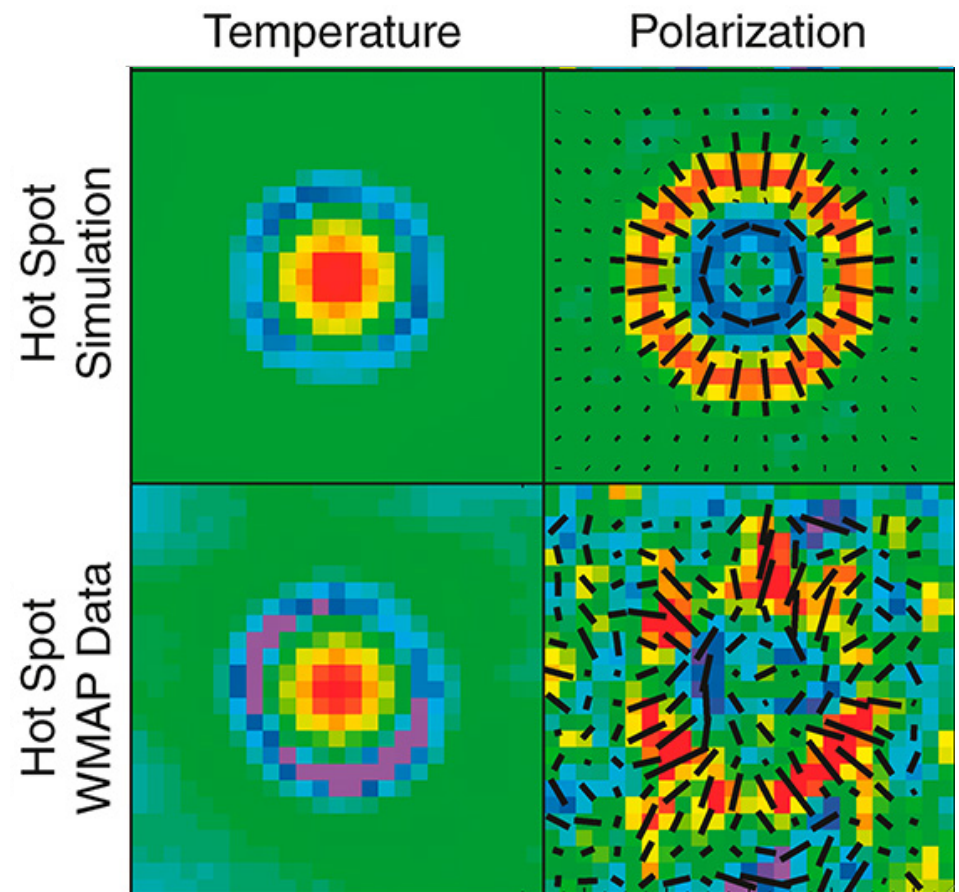


Première possibilité de détection des ondes gravitationnelles primordiales générées pendant la phase d'inflation

polarization data !



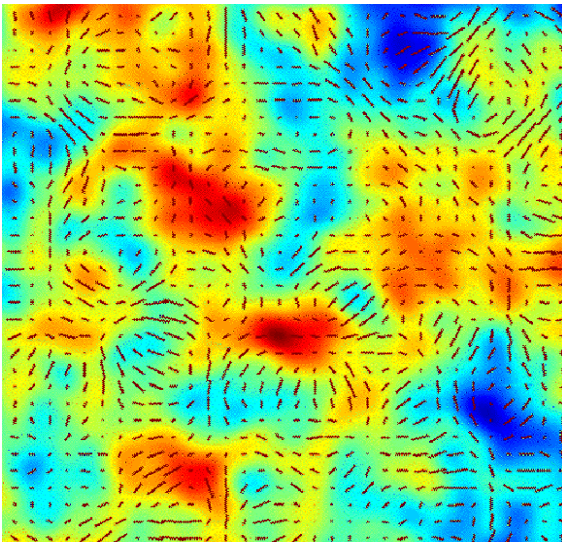
Planck data (embargoed) really look like the simulations !



WMAP7 Komatsu et al., 2009

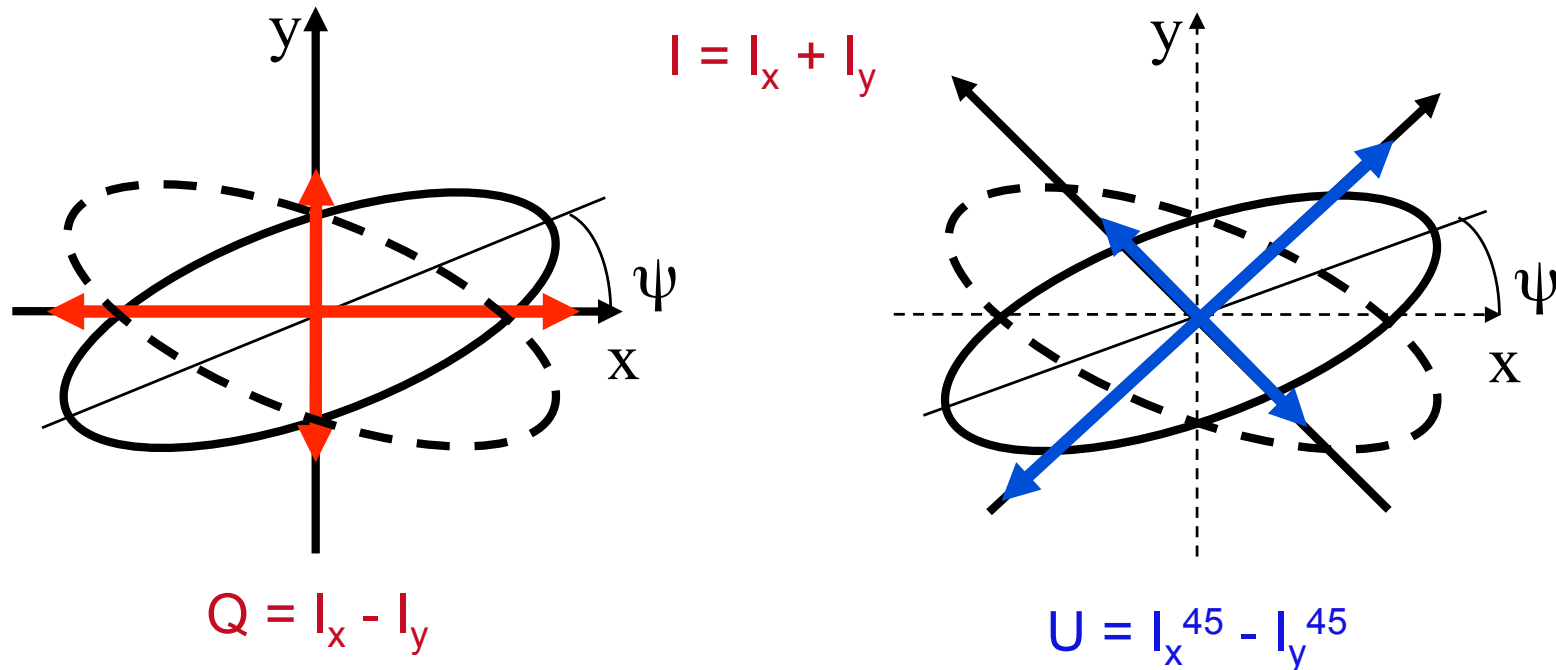
polarisation: bilan

- ✓ 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



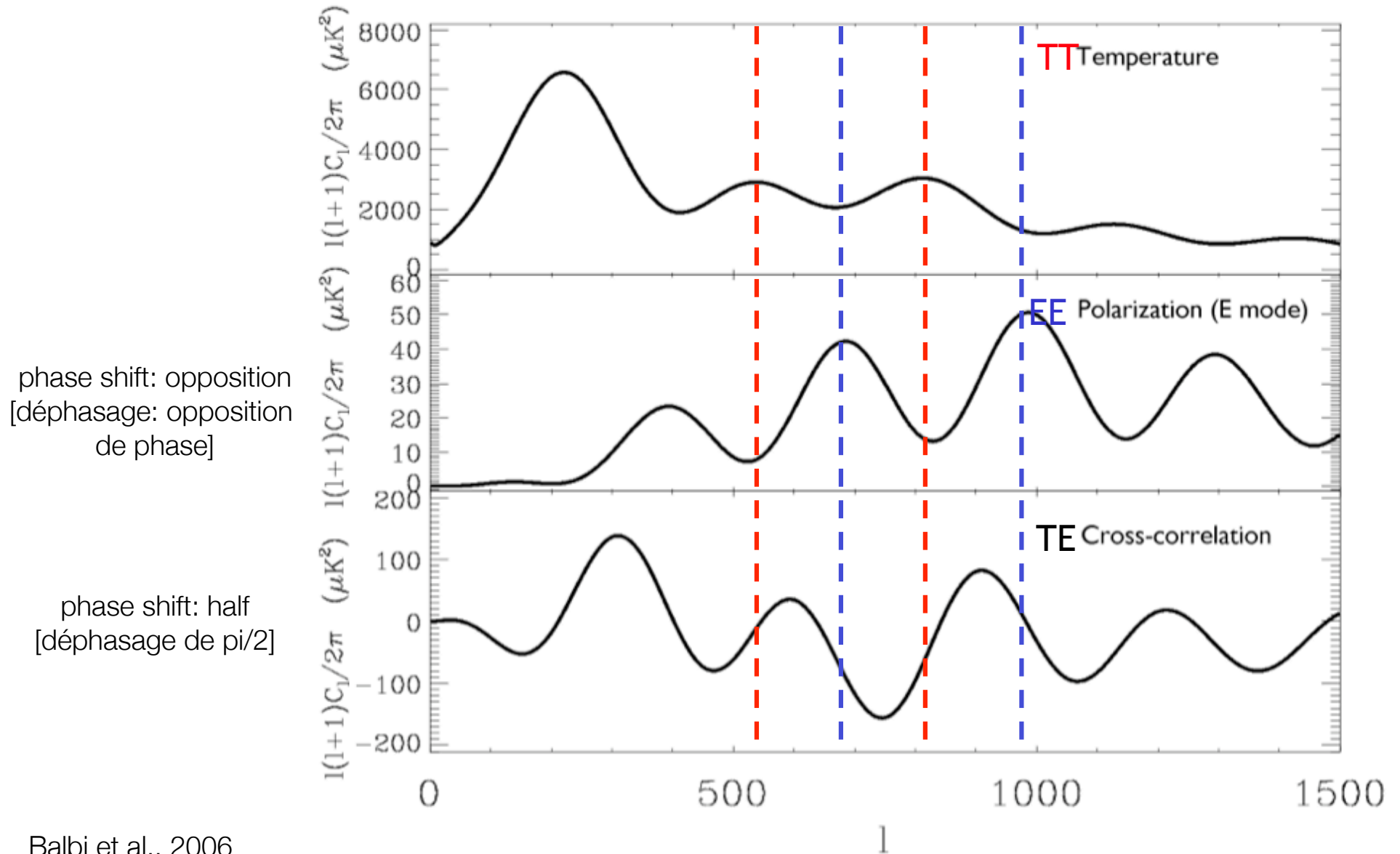
Spectre de puissance et physique...

