Cosmology (2)

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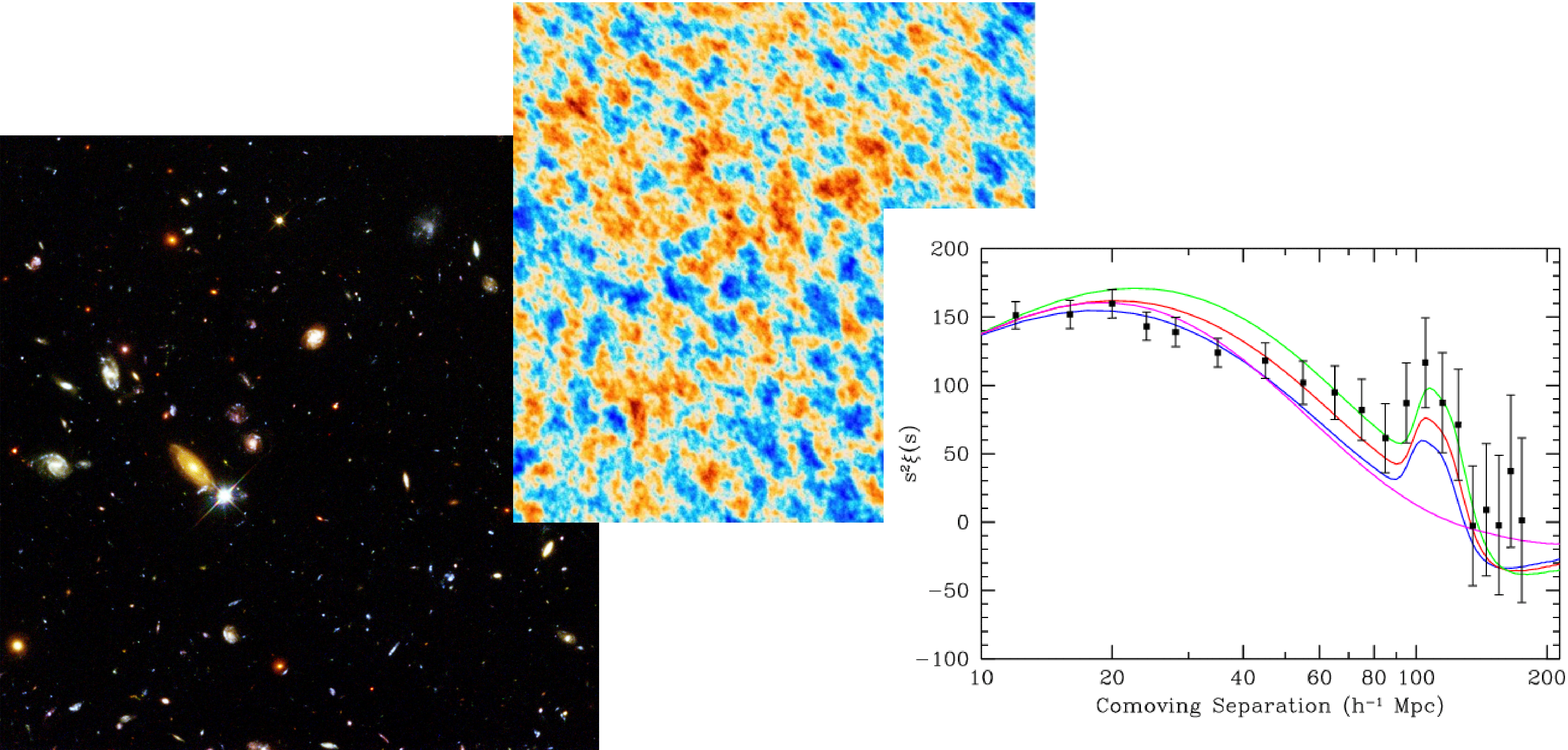


Expanding universe

“Initial singularity”
“Hot Big Bang”
14 Gy ago.

velocity

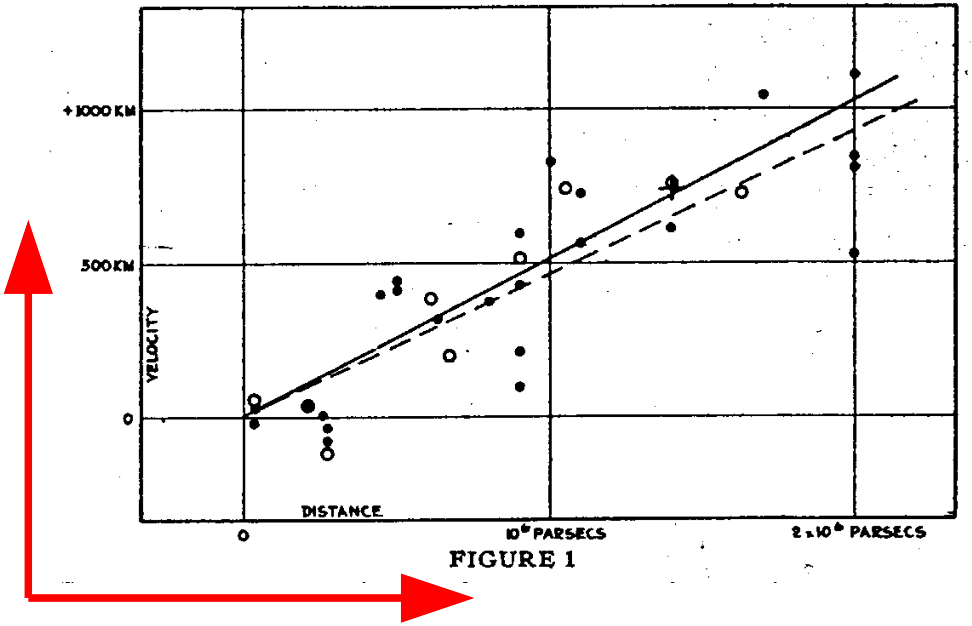
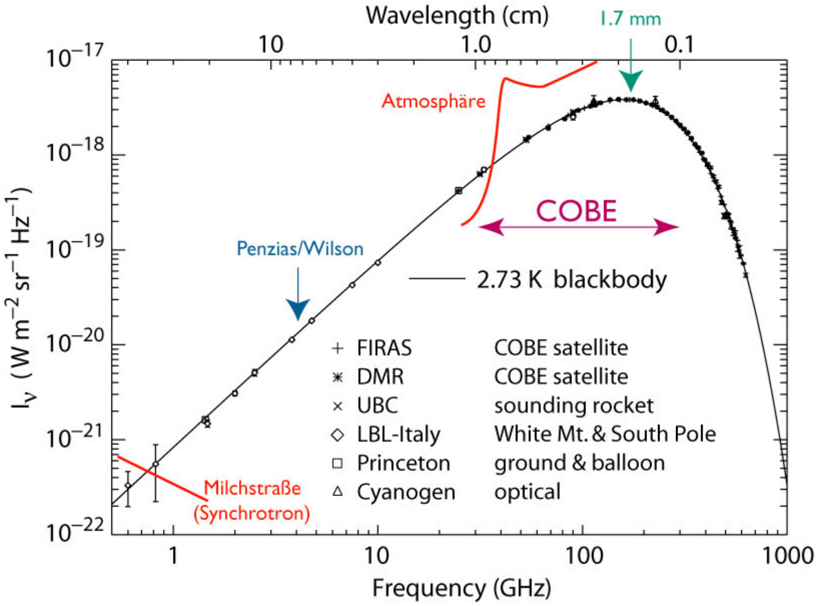


FIGURE 1

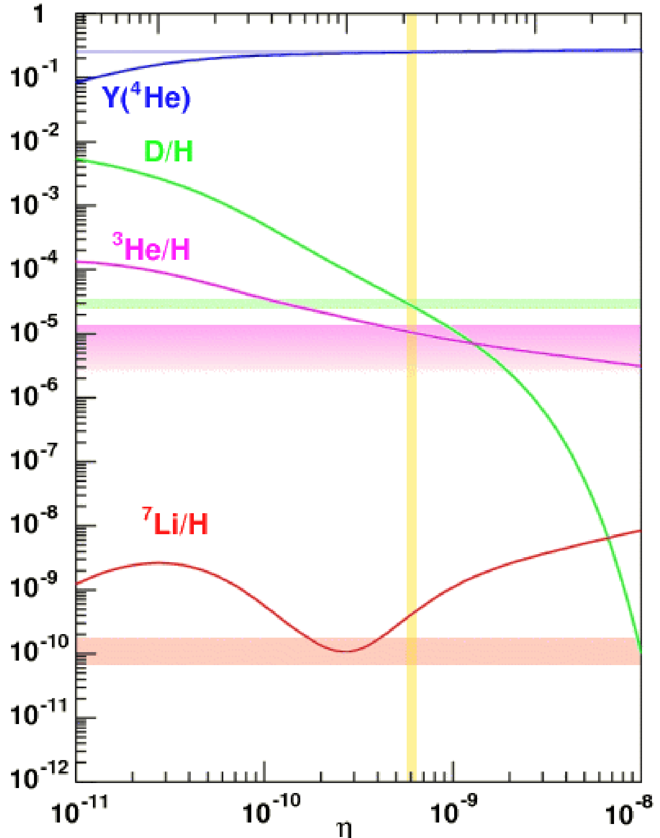
Distance (from flux)

Relics

CMB : thermal radiation



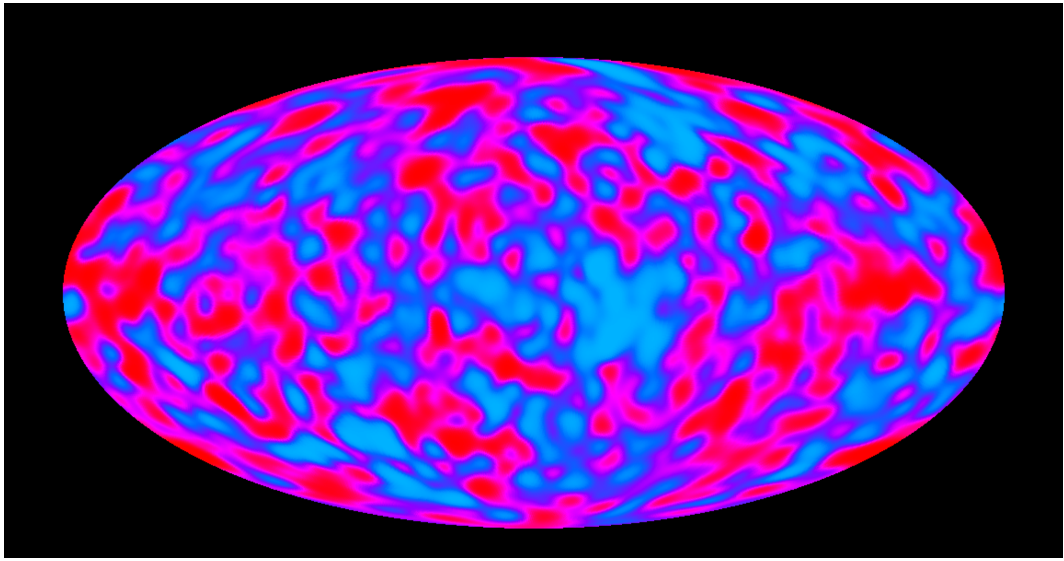
Light
Nuclei



T

Cloud #1: the horizon problem (the smoothness problem)

$$\frac{\delta T}{T} \sim 10^{-5}$$



- The CMB is extremely uniform
- It was emitted at BB+~400,000 y
- In a matter+radiation dominated universe, this corresponds to an horizon of ~250 Mpc, i.e. ~ 2 degrees on the sky at z~1100.

→ CMB patches more than ~ 2 degrees apart were never causally connected in the past

- How comes that they have the same temperature ?

→ invent a fast expansion phase in the early universe

→ need some extra component to achieve that

Cloud #2 : the flatness problem

Friedman equation : $$H^2(a) = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$1 - \frac{8\pi G\rho}{3H^2} \equiv 1 - \Omega(a) = -\frac{k}{(Ha)^2}$$

Ha decreases with time, so $|1-\Omega(a)|$ increases with time

We have today $|1-\Omega| < 0.1$, so it had to be much smaller in the past.

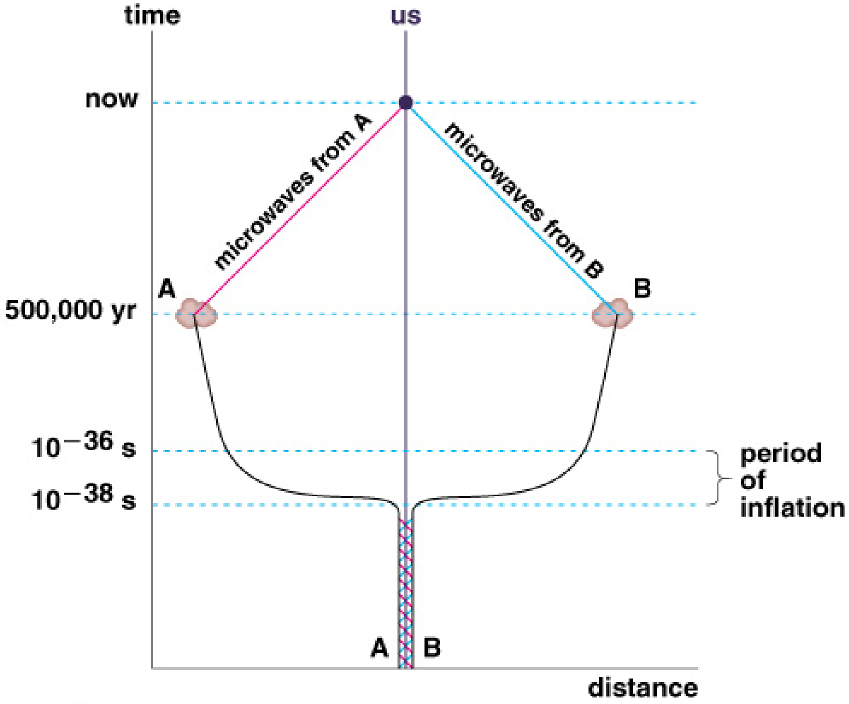
→ fine tuning required

→ a dynamical process setting curvature to 0 would be nice.

Inflation: an accelerated expansion phase

- Pulls things apart.

Apparently unconnected places were indeed connected before



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- Dilutes any curvature.

  - In an exponential expansion phase, H~Cst
  - Curvature contributes to H as $1/a^2$, it just decays.

Inflation : one more scalar

$$H(t) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

With ρ=Cst, we have an exponential expansion

For an homogeneous scalar field, $\rho = \frac{\dot{\phi}}{2} + V(\phi)$

So, a quasi-static scalar field $\dot{\phi} \simeq 0$,
- slowly rolling down its potential,
- has an almost constant density
- … and provides a quasi-exponential expansion.

A purely static scalar field delivers a never ending inflation, which is not what we want. So the potential should ensure that inflation ends.

Inflation predictions

- The universe is flat (at the 10^{-5} level)

- The universe is very homogeneous (to the same level).

- Quantum fluctuations of the inflation field are the initial conditions of the perturbations we see.
  → sets the energy scale to ~ 10^{16} GeV (in the radiation era, $T \sim \rho^{1/4}$)

- The initial power spectrum of scalar perturbations is $P(k) = A\,k^n$
  with $n<1$ and close to 1.

- A specific model of inflation predicts both the spectral index and the ratio of tensor to scalar perturbations.
  But there are a lot of models...

Initial power spectrum

Definition of P(k) $< \delta\rho(\mathbf{k})\delta\rho(\mathbf{k}') >= (2\pi)^3 P(k)\delta(\mathbf{k}-\mathbf{k}')$

No natural scale → has to be a power law

$$P(k) = Ak^n$$

n=1 is called Harrison-Zeldovitch-Peebles spectrum. ("scale invariant" because $k^3P_\phi(k)$ (dimensionless) does not depend of k)

→ We expect n=~1. It turns out that we measure n ~= 0.96 We are fairly sure we understand the small difference.

Evolution of perturbations

Computations to first order. Few results to second order.
Complex subject: typically more than 50 pages in cosmology textbooks.

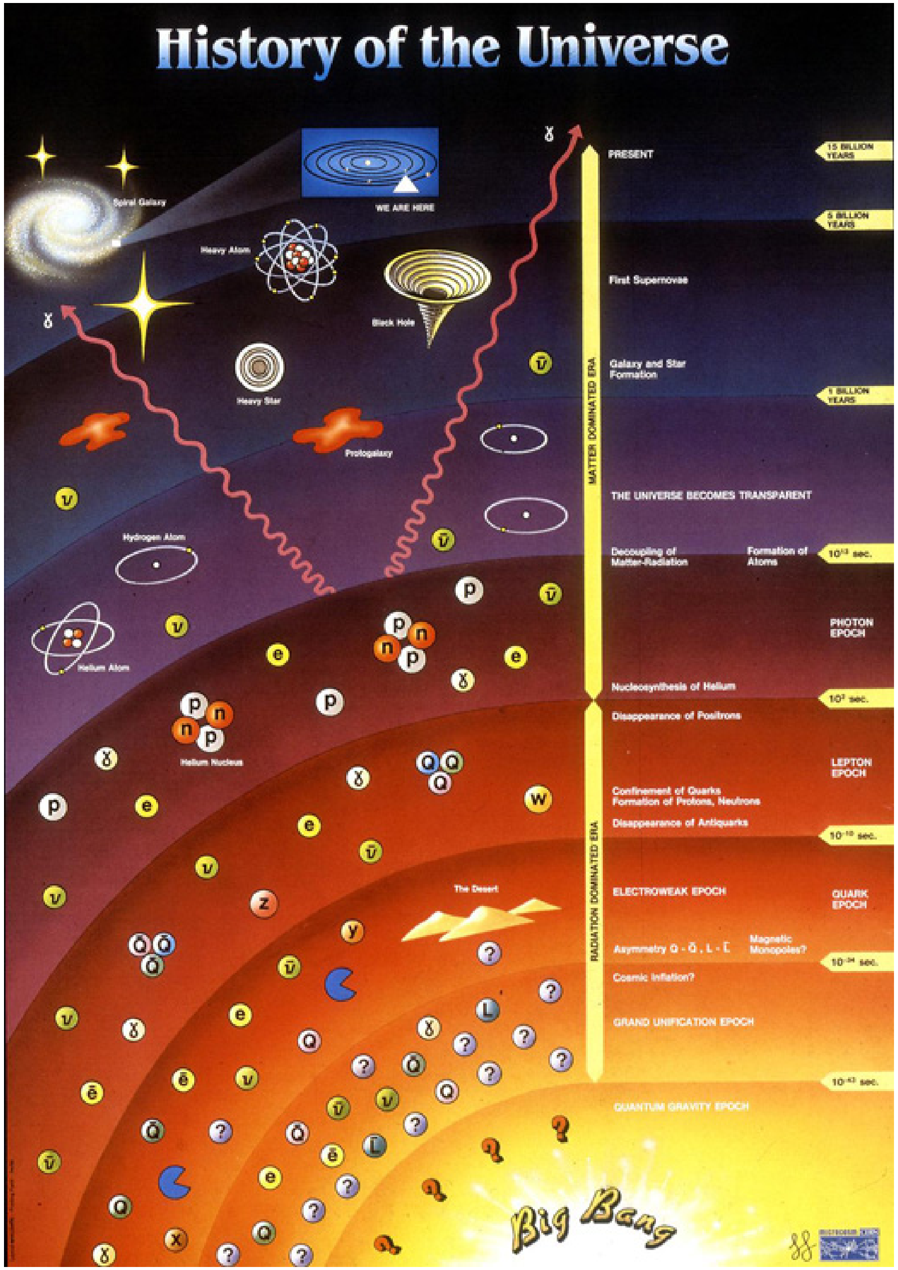
Only a qualitative discussion here...

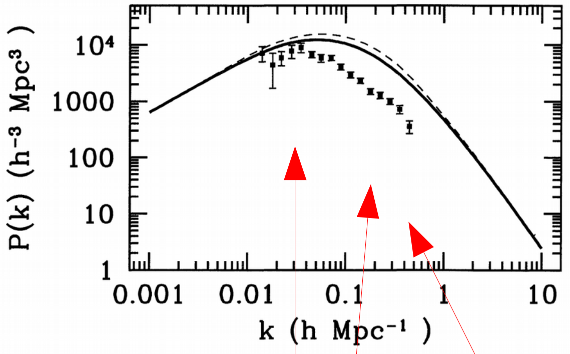
Simple example: evolution of matter perturbations in a matter dominated universe without radiation:

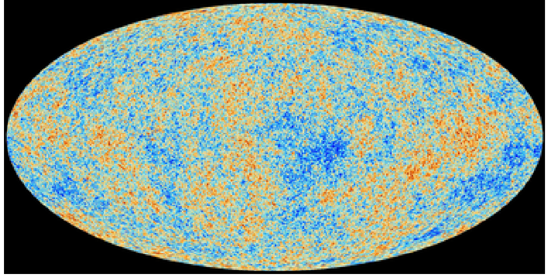
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\rho_M \delta$$

The evolution of a perturbation is (in this case) independent of its size
Two solutions: one decaying (uninteresting), one growing $\delta \propto a(t)$
This is what happens after recombination.

The sketch







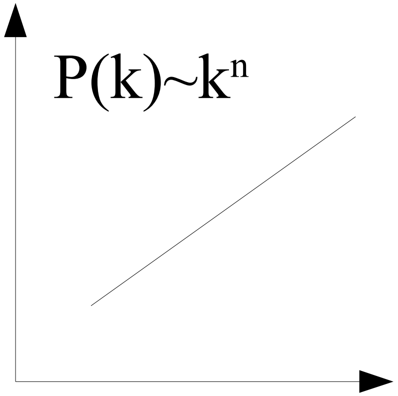
Structures keep forming

Recombination

Radiation-matter equality

Nucleosynthesis (He fraction)

End of inflation,
sets initial conditions

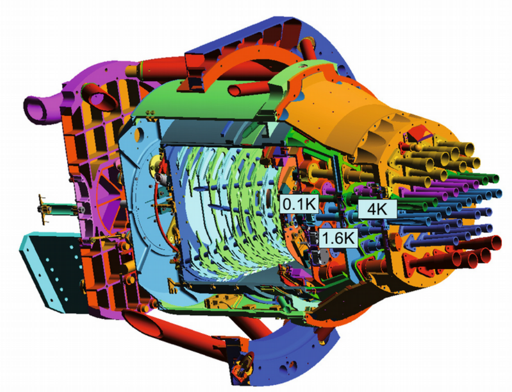


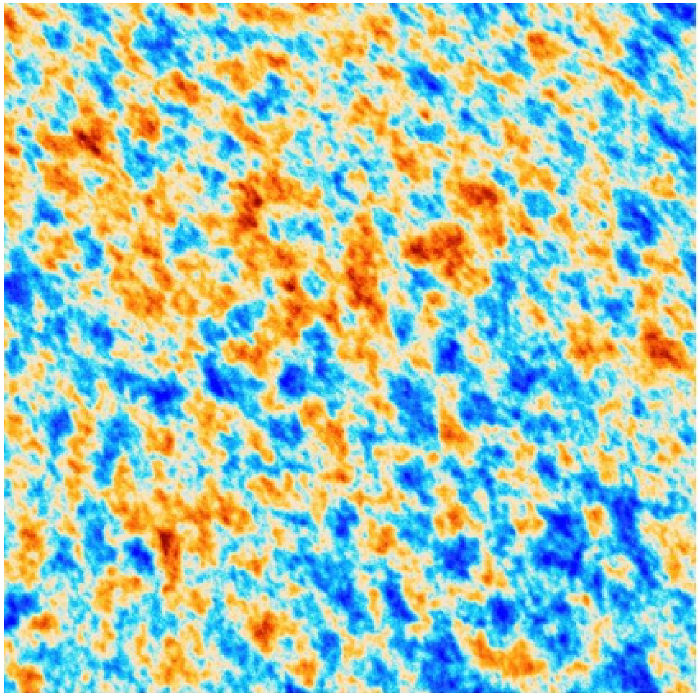
$P(k) \sim k^n$

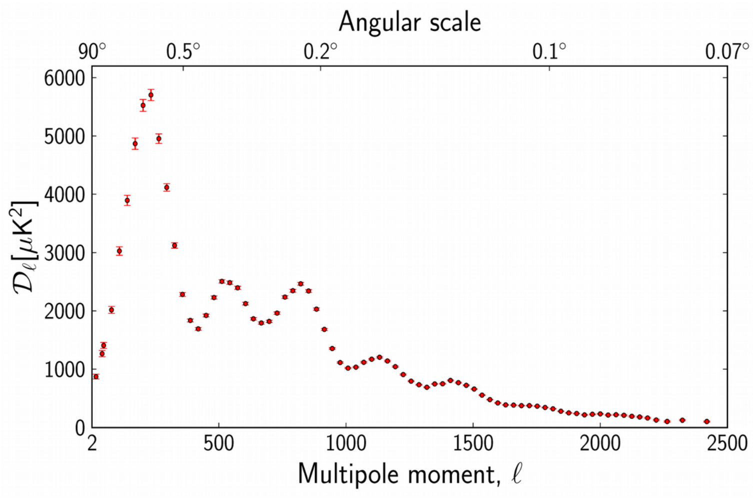
k

Planck

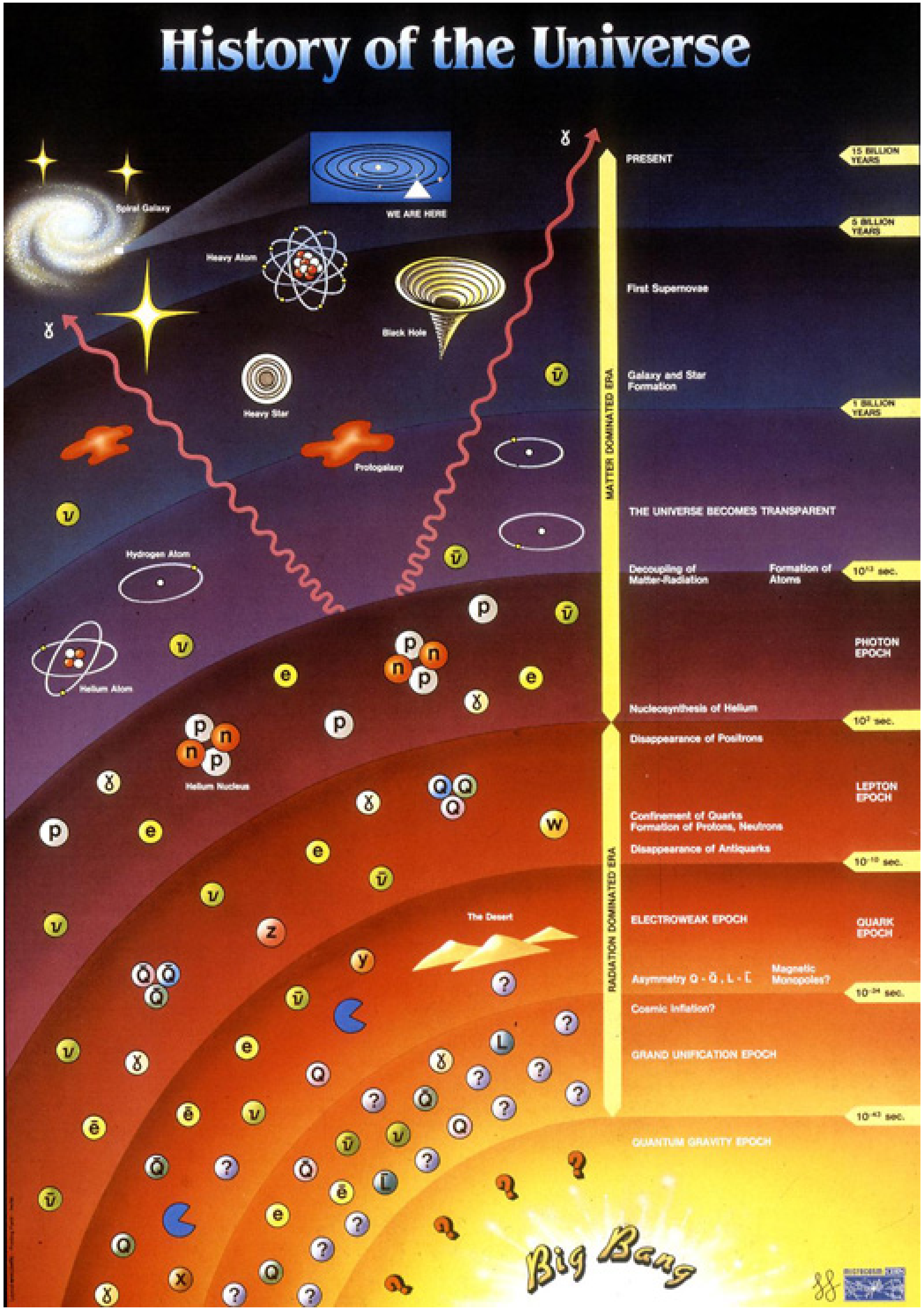
I borrowed a lot from publicly available information, and in particular from slides by François Bouchet (IAP)





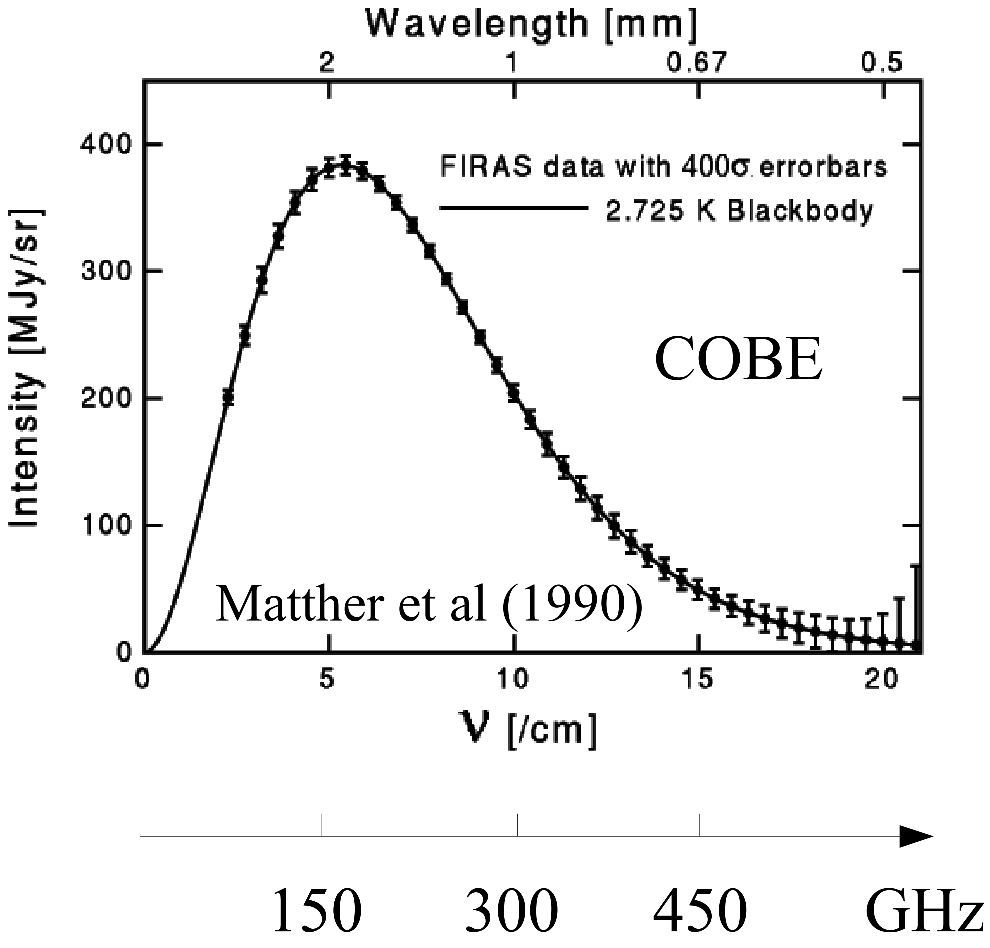


The Cosmic Microwave Background



CMB is emitted here

Spectrum ?

