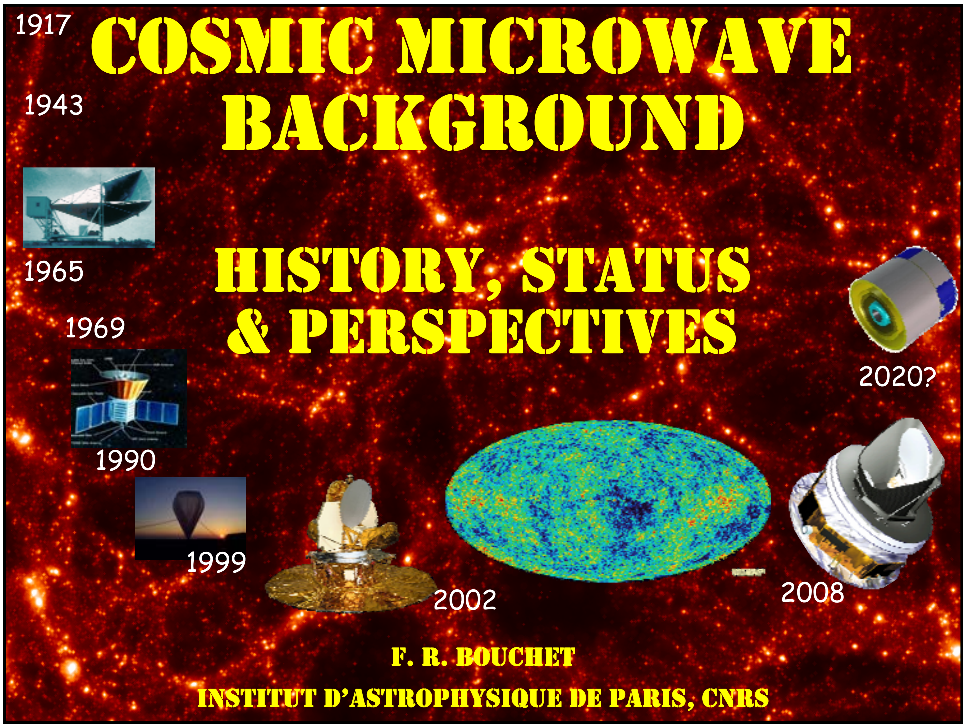


COSMIC MICROWAVE BACKGROUND

HISTORY, STATUS & PERSPECTIVES

F. R. BOUCHET
INSTITUT D'ASTROPHYSIQUE DE PARIS, CNRS

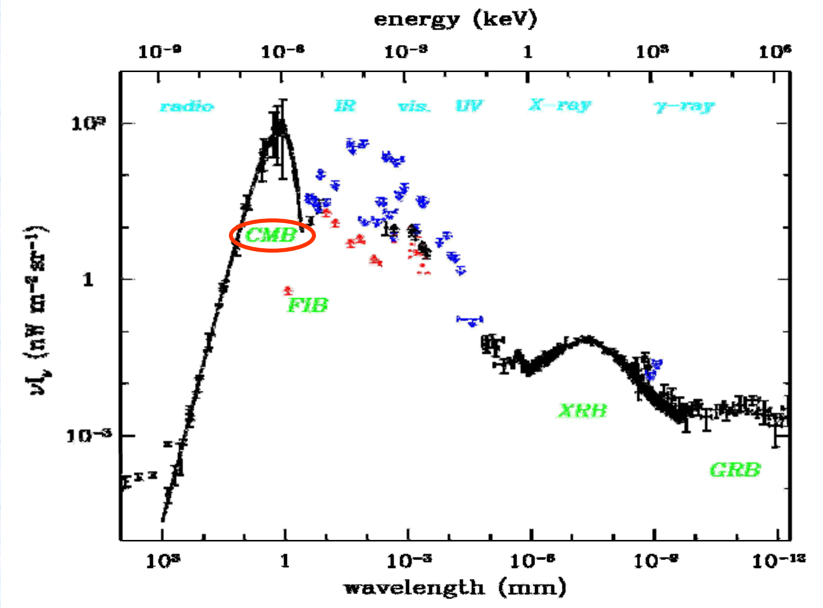
MENU

- Cosmology has been covered by Silk & Uzan. See in particular Uzan for perturbation theory, which will be discussed in depth by Mukhanov
- Inflation & DM also, cf. Starobinsky
- I will therefore mostly focus on other aspects concerning the CMB

- The CMB Introduction & Historical overview
  - Spectrum
  - Anisotropies
- WMAP
- Planck & beyond
- Time permitting:
  - Secondary fluctuations (Gravitational effects & Thomson (re-) scattering)
  - Component separation
  - Practical statistics (Estimating C(l), Higher order, E/B separation…)

- Some useful web sites:
  - http://background.uchicago.edu/~whu (Wayne Hu)
  - http://www.astro.ucla.edu/~wright/cosmolog.htm (Ned Wright)
  - http://space.mit.edu/home/tegmark (Max Tegmark)
  - http://cosmologist.info (Anthony Challinor)
  - http://www.planck.fr (Planck/HFI Consortium site)

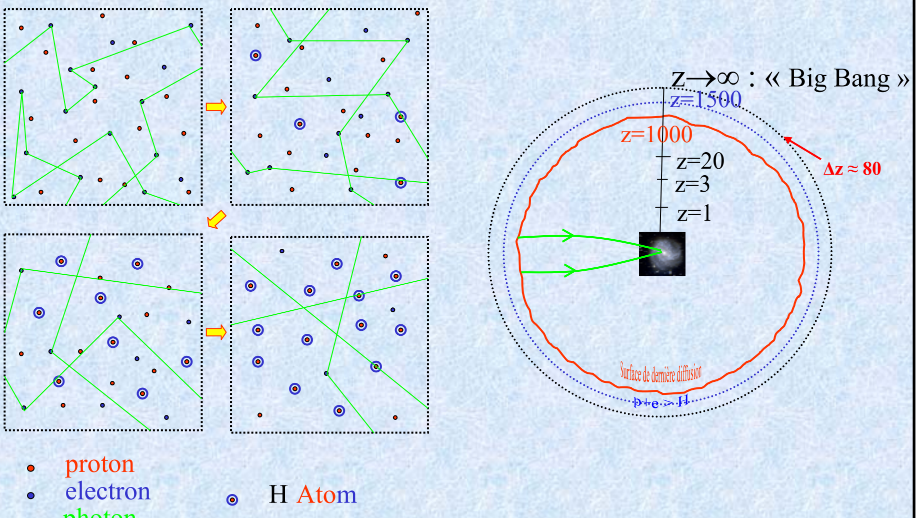
CMB NUMERICAL DOMINATION (~93%)



STANDARD BB REMINDER 1/2

- At early times, matter & radiation are in quasi-perfect thermal equilibrium > BB distribution
- If deviations are created, then free-free interactions provide thermalisation at all $z > 3 \times 10^7$.
- Afterwards, the ff interaction time scale Γ^{-1} becomes longer than the expansion timescale H^{-1} : this process is «frozen ».
- Elastic (Thomson) scattering interaction has a mean free path $\lambda = 8.3\ H^{-1}/[x_e(1+z)]$. As long as the plasma is ionized, $x_e = 1$ at $z > 1100$, the universe is opaque.
- At t <~3000K, x_e falls quickly (Δz~80) to $x_e < 10^{-2}$ at z <~ 1000, the universe is transparent, till reionisation by galaxies & quasars
- Thomson optical depth from now till reionisation is rather weak, $\tau \sim 0.1$: expect only small secondary distortions

CMB & LAST SCATERING SURFACE



One of the 3 pillars of the standard model

STANDARD BB REMINDER 2/2

- Expected temperature can be evaluated simply from basic physics.
- Alpher, Beth, Gamow (48) showed that chemical elements could have formed in the expanding BB, although forgetting that radiation dominates over matter, which was corrected by Gamow the same year & further corrected for a numerical error by Alpher & Herman, who finally predicted T ~5K.
- Indeed, to get ~25% He, need to synthesize D first, which can only happen at T $\sim 10^9$K, when the fusion can take place but without immediate photo-dissociation (1MeV $\sim 10^{10}$K).
- Then H^{-1} ~200s, and substantial production ($H^{-1} \sim 1/[n_B\, \sigma_{pn>D}\, v]$, ie the Gamow condition) requires a baryon density $n_B \sim 10^{18}\mathrm{cm}^{-3}$, to be compared to today, $\sim 10^{-7}\mathrm{cm}^{-3}$, which then fixes $1+z_{NS} \sim 2 \times 10^8$.
- Therefore $T_{CMB} = 10^9/(1+z_{NS}) \sim 5$K !

On the CN non-discovery

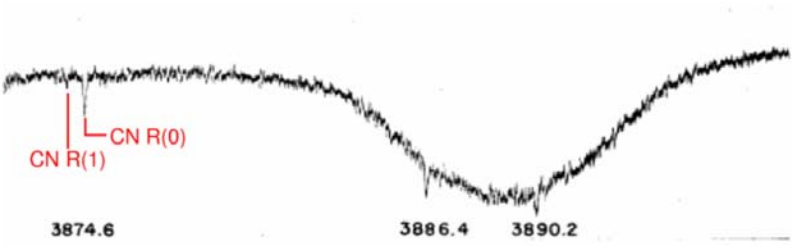


Plate 3 of Adams (1941, ApJ, 93, 11-23)

Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

"From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3° K follows, which has of course only a **very restricted meaning**."

There went Herzberg's [second] Nobel Prize.

From a Ned Wright talk

Fred Hoyle missed the Nobel Prize

- Hoyle (1950), reviewing a book by Gamow & Critchfield: "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- This book implied T_o = 11 K. Gamow in 1956 Scientific American implied 6 K. Alpher & Herman explicitly gave 5 K or 1 K.
- Nobody followed this up!

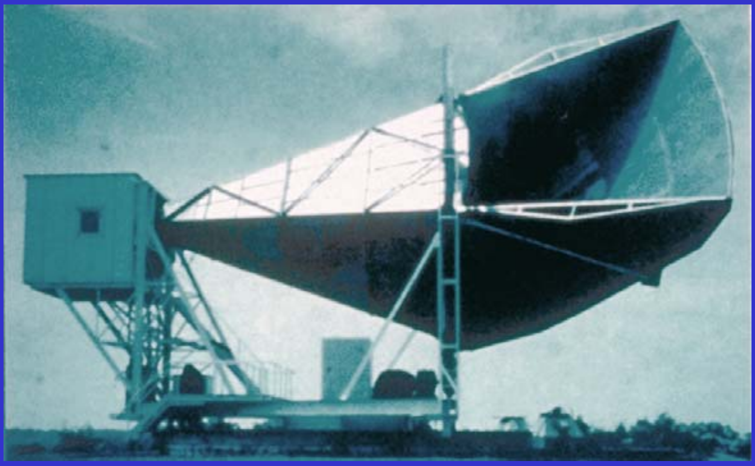
From a Ned Wright talk

On Dicke's non-discovery

- Dicke et al. (1946) reported on war-time work done to see if K band radar was practical. The atmospheric absorption was low enough.
- $T_{sky} < 20$ K
- Dicke invented the differential radiometer for this work. This compares a source to a reference source. The switch used to connect the two sources alternately to the radiometer is called a *Dicke switch*.
- Dicke had all the tools needed to measure the 3 K CMB in 1945, but didn't look for the CMB until 1964 and got scooped.

From a Ned Wright talk

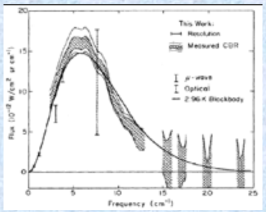
Penzias et Wilson antenna…
(Physics Nobel prize winners in 1978)

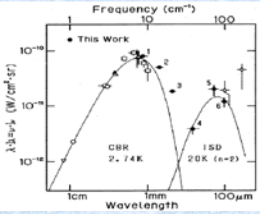


Cosmic Background predicted by Gamow in 1948, and by Ralph Alpher & Robert Herman in 1950. Serendipitously observed in 1965 par Arno Penzias and Robert Wilson at the Murray Hill Centre (NJ) of the Bell Telephone Laboratories *as « A source of excess noise in a radio Receiver ». Joint interpretation article in Physical Review by Dicke, Peebles, Roll, Wilkinson…(Princeton), contacted via Bernie Burke.*

A LONG MARCH ENSUES

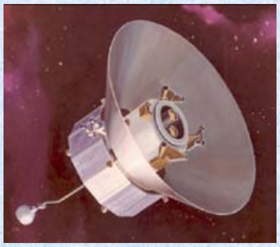
- Many ground-based and mountain-top measurements filled in the 0.3-20 cm wavelength range, giving T = 2.73±0.08 K.
- Reworking and reobservingthe CN lines gave 2.78±0.10 K at 2.64 mm. (Thaddeus, 1972, ARAA, 10, 305-334), 2.73±0.05 K (ςOph) and 2.75±0.04 K (ςPer) by M.B. Kaiser & EL Wright (1990)
- Big excesses over blackbody seen or not seen by different rocket and balloon experiments.
  - 2000 MJy/sr excess at 0.8 mm seen by Houck & Harwit(1969, ApJL, 157, L45)
  - No excess seen by MIT group (Muehlner& Weiss 1972)
  - Woody & Richards 2 mm excess in rocket (Phys. Rev. Lett. 42, 925 – 929 -1979)
  - Berkeley-Nagoya rocket experiment (Matsumoto *et al.* 1988, ApJ, 329,567) with TB= 2.80 K at 1.1 mm; 2.96 K at 0.7 mm & 3.18 K at 0.5 mm.





IN PARALLEL…

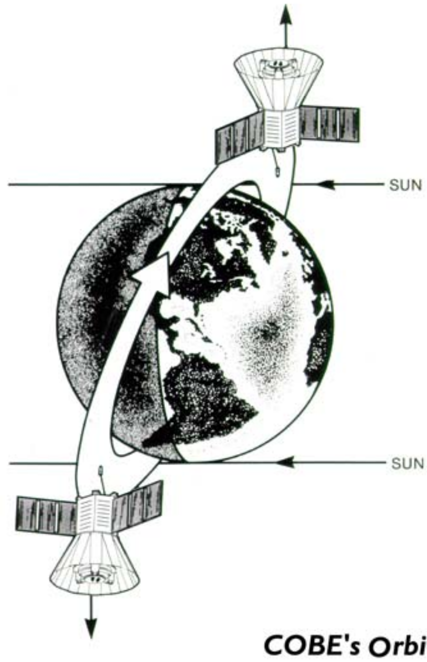
- Original COBE design was for a Delta rocket
- COBE was directed to use the shuttle and the design was actually nearly completed in Jan 1986.
- Then the Challenger blew up on launch… So back to a Delta
  - The shuttle version of COBE weighed 5,000 kg and also needed a 700 kg vacuum pump in the shuttle bay.
  - It was the full shuttle payload from Vandenberg AFB. A > 500 M$ launch.
  - Redesigned to fit on a Delta implied
    - The mass went down to 2300 kg.
    - The launch cost went down to about 30 M$.
    - No science was lost, but the schedule took a 2 year hit.



COBE

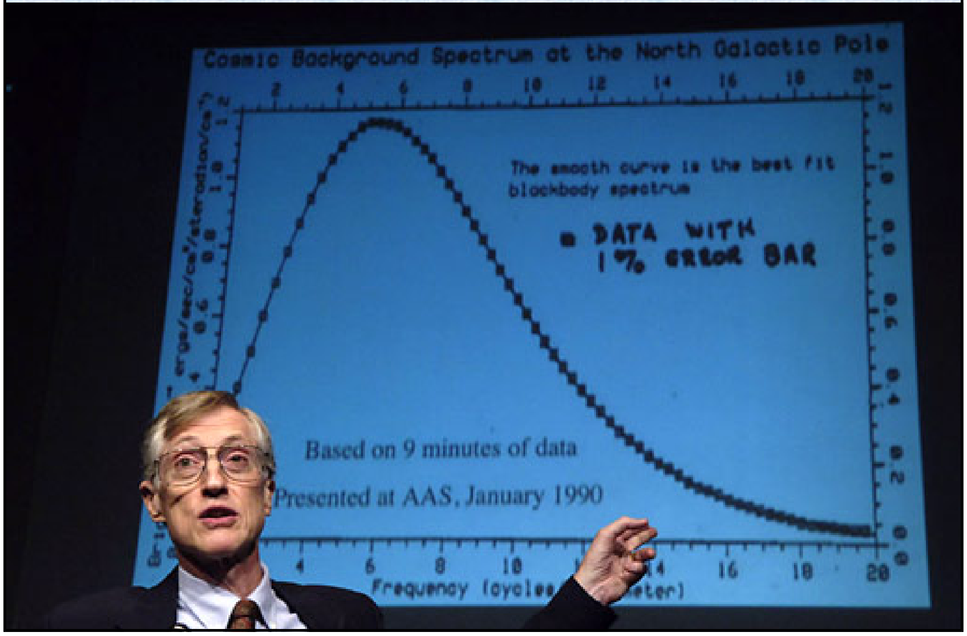
Lancé par la NASA
en Novembre 1989


The Nobel Prize in Physics 2006

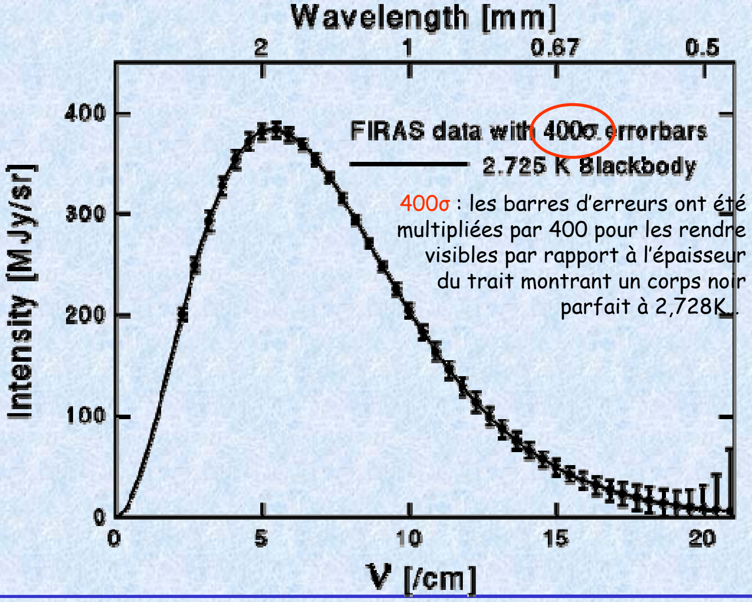


COBE's Orbit

EARLY FIRAS RESULTS

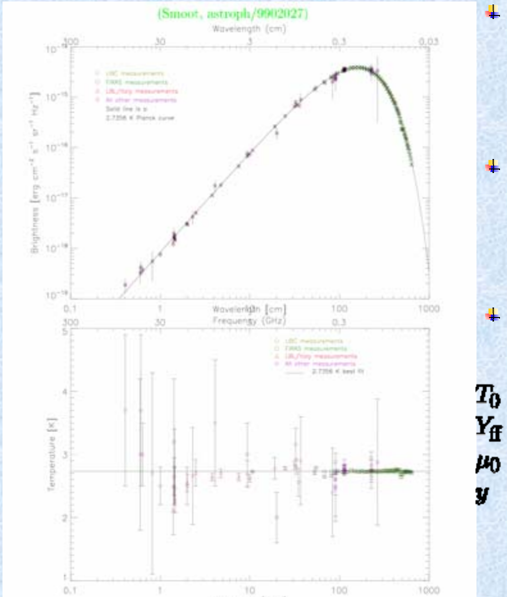


FINAL SPECTRUM



400σ : les barres d'erreurs ont été multipliées par 400 pour les rendre visibles par rapport à l'épaisseur du trait montrant un corps noir parfait à 2,728K.

