Cosmic Microwave Background Then and Now

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

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

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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 $\delta T/T = 0.00015$.

1965+5…

I. INTRODUCTION

a) *Purpose*

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).

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Initial CMB Calculations

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_c 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_c 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_c 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_c. In § III we give the resulting equations valid to first order in t_c, 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

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

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

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COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES DOMINATED BY NONBARYONIC DARK MATTER

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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 ($h \approx 0.2$, where h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1}).

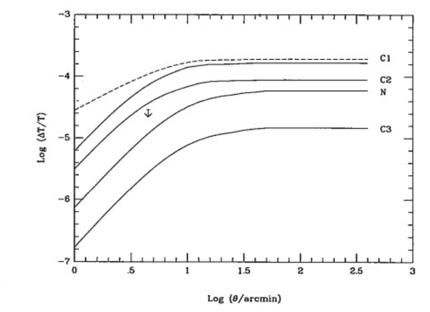

FIG. 1.—Temperature fluctuation as a function of angular scale. Curves C1–C3 show results for cold particle models with the following parameters: (C1) $\Omega = 0.2$, $h = 0.5$; (C2) $\Omega = 0.2$, $h = 0.75$; (C3) $\Omega = 1.0$, $h = 0.75$. The curve labeled (N) shows results for a massive neutrino model with $\Omega = 1.0$, $h = 0.75$, normalized so that $\xi(0, z_{nl}) = 1$ at $z_{nl} = 3$. 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.

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[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).

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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

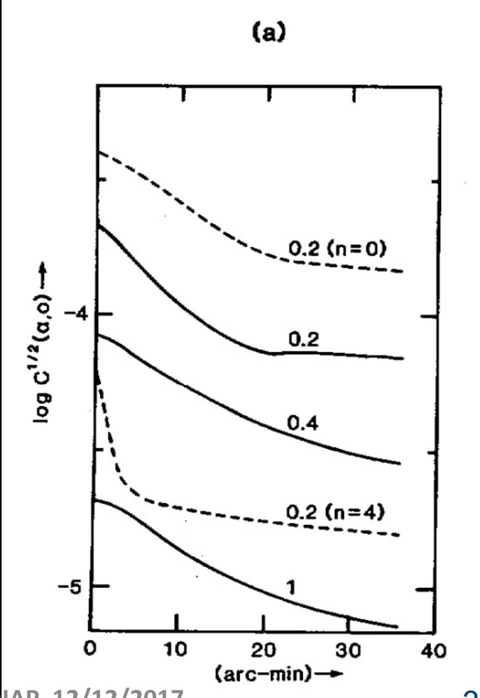
The fine-scale anisotropy of the cosmic microwave background radiation has been studied in cosmological models with a scale-invariant primordial adiabatic density fluctuation spectrum that are dominated by cold, weakly interacting particles such as axions or photinos. Normalization of the present fluctuation 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, $0.4 \lesssim \Omega_0 \lesssim 1$ and 60 km s^{-1} Mpc^{-1} $\gtrsim H_0 \gtrsim$ 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, 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 $h \equiv H_0/100$ km s^{-1} Mpc^{-1}.



1988 (Pre-COBE), Berkeley, Fermilab, Princeton…

Where the Wild Things Are

The strange theories of cosmologists might explain how the universe was born

Before there were planets circling the sun, before there were stars in the night sky, before there were galaxies beyond end, there was nothing, nothing at all. Understanding how the universe and all its denizens arose from that primal void may be the greatest intellectual quest ever. If the intellect of mere mortals seems too puny for the challenge, the imagination may be up to it. Cosmologists, scientists who study how the universe began and evolved, have let their fancy run free. They talk excitedly, and with perfectly straight faces, about the first quadrillionth of a second after creation as if it were yesterday. They play with the idea of "cosmic strings," strange warps in the fabric of space-time whose only failing is that there is no evidence yet of their existence. And they furiously fill blackboards with equations showing that new universes may be percolating out of our own, pinching off into a never-never land that we cannot see. But in the greatest leap of imagination, most cosmologists now believe that the universe arose from nothing, and that nothing is as certain to give rise to something as the night is to sire the dawn.

JAMES D. WILSON—NEWSWEEK

Relics of creation: *Bouchet (left), Silk and a screen of radiation*

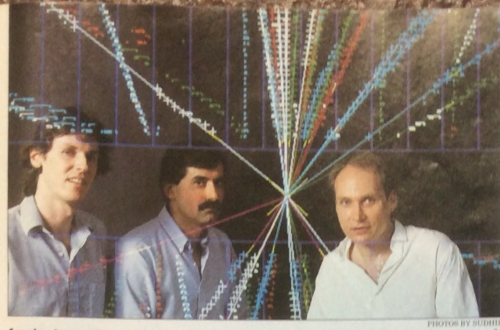
There is room for plenty of whimsy in all of this, but the theories come remarkably close to explaining the universe we observe. Much of the success (and a lot of the whimsy) was triggered around 1980, when cosmologists and particle physicists became traveling companions on the journey back to the creation. Two unlikelier partners are difficult to imagine. Cosmology is the study of the birth and evolution of the universe, the largest entity known; particle physics is the study of the basic building blocks of matter, the smallest things known. The union of the two fields ushered in "a revolution," as Joseph Silk of the University of California, Berkeley, puts it. Particle accelerators mimic the era when the universe was extremely hot and dense, near the beginning of time. At the Fermi National Accelerator Laboratory near Chicago, for instance, physicists can re-create conditions prevailing one trillionth of a second after the creation. The higher the energies achieved in an accelerator, the earlier the universe it simulates. "Accelerators have become time machines," says Fermilab director Leon Lederman. The other boon has been supercomputers. Cosmologists use these silicon behemoths to model the universe's structure—its array of galaxies and clusters of galaxies—in hopes of understanding how it evolved.

Modern cosmology is a child of this century. It was only in the 1920s that scientists realized that our Milky Way is not the only galaxy. The leading theory of cosmology, the big-bang model, has been accepted wisdom only since 1965. This theory holds that the universe began as an infinitely dense, infinitely hot point called a singularity. Then, 10 billion to 20 billion years ago, the singularity exploded. This was not an explosion *into* space, as popularly thought, but a smooth, slow explosion *of* space itself. Its effects are still unfolding today. Most dramatically, the universe is expanding, as one would expect if it exploded: galaxies, bundles of 100 billion stars, fly apart from each other, and new space is created between them. A second lingering effect is the cool radiation that bathes the cosmos. (The current reading is 3 degrees Kelvin or minus 270 degrees Celsius.) From these temperatures, physicists extrapolate and conclude that, once, the universe was a searing fireball.

Sequined gown: Yet the big-bang theory cannot account for much of what appears in the firmament. Most critically, it does not address how the universe came to be so uniform in all directions, with particles of radiation distributed across the heavenly vault as regularly as sequins on a gown. Nor does it explain the size and clustering of galaxies. "We all had to say that those were just the God-given conditions," says Berkeley's Marc Davis.

Cosmologists are no longer content to invoke the deity. Instead, they are determined to understand how the world came to be, and to explain it with such elegant simplicity that, as Lederman is fond of saying, their equation for the universe can be stenciled onto T shirts. The first step toward a new cosmology came in the early 1980s, when Alan Guth at the Massachusetts Institute of Technology proposed his "inflation" scenario. The theory now has several versions, but each shares one theme: before 10^{-35}* second after the big bang, all the forces of nature were rolled up into a single superforce, as particle physics predicts. Perhaps our own universe pinched off from some granddaddy cosmos billions of years ago. But there is no way we could reach another cosmos. "There's no sign we could part the curtain of space-time and enter into a different universe," says James Hartle of UC, Santa Barbara.

*A 1 preceded by 34 zeros: .00000000000000000000000000000000001, or a 100,000th of a quadrillionth of a quadrillionth of a second.



PHOTOS BY SUDHIR

Accelerators as time machines: *Albrecht, Kolb, Turner with particle-experiment result*

That's just as well: cosmologists have a hard enough time explaining our own. The events of the first fractured second are an enigma wrapped in mystery; the events of a few million years later are not much clearer. One of the most vexing questions is how large structures such as galaxies formed as early as 12 billion years ago. In trying to explain the starry vault we see today, cosmologists have turned to material that is invisible—and sometimes imaginary. Astronomers now know that luminous galaxies are immersed in a dark veil. Although they have seen its gravitational effects, no one has ever spied this "dark matter," much less identified what it's made of. But apparently there is a phantom universe out there, consisting of 90 or even 99 percent of the mass of the cosmos, and we have little inkling what it is.

Seven Samurai: The mystery matter might come in any of several forms. One candidate is neutrinos, ghostly subatomic particles that may or may not have any mass. Neutrinos are described as "hot dark matter" because they fly through space at nearly the speed of light. One team of researchers has been filling a Cray supercomputer with simulations of tens of thousands of neutrinos to see what kind of universe they would make. They start their model 1 million years after the big bang, when ordinary matter appears and can be corralled, by neutrinos' gravity, into galaxies. As billions of years of cosmic evolution unfold before their eyes, the researchers see neutrinos first make clusters and superclusters of galaxies, reports Joan Centrella of Drexel University. Happily, the clusters are just the size of many real superclusters. These clumps then fragment into galaxies.

The rival candidate for the mystery particles is "cold dark matter," so called because it moves more slowly than neutrinos. It includes particles with names like axions and photinos that, unlike real-life neutrinos, are purely figments of theorists' cerebrations. "It's absurd, how uncertain it all is," admits Berkeley's Davis. Still, he is doggedly using a Cray to model about 250,000 clouds of cold dark matter particles. During each 20-hour run, Davis watches as the particles' gravity first attracts enough ordinary matter to form galaxies. In his simulation, this takes place about 10 billion years ago. The computer galaxies then bunch into clusters about 5 billion years later.

For all the brilliance of logic and math that goes into such ideas, how can you prove, or disprove, theories about events no one witnessed and that cannot be repeated?

Warp in space: *Gott's noncosmic string*

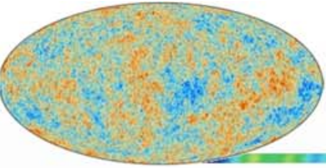
One way is to dust off the telescope and look for clues. "Astronomy has always been the driving force of cosmology," says Craig Hogan of the Steward Observatory in Arizona.

Lately astronomy has undermined some of the theories. This spring, telescope-gazers in Hawaii announced the discovery of a galaxy 12 billion years old, 2 billion years earlier than Davis's computer runs had predicted. And, since 1986, a group of astronomers who call themselves the Seven Samurai (paladins who will ride to the defense of scientific truth and honor) has been reporting that 400 galaxies in a huge swatch of sky, 300 million light-years across, are moving hellbent toward some mysterious "great attractor" in the southern sky. To generate enough gravity to make galaxies fly through space at 350 miles a second requires something millions of light-years across, something bigger than any dark matter can create. Moreover, hot dark matter "has problems generating galaxies soon enough," says David Schramm of the University of Chicago. "[Cold dark matter] has trouble getting them into superclusters."

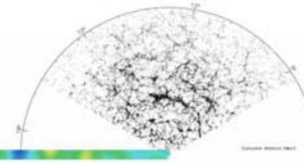
Cosmic strings: Undaunted, physicists are plucking still more ideas from their theoretical quivers. The latest member of what Hogan calls "the bulging bestiary of imagined fauna [in] . . . the cosmos" is cosmic strings. They supposedly formed sometime in the first second, when the universe underwent a "phase transition." Freezing is one example of a phase transition. Just as the transition from water to ice produces defects, such as cracks, so the cooling universe may have been riddled with defects, explains Andreas Albrecht of Fermilab. Cosmic strings are these defects. They are so dense that an inch of string would be as heavy as the Swiss Alps, and 10 quadrillion times thinner than an atomic nucleus. Infinitely long lines, cosmic strings would continually break into loops, filling the cosmos like wiggles in a Joan Miró canvas. Unfortunately, there is as yet no evidence that strings exist.

That has only whetted cosmologists' enthusiasm for them. Strings appeal because they might act as seeds of galaxies. Perhaps a small loop of string attracts, with its gravity, enough matter to form a galaxy; a bigger loop might attract enough to form a galactic cluster. Or, strings might blast matter into galaxies. If strings emit radiation, suggest Jeremiah Ostriker and colleagues at Princeton, the radiation would build up immense pressure and start blowing a bubble. The bubble would expand and push surrounding matter into shells, where galaxies would form.

Cosmic strings seem to do a good job of explaining the pattern of galaxies as well as the voids between them, claims Albrecht. And last month physicists at Los Alamos National Laboratory suggested



CMB spectrum: FIRAS

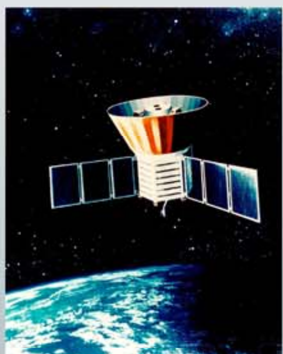


$$T_0 = 2.725 \pm 0.002\,\mathrm{K}$$

95% CL from template fits:

