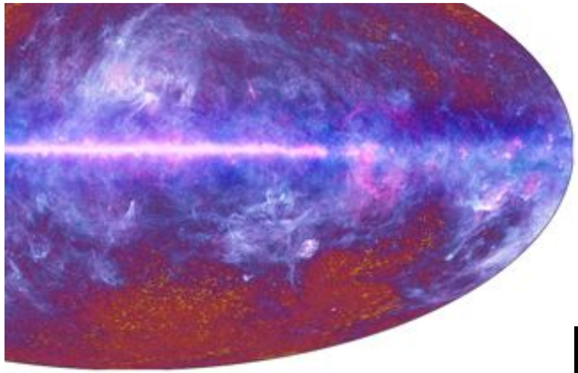


the Cosmic Microwave Background

angular power spectrum on the sphrere: cl I
observations of the CMB II
Cl and cosmological parameters III
polarization IV

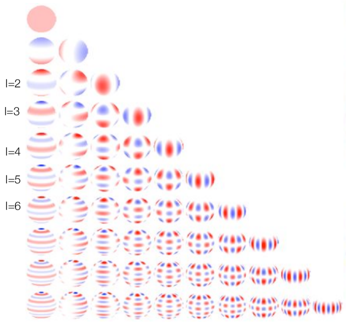
Hervé Dole

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

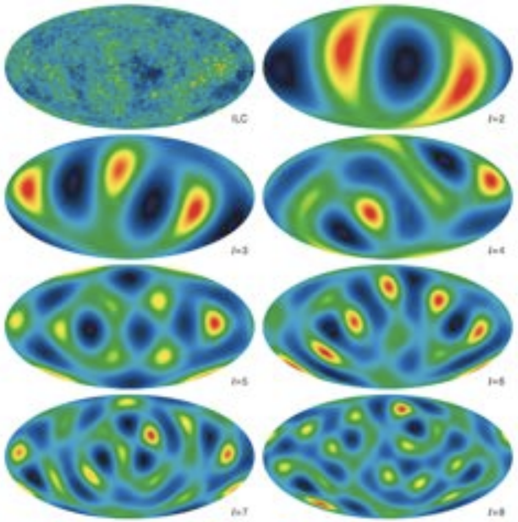
I. Angular Power Spectrum on the sphere: C_l

2. What is l (ell) ?

multipoles applied to the CMB



Ylm courtesy Benoit Mosser, LESIA

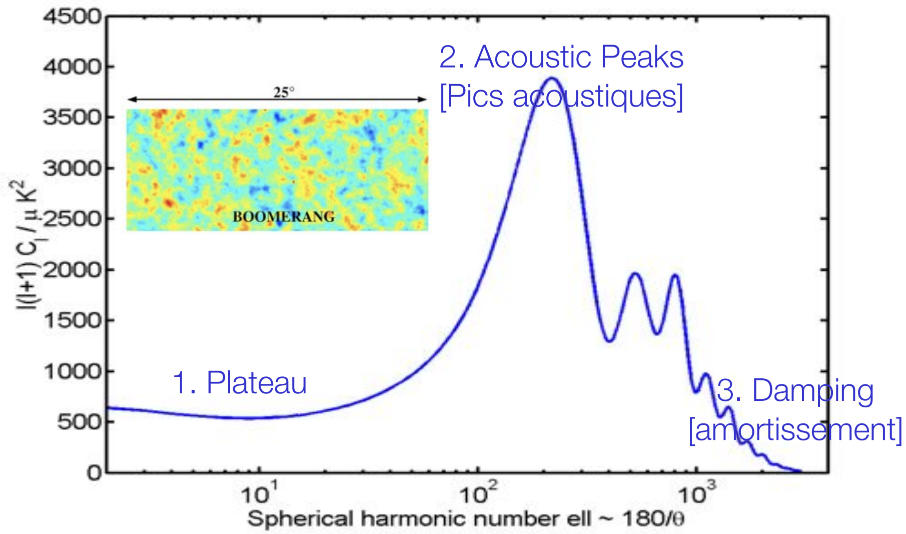


Hinshaw et al., 2007, WMAP3

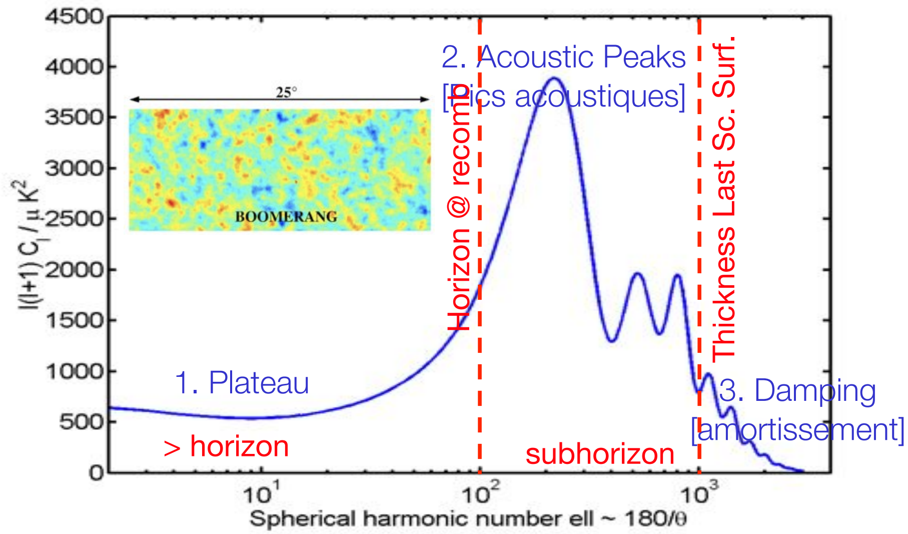
I. Angular Power Spectrum on the sphere: C_l