TIGHT CONTRAINTS RESULT

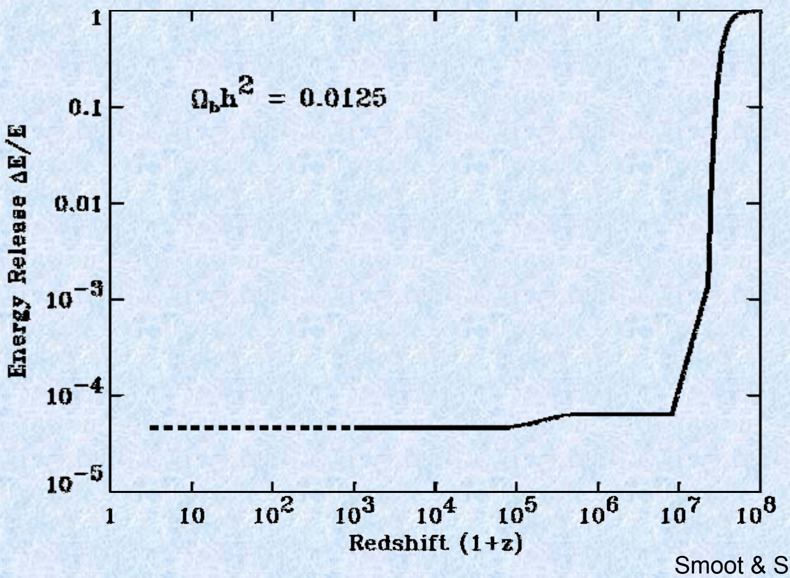

(Smoot, astroph/9902027)

- Compton scatterings of γ by hot e depletes low E (Rayleigh-Jeans, hv/kT <1) for high E (Wien), thereby imposing a well defined distortion characterised by the single Compton parameter y (if non-relativistic) $y = \int n_e \sigma_T dl$
- At z > 10^5, y > 1 (in standard BB), the plasma can reach statistical equilibrium. But when z < 10^7, there is no photon production, therefore no thermodynamical equilibrium; leads to a Bose-Einstein spectrum characterised by a chemical potential μ
- Very late energy release, at z << 10^3, can create free-free distortion, characterised by Y_{ff}.

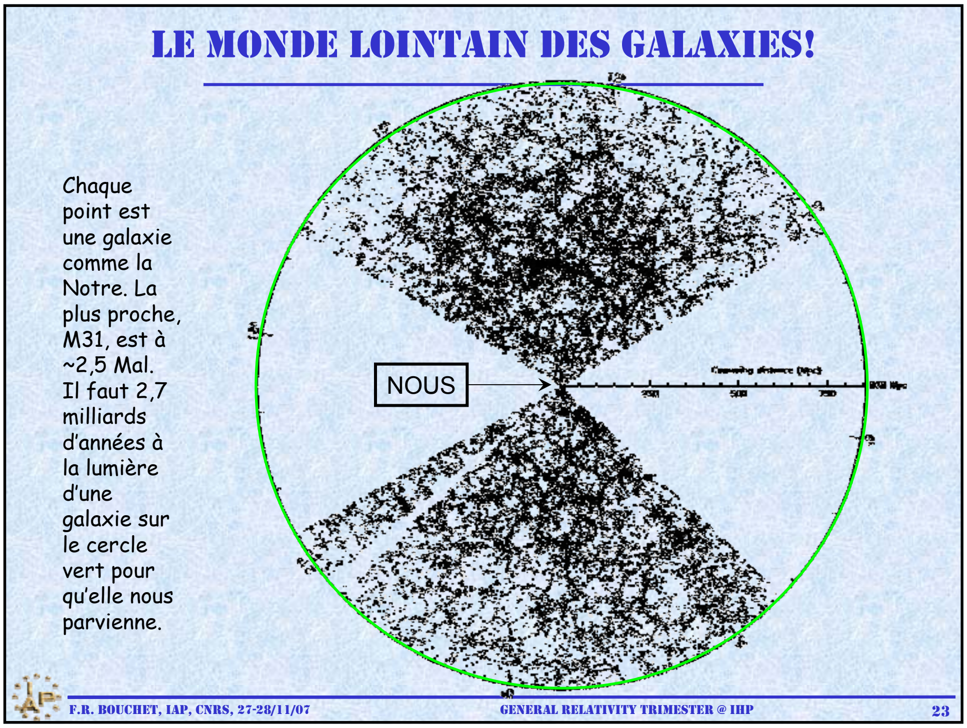
$$
\begin{aligned}
T_0 &= 2.7377 \pm 0.0038\ \mathrm{K} && (95\%\ \mathrm{CL}) \\
Y_{\mathrm{ff}} &= -1.1 \times 10^{-5} \pm 2.3 \times 10^{-5} && (95\%\ \mathrm{CL}) \\
\mu_0 &= -3.0 \times 10^{-5} \pm 1.2 \times 10^{-4} && (95\%\ \mathrm{CL}) \\
y &= 1.6 \times 10^{-6} \pm 9.6 \times 10^{-6} && (95\%\ \mathrm{CL})
\end{aligned}
$$

$$
\text{Correlation matrix} = \begin{array}{c|cccc}
 & T_0 & Y_{\mathrm{ff}} & \mu_0 & y \\
\hline
T_0 & 1.00 & 0.01 & 0.06 & 0.09 \\
Y_{\mathrm{ff}} & 0.01 & 1.00 & -0.27 & -0.18 \\
\mu_0 & 0.06 & -0.27 & 1.00 & 0.82 \\
y & 0.09 & -0.18 & 0.82 & 1.00
\end{array}
$$

95% C.L. LIMITS TO ENERGY RELEASE

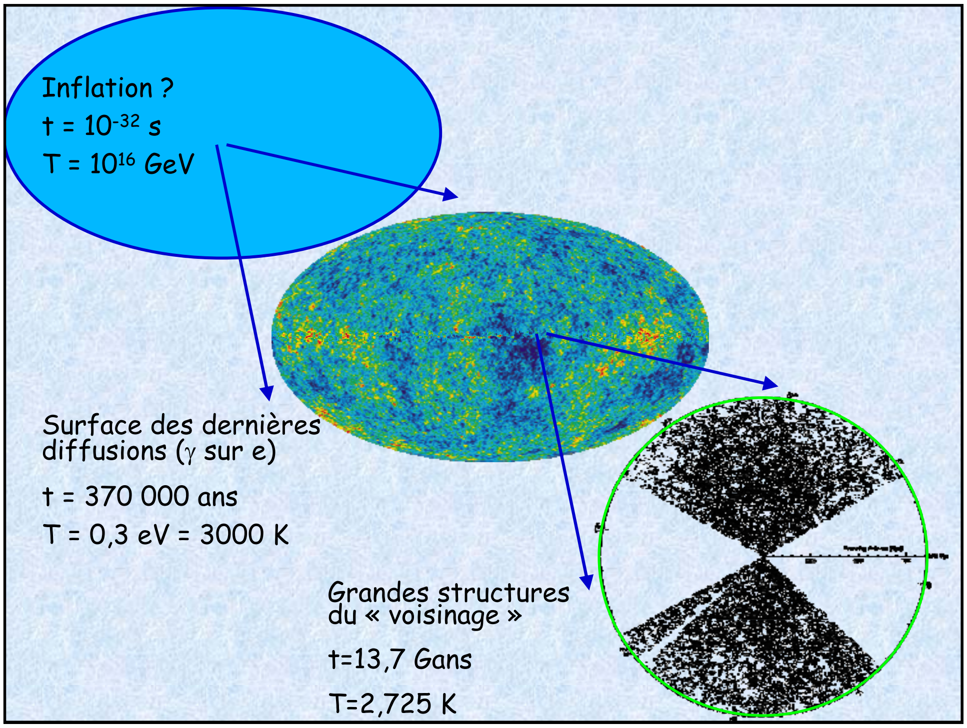


Smoot & Scott 1997



LE MONDE LOINTAIN DES GALAXIES!

Chaque point est une galaxie comme la Notre. La plus proche, M31, est à ~2,5 Mal. Il faut 2,7 milliards d'années à la lumière d'une galaxie sur le cercle vert pour qu'elle nous parvienne.



Inflation ?

t = 10^{-32} s

T = 10^{16} GeV

Surface des dernières diffusions (γ sur e)

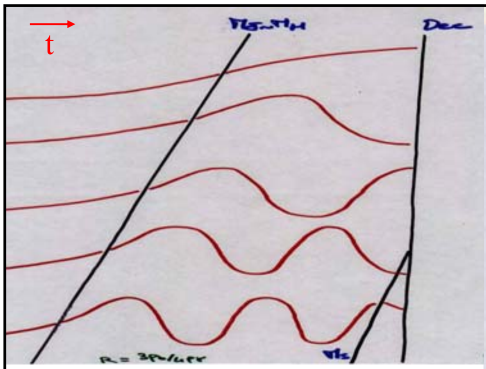
t = 370 000 ans

T = 0,3 eV = 3000 K

Grandes structures du « voisinage »

t=13,7 Gans

T=2,725 K



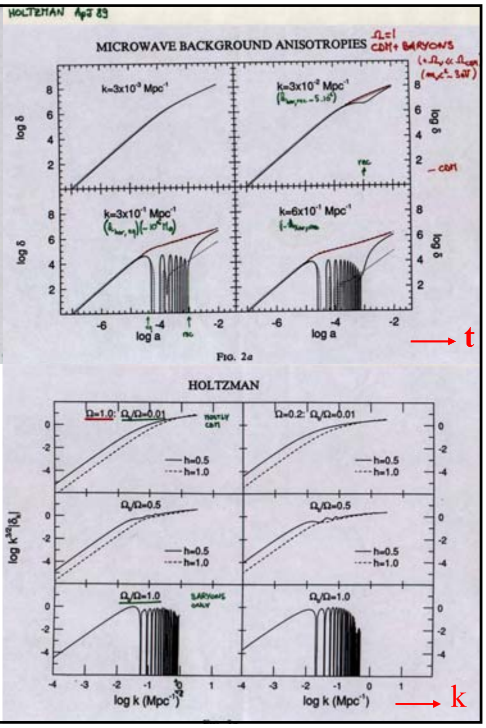


Fig. 2a

Given “initial” conditions (type & statistics, e.g. Adiabatic fluctuations only, Gaussian with $P(k) = A k^n$), and an energy census of the Universe (cosmological parameters, τ), one can compute the temporal evolution of each and every (linear) mode and obtain the “evolved” matter power spectrum, or it’s transfer function at LSS (depending mostly on sound speed history at $M < M_J$). *Idem for the radiation Transfer Function*.

The Astrophysical Journal, 162:815–836, December 1970

PRECISION COSMOLOGY…
First numerical CMB calculation (to go through recombination)

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

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Joseph Henry Laboratories, Princeton University

and

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Goddard Institute for Space Studies, NASA, New York

Received 1970 January 5; revised 1970 April 1

ABSTRACT

The general qualitative behavior of linear, first-order density perturbations in a Friedmann-Lemaître cosmological model with radiation and matter has been known for some time in the various limiting situations. An exact quantitative calculation which traces the entire history of the density fluctuations is lacking because the usual approximations of a very short photon mean free path before plasma recombination, and a very long mean free path after, are inadequate. We present here results of the direct integration of the collision equation of the photon distribution function, which enable us to treat in detail the complicated regime of plasma recombination. Starting from an assumed initial power spectrum well before recombination, we obtain a final spectrum of density perturbations after recombination. The calculations are carried out for several general-relativity models and one scalar-tensor model. One can identify two characteristic masses in the final power spectrum: one is the mass within the Hubble radius *ct* at recombination, and the other results from the linear dissipation of the perturbations prior to recombination. Conceivably the first of these numbers is associated with the great rich clusters of galaxies, the second with the large galaxies. We compute also the expected residual irregularity in the radiation from the primeval fireball. If we assume that (1) the rich clusters formed from an initially adiabatic perturbation and (2) the fireball radiation has not been seriously perturbed after the epoch of recombination of the primeval plasma, then with an angular resolution of 1 minute of arc the rms fluctuation in antenna temperature should be at least $\delta T/T = 0.00015$.

I. INTRODUCTION

a) Purpose

1965+5…

The possible discovery of radiation from the primeval fireball opens a promising lead toward a theory of the origin of galaxies. This primeval radiation would serve, first, to fix an epoch at which nonrelativistic bound systems like galaxies can start to develop (Peebles 1965*a*), and second, to impress on the power spectrum of initial density fluctuations characteristic lengths and masses (Gamow 1948; Peebles 1965*a*, 1967*a;* Michie 1967; Silk 1968). These characteristic features in the power spectrum hopefully result from all the complicated details of the evolution of the Universe *after* the initial power spectrum is arbitrarily set at some very early epoch. If one can make a reasonable argument for a coincidence of these features with observed phenomena, it will provide an important encouragement and guide to the further development of the theory. A more direct observational test of these processes might be provided by the residual small-scale fluctuations in the microwave background (Peebles 1965*b;* Sachs and Wolfe 1967; Silk 1968; Wolfe 1969; Longair and Sunyaev 1969), if we assume that this radiation has not been further scattered (Dautcourt 1969).

Initial CMB Calculations

---

* Research supported in part at Princeton by the National Science Foundation and the Office of Naval Research of the U.S. Navy, and at the California Institute of Technology by the National Science Foundation [GP-15911 (formerly GP-9433) and GP-9114] and the Office of Naval Research [Nonr-220(47)].

† Alfred P. Sloan Fellow.

‡ NAS-NRC Postdoctoral Research Associate.

Matter calculations

According to Zel'dovich (1967) there are two kinds of perturbations that are of interest: initial isothermal perturbations and initially adiabatic perturbations. It has been suggested that the globular clusters are the remnants of an isothermal perturbation in the early Universe (Peebles and Dicke 1968; Peebles 1969). Our purpose here is to discuss in some detail the evolution of adiabatic density fluctuations in the primeval-fireball picture.

An initially adiabatic perturbation evolves through four regimes: (*a*) When the age t of the Universe is much less than λ/c, where λ is the characteristic scale of the perturbation, a fractional perturbation $\delta\rho/\rho$ to the total mass density grows with time, but the entropy per nucleon is conserved (hence adiabatic). (*b*) When $\lambda \ll ct$, the perturbation oscillates like an acoustic wave. (*c*) As the Universe expands through the recombination phase, the photon mean free path becomes comparable to λ, and the oscillating wave is attenuated, leaving some residual perturbation in the matter distribution. (*d*) When $T \lesssim 2500°$ K, recombination is sufficiently complete that radiation drag on the matter may be neglected, and the residual perturbation may start to grow into bound systems like protogalaxies.

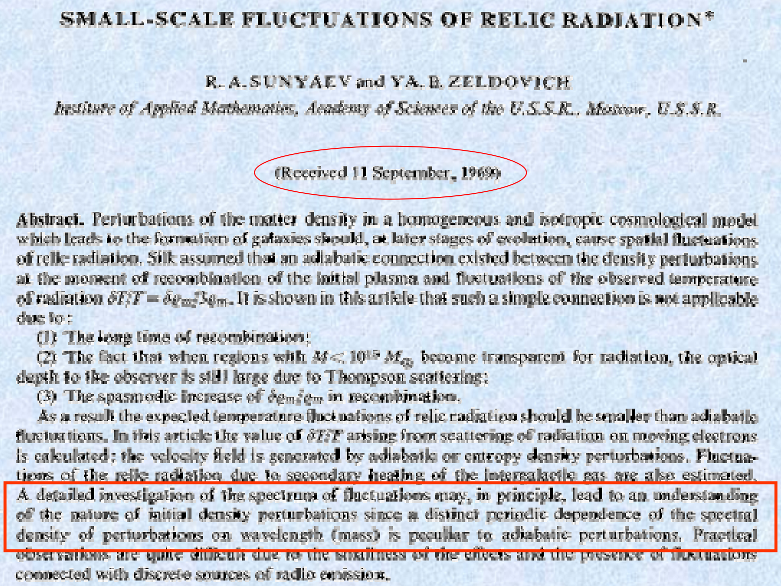
The above general scheme for initially adiabatic perturbations was already given by Lifshitz (1946). The very complicated regime (*c*) has been considered by a number of people in a variety of approximations, with the general conclusion that initially adiabatic perturbations on a characteristic mass scale $\lesssim 10^{11}$–$10^{13}\ \mathfrak{M}_\odot$ are strongly attenuated. This problem was first considered in approximations to first order in the photon mean free time t_e independently by Michie (1967), Peebles (1967*a*), and Silk (1968). It has since been considered by Bardeen (1968) in the first twenty moments of the radiation distribution function, and by Field (1970*a*), who solves the problem to all orders in t_e when the expansion of the Universe may be neglected. However, these approximation schemes run afoul of the enormous variation and rate of variation of the photon mean free path through the epoch of recombination. As a result, previous workers on this subject (Peebles 1967*a;* Michie 1967; Silk 1968; Field and Shepley 1968) could give only qualitative estimates of the different characteristic masses involved here. To obtain a more accurate description of the evolution through this complicated phase of recombination, we have resorted to direct numerical integration of the collision equation for the photon distribution function.

The more quantitative results of the present calculation are compared with the earlier estimates in § VII. We also discuss there the possible significance of these results. In § II we derive the differential equations to be integrated. It is impractical to integrate the collision equation numerically in the very early Universe because the photon mean free path t_e is so short, but here it becomes a good approximation to describe the radiation as a fluid with viscosity. This description of the radiation was used in all the previous work (Lifshitz 1946; Michie 1967; Silk 1968; Field and Shepley 1968), and is indeed a good approximation in this early epoch. The fluid description of radiation is equivalent to an expansion and integration of our collision equation to first order in t_e. In § III we give the resulting equations valid to first order in t_e, and we present solutions to these approximate equations under various limiting conditions. These results are used to start the numerical integration and to check numerical accuracy. In § IV we consider the residual perturbation to the microwave background. The numerical integrations are described in §§ V and VI.

b) Assumptions and Approximations

In the following calculations we use either conventional general-relativity theory, with cosmological constant Λ equal to zero, or the scalar-tensor theory (Brans and Dicke 1961). We start from a homogeneous, isotropic cosmological model, in which the present parameters are

$$H_0^{-1} = 1 \times 10^{10}\ \text{years}, \quad T_0 = 2.7°\ \text{K}. \qquad (1)$$



SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

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(Received 11 September, 1969)

Abstract. Perturbations of the matter density in a homogeneous and isotropic cosmological model which leads to the formation of galaxies should, at later stages of evolution, cause spatial fluctuations of relic radiation. Silk assumed that an adiabatic connection existed between the density perturbations at the moment of recombination of the initial plasma and fluctuations of the observed temperature of radiation $\delta T/T = \delta\varrho_m/3\varrho_m$. It is shown in this article that such a simple connection is not applicable due to:

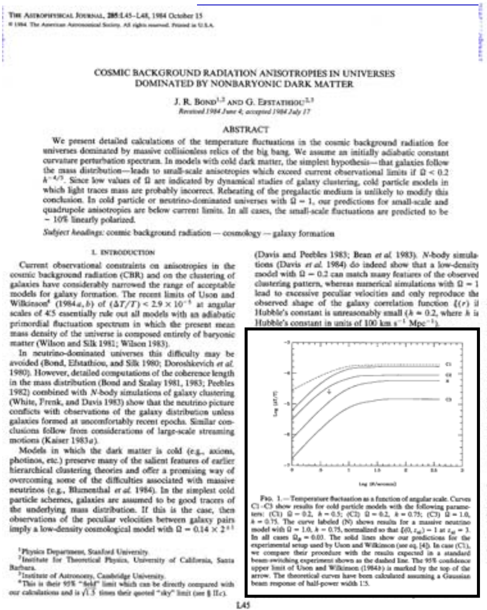
(1) The long time of recombination;

(2) The fact that when regions with $M < 10^{15} M_{\odot}$ become transparent for radiation, the optical depth to the observer is still large due to Thompson scattering;

(3) The spasmodic increase of $\delta\varrho_m/\varrho_m$ in recombination.

