Planck Highlights

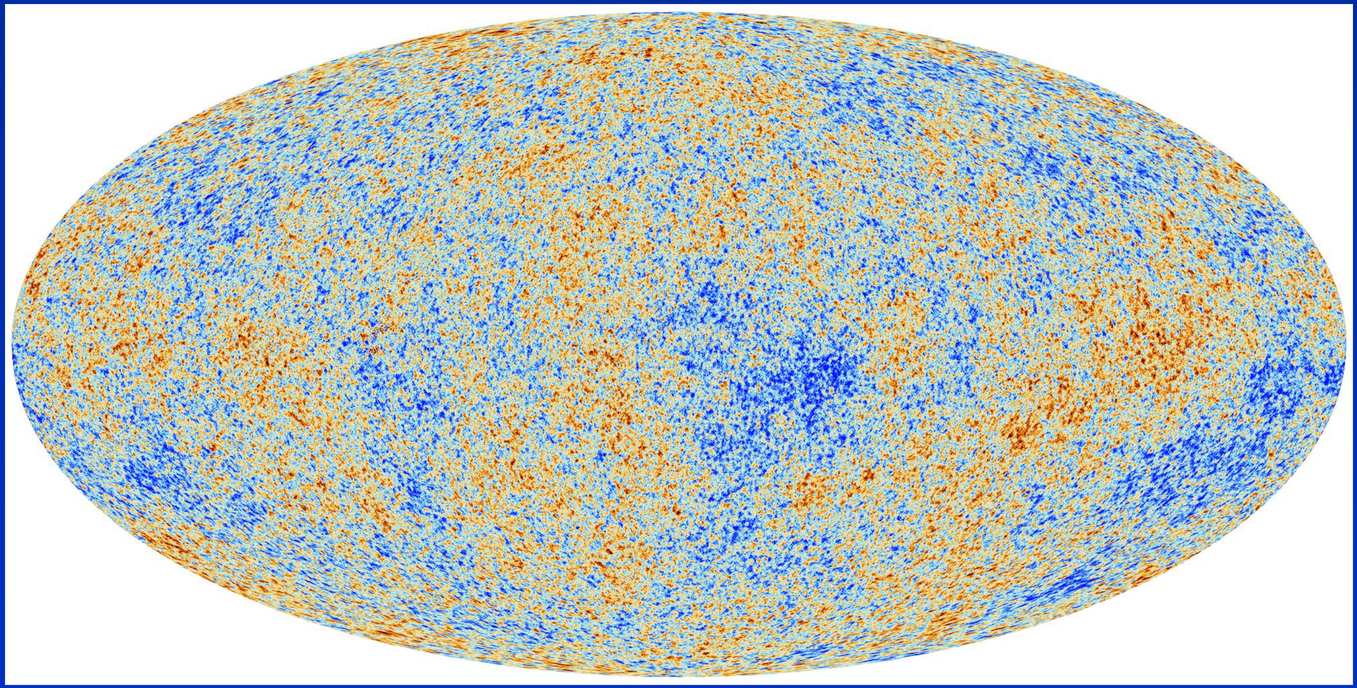
Alain Riazuelo

Institut d'astrophysique de Paris

(and weakly bounded member of the Planck collaboration)

riazuelo AT iap.fr

Erice, 29 June 2015



Overview

of a gziped summary of the 2013 ~ 900 pages Planck collaboration papers split into ~ 30 papers,
plus the $\sim xxx$ pages 2015 (still ongoing) release of $\lesssim 30$ papers

1. **A short introduction to CMB**

2. **Some Planck fact sheets**

3. **Cosmological parameter extraction**

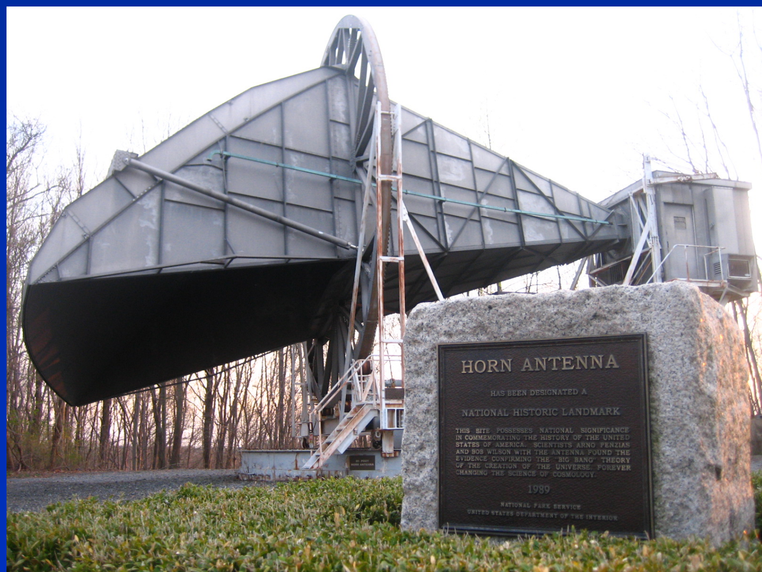
4. **Various crosschecks**

5. **Surprises and outlook**

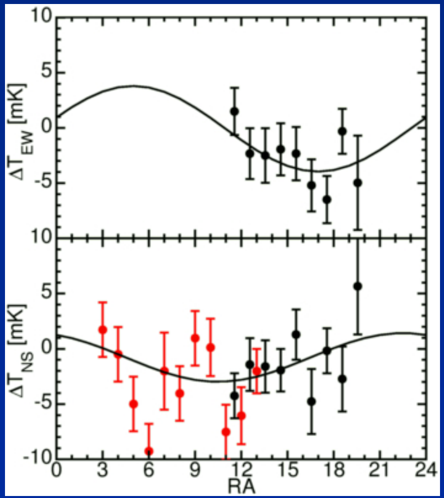
6. **What about BICEP2?**

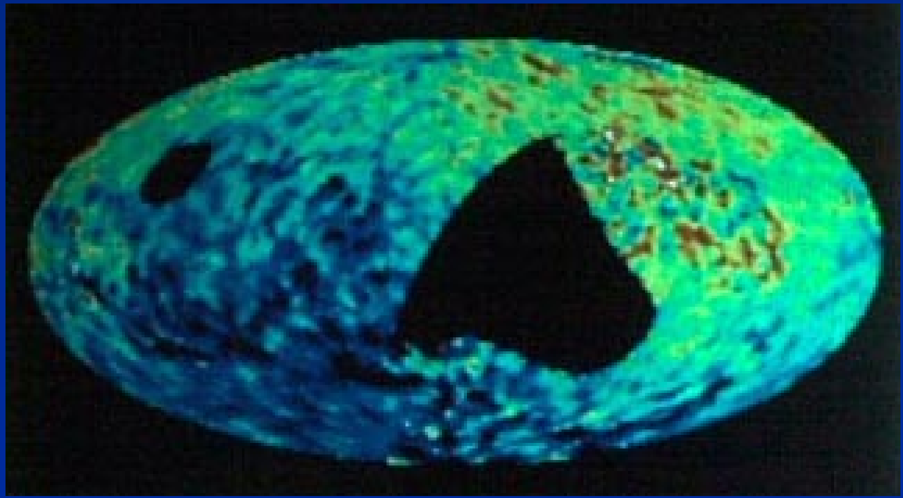
What is the CMB

- CMB = Cosmic Microwave background radiation, the light echo from the Big Bang
- General relativistic "Conservation equation", $D_\mu T^{\mu\nu}$ translates (in a homogeneous and isotropic universe) into $\dot{\rho} = -3H(P+\rho)$, i.e. $\mathrm{d}U = -P\mathrm{d}V$.
- As the Universe expands, any photon wavelength grows with time following the scale factor evolution $a(t)$
- A black body of temperature T remains a blackbody of temperature $T(t) \propto 1/a(t) \rightarrow$ Radiation energy is not conserved (Noether theorem does not apply in an expanding Universe)
- Light echo of the Big Bang was predicted by Gamow in $\sim$ 1948. Was later predicted to be a black body by Doroshkevitch
- Was soon after (1964) serendipitously discovered by Penzias and Wilson (Nobel Prize in 1978)

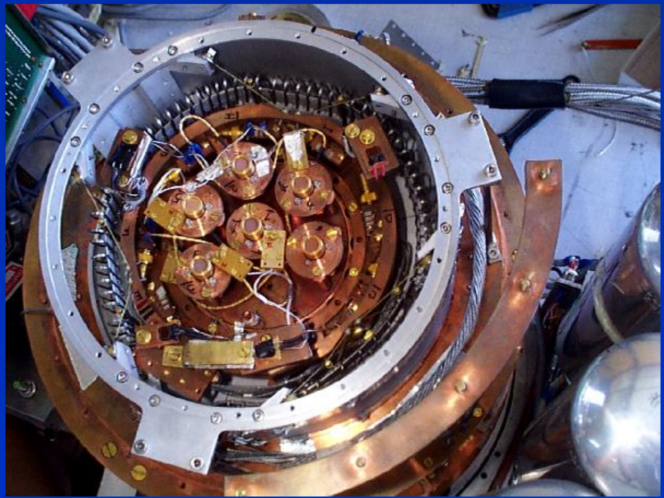


- Cosmological dipole (= motion of Earth + Sun + Milky Way wrt CMB) was discovered by Henry (and not Smoot) in the early 70's



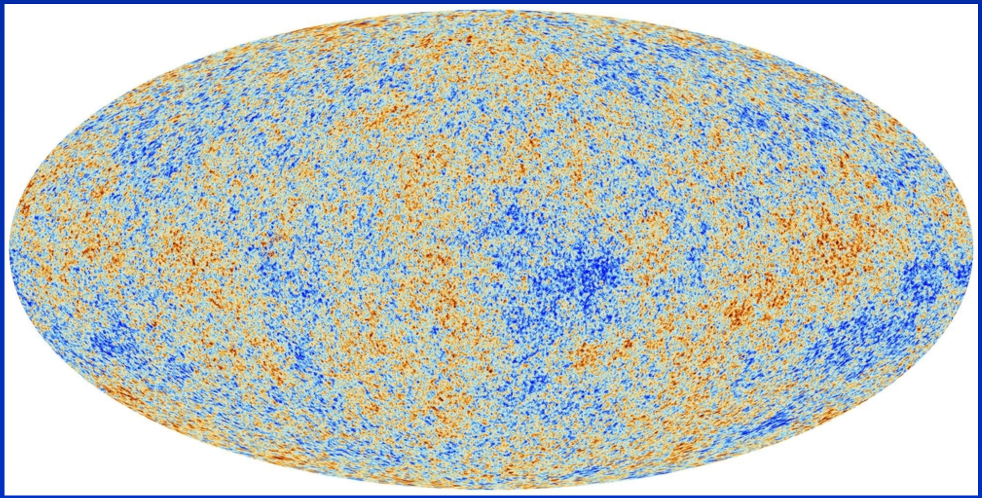


- Smaller scale anisotropy ($> 7\,\mathrm{deg}$) were first detected by COBE (or Relikt-1?) in 1992 (Nobel Prize in 2006), which also proved that is was the most perfect blackbody known – Begining of modern era of CMB study
- Many ground based / balloon borne observations observe small scale anisotropy, one of which, Archeops was a testbed for Planck and did a test flight from Trapani!



Why is CMB so useful?

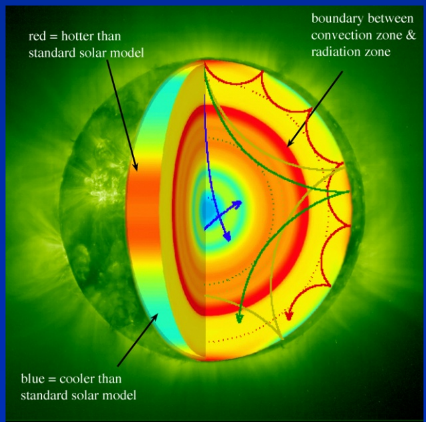
- At early times, matter is ionised. Compton scattering of CMB on electrons make the Universe opaque
- When the Universe cools down, electrons combine to atomic nuclei
- Hydrogen recombination is rather sudden and make opacity to drop very rapidly
- Most of CMB photons we see today were last scattered when $T \sim 3000\ \mathrm{K}$, i.e. close to a redshift of 1089. ($T_{\mathrm{rec}} \ll 13.6\ \mathrm{eV}$ because of very high photon to baryon ratio.)
- We see a picture of the Universe when T was $3000\ \mathrm{K}$, i.e. when $t \sim 370\,000\ \mathrm{yr}$.
- CMB photons we see originate from a sphere, the last scattering surface, who distance today is $\sim 45\ \mathrm{Gly}$, but which was then $\sim 1\,100$ times smaller

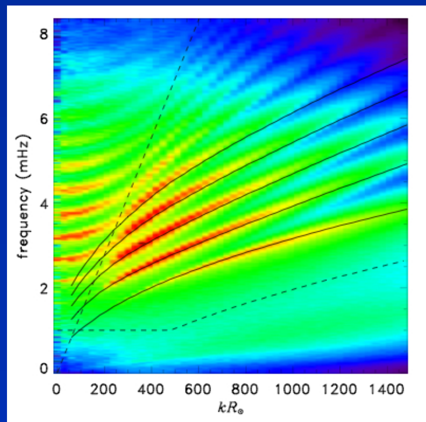


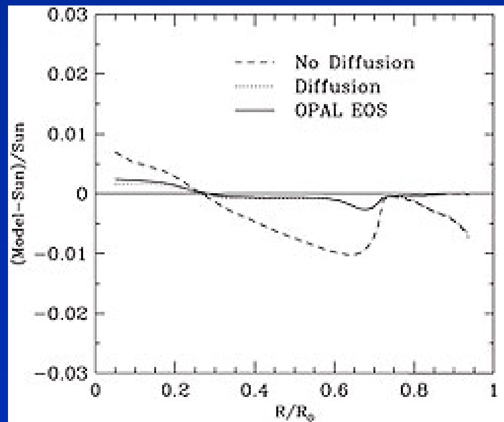
Why is CMB so useful?

- Compare the situation between heliosismology and CMB

Solar System is transparent till Sun's surface	Universe is tranparent from now to $z = 1100$
Sun interior is very opaque below the photosphere	Universe becomes rapidly opaque at early epochs
Only neutrino stream freely from the Sun and give direct access to its core	We cannot have direct access to earlier epoch unless we leave the electromagnetic domain
Vibrations seen on the photosphere propagate more or less deeply within Sun interior $\rightarrow$ their study allows to reconstruct the Sun material mechnical properties on a large fraction of its volume	CMB anisotropies are (mostly) produced by density waves that have propagated since very early epochs $\rightarrow$ One can have access to the matter content of the Universe at that epoch.







- Dark matter is ~ 6 times more abundant than ordinary matter
- CMB is of similar abundance with neutrinos
- There are $\sim 5 \times 10^9$ times more 2.725 K photons than 1 GeV nucleons, so that today
- At recombination, all four species contributed to the cosmic recipe at more than 10% each! ($\nu = 10\%$, $p + n = 12\%$, $\gamma = 15\%$, $\chi = 63\%$)

Why is CMB so useful?

- Moreover,
  - Neutrinos are relativistic, non intereacting
  - Photons are relativistic, interacting
  - Baryons are non relativistic, interacting
  - Dark matter is non relativistic, non interacting
- So that all four behave differently...
- ... and play a role since their contribution to the total energy budget of the Universe is not negligible
- ... and their perturbations can be easily computed are linear level since $\delta\rho/\rho \sim 4\delta T/T \sim 10^{-4}$ at most for photon, baryons and neutrinos, $\sim 10^{-2.5}$ for dark matter
- BUT there is also a crucial difference...

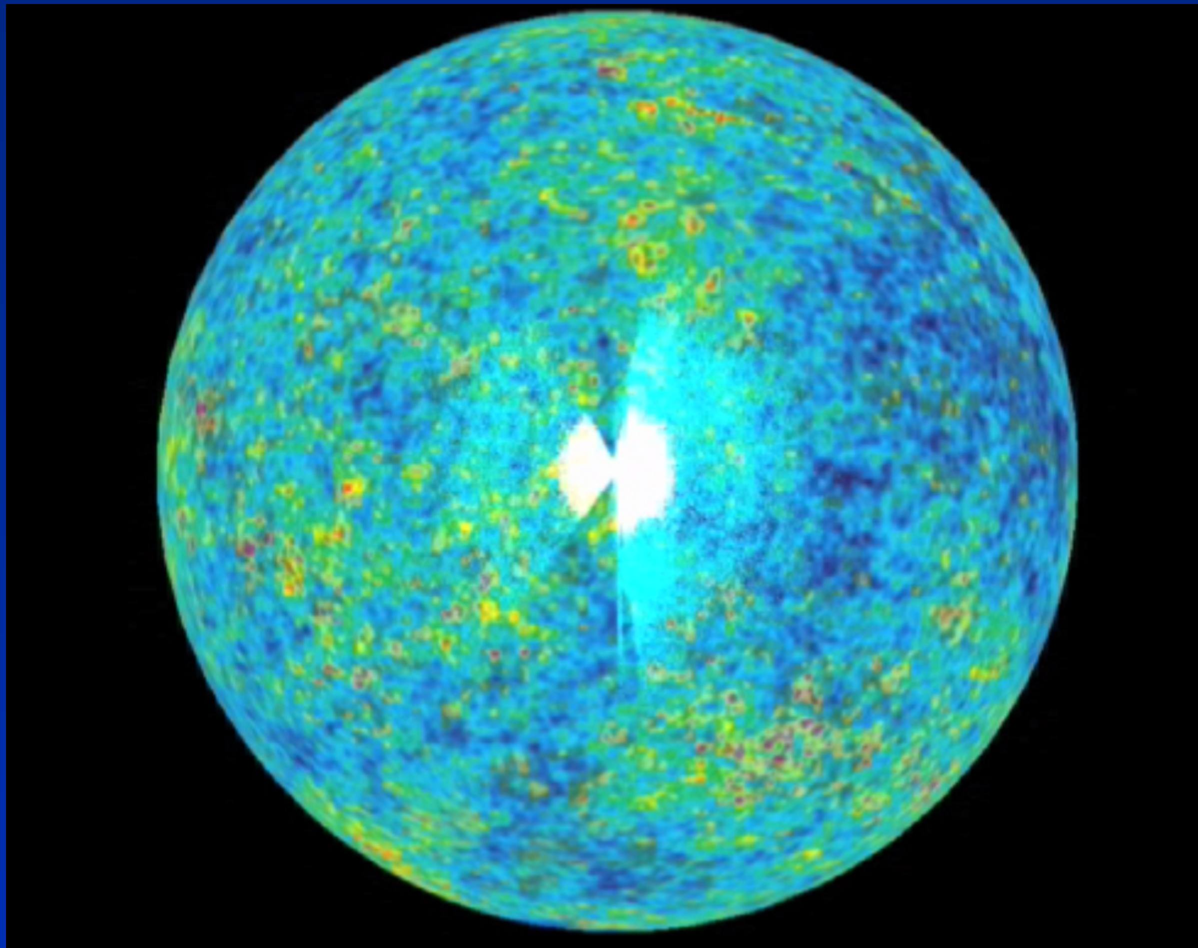
Vibrations within the Sun are produced by the presence of a convective zone	**No known physics** explains the existence of density perturbations on cosmological scales

- It is very hard NOT to have something like

$$\frac{\delta T}{T} \propto \left(\frac{E}{M_{\rm Planck}}\right)^n$$

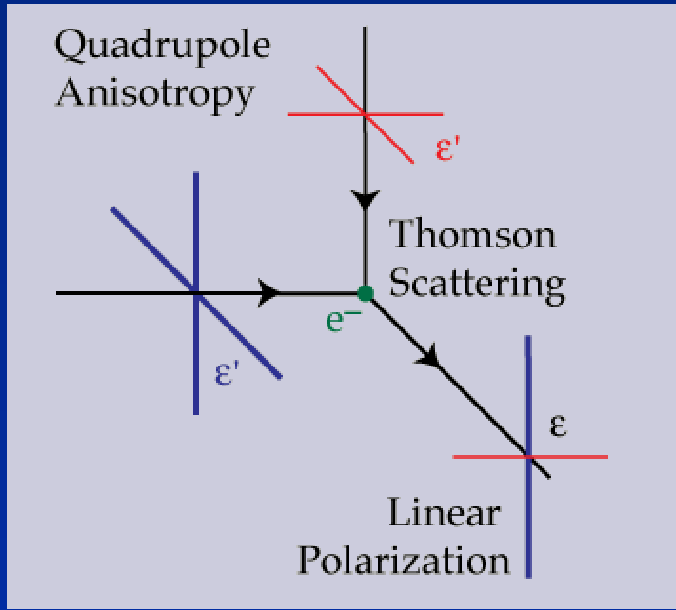
- The Universe therefore behaves as the ultimate high energy physics laboratory which we study through its most pristine, less evolved, observable state

Why is CMB so useful?



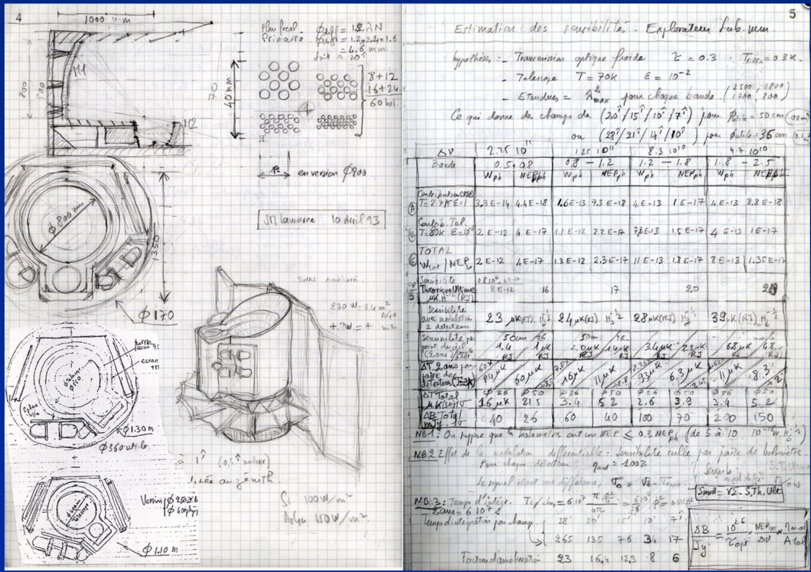
- Also, CMB give, by definition access to the largest observables scales
- With an unbiased sky coverage that is far better, despite Galactic emission, than any galaxy catalog

Why is CMB so useful? – Also thanks to polarization!



- When an unpolarized plane wave is scattered over an electron, it becomes linearly polarized in the orthogonal direction to the scattering plane
- When considering a full photon distribution function, a quadrupole anisotropy will produce a net polarization
- Quadrupole anisotropy in a photon distribution is produced by the gradient of its dipole, which itself is produced by the gradient of its temperature.
- Not only there will be polarization fluctuations, but they will be (partially) correlated with temperature
- In addition to TT spectrum, we also have a TP and a PP spectrum (see more later)
- Largest part of the polarization comes from so-called E-modes, which have been detected since 2001.

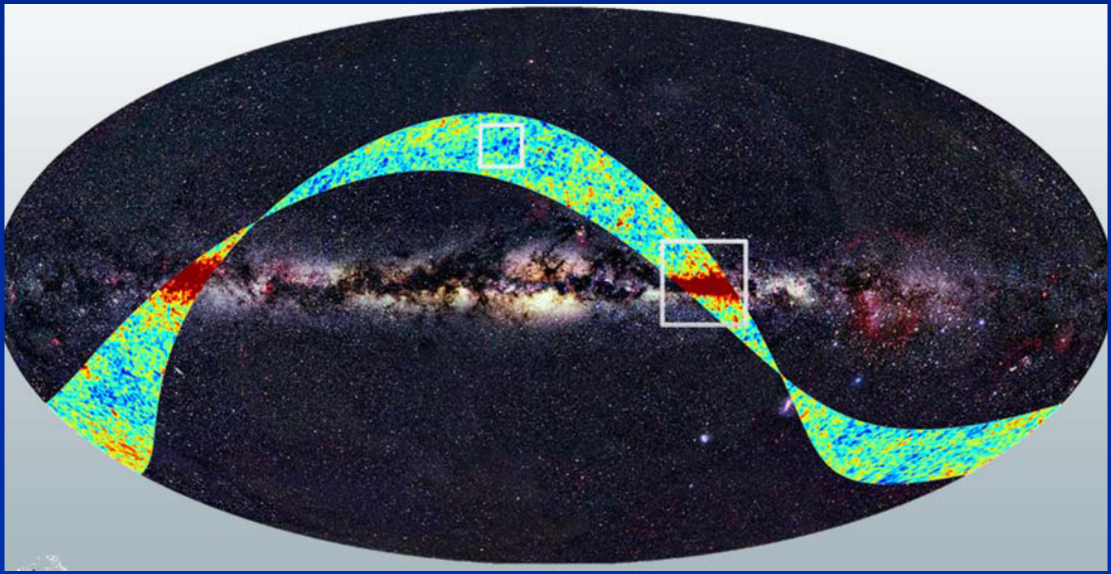
A short timeline of Planck



- First sketch of the satellite in 1993 (French side), following COBE-DMR results
- Forced marriage with Italian project $\rightarrow$ two very different detectors, HFI (French) and LFI (Italian)
- Accepted by ESA in 1996, launch then expected in 2003, just as its American equivalent, WMAP
- Specs targeted at an "ideal" temperature measurement mission, i.e.:
  - Full sky coverage at best resolution where primary fluctuations are still dominant ($\sim 5'$)
  - $5'$ resolution $\rightarrow 2.5'$ pixels, i.e. 30M pixel full sky map
  - Sensivity adjusted so as to remove foregrounds ($30\,\mathrm{GHz} \rightarrow 1\,\mathrm{THz}$)
  - $\rightarrow$ photon noise limited for 1 year of observation in CMB dominated window (Note: 1 year / 30M pixel map means $1\,\mathrm{s}$/pixel)
  - Do what we can for polarization

A short timeline of Planck

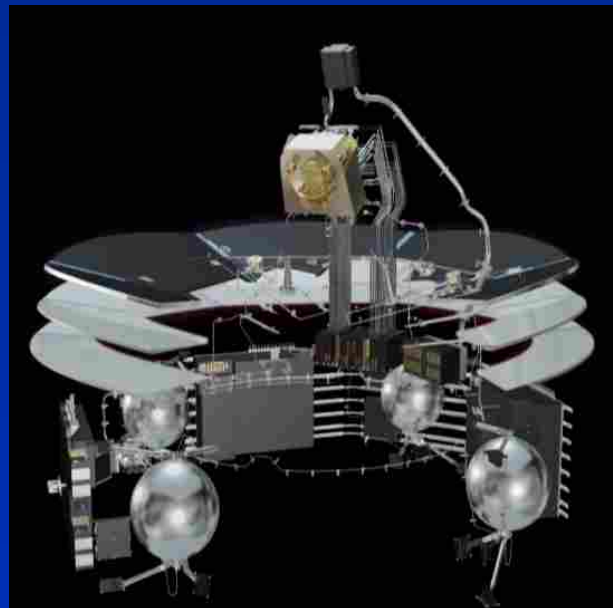
- Ariane-V first flight failure lead to large delay in Planck launch (4 years, i.e. necessarily long after WMAP)
- $\longrightarrow$ Need to improve polarization specs so as to make it become major goal
- Actual launch in May 2009 together with Herschel infrared telescope (WMAP launched in 2001)
- Scientific observations started in August 2009



- Nominal mission ended in fall 2010, but mission could continue as cooling system was OK
- End of HFI cooling in February 2012, LFI kept functioning longer
- First cosmological results in March 2013
- End of LFI observations early 2014 and next results expected in spring 2014 $\longrightarrow$ 21st June 2014 $\longrightarrow$ October 2014 $\longrightarrow$ November 2014 $\longrightarrow$ early 2015 (polarization)

Planck fact sheet

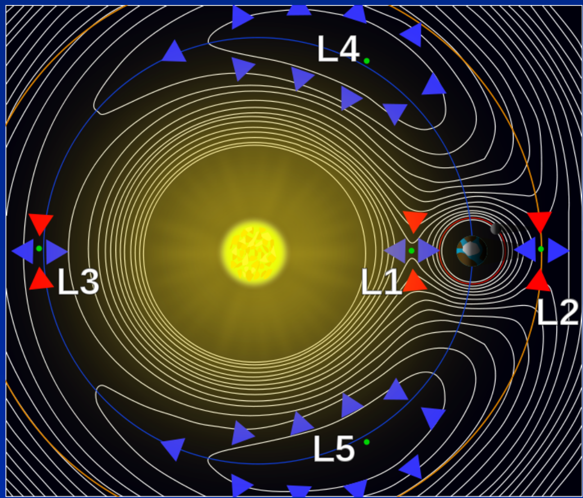
- Launch from an Ariane-V rocket $\longrightarrow$ quite lage satellite $(4.2 \times 4.2\ \mathrm{m},\ 1.9\ \mathrm{t})$
- Multifrequency $30\,000\,000$ pixel maps of the whole sky in several frequency chanels $(\Delta\nu/\nu \sim 30\%)$ of 30, 44, 70 GHz (LFI, 22 radiometers) and 100, 143 217, 353, 545 and 857 GHz (HFI, 52 bolometers)
- Detectors cooled down to $20\ \mathrm{K}$ (LFI) and $0.1\ \mathrm{K}$ (HFI), for the first time in space. Passive cooling reaches $50\ \mathrm{K}$, then a four stage cooling system reaches 20, 4, 1.6 and 0.1 K. HFI has spent around 500 g of helium-3 for this (significant part of yearly world production).

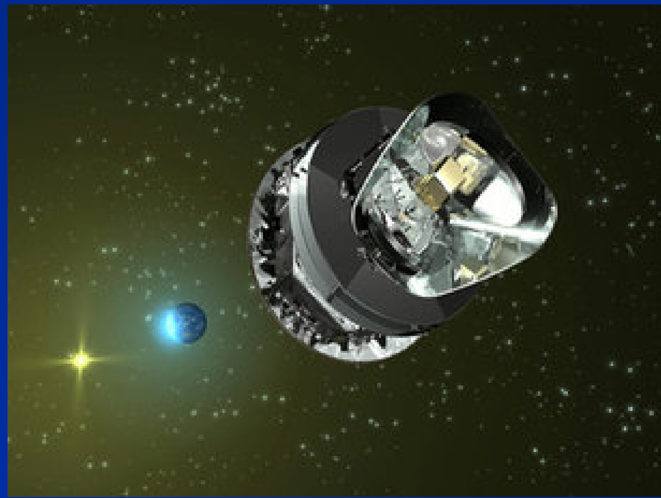



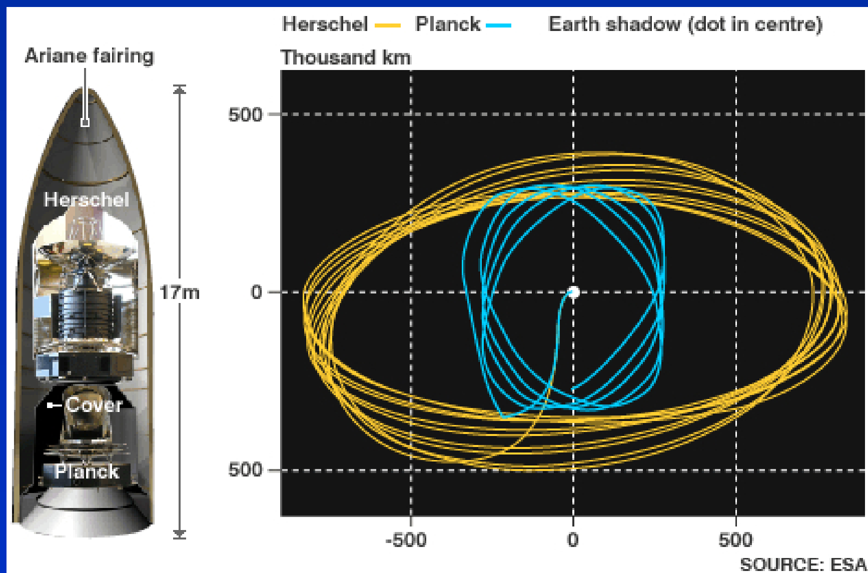
- Near to perfect thermal insulation of the scientific instruments $\longrightarrow$ no external solar panels, and limited power $(1600\ \mathrm{W}$, half of which devoted to the cooling system itself)

Planck fact sheet

- Thermal stability requires Earth, Moon and Sun to be always in the same region of the sky $\longrightarrow$ cruise toward L2 Lagrange point







A fairly large collaboration

- Total collaboration include close to 600 members, with range from the few founding fathers who work on the project since 1993 to weakly bounded people who only work on few specific issues
- More than 100 institutions, mostly in Europe, but also in US and Canada
- ESA Class "M" (= medium) mission $\rightarrow$ Cost $\sim$ 650 M EUR (1.3 euro per European citizen)

What we see is almost what we get

- What we see along a direction $\hat{\boldsymbol{n}}$ is what there is on the last scattering surface + blue- or redshift in this direction at distance r (Sachs-Wolfe effect), plus some Doppler shift, plus gravitational interactions of CMB photons (integrated Sachs-Wolfe effect)

$$\frac{\delta T}{T}(\hat{\boldsymbol{n}}) = \frac{\delta T}{T}(r\hat{\boldsymbol{n}}) + \Phi(r\hat{\boldsymbol{n}}) + \Psi(r\hat{\boldsymbol{n}}) - \boldsymbol{n}\cdot\boldsymbol{v}_{\rm bar}(r\hat{\boldsymbol{n}}) + \int_{\text{line of sight}} \dot{\Phi} + \dot{\Psi}\ (+\,\text{lensing})$$

- to which one may add similar term due to gravitational waves

$$\left.\frac{\delta T}{T}(\hat{\boldsymbol{n}})\right|_{\rm GW} = \int_{\text{line of sight}} 2n^i n^j h_{ij}$$

- Cosmological perturbations are produced by some random process whose observable Universe is an realization.
- Models predict the to-point correlation function :

$$\left\langle \frac{\delta T}{T}(\hat{\boldsymbol{n}})\frac{\delta T}{T}(\hat{\boldsymbol{n}}') \right\rangle_{\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{n}}'=\cos\theta} = \sum_\ell C_\ell P_\ell(\cos\theta)$$

- And this is compared reconstructed function from real data

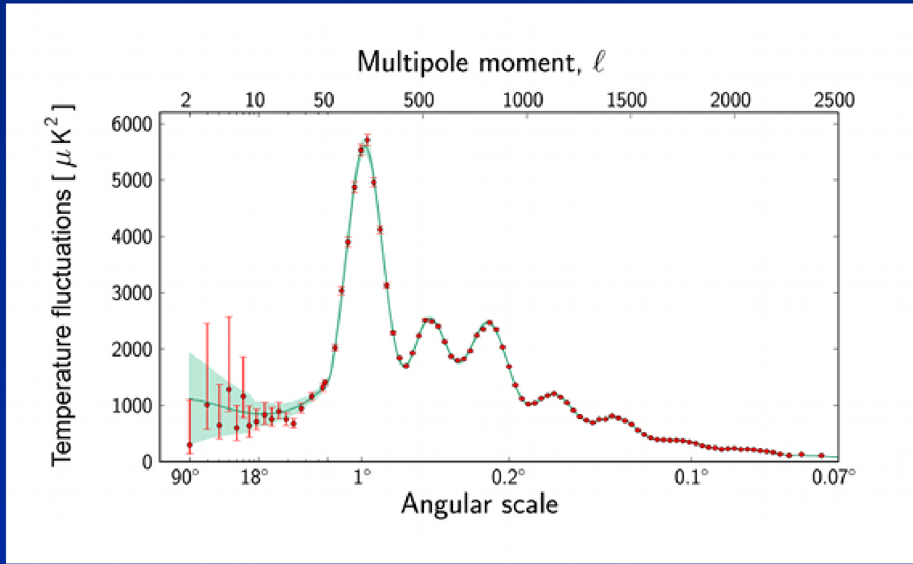
$$\frac{\delta T}{T}(\hat{\boldsymbol{n}}) = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\hat{\boldsymbol{n}})$$

,

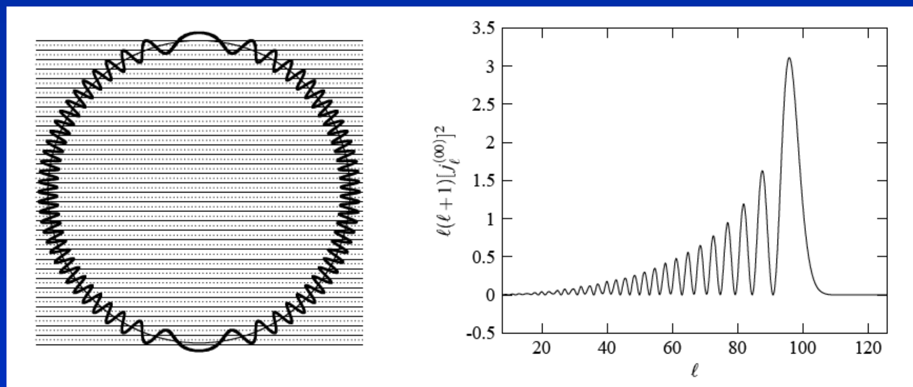
$$C_\ell^{\rm est} = \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2$$

- Estimator is never perfect because of finiteness of observable Universe → cosmic variance absolute limitation