$$|y| < 1.5 \times 10^{-5}$$

$$|\mu/kT| < 3.3 \times 10^{-4}$$



Physics 2006

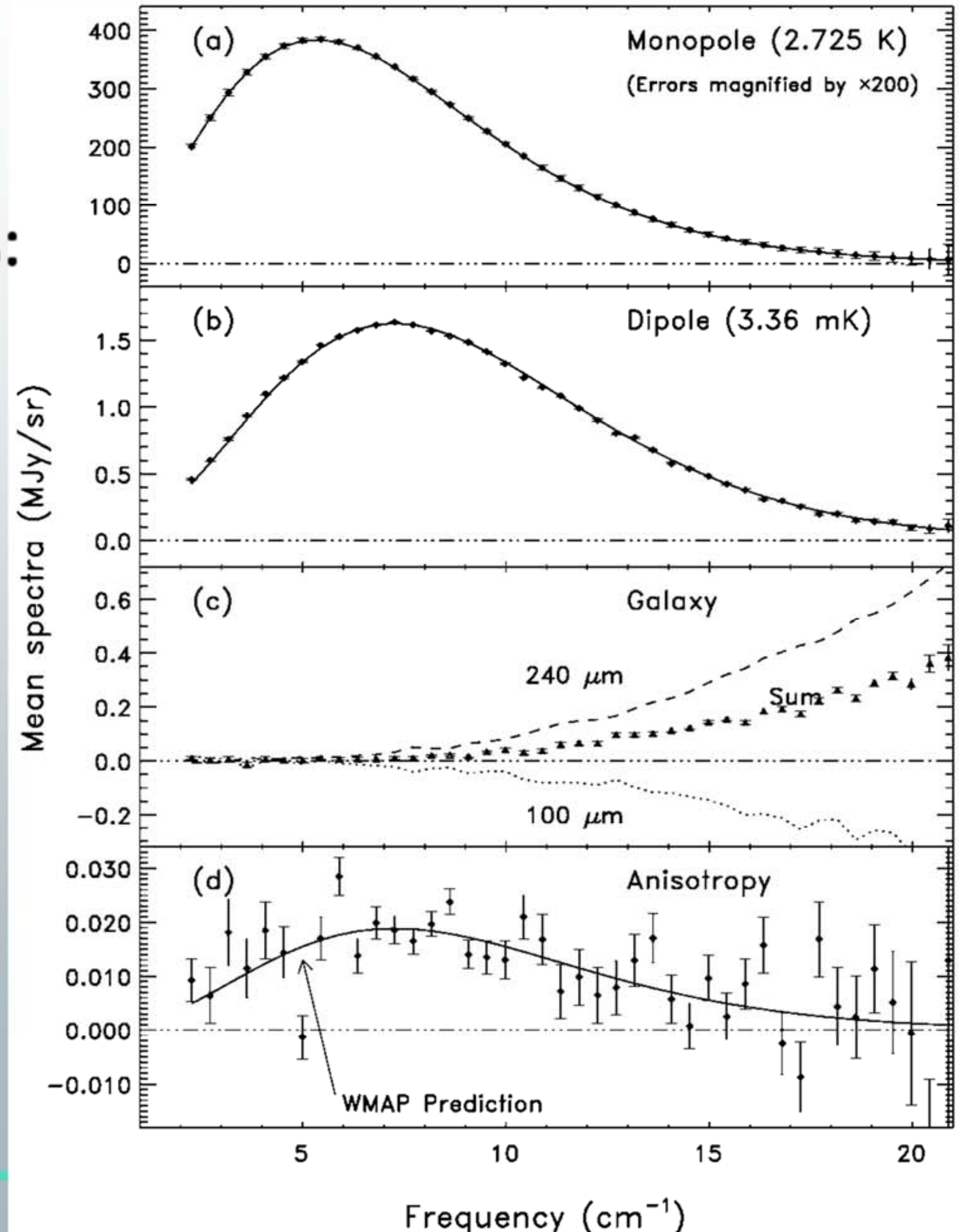
Mather@ AAS 1990, 9mn of data

Mather et al., 1994, ApJ, 420, 439

Fixsen et al., 1996, ApJ, 473, 576

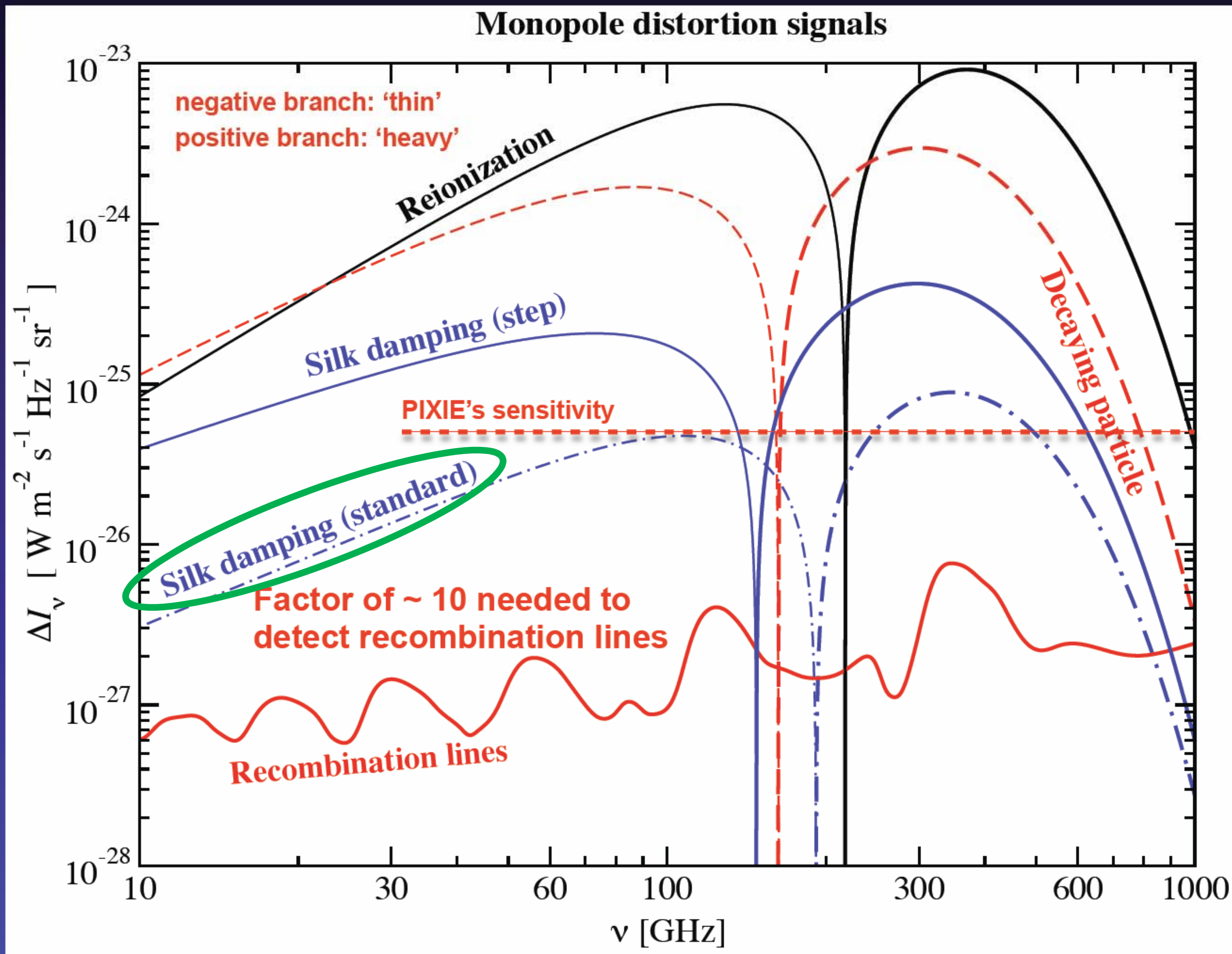
Mather et al., 1999, ApJ, 512, 511

Fixsen et al., 2003, ApJ, 594, 67 →



"Cosmic Microwave Background, then and now"

Average CMB spectral distortions



Absolute value of Intensity signal

And < μT>…

J. Chluba slide (I think)

Prospects

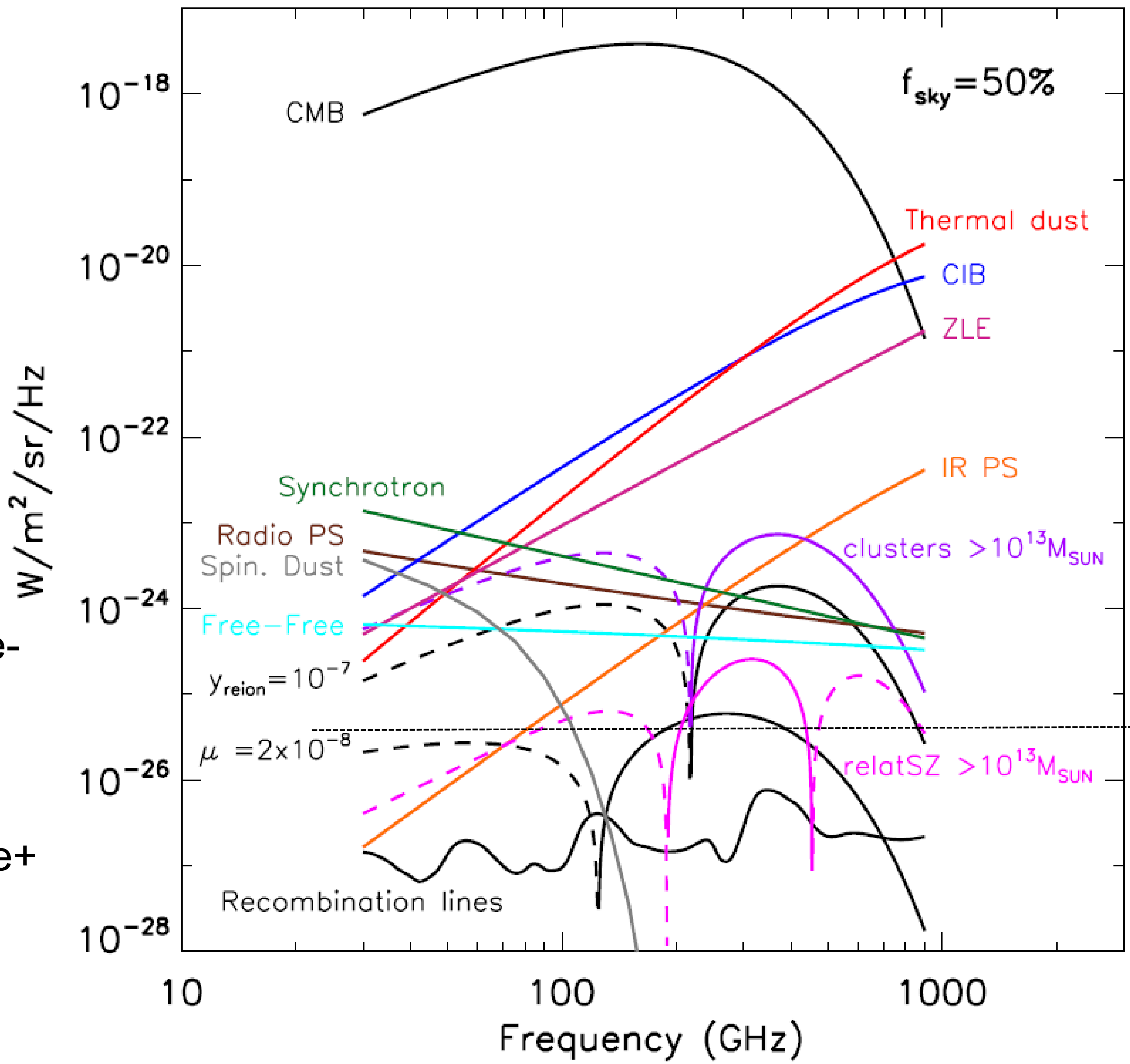


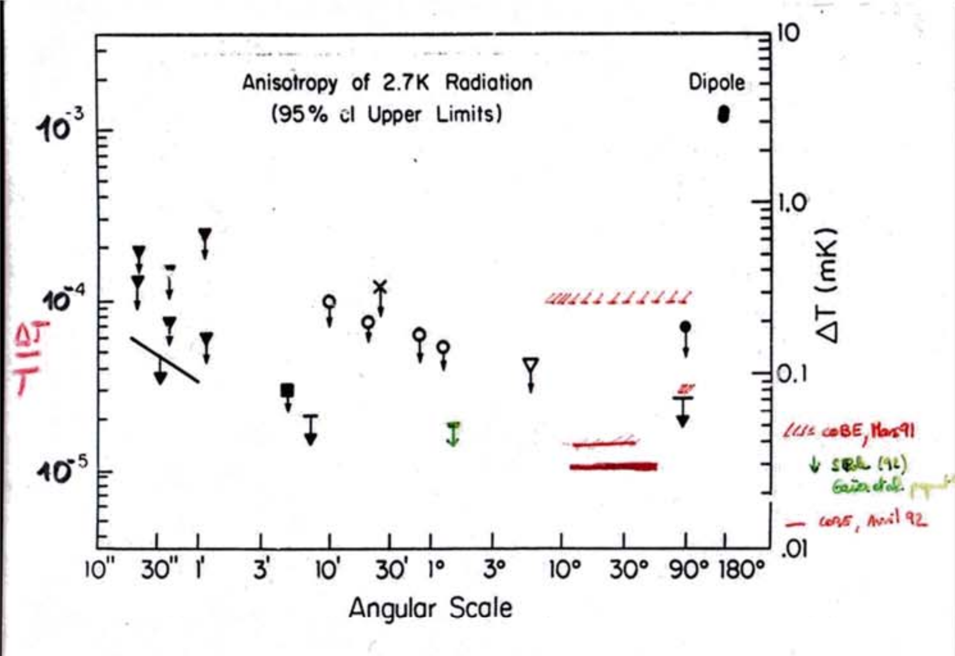
Fig. Delabrouille

? Pixie-

? Pixie+

Very rich cosmology and foregrounds distortion physics

Pixie 4 years 50% sky
proposed to NASA explorer Pgm In 12/2016 For 2023 launch (with also r cap.)



1.6: **RMS variation of the CMBR temperature as a function of the angular** ...n of the two antennas (from [13]).

Bond, revue IAU130 ~1987

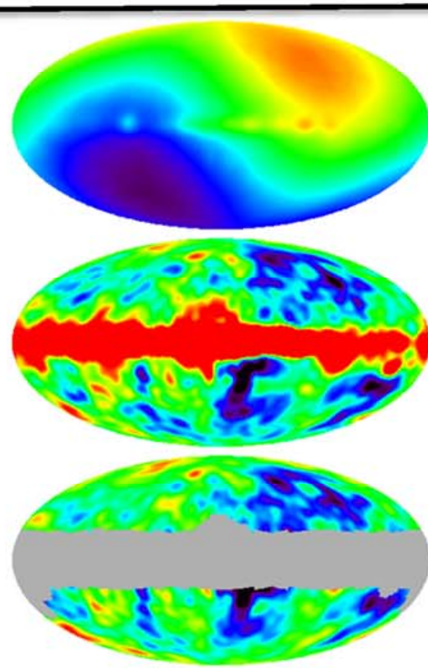
Table 1: Primary Anisotropies for Primordial Gaussian Fluctuations

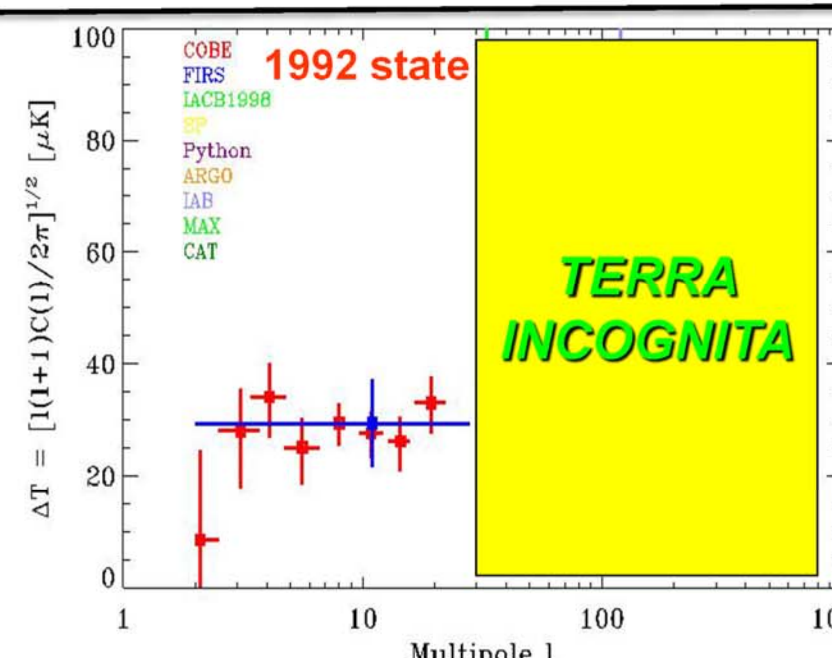
MODEL	Small Angle $10^6(\Delta T/T)$ 4.5'[7.15']	Large Angle $10^6(\Delta T/T)$ 6°
OBSERVATIONS	< 50 [< 15]	< ~~48~~ = 10
Unbiased Adiabatic B-dom		
B-dom $\Omega = \Omega_B = 0.1$	1000	-
B-dom $\Omega = \Omega_B = 1$	50	-
Unbiased Isocurvature B-dom		
B-dom ISOC 0 $\Omega = 1$ $\Omega_B = 1$	36	7
B-dom ISOC -1 $\Omega = 1$ $\Omega_B = 1$	28	~~14~~
OPEN B-dom ISOC 0 $\Omega = 0.2$ $\Omega_B = 0.2$	61	3 ✓
OPEN B-dom ISOC -1 $\Omega = 0.2$ $\Omega_B = 0.2$	84	~~16~~
OPEN ION B-dom ISOC 0 $\Omega = 0.2$ $\Omega_B = 0.2$	11	4 ✓
OPEN ION B-dom ISOC -1 $\Omega = 0.2$ $\Omega_B = 0.2$	14	~~31~~
Ω=1 biased CDM		
CDM-dom $\Omega = 1$ $\Omega_B = 0.03$	3 [5]	(7)
CDM-dom $\Omega = 1$ $\Omega_B = 0.1$	5 [7]	7
CDM-dom $\Omega = 1$ $\Omega_B = 0.2$	6	8
CDM+B hybrid $\Omega = 1$ $\Omega_B = 0.5$	8	~~16~~
Biased Isocurvature Axion		
CDM-dom ISOC $\Omega = 1$ $\Omega_B \ll \Omega$	-	~~60~~
Anti-biased Massive Neutrino $z_{nl} = 1$		
HOT (m_ν=24 ev) $\Omega = 1$ $\Omega = 0.1$, $b = .53$	20	~~20~~
HOT/COLD hybrid $\Omega_\nu = 0.4$ $\Omega_X = 0.5$ $\Omega_B = 0.1$	-	(8)
$\Omega < 1$ Unbiased CDM		
OPEN/CDM-dom $\Omega = .2$ $\Omega_X = .17$ $\Omega_B = .03$	70 [150]	~~40~~
OPEN/CDM/B $\Omega = .2$ $\Omega_X = .1$ $\Omega_B = .1$ $h = .75$	80 [170]	~~50~~
$\Lambda \neq 0$ Unbiased CDM		
VAC/CDM hybrid $\Omega = 1$ $\Omega_{vac} = .8$ $\Omega_X = .17$ $\Omega_B = .03$	20 [30]	~~20~~
VAC/CDM/B $\Omega = 1$ $\Omega_{vac} = .8$ $\Omega_X = .1$ $\Omega_B = .1$ $h = .75$	20 [30]	~~25~~
Non-Scale-Invariant IC's		
CDM-dom + Extra Power Mountain $\Omega = 1$ $\Omega_B \ll \Omega$	-	~~20~~
CDM-dom + Extra Power Plateau $\Omega = 1$ $\Omega_B \ll \Omega$	-	~~50~~

"Cosmic Microwave Background, then and now"

DMR/Smoot

Physics 2006





March 1996, Unesco (Paris)