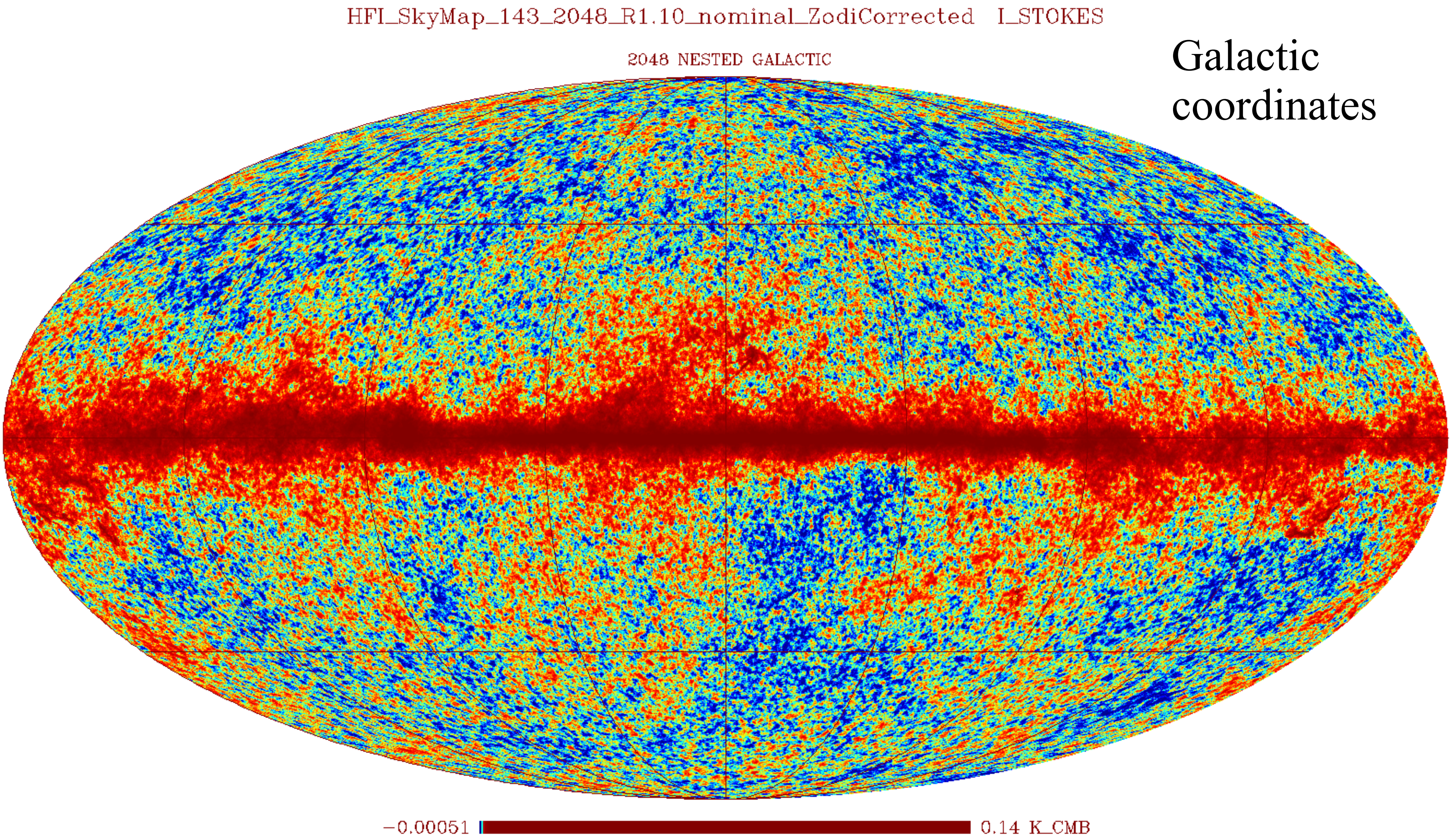


T=2.72 K

Peak at ~:

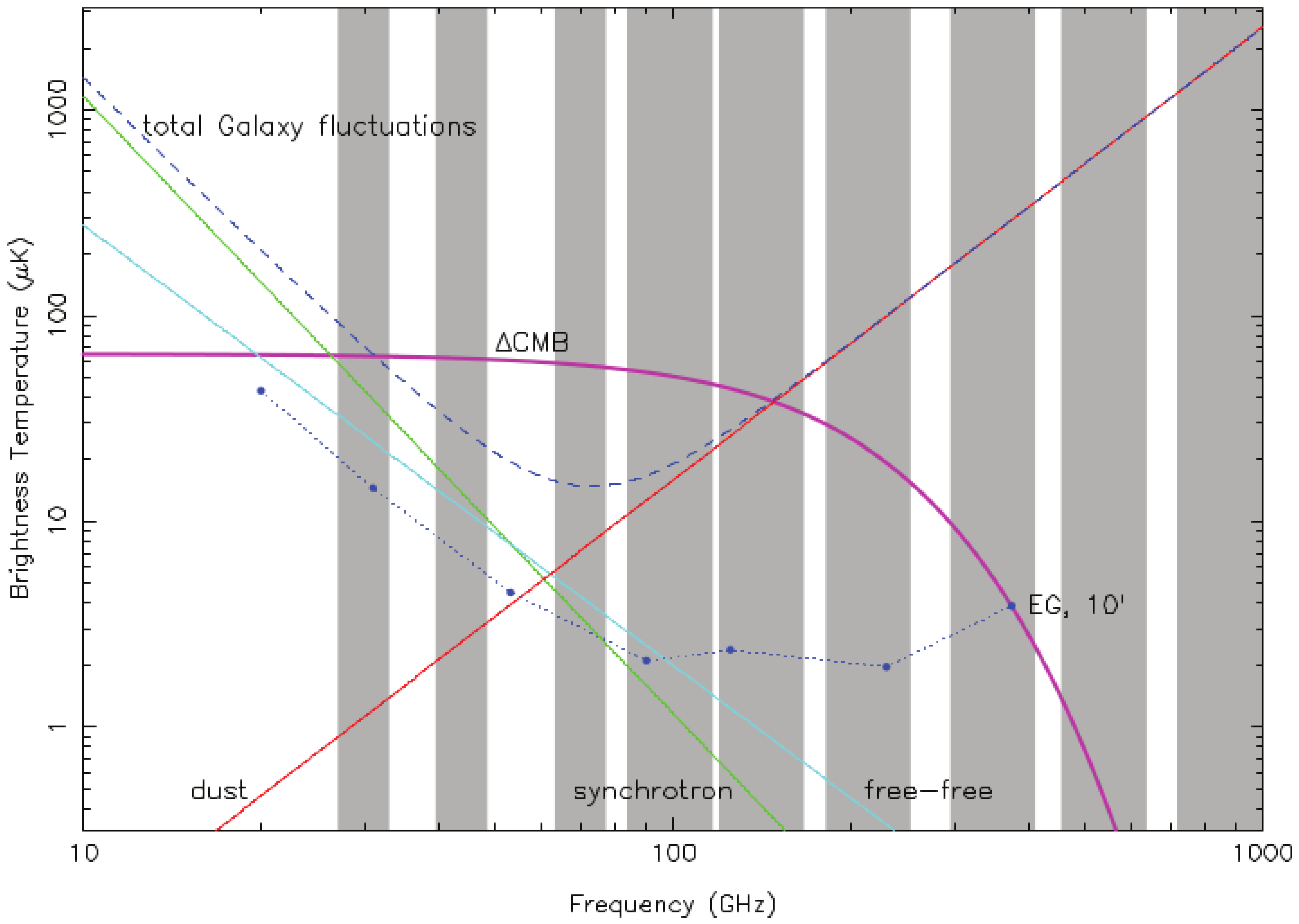
- 5 cm^{-1}
- 2 mm
- 150 GHz

The anisotropies at ~143 GHz



Galactic
coordinates

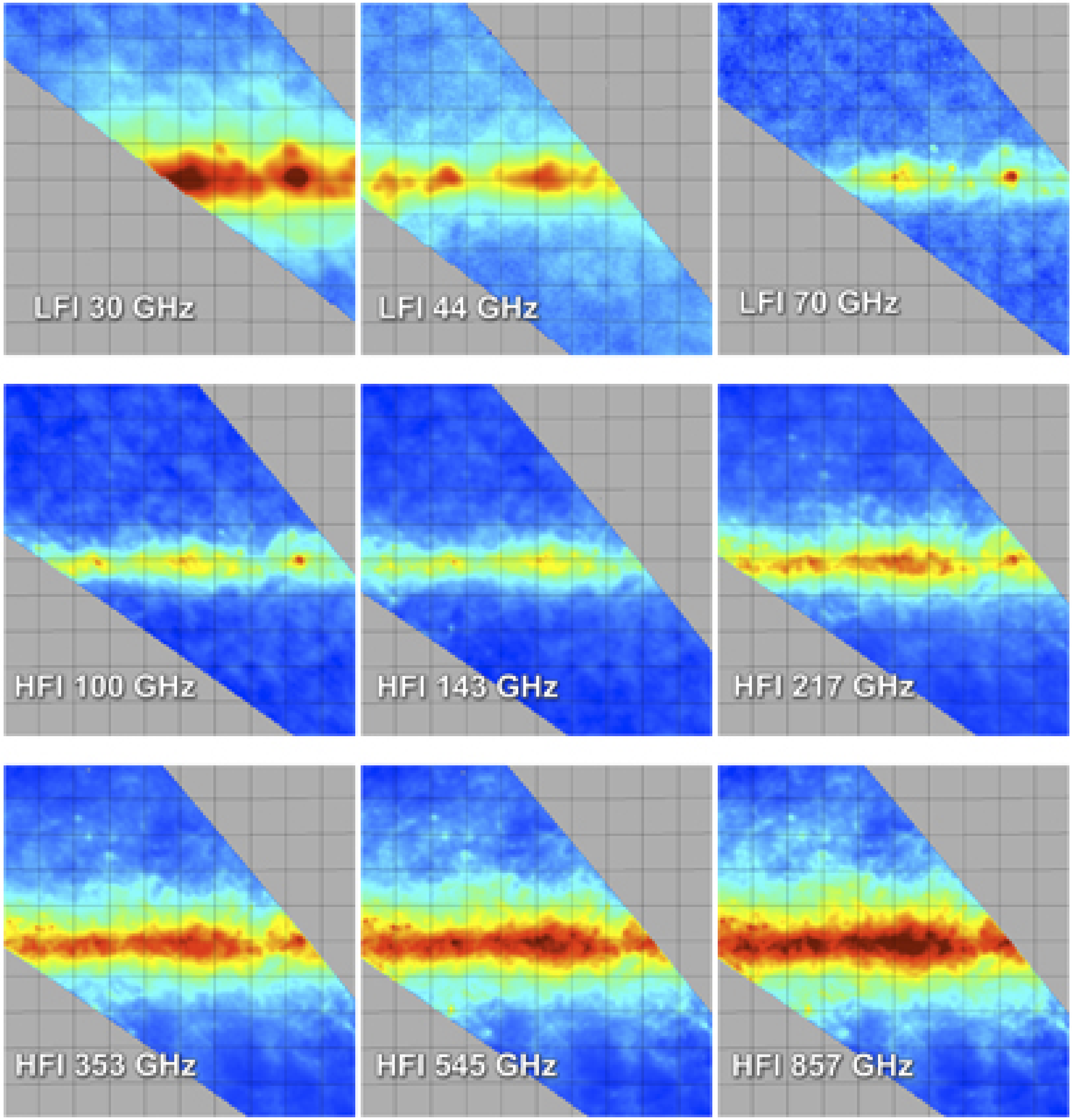
Emissions at 30 → 900 GHz



Intensity of fluctuations at the degree angular scale.

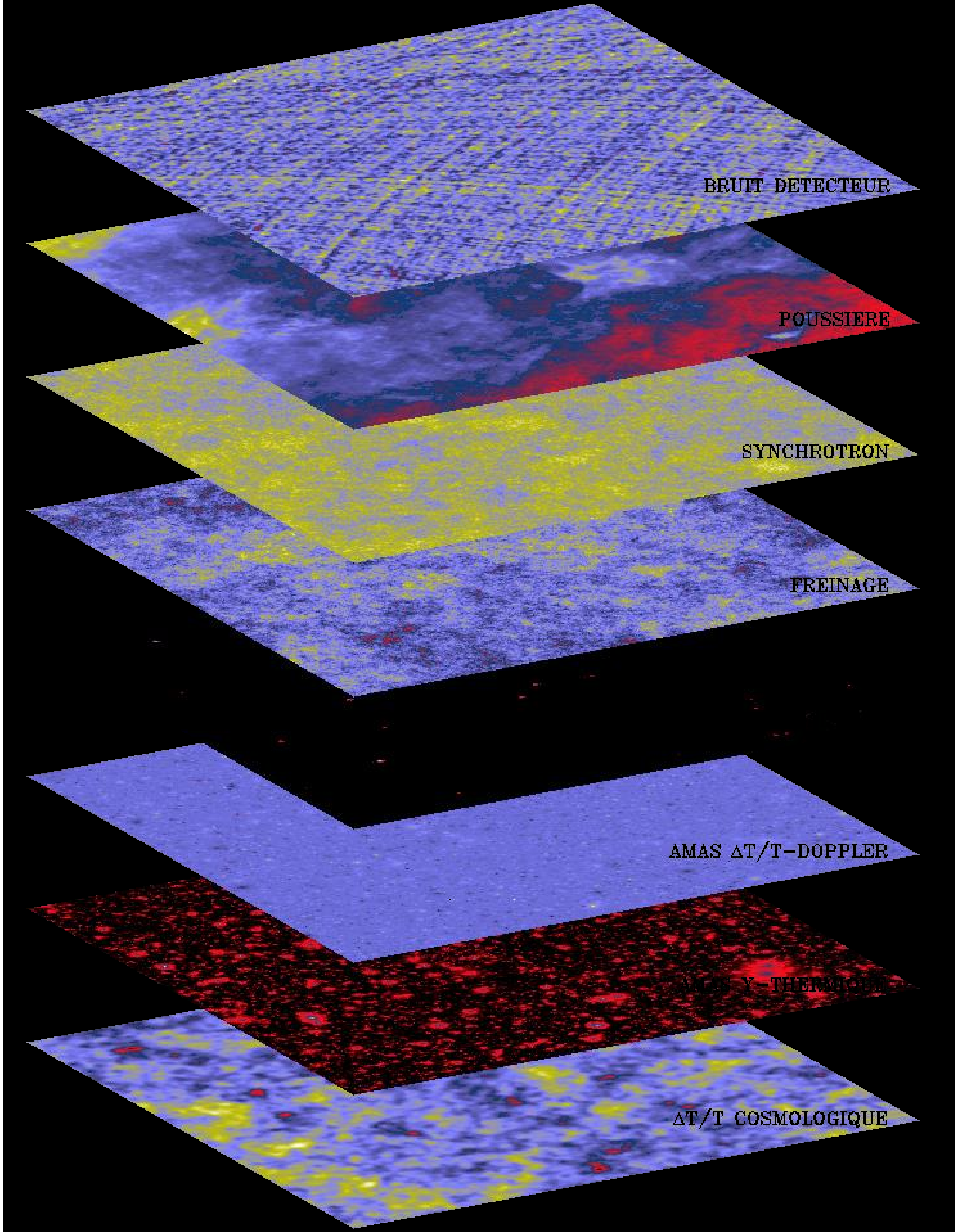
The way out: multi-band observations

Galactic
plane



synchrotron

Dust



The cosmic layered cake

Detector noise
Dust
Synchrotron, Brems
Clusters
mm sources
CMB

The Planck concept (1996)

To perform the "ultimate" measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:
- full sky coverage
- angular resolution to 5' (below, foregrounds dominate)
- sensitivity limited by foregrounds
  → spectral coverage : 30 → 850 GHz.

Milestones:

- Mission selected by ESA in 1996 (studies started in 93...)
  for a launch in 2003.
- Crash of Ariane 501 in 2001

→ launch delayed (2003 → 2007)
→ polarisation capabilities became a "must-do"
→ more delays
- Launch in May 2009.

14, May 2009
Ariane V joint launch
of Herschel & Planck

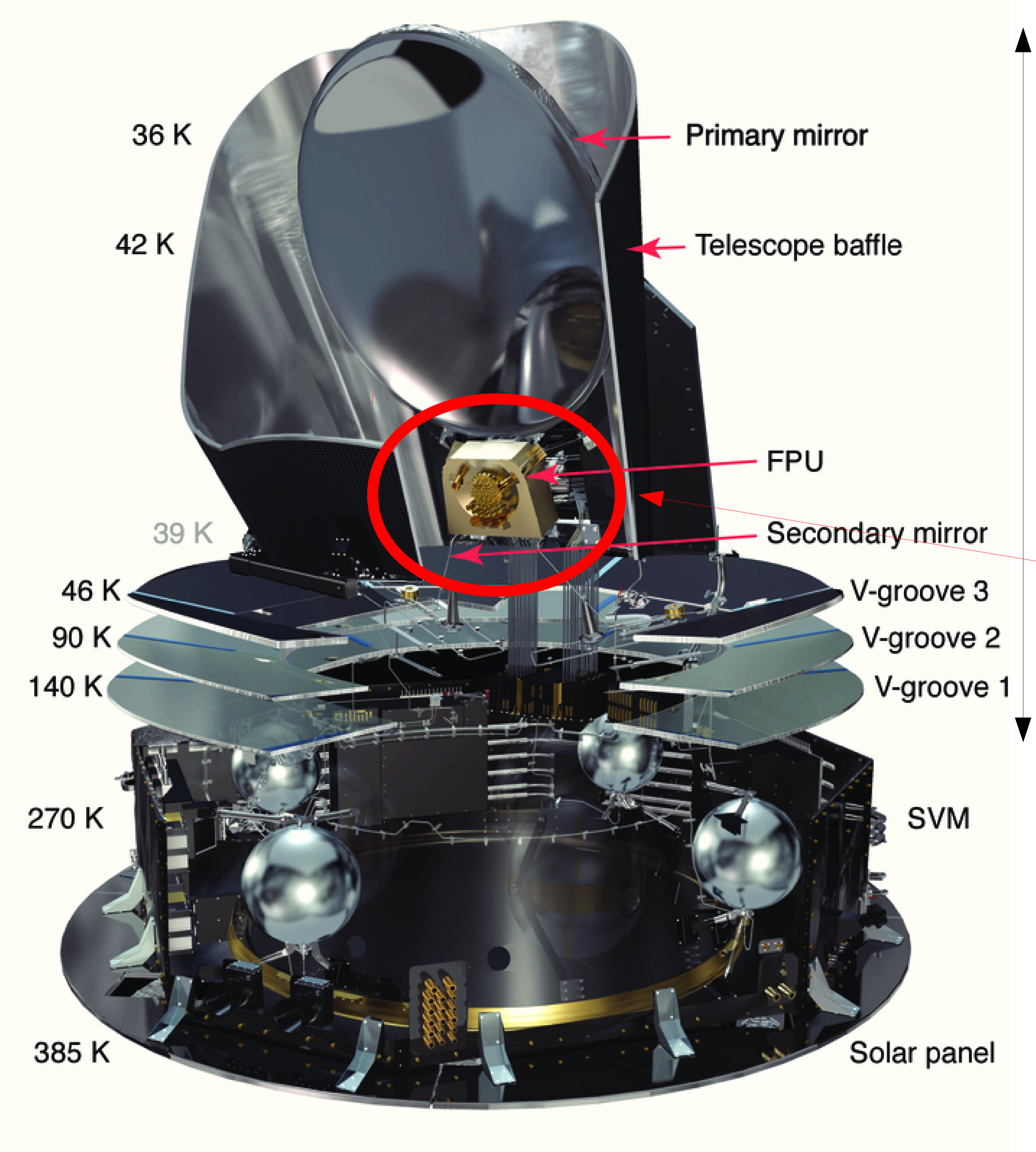
2000 Kg
1600 W consumption
2 instruments - HFI & LFI
15 months nominal survey+4

The mission

50 000 electronic components
36 000 l 4He
12 000 l 3He
11 400 documents

20 years between the first project and first results (2013)

6c per European per year
16 countries
400 researchers among 1000

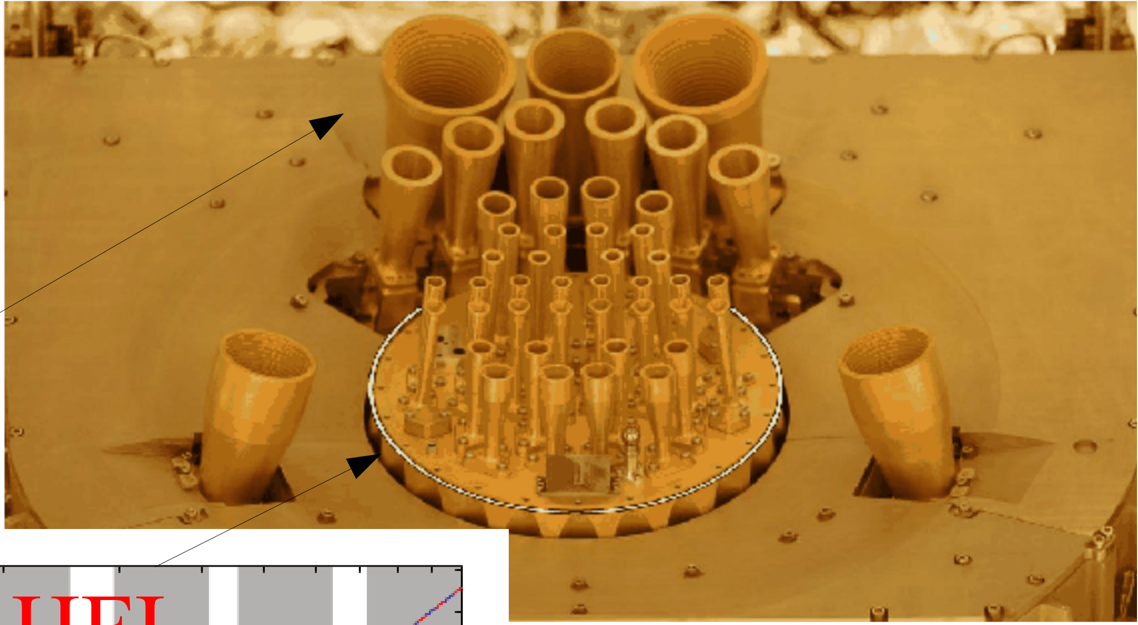


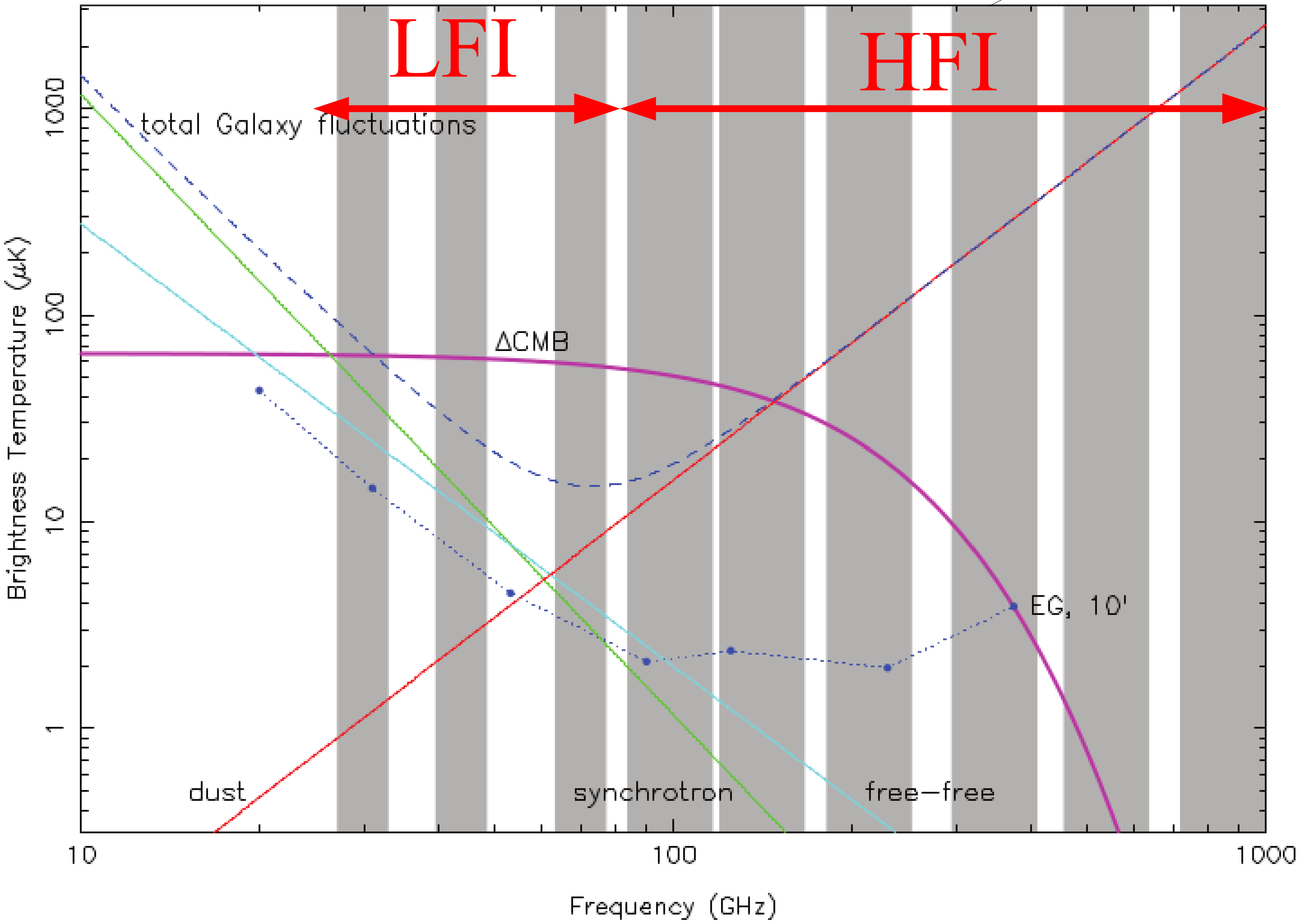
Cold part

Very cold part

Sun is this way

Focal plane

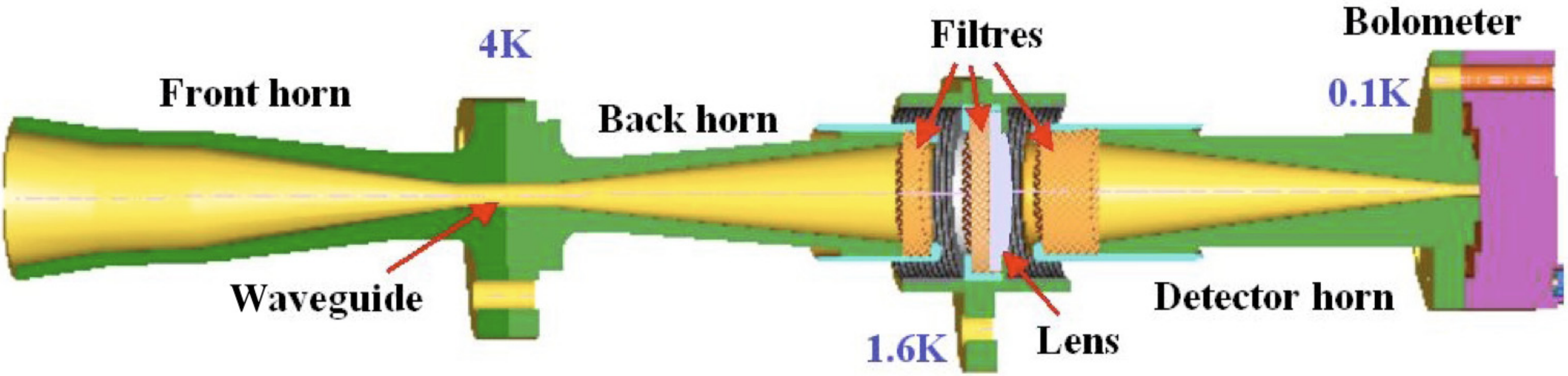


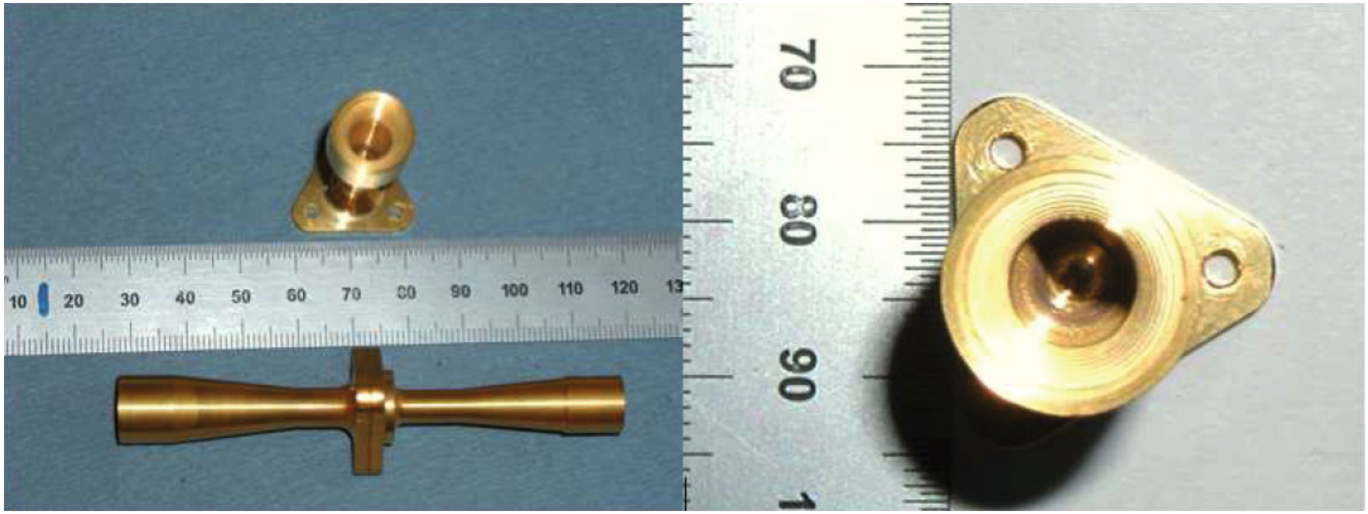


LFI : radiometers
(Similar to WMAP)

