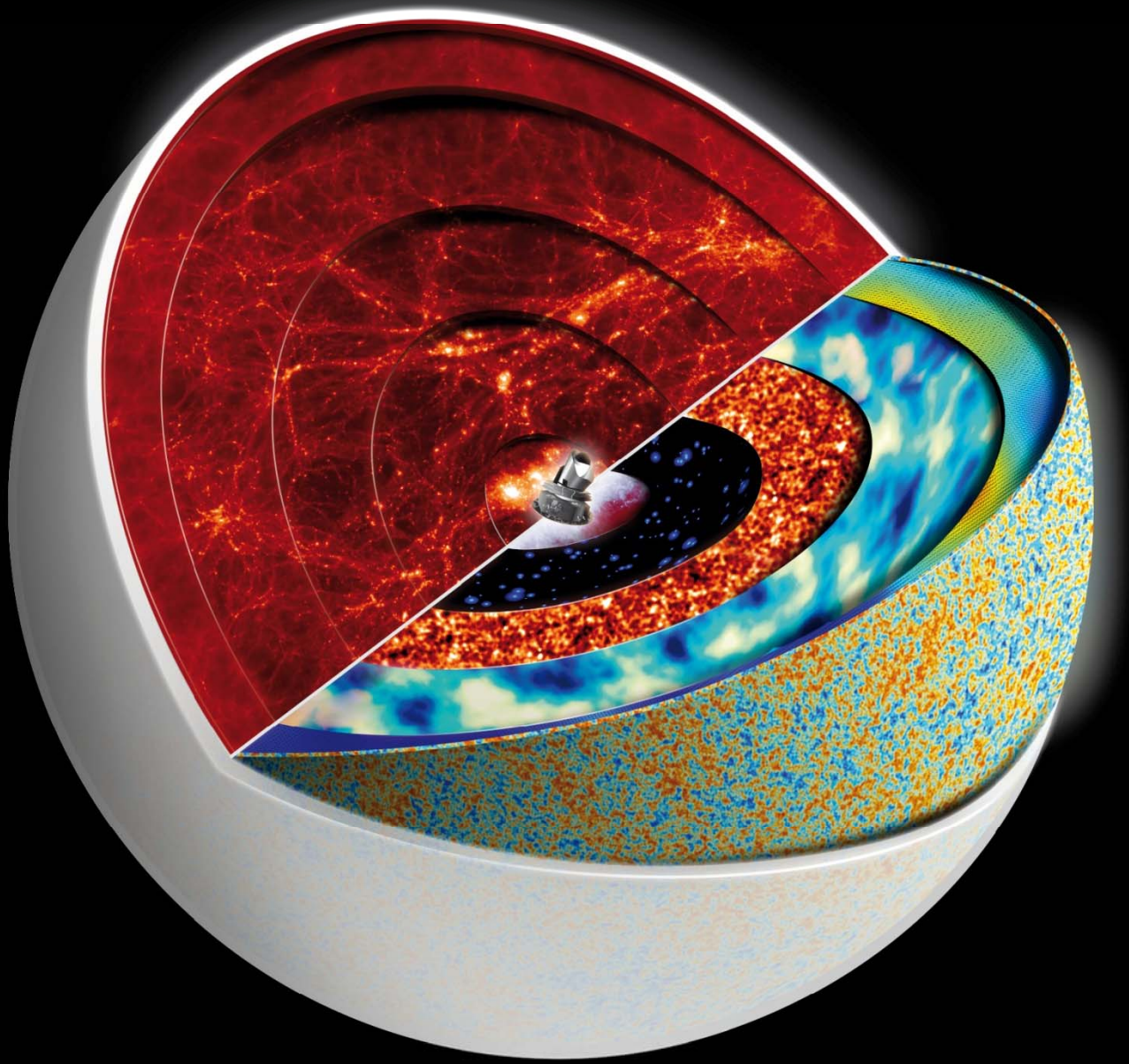
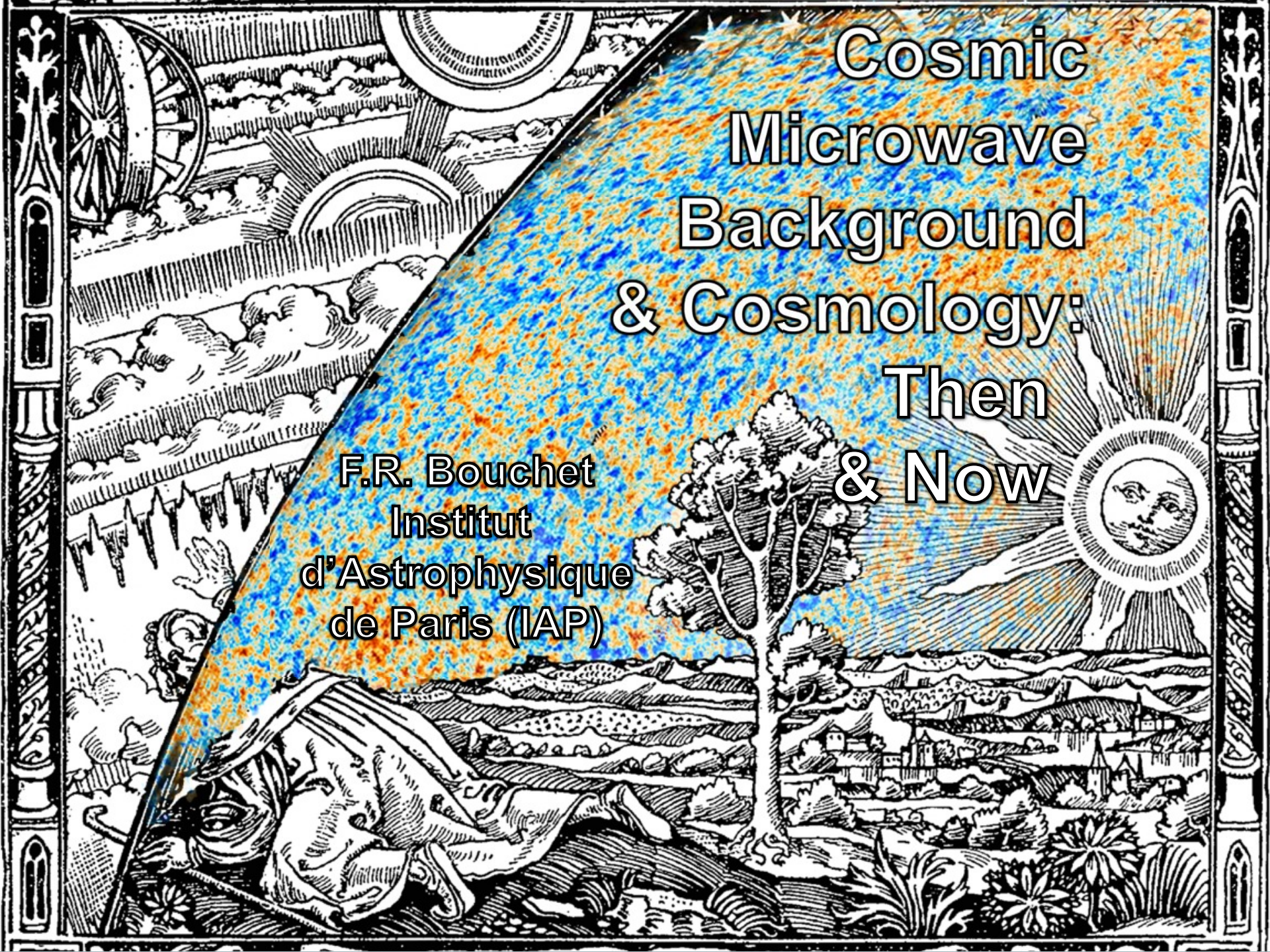
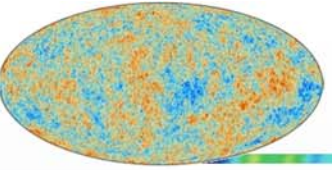
From quantum foam to the cosmic sponge

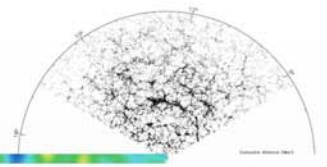


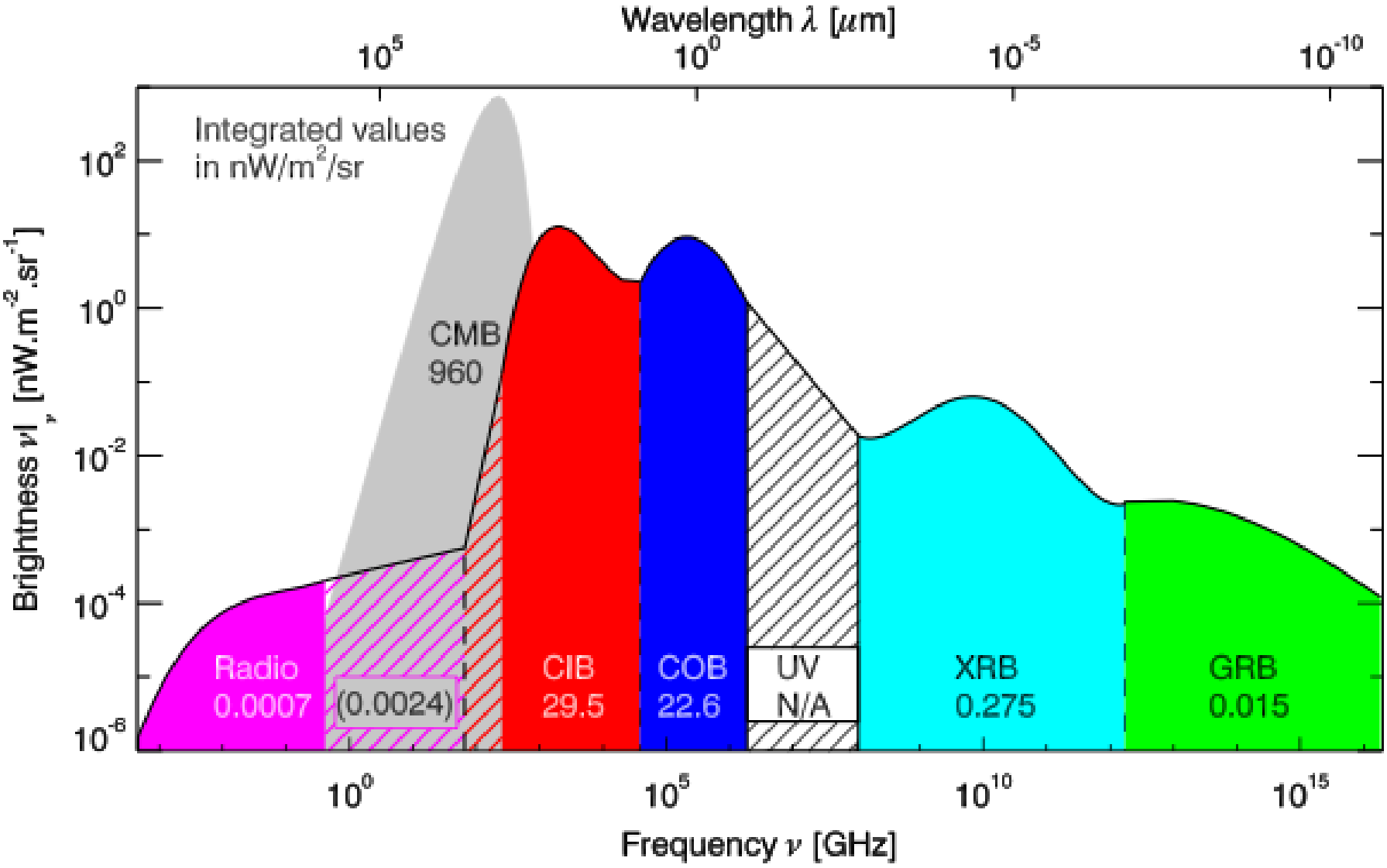
A journey to the confines of space, time, and known physics


Cosmic
Microwave
Background
& Cosmology:
Then
& Now
F.R. Bouchet
Institut
d'Astrophysique
de Paris (IAP)

The photonic background





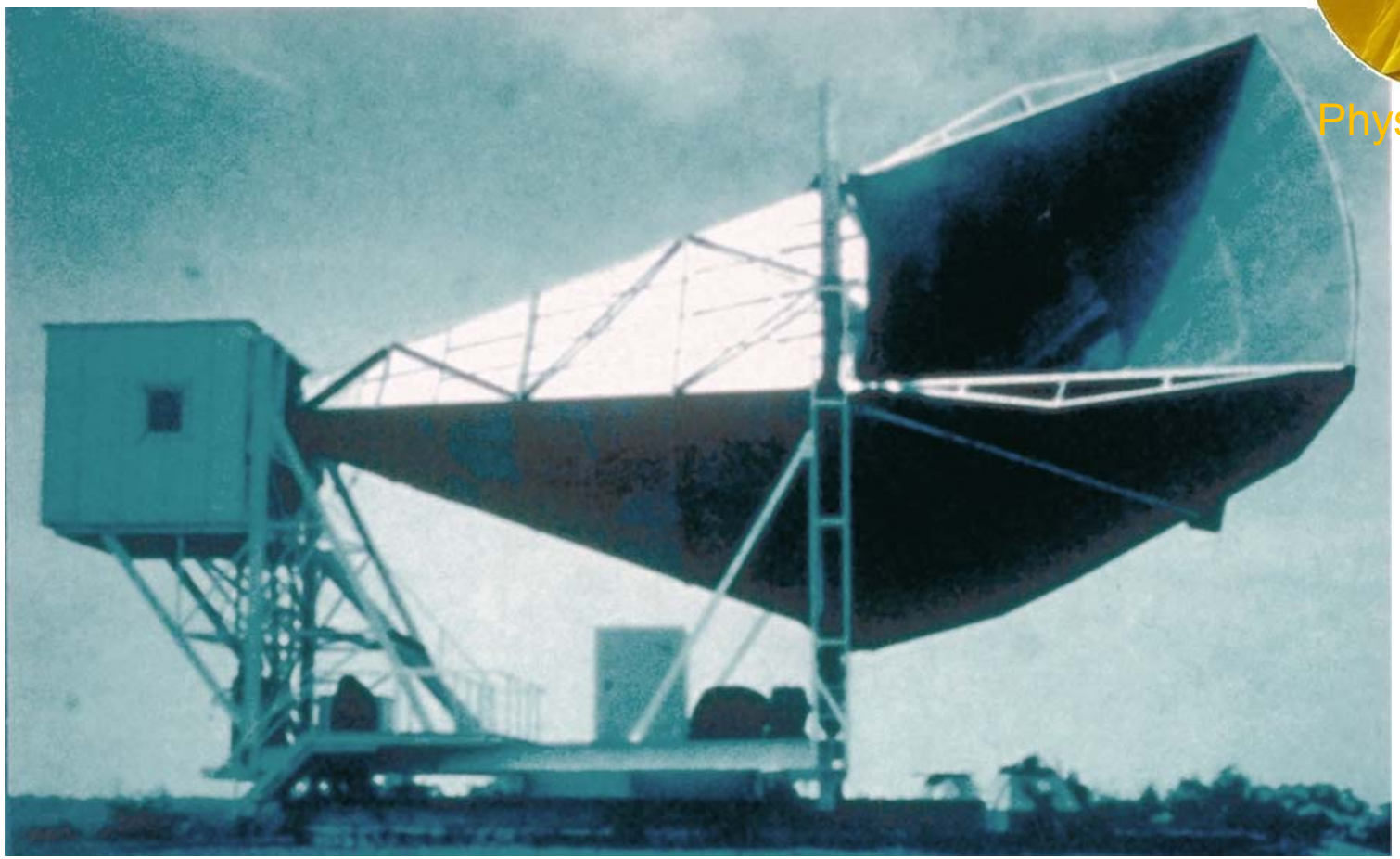


Lacasa 2014 arXiv:1406.0441

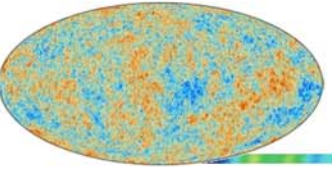
Penzias et Wilson discovery antenna…



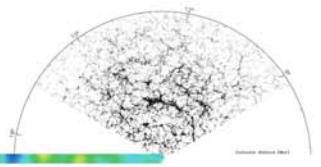
Physics 1978



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.*



CMB spectrum: FIRAS

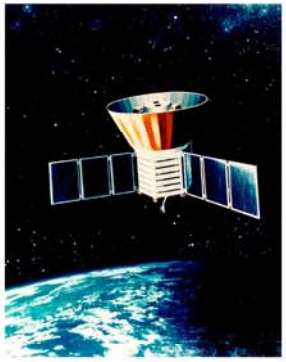


$$T_0 = 2.725 \pm 0.002\,\mathrm{K}$$

95% CL from template fits:

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

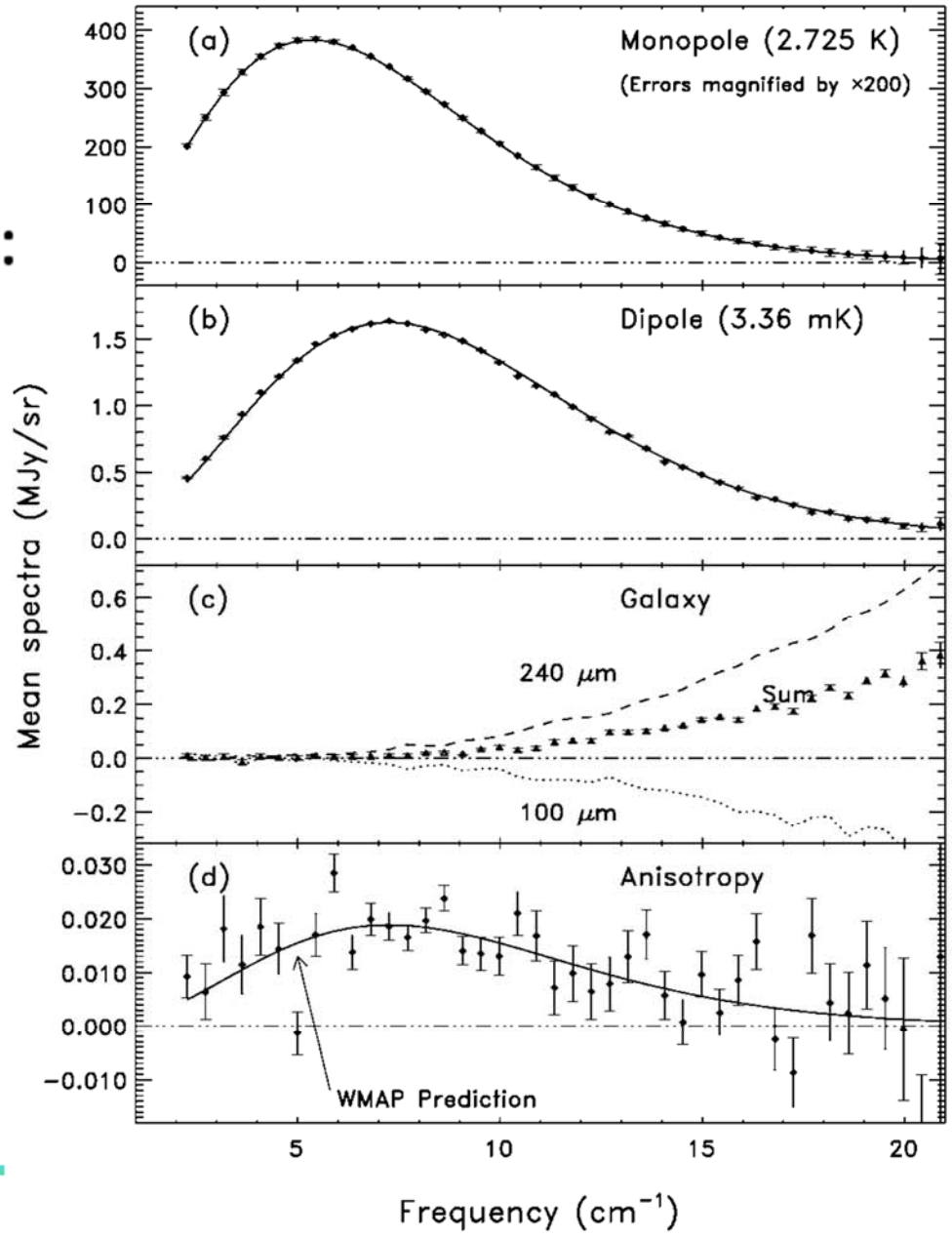
$$|\mu/kT| < 3.3 \times 10^{-4}$$



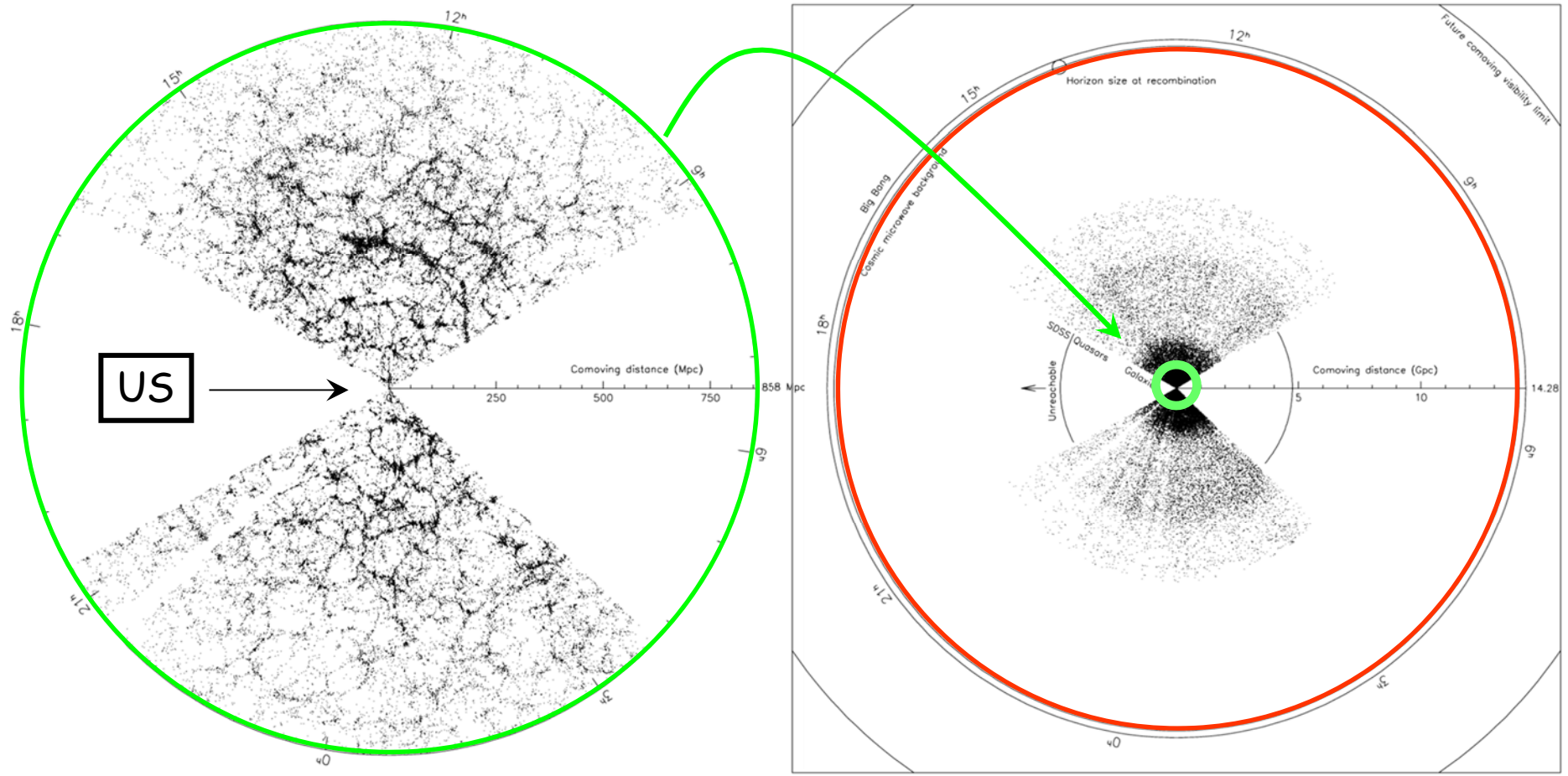


Physics 2006

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



To look far away is watching a remote past!



Light takes 2,7 billion years to travel to us from a galaxy on the green circle .
The **millimetric light** took ~13 billion years to travel to us from the LSS (red circle). This is the fossil from the primordial furnace, 400 000 years after the Bang, when the universe became transparent.

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970
© 1970 The University of Chicago All rights reserved Printed in U.S.A.

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

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University
AND
J. T. YU‡
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 $\delta T/T = 0.00015$.

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).

* 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.

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

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

Generating the primordial fluctuations: When and How?

- Then the **Inflation** "framework" came along (in the 70's); see the presentation tomorrow by Professor Misao Sasaki.
- For now, just note and remember that this class of models proposes that
  - the initial conditions for the standard Hot Big Bang model were set during a phase of very fast expansion (with ~constant expansion rate for >~50 e-folds), dominated by the energy density of the (quantum) vacuum, which at the end of that phase decays into matter and radiation. The existence of such a phase solves a number of cosmological conundrums (Monopoles, Flatness, Homogeneity…).
  - During that period, unavoidable quantum fluctuation of the vacuum energy density (which sources the metrics) are expanded to cosmological scales and leave a quasi scale invariant spectrum of curvature perturbations. These will later initiate the growth to complexity which, 13.8 billions later, is visible in the sponge-like topology of the large scale structures of the Universe which are revealed by the inhomogeneities of the galaxy distribution.
  - Generic predictions follow (flat spatial geometry, adiabatic initial fluctuations, quasi Gaussian distributed, quasi scale invariant, but not quite, etc…) but with considerable variations in the implementation and detailed properties. Of particular note, first calculation of vacuum quantum fluctuations during a de Sitter phase by Mukanov and Chibisov in 1981.
  - During the early phase of the Universe., before 380 000 years, adiabatic fluctuations oscillate like acoustic fluctuations under the influence of the photon pressure, before the time when photons cease to interact with electrons and the Universe becomes neutral and transparent.
- Later on, other proposals to seed the growth of structure, but all are still related to fluctuations of the vacuum (Topological defects, and lately, bouncing models). Thus we may be the the children of the stars, but ultimately, we are children of the quantum vacuum!

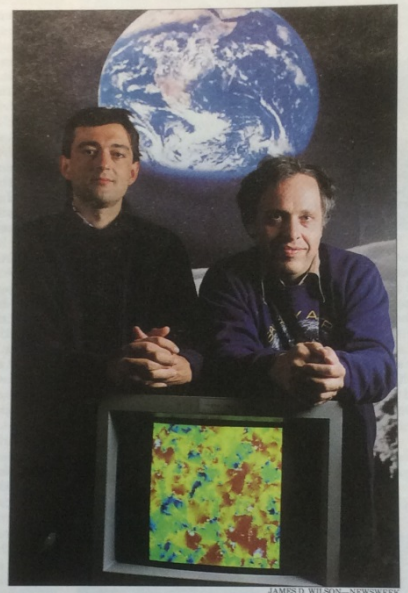
1988 (Pre-COBE), Berkeley, Fermilab, Princeton…

SOCIETY

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 widom 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

*A 1 preceded by 34 zeros: .00000000000000000000000000000001, 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*

dicts. 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.

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.

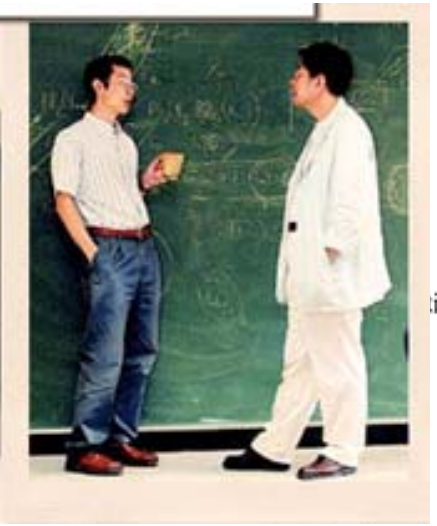
That has only whetted cosmologists' enthusiasm for them. Strings appeal because they might act as seeds of galaxies. Perhaps a small loop of string attracts, with its gravity, enough matter to form a galaxy; a bigger loop might attract enough to form a galactic cluster. Or, strings might blast matter 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

THE ASTROPHYSICAL JOURNAL, 352:1–14, 1990 March 20
© 1990. The American Astronomical Society. All rights reserved. Printed in U.S.A.

Senior people were once young…

TOPOLOGY OF MICROWAVE BACKGROUND FLUCTUATIONS: THEORY



J. RICHARD GOTT III AND CHANGBOM PARK
Department of Astrophysical Sciences, Princeton University
ROMAN JUSZKIEWICZ
Institute for Advanced Study, Princeton; and Copernicus Center, Warsaw, Poland
WILLIAM E. BIES AND DAVID P. BENNETT
Physics Department and Department of Astrophysical Sciences, Princeton University
FRANÇOIS R. BOUCHET
itut d'Astrophysique de Paris, Paris, France; and Centre de Physique Theorique Ecole Polytechnique
AND
ALBERT STEBBINS
Canadian Institute for Theoretical Astrophysics, Toronto, Canada
Received 1989 July 3; accepted 1989 September 19

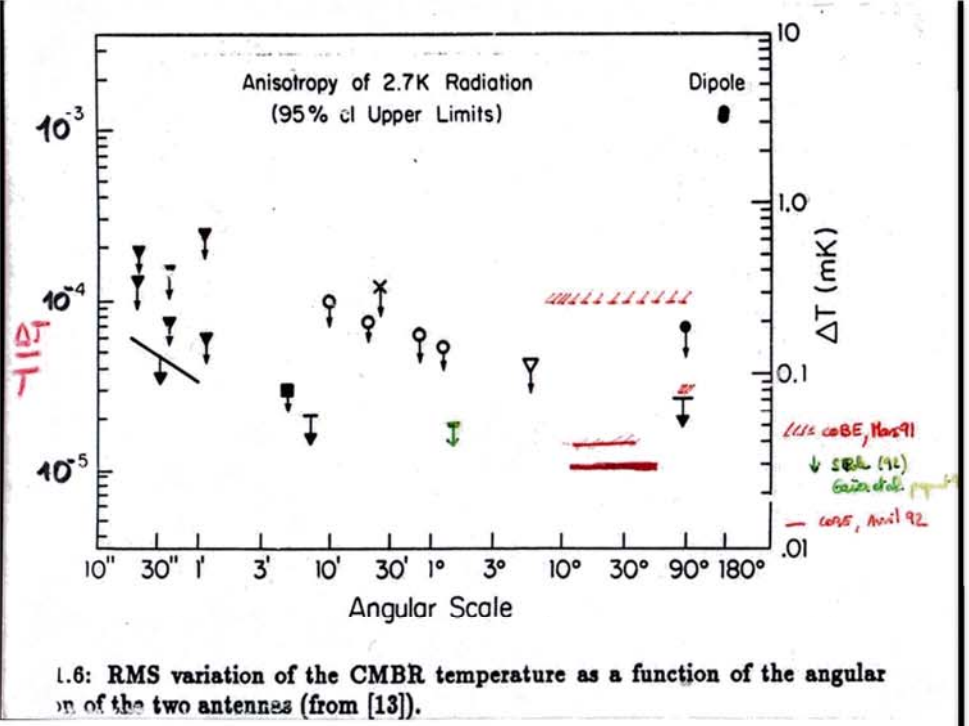


ABSTRACT

Topological measures are used to characterize the microwave background temperature fluctuations produced by "standard" scenarios (Gaussian) and by cosmic strings (non-Gaussian). Three topological quantities: total area of the excursion regions, total length, and total curvature (genus) of the isotemperature contours, are studied for simulated Gaussian microwave background anisotropy maps and then compared with those of the non-Gaussian anisotropy pattern produced by cosmic strings.

In general, the temperature gradient field shows the non-Gaussian behavior of the string map more distinctively than the temperature field for all topology measures. The total contour length and the genus are found to be more sensitive to the existence of a stringy pattern than the usual temperature histogram. Situations when instrumental noise is superposed on the map, are considered to find the critical signal-to-noise ratio for which strings can be detected. With current observational sensitivity (5 mK $Hz^{-1/2}$) and a 32 receiver array, 660 hr of mapping would demonstrate the non-Gaussian behavior due to cosmic strings if $G\mu > 6 \times 10^{-6}$. If such an observational program failed to detect any signals beyond instrumental noise, using our topological analysis we would be able to set limits of $G\mu < 4 \times 10^{-7}$ for strings and $\langle a_2^2 \rangle^{1/2} \leq 8 \times 10^{-7}$ for the Zel'dovich spectrum.

