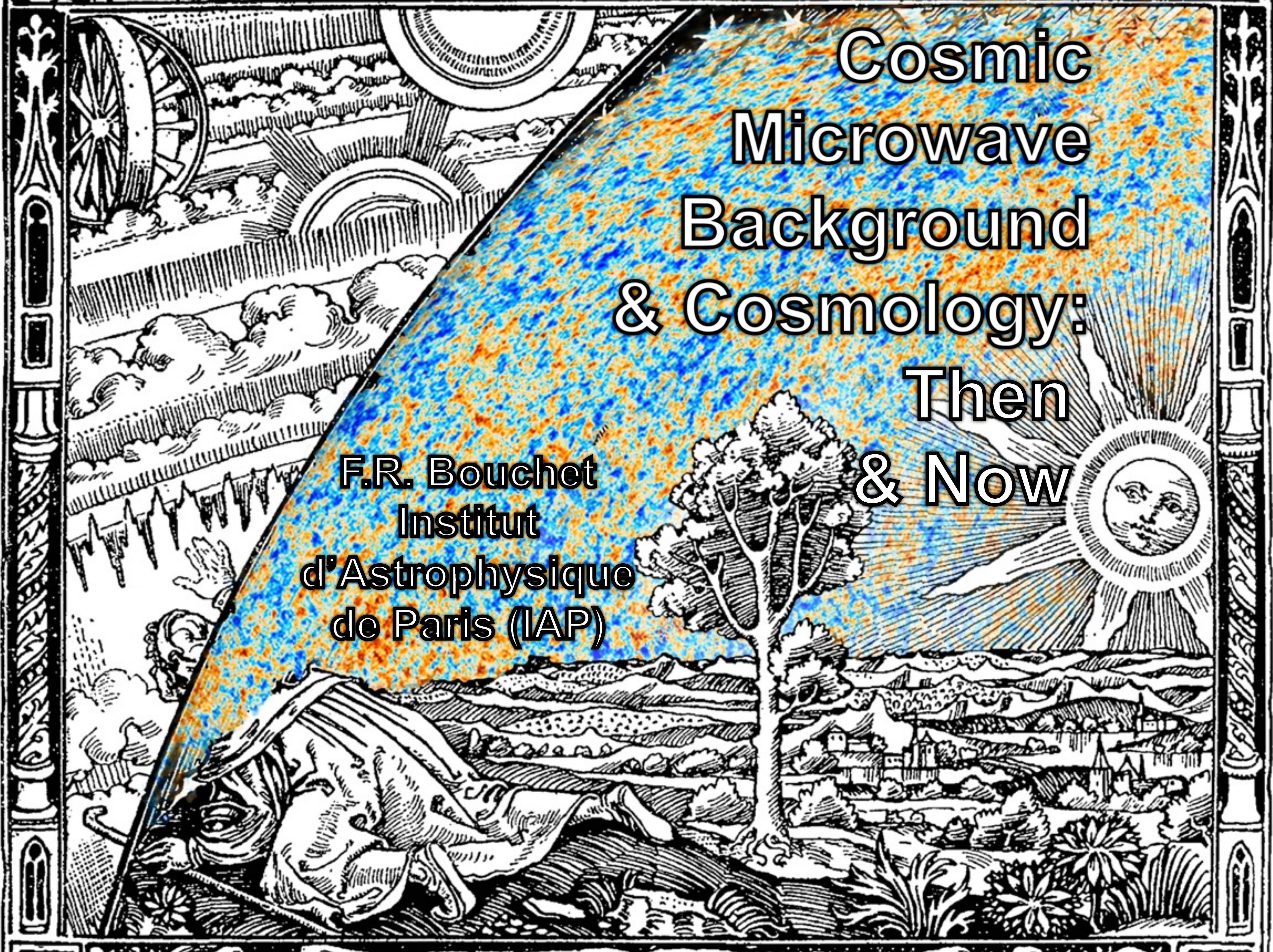
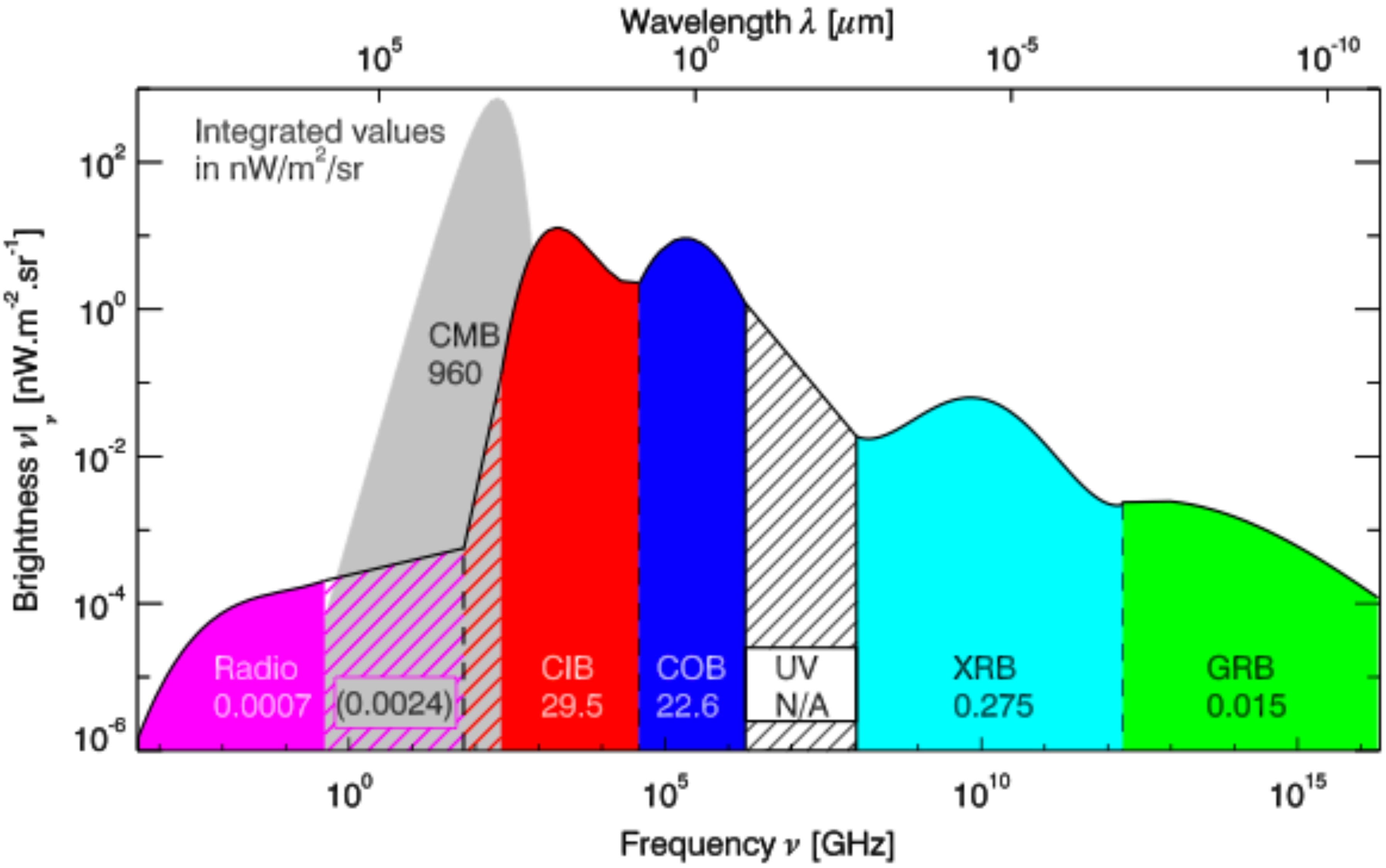


Cosmic Microwave Background & Cosmology: Then & Now

F.R. Bouchet
Institut d'Astrophysique de Paris (IAP)

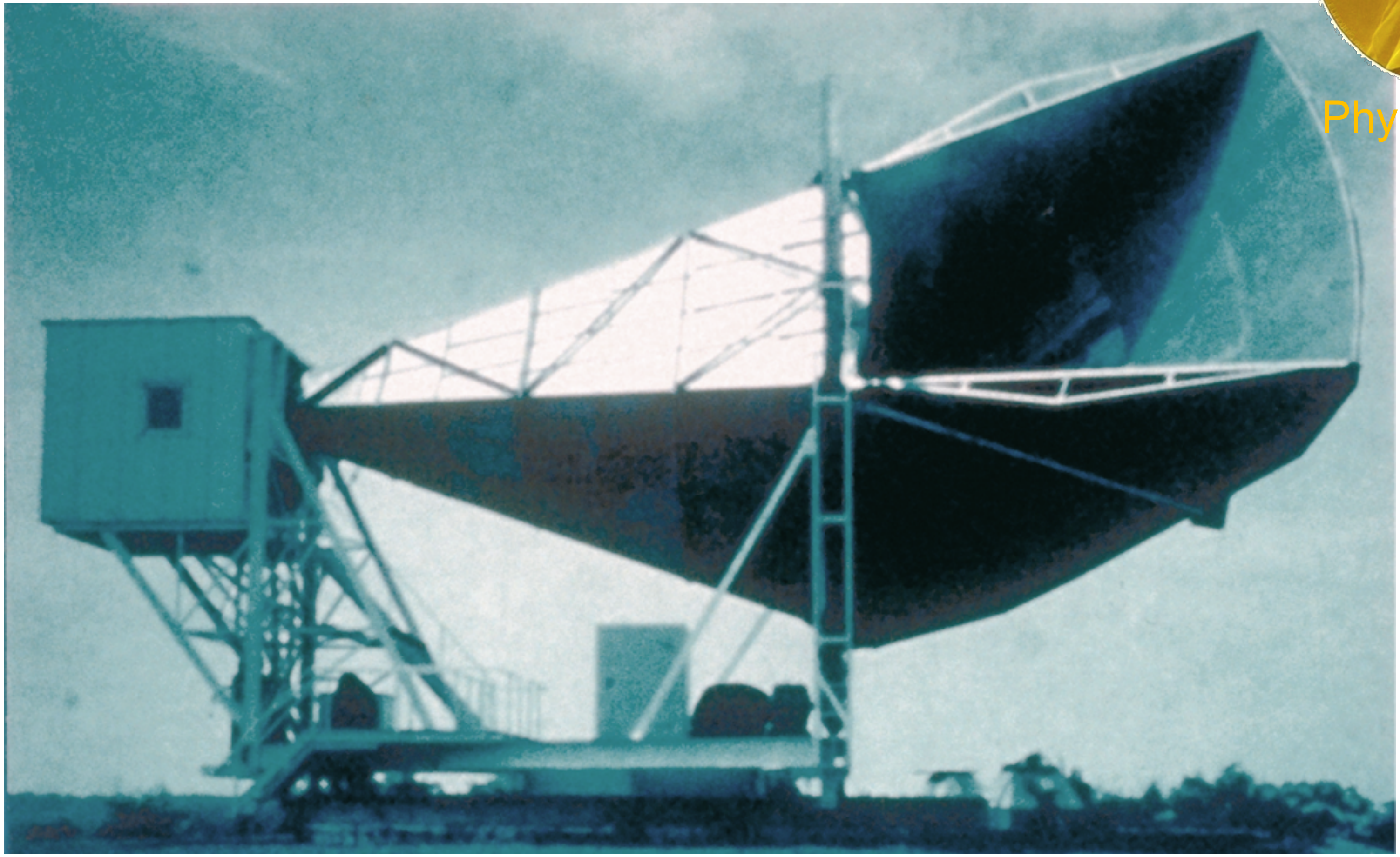
The photonic background



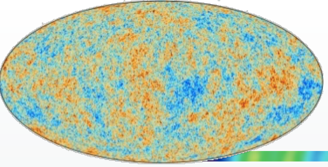
Lacasa 2014 arXiv:1406.0441

Penzias et Wilson discovery antenna…

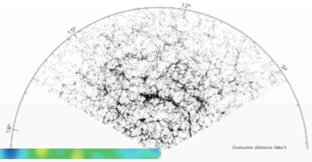
Physics 1978



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

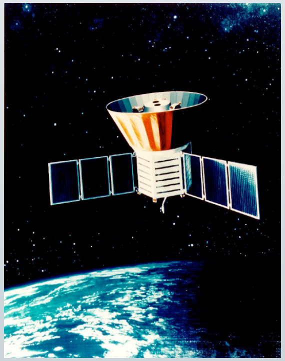


$$T_0 = 2.725 \pm 0.002\,\mathrm{K}$$

95% CL from template fits:

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

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



Physics 2006

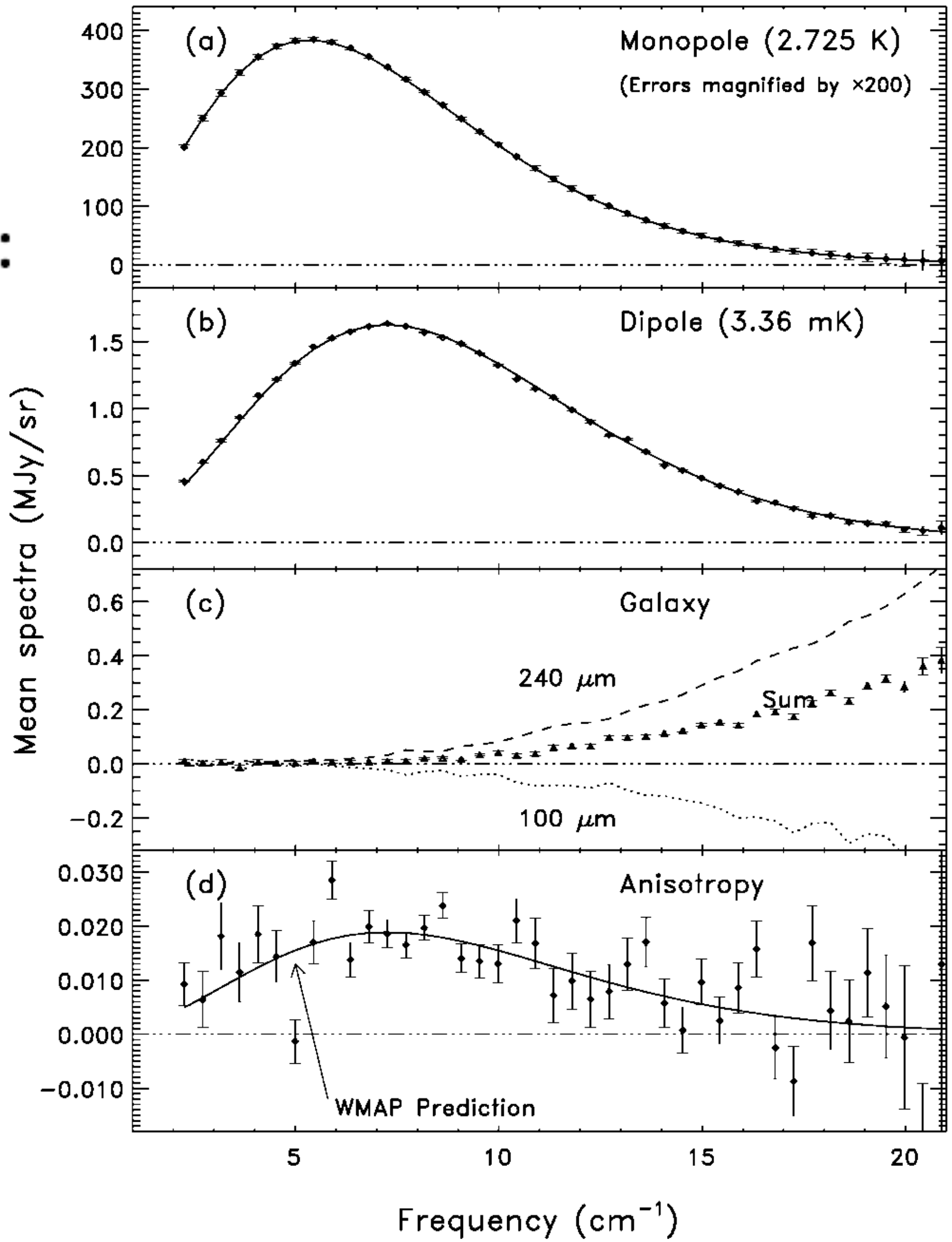
Mather@ AAS 1990, 9mn of data

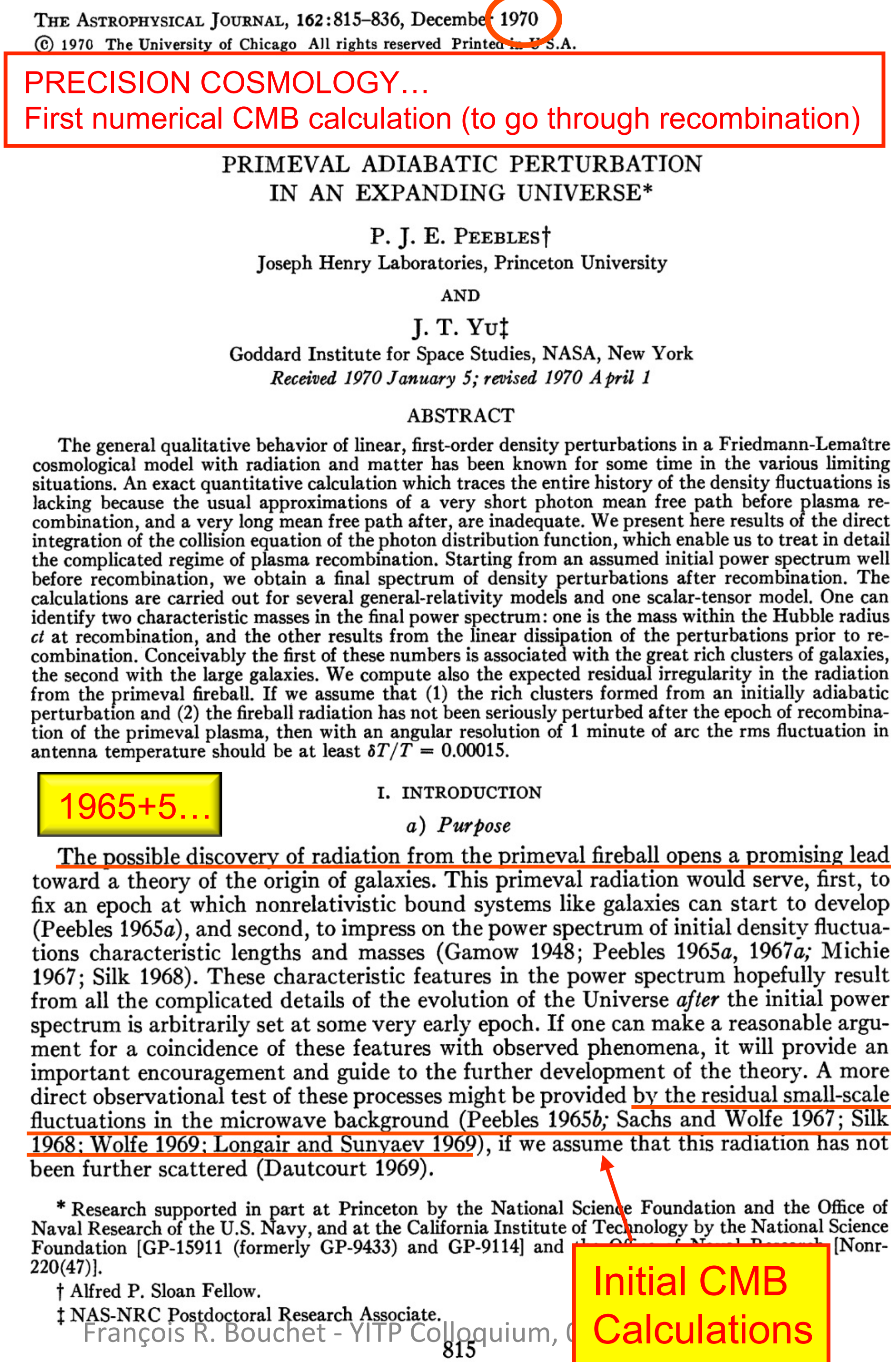
Mather et al., 1994, ApJ, 420, 439

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

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

Fixsen et al., 2003, ApJ, 594, 67 →





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).

---

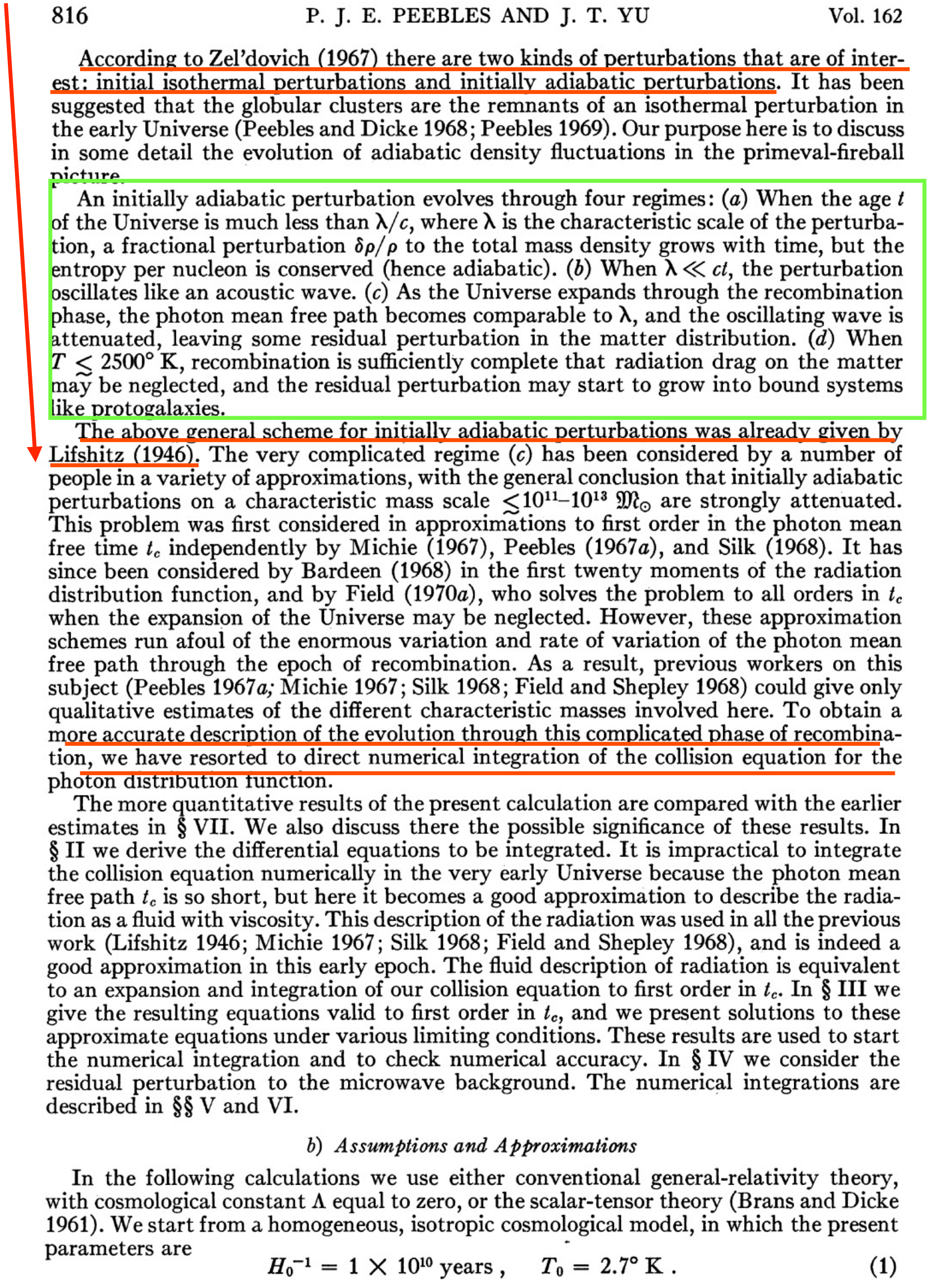
* Research supported in part at Princeton by the National Science Foundation and the Office of Naval Research of the U.S. Navy, and at the California Institute of Technology by the National Science Foundation [GP-15911 (formerly GP-9433) and GP-9114] and [Nonr-220(47)].

† 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.

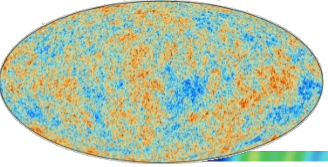
The above general scheme for initially adiabatic perturbations was already given by Lifshitz (1946). The very complicated regime (*c*) has been considered by a number of people in a variety of approximations, with the general conclusion that initially adiabatic perturbations on a characteristic mass 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.