HFI : bolometers

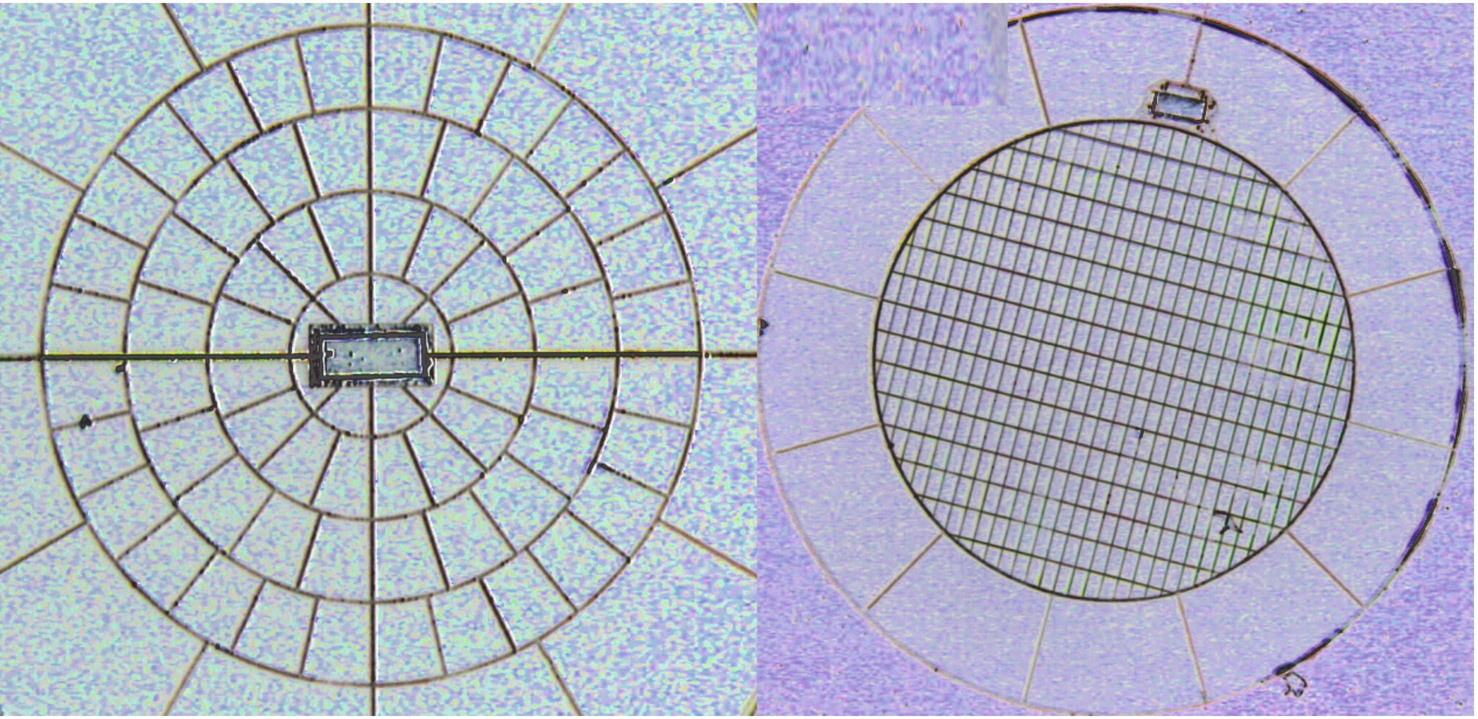
Horns



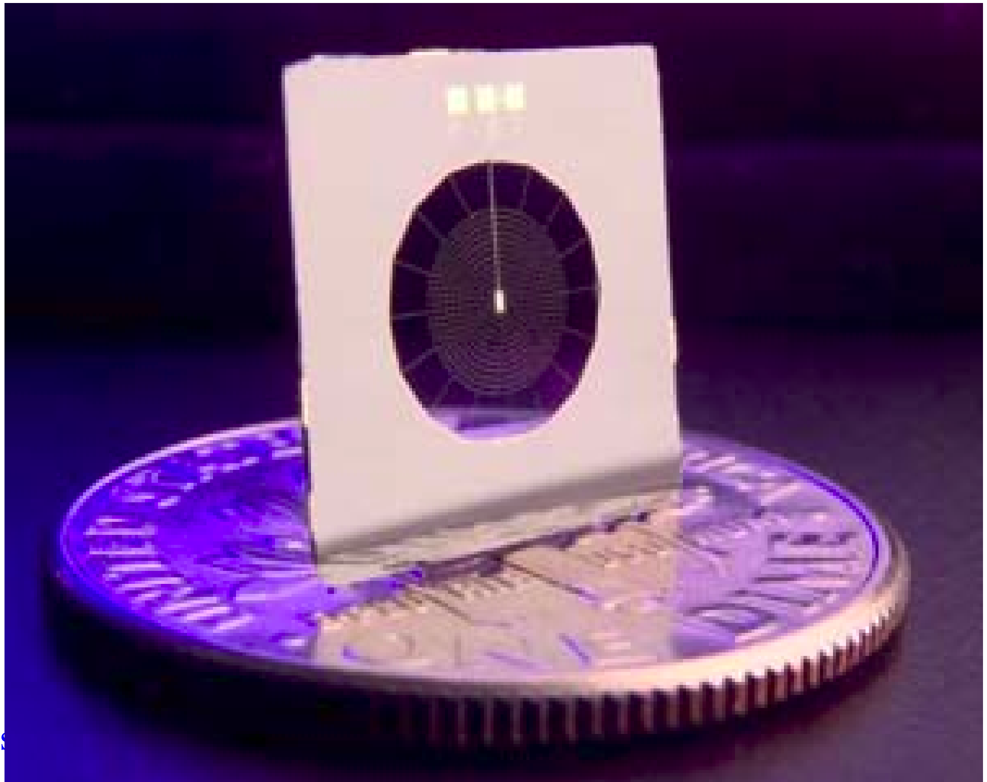


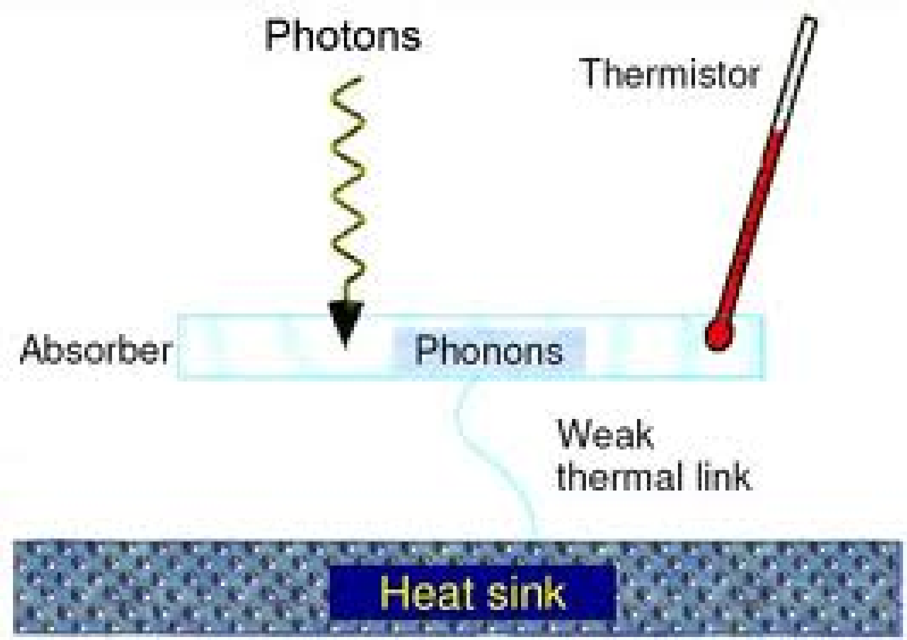
Mechanical
filtering of waves

(Lamarre et al, A&A 2009)

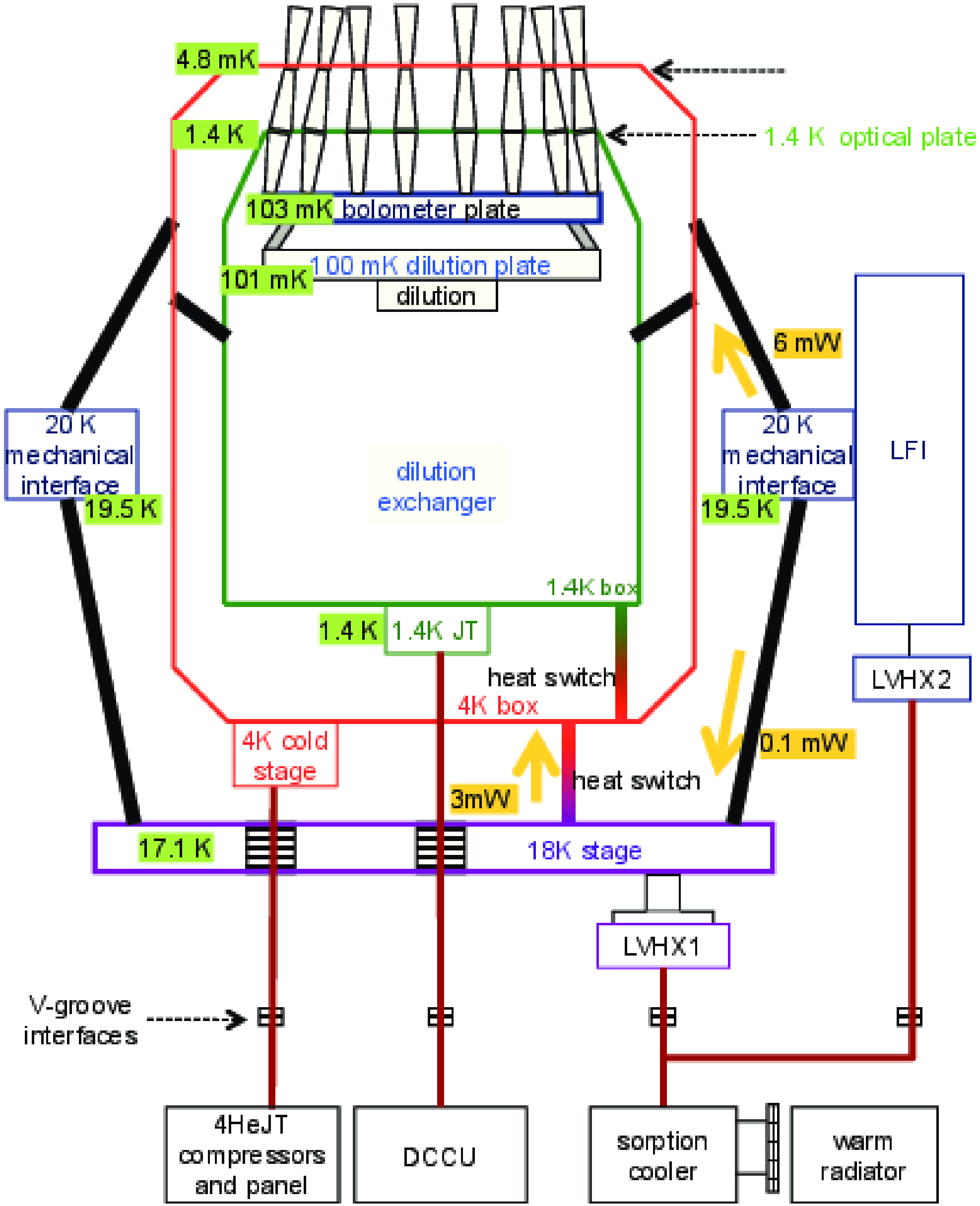


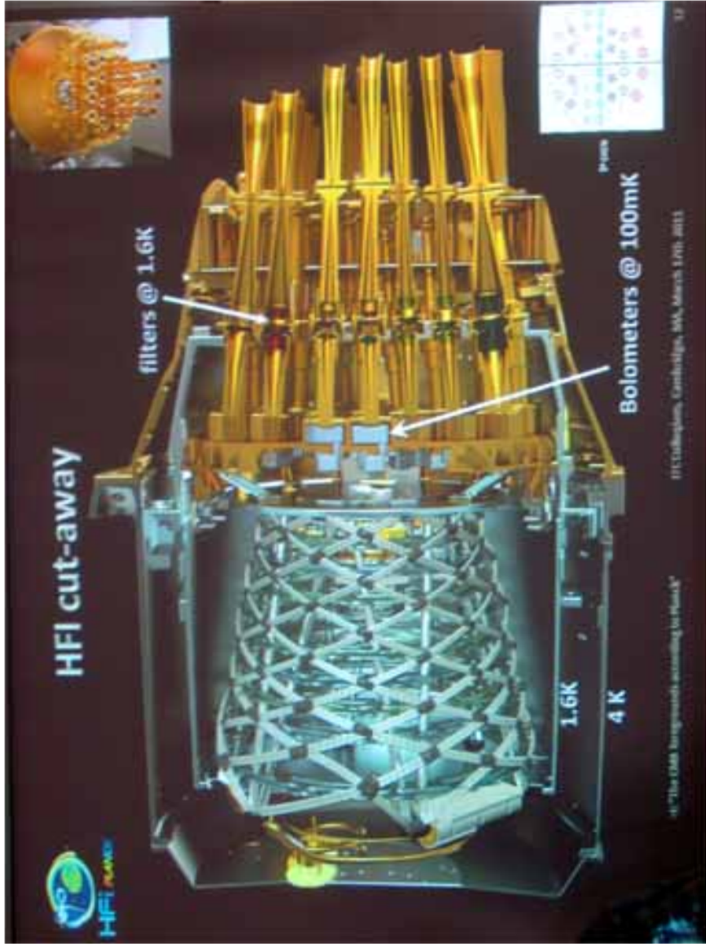
HFI bolometers: minimum amount of matter





HFI: cryogenic schematics



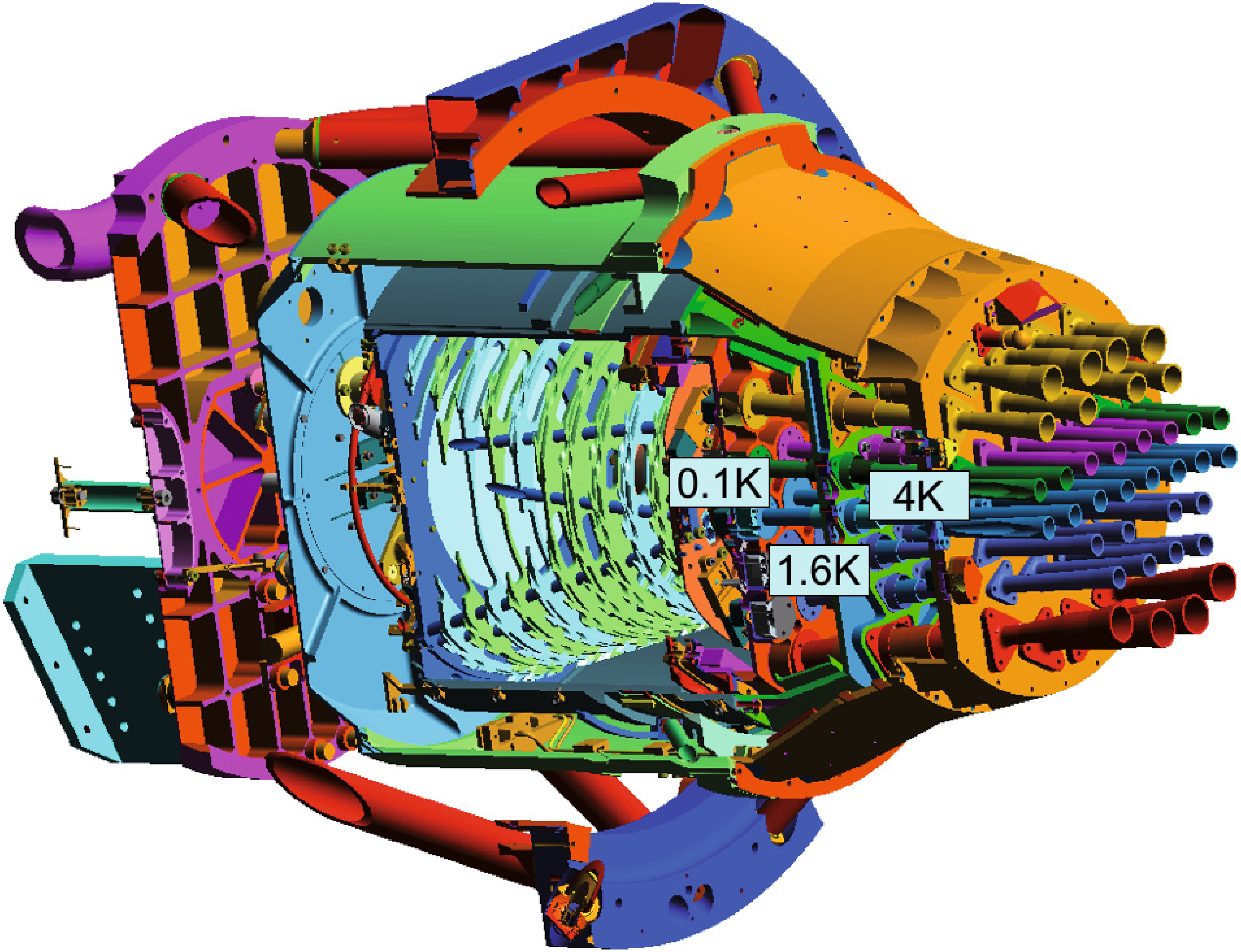


4 active stages :

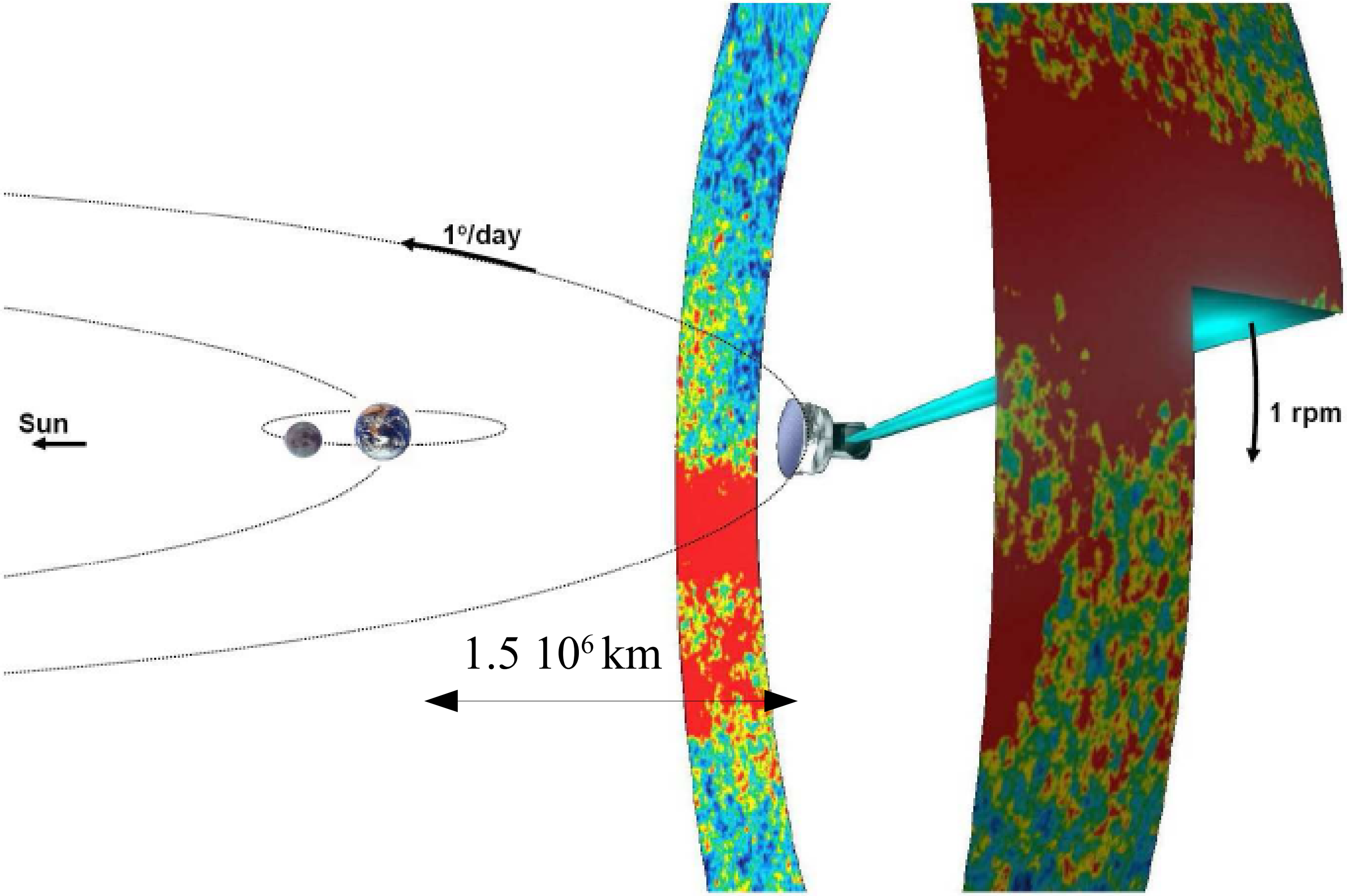
0.1 K (dilution)
1.4 K (JT)
4 K (JT)
18 K (sorption cooler)

50 K : passive

A Russian doll arrangement



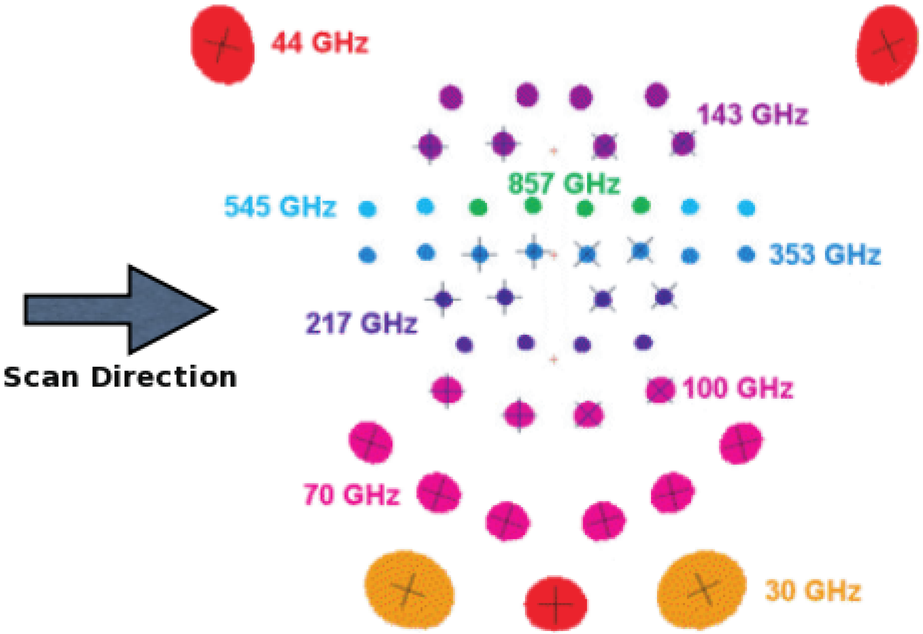
Observing mode



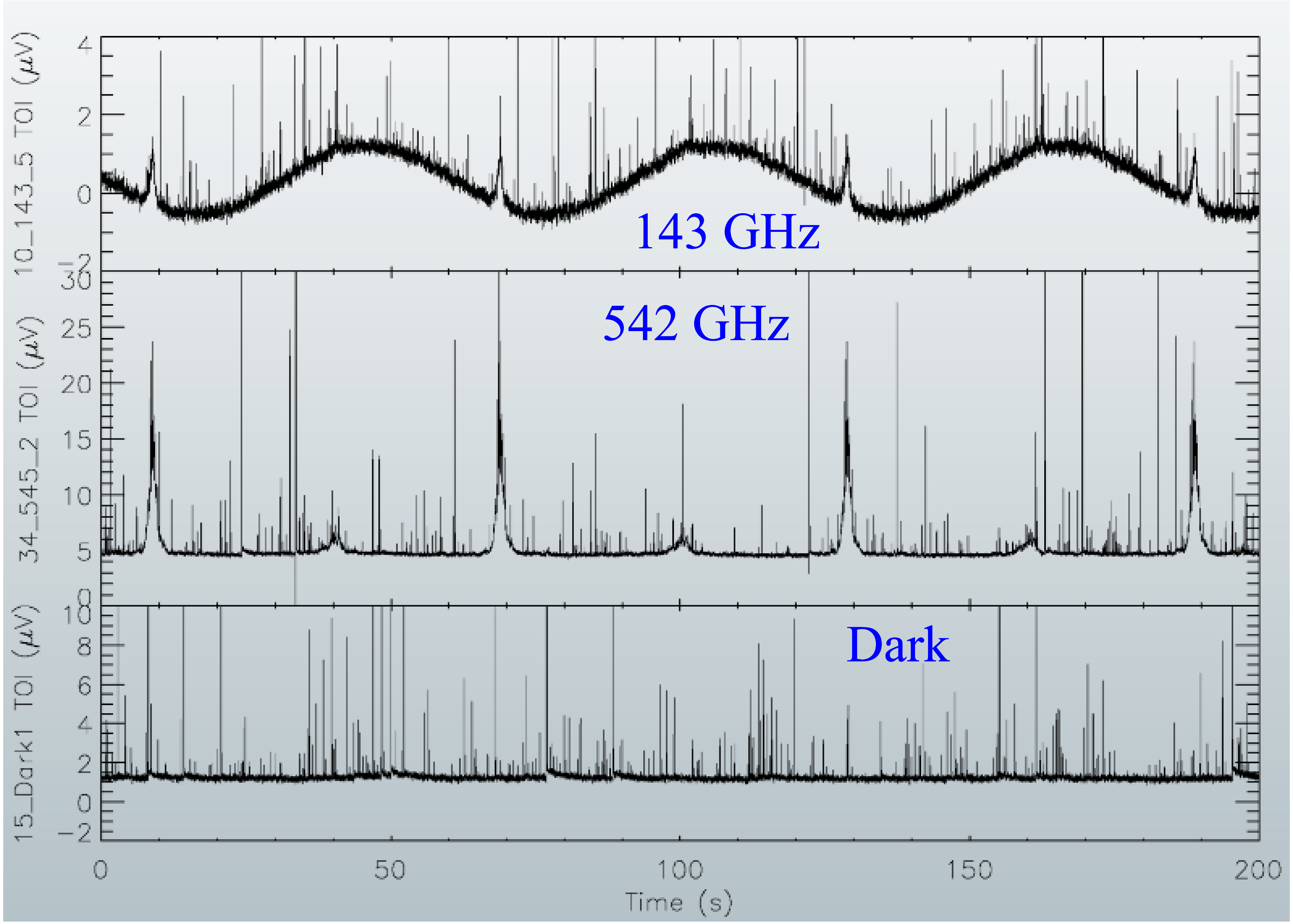
Observe at 85 deg. from spin axis.

Spin axis can be moved by at most 10 deg.

