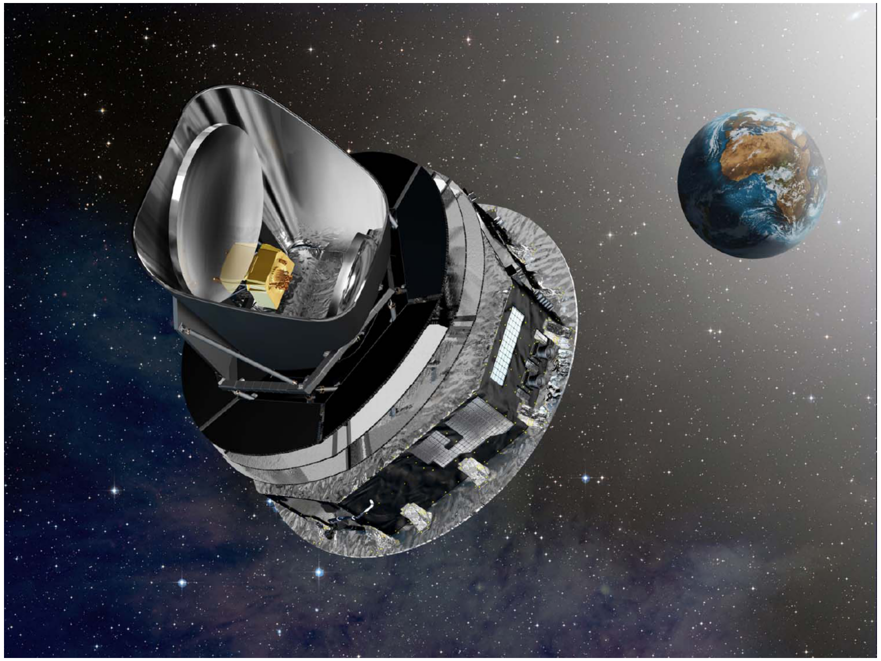


Results from Planck

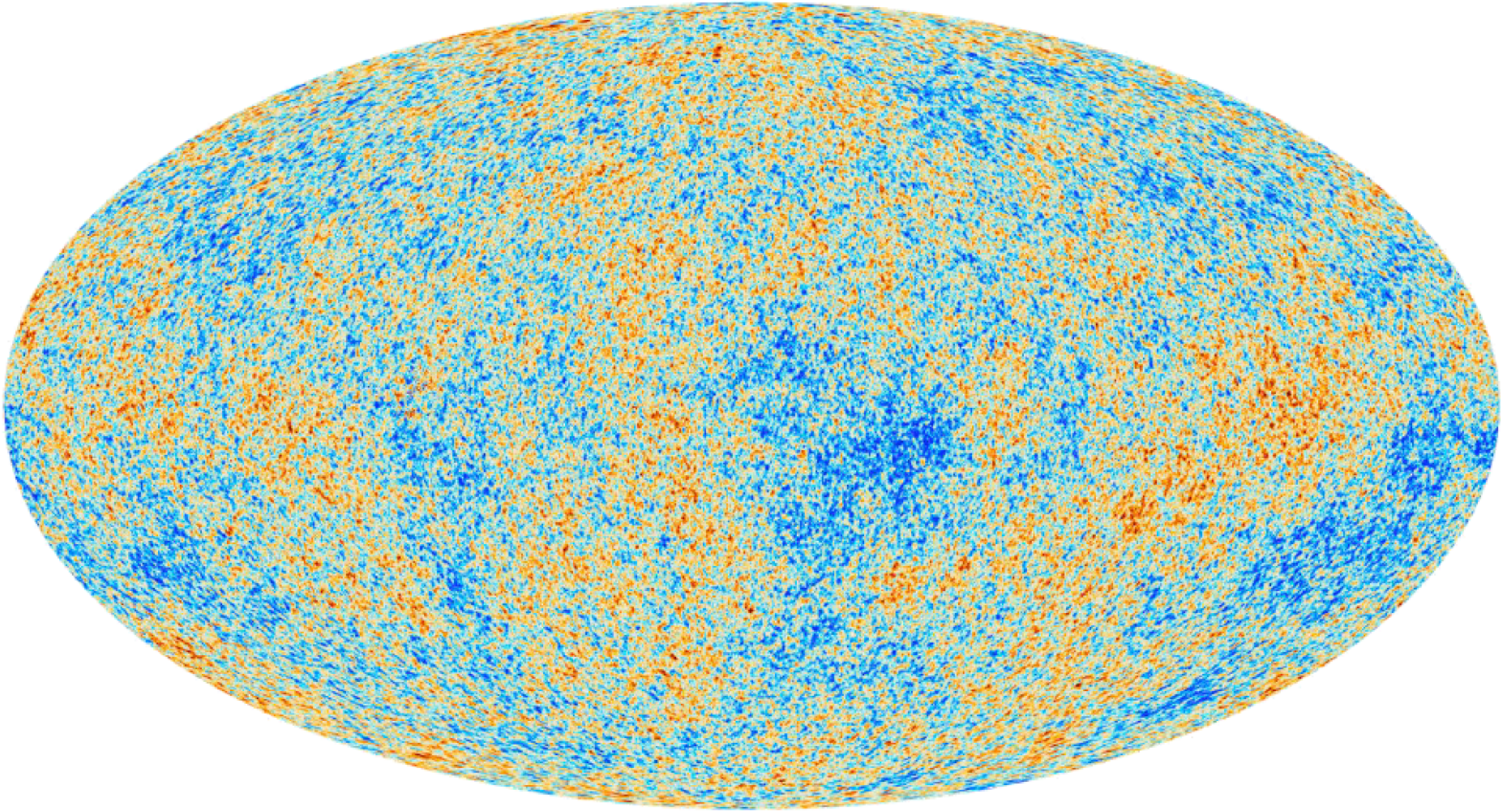
Invisibles Workshop, Durham, 15.07.2013
J. Lesgourgues (EPFL, CERN, LAPTh)