As a result the expected temperature fluctuations of relic radiation should be smaller than adiabatic fluctuations. In this article the value of $\delta T/T$ arising from scattering of radiation on moving electrons is calculated; the velocity field is generated by adiabatic or entropy density perturbations. Fluctuations of the relic radiation due to secondary heating of the intergalactic gas are also estimated. A detailed investigation of the spectrum of fluctuations may, in principle, lead to an understanding of the nature of initial density perturbations since a distinct periodic dependence of the spectral density of perturbations on wavelength (mass) is peculiar to adiabatic perturbations. Practical observations are quite difficult due to the smallness of the effects and the presence of fluctuations connected with discrete sources of radio emission.

CDM & scale-invariant initial conditions in some detail:
ApJ, 1984, L45-48 & L 39-43 (Inflation is 1982)



THE ASTROPHYSICAL JOURNAL, 285:L45–L48, 1984 October 15
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COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES DOMINATED BY NONBARYONIC DARK MATTER

J. R. BOND[1,2] AND G. EFSTATHIOU[2,3]

Received 1984 June 4; accepted 1984 July 17

ABSTRACT

We present detailed calculations of the temperature fluctuations in the cosmic background radiation for universes dominated by massive collisionless relics of the big bang. We assume an initially adiabatic constant curvature perturbation spectrum. In models with cold dark matter, the simplest hypothesis—that galaxies follow the mass distribution—leads to small-scale anisotropies which exceed current observational limits if $\Omega < 0.2\ h^{-4/3}$. Since low values of Ω are indicated by dynamical studies of galaxy clustering, cold particle models in which light traces mass are probably incorrect. Reheating of the pregalactic medium is unlikely to modify this conclusion. In cold particle or neutrino-dominated universes with $\Omega = 1$, our predictions for small-scale and quadrupole anisotropies are below current limits. In all cases, the small-scale fluctuations are predicted to be ~ 10% linearly polarized.

Subject headings: cosmic background radiation — cosmology — galaxy formation

I. INTRODUCTION

Current observational constraints on anisotropies in the cosmic background radiation (CBR) and on the clustering of galaxies have considerably narrowed the range of acceptable models for galaxy formation. The recent limits of Uson and Wilkinson[4] (1984*a*, *b*) of $(\Delta T/T) < 2.9 \times 10^{-5}$ at angular scales of 4'.5 essentially rule out all models with an adiabatic primordial fluctuation spectrum in which the present mean mass density of the universe is composed entirely of baryonic matter (Wilson and Silk 1981; Wilson 1983).

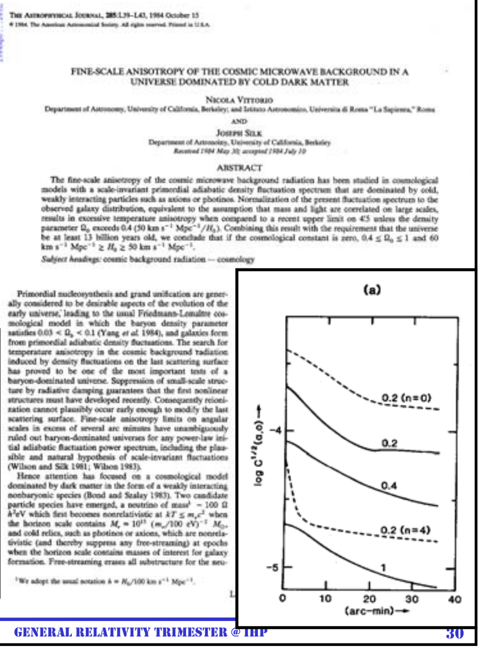
In neutrino-dominated universes this difficulty may be avoided (Bond, Efstathiou, and Silk 1980; Doroshkevich *et al.* 1980). However, detailed computations of the coherence length in the mass distribution (Bond and Szalay 1981, 1983; Peebles 1982) combined with *N*-body simulations of galaxy clustering (White, Frenk, and Davis 1983) show that the neutrino picture conflicts with observations of the galaxy distribution unless galaxies formed at uncomfortably recent epochs. Similar conclusions follow from considerations of large-scale streaming motions (Kaiser 1983*a*).

Models in which the dark matter is cold (e.g., axions, photinos, etc.) preserve many of the salient features of earlier hierarchical clustering theories and offer a promising way of overcoming some of the difficulties associated with massive neutrinos (e.g., Blumenthal *et al.* 1984). In the simplest cold particle schemes, galaxies are assumed to be good tracers of the underlying mass distribution. If this is the case, then observations of the peculiar velocities between galaxy pairs imply a low-density cosmological model with $\Omega = 0.14 \times 2^{\pm 1}$ (Davis and Peebles 1983; Bean *et al.* 1983). *N*-body simulations (Davis *et al.* 1984) do indeed show that a low-density model with $\Omega = 0.2$ can match many features of the observed clustering pattern, whereas numerical simulations with $\Omega = 1$ lead to excessive peculiar velocities and only reproduce the observed shape of the galaxy correlation function $\xi(r)$ if Hubble's constant is unreasonably small ($h = 0.2$, where h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1}).

FIG. 1.—Temperature fluctuation as a function of angular scale. Curves C1–C3 show results for cold particle models with the following parameters: (C1) $\Omega = 0.2$, $h = 0.5$; (C2) $\Omega = 0.2$, $h = 0.75$; (C3) $\Omega = 1.0$, $h = 0.75$. The curve labeled (N) shows results for a massive neutrino model with $\Omega = 1.0$, $h = 0.75$, normalized so that $\xi(0, r_{s\dot{a}}) = 1$ at $r_{s\dot{a}} = 3$. In all cases $\Omega_B = 0.03$. The solid lines show our predictions for the experimental setup used by Uson and Wilkinson (see eq. [4]). In case (C1), we compare their procedure with the results expected in a standard beam-switching experiment shown as the dashed line. The 95% confidence upper limit of Uson and Wilkinson (1984*b*) is marked by the top of the arrow. The theoretical curves have been calculated assuming a Gaussian beam response of half-power width 1'.5.

[1] Physics Department, Stanford University.
[2] Institute for Theoretical Physics, University of California, Santa Barbara.
[3] Institute of Astronomy, Cambridge University.
[4] This is their 95% "field" limit which can be directly compared with our calculations and is $\sqrt{1.5}$ times their quoted "sky" limit (see § IIc).

L45



THE ASTROPHYSICAL JOURNAL, 285:L39–L43, 1984 October 15
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FINE-SCALE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND IN A UNIVERSE DOMINATED BY COLD DARK MATTER

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ABSTRACT

The fine-scale anisotropy of the cosmic microwave background radiation has been studied in cosmological models with a scale-invariant primordial adiabatic density fluctuation spectrum that are dominated by cold, weakly interacting particles such as axions or photinos. Normalization of the present fluctuation spectrum to the observed galaxy distribution, equivalent to the assumption that mass and light are correlated on large scales, results in excessive temperature anisotropy when compared to a recent upper limit on 4'.5 unless the density parameter Ω_0 exceeds 0.4 (50 km s^{-1} Mpc$^{-1}/H_0$). Combining this result with the requirement that the universe be at least 13 billion years old, we conclude that if the cosmological constant is zero, $0.4 \le \Omega_0 \le 1$ and 60 km s^{-1} Mpc$^{-1} \ge H_0 \ge 50$ km s^{-1} Mpc^{-1}.

Subject headings: cosmic background radiation — cosmology

Primordial nucleosynthesis and grand unification are generally considered to be desirable aspects of the evolution of the early universe,[1] leading to the usual Friedmann-Lemaître cosmological model in which the baryon density parameter satisfies $0.03 < \Omega_b < 0.1$ (Yang *et al.* 1984), and galaxies form from primordial adiabatic density fluctuations. The search for temperature anisotropy in the cosmic background radiation induced by density fluctuations on the last scattering surface has proved to be one of the most important tests of a baryon-dominated universe. Suppression of small-scale structure by radiative damping guarantees that the first nonlinear structures must have developed recently. Consequently reionization cannot plausibly occur early enough to modify the last scattering surface. Fine-scale anisotropy limits on angular scales in excess of several arc minutes have unambiguously ruled out baryon-dominated universes for any power-law initial adiabatic fluctuation power spectrum, including the plausible and natural hypothesis of scale-invariant fluctuations (Wilson and Silk 1981; Wilson 1983).

Hence attention has focused on a cosmological model dominated by dark matter in the form of a weakly interacting nonbaryonic species (Bond and Szalay 1983). Two candidate particle species have emerged, a neutrino of mass[1] ~ 100 Ωh^2eV which first becomes nonrelativistic at $kT \lesssim m_\nu c^2$ when the horizon scale contains $M_\nu \approx 10^{15} (m_\nu/100\ \text{eV})^{-2} M_\odot$, and cold relics, such as photinos or axions, which are nonrelativistic (and thereby suppress any free-streaming) at epochs when the horizon scale contains masses of interest for galaxy formation. Free-streaming erases all substructure for the neu-

[1] We adopt the usual notation $h = H_0/100$ km s^{-1} Mpc^{-1}.

Mon. Not. R. astr. Soc. (1987) **226,** 655–687

1987: Detailed Statistics…

The statistics of cosmic background radiation fluctuations

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Summary. We present computations of the radiation correlation functions and angular power spectra for microwave background anisotropies expected in $\Omega=1$ cold dark matter dominated universes with scale-invariant adiabatic or isocurvature initial conditions. The results are valid on all angular scales. We describe the statistical properties of the radiation pattern and develop the theory of two-dimensional Gaussian random fields. A large number of properties of such fields may be derived analytically or semi-analytically, such as the number densities of hotspots and coldspots, the eccentricities of peaks and peak correlation properties. The formulae presented here provide valuable insight into the textural characteristics of the microwave background anisotropies and must be satisfied if the primordial fluctuations are Gaussian. The assumption of Gaussian initial conditions allow us to make highly specific predictions for the pattern of the temperature anisotropies. This is demonstrated by the construction of maps of the fluctuations predicted for the total intensity and the polarization.

1 Introduction

The origin of density irregularities in the Universe represents one of the most important problems in cosmology which, until recently, was largely considered intractable. The inflationary model of the early Universe has, however, led to a potentially viable mechanism for the origin of primordial density fluctuations (e.g. Starobinskii 1982; Guth & Pi 1982; Bardeen, Steinhardt & Turner 1983). Although these calculations are hardly definitive, they have succeeded in drawing attention to a particular set of initial conditions, namely scale-invariant, Gaussian fluctuations superimposed on an $\Omega=1$ Friedman background.

In this paper, we investigate the statistical properties of the cosmic microwave background radiation (CMB), assuming that the initial fluctuations are Gaussian. The background radiation will then form a 2D Gaussian random field and should provide a clean and direct test of the statistics of the initial conditions. Given a particular cosmological model, we can compute all statistical aspects of the radiation pattern. It is unfortunate, then, that CMB anisotropies have yet

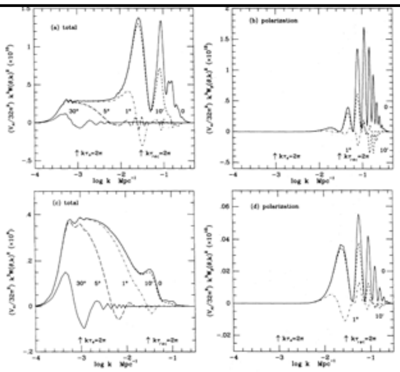


Figure 4. Integrands of the radiation autocorrelation function $k^3W_T(\theta, k)$ plotted against log k for various θ. (a, b) Show the integrands for the total and polarization correlation functions, respectively for a scale-invariant adiabatic CDM model with $\Omega=1$, $\Omega_B=0.03$, $h=0.75$. (c, d) Show the equivalent plots for a scale-invariant isocurvature CDM model with identical cosmological parameters. The area under each curve gives $C(\theta)$ thus it is easy to assess how fluctuations on various scales would contribute to experiments probing any particular angle. These curves have been normalized according to the prescription given in Section 4.2 with the biasing parameter $b=1$.

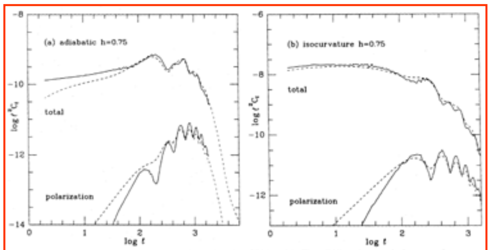


Figure 7. Power spectra for the two $h=0.75$ scale-invariant CDM models. The solid lines show results from equation (4.17) and the dotted lines show approximate results derived from equation (4.19).

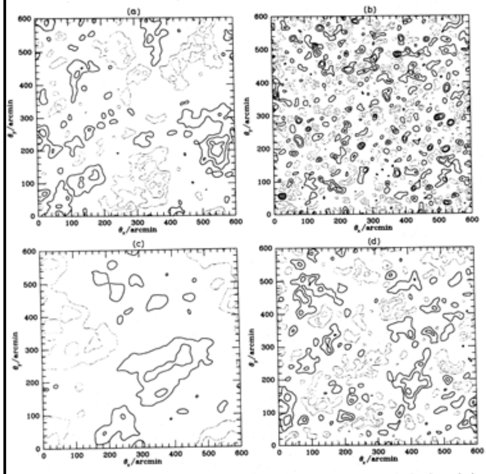


Figure 8. Realization of the Gaussian temperature and polarization fluctuations constructed using the method described in Section 5. (a, b) Show maps of the total and polarization fluctuations respectively for the $h=0.75$ scale-invariant adiabatic CDM model. (c, d) Show analogous maps for the $h=0.75$ scale-invariant isocurvature model. In constructing these plots, we used a 512×512 grid and a smoothing angle of $\theta_s=5$ arcmin. The heavy contours correspond to $\nu=1$, 2 and 3 upward fluctuations and the light lines show equivalent contours for the downward fluctuations.

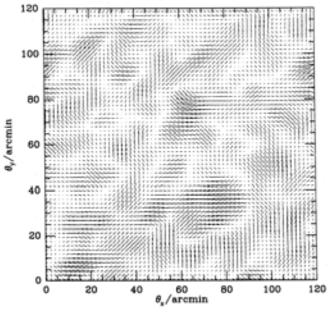


Figure 9. Simulation of the degree and spatial variation of the plane of polarization in a $2°\times2°$ patch for the $h=0$ adiabatic model simulated in Fig. 8. The length of each vector is proportional to the degree of polarization and orientation gives the plane of polarization. This picture was constructed on a 128×128 grid using a smoothing angl $\theta_s=1$ arcmin. For visual clarity, we only plot 64×64 vectors.

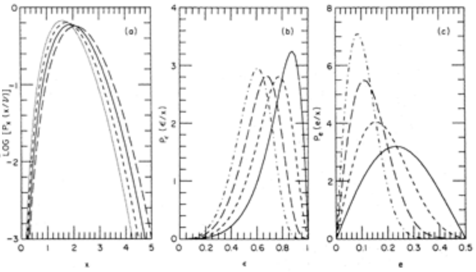
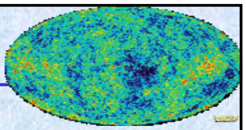


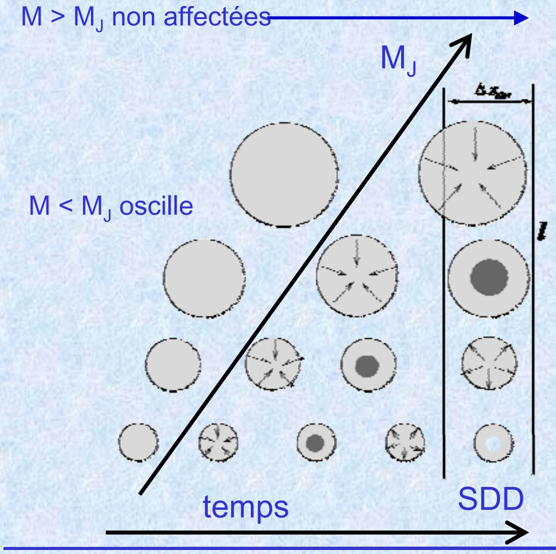
Figure 2. (a) The conditional probability of the curvature parameter $x=|\nabla^2F/\sigma_2|$ given the height $\nu=0$ (dot), 1 (short dash), 2 (solid), 3 (long dash) of the maximum (or minimum) is plotted for $\gamma=0.347$, the value appropriate to the $h=0.75$ adiabatic CDM model. The eccentricity (b) and ellipticity (c) distributions for $x=1$ (solid), 2 (short dash), 3 (long dash) and 4 (dot-dash) are independent of the spectral parameters and ν. Integration over x gives the ε and e distributions for specified values of the peak height ν [equation (A2.6), Appendix 2].

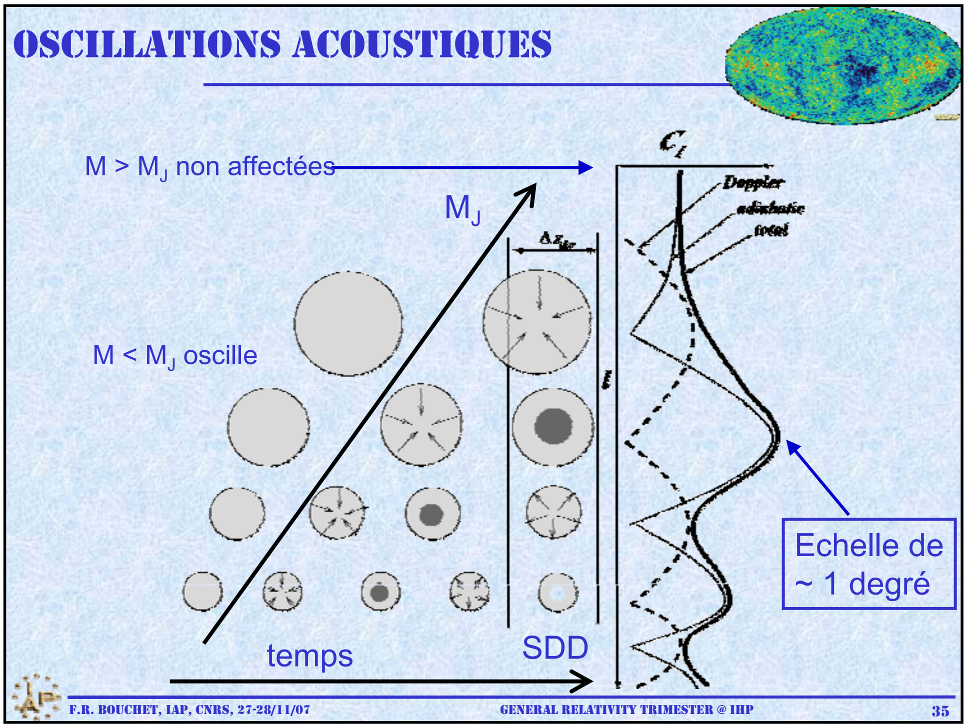
SINCE THEN…

- Angular power spectra $C(l)$ became the norm
  - $T(n) = \Sigma_{lm}\, a_{lm}\, Y_{lm}(n)$; $a_{lm} = \int d\Omega\, T\, Y^*_{lm}$
  - $\langle a_{lm}\, a_{l'm'} \rangle = \delta_{ll'}\, \delta_{mm'}\, C(l)$ (If statistical isotropy)
  - $\langle T_p T_{p'} \rangle = C_{pp'} = \Sigma\, (2l+1)/4pi\, C(l)\, P_l(n_p, n_{p'})$
  - \hat $C(l) = 1/(2l+1)\, \Sigma_m\, |a_{lm}|^2$
- $\Omega_K \neq 0$ calculations
- Elegant reformulations, introduce E & B to represent polarisation, many gauges (or absence of)…
- Precision of predictions increased (Δ < 1 %)
- Speed also (tremendously).
- Off the shelf codes: CMBFAST [Seljack & Zaldarriaga 96], CAMB [Lewis et al. 2000] & CMBSLOW [Riazuelo], CMBEASY, etc
- With further options, e.g. lensing correction, isocurvature modes, reionisation… (still ongoing)
- Detailed degeneracy studies