Observe from L2:
- thermally stable environment
- away from human perturbations

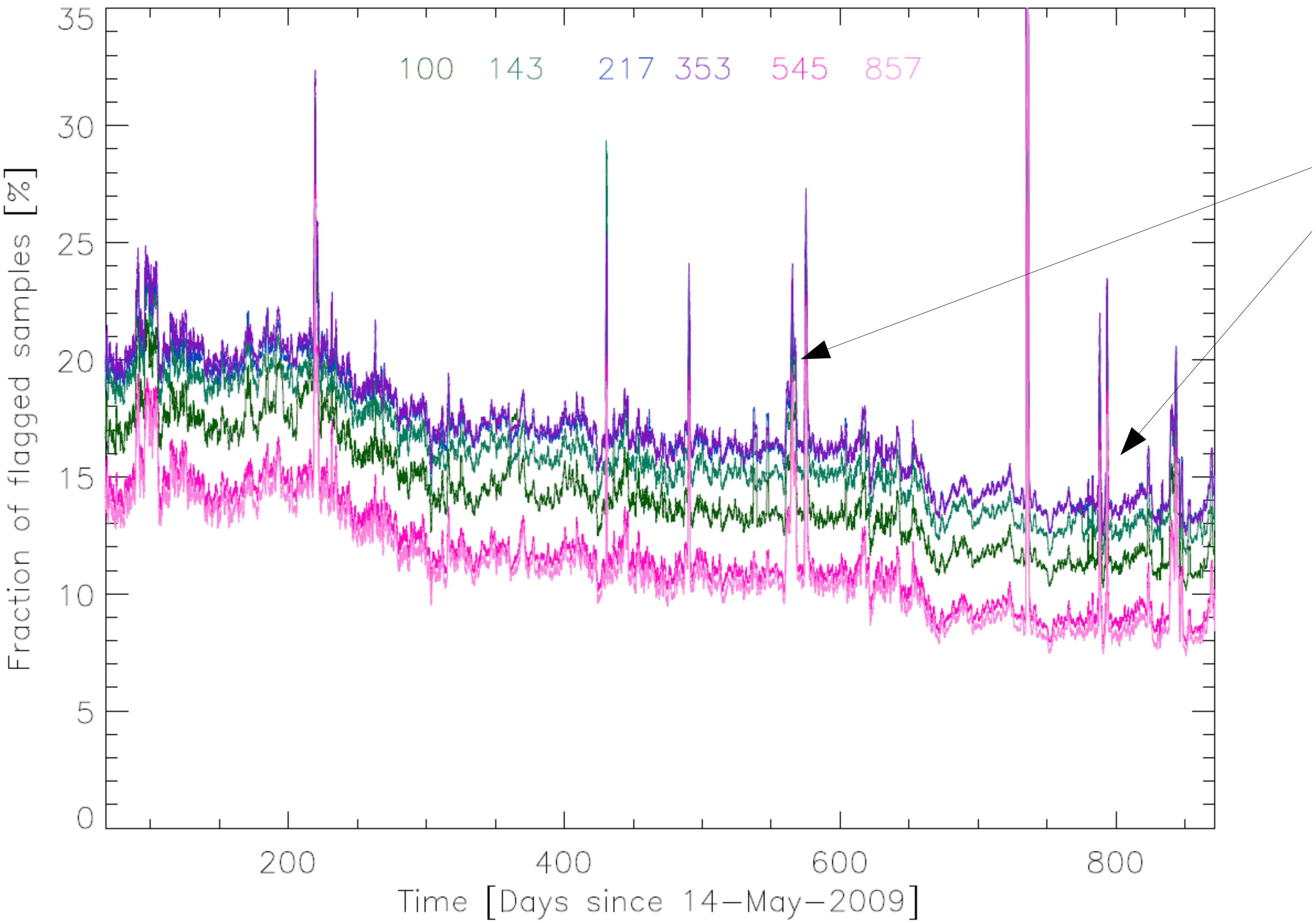


Time ordered information from HFI

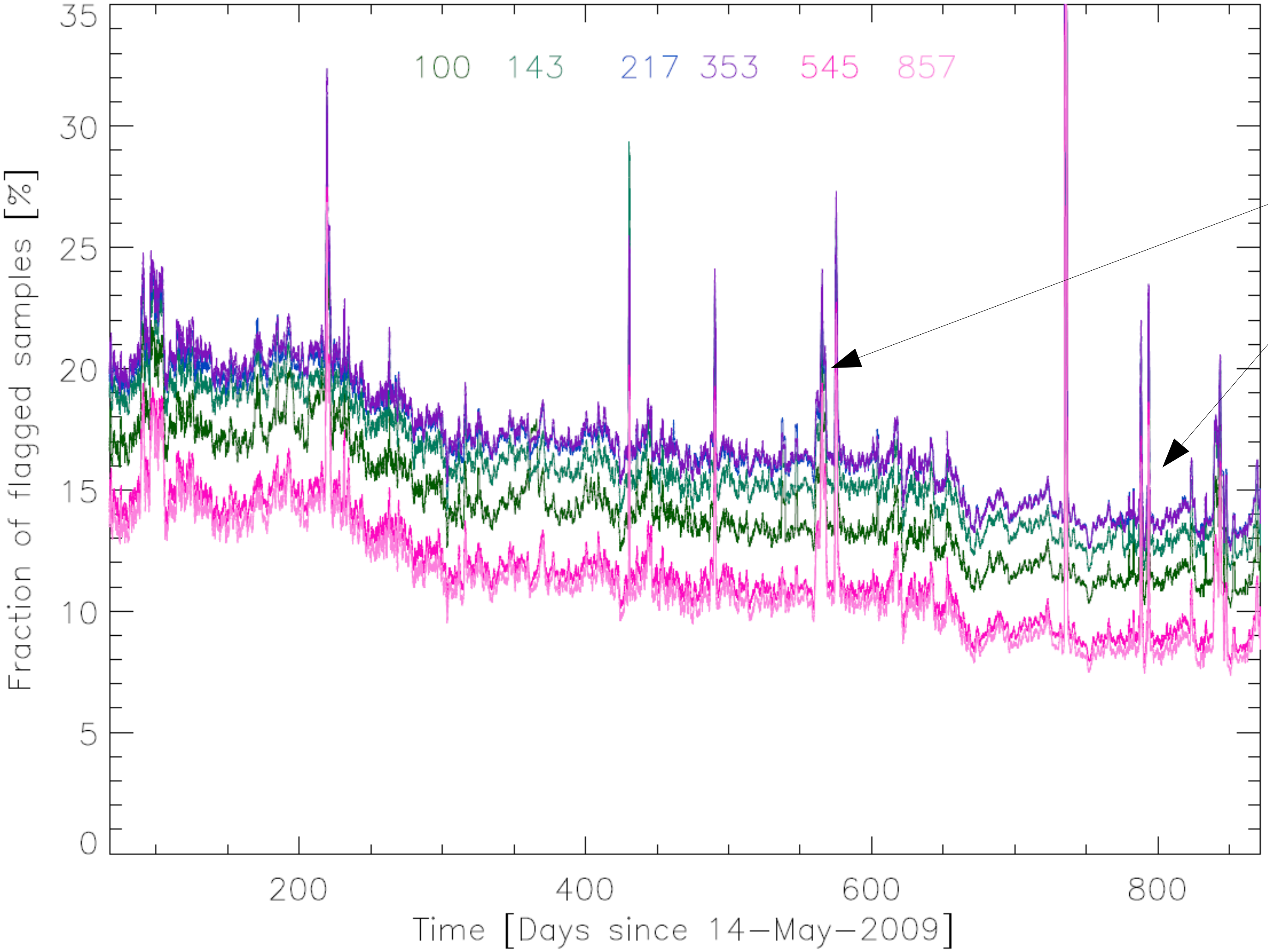


1 turn

15 to 20 % of data ignored

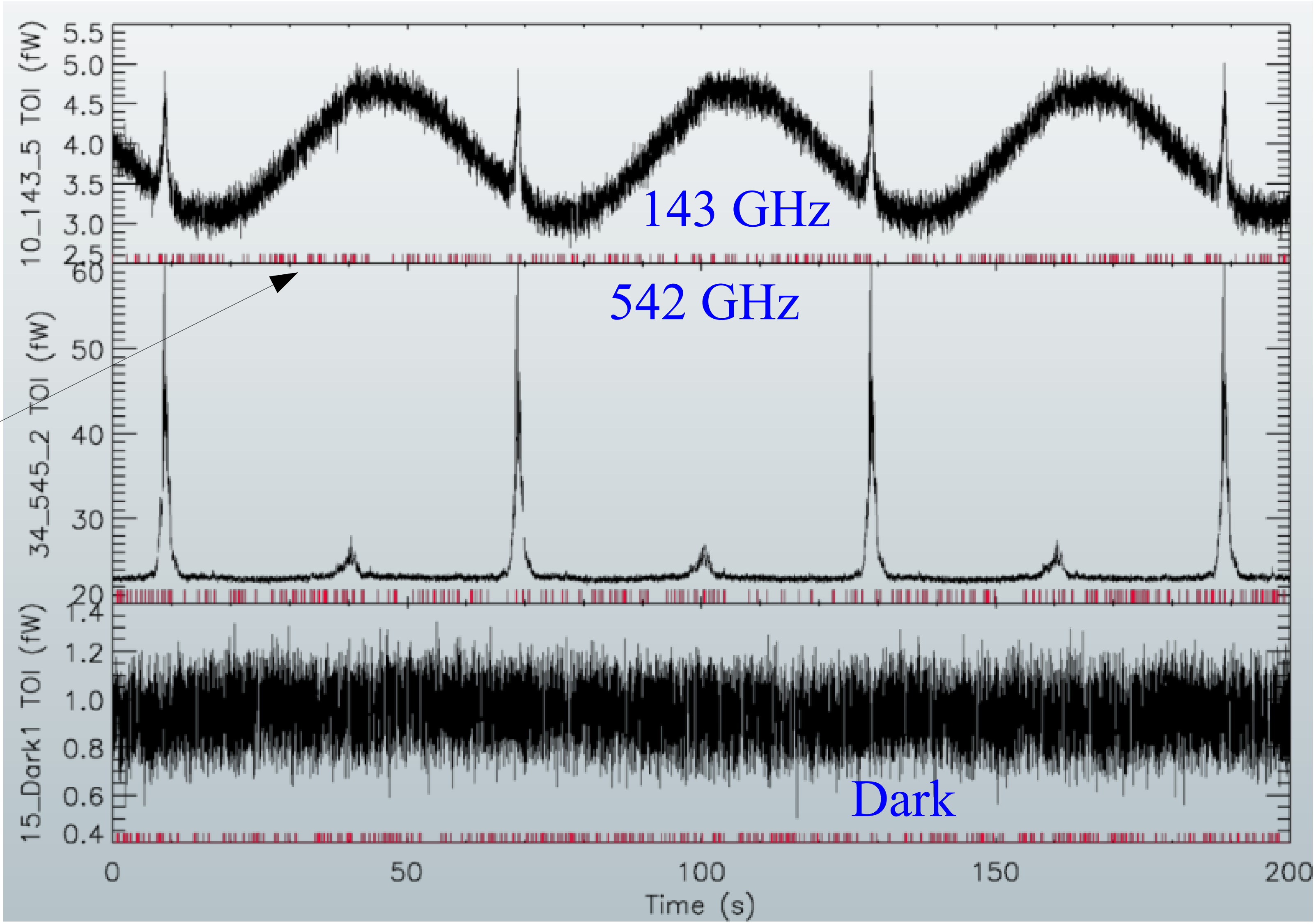


15 to 20 % of data ignored (flagged)



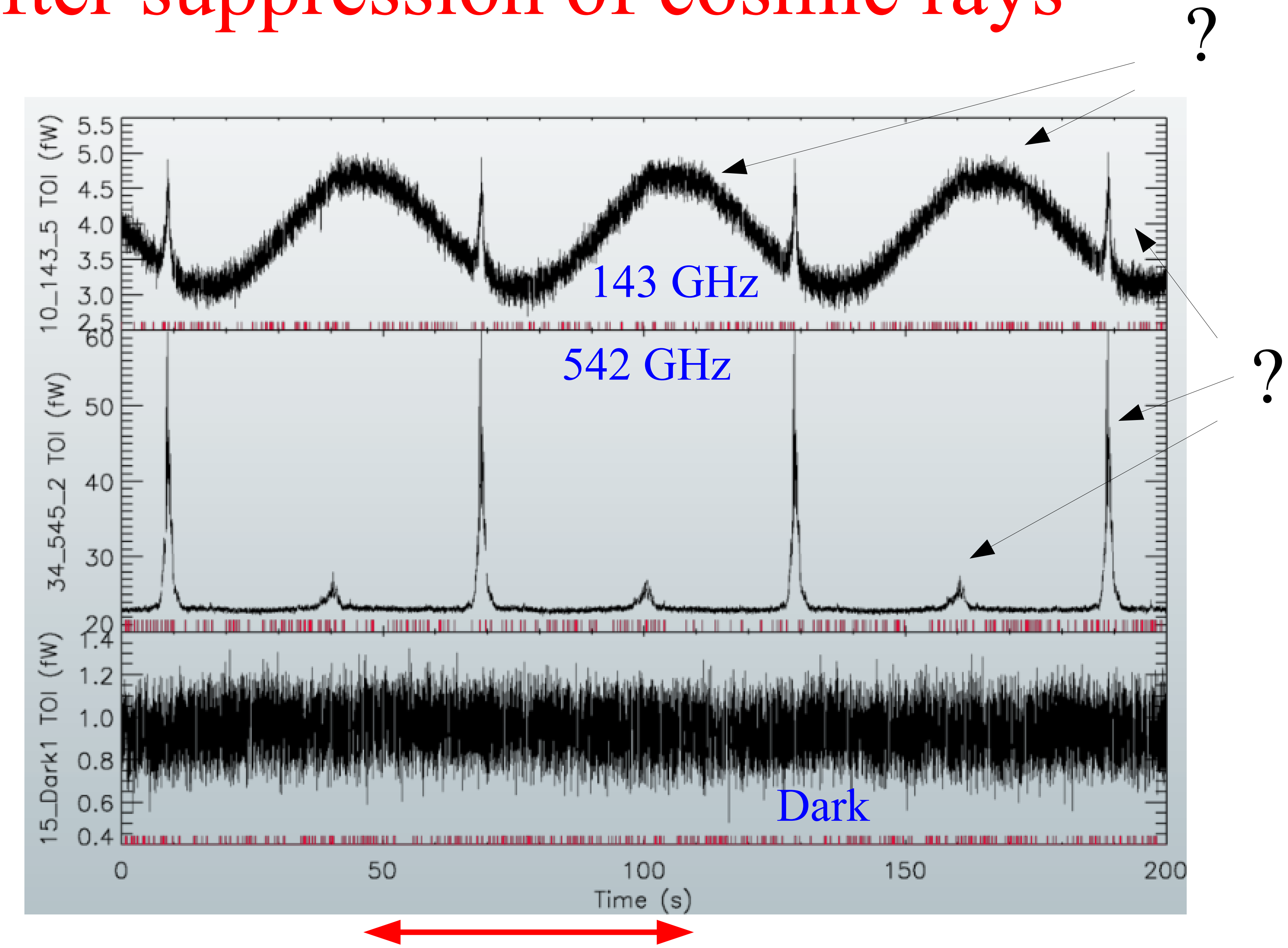
Solar flares

After suppression of cosmic rays



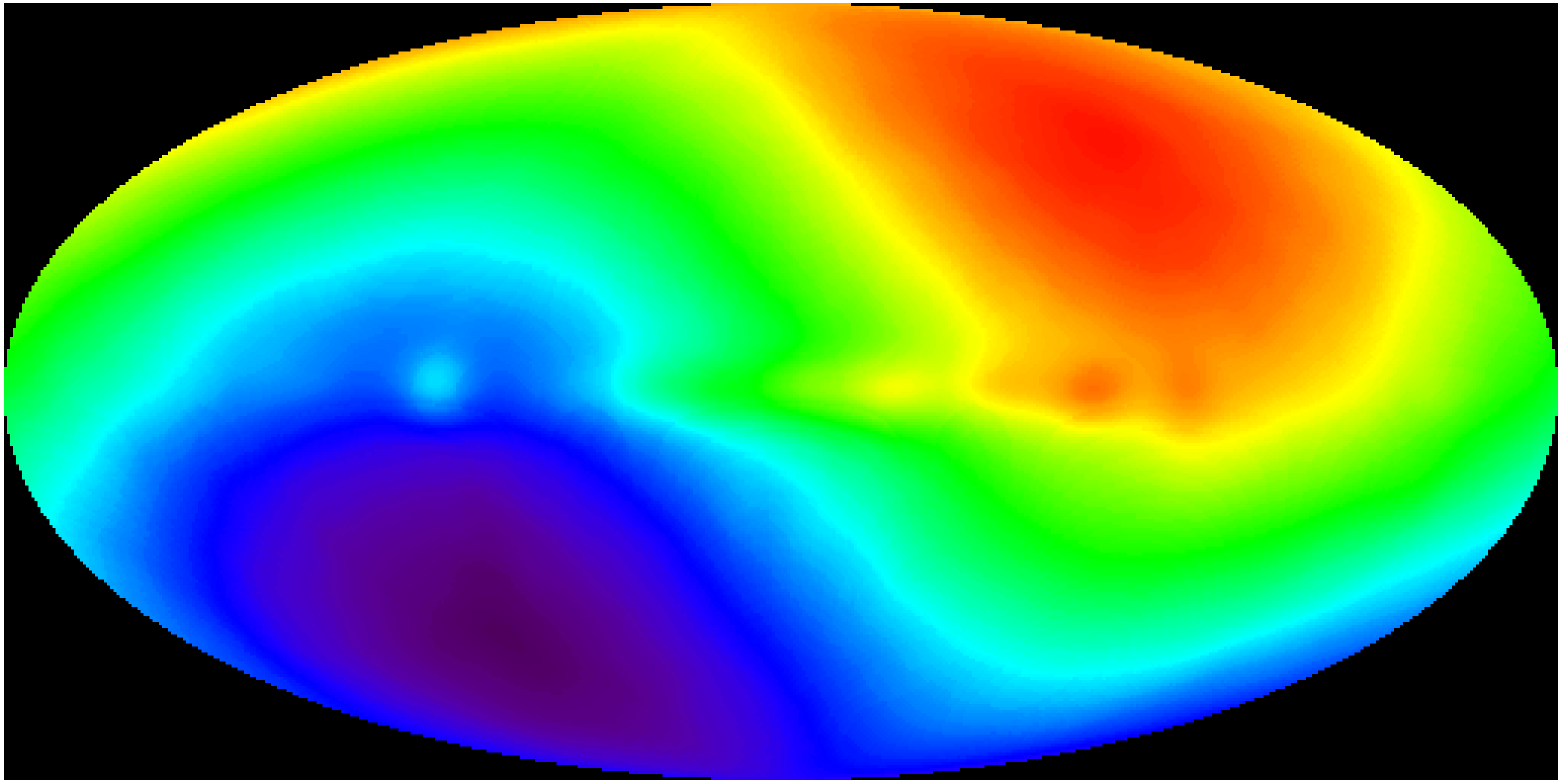
Flagged data

After suppression of cosmic rays



1 turn

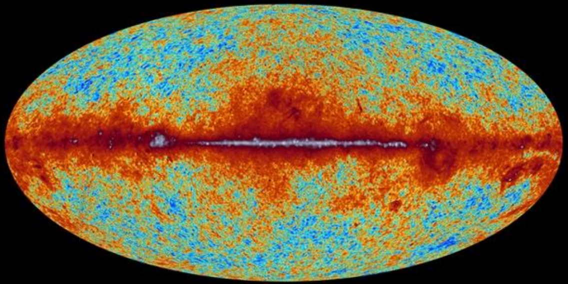
The dipole: the ether's revenge



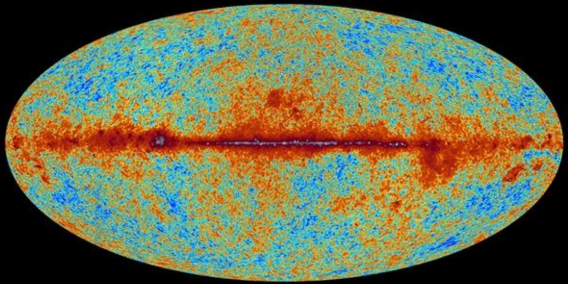
We are not at rest w.r.t CMB

Average CMB temperature : 2.7 K
Amplitude of the dipole : 3.35 mK
→ velocity w.r.t CMB = 369 km/s
Amplitude of the CMB anisotropies : ~ 30 μK