Silvia
Belen
Celine


Lumley Castle

The Planck release of March 2013

Restricted to temperature map for “nominal mission”, 15 months, > 2 sky scans by HFI+LFI.



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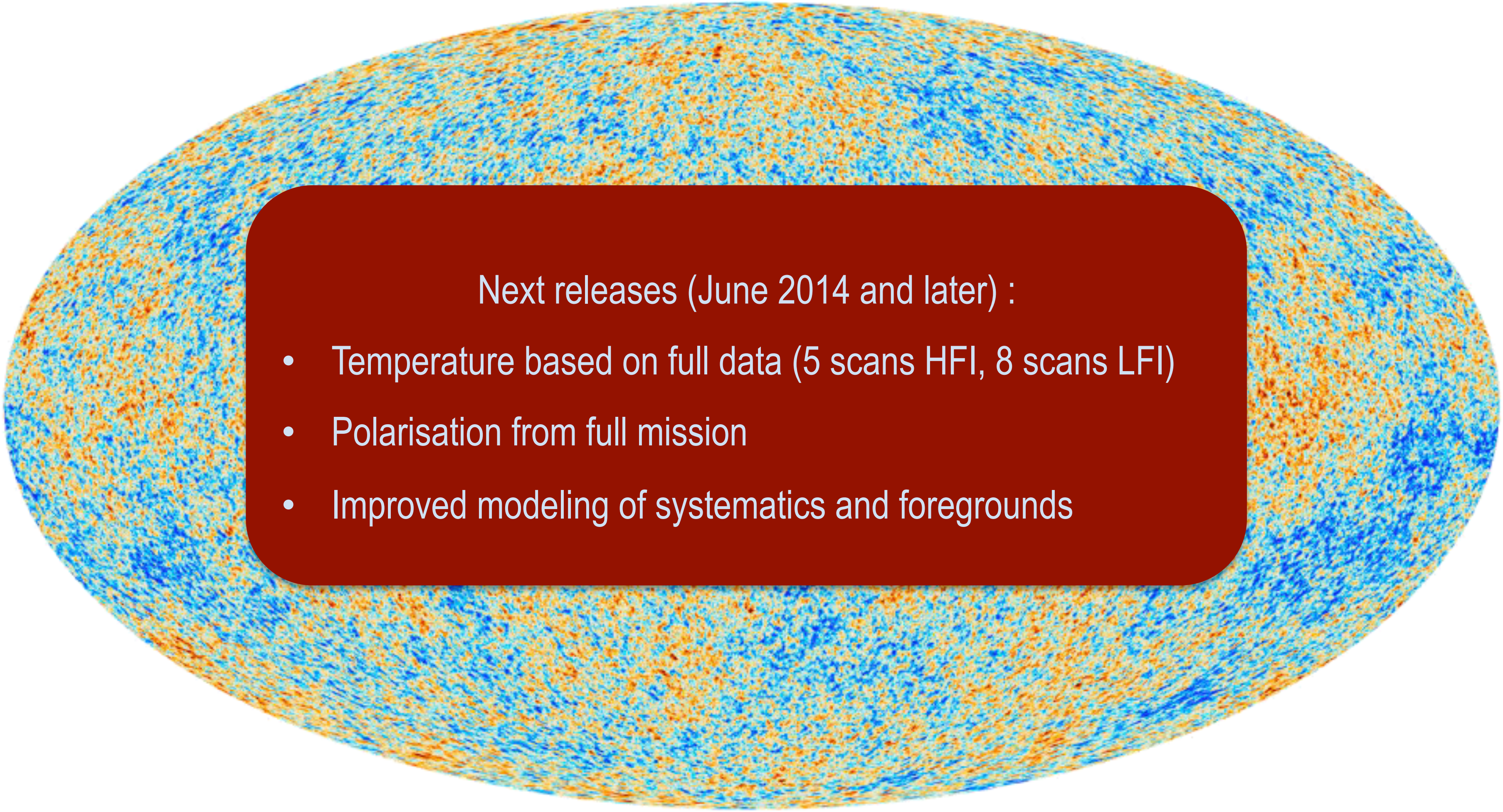

