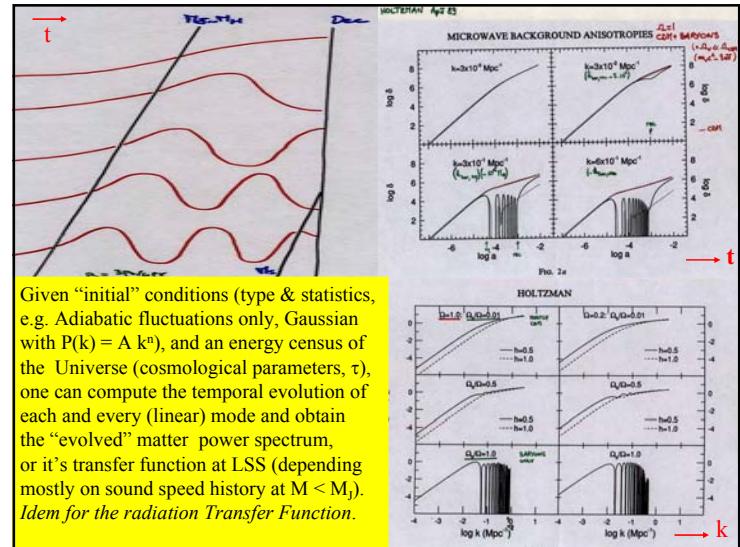
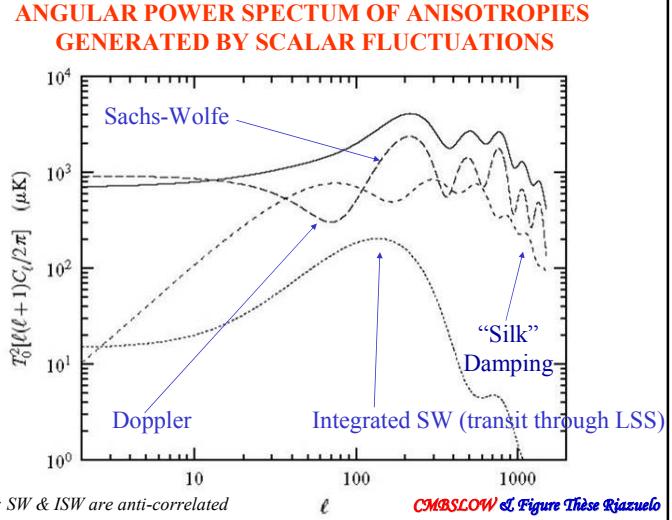
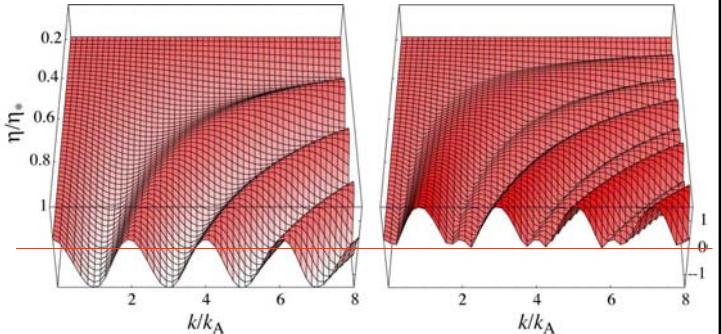


CMB ANISOTROPIES AND COSMIC STRUCTURES, LINKING INITIAL CONDITIONS & COSMOLOGICAL PARAMETRES



PHYSIQUE ANISOTROPIES

Temporal evolution of the effective temperature, $\theta + \psi$, for $R = \text{cste}$



Amplitude. Note the zero point displacement and compression enhancement

rms. Note enhanced odd-numbered peaks

Hu 0210696

EQUATION DE BOLTZMANN :

dans la limite du couplage fort $e - \gamma$
 $(\tau \ll H^{-1}, (c_s k)^{-1})$
 $n_\gamma \propto n_B \propto T^3, \theta(x, t) = \frac{\Delta T}{T}(x, t) = \frac{1}{3}\delta(x, t)$

- dans la jauge Newtonienne
(& temps conforme $d\eta = dt/a$)
pour des modes de Fourier (indépendants) en espace plat
(In this limit, nothing else that conservation + Euler equations)

$$\frac{d}{d\eta} [(1+R) \dot{\theta}] + \frac{k^2}{3} \theta = F(\eta)$$

$$R = \frac{3 \rho_B}{4 \rho_\gamma} = \frac{450}{1+z} \left(\frac{\Omega_B h^2}{0.015} \right) \rightarrow 1/2 \text{ à } z=1000$$

$$F(\eta) = -\frac{k^2}{3} (1+R) \Psi$$

- Propagation le long d'une géodésique :

$$\frac{\Delta T}{T} = [\theta - \hat{\mathbf{r}} \cdot \mathbf{v} + \Psi]_{\eta=\eta_{SDD}}$$

Cette séparation dépend de la jauge
(e.g. $\frac{\Delta T}{T} = \left[\frac{\Delta T}{T}_{int} - \hat{\mathbf{r}} \cdot \mathbf{u} + \frac{1}{3}\phi \right]$ en synchrone)

SOLUTIONS :

- Supposons des Conditions initiales adiabatiques
 $(\dot{\theta}(0) = 0, \theta(0) = -\frac{2}{3}\Psi)$

- Quand R est négligeable et Ψ constant :
 $\theta(\eta) + \Psi = \frac{\Psi}{3} \cos k c_s \eta$

a des oscillations quand $\lambda \sim k^{-1} = c_s \eta / \pi$.
Si $\eta = \eta_{SDD}$, la lère a $\lambda \sim 30 \text{ Mpc}$;
 $R_{SDD} \sim 6000 \text{ Mpc} \implies \lambda/R \sim 0.25^\circ$

- $v = \frac{3k}{\lambda} \dot{\theta} = -\frac{\Psi}{3\sqrt{3}} \sin k c_s \eta$

En quadrature : $\left(\frac{\Delta T}{T} \right)^2 = \text{constante !}$

- Supposons la masse effective $R \sim \text{constante} :$
 $c_s \searrow \frac{c_s}{\sqrt{1+R}}, F \nearrow (1+R)F$

$$\theta(\eta) = \frac{1}{3}(1+R)\Psi \cos k c_s \eta - (1+R)\Psi \nearrow \cos \nearrow \text{par } (1+3R), v \propto c_s \theta \searrow \theta + \Psi \text{ oscille autour de } -R\Psi,$$

$$\implies \text{Oscillations de } \left(\frac{\Delta T}{T} \right)^2$$

- WKB : $\phi = k \int c_s d\eta$, Amplitude croît $\propto c_s^{1/2}$

IMPLICATIONS :

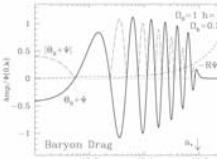
- la hauteur des pics dépend du contenu baryonique :

$$\Omega_B \nearrow \implies \text{Amplitude des oscillations } \nearrow \\ (\text{et différences pair } \nearrow / \text{impairs } \searrow)$$

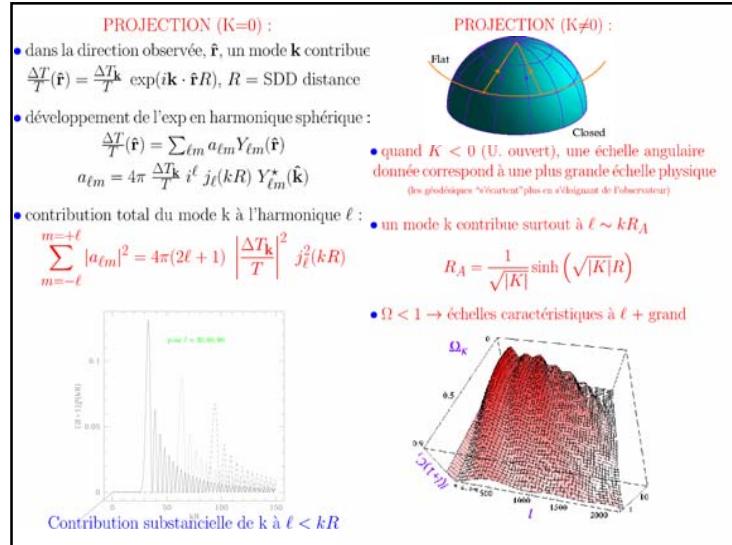
- $F = \text{constante}$ n'est vrai que durant l'ére de matière :

des modes entrant avant t_{eq} oscillent quand $\Psi \searrow$
 $\implies \text{Amplitude } \nearrow \text{ pour } k > k_{eq} = (14 \text{ Mpc})^{-1} \Omega_0 h^2$

- Amortissement diffusif (Silk)
augmente quand $\eta \rightarrow \eta_{SDD}$



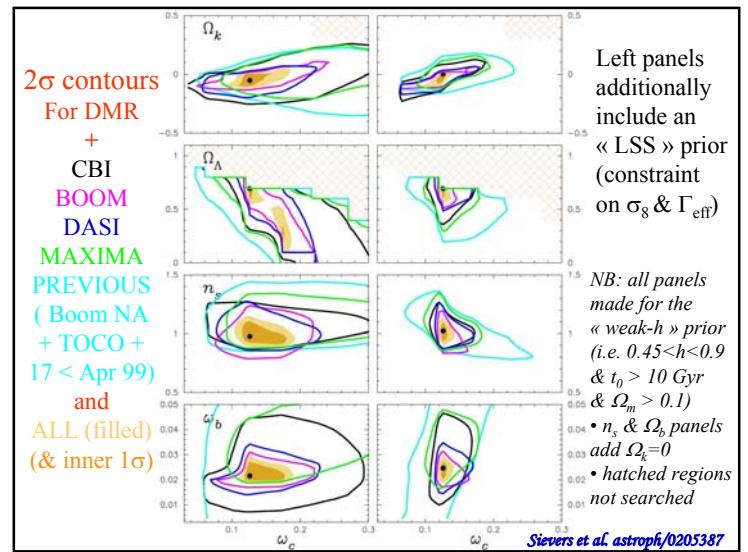
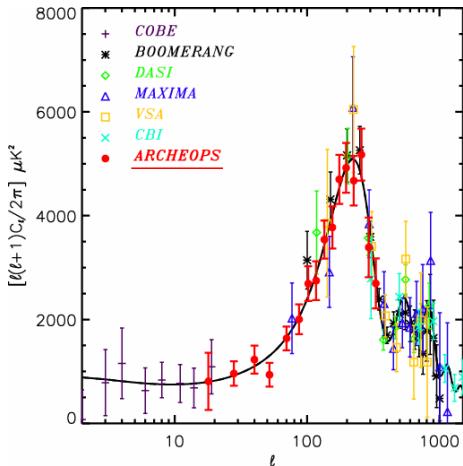
- Sachs-Wolf Intégré
 $\left(\frac{\Delta T}{T} \right)_{SIW} = \int (\Psi - \Phi)(x(\eta), \eta) d\eta$
 SIW tardif, quand $\Omega_0 h^2$ faible...