5. Description of the Angular Power Spectrum

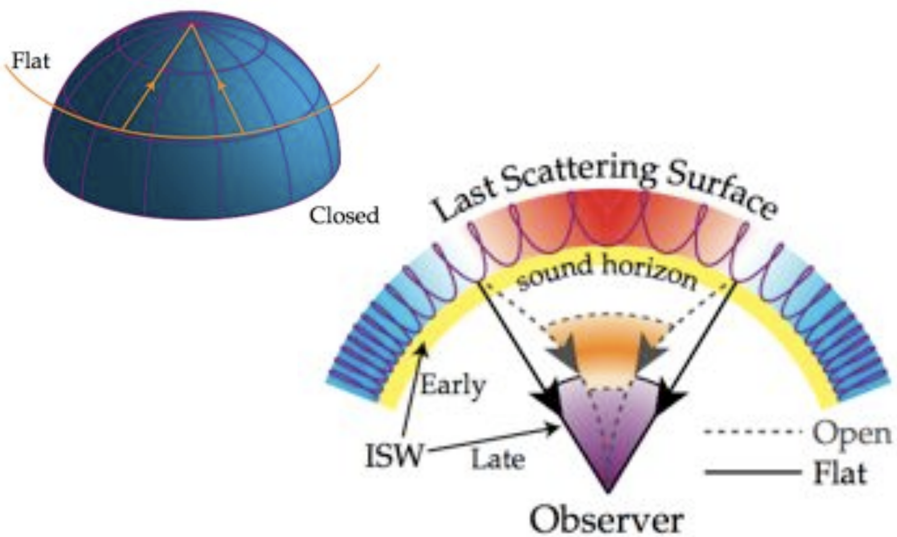
TT angular power spectrum: 3 regimes



TT angular power spectrum: 3 regimes

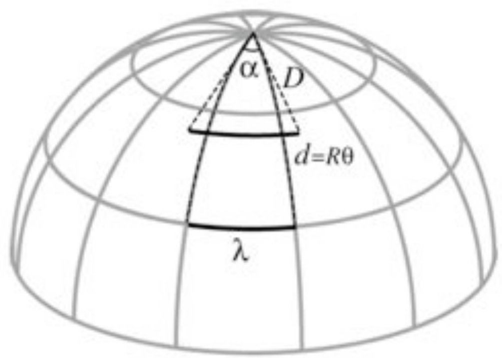


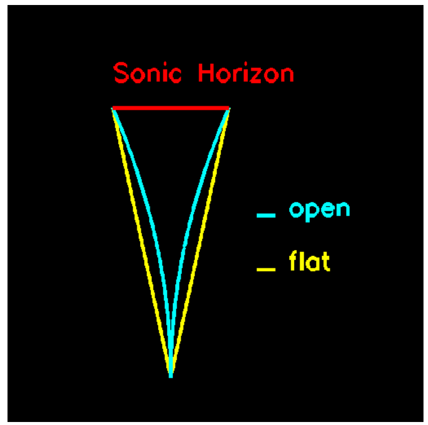
angle and geometry



Hu, Sugiyama, Silk, 1999

angular distance

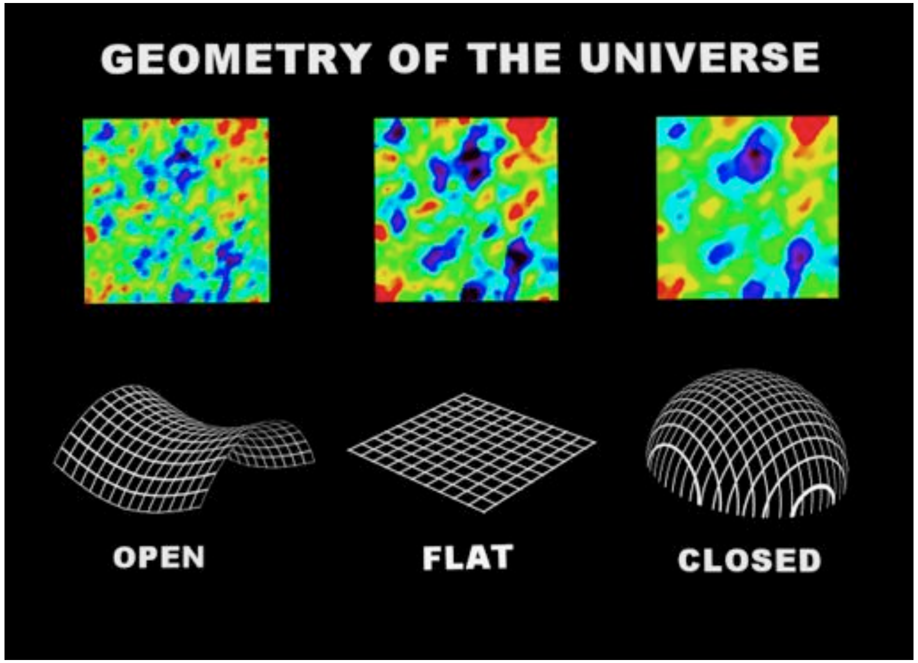




@z~1100

Hu & Dodelson, 2002, ARAA

WMAP



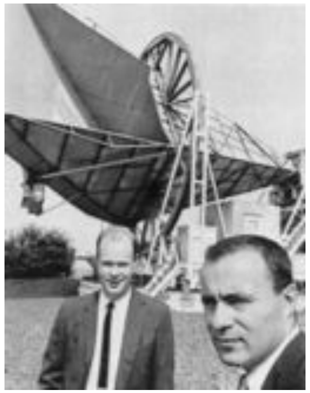
II. Observations of the Cosmic Microwave Background

1. Measurements

Cosmic Microwave Background

Découvert en 1965 par
Arno Penzias & Robert Wilson.

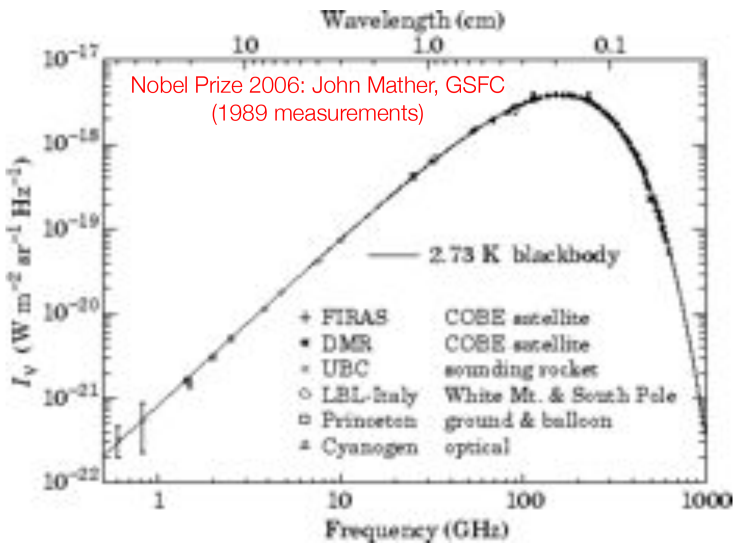
Nobel Prize 1978 "for their discovery of the cosmic microwave background radiation"