What we see is almost what we get

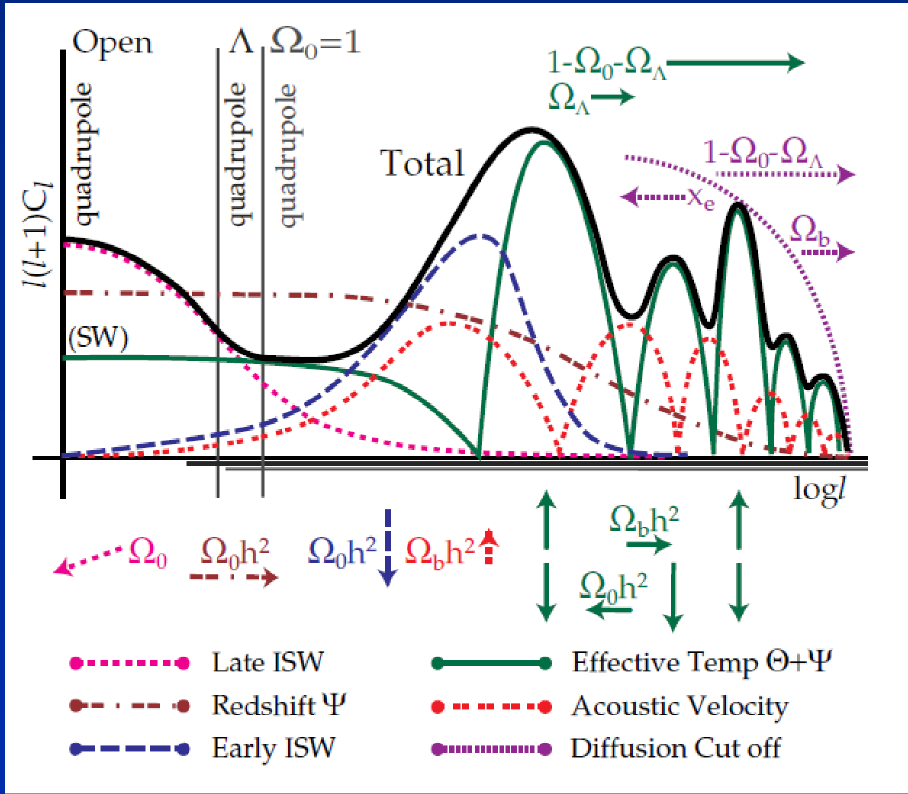


- Thing are computed at linear order in k space
- And then projected on a sphere



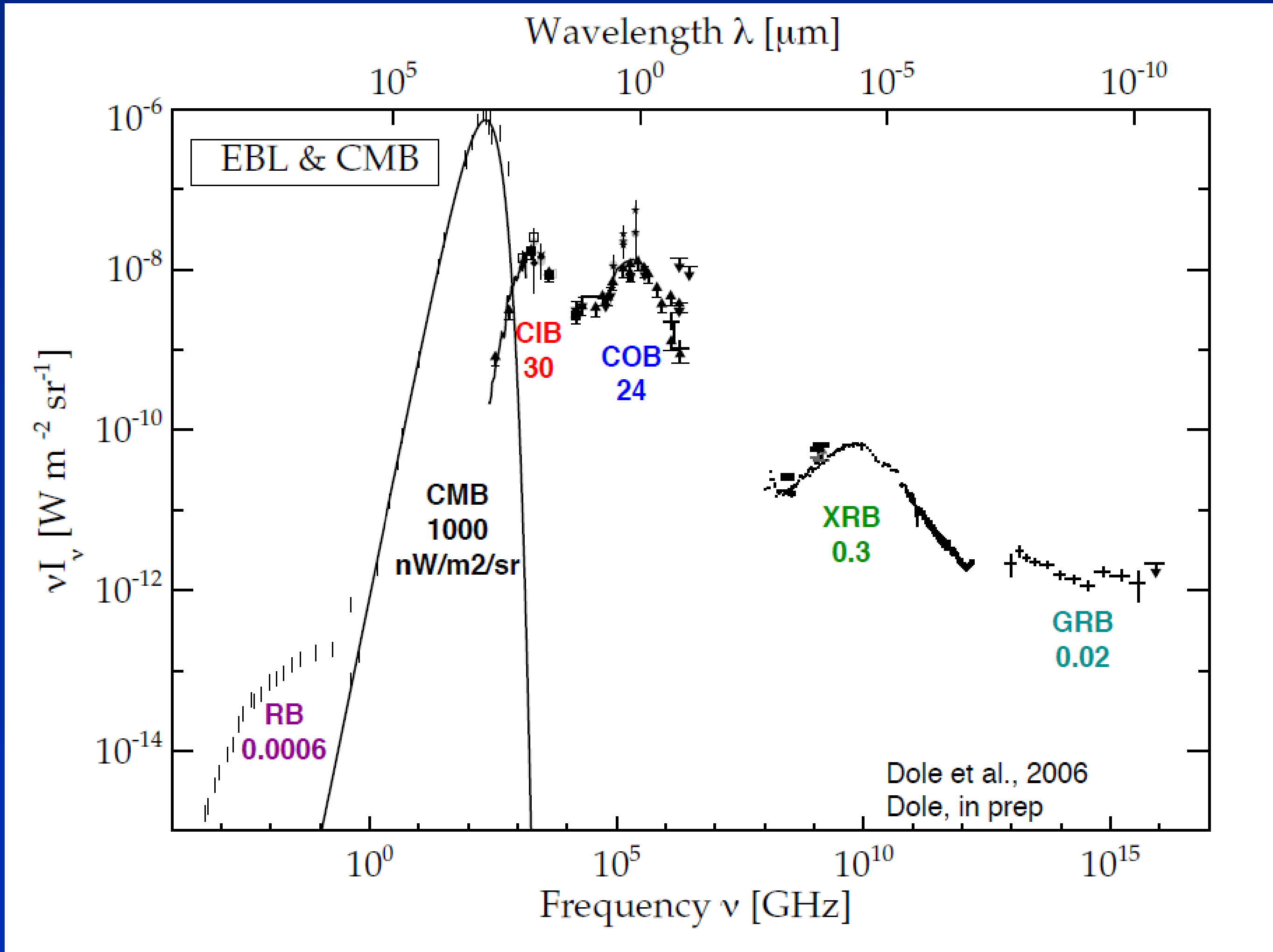
- with some no so big blurring of the k spectrum

What we see is almost what we get



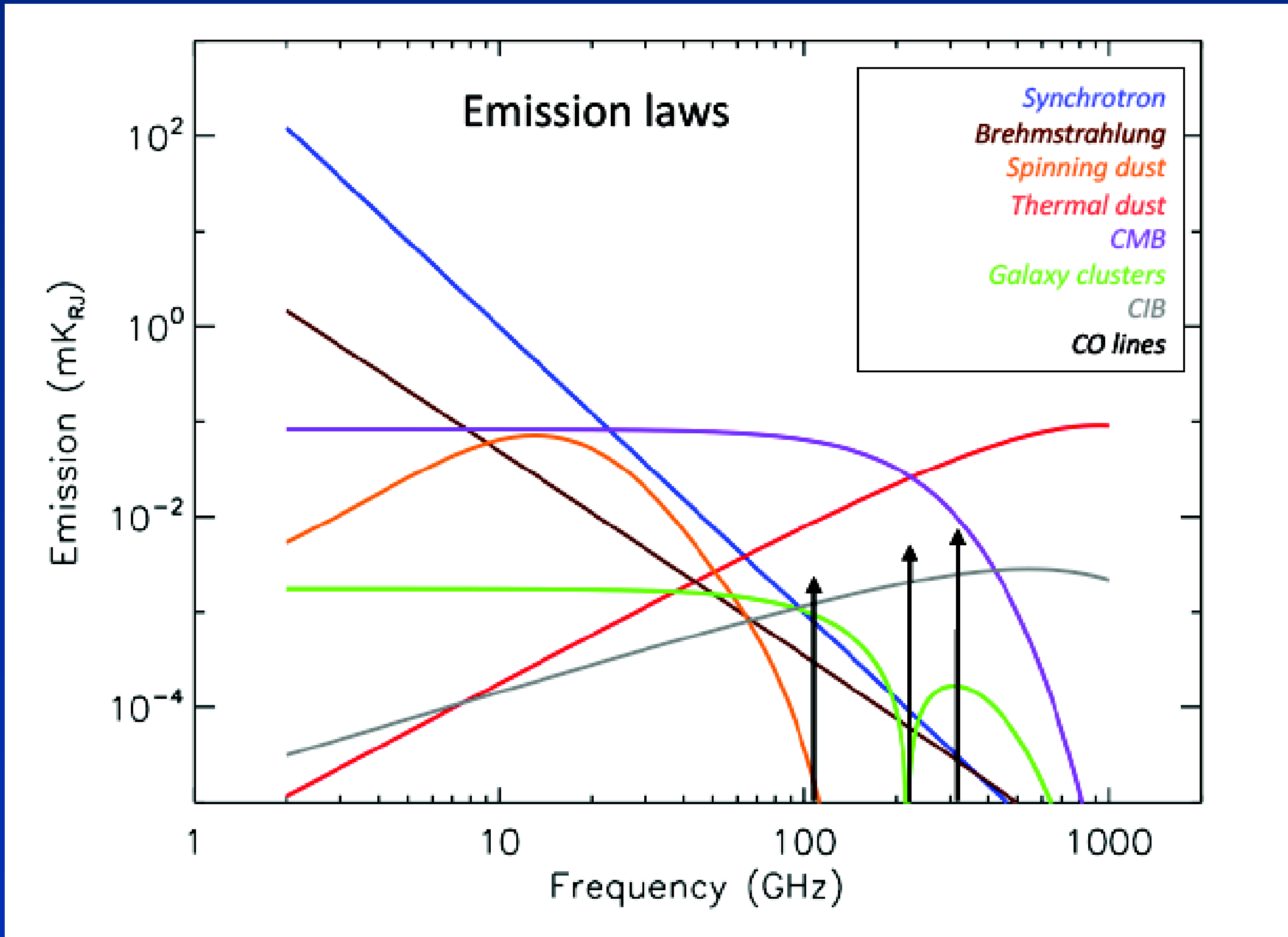
- One start from initial spectrum in k space (inflation or anything else)
- This initial spectrul is modulated by cosmological perturbation evolution at linear order till recombination ($\rho_{\rm b}/\rho_\gamma$, $\rho_{\rm DM}/\rho_\gamma$, ρ_ν/ρ_γ)
- And then projected on a sphere of radius r (dark energy, curvature)
- with the (last) complication that some photons have been rescattered after a few 10^7 years when first stars reionized neutral matter.

Why we are lucky to get it



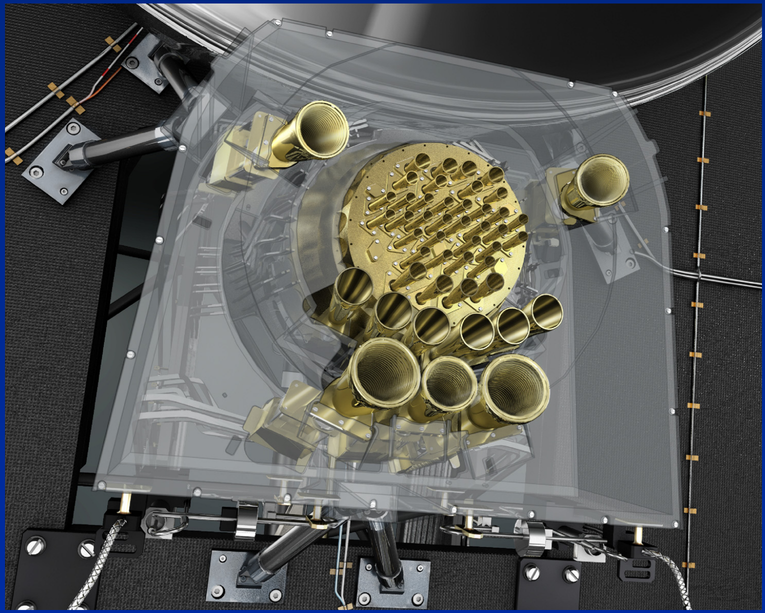
- CMB dominates everything in the Universe:
- Radiation budget is $\sim 94.6\%$ for CMB, 3% for starlight, 2.4% for thermal emission of dust, and ε for the rest.

Why we are lucky to get it



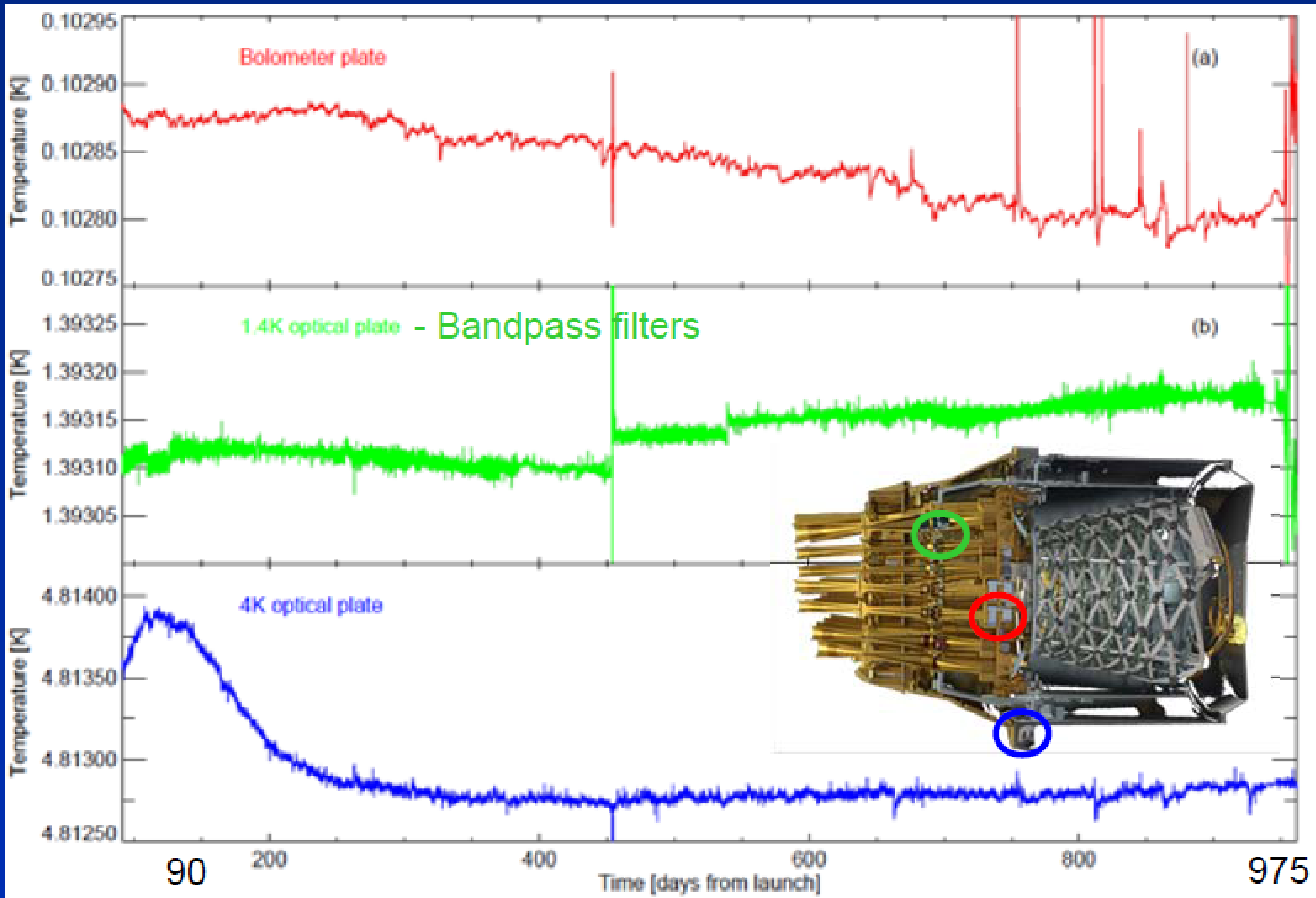
- CMB dominates everything in the Universe...
- But CMB fluctuations are $\sim 10^{-5}$ times smaller
- And fortunately, they are still dominant in a narrow frequency window

Detector characteristics



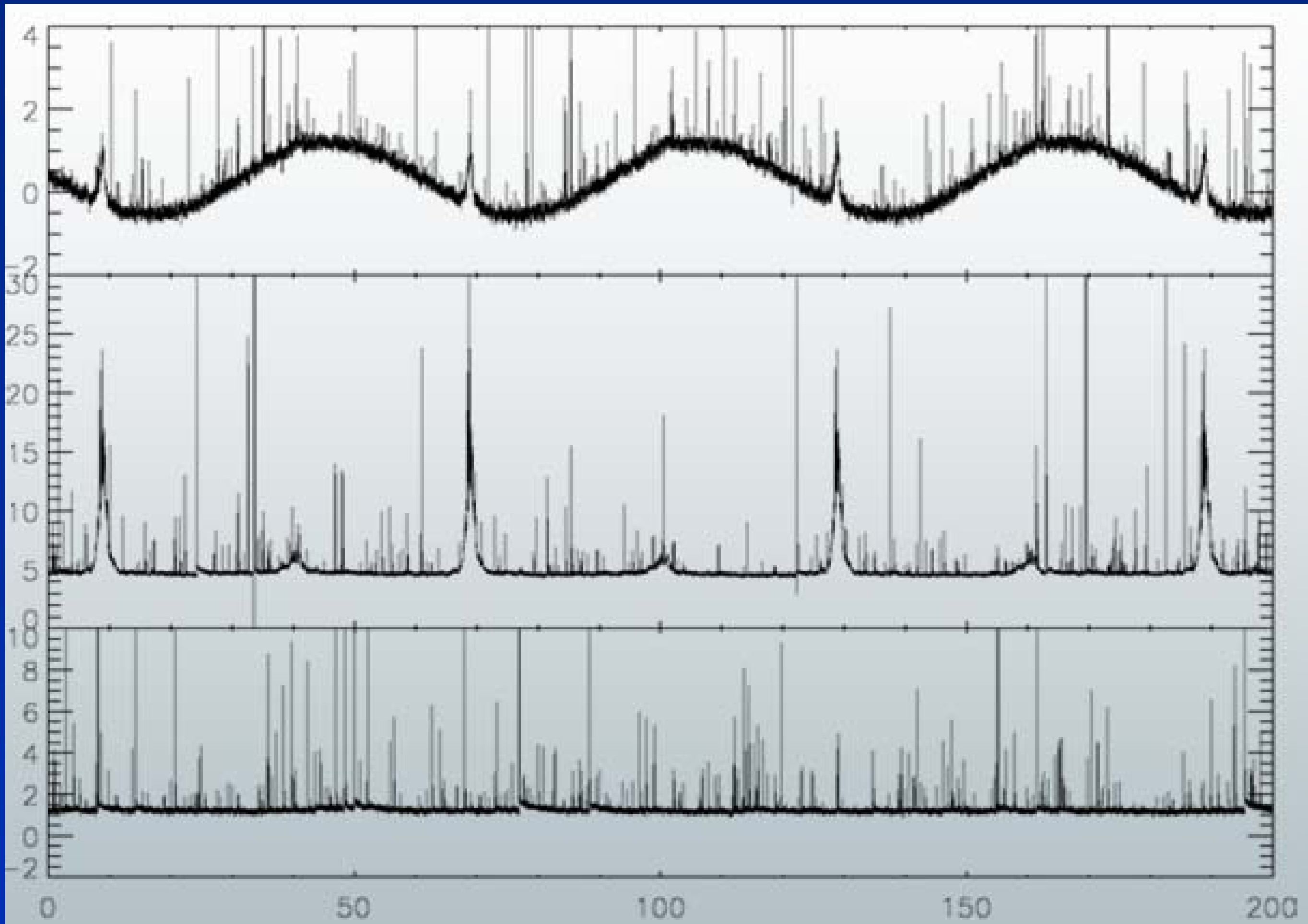
Instrument	LFI	LFI	LFI	HFI	HFI	HFI	HFI	HFI	HFI
Frequency (GHz)	30	44	70	100	143	217	353	545	857
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Detector type	HEMT	HEMT	HEMT	Bol.	Bol.	Bol.	Bol.	Bol.	Bol.
Op. Temp. (K)	20	20	20	0.1	0.1	0.1	0.1	0.1	0.1
# detectors	4	6	12	8	12	12	12	4	4
Incl. pol.	4	6	12	8	8	8	8	0	0
Resolution	33'	24'	14'	9.5'	7.1'	5'	5'	5'	5'
Sensitivy (T)	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Sensitivity (Pol.)	2.8	3.9	6.7	4.0	4.2	9.8	29.8	—	—

The extreme temperature stability of the instruments



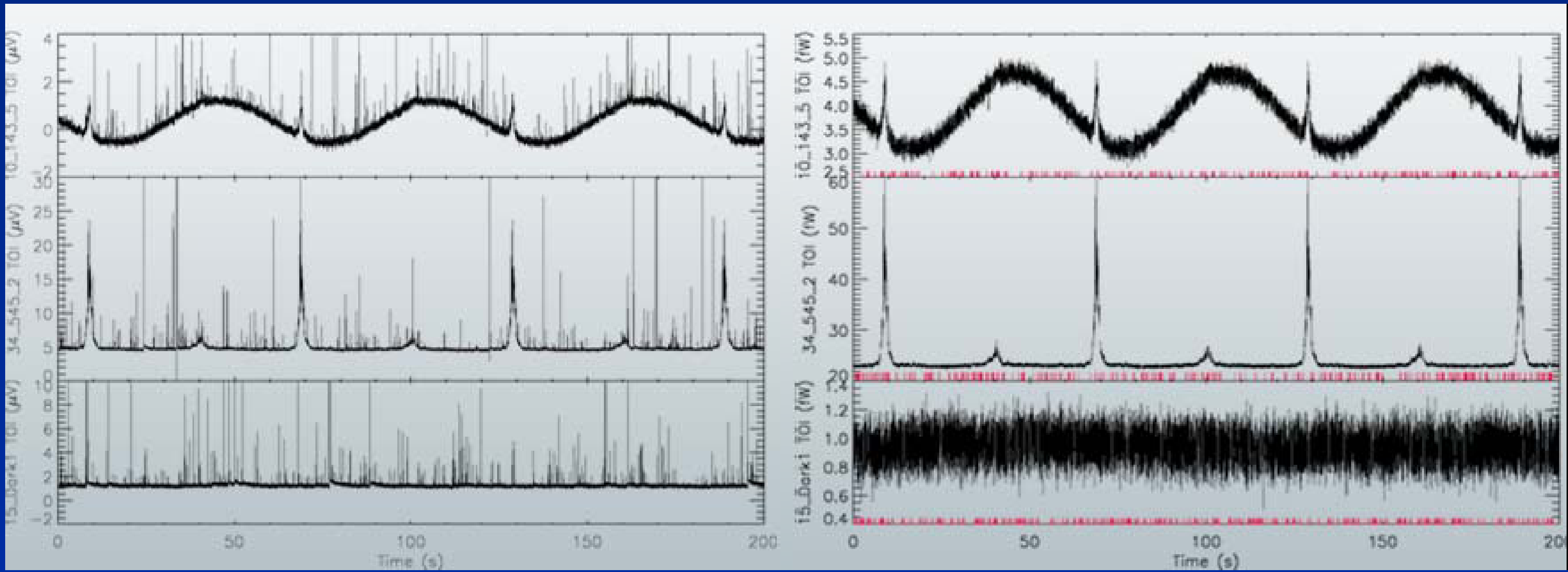
♣ 4 K cooling stage stable at 1 mK level. 1.6 K and 0.1 K stable at 0.1 mK level!

Starting from raw data



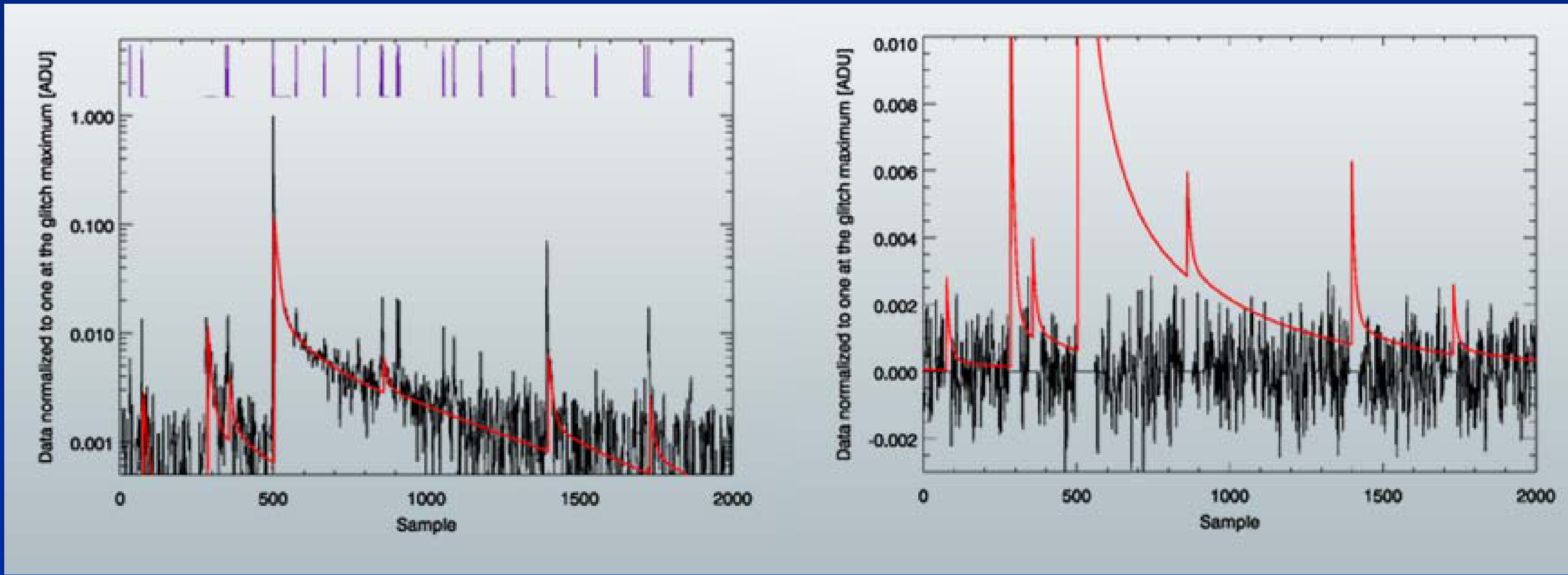
- From top to bottom: 143 GHz, 545 GHz, dark
- Dipole (top) and Galaxy middle are clearly visible
- Dark is NOT dark!

Starting from raw data



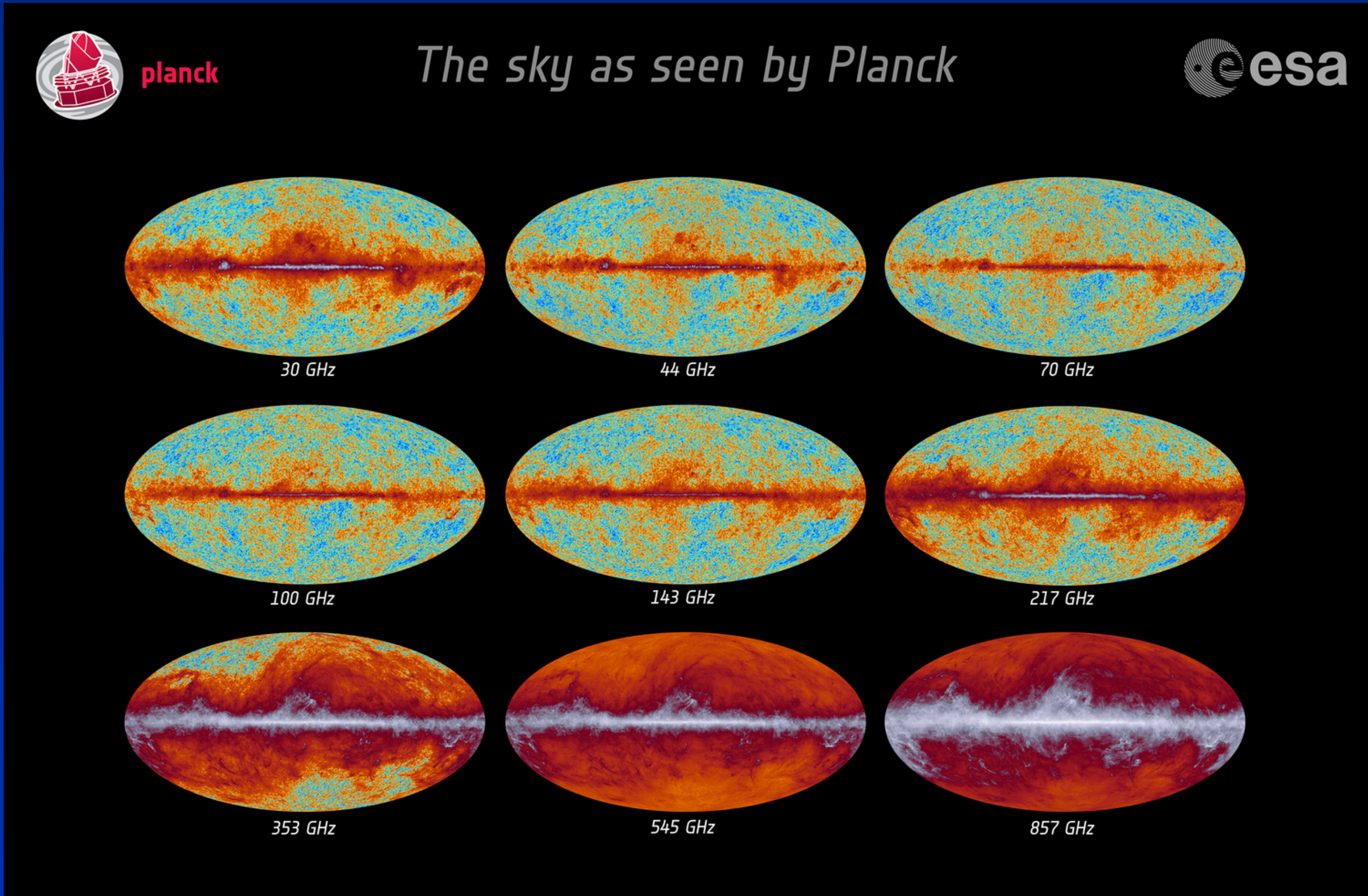
♣ Deglitching was unanticipated, mandatory... and successful (up to 12% of data loss)

Deglitching

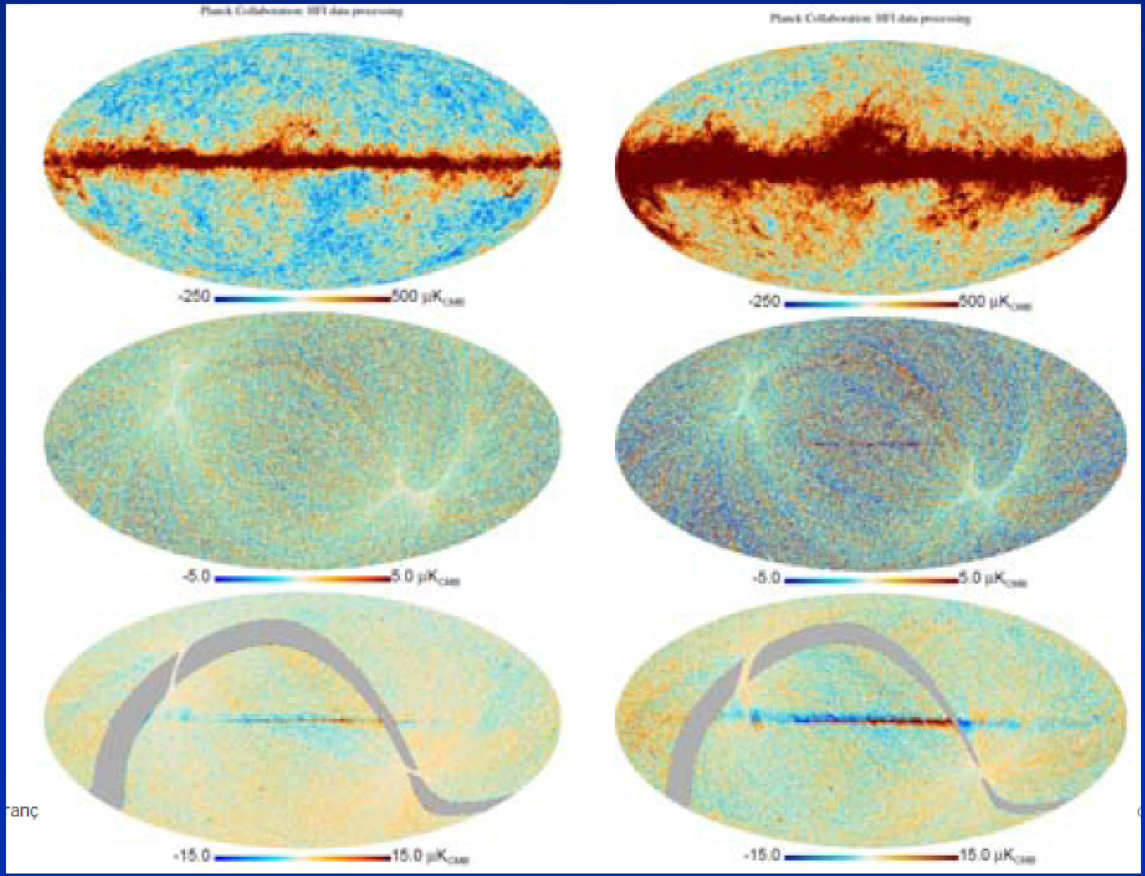


- ♣ Glitch ∼ sum of a few exponential decays
- ♣ Identified thanks to redundancy
- ♣ Efficiently removed up to initial part

Frequency maps...

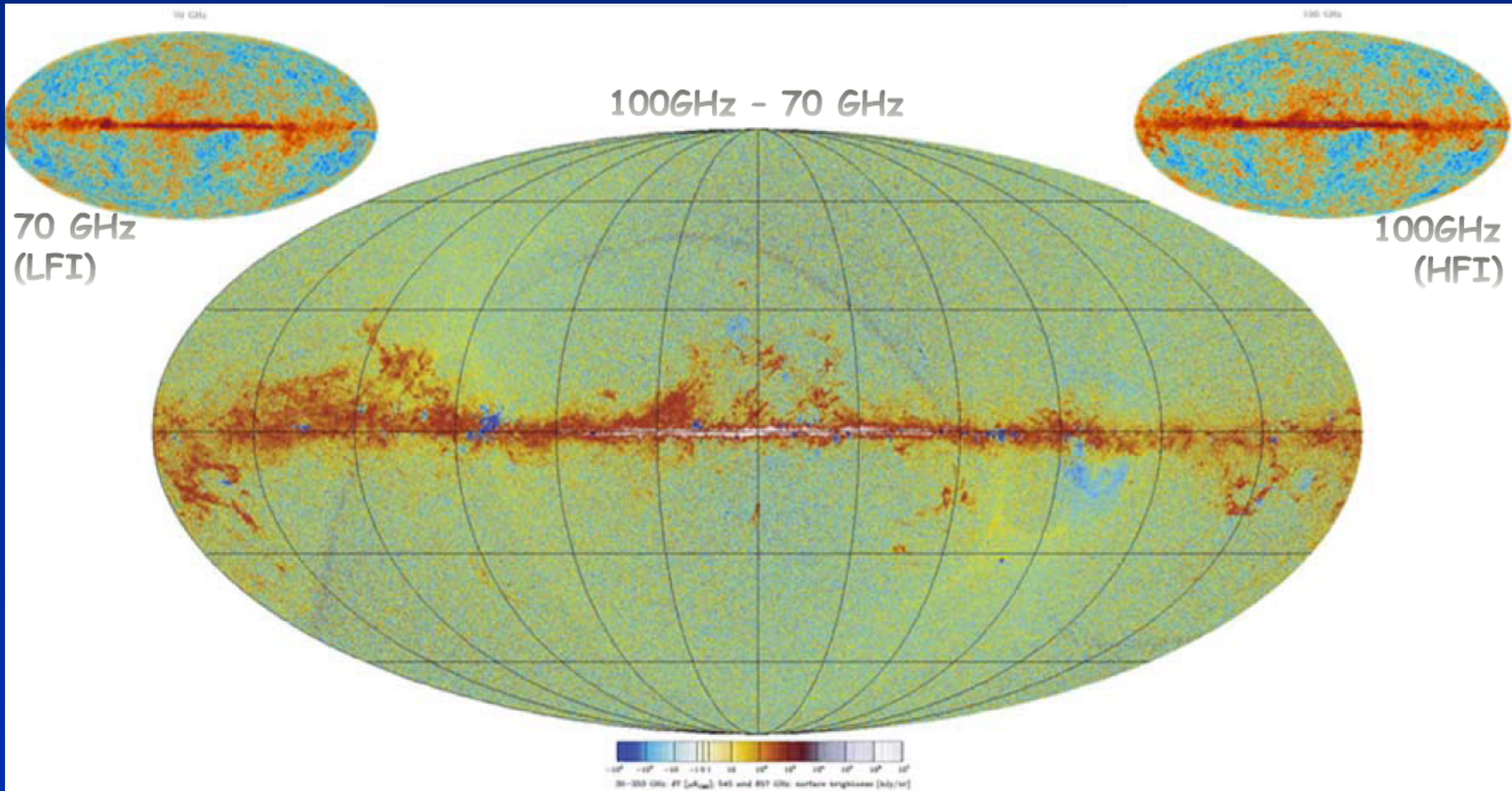


… and their stability



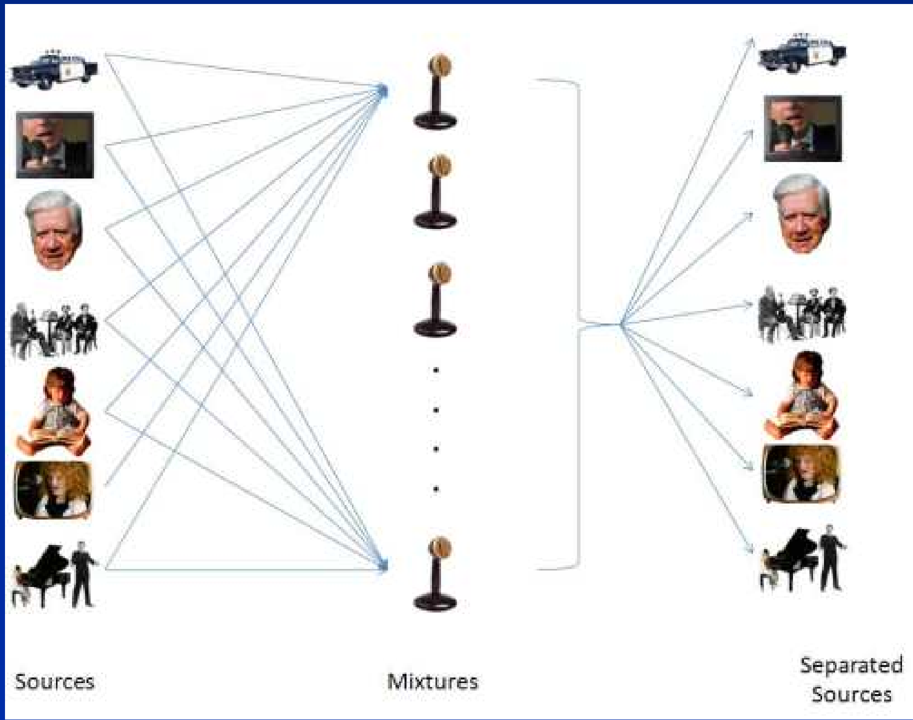
♣ 143 and 217 GHz intensity maps (top), "half ring" differences (30 min – 30 min, middle), survey differences (6 months – 6 months, bottom)

… throughout both instruments



♣ LFI could not build the planned 100 GHz bolometers which would have insured straightforward cross calibration, but it can efficiently be done through CMB nulling in 100 and 70 GHz maps (what remains is mostly CO — free-free)

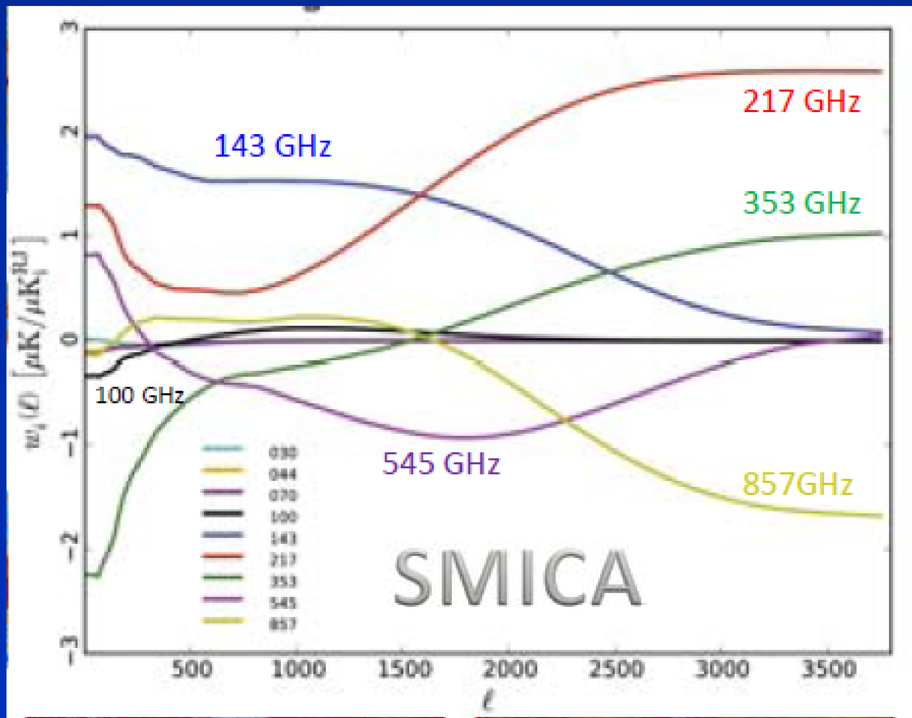
The "cocktail party problem"



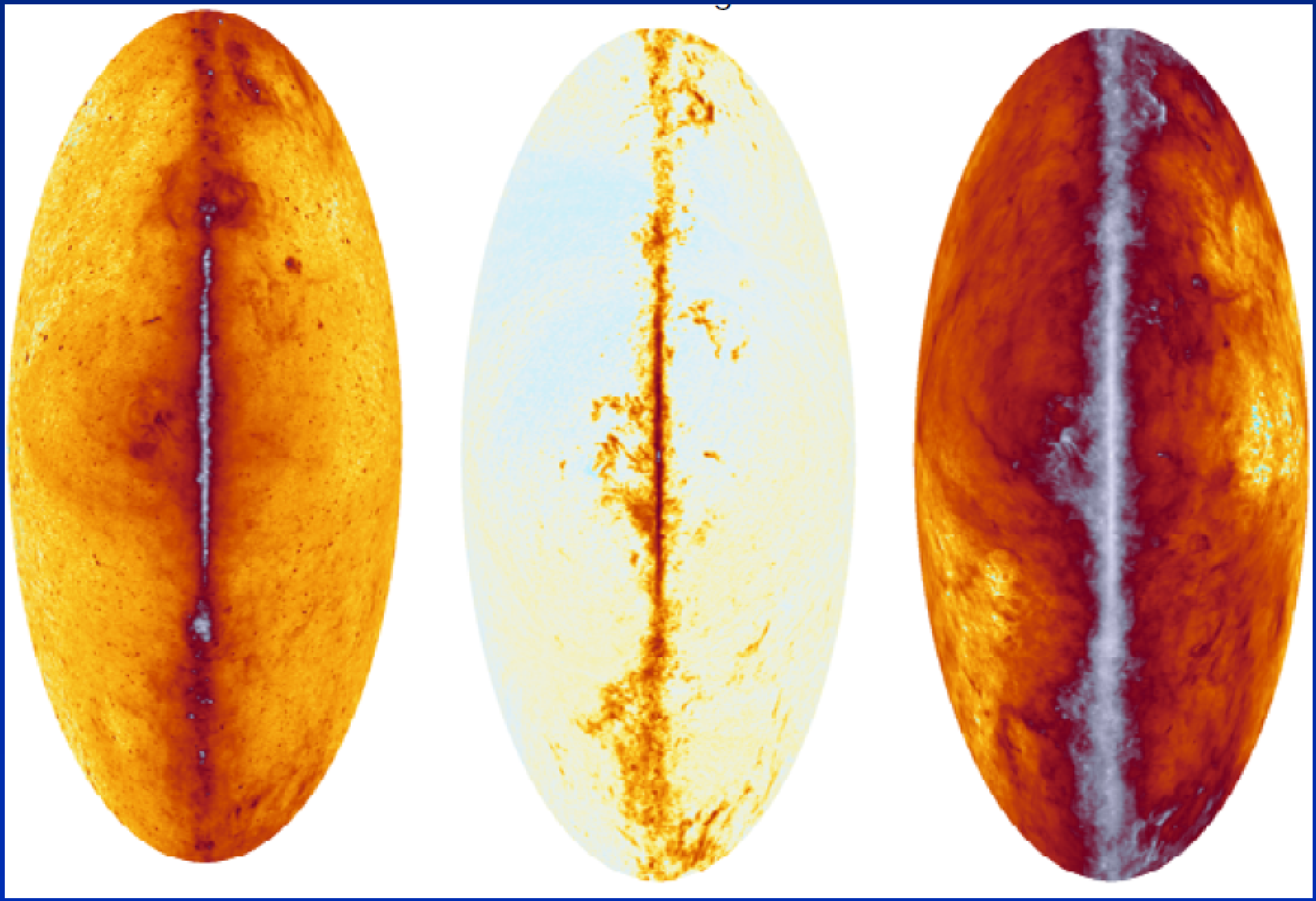
- From the frequency maps, one build a set of component maps which are more or less linear combination of the frequency maps
- One needs at least as many channels as there are sources
- Exquisite foreground removal necessitate to have maps where foreground dominate signal, hence the high frequency channels

Mapmaking...