les paramètres de Stokes



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

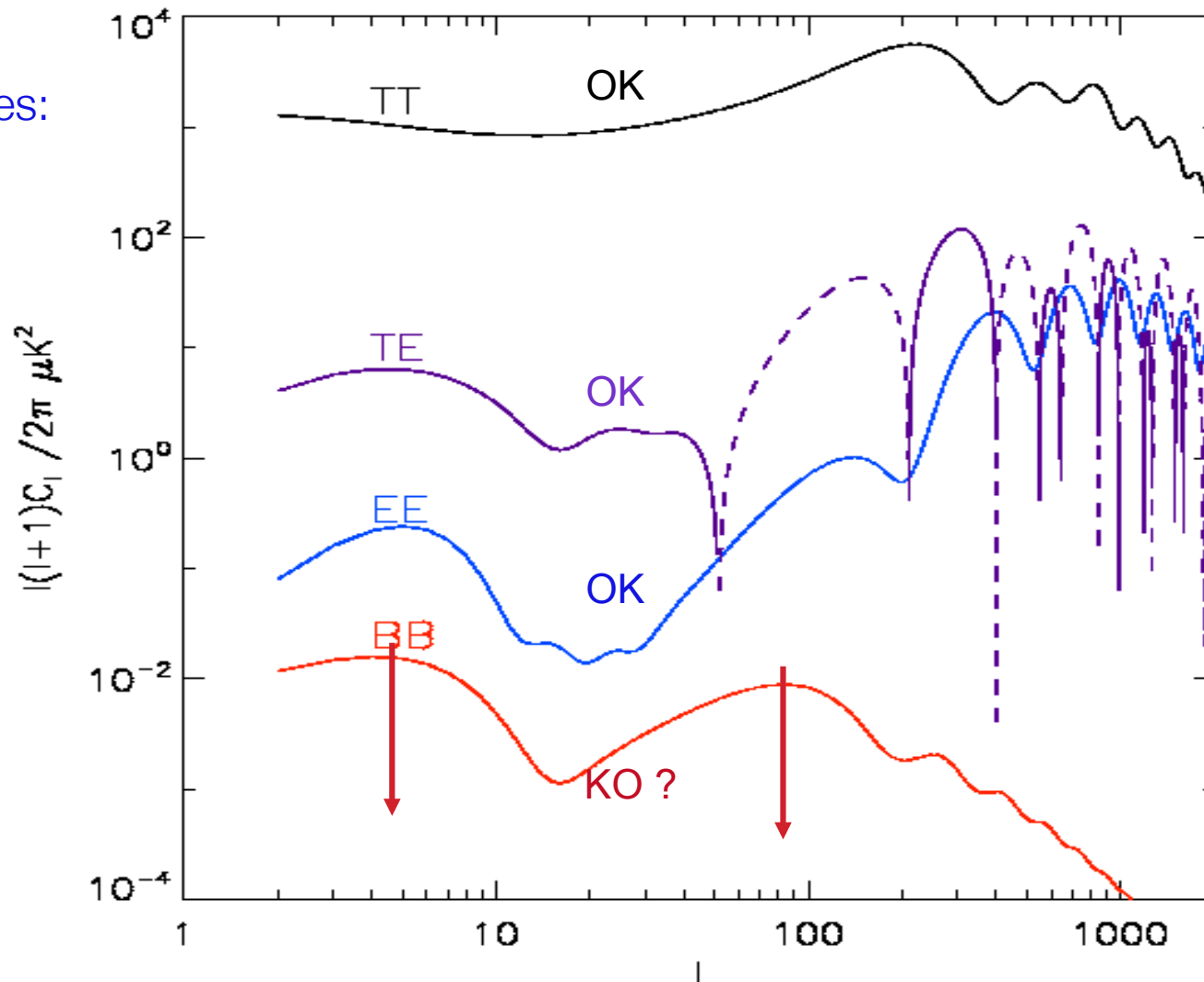
TT, EE, TE: behaviour



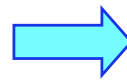
Balbi et al., 2006

4 CMB anisotropies power spectra

3 observables:
T, E, B

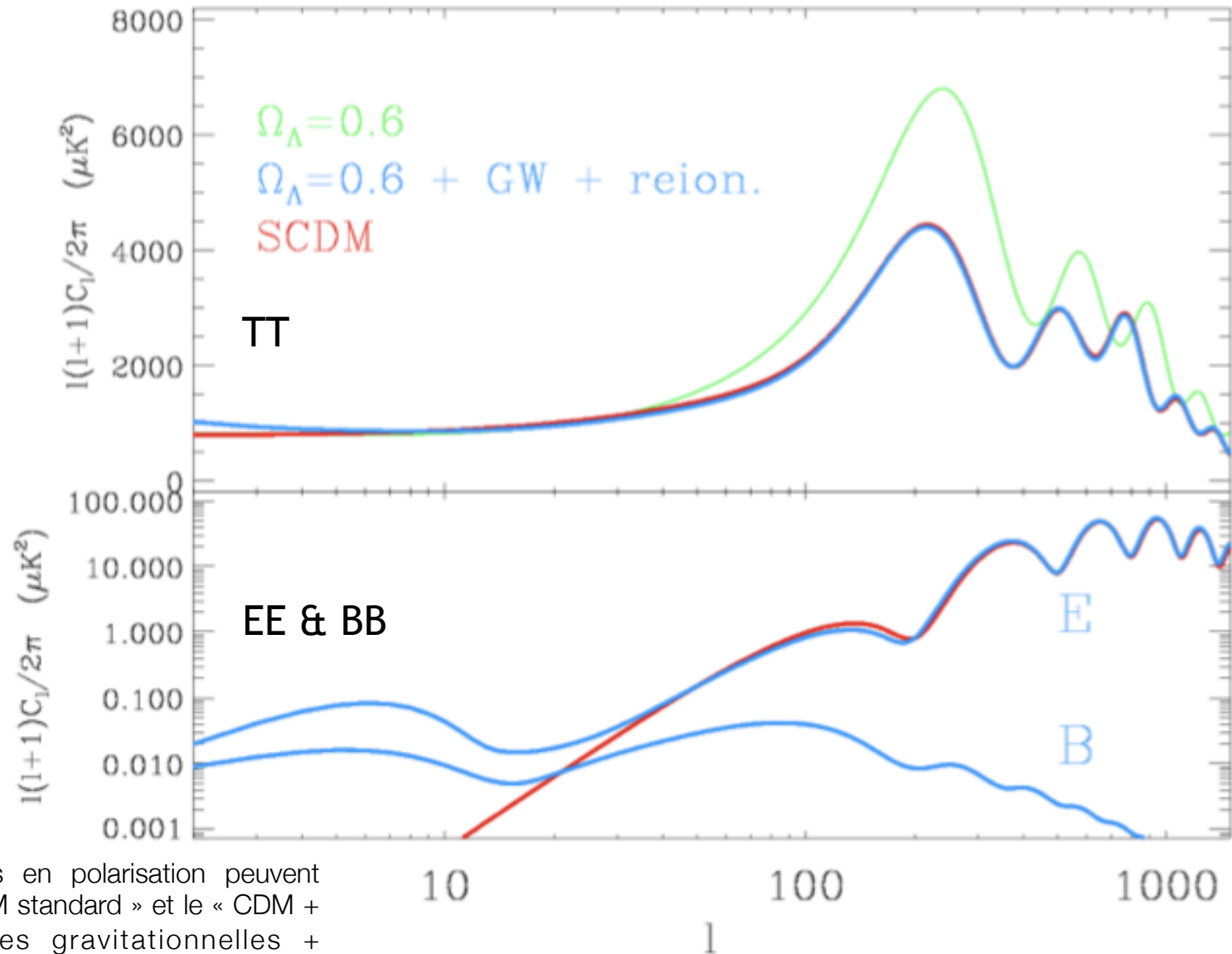


T, E : scalaire
B : pseudo-scalaire



TB, EB = 0

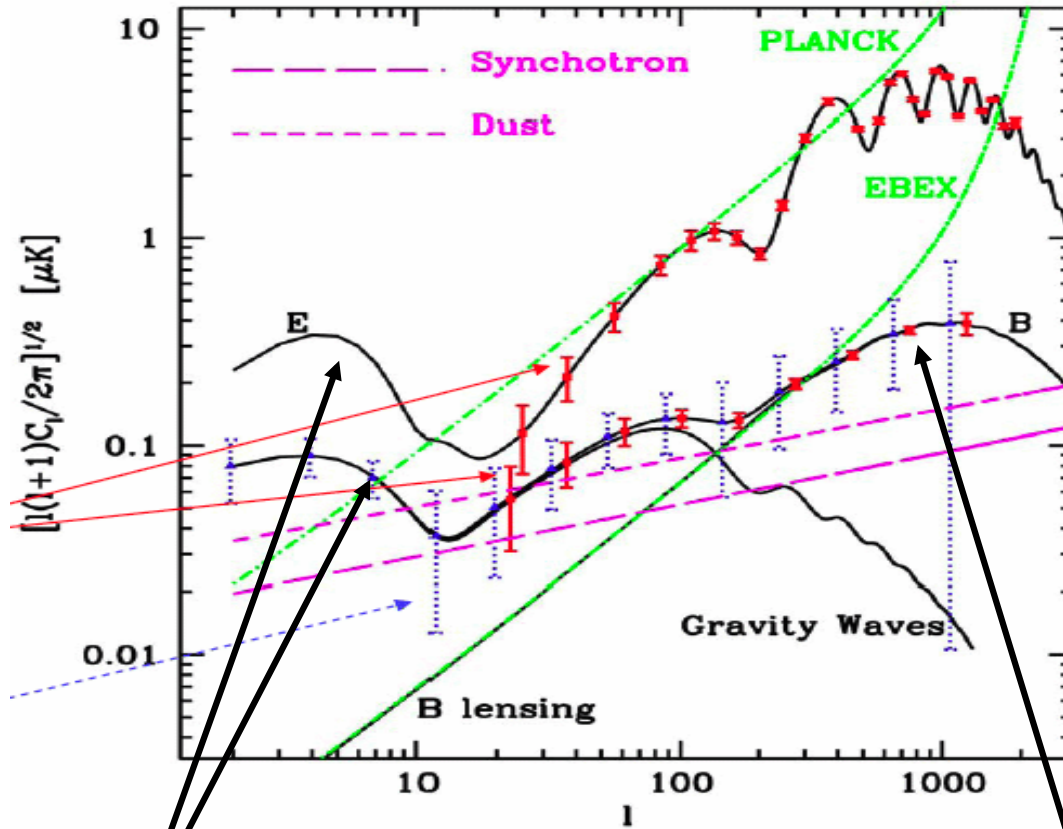
why polarization helps



Balbi et al., 2006

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

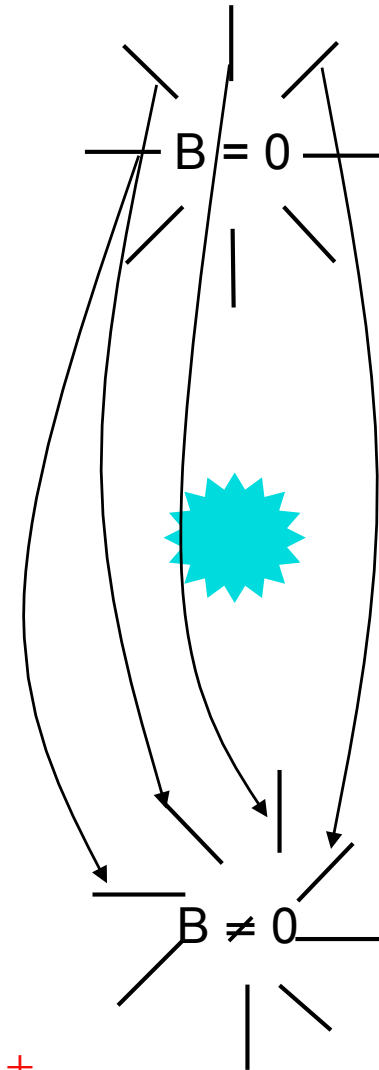
anisotropies secondaires



2^{ème} diffusion
Thomson lors de la
Réionisation

Distorsion par effet de
lentilles faibles

**Dark Energy + Neutrinos +
Large Scale Structures**



nos résultats WMAP5

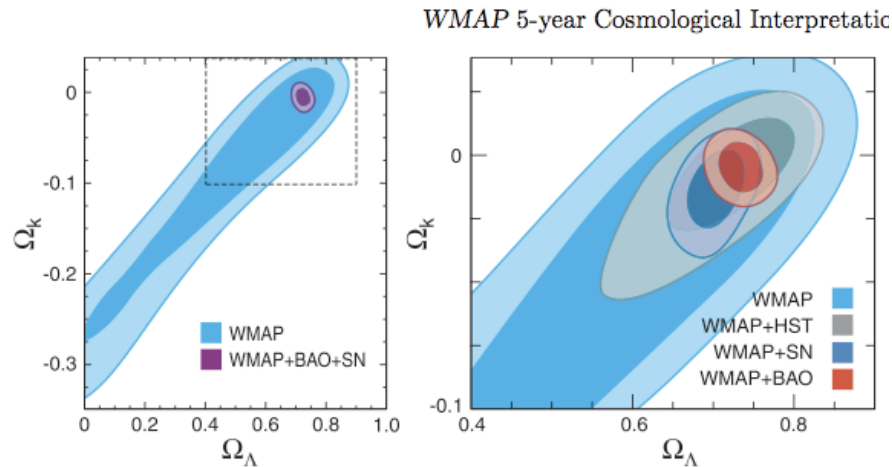
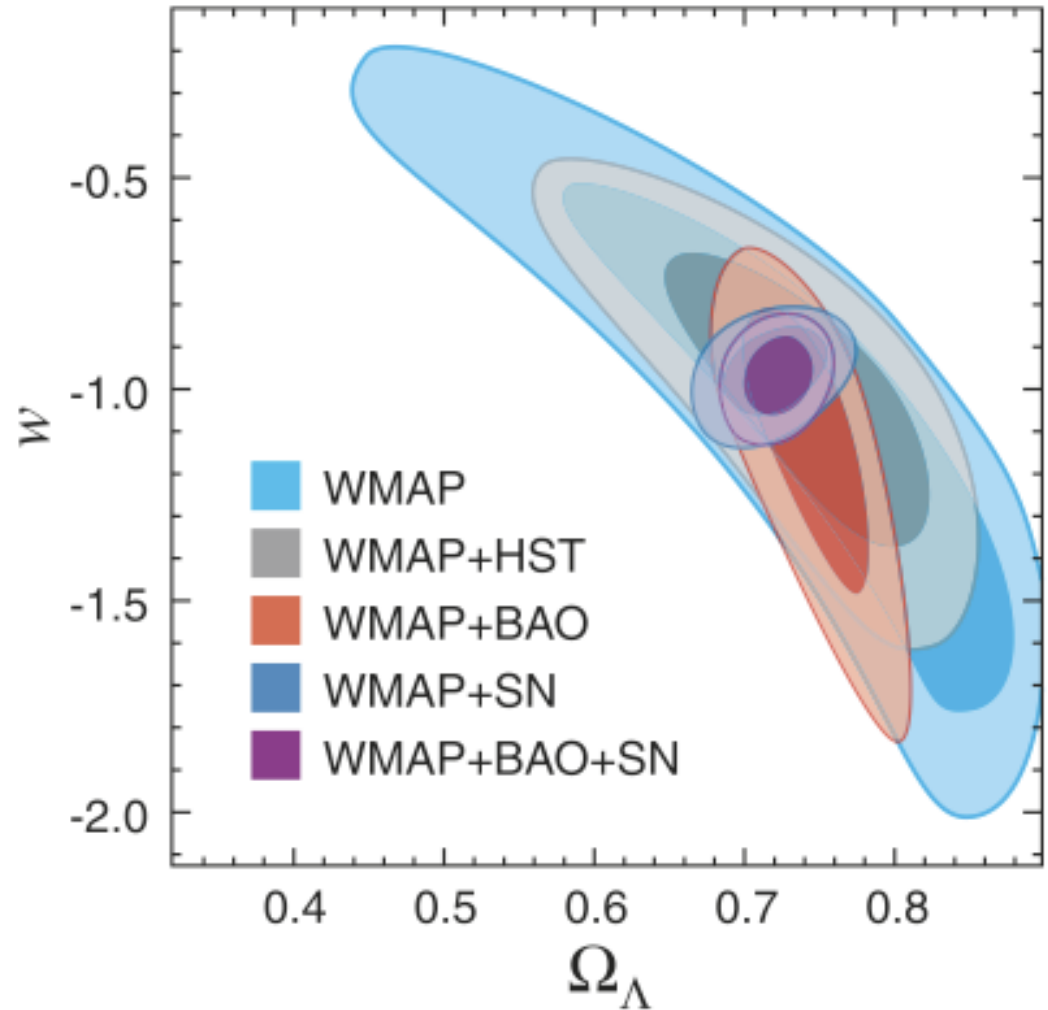
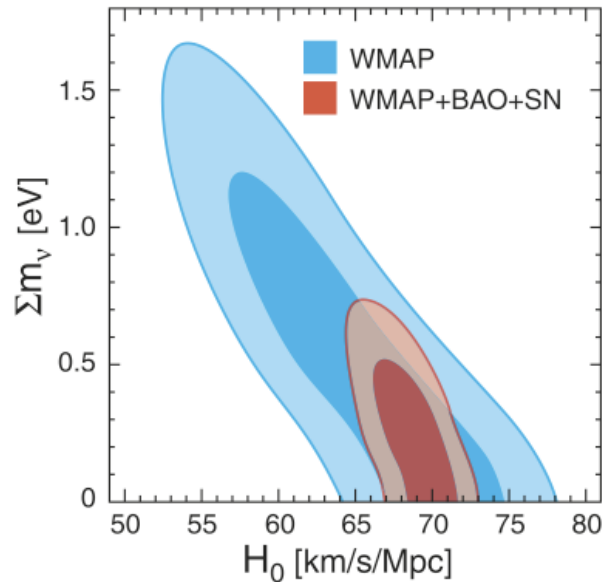