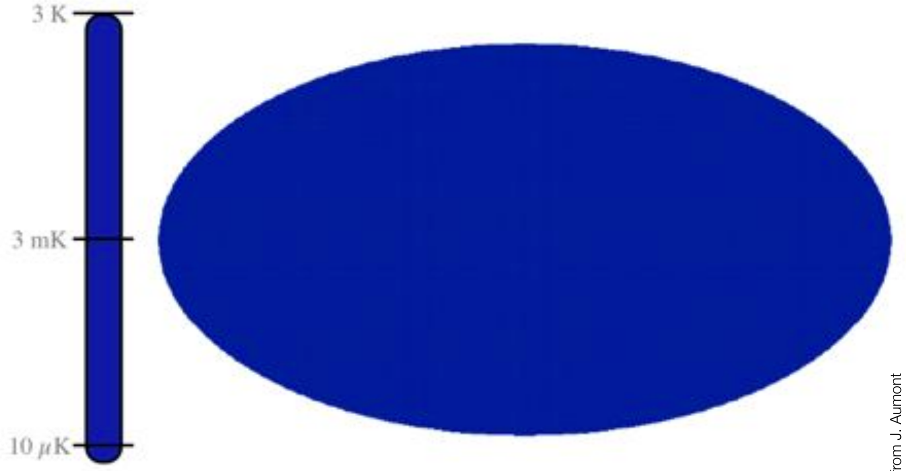
properties

Blackbody Radiation
T=2.725 K

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

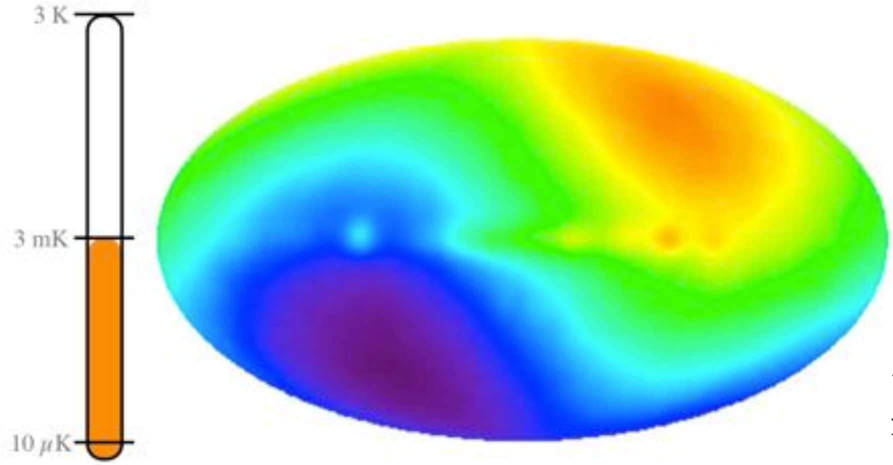


fond cosmologique CMB



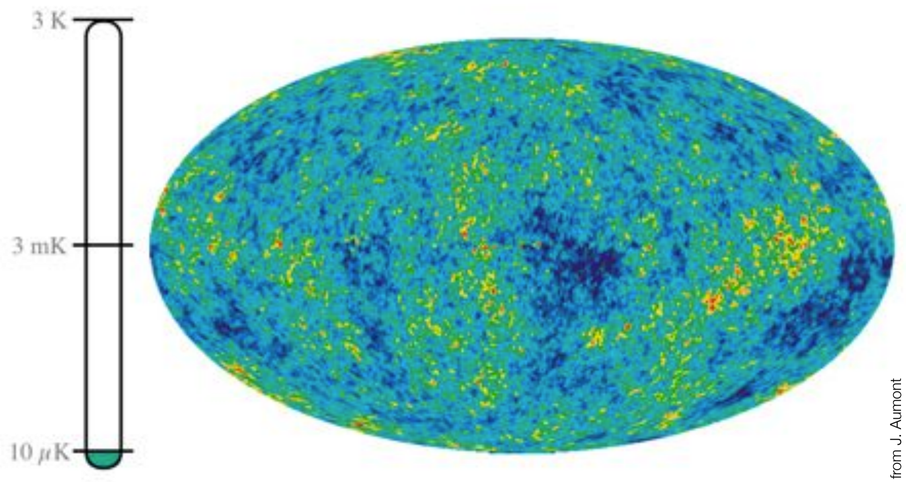
from J. Aumont

fond cosmologique CMB



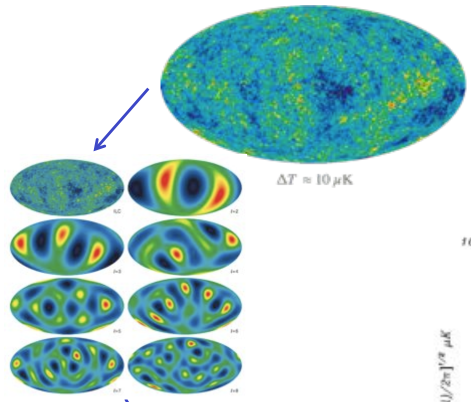
from J. Aumont

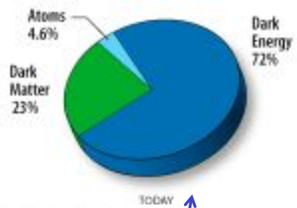
fond cosmologique CMB



from J. Aumont

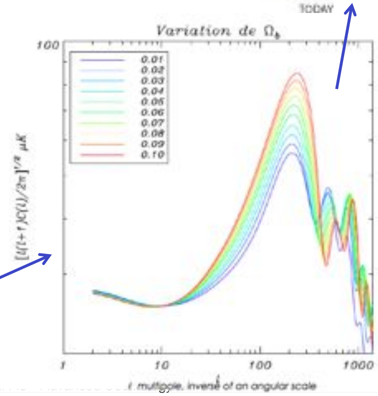
statistics of anisotropies



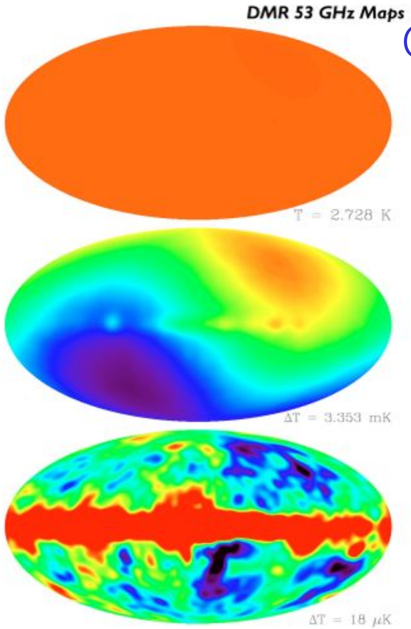


$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell m}(\mathbf{n})$$

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



CMB by COBE in 1992

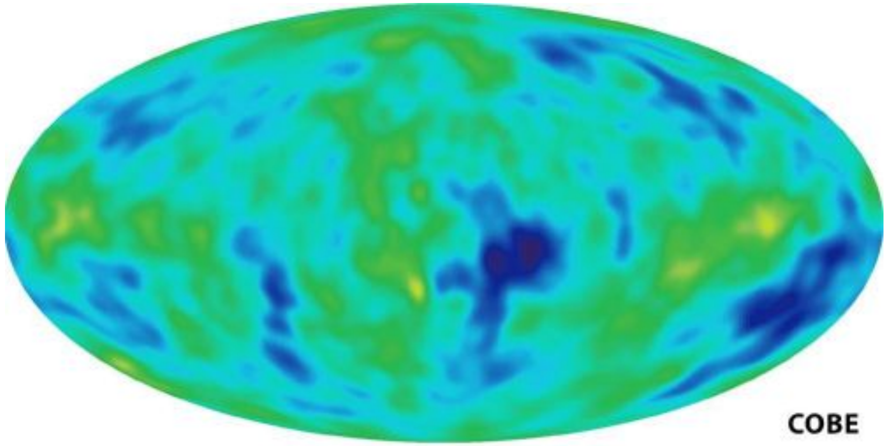


Nobel Prize 2006: G. Smoot, GSFC (1992 measurements)

« for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation »

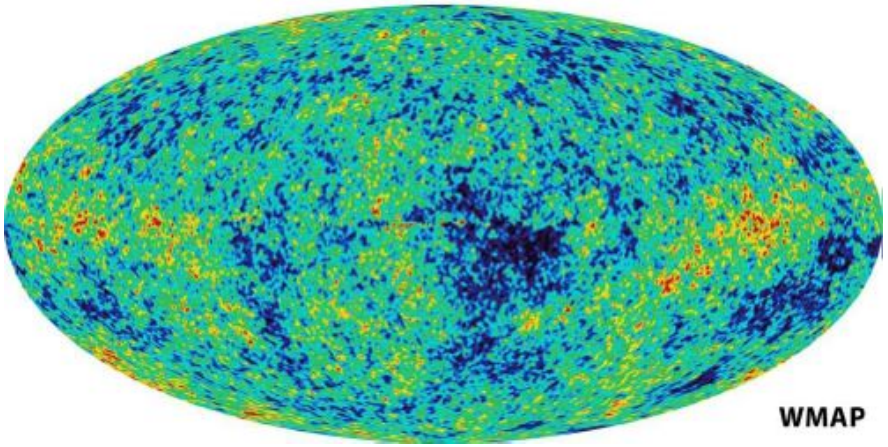
fluctuations de température

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



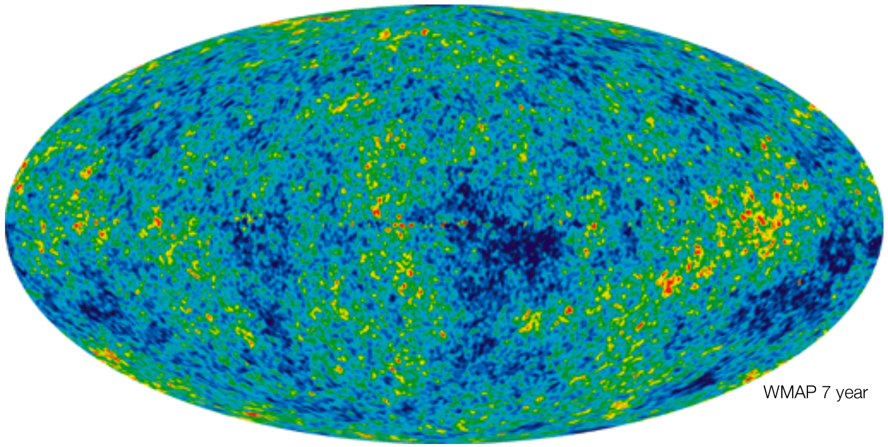
WMAP Web Site

fluctuations de température



WMAP Web Site

fluctuations de température

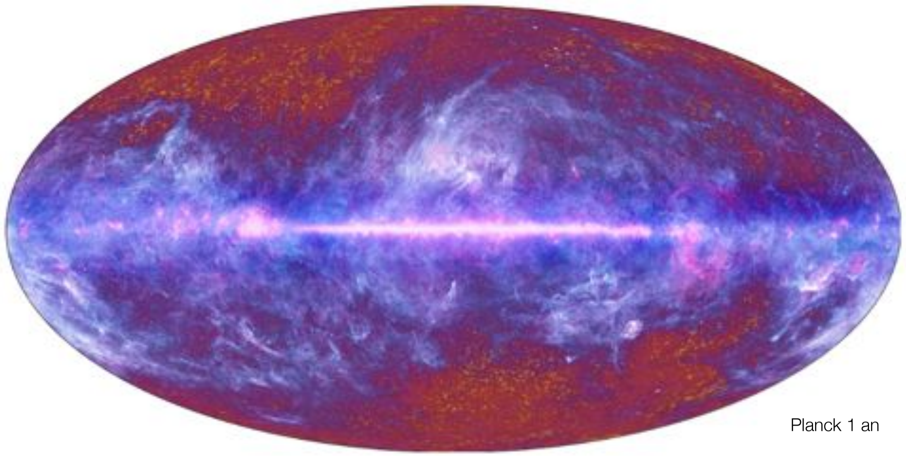


WMAP 7 year

WMAP Web Site

fluctuations de température

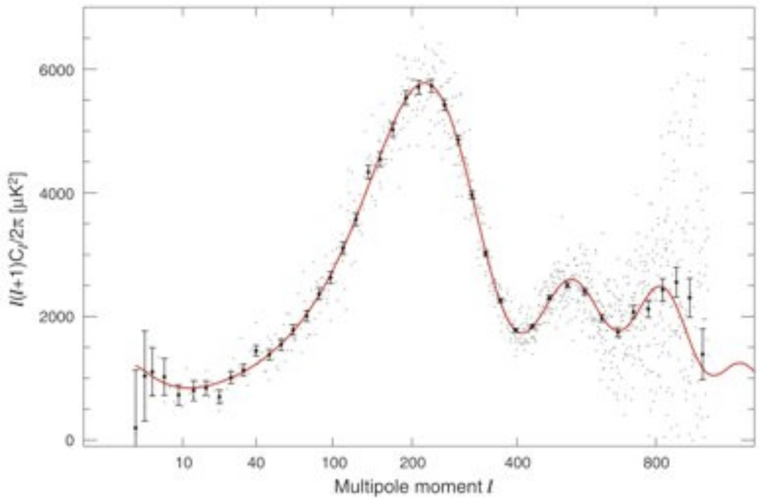
+ Galaxie et galaxies, amas etc.



Planck 1 an

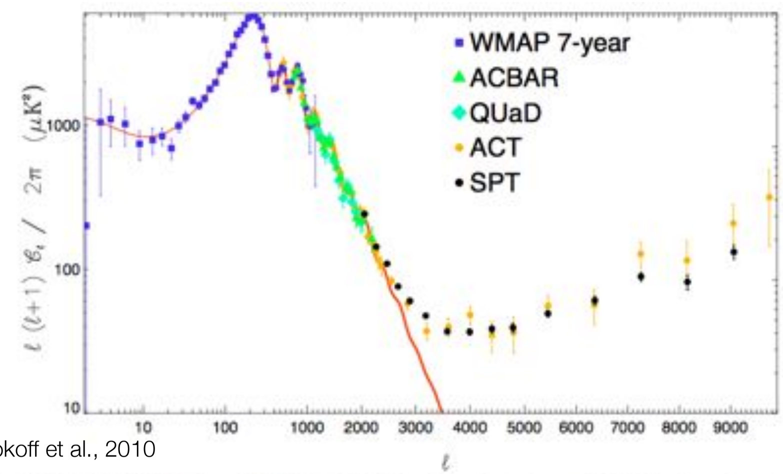
Planck ESA HFI LFI consortia

WMAP 5 TT



Dunkley et al., 2008, WMAP5

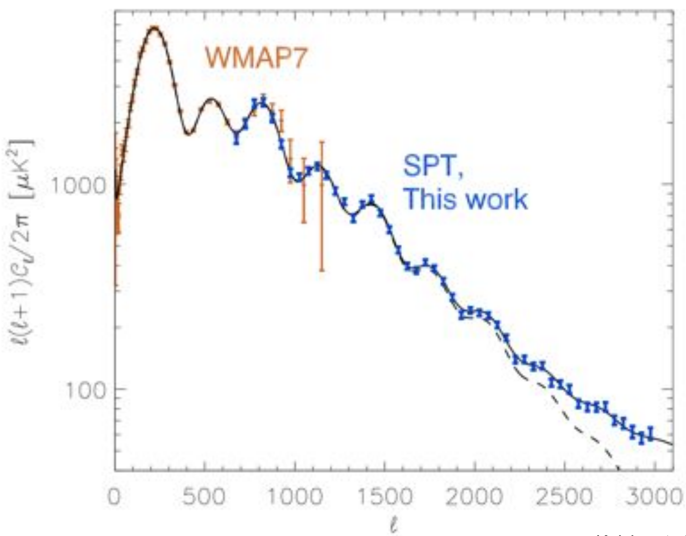
TT power spectrum at high ell



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.