- Several methods are possible to make maps:
  - Blind needlet space approach (NILC)
  - Blind harmonic space approch (SMICA)
  - Template based approch (SEVEM)
  - Parametrised model approch (Commander-Ruler)
- Each of them is best suited for some specific task (e.g. SMICA → non Gaussianities)

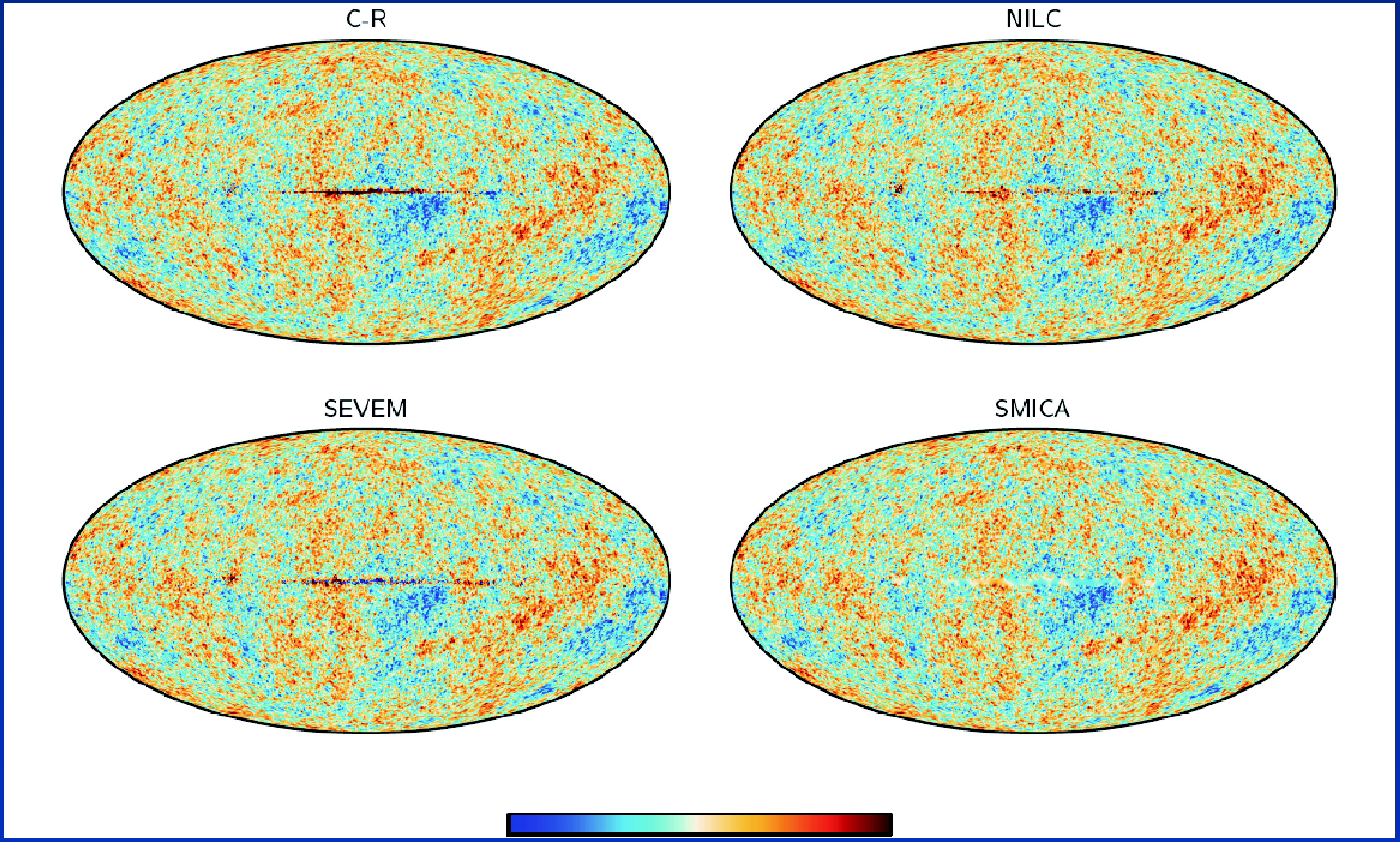


It gives all the foregrounds (here, the Galactic ones)...

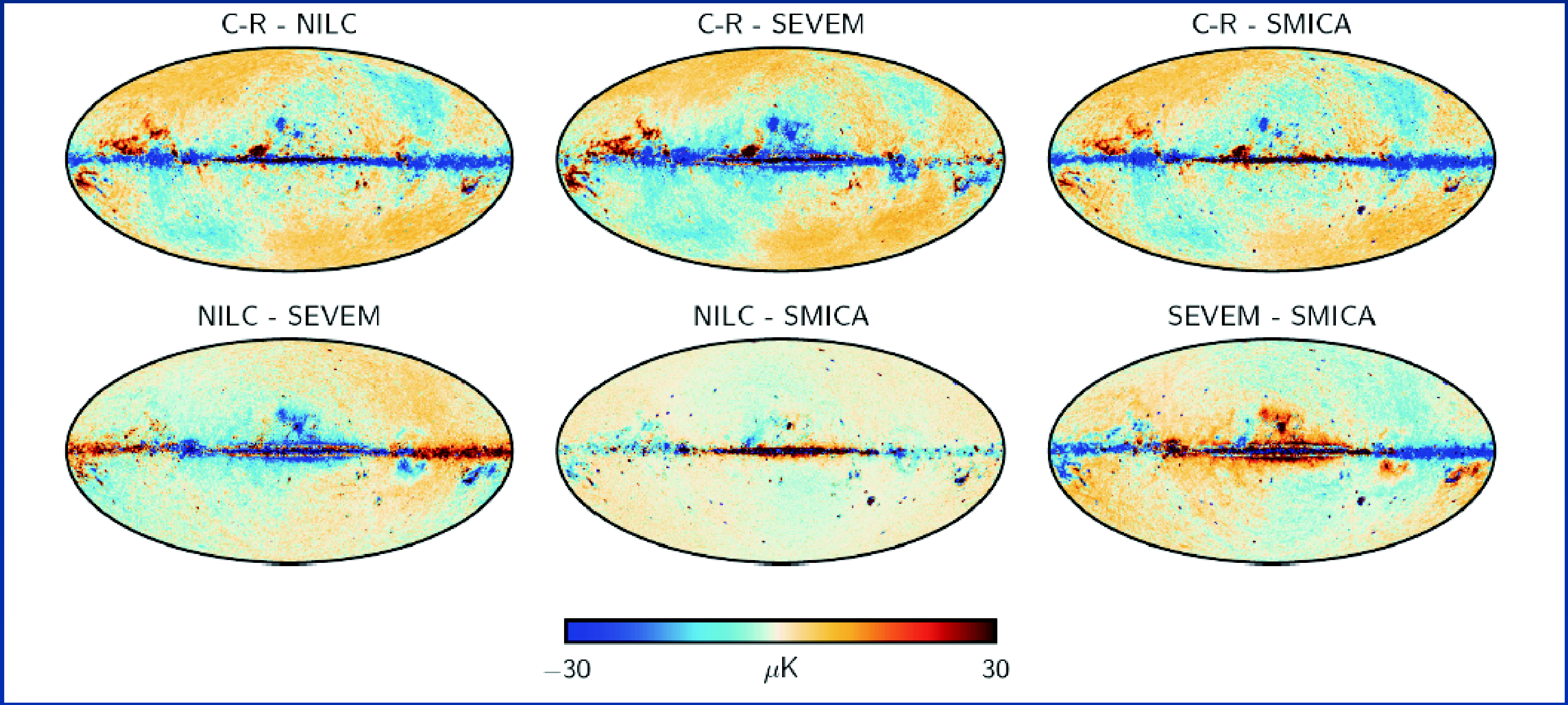


♣ From left to right, low frequency (synchrotron + free-free), CO lines, and dust

and the CMB, for which they agreed in 2013...

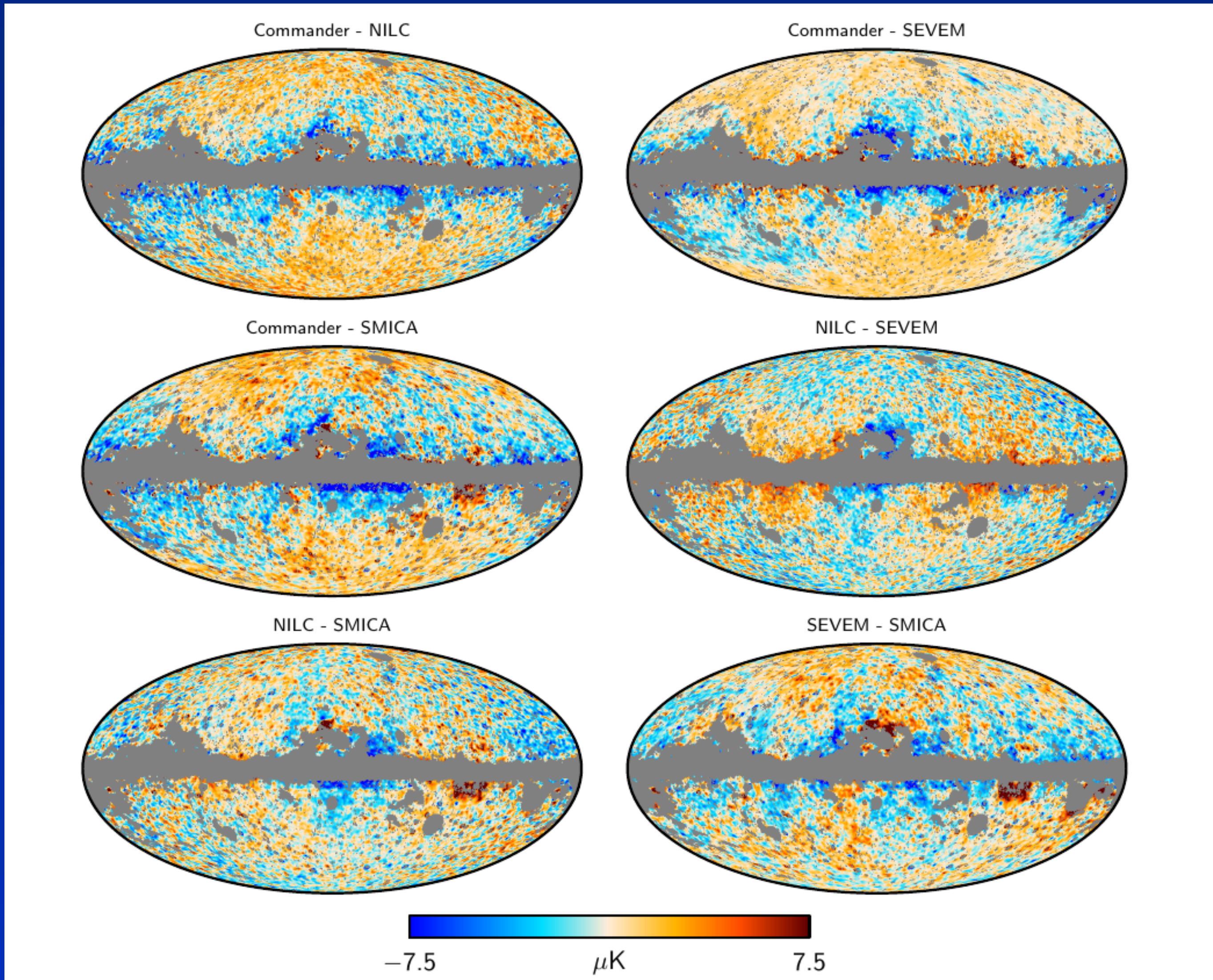


(well, almost!)



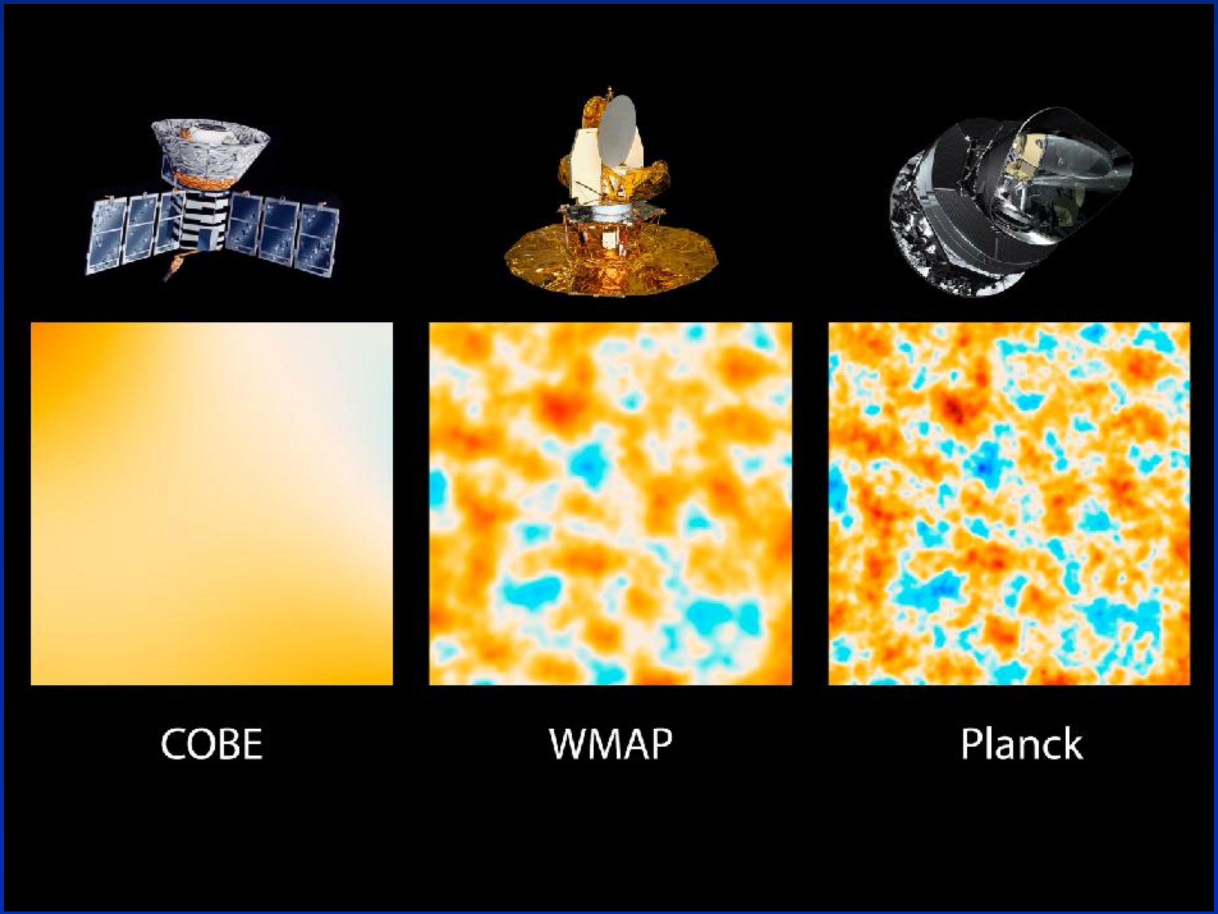
(but difference often $< 5\,\mu\mathrm{K}$ at high Galactc latitude; see Planck 2013 XII, arXiv:1303.5072)

But getting much better now!



(see Planck 2015 IX, arXiv:1502.05956)

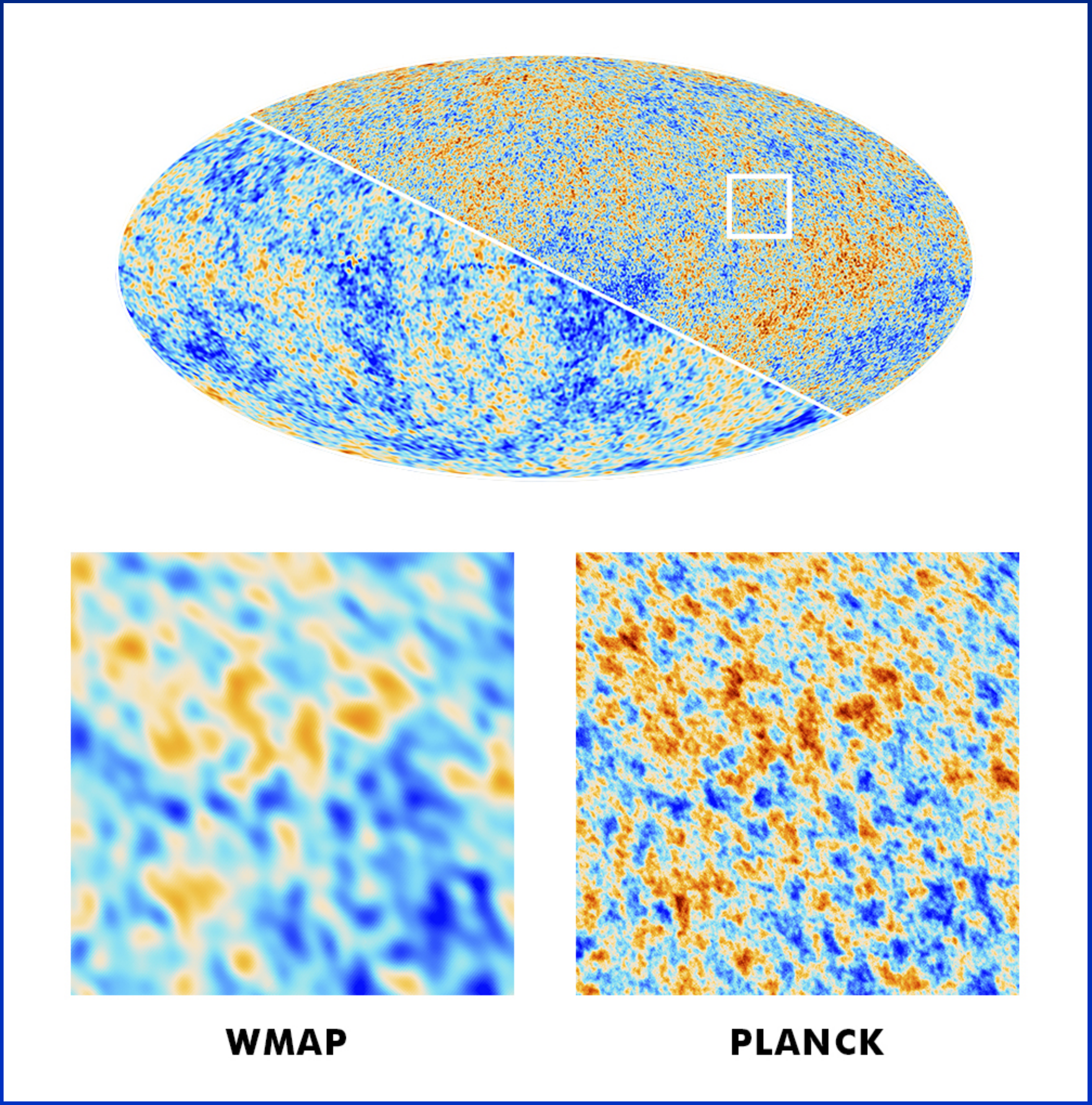
... and all is much better than previously (I)



But also:

- Somehow misleading because error bars are more important than resolution
- Better sensitivity (1 HFI year = 400 WMAP years!)
- Better frequency coverage $\rightarrow$ better foreground removal

In the end, all is much better than previously (I)



Power Spectra

- Just as for the mapmaking, the power spectrum estimate can be done by several methods, CamSpec & Plik
- Conservative masks are used (sky coverage of 31%, 39%, 49%) which take account both Galactic emission and point sources
- Final processed spectrum goes from $\ell = 2$ to $\ell = 2500$, being cosmic variance limited till $\ell < 1500$
- First 2013 release: useful part of the spectrum was $50 < \ell < 1500$, temperature only, i.e. 5 peaks, plus higher ℓ data which did not improve the fit, but improved constraints on alternative models (7 peaks)
- See Planck 2013 XV, arXiv:1303.5075
- This year release: polarization data included, i.e., $\sim$ 20 peaks in the spectra
- See Planck 2015 XIII, arXiv:1502.01589

Cosmological parameters estimation

- We know we need at least 6 parameters to describe the Universe
  1. A two parameter description of initial power spectrum $\rightarrow A_{\rm S}$, $n_{\rm S}$
  2. Baryon energy density $\rho_{\rm bar}$, dark matter density $\rho_{\rm DM}$, vacuum energy contribution to the critical density Ω_Λ, exchanged with angular size of sound horizon (DE independent quantity)
  3. Reionization epoch, which leads to a partial rescattering of CMB photons $\rightarrow \tau$, NOT independent from the others, but too complicated to compute from first principles
     $e^{-\tau}$ represents the fraction of CMB which were not rescattered since $z \sim 1100$
- Hubble constant H is then deduced through

$$H \propto \sqrt{\frac{\rho_{\rm b} + \rho_{\rm DM}}{1 - \Omega_\Lambda}}$$

- Then, extra parameters are hoped to be found large enough to leave an imprint on the data. Some leading candidates are
  1. Departure from power law spectrum $\rightarrow$ running of the spectral index, i.e. $\alpha \propto {\rm d}n_S/{\rm d}\ln k$
  2. More complicated initial conditions (non Gaussian features, etc)
  3. Primordial gravitational waves
  4. Non trivial neutrino abundance / Measurable neutrino masses
  5. Departure of dark energy from vacuum energy
  6. Variation of fine structure constant
- This parametrization is anything but new: it is the concordance model that was “born” in 1995

The birth of the concordance model (1995)

H_0 and Odds on Cosmology

Andrew Jaffe
Canadian Institute for Theoertical Astrophysics,
60 St. George St., Toronto, Ontario M5S 1A1, Canada

ABSTRACT

Recent observations by the Hubble Space Telescope of Cepheids in the Virgo cluster imply a Hubble Constant $H_0 = 80 \pm 17$ km/sec/Mpc. We attempt to clarify some issues of interpretation of these results for determining the global cosmological parameters Ω and Λ. Using the formalism of Bayesian model comparison, the data suggest a universe with a nonzero cosmological constant $\Lambda > 0$, but vanishing curvature: $\Omega + \Lambda = 1$.

COSMIC CONCORDANCE

J. P. Ostriker

Paul J. Steinhardt

in which the matter density is substantially less than critical density. Particularly noteworthy are those which are consistent with inflation. For these models, microwave background anisotropy, large-scale structure measurements, direct measurements of the Hubble constant, H_0*, and the closure parameter,* $\Omega_{\rm Matter}$*, ages of stars and a host of more minor facts are all consistent with a spatially flat model having significant cosmological constant* $\Omega_\Lambda = 0.65 \pm 0.1$, $\Omega_{\rm Matter} = 1 - \Omega_\Lambda$ *(in the form of "cold dark matter") and a small tilt:* $0.8 < n < 1.2$.

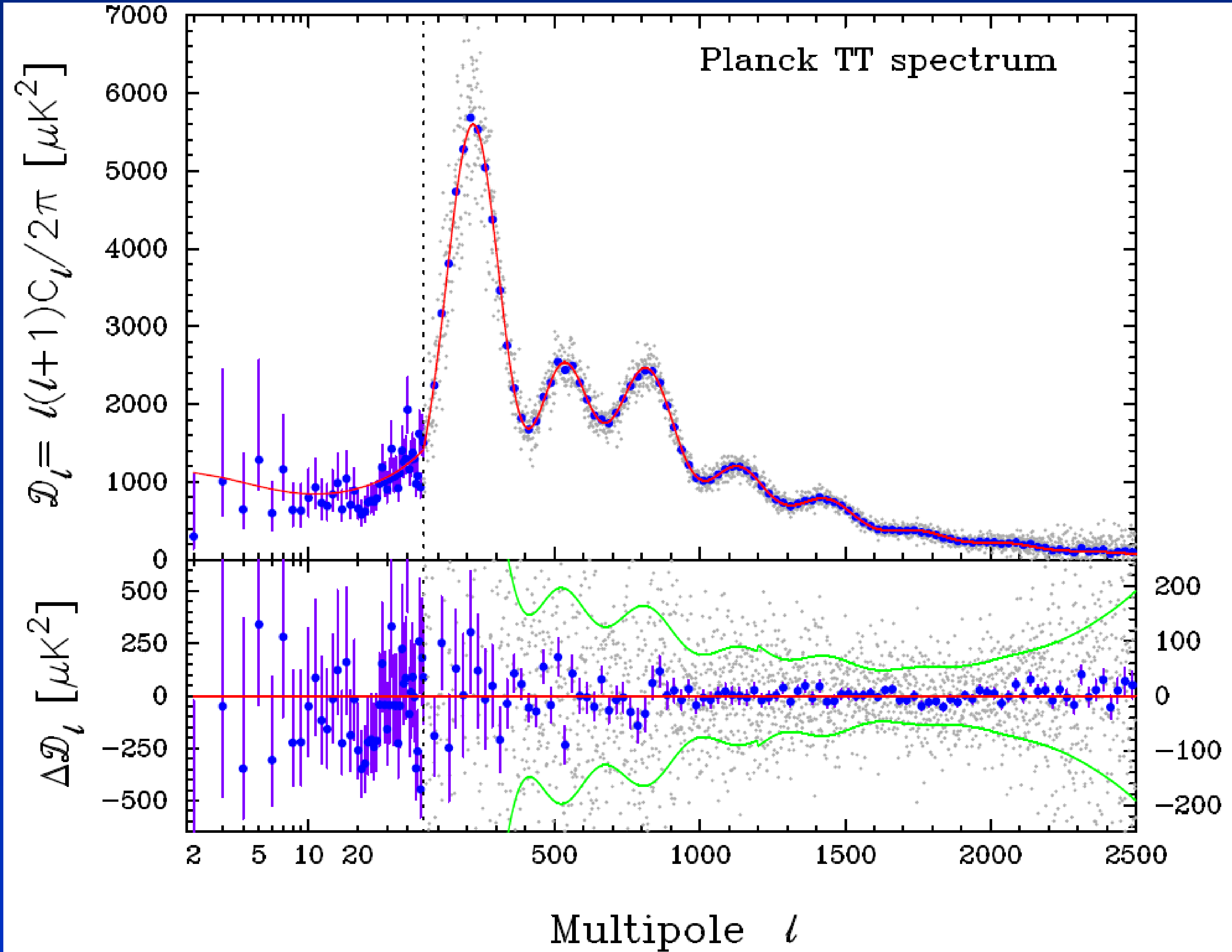
Combining datasets

- In addition to Planck CMB data, we may add other datasets
  1. Other CMB datasets, either WMAP for comparison (still important), or ground-based experiments at small angular scales (see below)
  2. Information from galaxy catalogs such as complete spectrum, most notably baryon acoustic oscillations (BAO), and amplitude in the weakly non linear regime (σ_8, i.e. variance of fluctuations at $8h^{-1}\,\mathrm{Mpc}$).
  3. Data about H_0
  4. Cross correlation between galaxy catalogs and CMB (lensing and ISW)

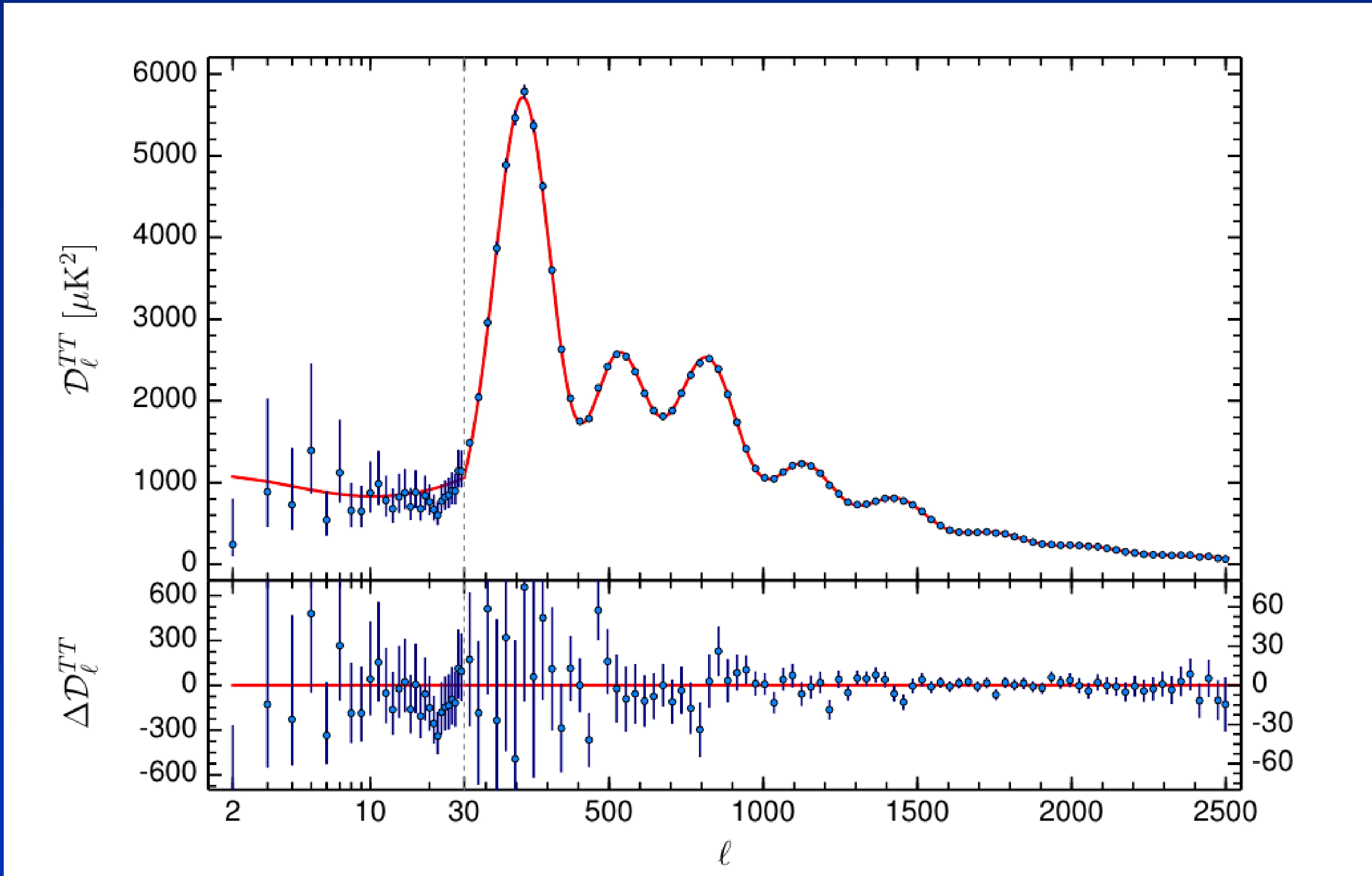
What's new since spring 2013?

- Planck Intermediate paper on "Dust polarisation angular power spectrum at high latitude from HFI". It is a foreground paper (353 GHz data), but which says important things about expected dust contamination at 100 GHz as seen by BICEP2.
- BICEP2-Planck joint paper!
- Comparison with WMAP (+ LFI/HFI comparison) strongly suggested some unaccounted for systematics
- Some were found:
  - Very long, low amplitude time constants that affect dipole direction precision measurement
  - HFI calibration wrt dipole inaccurate at 0.1% level
  - Corrected beams significantly reduce Planck/WMAP tension on height of first peak
  - Better glitch removal
- Polarization

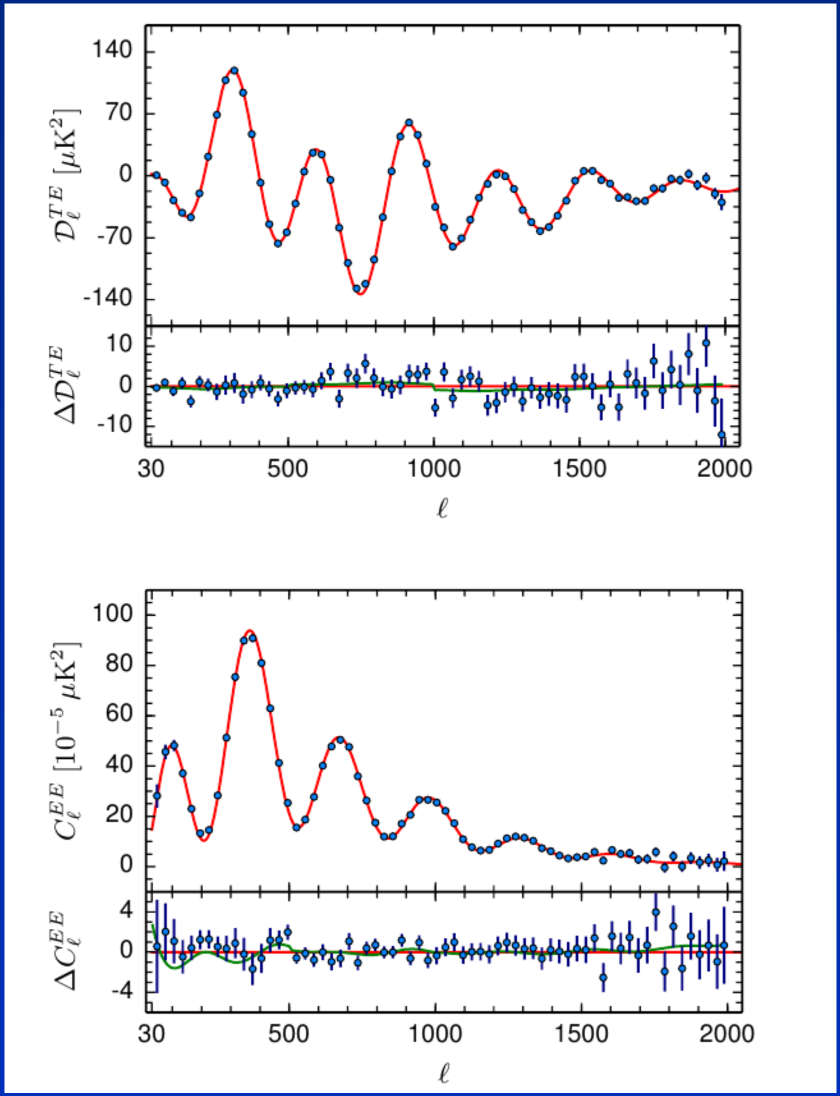
Results – arXiv:1303.5076



Results – arXiv:1502.01589



Results now include polarization!