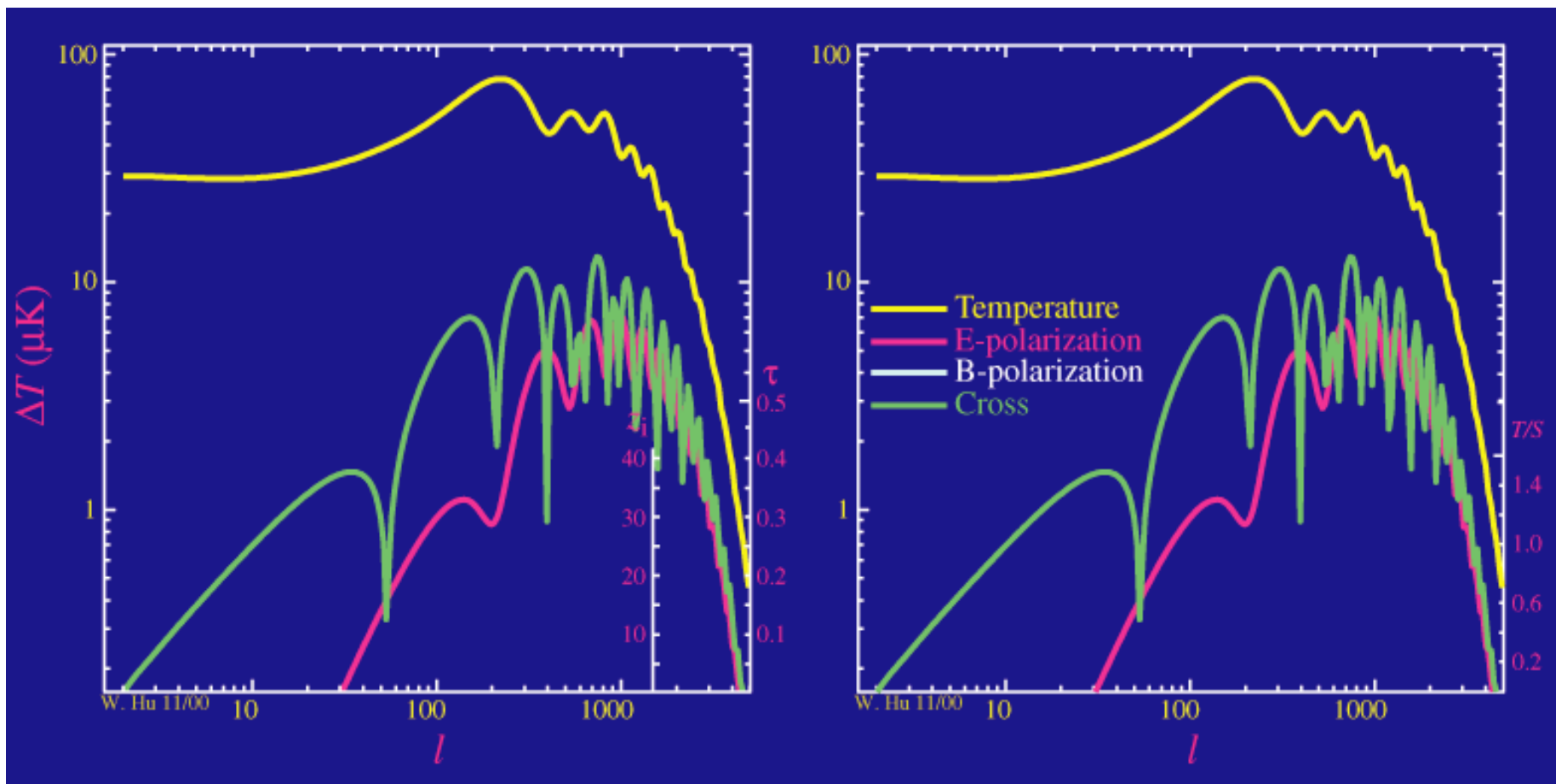
FIG. 6.— Joint two-dimensional marginalized constraint on the vacuum energy density, Ω_Λ (see §3.4.3). The contours show the 68% and 95% CL. (Left) The WMAP-only constraint (light blue). Note that we have a prior on Ω_Λ , $\Omega_\Lambda > 0$. This figure shows how powerful the extra distance measurements are. (Right) A blow-up of the region within the dashed lines in the left panel, showing WMAP-only (light blue) and WMAP+BAO+SN (dark purple) constraints. We find the best fit $\Omega_\Lambda \approx 0.7$, $\Omega_k \approx -0.05$. See Fig. 12 for the constraints on 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

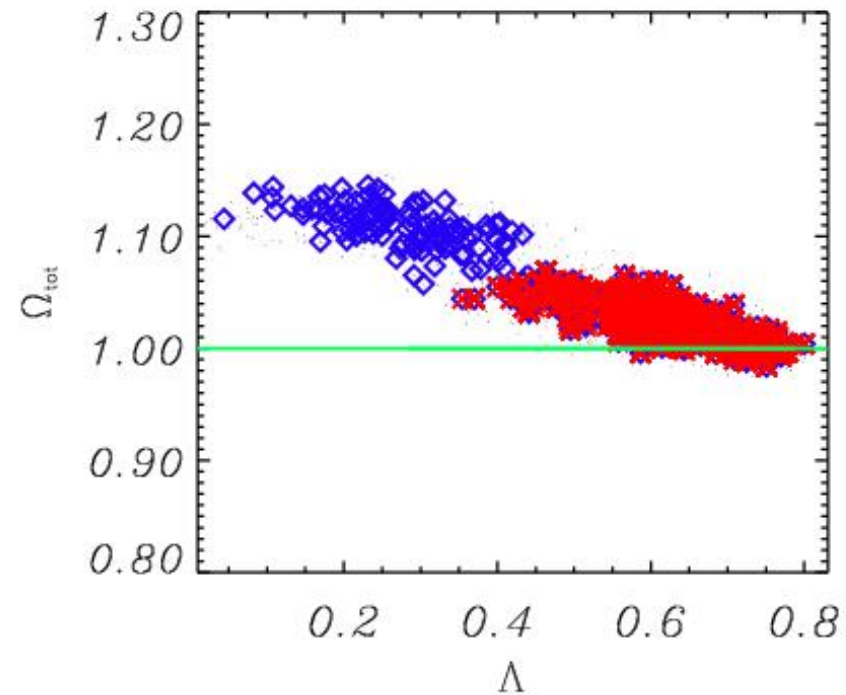
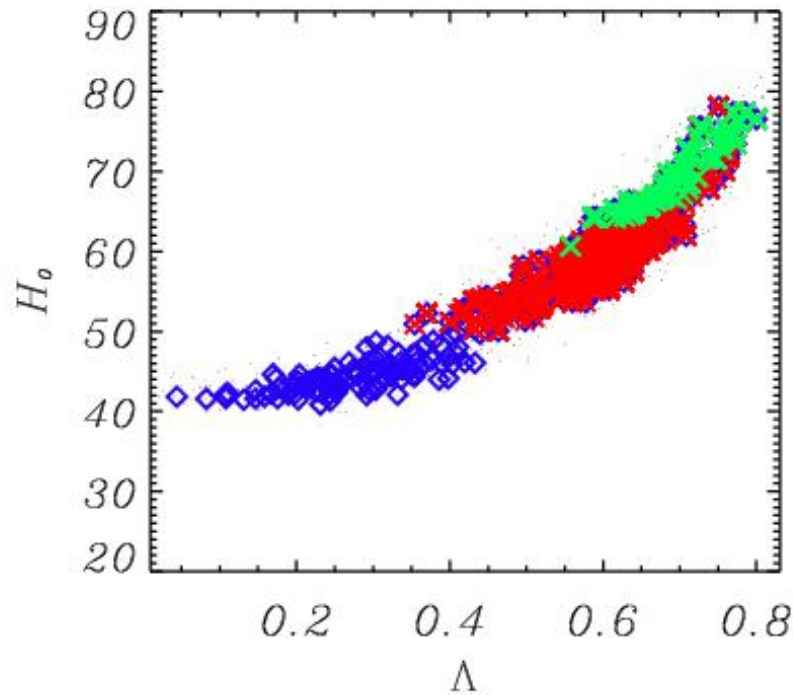
II. Observations of the Cosmic Microwave Background

6. Degeneracies

1. Dégénérescence « essentielle »

From CMB physics

$\Omega h^2, H_0, \Lambda$



$\Omega_{\text{tot}} = 1$ "fixes" H_0 and Λ (cf. WMAP)