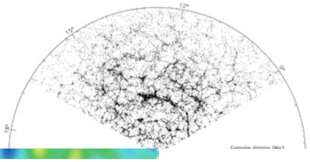
b) *Assumptions and Approximations*

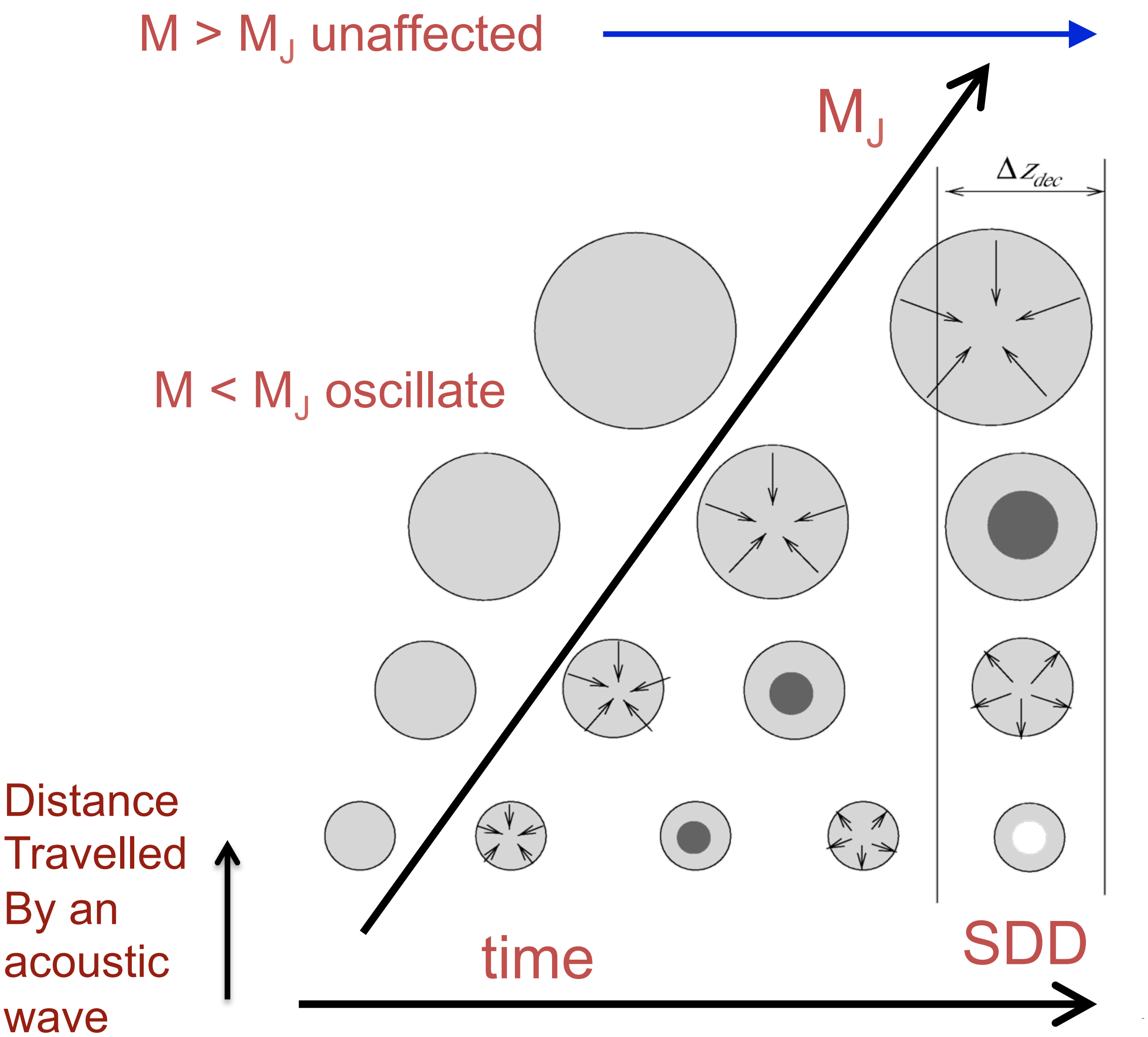
In the following calculations we use either conventional general-relativity theory, with cosmological constant Λ equal to zero, or the scalar-tensor theory (Brans and Dicke 1961). We start from a homogeneous, isotropic cosmological model, in which the present parameters are

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



Acoustic Oscillations





M > M_J unaffected

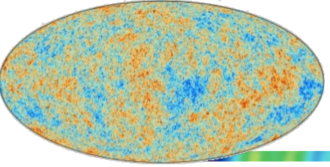
M_J

M < M_J oscillate

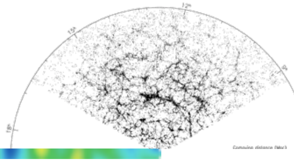
Distance Travelled By an acoustic wave

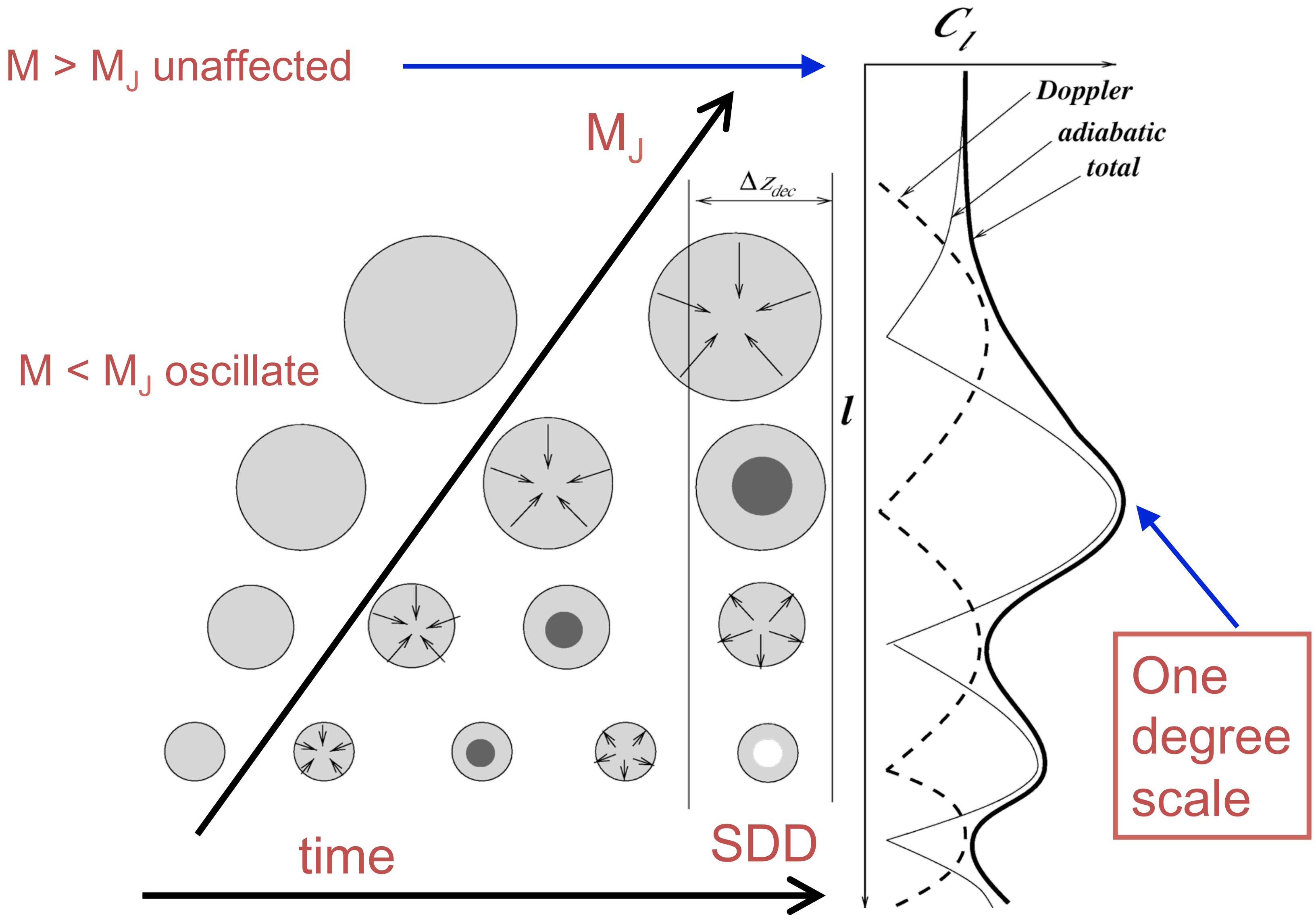
time

SDD



Acoustic Oscillations





M > M_J unaffected

M_J

M < M_J oscillate

time

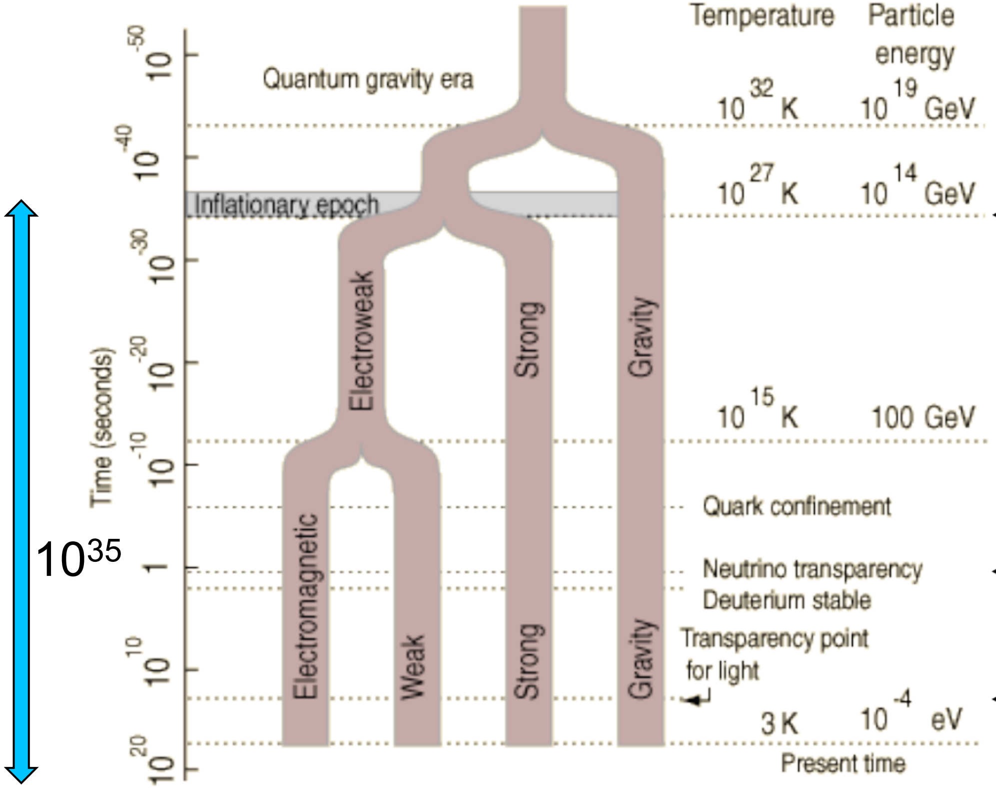
SDD

One degree scale

Generating the primordial fluctuations: When and How?

- Then the **Inflation** “framework” came along in 1979-1980 (Guth; Starobinsky), followed by Kazanos, Linde, Sato, Steinhardt, etc….
- 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!

The primordial Universe, ultimate laboratory for fundamental physics



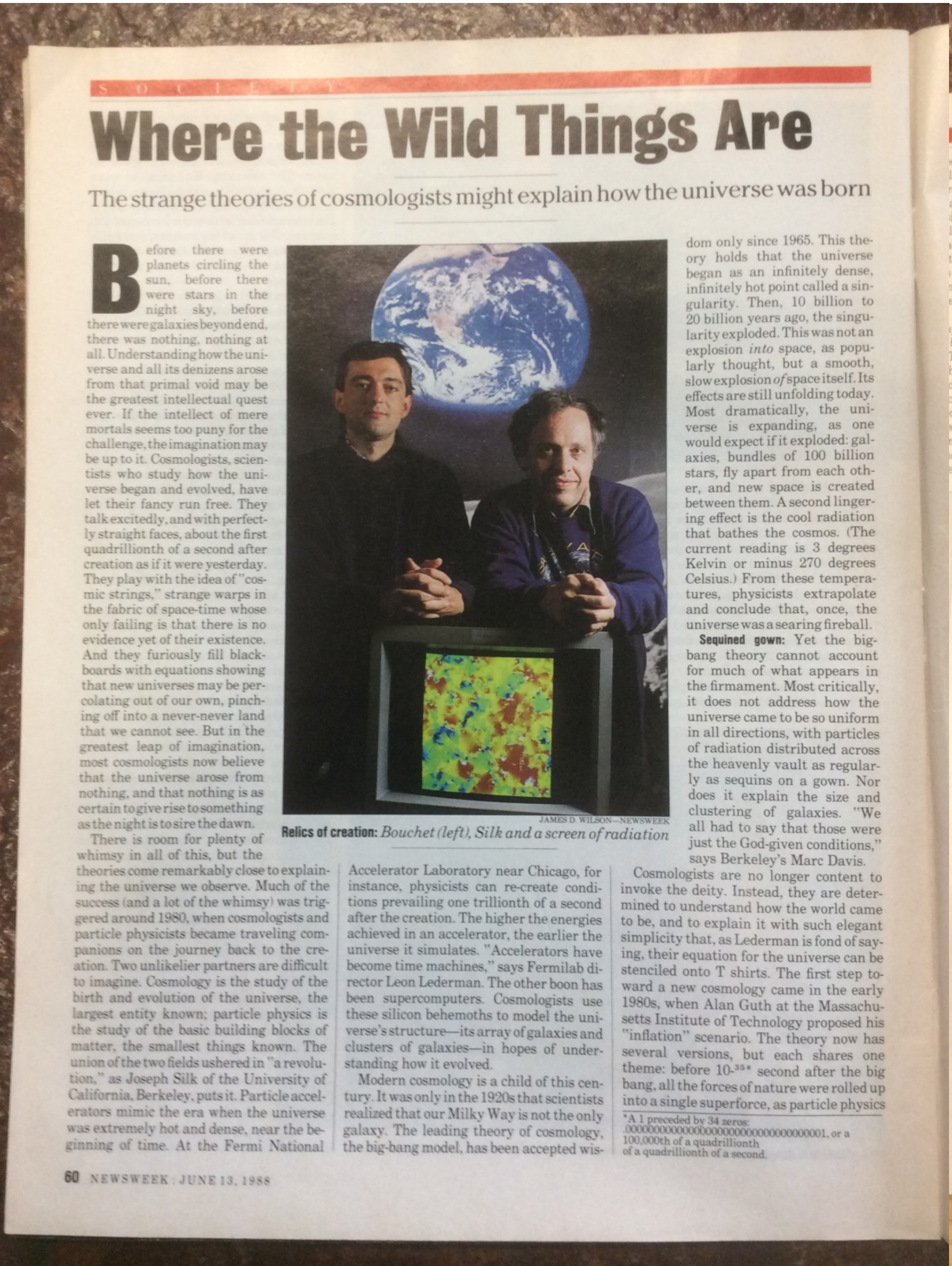
Inflation

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

Cosmic neutrino background

Cosmic microwave background

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 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

---

*A 1 preceded by 34 zeros: .0000000000000000000000000000000001, 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.

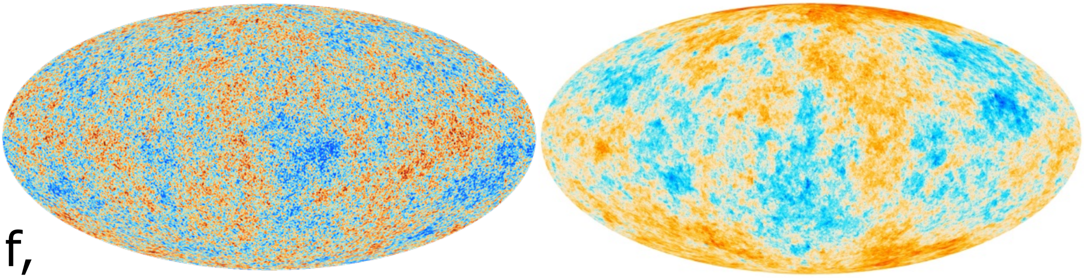
Lately astronomy has undermined some of the theories. This spring, telescope-gazers in Hawaii announced the discovery of a galaxy 12 billion years old, 2 billion years earlier than Davis's computer runs had predicted. And, since 1986, a group of astronomers who call themselves the Seven Samurai (paladins 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.

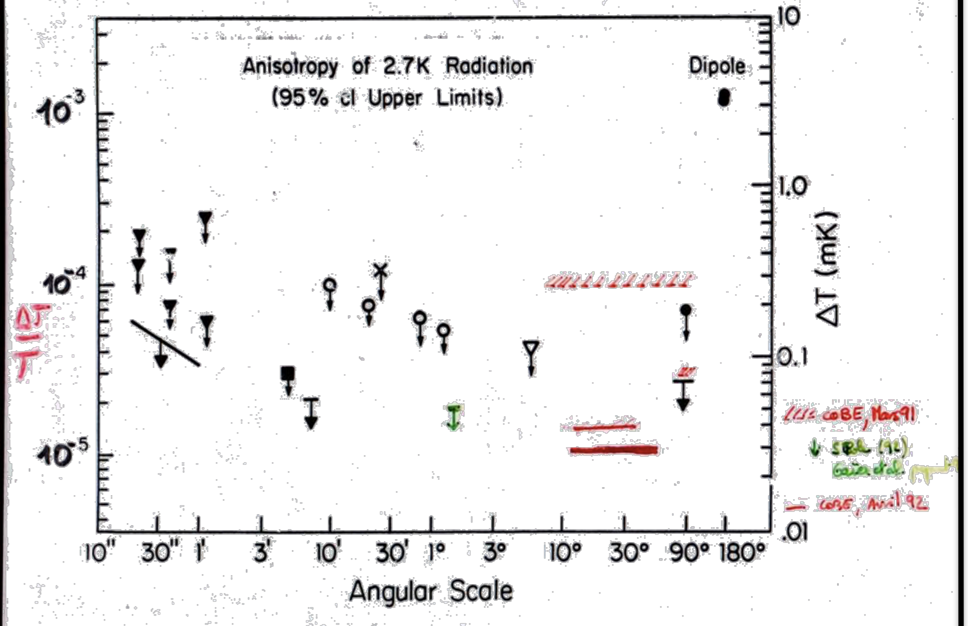
Cosmic strings seem to do a good job of explaining the pattern of galaxies as well as the voids between them, claims Albrecht. And last month physicists at Los Alamos National Laboratory suggested

Theorists precomputed possible imprints in various scenarii

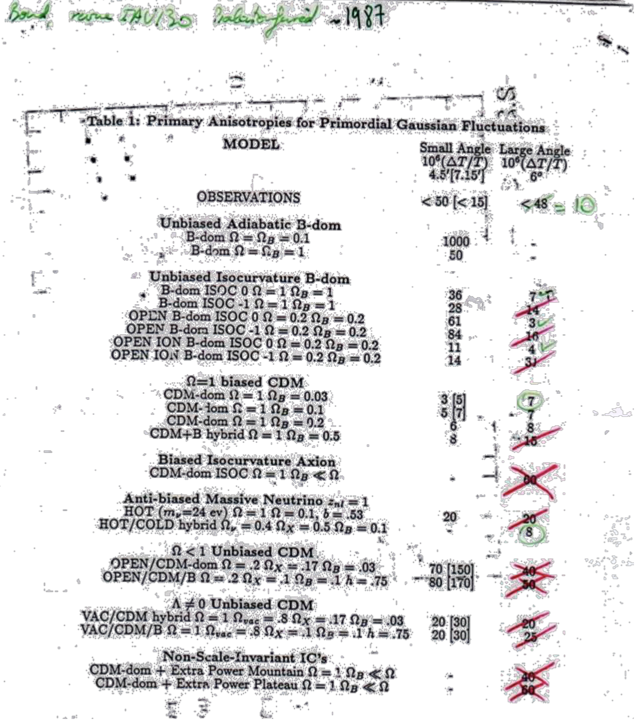


Gamow, Peebles, Yu, Sachs & Wolf, Sunyaev, Zeldovich, Silk, Vittorio, Wilson, Mukhanov, Chibisov, Bardeen, Linde, Bond, Efstathiou, Bouchet, Bennett, Gott, Kaiser, Stebbins, Allen, Shellard, Seljack, Zaldariaga, Kamionkowski, Hu, …

For different models and their *cosmological* parameters, which turn out to encode the content and determine the dynamics of the Universe and the origin of its large scale structures!



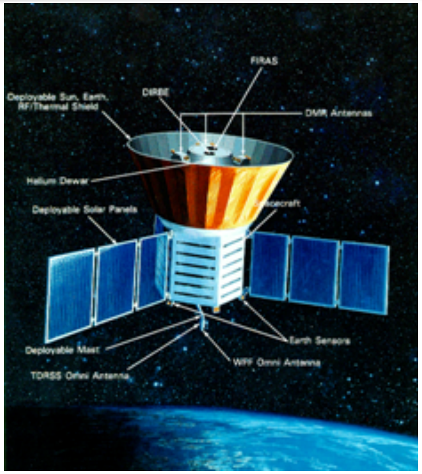
1.6: RMS variation of the CMBR temperature as a function of the angular
n of the two antennas (from [13]).



Bond revue IAU 130 Balatonfured ~1987

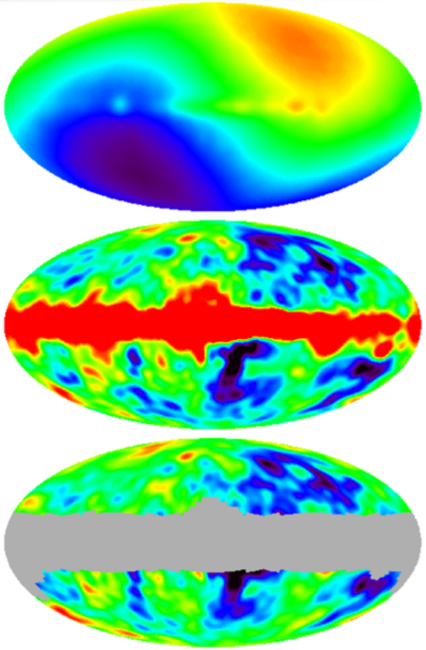
Table 1: Primary Anisotropies for Primordial Gaussian Fluctuations

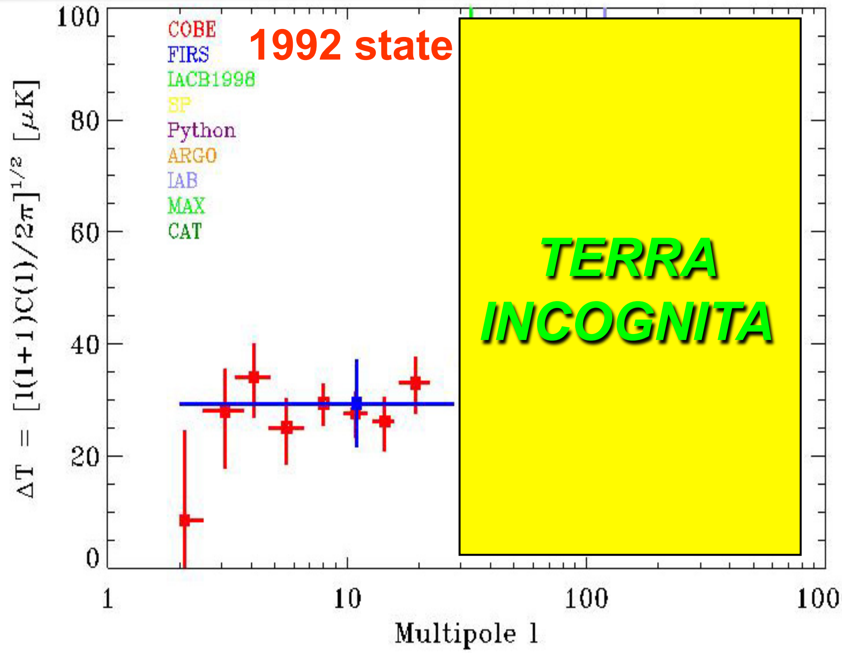
MODEL	Small Angle $10^6(\Delta T/T)$ $4.5'[7.15']$	Large Angle $10^6(\Delta T/T)$ $6°$
OBSERVATIONS	< 50 [< 15]	< 48 = 10
Unbiased Adiabatic B-dom		
B-dom $\Omega = \Omega_B = 0.1$	1000	-
B-dom $\Omega = \Omega_B = 1$	50	-
Unbiased Isocurvature B-dom		
B-dom ISOC 0 $\Omega = 1$ $\Omega_B = 1$	36	7 ✓
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	~~15~~
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 $\Omega = 1$ $\Omega_B \ll \Omega$	-	~~40~~
CDM-dom + Extra Power Plateau $\Omega = 1$ $\Omega_B \ll \Omega$	-	~~60~~