COBRAS/SAMBA

COBRAS/SAMBA

- Candidate to become the next medium-sized mission in ESA's Horizon 2000 Scientific Programme
- Selection: June 1996
- Launch: 2004-2005

esa ~3 years Phase A Study - Final Presentation

COBRAS/SAMBA

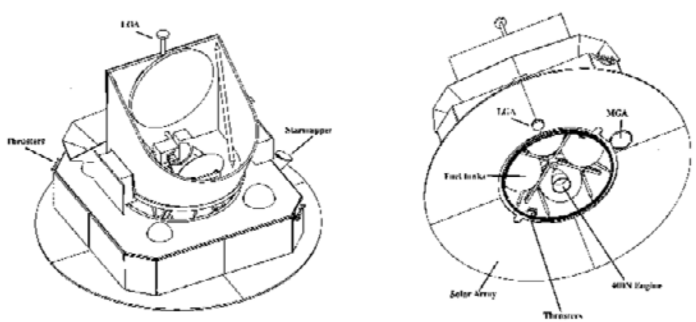
Model Payload Characteristics

Telescope	1.5 m Diam. Gregorian; shared focal plane; system emissivity 1%								
	Viewing direction offset 70 degrees from spin axis.								
Center Frequency (GHz)	31.5	53	90	125	143	217	353	545	857
Detector Technology	HEMT radio receiver arrays				Bolometer arrays				
Detector Temperature	~100 K				0.1-0.15 K				
Cooling Requirements	Passive				Cryocooler + Dilution system				
Number of Detectors	4	14	26	12	8	12	12	12	12
Angular Resolution (arcmin)	30	18	12	12	10.3	7.1	4.4	4.4	4.4
Optical Transmission	1	1	1	1	0.3	0.3	0.3	0.3	0.3
Bandwidth ($\Delta \nu / \nu$)	0.15	0.15	0.15	0.15	0.37	0.37	0.37	0.37	0.37
$\Delta T/T$ Sensitivity per res. element (14 months, 1σ, 10^{-6} units)	7.8	7.5	14.4	35.4	1.2	2.0	12.1	76.6	4166

esa Phase A Study - Final Presentation

COBRAS/SAMBA

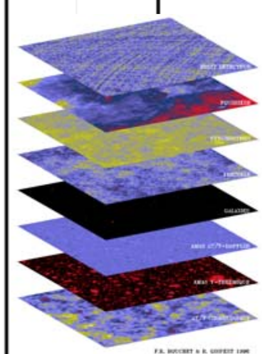
The spacecraft

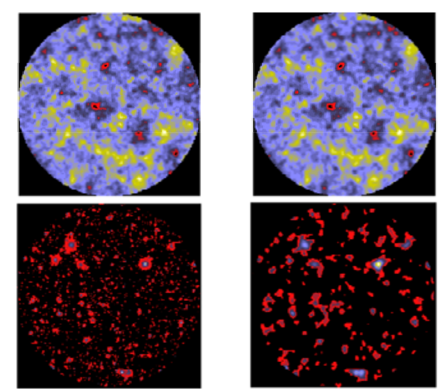


esa Phase A Study - Final Presentation

COBRAS/SAMBA

Component separation



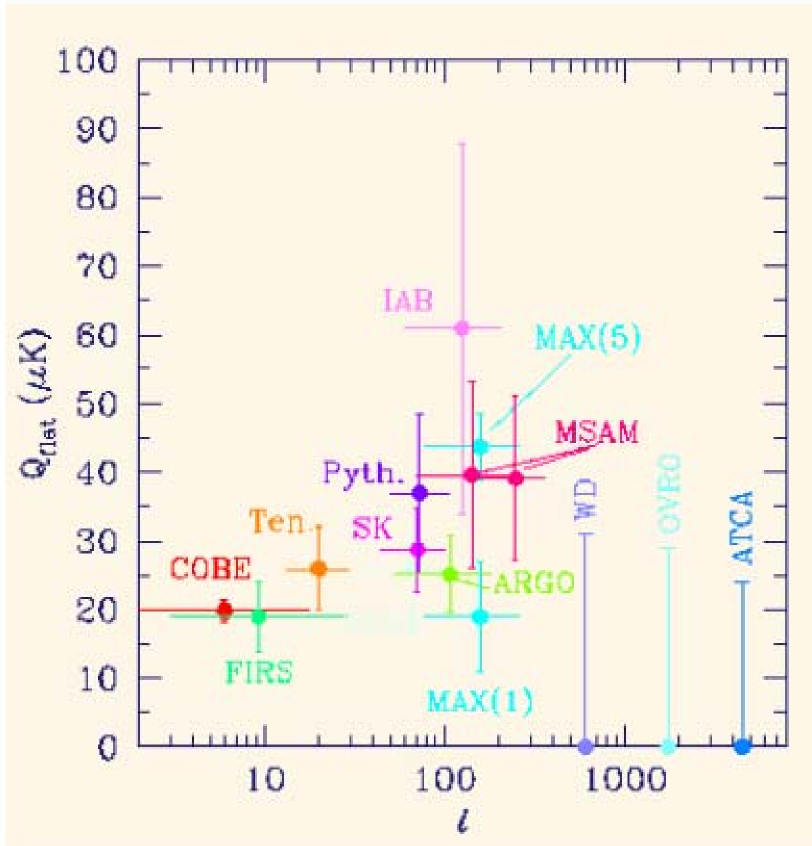


esa Phase A Study - Final Presentation

March 1996, Unesco (Paris)

COBRAS/SAMBA

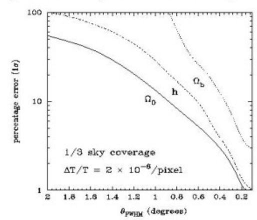
Observational Status



Phase A Study - Final Presentation

COBRAS/SAMBA

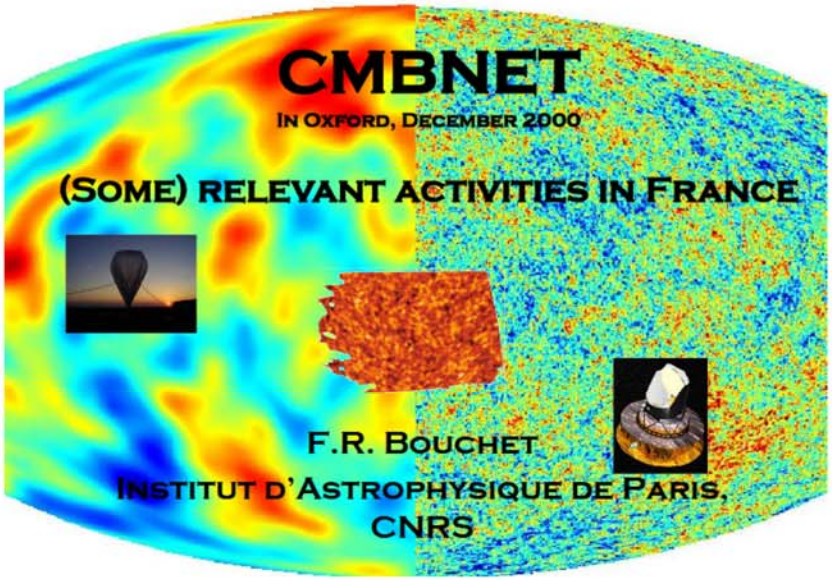
Accuracy of recovery of fundamental parameters



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})

Phase A Study - Final Presentation

Dec 2000, Oxford…



"PARIS" CMBNET NODE

* Paris-Orsay-Saclay:

•IAP (Bouchet, Colombi, Doré, Guiderdoni, Vibert
+ Fosalba soon + Lensing & U' teams)

•IAS (Aghanim, Bernard, Lagache, Puget…)

•LAL (Ansari, Bourachot, Couchot, Versillé…)

•CdF (Amblard, Delabrouille, Giraud-Héraud, Hamilton, Kaplan)

•CEA/DAPNIA (SAp+SPP) (Teyssier + Aubourg, Hivon, Magneville)

* Grenoble:

•CRTBT+LAOG+ISN (Benoit+Désert+Filliatre, Santos…)

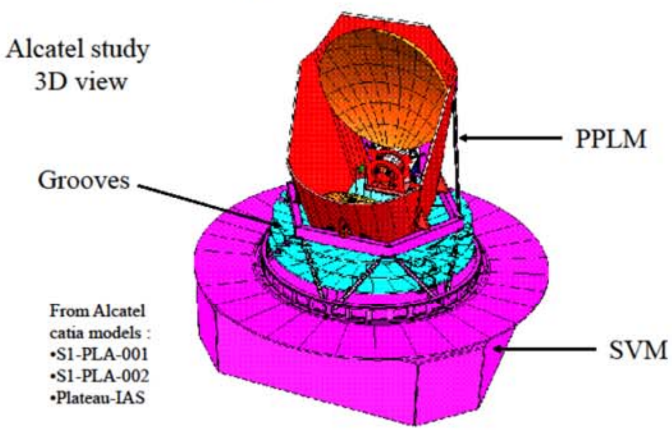
* Toulouse:

•LAT+CESR (Bartlett, Blanchard… + Giard, Pointecouteau)

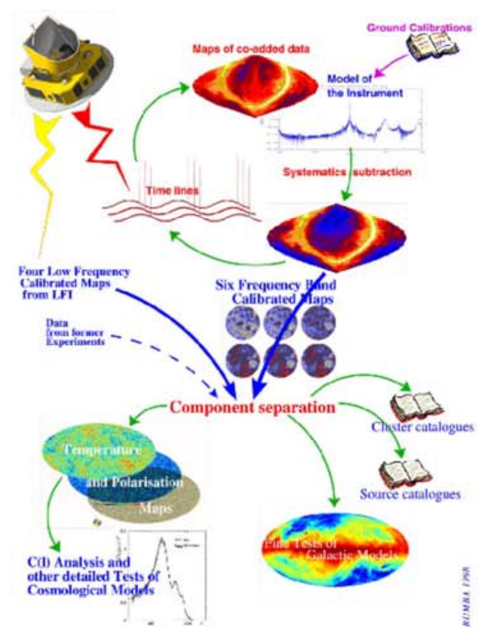
All involved to various deg. in ARCHEOPS & PLANCK

HFI Optics Status October 2000

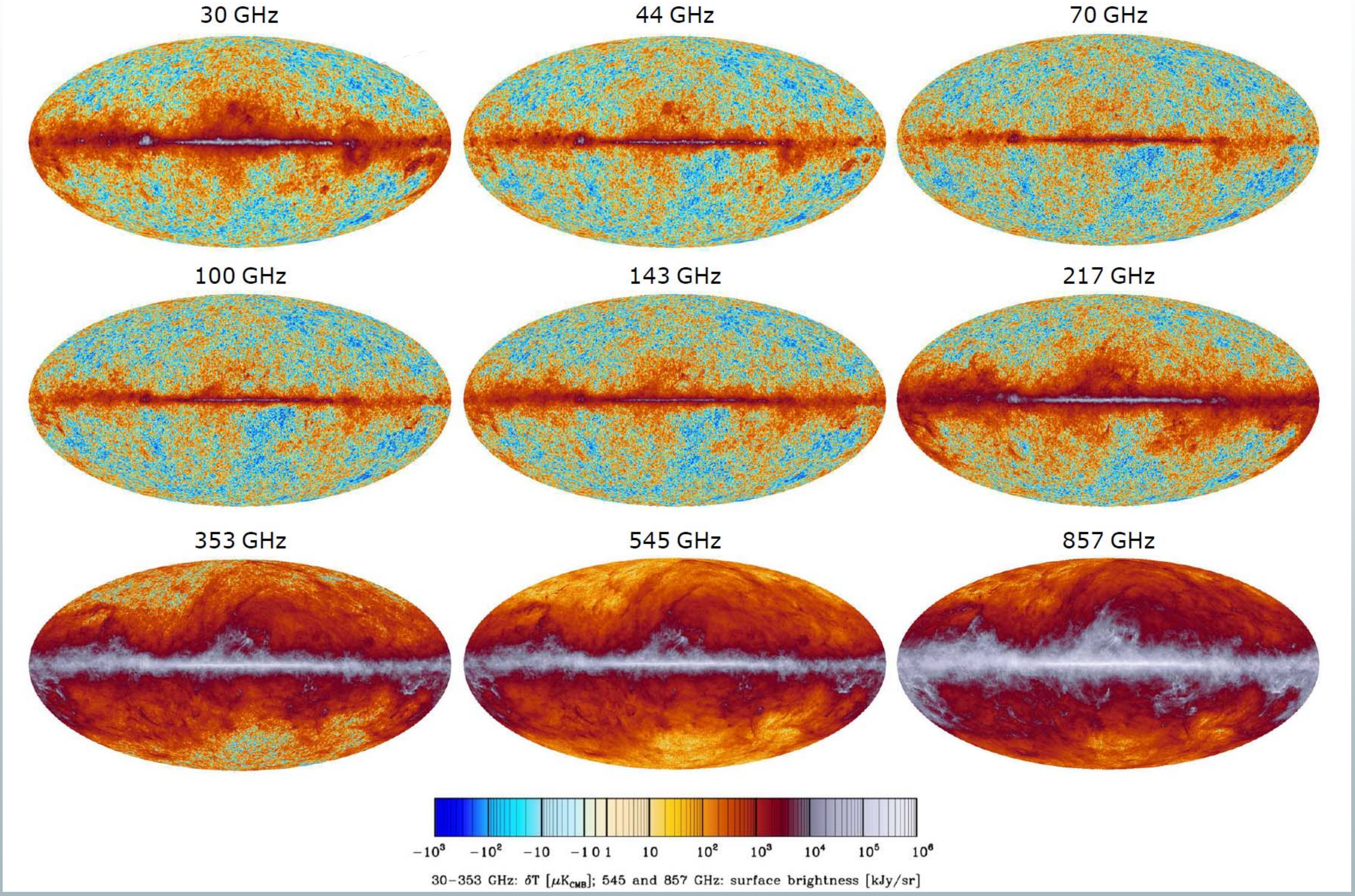
Alcatel study
3D view

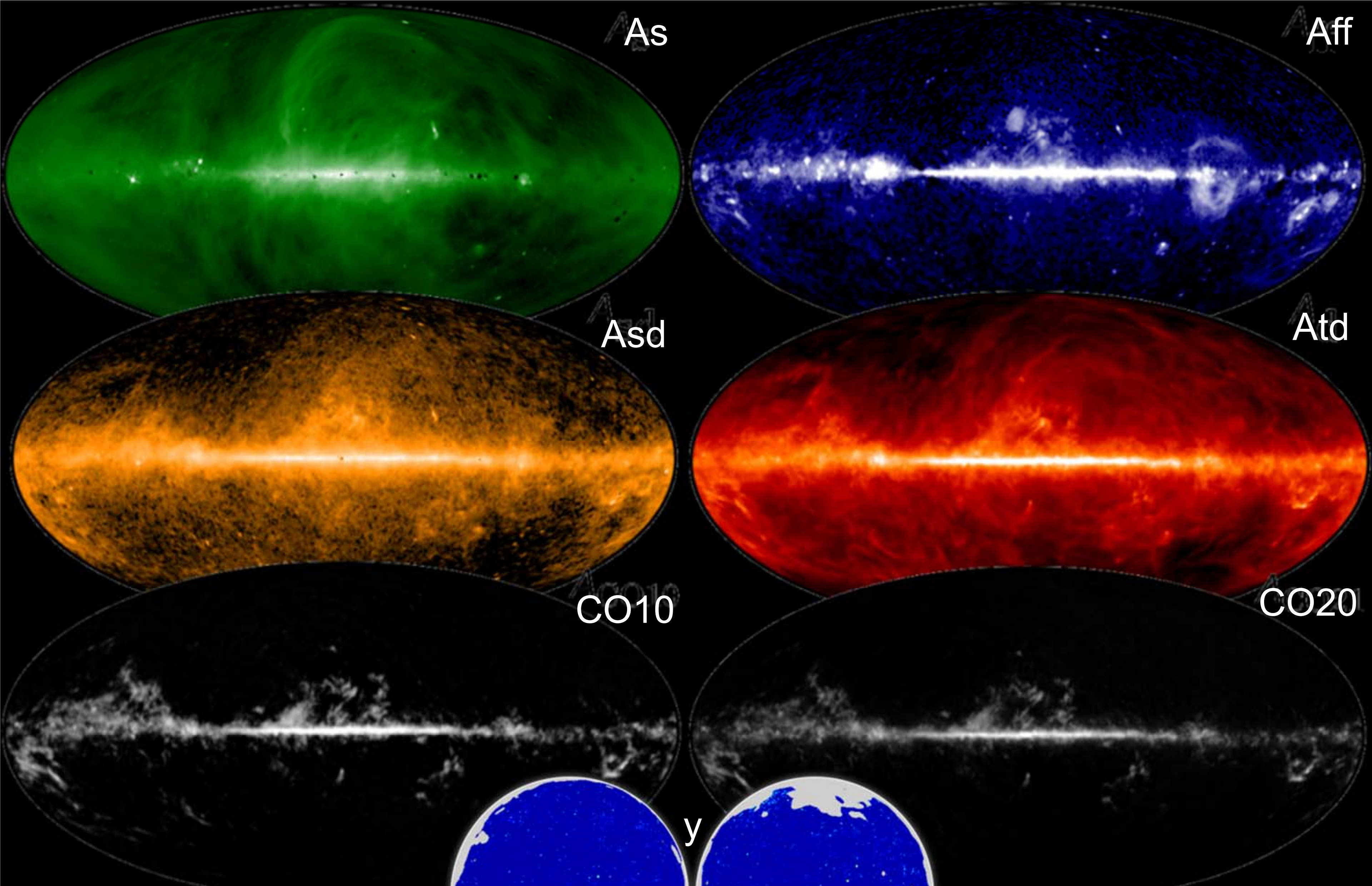


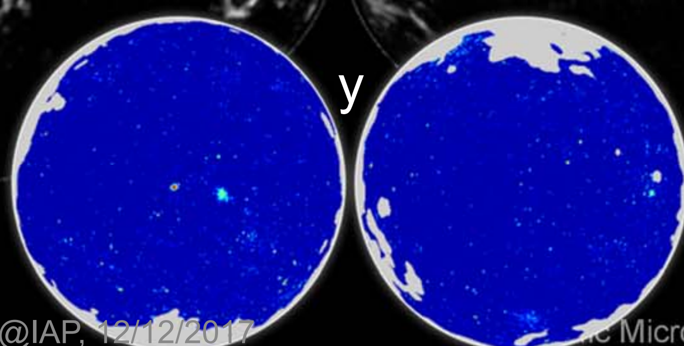
From Alcatel
catia models :
•S1-PLA-001
•S1-PLA-002
•Plateau-IAS