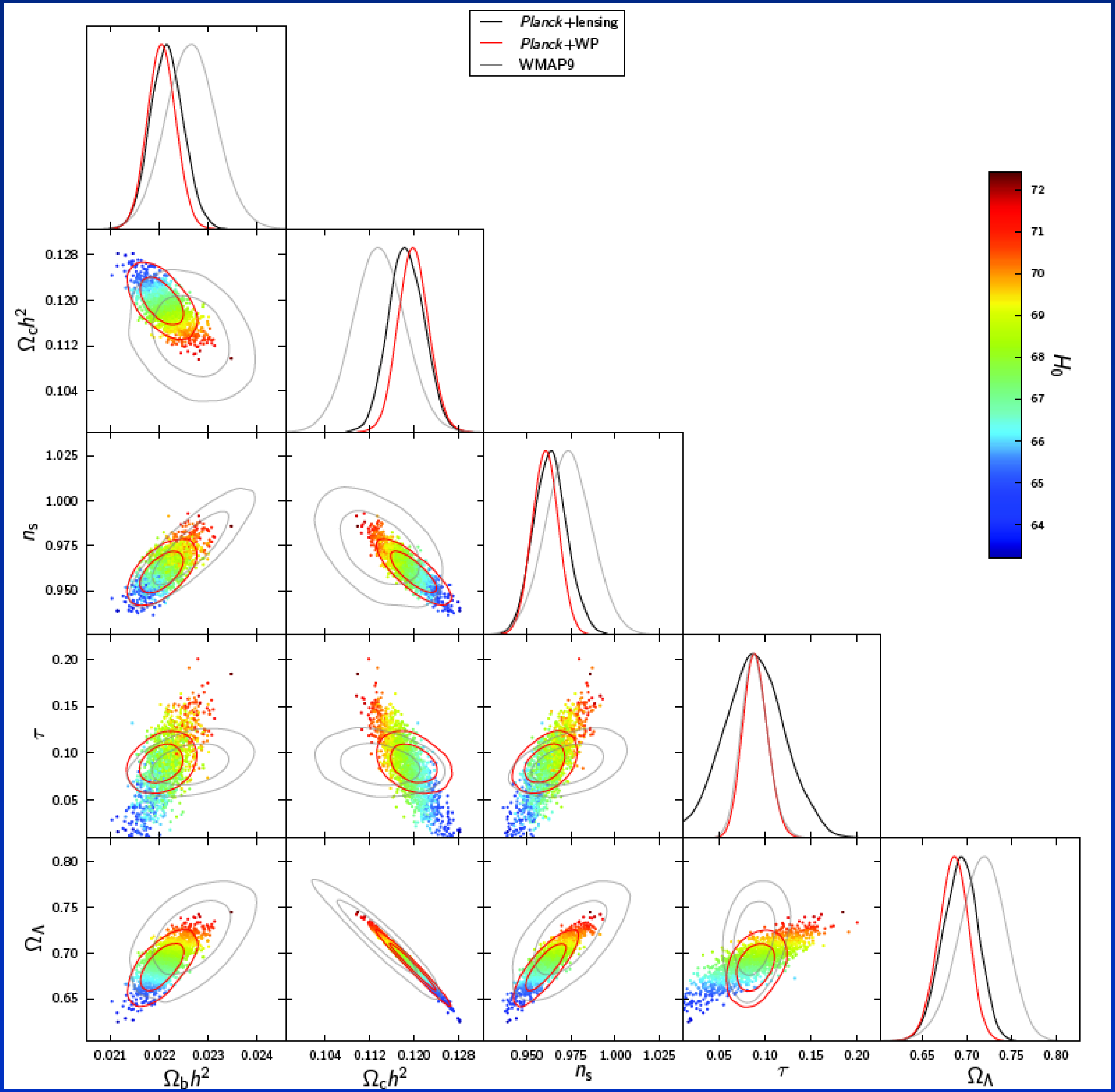


Large angular scale polarization come only from the less sensitive LFI – some improvement are expected when low ℓ polarized HFI data will be included

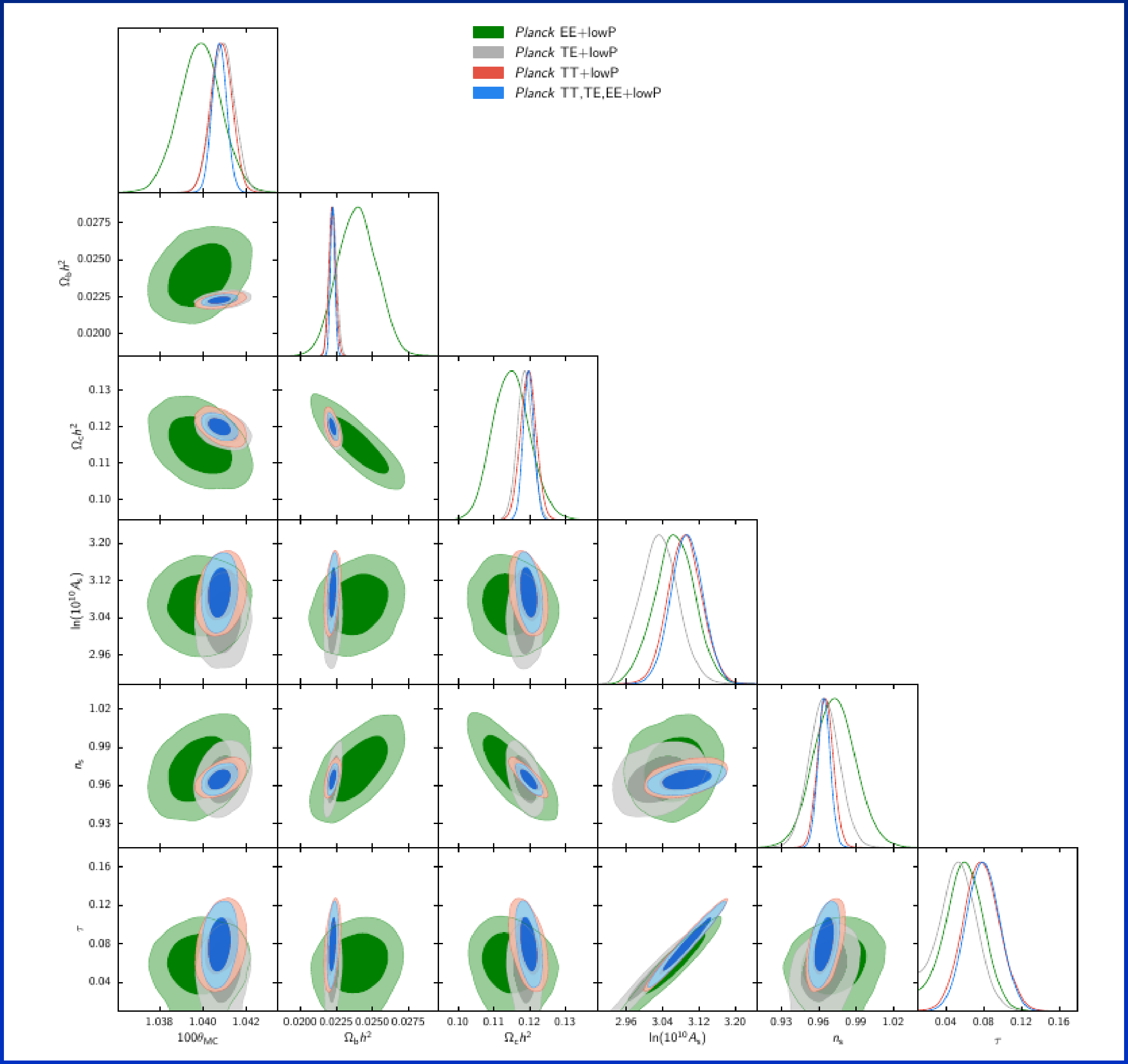
One thing to remember about this talk...

Physics works!

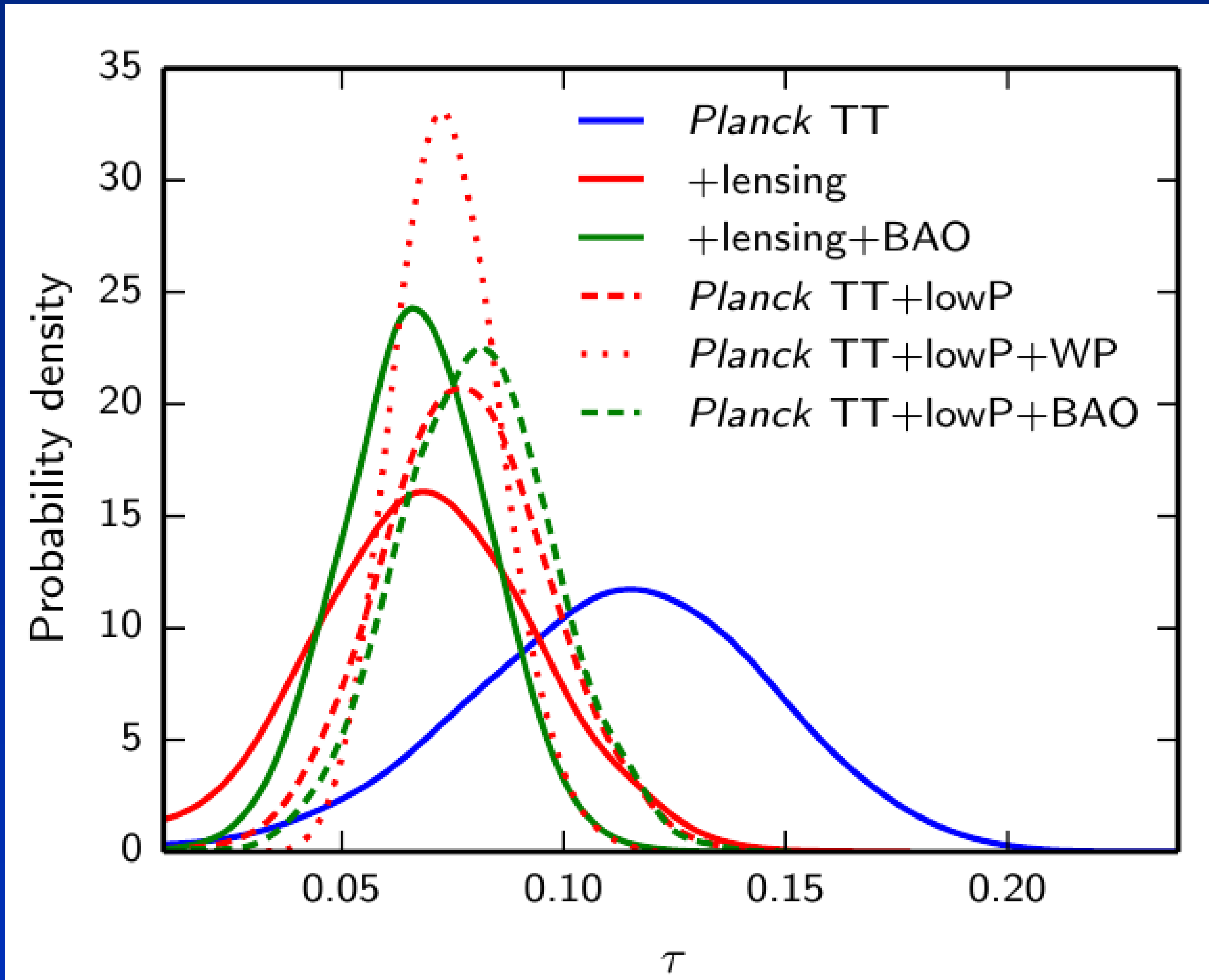
Parameter estimations – 2013



Parameter estimations – 2015

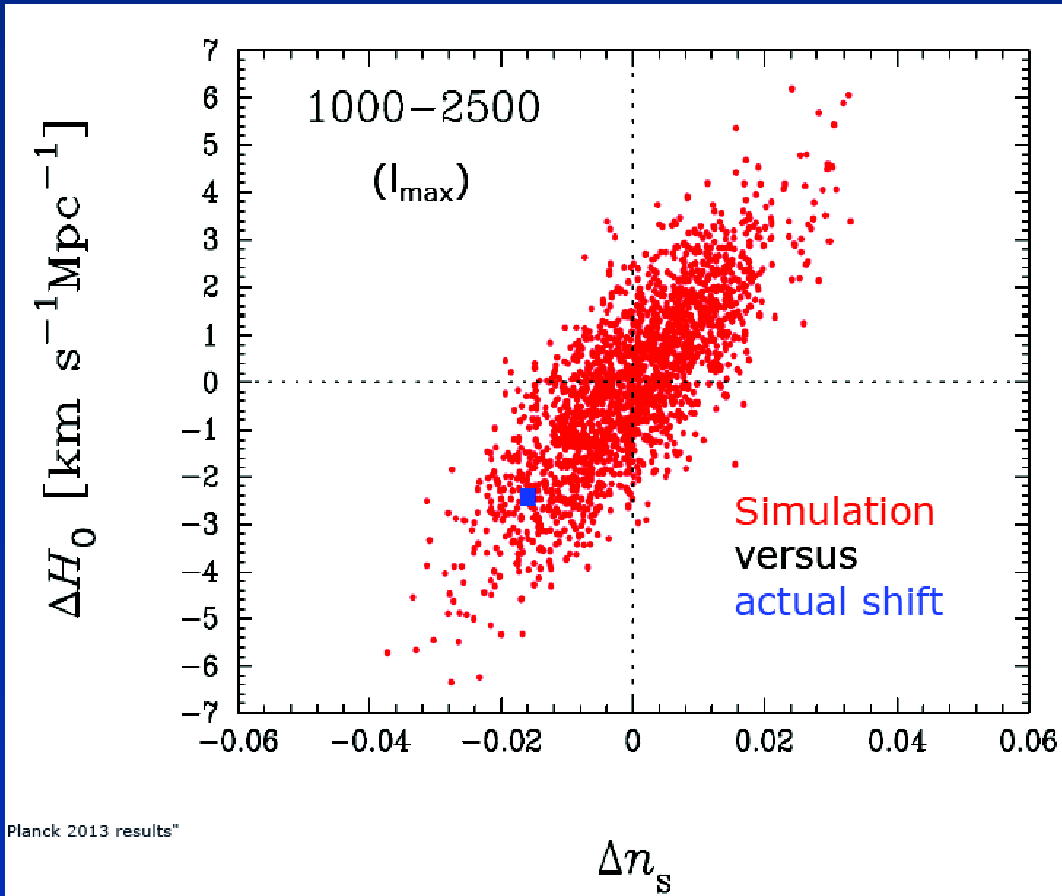


Reionization remains the main source of uncertainty



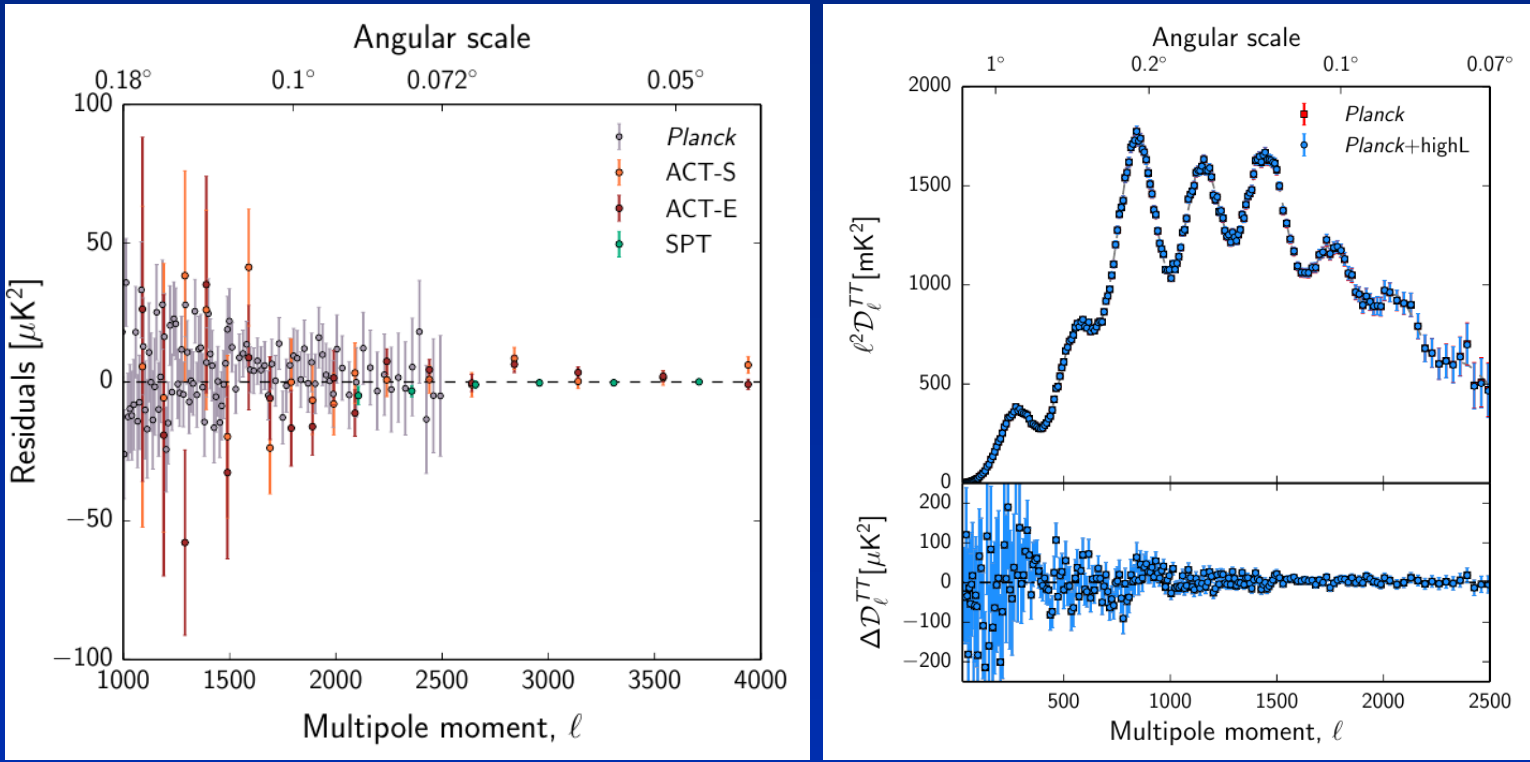
- This was the reason the 2013 analysis almost always included low ℓ WMAP polarization data
- Unfinished processing of HFI low ℓ polarized data prevents from having better control on this parameter.

2013: How large Planck vs. WMAP differences have to be expected?



- ♣ Planck restricted to WMAP ℓ range should not vary wrt WMAP
- ♣ But adding higher ℓ allows for some shift

2015: Planck is compatible with, and nolonger needs, other CMB data

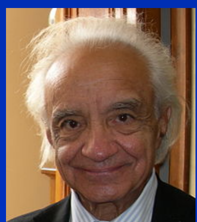


Parameter estimations

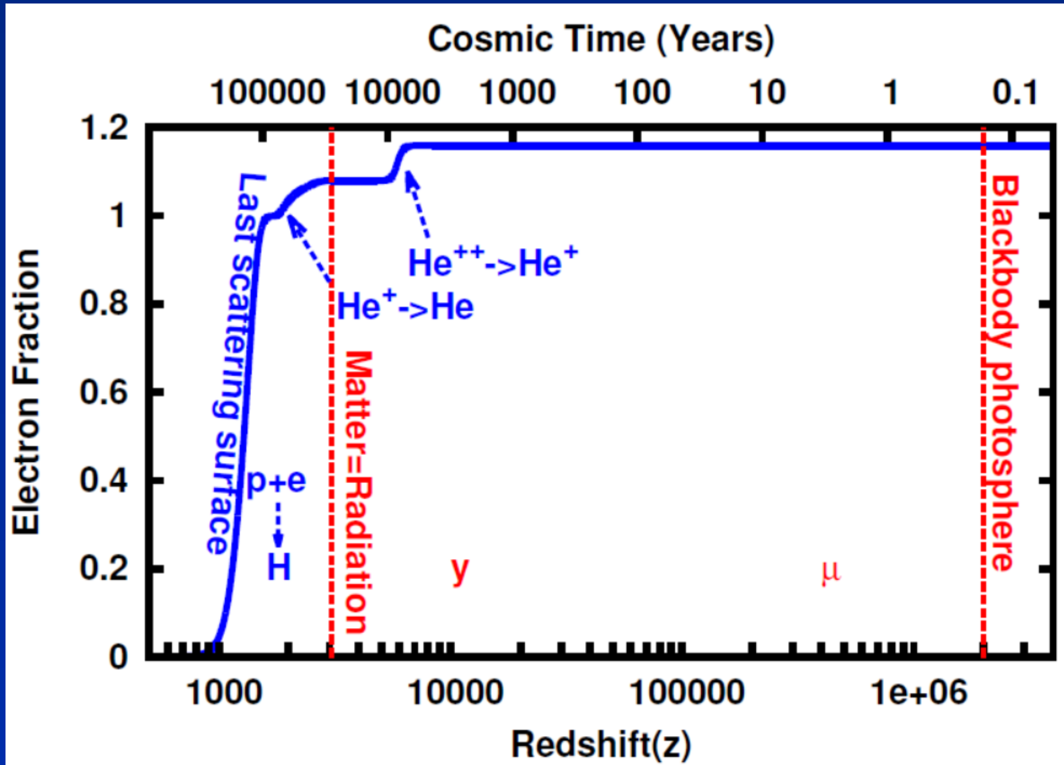
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

- First six quoted parameters are now known with a precision (1σ) of 1%, 2%, 0.06%, 15%, 0.9%, 0.8% (2013) $\rightarrow$ 0.7%, 1.25%, 0.03%, 21%, 1.1%, 0.5% (2015)
- Other, derived parameters may be known more or less precisely depending on how they align with Fisher matrix eigenvectors (here : 0.6%, 0.35% (2013) $\rightarrow$ 0.3%, 0.15% (2015)).

$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021

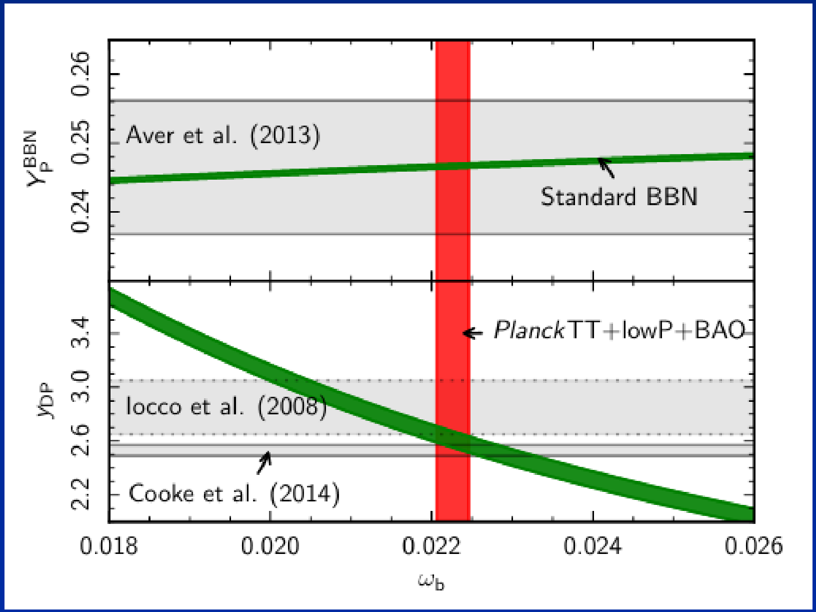
- (amounts to claim that 's birthdate is 15 October 1929 $\pm$ 7 weeks (1σ)

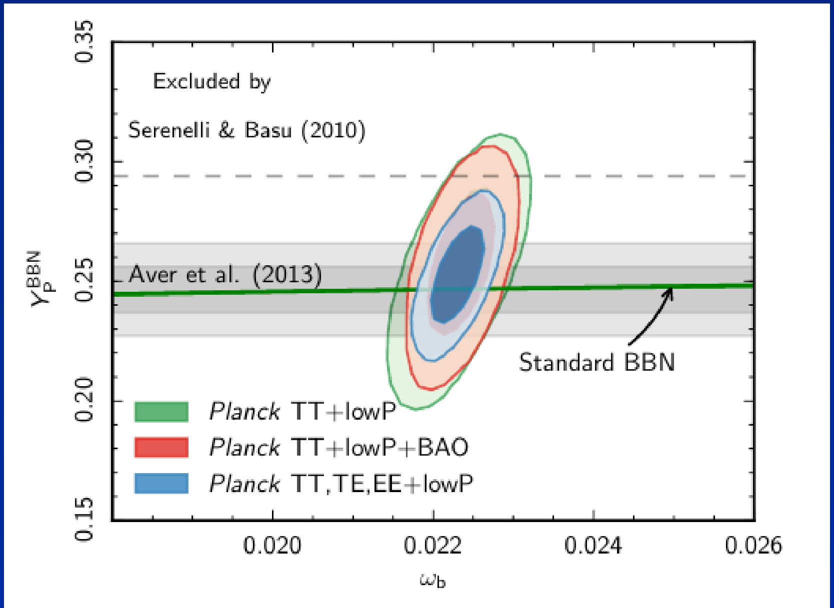
Consistency checks – Deuterium and Helium fraction



- Long ago, baryon to photon ratio (η) was estimated through nucleosynthesis as helium fraction Y_{He} was a function of η.
- Since we estimate baryon density here, we can check whether it is consistent with helium fraction determination from high redshift quasar spectra.
- But there is more with CMB: baryon/photon coupling made through Compton scattering, which depends on electron fraction…
- … Which varies before last scattering because of helium recombination which occured earlier.
- CMB spectrum therefore marginally depends on helium fraction, independently of baryon-to-photon ratio

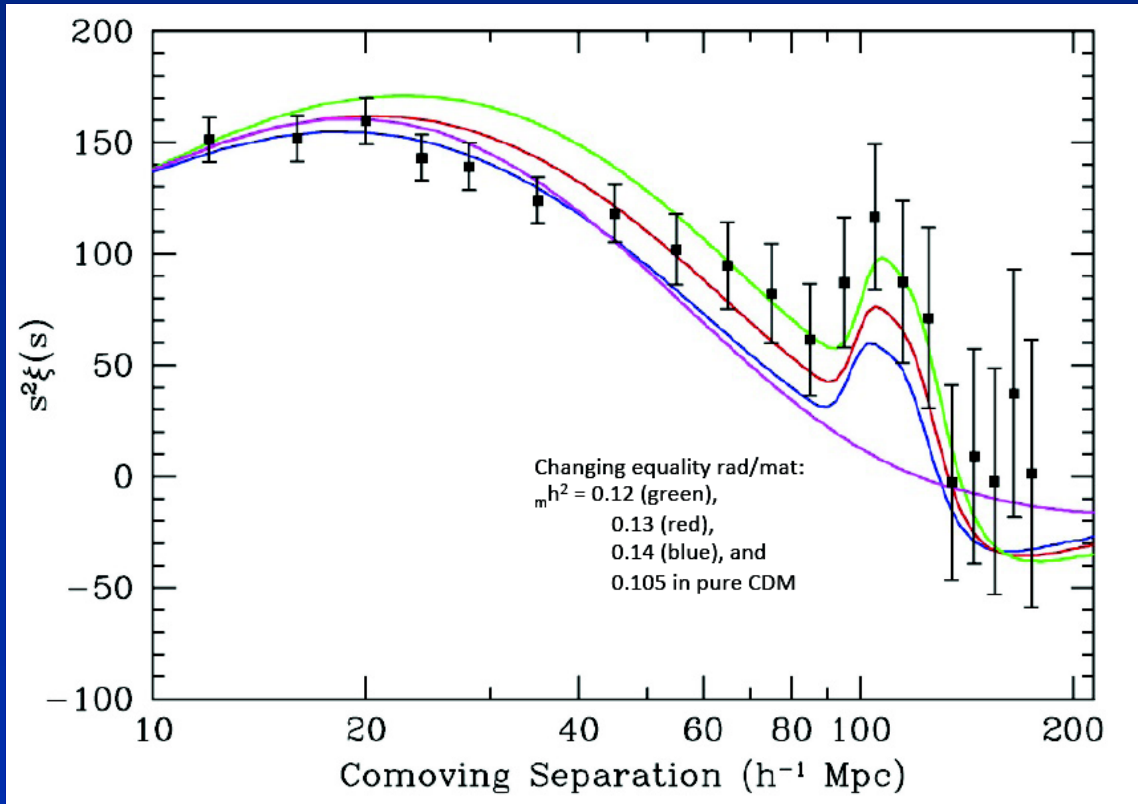
Consistency checks – Deuterium and Helium fraction





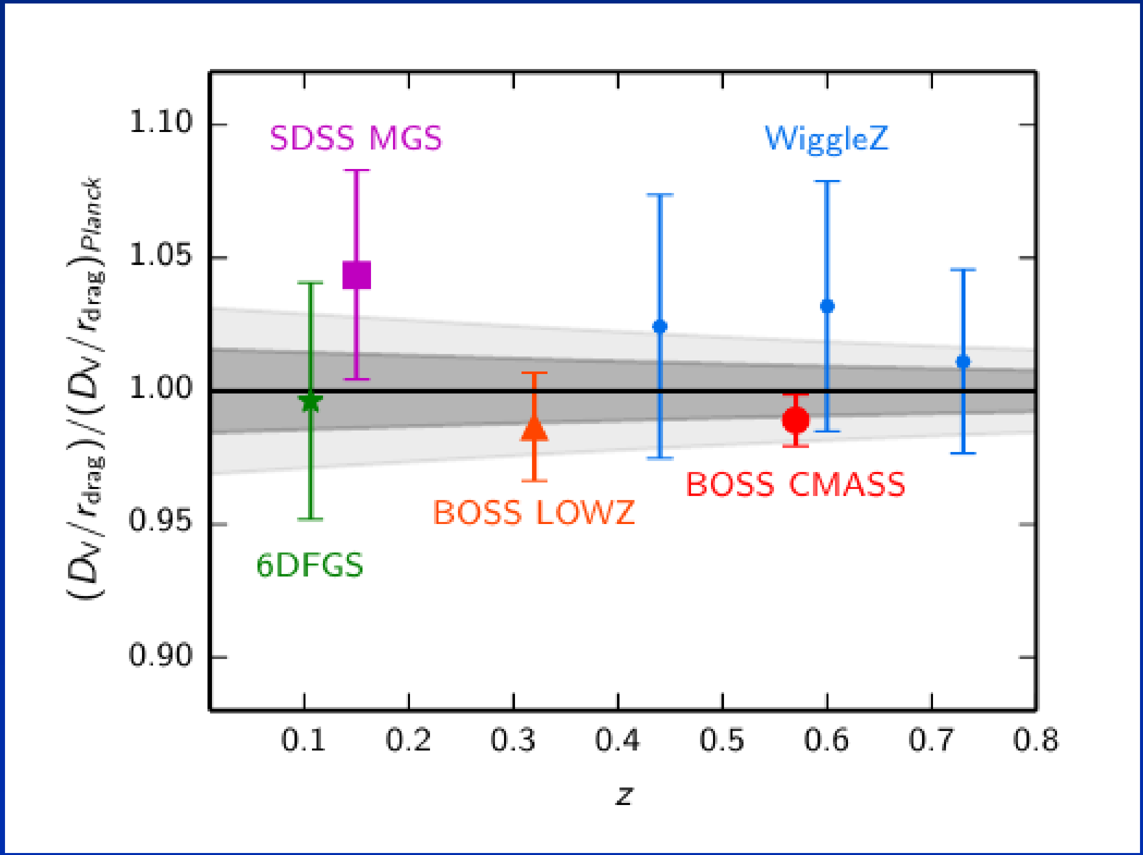
- It is quite astonishing to think that nuclear physics at ~ 1 Mev agrees so well with hydrodynamics in an expanding Universe at 0.3 eV
- Of course, all this relies on no non standard neutrino properties... (see later)

Consistency check – BAO



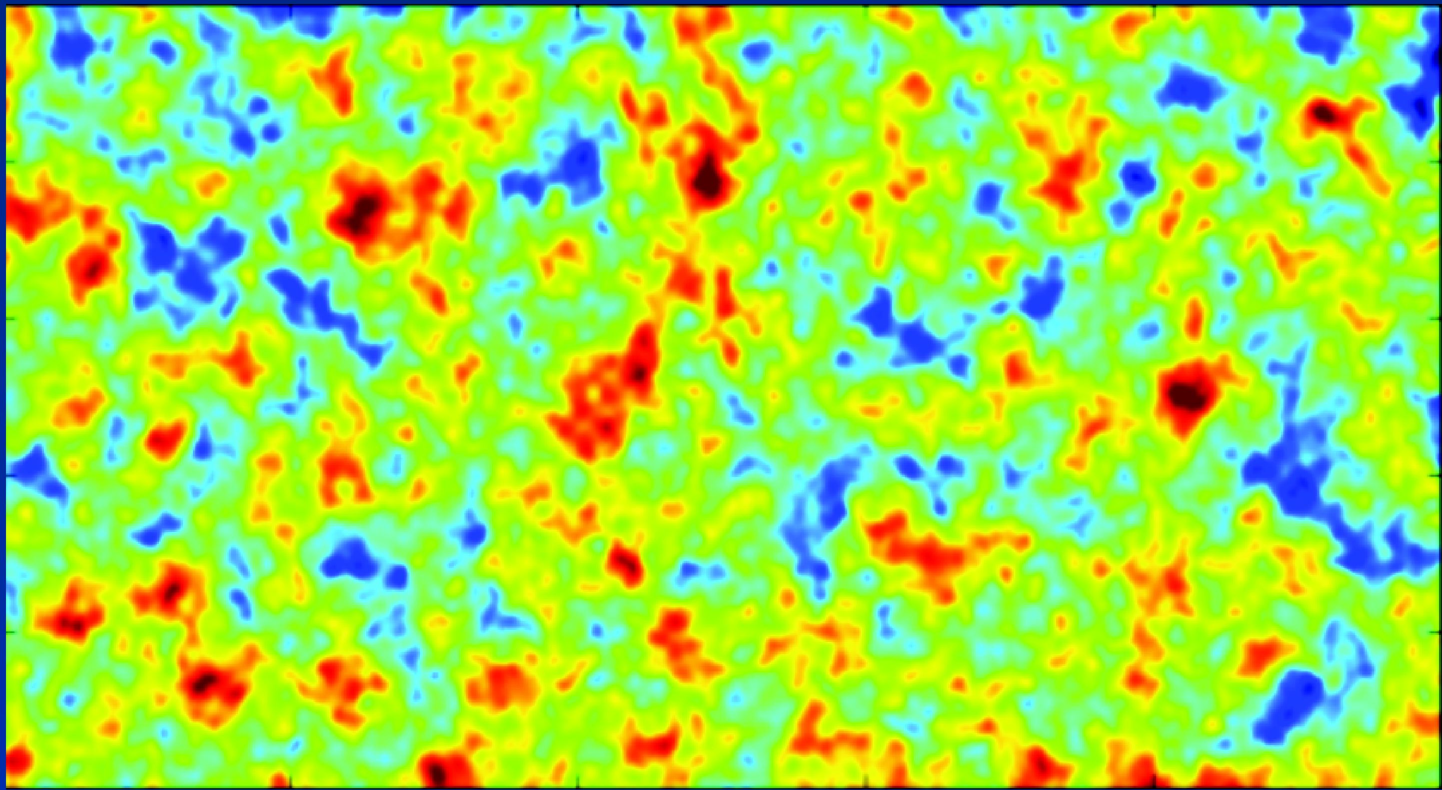
- ♣ Although dominant, dark matter gets the imprint of the baryon photon sound waves that existed prior to recombination
- ♣ This leaves some characteristic scale in the matter two point correlation function (in real space)

Consistency check – BAO



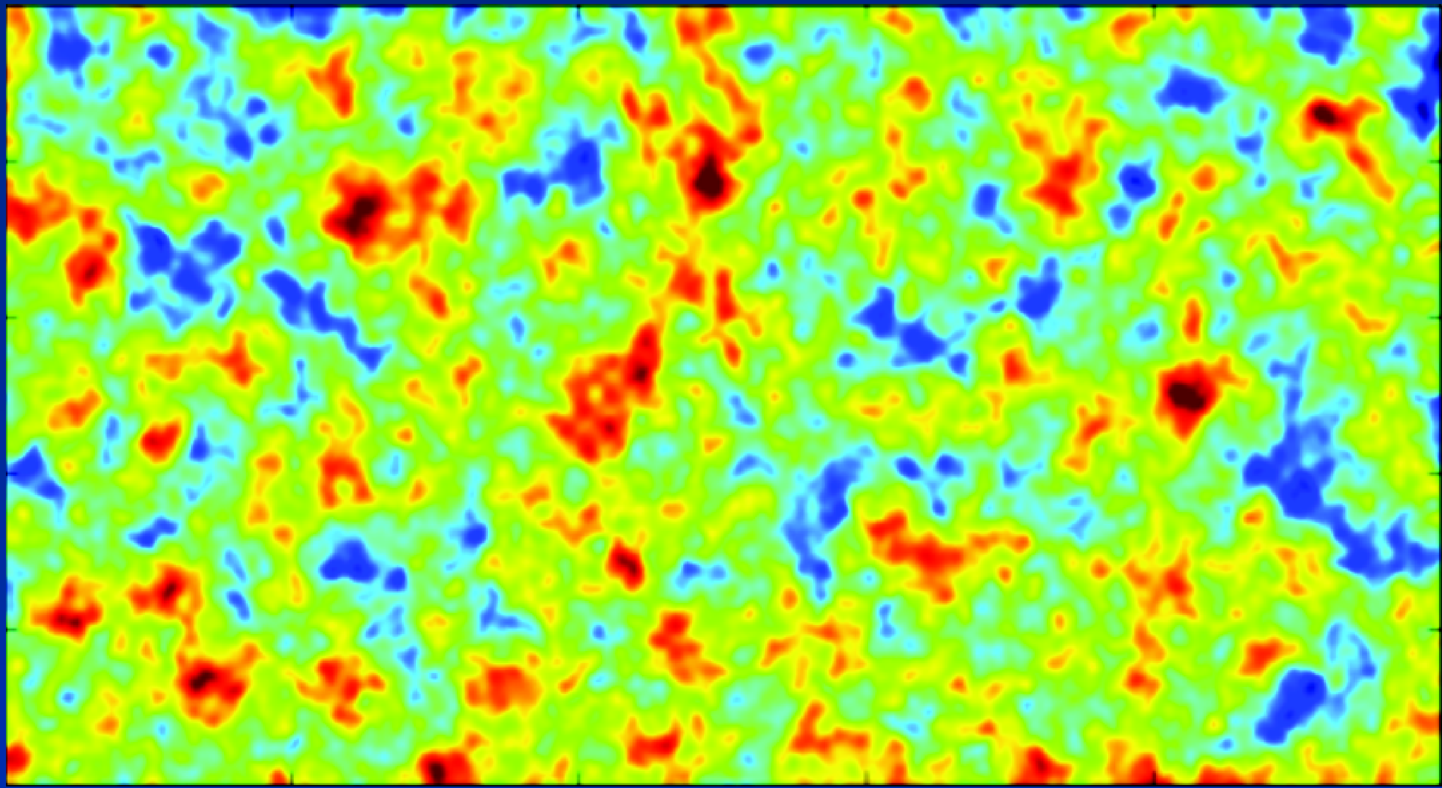
- Galaxy catalogs at various redshift thereore see this redshift propagated characteristic under some angular scale
- Planck predicts what galaxy catalogs should see, and in return (if compatible), they can contribute to extra constraints in parameter estimation

Consistency check – Lensing



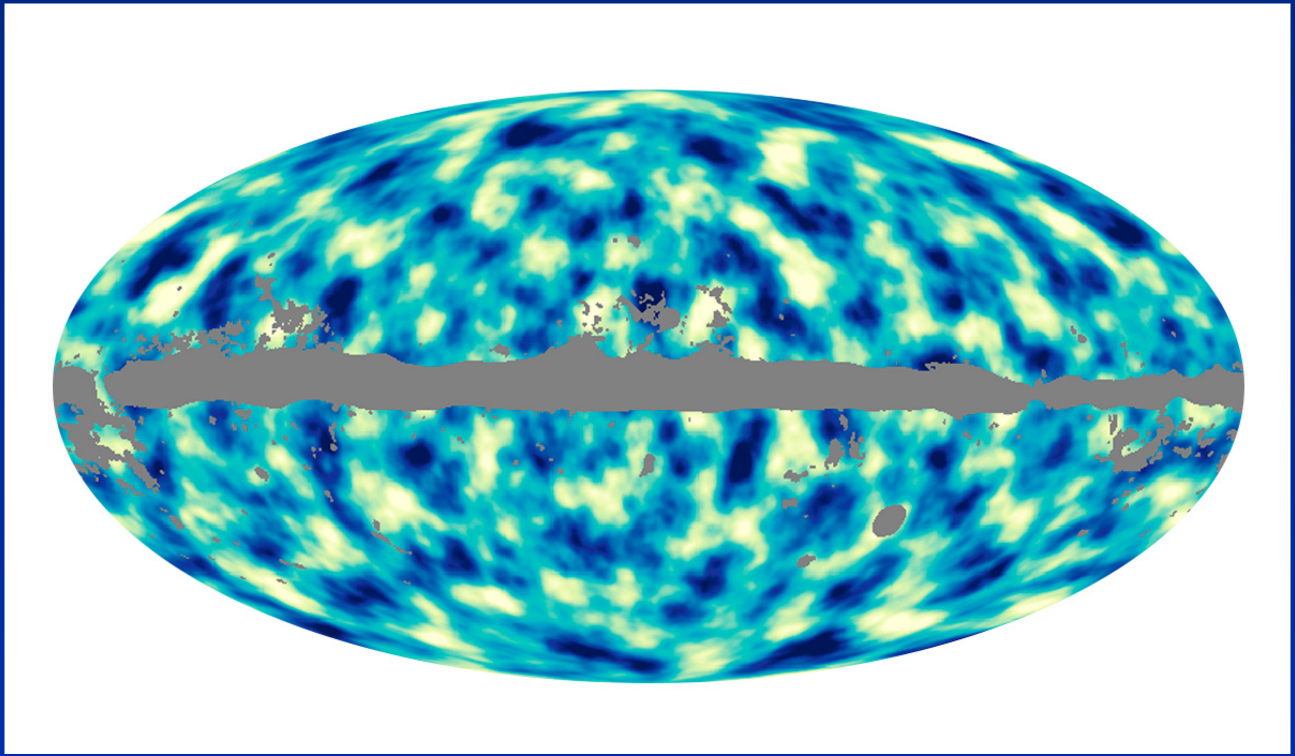
♣ We naively expect to see a pure CMB map...