Subject heading: cosmic background radiation

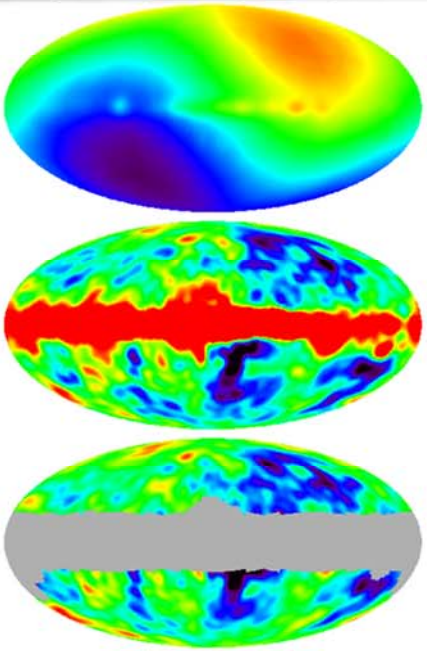


1.6: RMS variation of the CMBR temperature as a function of the angular
n of the two antennas (from [13]).

Table 1: Primary Anisotropies for Primordial Gaussian Fluctuations

MODEL	Small Angle $10^5(\Delta T/T)$ $4.5'[7.15']$	Large Angle $10^5(\Delta T/T)$ $6°$
OBSERVATIONS	< 50 [< 15]	< 45 = 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+1
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	10
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	10
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) $\Omega = 1$ $\Omega = 0.1$, $h = .53$	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]	30
OPEN/CDM/B $\Omega = .2$ $\Omega_X = .1$ $\Omega_B = .1$ $h = .75$	80 [170]	30
$\Lambda \neq 0$ 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 $\Omega = 1$ $\Omega_B \ll \Omega$	-	30
CDM-dom + Extra Power Plateau $\Omega = 1$ $\Omega_B \ll \Omega$	-	30

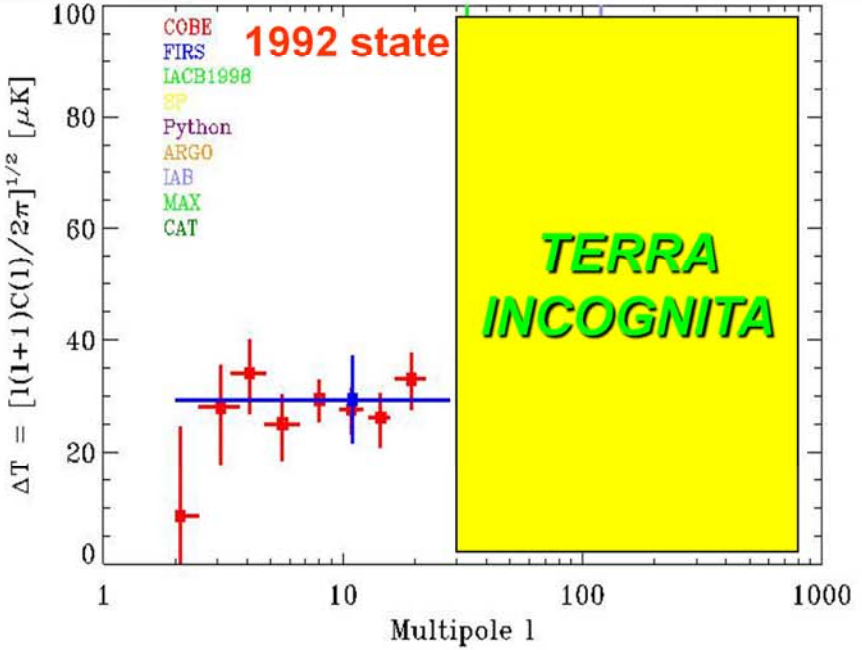




DMR/Smoot



Physics 2006



March 1996 presentation, Unesco (Paris), for an ultimate T anisotropies cosmological mission

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

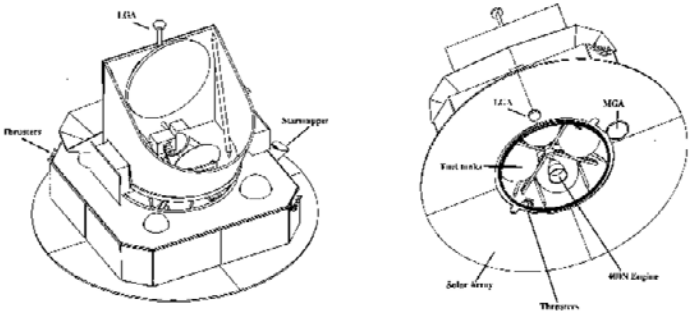
Model Payload Characteristics

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

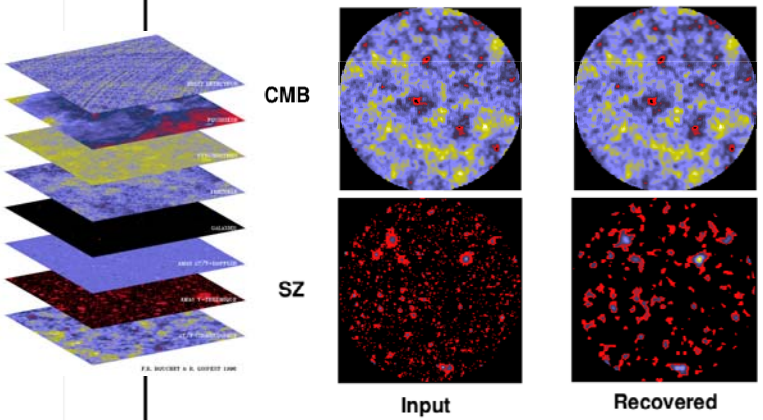
The spacecraft



esa Phase A Study - Final Presentation

COBRAS/SAMBA

Component separation

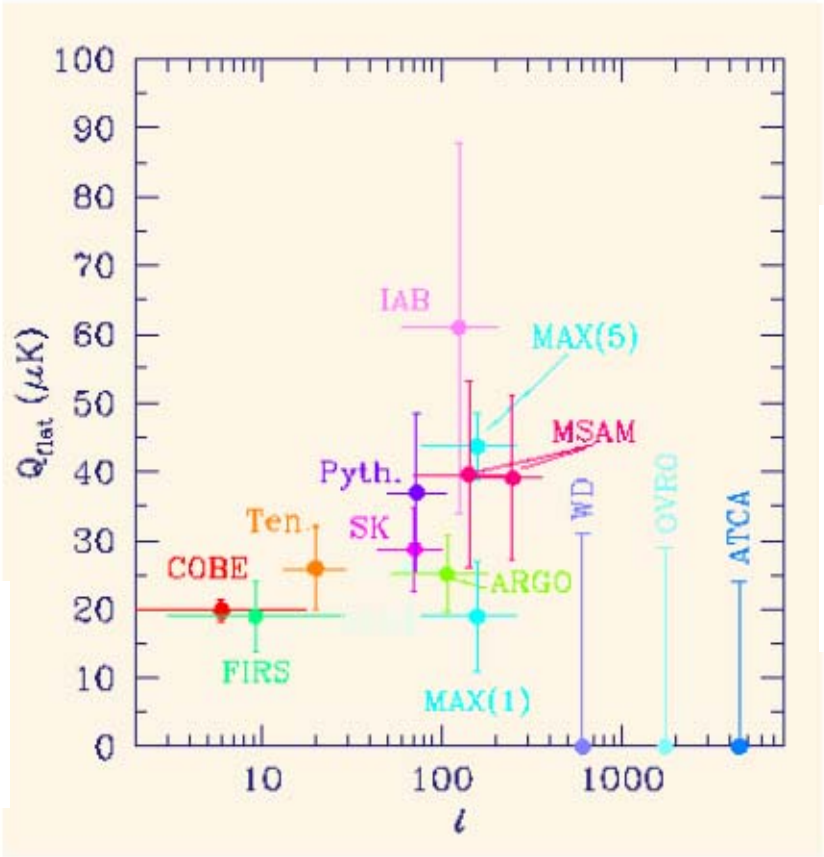


esa Phase A Study - Final Presentation

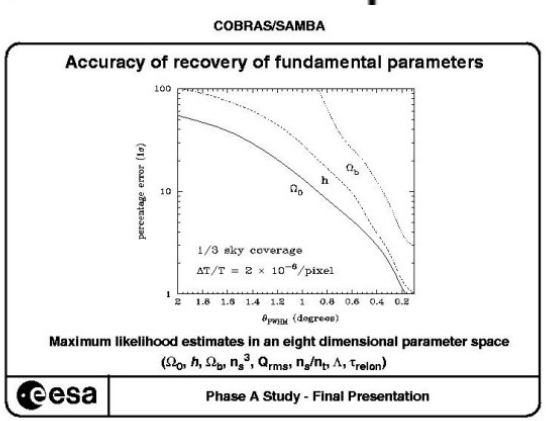
March 1996 selection, Unesco (Paris)

COBRAS/SAMBA

Observational Status



This plot was showing the typical amplitude of CMB fluctuations within different ranges of angular scales



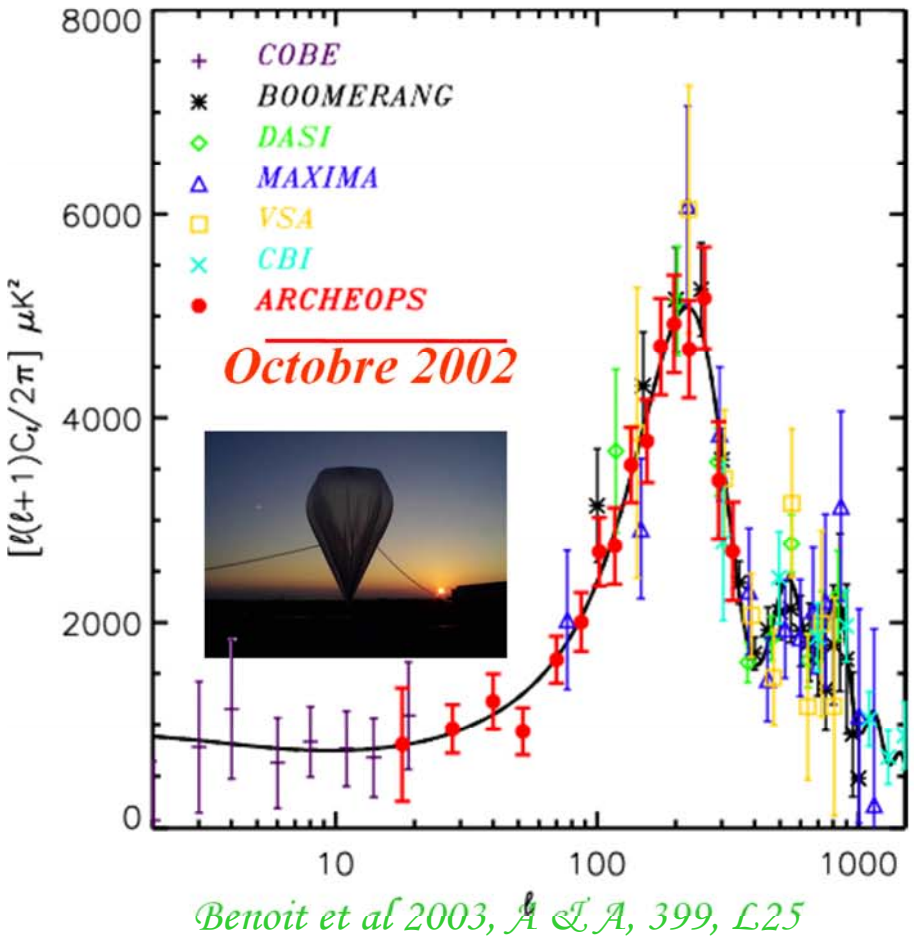
Boldly targeting per cent accuracy on cosmological parameters, or surprises…

esa

Phase A Study - Final Presentation

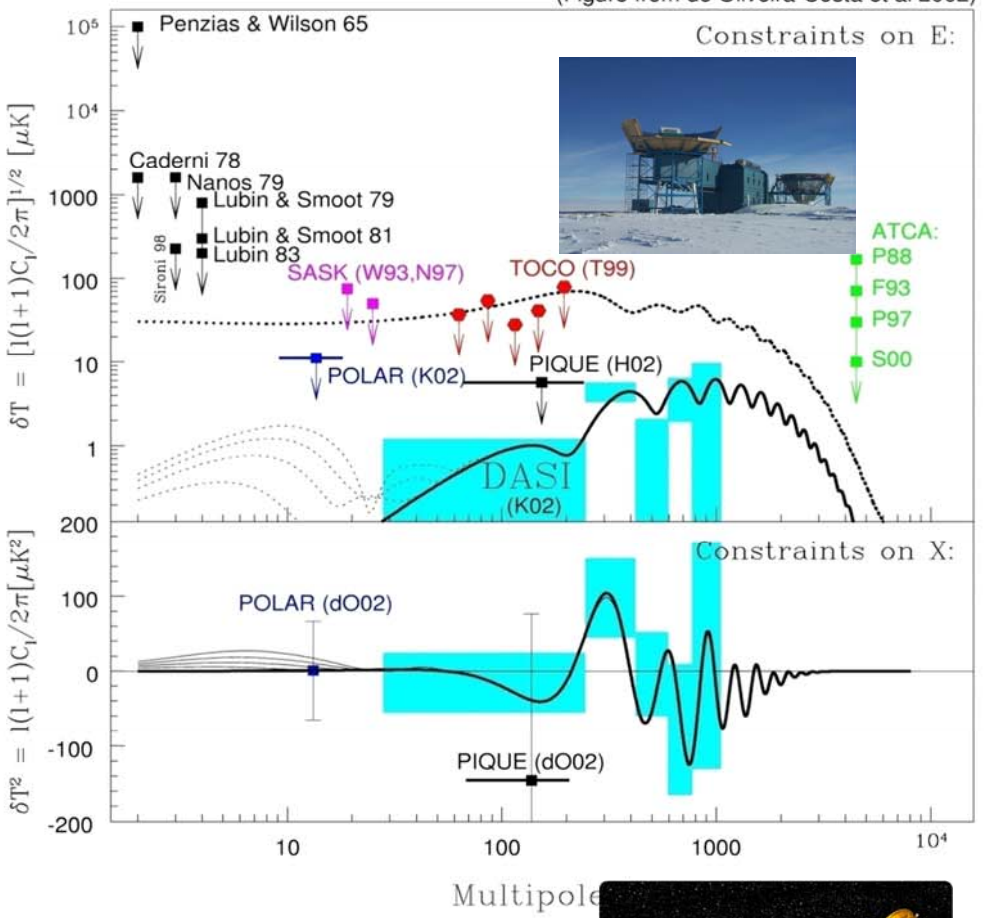
Fast forward: end of 2002 Status (pre-WMAP)…

Many experiments progressively reveal our sky! (+many further theoretical developments)

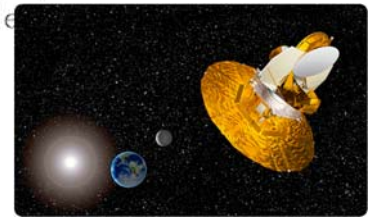


Benoit et al 2003, A & A, 399, L25

(Figure from de Oliveira-Costa et al 2002)

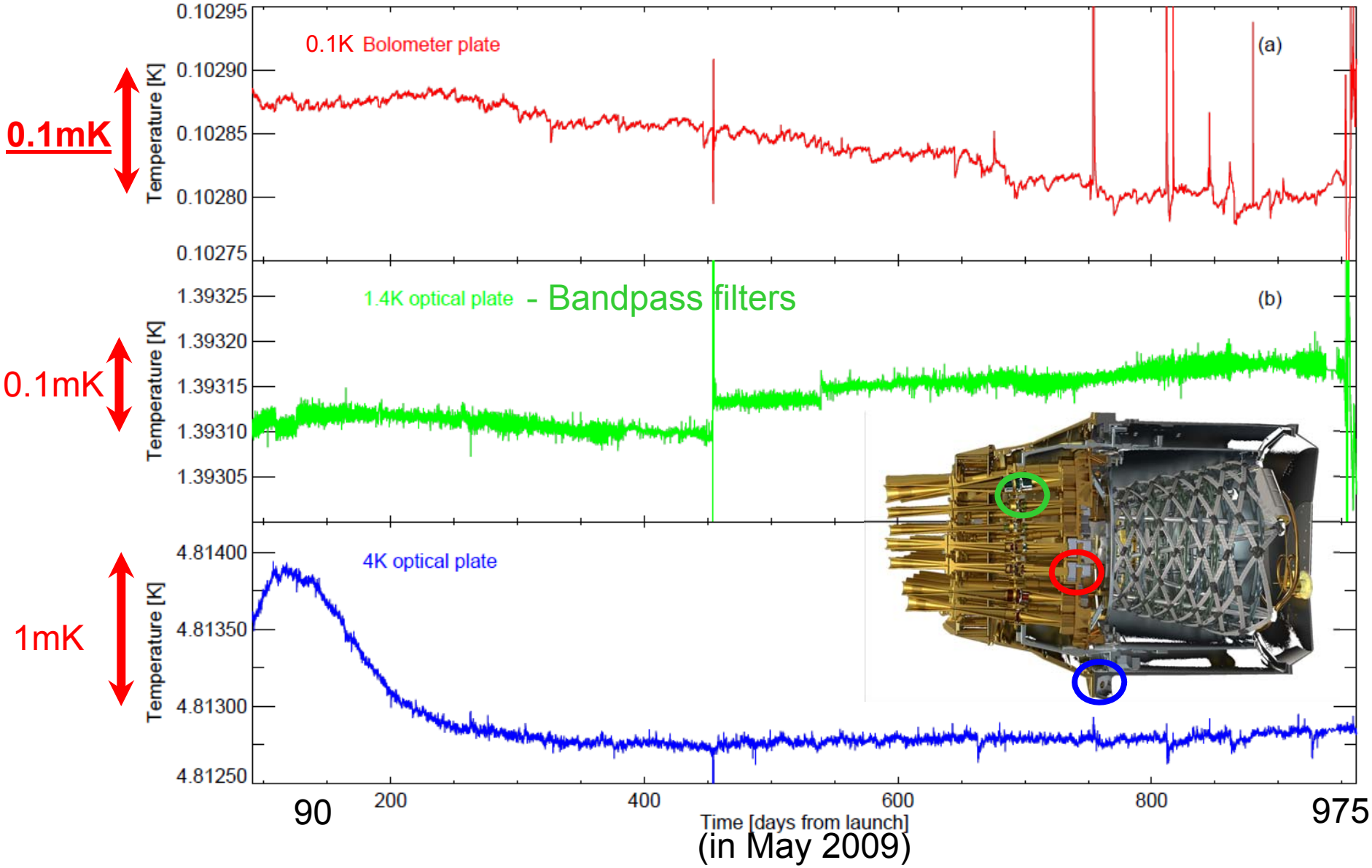


…Followed shortly thereafter by the WMAP 3, 5, 7 and 9 years results

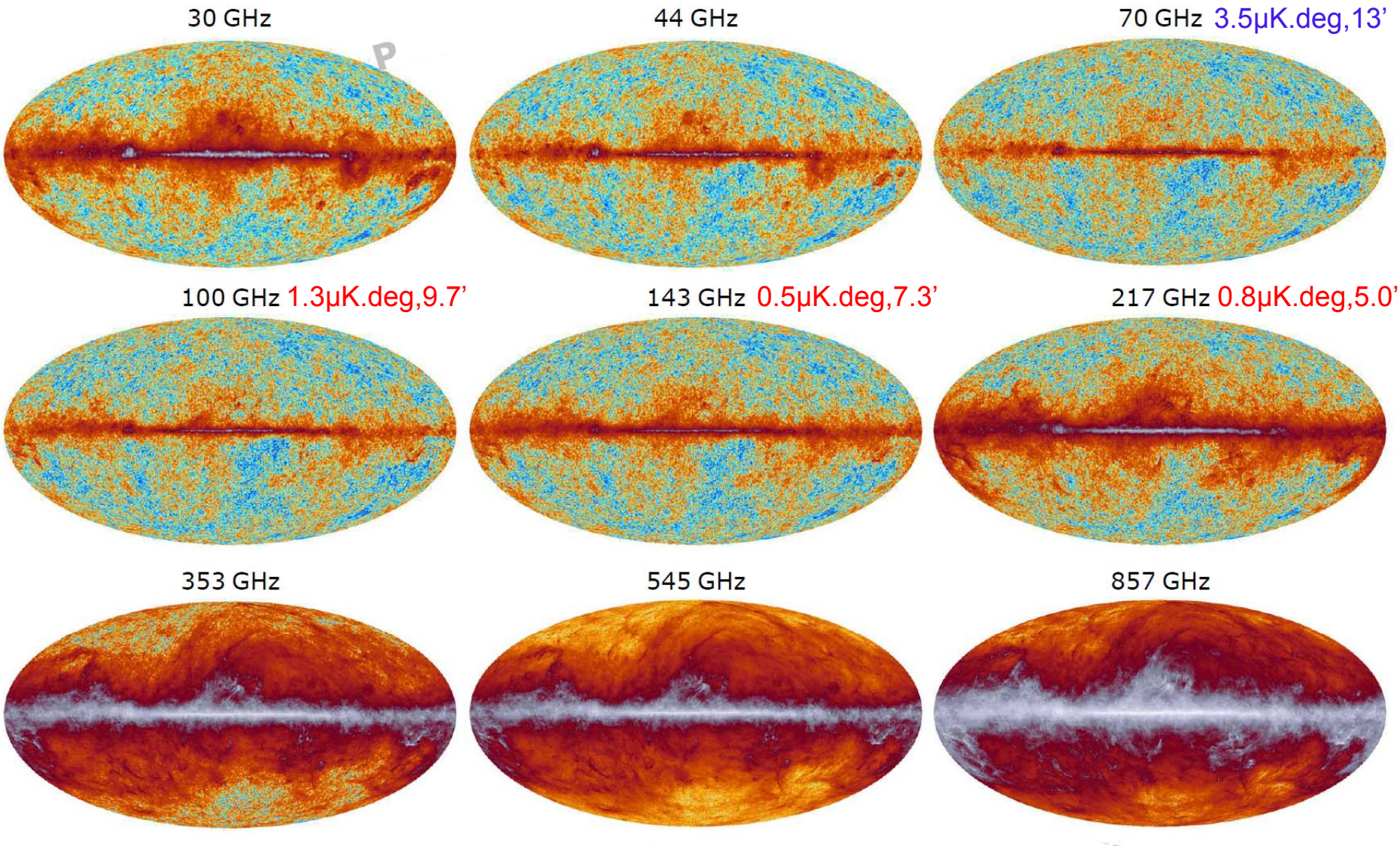



DUSTING IT OFF...
AFTER 16 YEARS
OF HOPES & WORK

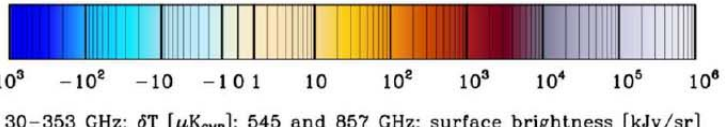
Very cold, very stable, a very long time…



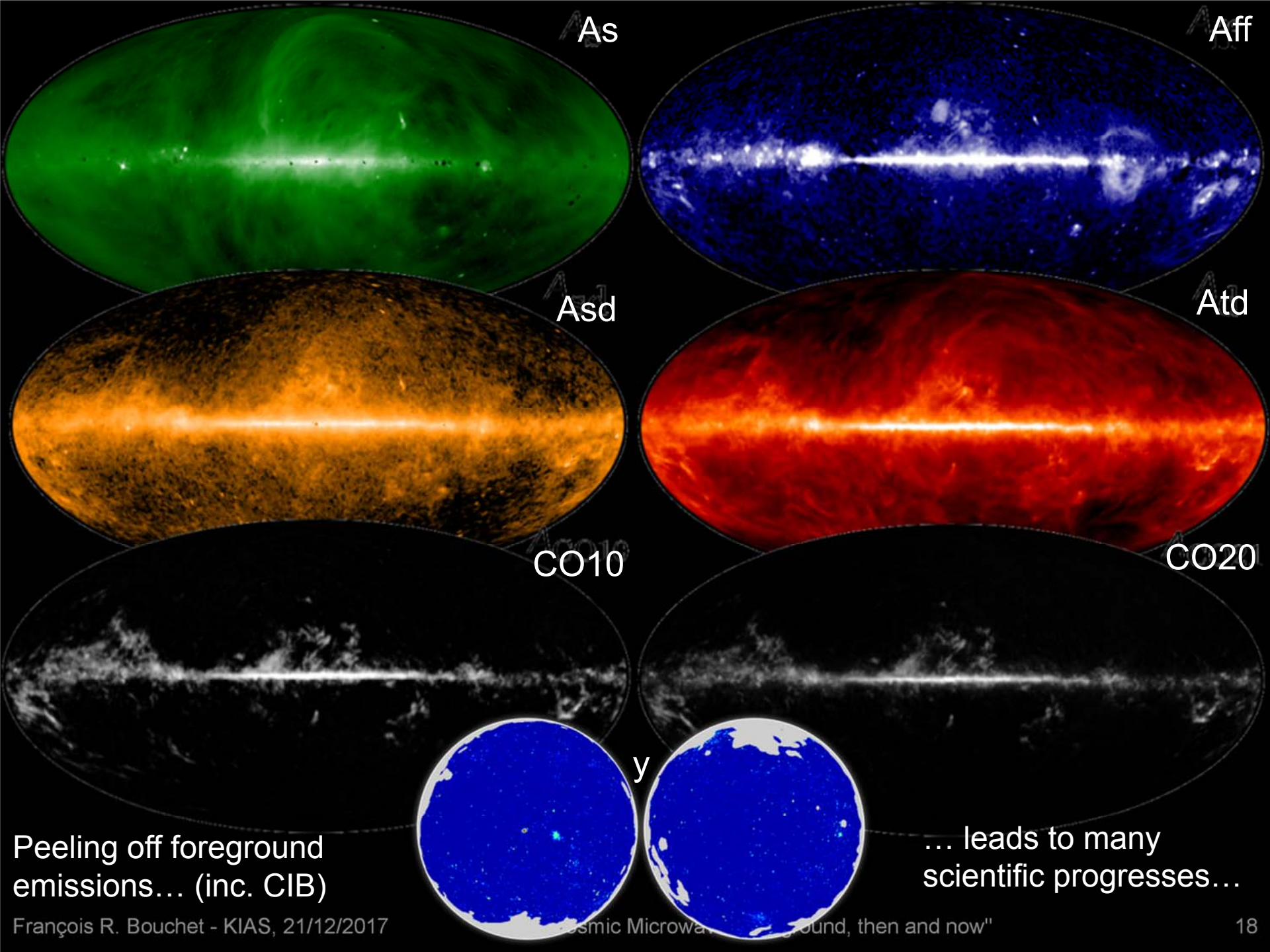
Planck 2015 Temperature maps



(pla.esac.esa.int)



(Intensities expressed as equivalent thermodynamic fluctuations at that frequency)



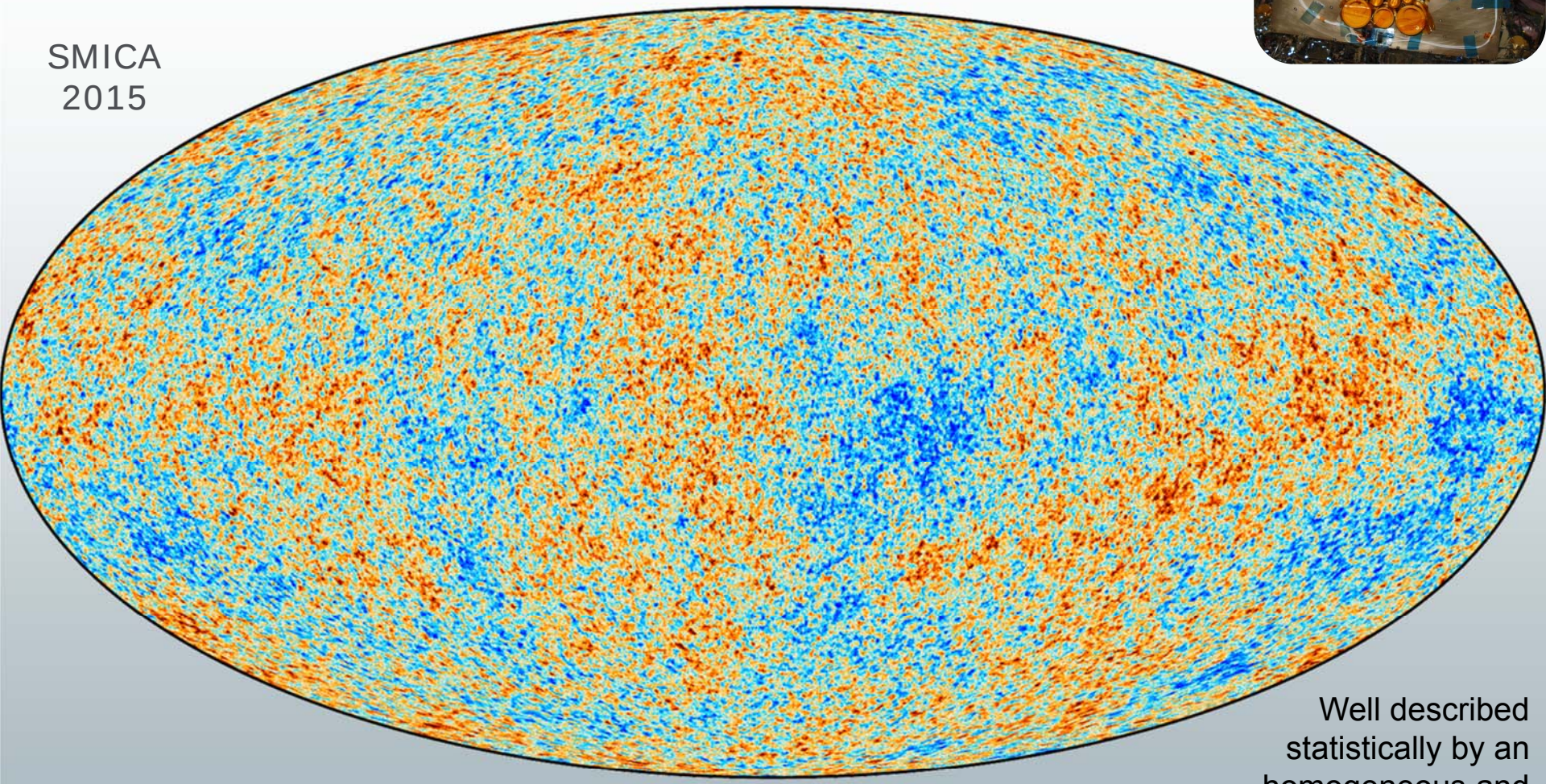
Peeling off foreground emissions… (inc. CIB)

… leads to many scientific progresses…

Planck 2015 T anisotropies map



SMICA
2015

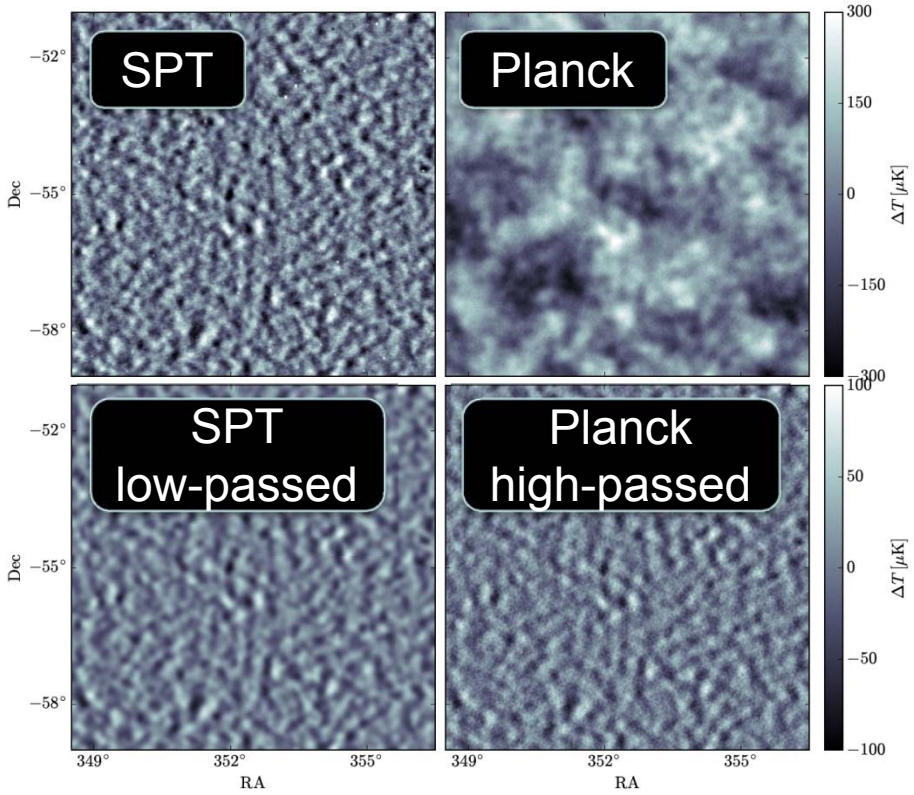




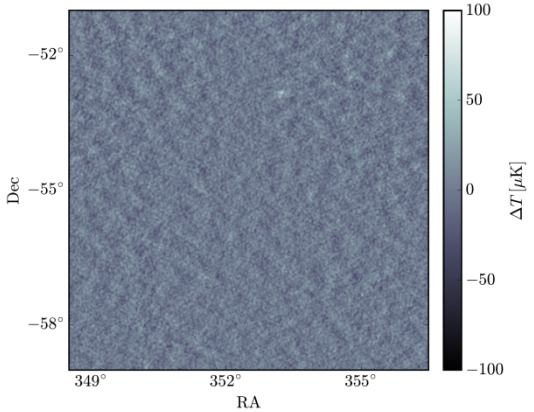
Well described statistically by an homogeneous and isotropic Gaussian field