TT power spectrum at high ell



Keisler et al., 2011

TT power spectrum at high ell

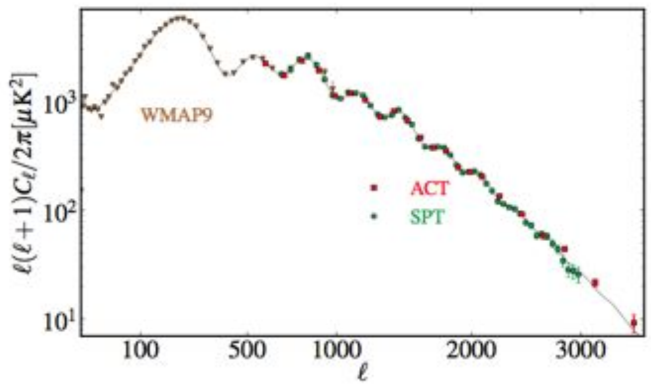
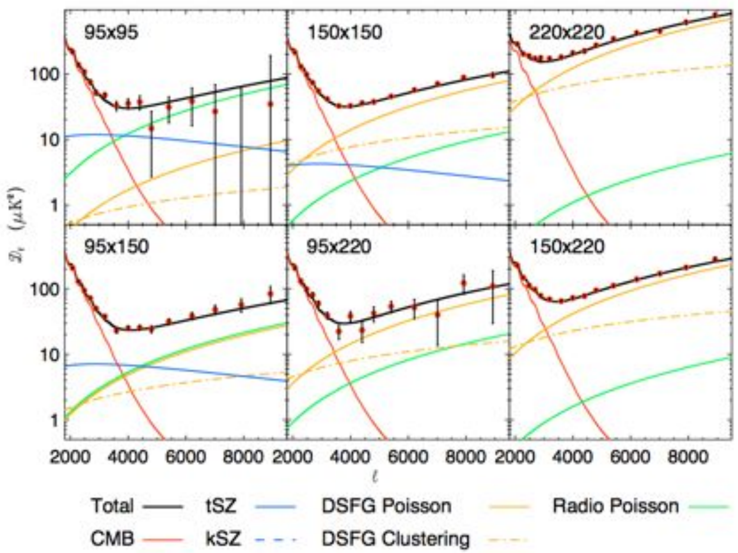


FIG. 1. WMAP9 temperature data and ACT and SPT CMB lensed bandpowers marginalized over secondary emissions. The ACT bandpowers are estimated separately for ACT-S and ACT-E and coadded here with an inverse variance weighting. The SPT bins are highly correlated, $(50-65\%)$ at small scales, $\ell \gtrsim 2000$, due to foreground uncertainty. The correlation is about 5% between neighbouring ACT bins. The solid line shows the lensed CMB best fit obtained combining the three datasets. The ACT and SPT bandpowers are available on LAMBDA (http://lambda.gsfc.nasa.gov/).

Calabrese et al., 2013

TT cross power spectra



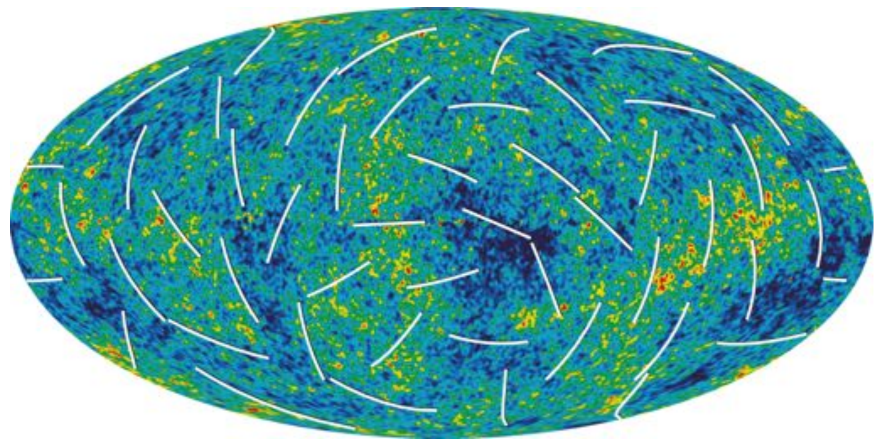
latest pre-Planck cosmo. params

TABLE I. Standard ΛCDM parameters from the combination of WMAP9, ACT and SPT.

Parameter	WMAP9 +ACT	WMAP9 +SPT	WMAP9 +ACT+SPT
$100\Omega_b h^2$	2.260 ± 0.041	2.231 ± 0.034	2.245 ± 0.032
$100\Omega_c h^2$	11.46 ± 0.43	11.16 ± 0.36	11.23 ± 0.36
$100\theta_A$	1.0396 ± 0.0019	1.0422 ± 0.0010	1.0420 ± 0.0010
τ	0.090 ± 0.014	0.082 ± 0.013	0.085 ± 0.013
n_s	0.973 ± 0.011	0.9650 ± 0.0093	0.9678 ± 0.0088
$10^9\Delta^2_{\mathcal{R}}$	2.22 ± 0.10	2.15 ± 0.10	2.17 ± 0.10
Ω_Λ[a]	0.716 ± 0.024	0.737 ± 0.019	0.734 ± 0.019
σ_8	0.830 ± 0.021	0.808 ± 0.018	0.814 ± 0.017
t_0	13.752 ± 0.096	13.686 ± 0.065	13.682 ± 0.063
H_0	69.7 ± 2.0	71.5 ± 1.7	71.2 ± 1.6
$100r_s/D_{V\,0.57}$	7.50 ± 0.17	7.65 ± 0.14	7.65 ± 0.14
$100r_s/D_{V\,0.35}$	11.29 ± 0.31	11.56 ± 0.26	11.55 ± 0.26
best fit χ^2	7596.0	7617.1	7660.0