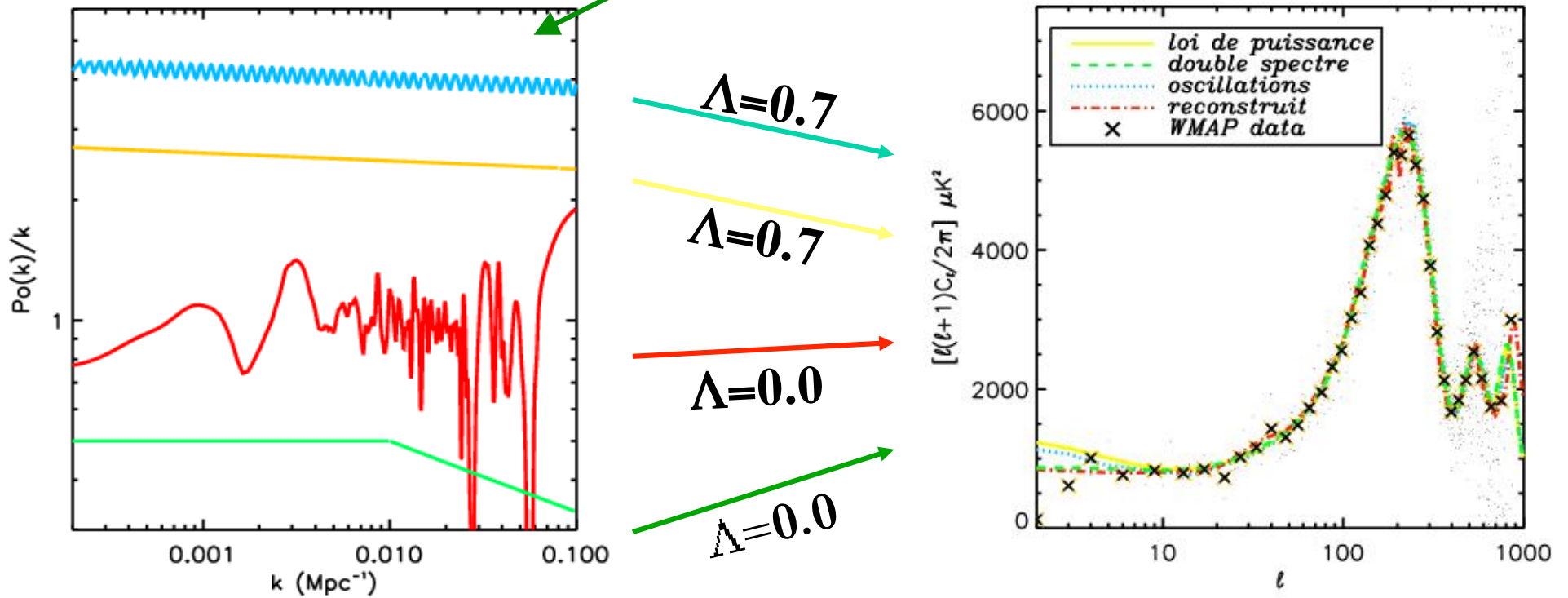
(MCMC with WMAP)