Consistency check – Lensing



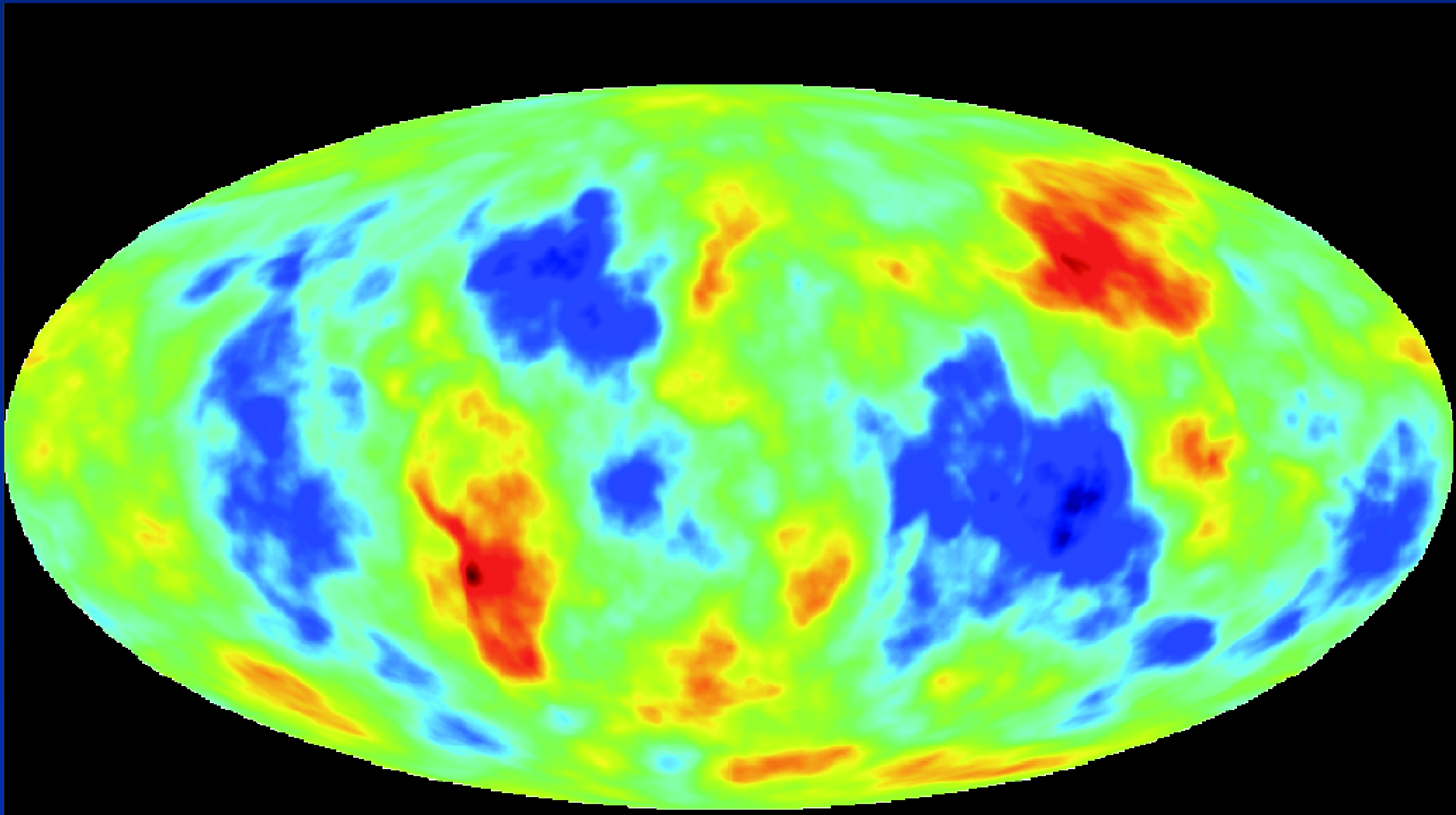
♣ ... but in fact, we see a distorted version of it because of lensing

Consistency check – Lensing



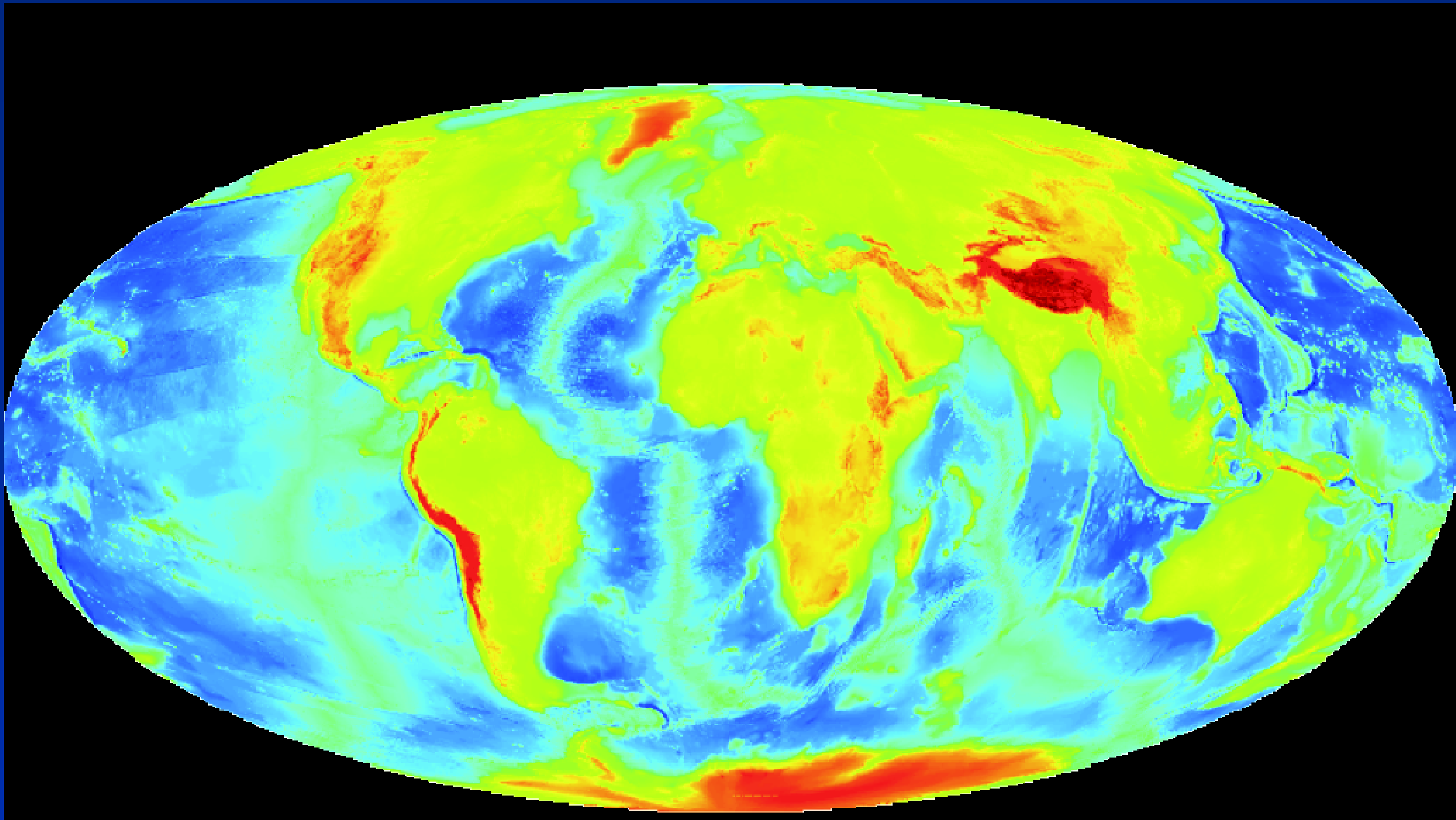
- A CMB map is distorted by the gravitational potential fluctuation along each line of sight
- $\rightarrow$ distortion of the map, but not blurring
- An initially Gaussian map (because fluctuations are Gaussian) will no longer be Gaussian
- This makes possible the extraction of the distortion field through its non Gaussian signature (four-point correlation function)
- One obtains a noisy map of the projected gravitational potential ($S/N < 1$ for each individual modes)... but an easy 26σ (2013) $\rightarrow$ 40σ (2015) detection of lensing!

How faithful is this reconstruction?



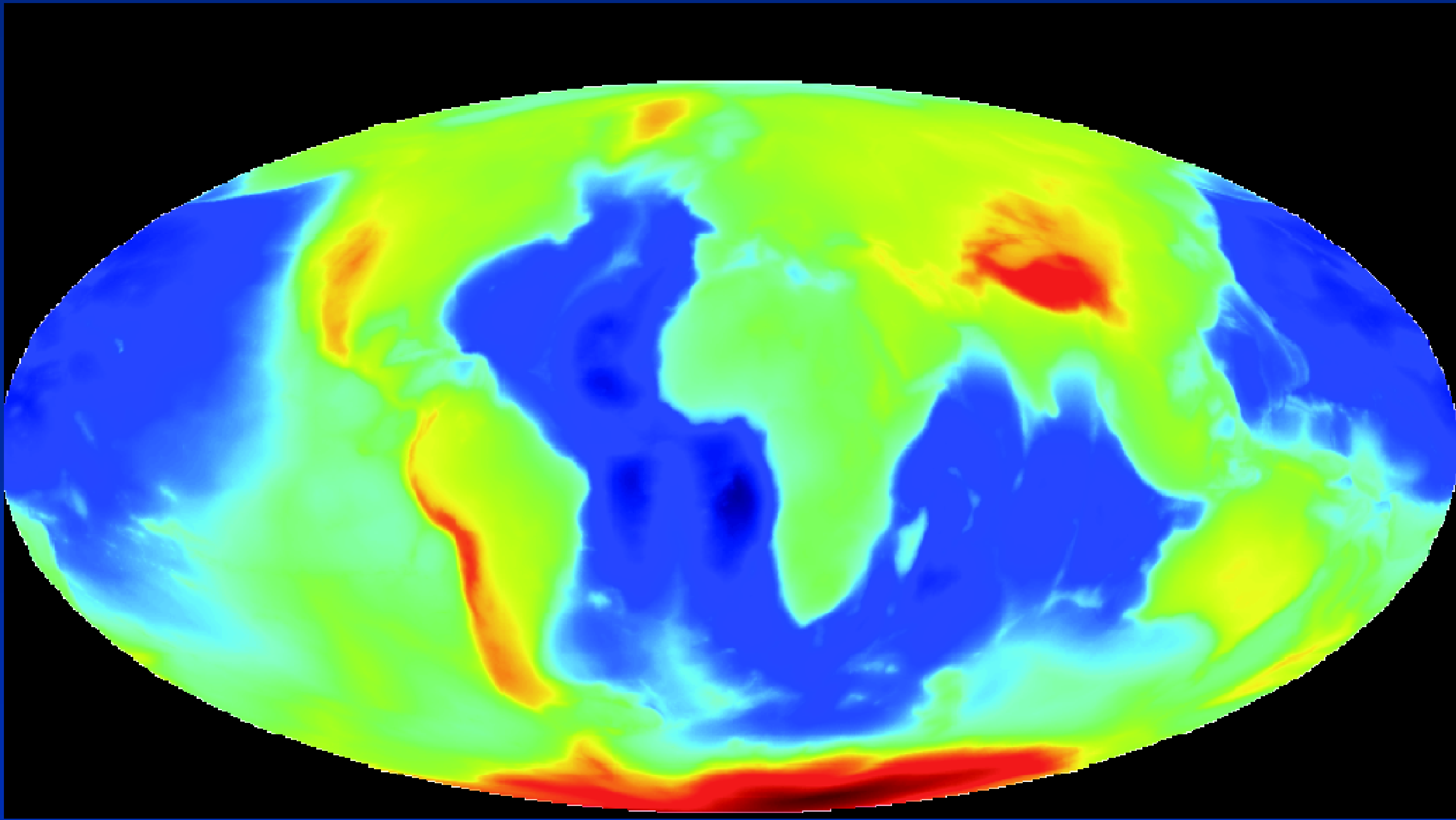
Do you recognize this?

How faithful is this reconstruction?



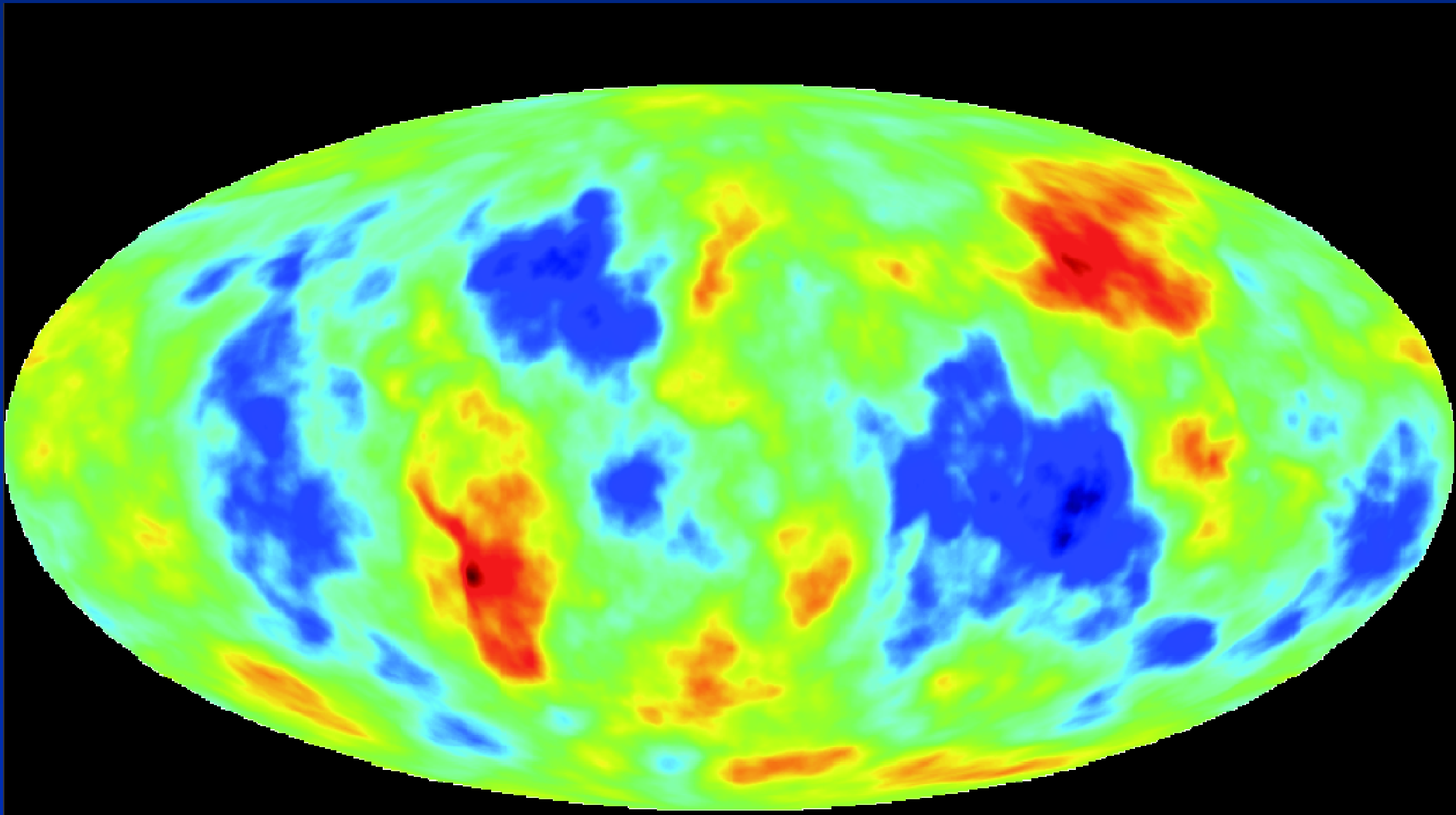
(True map)

How faithful is this reconstruction?



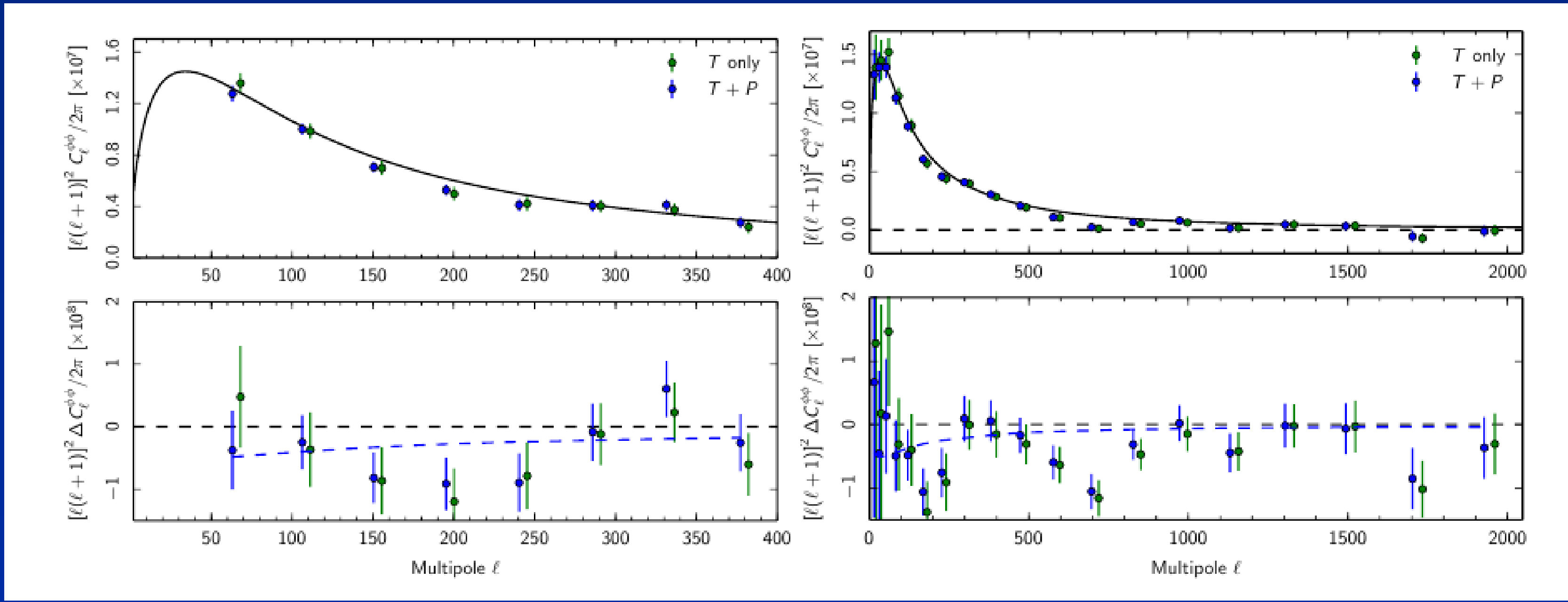
(Seen at Planck resolution)

How faithful is this reconstruction?



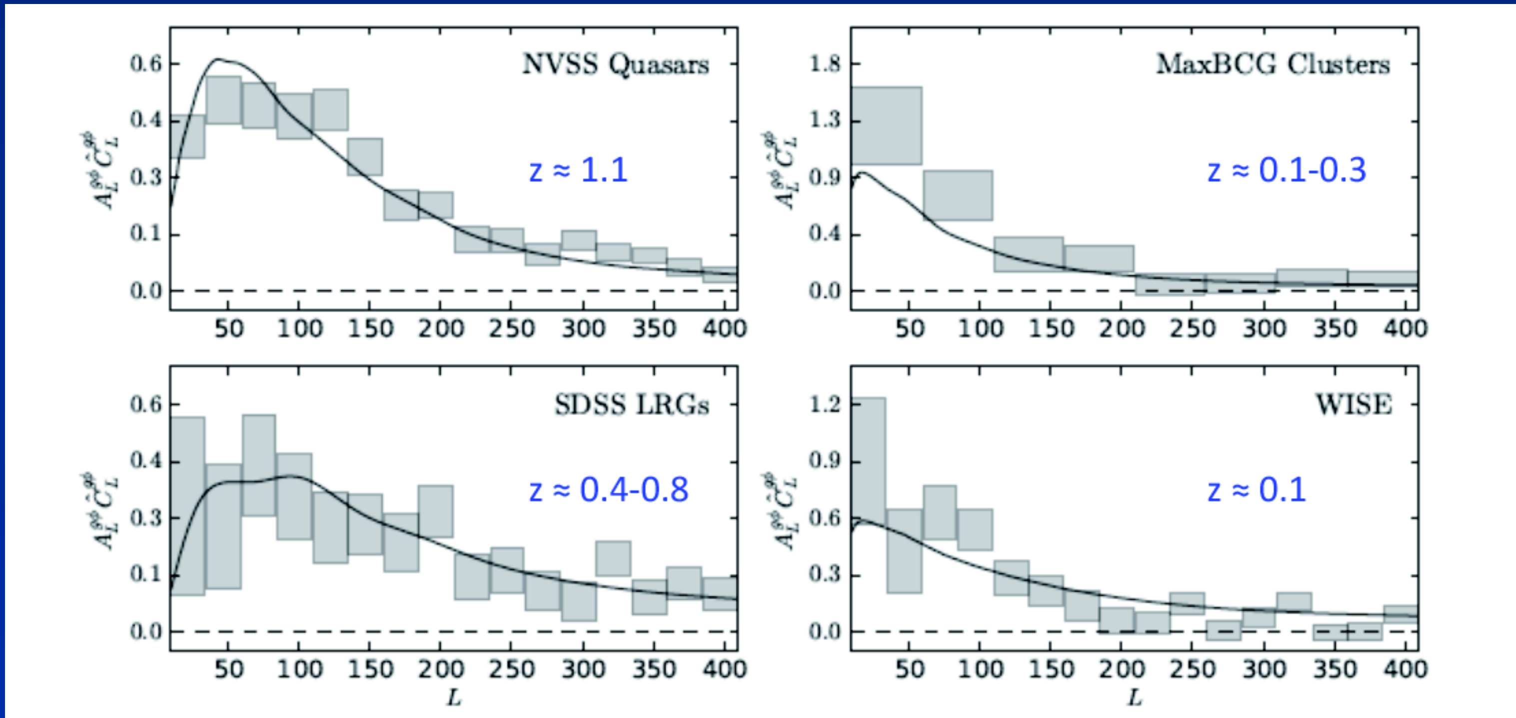
(including reconstruction noise)

But we don't care!



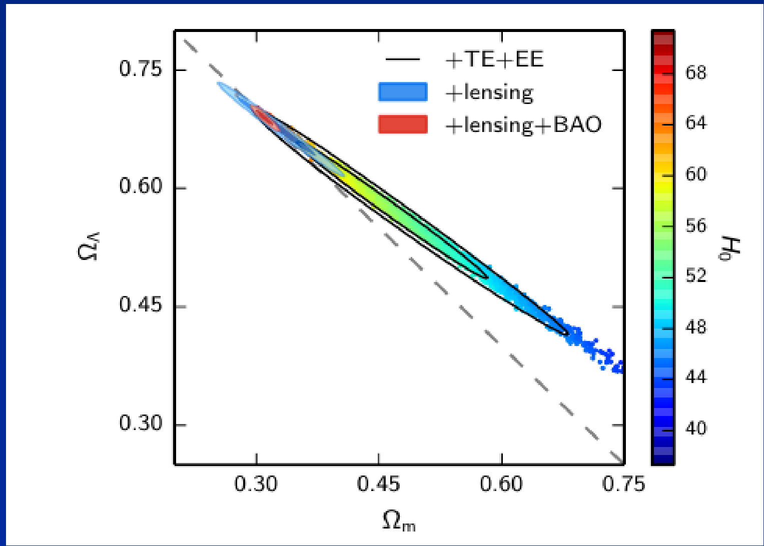
- But the lensing potential power spectrum is less noisy, especially if we bin the data and accurately combine the reconstructed maps at different frequencies
- And what we fonud independently of the fitted cosmological model agrees with it.
- More on lensing soon...

... and we know that we are right



- Previous success with WMAP/NVSS (3σ), SPT/BCS-WISE-Spitzer (4-5σ), ACT/SDSS (3.8σ)...
- But here: NVSS $= 20\sigma$, SDSS $= 10\sigma$, MaxBCG $= 7\sigma$, WISE $= 7\sigma$!
- See Planck 2013 XVII, arXiv:1303.5077

Consistency check – Curvature

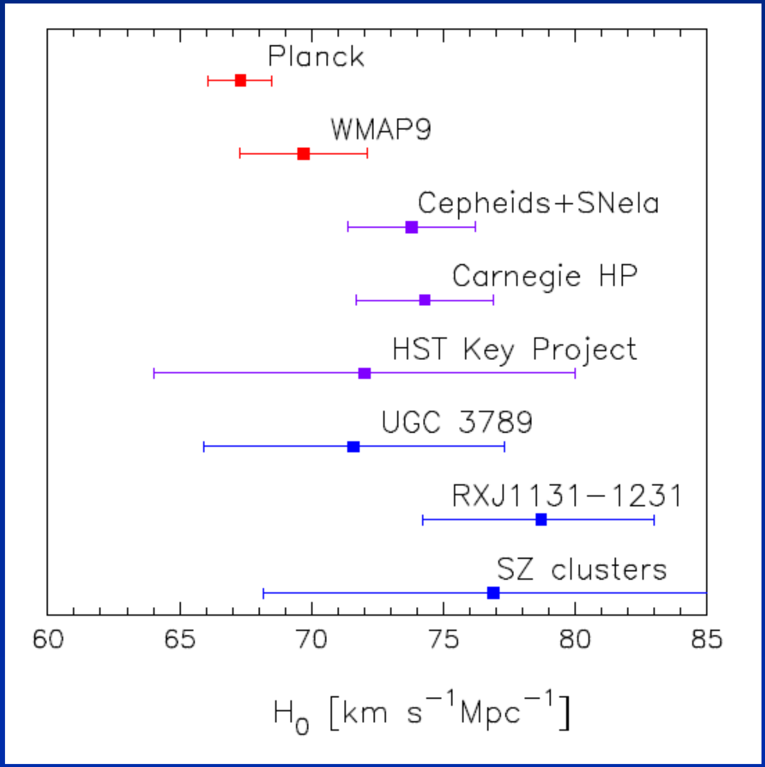


- Friedmann equations

$$3\left(\frac{H^2}{c^2}+\frac{K}{a^2}\right)=\frac{8\pi G}{c^4}\sum\rho$$

- Inflation as well as possible alternative associate large scale homogeneity and isotropy to flatness of space
- Deriving cosmological constraint assumes this flatness: we check consistency of flatness assumption rather than prove it.
- Lensing is made at a distance scale that is closer to that of the CMB (few Gpc vs. 45 Gpc), hence explores the angular size vs. redshift relation, which depends on curvature. Same for BAO's:
- $\Omega_K=-0.040^{+0.038}_{-0.041}(2\sigma)\rightarrow\Omega_K=-0.005^{+0.016}_{-0.017}\rightarrow\Omega_K=0.000^{+0.005}_{-0.005}$
- Said otherwise, curvature radius is constrained to be more than four times larger than radius of observable universe

Consistency check / Hint for exotica – H_0



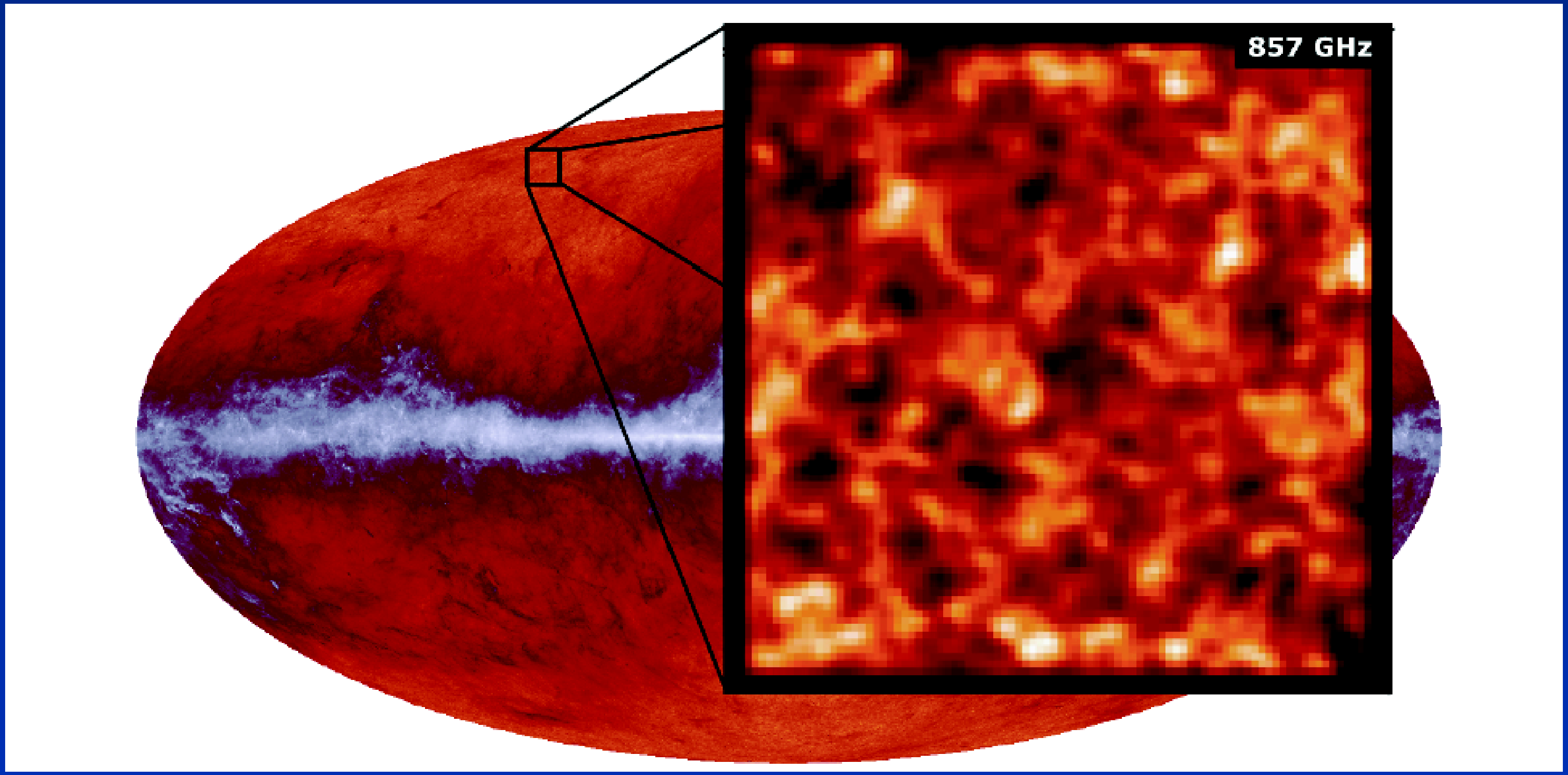
(2013)

- Historically, H_0 was the first cosmological to be ever identified as such and to be estimated.
- Estimations were always controversial: 30's $\rightarrow H_0 > 500\ \mathrm{km/s/Mpc}$, thus making cosmology inconsistent with age of Earth; later, H_0 was either 50 ± 1 or $100 \pm 1\ \mathrm{km/s/Mpc}$ (the Tamman/Sandage controversy).
- In modern CMB era, some tension were advertised because of a $> 2\sigma$ discrepancy wrt Cepheid H_0 estimates, but

Consistency check / Hint for exotica – H_0

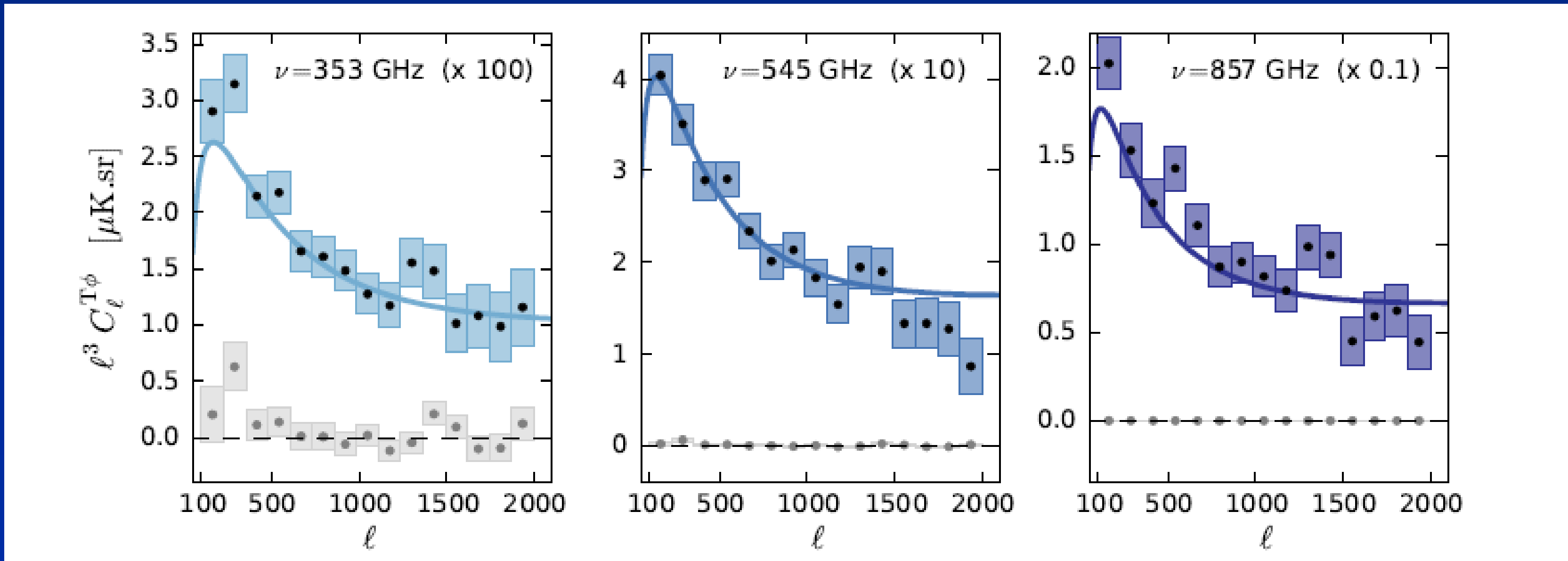
- In modern CMB era, some tension were advertised because of a $> 2\sigma$ discrepancy wrt Cepheid H_0 estimates, but
  1. CMB has low systematics but is model dependent
  2. Cepheids and others are direct measurement with nasty (possibly incompletely unaccounted for) systematics. For example, $H_0 = 73.9 \pm 2.7$ km/s/Mpc was found using LMC + MW Cepheids, hoping that metallicity difference between galaxies would not induce unwanted biases
- Planck alone, and Planck + BAO claim, on the contrary, *assuming concordance model*, $H_0 = 67.3 \pm 1.0$ and $H_0 = 67.6 \pm 0.6$ km/s/Mpc
- It is unclear one has to be concerned about this, but new physics (e.g. neutrinos) might show up that way
- More recently a maser distance to a further away galaxy (NGC 4258) led to reestimate $H_0 = 70.6 \pm 3.3$ km/s/Mpc (Warning: result obtained by a member of Planck coll.)