SPT@150GHz vs planck@143GHz

Hou+ arXiv:1704.00884v1

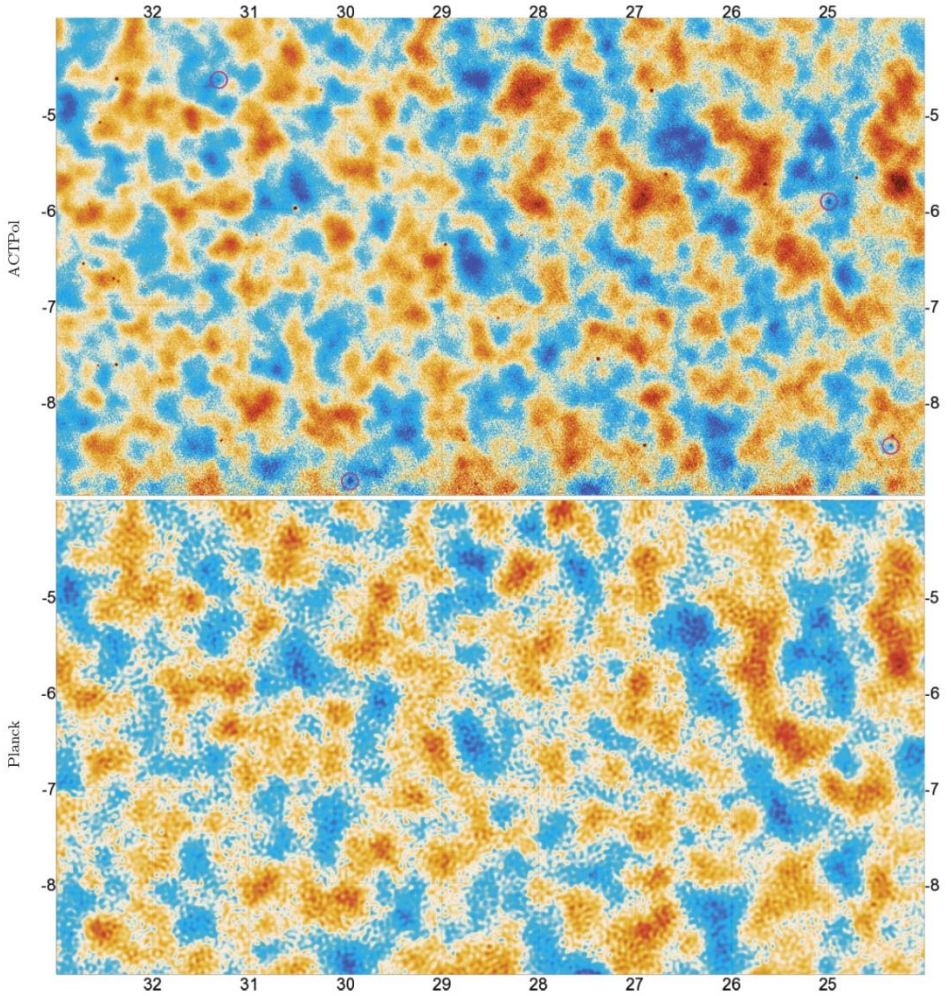


Little residual in SPT-low minus Planck-high, but a variable source



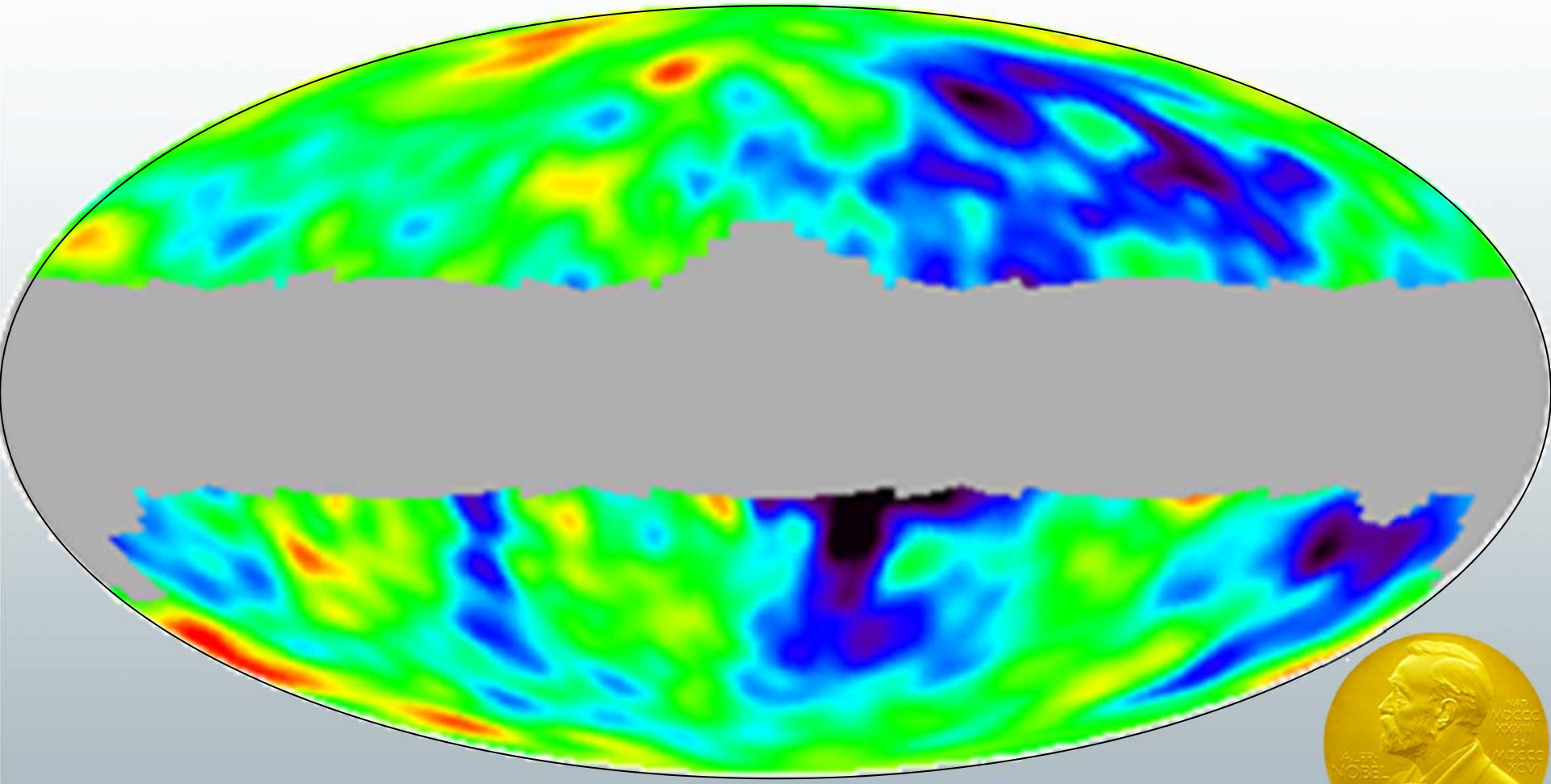
ACT@150GHz vs planck@143GHz

Louis+ arXiv:1610.02360v1



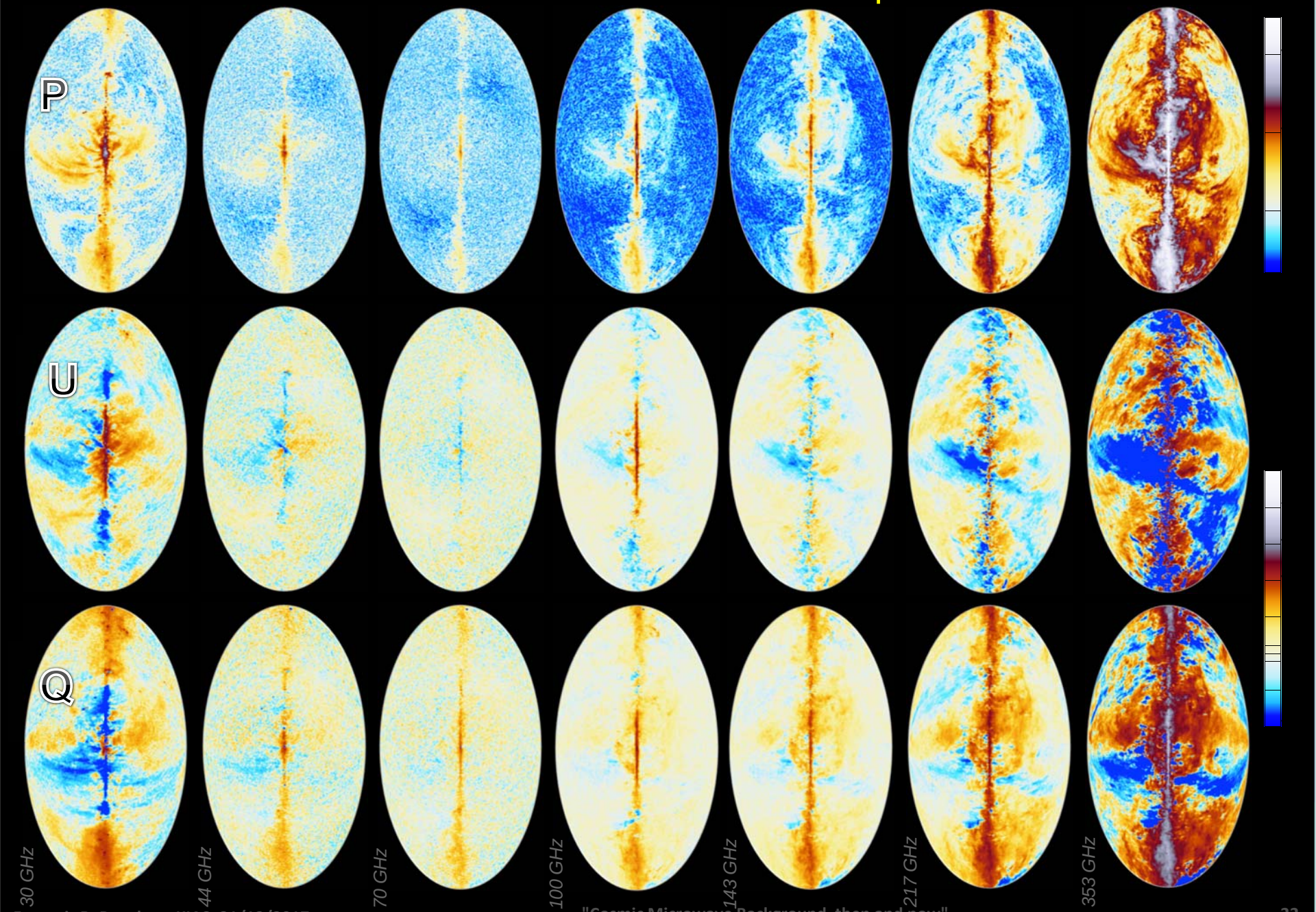
NB: Planck also agrees with the largest scale modes previously mapped by COBE/DMR and WMAP.

COBE/DMR T anisotropies map



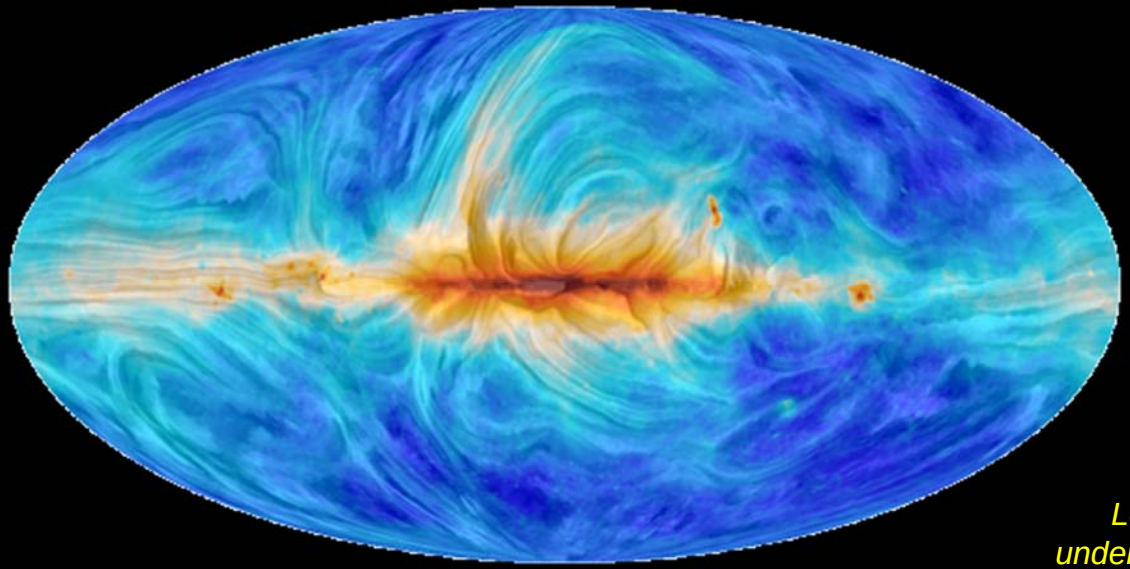
We have essentially finished mining the cosmological Temperature anisotropies revealed by DMR

Planck 2015 Polarisation maps



Planck 2015 Polarisation & Galactic foregrounds

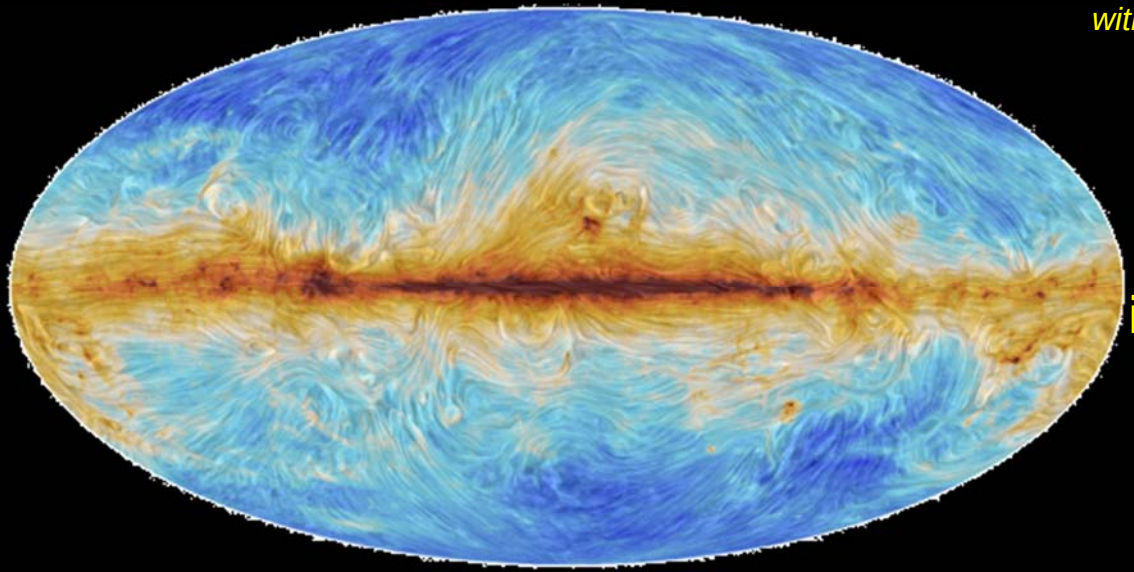
30 GHz



Synchrotron

Lots of information to understand better our cradle, with details inaccessible in other galaxies

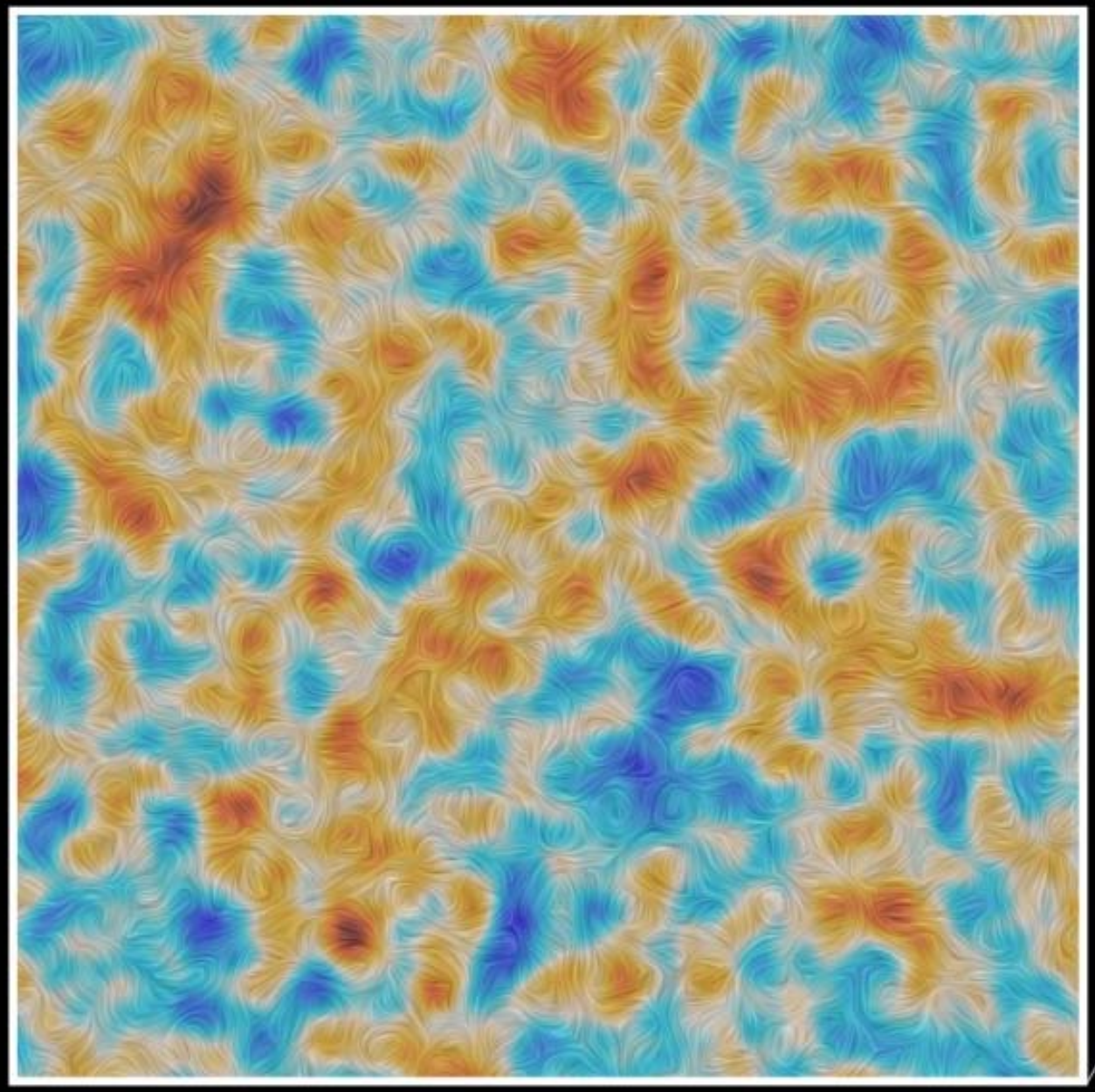
357 GHz

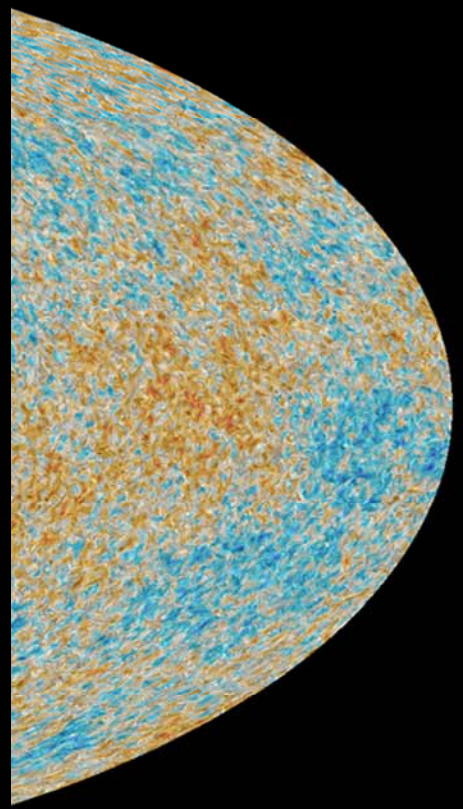


Thermal dust in magnetic field

Lines indicate the magnetic field direction, Colors indicate the emission intensity

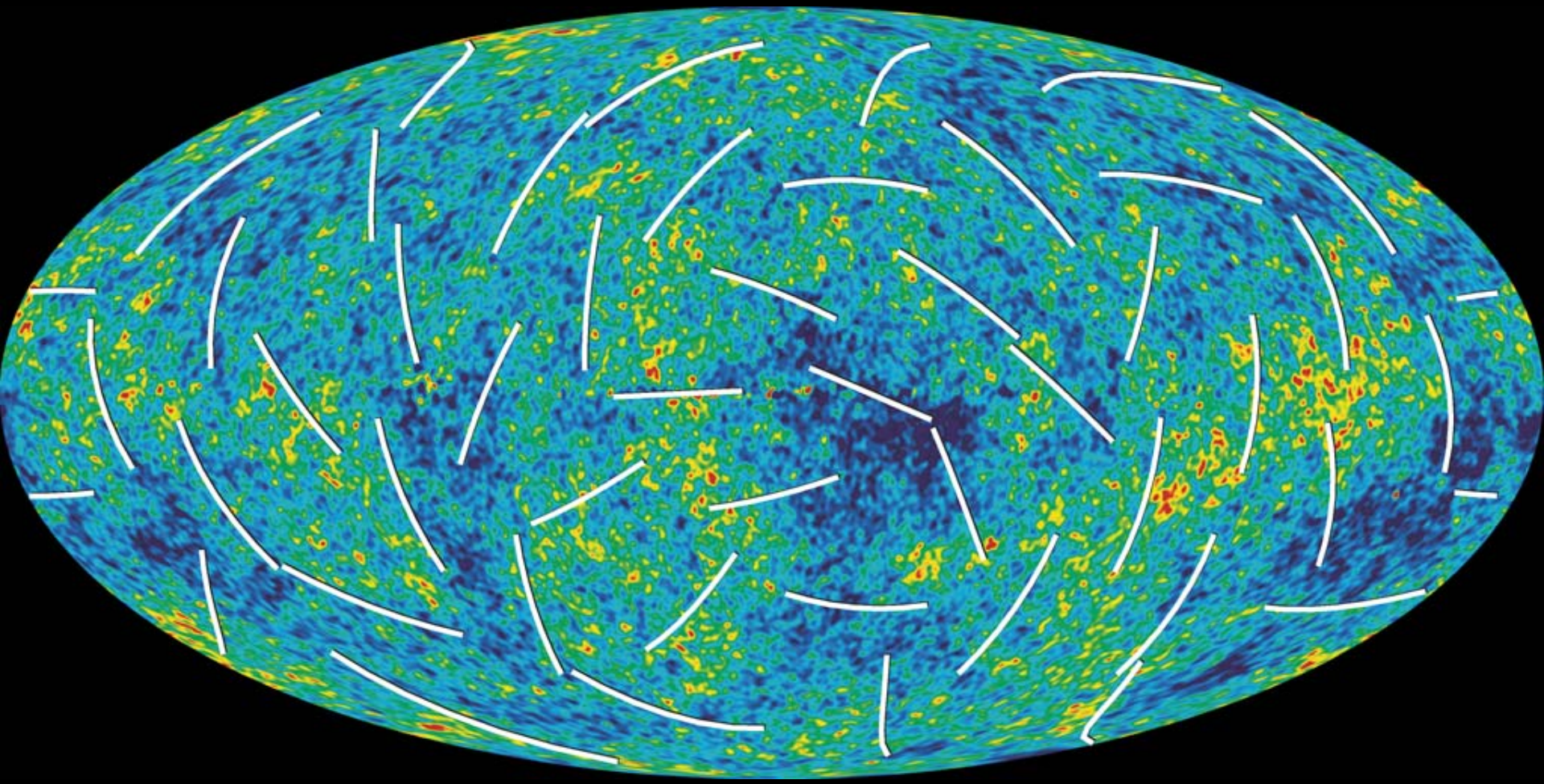
ation sky





Filtered at 20 arcminutes

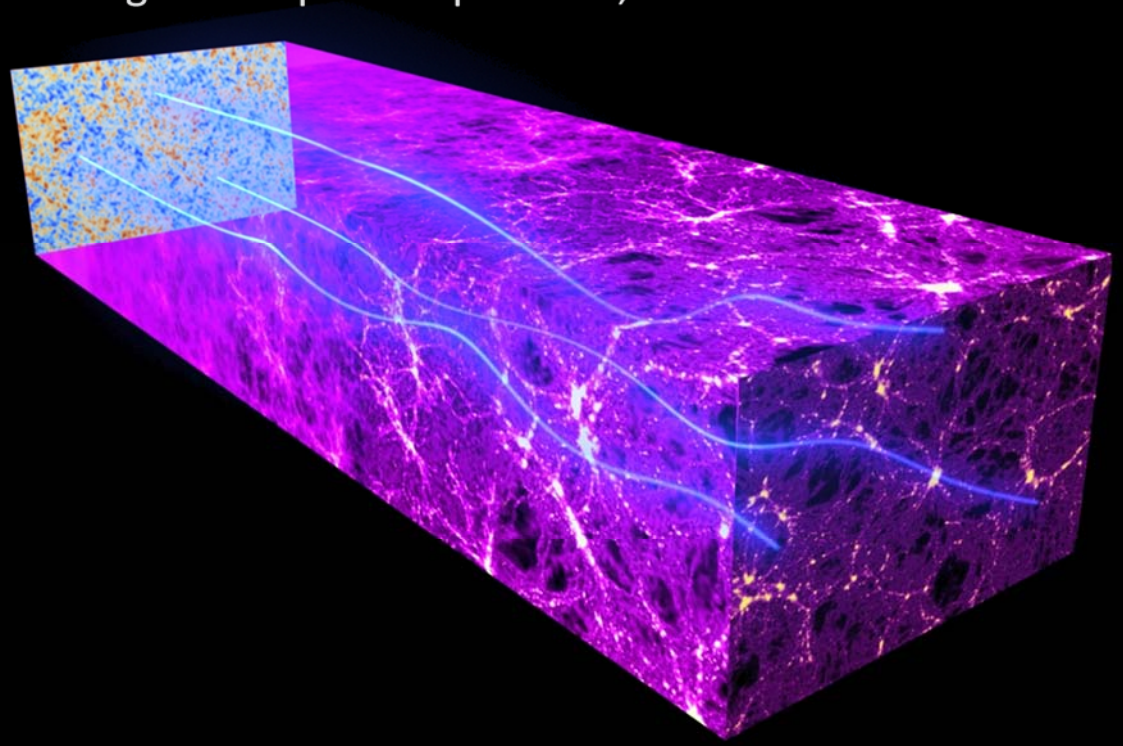
What we already knew (from WMAP)



HOT (dec 23): WMAP team was awarded the 3M$ 2018 Breakthrough Prize in Fundamental Physics

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)



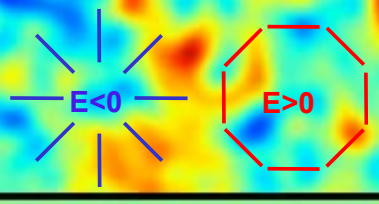
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + ...$$

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

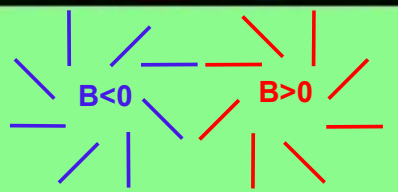
$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$

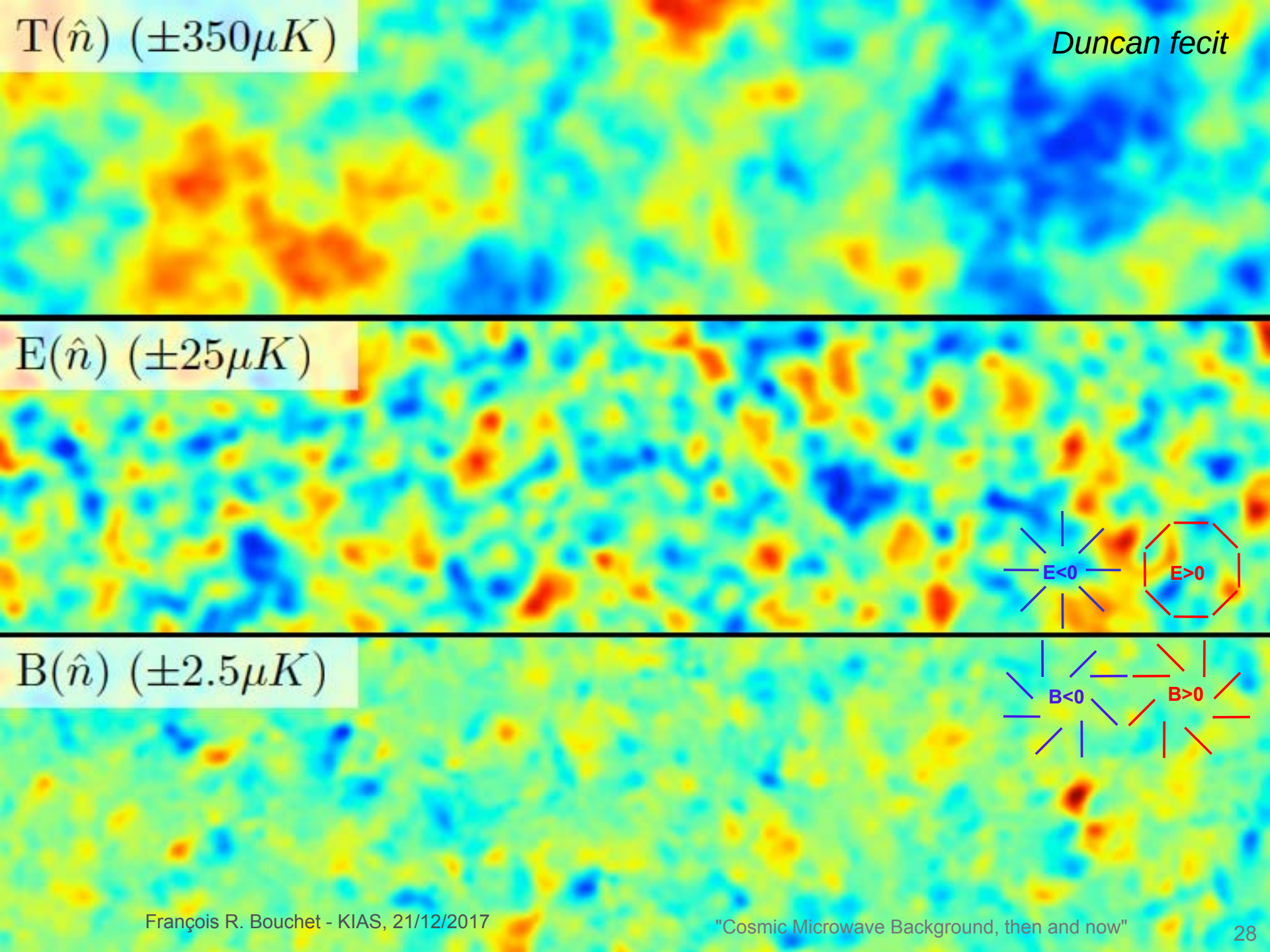
Duncan fecit

$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$

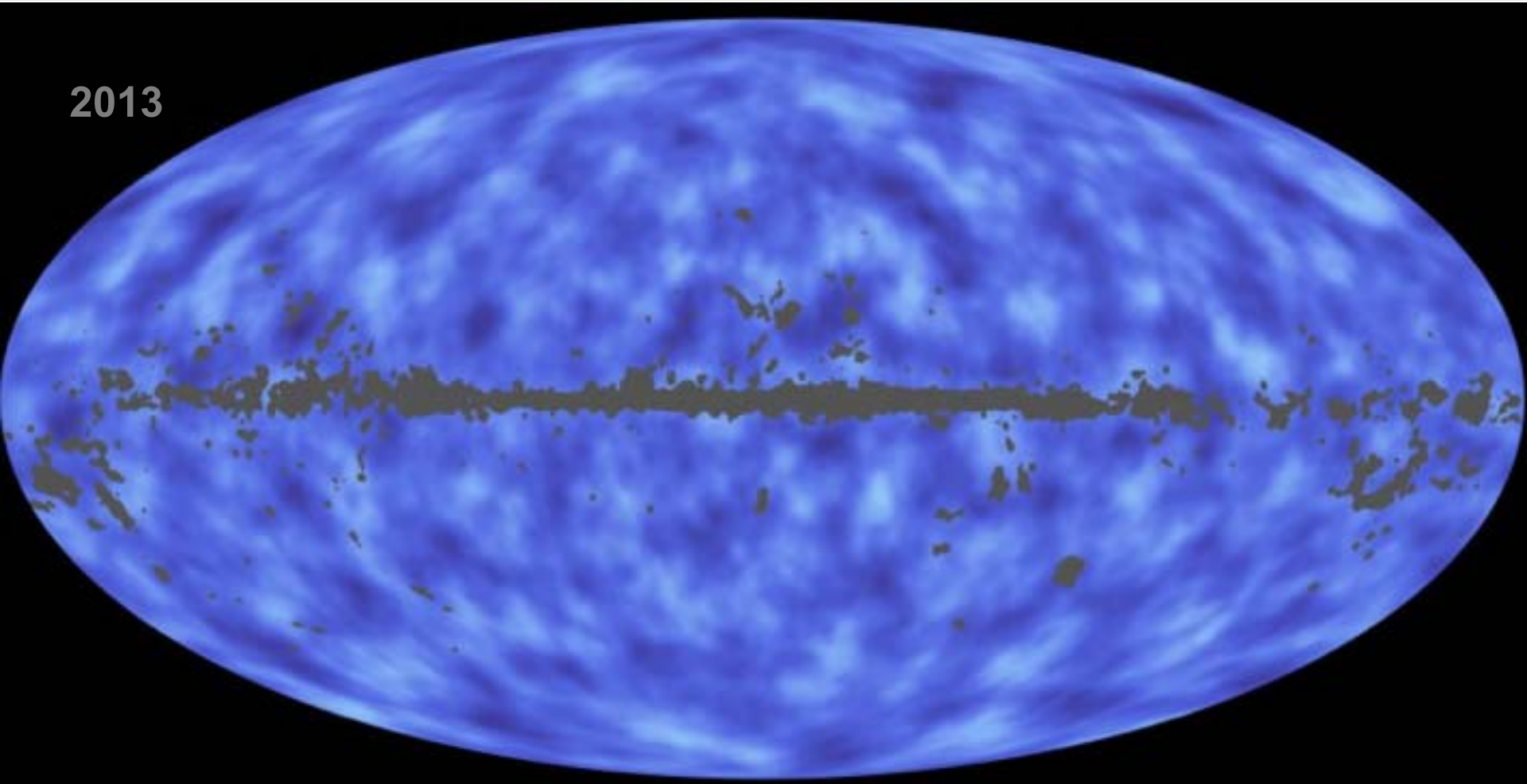


$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$




$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
Duncan fecit
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
E<0
E>0
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$
B<0
B>0