Courtesy M. Douspis, IAS

1. Dégénérescence « essentielle »

From CMB physics Initial conditions versus Evolution

$$C_l \propto \int P_0(k) \Delta^2(k, l) dk$$

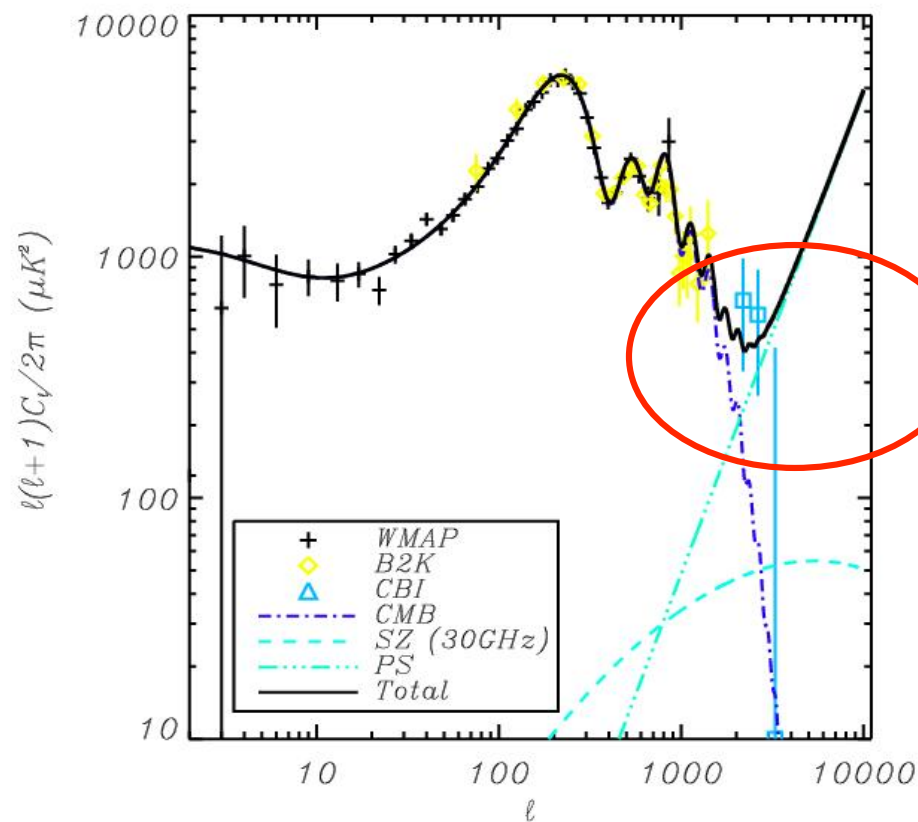


Courtesy M. Douspis, IAS

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

2. Dégénérescence « intégrale »

From additional physics Secondaries and Foregrounds



**Power excess
@ small scales
compared to
primary CMB**

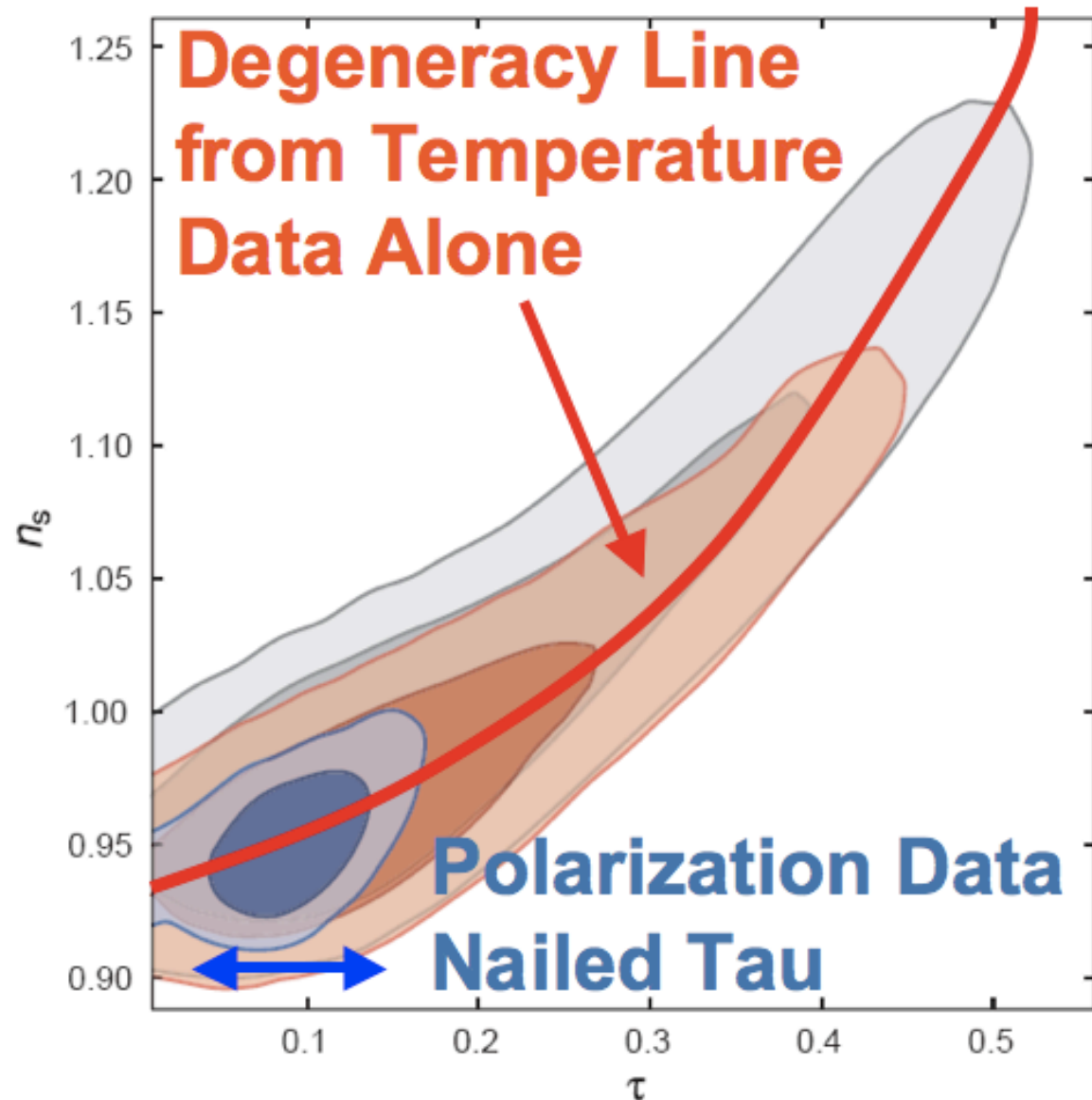
Courtesy M. Douspis, IAS