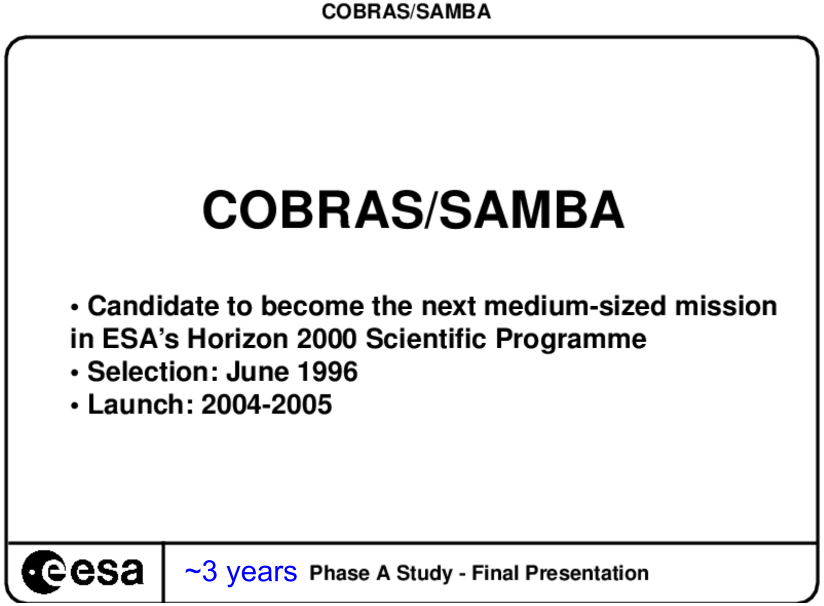
DMR/Smoot

Physics 2006





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

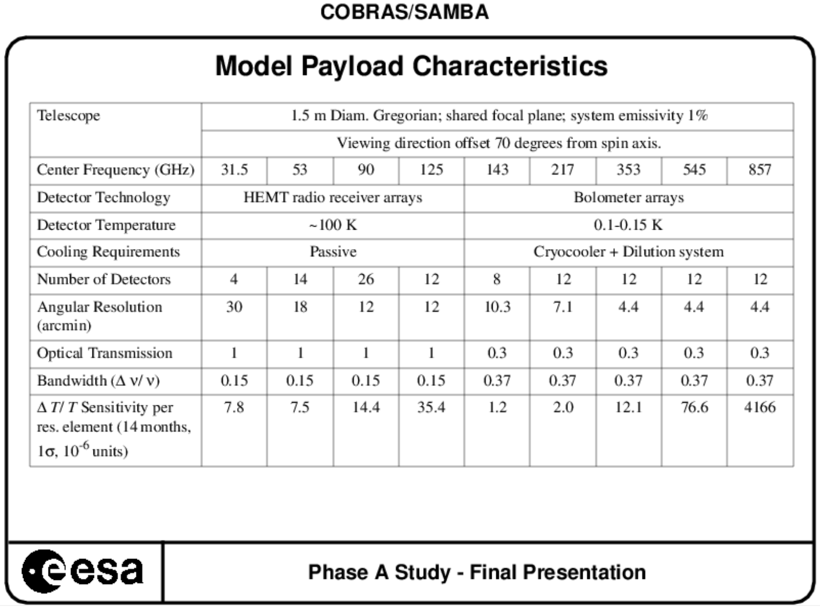


COBRAS/SAMBA

COBRAS/SAMBA

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

~3 years **Phase A Study - Final Presentation**

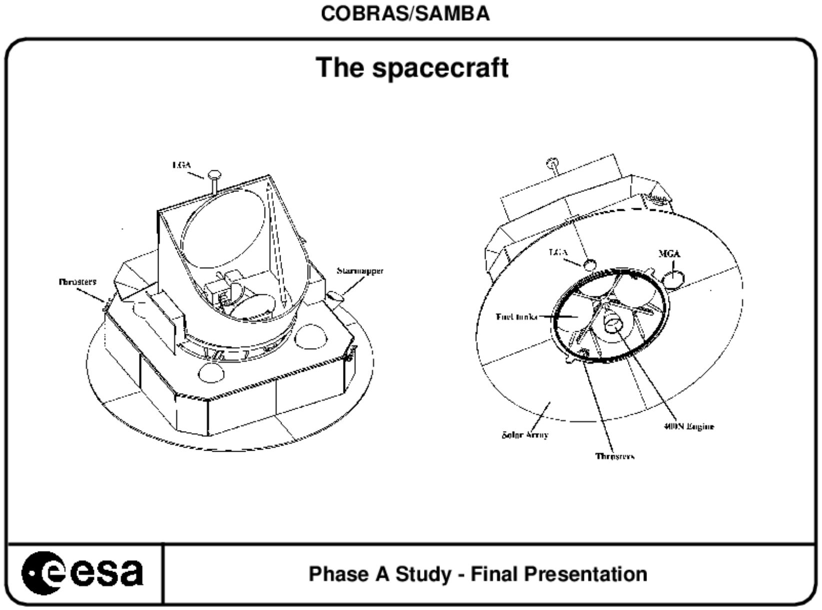


COBRAS/SAMBA

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

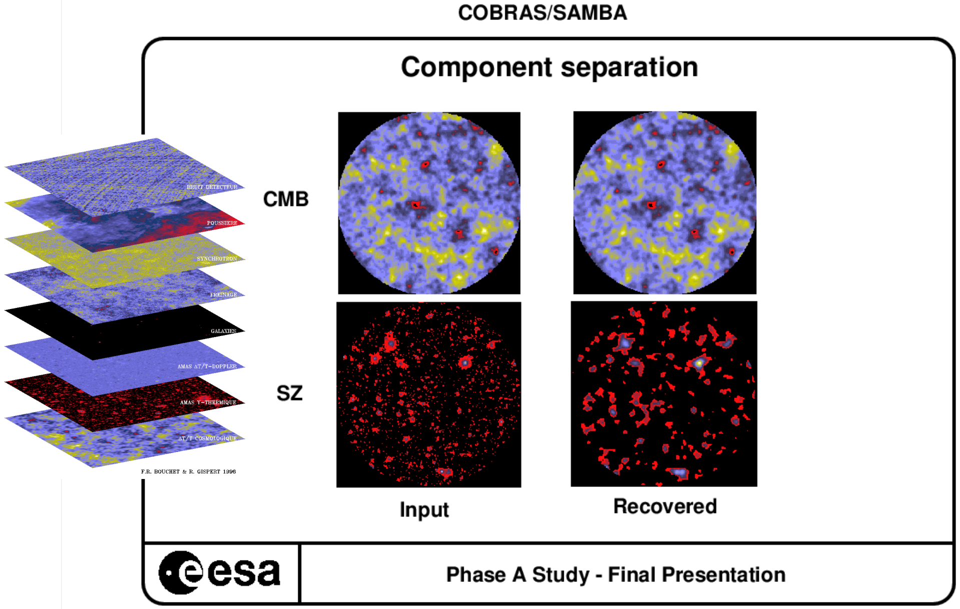
Phase A Study - Final Presentation



COBRAS/SAMBA

The spacecraft

Phase A Study - Final Presentation



COBRAS/SAMBA

Component separation

F.R. BOUCHET & R. GISPERT 1996

Phase A Study - Final Presentation

March 1996 selection, Unesco (Paris)

COBRAS/SAMBA

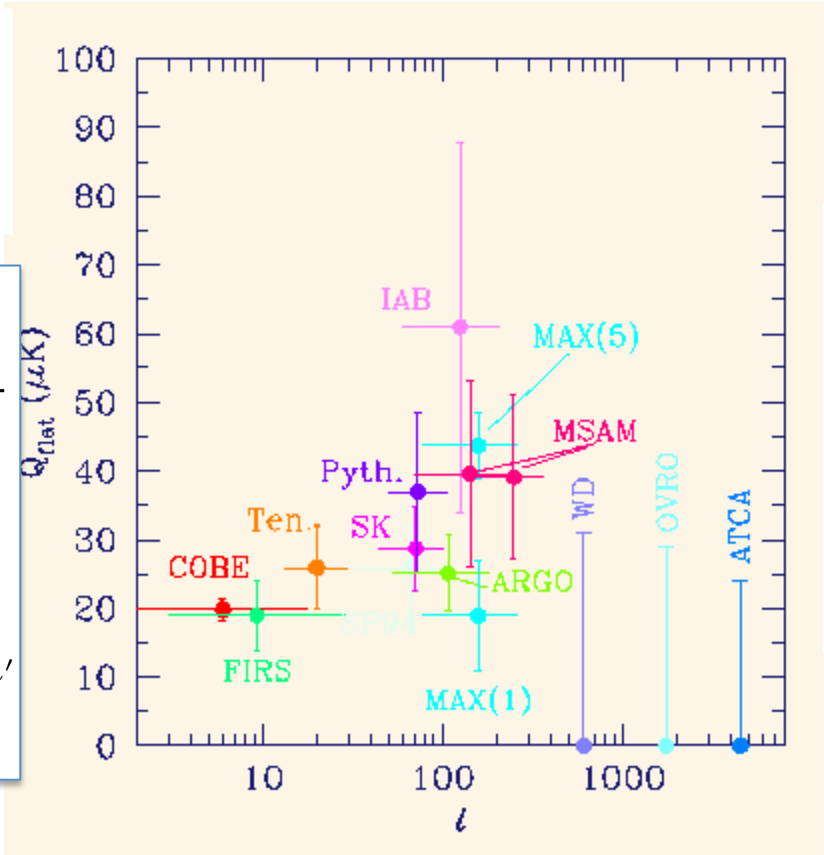
Observational Status

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

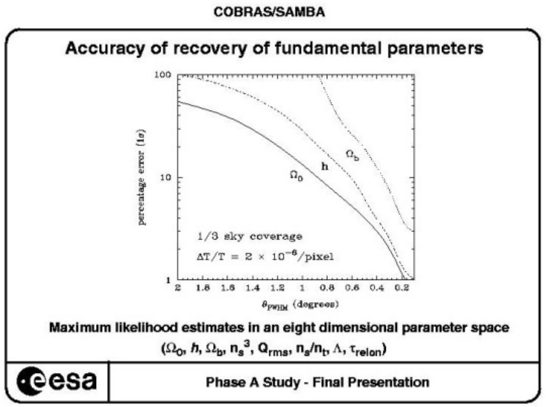
$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell+1}$$

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

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



Phase A Study - Final Presentation



COBRAS/SAMBA

Accuracy of recovery of fundamental parameters

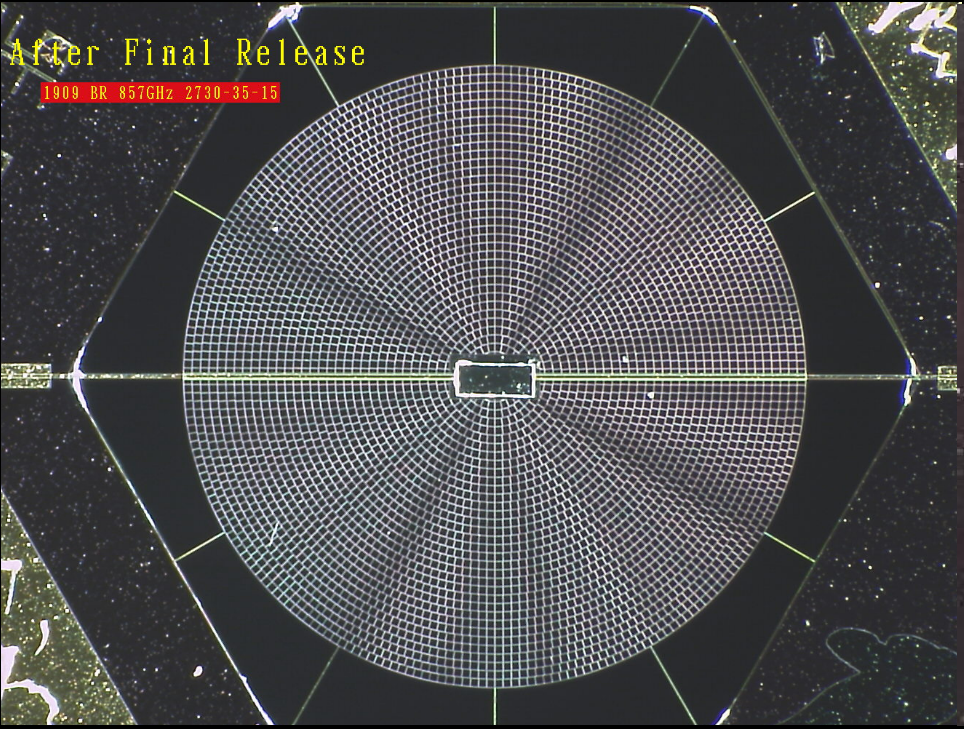
Maximum likelihood estimates in an eight dimensional parameter space

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

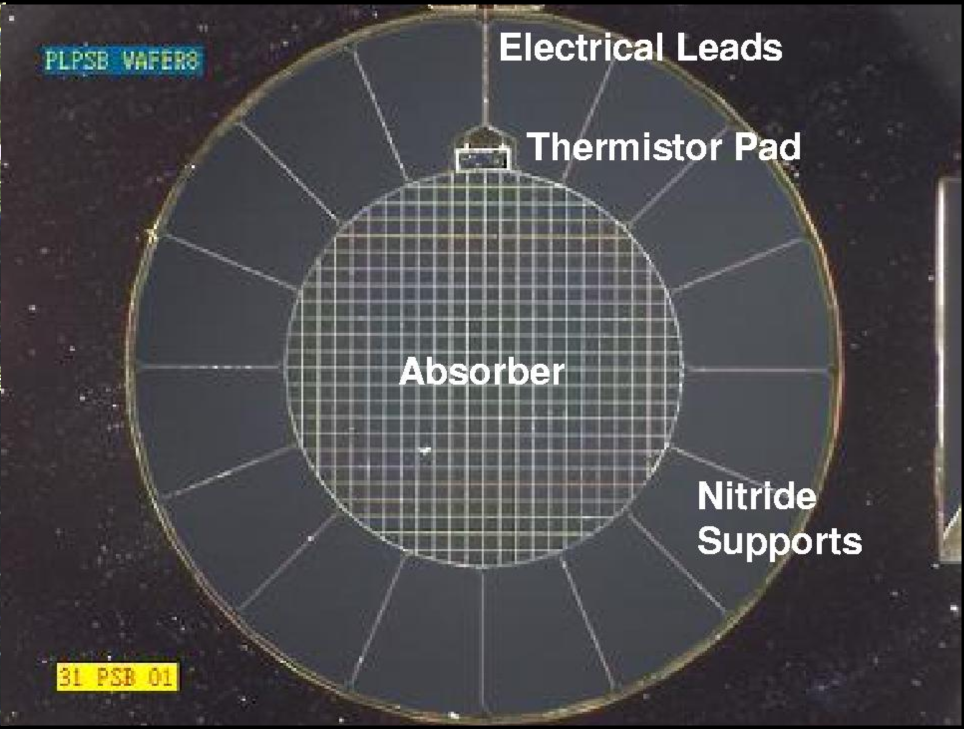
Phase A Study - Final Presentation

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

HFI Spider Web Bolometers & PSBs



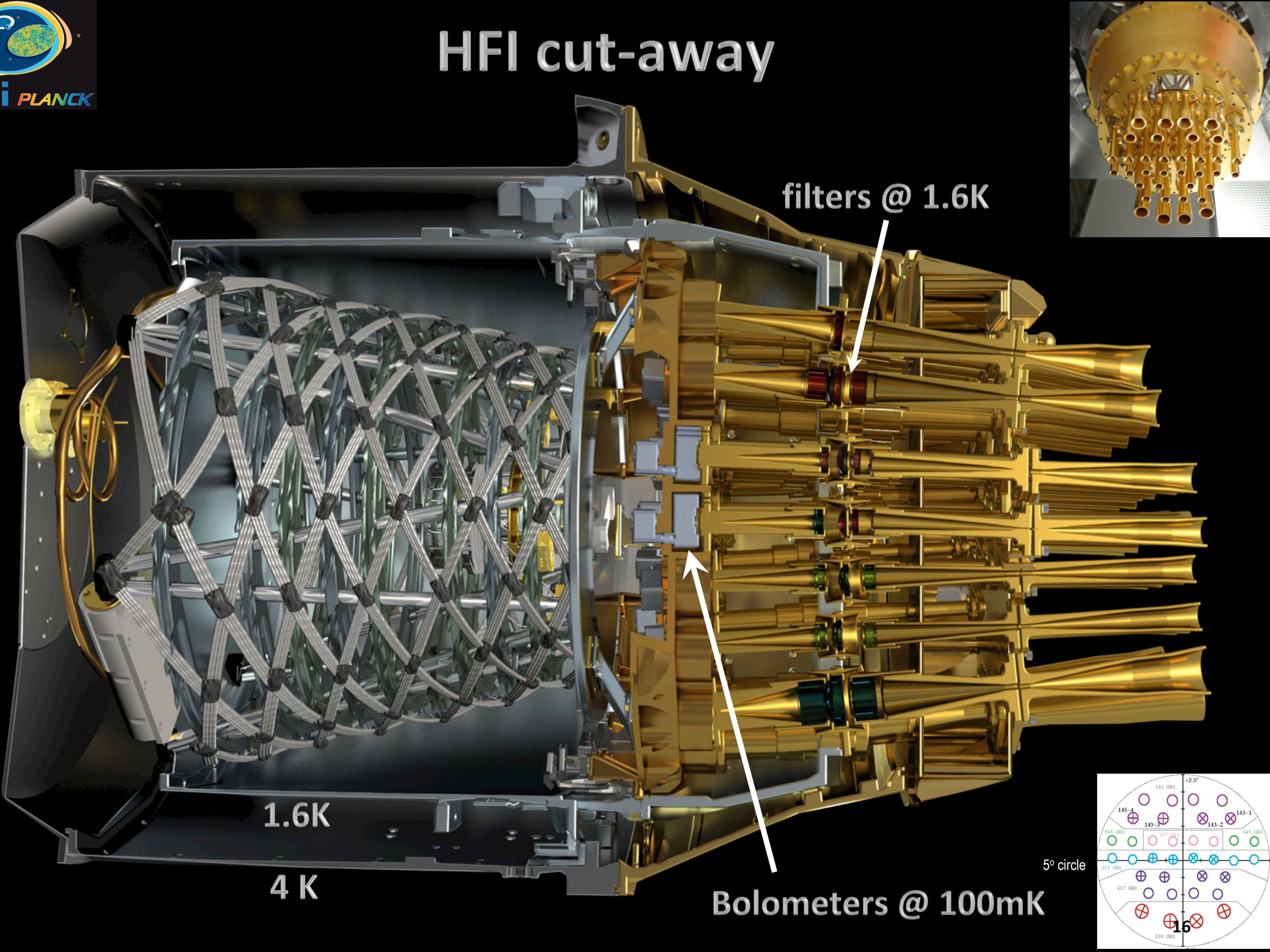
857 GHz SpiderWeb Bolometer



145 GHz PolarSensitiveBolometers

HFI flight bolometers have been built by Caltech/JPL,
integrated into pixels and tested in Cardiff,
integrated into HFI – notably: IAS + JFET (Rome) + REU (CESR) + DPU (LAL)
and then tested at instrument level @ IAS, Orsay.
(and all their data is collected/processed @ IAP, Paris)

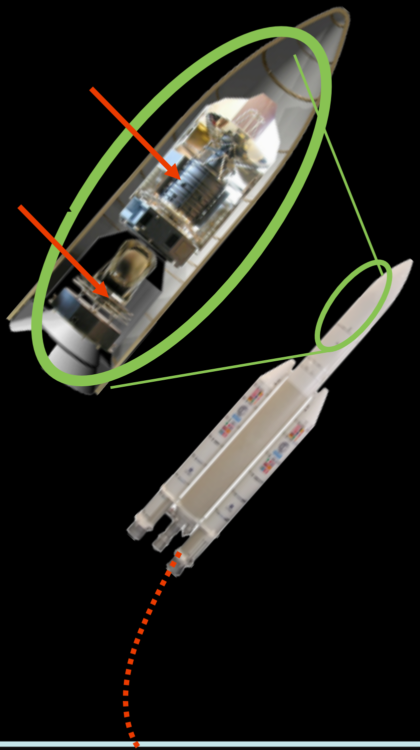
HFI cut-away

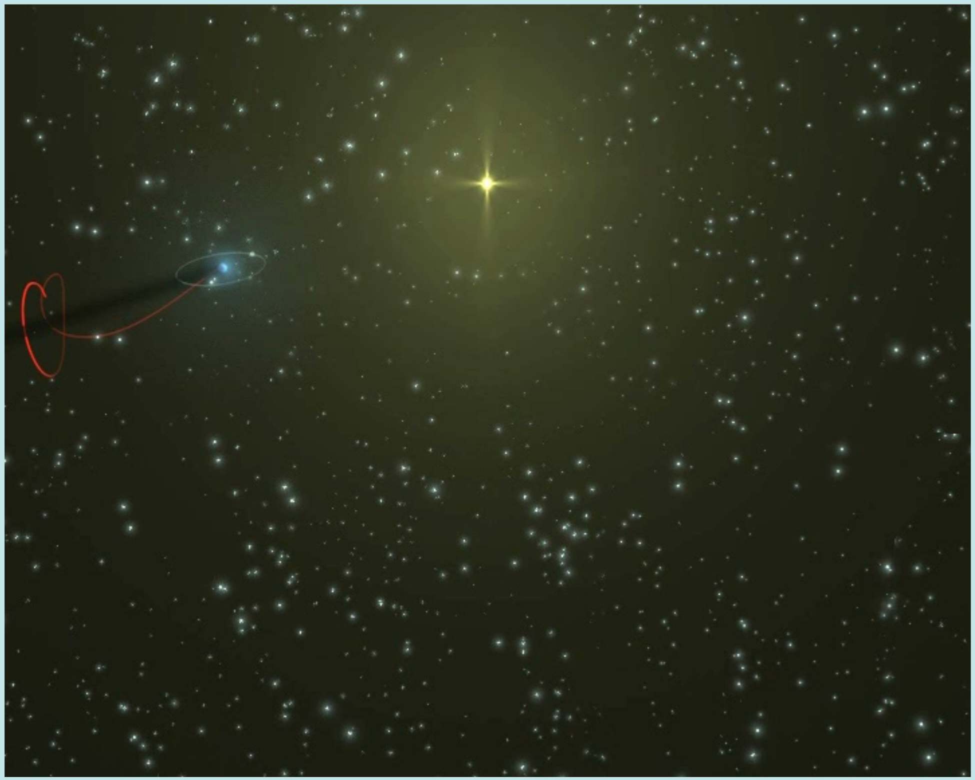

filters @ 1.6K
1.6K
4 K
Bolometers @ 100mK
5° circle
+2.5°
143 GHz
143–4
143–3
143–2
143–1
545 GHz
857 GHz
545 GHz
353 GHz
217 GHz
100 GHz

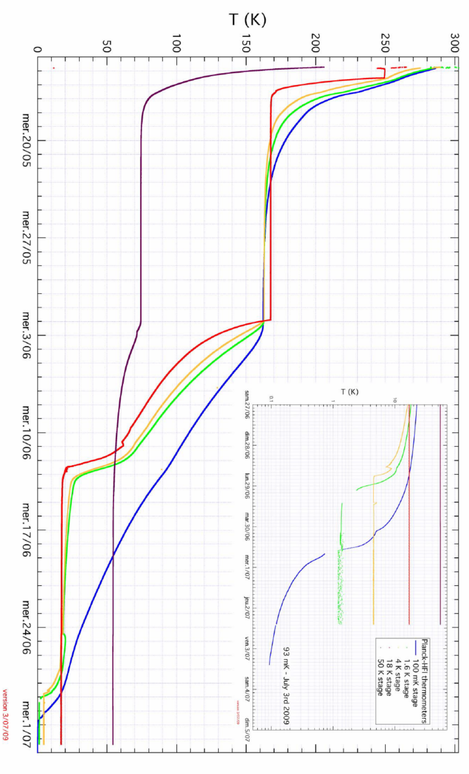
Birth of the Cool

DUSTING IT OFF...

AFTER 16 YEARS
OF HOPES & WORK






T (K)
0
50
100
150
200
250
300
mer.20/05
mer.27/05
mer.3/06
mer.10/06
mer.17/06
mer.24/06
mer.1/07
version 3/07/09
T (K)
0.1
1
10
sam.27/06
dim.28/06
lun.29/06
mar.30/06
mer.1/07
jeu.2/07
ven.3/07
sam.4/07
dim.5/07
Planck-HFI thermometers
100 mK stage
1.6 K stage
4 K stage
18 K stage
50 K stage
93 mK - July 3rd 2009

Slow revelation…

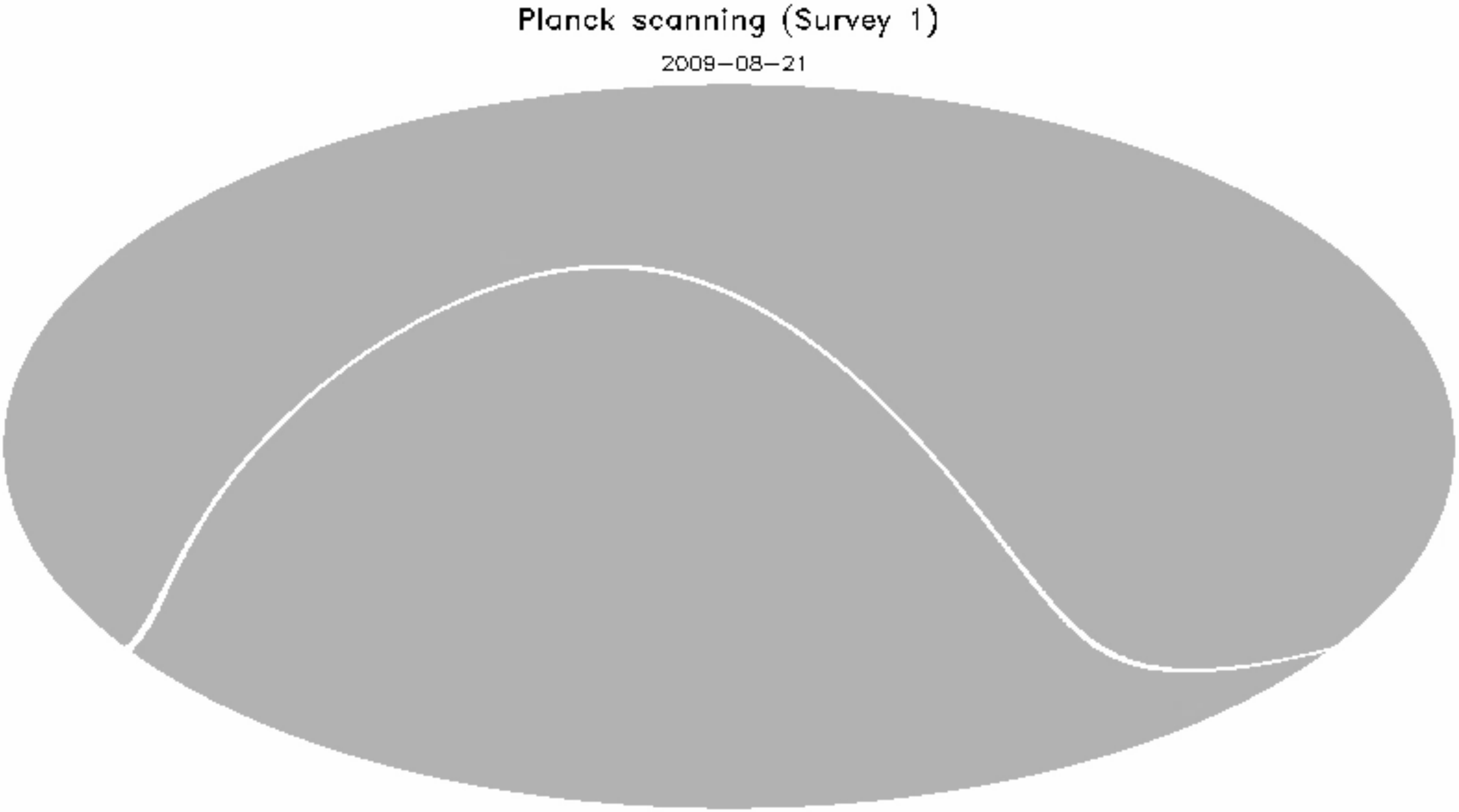
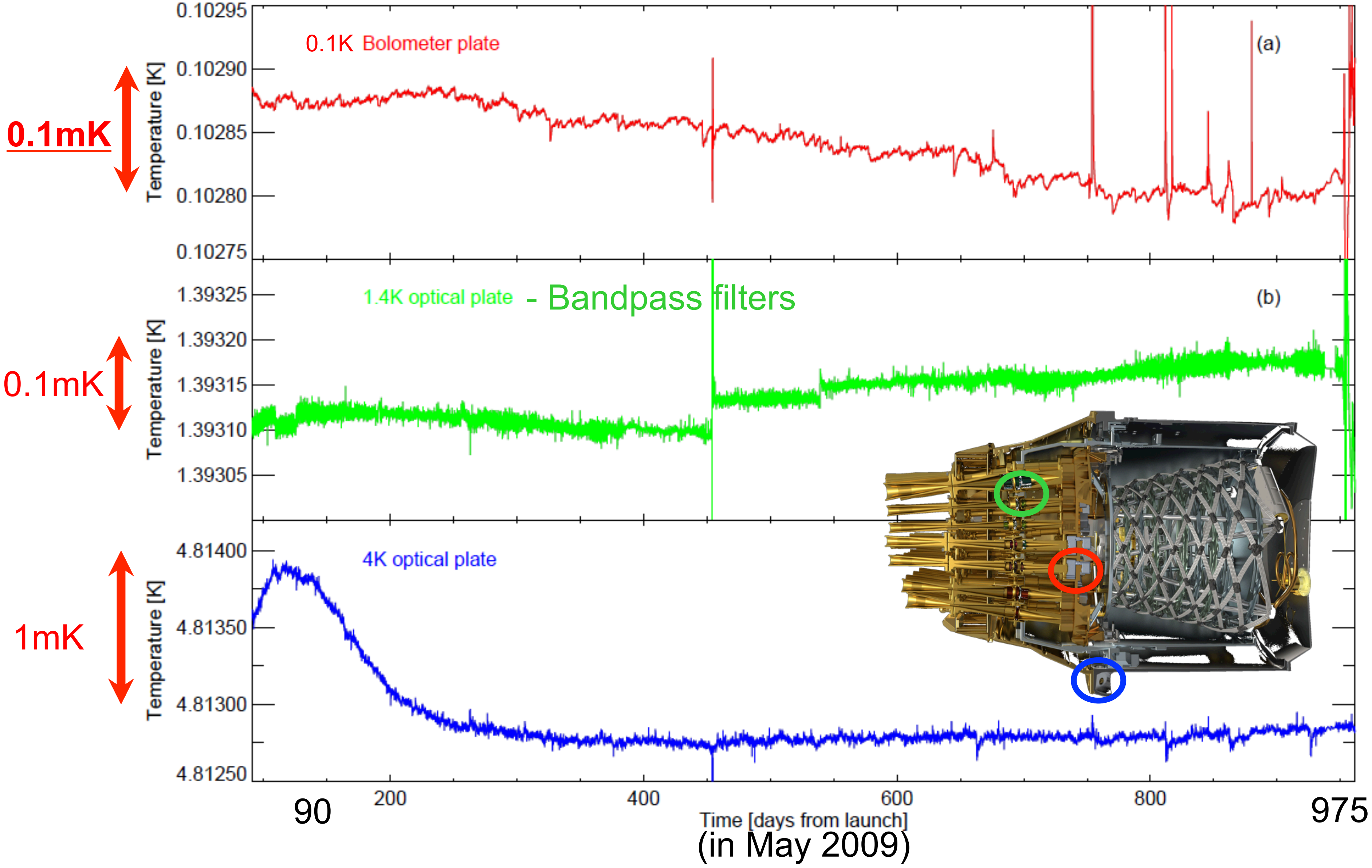