OSCILLATIONS ACOUSTIQUES







OSCILLATIONS ACOUSTIQUES

M > M_J non affectées

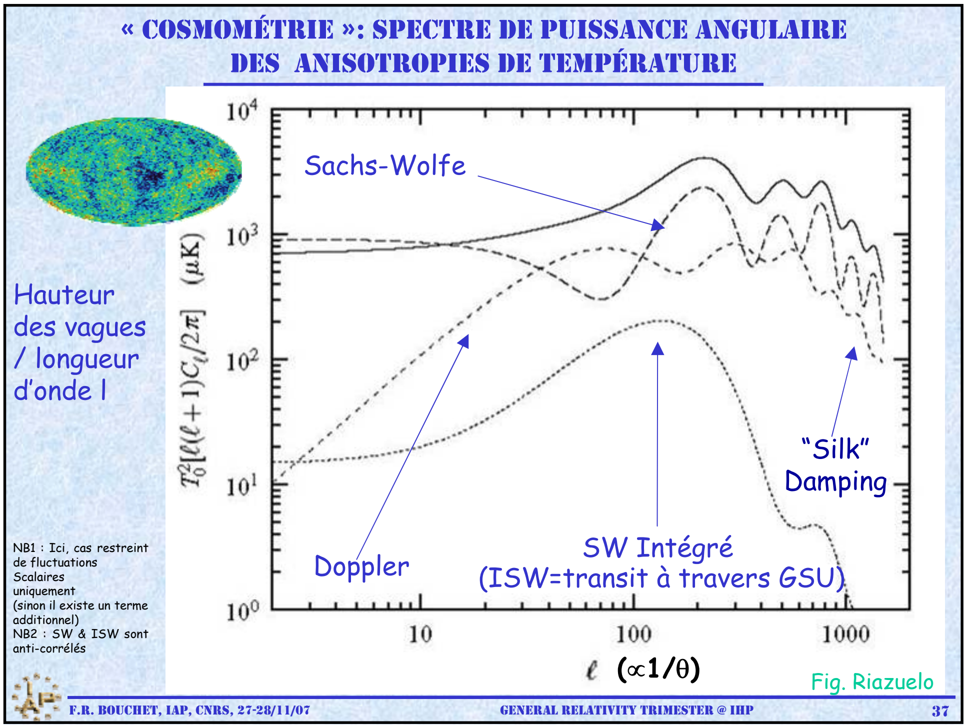
M_J

M < M_J oscille

temps

SDD

Echelle de
~ 1 degré



« COSMOMÉTRIE »: SPECTRE DE PUISSANCE ANGULAIRE DES ANISOTROPIES DE TEMPÉRATURE

Hauteur
des vagues
/ longueur
d'onde l

Sachs-Wolfe

Doppler

SW Intégré
(ISW=transit à travers GSU)

"Silk"
Damping

ℓ ($\propto 1/\theta$)

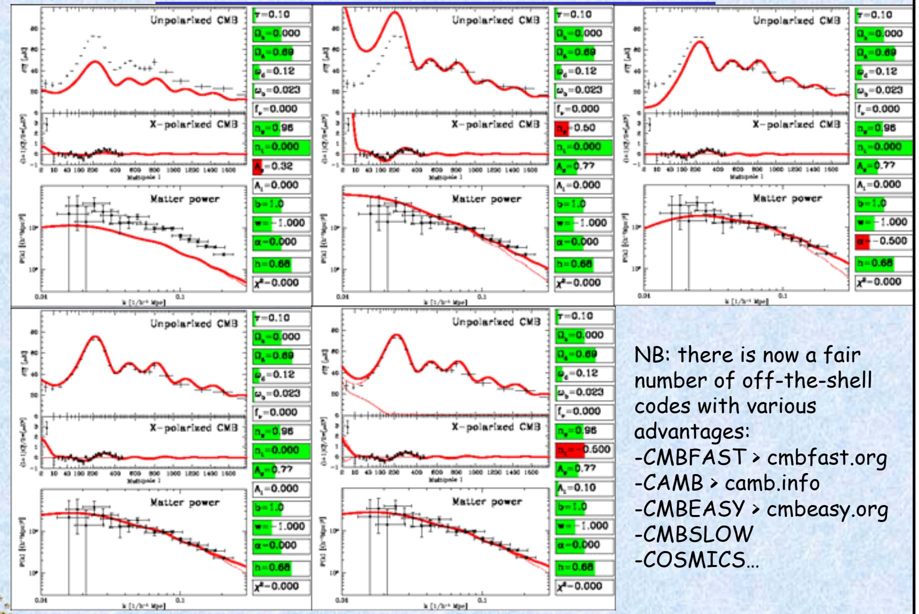
Fig. Riazuelo

NB1 : Ici, cas restreint
de fluctuations
Scalaires
uniquement
(sinon il existe un terme
additionnel)
NB2 : SW & ISW sont
anti-corrélés

RECAP

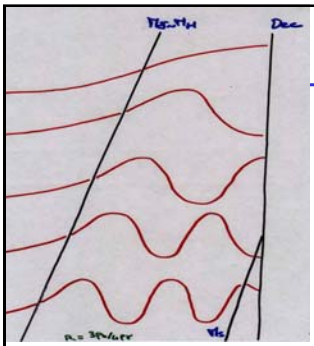
- We can (maybe) compute properties of "Initial conditions", or at least parametrize them > As, ns, At, nt
- Perturbation theory
  - Linear regime (As ~10^{-5}) > can conveniently analyse Fourier modes independently
  - Well understood physics
    - Thomson elastic scatterings, coupling of electron and photons
    - Recombination (simplest = Saha equilibrium)
    - General relativity, in linear regime
    - Statistical mechanics – Boltzmann eq. for angular distribution of photons
  - Few scales involved
    - Sound wave travel distance ~$c_s t$
      - determines when starts to oscillate (pressure support)
    - Diffusion damping length $\propto$ $\text{Ndiff}^{1/2}$
      - determines smallest surviving fluctuations (in baryons-photon fluids)
    - Time from big bang to last scattering (~300Mpc comoving; ~300 000 years)
      – determines physical size of largest overdensity (or underdensity)
    - Distance of last scattering from us (~14Gpc comoving; 14 Gyr)
      - determines angular size seen by us
    - Thickness of last scattering (~Hubble time, 100Mpc)
      - determines line of sight averaging
      - determines amount of polarization (later)
  - Interplay of several related effects allows rich phenomenology > opportunities
    - Intrinsic (compressed photons > hotter)
    - SW (redshift to clim out of potential wells at LS
    - Doppler (from oscillating e b fluid)
    - ISW (from evolving potential on los – Om .NE.1)
    - + smaller (second order effects) – lensing, SZ, etc

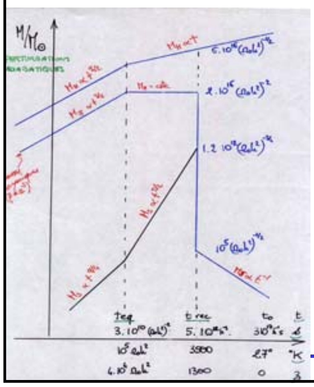
INITIAL CONDITIONS DEPENDENCE



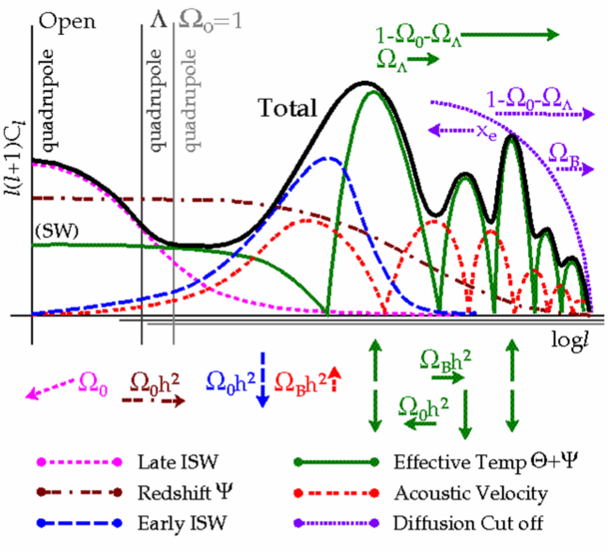
From Tegmark's web site

NB: there is now a fair number of off-the-shell codes with various advantages:
-CMBFAST > cmbfast.org
-CAMB > camb.info
-CMBEASY > cmbeasy.org
-CMBSLOW
-COSMICS…





POWER SPECTRUM SHAPE AND COSMOLOGICAL PARAMETERS

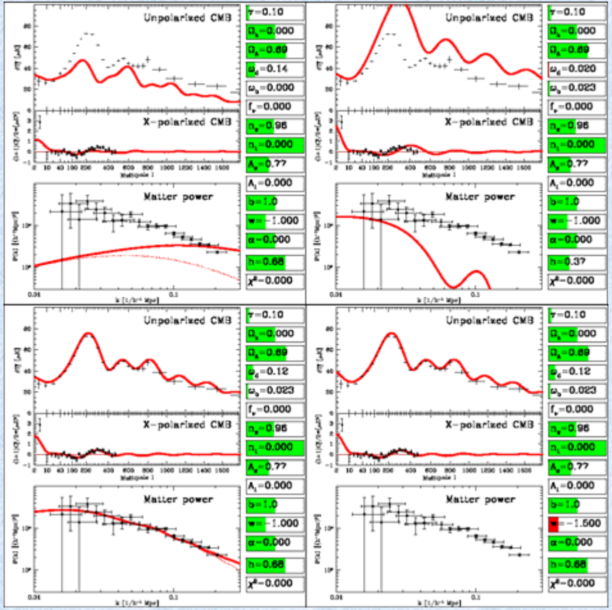


Hu, Sugiyama, & Silk (1995)

CENSUS

Baryons

Dark matter



Neutrino Fraction

w in p=wp

CMB IS A RICH INFORMATION MINE

- Initial conditions
  What types of perturbations, power spectra, distribution function (Gaussian?); => learn about inflation or alternatives.
  (distribution of ΔT; power as function of scale; polarization and correlation)
- What and how much stuff
  Matter densities (Ω_b, Ω_{cdm});. neutrino mass
  (details of peak shapes, amount of small scale damping)
- Geometry and topology
  global curvature Ω_k of universe; topology
  (angular size of perturbations; repeated patterns in the sky)
- Evolution
  Expansion rate as function of time; reionization
  - Hubble constant H_0 ; dark energy evolution w = pressure/density
  (angular size of perturbations; l < 50 large scale power; polarizationr)
- Astrophysics
  S-Z effect (clusters), foregrounds, etc.

COSMIC VARIANCE: ONLY ONE SKY

Use estimator for variance: $C_l^{obs} = \frac{1}{2l+1}\sum_m |a_{lm}|^2$

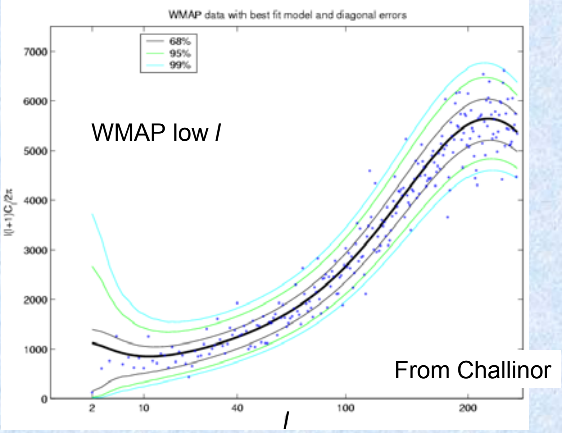
Assume a_{lm} gaussian:
$C_l^{obs} \sim \chi^2$ with $2l+1$ d.o.f.

“Cosmic Variance”

$$\left\langle |\Delta C_l^{obs}|^2 \right\rangle \approx \frac{2C_l^2}{2l+1}$$

$P(C_l \mid C_l^{obs})$

- inverse gamma distribution
(+ noise, sky cut, etc).



WMAP low l

From Challinor

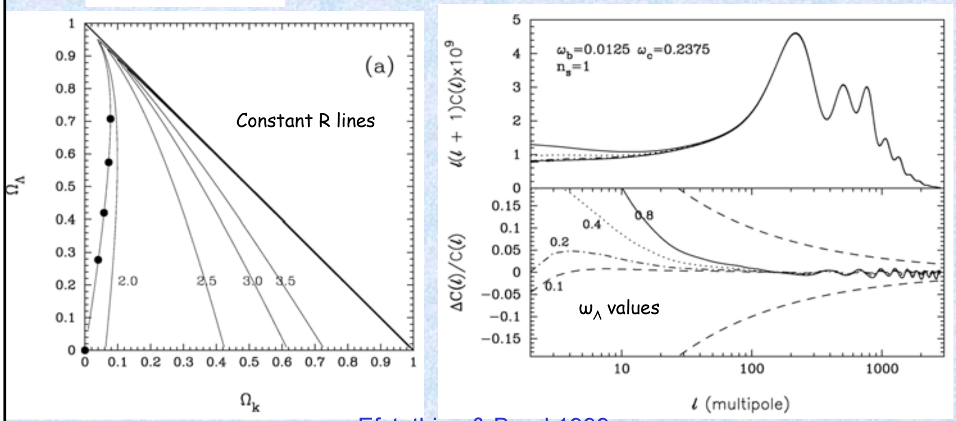
Cosmic variance gives fundamental limit on how much we can learn from CMB

GEOMETRICAL DEGENERACY

Angular diameter distance controls the mapping from k to l
Models with same R (and IC & matter content - Ωb & Ω c)
Have very similar spectra, but at Low l (SW)

$$\mathcal{R} = \frac{\omega_m^{1/2}}{\omega_k^{1/2}} \sinh\left[\omega_k^{1/2} y\right]$$

$$y = \int_{a_r}^{1} \frac{da}{[\omega_m a + \omega_k a^2 + \omega_\Lambda a^4 + \omega_Q a^{1-3w_Q}]^{1/2}}.$$



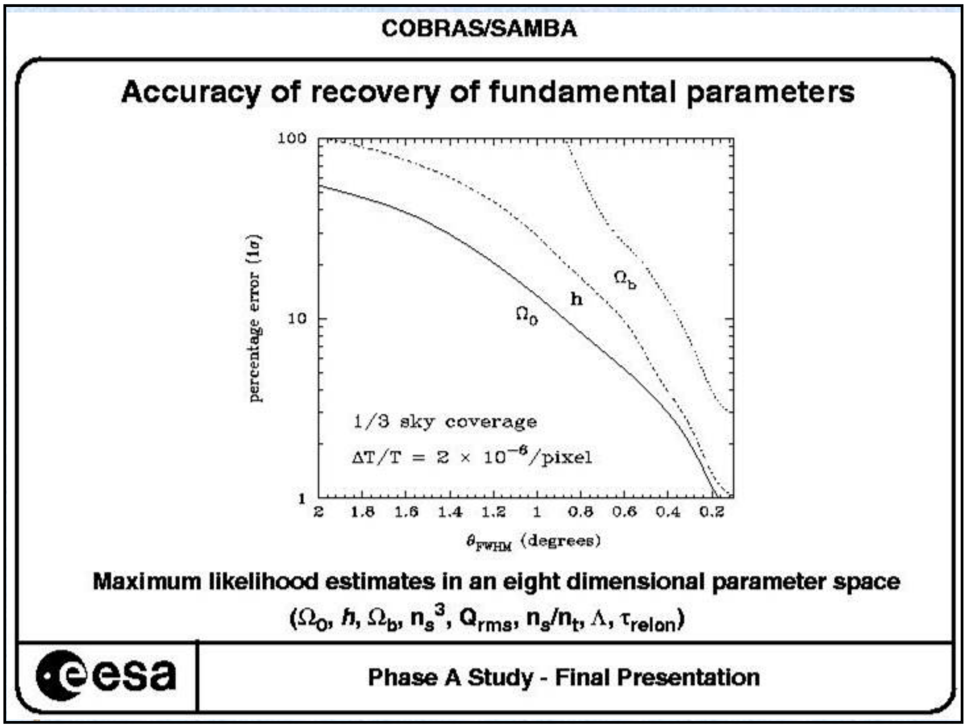
Efstathiou & Bond 1999

FISHER MATRIX GUIDELINES

- Microwave sky = primary + secondary + foregrounds
- Measured sky = Microwave sky + random errors + systematic errors.
- Theory $T_i = f(\theta_{p,}, IC_j)$
- Constraining theory with data : $P(T|D) \propto L(D|T)\, P(T)$
- Fisher matrix, $F_{ij} = \frac{\partial^2 \ln L}{\partial T_j \partial T_i}$, encodes the power of the data
- *Assume* we succeed in isolating *only* primary fluctuations and noise..

- Quantifies the (remaining) obstacles ($\sigma_i >= F_{ii}^{-1/2}$):
  - Degeneracies within the θ_p
  - Degeneracies within the IC, and IC vs. θ_p
  - Cosmic variance (one sky), noise (i.e. sensitivity), resolution

$$F_{ij} = \sum_l \frac{(2l+1) f_{sky}}{2} [C_l + C_N \exp \theta_b^2 (l^2)]^{-2} \frac{\partial C_l}{\partial T_j} \frac{\partial C_l}{\partial T_j}$$



COBRAS/SAMBA

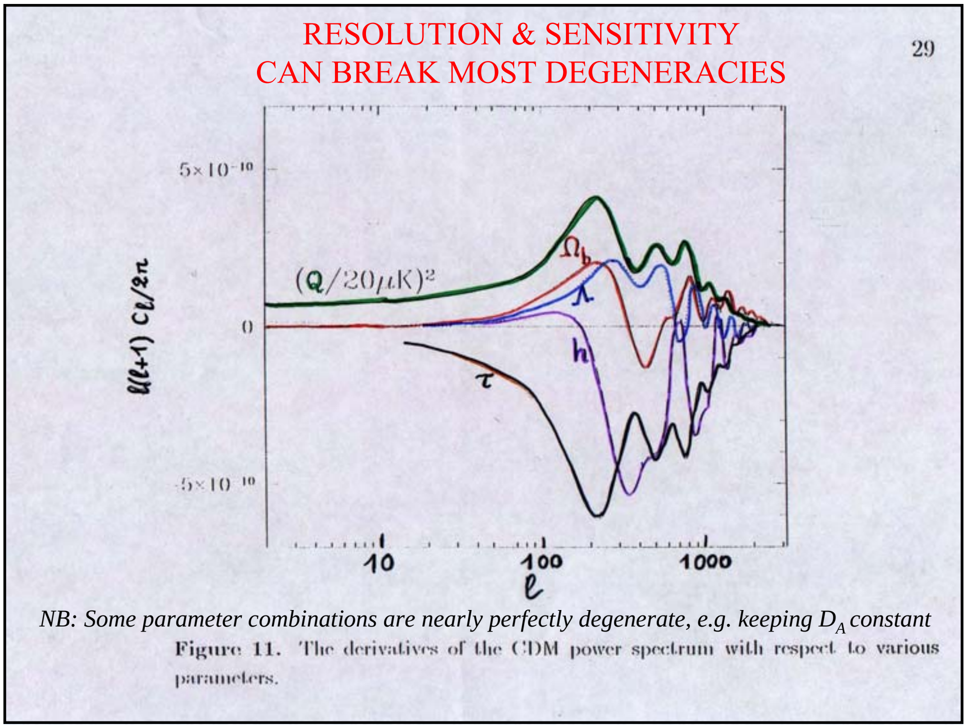
Accuracy of recovery of fundamental parameters

Maximum likelihood estimates in an eight dimensional parameter space

(Ω_0, h, Ω_b, n_s^3, Q_{rms}, n_s/n_t, Λ, τ_{relon})

esa

Phase A Study - Final Presentation

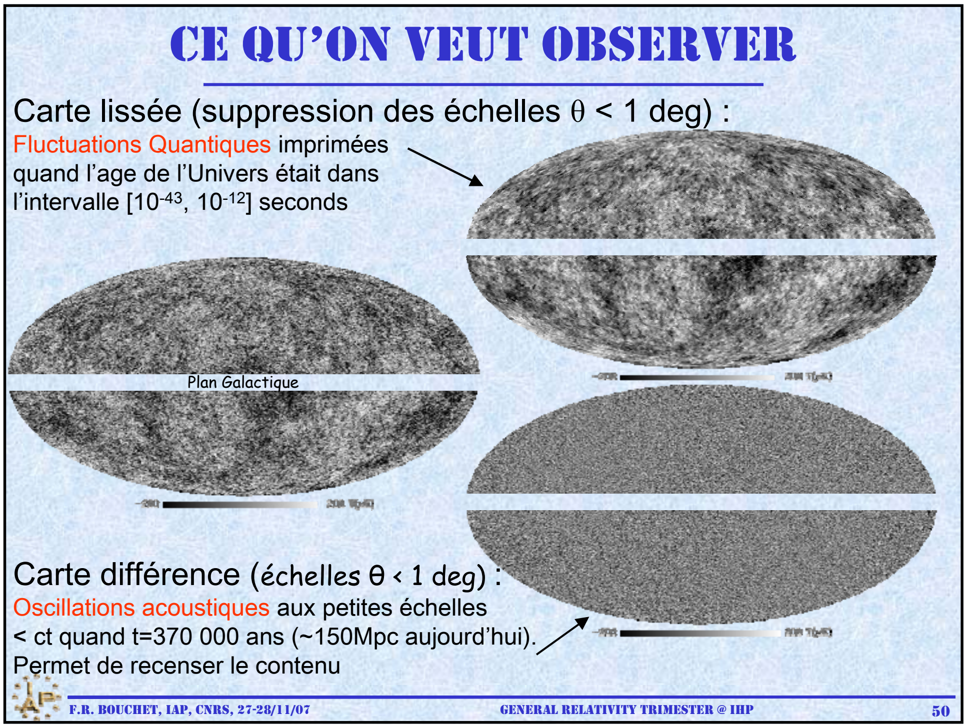


RESOLUTION & SENSITIVITY
CAN BREAK MOST DEGENERACIES

29

NB: Some parameter combinations are nearly perfectly degenerate, e.g. keeping D_A constant

Figure 11. The derivatives of the CDM power spectrum with respect to various parameters.