Douspis, Aghanim & Langer 06

2. Dégénérescence « intégrale »

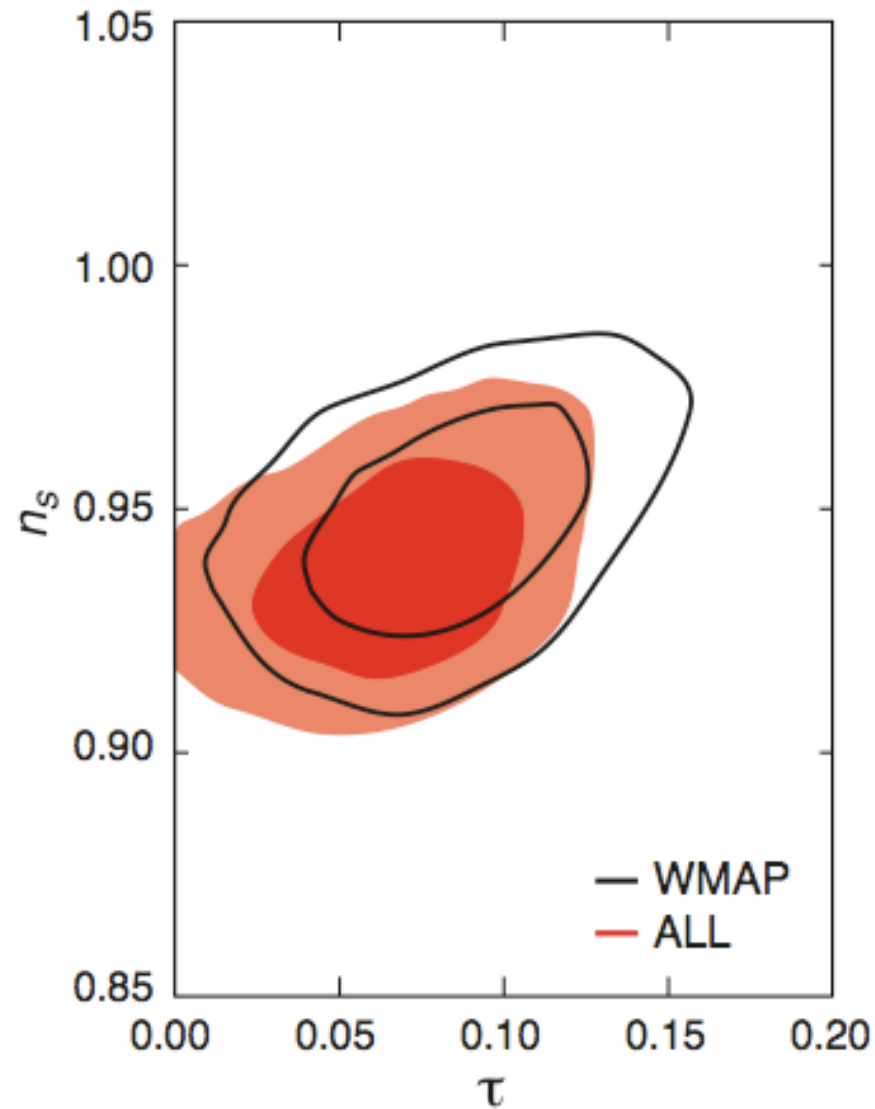
τ : Profondeur optique

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



Spergel et al., 2007, WMAP3

2. Dégénérescence « intégrale »



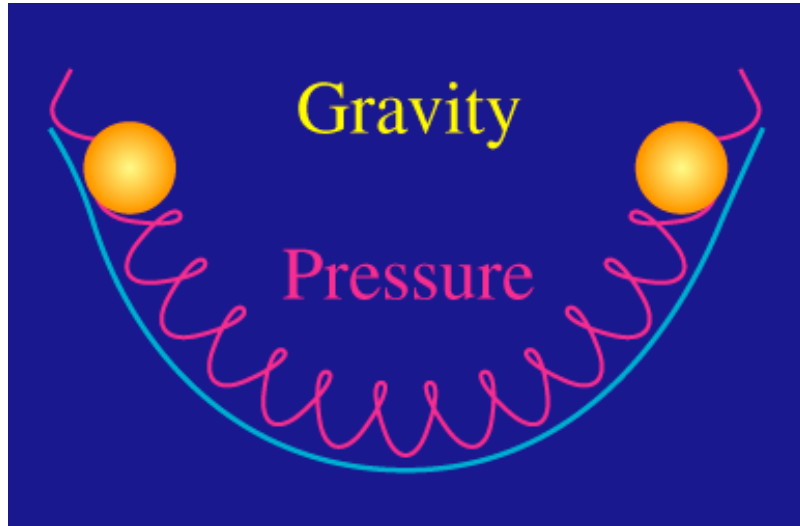
Spergel et al., 2007, in press WMAP3

3. Dégénérescence «instrumentale»

II. Observations of the Cosmic Microwave Background

7. Origin of fluctuations

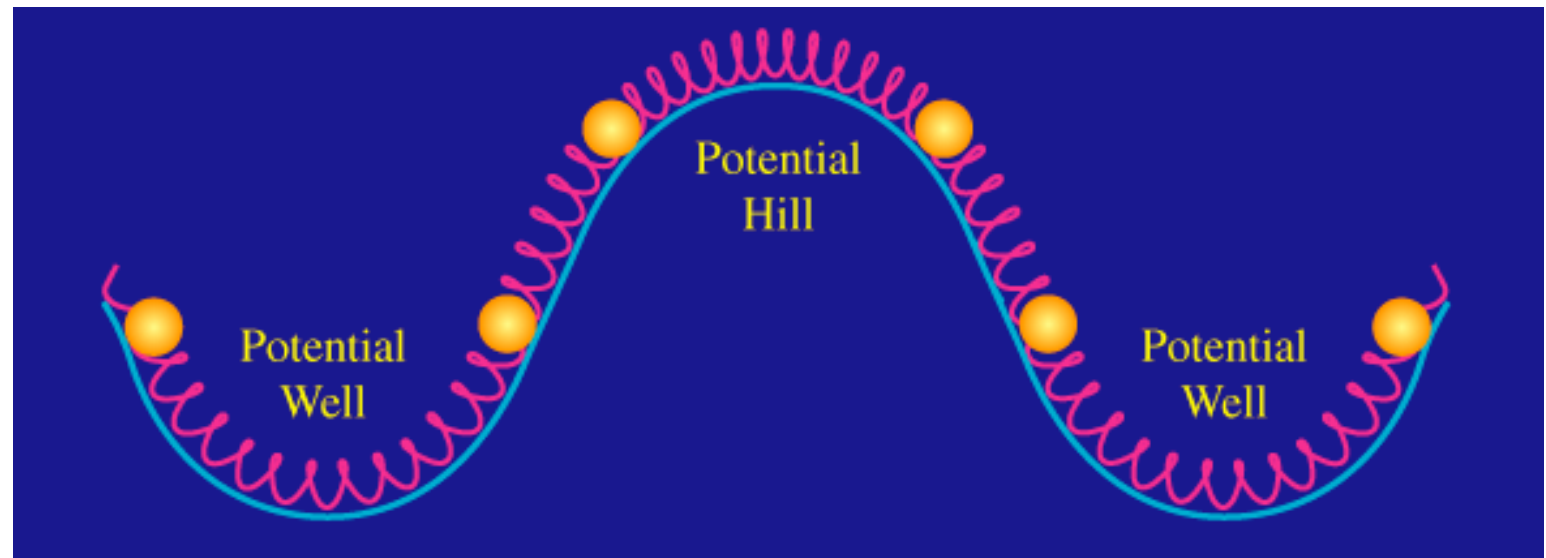