Image credit: ESA/Planck/C.North

Very cold, very stable, a very long time…



The HFI DPC in IAP Cellar…

+ CC/CINECA/ Darwin/NERSC…

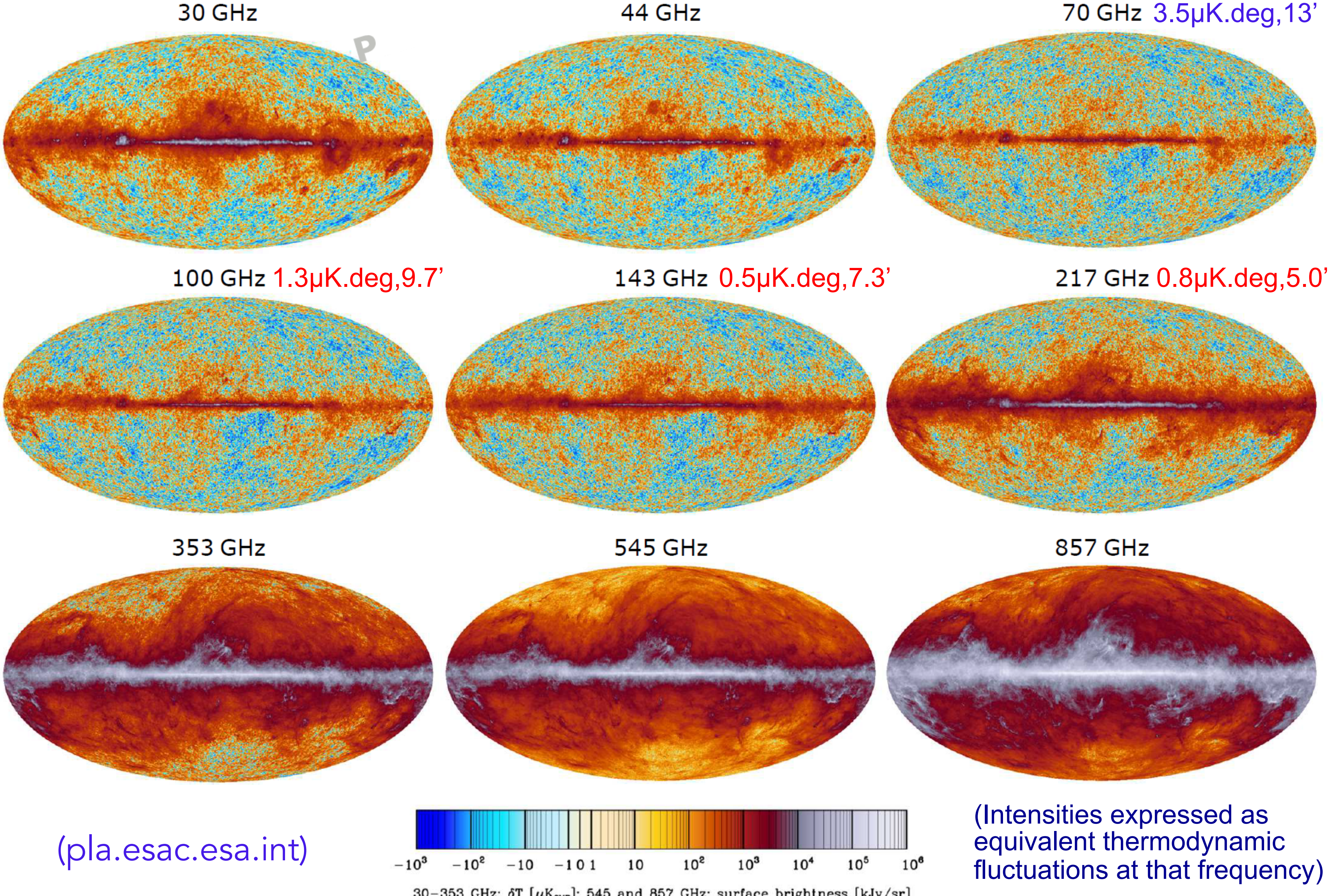
Data Processing

- Physics → CMB sky → Frequency skies → TOI
- TOI → frequency maps → CMB maps → Physics

- One needs to write and verify a model of TOI = f(Physics) and to "invert" it and to assess errors (or to sample parameters).
  - *The frequency response is measured on the ground.*
  - *The optical response is measured on the ground, modelled, and partially verified on planets, Crab, etc.*
  - *The detector chain response is measured on ground*
  - *A full simulation phase was built (MC)...*
- One uses templates (Thermometers, foreground tracers) and redundancy

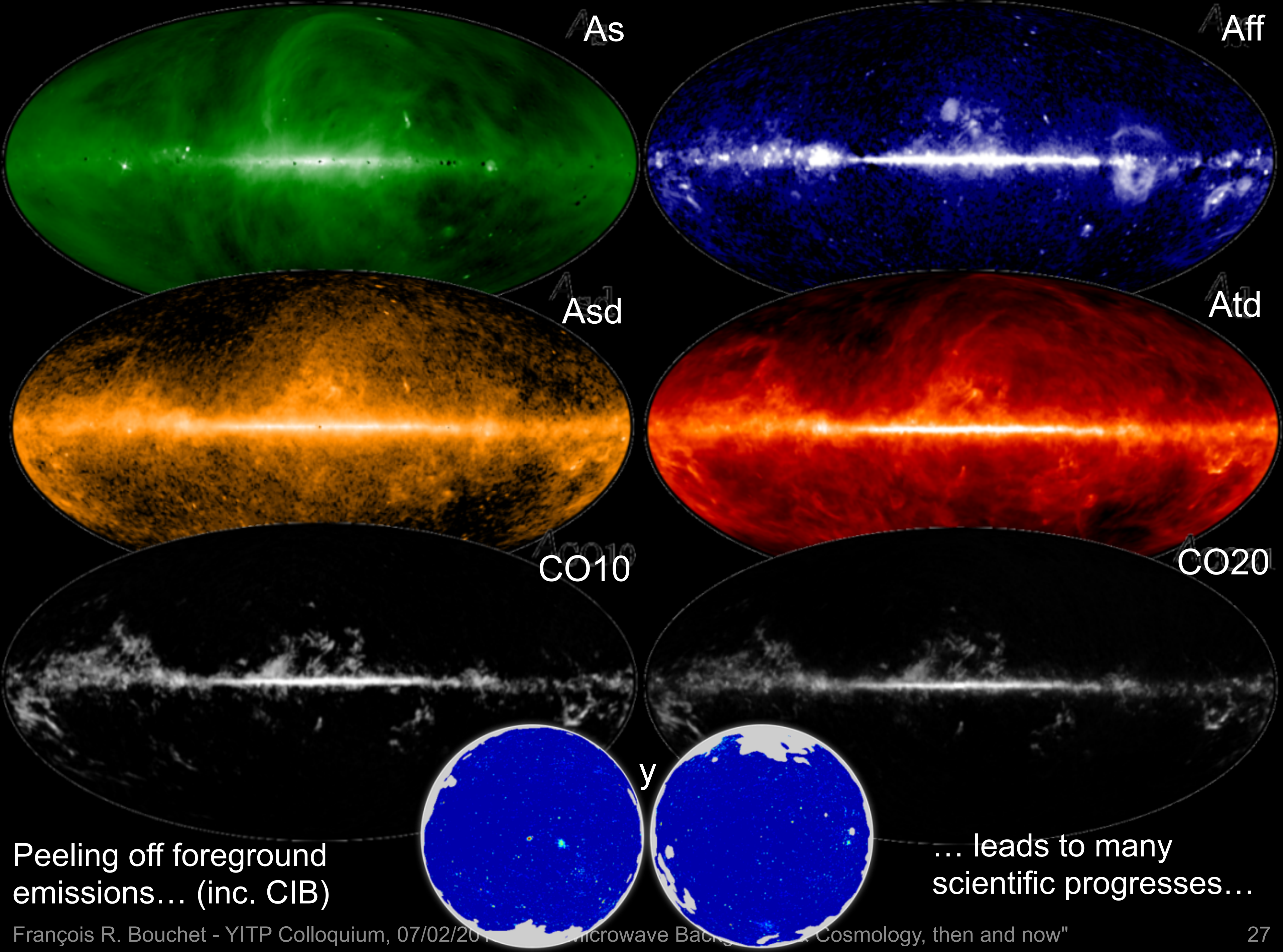
- Many Interesting challenges: *optimality/speed, propagation of separation errors, exploration of large dimensionality spaces... in addition to herding a large cat population, and taming surprises in the data*

Planck 2015 Temperature maps



(pla.esac.esa.int)

(Intensities expressed as equivalent thermodynamic fluctuations at that frequency)

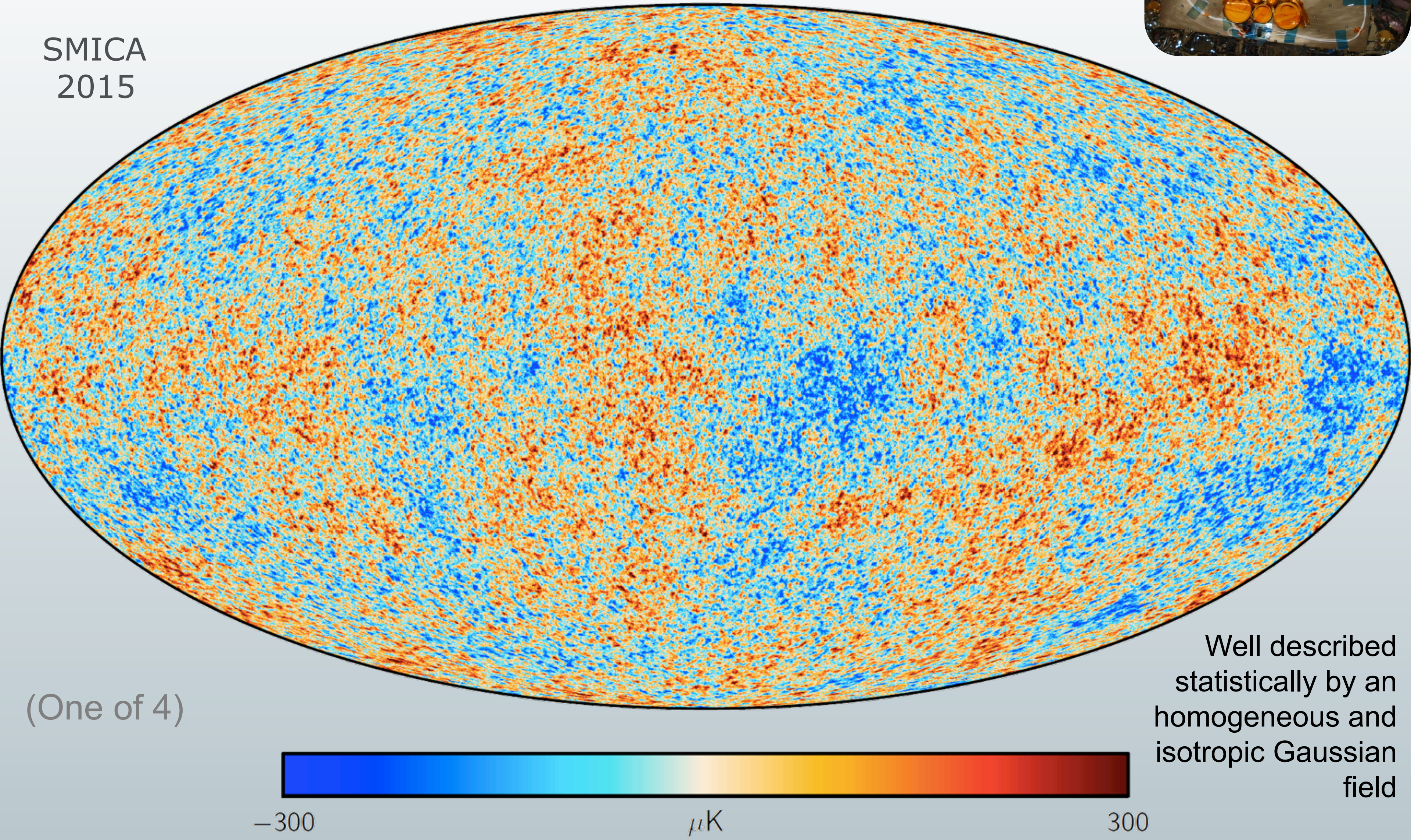


Peeling off foreground emissions… (inc. CIB)

… leads to many scientific progresses…

Planck 2015 T anisotropies map

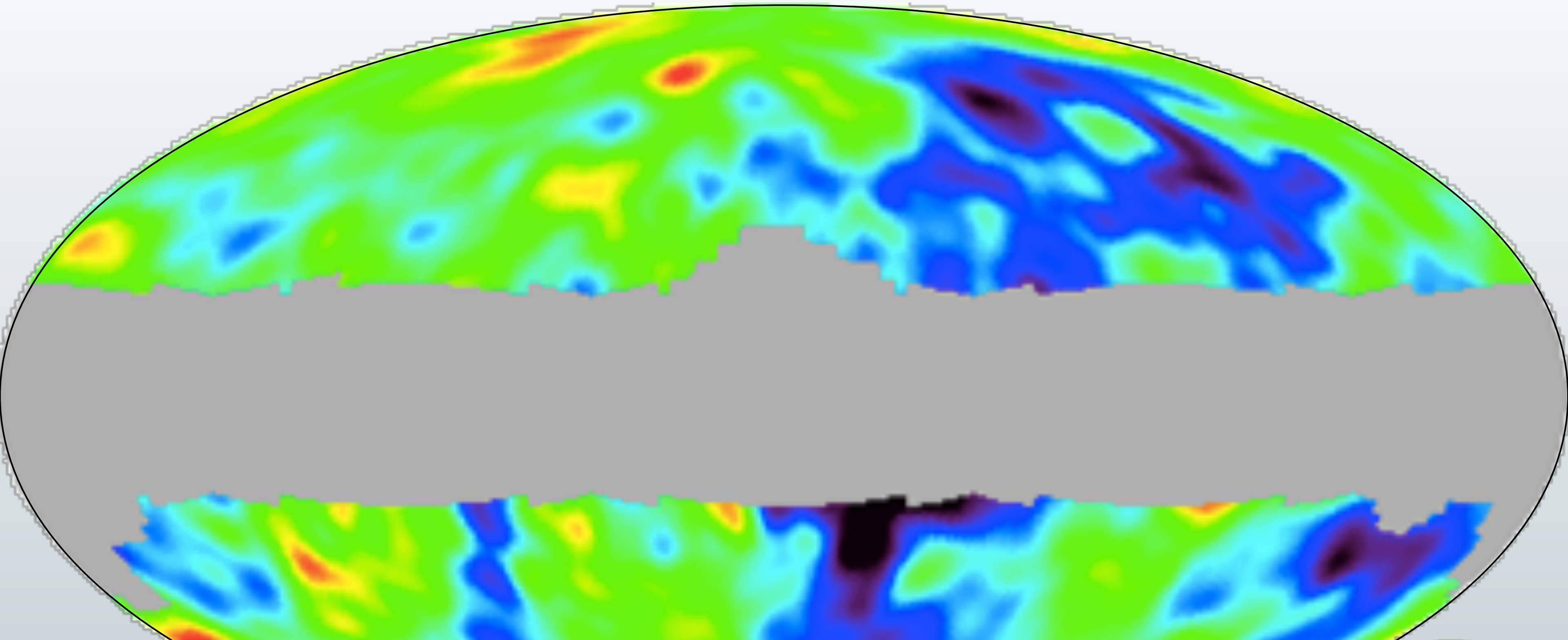
SMICA
2015



(One of 4)

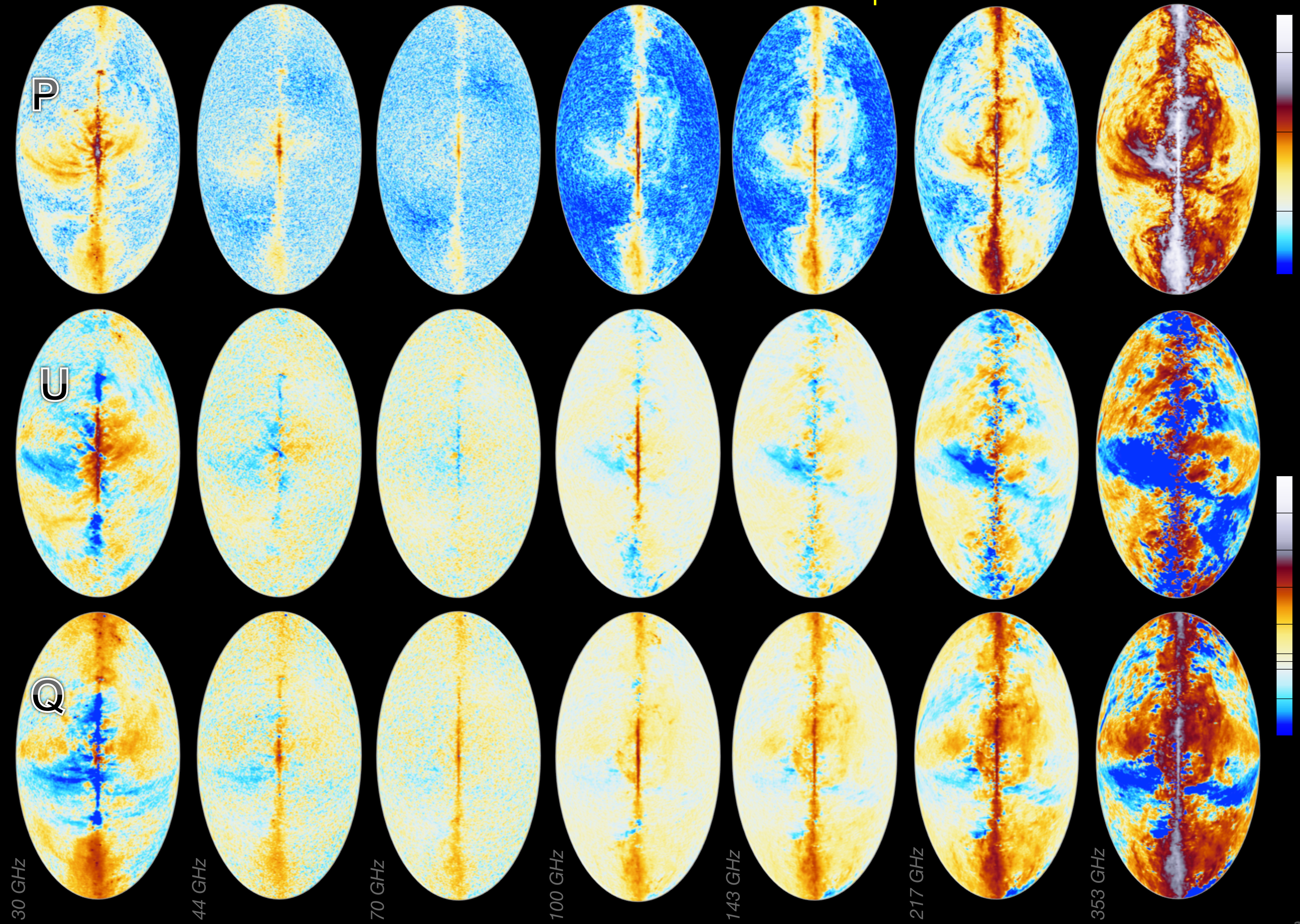
Well described statistically by an homogeneous and isotropic Gaussian field

COBE/DMR T anisotropies map

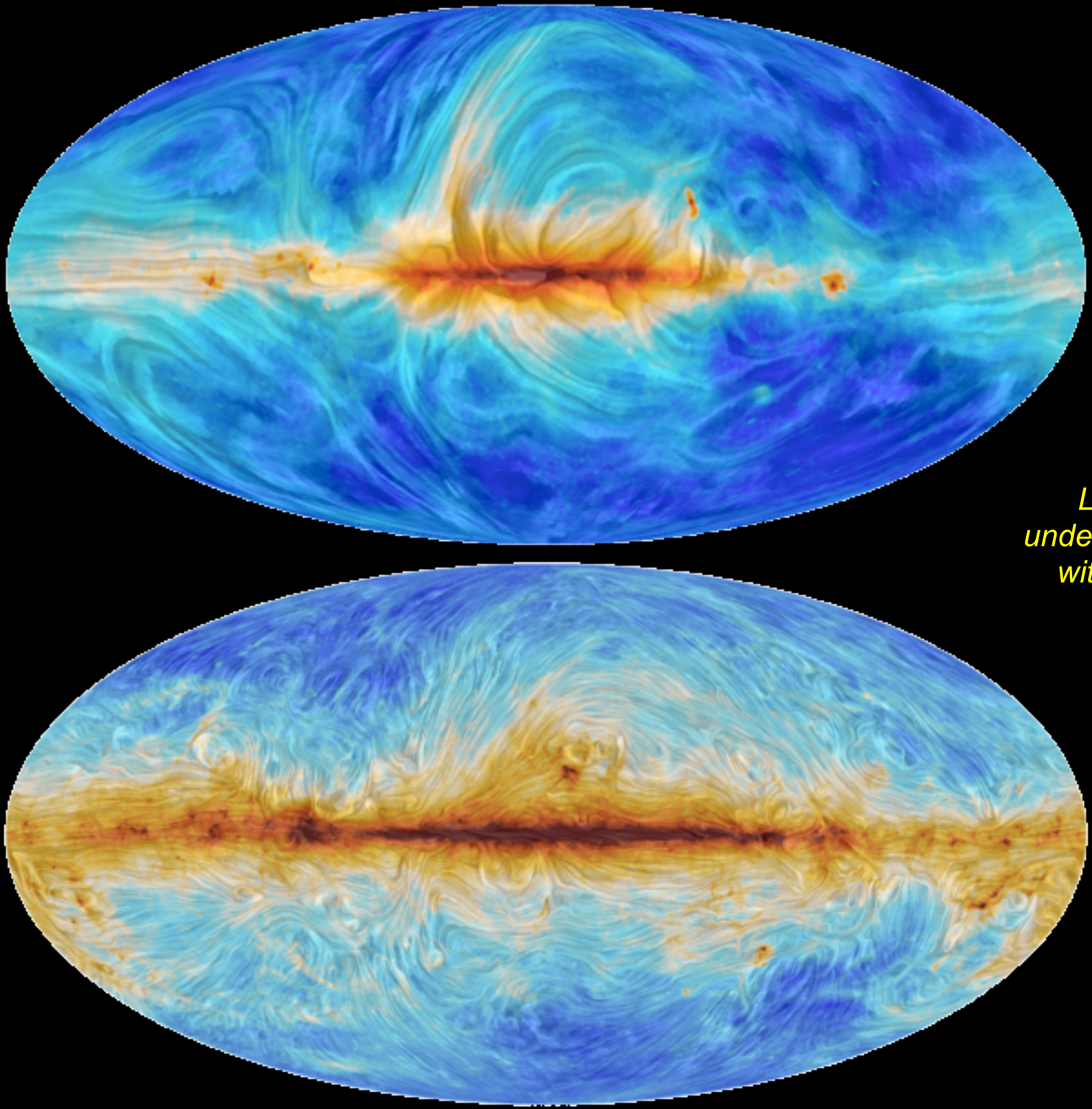


We have essentially finished mining the cosmological Temperature anisotropies revealed by DMR (and improved upon by WMAP)