Planck 2015 temperature maps





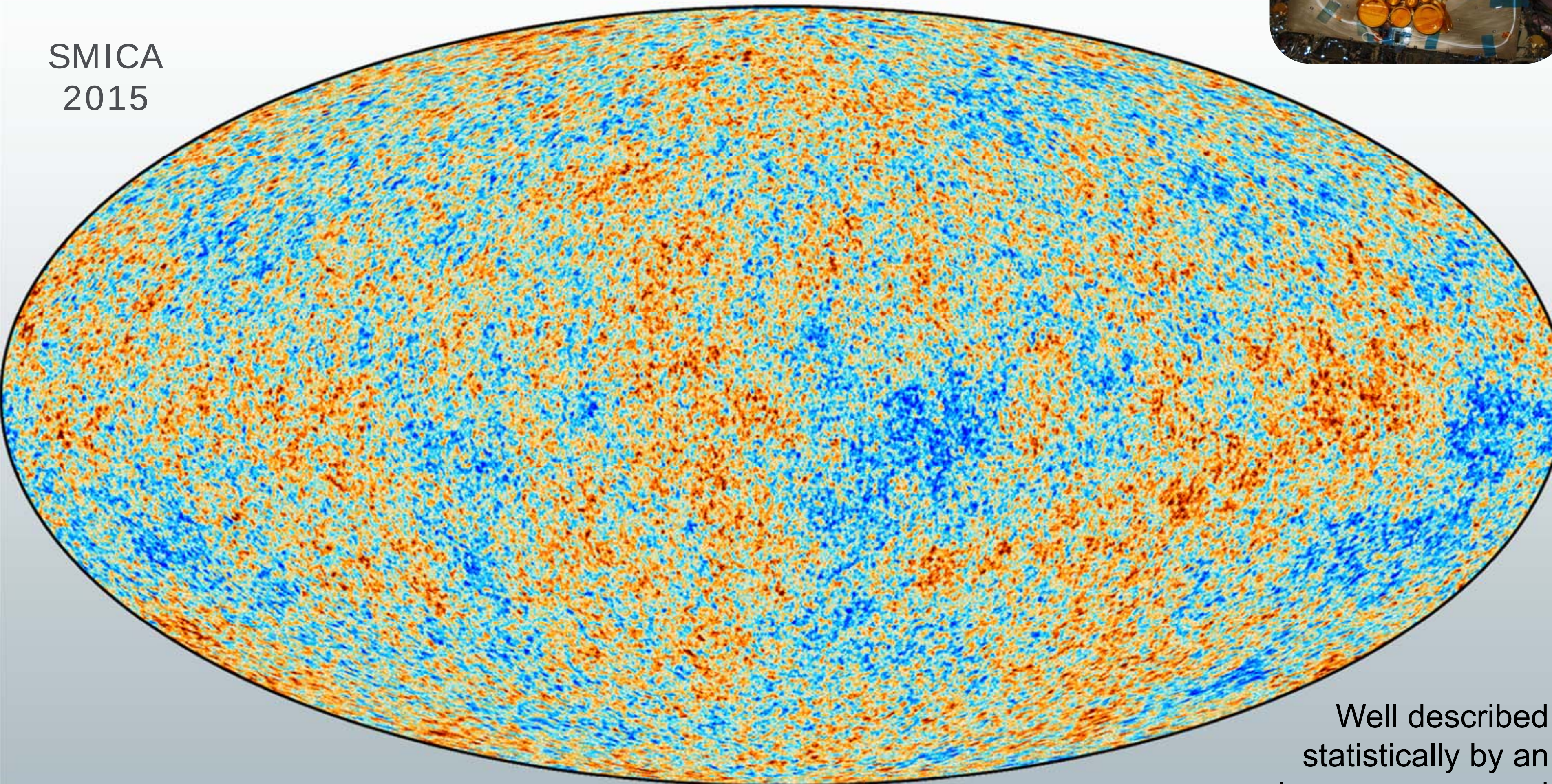


Peeling off foreground emissions… (inc. CIB)

… leads to many scientific progresses…

Planck 2015 T anisotropies map

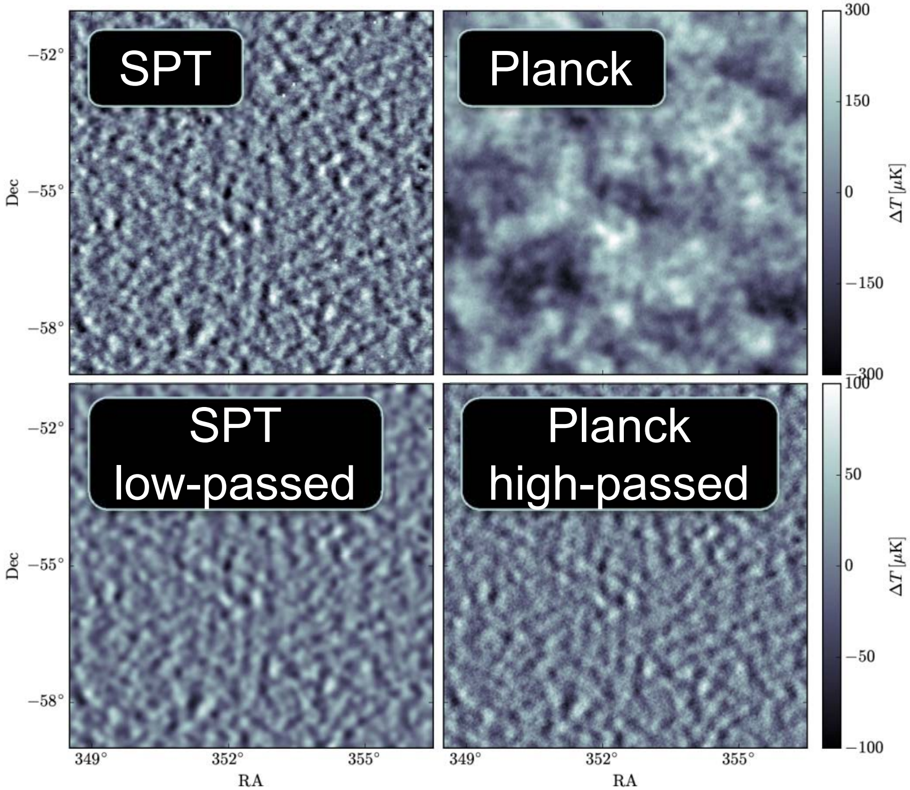
SMICA
2015



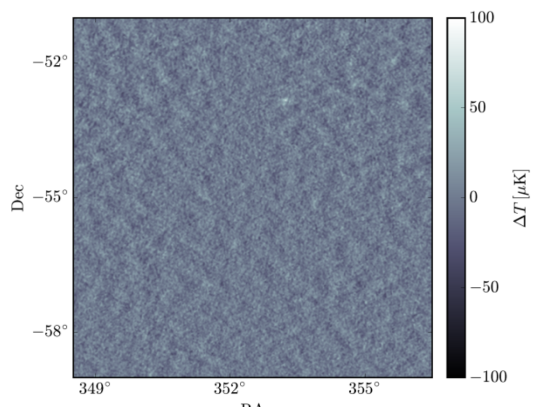
Well described statistically by an homogeneous and isotropic Gaussian field