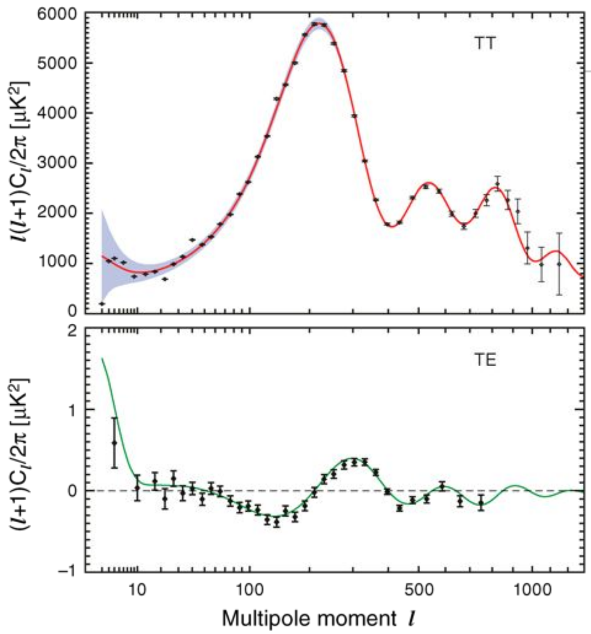
Calabrese et al., 2013

polarized microwave sky

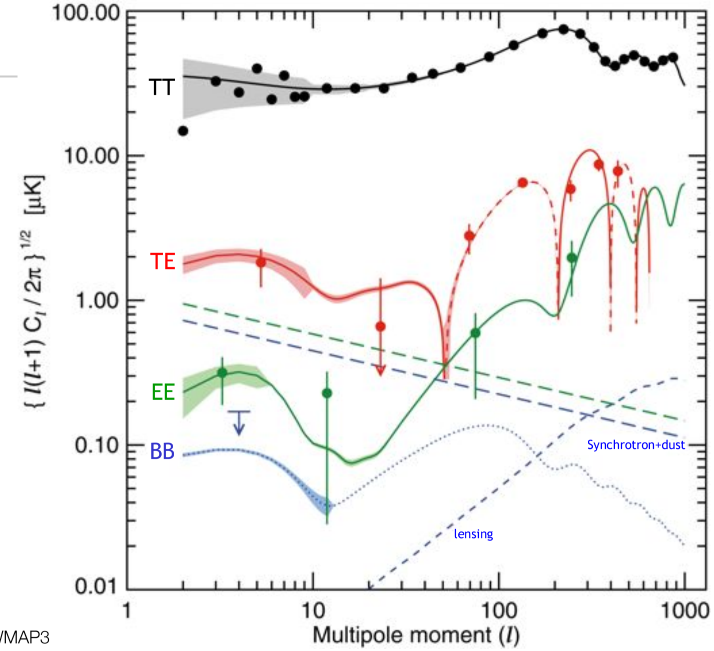


WMAP 3

TT & TE



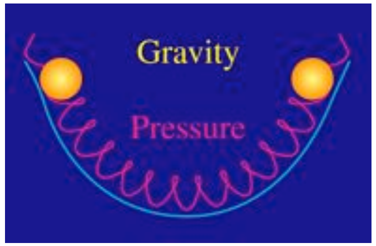
Jarosik et al., 2009, WMAP7



Page et al., 2007, WMAP3

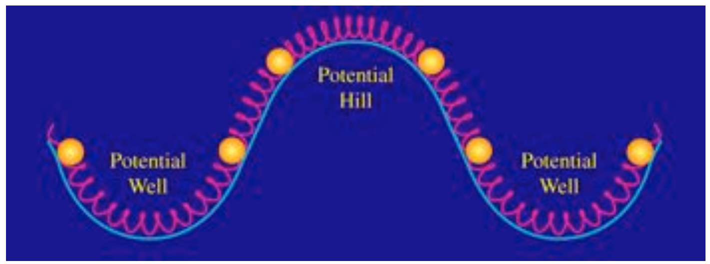
III. C_l and cosmological parameters

origine of fluctuations

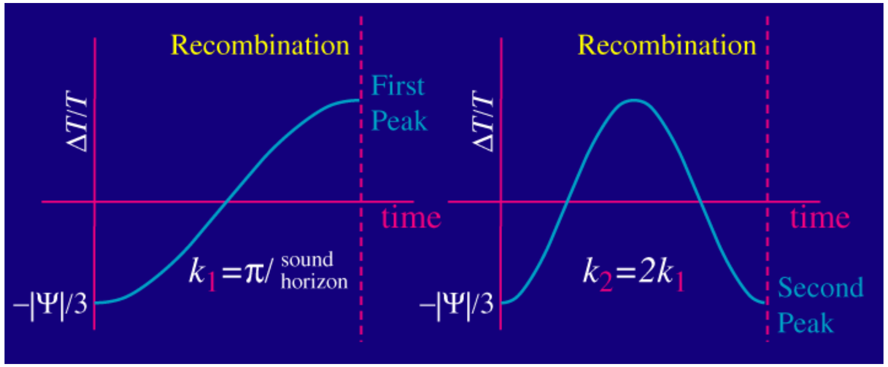


Matière => puits de potentiel

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

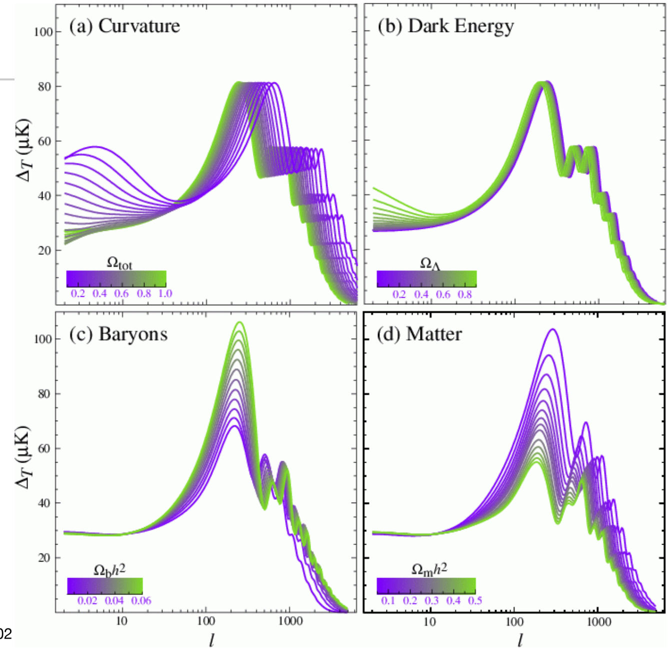


acoustic waves at recombination



La physique de ces ondes dépend des paramètres cosmologiques

C_l



Hu & Dodelson, ARAA, 2002

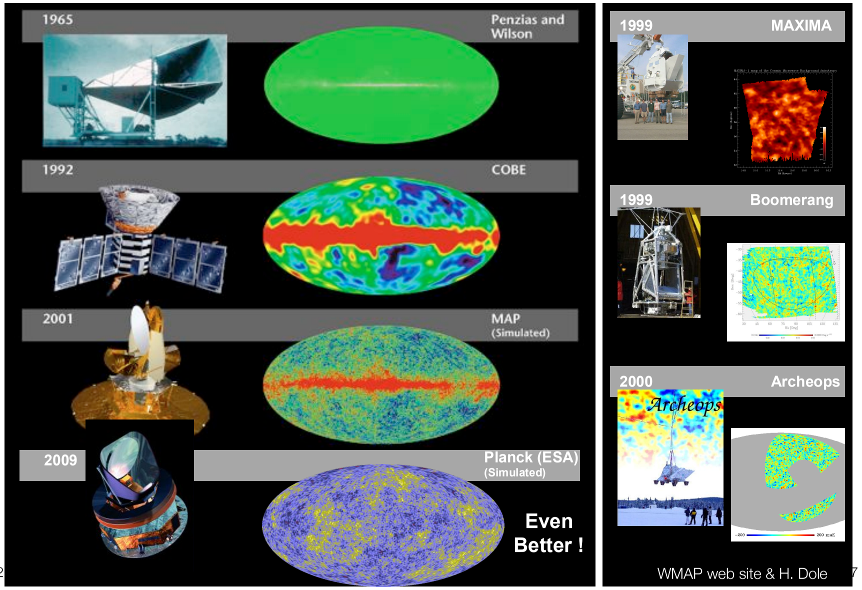
II. Observations of the Cosmic Microwave Background

2. Strategy and Difficulties

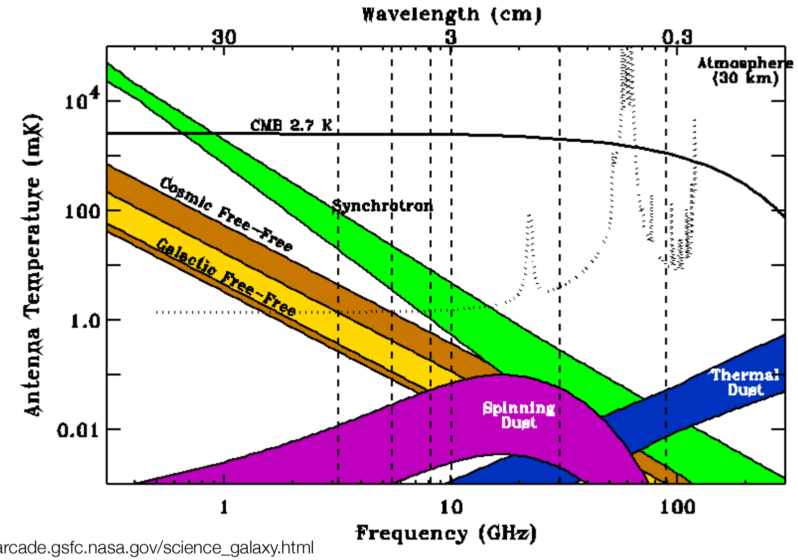
you play !

- we give you 600 ME to accurately measure the CMB
- its temperature and polarization anisotropies
- what telescope and instrument would you build ?

CMB observations

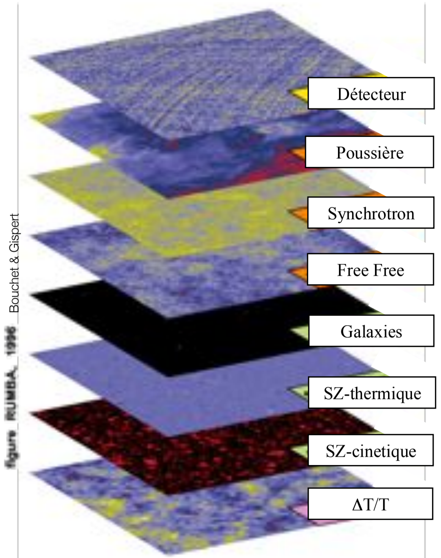


difficulties

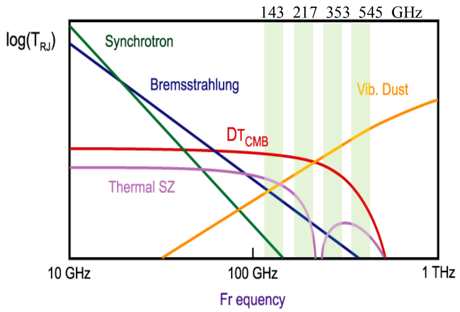


http://arcade.gsfc.nasa.gov/science_galaxy.html

foregrounds



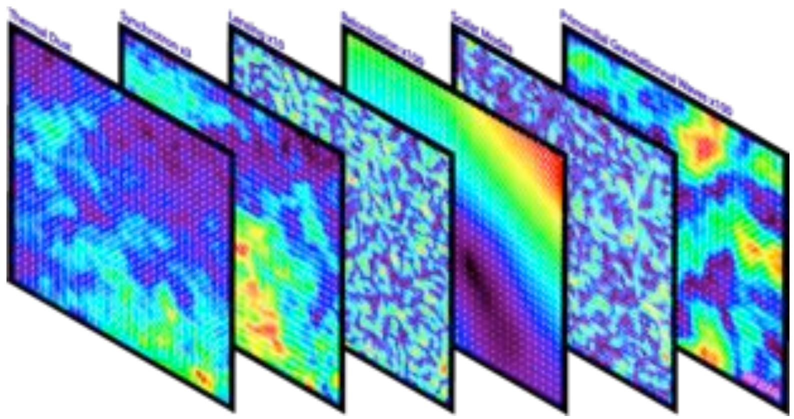
« Sandwich Cosmique »