Projected mass map



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

30th Institut d'astrophysique de Paris Colloquium

THE PRIMORDIAL UNIVERSE

AFTER PLANCK

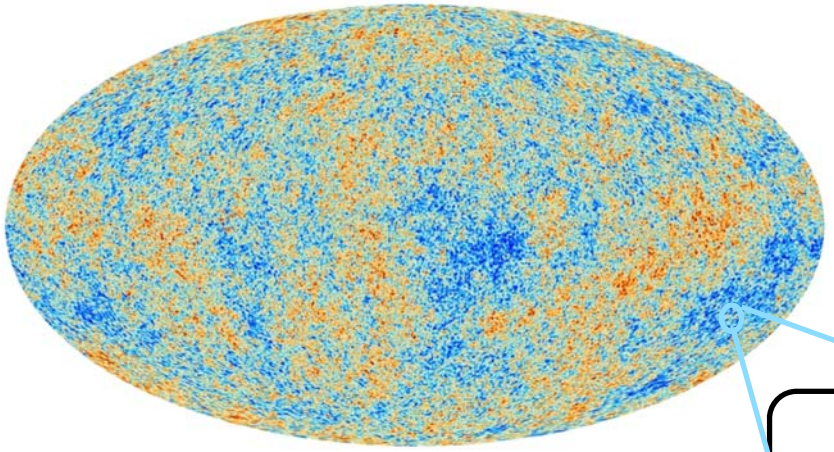
MONTAGNE SAINT ÉMILION

CHÂTEAU LES HAUTES GRAVES

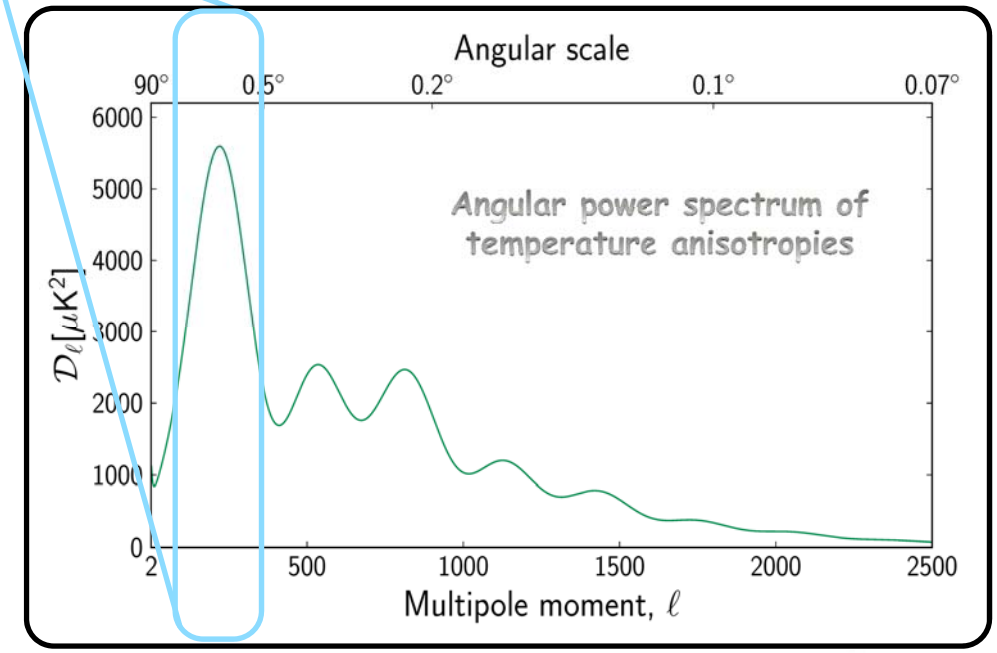
2009

December 15-19, 2014

What theory said…
(well before any observations…)



We cannot predict the map of the anisotropies…



But we can predict its statistical properties ! (like the typical height of the waves as a function of their length

A theories-measurements contact

The harmonic modes

$$a_{lm} = \int d^2\hat{n}\, T(\hat{n})\, Y^*_{lm}(\hat{n})$$

obey, for a statistically homogeneous and isotropic field,

$$< a_{\ell m}\, a_{\ell' m'} > = C_\ell\, \delta_{\ell\ell'}\, \delta_{mm'}$$

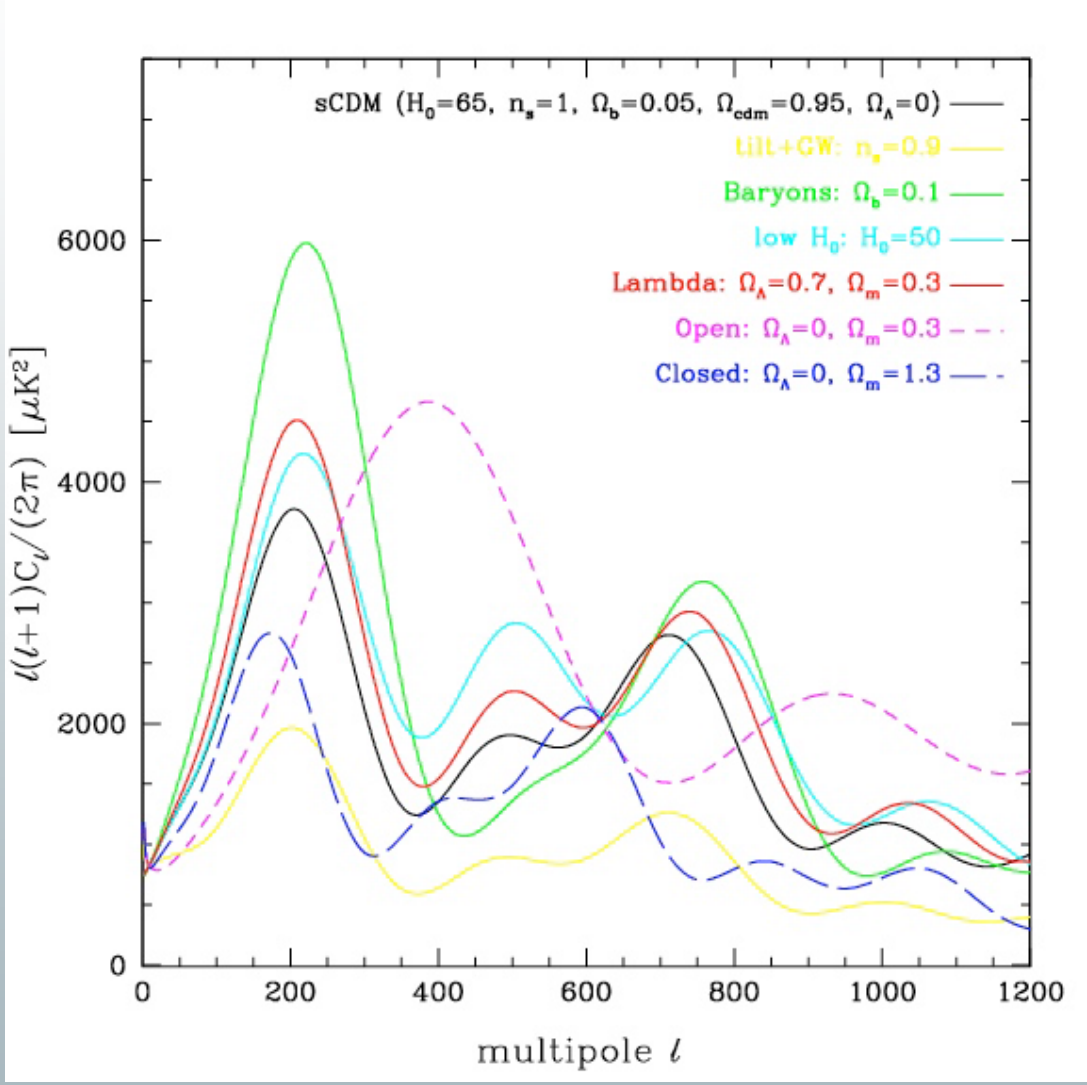
The temperature angular **power spectrum** is estimated in practice by

$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell + 1}$$

The bi- and tri-spectra may be used to test for NG, NB: biposh coeff.

Similar expressions for polarisation (on spin2 harmonics)

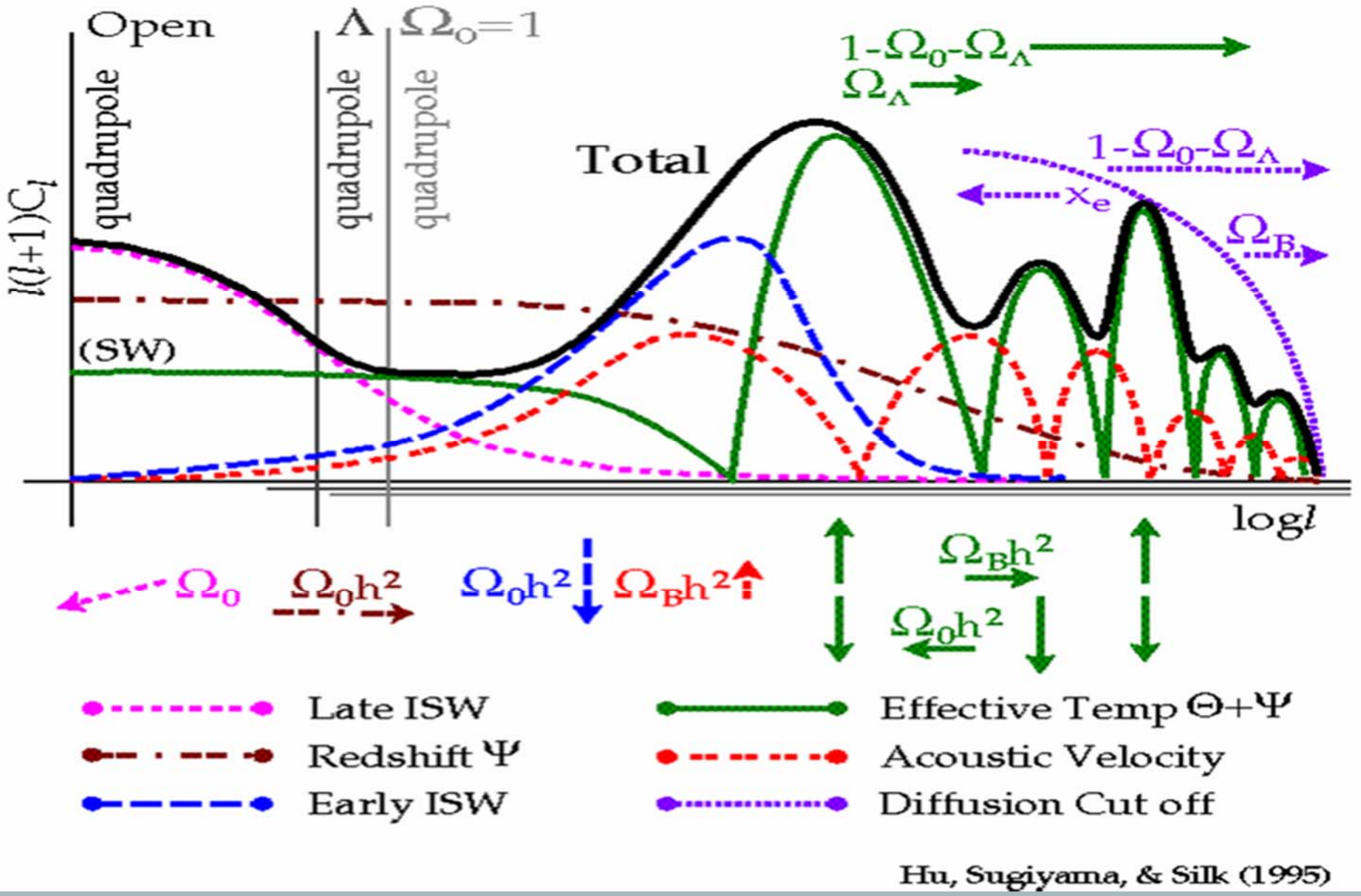
Cosmic imprints





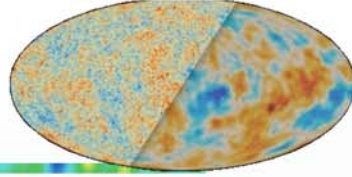
Peebles, Yu, Sachs & Wolf, Sunyaev, Zeldovich, Silk, Vittorio, Wilson, Mukhanov, Chibisov, Sasaki, Bardeen, Linde, Bond, Efstathiou, Bouchet, Bennett, Gott, Kaiser, Stebbins, Allen, Shellard, Seljack, Zaldariaga, Kamionkowski, Hu, …

Power spectrum shape and cosmological parameters



Hu, Sugiyama, & Silk (1995)

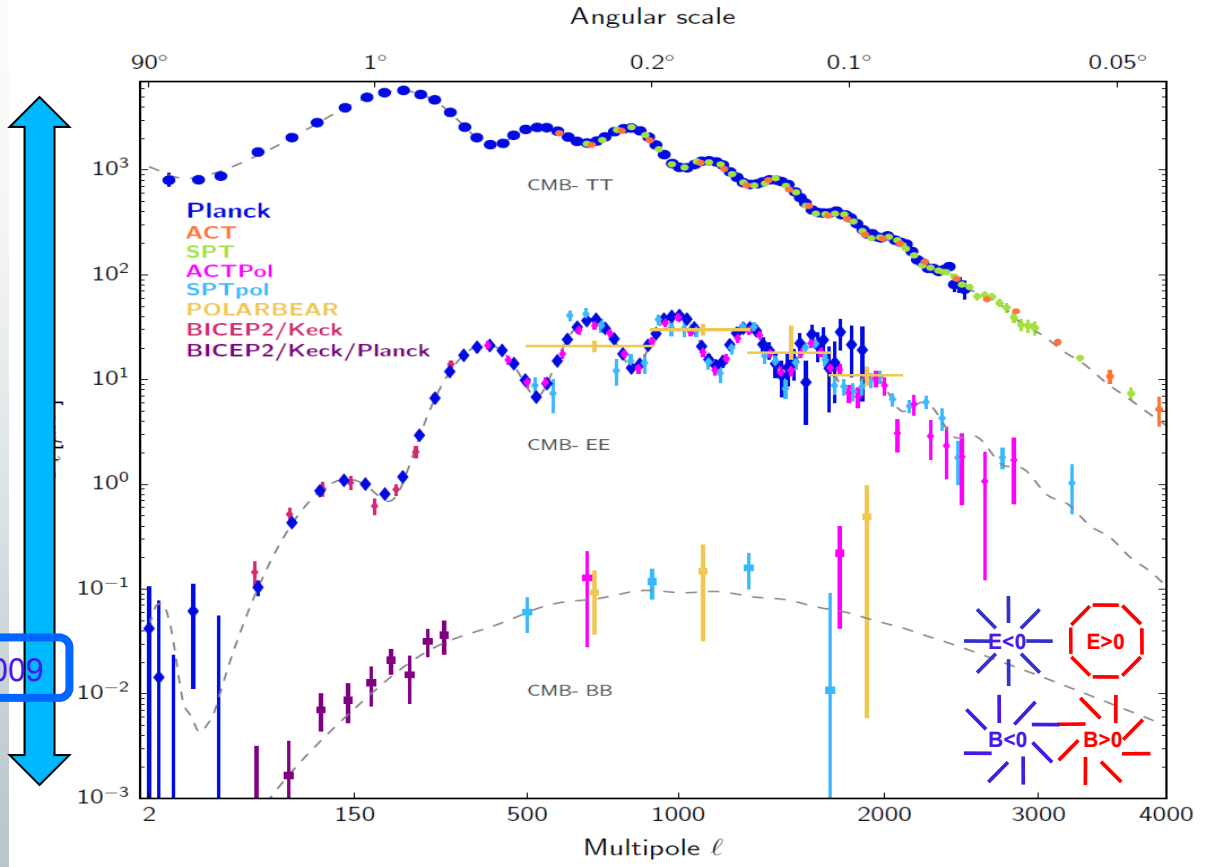
TT, EE, BB, ΦΦ – 2017 status

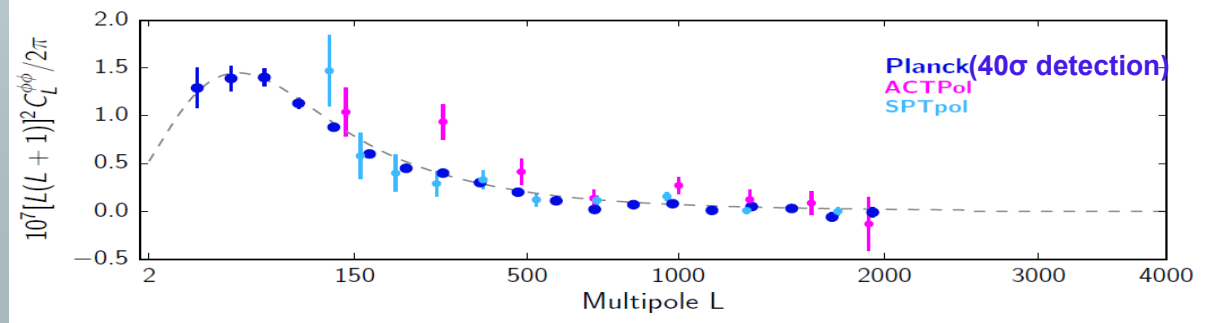


Only keeping points w. sufficiently small error bars, Fig. E Calabrese

10^7

$\tau = 0.055 \pm 0.009$





And statistically isotropic…

1 114 000 Modes measured with TT,

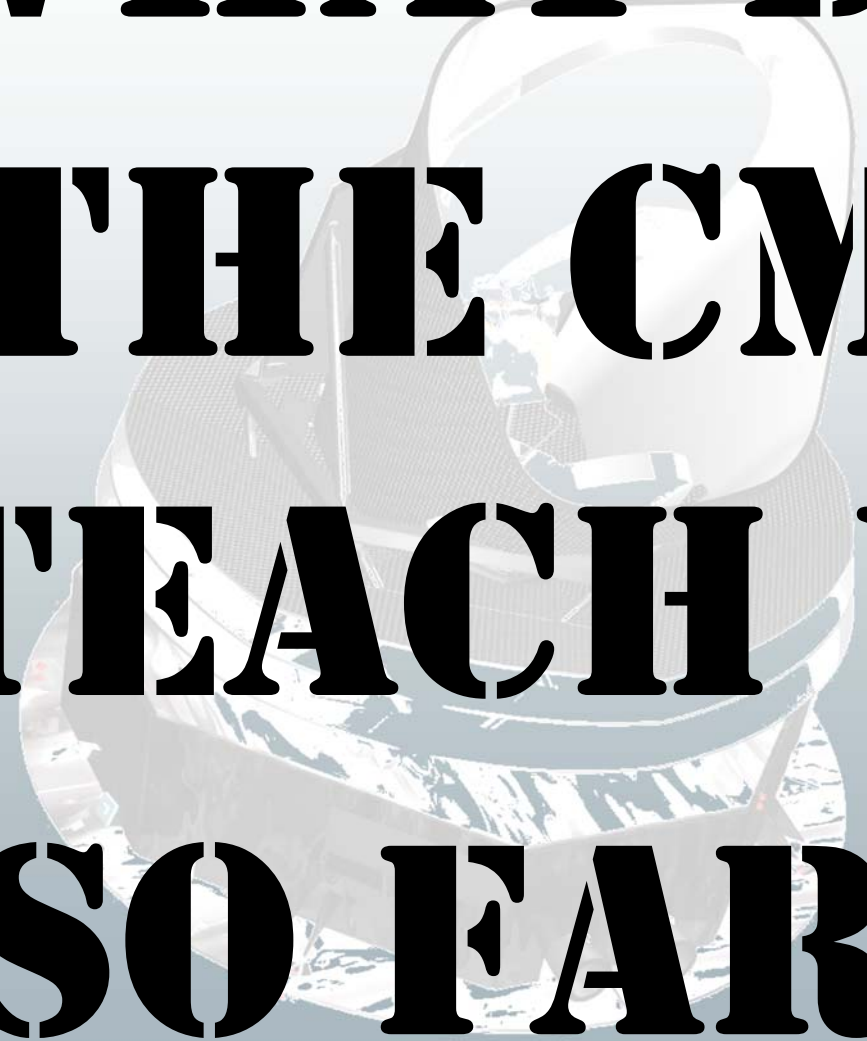
60 000 with TE (not shown)

96 000 with EE

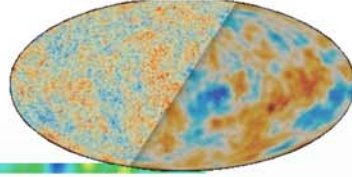
… and 10's in BB and φφ

+ weak constraints with TB and EB

WHAT DID THE CMB TEACH US SO FAR ?

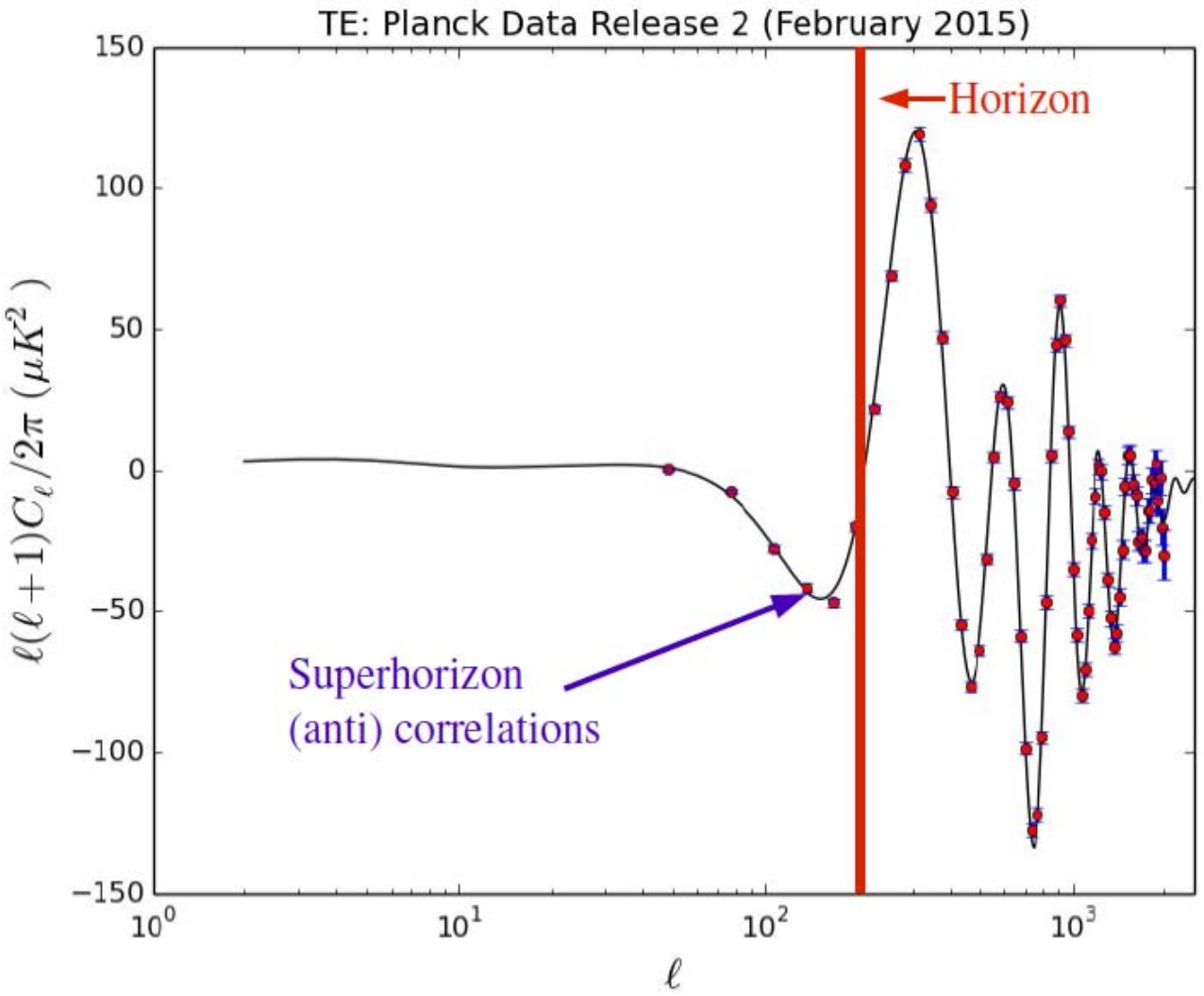


CMB Anisotropies post-Planck



- The LCDM model fits all CMB data in T, E, B, ϕ.
  - *No need for an extension. A lavish source of constraints /papers…*
  - *Same model parameters, determined at the per cent level, also fit other data (BAO, and 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 source of information remains in the CMB polarisation anisotropies (millions of modes).

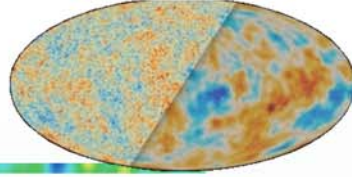
TE large scale correlation



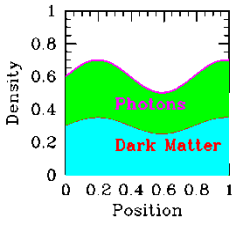
apparently a-causal physics, calling for a period of accelerated expansion (Spergel & Zaldariaga 97)

So the (apparent) horizon is actually only the Hubble length

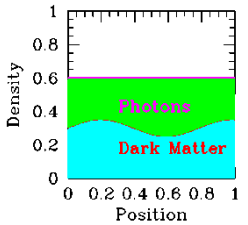
Adiabaticity ?