SPT@150GHz vs planck@143GHz

Hou+ arXiv:1704.00884v1

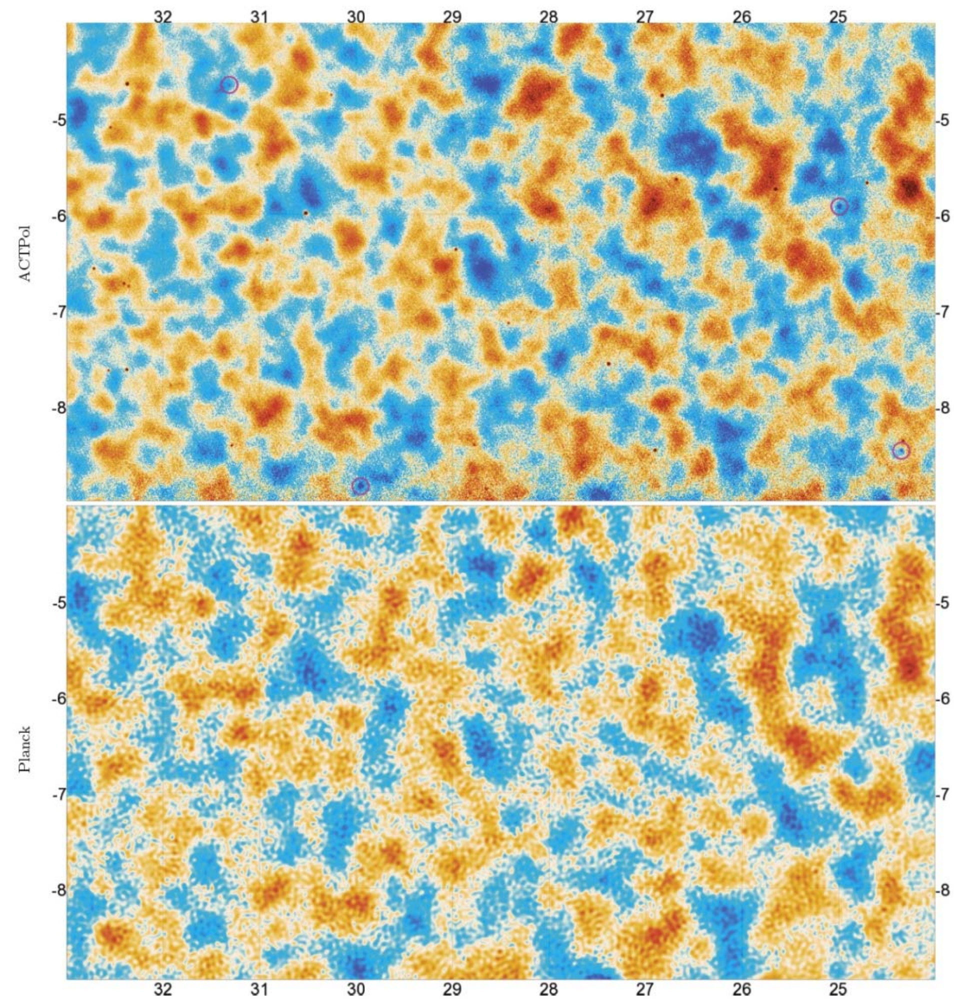


Little residual in SPT-low minus Planck-high, but a variable source



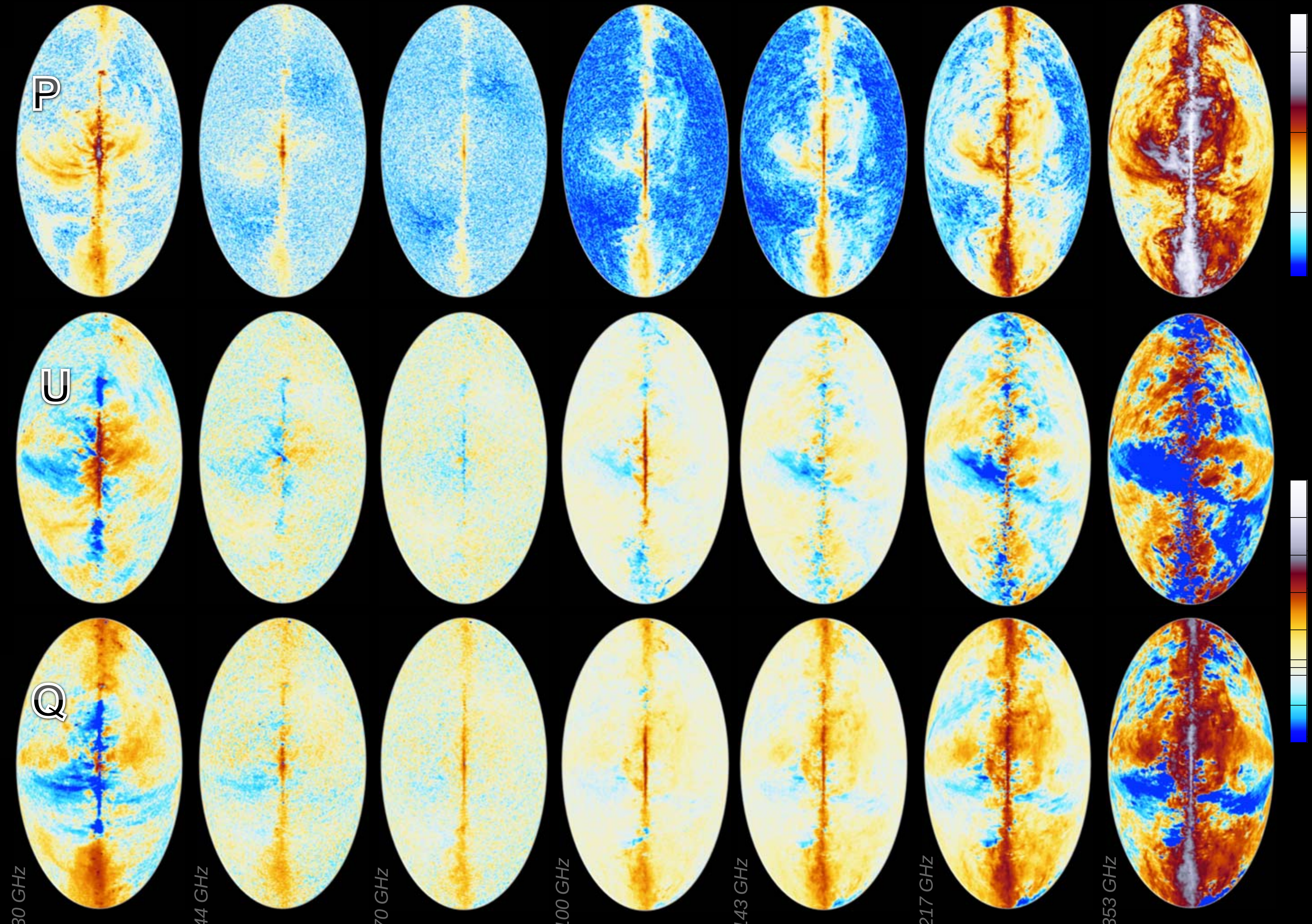
ACT@150GHz vs planck@143GHz

Louis+ arXiv:1610.02360v1

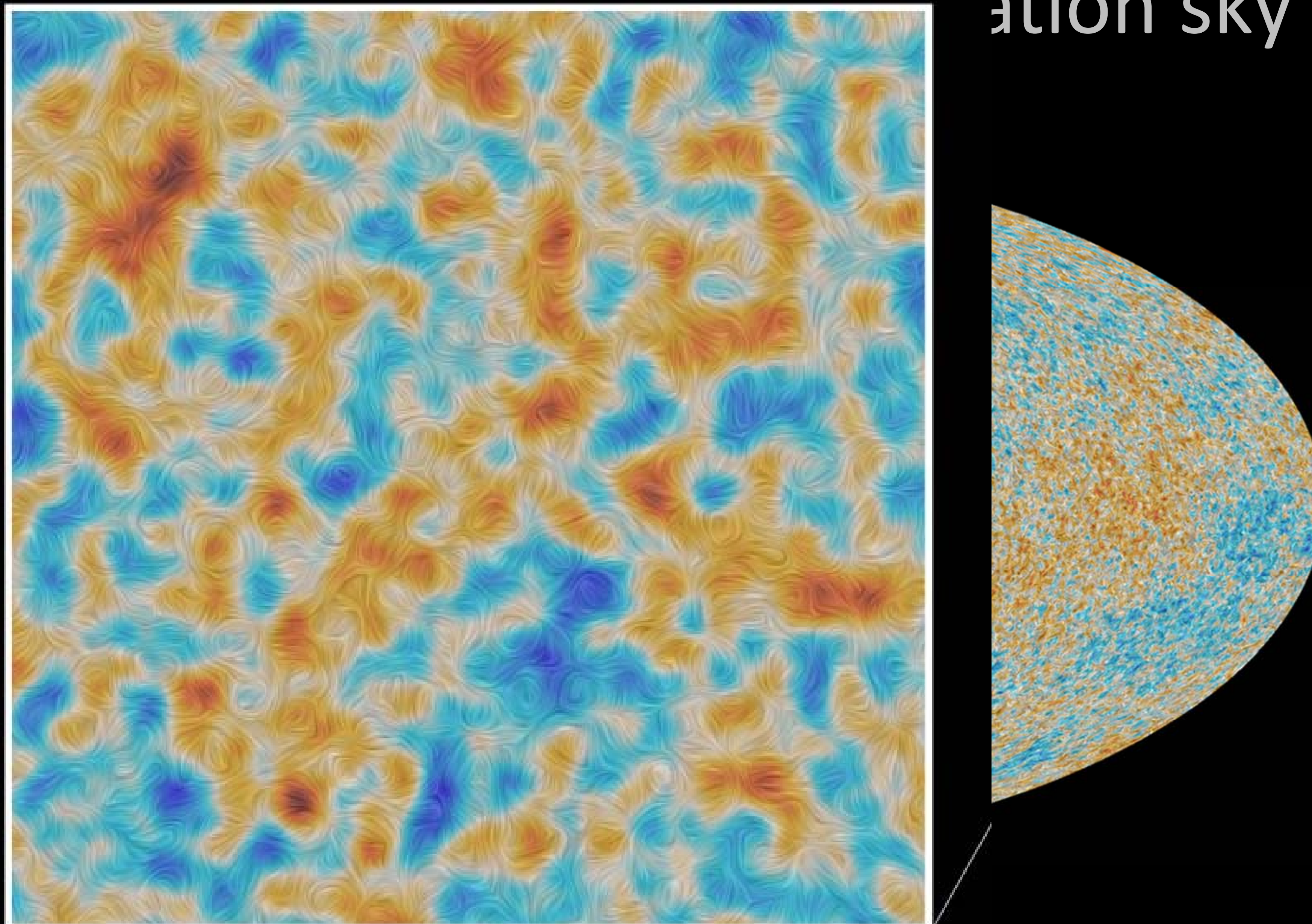


A magnificent consistency in CMB data

Planck 2015 Polarisation maps

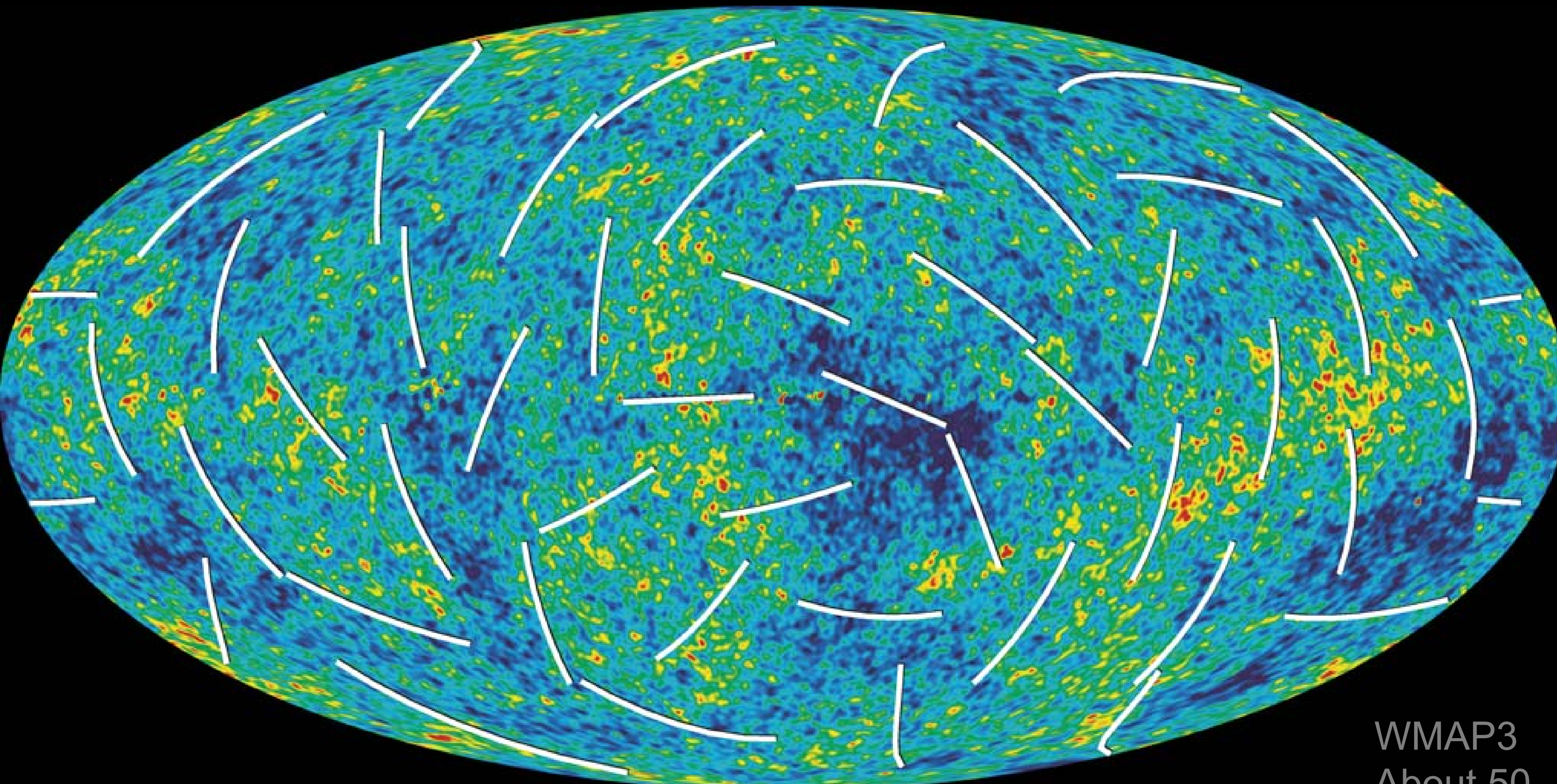


ation sky



Filtered at 20 arcminutes

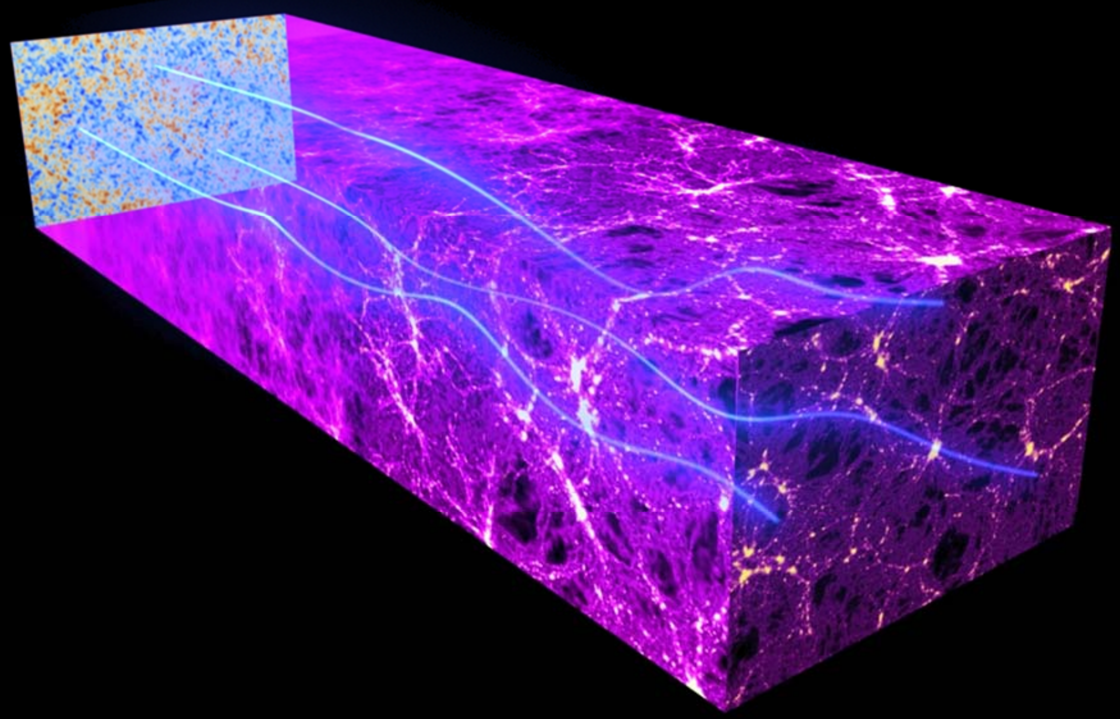
What we already knew



WMAP3
About 50
locations?

GRAVITATIONAL LENSING DISTORTS IMAGES

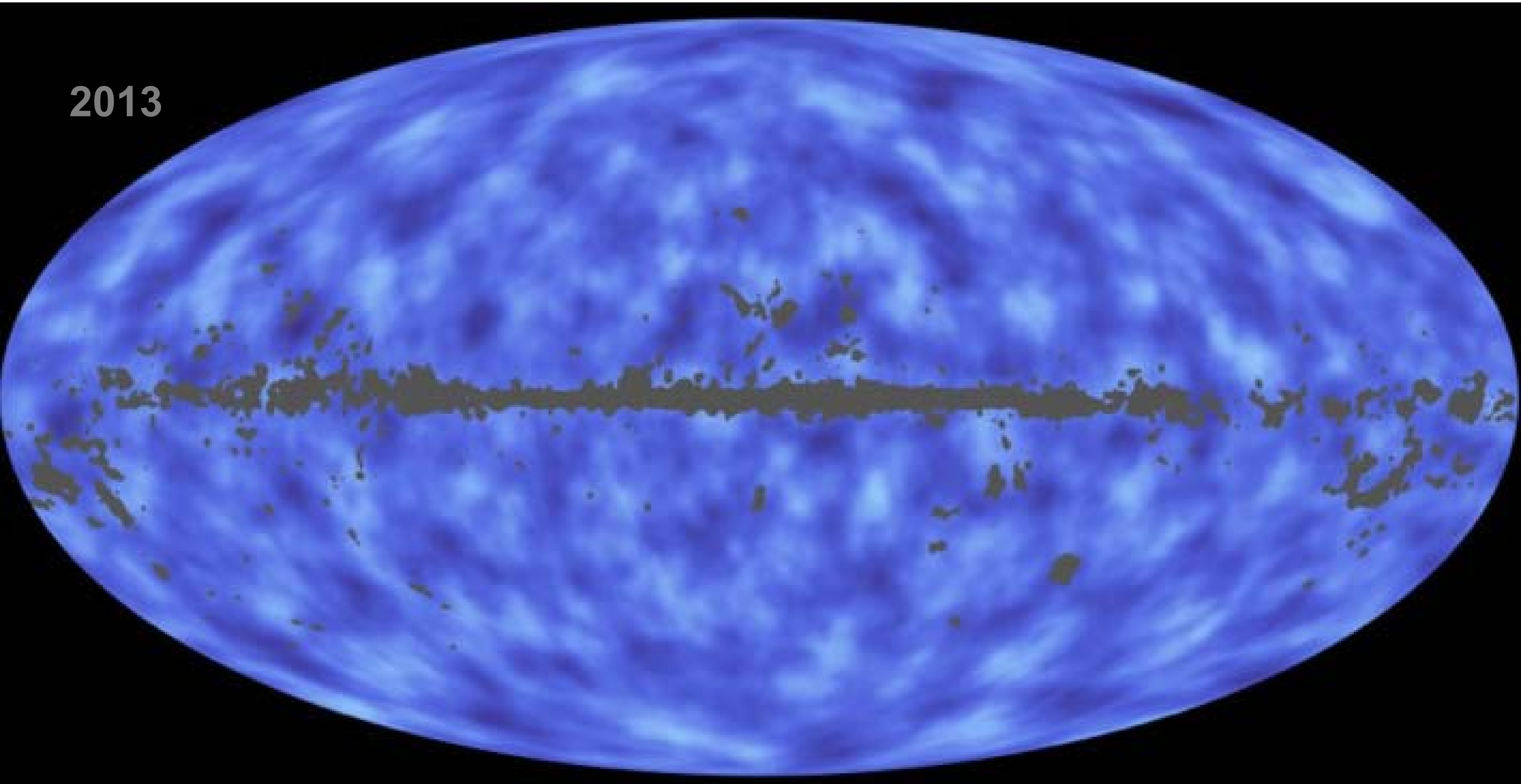
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + ...$$

$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$

Projected mass map



The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

"Cosmic Microwave Background, then and now"

30th Institut d'astrophysique de Paris Colloquium

THE PRIMORDIAL UNIVERSE AFTER PLANCK

MONTAGNE SAINT ÉMILION

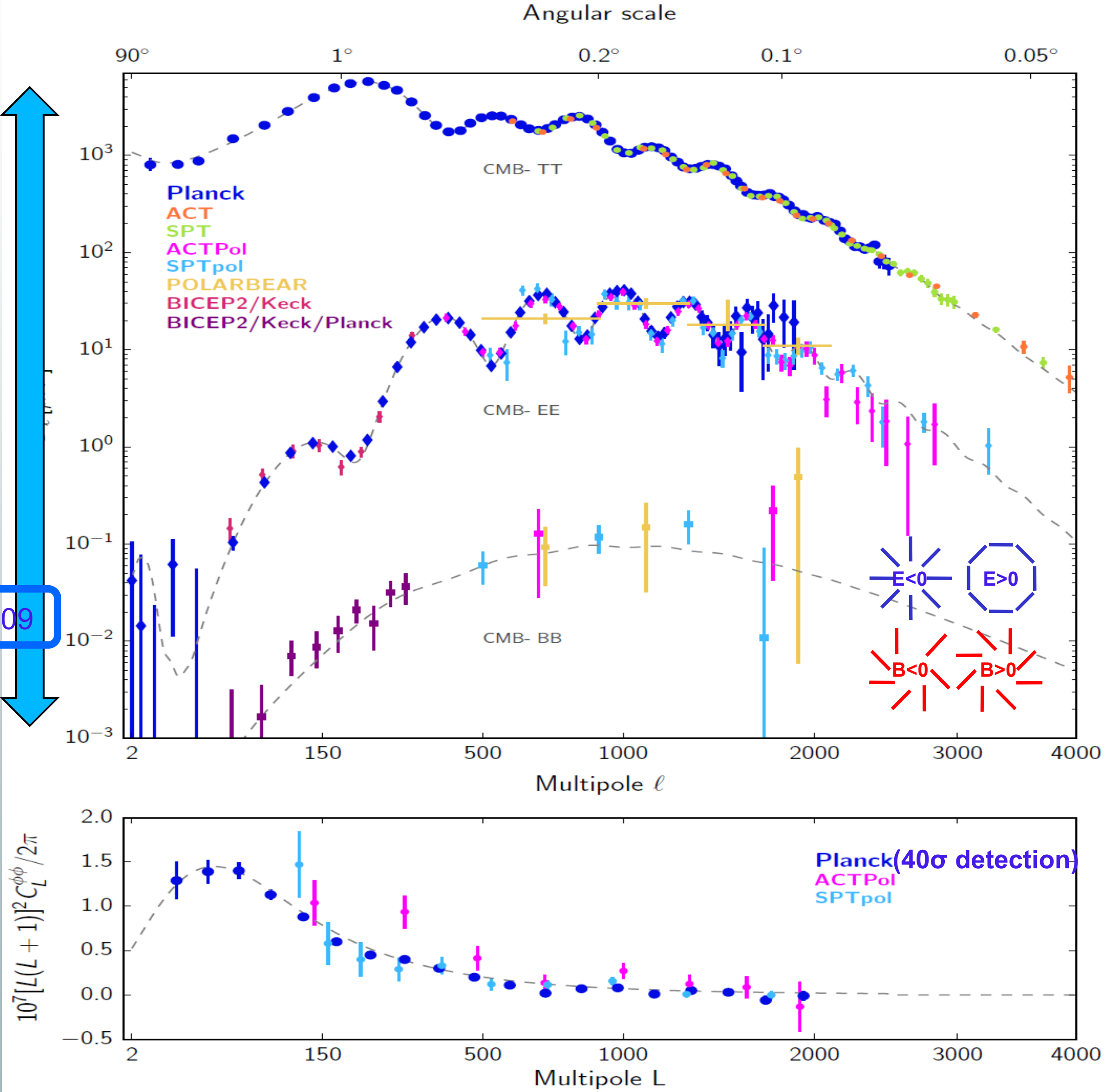
CHÂTEAU LES HAUTES GRAVES

2009

December 15-19, 2014

TT, EE, BB, ΦΦ – 2017 status

Only keeping points w. sufficiently small error bars, Fig. E Calabrese



10^7

τ = 0.055±0.009

Planck:

1 114 000 Modes measured with TT,

60 000 with TE (not shown)

96 000 with EE

… and **10's** in BB and φφ

+ constraints on TB and EB

And SZ & CIB PS, f_{NL}, etc.