Planck 2015 Polarisation maps



Planck 2015 Polarisation & Galactic foregrounds



30 GHz

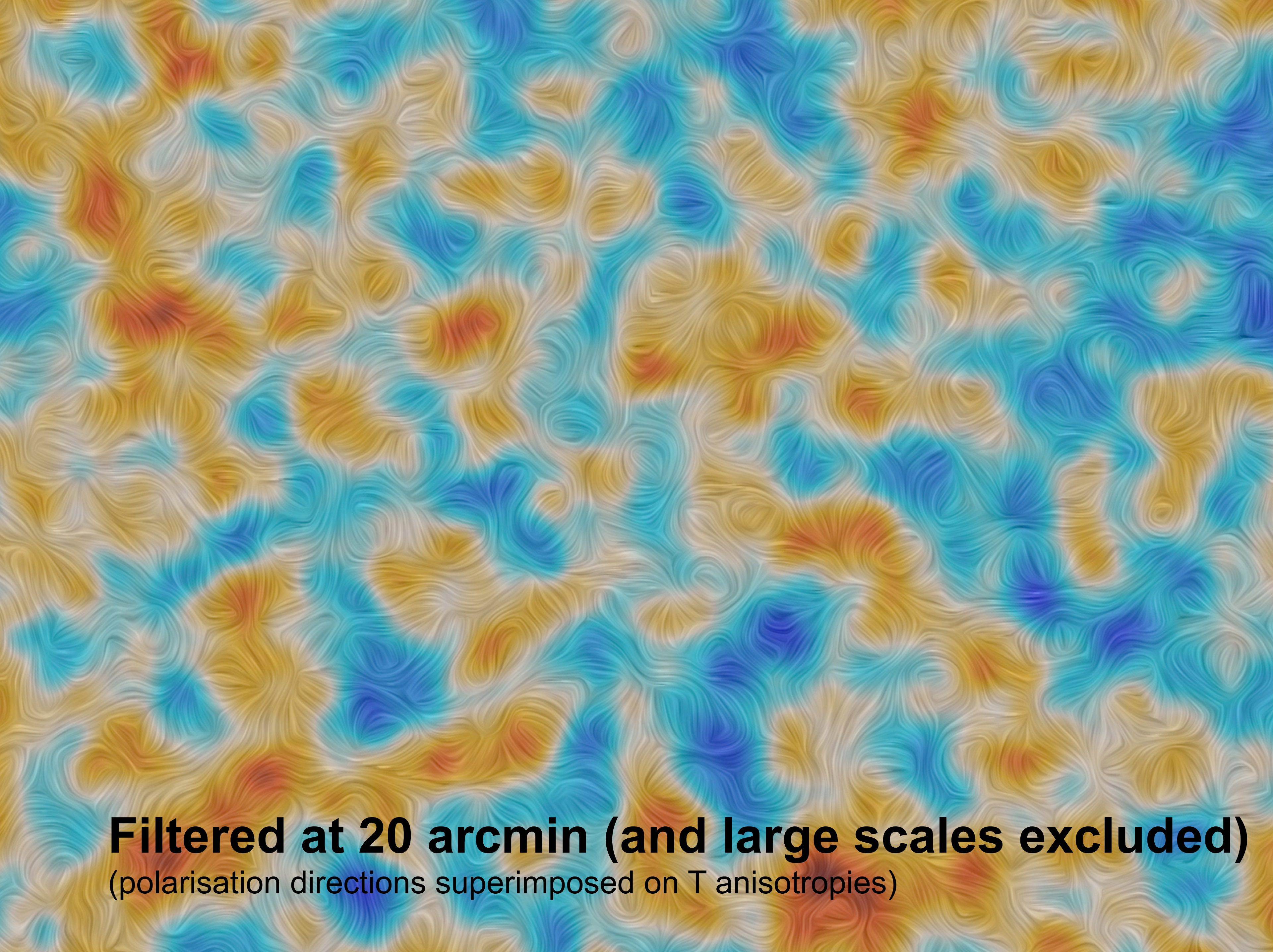
Synchrotron

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

357 GHz

Thermal dust in magnetic field

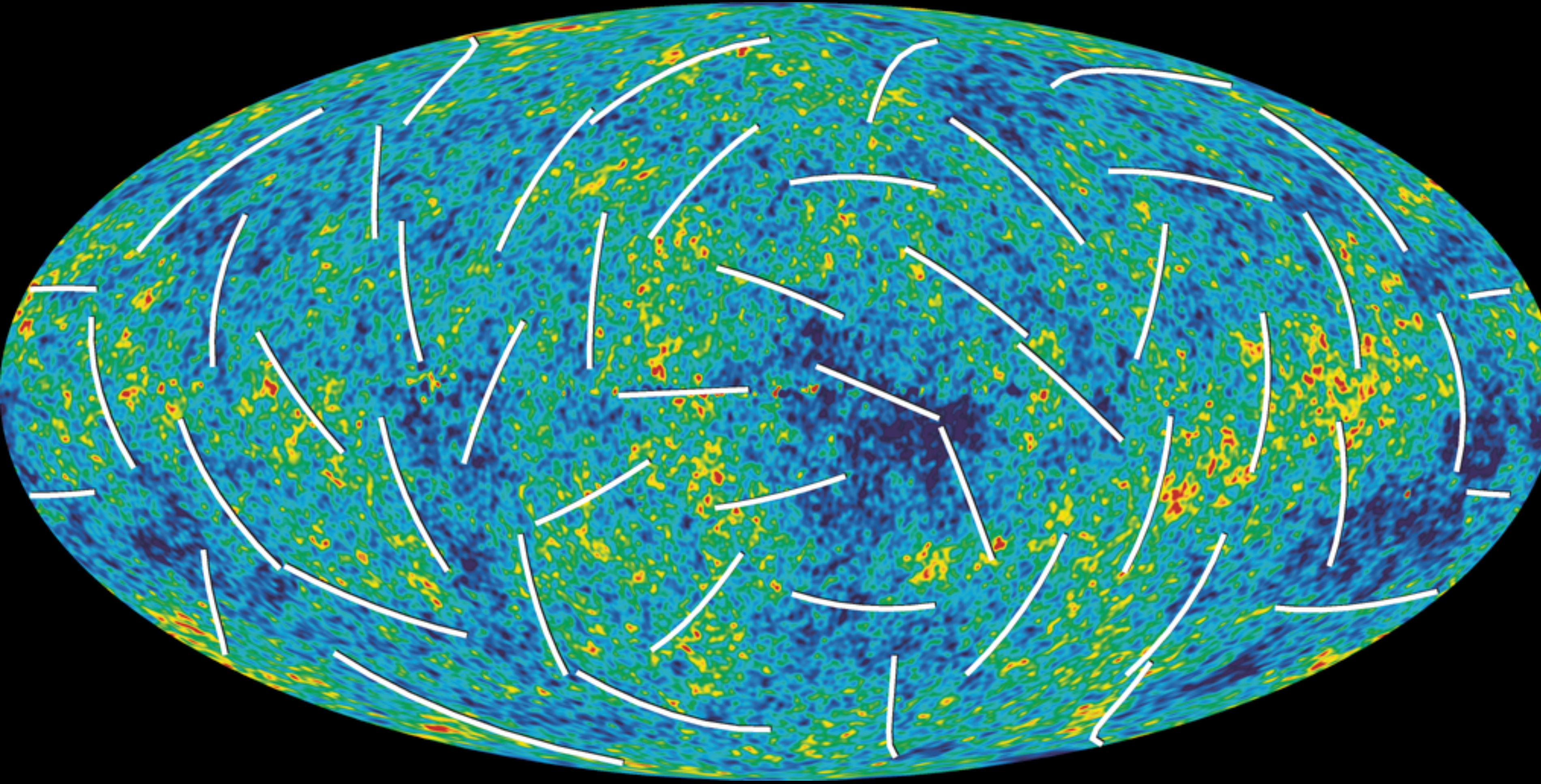
Lines indicate the magnetic field direction, Colors indicate the emission intensity



Filtered at 20 arcmin (and large scales excluded)

(polarisation directions superimposed on T anisotropies)

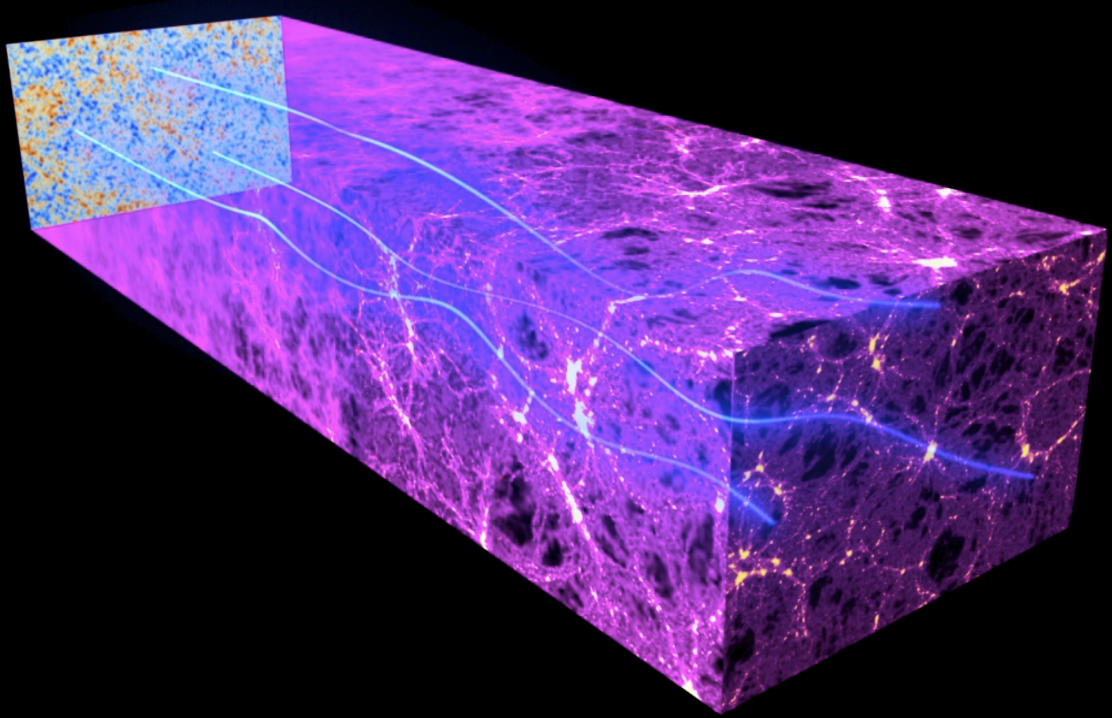
What we already knew (from WMAP)



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

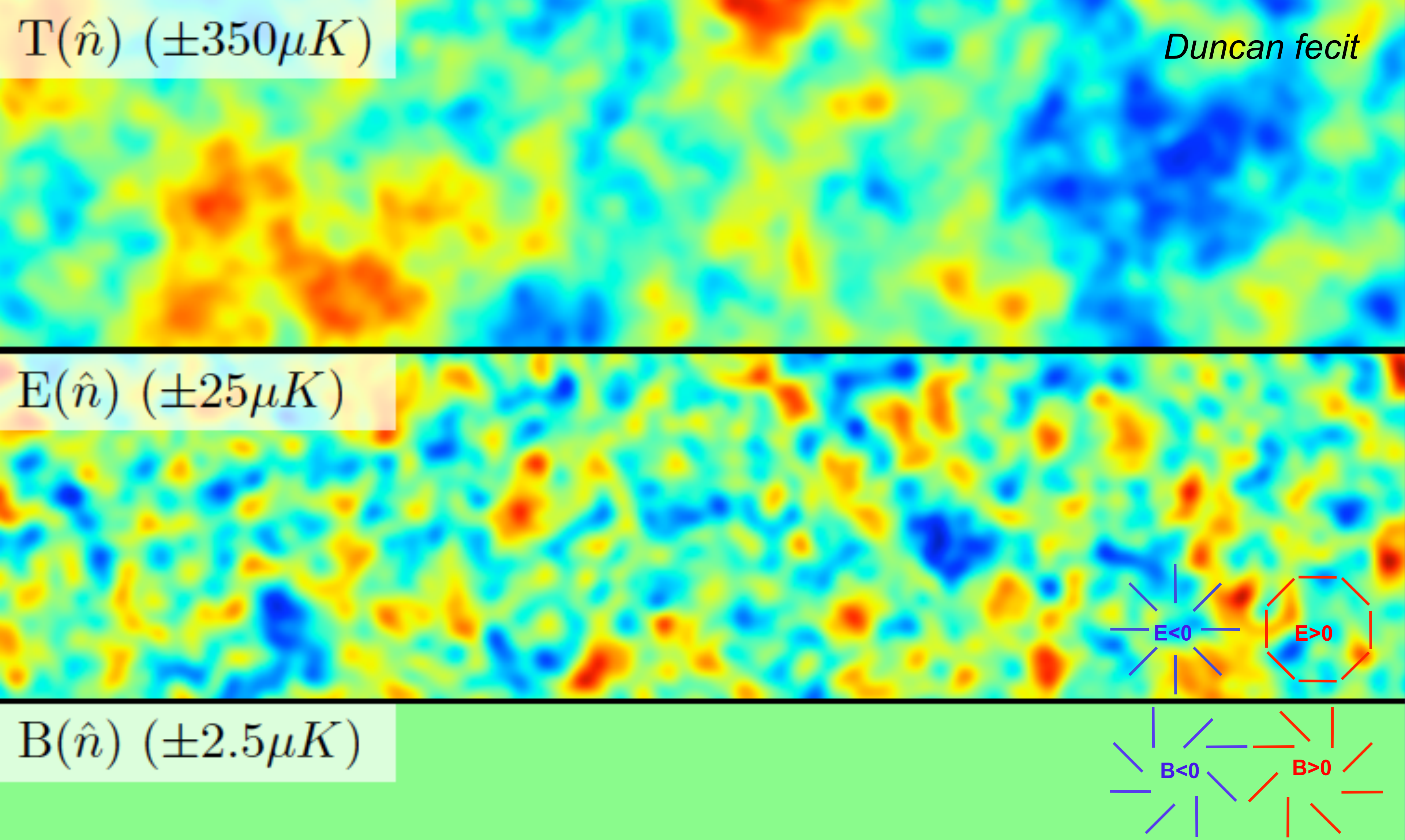
GRAVITATIONAL LENSING DISTORTS IMAGES

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)

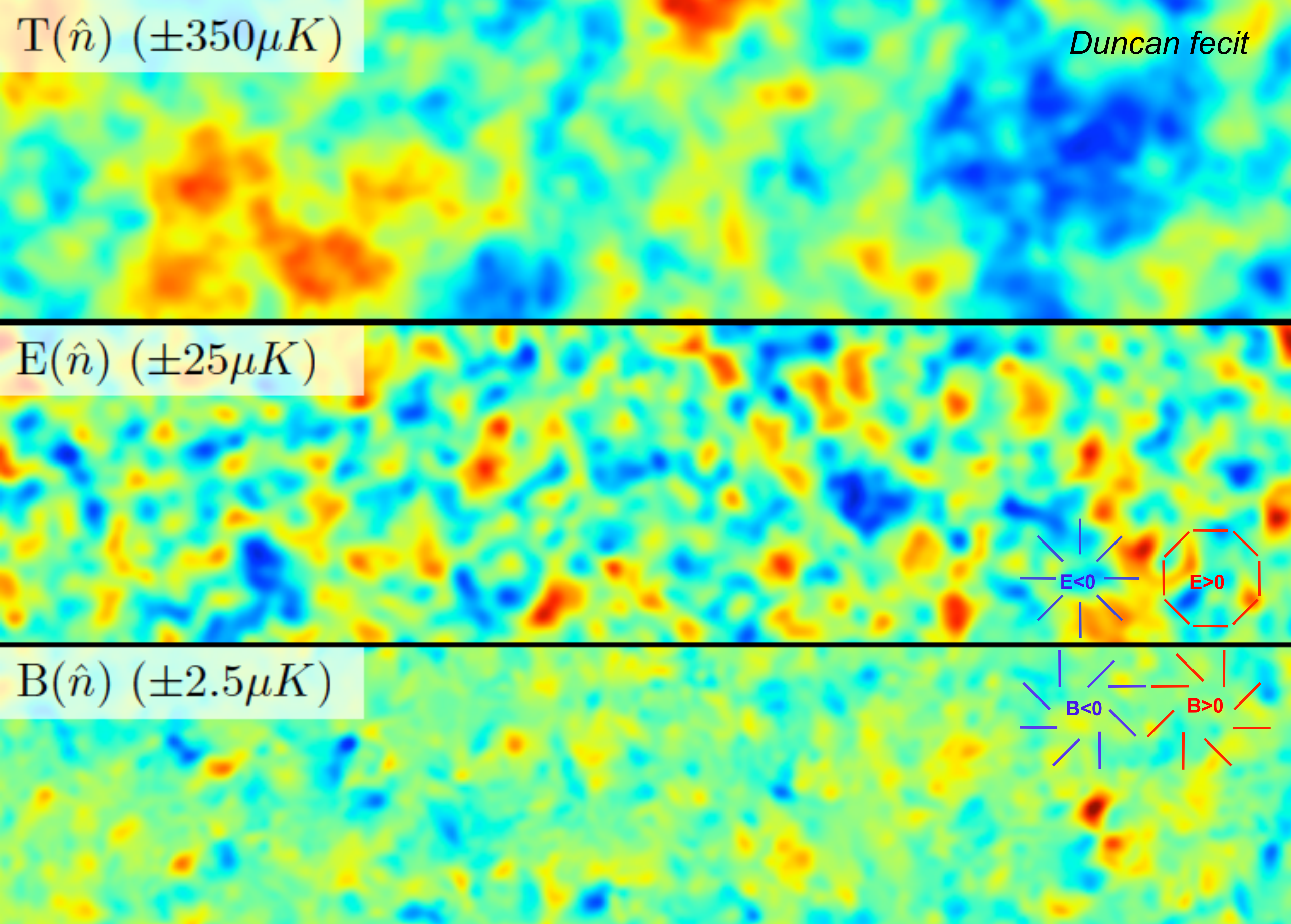


$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

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

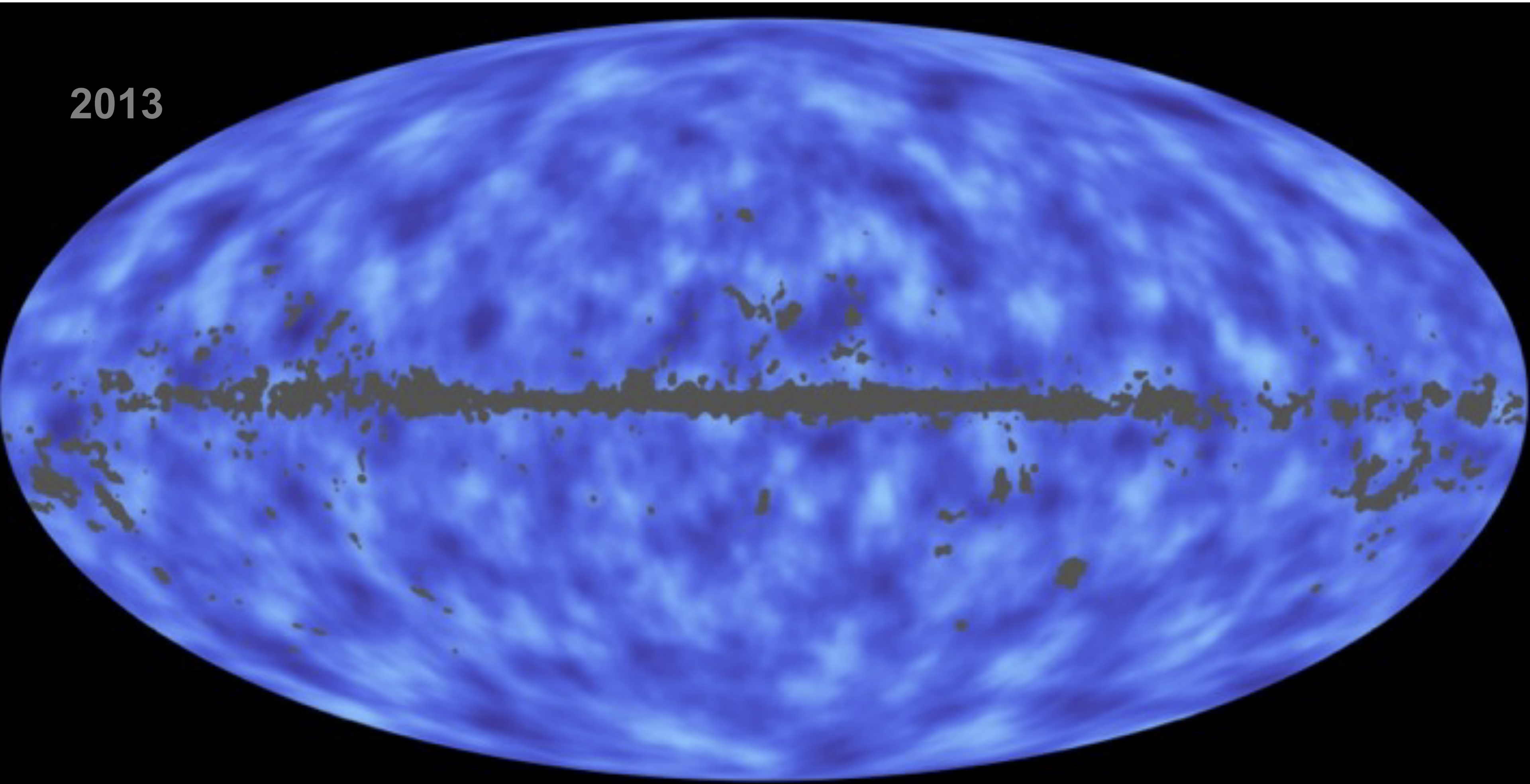


Duncan fecit



Duncan fecit

Projected mass map



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

Making contact between theories & measurements

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

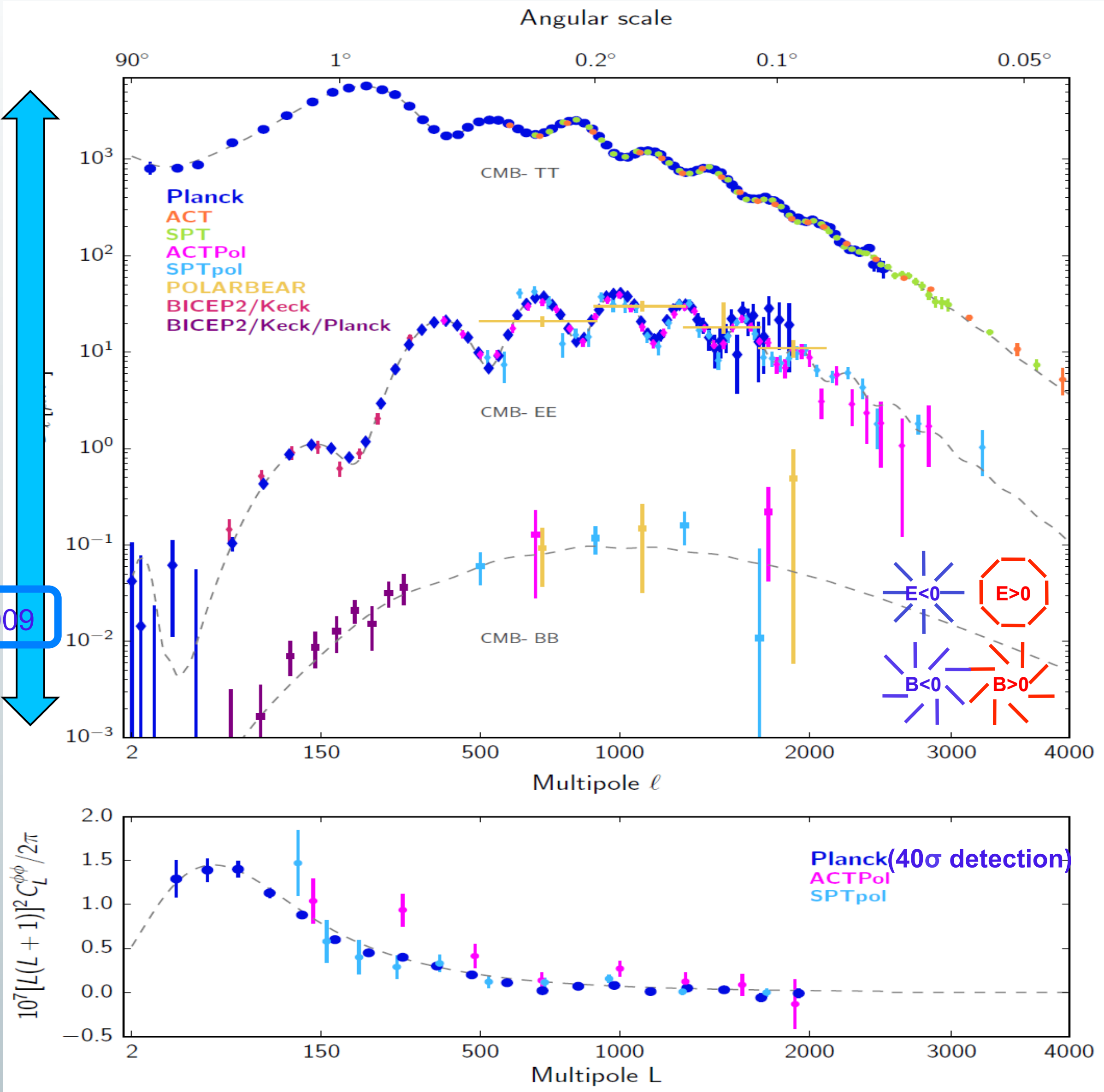
$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell + 1}$$

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

Similar expressions for polarisation (on spin 2 harmonics)