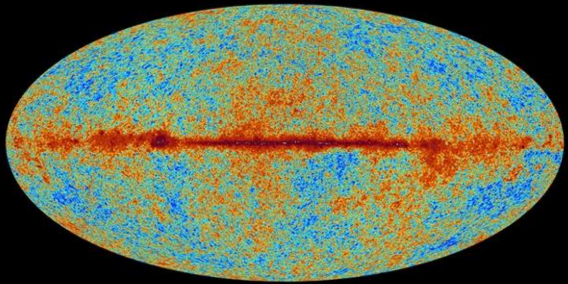
The sky as seen by Planck



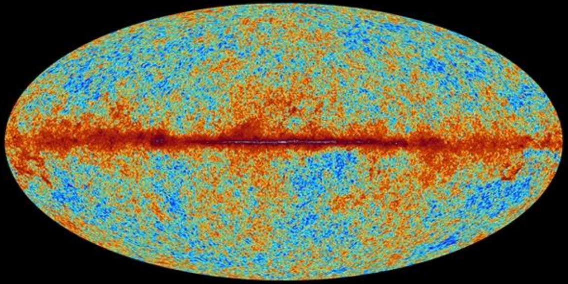
30 GHz



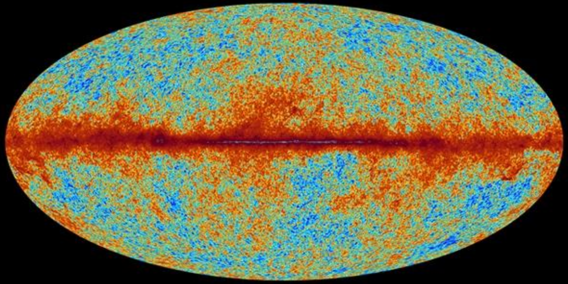
44 GHz



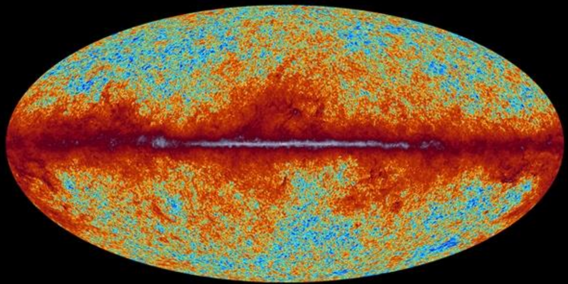
70 GHz



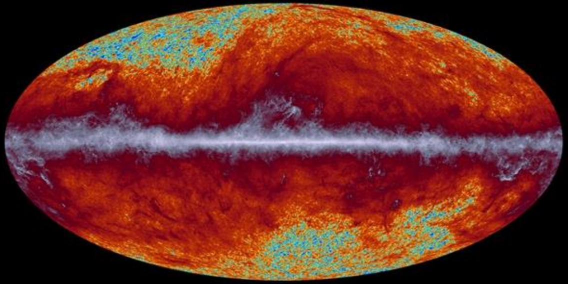
100 GHz



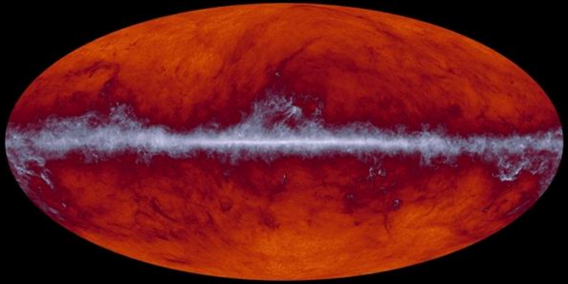
143 GHz



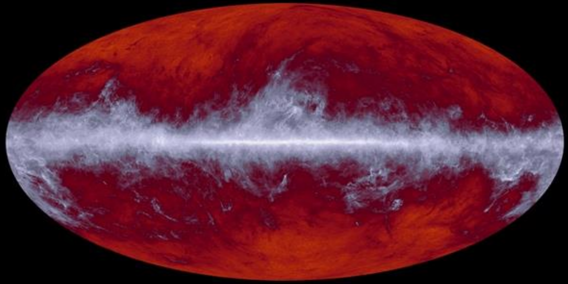
217 GHz



353 GHz

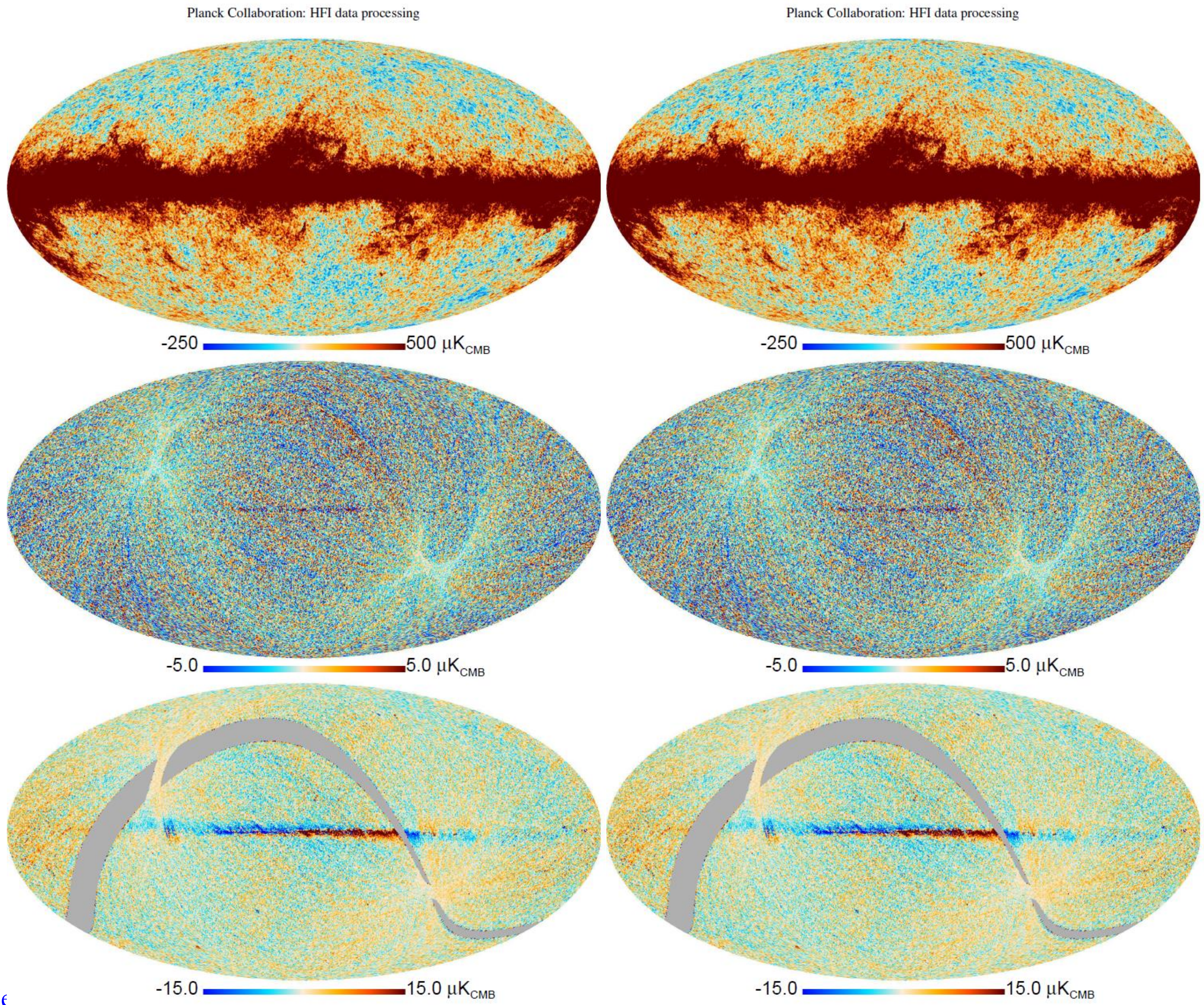


545 GHz



857 GHz

143 & 217 GHz maps

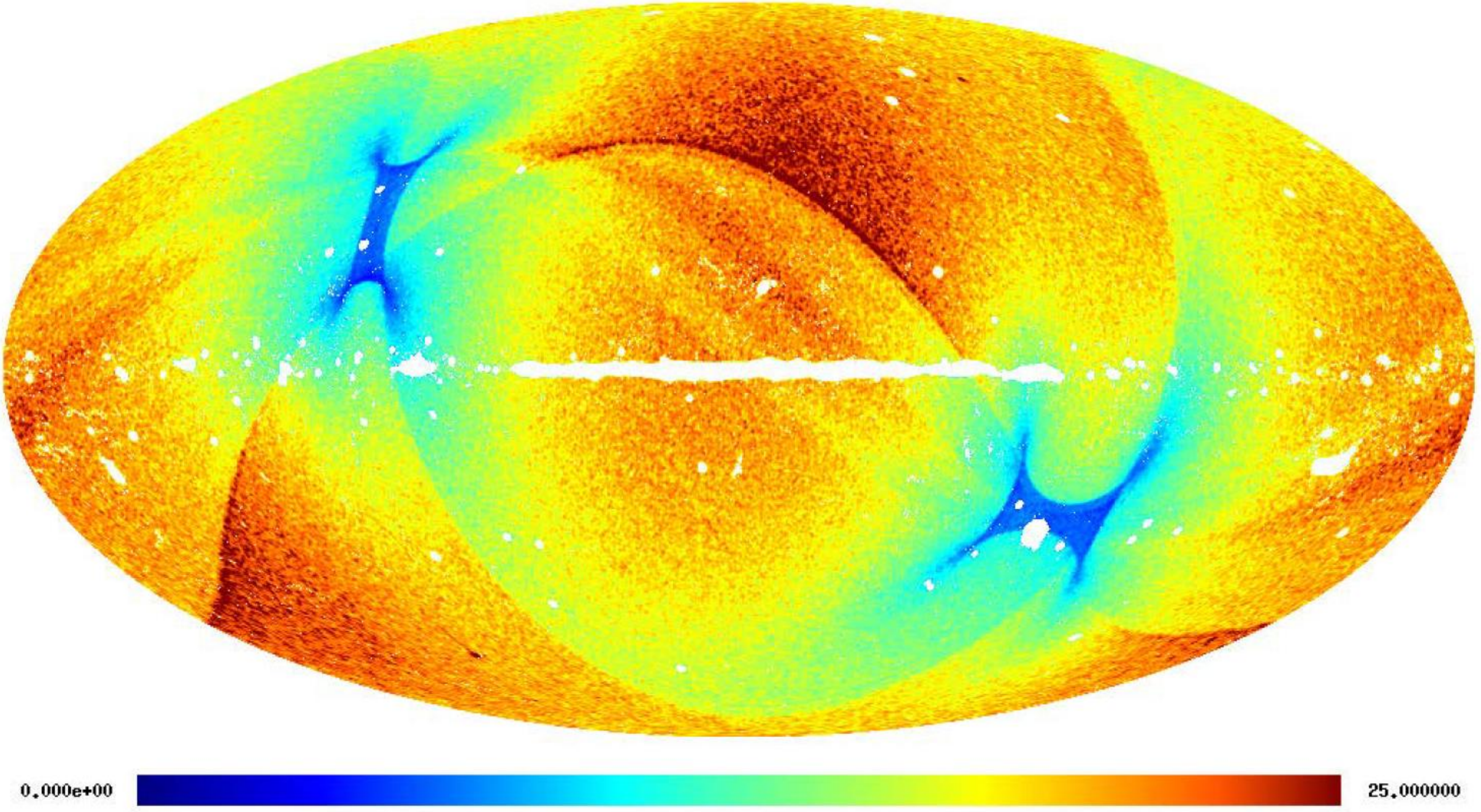


Intensity

Difference
Between
Half rings

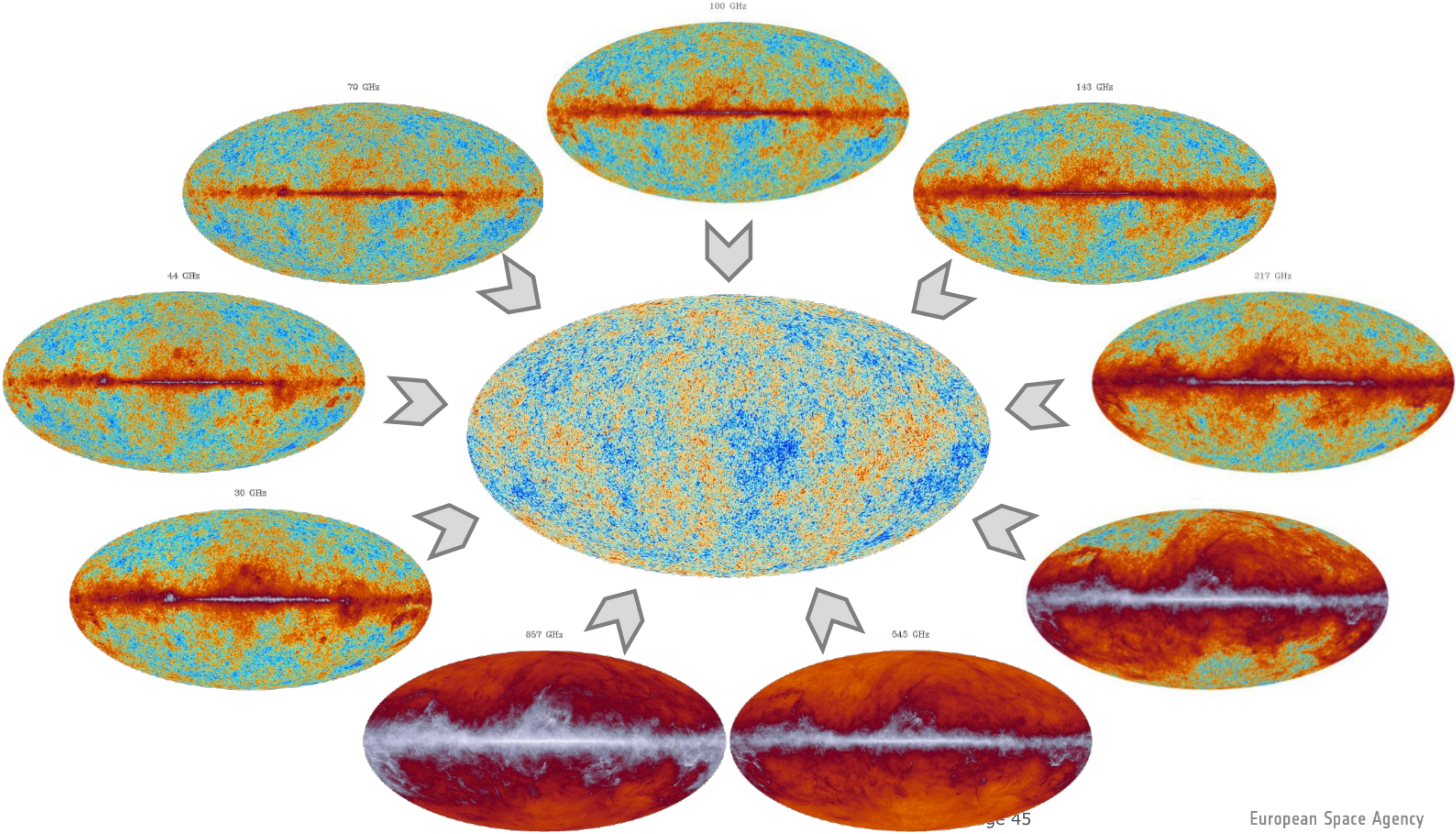
Difference
Between
surveys

Noise distribution



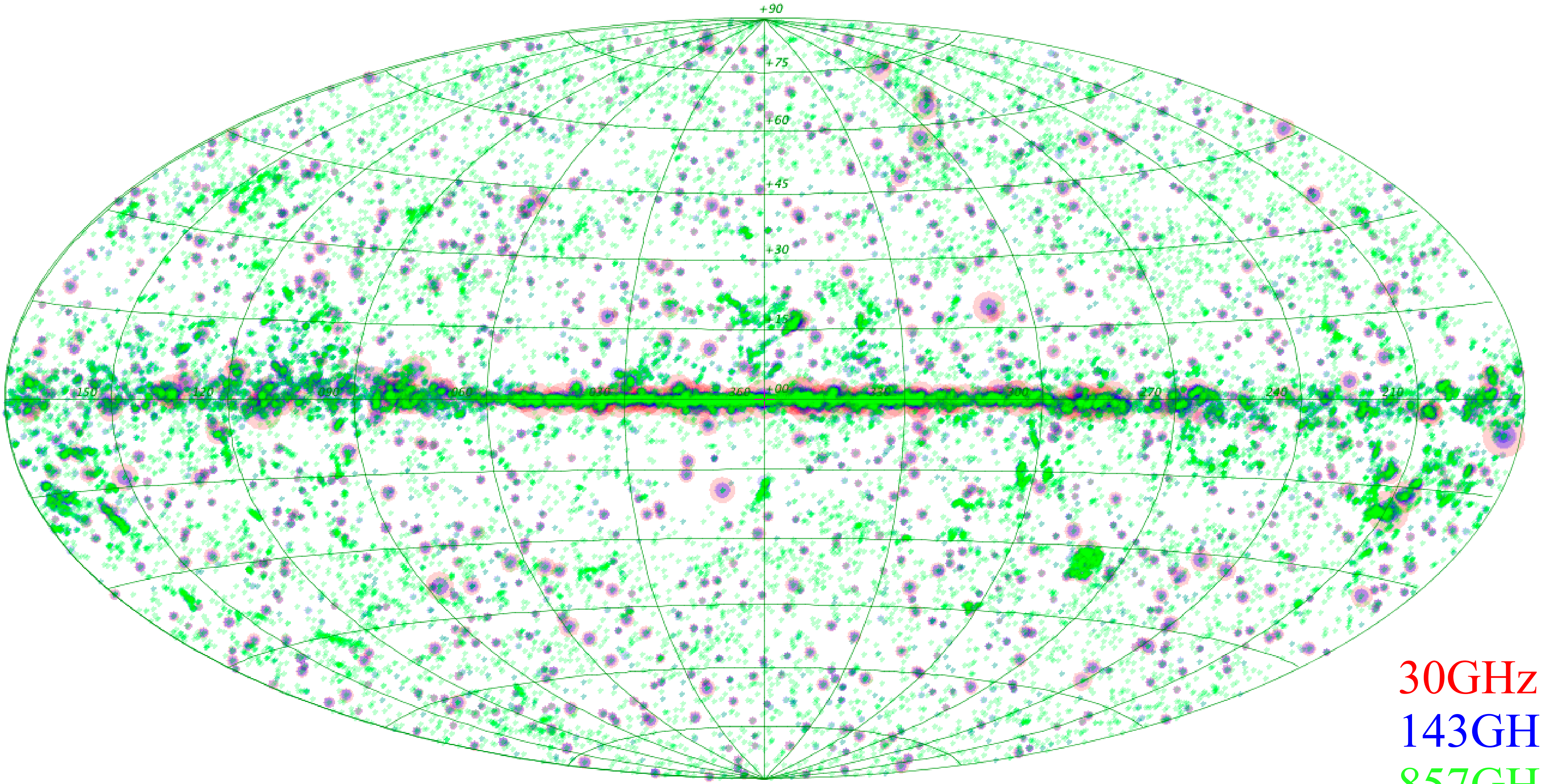
Reflects the scanning

Combine the data to get the CMB



European Space Agency

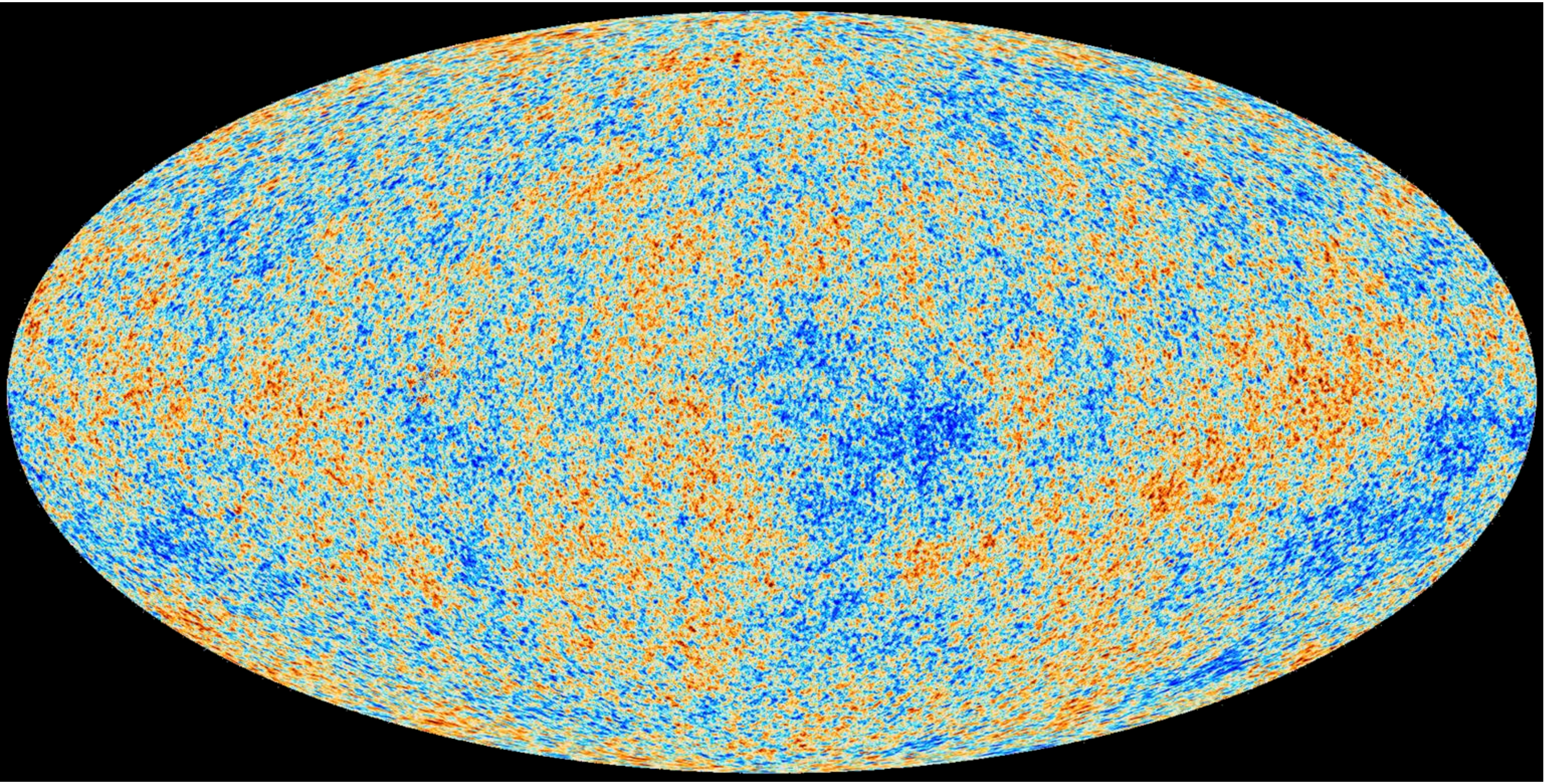
Point sources are removed



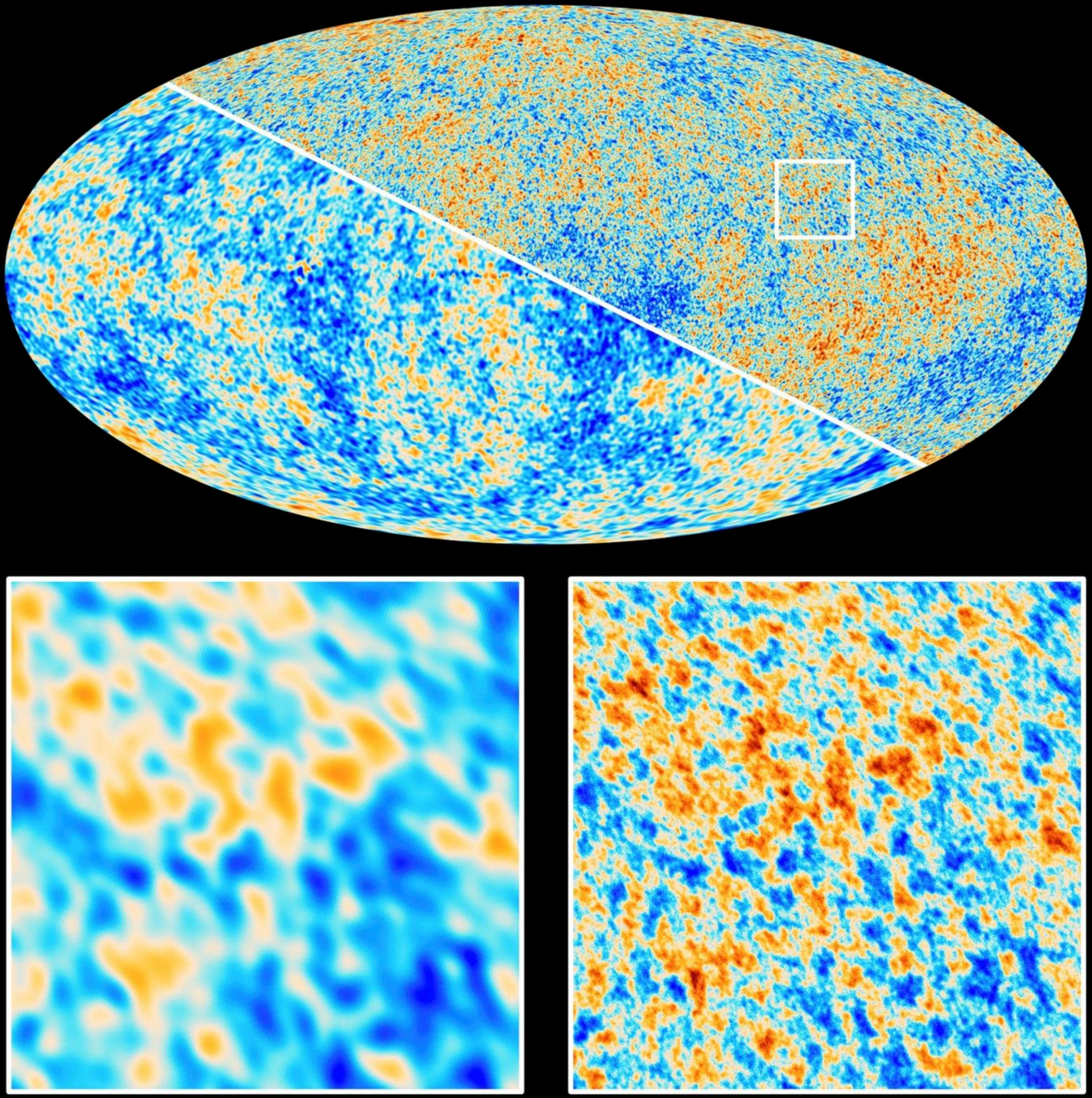
30GHz
143GHz
857GHz

~ 25000 point sources

Here is the temperature map:



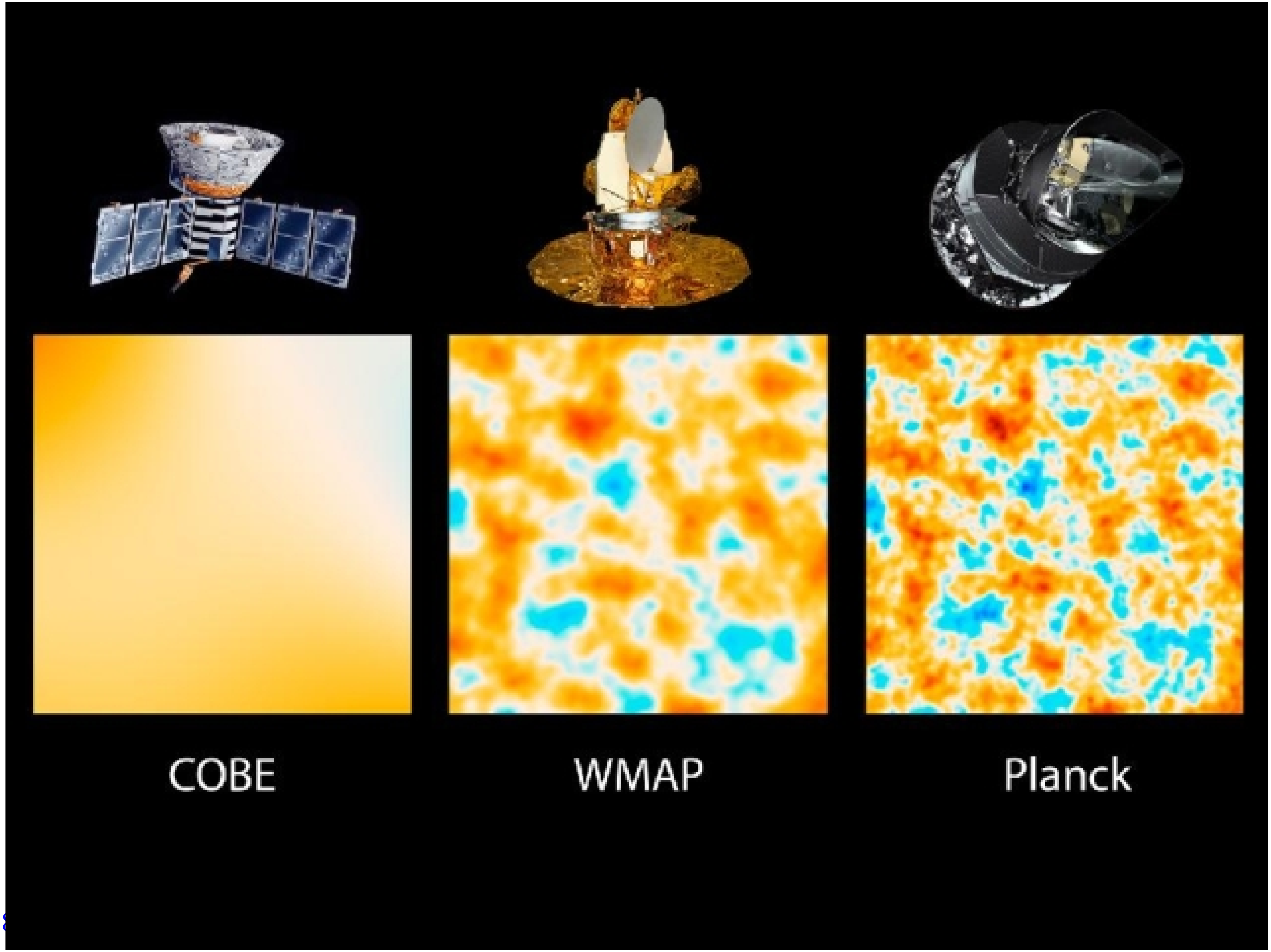
The Cosmic Microwave Background as seen by Planck and WMAP



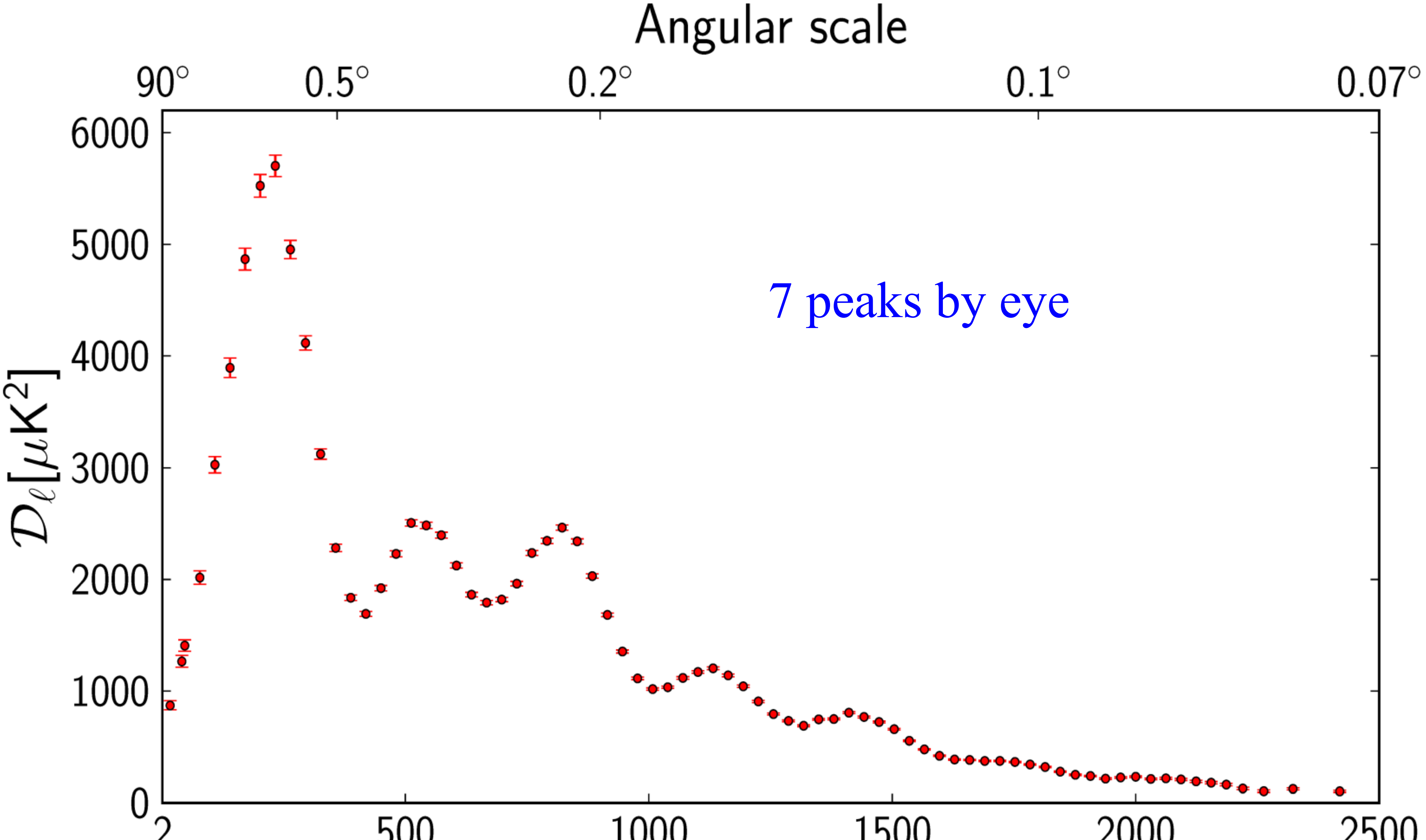
WMAP

Planck

Two decades of CMB anisotropies

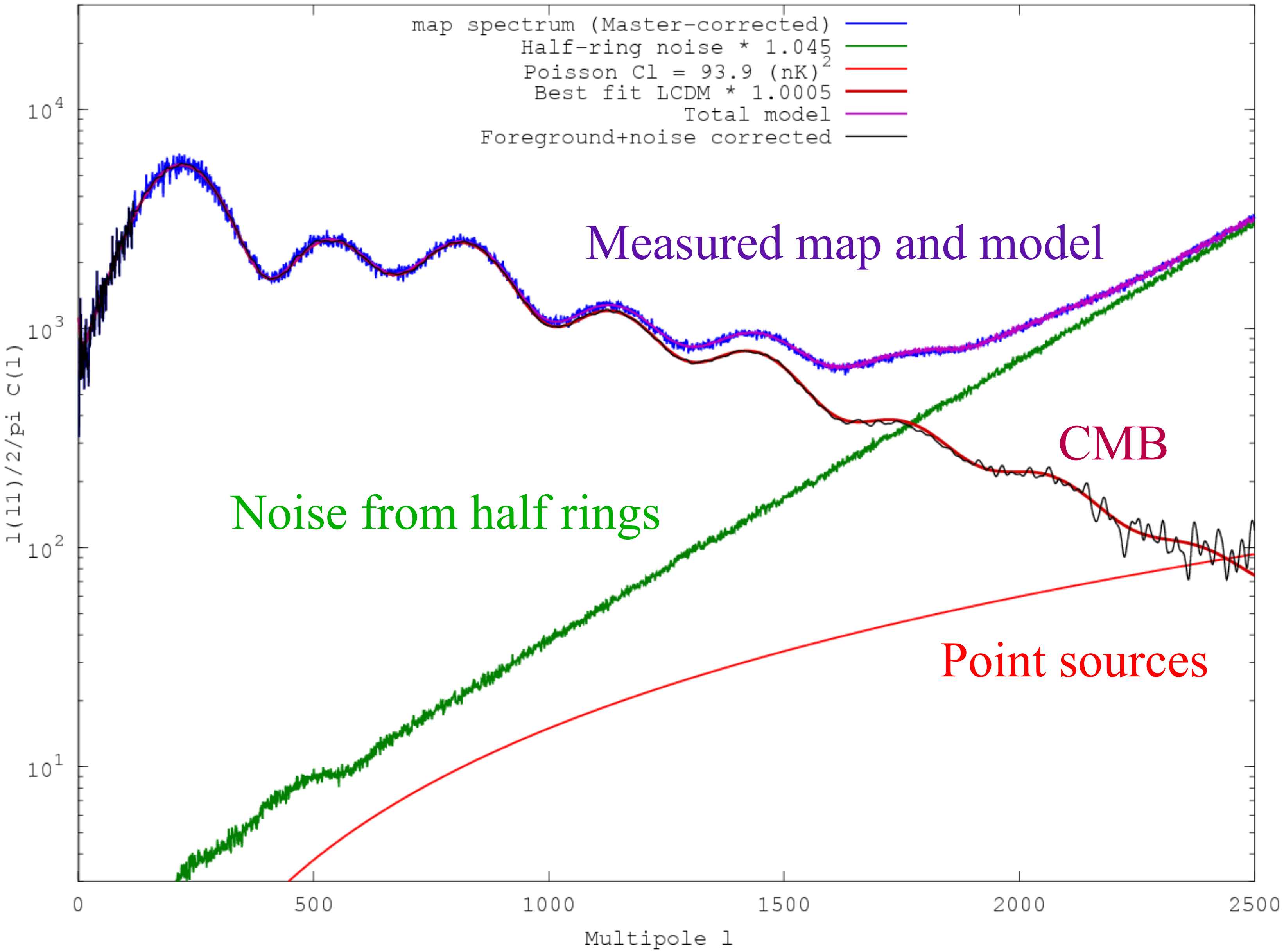


The Planck temperature angular power spectrum



7 peaks by eye

Noise contributions to signal



Measured map and model

CMB

Noise from half rings

Point sources

A 6-parameter cosmological model

Assume flatness (wait a while for a measurement)

3 parameters drive the dynamics :

$\Omega_c h^2$: Cold Dark matter density

$\Omega_b h^2$: Baryonic matter density

ϑ : angle on the sky of the acoustic horizon at recombination

2 parameters describe the initial conditions

n_s : spectral index of the primordial power spectrum

A_s : overall normalisation of the power spectrum of primordial fluctuations

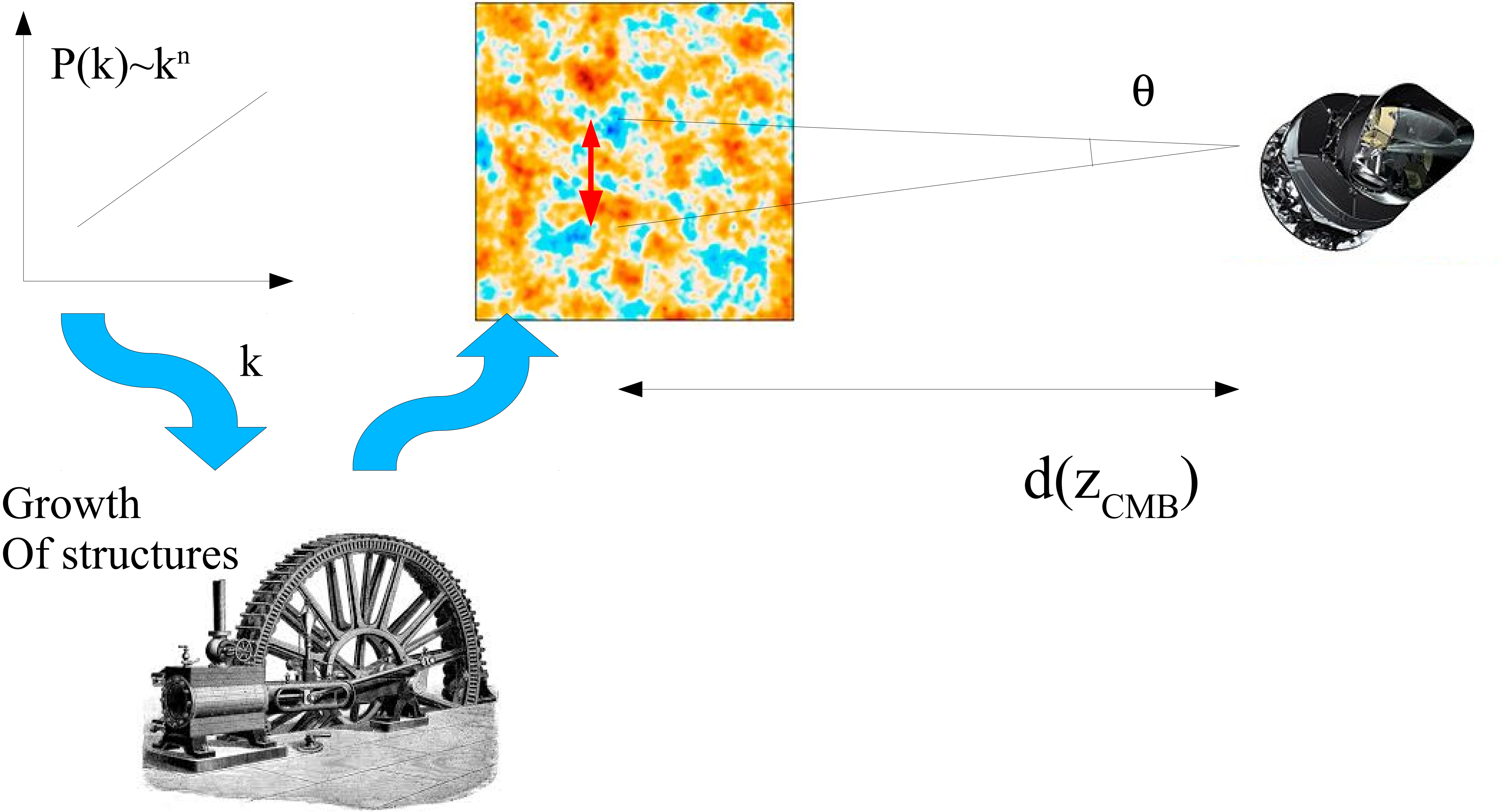
1 “nuisance” parameter (related to “dirty” astrophysics)

τ : optical depth at reionisation.

(→ scattering probability between recombination and now)

…. + a lot of “instrumental” parameters ….