origine des fluctuations



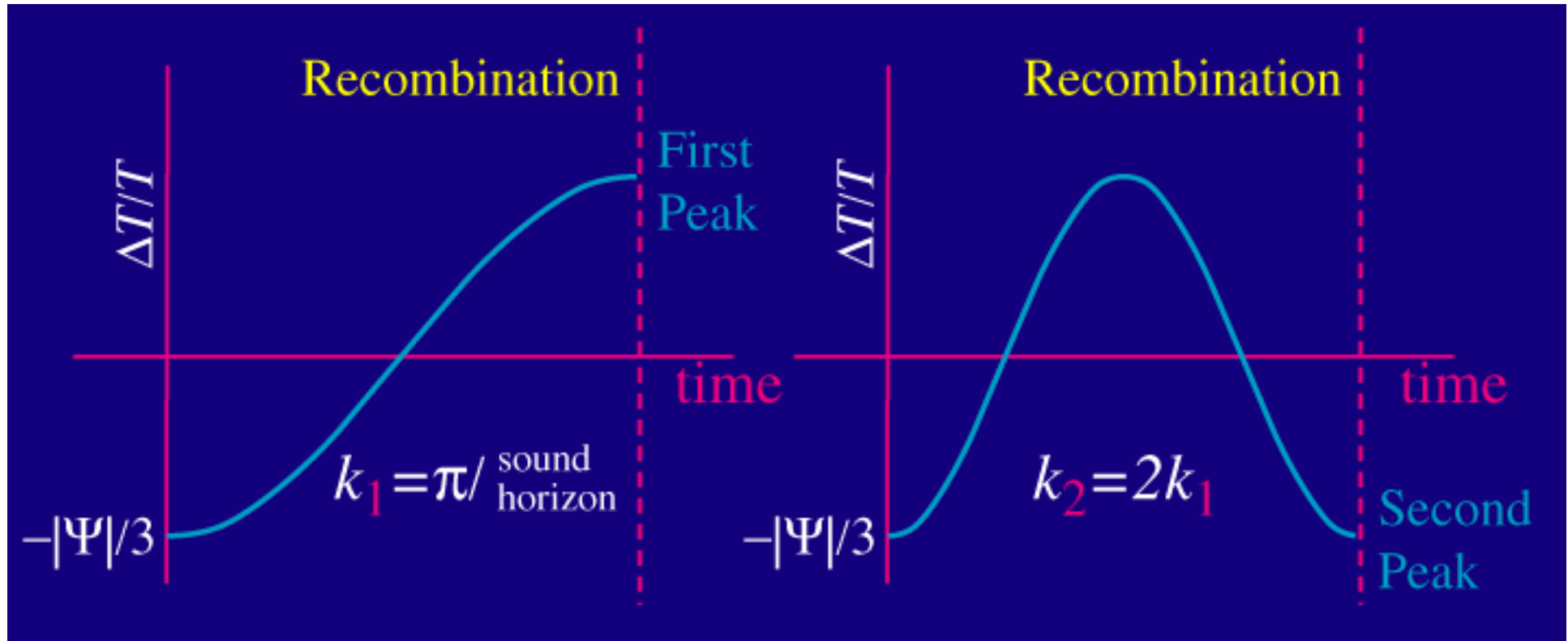
Matière => puits de potentiel

Puits de potentiel

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

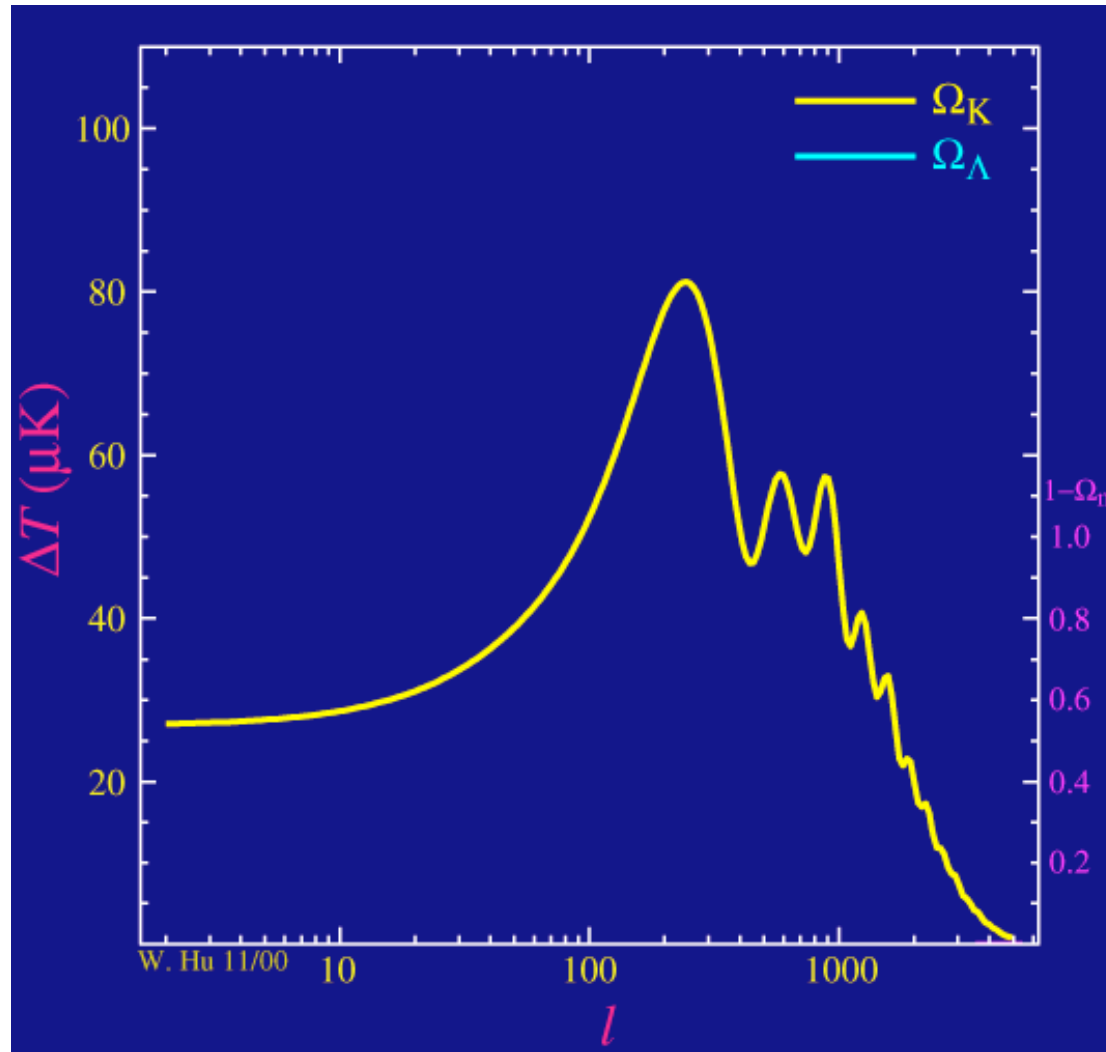


Ondes Acoustiques à la Recomb.



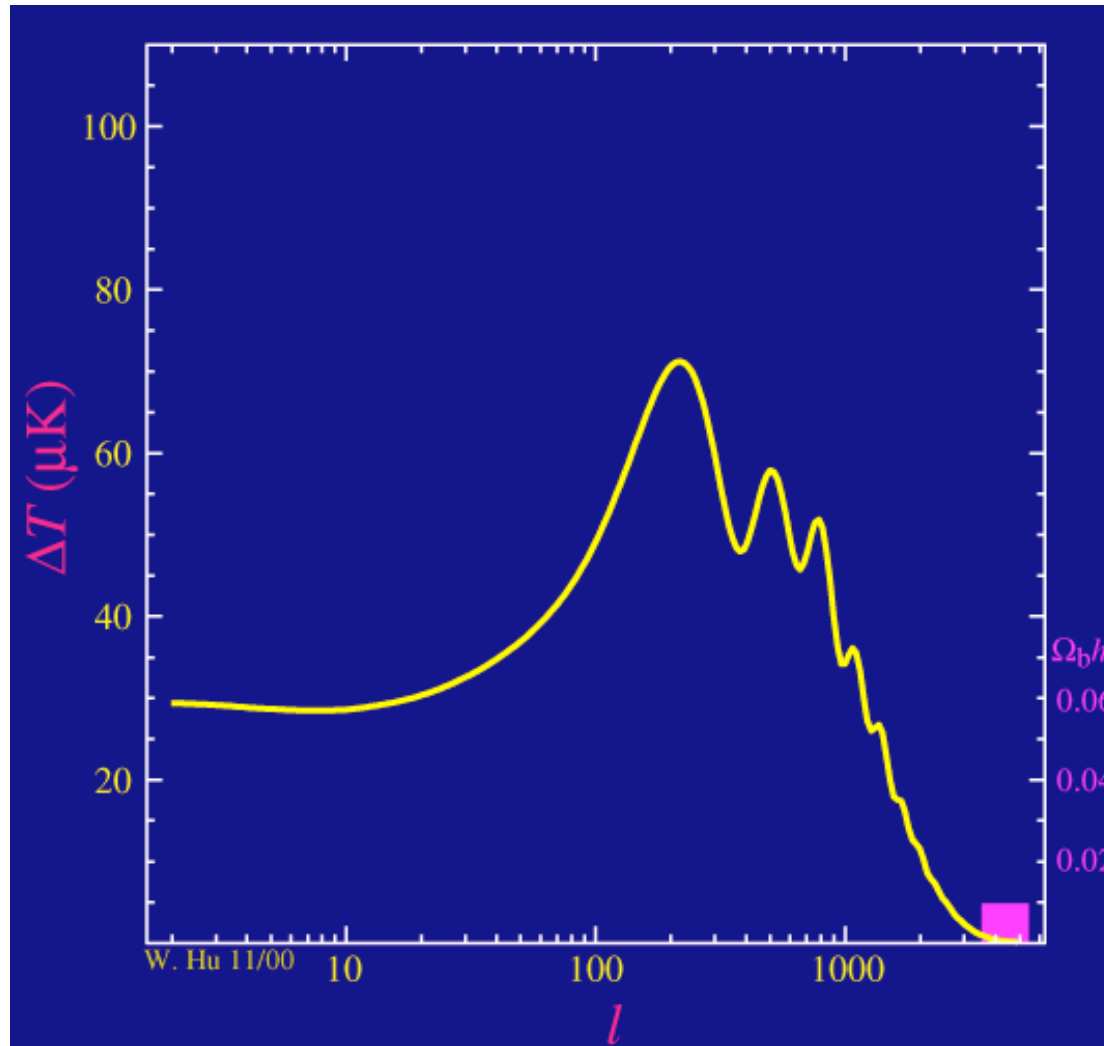
La physique de ces ondes dépend des paramètres cosmologiques

Courbure



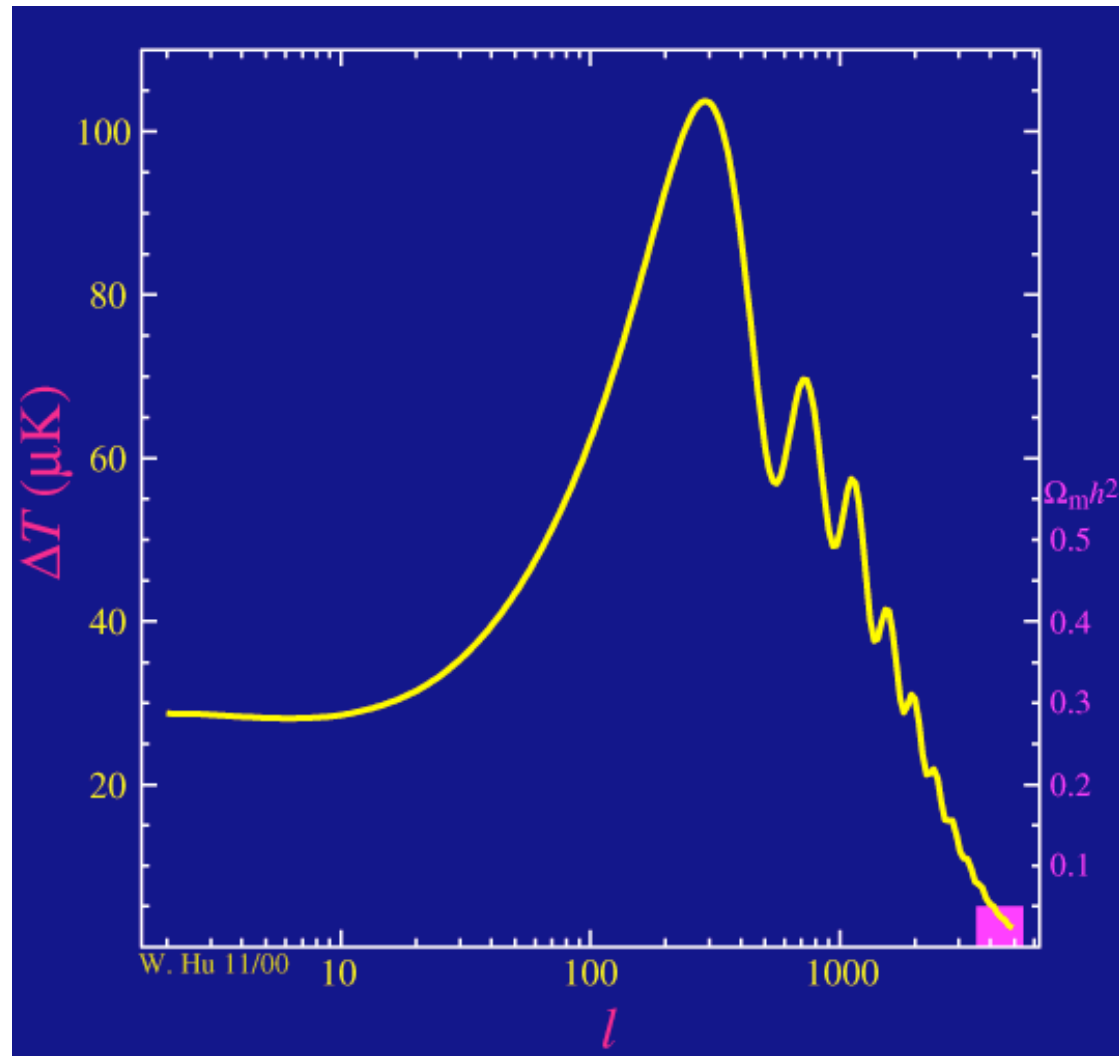
Position du 1er pic acoustique \Leftrightarrow courbure de l'Univers