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

Courtesy N. Ponthieu, IAS

foregrounds

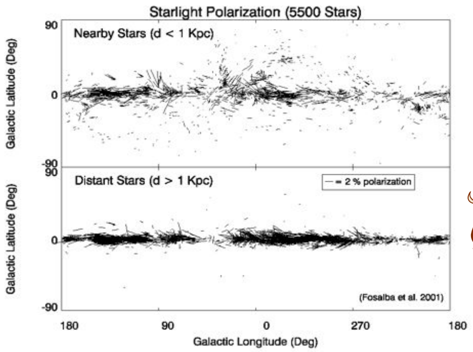


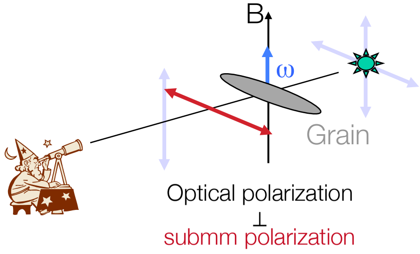
Courtesy N. Ponthieu, IAS

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)





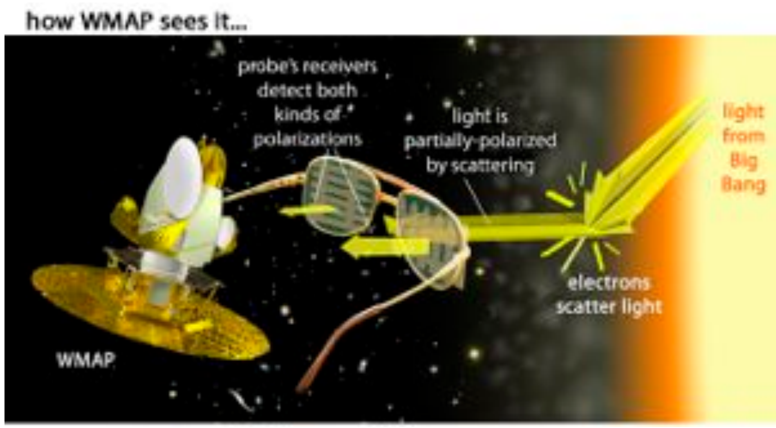
Serkowski et al 75
Heiles 01
Fosalba et al 02

+ Manque de mesures à grandes échelles

Courtesy N. Ponthieu, IAS

IV. Polarization of the Cosmic Microwave Background

CMB polarization for dummies

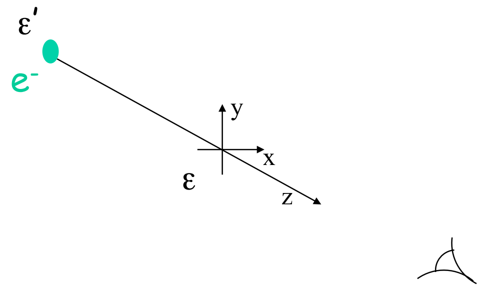


Recombination

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

avec σ_T~1/m² -> e-
et dΩ: angle solide

Rayonnement isotrope
(monopole)

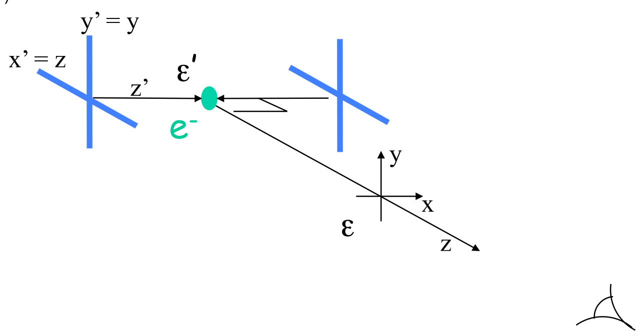


Courtesy N. Ponthieu, IAS

Recombination

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

Rayonnement isotrope
(monopole)

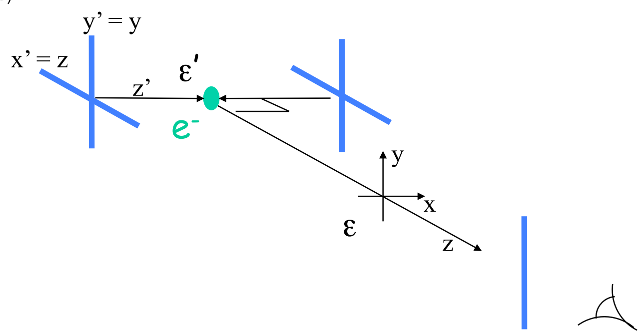


Courtesy N. Ponthieu, IAS

Recombination

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

Rayonnement isotrope
(monopole)

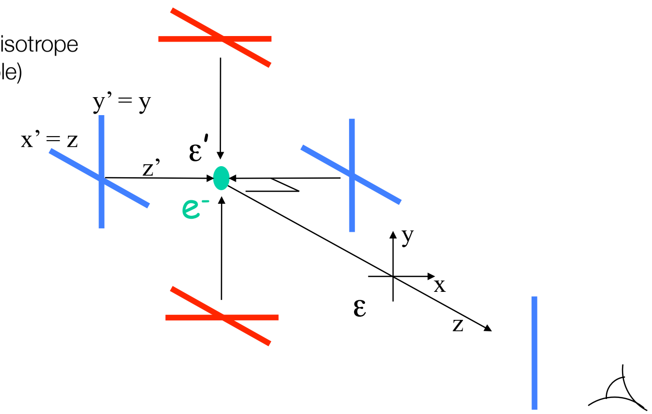


Courtesy N. Ponthieu, IAS

Recombination

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

Rayonnement isotrope
(monopole)

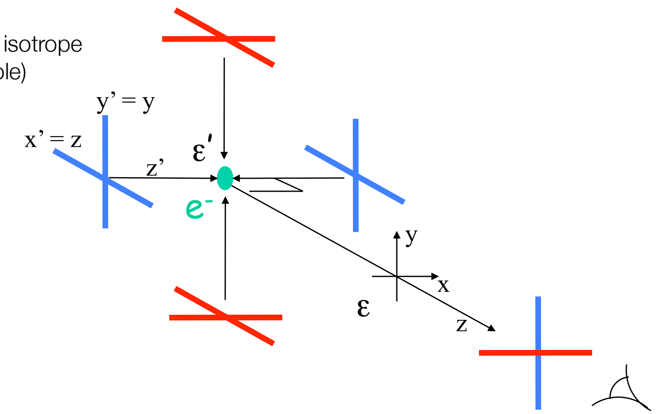


Courtesy N. Ponthieu, IAS

Recombination

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

Rayonnement isotrope
(monopole)

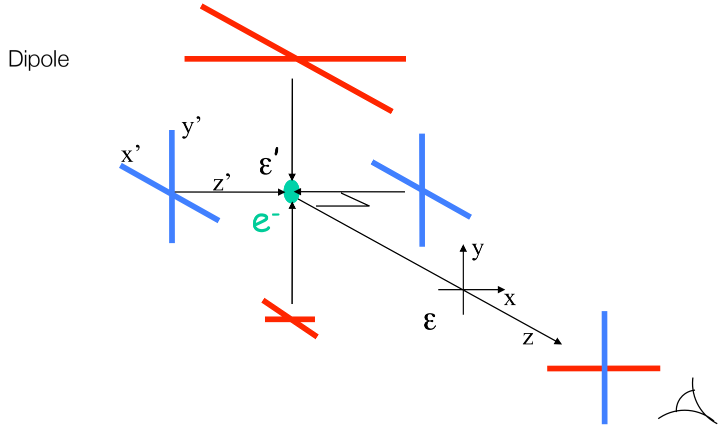


Pas de polarisation

Courtesy N. Ponthieu, IAS

Recombination

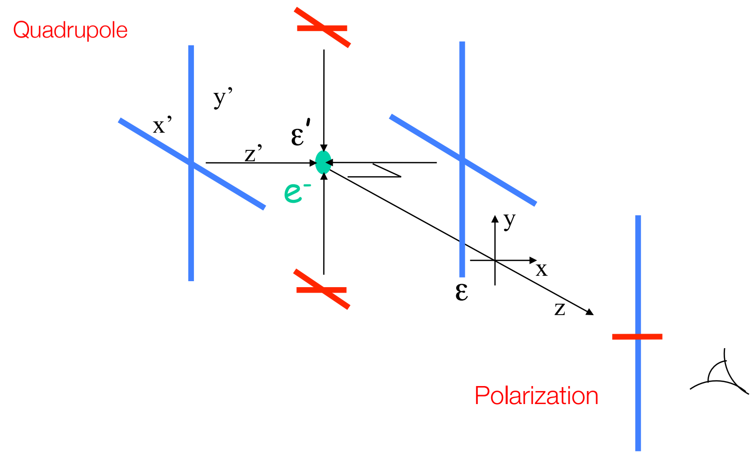
Diffusion Thomson : $d\sigma/d\Omega \sim |\varepsilon.\varepsilon'|^2$