CE QU'ON VEUT OBSERVER

Carte lissée (suppression des échelles $\theta < 1$ deg) :

Fluctuations Quantiques imprimées quand l'age de l'Univers était dans l'intervalle [10^{-43}, 10^{-12}] seconds

Carte différence (*échelles* $\theta < 1$ *deg*) :

Oscillations acoustiques aux petites échelles < ct quand t=370 000 ans (~150Mpc aujourd'hui). Permet de recenser le contenu

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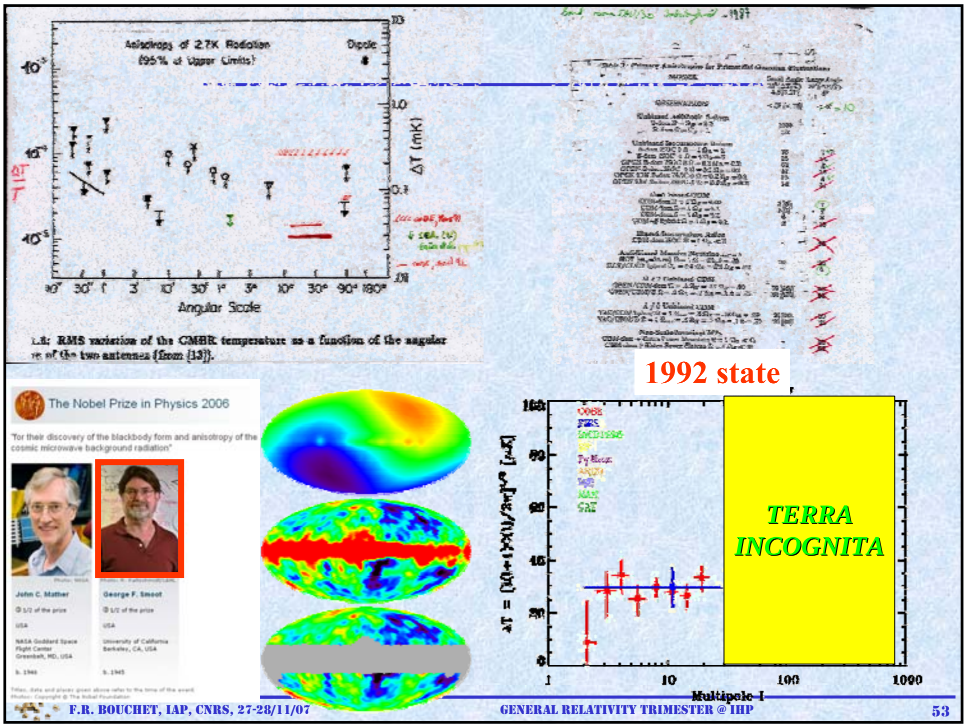
PAUSE APRES 1H+15MN



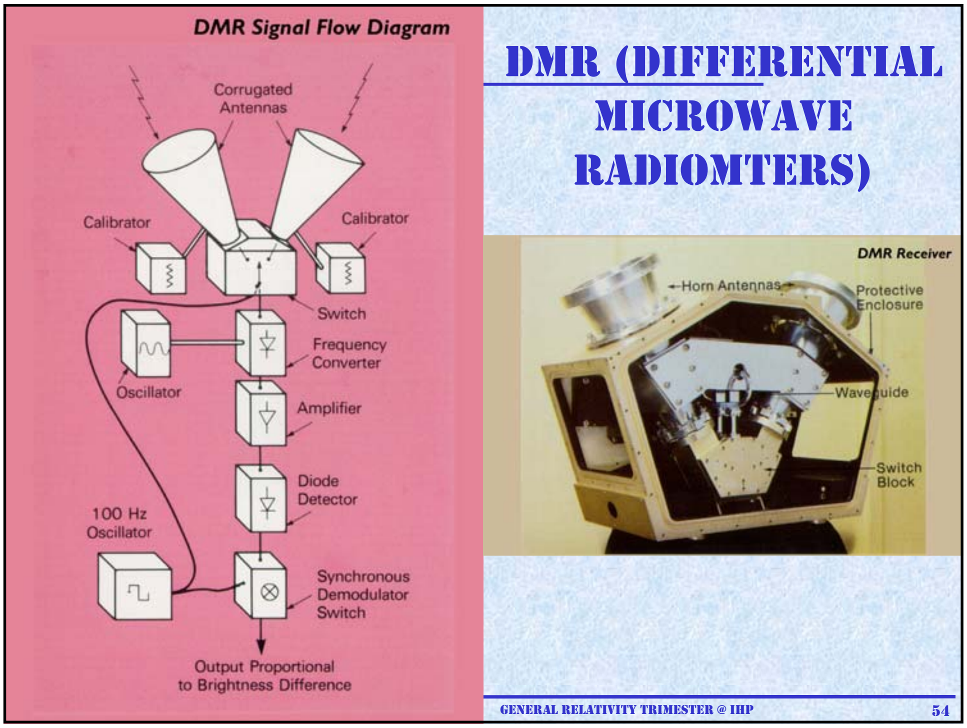
1.8: RMS variation of the CMBR temperature as a function of the angular ... of the two antennas [from [13]].

The Nobel Prize in Physics 2006

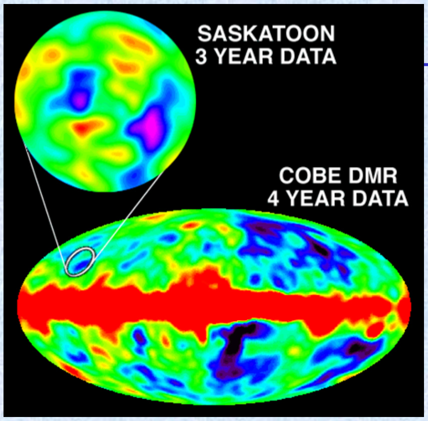
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

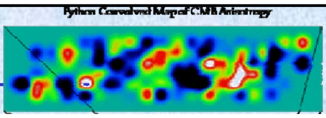
John C. Mather	**George F. Smoot**
1/2 of the prize	1/2 of the prize
USA	USA
NASA Goddard Space Flight Center Greenbelt, MD, USA	University of California Berkeley, CA, USA
b. 1946	b. 1945

Titles, data and places given above refer to the time of the award.
Photos: Copyright © The Nobel Foundation



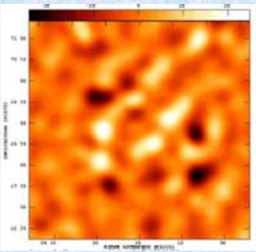
DMR (DIFFERENTIAL MICROWAVE RADIOMTERS)

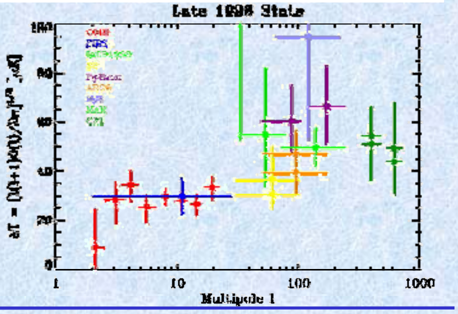




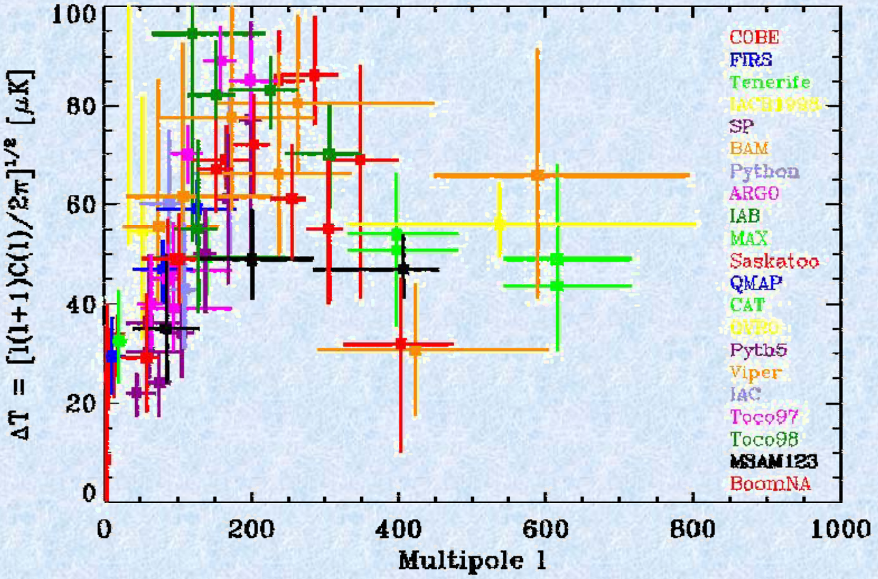
NB: 1996 is the year of the selection
- by NASA of WMAP (against FIRE & PSI) and
-by ESA of COBRAS/SAMBA as M3 of Horizon 2000+ (to become Planck)

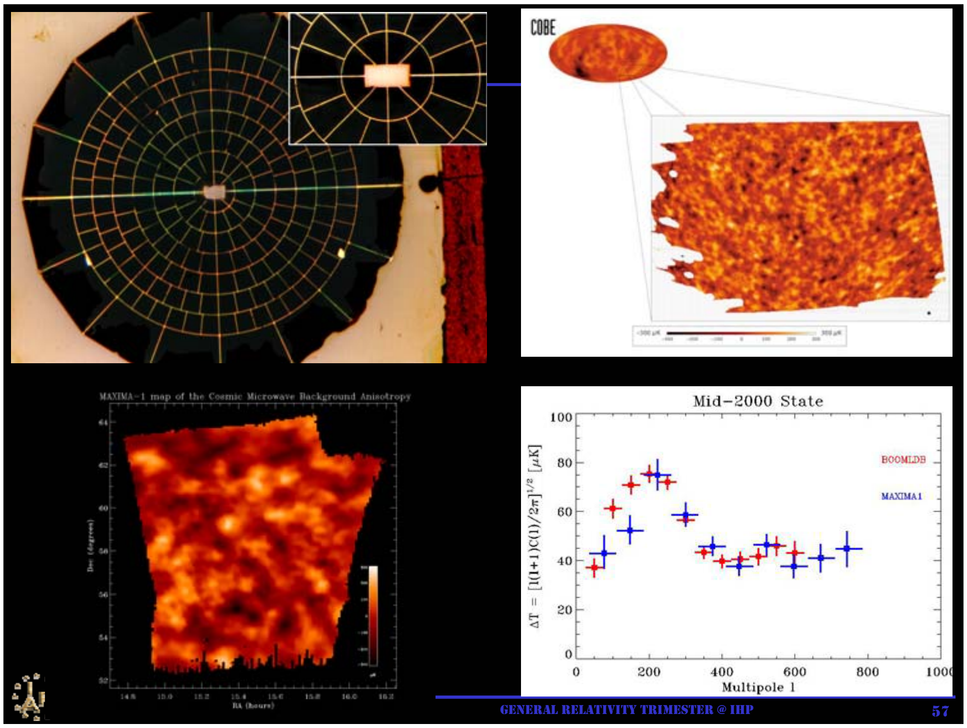
By 1994,
Scott & White
Give 95% CL
that Doppler
Peak is
present
9407073