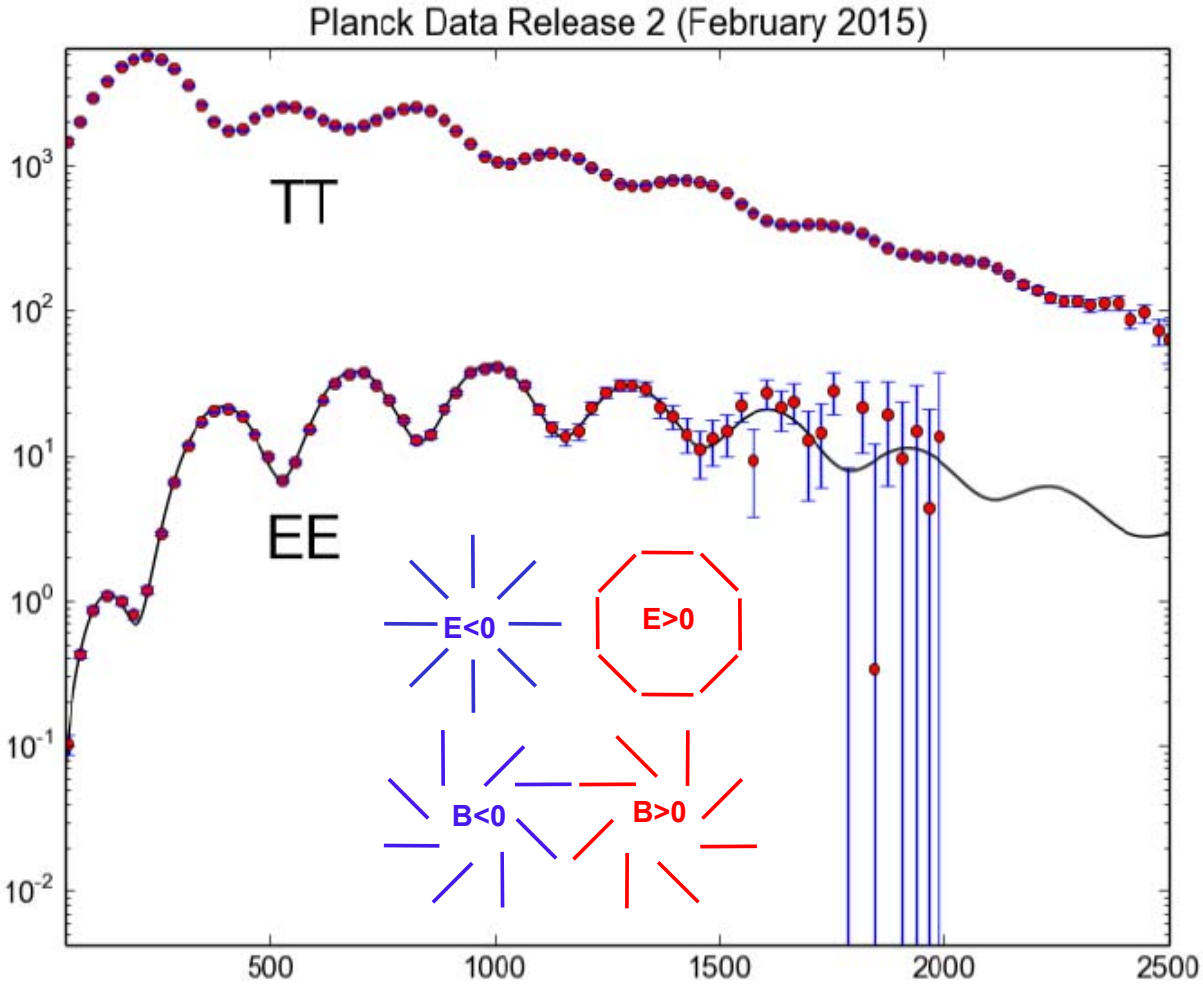


Adiabatic IC

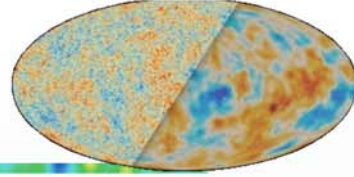


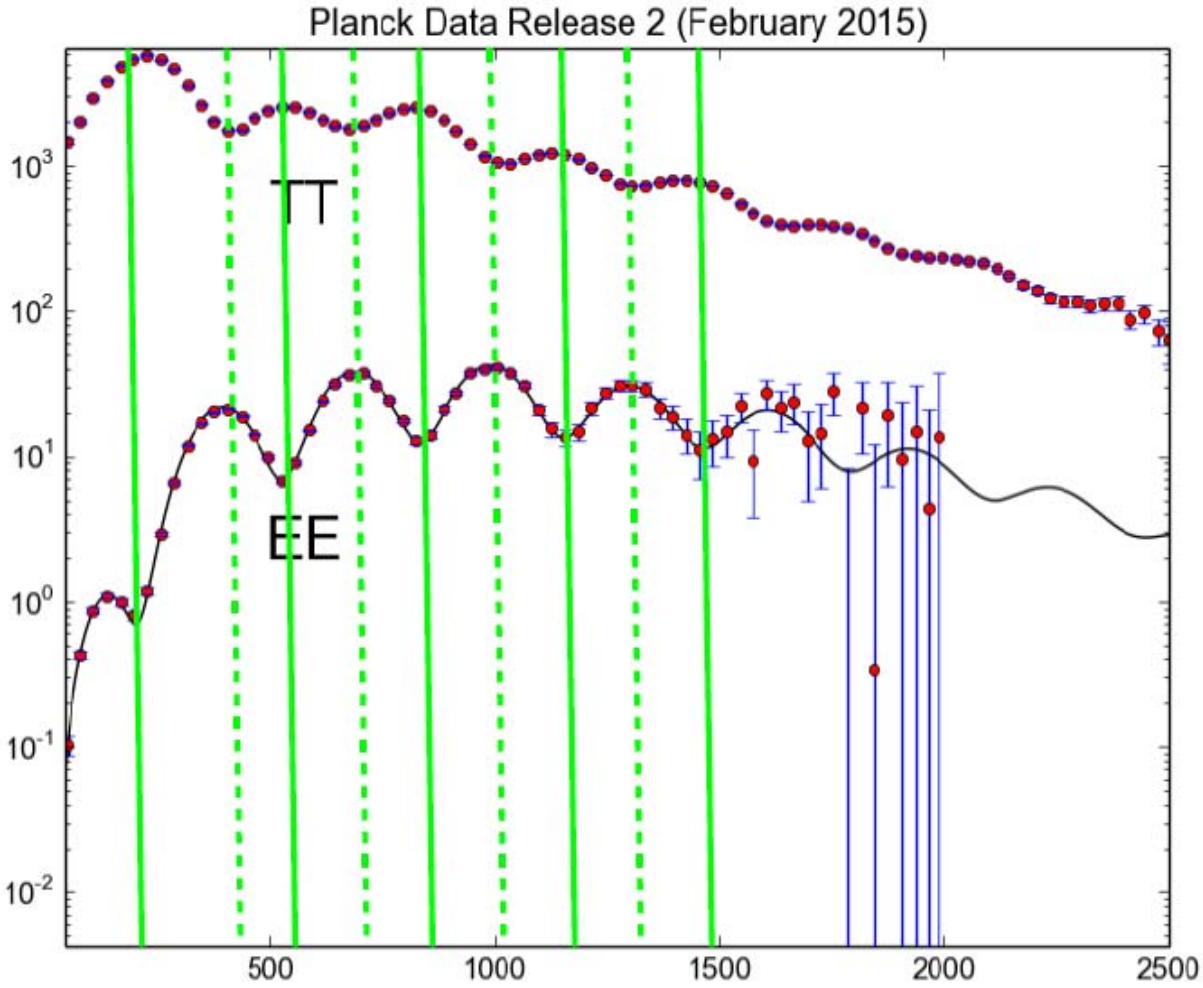
Isocurvature IC



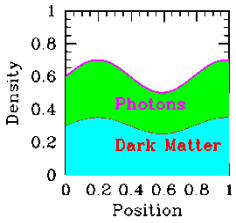


Adiabaticity ✔

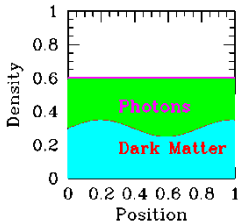




Adiabatic IC

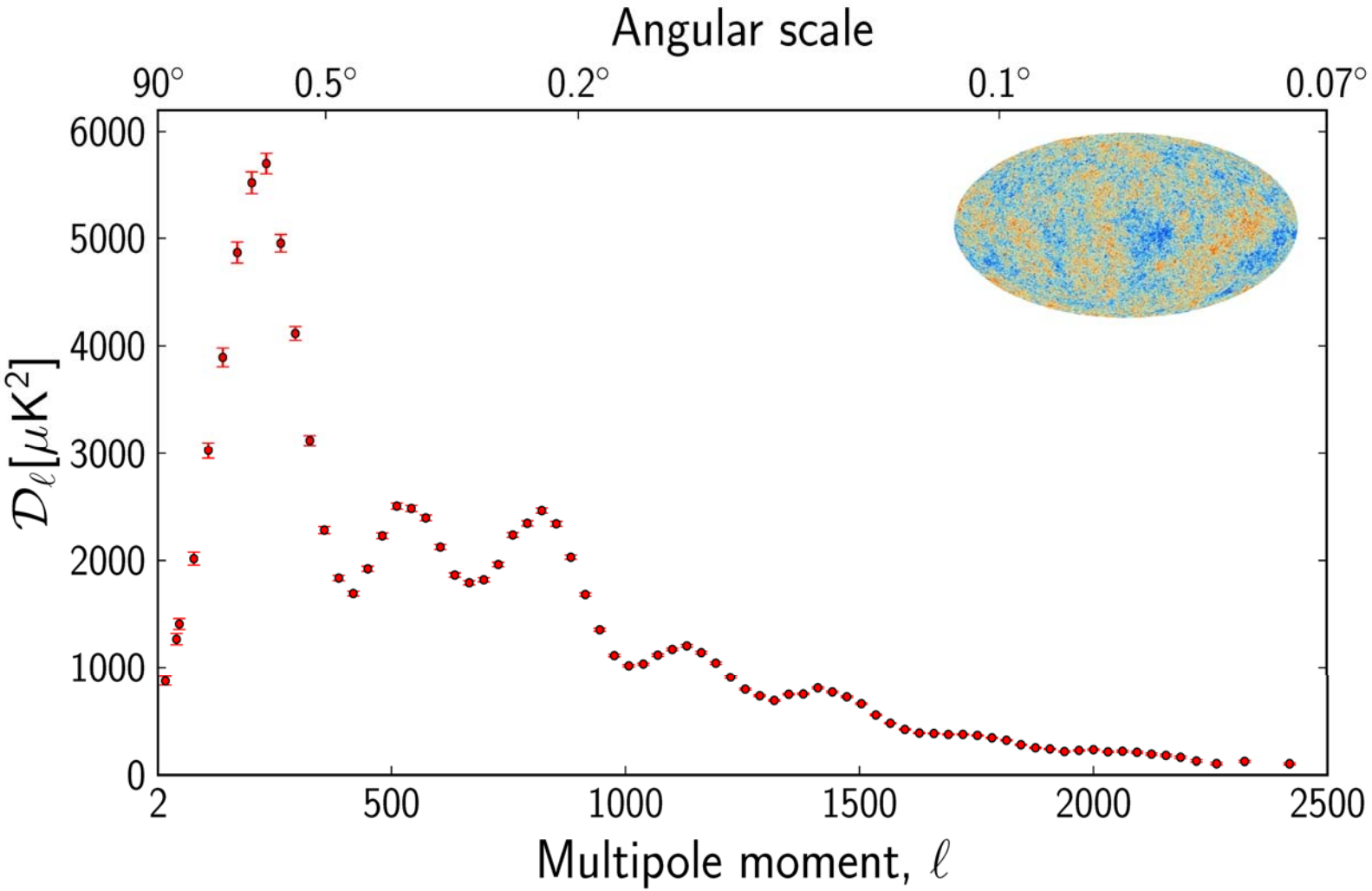


Isocurvature IC



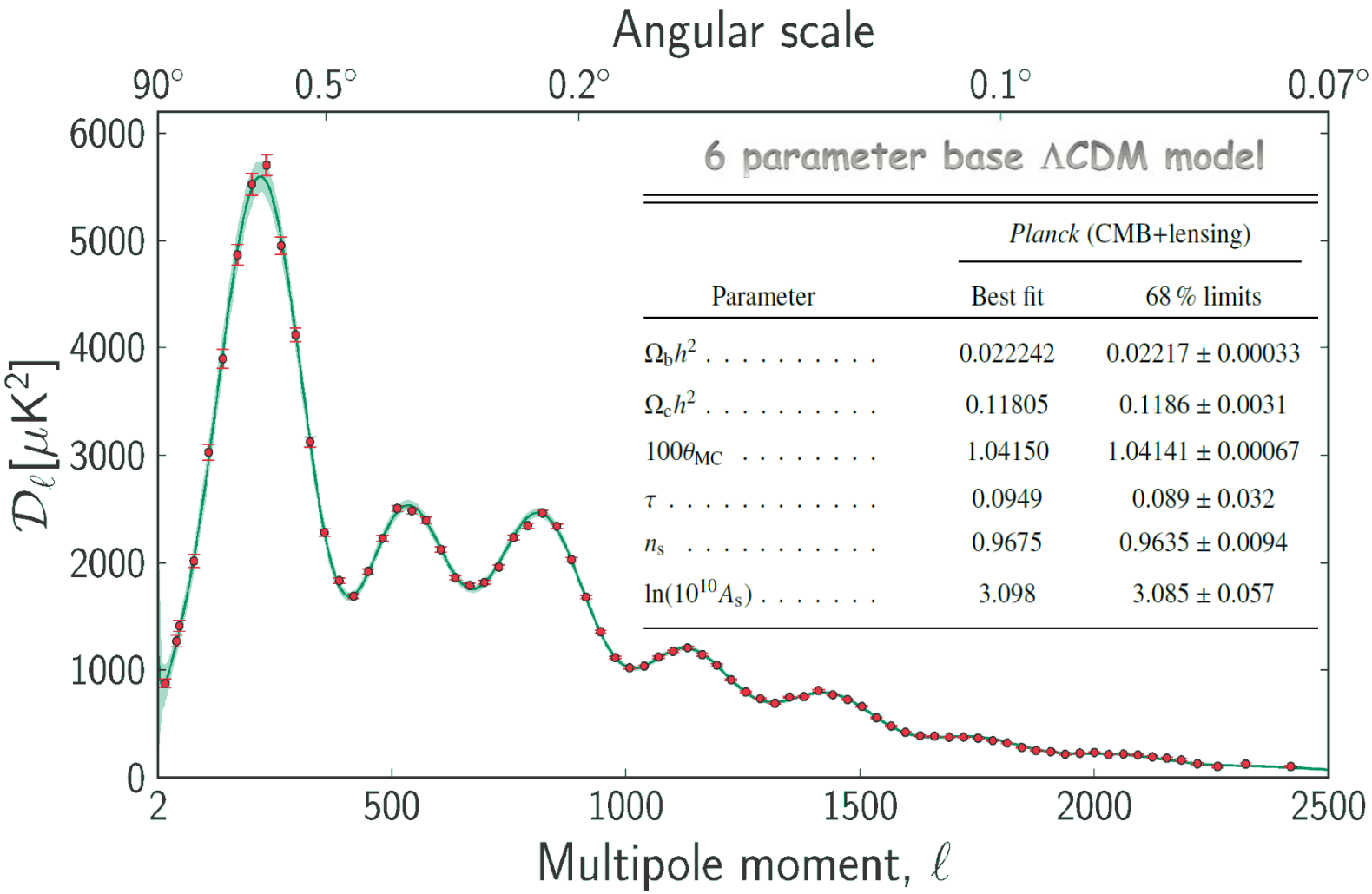
Kinney

The Planck power spectrum of Temperature anisotropies



2013 data

Theory confronts data



6 parameter base ΛCDM model

Parameter	*Planck* (CMB+lensing) Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

2013 data

Base ΛCDM model with 6 parameters

3 parameters to set (though General Relativity) the dynamics of the universe,
1 parameter to capture the effect of reionisation (end of the dark ages),
2 parameters to describe the primordial fluctuations.
Flat spatial geometry.

- $\Omega_b h^2$ Baryon density today - The amount of ordinary matter
- $\Omega_c h^2$ Cold dark matter density today – only weakly interacting
- Θ Sound horizon size when optical depth τ reaches unity
  (Distance travelled by a sound wave since inflation, when universe became transparent at recombination at t ~380 000 years)

- τ Optical depth at reionisation (due to Thomson scattering of photons on e^-), i.e.
  fraction of the CMB photons re-scattered during that process

- A_s Amplitude of the curvature power spectrum
  (Overall contrast of primordial fluctuations)
- n_s Scalar power spectrum power law index
  (n_s-1 measures departure from scale invariance)

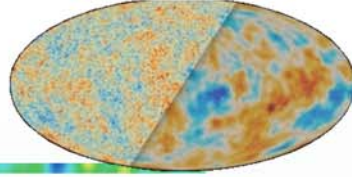
- Others are *derived* parameters within the model, in particular
  - *Ω "Dark Energy" fraction of the critical density (derived only if assumed flat)*
  - *H_0 the expansion rate today (in km/s per Mpc of separation)*
  - *t_0 the age of the universe (in Gy)*

“CMB-Hand-Wave” code

- Normalisation of P(k)← Amplitude at low-ell.
- Logarithmic Slope of P(k) ← ratio low/high-ell.
- Acoustic Horizon ← localisation of 1st peak (H_0)
- Density of matter ←contrast between peaks.
- Density of baryons ← ratio of odd/even peak amplitudes.
- Optical depth to reionisation: mostly EE bump.
- Etc.. (think non-std Neutrinos)
- There are degeneracies (more or less lifted with increasing precision).
- This is now textbook physics. See, eg Mukanov book.

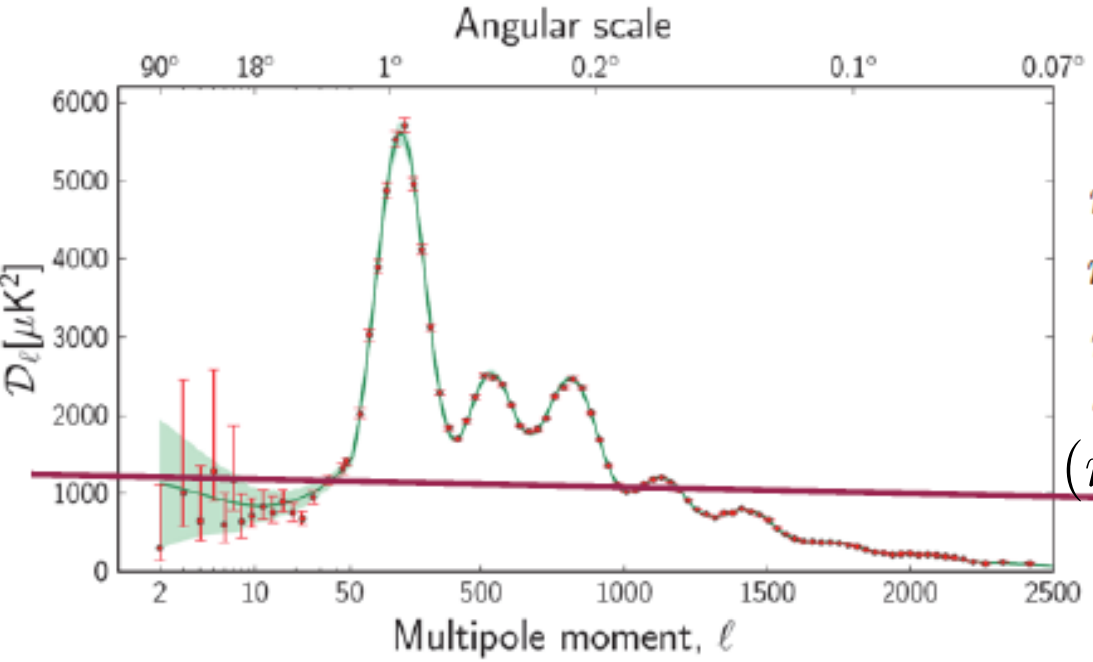
CMBslow, CMBfast, CMBeasy, CAMB, CLASS, etc.

The value of n_s



Initial Conditions: quasi-scale invariant

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



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

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

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

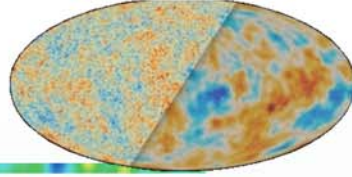
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

($n_s = 0.965 \pm 0.006$ 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.

Inflation has a few variants...

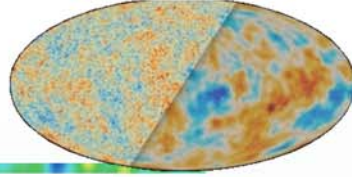


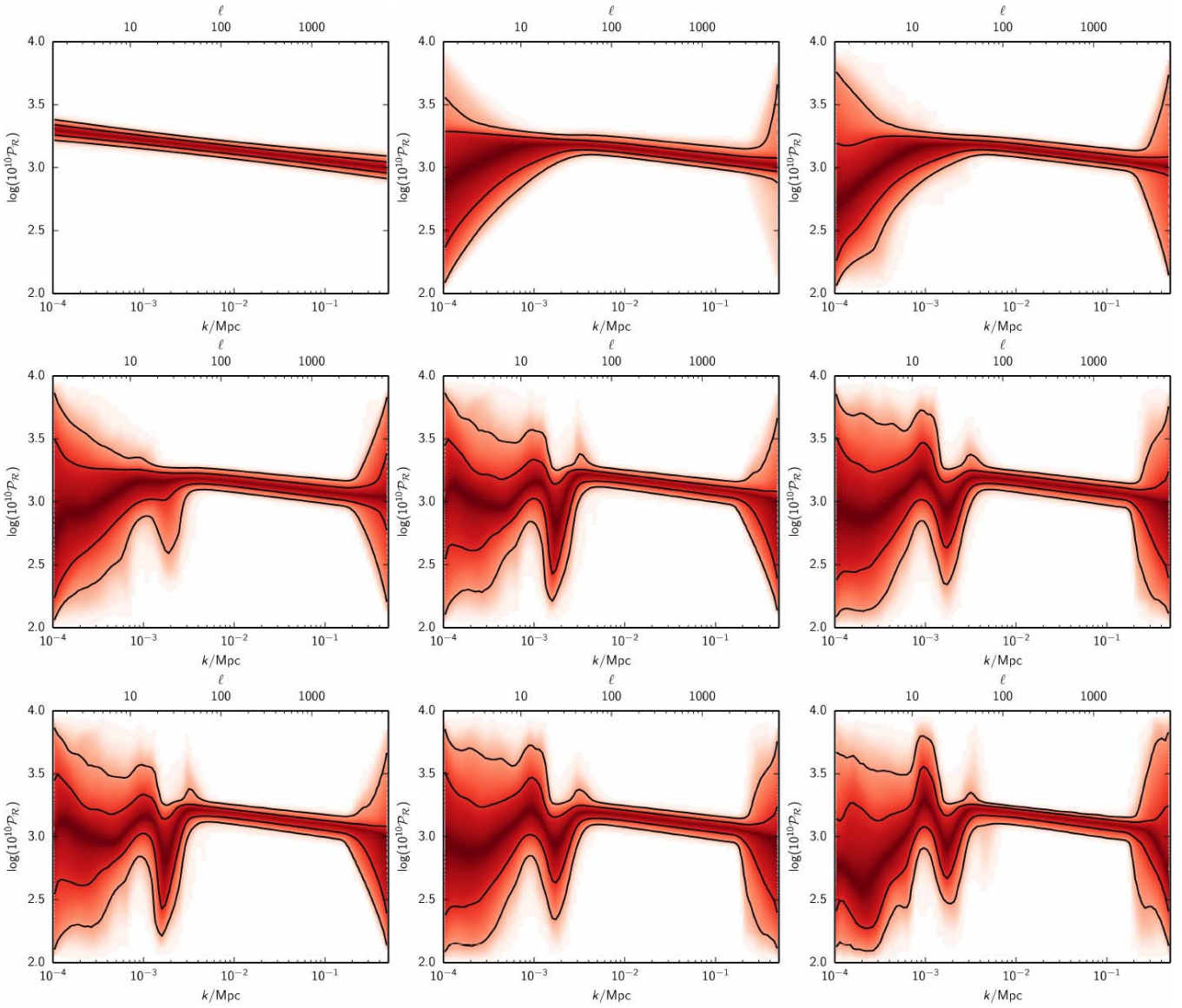
- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- B-inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke inflation
- bulky brane inflation
- chaotic inflation
- chaotic hybrid inflation
- chaotic new inflation
- Chromo-Natural Inflation
- D-brane inflation
- D-term inflation
- dilaton-driven inflation
- dilaton-driven brane inflation
- double inflation
- double D-term inflation
- dual inflation
- dynamical inflation
- dynamical SUSY inflation
- S-dimensional assisted inflation
- eternal inflation
- extended inflation
- extended open inflation
- extended warm inflation
- extra dimensional inflation
- ...



- F-term inflation
- F-term hybrid inflation
- false-vacuum inflation
- false-vacuum chaotic inflation
- fast-roll inflation
- first-order inflation
- gauged inflation
- Ghost inflation
- Hagedorn inflation
- higher-curvature inflation
- hybrid inflation
- Hyper-extended inflation
- induced gravity inflation
- intermediate inflation
- inverted hybrid inflation
- Power-law inflation
- K-inflation
- Super symmetric inflation
- Quintessential inflation
- Roulette inflation
- curvature inflation
- Natural inflation
- Warm natural inflation
- Super inflation
- Super natural inflation
- Thermal inflation
- Discrete inflation
- Polarcap inflation
- Open inflation
- Topological inflation
- Multiple inflation
- Warm inflation
- Stochastic inflation
- Generalised assisted inflation
- Self-sustained inflation
- Graduated inflation
- Local inflation
- Singular inflation
- Slinky inflation
- Locked inflation
- Elastic inflation
- Mixed inflation
- Phantom inflation
- Non-commutative inflation
- Tachyonic inflation
- Tsunami inflation
- Lambda inflation
- Steep inflation
- Oscillating inflation
- Mutated hybrid inflation
- Inhomogeneous inflation
- ...

Bayesian moveable knot PS reconstruction





Adding 0 to 8 knots

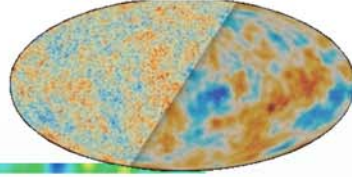
(in addition to the minimum 2 to define a slope)

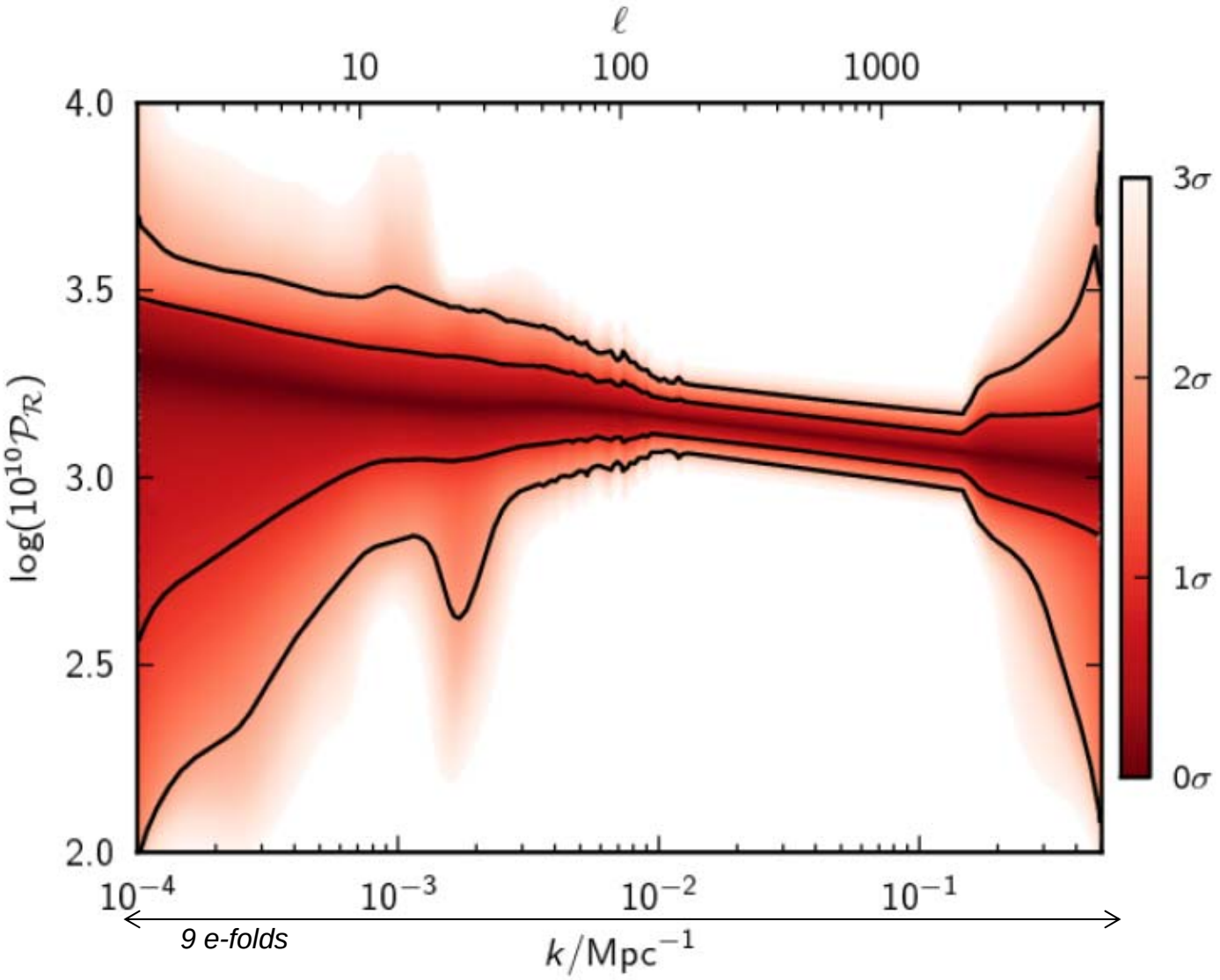
Other techniques possible

No truly significant deviation found

i.e., l=20 dent is only tantalising (as all other anomalies so far)

Power spectrum reconstruction



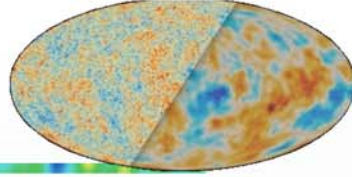


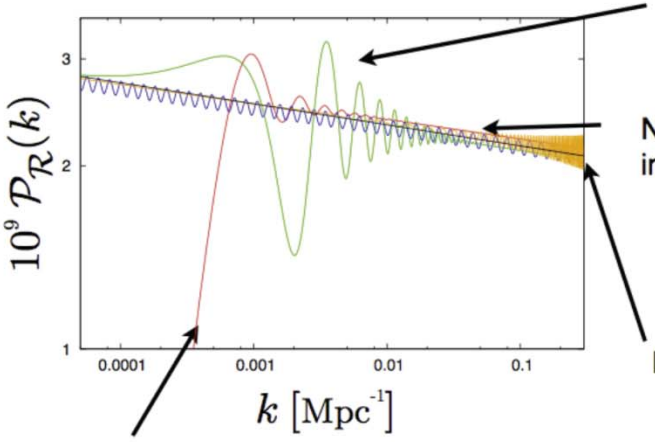
Bayesian reconstruction with varying number of nodes (<11) reconstructions weighted by their respective evidence.

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

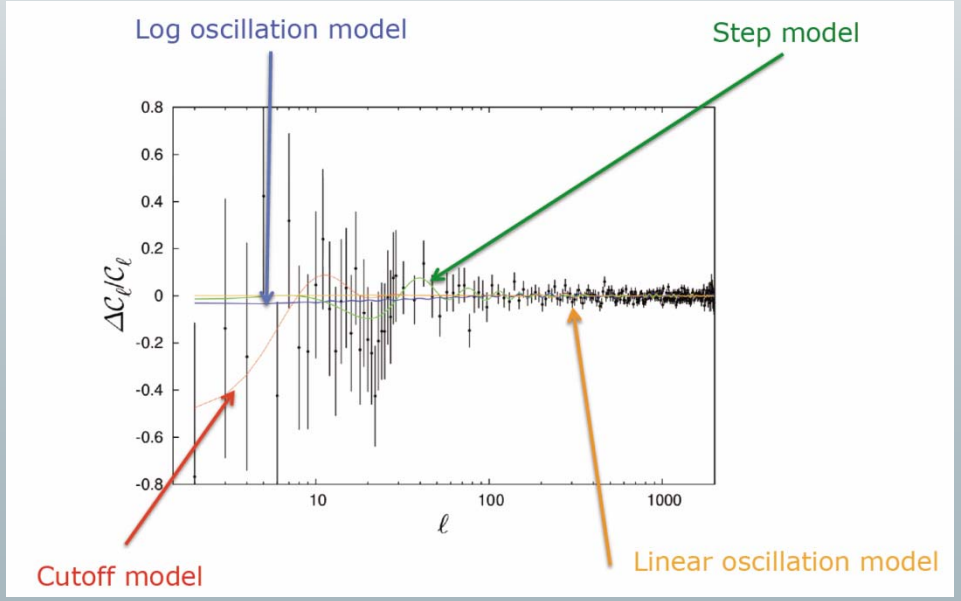
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

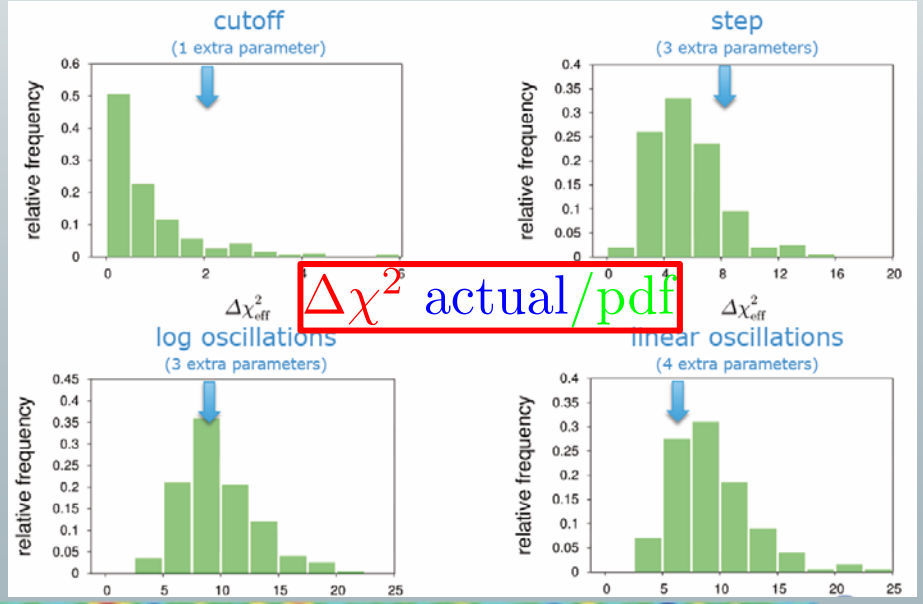
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

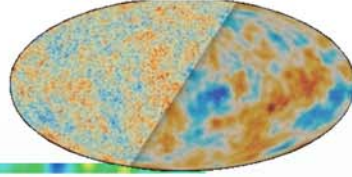
$$\mathcal{P}_\mathcal{R}^{\mathrm{lin}}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\mathrm{lin}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{lin}}}\cos\left(\omega_{\mathrm{lin}}\frac{k}{k_*} + \varphi_{\mathrm{lin}}\right)\right]$$