Courtesy N. Ponthieu, IAS

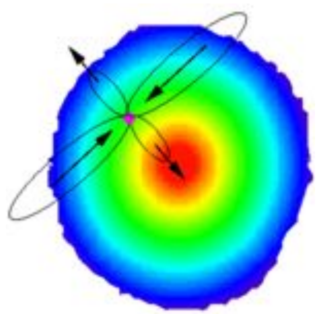
Recombination

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

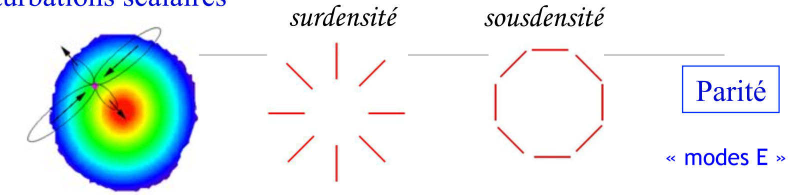
Over (under) densities generate polarization (speed)

Polarization: a direct probe of recombination processes

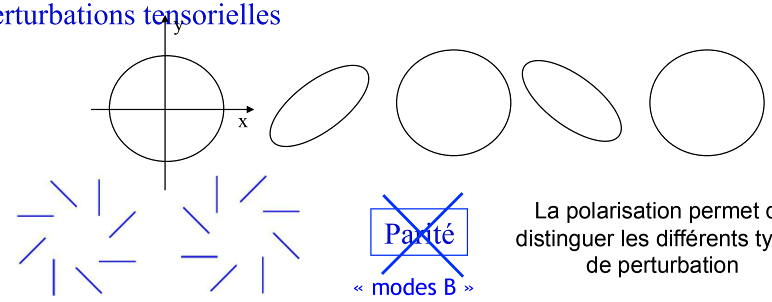
Rees, 1968

Courtesy N. Ponthieu, IAS

Perturbations scalaires



Perturbations tensorielles

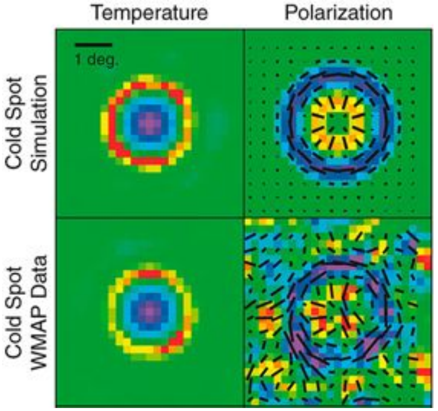


La polarisation permet de distinguer les différents types de perturbation

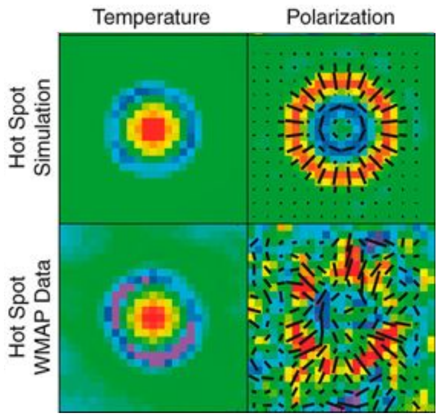
Première possibilité de détection des ondes gravitationnelles primordiales générées pendant la phase d'inflation

Courtesy N. Ponthieu, IAS

polarization data !



Planck data (embargoed) really look like the simulations !



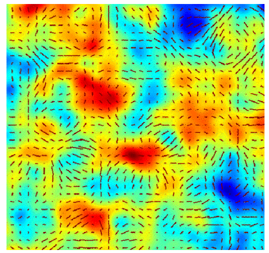
WMAP7 Komatsu et al., 2009

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

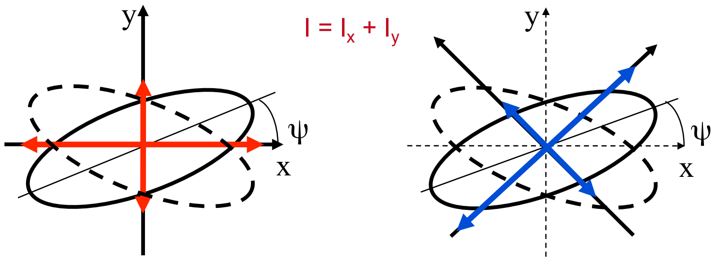
✓ Les figures de polarisation sont différentes



Spectre de puissance et physique…

Courtesy N. Ponthieu, IAS

les paramètres de Stokes



$I = I_x + I_y$

$Q = I_x - I_y$

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

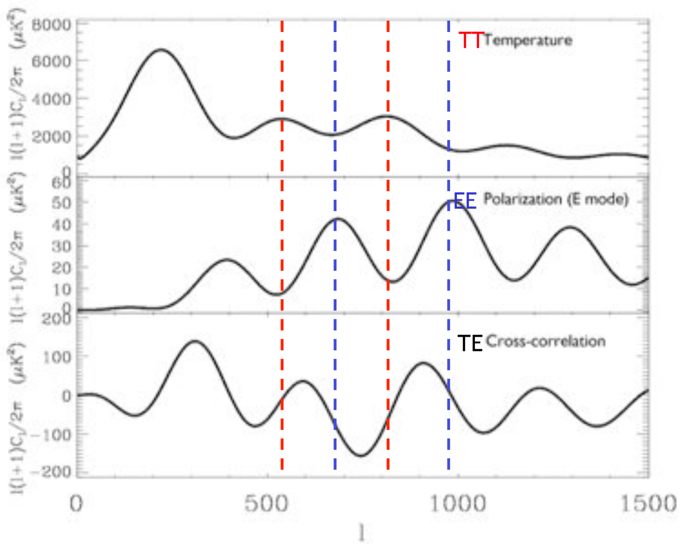
I, Q, U donnent une description complète de l'etat de polarisation

Courtesy N. Ponthieu, IAS

TT, EE, TE: behaviour

phase shift: opposition [déphasage: opposition de phase]

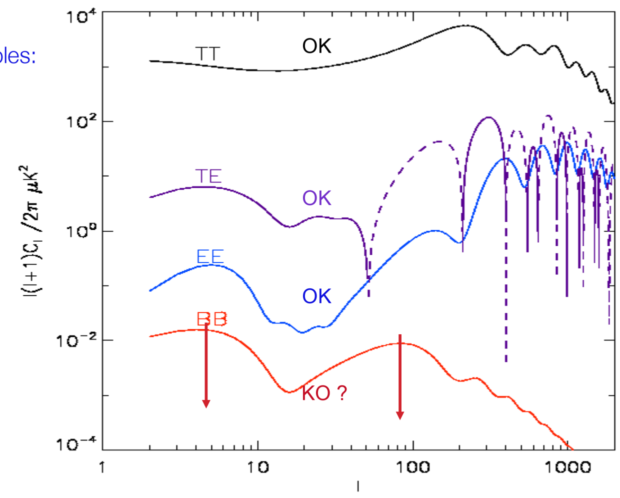
phase shift: half [déphasage de pi/2]