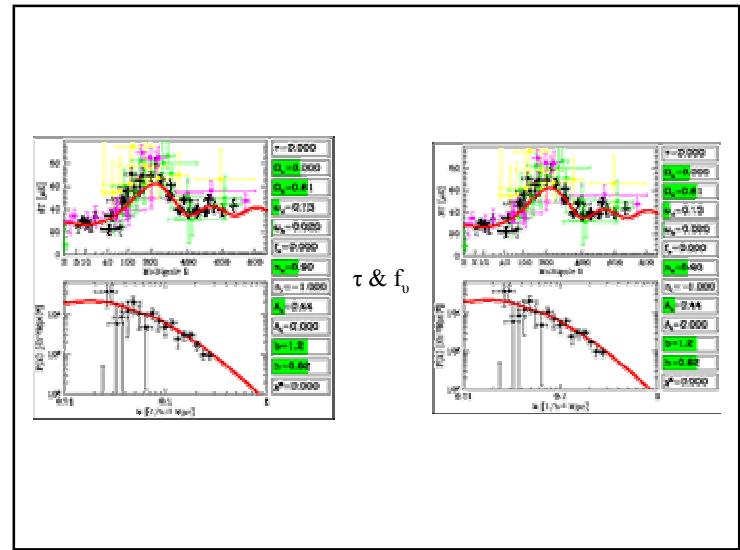
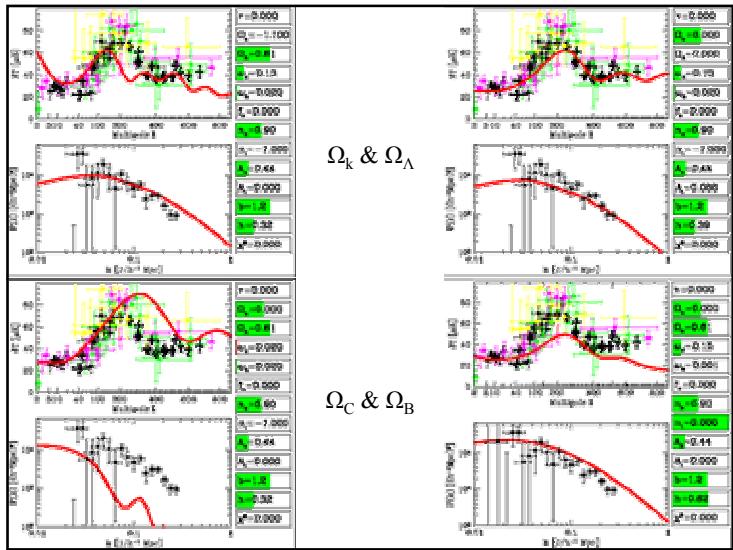
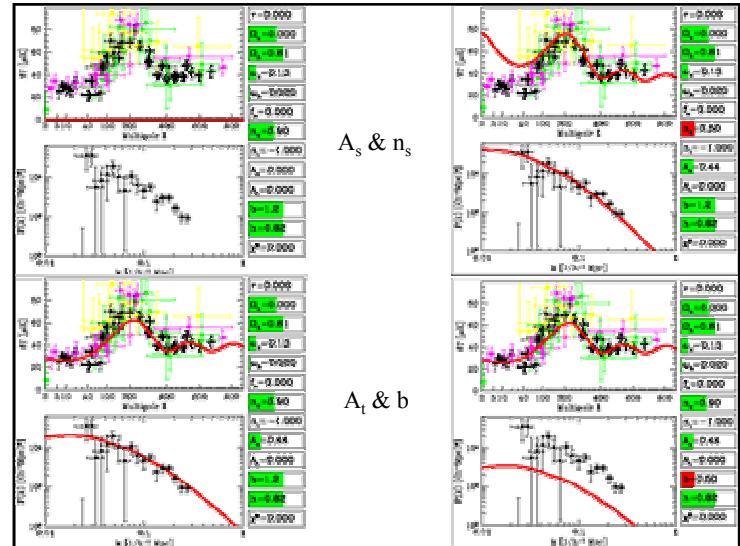
Foof for thoughts:

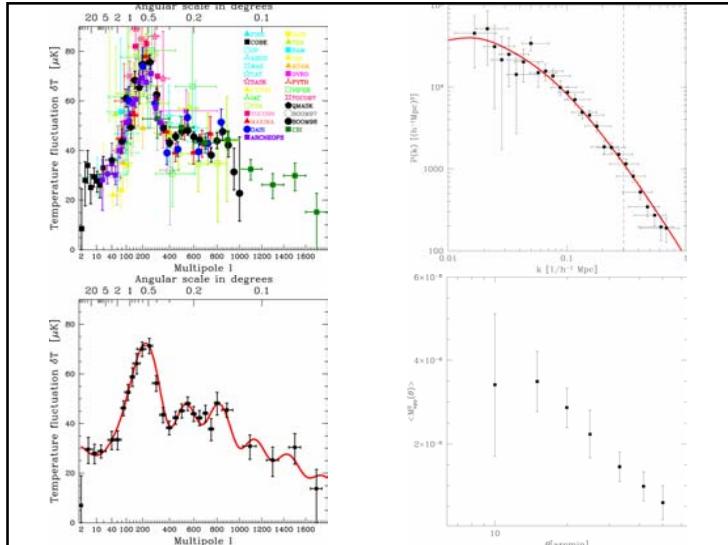
- In addition to Peebles & Yu 1970, Bond & Efstathiou + Seljak & Zaldarriaga 1977 and Kamionkowski et al. 1977 (polarisation), generalised by Hu & White 1997 (flat space) + Hu et al. 1998 (open) + Lewis et al. 2000 (closed).
- See For pedagogical approach, e.g.
 - These W. Hu astroph 9504057
 - Or preferably: Riazuelo (but in french)

SITUATION AUJOURD'HUI

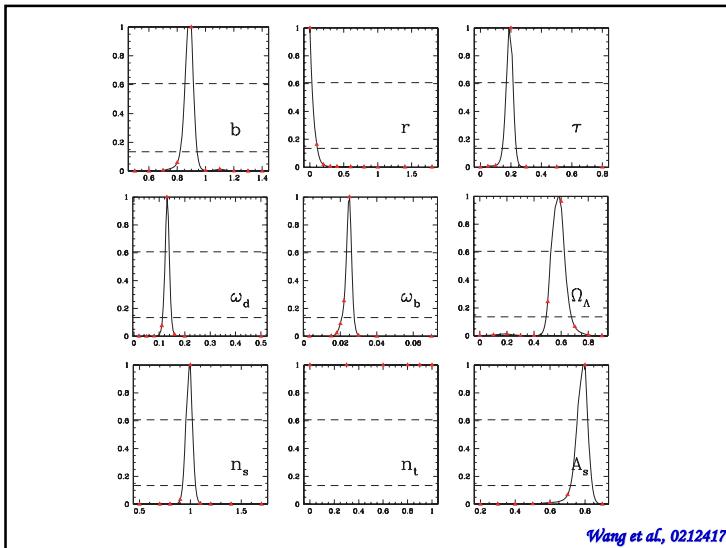
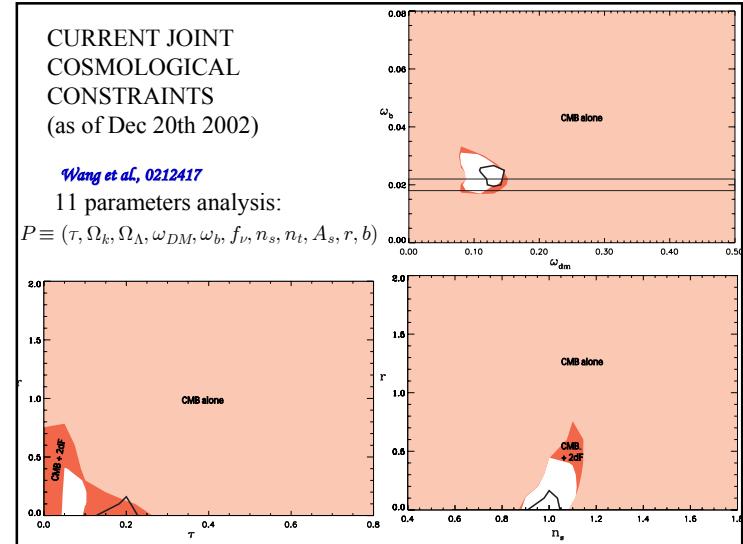