Consistency check – When noise is nolonger noise



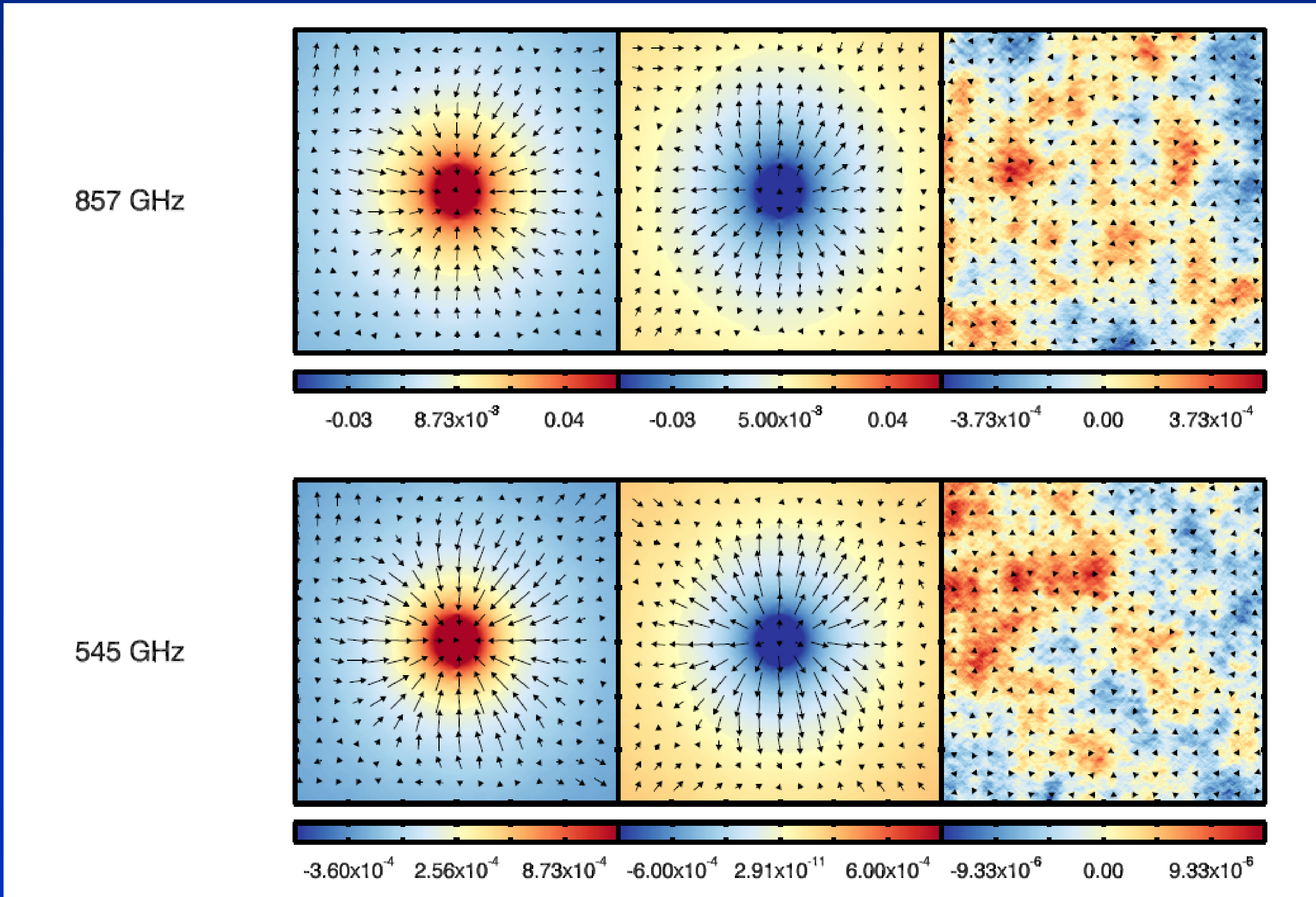
- The furthest foreground we have is the CIB, the Cosmic Infrared Background

Consistency check – When noise is nolonger noise

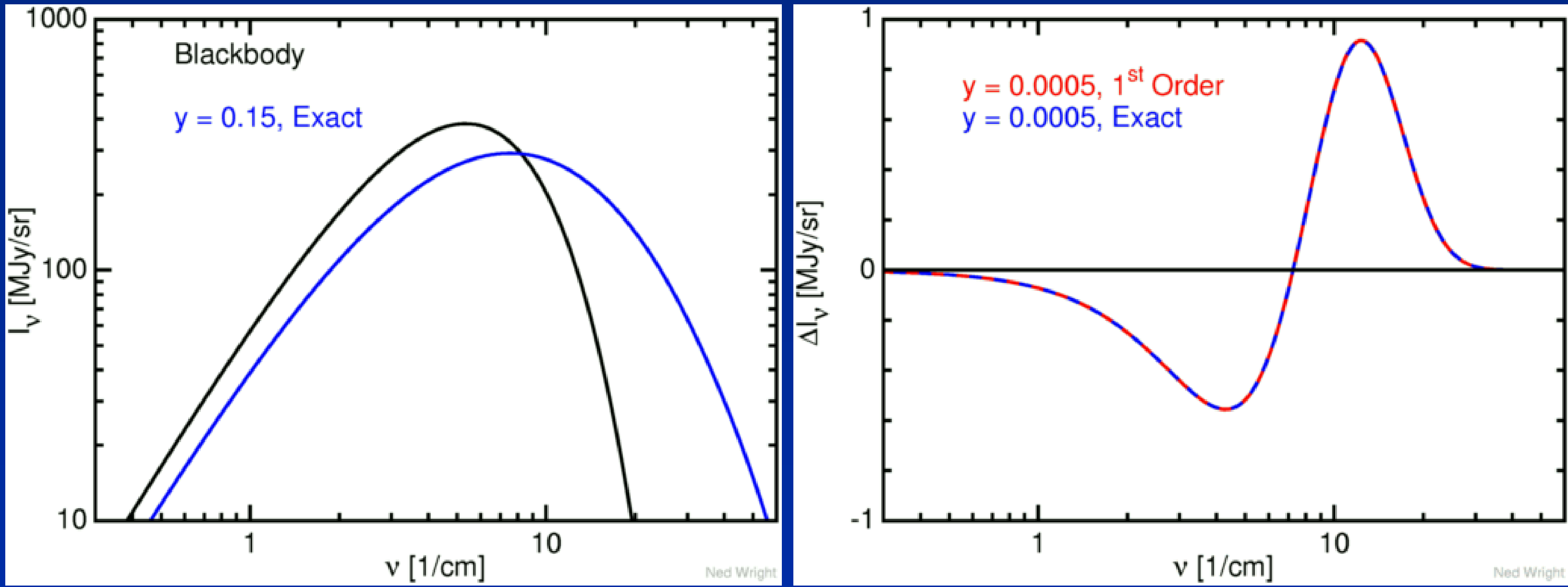


- CIB is a foreground noise...
- ... but CIB detailed structure is an consequence of structure formation scenario, just as CMB is
- Moreover, CIB contribution peaks at $z \sim 2 - 3$, just as lensing peaks at $z \sim 1 - 2$
- Therefore CIB and lensing maps shoud show some correlation
- Whereas CMB and lensing should not (well, almost not, see later)
- See Planck 2013 XVIII, arXiv:1303.5078

Consistency check –
When stacked noise becomes a pure signal



Consistency check – When noise is nolonger noise



- Among foreground contributions, we have Sunyaev-Zeldovitch effect, i.e., spectral distortion induced by hot gas scattering CMB
- No energy transfer, but mometum transfer
- Only happens in the vicinity of galaxy clusters
- Those cluster counts can be compared to observations or theoretical expectations.

Consistency check – Integrated Sachs-Wolfe effect

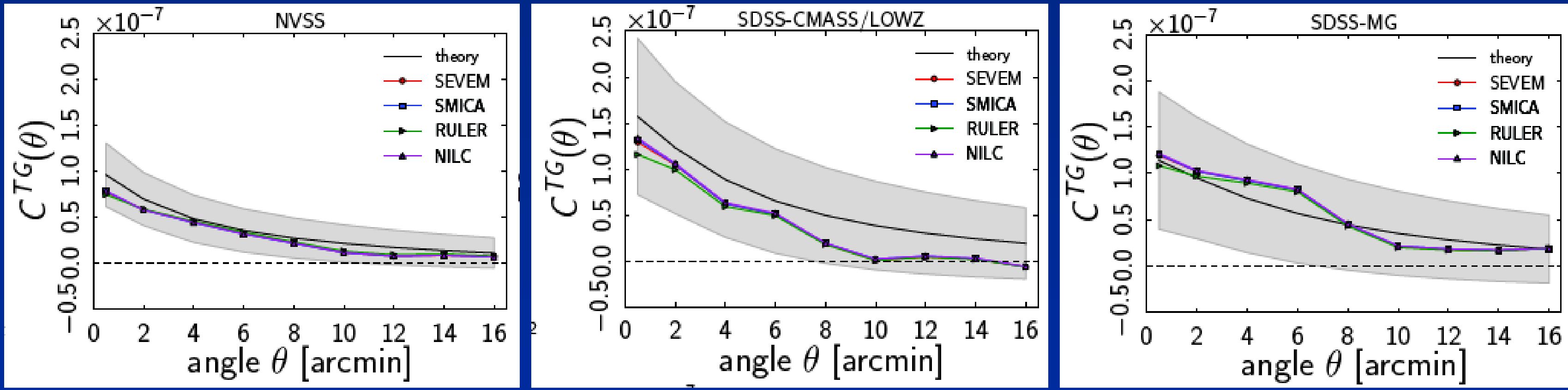
- Recall: What we see along a direction $\hat{\boldsymbol{n}}$ is what there is on the last scattering surface + blue- or redshift in this direction at distance r (Sachs-Wolfe effect), plus some Doppler shift, plus gravitational interactions of CMB photons (integrated Sachs-Wolfe effect)

$$\frac{\delta T}{T}(\hat{\boldsymbol{n}}) = \frac{\delta T}{T}(r\hat{\boldsymbol{n}}) + \Phi(r\hat{\boldsymbol{n}}) + \Psi(r\hat{\boldsymbol{n}}) - \boldsymbol{n}\cdot\boldsymbol{v}_{\rm bar}(r\hat{\boldsymbol{n}}) + \int_{\text{line of sight}} \dot{\Phi} + \dot{\Psi} \ (+\,\text{lensing})$$

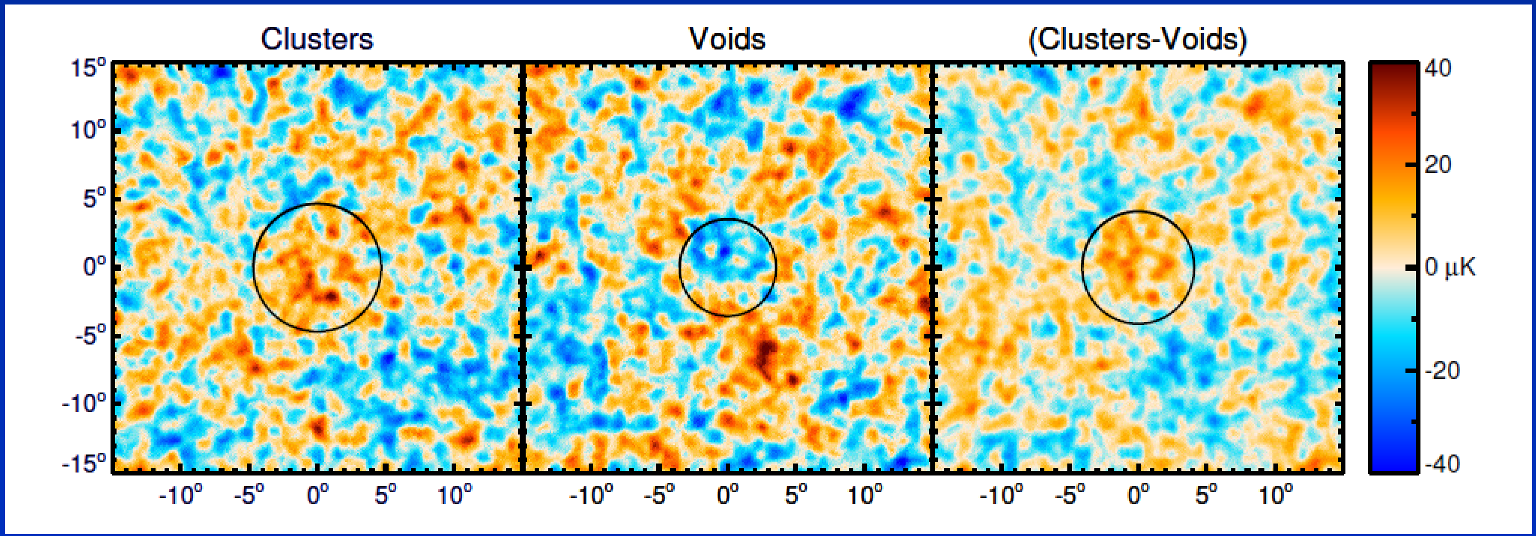
- There is a line of sight term (the magenta one), the so-called Integrated Sachs-Wolfe effect
- In a matter dominated Universe, this term is negligible: growth of structures due to gravitational instability and dilution from expansion somehow compensate and make structure possess a gravitational potential that is constant in time
- But in with dark energy, this no longer happens, and gravitational potentientals are no logner constant (they decay with time).
- Therefore, CMB map has to be somehow correlated with structures that lie in between last scattering surface and us, and, therefore, also with lensing
- See Planck 2013 XIX, arXiv:1303.5079

Consistency check – Integrated Sachs-Wolfe effect

- CMB-galaxy catalogs cross correlation ($2-3\sigma$-ish – no precision stuff from it)

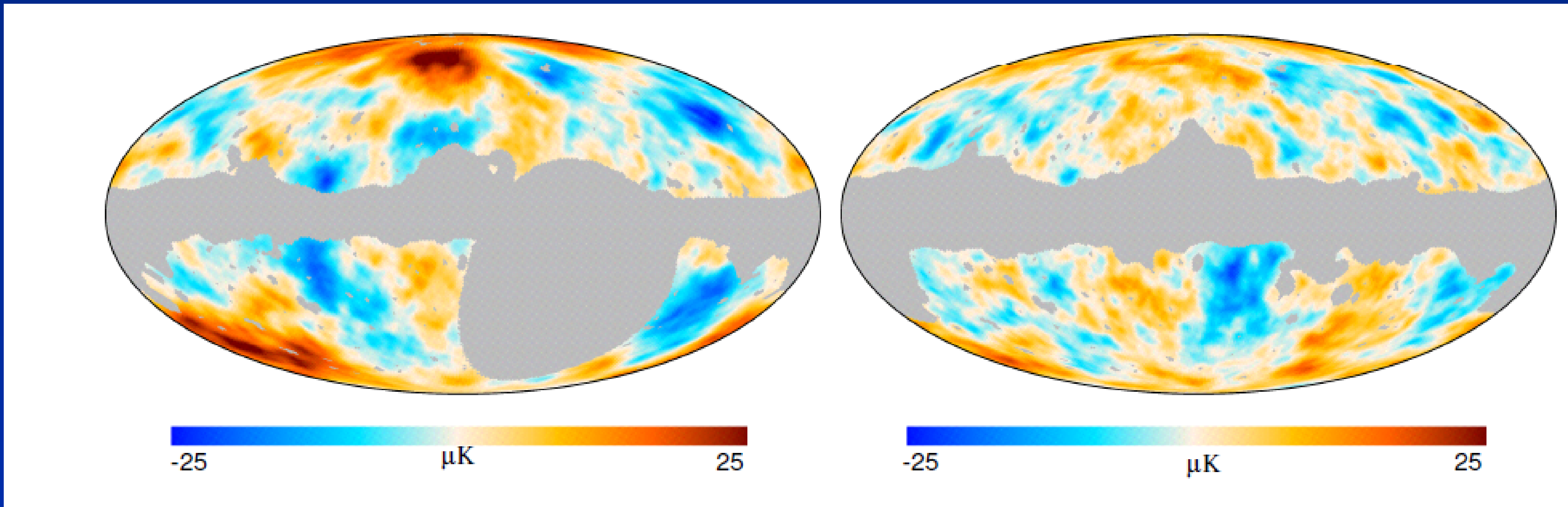


- Stacked patches of CMB on clusters/voids location

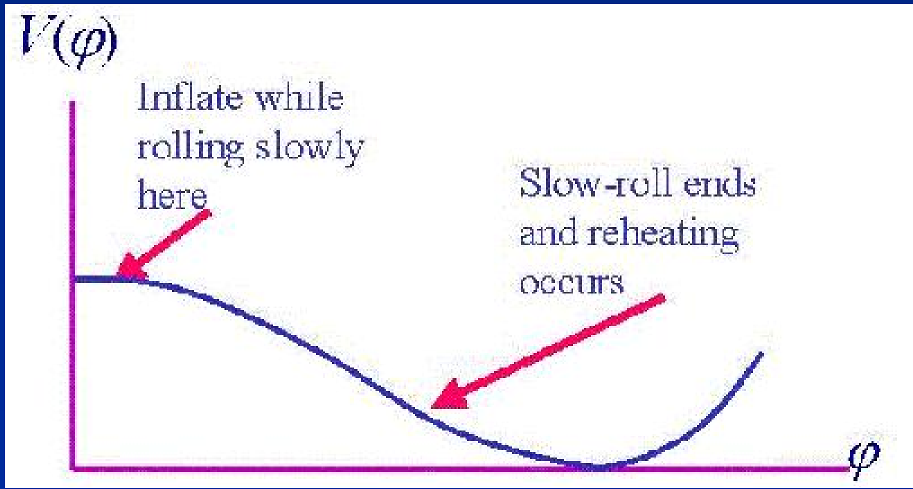


Consistency check – Integrated Sachs-Wolfe effect

- Model dependent ISW map using galaxy catalogs (left) and CMB lensing (right)



What it might say about inflation



- (Single field) inflation corresponds to a scalar field that deviates at some epoch from its minimum (whatever the reason) and rolls slowly towards its minimum
- $\longrightarrow$ de Sitter like expansion that erases any classical inhomogeneities
- Production of quantum fluctuations that are enlarged and converted into very large scale classical fluctuations.
- Testing the paradigm amount to see if there is some (simple) model that fist the data

What it might say about inflation

- Inflation produces density fluctuations (through quantum fluctuation of inflaton field) and gravitational waves (through amplification of quantum fluctuation of space-time itself) with power spectra

$$P_\Phi = A_\mathrm{S}\left(\frac{k}{k_*}\right)^{n_\mathrm{S}-1+\frac{1}{2}\frac{\mathrm{d}n_\mathrm{S}}{\mathrm{d}\ln k}\ln(k/k_*)+\ldots}$$

$$P_h = A_\mathrm{T}\left(\frac{k}{k_*}\right)^{n_\mathrm{T}+\frac{1}{2}\frac{\mathrm{d}n_\mathrm{T}}{\mathrm{d}\ln k}\ln(k/k_*)+\ldots}$$

- Slow-roll means several quantities involving the inflation potential V are small:

$$\epsilon = \frac{M_\mathrm{Pl}^2 V'^2}{2V^2}, \quad \eta = \frac{M_\mathrm{Pl}^2 V''}{V^2}, \quad \xi = \frac{M_\mathrm{Pl}^4 V' V'''}{V^2}$$

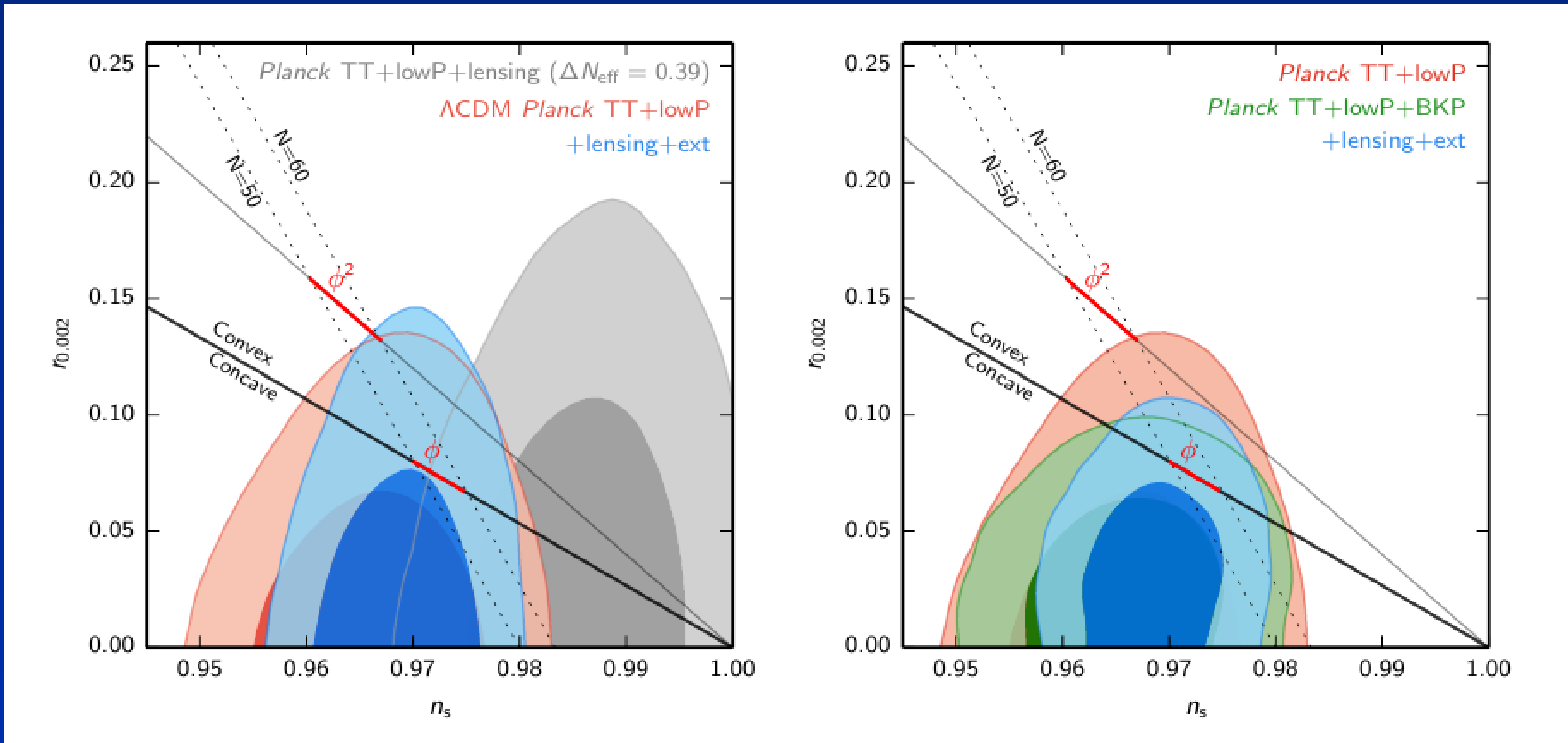
- And one has

$$A_\mathrm{T} = \frac{2V}{3\pi^2 M_\mathrm{PL}^4}, \quad r = \frac{A_\mathrm{T}}{A_\mathrm{S}} = 16\epsilon$$

$$n_\mathrm{S} - 1 = 2\eta - 6\epsilon, \quad n_\mathrm{T} = -2\epsilon$$

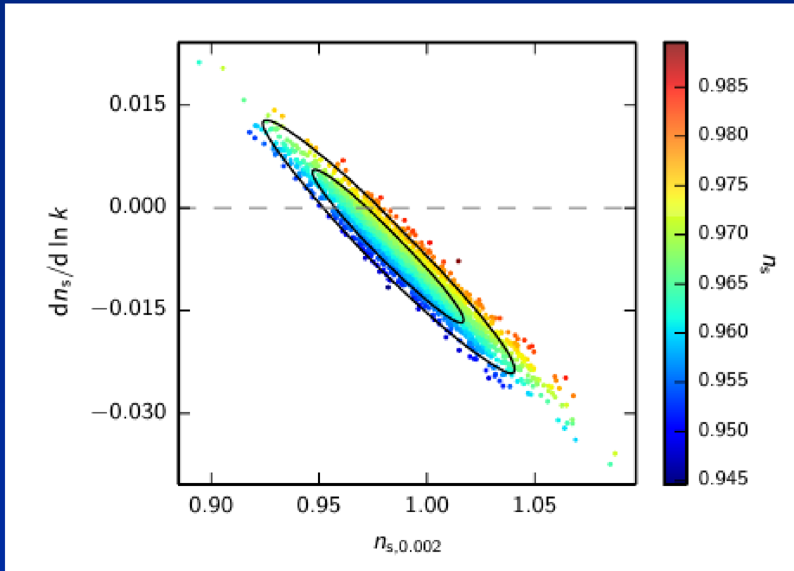
$$\frac{\mathrm{d}n_\mathrm{S}}{\mathrm{d}\ln k} = -16\epsilon\eta + 24\epsilon^2 + 2\xi, \quad \frac{\mathrm{d}n_\mathrm{T}}{\mathrm{d}\ln k} = -4\epsilon\eta + 8\epsilon^2$$

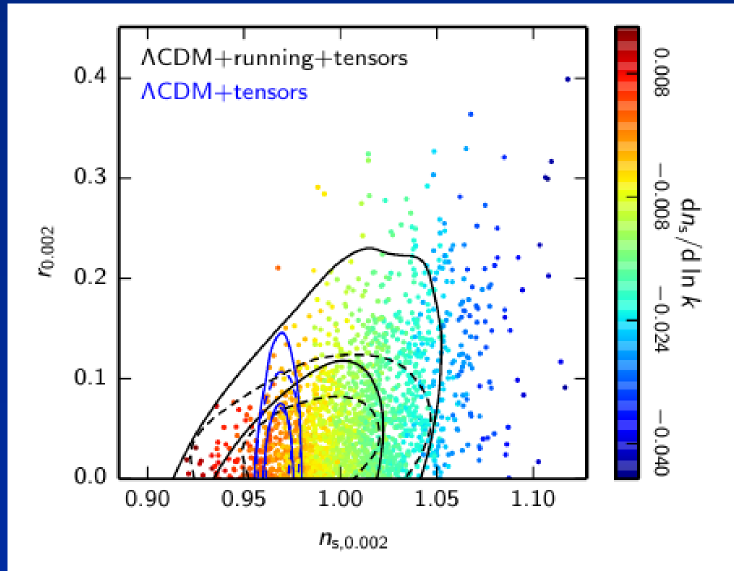
Today, we are here



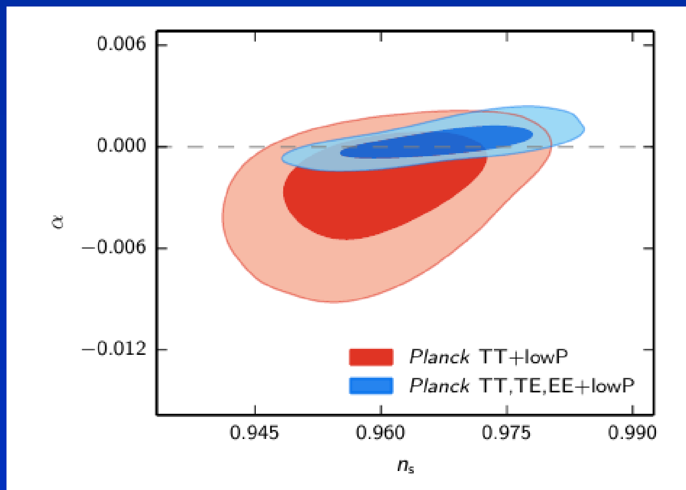
What is shown is a very limited subset of the published single field inflationary model, see "Encyclopaedia Inflationaris", arXiv:1303.3787

And we cannot say much more (yet)



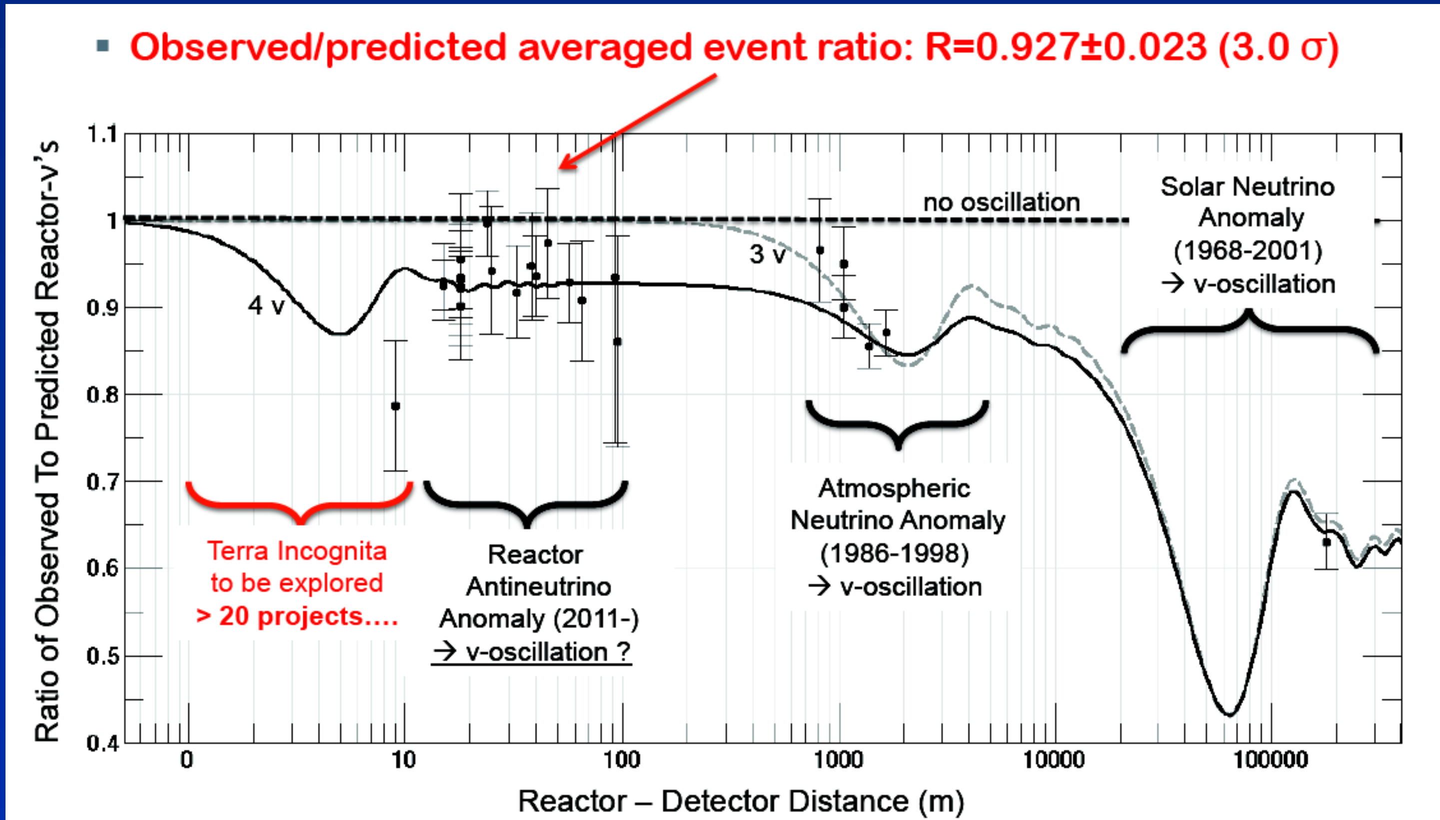


"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk" (von Neumann?)



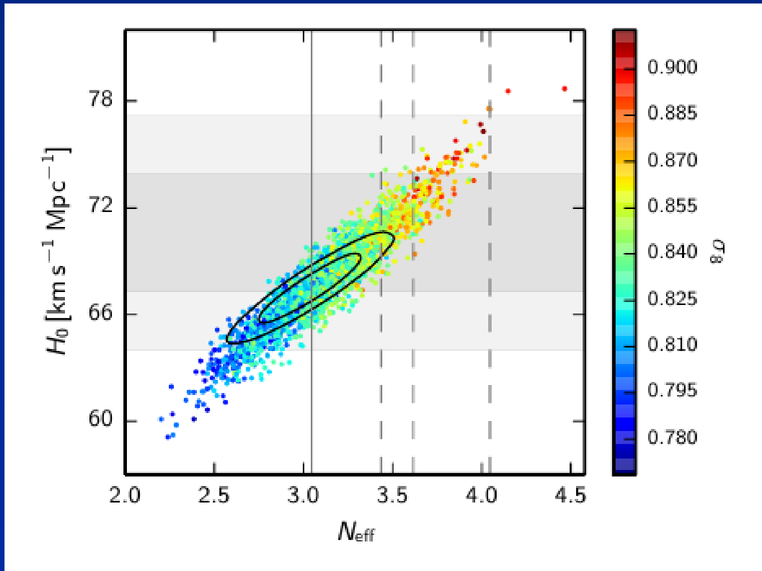
(including some other type of density perturbations instead of GW)

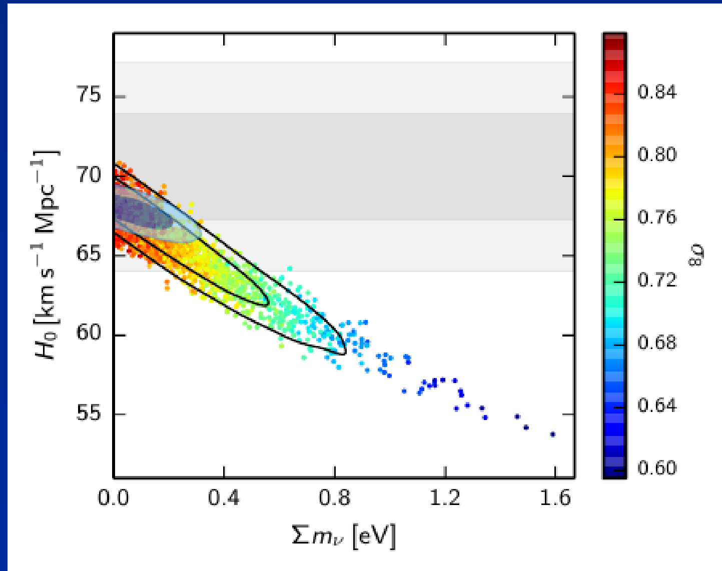
Planck and neutrinos



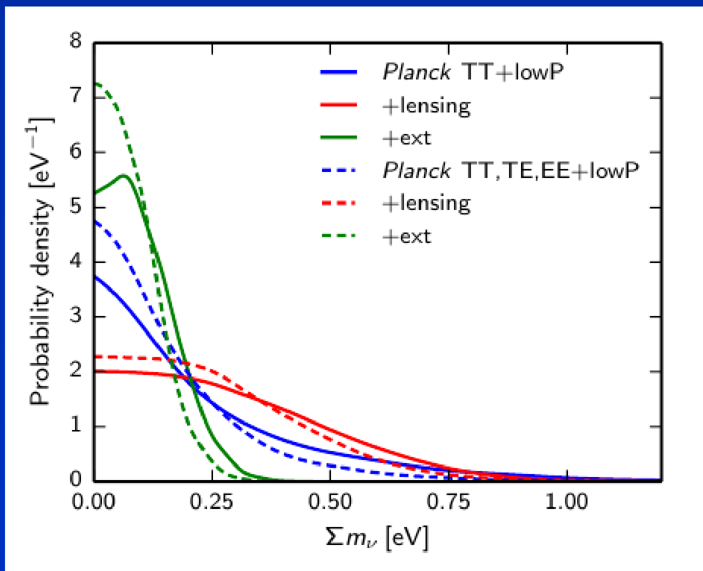
- Some controversial claims exist about a fourth family of "sterile" neutrinos in order to explain some neutrino data ("reactor anomaly" + LSND & Miniboone)
- Since neutrino energy density is non negligible at recombination, sterile neutrino may be seen as extra "dark" radiation
- Also, neutrino mass of order of few eV leave an imprint on structure formation as they become non relativistic during that epoch

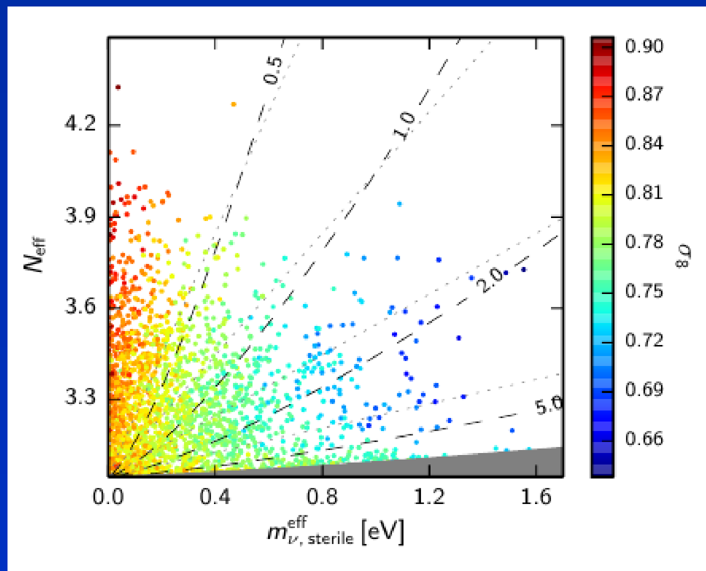
Planck and neutrinos (2015)



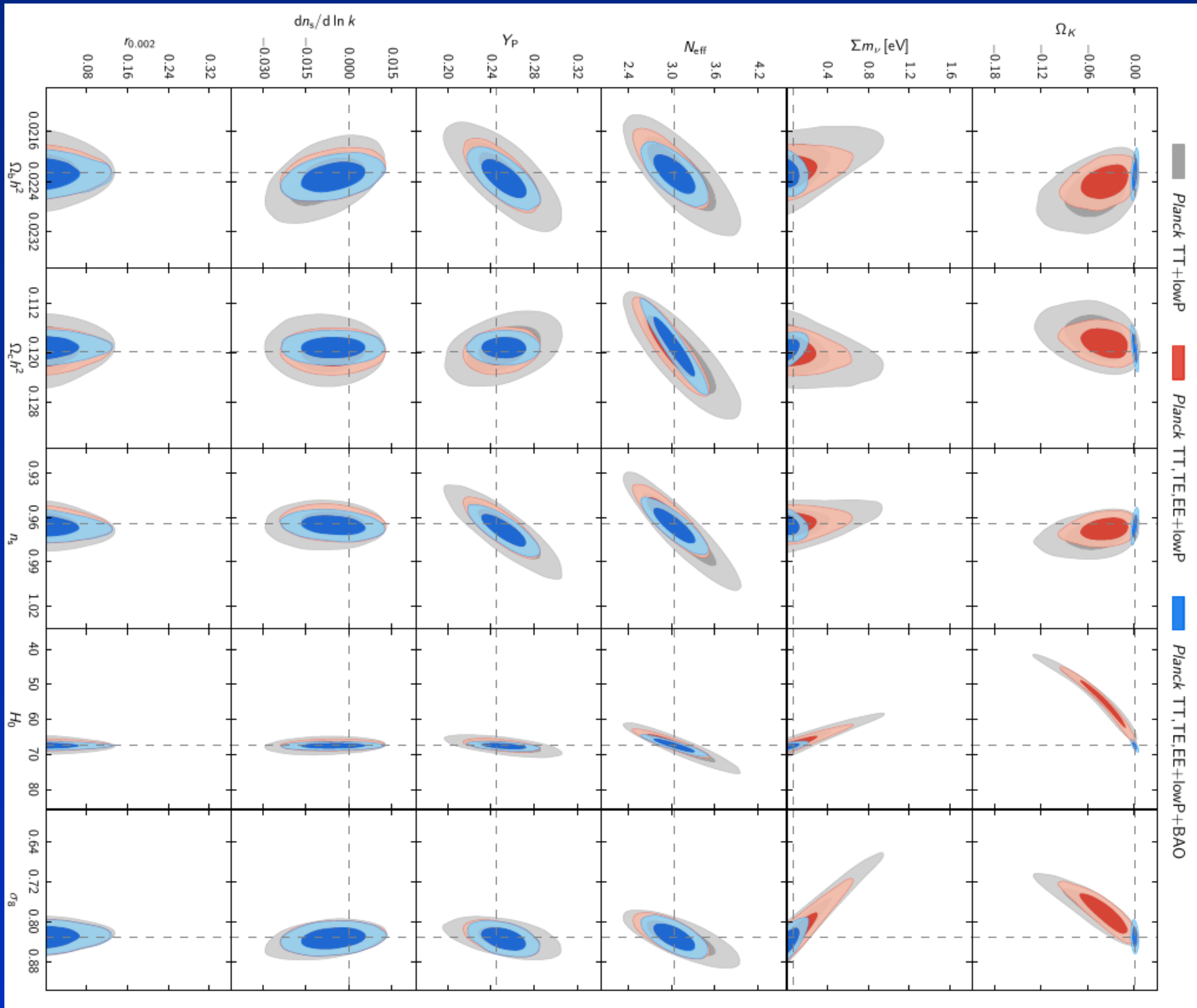


Warning: constraints are model dependent!