Balbi et al., 2006

4 CMB anisotropies power spectra

3 observables:
T, E, B

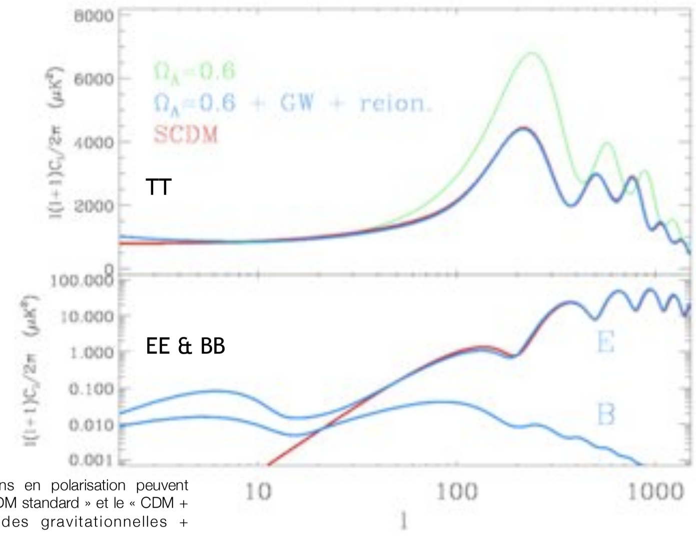


T, E : scalaire
B : pseudo-scalaire

TB, EB = 0

Courtesy N. Ponthieu, IAS

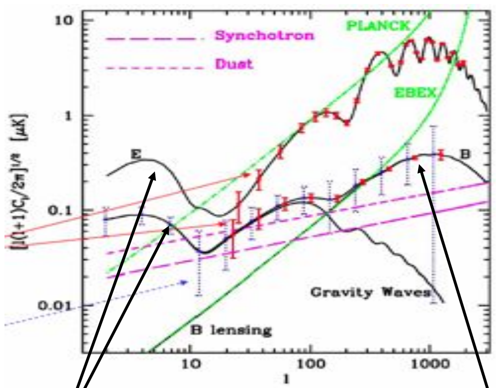
why polarization helps

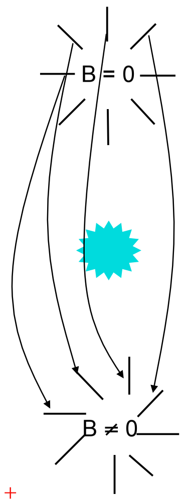


Balbi et al., 2006

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

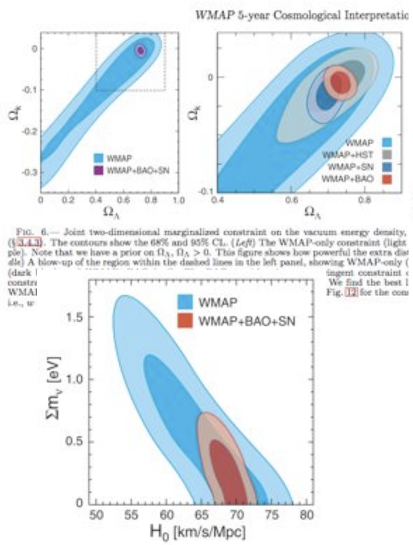
anisotropies secondaires

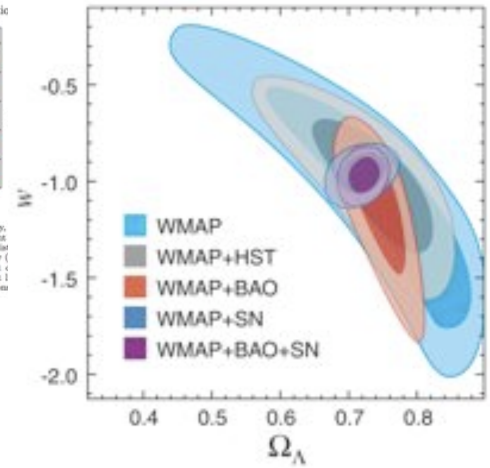




Courtesy N. Ponthieu, IAS

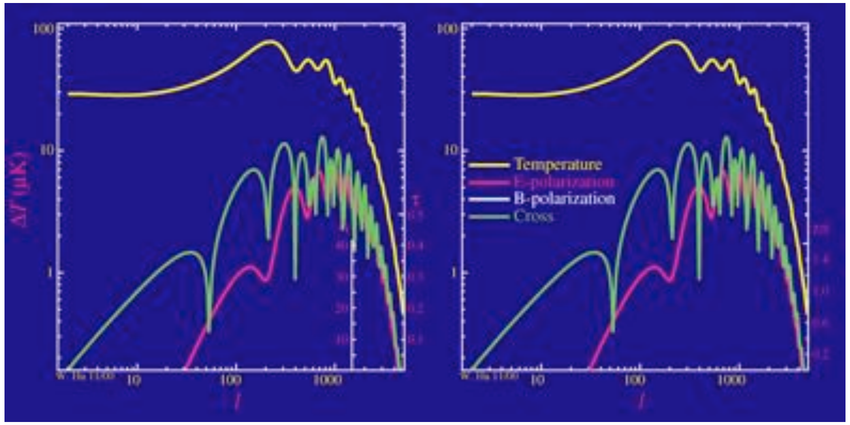
qques résultats WMAP5





Komatsu et al., 2008, WMAP5

polarisation et spectre de puissance



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

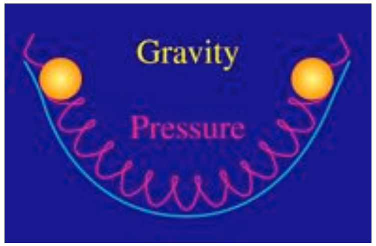
create your own CMB !

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

II. Observations of the Cosmic Microwave Background

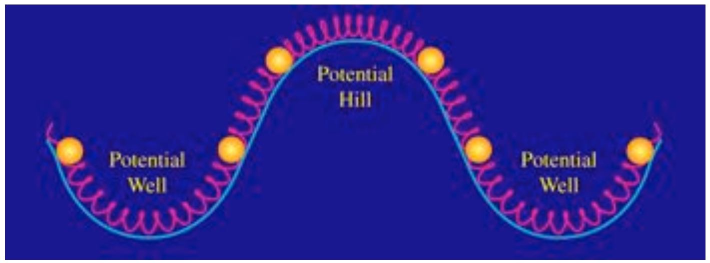
7. Origin of fluctuations

origine des fluctuations

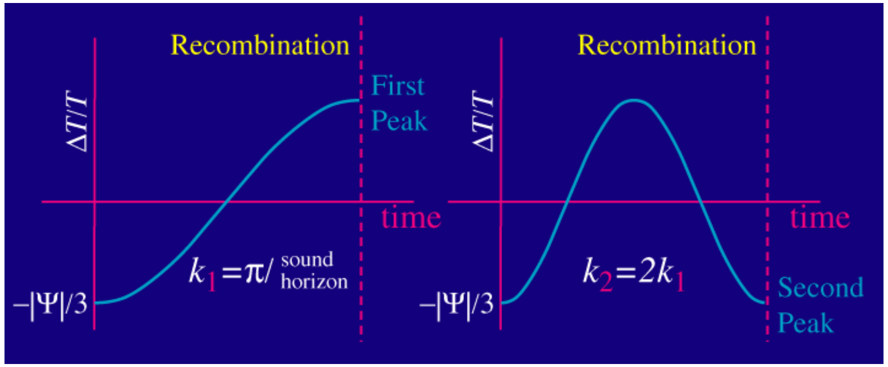


Matière => puits de potentiel

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

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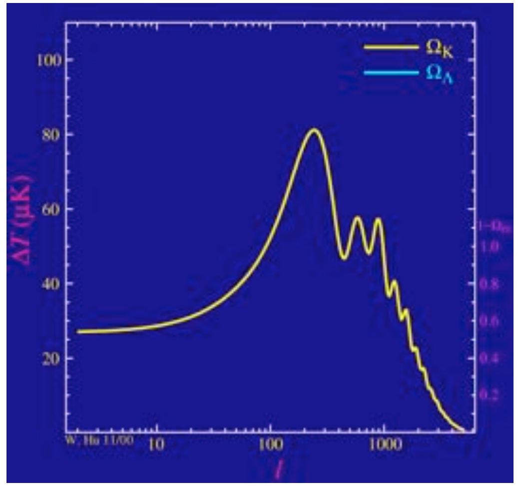

Position du 1er pic acoustique <=> courbure de l'Univers

Contenu en Baryons

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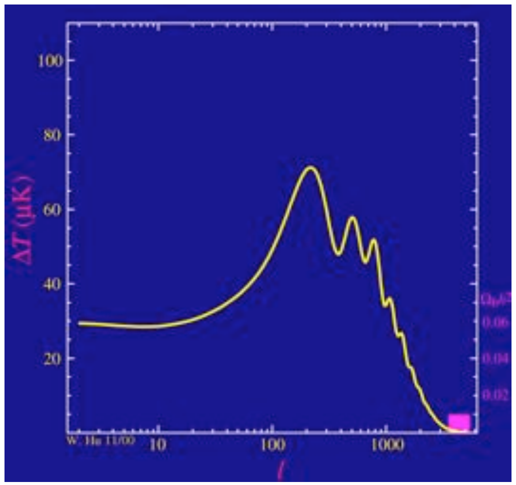

Position du 2nd pic acoustique <=> contenu en baryons

Matière Noire

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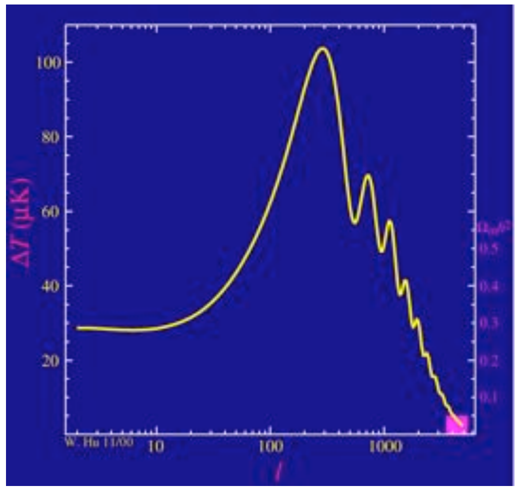
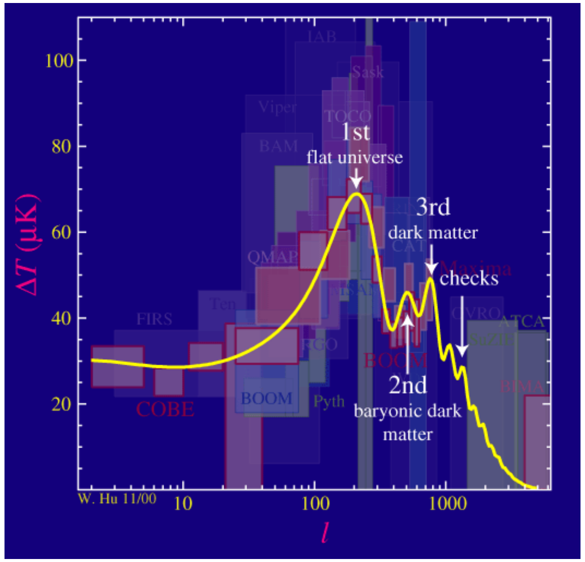


Position du 3ème pic acoustique <=> contenu en matière noire

Pics Acoustiques dans le Sp. P.



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