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

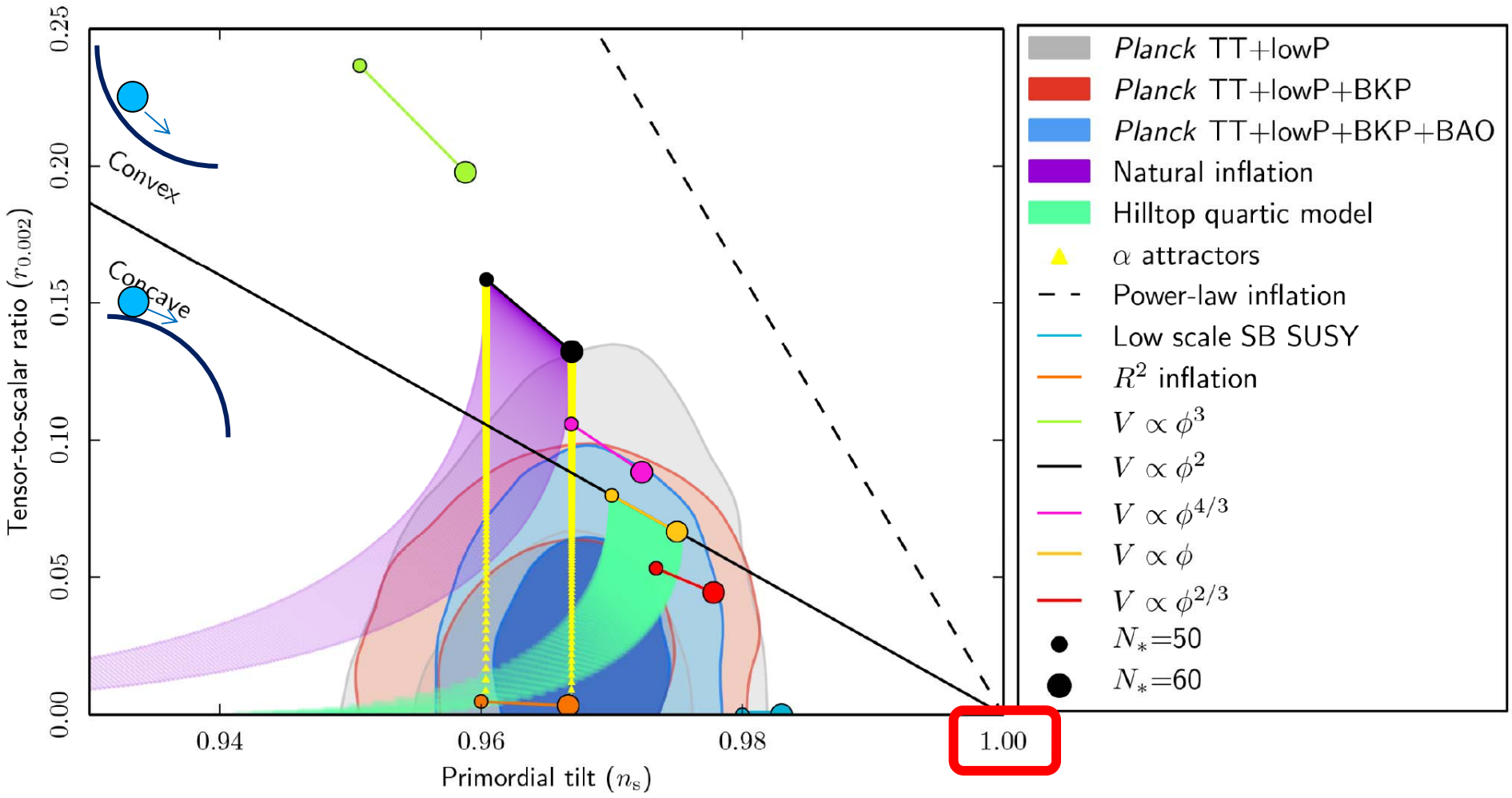




Planck 2015: n_s vs r

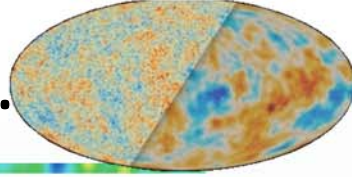


$V_*=(1.9 \times 10^{16}\ \mathrm{GeV})^4\ (r/0.12)$

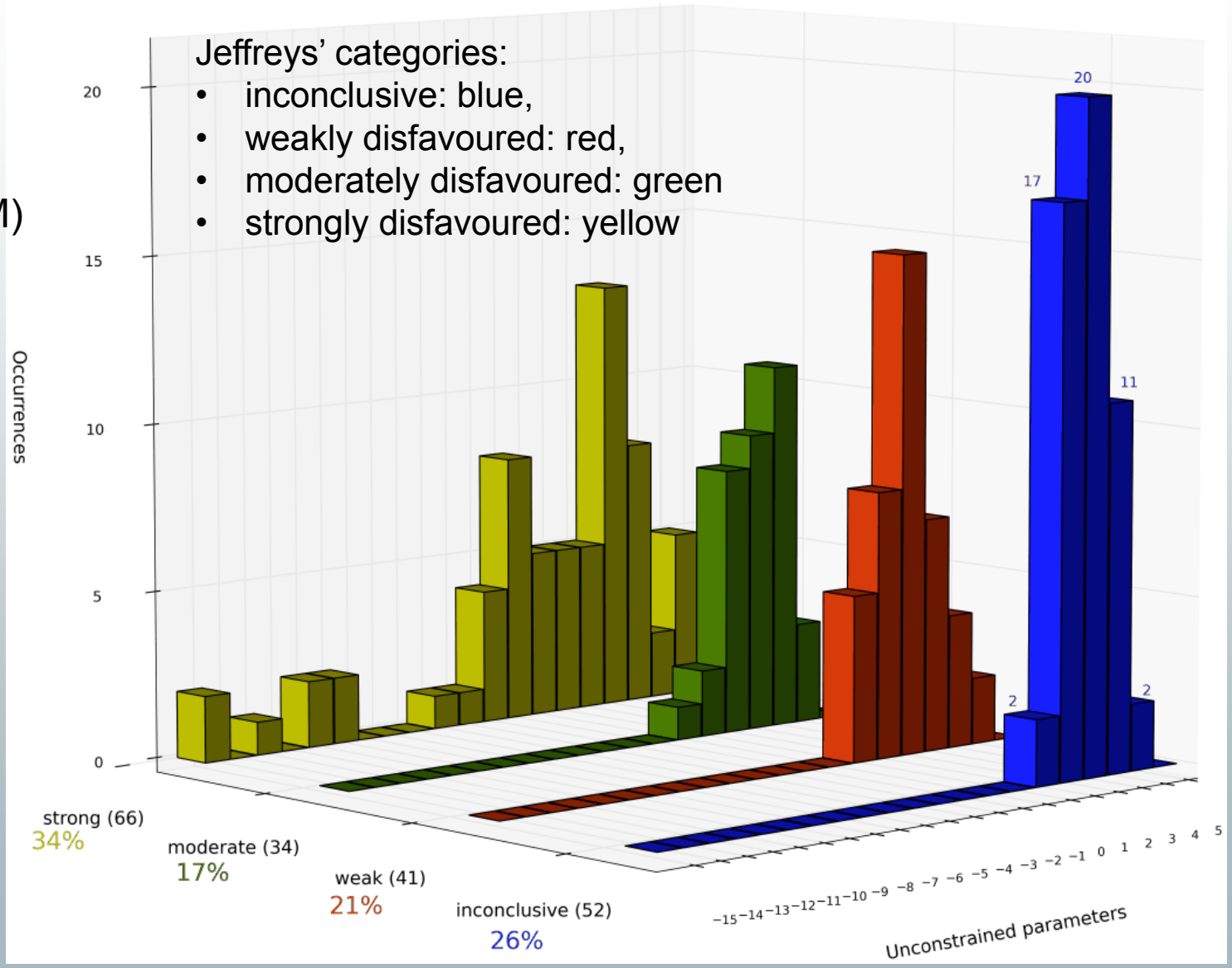


Similar (indirect) r constraint than with 2013 release ($r_{0.002} < 0.10$ @ 95% CL vs 0.11)

Sorting out Single field slow-roll models…



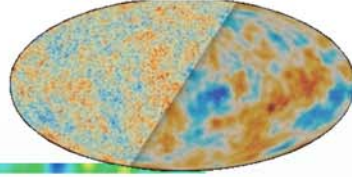
(ranking vs LCDM)



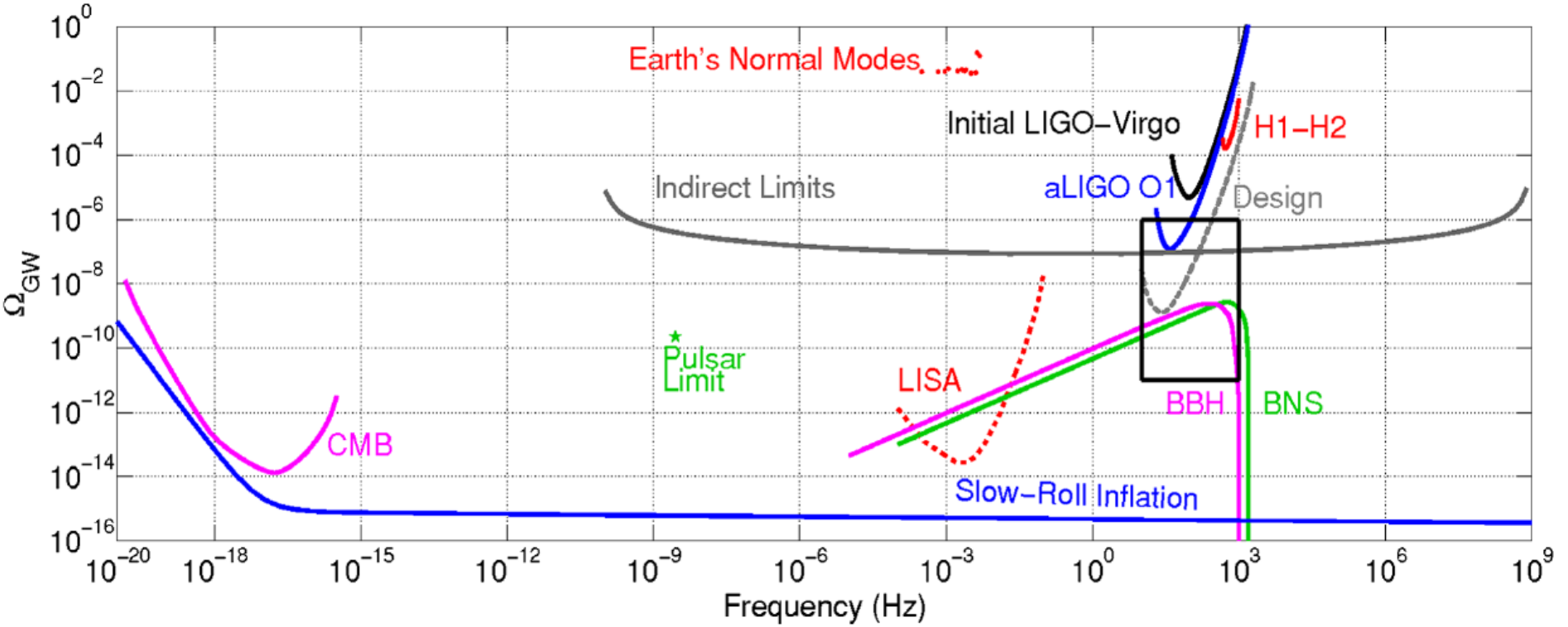
ASPIC *arXiv*/1303.3787

"models" include different priors

CMB versus other GW detectors



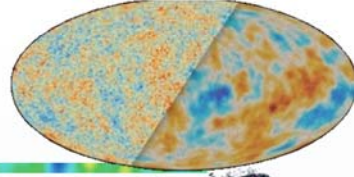
2017) March 27 PHYSICAL REVIEW LETTERS



For the not-too-distant future, direct local detections can only constrain non-scale invariant (blue) primordial GW backgrounds.

➔ Detection by dedicated CMB experiments is a major goal.

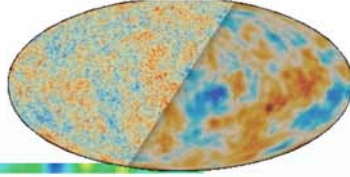
Planck 353GHz reveals the Galactic magnetic field

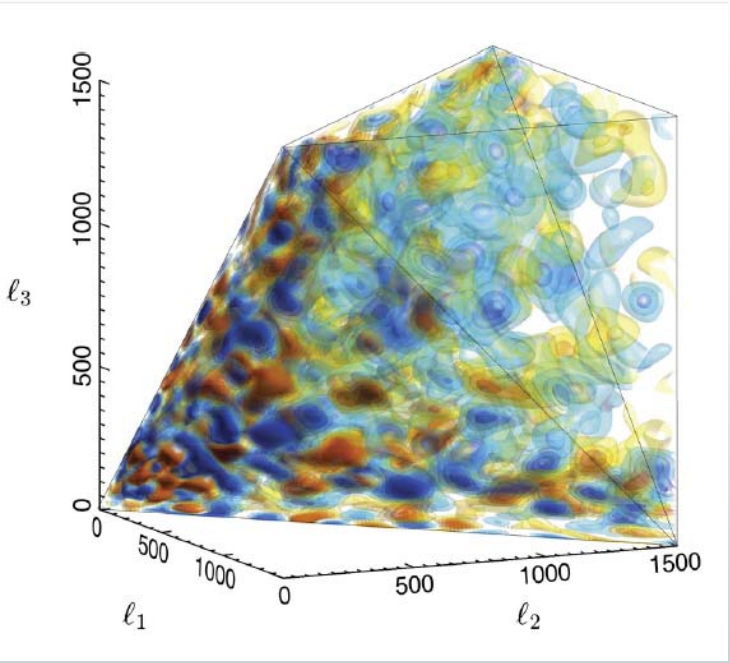


(whose effect can account for at least about ½ of the initial BICEP claim)



Planck 2015 - Bispectrum constraints





Planck 2015 – 2000 modes

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	

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

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

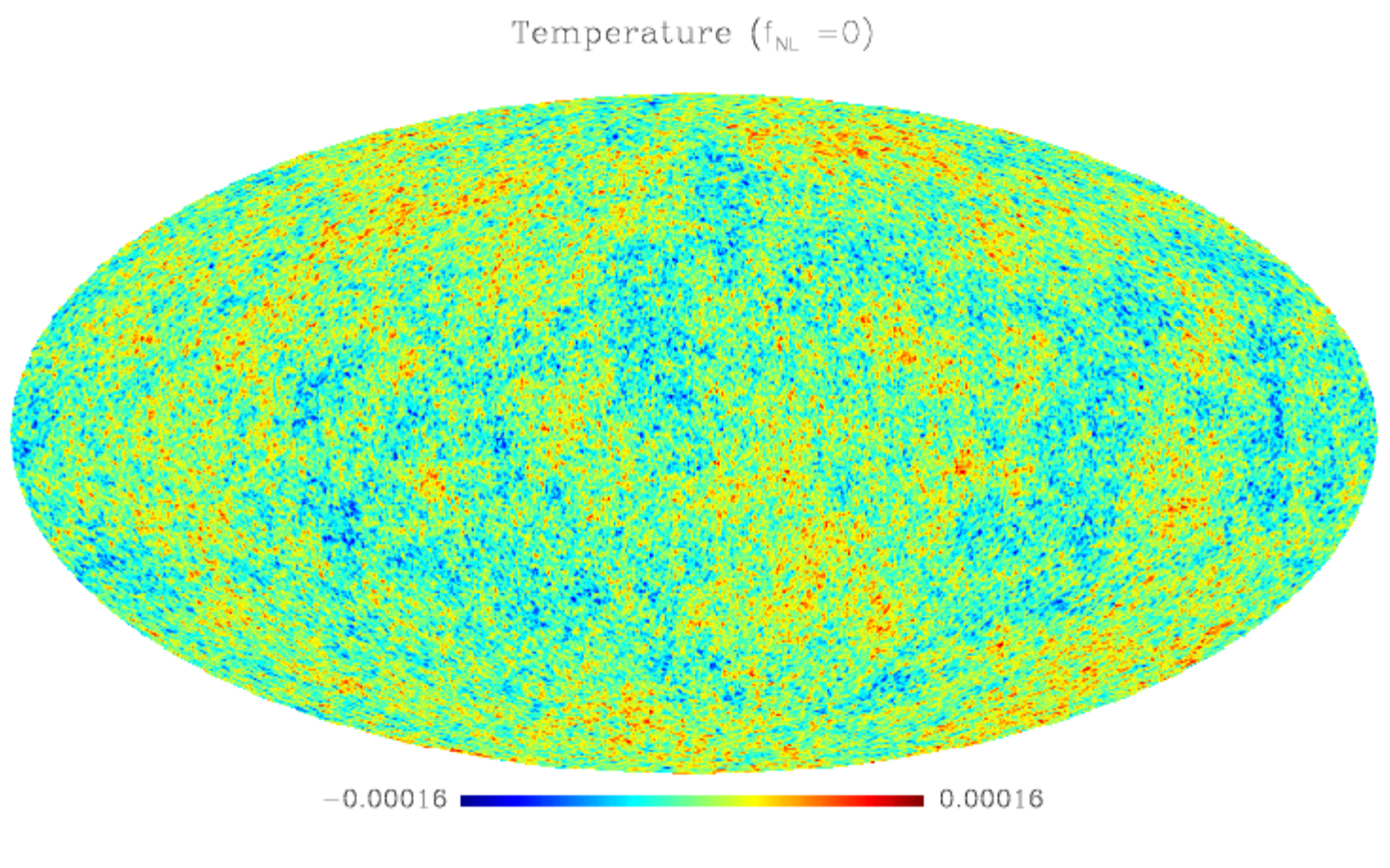
non-Gaussian potential

Gaussian field

$|f^{Loc}_{NL}| <$ 10^3 (Maxima 2001),
10^2 (WMAP7),
10 (Planck15)

A hundred-fold improvement in 14 years

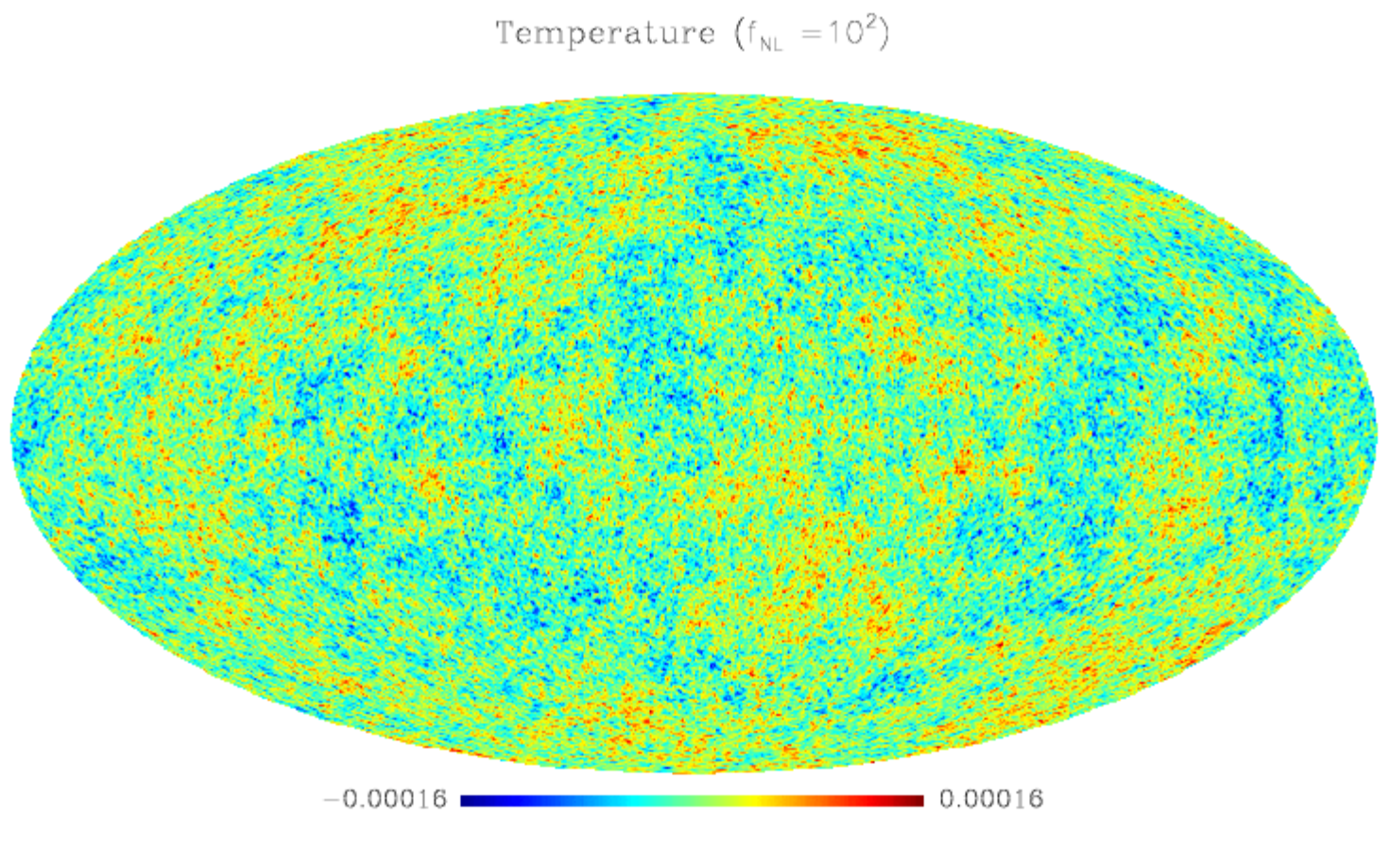
$f_{NL} = 0$



Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

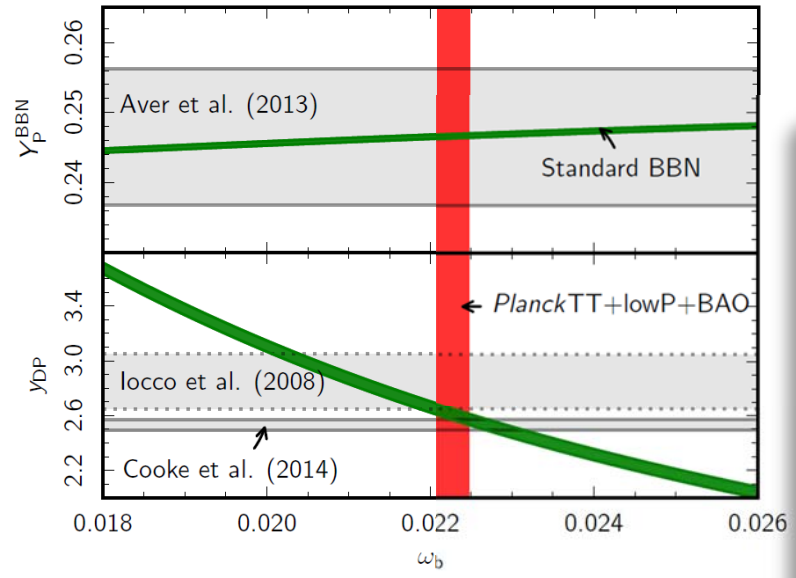
$f_{NL} = 100$

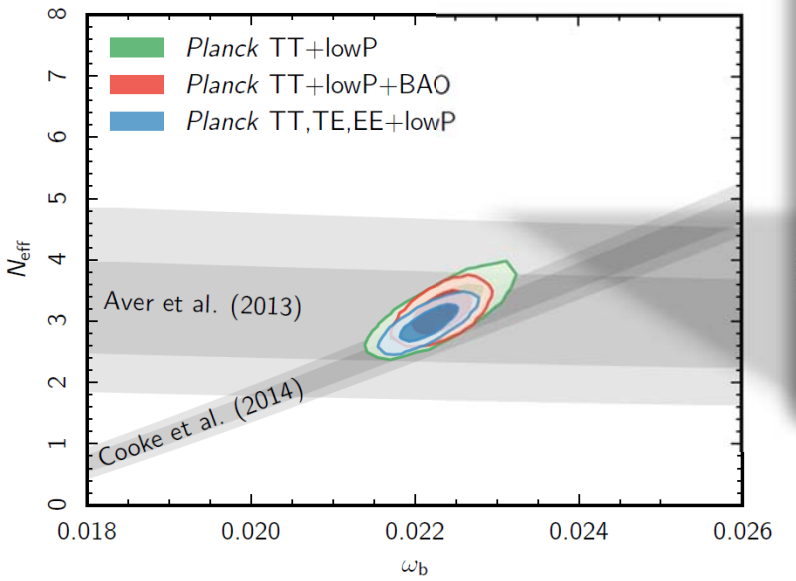
Positive f_{NL} = More Cold Spots

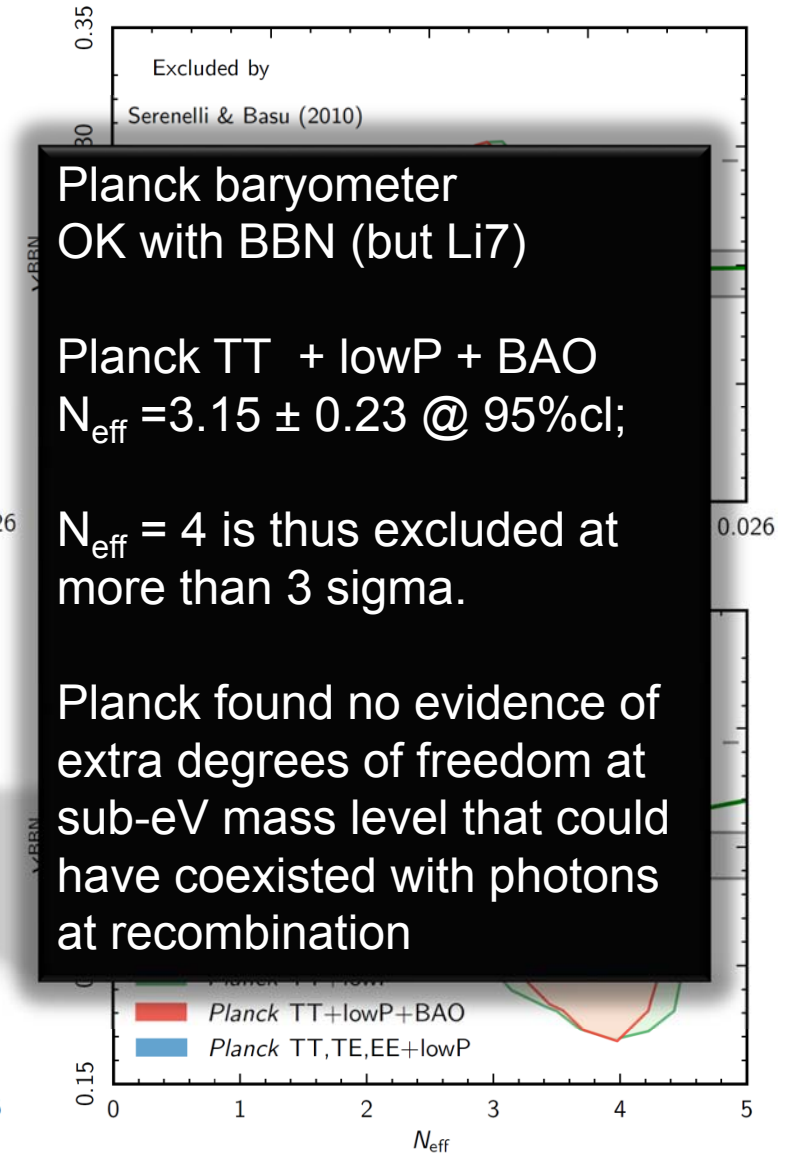


Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

BBN – N_{eff}, Y_p







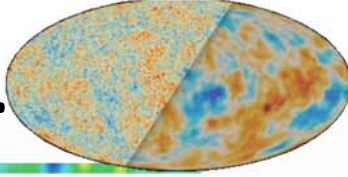
Planck baryometer
OK with BBN (but Li7)

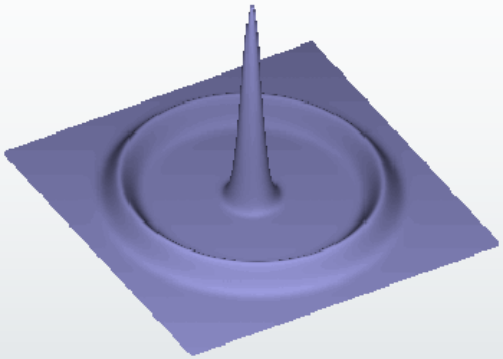
Planck TT + lowP + BAO
N_{eff} =3.15 ± 0.23 @ 95%cl;

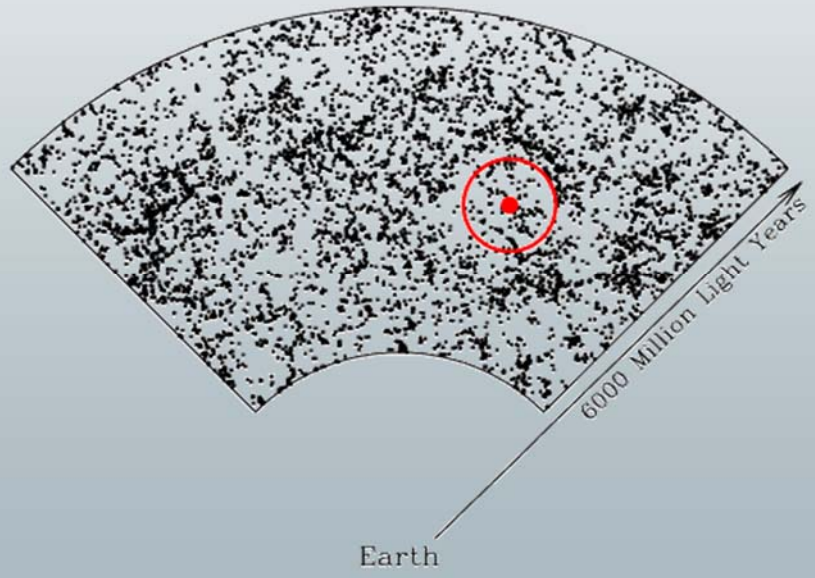
N_{eff} = 4 is thus excluded at more than 3 sigma.