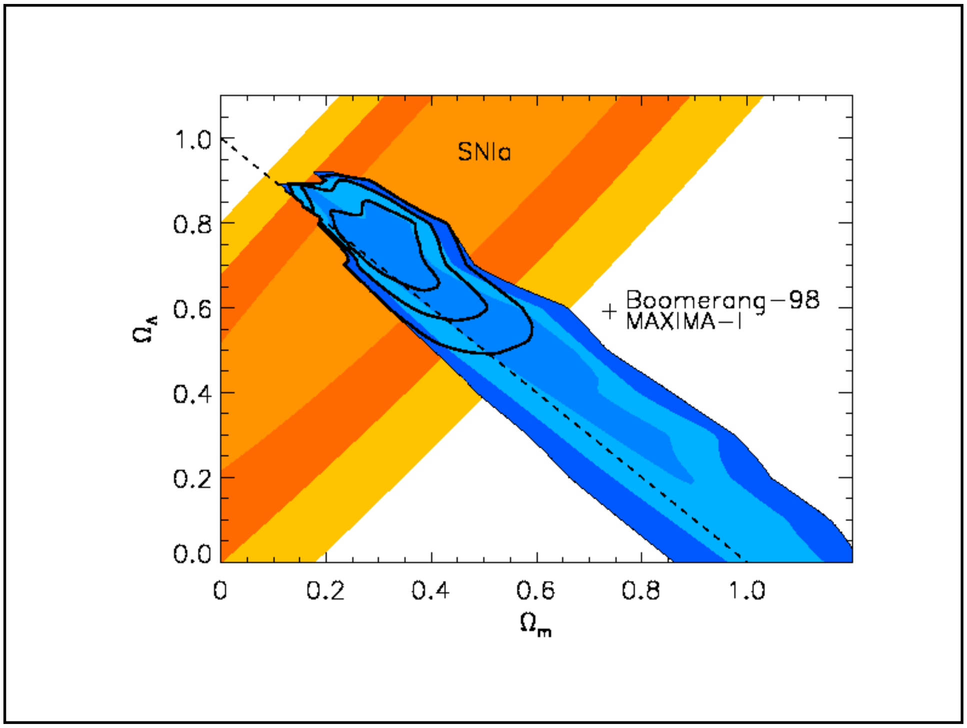


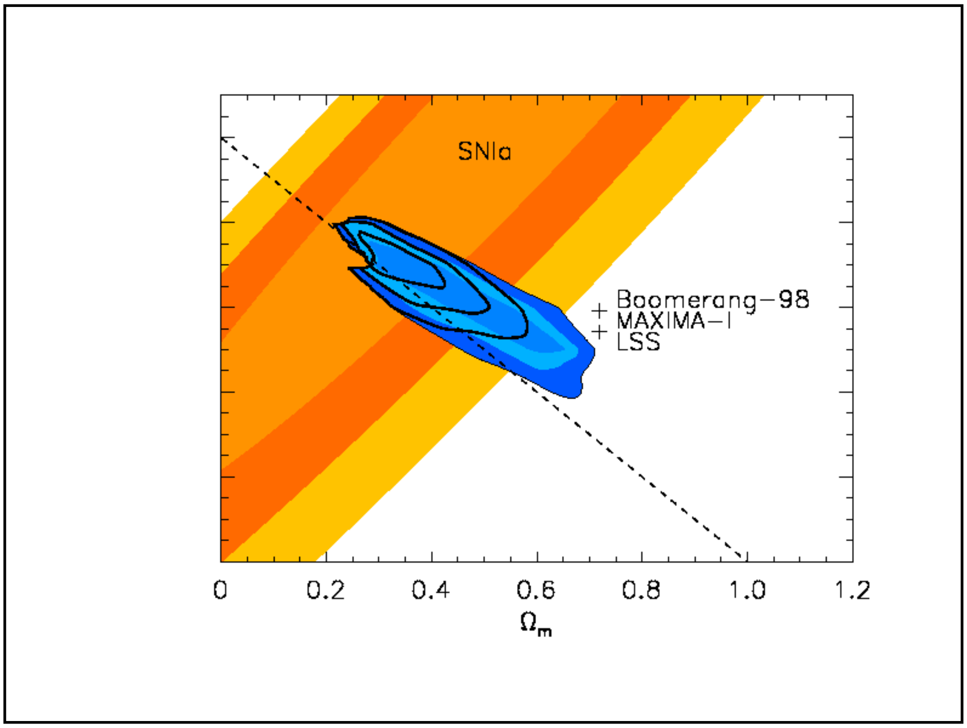
LATE 1999 STATE

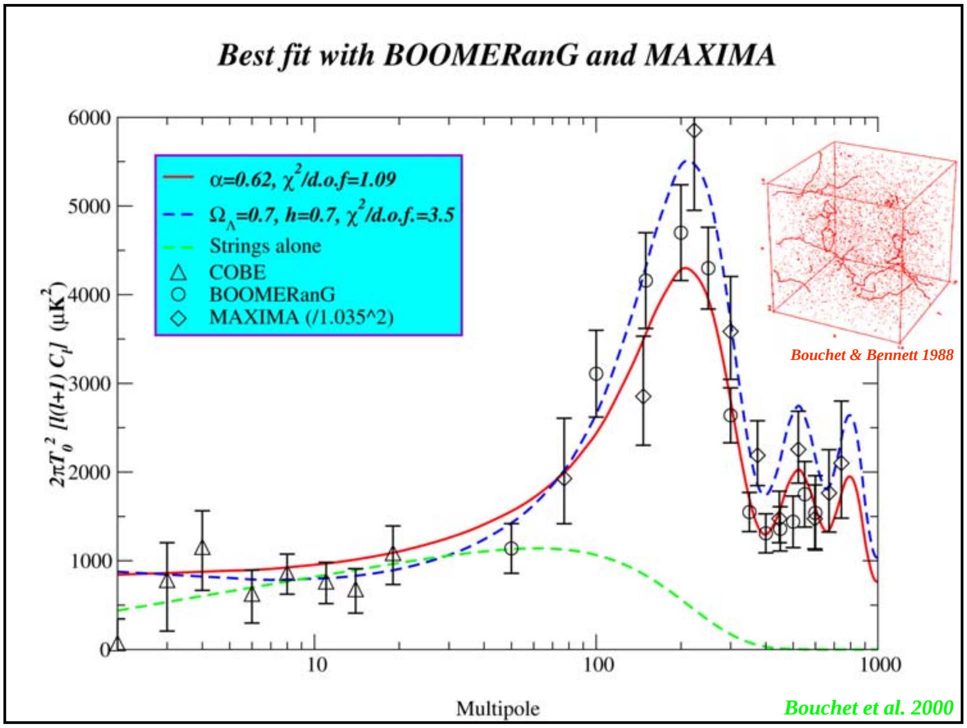




GENERAL RELATIVITY TRIMESTER @ IHP





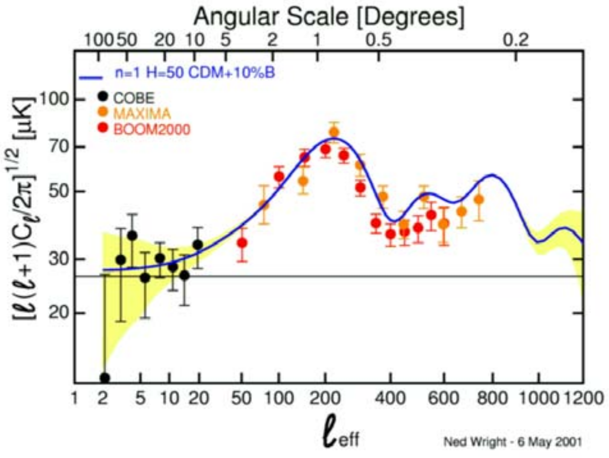


Best fit with BOOMERanG and MAXIMA

Bouchet & Bennett 1988

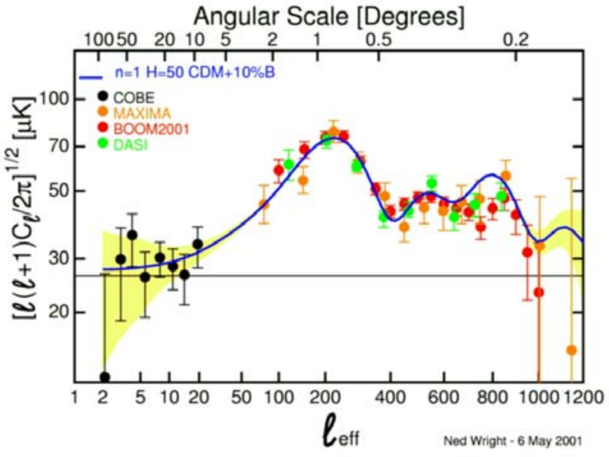
Bouchet et al. 2000

2000 Power Spectrum



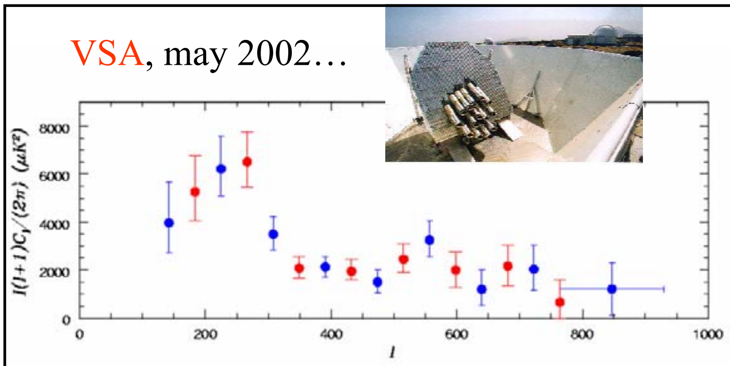
Ned Wright - 6 May 2001

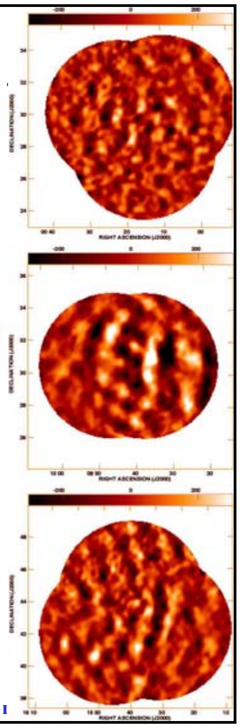
2001 Power Spectrum



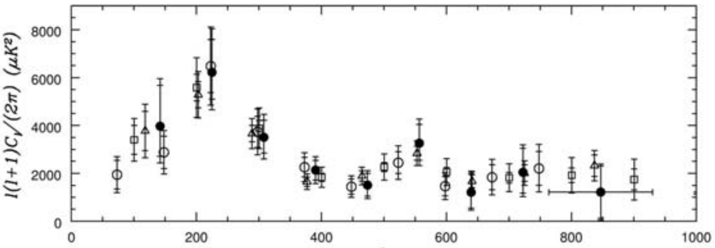
Ned Wright - 6 May 2001

VSA, may 2002…



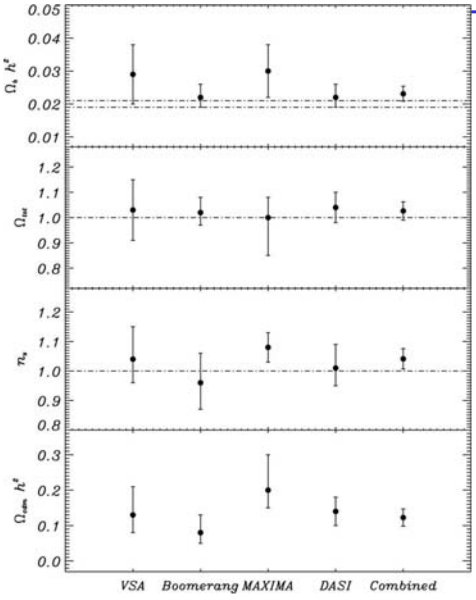


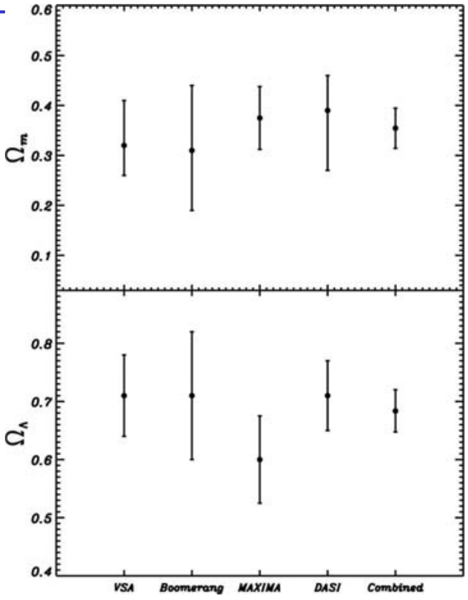
Compares well with BOOM, MAXIMA, DASI



VSA III, Scott et al. astroph/0205380

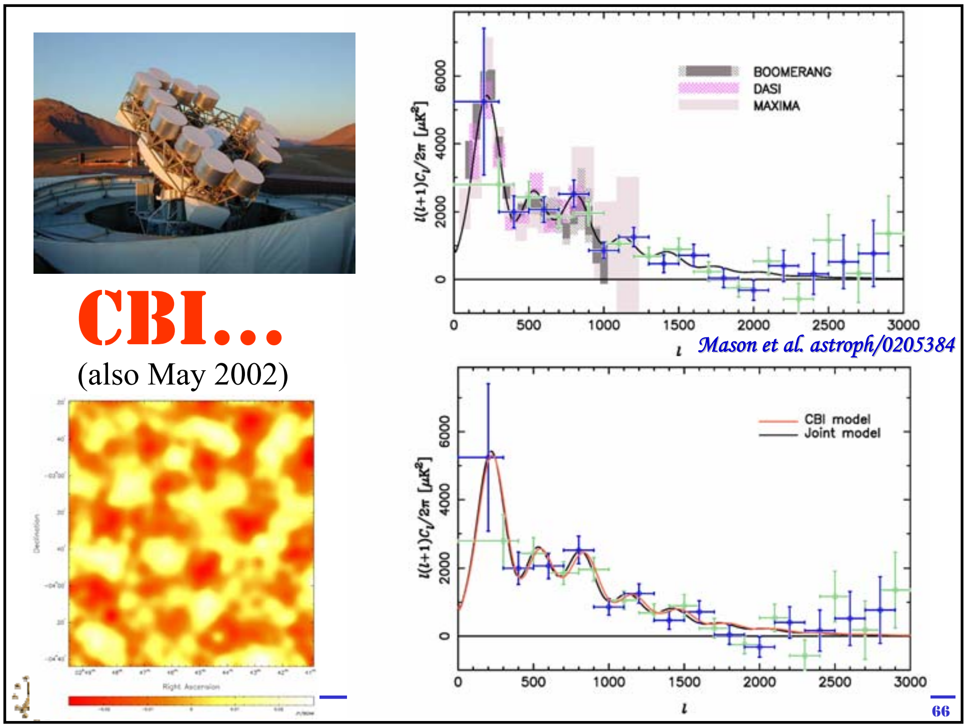
And appears *quantitatively* consistent with BOOM, MAX & DASI…





(All using DMR + similar prior)

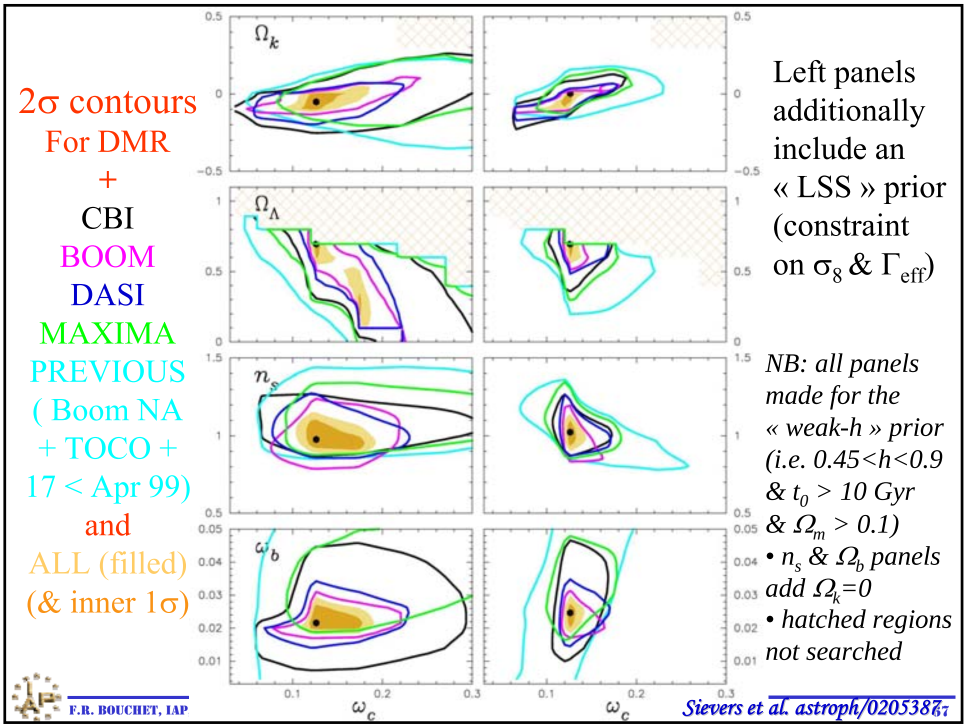
VSA IV, Rubino-Martin et al. astroph/0205367



CBI…

(also May 2002)

Mason et al. astroph/0205384



2σ contours
For DMR
+
CBI
BOOM
DASI
MAXIMA
PREVIOUS
(Boom NA
+ TOCO +
17 < Apr 99)
and
ALL (filled)
(& inner 1σ)

Left panels additionally include an « LSS » prior (constraint on σ_8 & Γ_{eff})

NB: all panels made for the « weak-h » prior (i.e. $0.45<h<0.9$ & $t_0 > 10$ Gyr & $\Omega_m > 0.1$)

- *n_s & Ω_b panels add $\Omega_k=0$*
- *hatched regions not searched*

Sievers et al. astroph/0205387

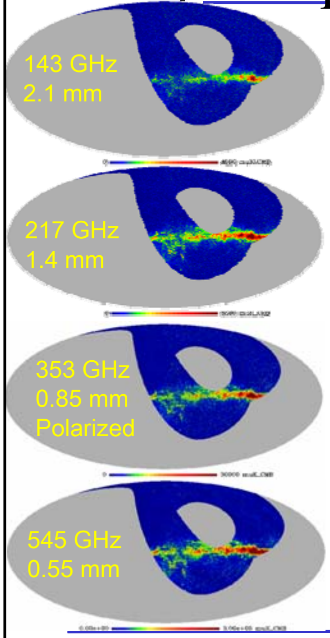
THE ARCHEOPS COLLABORATION

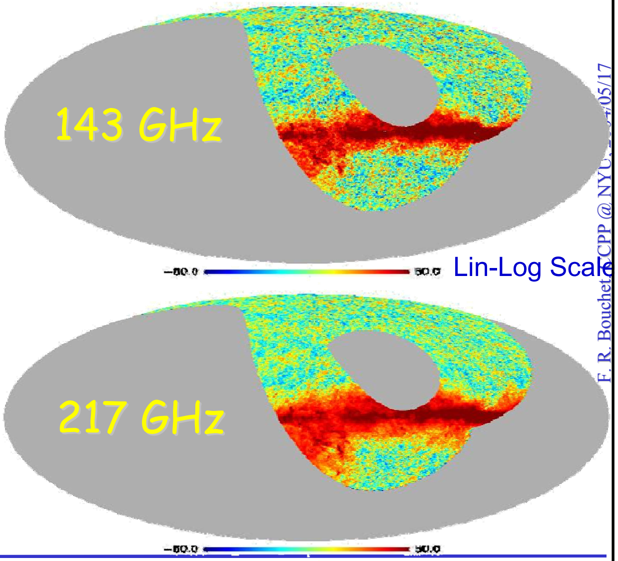
- P.I. A. Benoit (**CRTBT**)
- France
  CESR, CRTBT, CSNSM, IAP, IAS,
  ISN, LAL, LAOG, PCC/CdF, OMP, SPP/CEA
- Italy
  Univ. La Sapienza (Rome), IROE CNR
- Russia
  Landau Ins. of Theoretical Physics
- U.K.
  QMW (London → Cardiff)
- U.S.A.
  CALTECH, JPL, Univ. Of Minnesota

http://www.archeops.org

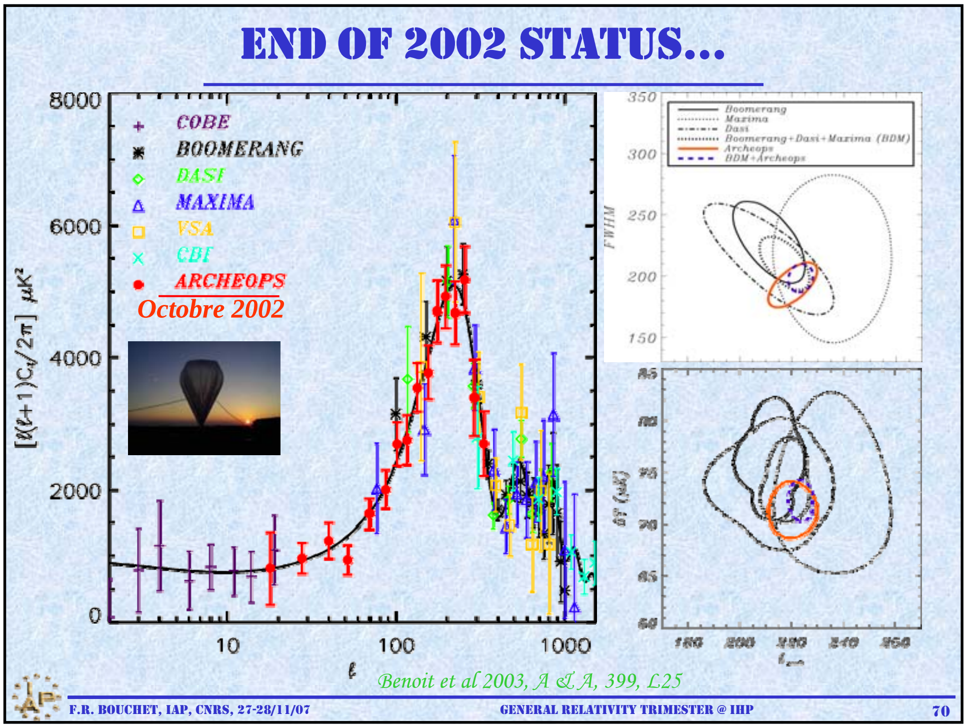
Archeops Maps

- First submillimetric maps at 15 arcmin resolution, 30% sky
- Pointing reconstruction with stellar sensor (*rms* < 1.2 arcmin)