TT, EE, BB, ΦΦ – 2017 status

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



10^7

τ = 0.055±0.009

And statistically isotropic…

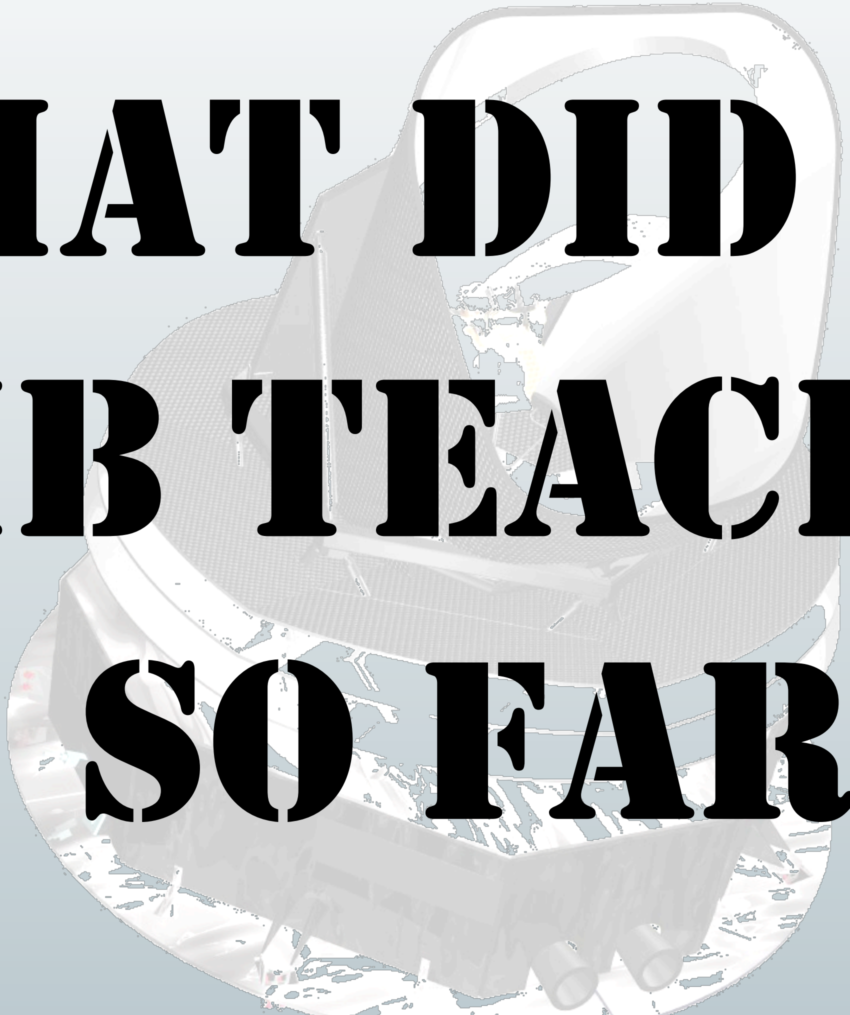
1 114 000 Modes measured with TT,

60 000 with TE (not shown)

96 000 with EE

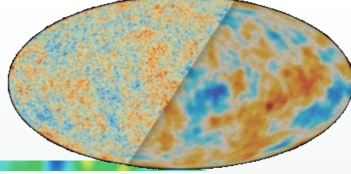
… and 10's in BB and φφ

+ weak constraints with TB and EB



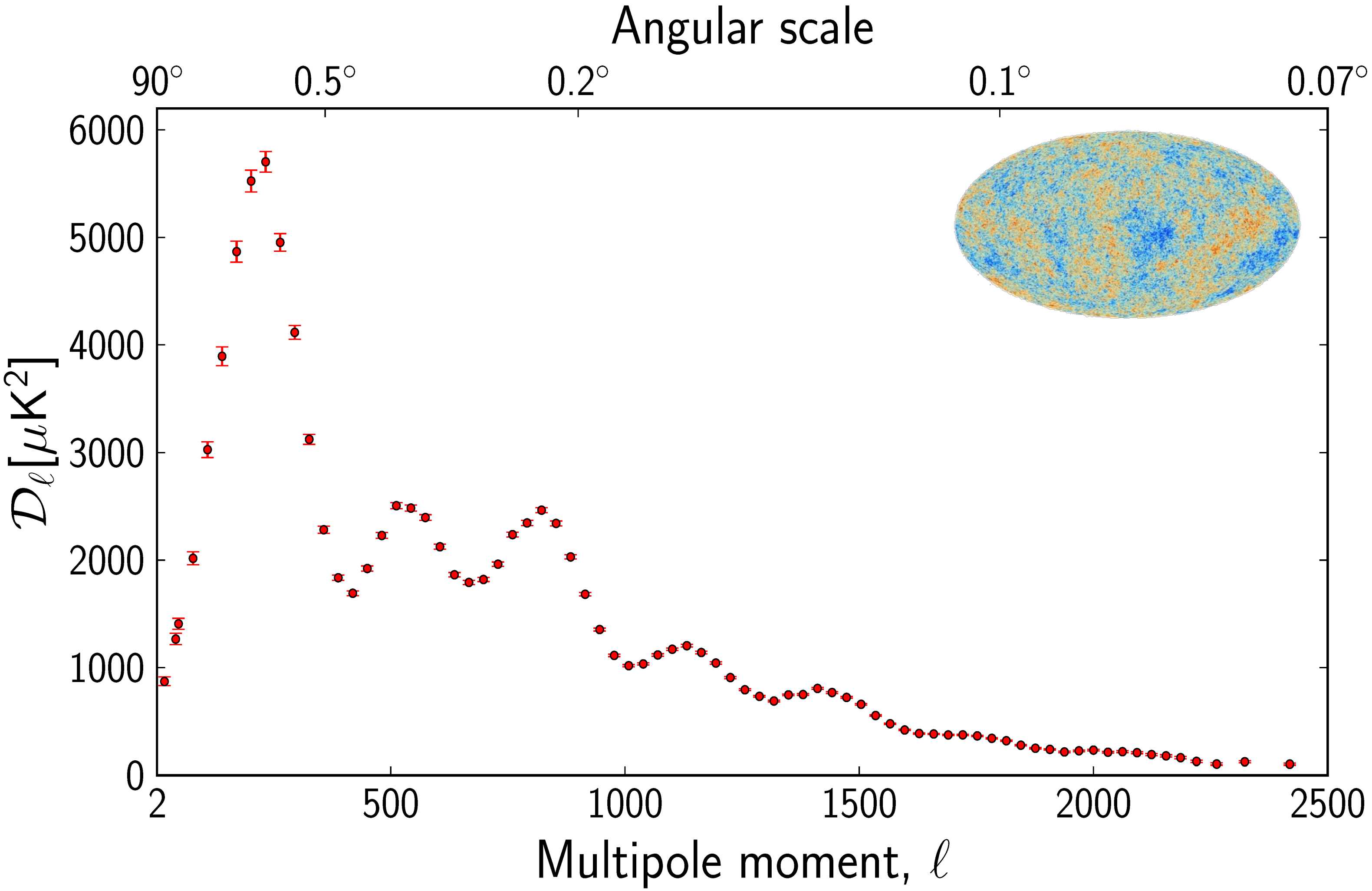
WHAT DID THE CMB TEACH US SO FAR?

Conclusions/CMB Anisotropies post-Planck



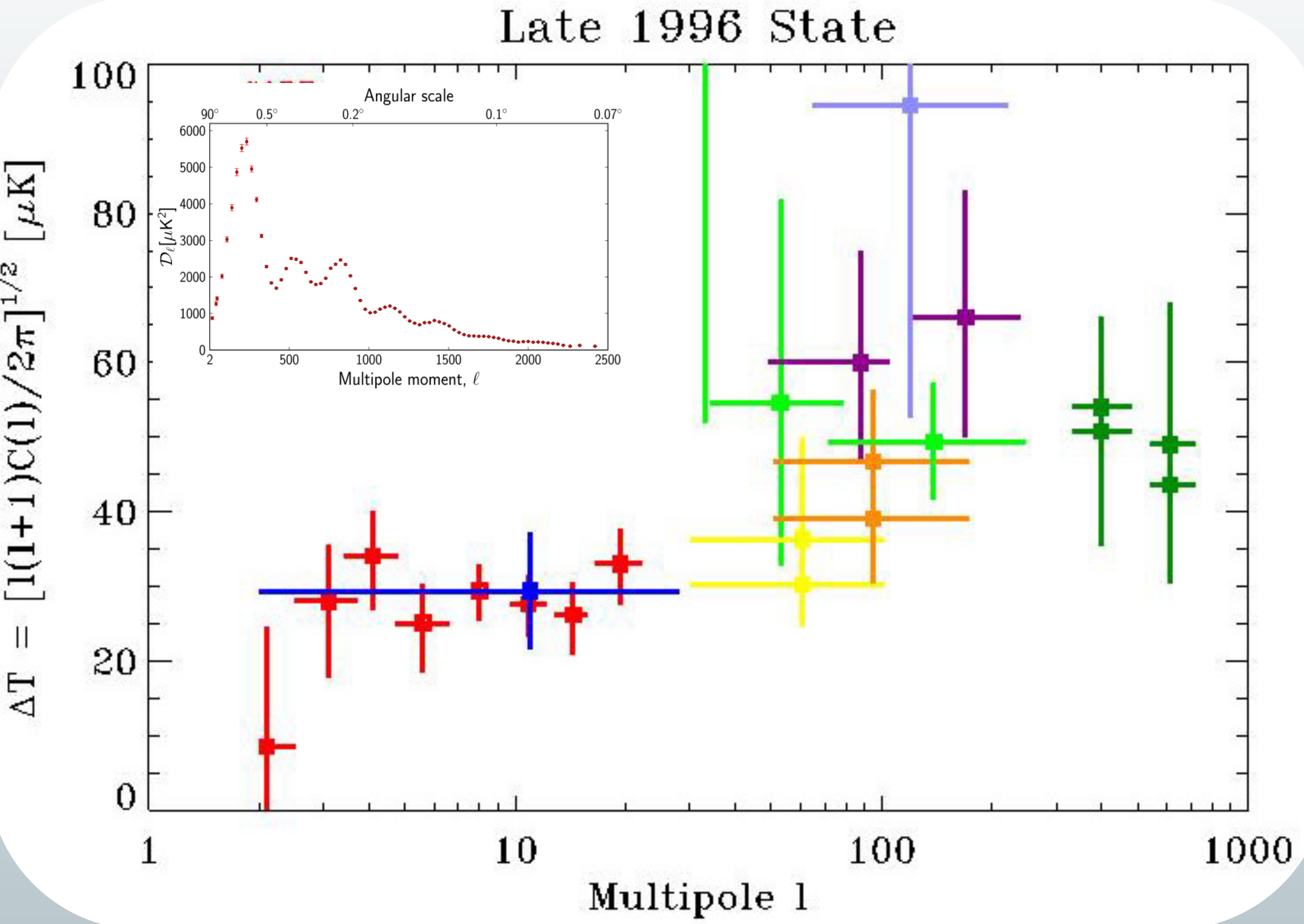
- **The LCDM model fits all CMB data in T, E, B, ϕ.**
  - *No need for an extension. A lavish source of unique constraints / papers…*
  - *Same model parameters, determined at the per cent level, also fit other data (BAO, and also BBN, SN1a…).*
  - *Some tensions (anomalies, SZ, H0, WL), whose meaning 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).

The Planck power spectrum of Temperature anisotropies



2013 data

When Planck (& WMAP) were selected

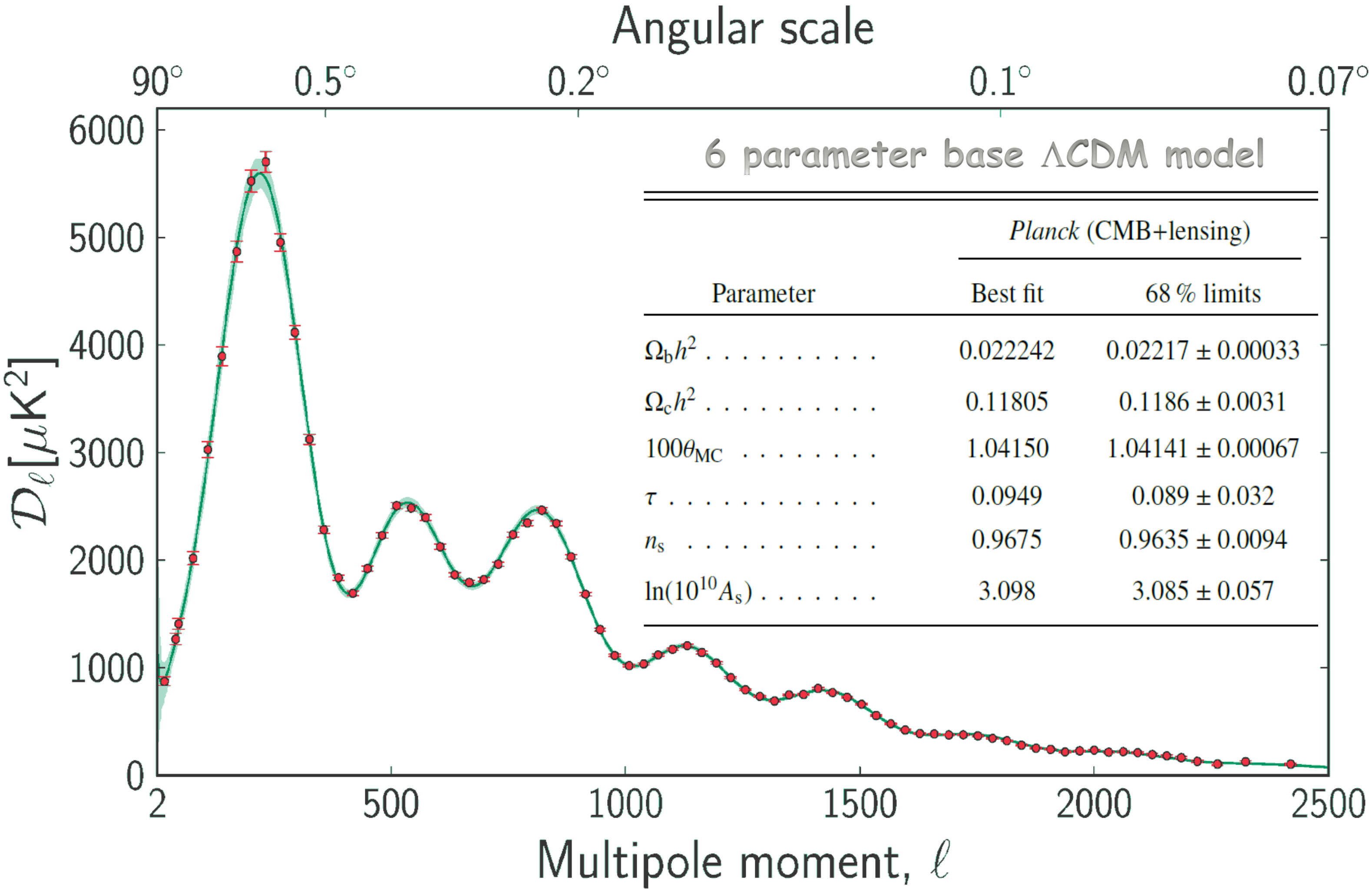


“CMB-Hand-Wave” code

- 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.

Theory confronts data



6 parameter base ΛCDM model

	Planck (CMB+lensing)	
Parameter	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.

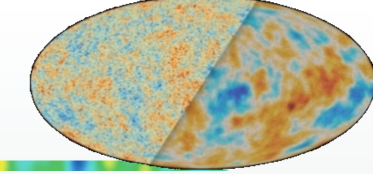
- $\Omega_b h^2$ Baryon density today - The amount of ordinary matter
- $\Omega_c h^2$ Cold dark matter density today – only weakly interacting
- Θ Sound horizon size when optical depth τ reaches unity
  (Distance travelled by a sound wave since inflation, when universe became transparent at recombination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

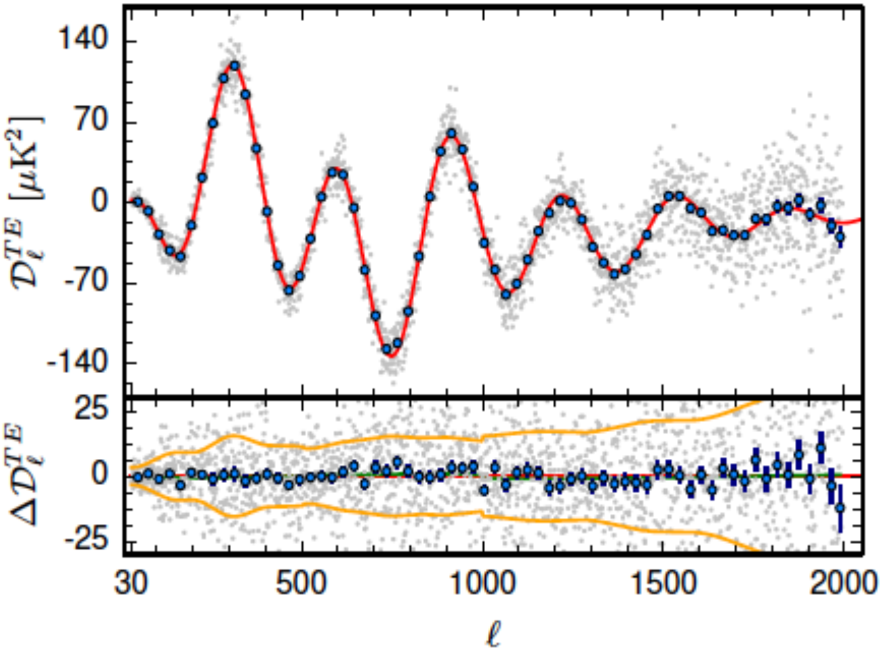
- τ Optical depth at reionisation (due to Thomson scattering of photons on e^-), i.e. fraction of the CMB photons re-scattered during that process

- 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)

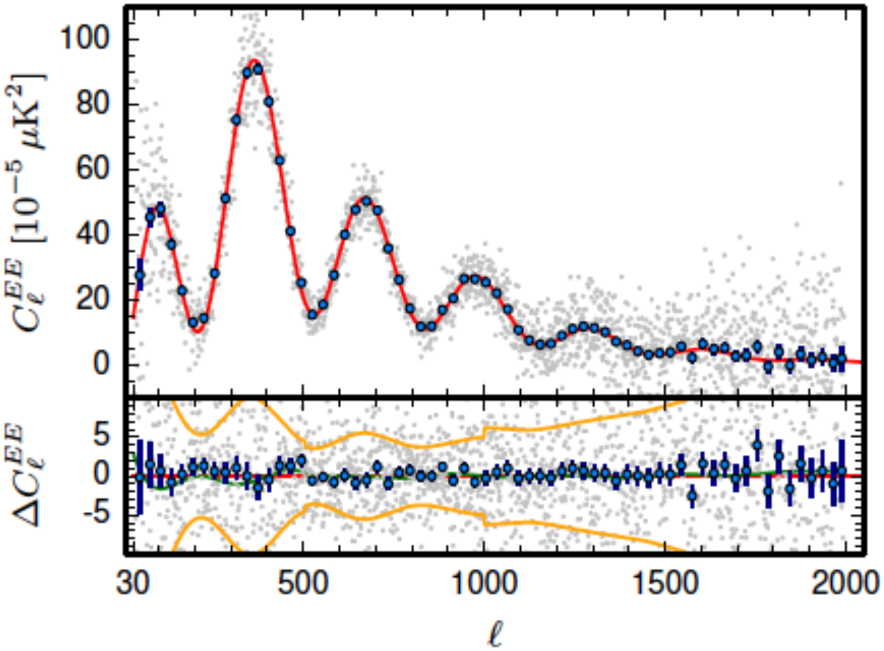
- Others are *derived* parameters within the model, in particular
  - *Ω "Dark Energy" fraction of the critical density (derived only if assumed flat)*
  - *H_0 the expansion rate today (in km/s per Mpc of separation)*
  - *t_0 the age of the universe (in Gy)*

Planck 2015 - TE & EE spectra





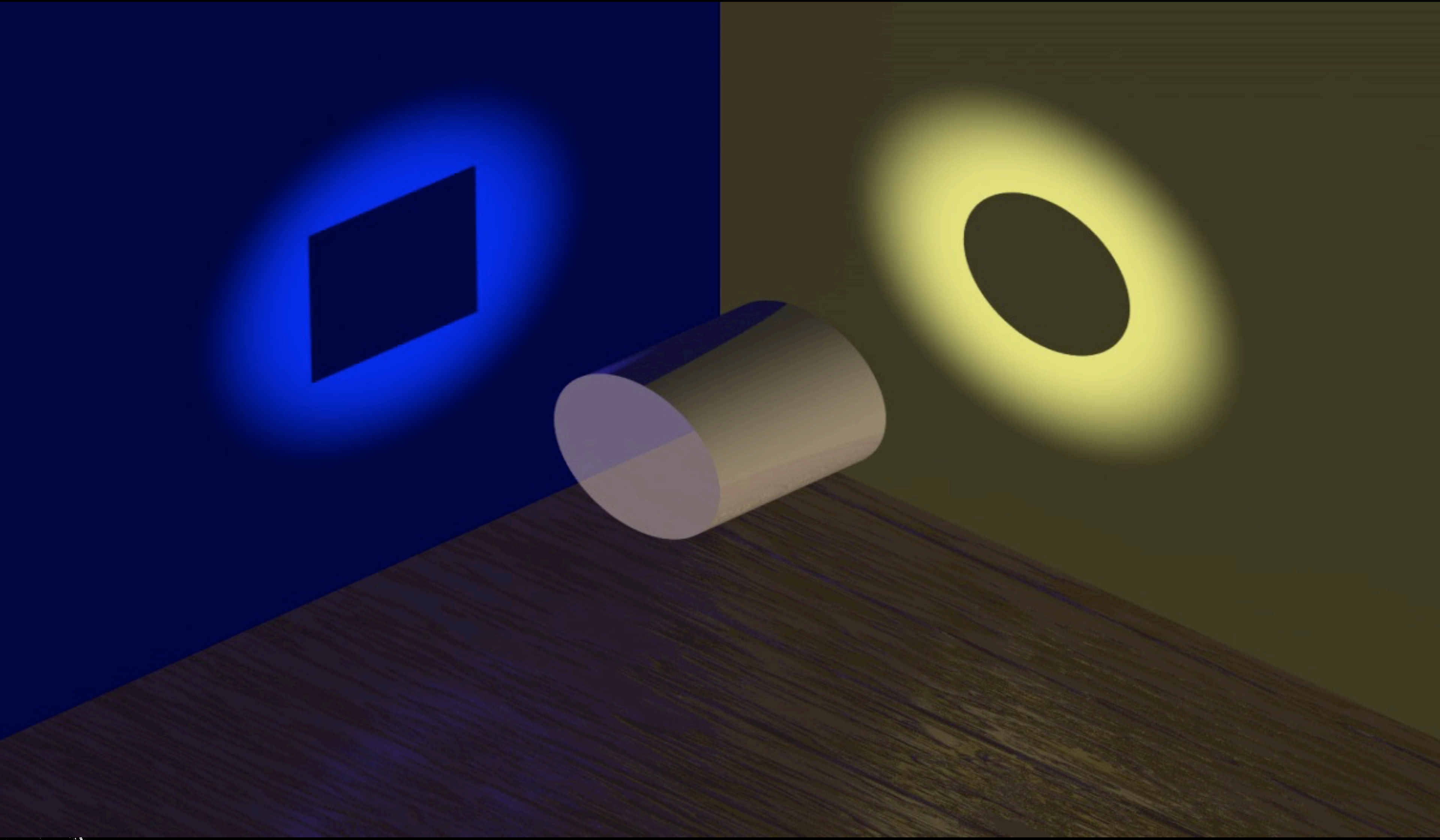
Frequency averaged spectrum reduced ^{2} = 1.04



Frequency averaged spectrum reduced ^{2} = 1.01

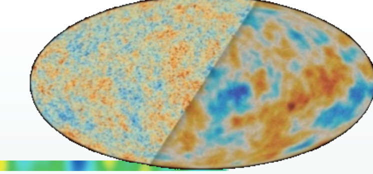
- ➢ Red curve is the *prediction* based on the best fit TT in base ΛCDM
- ➢ Albeit *magnificent*, 2015 polarisation data and results are *preliminary* because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

It could have been otherwise!



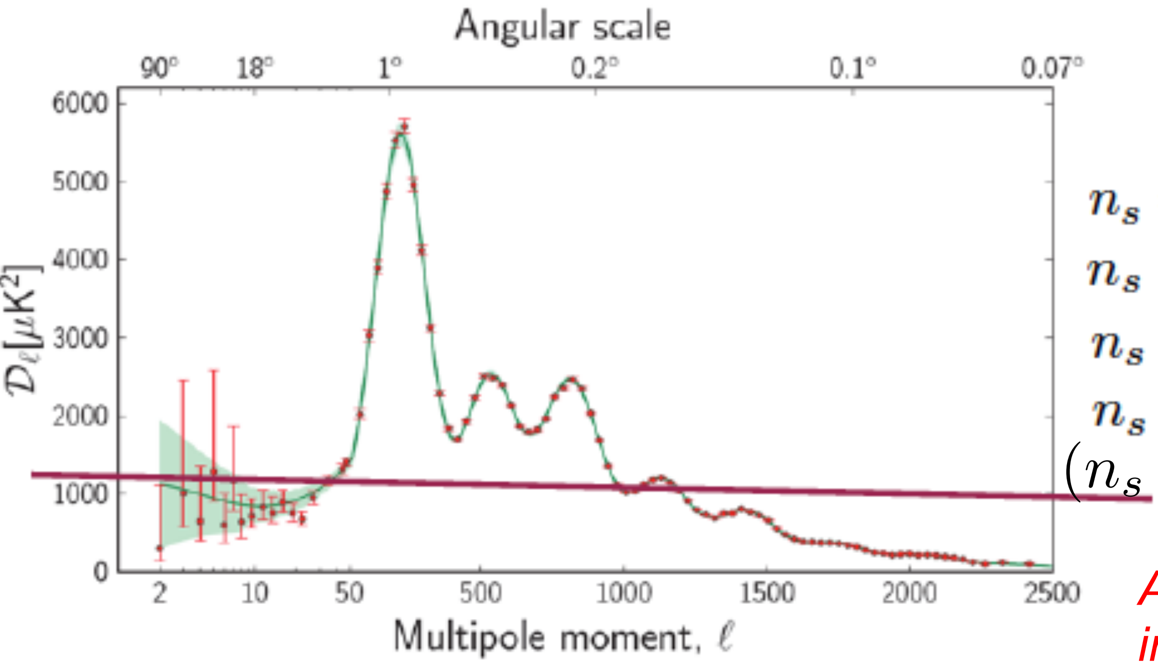
And it further constrains potential deviations from the base tilted LCDM model/physics

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.