A 6-parameter model



$P(k) \sim k^n$

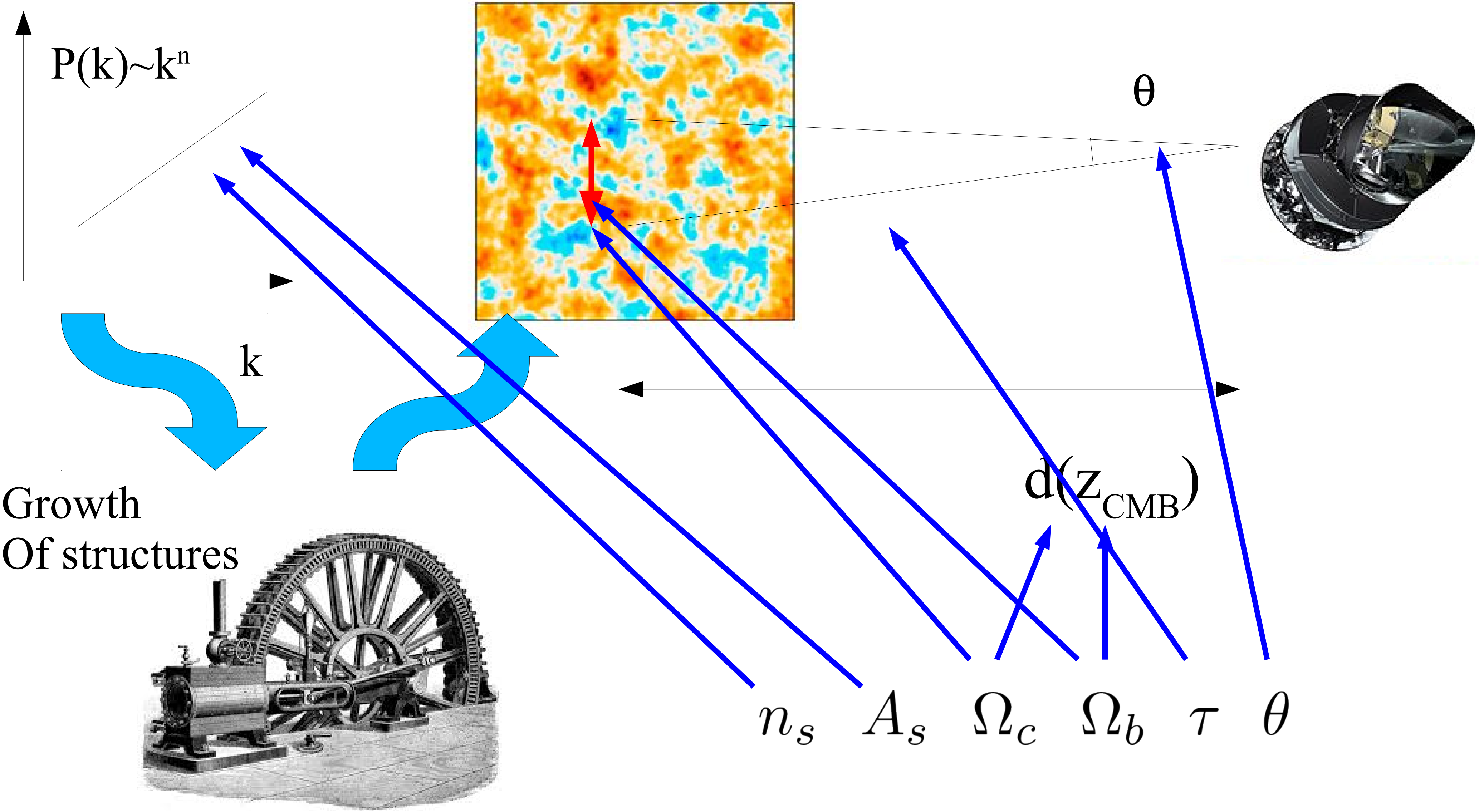
θ

k

$d(z_{CMB})$

Growth
Of structures

A 6-parameter model



$P(k) \sim k^n$

k

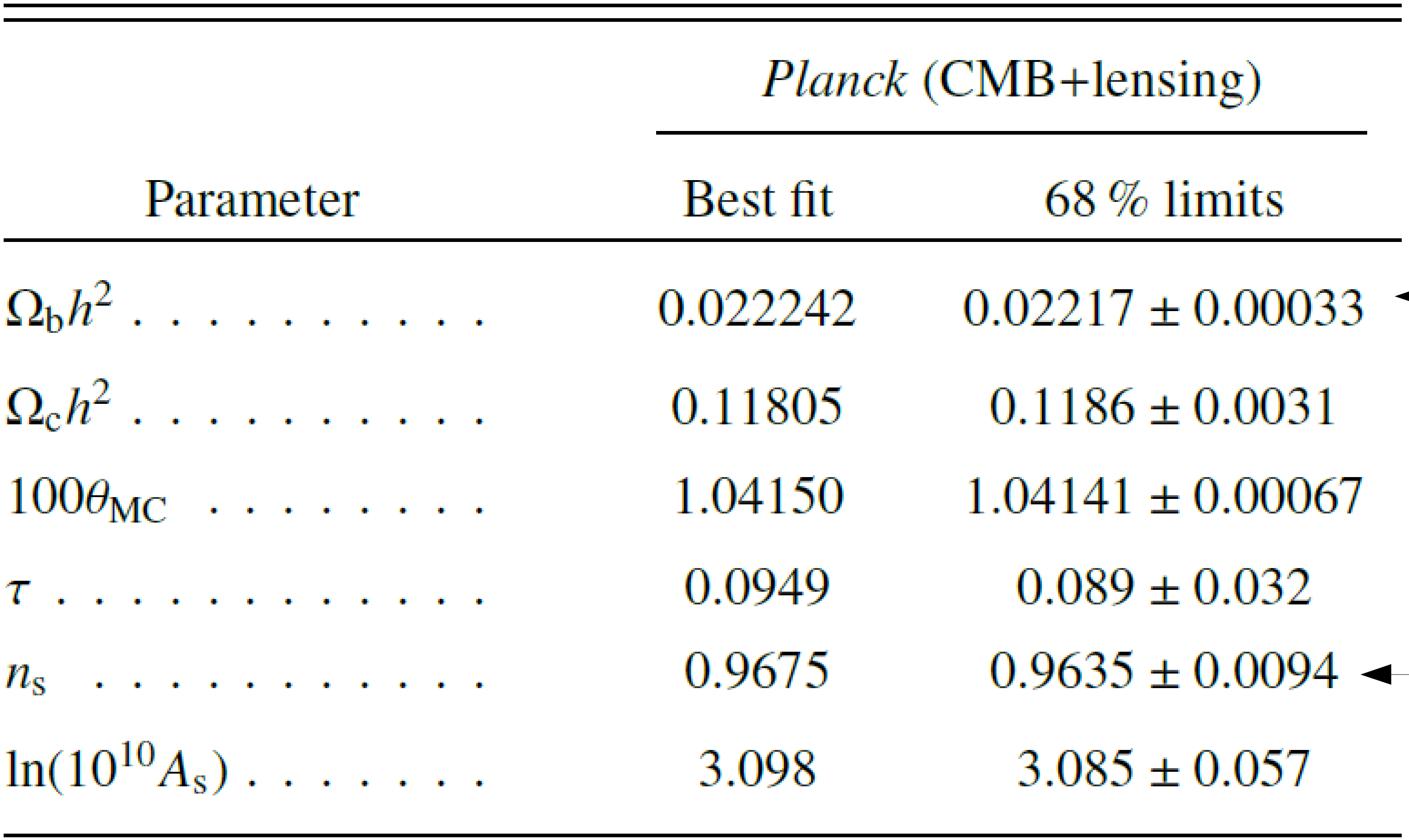
θ

Growth
Of structures

$d(z_{CMB})$

$n_s \quad A_s \quad \Omega_c \quad \Omega_b \quad \tau \quad \theta$

Great results for a flat ΛCDM universe

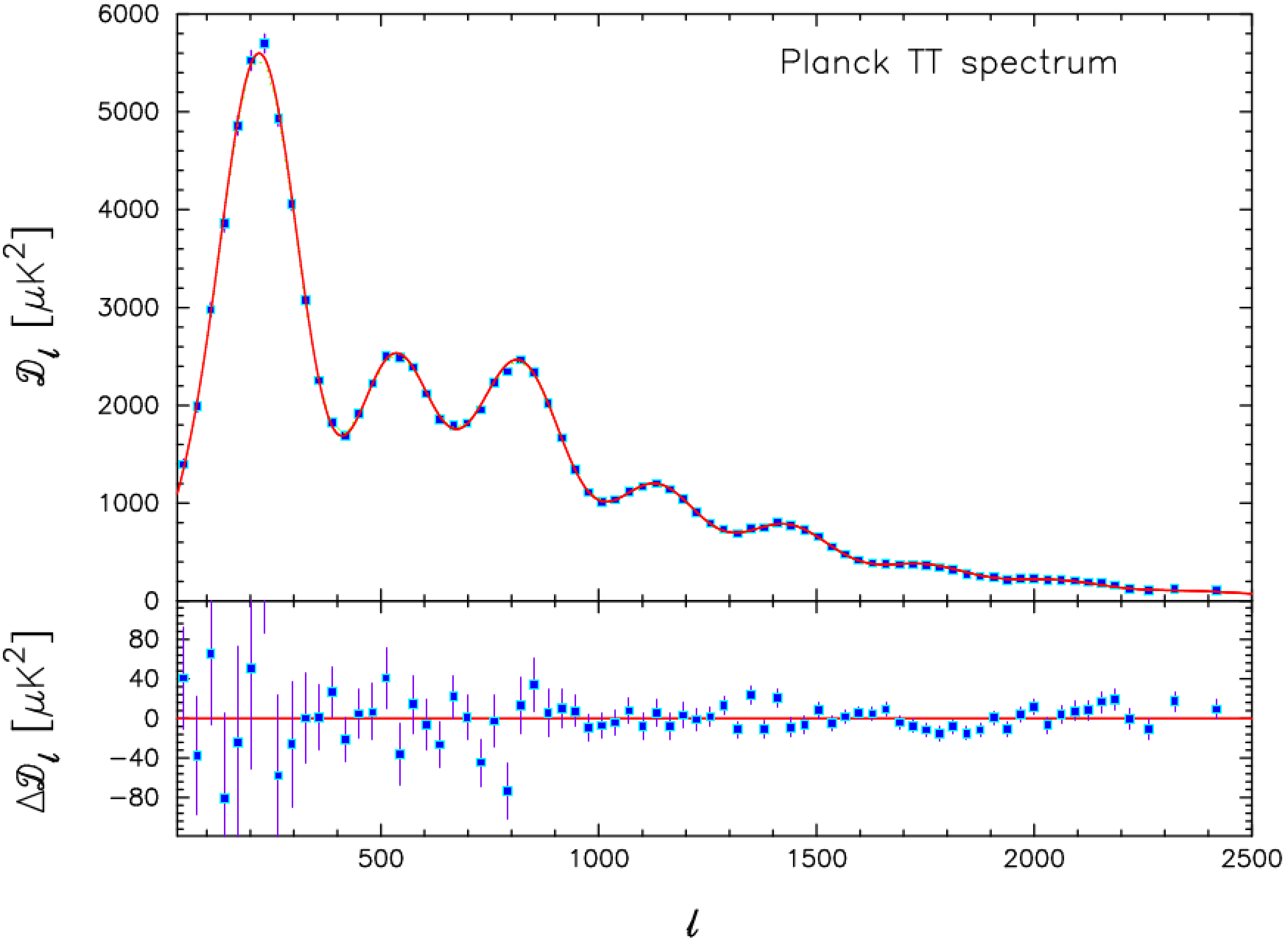


	Planck (CMB+lensing)	
Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

Same as BBN

Different from 1, as predicted by inflation

(Planck, 2013)


Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
80
40
0
−40
−80
$\Delta\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
500
1000
1500
2000
2500
ℓ

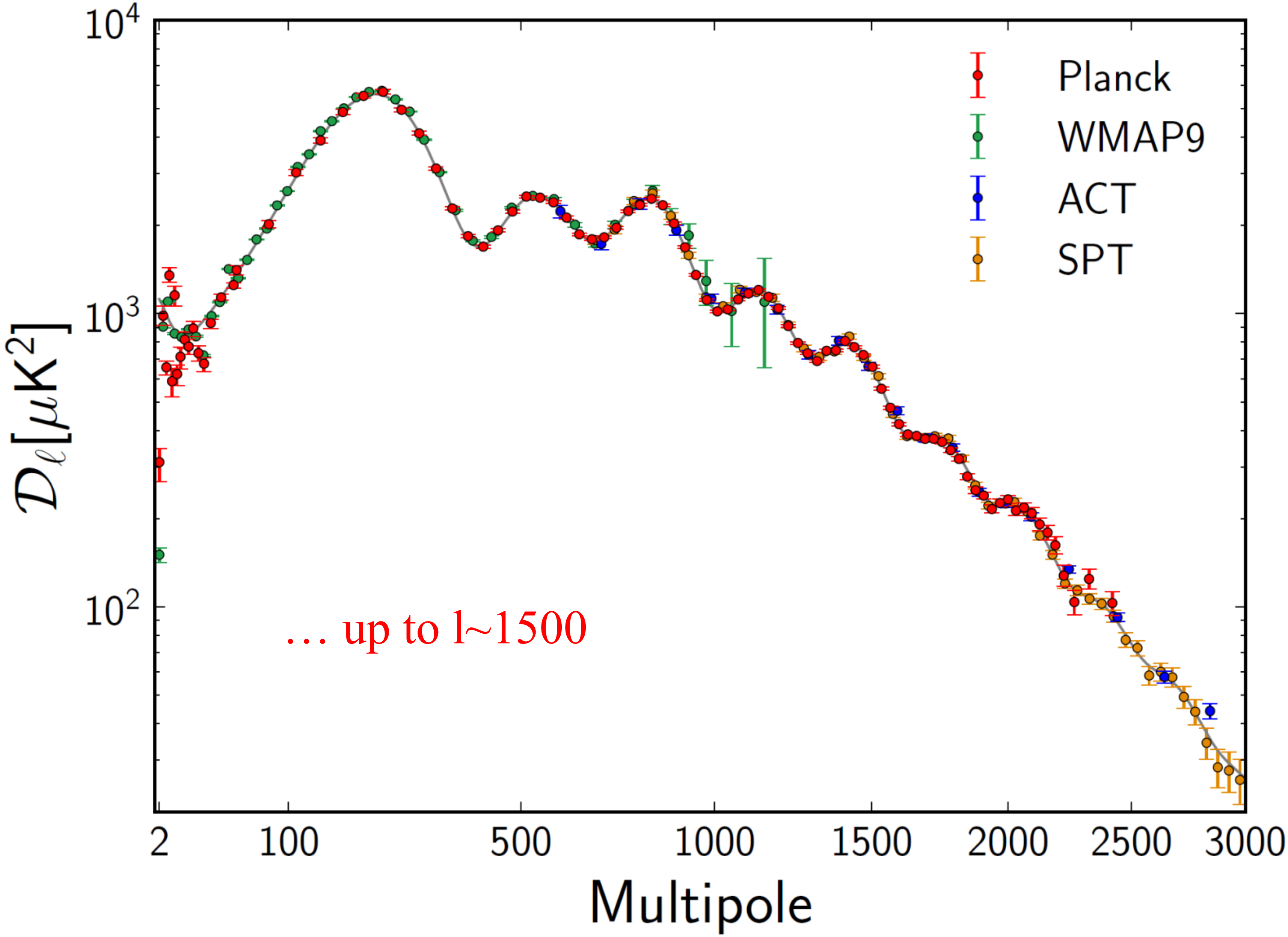
Fit quality

$$\chi^2 = \sum_{\ell\ell'} (C_\ell^{\rm data} - C_\ell^{\rm CMB} - C_\ell^{\rm fg}) \mathcal{M}^{-1}_{\ell\ell'} (C_{\ell'}^{\rm data} - C_{\ell'}^{\rm CMB} - C_{\ell'}^{\rm fg})$$

Spectrum	$\ell_{\rm min}$	$\ell_{\rm max}$	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

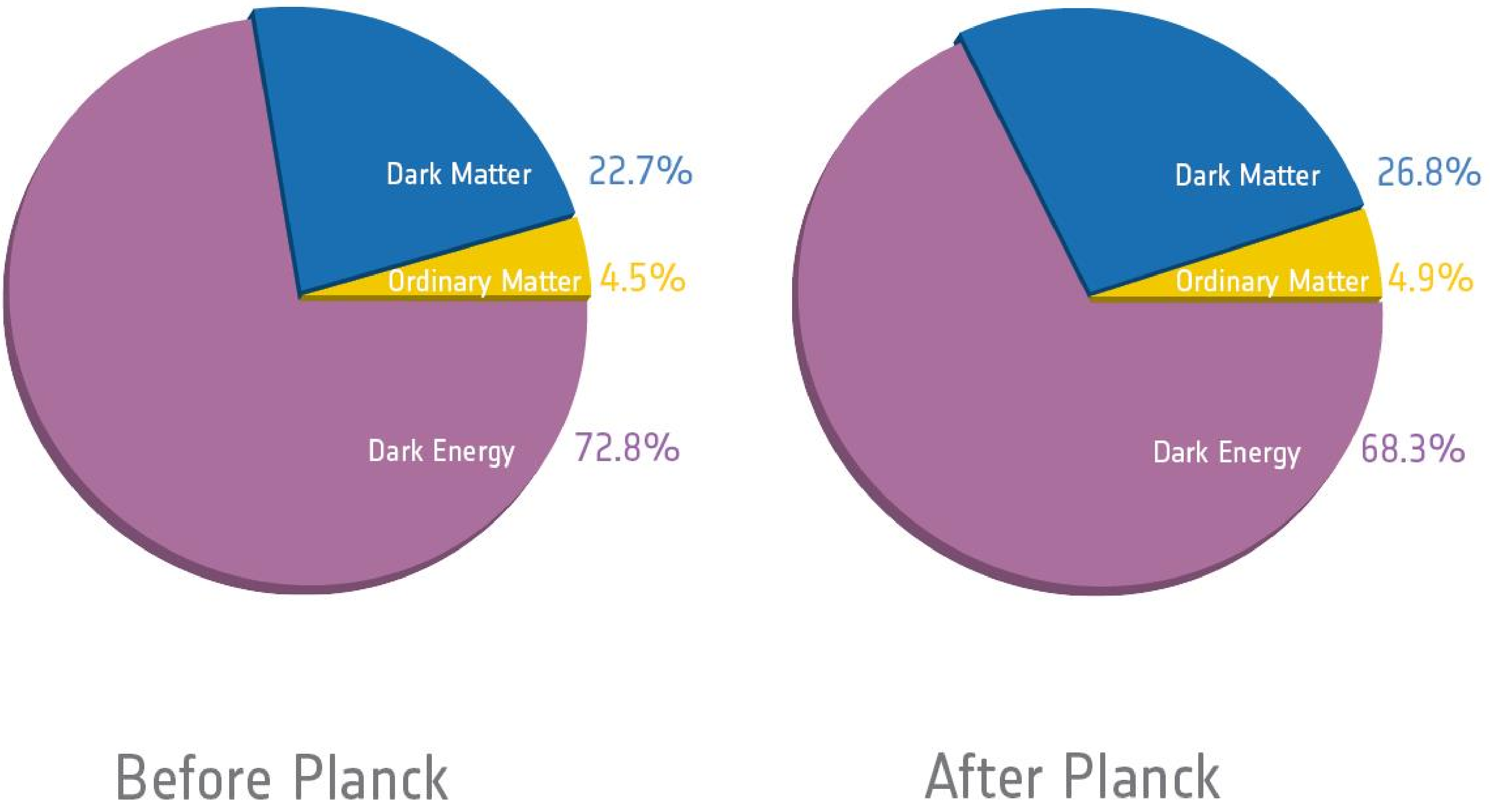
→ OK. This is highly non-trivial!

Planck totally dominates the landscape....



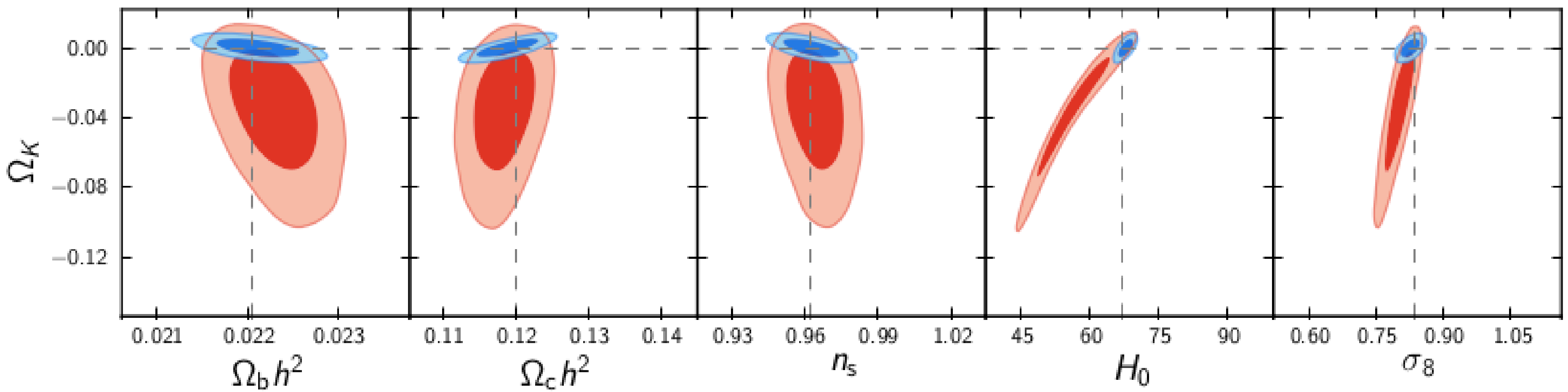
… up to l~1500

Planck confirms: a strange brew



Extensions to the minimal model

Curvature



Planck+BAO : $\Omega_k = 0.000 \pm 0.006$

Planck : $\Omega_k = -0.01 \pm 0.04$

Counting neutrino species (1)

How do neutrinos impact CMB ?

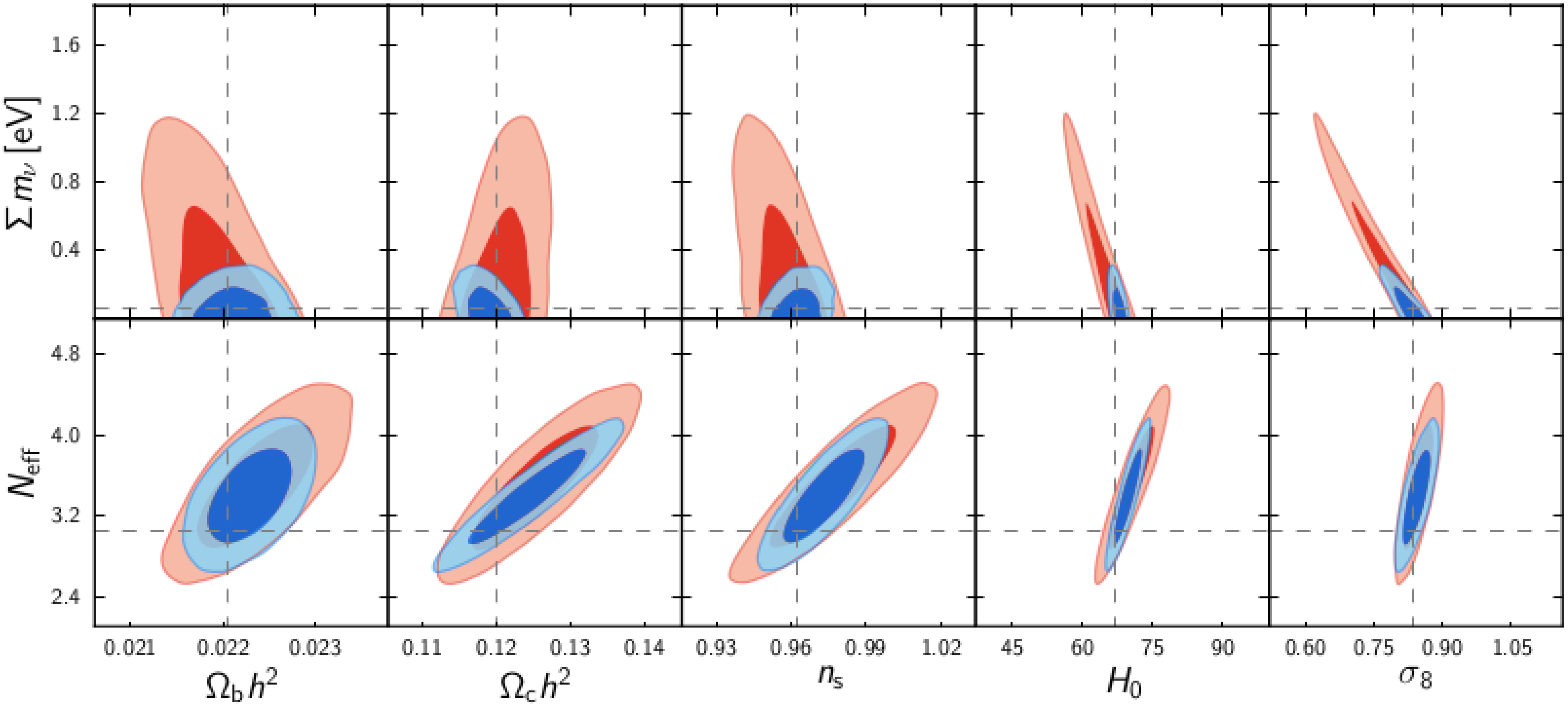
Neutrinos are radiation, so:

- more neutrinos delay the equality redshift
- mode neutrinos change the expansion rate before equality

  And hence the growth of structures.
- more neutrinos damp more the high-l CMB.

Beware, nothing there is specific to neutrinos, in particular
Their weak interaction properties are not at play.
We are just counting "relativistic degrees of freedom"

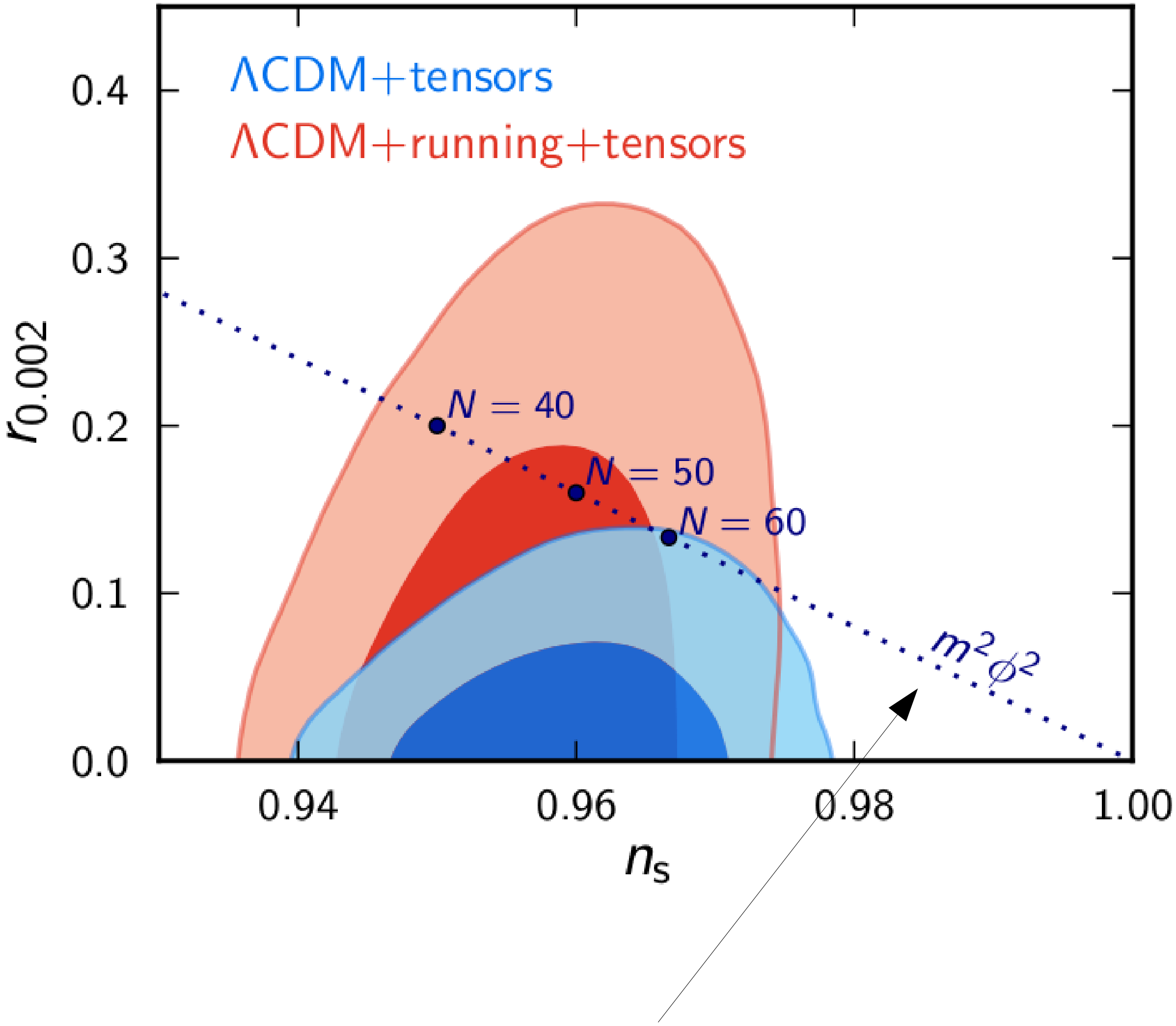
Counting neutrino species (2)



Planck +BAO

Planck

Initial conditions (inflation)

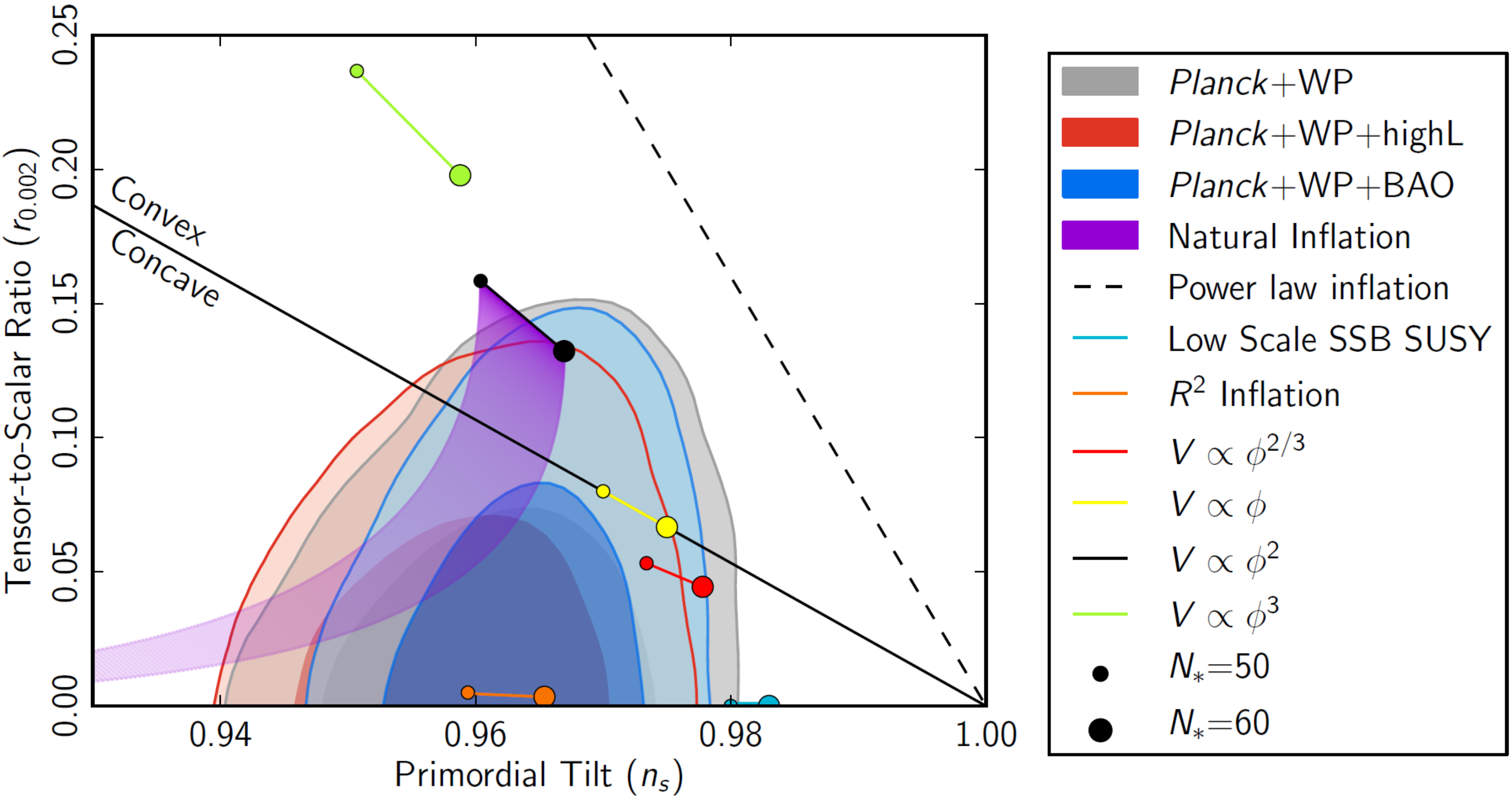


Planck confirms
a generic prediction
of inflation scenarios
n_s is slightly smaller than 1

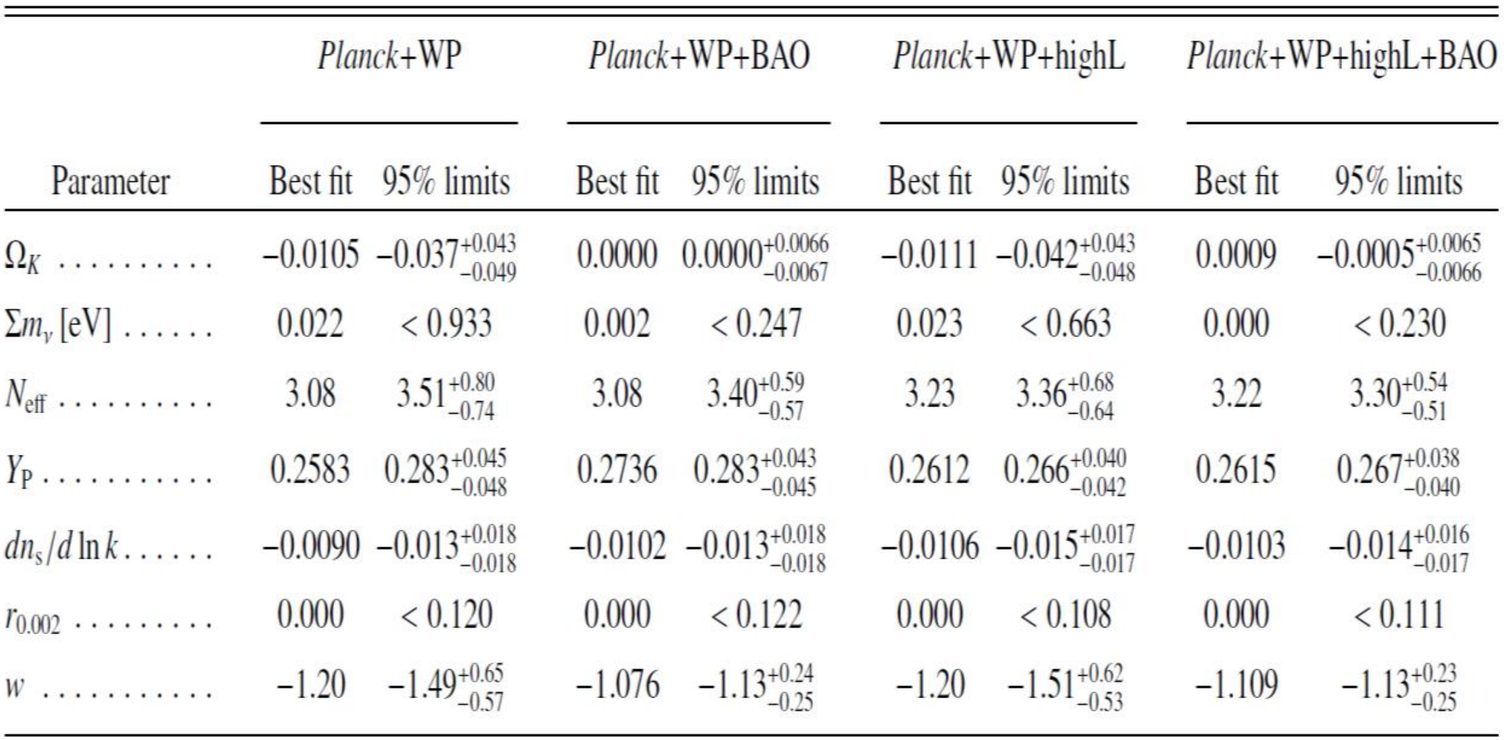
And the simplest model
is disfavoured.