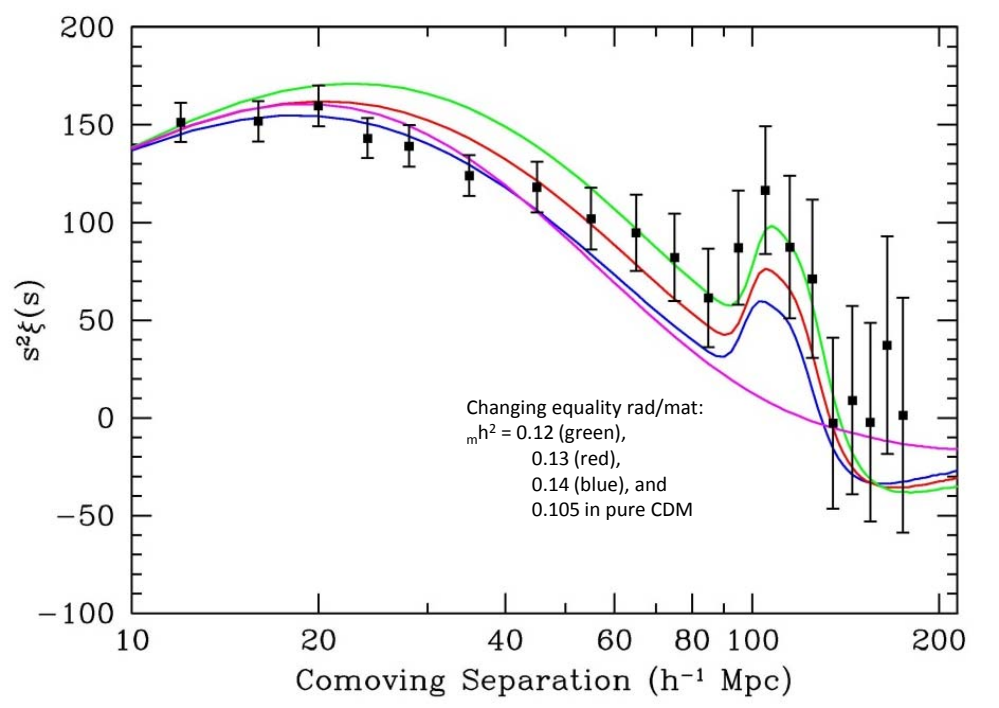
Planck found no evidence of extra degrees of freedom at sub-eV mass level that could have coexisted with photons at recombination

Echoes of the primordial drum…



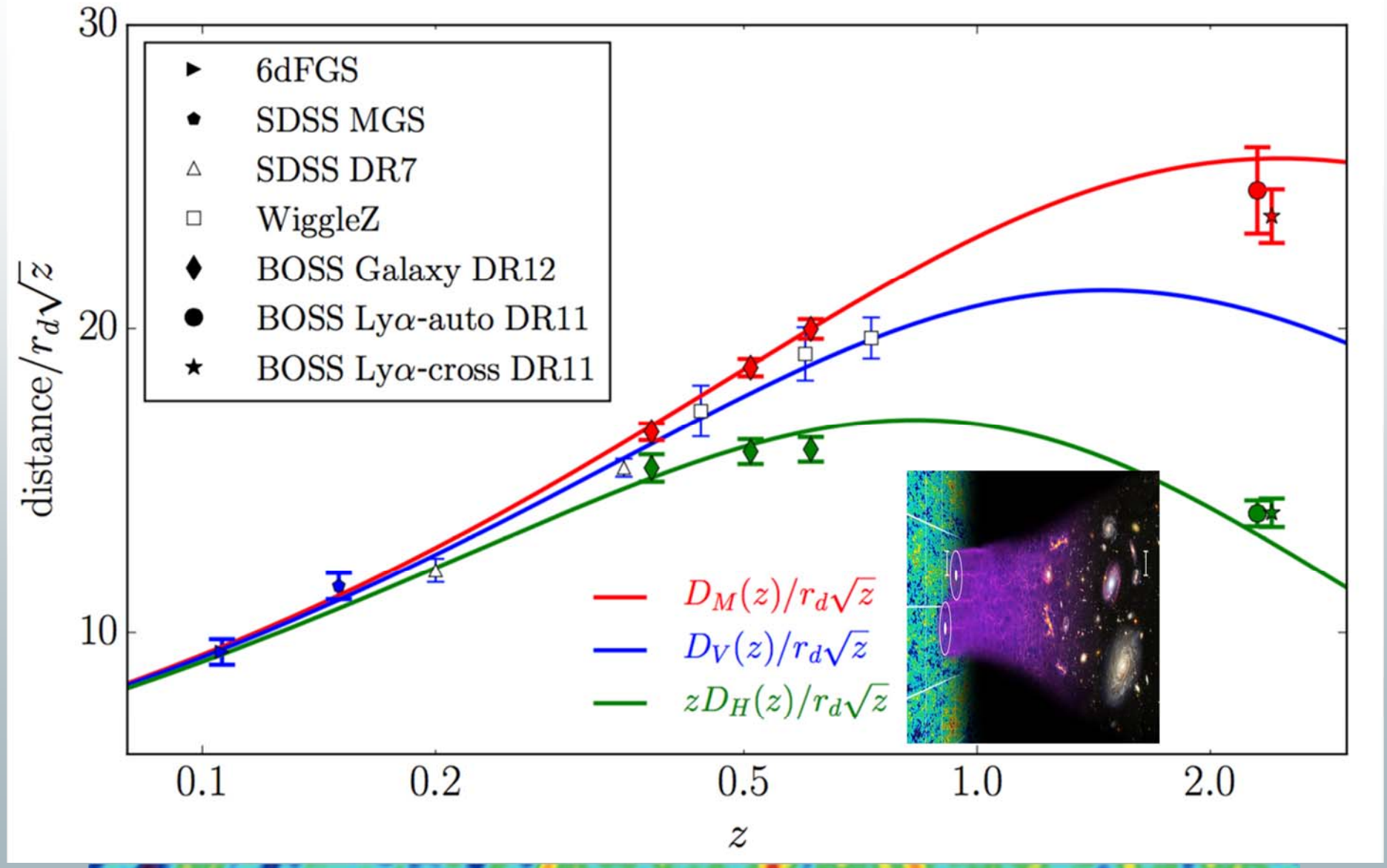




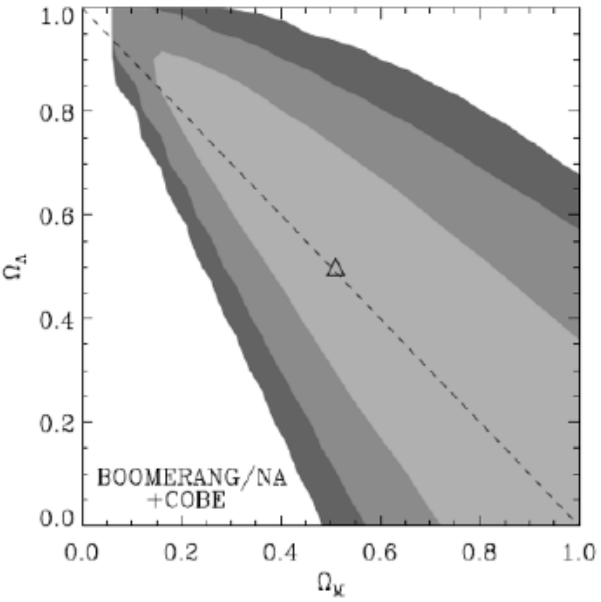


BAO (Baryon Acoustic Oscillations) probe the sound travel distance at z close to 0

BOSS RD12, Alam+2016, arXiv:1607.03155

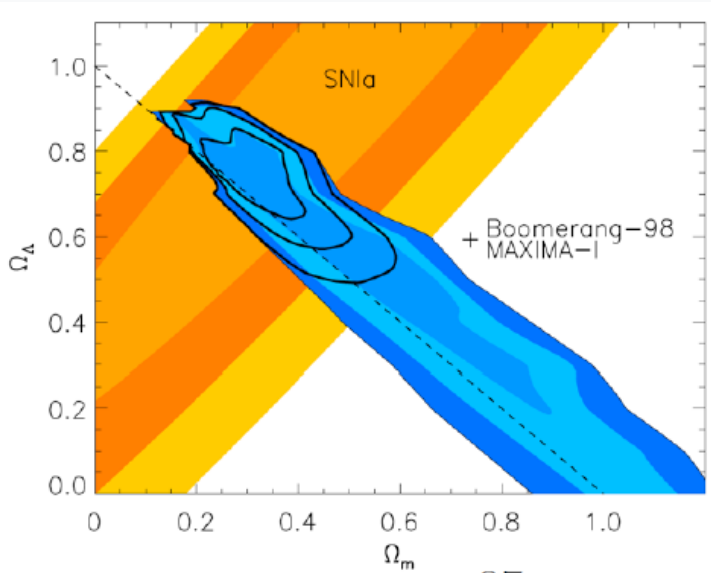


Spatial curvature constraint



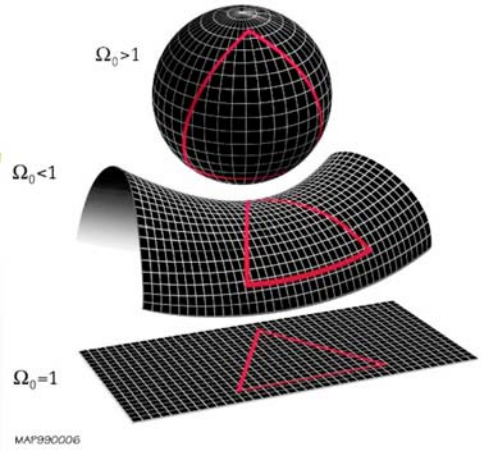
$$\Omega_K = -0.05^{+.40}_{-.40}$$

Melchiorri et al. 2000



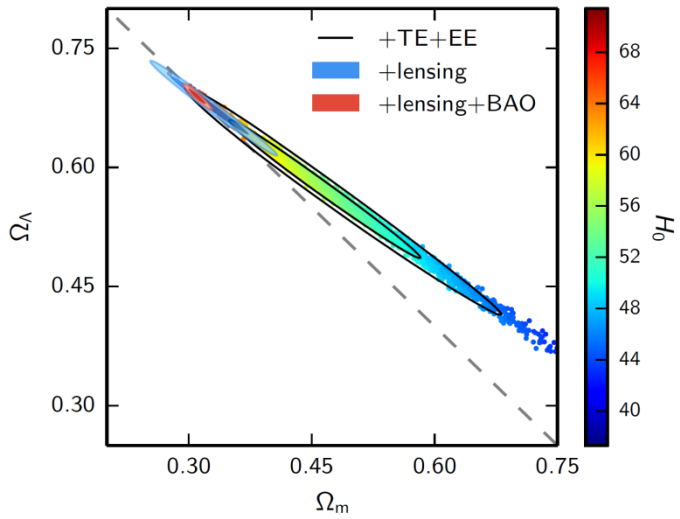
$$\Omega_K = -0.11^{+.07}_{-.07}$$

Jaffe et al. 2001



Flat space ←→ Ω_k=0

Note the change of axes
For Planck below



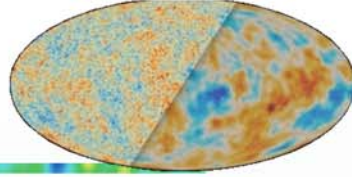
Planck 2015

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

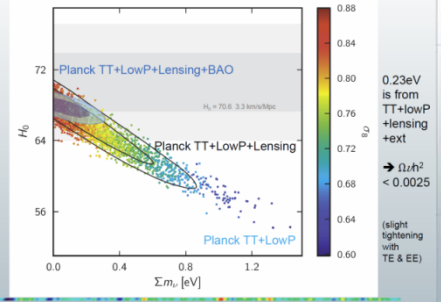
A hundred-fold improvement in 15 years



We tested & constrained a lot more…



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

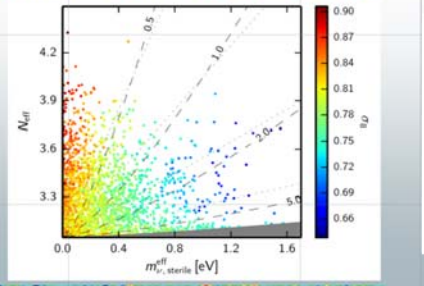


0.23eV is from TT+lowP +lensing +ext

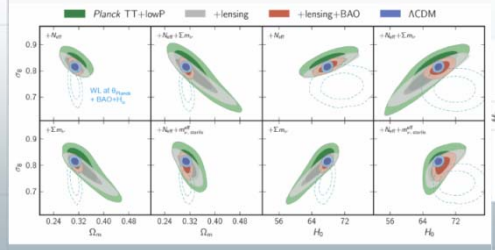
➔ $\Omega_\nu h^2 < 0.0025$

(slight tightening with TE & EE)

Adding a 4th sterile neutrino

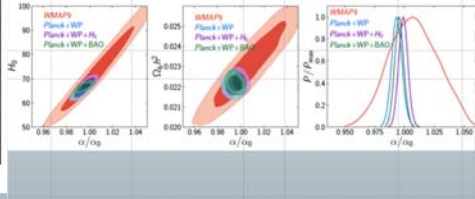


Allowing neutrinos extensions

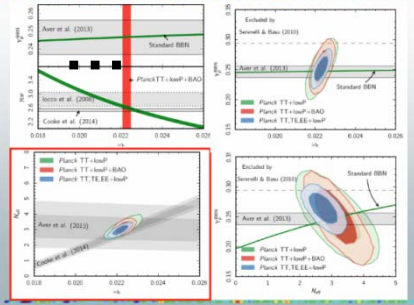


($\Omega_m H^3$ is tightly constrained by θ_{MC})

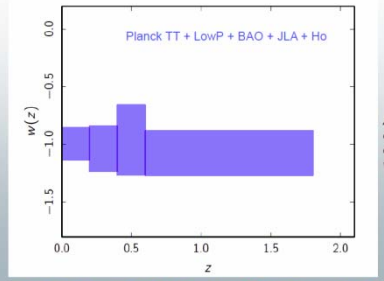
Fine structure constant variation?



BBN – Neff, Yp



PCA of w(z)

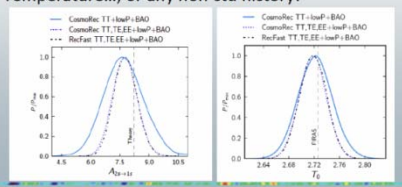


A cosmological constant, Λ, corresponds to w(z)=-1

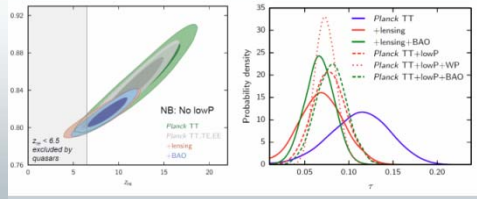
Recombination history

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

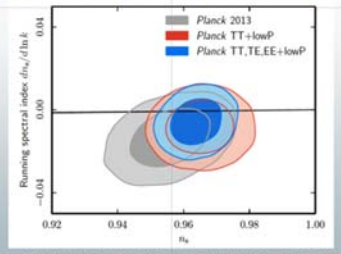


A new, independent, way to look at τ

➔Consistency of lensing versus LowP constraints on τ

Pointing to lower values than previous WMAP based values

Planck 2015 on running



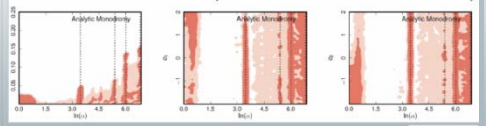
The thin black stripe shows the prediction for single-field monomial chaotic inflationary models with 50 < N < 60 .

Axion monodromy inflation

Periodic potential, analytical template from Flauger et al.

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

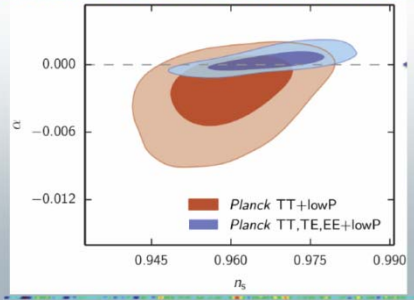
$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_\mathcal{R}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left\{1 + \delta n_s \cos\left[\frac{\phi_0}{f}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\phi\right]\right\}$$



▸Chi² improvement insufficient. There are expected bispectrum oscillations $f_{NL}^{res} = \frac{\delta n_s}{8}\alpha^2$

owest frequency checked already (KO). Others imminent.

Isocurvature modes fraction



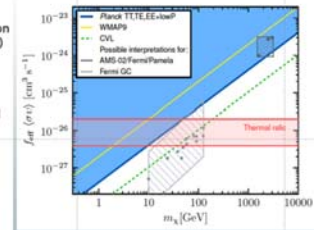
Dark matter annihilation?

Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption $\langle\sigma v\rangle(z=100) = \langle\sigma v\rangle(z=0)$

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

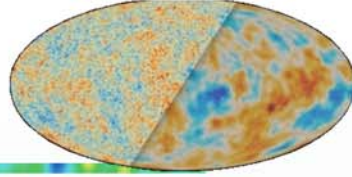
m~<40GeV (e^-e^+)
m~<20GeV ($\mu^+\mu^-$)
m~<10 GeV ($\tau^+\tau^-$).

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



See 1501.01618 for powerful other constraints

CMB Anisotropies post-Planck 1/2



- The LCDM model fits all CMB data in T, E, B, ϕ.
  - *No need for an extension. A lavish source of constraints /papers…*
  - *Same model parameters, determined at the per cent level, also fit other data (BAO, and also BBN, SN1a…).*
  - *Some tensions (anomalies, SZ, H0, WL), whose meaning remains unclear as of now.*
- LCDM is a tilted model (n_s <1) and the inflationary phase models check all the generic boxes. Many specific models have been ruled out though.
- Alternatives have either been falsified, or they mostly/only do post-dictions so far. E.g., bouncing model are not expected to produce Gravitational Waves; they may thus be falsified by an incoming detection. Otherwise, Occam's razor?
- T anisotropies information essentially exhausted (but much still to learn on foregrounds, e.g. from SZ). Polarisation promises a very rich harvest.
- A new field, CMB lensing, has emerged (observationally), with a great scientific potential. It has unique advantages (known source plane, well understood, mostly linear physics at work); but it is a foreground to be removed for improving the detection capability of a Primordial Gravitation wave stochastic background. In any case, it is a great source of problem to solve for astronomers.

Planck results 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.

A full cryogenic life

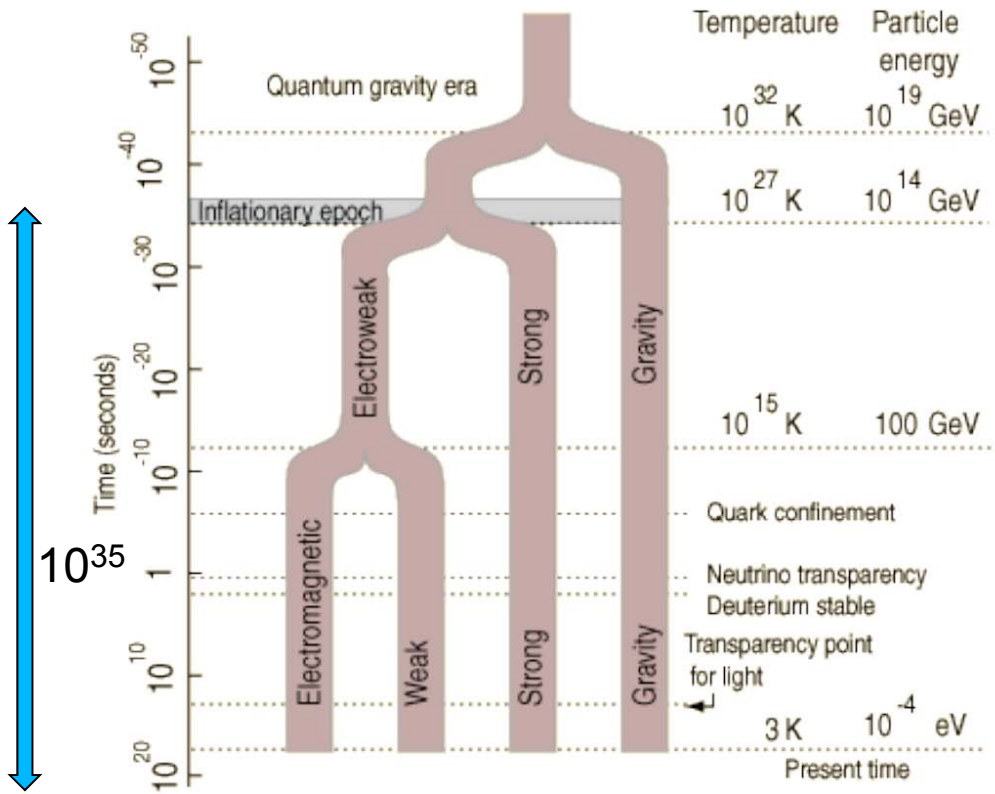


HFI starts cooling,
Hotel des roches,
Kourou
14 mai 2009



HFI starts warming up
HFI Core team meeting
Institut d'Astrophysique de Paris,
14 janvier 2012

The primordial Universe, Fundamental physics Ultimate laboratory



10^{35}

Inflation

$$V^{1/4} = 1.06 \times 10^{16}\ \text{GeV} \left(\frac{r}{.01}\right)^{1/4}$$

Cosmic neutrino background

Cosmic microwave background

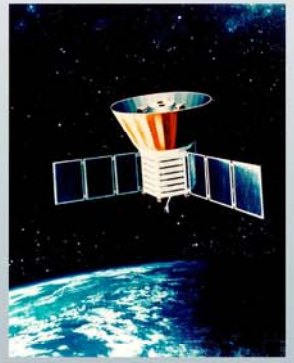
CMB spectrum: FIRAS

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

95% CL from template fits:

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

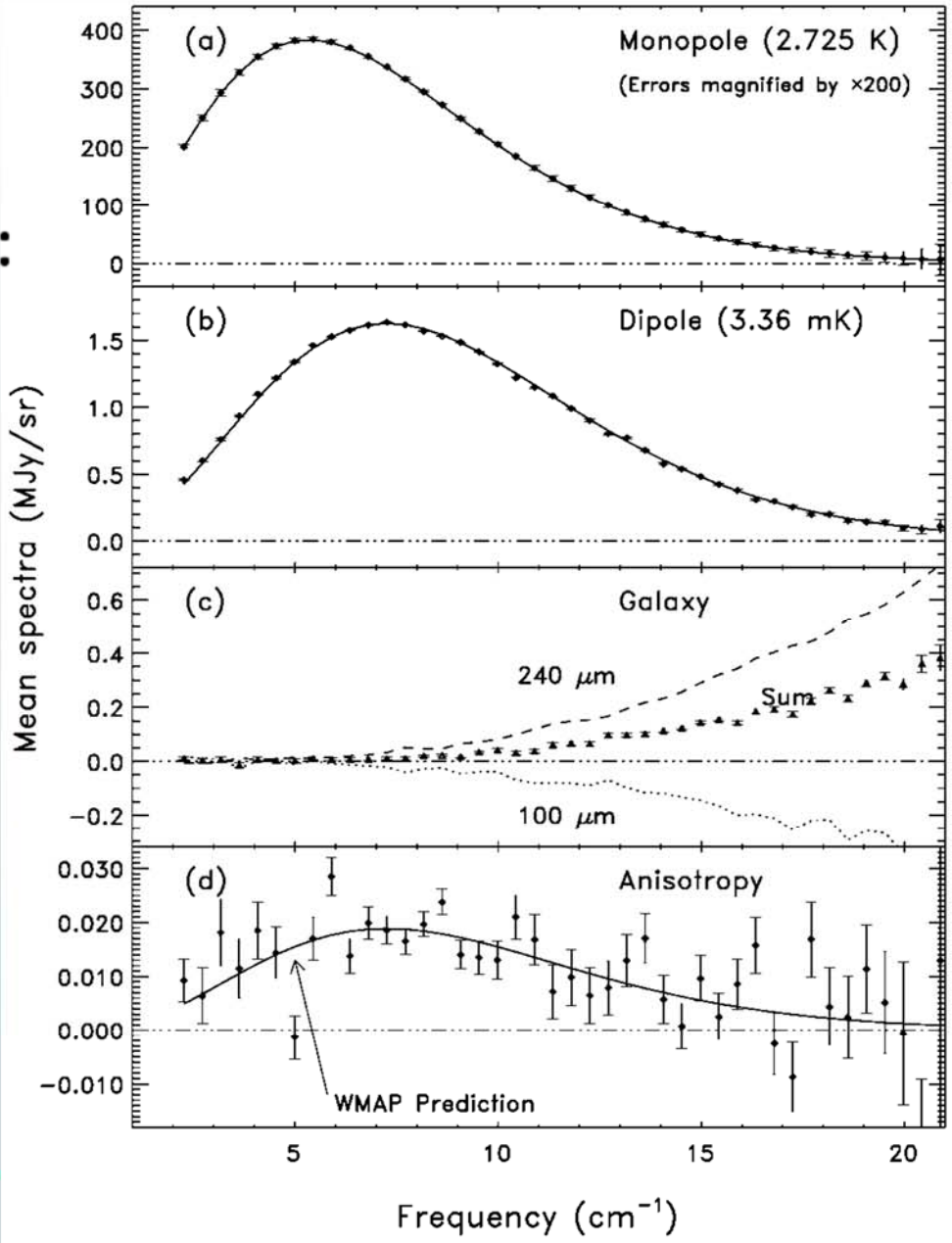
$$|\mu/kT| < 3.3 \times 10^{-4}$$



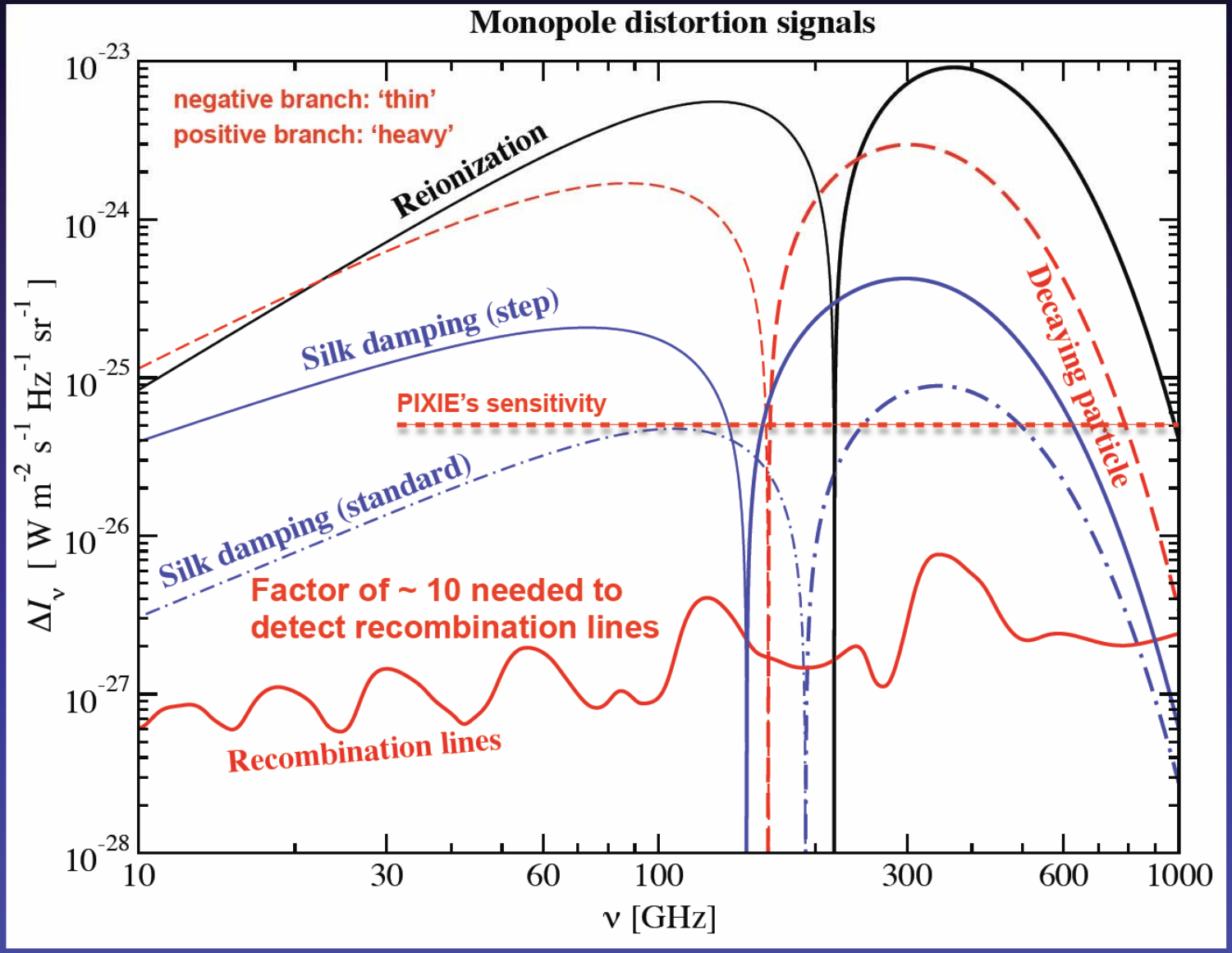


Physics 2006

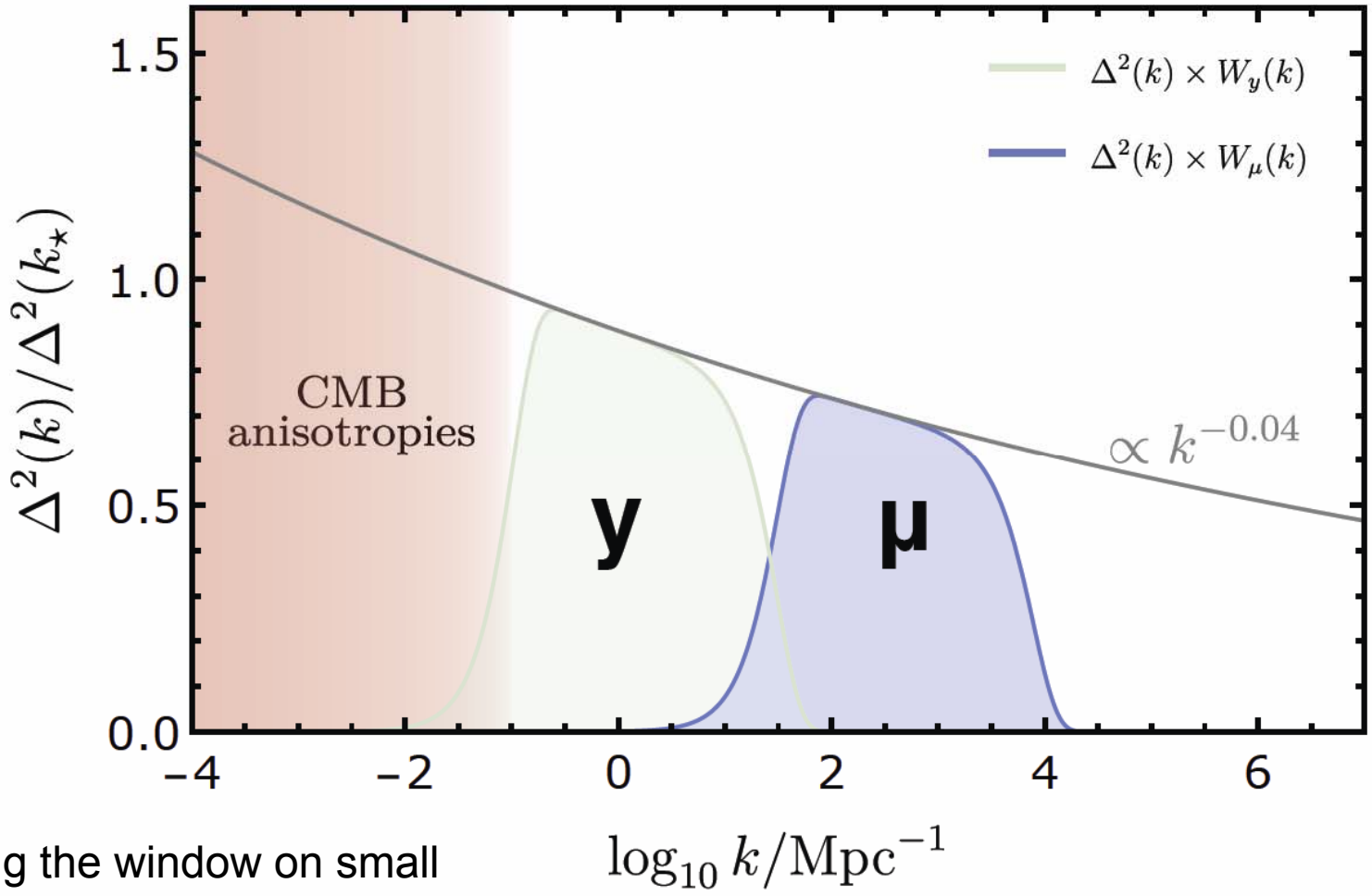
Mather@ AAS 1990, 9mn of data
Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Mather et al., 1999, ApJ, 512, 511
Fixsen et al., 2003, ApJ, 594, 67



Average CMB spectral distortions



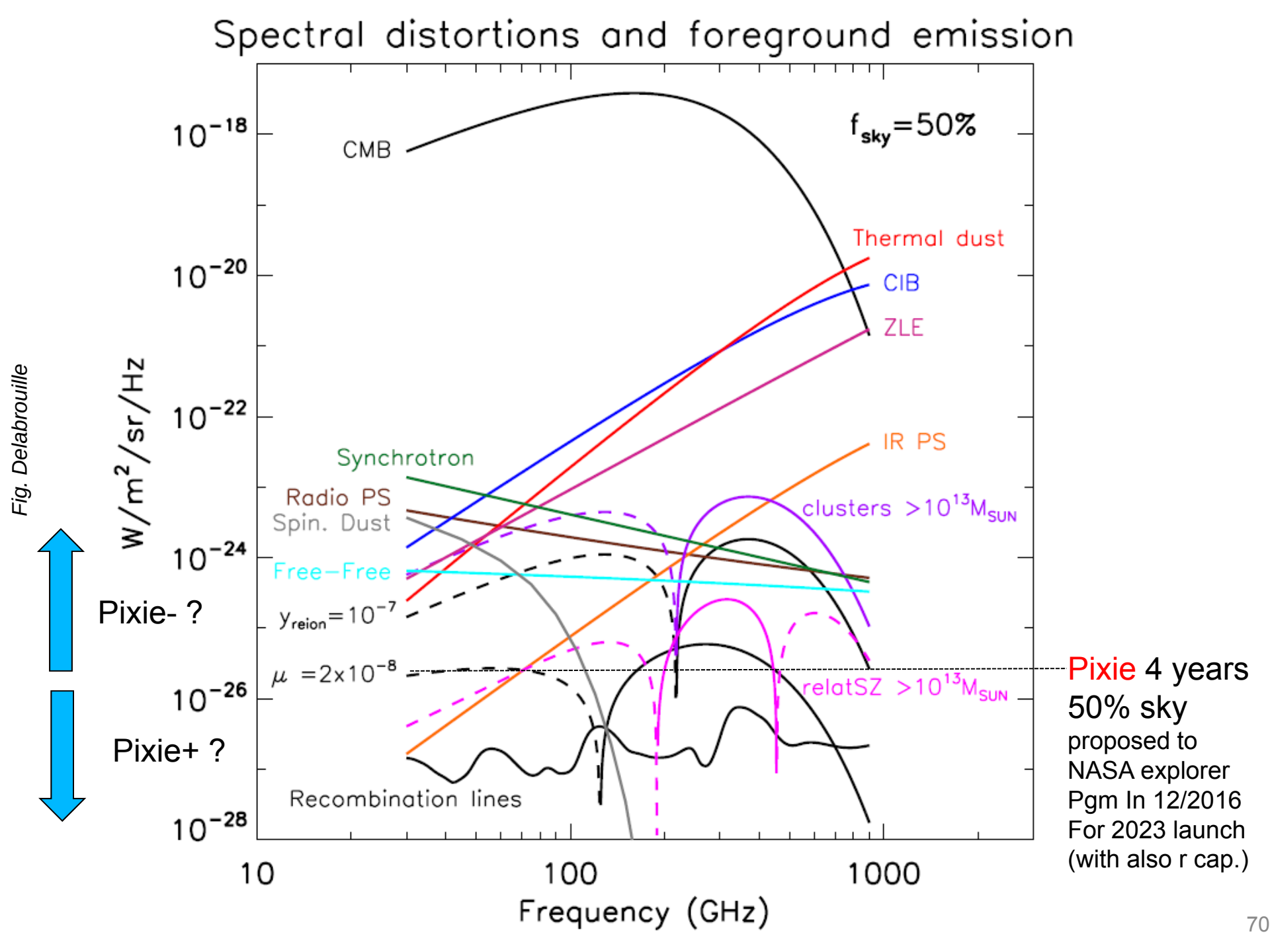
y and mu distorsions from standard inflationary models of the CMB spectrum



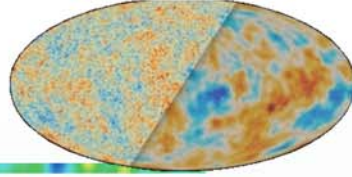
Extending the window on small scale scalar primordial power spectrum (+9 e-folds)

Broad band windows.