Contenu en Baryons



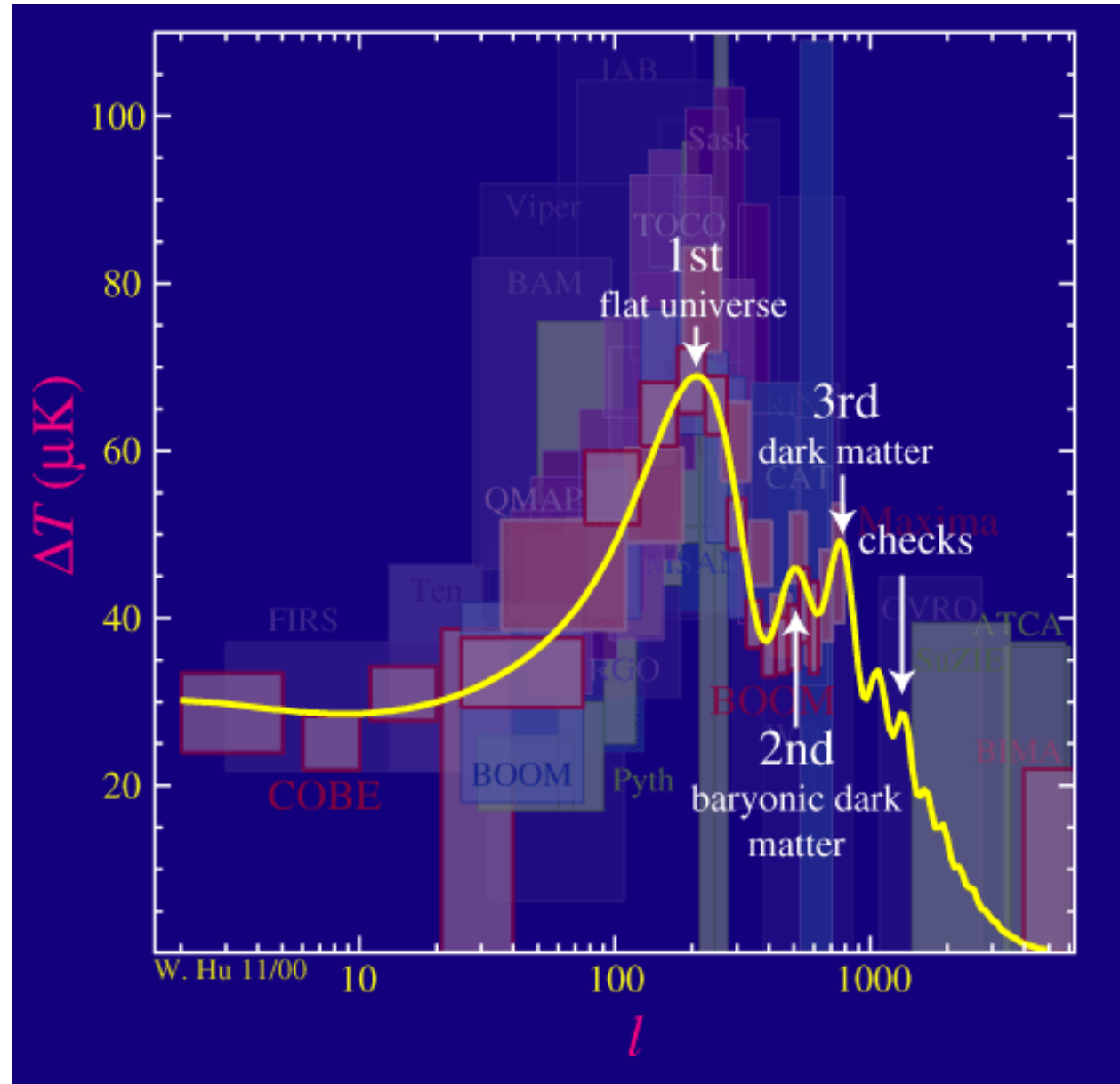
Position du 2nd pic acoustique \Leftrightarrow contenu en baryons

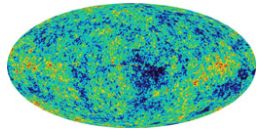
Matière Noire



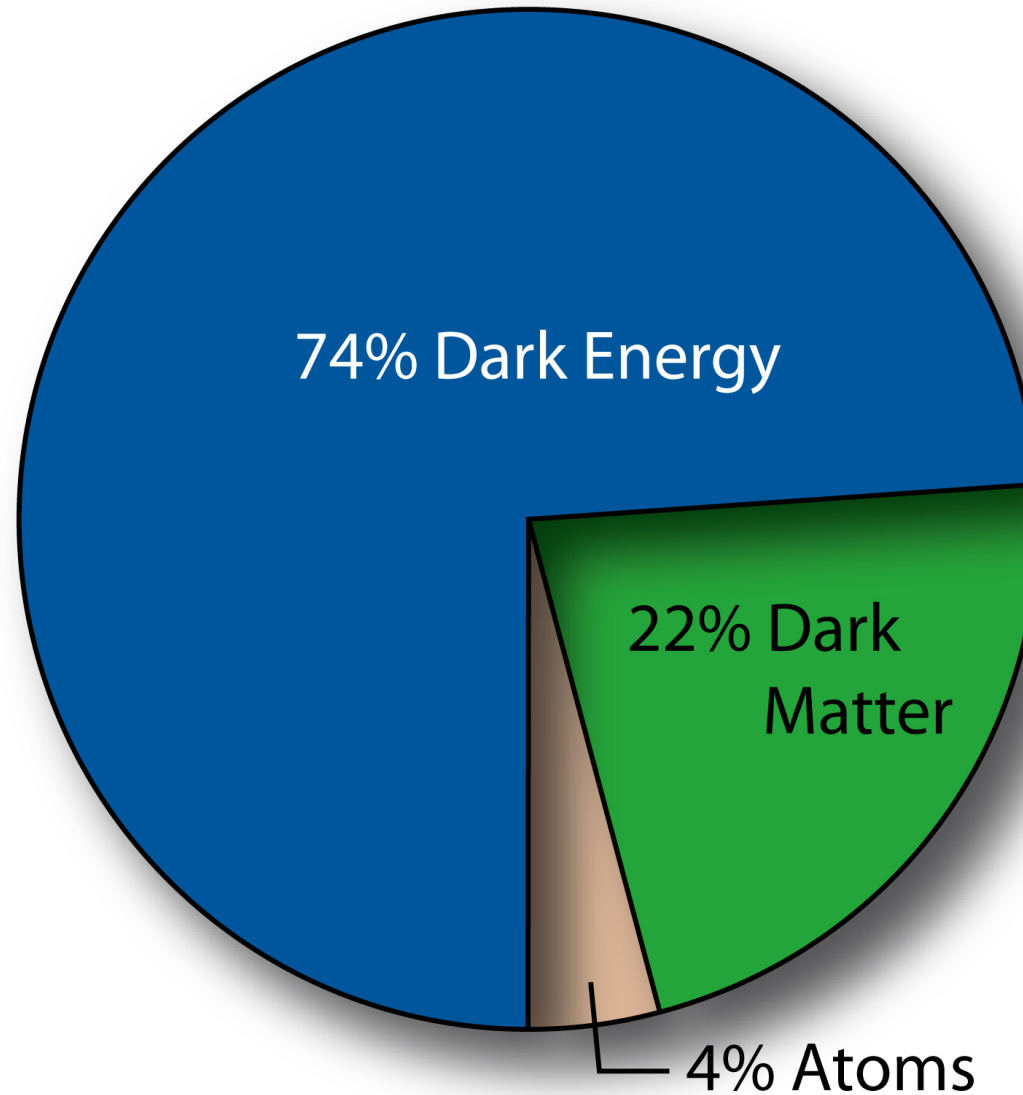
Position du 3ème pic acoustique \Leftrightarrow contenu en matière noire

Pics Acoustiques dans le Sp. P.





Cosmic Microwave Background



WMAP 3 yr