Prediction for a specific potential

Planck is starting to exclude inflation models



Extensions to the base model



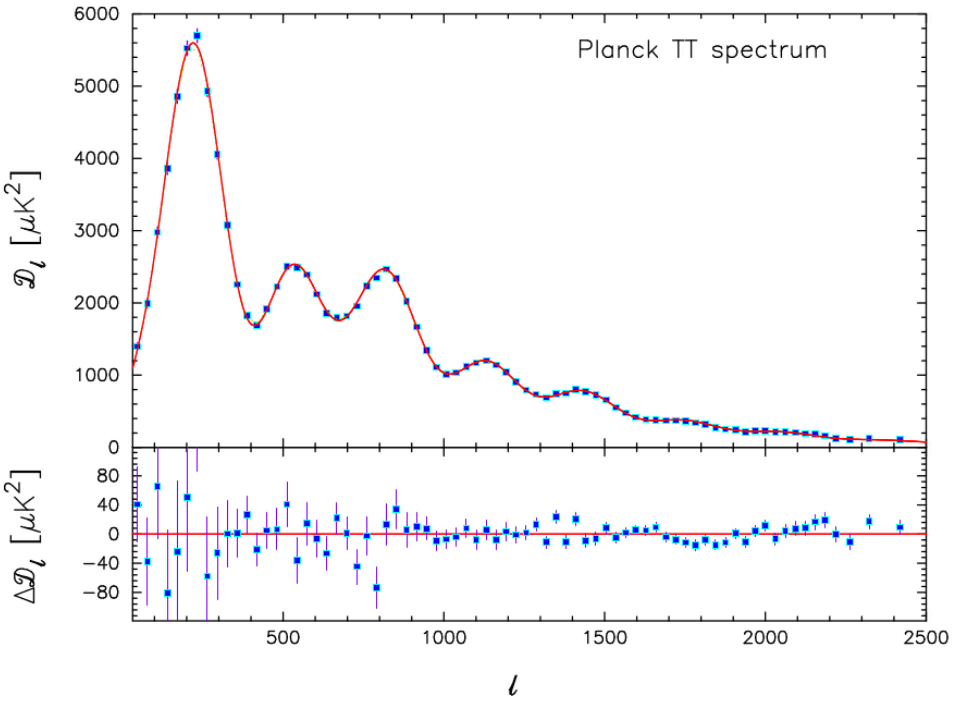
	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

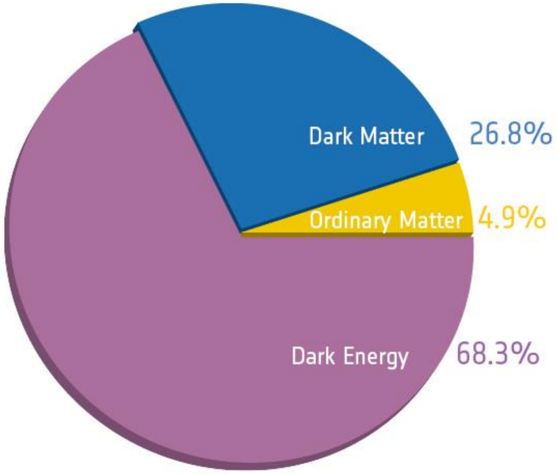
No need for:

- Non flat models
- Heavy neutrinos (>1 eV)
- $N_\nu > 3$

- Non standard He content
- Not so-simple initial spectrum
- Tensor modes
- Non Λ Dark energy

Summary





A 6-parameter model describes the CMB anisotropies ans is compatible with other cosmological probes

	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
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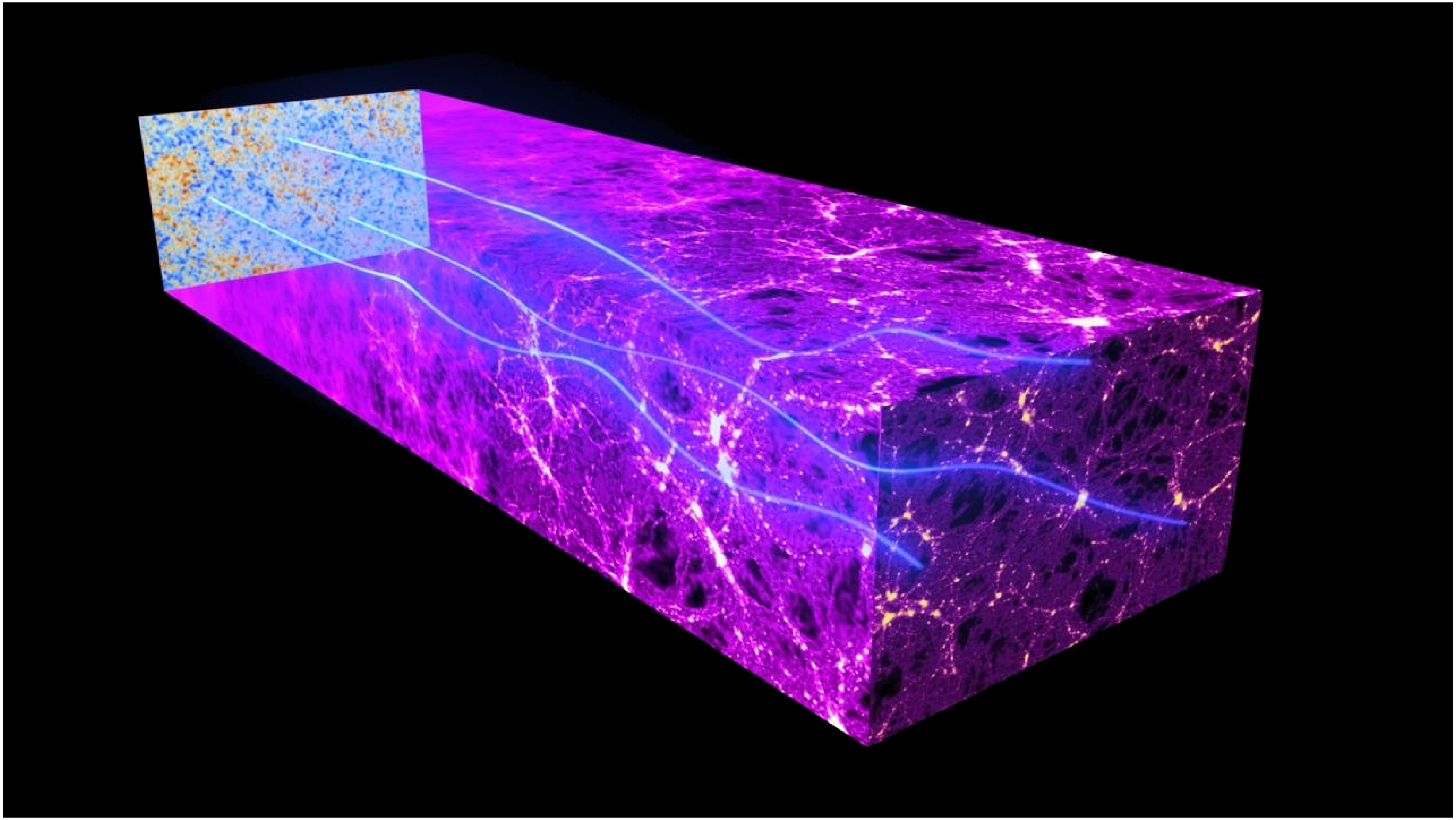
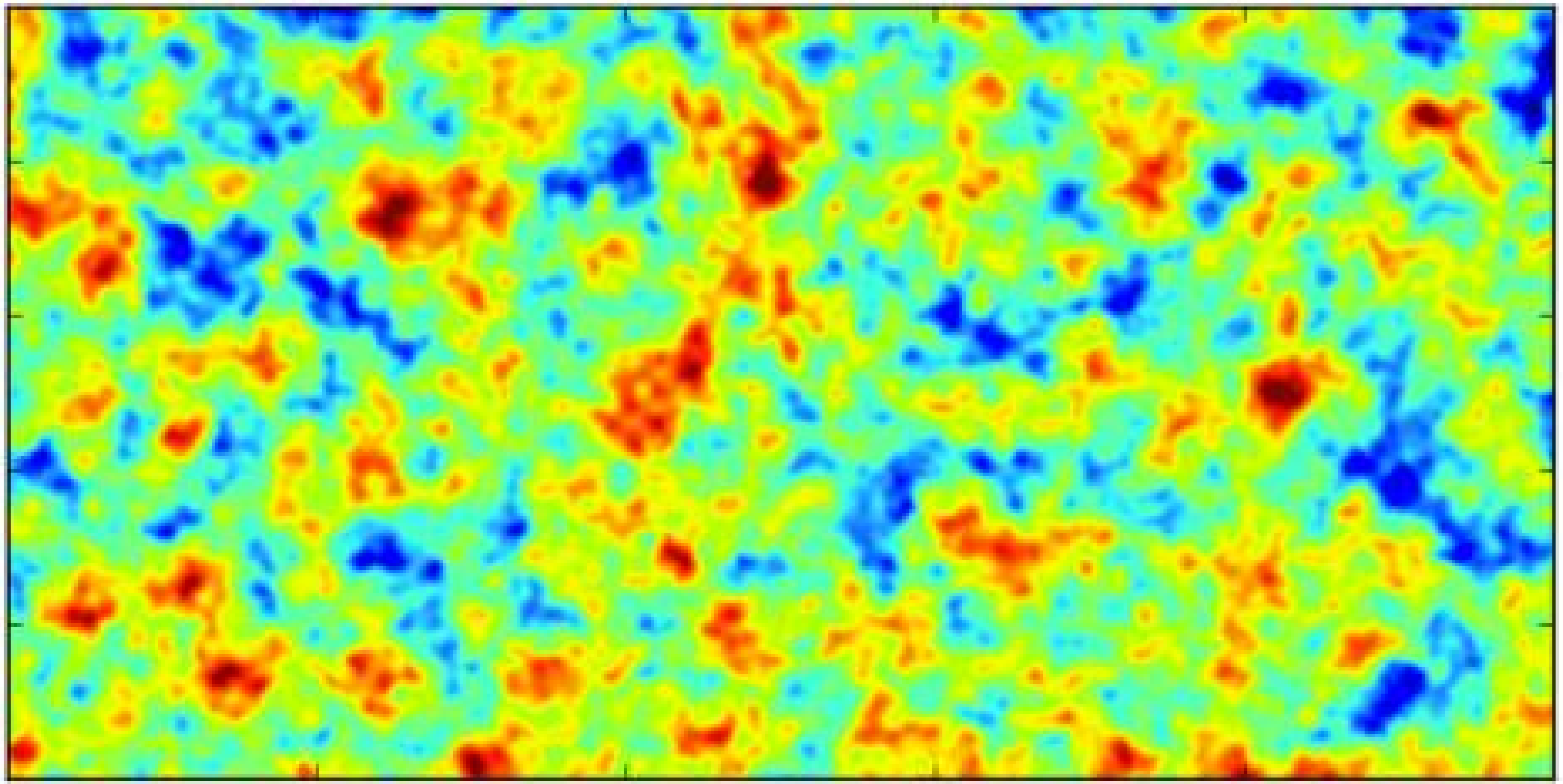
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

Gravitational lensing (of CMB)

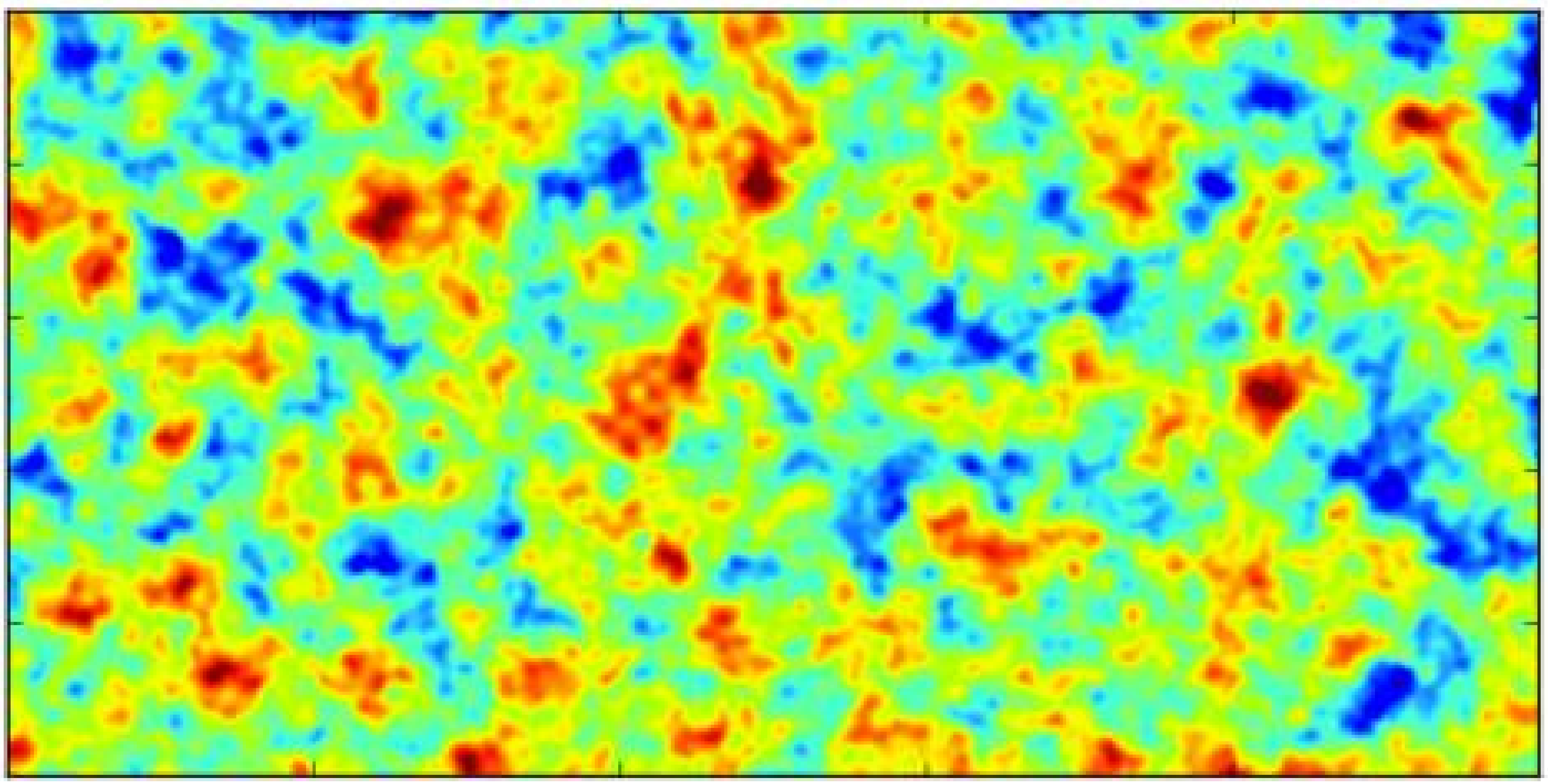


Mass density gradients between recombination and us distorts the light paths

Simulated patch

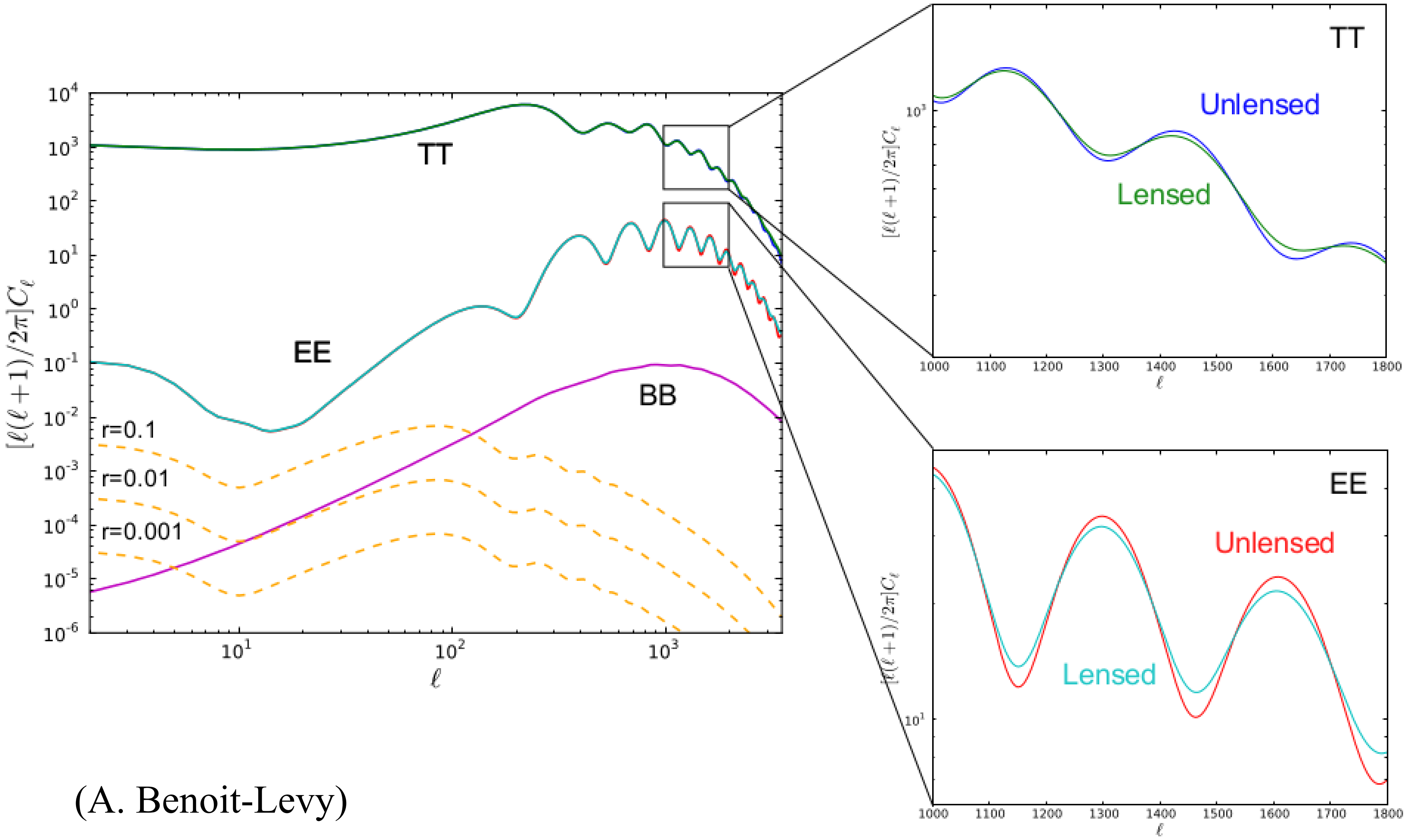


Simulated patch with lensing



r.m.s displacement : 2.5', coherent on degree scales

Smears the acoustic peaks



(A. Benoit-Levy)

Lensing reconstruction

$$\Theta[\hat{\mathbf{n}}] = \tilde{\Theta}[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})] \longrightarrow \Theta(\hat{\mathbf{n}}) = \tilde{\Theta}(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\tilde{\Theta}(\hat{\mathbf{n}}) + \cdots$$

Observed map

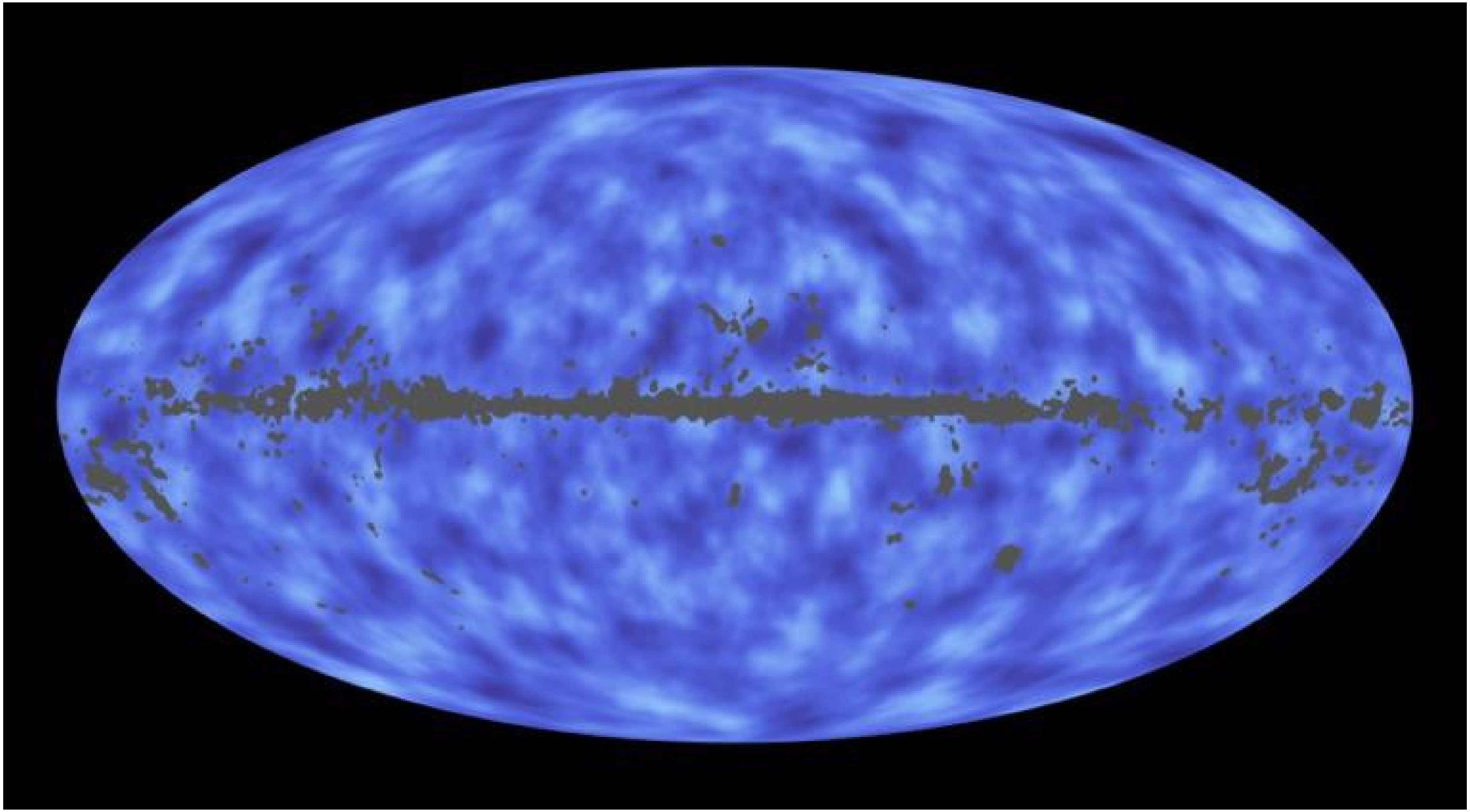
Undistorted map

Gravitational potential

$$\hat{\phi}_L^M \propto A_L \int d\hat{\mathbf{n}} Y_L^{M*} \left(\sum_{\ell_1 m_1} \frac{1}{C_{\ell_1}^{\rm tot}} \Theta_{\ell_1}^{m_1} Y_{\ell_1}^{m_1}\right) \nabla \left(\sum_{\ell_2 m_2} \frac{\tilde{C}_{\ell_2}}{C_{\ell_2}^{\rm tot}} \Theta_{\ell_2}^{m_2} Y_{\ell_2}^{m_2}\right)$$

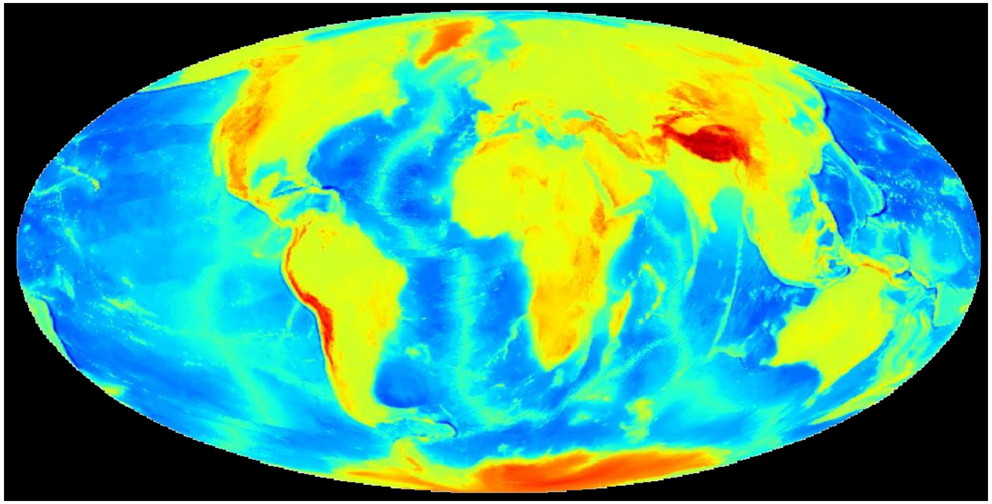
Measured map

Projected mass map

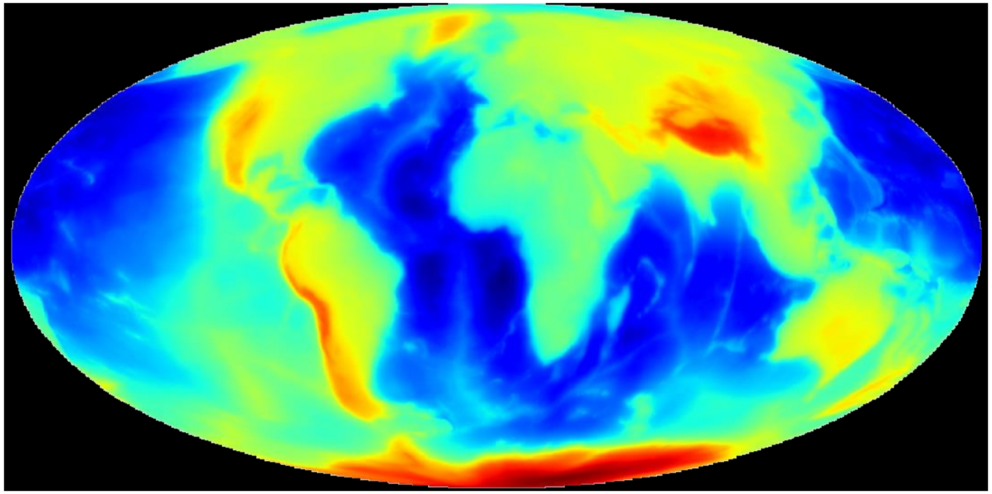


$$\bar{\phi} = \Delta^{-1}\vec{\nabla}\cdot\left[C^{-1}T\,\vec{\nabla}(C^{-1}T)\right]$$