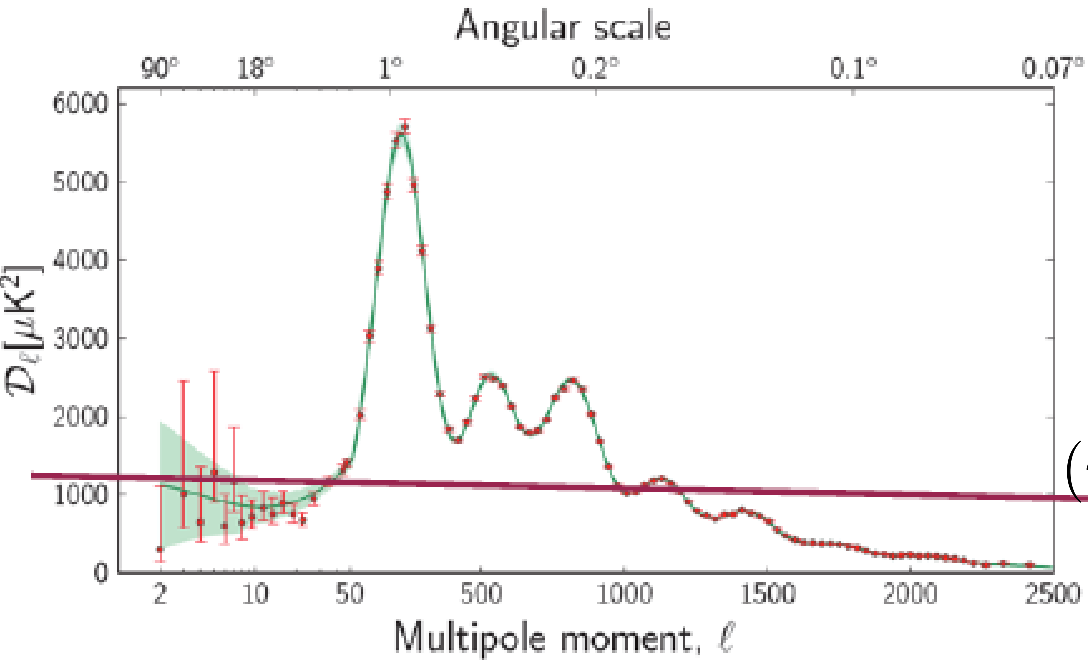
CMB Anisotropies

- LCDM fits all CMB data in T, E, B, ϕ.
  - *No need for an extension. A great source of constraints/papers…*
  - *Same parameters, determined at the per cent level, fit other data (BAO, but also BBN, SN1a…).*
  - *Some tensions (anomalies, SZ, H0, WL), whose meaning remains unclear as of now.*
- T anisotropies information essentially exhausted (but much still to learn on foregrounds, e.g. from SZ).
- A new field, CMB lensing, has emerged (observationally).
- Much untapped and unique information remains in the CMB polarisation anisotropies (millions of modes).
  - *Ground observations will now be the dominating source of new information in the next decade. See next talks. But intrinsic limitations, i.e., we need space too for large scales, nu coverage, and for spectral distortions.*

What is the value of n_s ?

Initial Conditions: quasi-scale invariant

$$g_{ij} = a^2(\tau)\,[1 - 2\Phi]\,\gamma_{ij} \longrightarrow k^3 \langle |\Phi_k| \rangle \propto k^{n_s - 1}$$



$n_s = 1 \pm 0.6$ 1992 (COBE)

$n_s = 1.03 \pm 0.09$ 2001 (MaxiBoom)

$n_s = 0.963 \pm 0.014$ 2009 (WMAP5)

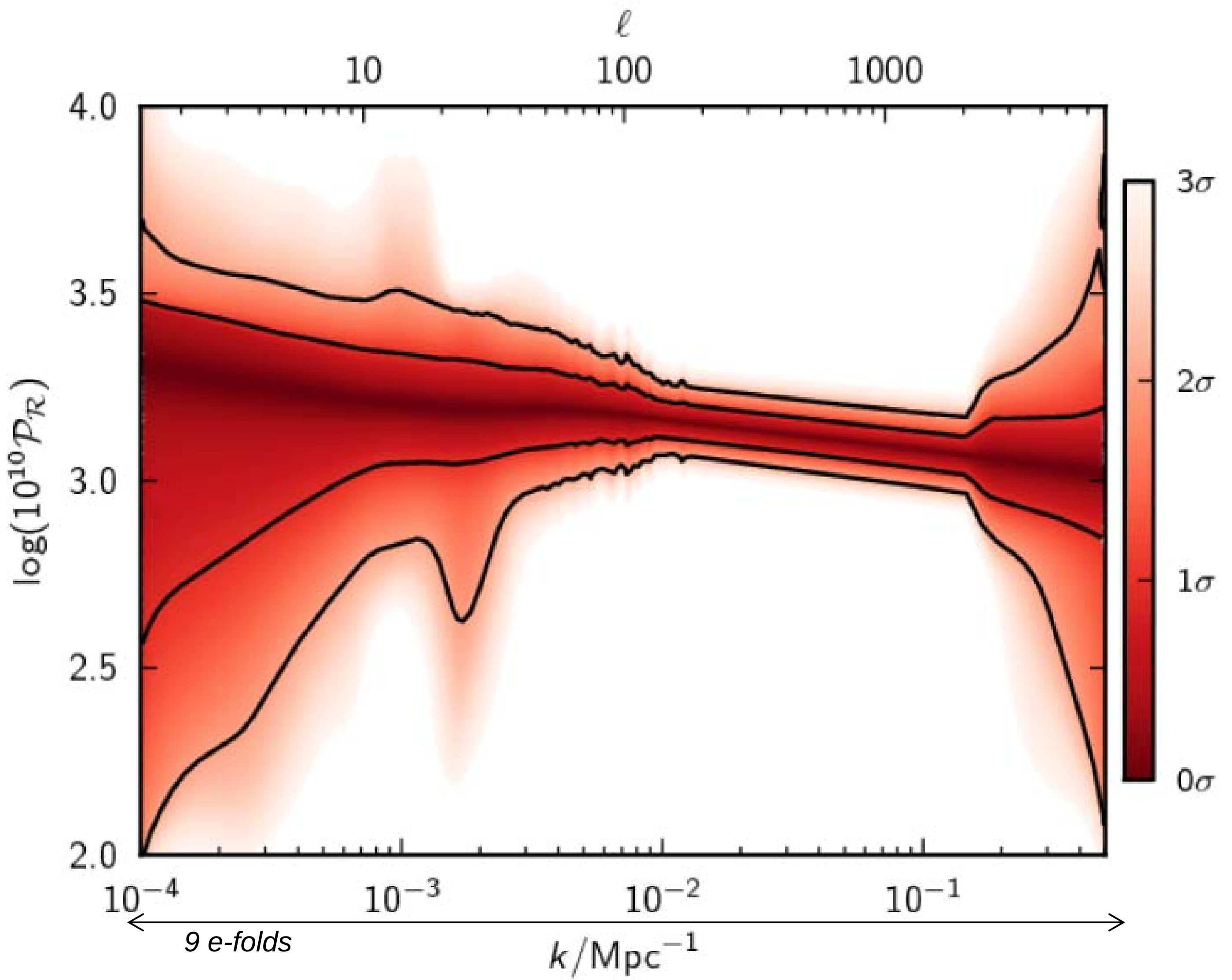
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

($n_s = 0.965 \pm 0.006$ 2015 Planck alone

A hundred-fold improvement in 20 years

Mukhanov & Chibisov (1981): 1st calculation of (scalar) quantum fluctuation of the vacuum in an inflating background. n_s must be ~0.96 < 1 for inflation to end.

Power spectrum reconstruction

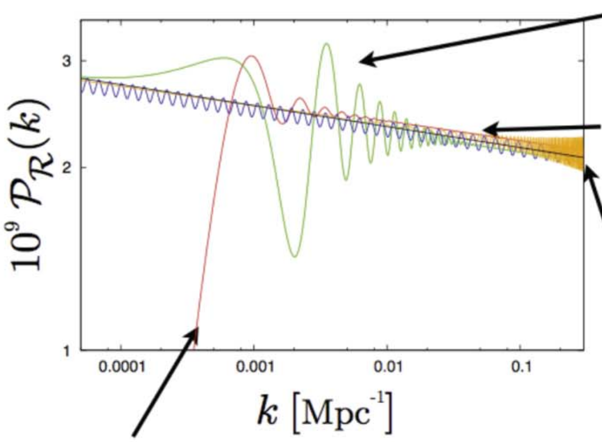


Bayesian reconstruction with varying number of nodes (<9) reconstructions weighted by their respective evidence.

No strong evidence for feature or anomaly.

(actually used 3 different methods, all with similar results)

(Unsuccessful) Search for features



Feature in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy

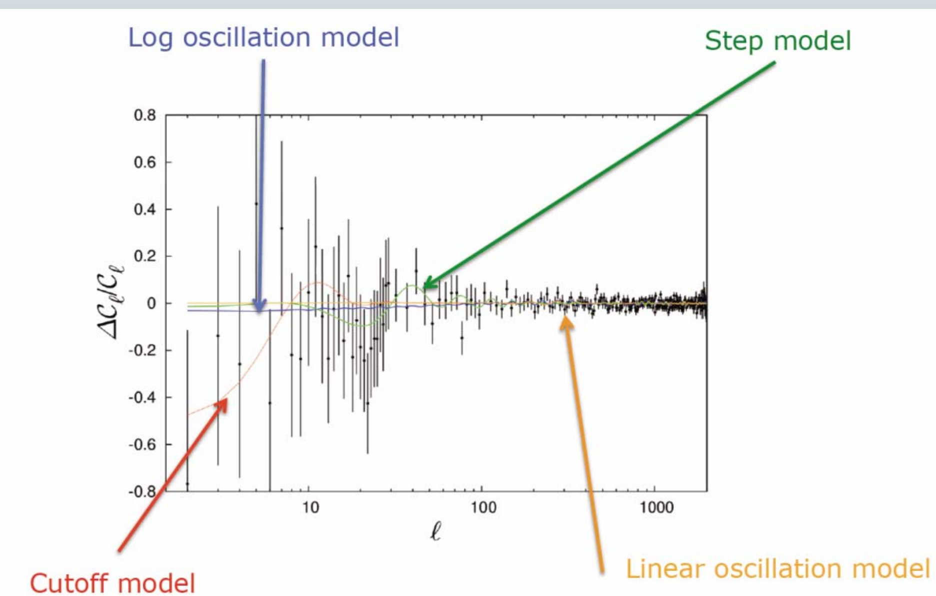
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

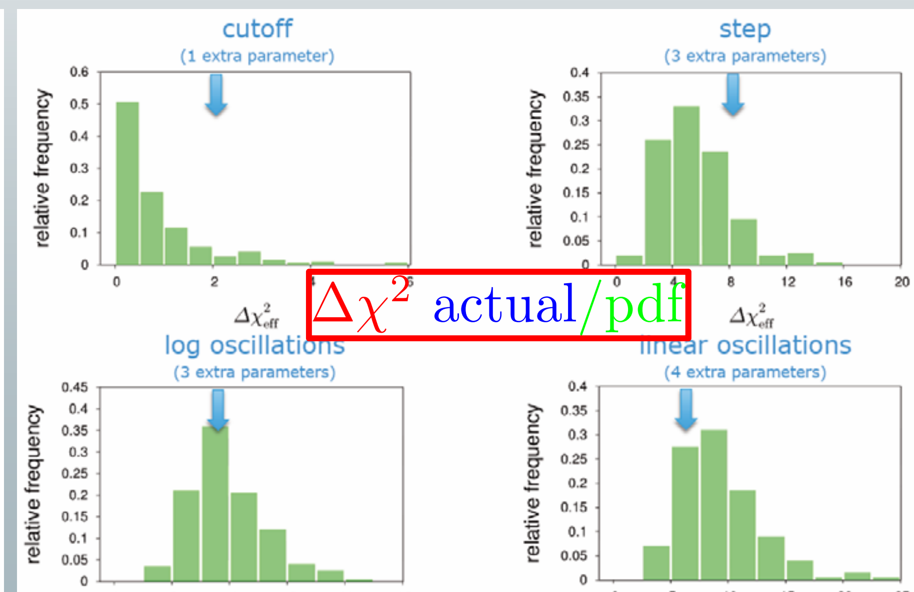
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

$$\mathcal{P}_\mathcal{R}^{\rm lin}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\rm lin}\left(\frac{k}{k_*}\right)^{n_{\rm lin}}\cos\left(\omega_{\rm lin}\frac{k}{k_*} + \varphi_{\rm lin}\right)\right]$$

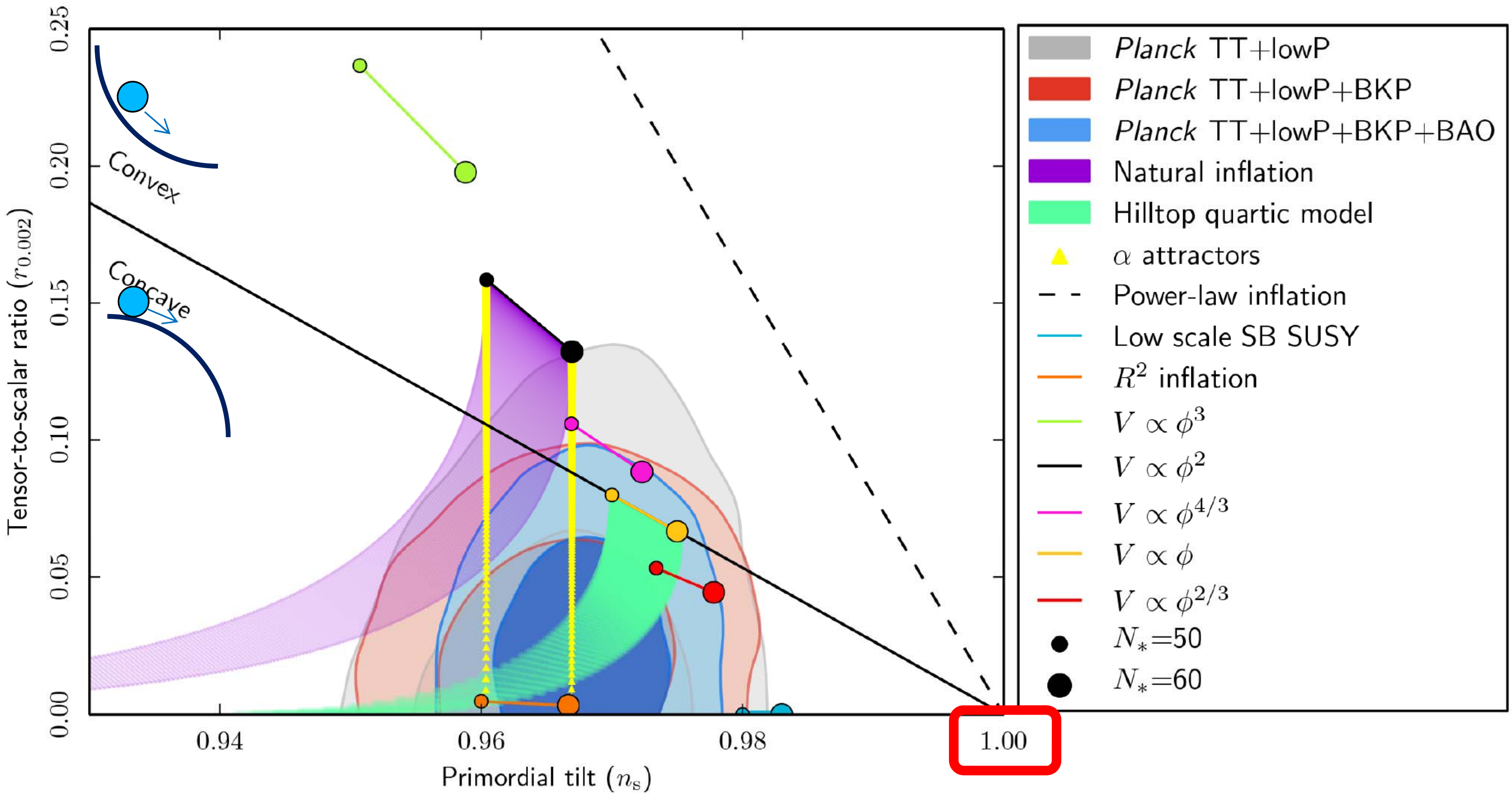
Just enough e-folds, i.e. inflation preceded by a kinetic stage