Also sensitive to any energy input – exotic or astrophysics – a very extended net


Spectral distortions and foreground emission
f_{sky}=50%
CMB
Thermal dust
CIB
ZLE
IR PS
Synchrotron
Radio PS
Spin. Dust
clusters >$10^{13}M_{SUN}$
Free−Free
$y_{reion}=10^{-7}$
μ =2x10^{-8}
relatSZ >$10^{13}M_{SUN}$
Recombination lines
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
W/m²/sr/Hz
10
100
1000
Frequency (GHz)
Fig. Delabrouille
Pixie- ?
Pixie+ ?
Pixie 4 years
50% sky
proposed to
NASA explorer
Pgm In 12/2016
For 2023 launch
(with also r cap.)

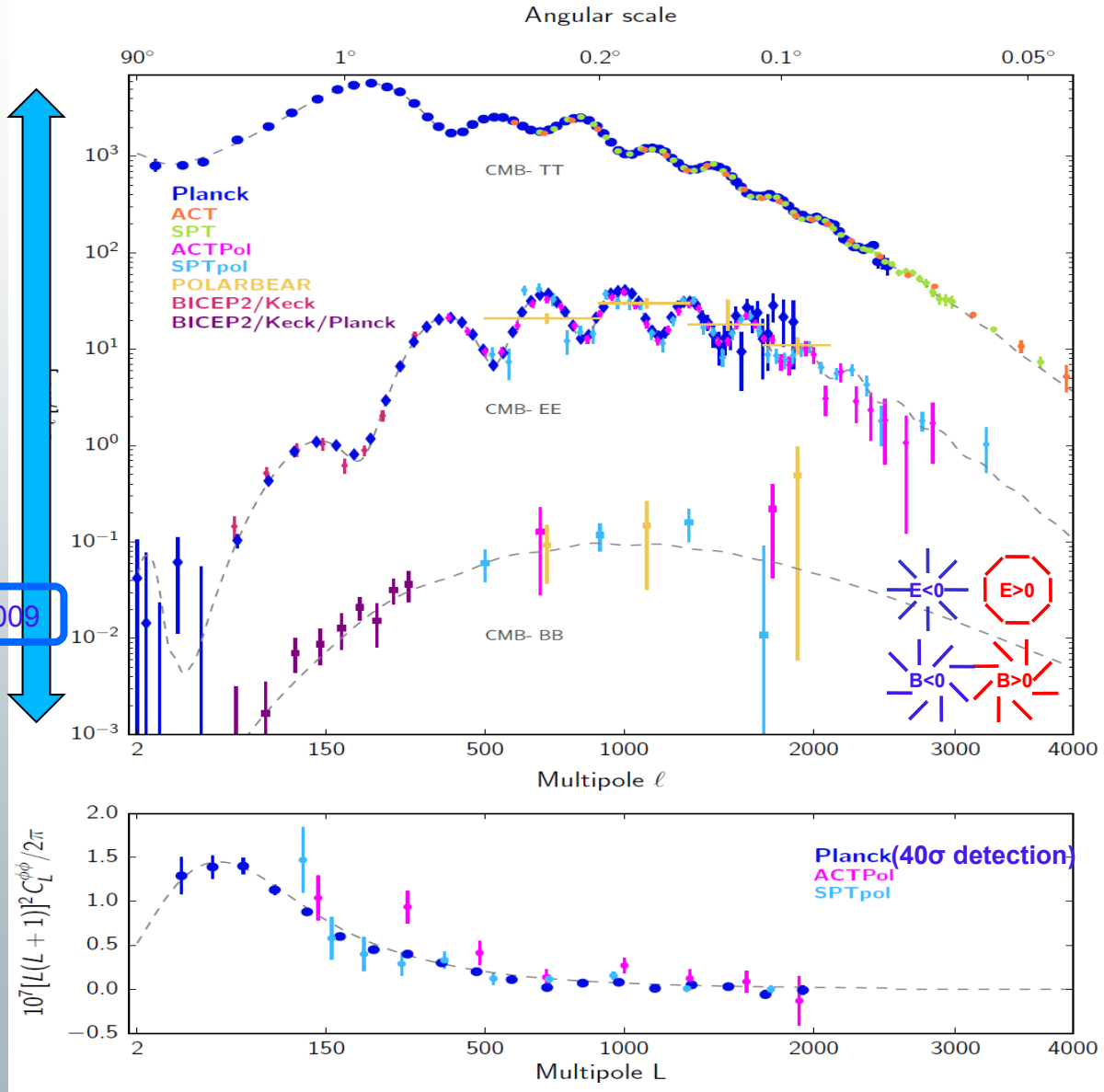
TT, EE, BB, ΦΦ – 2017 status



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

10^7

$\tau = 0.055 \pm 0.009$



And statistically isotropic…

1 114 000 Modes measured with TT,

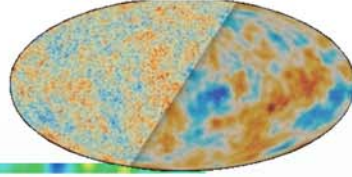
60 000 with TE (not shown)

96 000 with EE

… and 10's in BB and φφ

+ weak constraints with TB and EB

TT, EE, BB, ΦΦ – Prospects



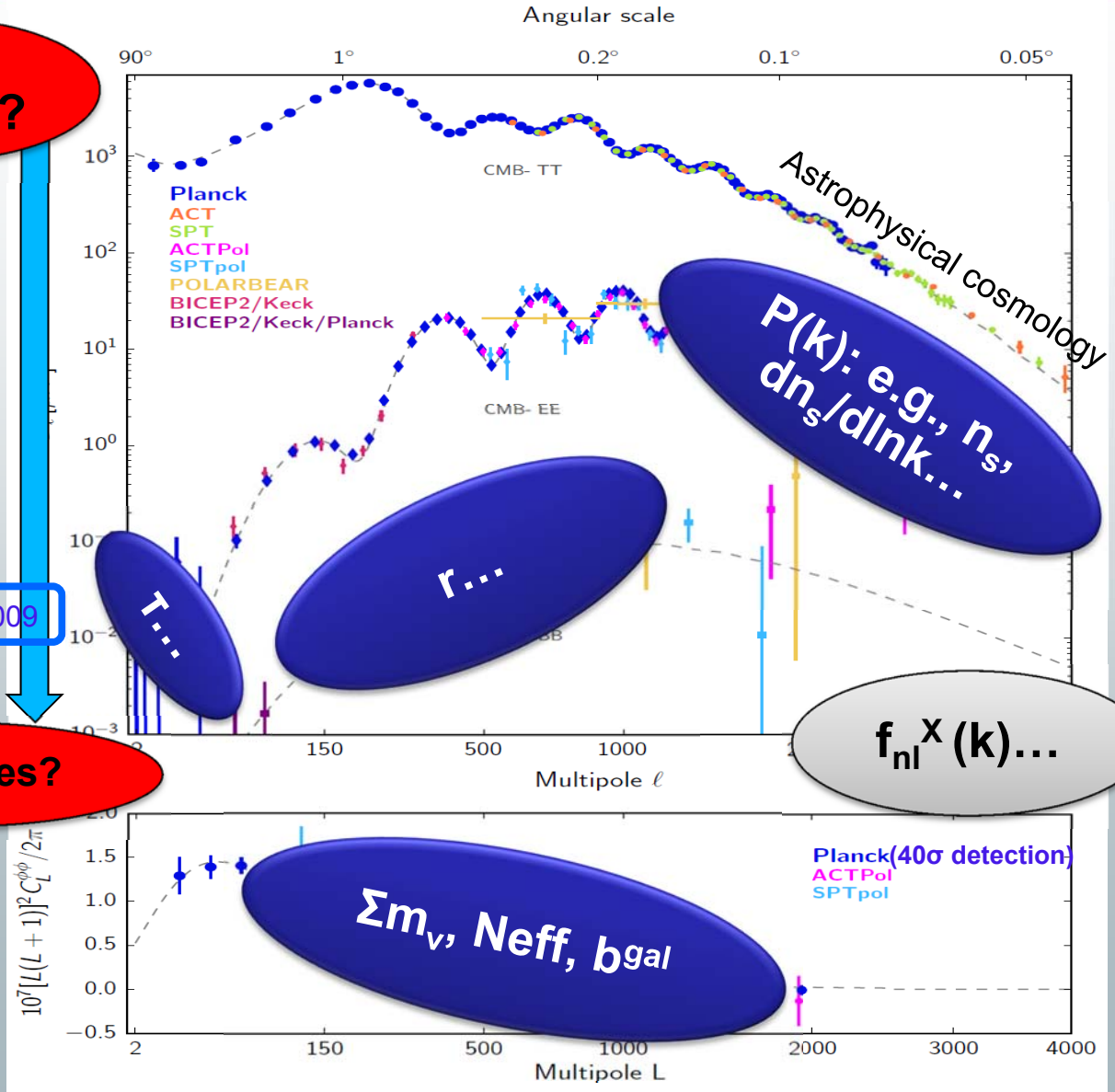
ΛCDM enough?

10^7

τ = 0.055±0.009

Anomalies?

And SZ & CIB PS, etc.



Planck:

1 114 000 Modes measured with TT,

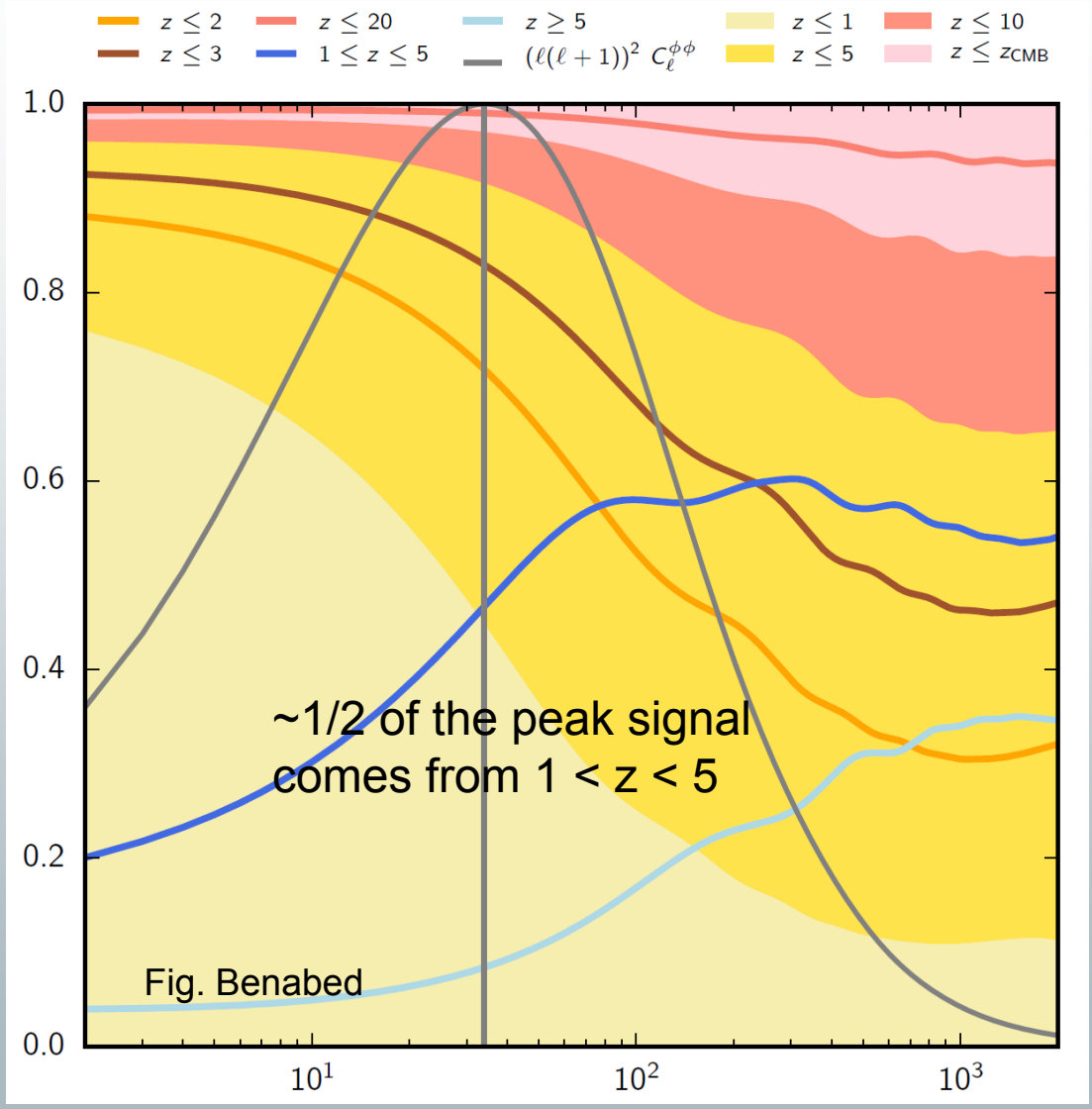
60 000 with TE (not shown)

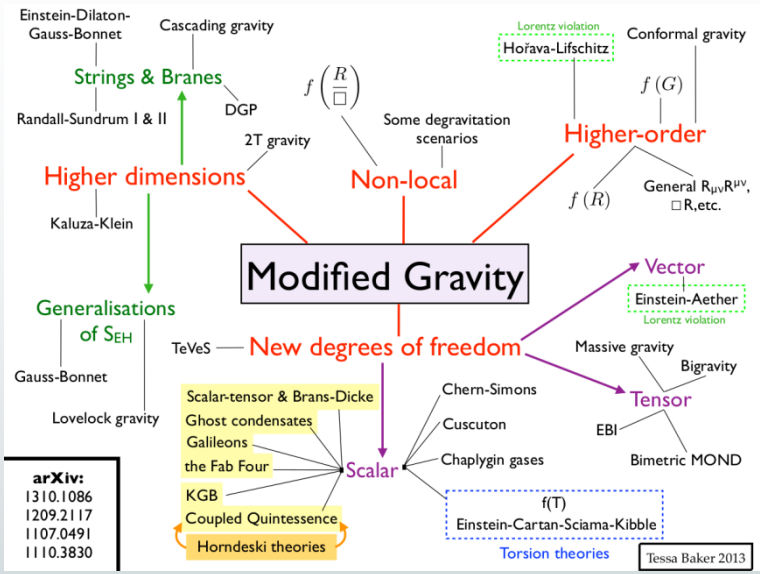
96 000 with EE

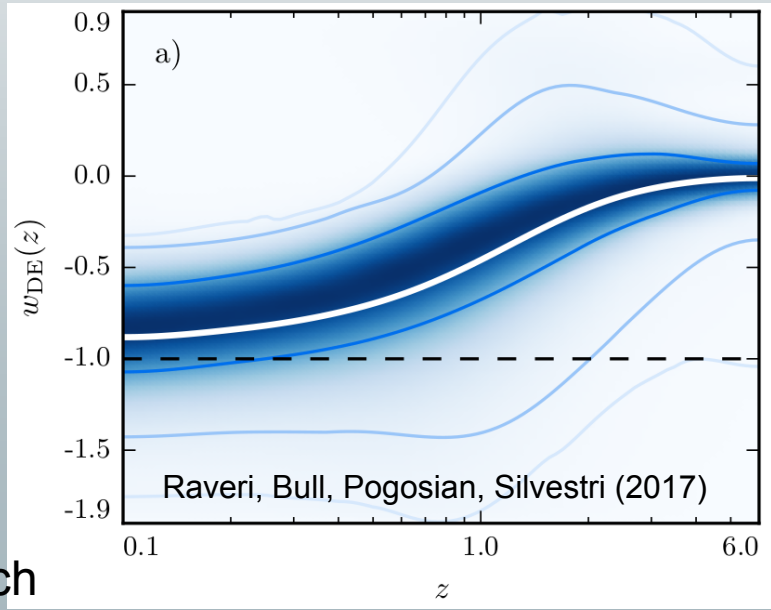
… and **10's** in BB and φφ

+ constraints on TB and EB

Lensing comes from a broad redshift range

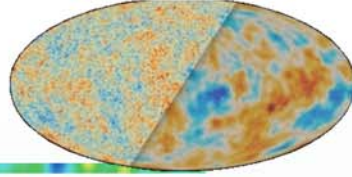




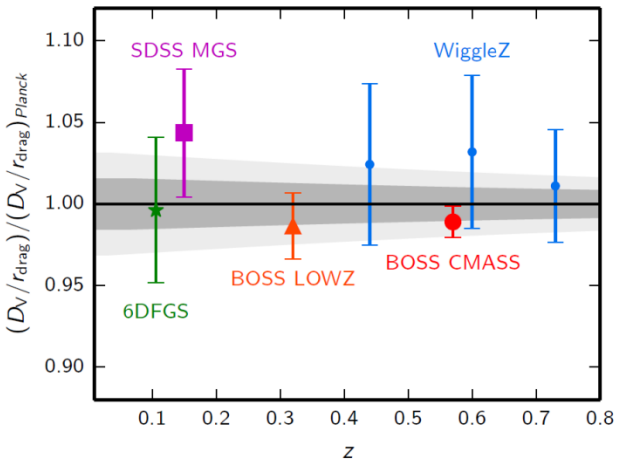


A unique contribution of CMB lensing to DE/MG search

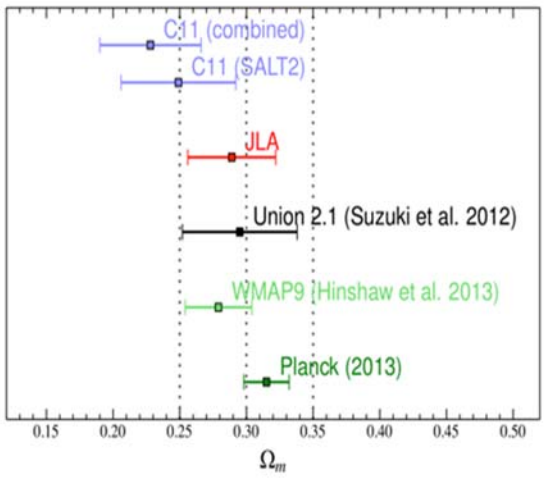
The good, the ?, the ??



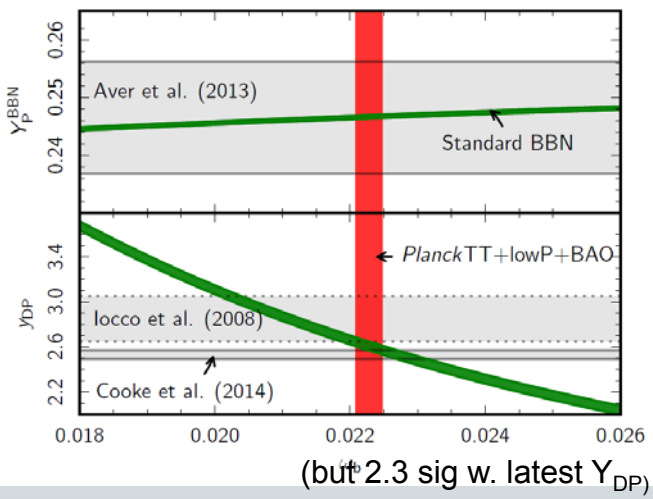
BAO D_v



SN Ω_m

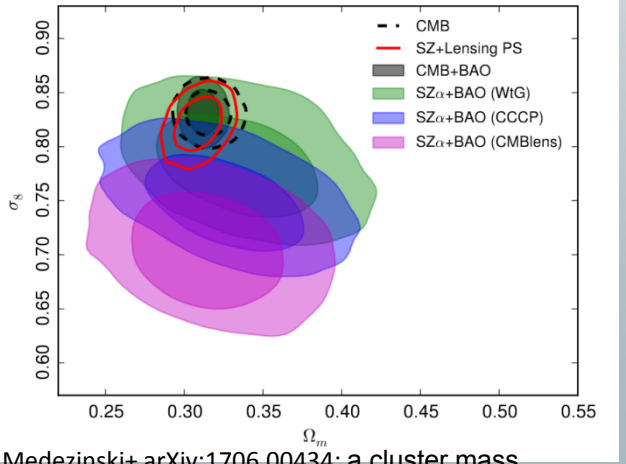


BBN Y_p Y_{DP}



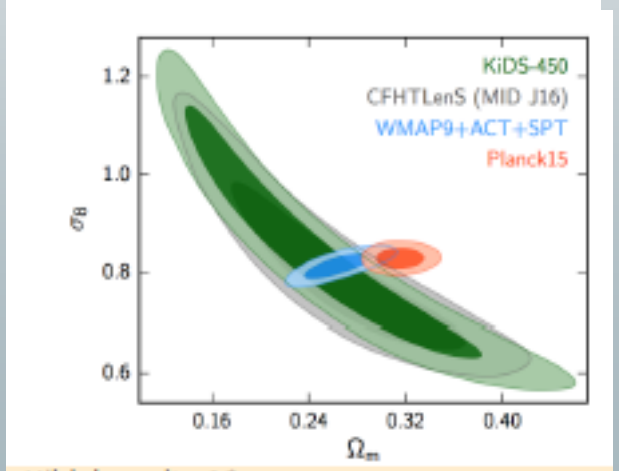
(but 2.3 sig w. latest Y_{DP})

SZ



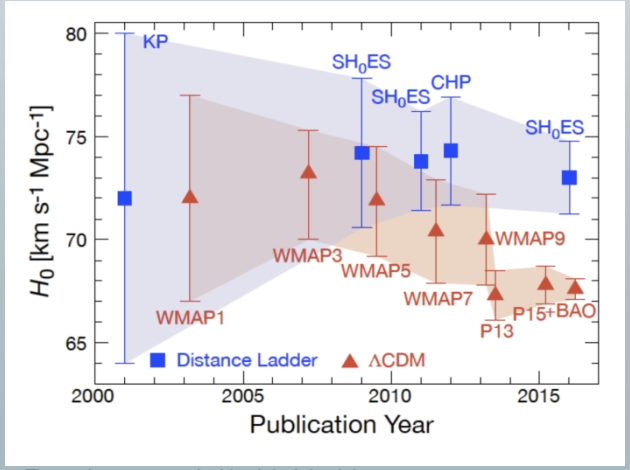
Medezinski+ arXiv:1706.00434: a cluster mass dependence of the bias?

WL



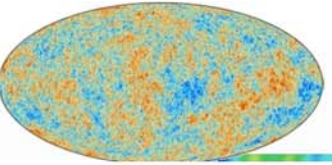
Hildebrandt+ 16 BUT GPE+ arXiv:1707.00483

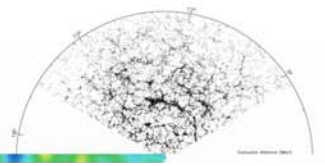
H0

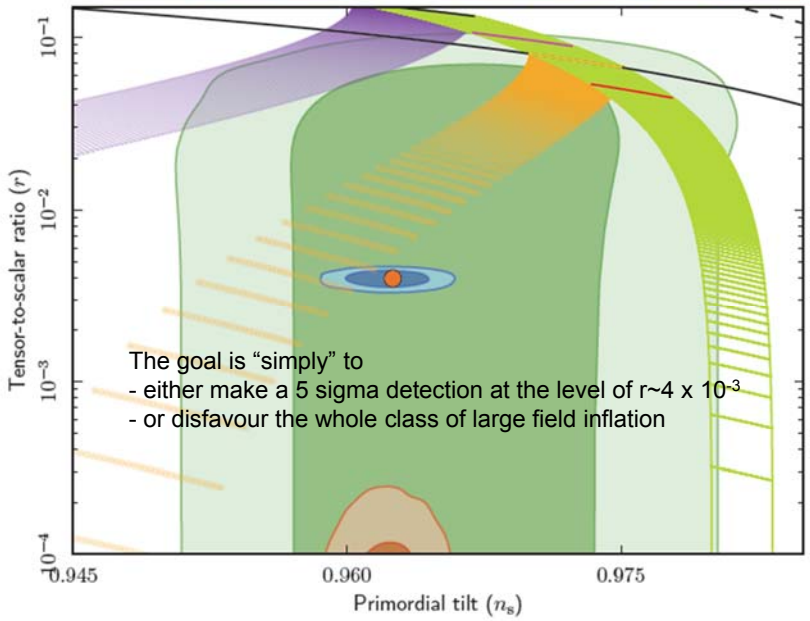


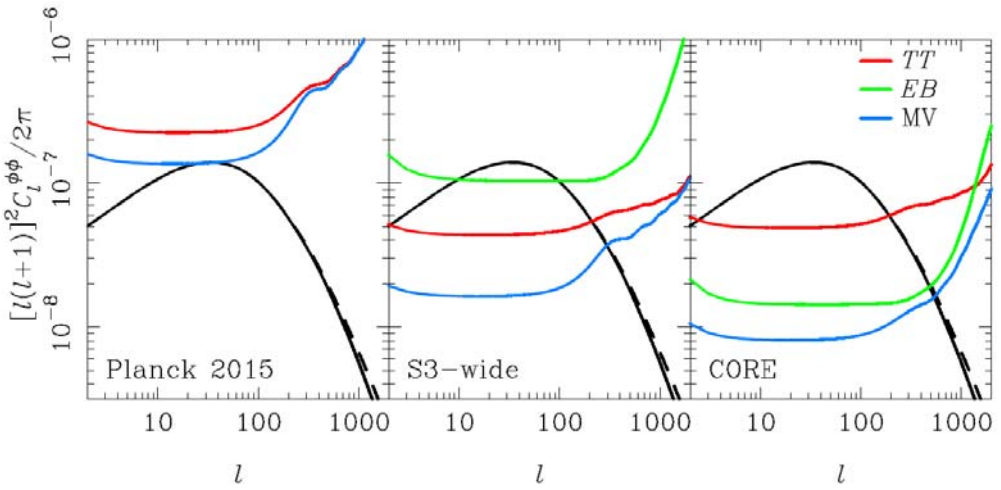
Freedman, arxiv/1706.02739

CORE examples of CMB potential

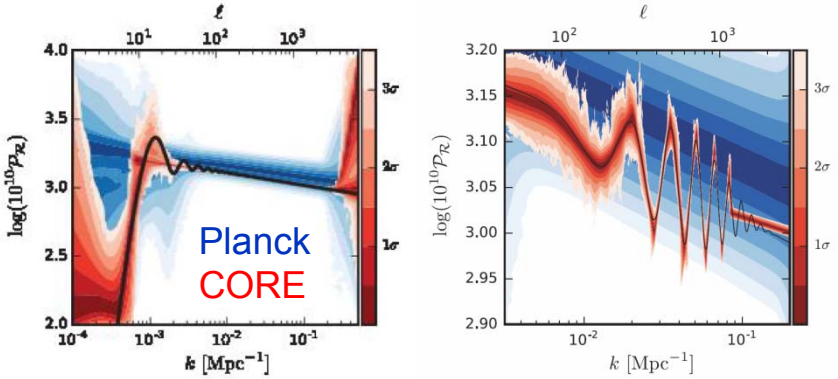








Reconstruction noise of the lensing detection power spectrum from Planck 2015 (left) and forecasts. The detection power spectrum is plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). [MV=minimum Variance]. ➔ M_ν, N_{eff} …



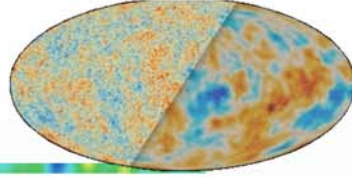
Model	*Planck*15+BAO	*CORE*	*CORE*+BAO
ΛCDM	3.3	2.3×10^3	2.3×10^3
$\Lambda\text{CDM} + \sum m_\nu$	11	8.9×10^3	2.0×10^4
$\Lambda\text{CDM} + w$	24	5.4×10^3	2.2×10^4
$\Lambda\text{CDM} + \sum m_\nu + N_{\rm eff}$	15	4.7×10^4	1.0×10^5
$\Lambda\text{CDM} + w_0 + w_a$	42	4.7×10^3	1.3×10^5
$\Lambda\text{CDM} + Y_{\rm P} + \sum m_\nu + N_{\rm eff}$			
$\Lambda\text{CDM} + r + dn_{\rm s}/d\ln k + \sum m_\nu + N_{\rm eff}$	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.

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

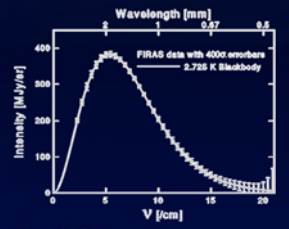
Capability to find limitations of ΛCDM

CMB Anisotropies post-Planck 2/2



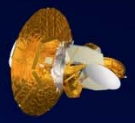
- Despite the amazing progresses of the last 25 years, much untapped and unique source of information remains in the CMB.
- The COBE/FIRAS are still the most constraining data on Spectral distortions.
  - *Many guaranteed signals, both relatively easy (SZ) or quite challenging (need 10^4 better sensitivity than FIRAS) for recombination lines and silk damping imprint. Wide net.*
  - *But also many not so well known astrophysical foregrounds that we shall have to learn to tame…*
- Polarisation anisotropies have millions of modes awaiting to be measured.
  - *Some relatively low hanging fruits (large-ell E modes), followed by lensing reconstructions (Neff, Mnu, DM…), and finally primordial gravitational waves (maybe) to disentangle from Lensing B modes.*
  - *Ground observations will now be the dominating source of new information in the next decade at least. But they suffer from intrinsic limitations, i.e., we need space too for large scales, nu coverage, and for spectral distortions.*

We've come a long way since 1965…





1989



2000



2009

COBE

WMAP

W-band temperature anisotropy

Internal Linear Combination of 5 bands, smoothed

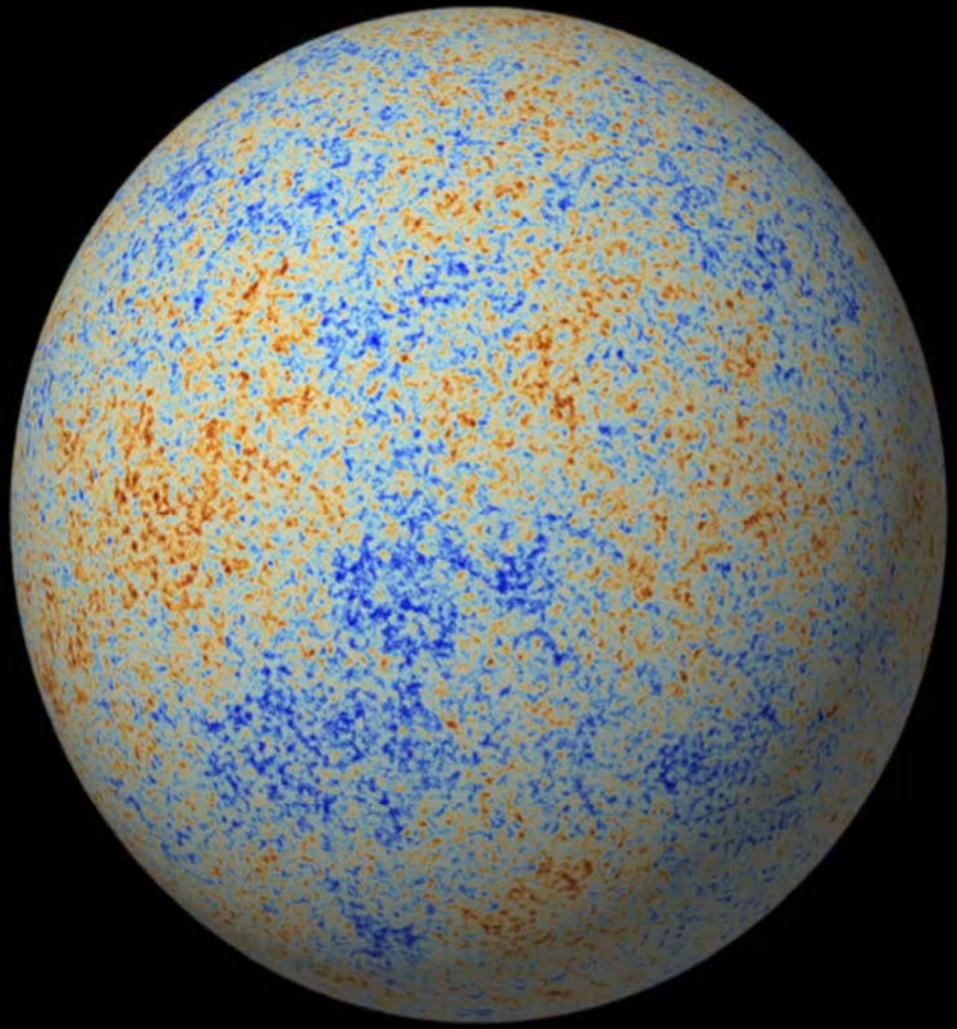
PLANCK

Simulated temperature anisotropy

Simulated temperature and polarisation anisotropy

& sub-orbital

With much more to come!



Starting with Planck 2018 “legacy” release!