CMB & P(k) vs PARAMS

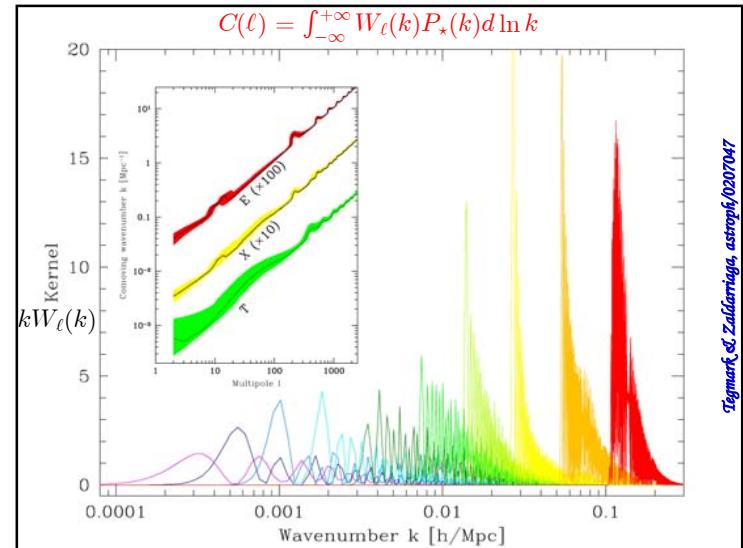




Wang et al., 0212417

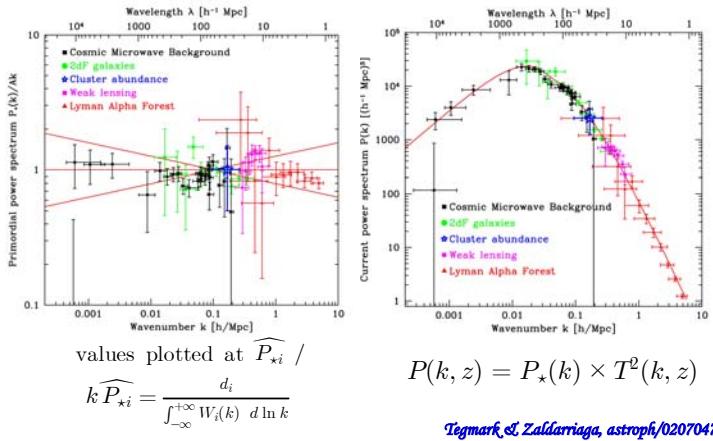


Tegmark & Zaldarriaga, astro-ph/0207047

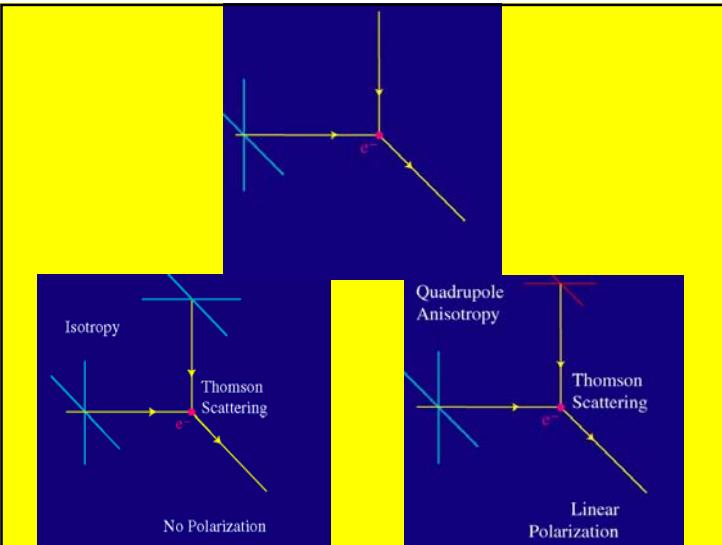


USING THE “CONCORDANCE MODEL” PARAMETERS...

$$h^2\Omega_m = 0.12, \quad h^2\Omega_b = 0.021, \quad \Omega_\Lambda = 0.71, \quad h = 0.7, \quad \tau = 0.05 \quad (\leftrightarrow z_r = 8), \quad \sigma_8 = 0.815$$



POLAR



NOTATIONS

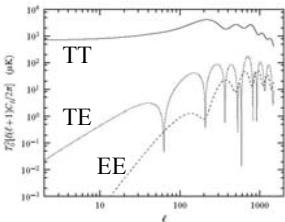
$P = \langle E(\hat{n})E^\dagger(\hat{n}) \rangle \propto \Theta(\hat{n})I + Q(\hat{n})\sigma_3 + U(\hat{n})\sigma_1 + V(\hat{n})\sigma_2$ in the Pauli basis
with $\Theta(\hat{n}) \equiv \Delta T(\hat{n})/T$; V is absent in cosmology
Under a rotation of the axes by ψ , $Q \pm iU \rightarrow \exp \mp 2i\psi (Q + iU)$

$\Theta_{lm} = \int d\hat{n} Y_{lm}^*(\hat{n}) \Theta(\hat{n})$
 $E_{lm} \pm iB_{lm} = - \int d\hat{n} \pm_2 Y_{lm}^*(\hat{n}) [Q(\hat{n}) \pm iU(\hat{n})]$
 $_s Y_{lm}$ = eigenfunctions of Laplace operator on rank s tensor; ${}_0 Y_{lm} \equiv Y_{lm}$
(NB : for small patch, spin - harmonic expansion \rightarrow Fourier expansion)
 $(Y_{lm} \rightarrow \exp il.\hat{n} \& \pm_2 Y_{lm} \rightarrow \exp \pm 2i\phi_l \exp il.\hat{n})$
(with $\phi_l \equiv$ azimuthal angle of Fourier wavevector l)
(E & B are then Q & U states in the coordinate system defined by l)

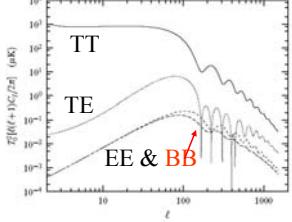
Observe Power spectra $\langle X_{lm}^* X_{l'm'} \rangle$ with $X \in \{\theta, E, B\}$
with $\langle X_{lm}^* X_{l'm'} \rangle = \delta_{ll'} \delta_{mm'}$ for statistically isotropic fields

POLARISATION DE TYPE B TRACE DU FOND PRIMORDIAL D'ONDES GRAVITATIONNELLES

Modes Scalaires



Modes Tensoriels

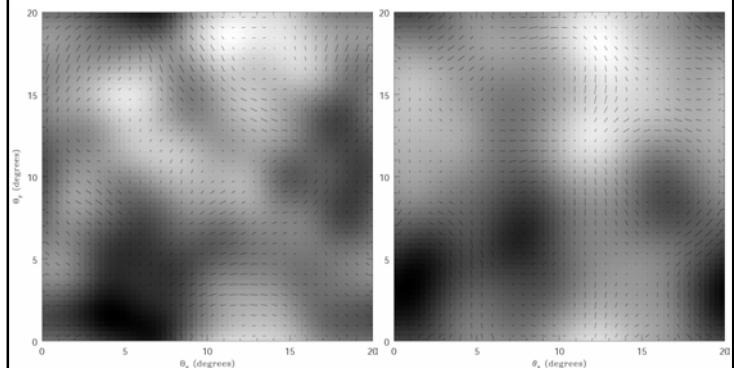


(Figures tirées de la Thèse de A.Riazuelo)

Au lieu d'utiliser les paramètres de Stockes Q & U , il est plus commode Ici d'utiliser 2 champs initialement E et B (resp. scalaire et pseudo-scalaire) qui sont indépendants de l'orientation du système de coordonnées (et reliés à (Q, U) par une transformation non-locale).

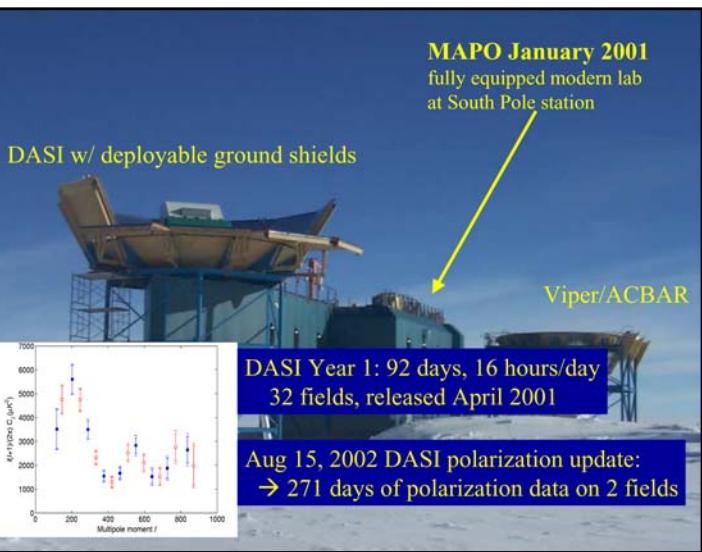
TEMPÉRATURE & POLARISATION

Cartes de 20 X 20 degrés, avec en fond le champ de température, avec la polarisation corrélée superposée

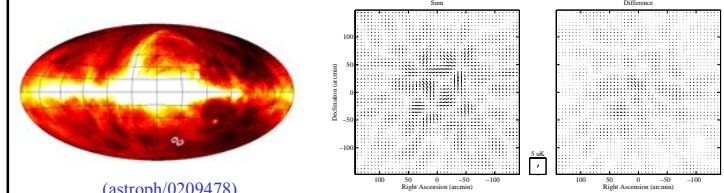


Perturbations scalaires adiabatiques
points chauds ↔ motifs tangentiels
points froids ↔ motifs radiaux

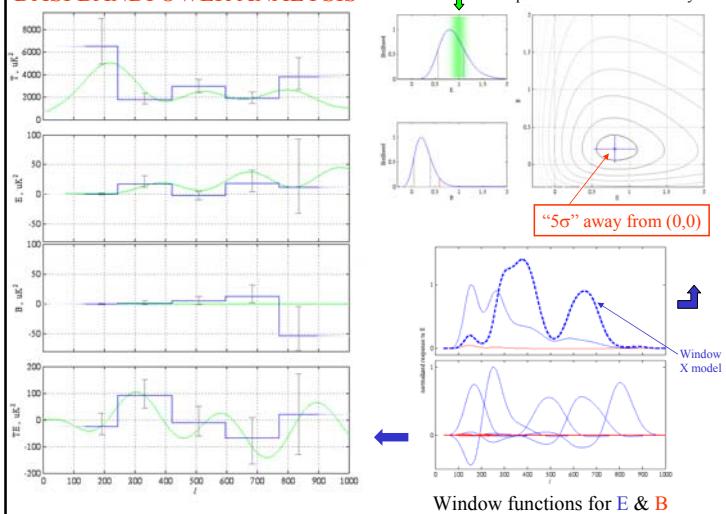
Perturbations tensorielles
L'association est inverse



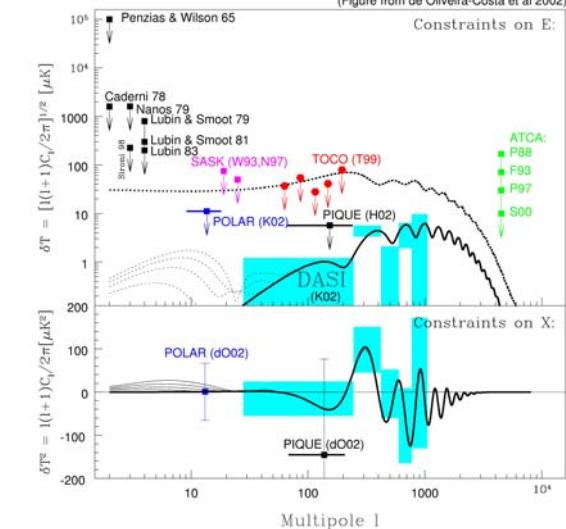
SITUATION AUJOURD'HUI PREMIERE DETECTION PAR DASI...