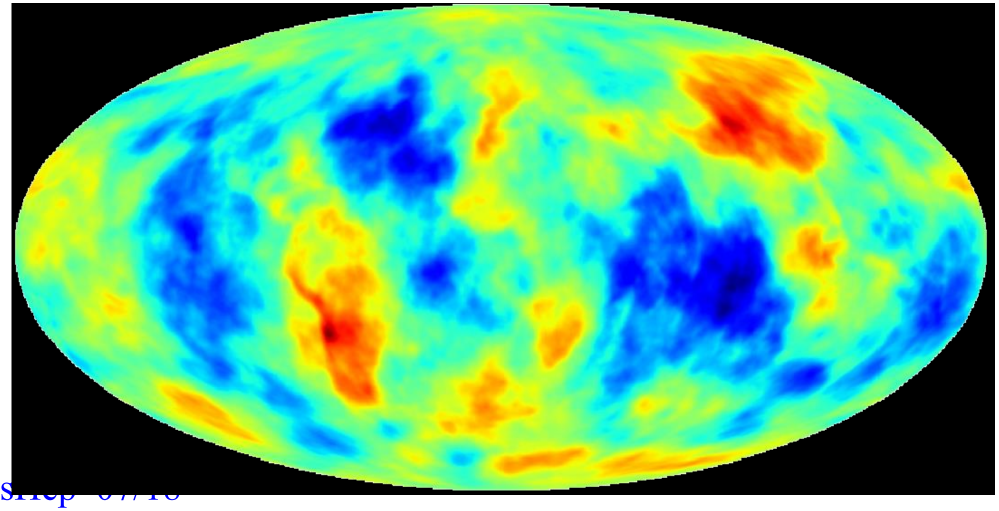
Not the best quality ever



Some spherical distribution

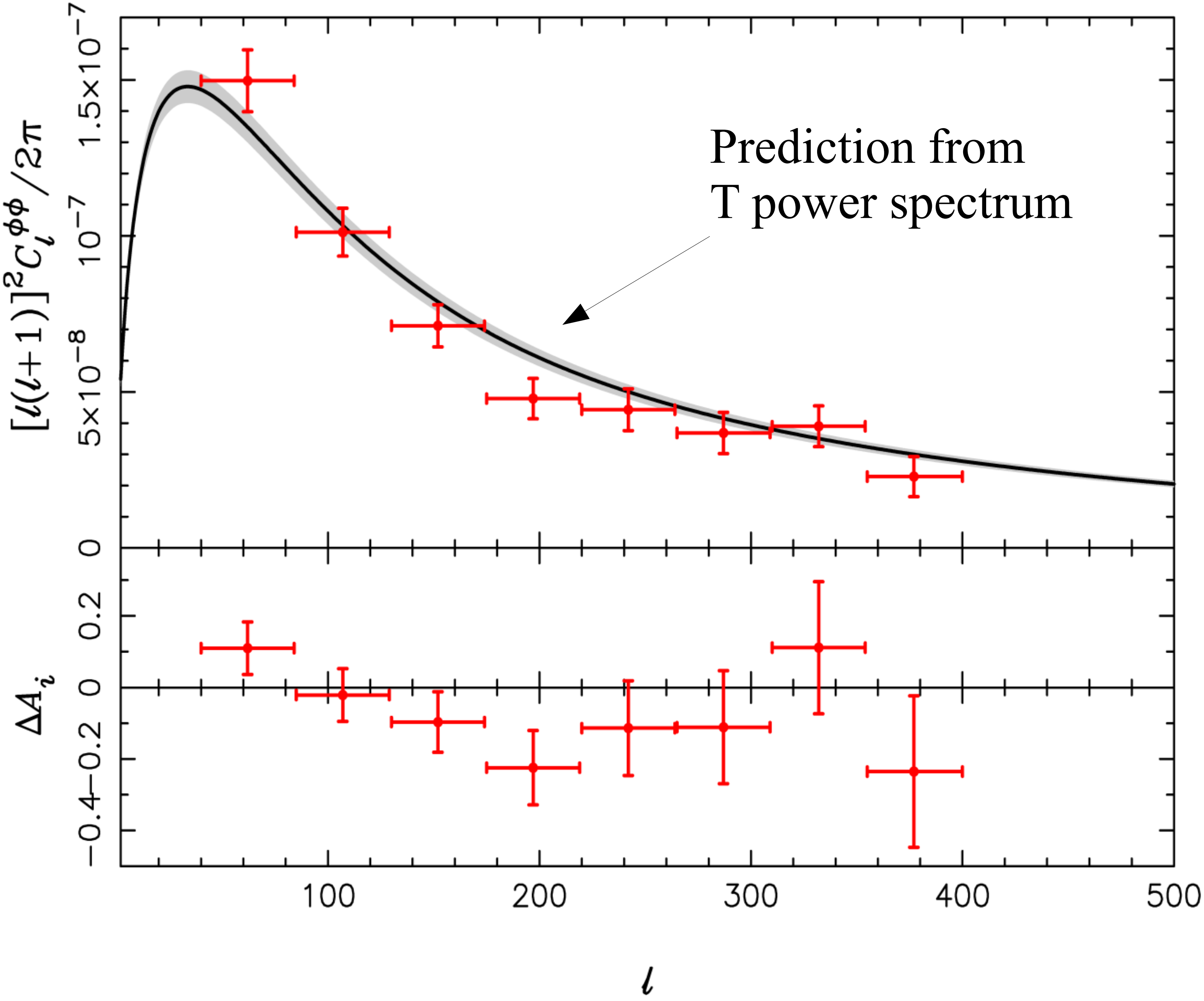


At the same angular resolution



Same angular resolution
Same noise

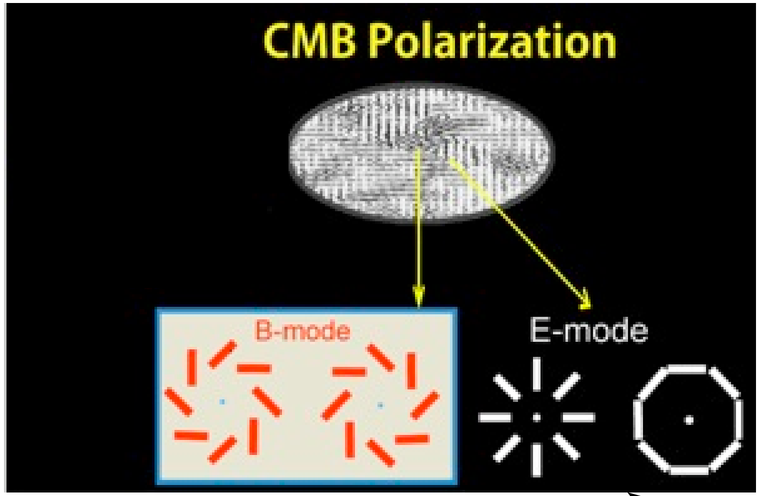
The lensing potential power spectrum



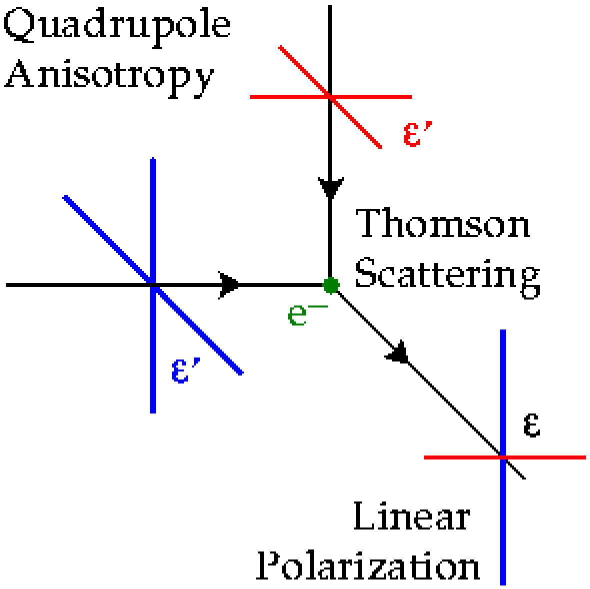
Prediction from
T power spectrum

CMB polarisation anisotropies

The CMB is slightly polarized, and there is valuable information to be gathered there



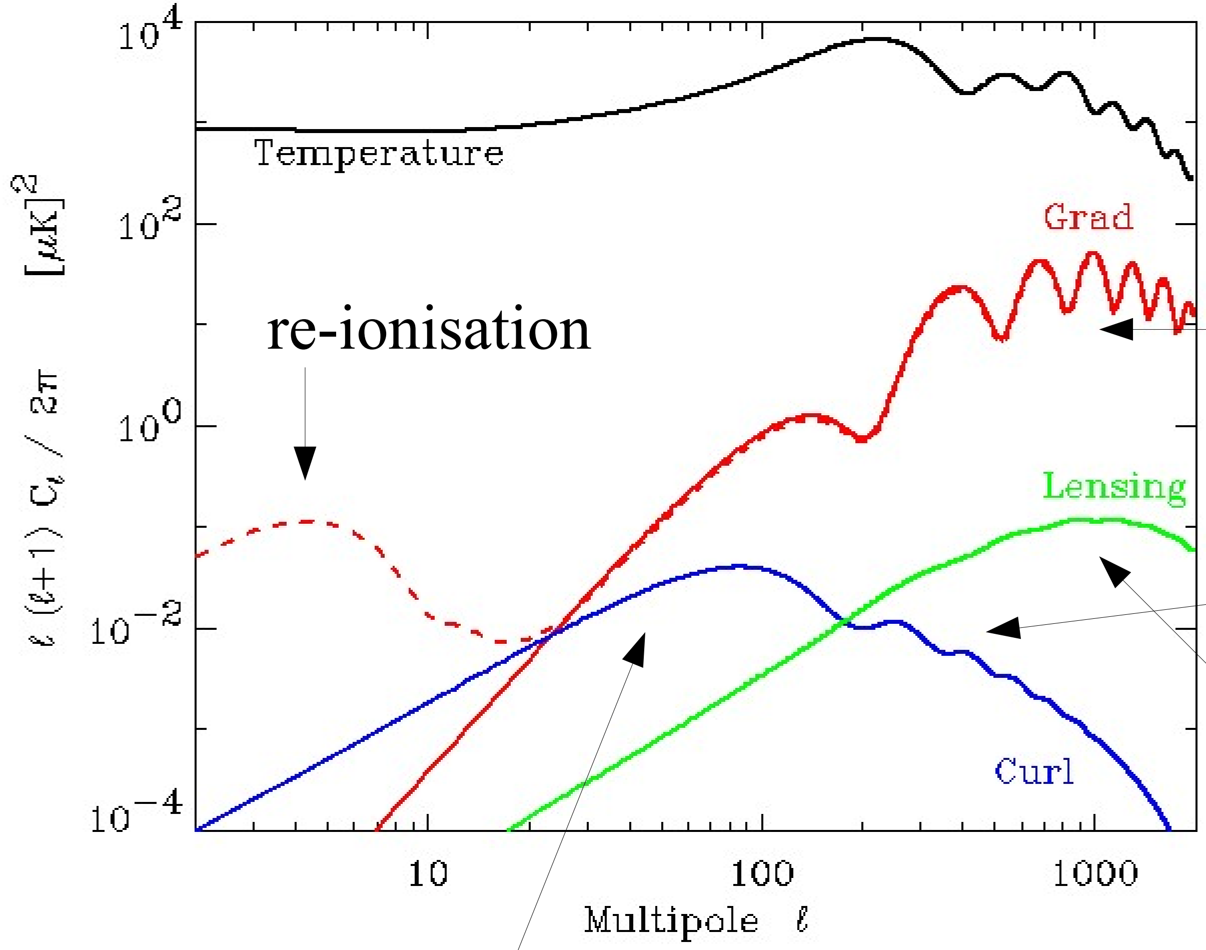
Polarisation at last scattering
(at recombination)



Tensor perturbations
From inflation

Lensing by
Large scale
structures

CMB polarisation anisotropies



re-ionisation

“E” modes
(positive parity)

“B” modes
(negative parity)

E modes
Through lensing

Primordial B modes from inflation

E and B modes

E modes are a basic check of the model:

they can be predicted from the temperature power spectrum.
They help lifting parameter degeneracies.

B modes are really interesting:

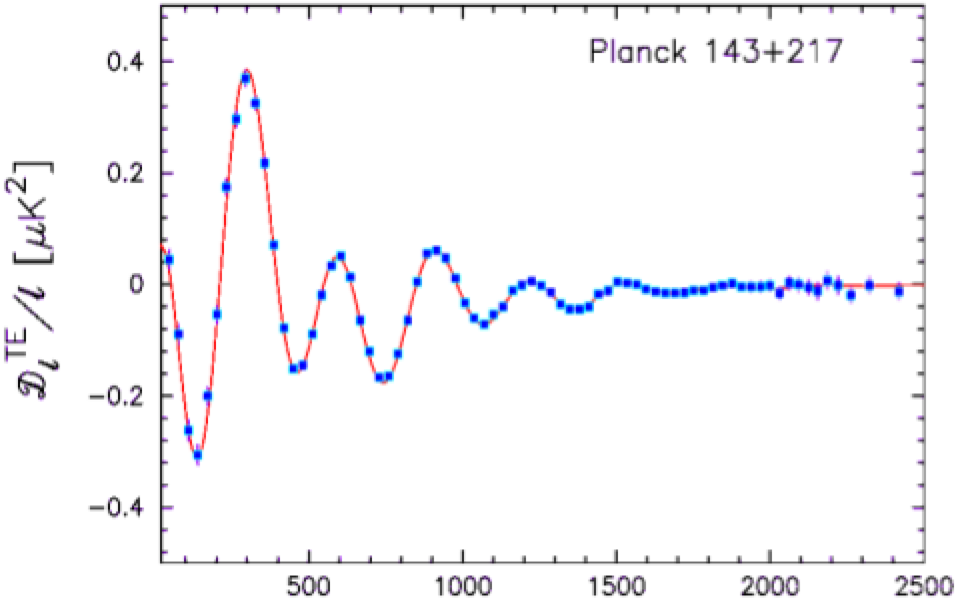
- on small angular scales they are almost entirely due to lensing by structures between recombination and us: → neutrino masses.

- on large angular scales, they probe the inflation model and energy scale.

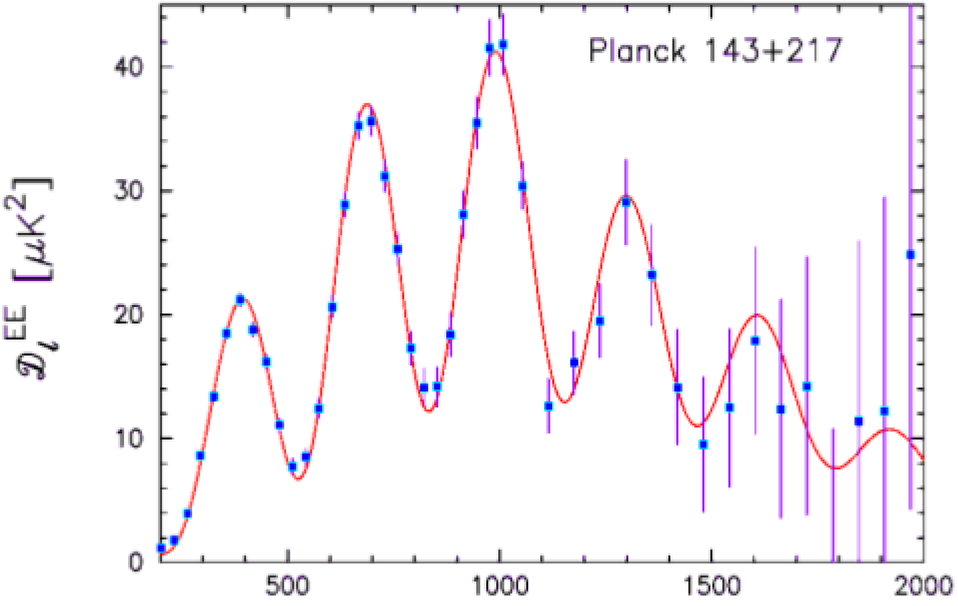
-... but they are very weak.

E modes in Planck

TE correlation

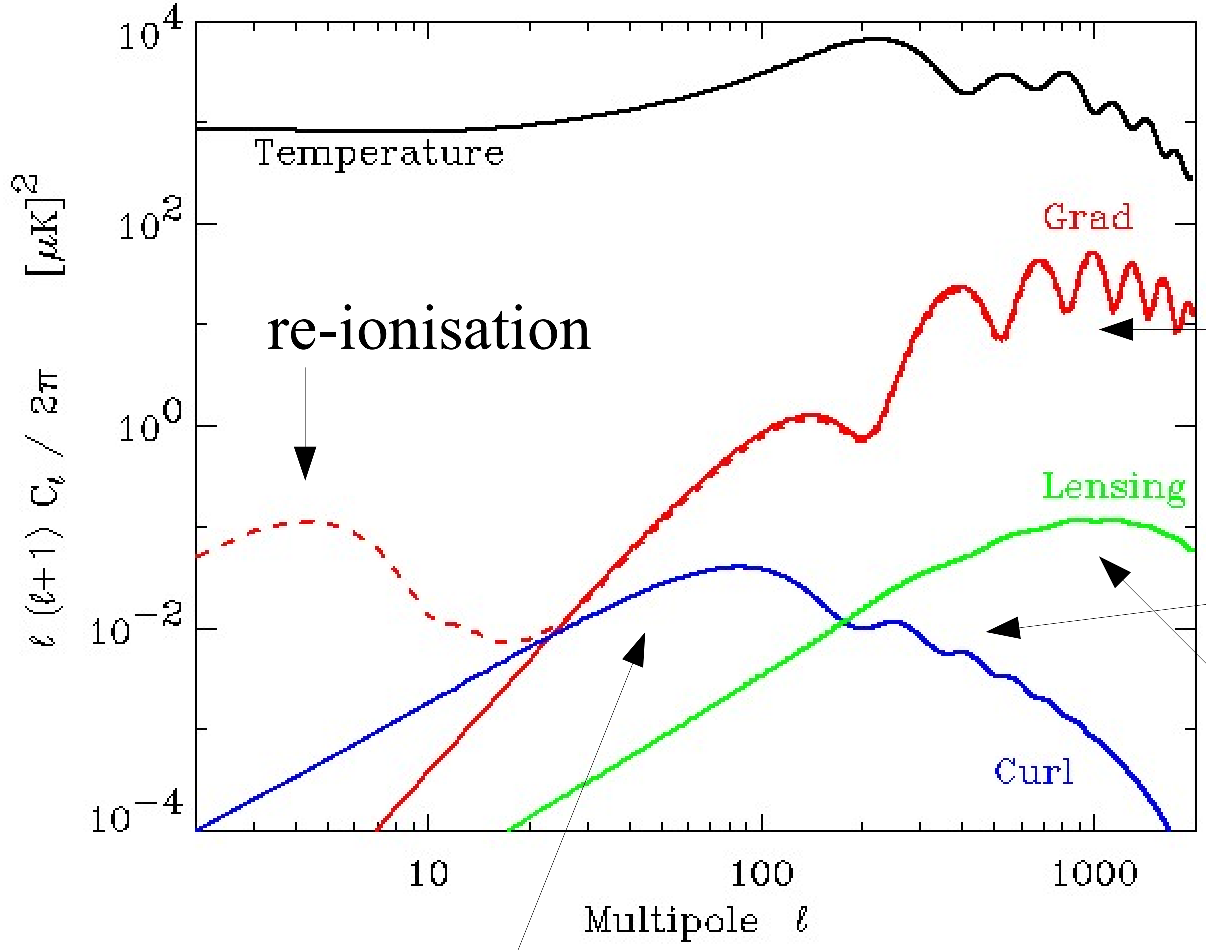


EE correlation



Red line is prediction from temperature anisotropies alone !

CMB polarisation anisotropies



re-ionisation

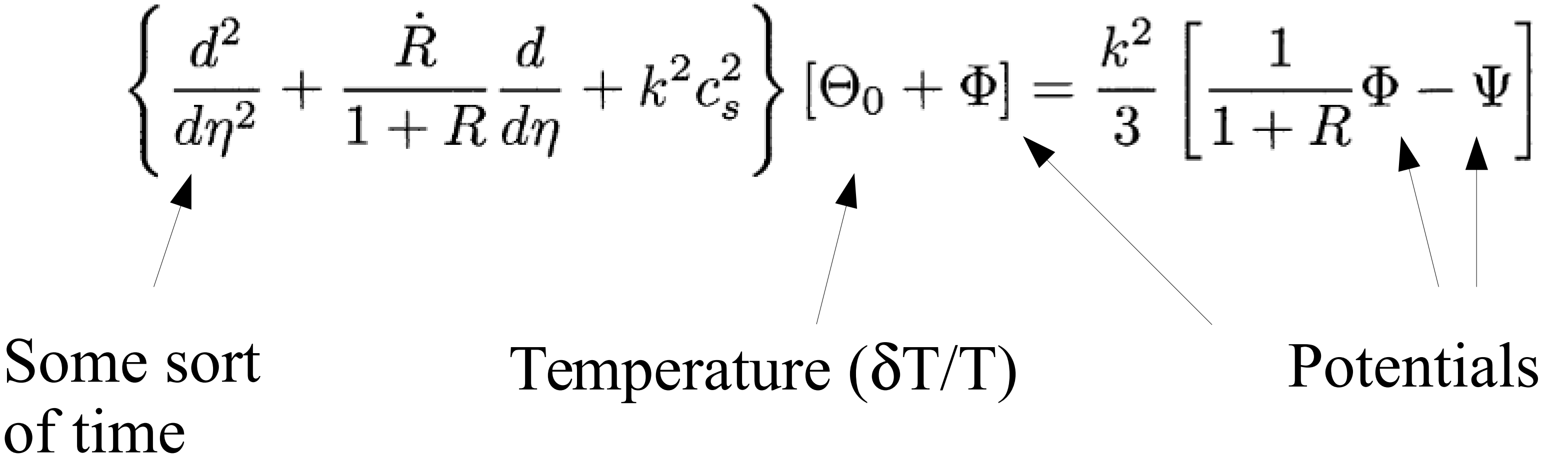
"E" modes (positive parity)

"B" modes (negative parity)

B modes from E modes through lensing

Primordial B modes from inflation

Physics of acoustic waves (1)



$$\left\{\frac{d^2}{d\eta^2}+\frac{\dot{R}}{1+R}\frac{d}{d\eta}+k^2c_s^2\right\}[\Theta_0+\Phi]=\frac{k^2}{3}\left[\frac{1}{1+R}\Phi-\Psi\right]$$

Some sort
of time

Temperature (δT/T)

Potentials

$$R \equiv \frac{4\rho_{\mathrm{photons}}}{3\rho_{\mathrm{baryons}}}$$

Sound velocity :

$$c_s \equiv c\sqrt{\frac{1}{3(1+R)}}$$

There are propagating solutions,
called sound waves

(S. Dodelson Modern Cosmology, chapter 8)

Physics of acoustic waves (2)
Sound horizon

At recombination sound waves just freeze as they are

The comoving length travelled by waves from big bang to recombination (t^*) (called *sound horizon*)

$$c_s \equiv c\sqrt{\frac{1}{3(1+R)}}$$

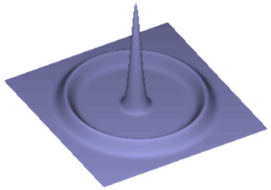
$$r_s = \int_0^{t_*} \frac{c_s(t)\ dt}{a(t)}$$

$$R \equiv \frac{4\rho_\gamma}{3\rho_b}$$

Depends on the “thermal history”:

- Ω_b in R
- Ω_m in a(t) and t^*

Physics of acoustic waves (3)



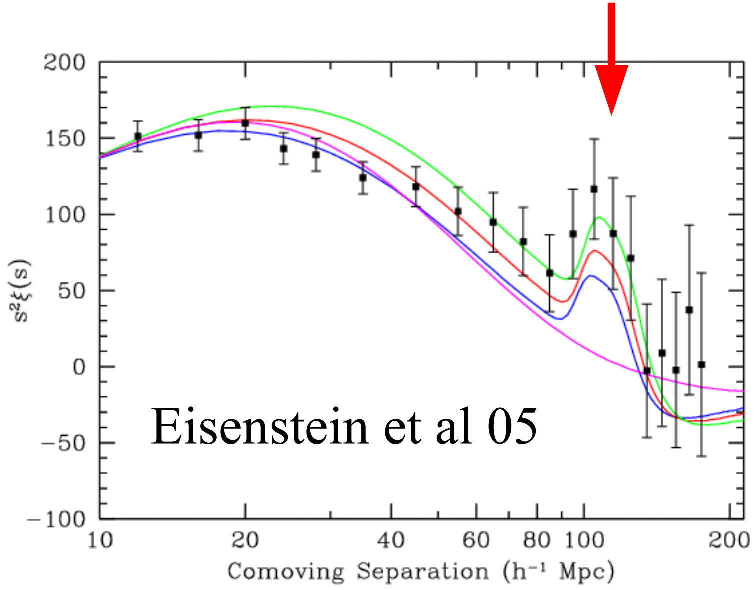
At recombination, there is
a favoured length in temperature
anisotropies of radiation:
the sound horizon at recombination

$$c_s \equiv \sqrt{\frac{1}{3(1+R)}}.$$

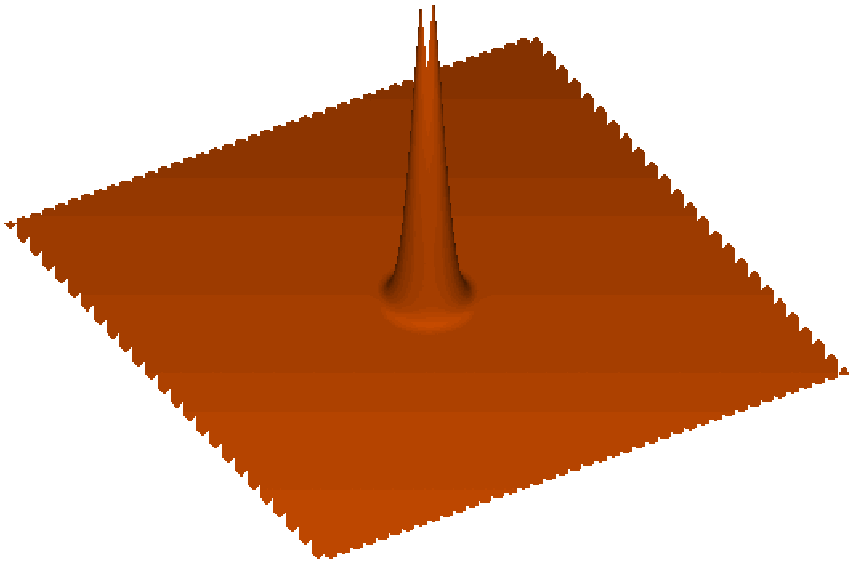
$$r_s = \int_0^{t_*} \frac{c_s(t)\ dt}{a(t)}$$

$$R \equiv \frac{4\rho_\gamma}{3\rho_b}$$

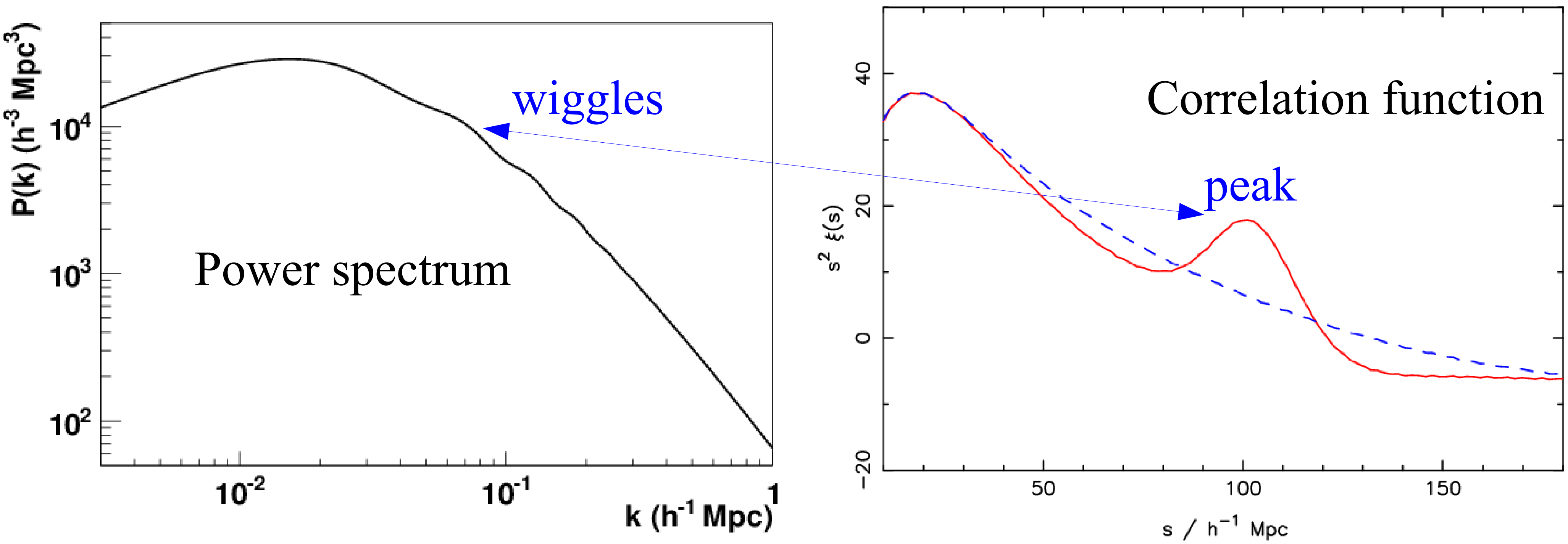
This favoured length is also imprinted
In galaxy correlations around us



Eisenstein et al 05



Correlation function and power spectrum



A single peak in the correlation function
→ harmonic peaks in the power spectrum

A redundant dataset

Allows many redundancy checks and null tests:

– Multiple sensitive detectors at a given frequency

– Compare the output from one detector to that of another

Planck spins at 1 rpm with axis fixed for 39–65 rotations (a "ring")

– Compare data from the first and second halves of a ring

– In "half-ring difference" maps, the sky signal subtracts out, leaving noise and possibly other systematic residuals

– Half-ring differences can be constructed for single or multiple detectors, and for any period of time

Multiple sky coverages

– In six months (one "survey") Planck covers most of the sky once

– In "survey difference" maps, the sky signal subtracts out, but the effects of different beam orientations and side lobes, etc. leave residuals

– LFI and HFI. Different technologies, different systematics.

– Multiple frequencies

– Foregrounds change, but (in appropriate units) the CMB doesn't

Observations/releases timeline

- August 13th 2009 : beginning of survey.

- November 27th 2010 : Nominal mission completed, having collected about 15.5 months of survey data insuring that all the sky at been seen at least twice by each detector:

- Jan 2012 : End of HFI observations (He tanks empty). Performance better than the "goals". Duration: about twice nominal mission (!)

- March 21st 2013 : public release of data (temperature on nominal mission) together with 28 "Planck 2013 results" papers.

- Early 2015: all data release, including polarisation.

L-dependent linear combination of maps