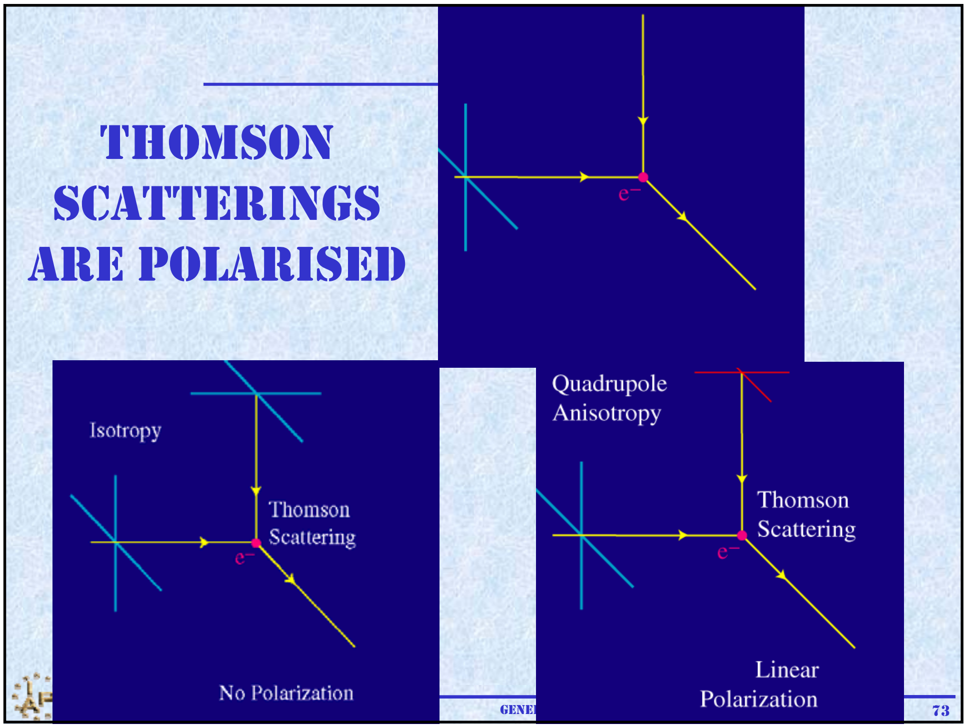


F. R. Bouchet, CCPP @ NYU, [illegible]/05/17

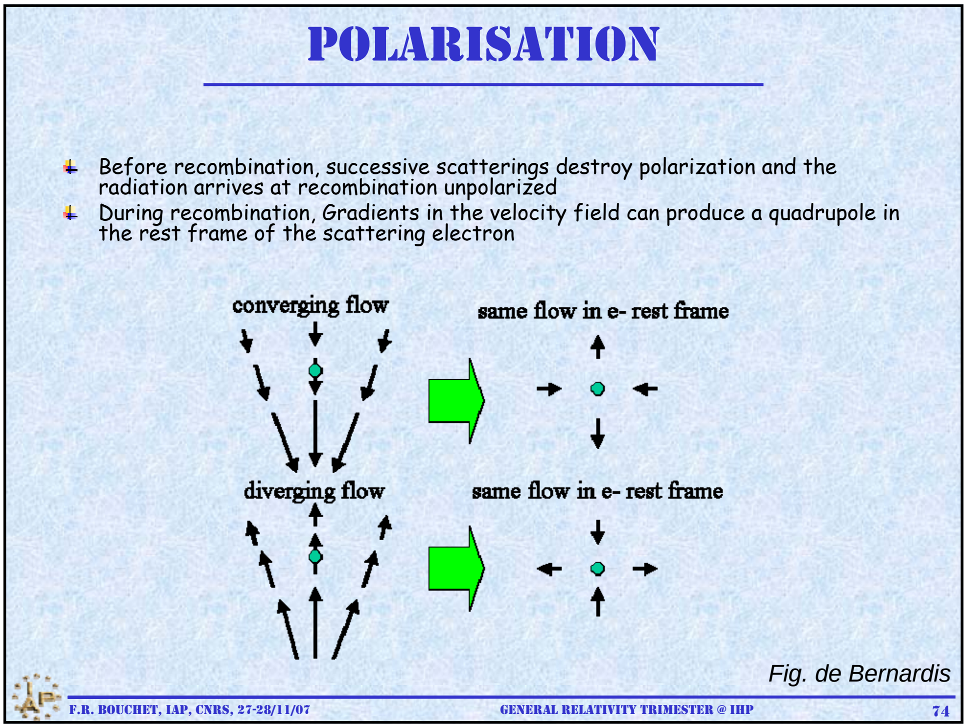


END OF 2002 STATUS…

Benoit et al 2003, A & A, 399, L25



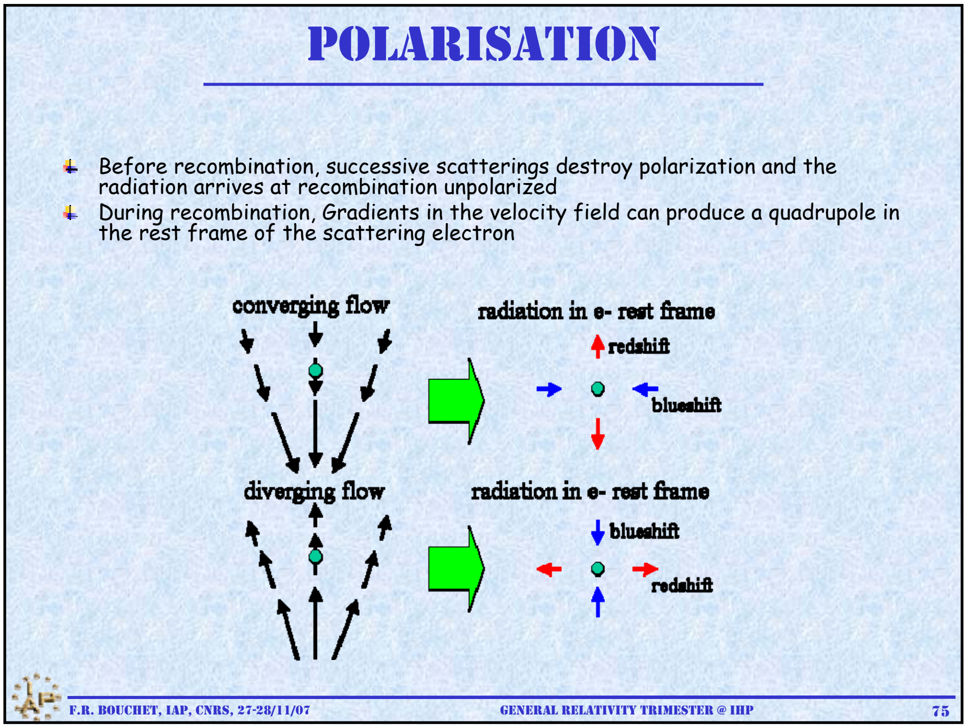
THOMSON SCATTERINGS ARE POLARISED



POLARISATION

- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron

Fig. de Bernardis



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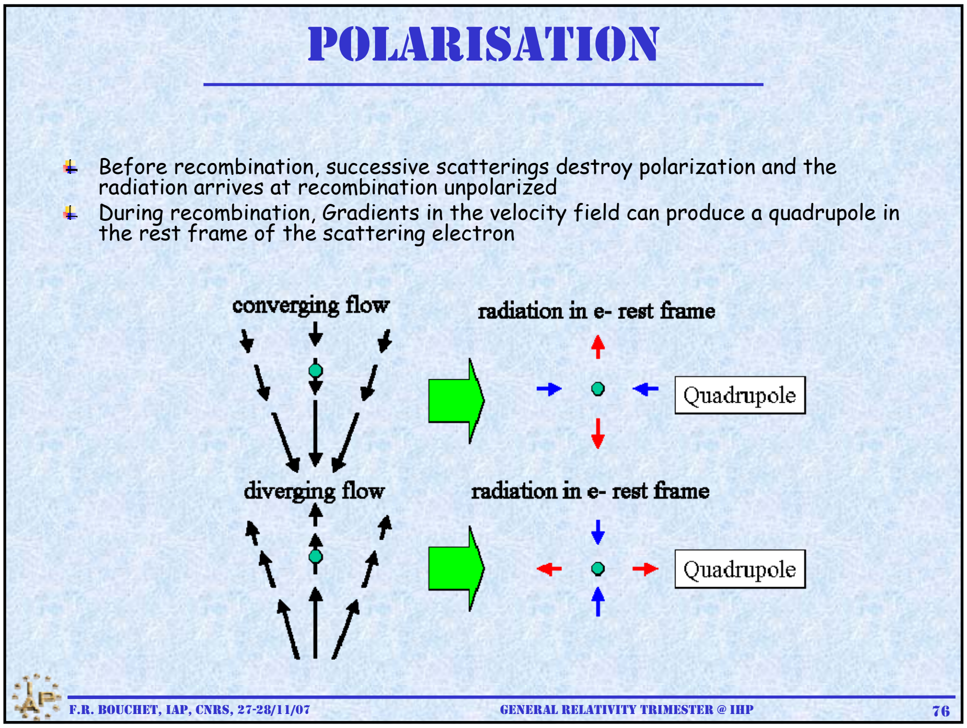

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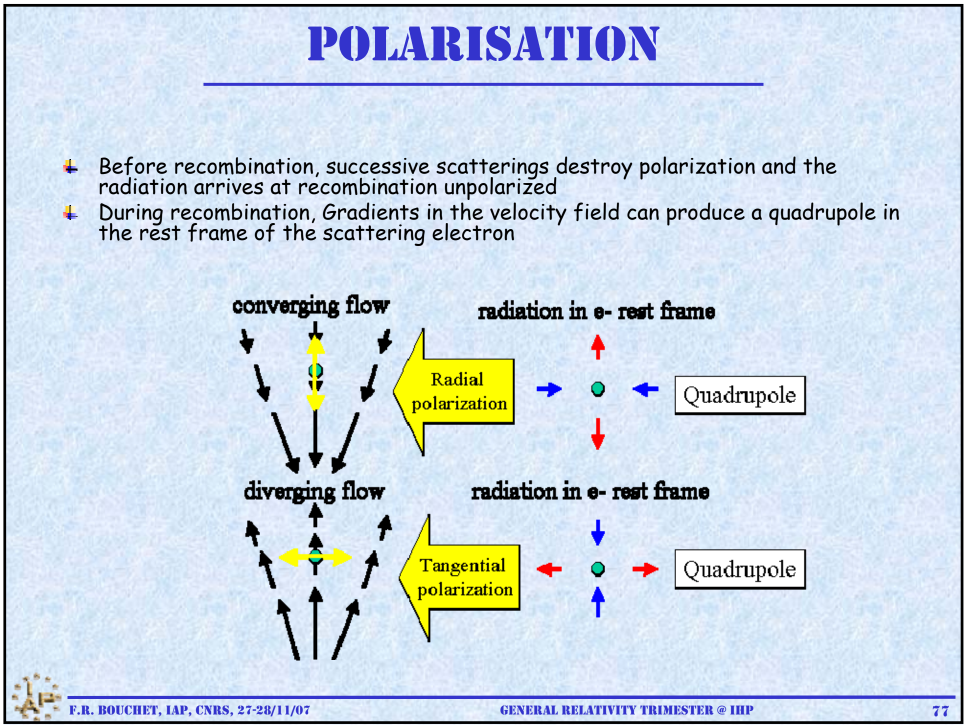

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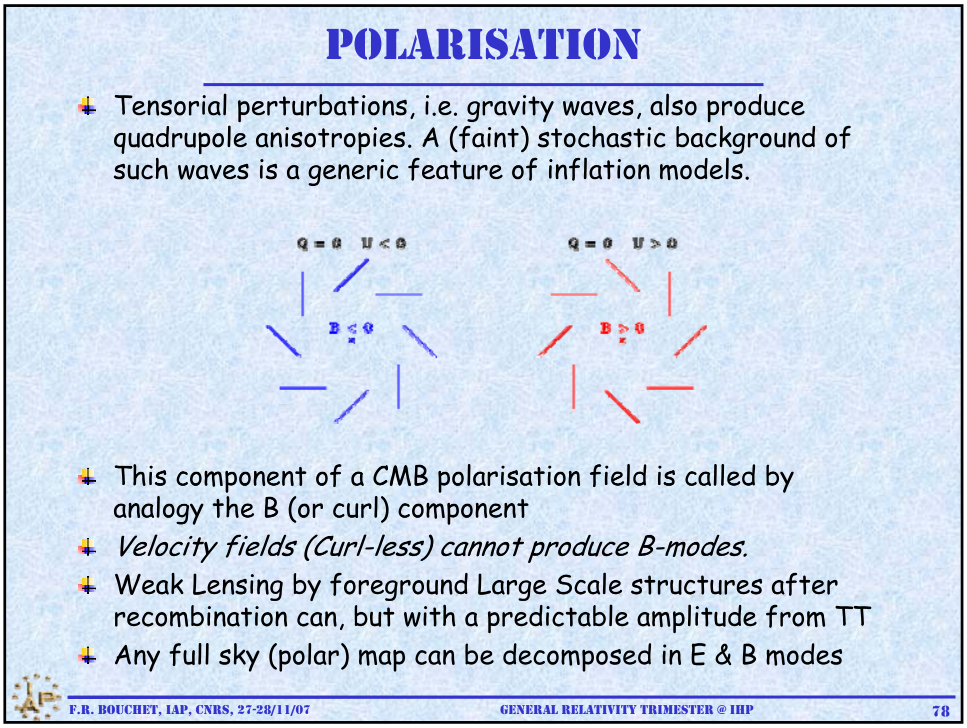
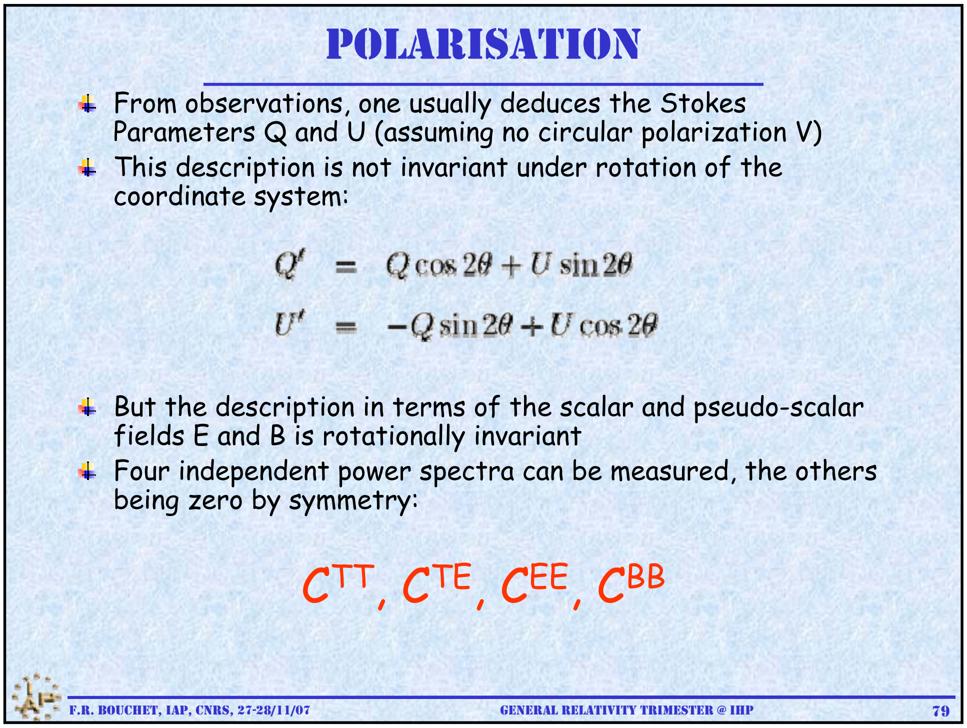


POLARISATION

- Tensorial perturbations, i.e. gravity waves, also produce quadrupole anisotropies. A (faint) stochastic background of such waves is a generic feature of inflation models.

- This component of a CMB polarisation field is called by analogy the B (or curl) component
- *Velocity fields (Curl-less) cannot produce B-modes.*
- Weak Lensing by foreground Large Scale structures after recombination can, but with a predictable amplitude from TT
- Any full sky (polar) map can be decomposed in E & B modes



POLARISATION

- From observations, one usually deduces the Stokes Parameters Q and U (assuming no circular polarization V)
- This description is not invariant under rotation of the coordinate system:

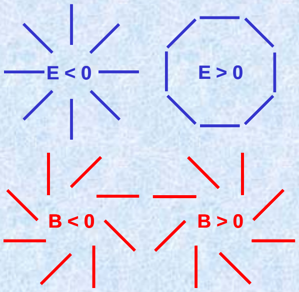
$$\begin{aligned} Q' &= Q\cos 2\theta + U\sin 2\theta \\ U' &= -Q\sin 2\theta + U\cos 2\theta \end{aligned}$$

- But the description in terms of the scalar and pseudo-scalar fields E and B is rotationally invariant
- Four independent power spectra can be measured, the others being zero by symmetry:

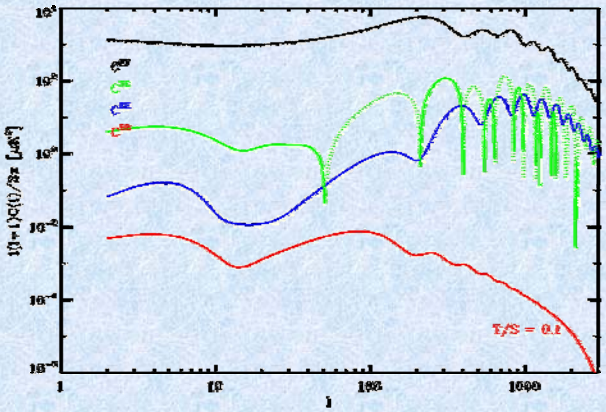
$$C^{TT}, C^{TE}, C^{EE}, C^{BB}$$

SPECTRES DE PUISSANCE DU RCF

- 3 observables : T, E, B

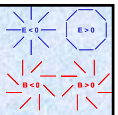


- Les modes B **ne peuvent pas** être générés par des fluctuations primordiales scalaires

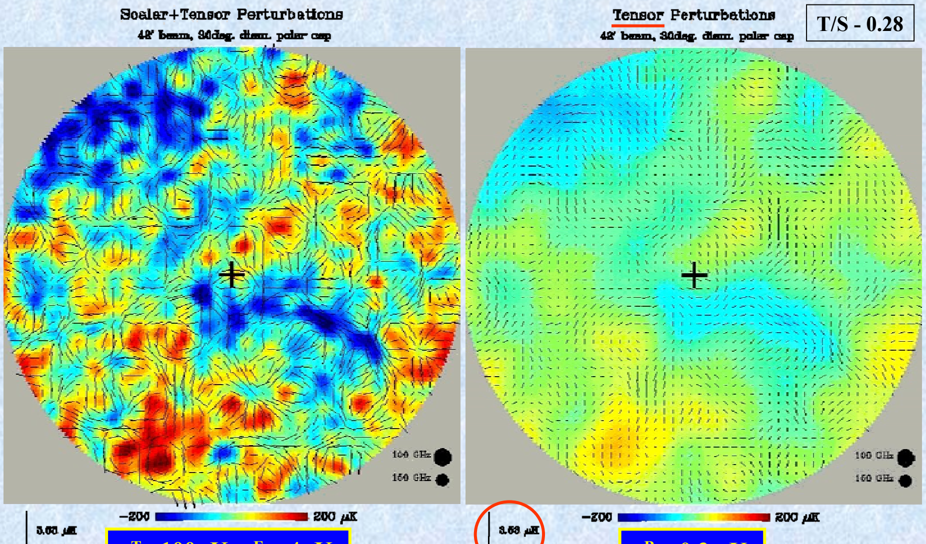


(∝1/θ)