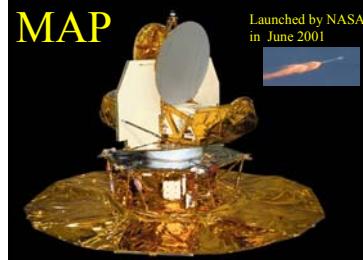
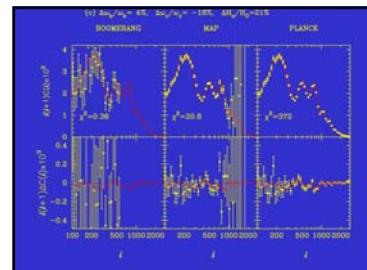
DASI BANDPOWER ANALYSIS



(Figure from de Oliveira-Costa et al 2002)



MAP & PLANCK



CMB experiments

	COBE/DMR	BOOMERanG	CB1	MAP	Planck
Freq. range	30-90	90-400 GHz	26-36 GHz	22-90 GHz	30-857 GHz
No. of freq. channels	3	4	10	5	9
Angular resolution	7°	10.5°-13°	4°-5.8°	12°-6.66°	5°-3.3°
Sky coverage	100%	3%	3%	100%	100%
$10^6 \Delta T$ Sensitivity ($10^6 \times 10^6$)	20 (in $10^6 \times 10^6$)	~40	~15	~50	~5
Polarisation	no	Future	yes	yes	yes
Raw data size	1 Gbyte	10 Gbyte		1 Tbyte	5 Tbyte
No of pixels	6×10^4	10^5		10^6	5×10^6
Time to reduce data	2 yrs	2 yrs		1 yr	1 yr

1st generation

2nd generation

3rd generation



PLANCK

EXPERIMENTAL CHARACTERISTICS

MAP & PLANCK both **full sky**, at **L2**, with **polarization** capability, making **highly redundant measurements**.

Differences:

Resolution: $\sigma_{\text{Beam}} \sim 10' \rightarrow 5', \sigma_M/\sigma_P \geq 2$

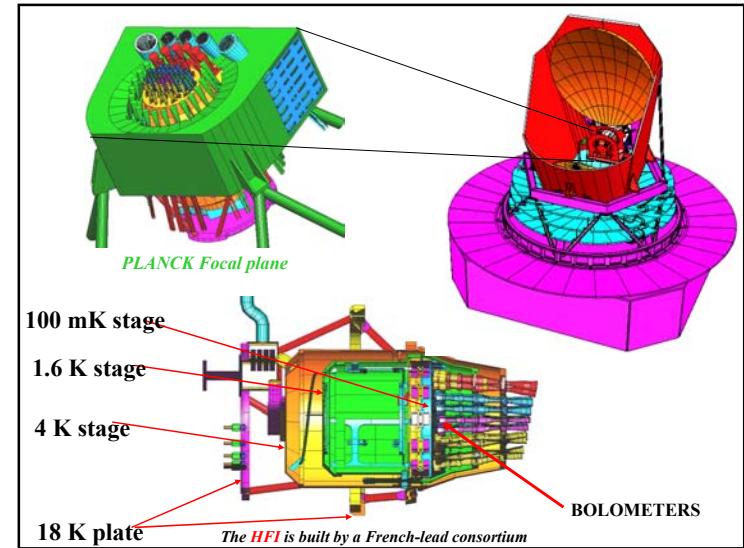
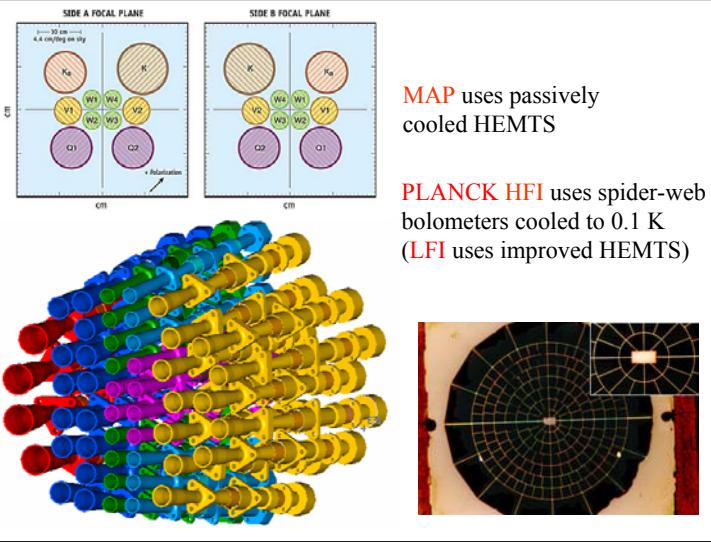
Sensitivity: $S = \sigma_{\text{pix}} \Omega_{\text{pix}}^{1/2} = 11.8 \mu\text{K.deg} \rightarrow 0.8 \mu\text{K.deg}, S_M/S_P > 10$ (mission duration sensitive, $\propto t^{1/2}$)

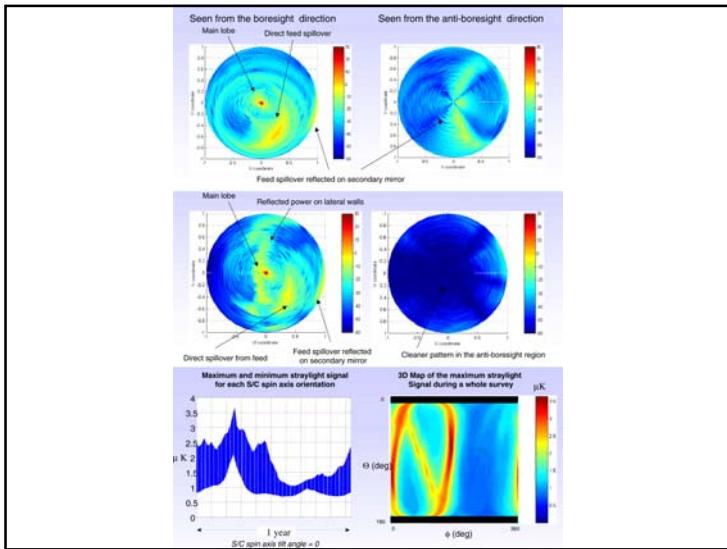
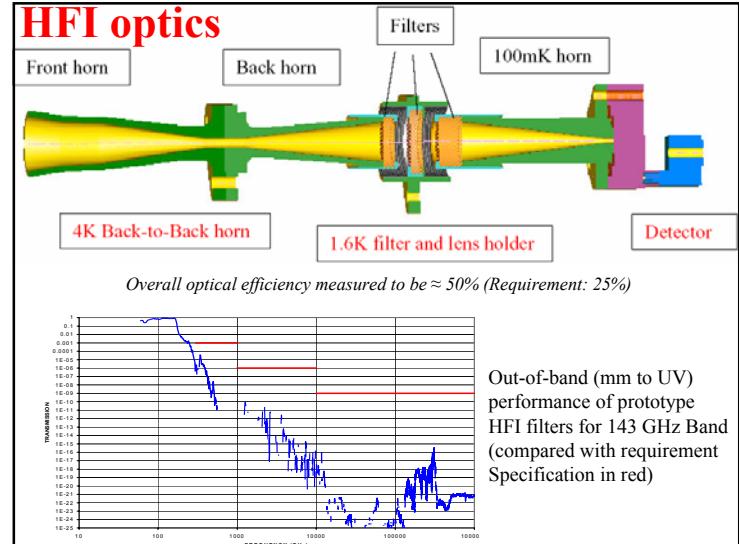
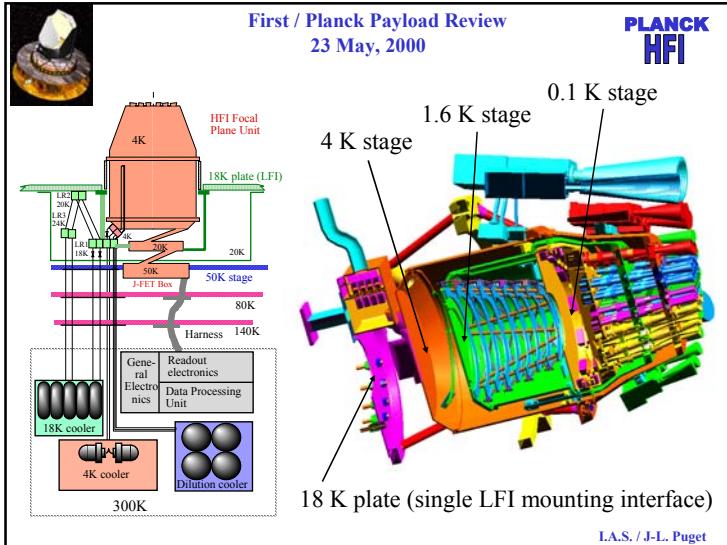
Frequency coverage: $[30, 44, 70, 90]_{\text{MAP}} \rightarrow [30, 44, 70, 100]_{\text{LFI}} + [100, 143, 217, 354, 550, 857]_{\text{HFI}}$, **a new window in space** (and foregrounds control)

Ground & balloon experiment will continue doing a wonderful job at (very) good σ_B & S on a (relatively low) fraction of the sky (& relatively short duration / 1 year)

NB:

$$F_{ij} = \sum_l \frac{(2l+1)f_{\text{sky}}}{2} [C_l + C_N \exp \theta_b^2(l^2)]^{-2} \frac{\partial C_l}{\partial T_j} \frac{\partial C_l}{\partial T_i}, \quad \sigma_i = F_{ii}^{-1/2}$$