Inflation has a few variants…

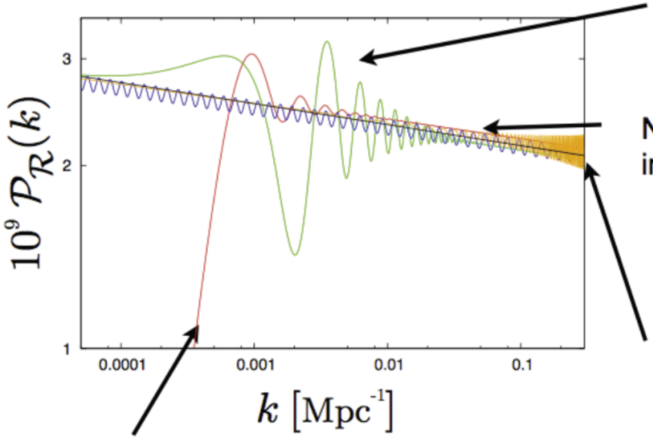
- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- B-inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke 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
- STOP << 2015

(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

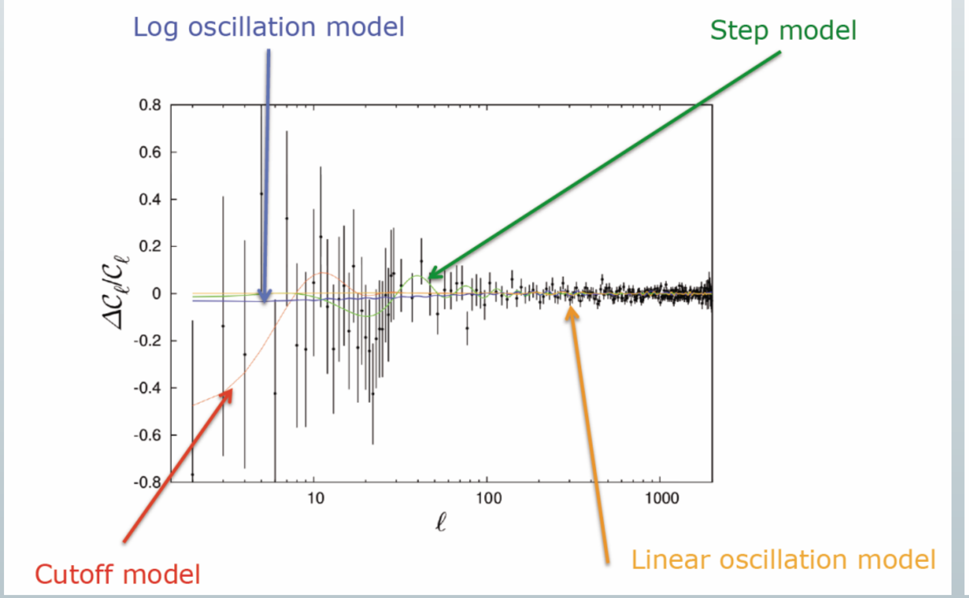
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

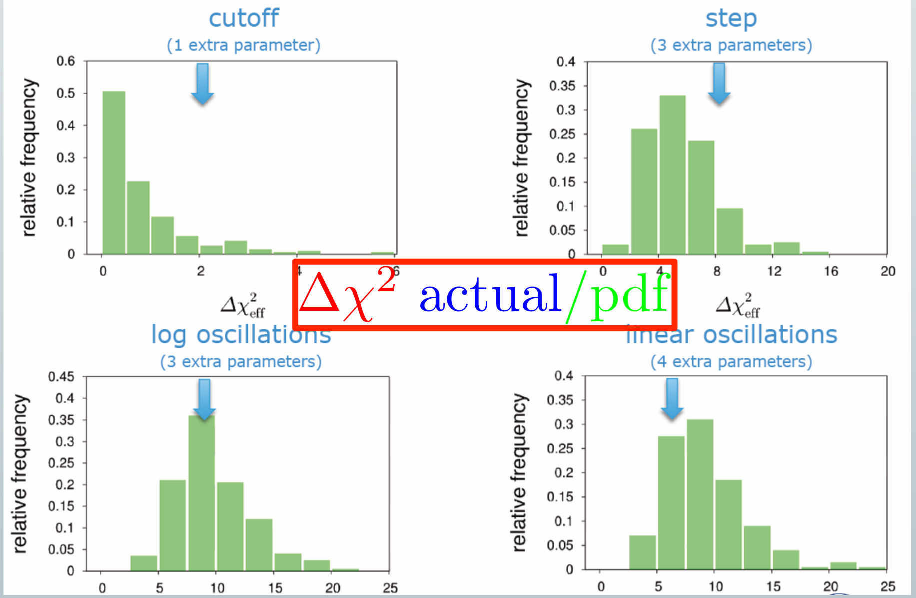
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

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

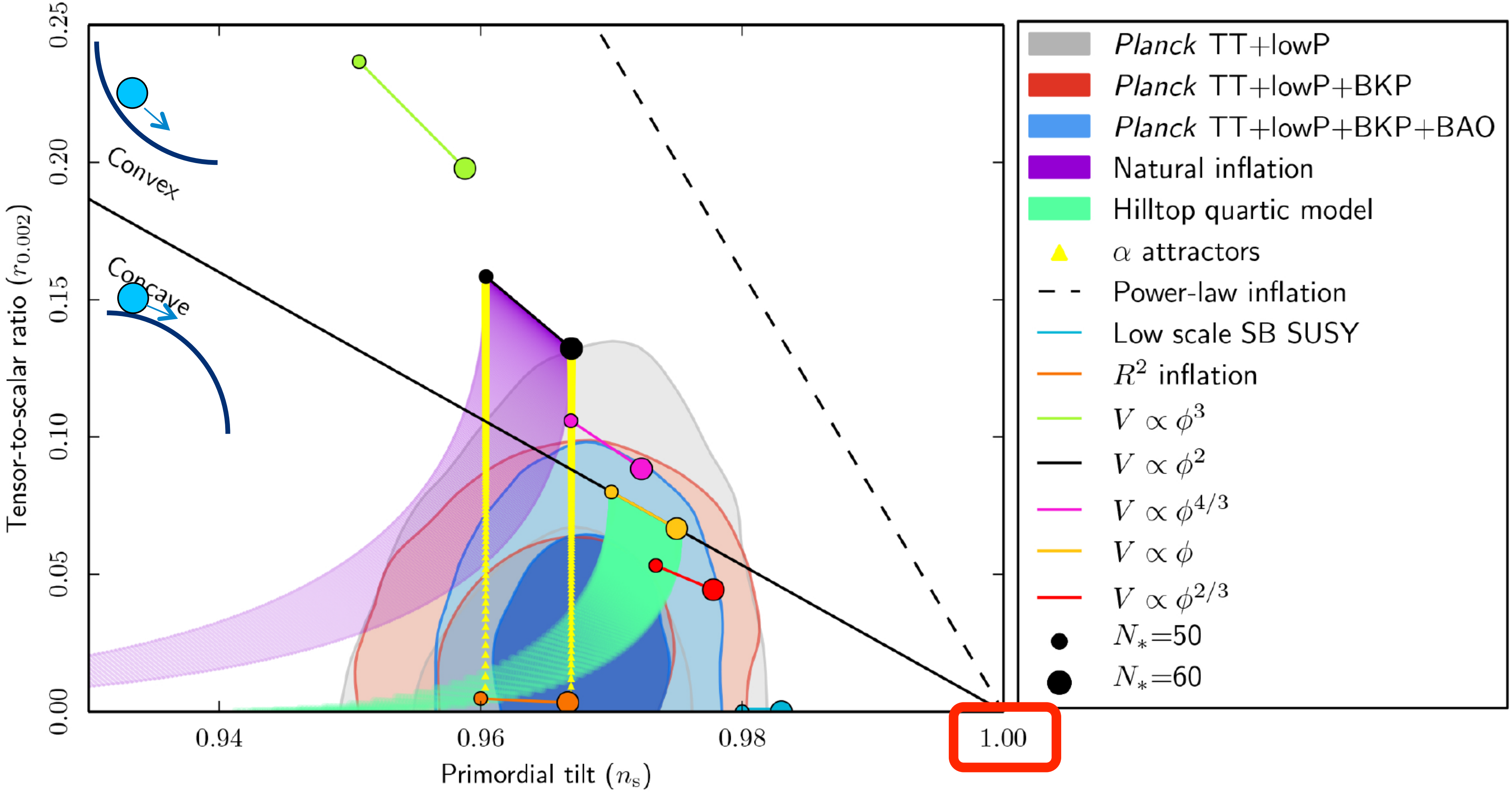




$\Delta\chi^2$ actual/pdf

Planck 2015: n_s vs r

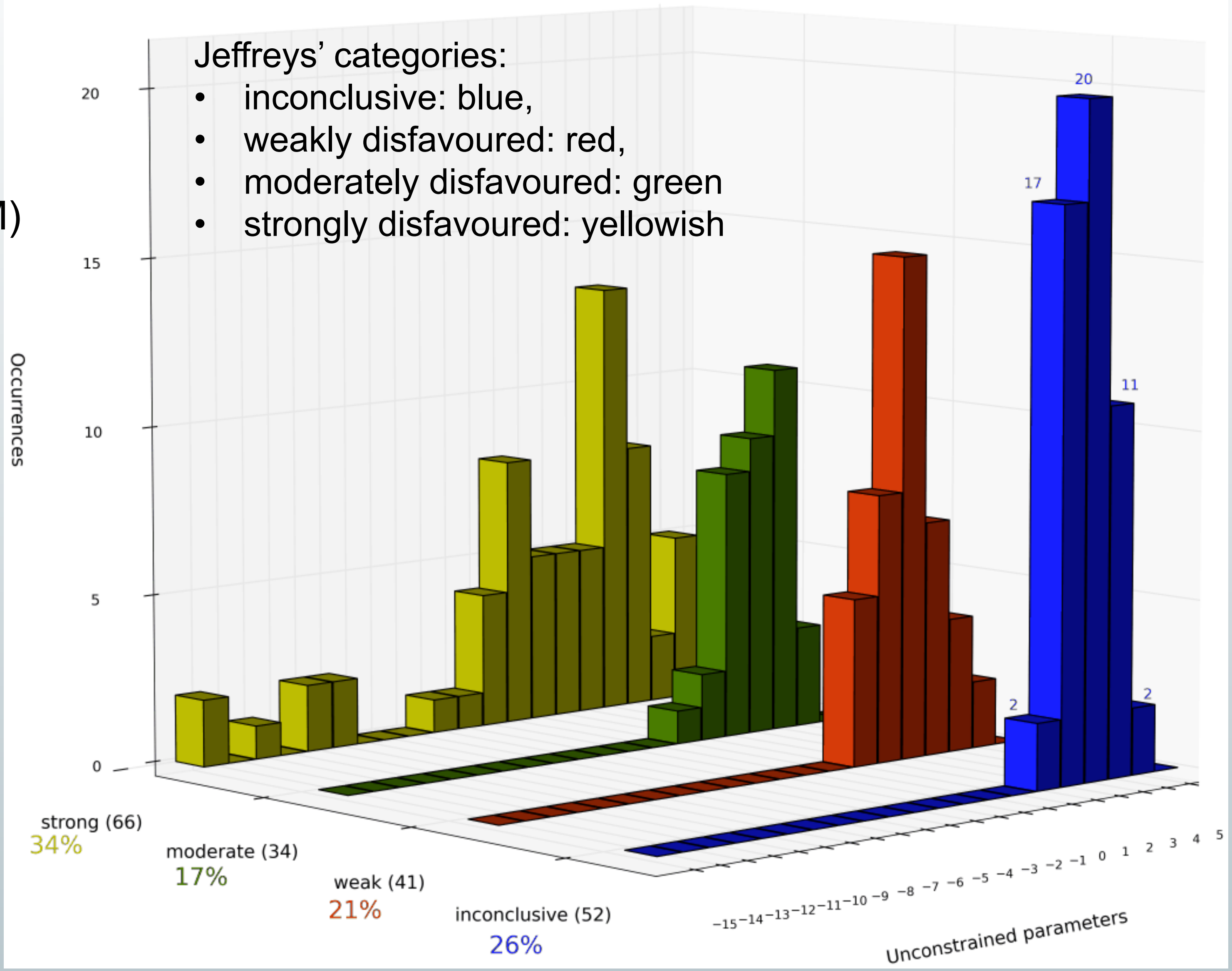
$V_* = (1.9 \times 10^{16}\ \mathrm{GeV})^4\ (r/0.12)$



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)



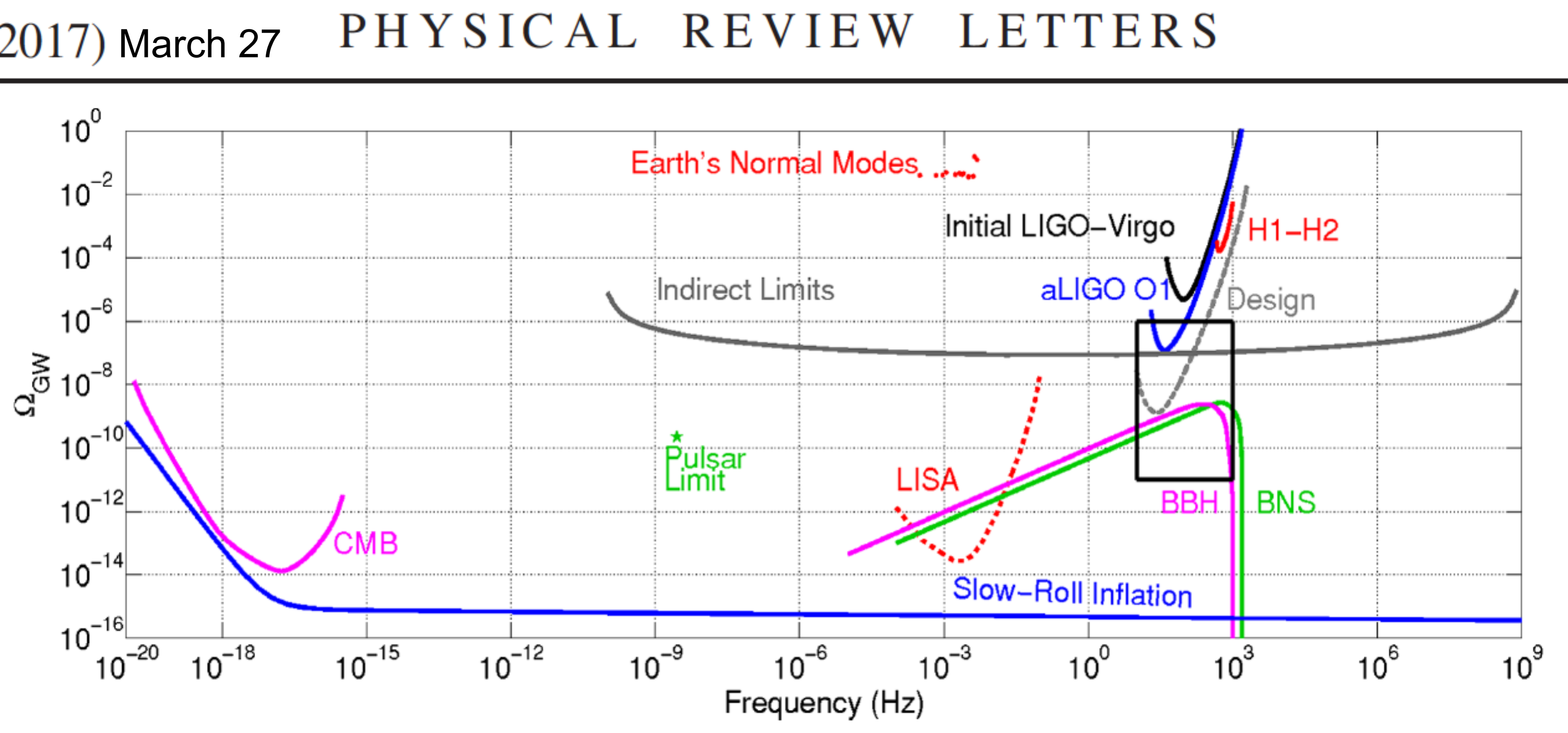
Jeffreys' categories:

- inconclusive: blue,
- weakly disfavoured: red,
- moderately disfavoured: green
- strongly disfavoured: yellowish

ASPIC arXiv/1303.3787

"models" include different priors

CMB versus other GW detectors



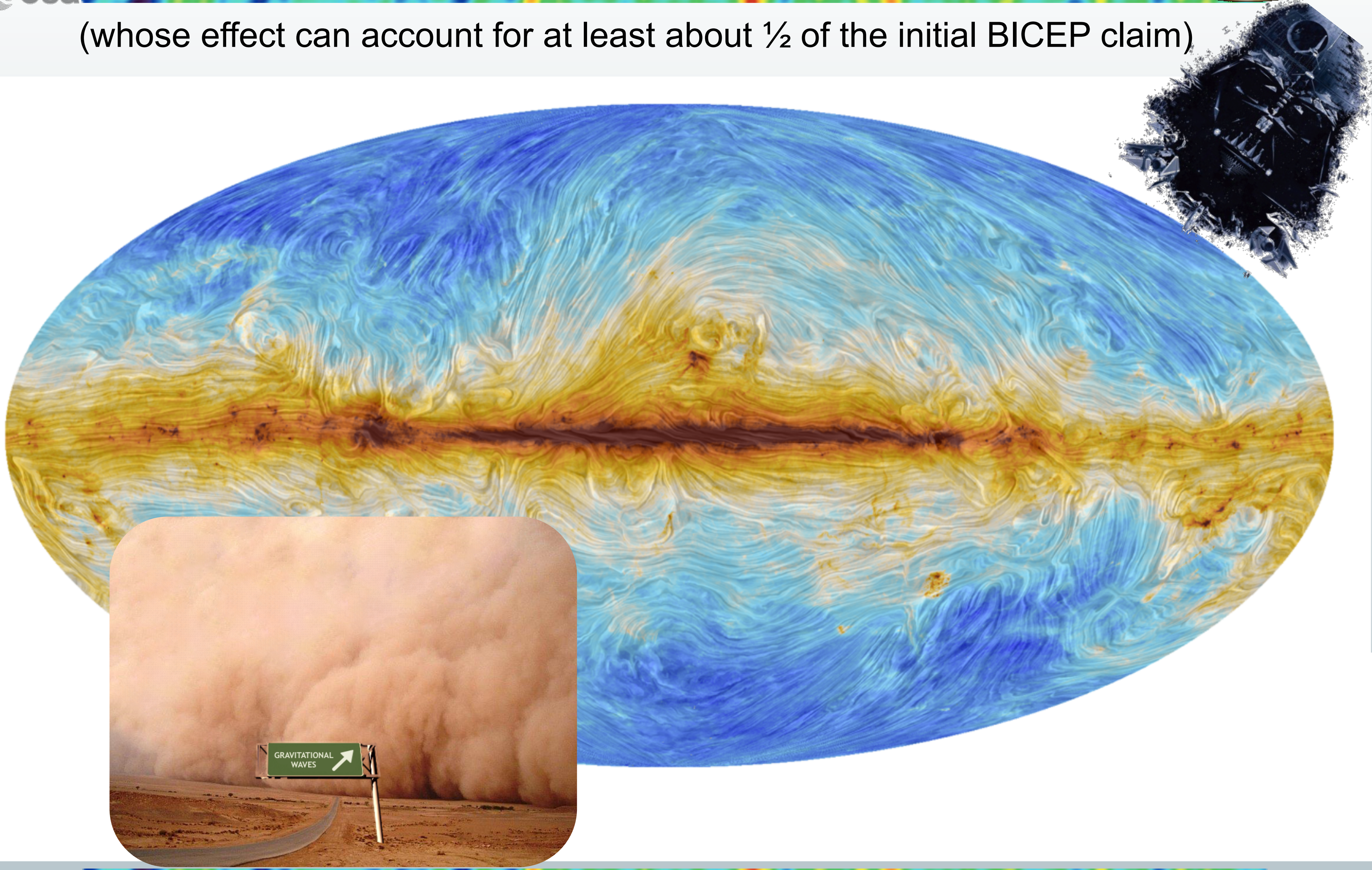
2017) March 27 PHYSICAL REVIEW LETTERS

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

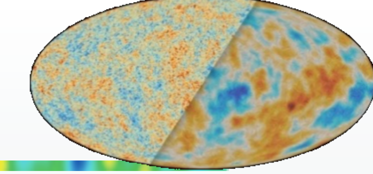
➔ Detection by dedicated CMB experiments is a major goal.

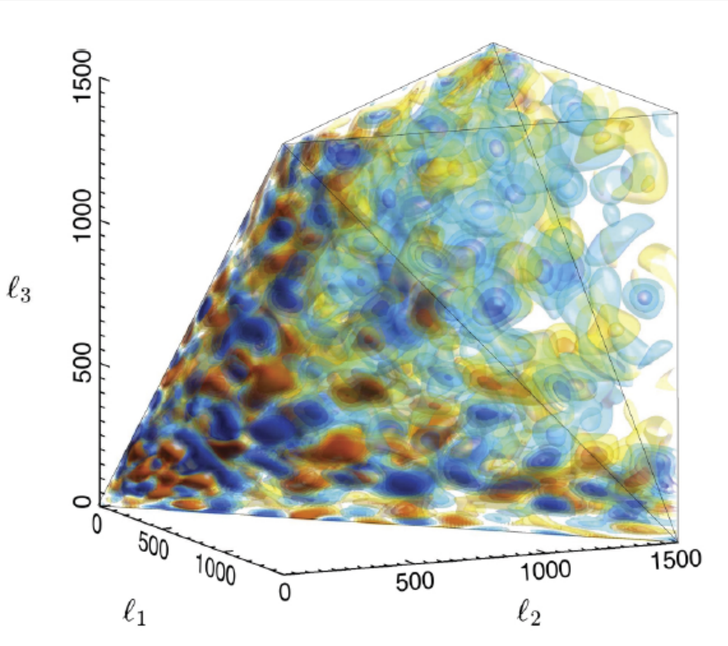
Planck 353GHz reveals the Galactic magnetic field

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

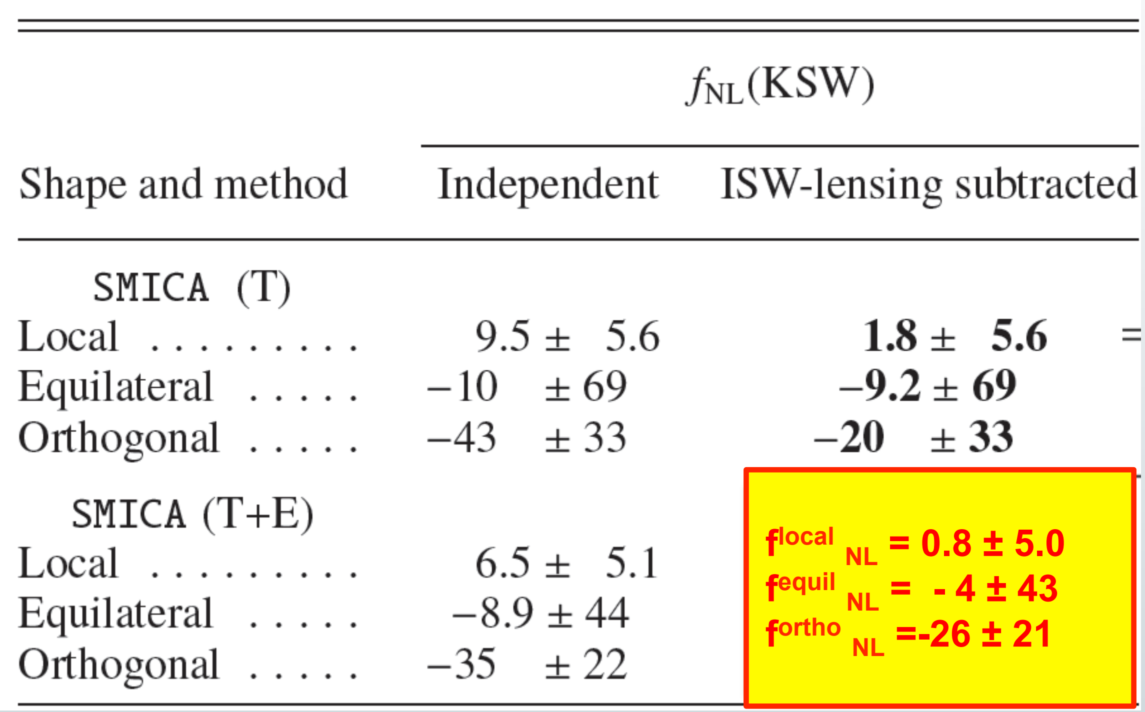


Planck 2015 – Bi-spectrum constraints



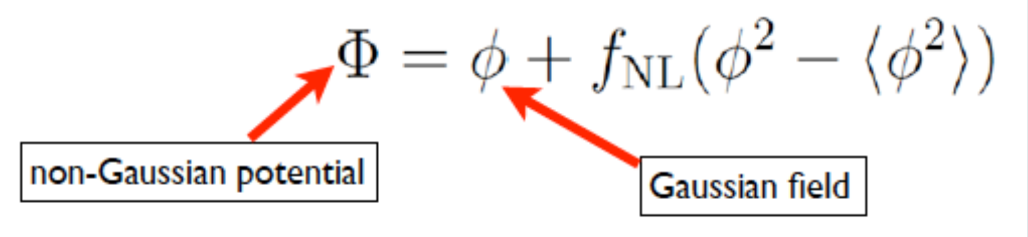


Planck 2015 – 2000 modes



	$f_{\rm NL}$(KSW)	
Shape and method	Independent	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	