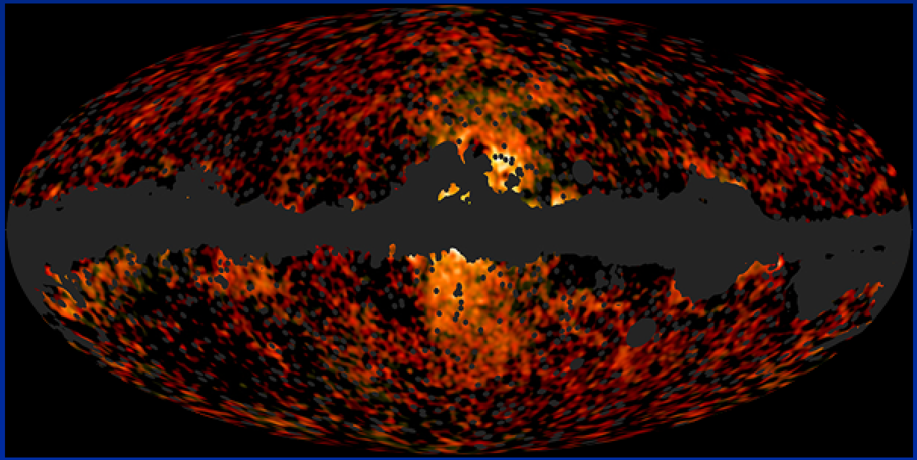




Summary of things we don't find evidence for



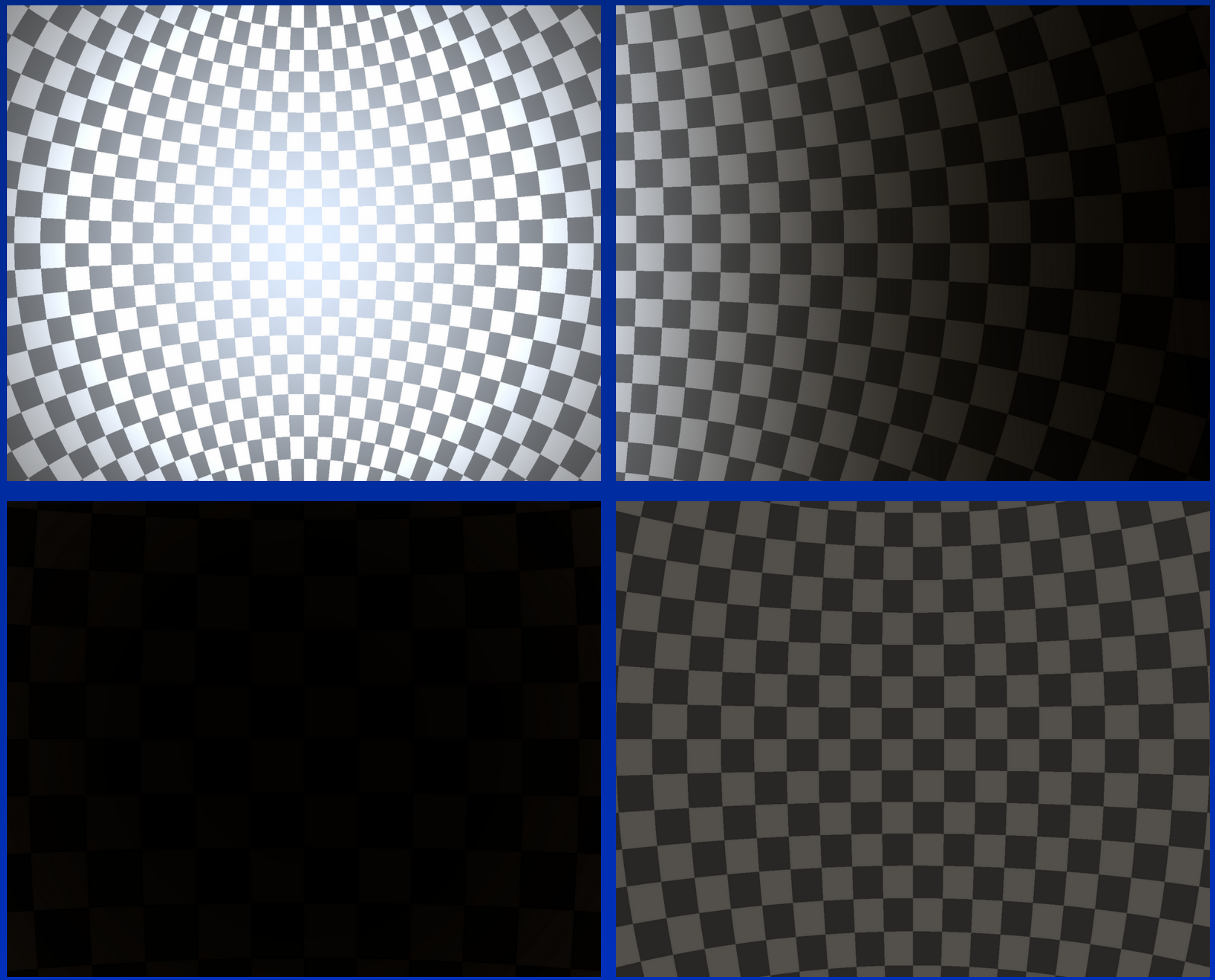
Did Planck indirectly detect Dark Matter? – arXiv:1208.5483



- Annihilating Dark Matter should produce matter-antimatter pairs close to the Galactic centre
- These charged pairs will propagate within the Galactic magnetic field and emit synchrotron radiation...
- ... that should be detectable as a "microwave haze" (spectrum $\neq$ free-free nor soft synchrotron, nor thermal or spinning dust) in the lowest frequency bands of Planck (30 GHz)...
- ... and this is something that we see here and that correlates well with the Fermi bubbles.
- Both need a hard electron-positron spectrum to be explained ($\mathrm{d}N/\mathrm{d}E \propto E^{-2.0}$) + reasonable Galactic magnetic field ($5\ \mu\mathrm{G}$)
- But weird features: sharp edges and flat profile within, which is not easily explained by annihilatig DM nor more conventional astrophysical acceleration processes.

Eppur, si muove (both beautiful & useless)

- A dipole is the first order main distortion produced by a Lorentz boost



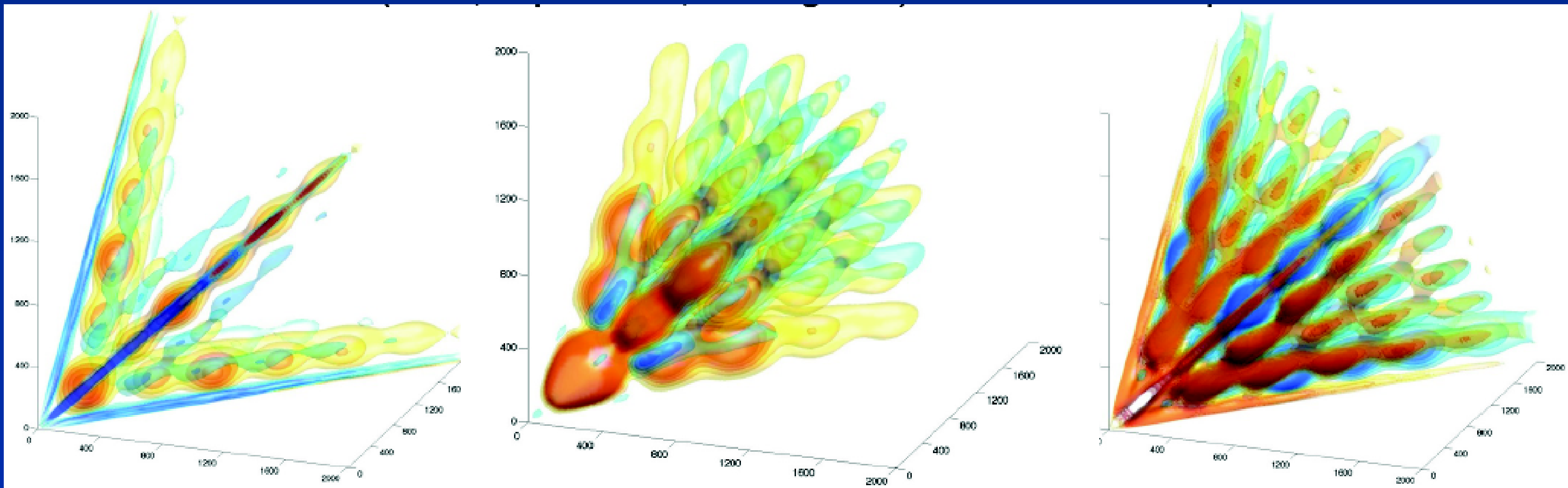
- Aberration shrinks and brightens patterns in the direction of motion / enlarges and darkens patterns in the opposite way

Eppur, si muove (both beautiful & useless)

- IF CMB dipole is of purely kinematical origin, a dipolar modulation of CMB should be visible in CMB anisotropy map
- This is seen in the dipole analysis, which gives $v = 384 \pm 74(\mathrm{stat}) \pm 115(\mathrm{syst})\,\mathrm{km/s}$ toward $l \sim 264\,\mathrm{deg}, b = 48\,\mathrm{deg}$ as compared to $v = 369 \pm 0.9\,\mathrm{km/s}$ toward $l = 263.99 \pm 0.14\,\mathrm{deg}, b = 48.26 \pm 0.03\,\mathrm{deg}$
- Result is unsurprising since observed dipole amplitude is consistent with expected late time large scale velocity flows and cosmological large dipole appear somewhat unnatural
- See Planck 2013 XXVII, arXiv:1303.5087

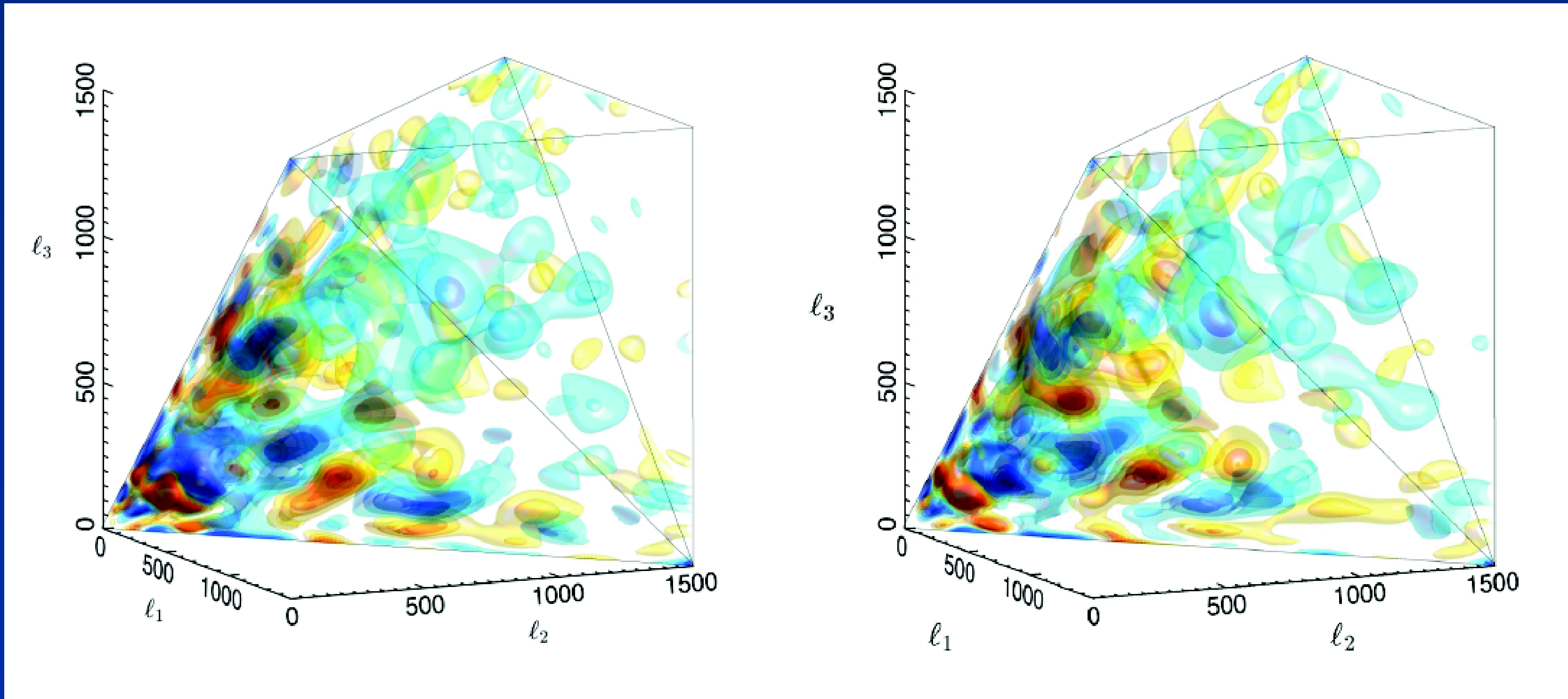
Exploring non Gaussianities (I)

- Non Gaussianities in single field inflationary scenrios are small (i.e. smaller that Planck upper limits)
- In general, non Gaussianities are manifest in the three point correlation function (i.e. when looking at correlations on triangles)
- But various extension can produce various types of non Gaussianities:



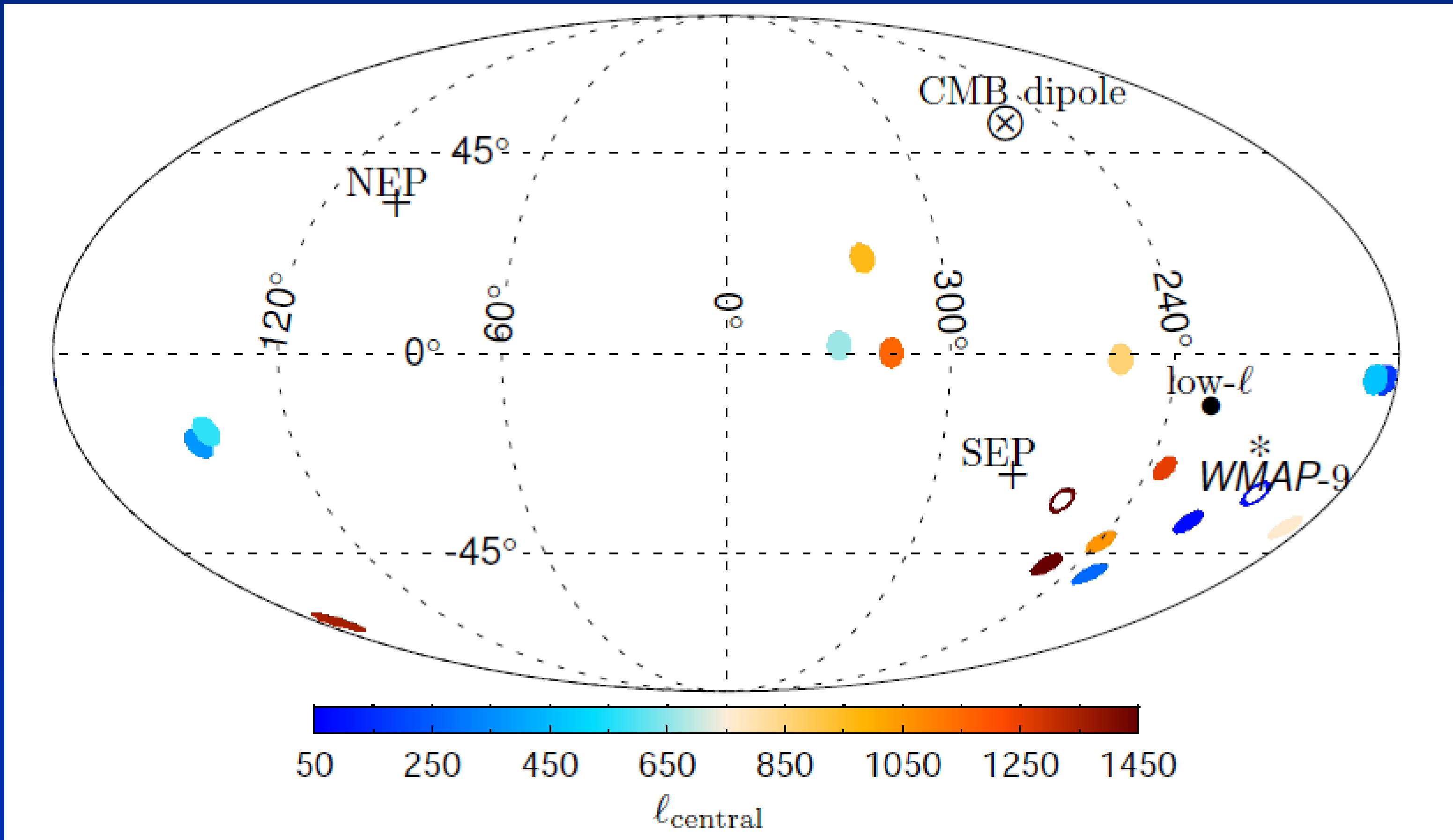
  - "Local type" $(k_1 \gg k_2 \sim k_3) \rightarrow$ Multi field models, curvaton, ekpyrotic/cyclic models
  - "Equilateral type" $(k_1 \sim k_2 \sim k_3) \rightarrow$ non standard kinetic term, higher derivative in Lagrangian
  - "Orthogonal type" $(k_1 \sim 2k_2 \sim 2k_3) \rightarrow$ subset of the previous one

Exploring non Gaussianities (II)



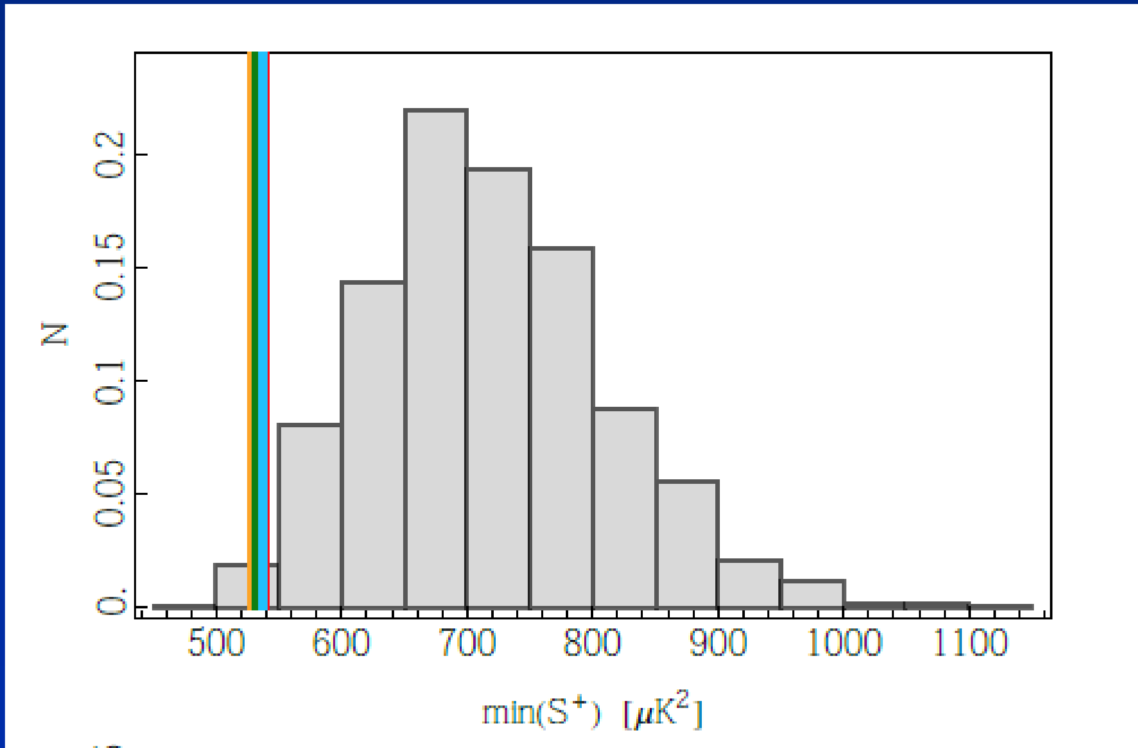
- Planck data do not show obvious non Gaussianities...
- ... but targetting the search to some specific features shows that some are preferred...
- ... But the number of possible features is so large that such outliers are not forbidden (Look elsewhere effect)
- Hard to say how it will evolve
- Ever improving low ℓ polarization spectrum ($\to \tau$) XXX

Does physics really works, anyway?



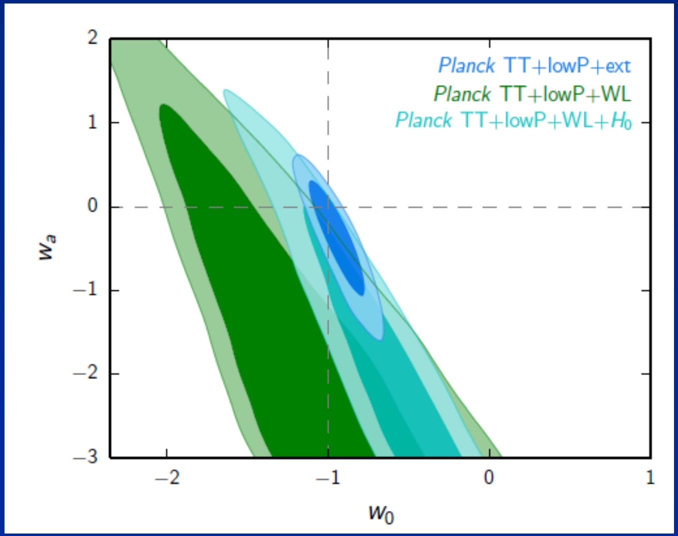
- Several strange features, in the data, mostly at large angular scales
- $\ell < 50$ vs. $\ell < 2500$ corresponds to only 2% of C_ℓ and 0.04% of $a_{\ell m}$'s, which have a very few % departure wrt expections
- $\rightarrow$ It is a small effect!

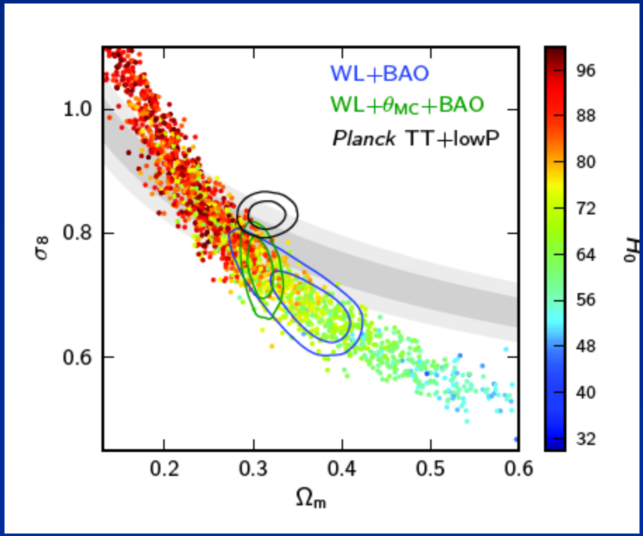
Does physics significantly fail?



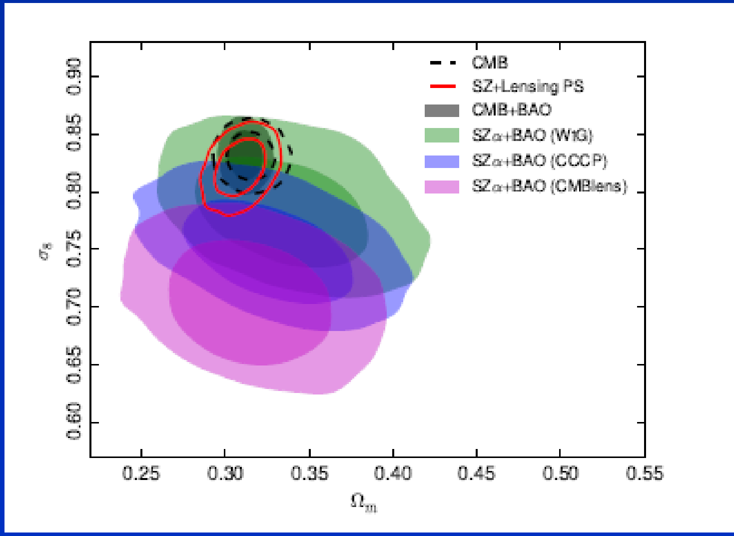
- But it seems real anyway
- (and already present in WMAP data)

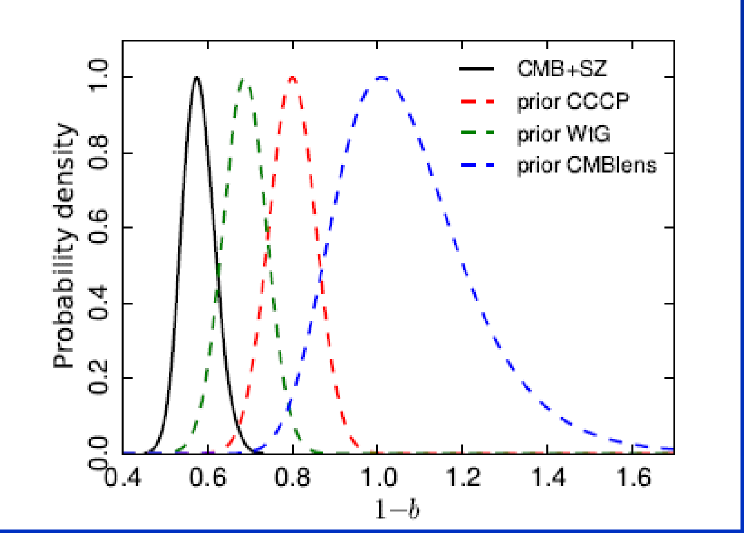
Does physics significantly fail? (II)



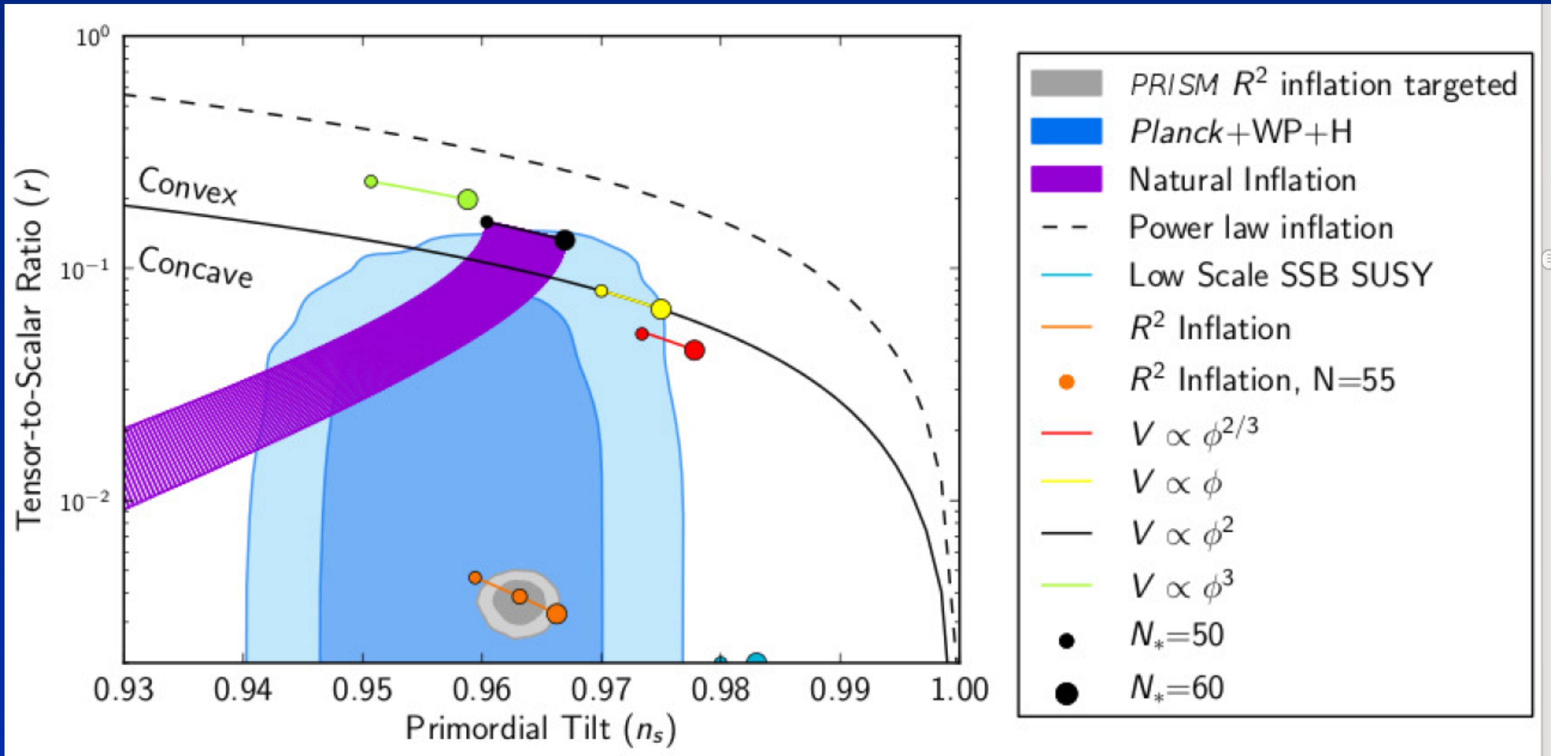


♣ Possible tension Planck/WL, as well as cluster counts, but discrepancy wery weak. Unsure it deserves being mentionned



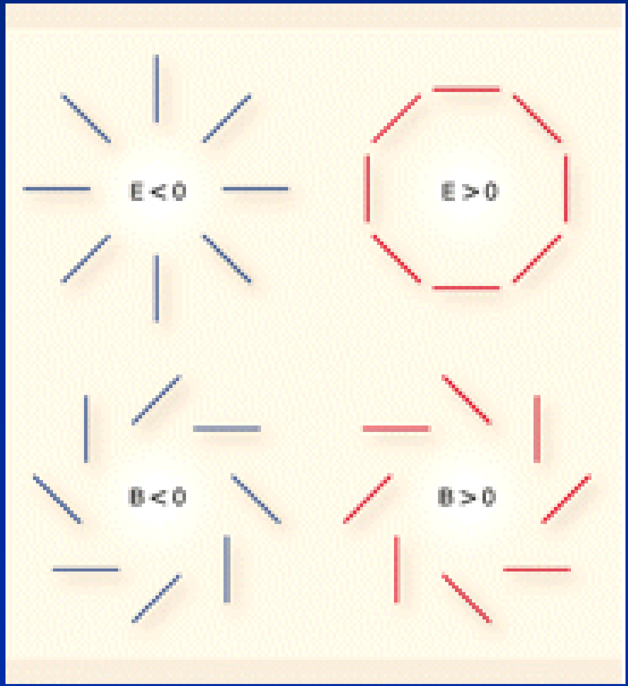


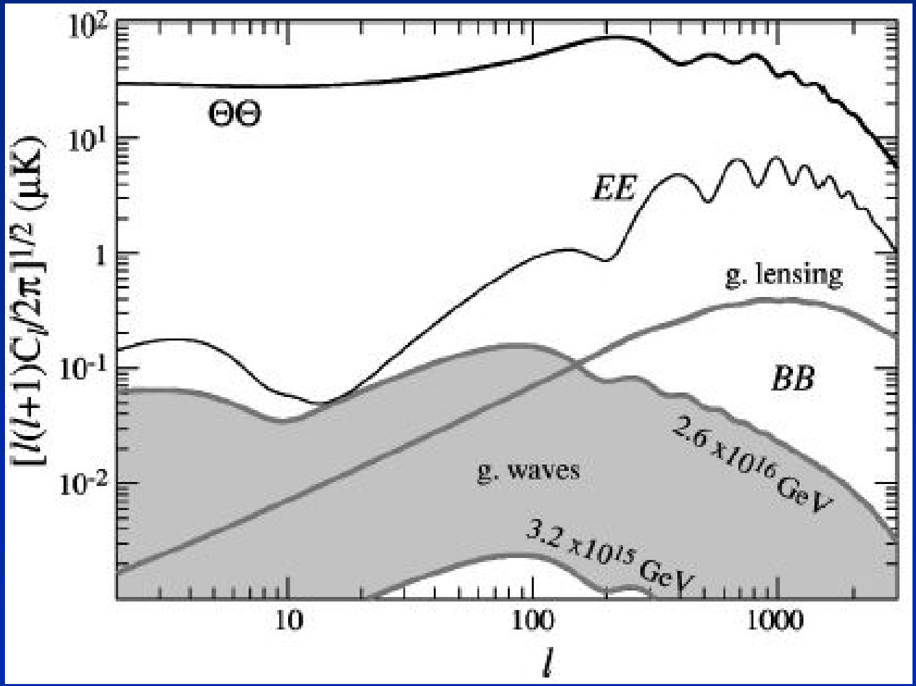
Reflections on the next step for the CMB



An exemple of something Planck is not able to investigate...

B modes as the ultimate frontier

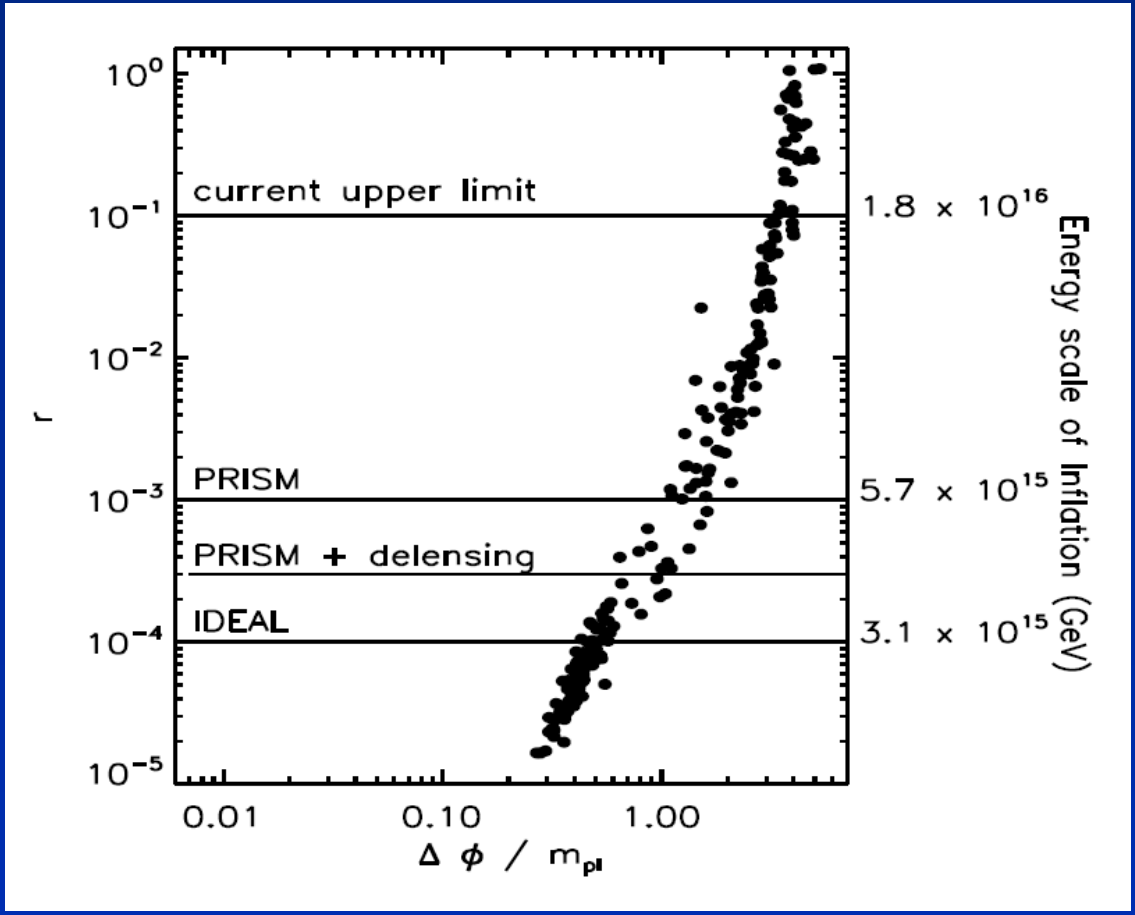




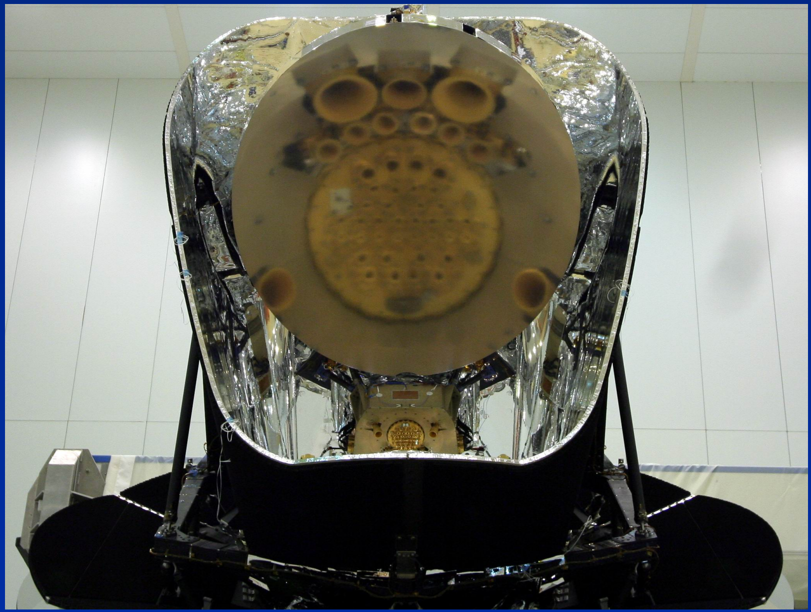
♣ Several predictions for single field inflation were made:

- Almost scale invariant spectrum (APM, 1990)
- Gaussian fluctuations (COBE, 1992)
- Adiabatic perturbations (Saskatoon, 1998)
- Euclidean spacelike sections (BOOMERanG, 2001)
- Superhorizon perturbations (WMAP, 2003)
- All these were exquisitely confirmed by Planck with a beautiful degree of precision
- Reddish, almost scale invariant spectrum (Planck, 2013)
- Some gravitational waves (???)