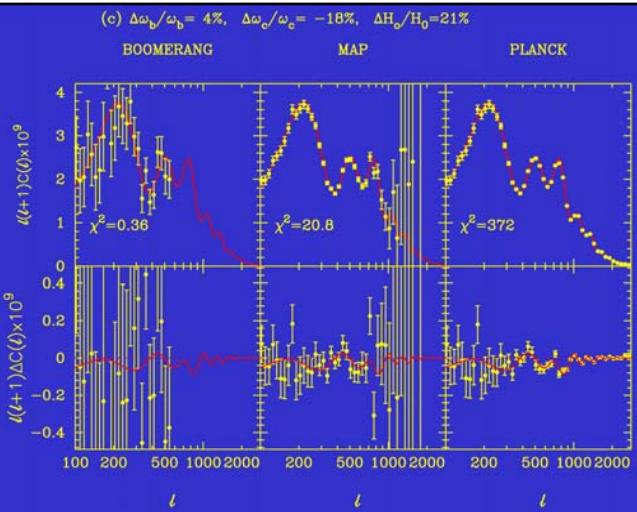
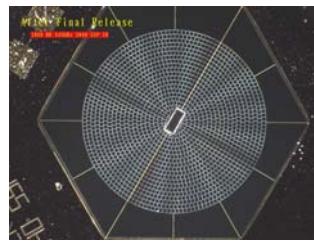
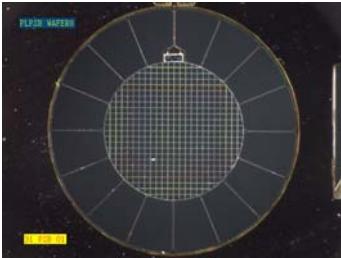




Bolomètres Planck

$\text{NEP} \approx 10^{-17} \text{ W Hz}^{-1/2}$

Time constant $\approx 2\text{ms}$



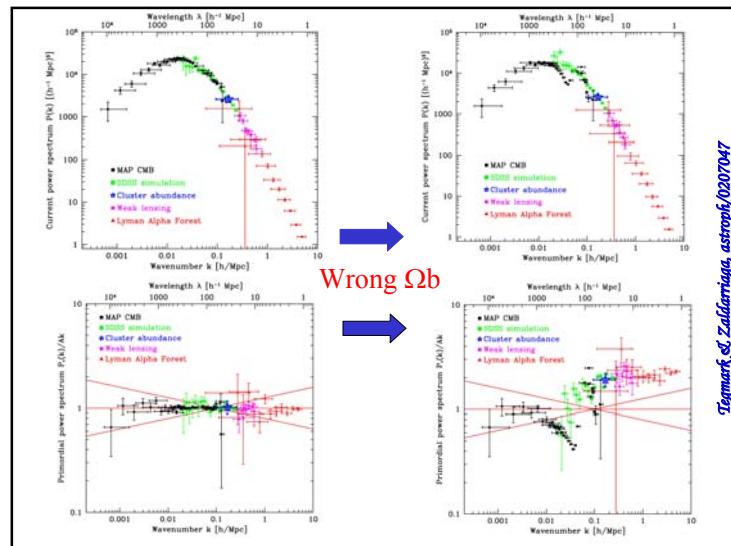
Planck References (voir aussi cours des Houches, FRB, Lamarre, Puget)

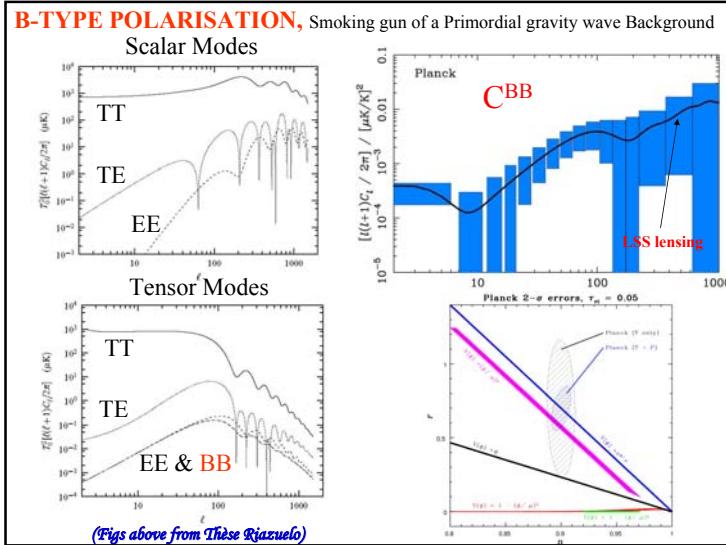
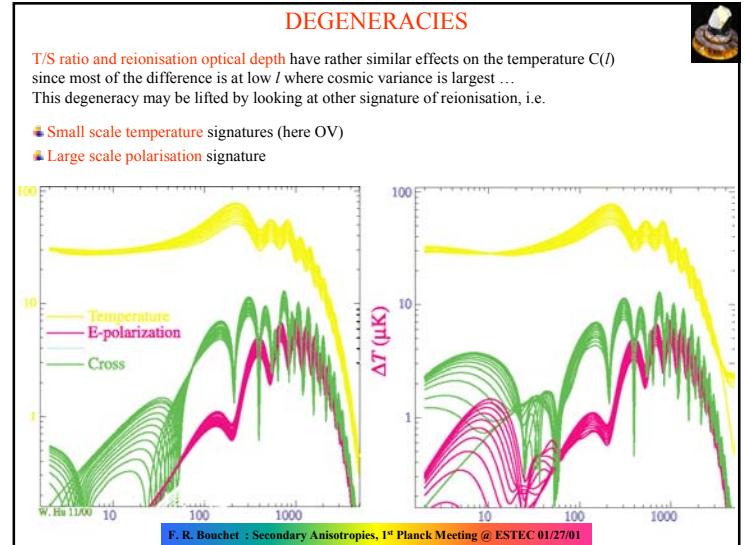
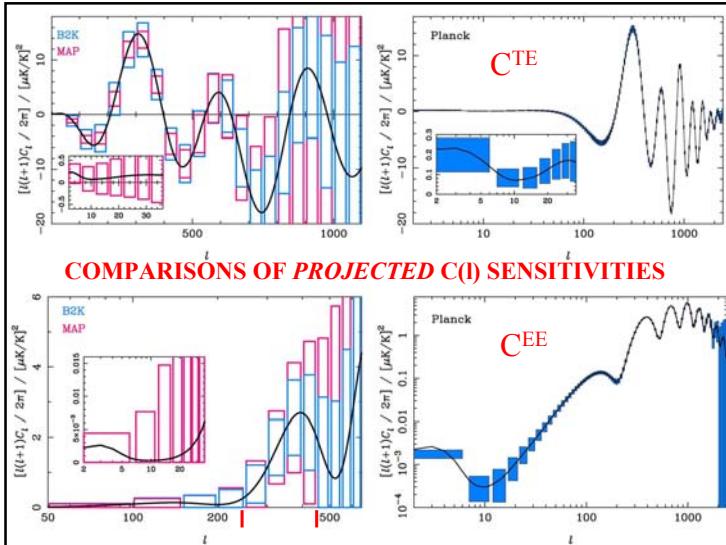
- The « red book » (end of phase A report)
<http://tonno.tesre.bo.cnr.it/Research/PLANCK/Redbook>

- AAOs for the instruments
http://tonno.tesre.bo.cnr.it/Research/PLANCK/ONLY_SOMEONE/AODO_CS/intro.html

- Science team web pages @ ESTEC
<http://astro.estec.esa.nl/SA-general/Projects/Planck/>

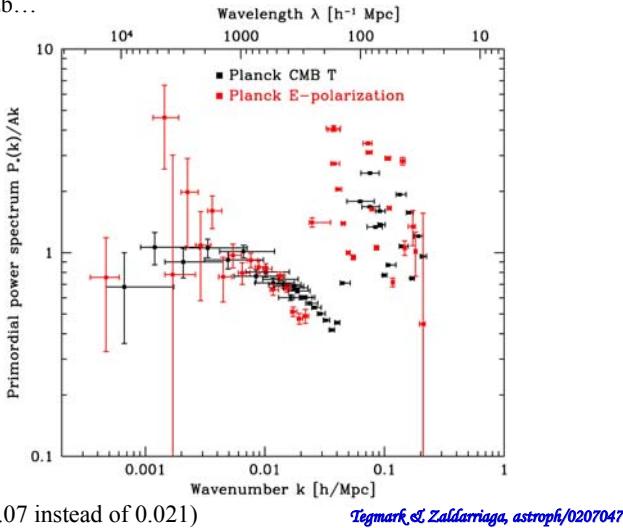
- The « blue book » (soon)
 « The scientific program of Planck »,
 as of 2002





- ## USING THE C(l)...
- Suppose the minimal model (standard inflation) holds; then :
 - Measure the parameters with phenomenal precision (if no inconsistency appears)
 - Verify consistency with other « clean » probes like gravitational lensing, and if OK, refine even further the parameters determinations
 - Check consistency with more indirect probes, and extract from that “gastrophysical” lessons...
 - Consider weak deviations around the minimal model by relaxing priors (prejudice?) on (the absence of) extra degrees of freedom (e.g. isocurvature modes, topological defects, extra scales in IC spectrum...)
 - Consider more radical deviations as in brane cosmologies [e.g. $H^2=8\pi/3(\rho+p^2/\sigma)$ for Randall-Sundrum type models], although detailed predictions might turn out difficult to compute (e.g. C.S.)
 - All tastes should be represented in a collaboration like Planck with ~ 350 physicists (today).
 - NB: $C(l)$ is only a first moment (transform of 2-pt correlation function)

Wrong Ω_b ...