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



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

non-Gaussian potential

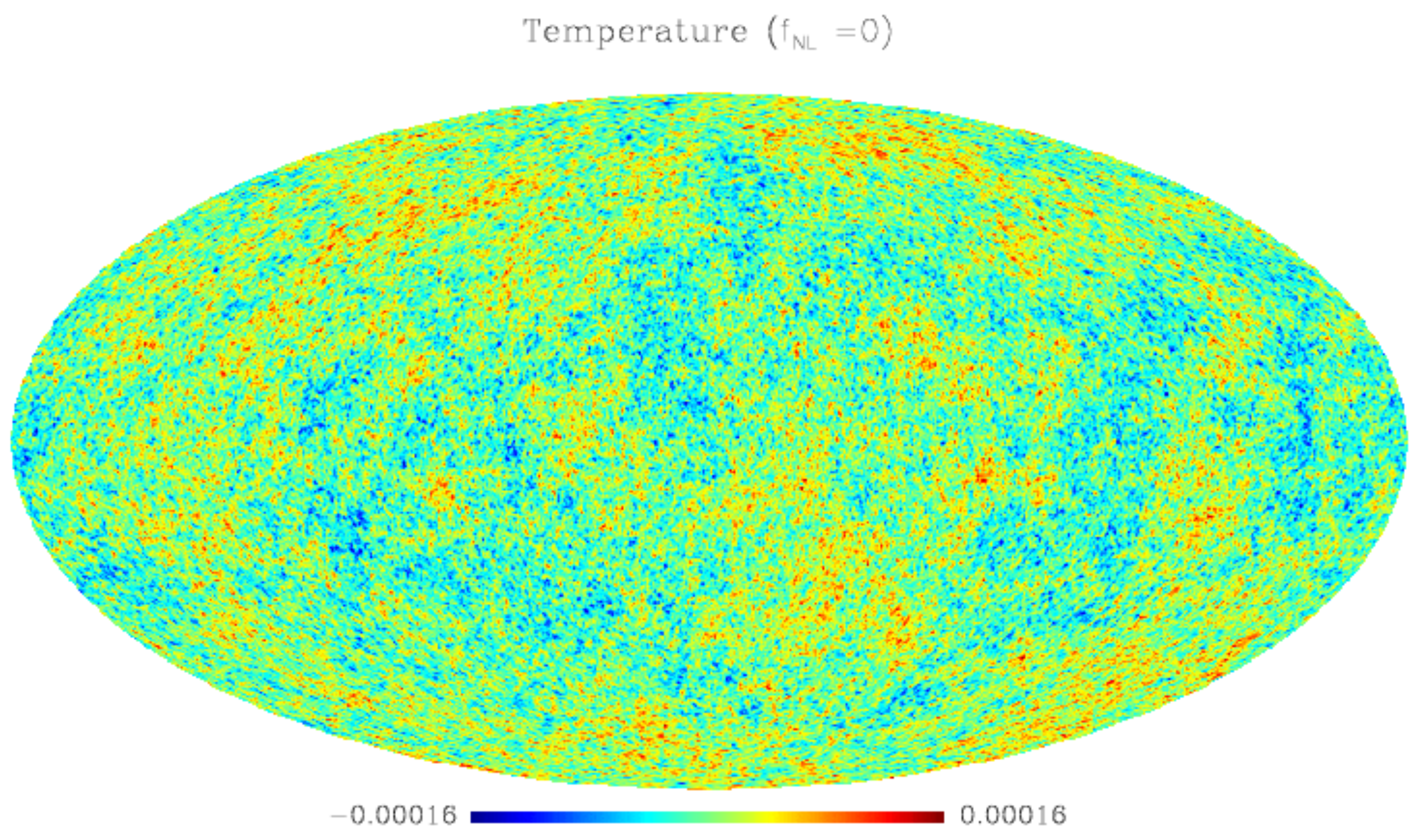
Gaussian field

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

A hundred-fold improvement in 14 years

(95%CL)

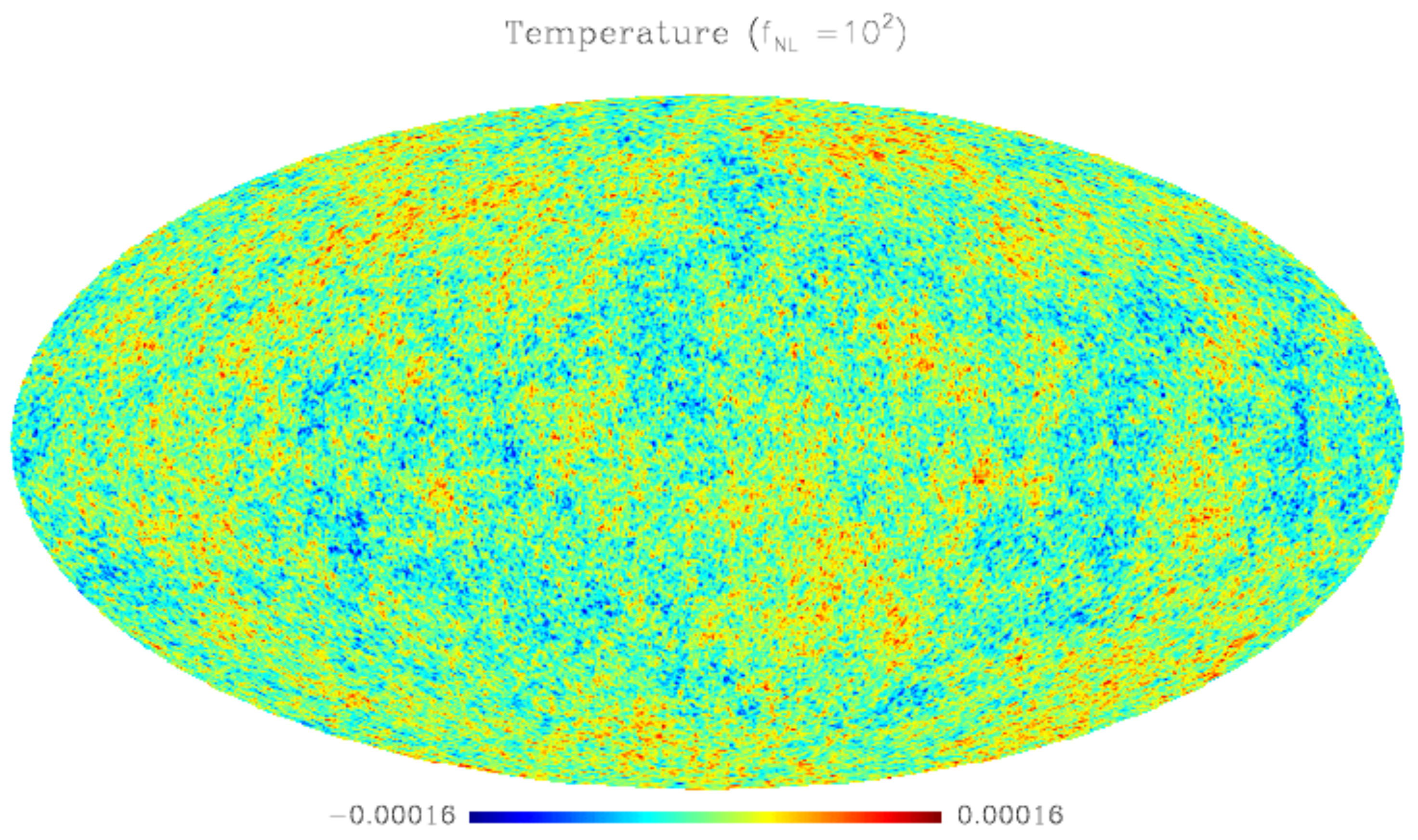
$f_{NL} = 0$



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

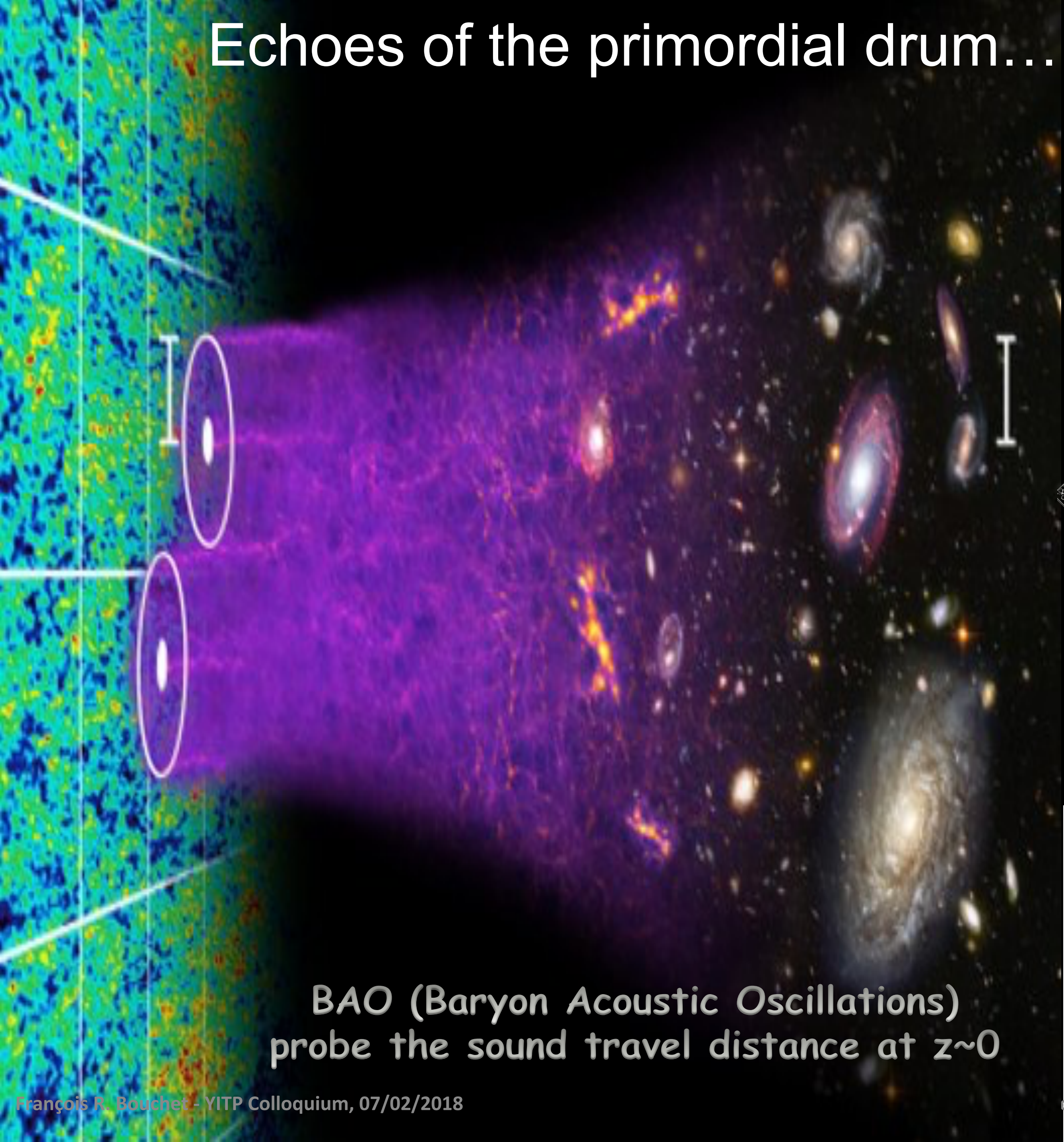
f_{NL}= 100

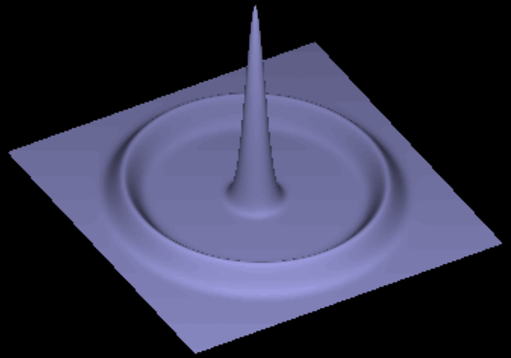
Positive f_{NL} = More Cold Spots

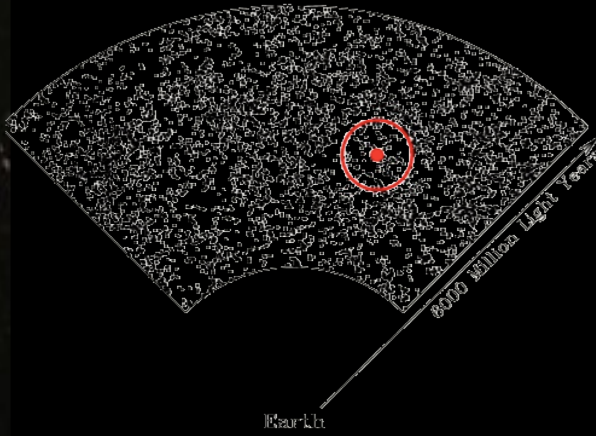


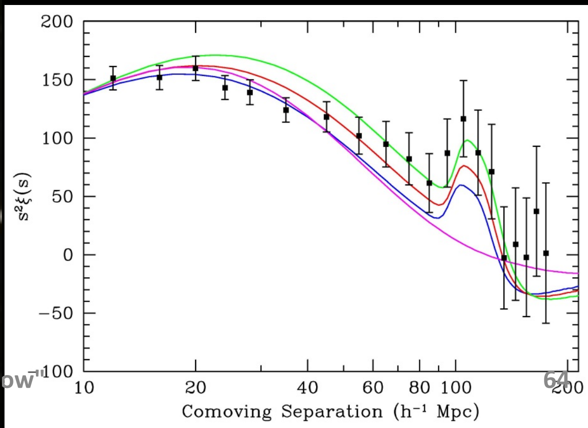
Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

Echoes of the primordial drum…

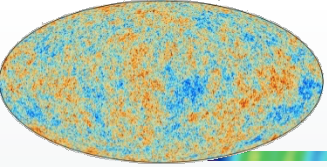




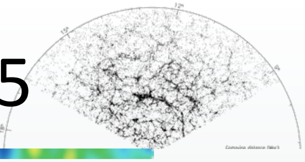


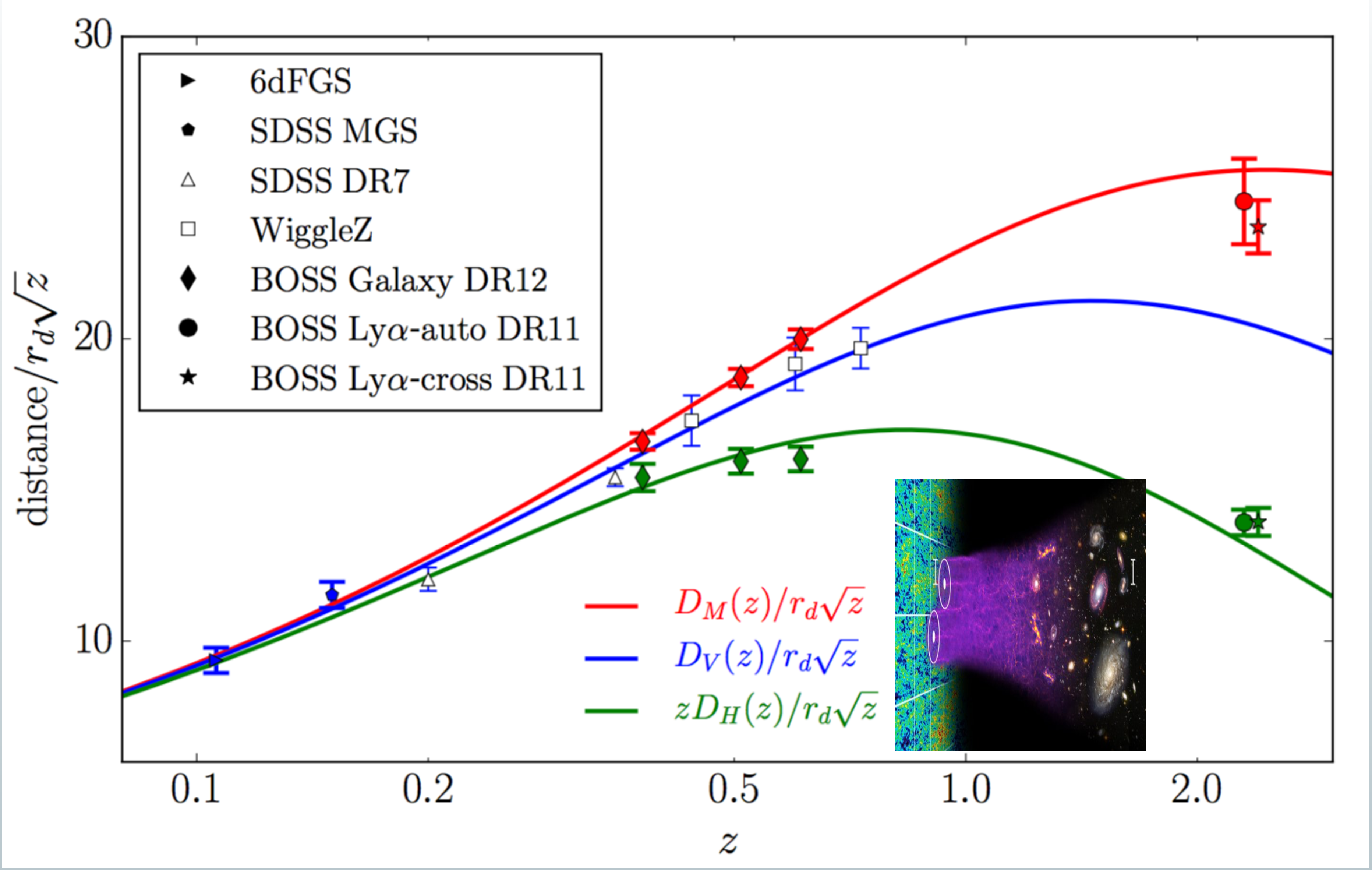


BAO (Baryon Acoustic Oscillations)
probe the sound travel distance at z~0

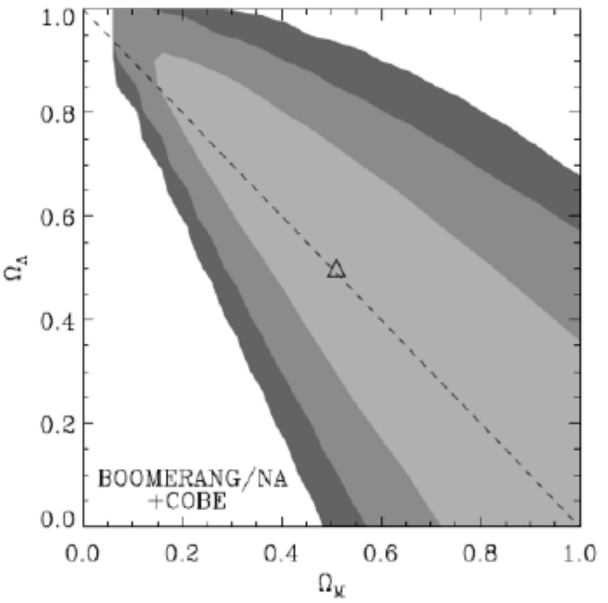


BOSS RD12, Alam+2016, arXiv:1607.03155



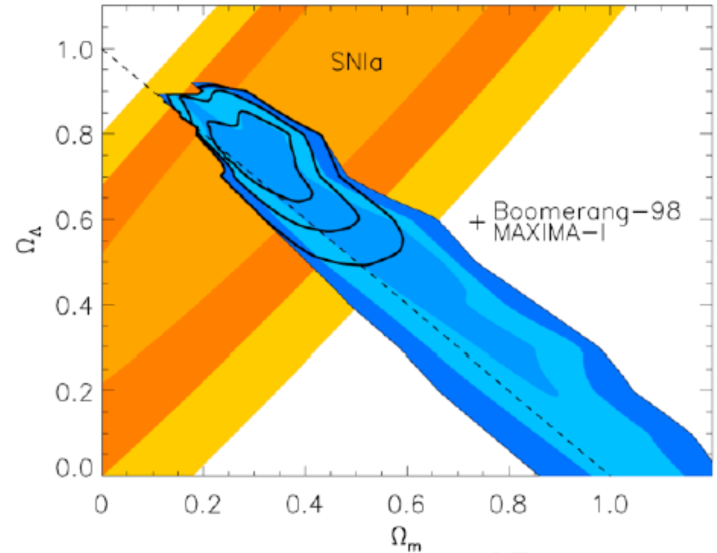


Spatial curvature constraint



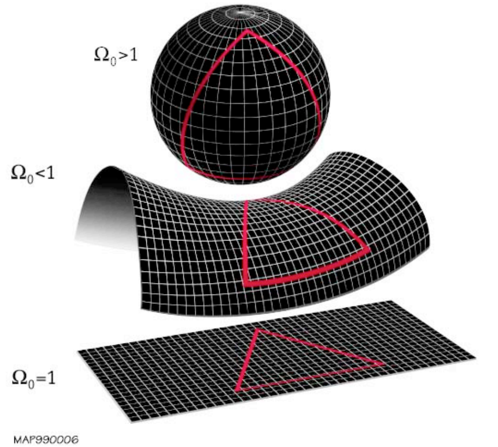
$$\Omega_K = -0.05^{+.40}_{-.40}$$

Melchiorri et al. 2000



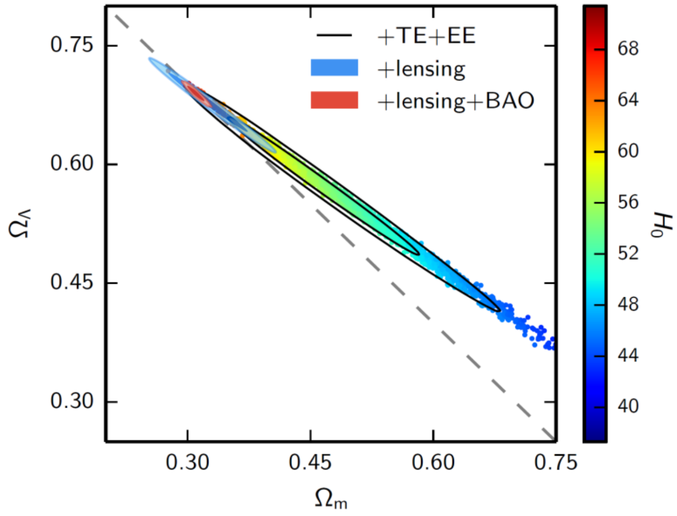
$$\Omega_K = -0.11^{+.07}_{-.07}$$

Jaffe et al. 2001



Flat space ←→ Ω_k=0

Note the change of axes
For Planck below



Planck 2015

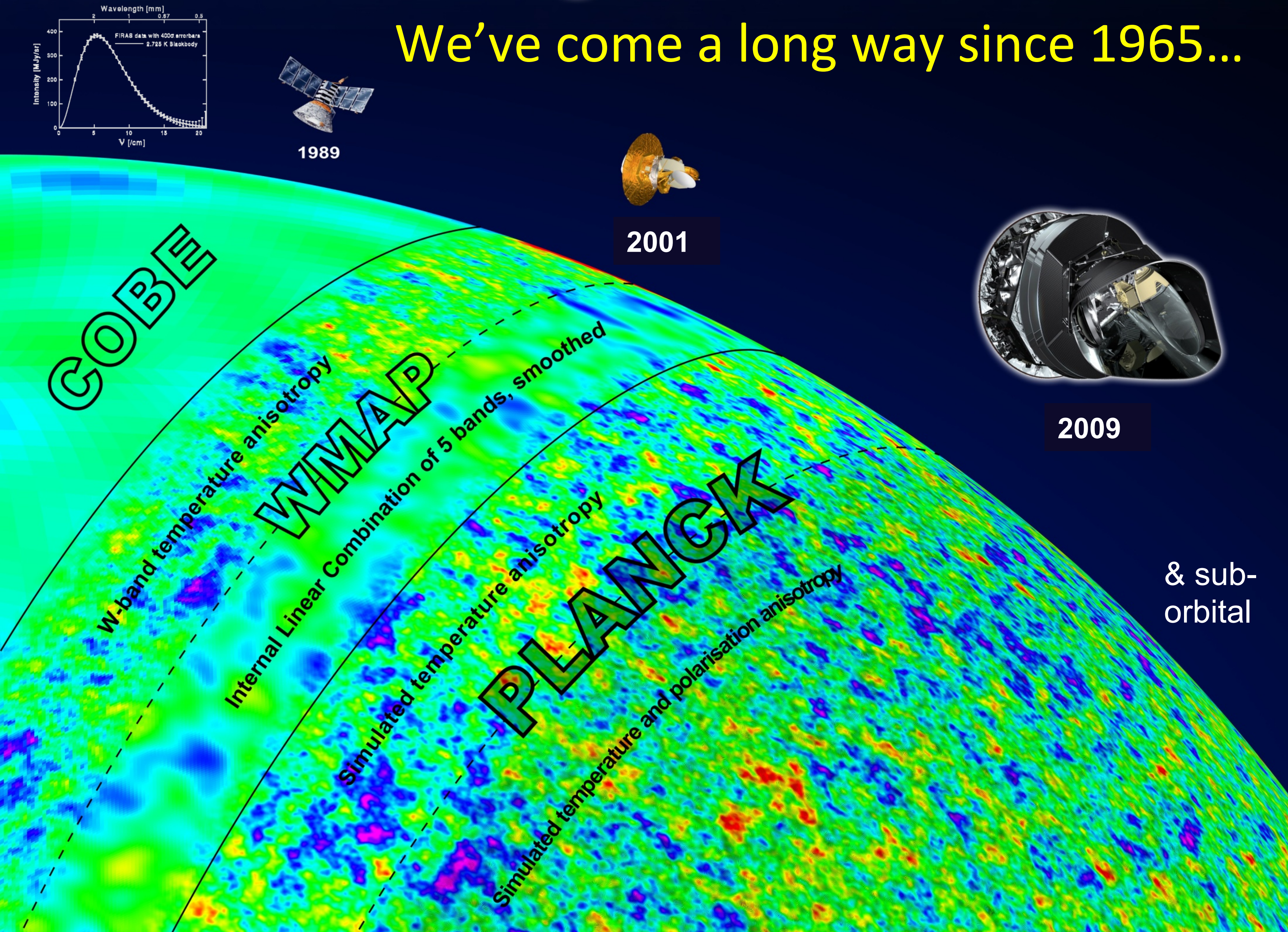
$$\Omega_k = 0.000 \pm 0.005 \;(95\%\;\mathrm{CL})$$

A hundred-fold improvement in 15 years

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.*
- 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 only by an incoming detection (or internal inconsistency). Otherwise, Occam's razor?
- T anisotropies information essentially exhausted (as promised back in 1996), 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 astrophysicists.

We've come a long way since 1965…



& sub-orbital

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.