MOTIFS POLARISÉS ATTENDUS



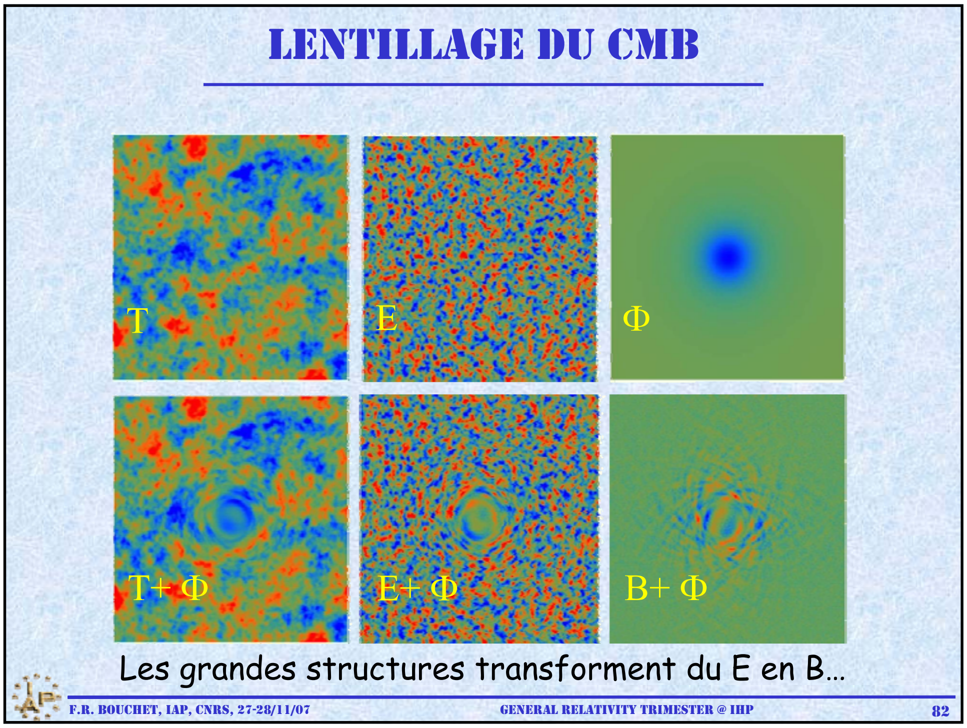
T/S - 0.28



$\sigma^T \sim 100\mu K$, $\sigma^E \sim 4\mu K$

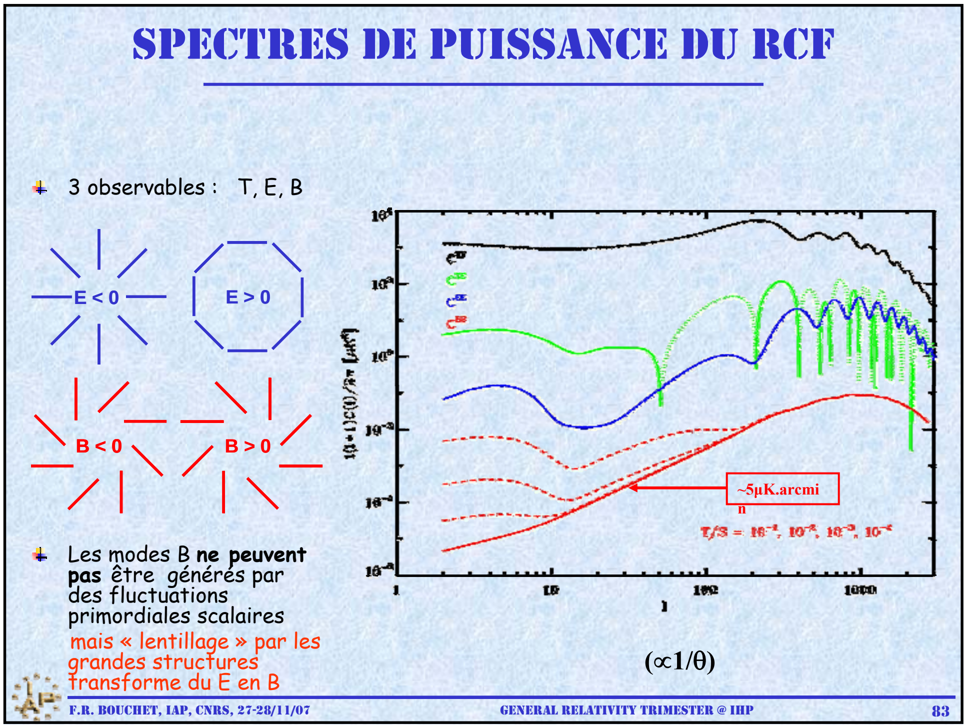
$\sigma^B \sim 0.3\ \mu K$

www.astro.caltech.edu/~lgg/bicep_front.htm



LENTILLAGE DU CMB

Les grandes structures transforment du E en B…

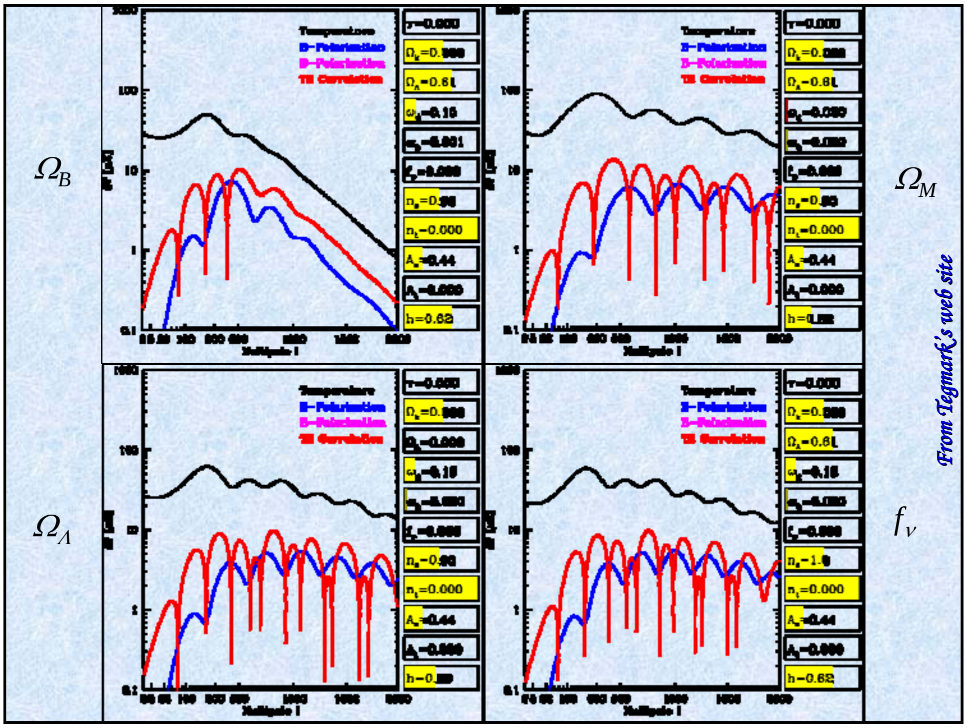


SPECTRES DE PUISSANCE DU RCF

- 3 observables : T, E, B

(∝1/θ)

- Les modes B **ne peuvent pas** être générés par des fluctuations primordiales scalaires mais « lentillage » par les grandes structures transforme du E en B



From Tegmark's web site

WHAT CAN WE LEARN FROM POLARISATION?

- Consistency check of the paradigm (may also include evolution – or lack of- of physical constants)
- Check whether there are super-horizon perturbations
- Improvement in parameter constraints (lifting degeneracies, eg, ns vs tau) and on features in the primordial spectrum
- Isocurvature perturbations (see later)

- Reionization history
- Help with lensing reconstruction of los-projected matter density properties (P_{kk})

- Gravitation wave from inflation – existence, maybe n_T
  (and indirectly on inflaton potential)

POLARISATION DATA

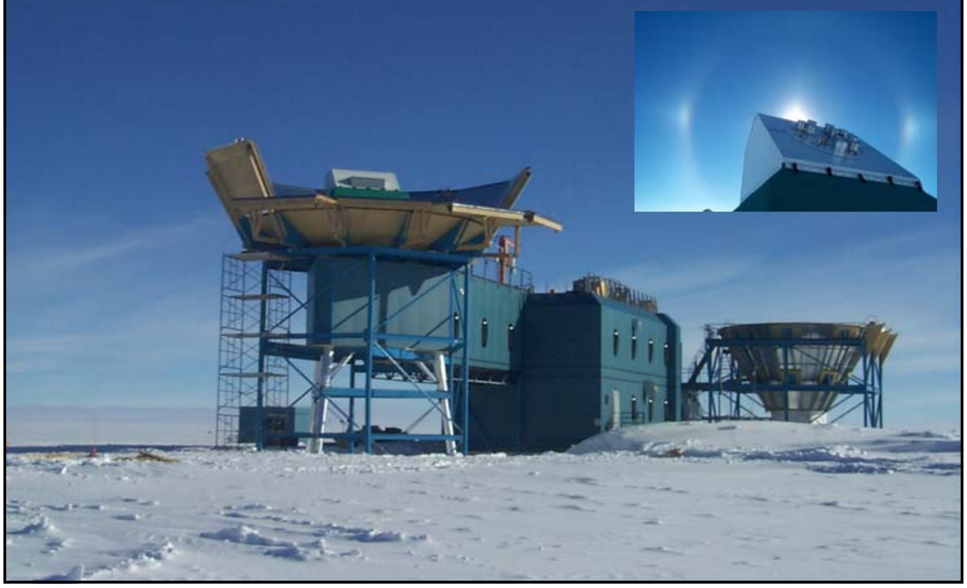
A long lasting effort, with tighter and tighter upper limits for 37 years !

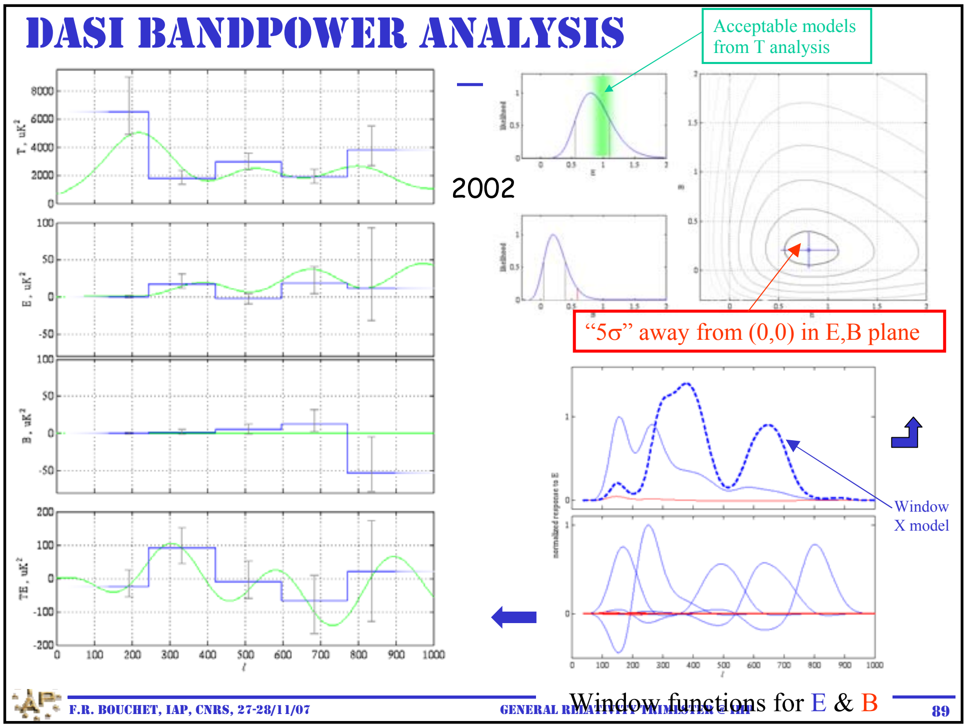
	Year	Frequency [GHz]	Angular scale	Upper limit
Penzias & Wilson	1965	4	-	10^{-1}
Caderni et al.	1978	100 - 600	0.5° ÷ 40°	10^{-3}
Nanos	1979	9.3	15 °	$6\ 10^{-4}$
Lubin & Smoot	1981	33	Quadr.÷Oct.	$6\ 10^{-5}$
Partridge et al.	1988	5	1' ÷ 3'	$4\ 10^{-5}$
Wollack et al.	1993	26 - 36	~1°	$9\ 10^{-6}$
Netterfield et al.	1995	26 - 46	~1°	$6\ 10^{-6}$
Hadman et al.	2001	90	~ 0.5°	$3\ 10^{-6}$
Keating et al.	2001	30	2-20°	$3\ 10^{-6}$

From de Bernardis

DASI (DEGREE ANGULAR SCALE INTERFEROMETER)

13 elements interferometer< 26-36GHz, at South Pole station





DASI BANDPOWER ANALYSIS

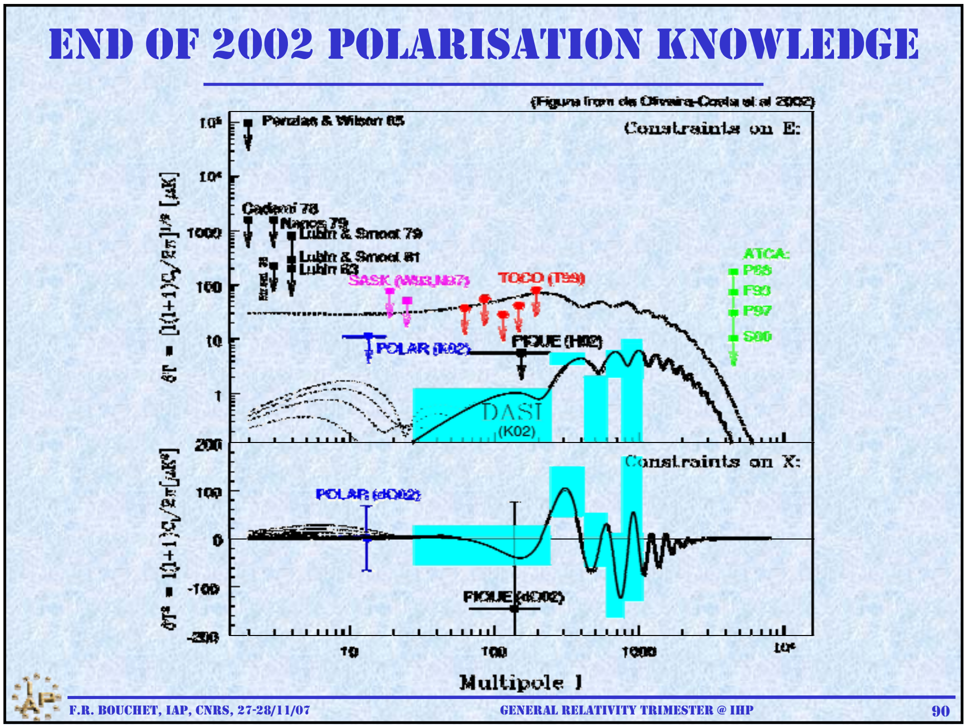
Acceptable models from T analysis

2002

"5σ" away from (0,0) in E,B plane

Window X model

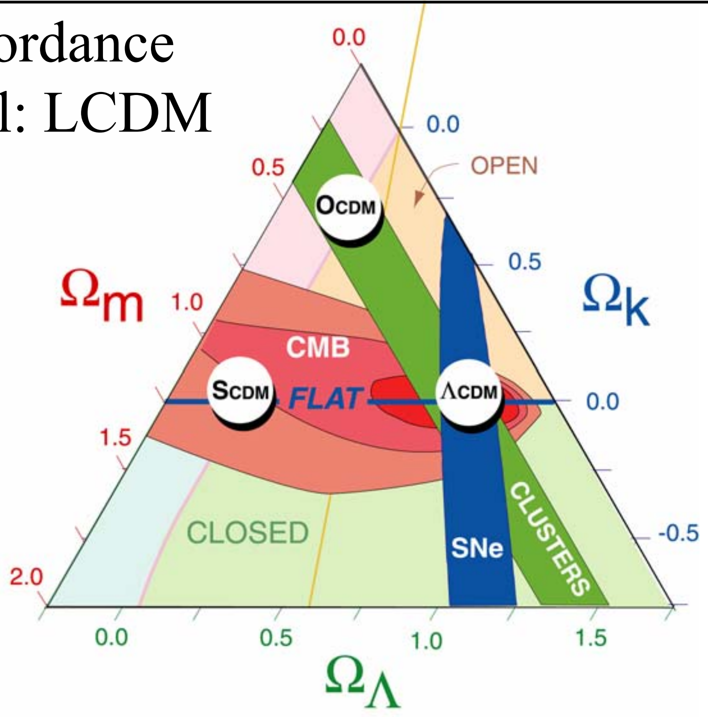
Window functions for E & B



END OF 2002 POLARISATION KNOWLEDGE

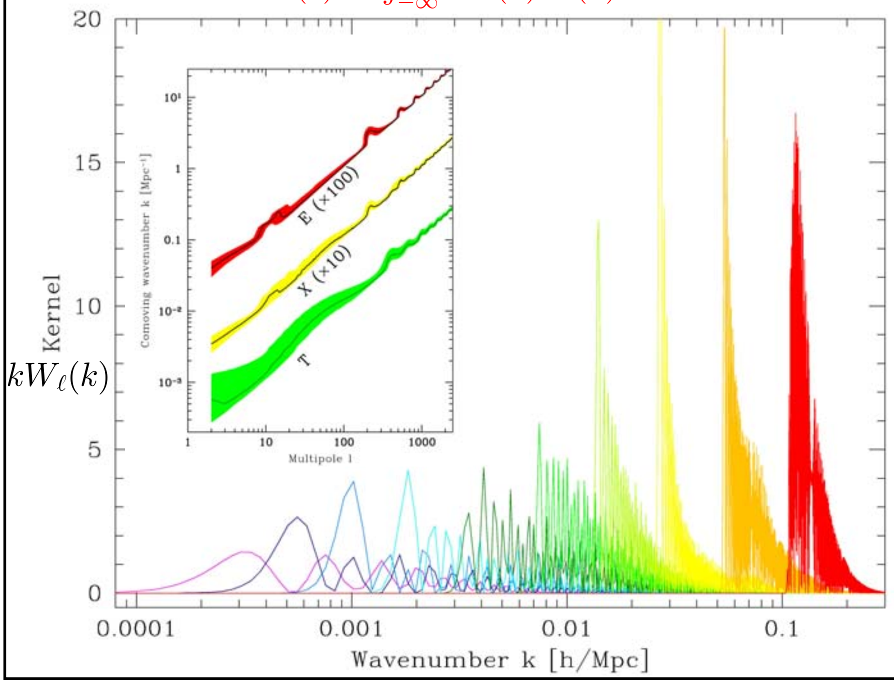
(Figure from de Oliveira-Costa et al 2002)

Concordance model: LCDM



F. R. Bouchet @ CDF. 2004/06/08

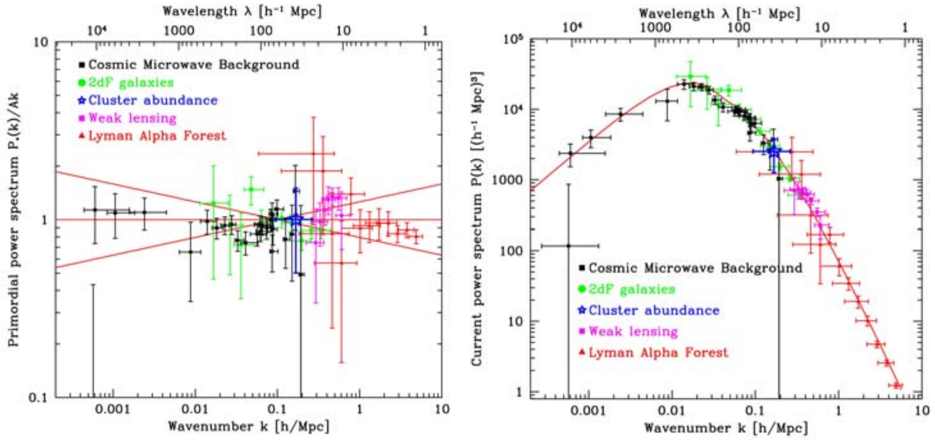
$$C(\ell) = \int_{-\infty}^{+\infty} W_\ell(k) P_\star(k) d\ln k$$



F. R. Bouchet @ CDF. 2004/06/08

USING THE "CONCORDANCE MODEL" PARAMETERS...

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

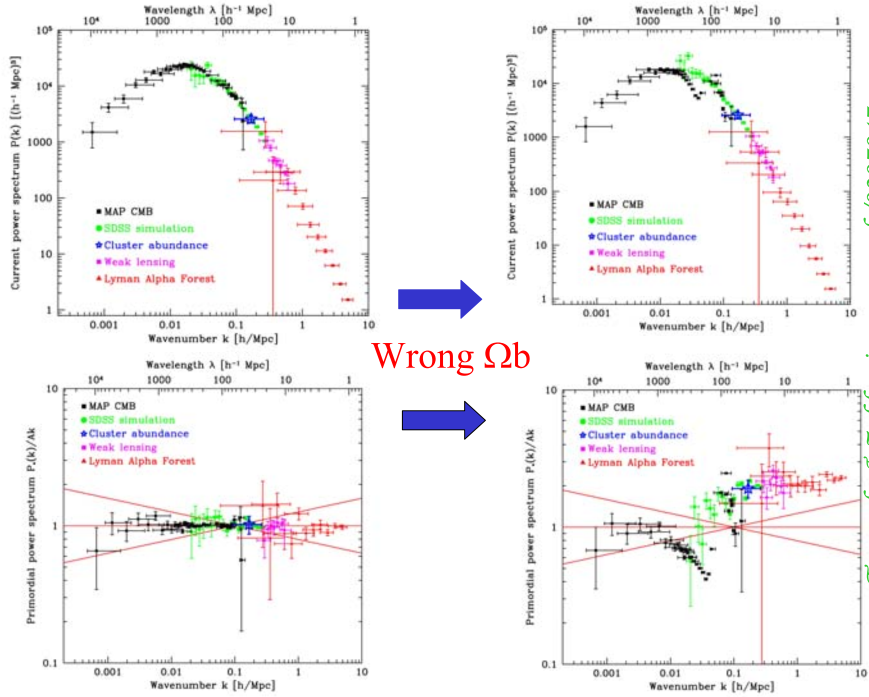


values plotted at $\widehat{P_{\star i}}$ /

$$k\,\widehat{P_{\star i}} = \frac{d_i}{\int_{-\infty}^{+\infty} W_i(k)\ \ d\ln k}$$

$$P(k,z) = P_\star(k) \times T^2(k,z)$$

Tegmark & Zaldarriaga, astroph/0207047



Wrong Ωb

Tegmark & Zaldarriaga, astroph/0207047

F. R. Bouchet @ CDF, 2004/06/08

NOW, LET'S TURN TO WMAP RESULTS