SECONDARY EFFECTS

SECONDARY ANISOTROPIES



By definition, secondary anisotropies occur after recombination, via two broad types of mechanisms:

Gravitational effects:

Photon path (relative) deflection through **Lensing**, a smoothing effect

Photon path through time-varying potentials

Integrated Sachs-Wolfe effect, or **Late ISW** (linear, large scales)

Rees-Scrima (non-linear, small scales)

“Moving lens” effect (Butterfly pattern from clusters, “Kaiser-Stebbins” from strings)

Thomson (re-) scattering:

from Reionisation

Damping of the primary (homogeneous)

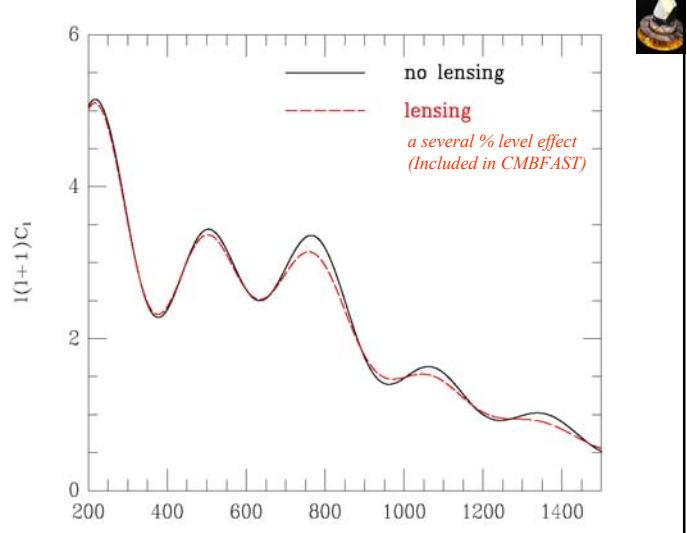
Vishniac-Ostriker (small scale, KSZ of weakly non-linear field)

Polarisation generation (large scales)

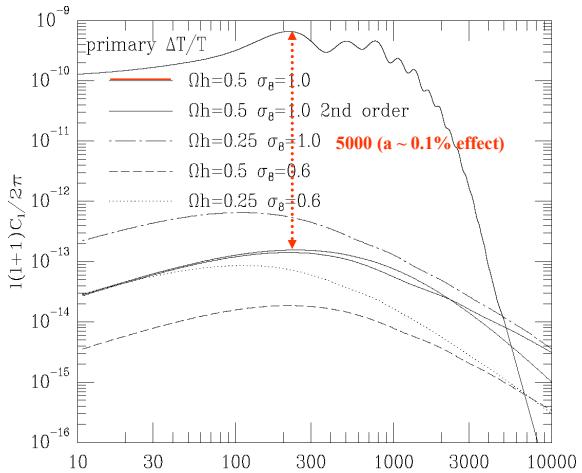
Inhomogeneous reionisation (KSZ from reionised bubble fronts)

from hot gas within LSS: (Late) **Kinetic SZ** (from clusters, filaments)

NB: Most effects are **weak** and are coming, or are traced by, from the **same (low-z)** structures.
Analyses will thus be difficult, since effects will be intertwined, but we can (maybe) learn a lot...



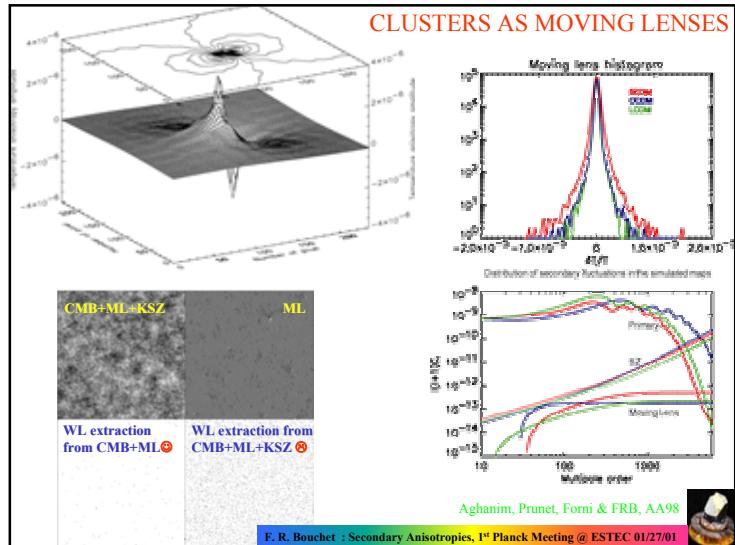
REES-SCIAMA CONTRIBUTION



F. R. Bouchet : Secondary Anisotropies, 1st Planck Meeting @ ESTEC 01/27/01

Seljak (1996).

CLUSTERS AS MOVING LENSES



Aghanim, Prunet, Forni & FRB, AA98



INHOMOGENEOUS REIONISATION...

Studies being made to study it with semi-analytical or hybrid models of galaxy formation together with “poor man”’s radiative transfer algorithms...

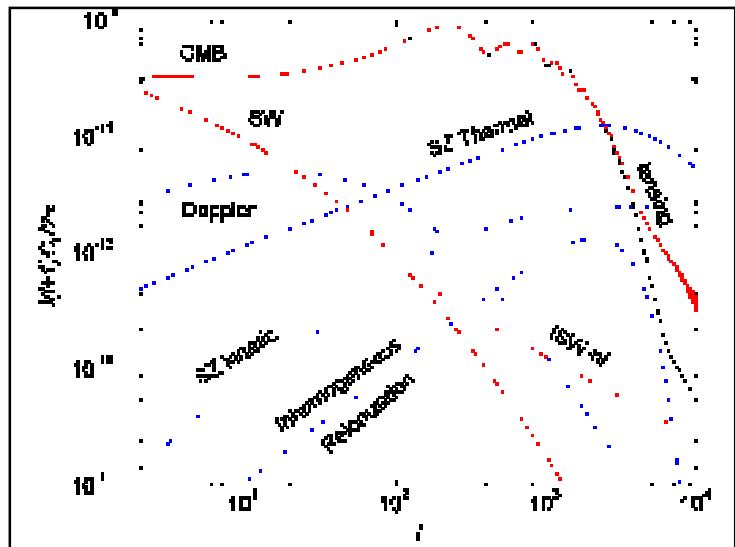
Will be a major theme of IGM TMR...

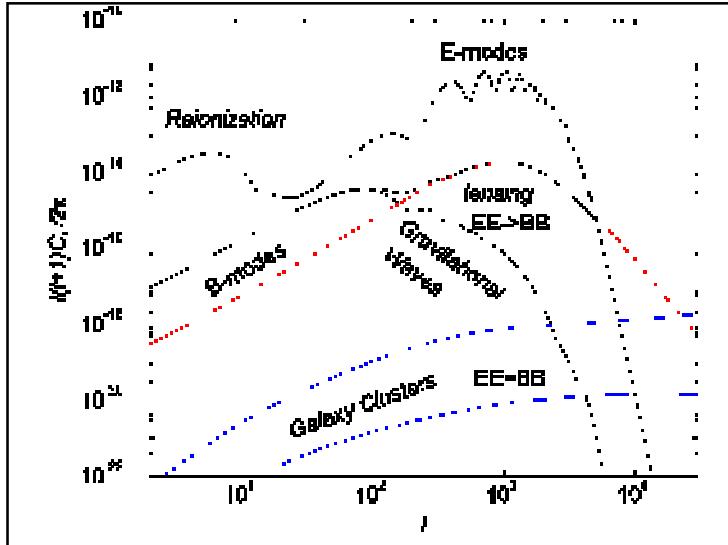
Direct optical studies of the end of dark ages should be rather challenging, even with NGST...

Disentangling various small scale “secondaries” will also be challenging, even with interferometers...

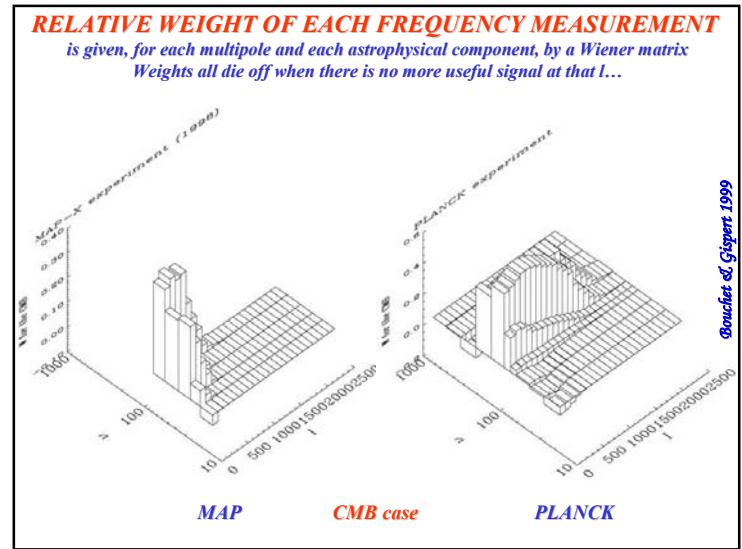
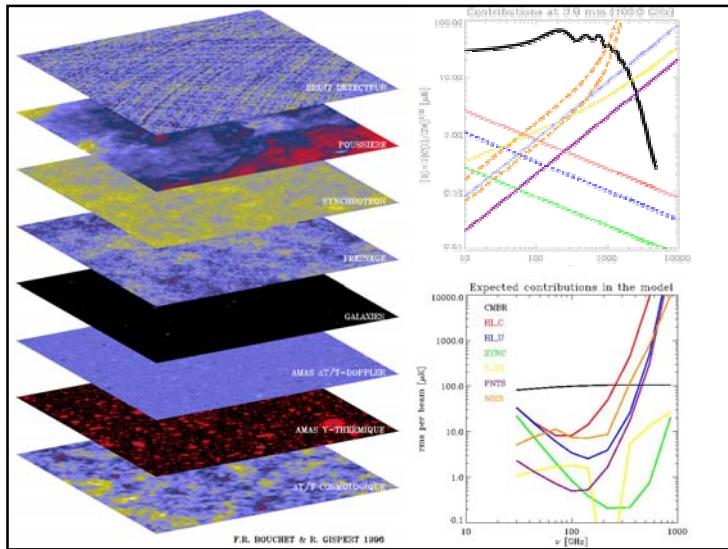
Ciardi, Ferrara, Marri, Raimondo, astroph/000581

Changing the IMF





FORE-GROUNDS

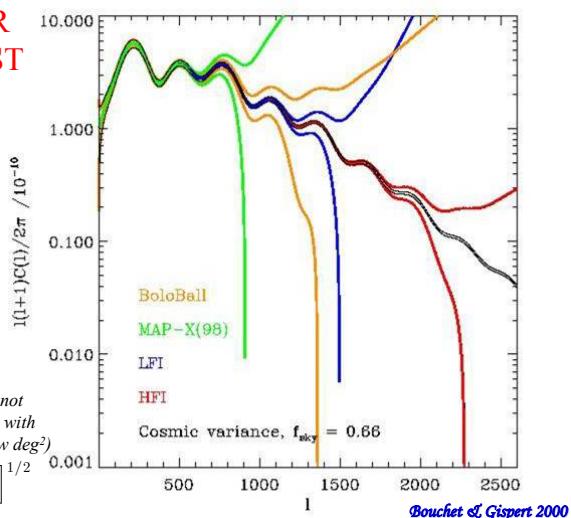


1 σ ERROR FORECAST

Foreground separation errors included;

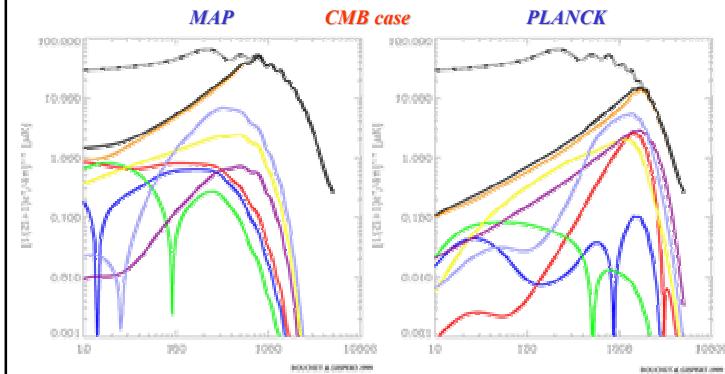
NO band averaging performed ($\ell \sim 2500$ OK)

NB: a BoloBall cannot map 66% of the sky with that sensitivity (-few deg 2)



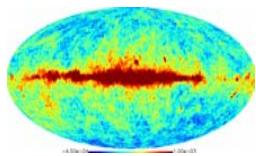
Bouchet & Gispert 2000

ANGULAR RESOLUTION, SENSITIVITY, FREQUENCY COVERAGE COMBINED EFFECT ON A FIDUCIAL SKY MODEL: RESIDUALS



Results turn out to be rather robust vs. « reasonable » foregrounds model variations. But we might be wrong about reason...