Designing something close to the best that could be done

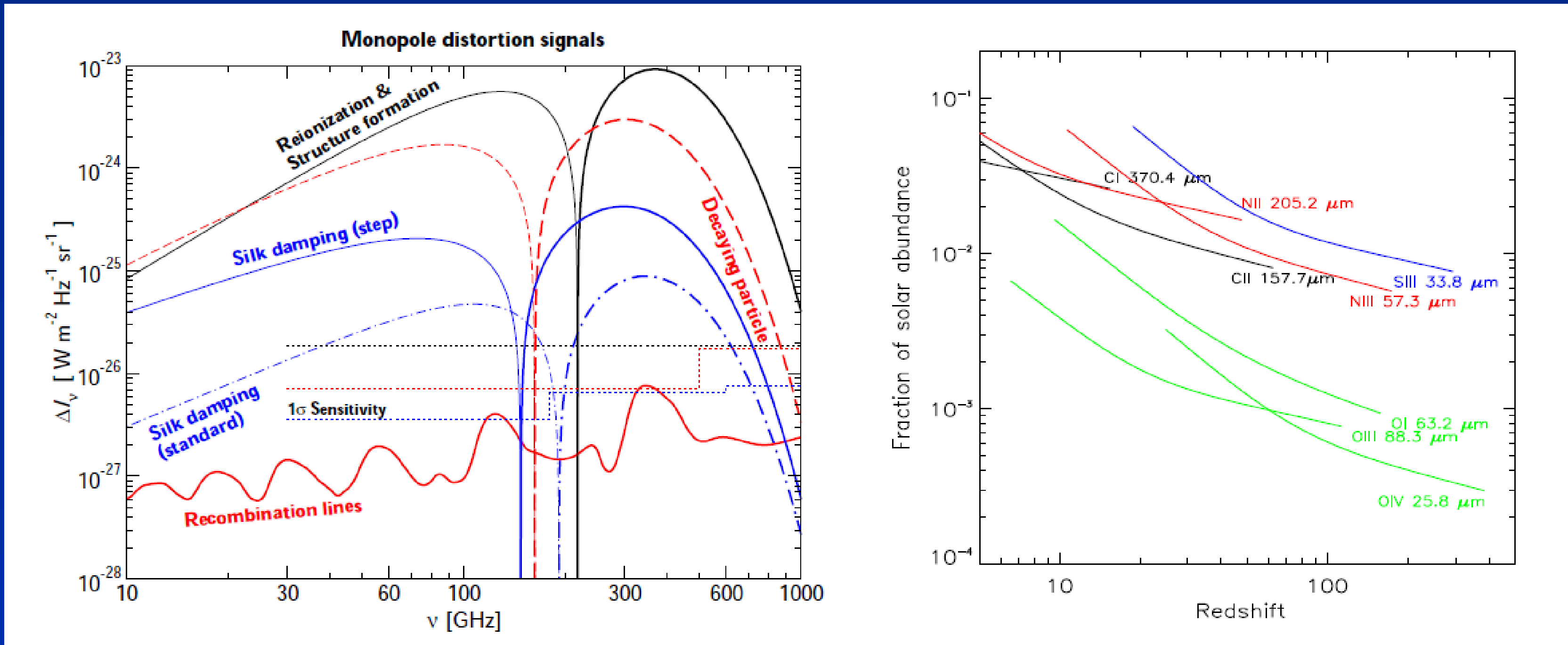


One has to be very ambitious...



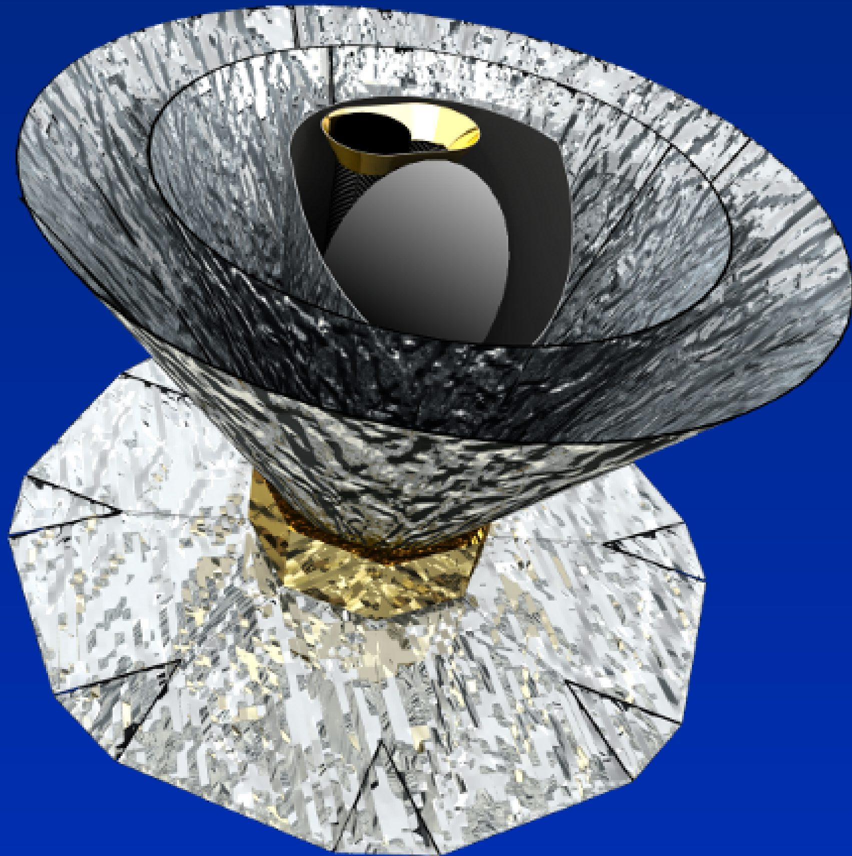
- Planck sensitivity significantly limited by diffraction limit and photon noise!
- Doing better means having bigger telescope and more detectors
- Which is feasible since less than 1% of photons hitting focal plane end in detectors
- One could think of 32 broad band chanels ($\Delta\nu/\nu = 0.25$) from 30 to 6000 GHz with between 50 and 350 detectors per band $\rightarrow$ a total of 7600 detectors (vs. 74 for Planck) + 3.5 m equivalent diameter telescope (vs. 1.5 m for Planck)

… But many possible outcomes regarding fundamental physics



- ♣ Very high precision spectroscopy might allow to see distortions from perfect black body spectrum if there is any energy injection, at $10^3 < z < 10^6$, from
  - Recombination lines!
  - Dark matter annihilation/decay
  - Cosmic strings decay and wakes
  - Primordial black hole evaporation
  - Structure formation/First stars (= dark stars?)

This is the (preliminary version of the) PRISM mission



- PRISM (= Polarized Radiation Imaging and Spectroscopy Mission) is a possible successor to Planck
- 3.5 m mirror main satellite + ancillary satellite for calibration and data transfer purpose
- Proposed as a Large ESA mission
- Two lauch slots: 2028 and... 2034
- Did not make it at ESA, but rescaled down version (M-class mission) under consideration

Conclusion

Physics works!

Conclusion (seriously)

- The Planck spacecraft has worked beyond expectations and brought us the (by far) best picture of the history, evolution and matter content of the Universe
- Data analysis still prefers the six parameter concordance model that was guessed ~ 20 years ago
- This makes the Universe a surprisingly (and, for some, frustratingly) simple system, depesite the fact that none of those six parameters are easy to predict, nor to explain without resorting to new physics
- Beyond this concordance model, no evidence for known unknown physics was found to date
- But a few strange issues are yet unsettled, maybe unknown unknown physics, such as [insert your favourite stuff here]?
- Better constraints about $\sum m_\nu$, $w_{\rm DE}(z)$/modified gravity are likely to be obtainable from EUCLID within the next decade, but it will be a difficult task
- The next frontier is the detection of cosmological B-modes, but no one knowns whether Nature was kind enough to produce any signal at an observable level.

Some words about the BICEP2 announcement

- March 2014/arXiv: The observed B-mode power spectrum is well-fit by a lensed-ΛCDM $+$ tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.
- June 2014/PRL: The observed B-mode power spectrum is well fit by a lensed-ΛCDM $+$ tensor theoretical model with tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Accounting for the contribution of foreground, dust will shift this value downward by an amount which will be better constrained with upcoming data sets.
- (Side note: CMB itself and accelerated expansion were initially detected at 3σ level only.)

The astonishing and undisputable achievement they made

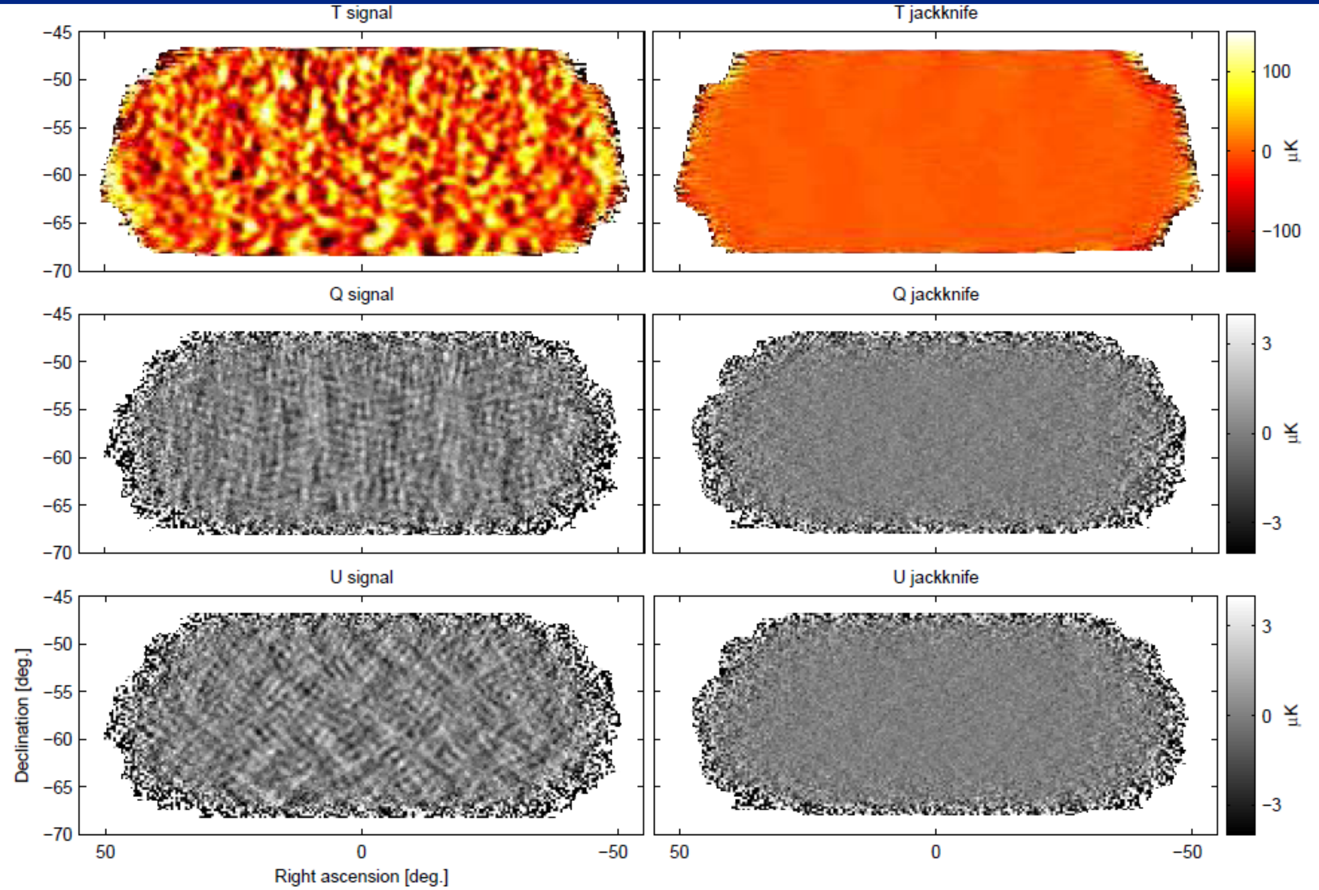
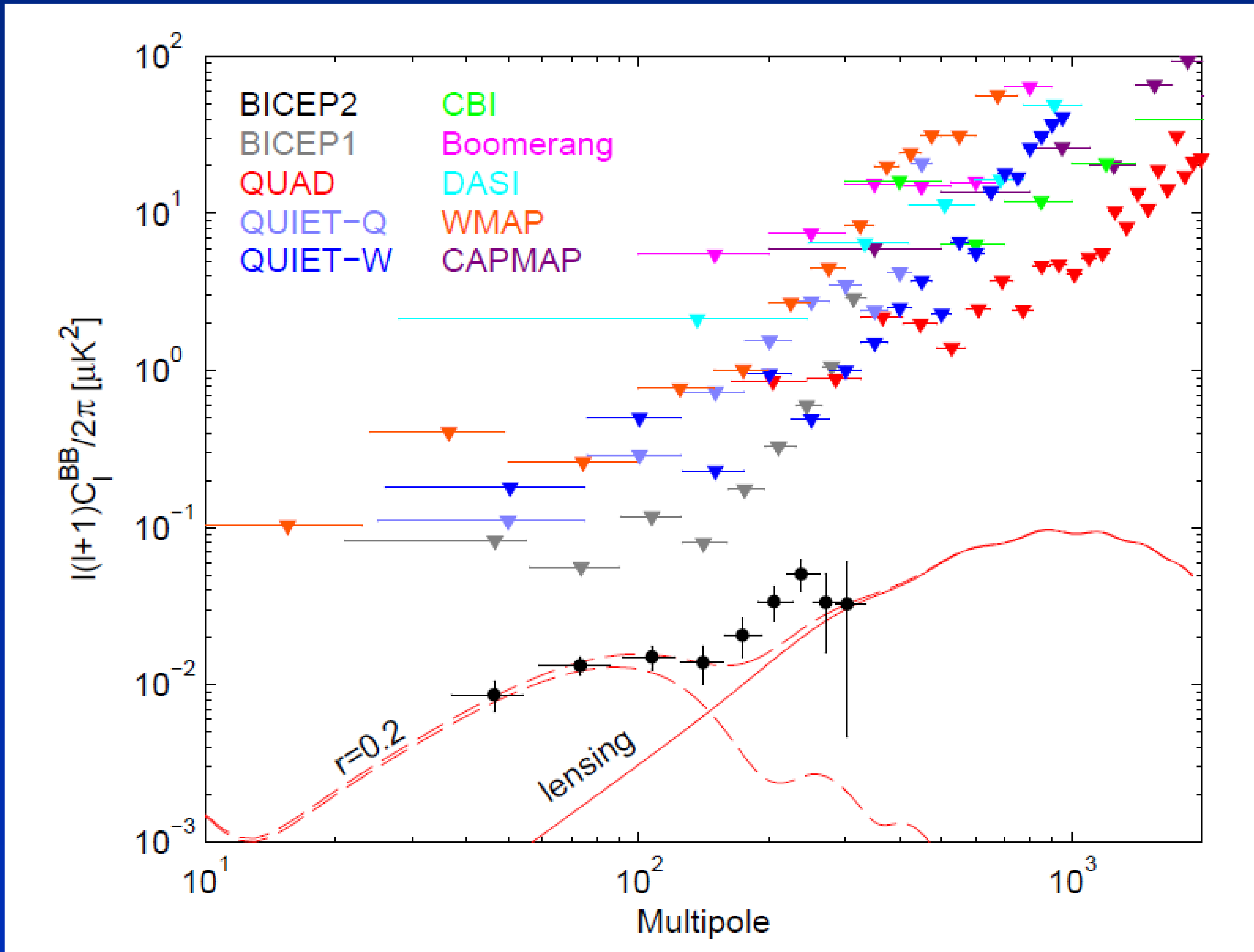


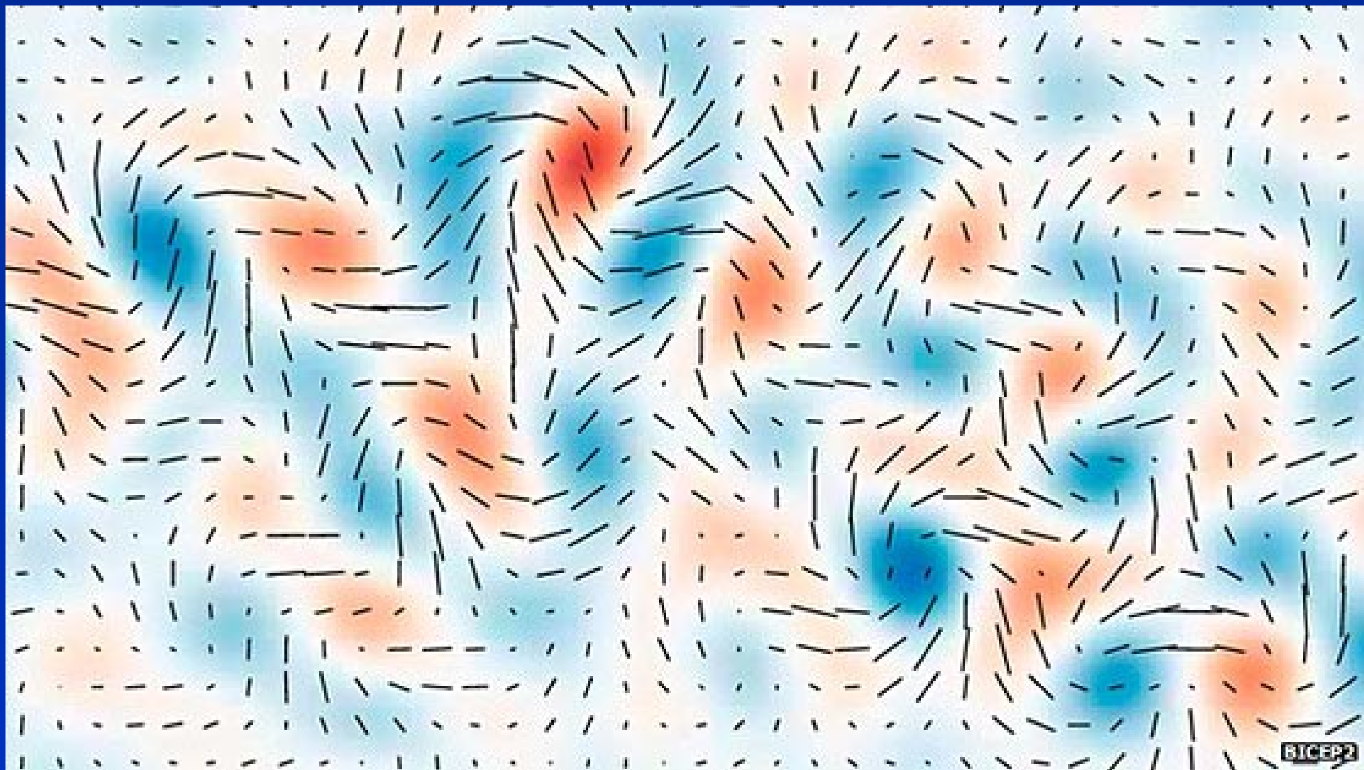
FIG. 1.— BICEP2 T, Q, U maps. The left column shows the basic signal maps with 0.25° pixelization as output by the reduction pipeline. The right column shows difference (jackknife) maps made with the first and second halves of the data set. No additional filtering other than that imposed by the instrument beam (FWHM 0.5°) has been done. Note that the structure seen in the Q&U signal maps is as expected for an E-mode dominated sky.

The astonishing and undisputable achievement they made

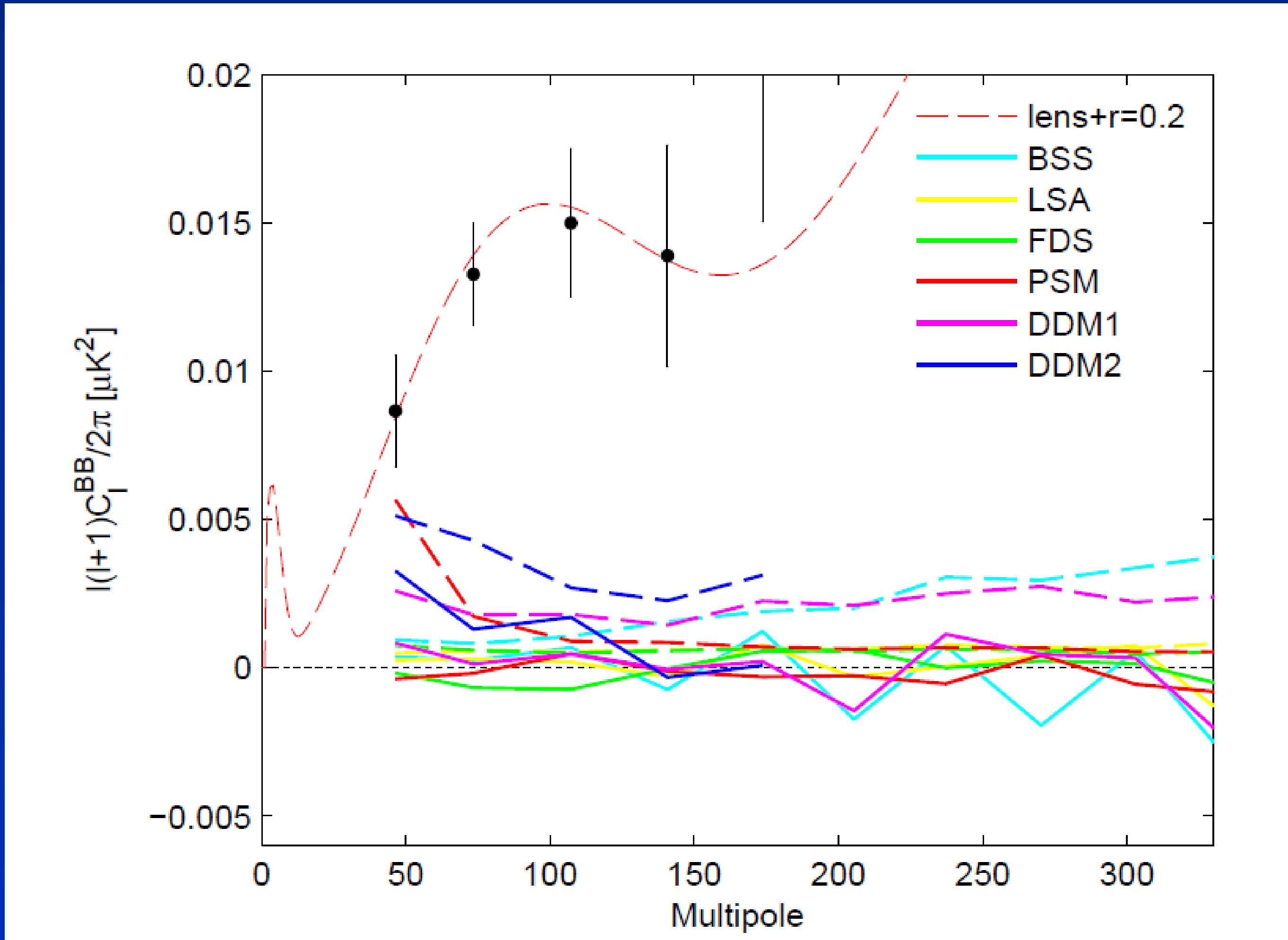


From signal to cosmological signal

- BICEP2 has only one frequency chanel (150 GHz)
- This makes foreground identification impossible from the data only
- Foreground estimates therefore rely on external inputs: toy models or leaked Planck data
- BICEP2 data alone just say: if the observed signal is of cosmological origin, then BICEP2 has detected something of cosmological origin.



A possible culprit



- DDM2 model comes from a talk given by a Planck collaboration members during Planck result conference at ESA, April 2013

DDM2 is...

The Planck Dust Polarization sky

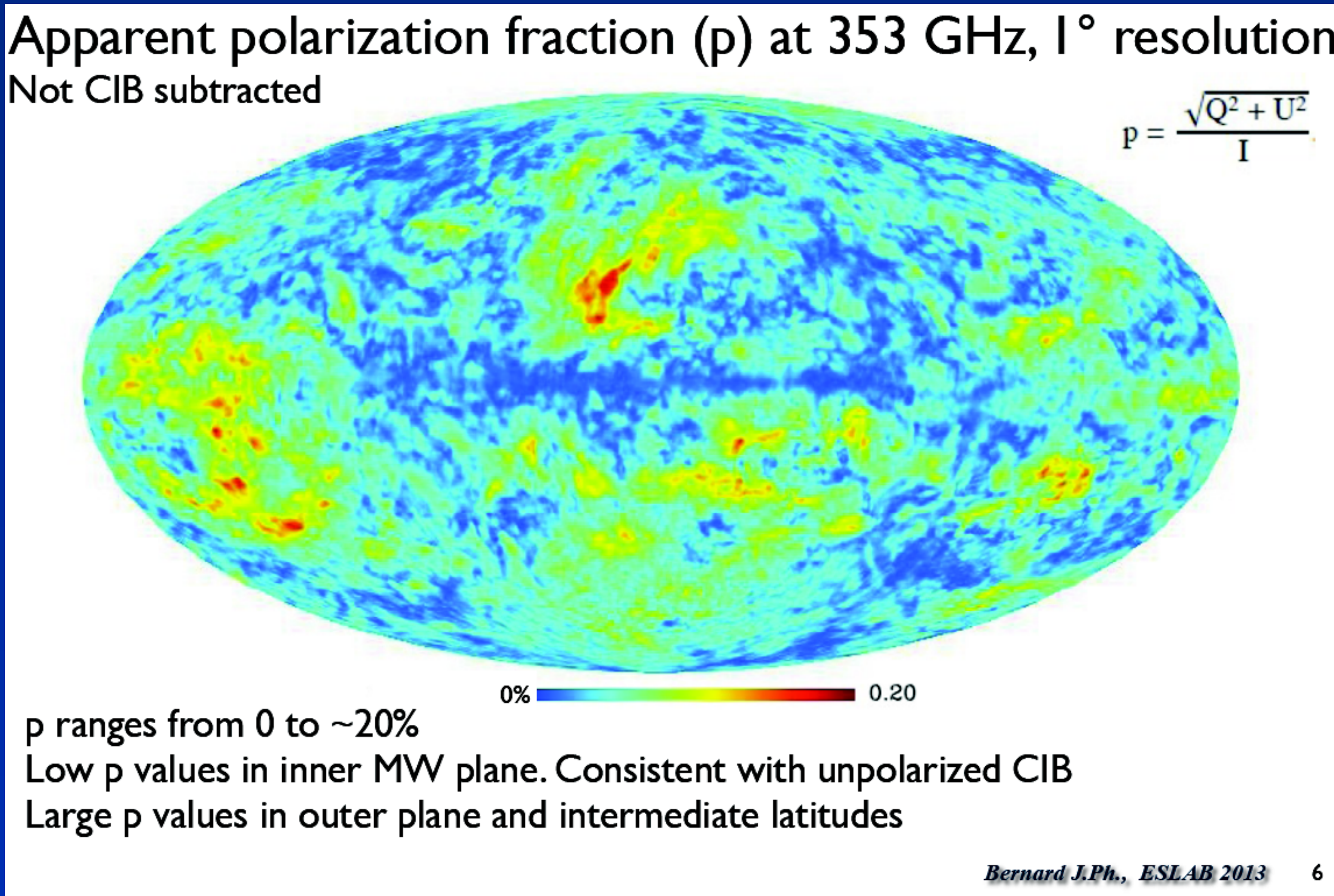
- Methods & data used
- All sky polarization at 353 GHz
- Highest dust polarization regions
- Spatial variations of polarization fraction
- Connections with large-scale MW B field, dust column density and small-scale B field structure

Planck Collaboration.
Presented by J.-Ph. Bernard
(IRAP) Toulouse

Bernard J.Ph., ESLAB 2013 1

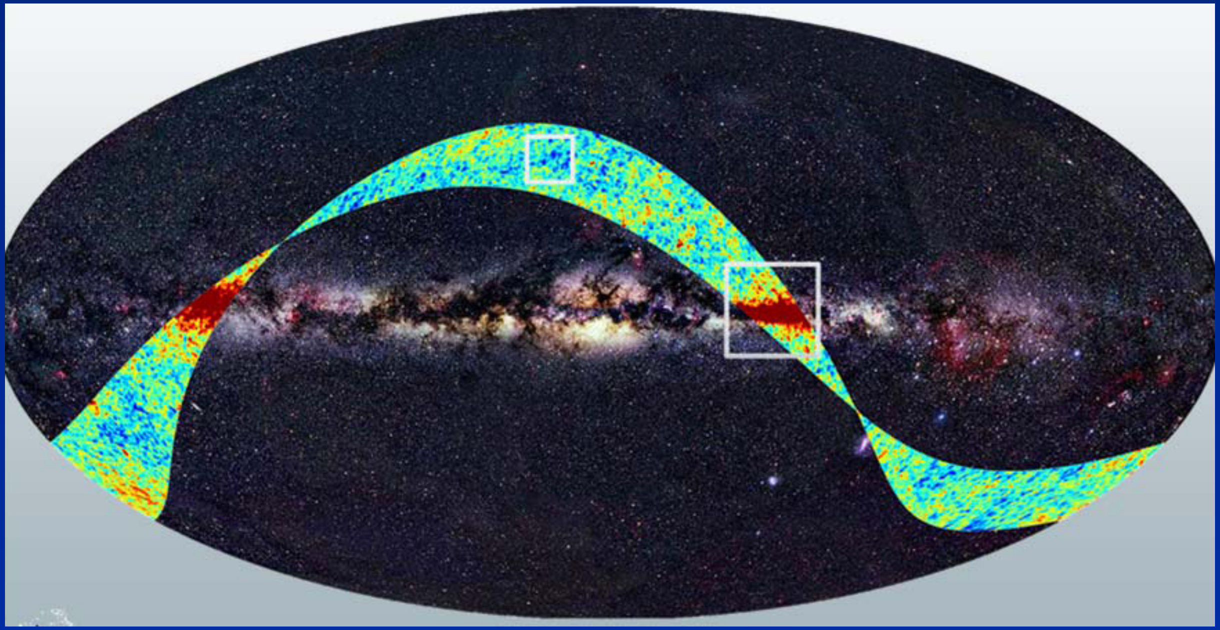
mercredi 3 avril 13

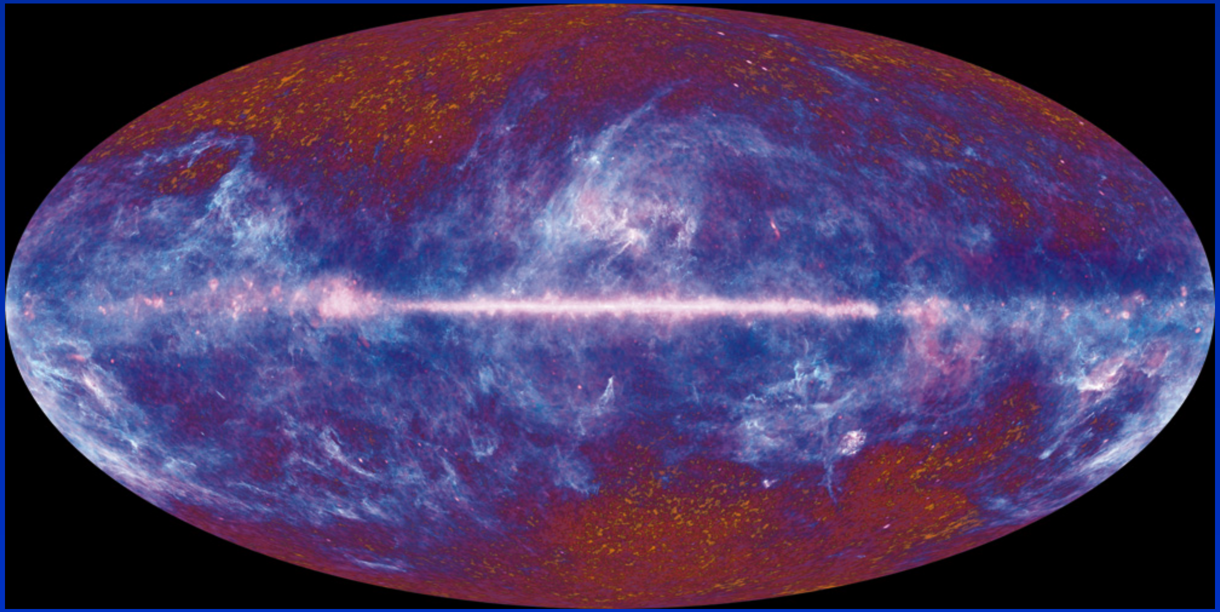
… most notably



♣ But what does it mean?

Side note: some released material is unusable



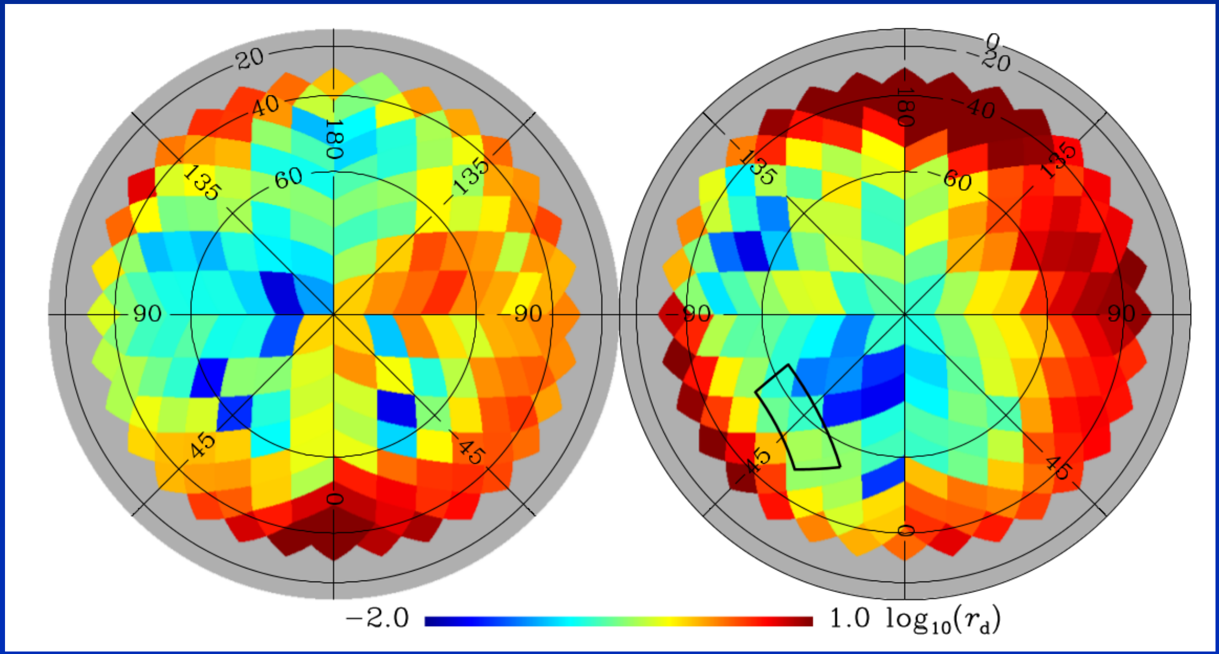


Independent analyses

- BICEP2: "DDM2 [is] constructed using all publicly available information from Planck."
- In practice: Real data $\longrightarrow$ HEALPIX $\longrightarrow$ JPEG $\longrightarrow$ ppt $\longrightarrow$ pdf available $\longrightarrow$ gif $\longrightarrow$ HEALPIX $\longrightarrow a_{\ell m}$
- Also: what is exactly shown here? What does "Not CIB substracted" actually imply?
- Foreground estimates from map have enter squared in power spectrum
- Flauger, http://www.pctp.princeton.edu/pctp/SpecialEventSimplicity2014/SpecialEventSimplicity2
, attempted to perform some reverse engineering procedure starting from the same data and found foreground estimate too uncertain wrt BICEP2 claim
- It seemed at least premature to conclude (in either direction) on whether BICEP2 claim is optimistic or pessimistic

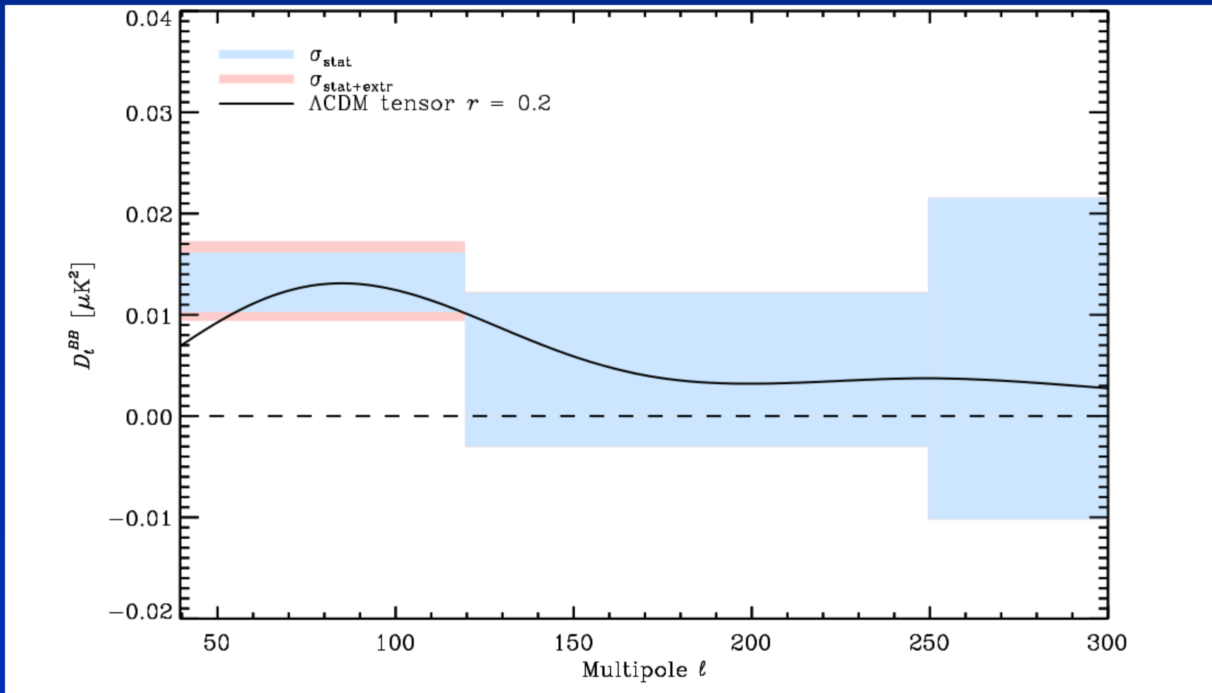
Planck's words

- Planck polarized foreground paper: dust polarization fraction is larger than anticipated, and inhomogeneous.
- Polarized dust contribution at 100 GHz is estimated from measurement polarization at 353 GHz
- BICEP2 field, chosen because it had low dust content, has *high* polarization fraction...



Planck's words

- Planck/BICEP2 paper, arXiv:1502.00061: $r \neq 0$ $(7\sigma) \to r < 0.12$ (2σ)
- No evidence that BICEP2 saw anything else than dust (through somehow indirect measurement)



- No indication that cosmological B-modes can be detected from ground