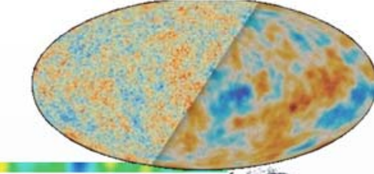
Planck 2015: n_s vs r

$V_* = (1.9 \times 10^{16}\ \text{GeV})^4\ (r/0.12)$

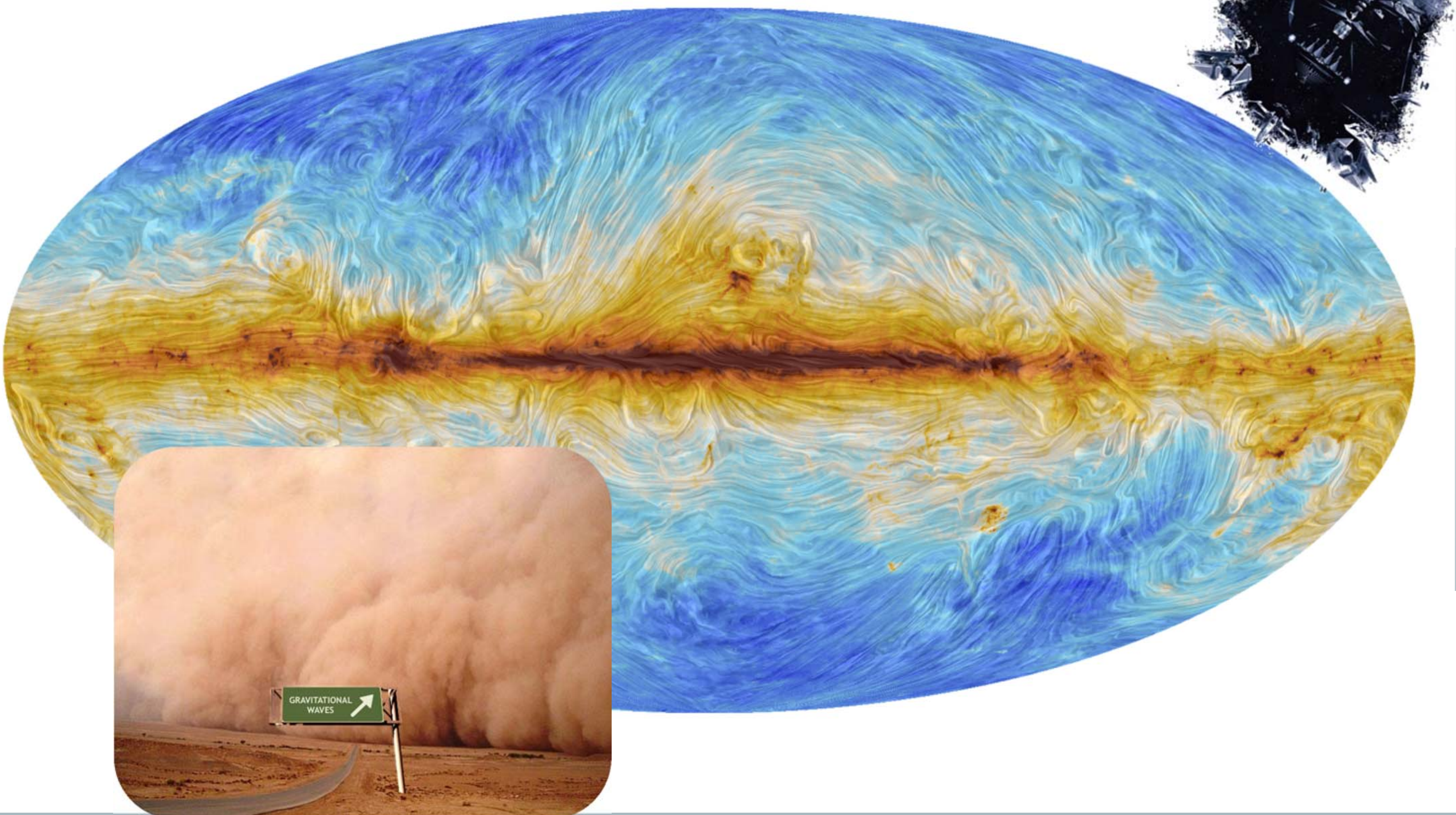


Similar (indirect) r constraint than with 2013 release ($r_{0.002}$ < 0.10 @ 95% CL vs 0.11)

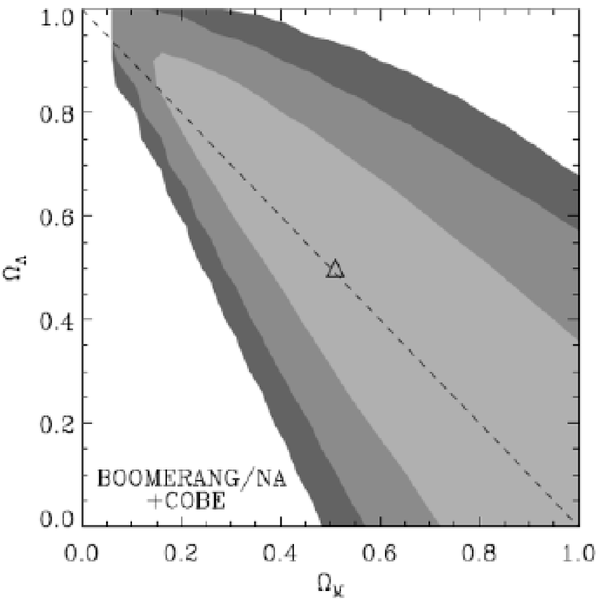
Planck 353GHz reveals the Galactic magnetic field



(whose effect can account for at least about ½ of the initial BICEP claim)

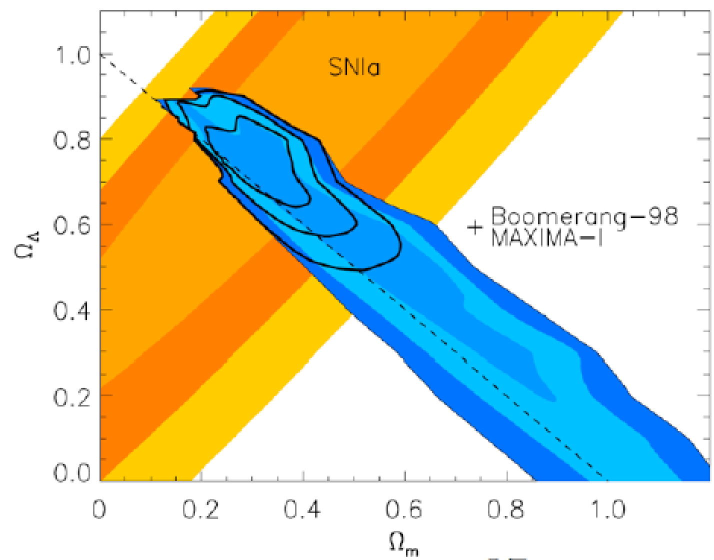


Spatial curvature constraint



$$\Omega_K = -0.05^{+.40}_{-.40}$$

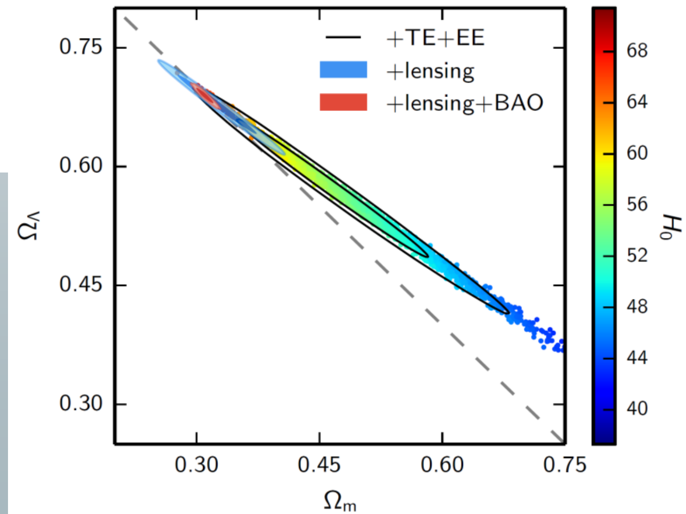
Melchiorri et al. 2000



$$\Omega_K = -0.11^{+.07}_{-.07}$$

Jaffe et al. 2001

Note the change of axes
For Planck below



Planck 2015

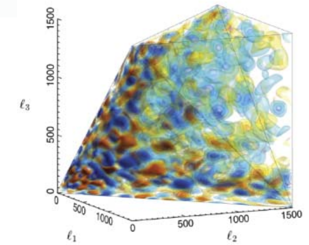
$$\Omega_k = 0.000 \pm 0.005 \ (95\% \ \mathrm{CL})$$

A hundred-fold improvement in 15 years

Planck 2015 - Bispectrum constraints

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

f^{local}_{NL} = 0.8 ± 5.0
f^{equil}_{NL} = - 4 ± 43
f^{ortho}_{NL} =-26 ± 21



Planck 2013

ISW-lensing subtracted KSW	Binned	Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

Constraint volume in LEO space shrunk by factor of 3. wrt Planck2013

$$\Phi = \phi + f_{\rm NL}(\phi^2 - \langle\phi^2\rangle)$$

non-Gaussian potential

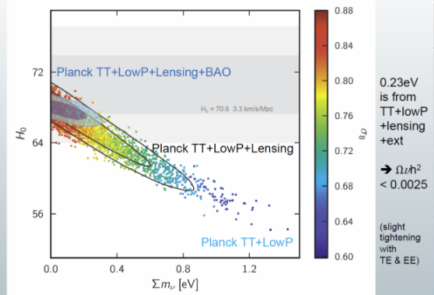
Gaussian field

$|f_{\rm NL}^{\rm Loc}| < 10^3$ (Maxima 2001), 10^2 (WMAP7), 10 (Planck15)

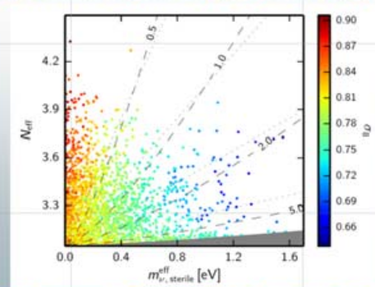
A hundred-fold improvement in 14 years

We tested & constrained a lot more…

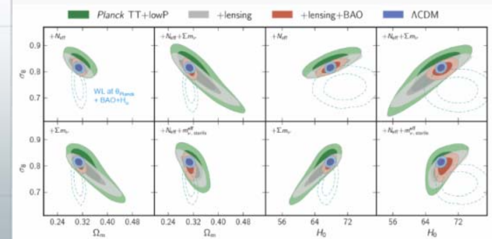
Neutrinos masses $\sum m_\nu < 0.23$ eV (95%)



Adding a 4[th] sterile neutrino

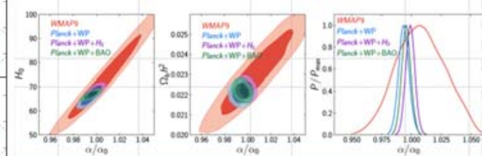


Allowing neutrinos extensions

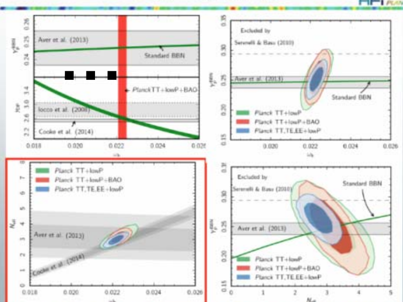


($\Omega_m H^3$ is tightly constrained by ϑ_{MC})

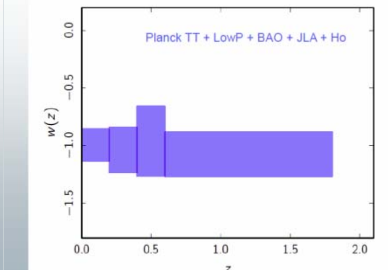
Fine structure constant variation?



BBN – Neff, Yp



PCA of w(z)

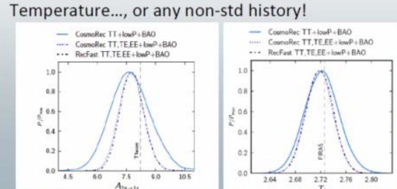


A cosmological constant, Λ, corresponds to w(z)=-1

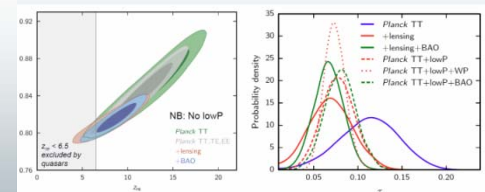
Recombination history

Planck is impressively sensitive to details of the recombination history… and is therefore sensitive to

- Variation of the fundamental constants
- The value of the 2 ϒ decay rate, or the recombination Temperature…, or any non-std history!

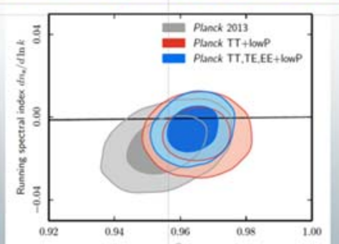


Optical depth constraints



A new, independent, way to look at τ
→ Consistency of lensing versus LowP constraints on τ
Pointing to lower values than previous WMAP based values

Planck 2015 on running



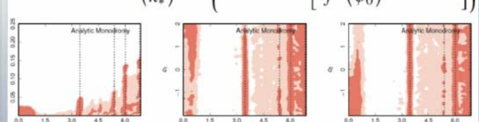
The thin black stripe shows the prediction for single-field monomial chaotic inflationary models with 50 < N < 60

Axion monodromy inflation

Periodic potential, analytical template from Flauger et al.

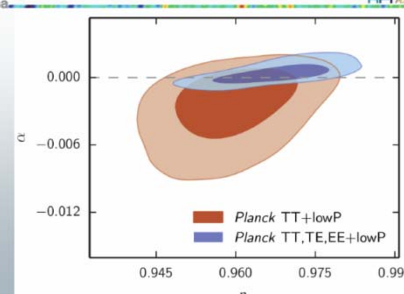
$$\phi_k = \sqrt{2p\,(N_0 - \ln(k/k_*))}$$

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left\{1 + \delta n_s \cos\left[\frac{\phi_0}{f}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\phi\right]\right\}$$



- Chi[2] improvement insufficient. There are expected bispectrum oscillations $f_{\rm NL}^{\rm res} = \frac{\delta n_s}{8}\alpha^2$ owest frequency checked already (KO). Others imminent.

Isocurvature modes fraction



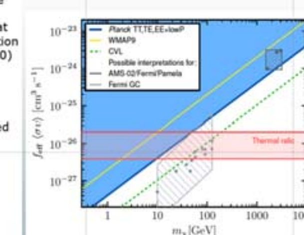
Dark matter annihilation?

Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption <σv>(z=100)=<σv>(z=0)

Thermal Relic cross sections at z~1000 ruled out for:

m~<40GeV (e^+e^-)
m~<20GeV ($\mu^+\mu^-$)
m~<10 GeV ($\tau^+\tau^-$).