MAP



22GHz

(30GHz)

40GHz

(60GHz)

90 GHz

Detector skies

CMB error map

-60 Jy

0.00 Jy

60 Jy

120 Jy

180 Jy

240 Jy

300 Jy

360 Jy

420 Jy

480 Jy

540 Jy

600 Jy

660 Jy

720 Jy

780 Jy

840 Jy

900 Jy

960 Jy

1020 Jy

1080 Jy

1140 Jy

1200 Jy

1260 Jy

1320 Jy

1380 Jy

1440 Jy

1500 Jy

1560 Jy

1620 Jy

1680 Jy

1740 Jy

1800 Jy

1860 Jy

1920 Jy

1980 Jy

2040 Jy

2100 Jy

2160 Jy

2220 Jy

2280 Jy

2340 Jy

2400 Jy

2460 Jy

2520 Jy

2580 Jy

2640 Jy

2700 Jy

2760 Jy

2820 Jy

2880 Jy

2940 Jy

3000 Jy

3060 Jy

3120 Jy

3180 Jy

3240 Jy

3300 Jy

3360 Jy

3420 Jy

3480 Jy

3540 Jy

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8100 Jy

8160 Jy

8220 Jy

8280 Jy

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8580 Jy

8640 Jy

8700 Jy

8760 Jy

8820 Jy

8880 Jy

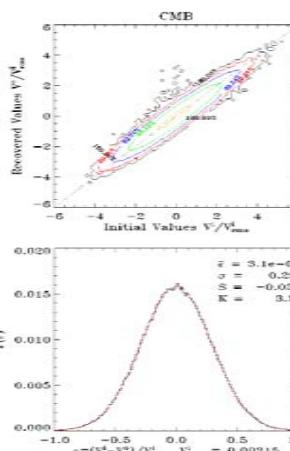
8940 Jy

9000 Jy

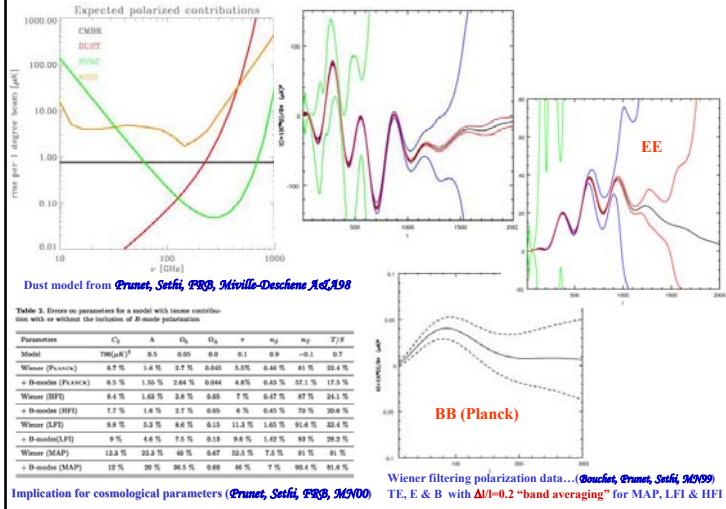
Prunet, Teyssier, Scully, Bouchet, Gispert, 2001 *ApJ*, 551, 13P

PRUNET - TEYSIER - BOUCHET - GISPERT - 9/9/9

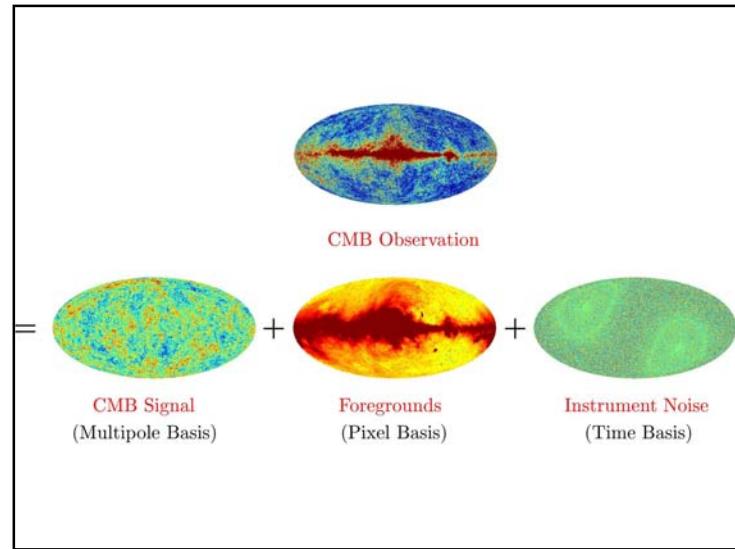
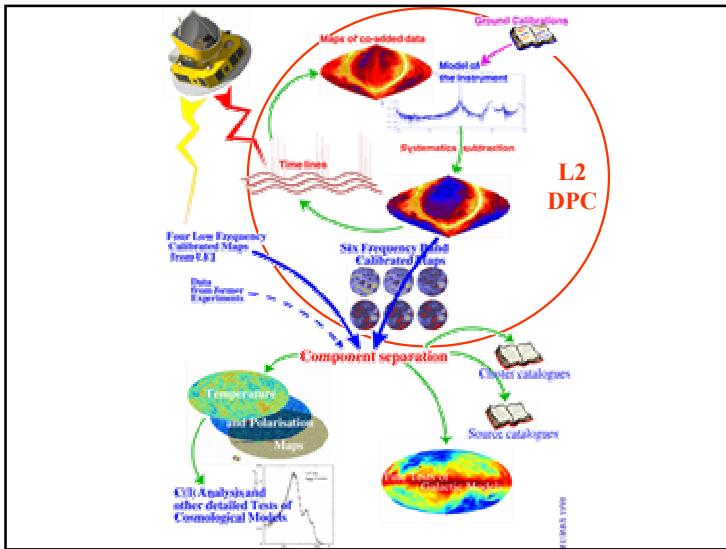
MAP



POLARISATION & FOREGROUNDS...

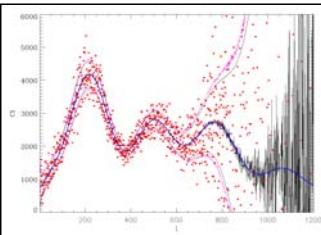


ANALYSIS CHALLENGE



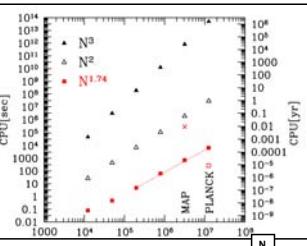
USED WITH ARCHEOPS

SpICE on simulated MAP experiment



- Central curves : Model/*SpICE* expectation (no apodization, 1000 realizations)
- Upper and lower pairs of curves : Optimal errors/errors from *spice* with $1/\sigma^2$ weighting
- Dots : Individual realizations

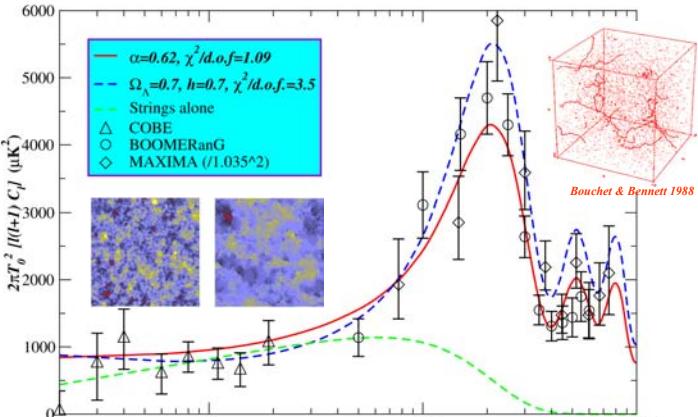
Timings of *SpICE* versus other methods on a 500MHz CPU



- N^3 : MADCAP
- N^2 : correlation function method with brute force (Szapudi et al. 2001)
- $N^{1.74}$: *SpICE* (speedup is obtained thanks to Healpix fast harmonic transform)
- Cross : Oh, Spergel & Hinshaw (1998) method
- Open square : expected speed for PLANCK in 2007

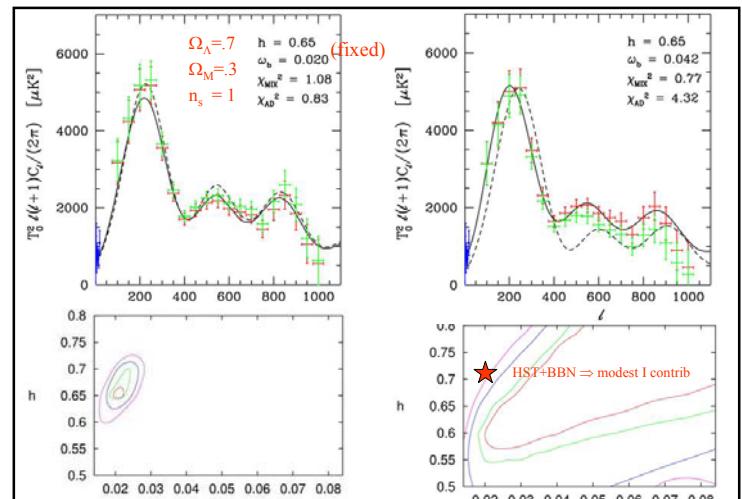
ISOCURVATURE DEGENERESCENCE VS MAP & PLANCK

Best fit with BOOMERanG and MAXIMA



En attente de la thèse de C. Ringeval (05/07/02) pour faire (beaucoup?) mieux.

Multipole Bouche, Peter, Riazuelo, Sakellariadou 2000



Mix à la Bucher et ω_b al. [0007360]
(Bucher et al. [0012141], $\Delta\Omega 2\% \rightarrow 577\%$)

Trotta, Riazuelo, Durrer [0104017]

ISOCURVATURE MODES WITH SAME POWER-LAW I.C.

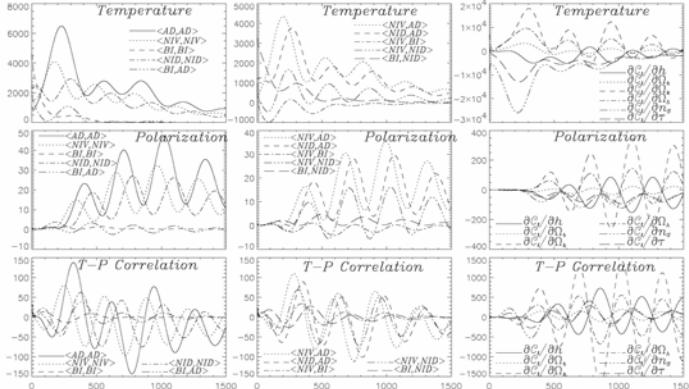


FIG. 1. CMB multipole spectra for the various modes, their cross-correlations, variations in the cosmological parameters. From top to bottom the rows show $(l+1)C_l/2\pi$ for the temperature, polarization, and temperature-polarization cross correlation, respectively, in μK . The C_l spectra for the various modes and their cross correlations are shown in the first two columns. The rightmost column shows the derivatives of the spectra with respect to the different cosmological parameters. The modes are indicated as follows: adiabatic (AD), neutrino isocurvature velocity (NIV), baryon isocurvature (BI), and neutrino isocurvature density (NID). A fiducial model with the parameter choices $\Omega_b = 0.06$, $\Omega_\Lambda = 0.69$, $\Omega_{\text{redm}} = 0.25$, $h = 0.65$, $\tau_{\text{reion}} = 0.1$ and $n_s = 1$ has been assumed. Because the CDM isocurvature mode produces a spectrum nearly identical to that of the BI mode, it is not considered separately.

[Bucher, Moodley, Turok, astroph/0012141](#)

	MAP T adia only	MAP TP adia only	MAP all modes	MAP TP all modes	PLANCK T adia only	PLANCK TP adia only	PLANCK T all modes	PLANCK TP all modes
$\delta h/h$	12.37	7.42	175.84	20.40	9.93	3.69	40.13	7.31
$\delta \Omega_b/\Omega_b$	27.76	13.34	325.38	28.57	19.37	7.26	68.85	14.42
$\delta \Omega_k$	9.79	2.72	75.32	4.55	4.92	1.83	20.56	3.59
$\delta \Omega_\Lambda/\Omega_\Lambda$	12.92	5.02	123.63	18.53	2.74	1.21	5.93	2.45
$\delta n_s/n_s$	7.02	1.62	89.89	6.53	0.73	0.37	3.92	0.90
τ_{reion}	37.39	1.81	104.81	2.23	8.25	0.41	35.35	0.74
(NIV, NIV)	..	..	114.34	11.47	..	..	43.45	1.36
(BI, BI)	..	..	573.46	29.71	..	..	53.29	6.16
(NID, NID)	..	..	351.79	29.87	..	..	19.18	4.77
(NIV, AD)	..	..	343.70	44.06	..	..	121.59	8.21
(BI, AD)	..	..	1035.02	59.25	..	..	58.75	15.03
(NID, AD)	..	..	1287.60	67.49	..	..	114.39	13.87
(NIV, BI)	..	..	601.70	32.29	..	..	46.91	7.72
(NIV, NID)	..	..	744.00	46.46	..	..	80.01	7.55
(BI, NID)	..	..	534.32	39.11	..	..	100.97	7.56

TABLE I. This table indicates the one sigma percentage errors on cosmological parameters and isocurvature mode amplitudes anticipated for the MAP and PLANCK satellite experiments. In the column headers, T denotes constraints inferred from temperature measurements alone, TP those from the complete temperature and polarisation measurements, and T+P those inferred if temperature and polarisation information is used separately without including the cross-correlation.

[Bucher, Moodley, Turok, astroph/0012141](#)

Phase space ““volume””:

	M-T-A	M-TP-A	M-T-F	M-TP-F	P-T-A	P-TP-A	P-T-F	P-T+P-F	P-TP-F
V1	1.10⁻⁵	4.10⁻⁹	5	7.10⁻⁷	2.10⁻⁸	9.10⁻¹²	5.10⁻⁵	6.10⁻¹⁰	5.10⁻¹¹
V2				3.10⁶	1.10⁻⁴			1.10⁻²	3.10⁻¹¹
VT					2.10⁷	8.10⁻¹¹		6.10⁻⁷	2.10⁻²⁰

NB: Still assuming simple scale-invariant (initial) $P(k)...$

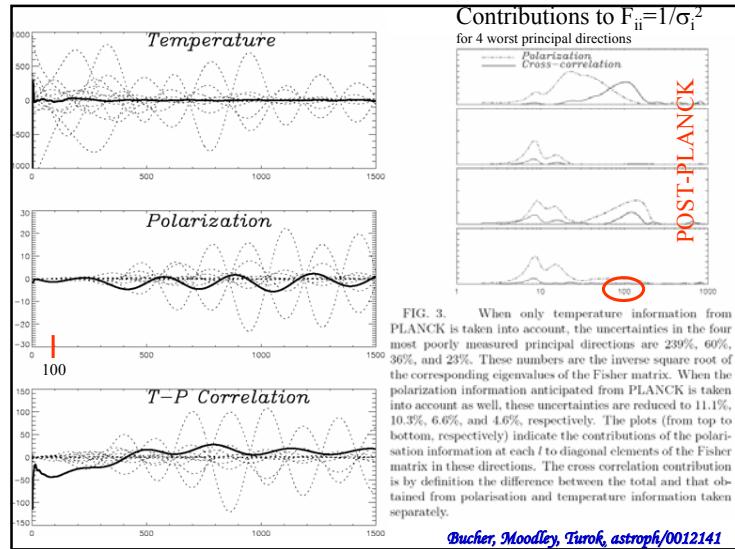
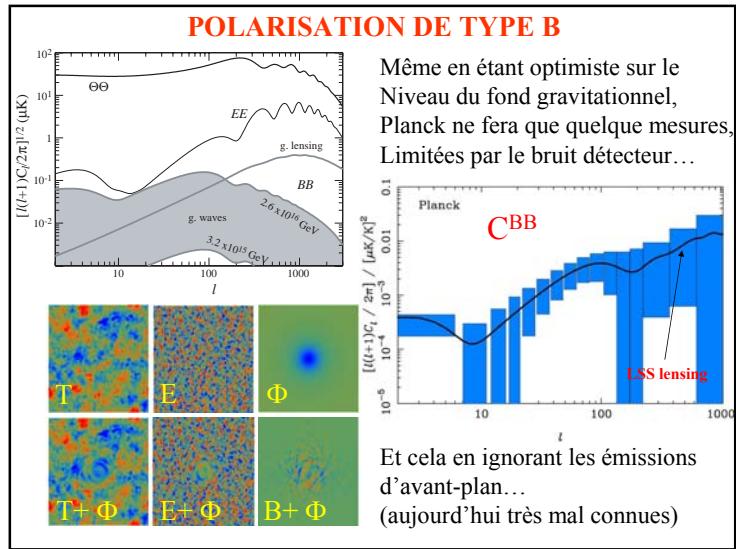


FIG. 3. When only temperature information from PLANCK is taken into account, the uncertainties in the four most poorly measured principal directions are 23%, 60%, 36%, and 23%. These numbers are the inverse square root of the corresponding eigenvalues of the Fisher matrix. When the polarization information anticipated from PLANCK is taken into account as well, these uncertainties are reduced to 11.1%, 10.3%, 6.6%, and 4.6%, respectively. The plots (from top to bottom, respectively) indicate the contributions of the polarization information at each l to diagonal elements of the Fisher matrix in these directions. The cross correlation contribution is by definition the difference between the total and that obtained from polarization and temperature information taken separately.

[Bucher, Moodley, Turok, astroph/0012141](#)



Même en étant optimiste sur le Niveau du fond gravitationnel, Planck ne fera que quelques mesures, Limitées par le bruit détecteur...

Et cela en ignorant les émissions d'avant-plan... (aujourd'hui très mal connues)

The sensitivity increase required

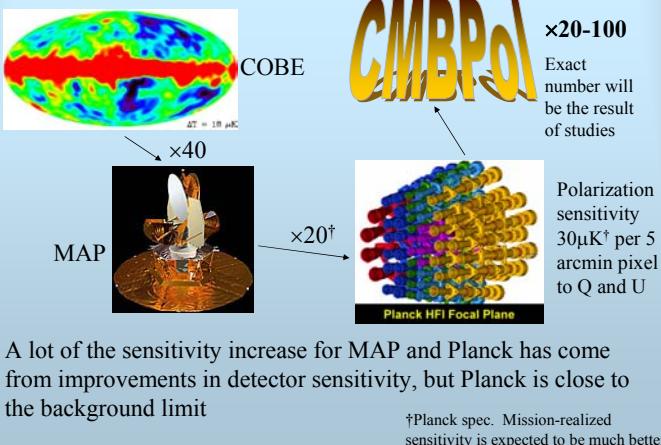


TABLE 1. CMB anisotropy milestones

Phenomena	Experiments	Date
Sachs-Wolfe	COBE DMR	'92
Degree-scale	many	'93-'99
First peak	Toco, Boom, Maxima	'99-'00
Secondary peaks	DASI, Boom	'01
Damping tail	CBI	'02
Polarization detection	DASI	'02
Secondary anisotropy	CBI?, BIMA?	'02?
Polarization peaks	—	future
non/Gaussianity	—	future
Reionization bump	—	future
Lensing of peaks	—	future
Dark energy ISW	—	future
Grav.-wave polarization	—	future

Hu 0210696