Only a small part of the parameter space preferred by Fermi GC is excluded



See 1501.01618 for powerful other constraints

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

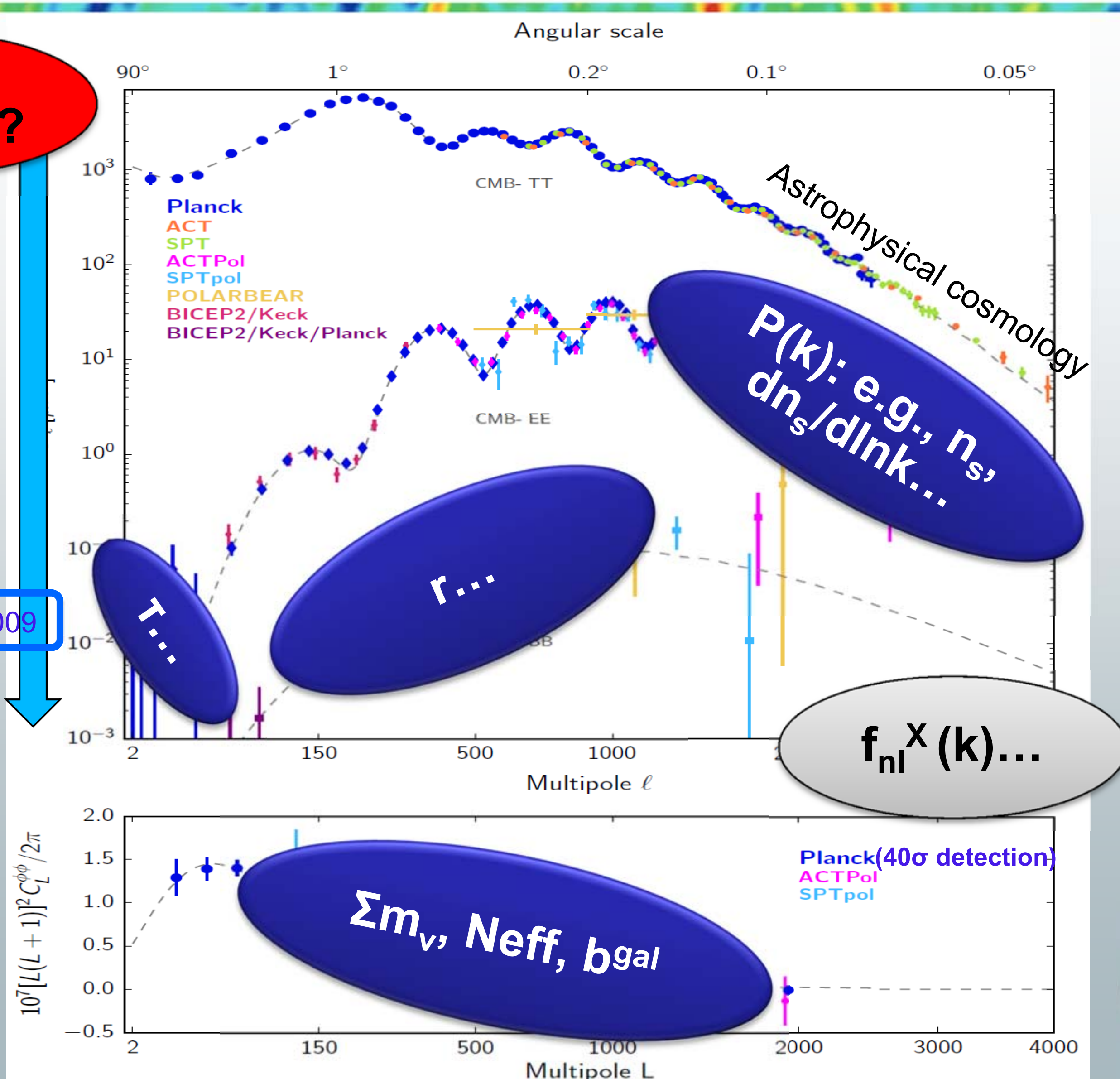
TT, EE, BB, ΦΦ – early 2017 status

ΛCDM enough?

Only keeping points w. sufficiently small error bars, Fig. E Cala

10^7

τ = 0.055±0.009



And SZ & CIB PS, etc.

Planck:

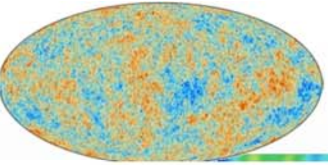
1 114 000 Modes measured with TT,

60 000 with TE (not shown)

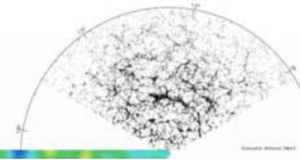
96 000 with EE

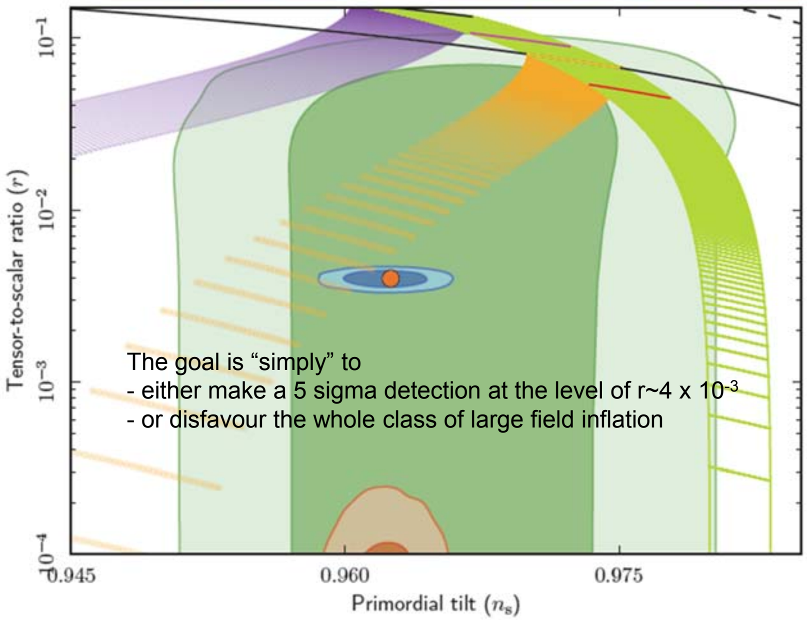
… and **10's** in BB and φφ

+ constraints on TB and EB

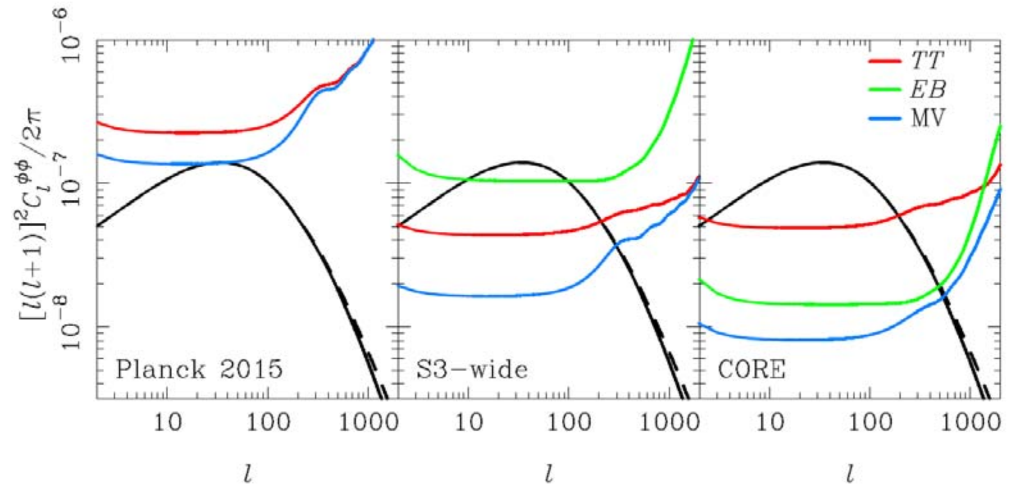


CORE examples of CMB potential

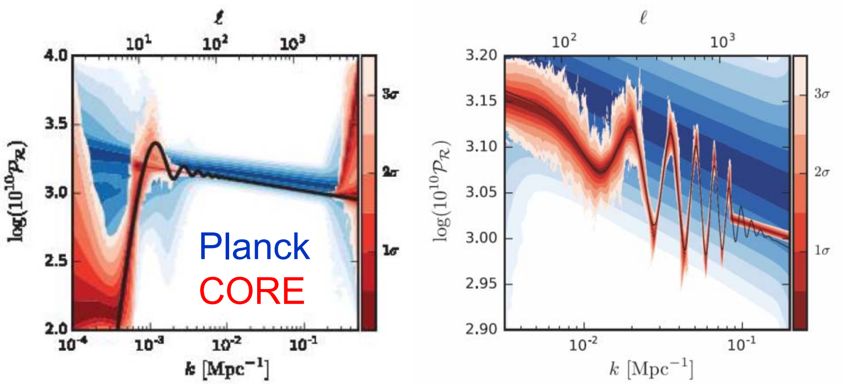




The goal is "simply" to
- either make a 5 sigma detection at the level of r~4 x 10^{-3}
- or disfavour the whole class of large field inflation



Reconstruction noise of the lensing detection power spectrum from Planck 2015 (left) and forecasts. The detection power spectrum is plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). [MV=minimum Variance]. ➔ M_ν, N_{eff} …



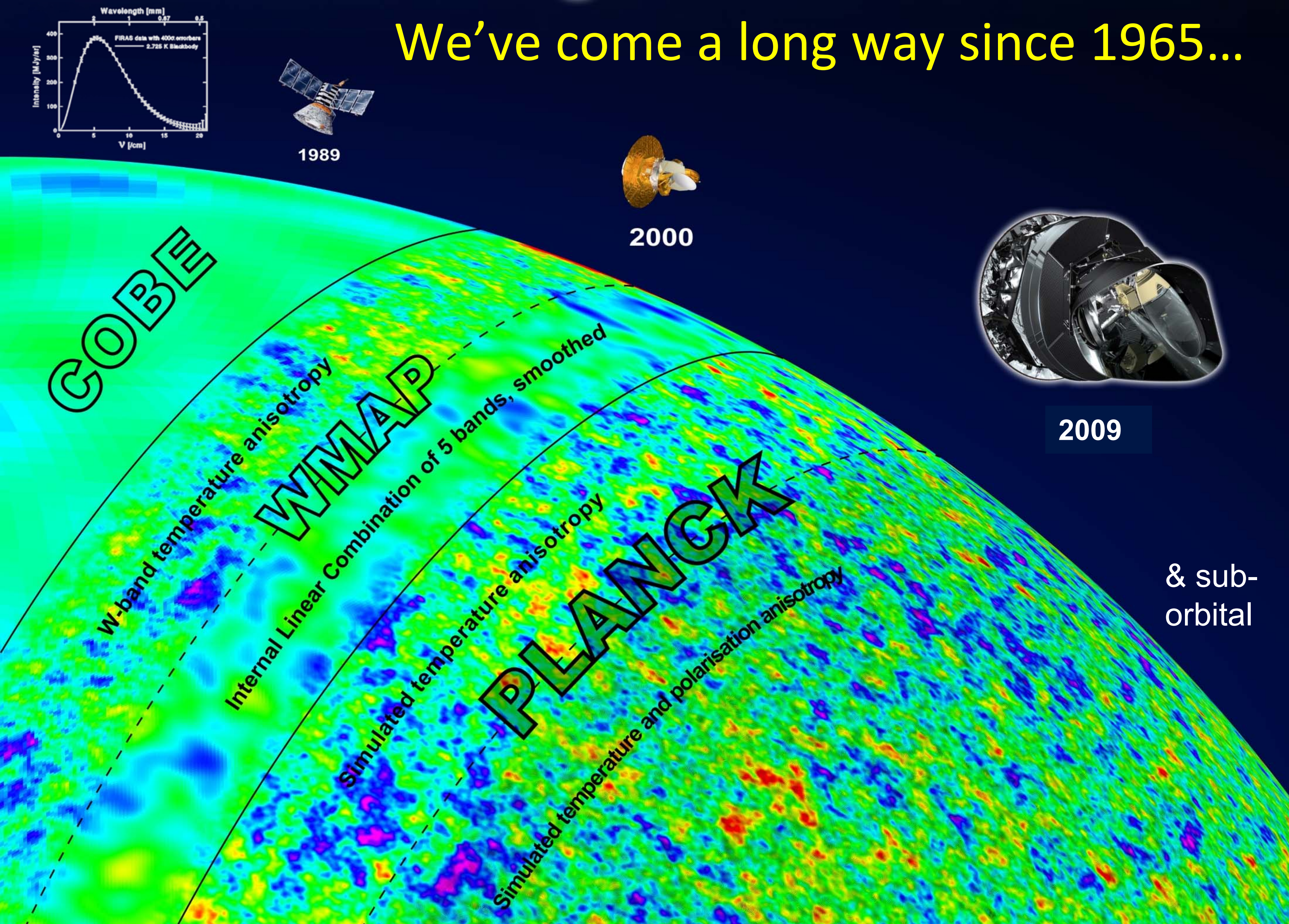
Power spectrum reconstruction
(linearly-sinusoidal wiggles generated by an inflaton cs reduction)

Model	*Planck*15+BAO	*CORE*	*CORE*+BAO
ΛCDM	3.3	2.3×10^3	2.3×10^3
$\Lambda\text{CDM} + \sum m_\nu$	11	8.9×10^3	2.0×10^4
$\Lambda\text{CDM} + w$	24	5.4×10^3	2.2×10^4
$\Lambda\text{CDM} + \sum m_\nu + N_{\rm eff}$	15	4.7×10^4	1.0×10^5
$\Lambda\text{CDM} + w_0 + w_a$	42	4.7×10^3	1.3×10^5
$\Lambda\text{CDM} + Y_{\rm P} + \sum m_\nu + N_{\rm eff}$	[illegible]	[illegible]	[illegible]
$\Lambda\text{CDM} + r + dn_{\rm s}/d\ln k + \sum m_\nu + N_{\rm eff}$	12	5.8×10^5	1.2×10^6
$\Lambda\text{CDM} + w + Y_{\rm P} + \sum m_\nu + N_{\rm eff}$	140	5.2×10^5	9.1×10^6
$\Lambda\text{CDM} + w + r + \sum m_\nu + N_{\rm eff}$	110	3.9×10^5	7.6×10^6

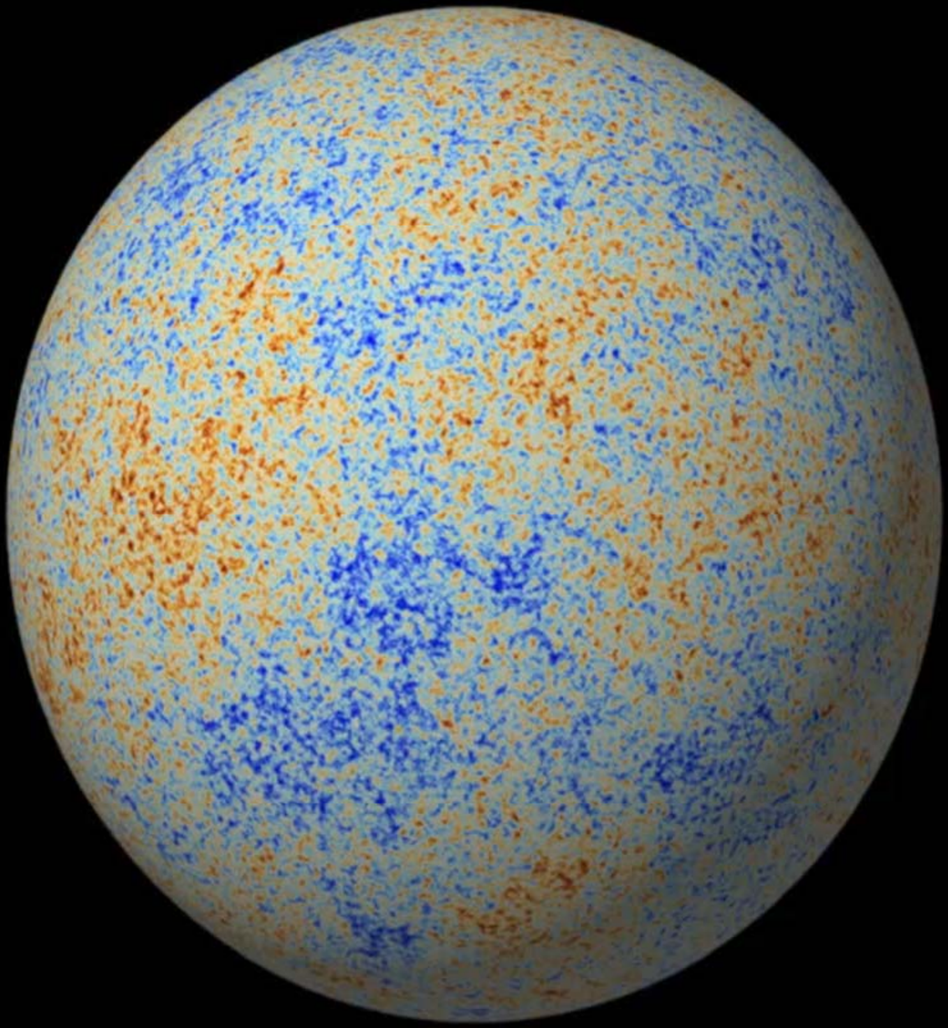
Table 2: Improvement with respect to *Planck*15 of the global figure of merit (see text) in the different cosmological scenarios specified in the first column for various data combinations involving *CORE* and future BAO measurements.

Capability to find limitations of ΛCDM

We’ve come a long way since 1965…



With much more to come!



Starting with Planck 2018 "legacy" release!