Next releases (June 2014 and later) :

- Temperature based on full data (5 scans HFI, 8 scans LFI)
- Polarisation from full mission
- Improved modeling of systematics and foregrounds

The Planck release of March 2013

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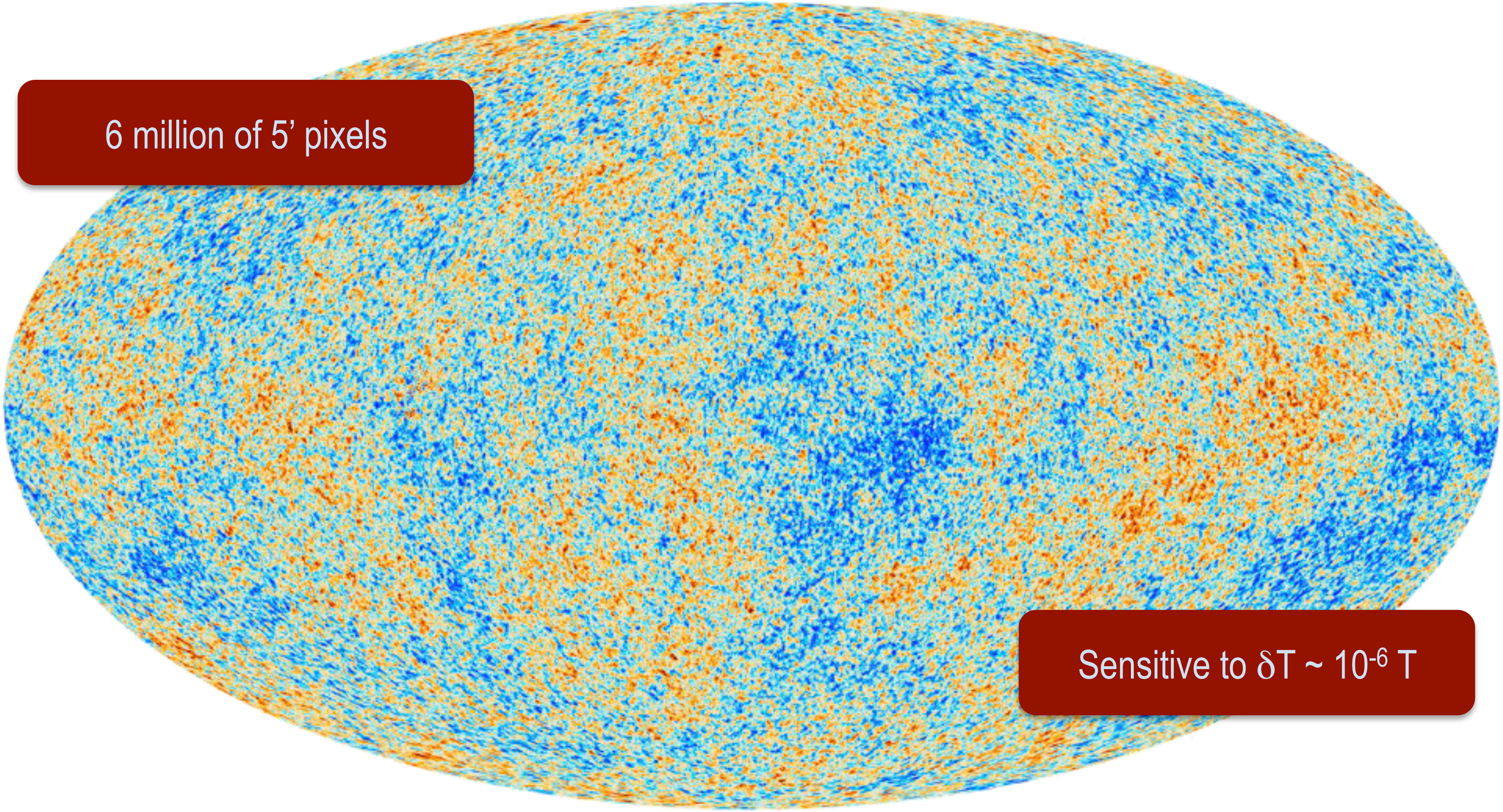

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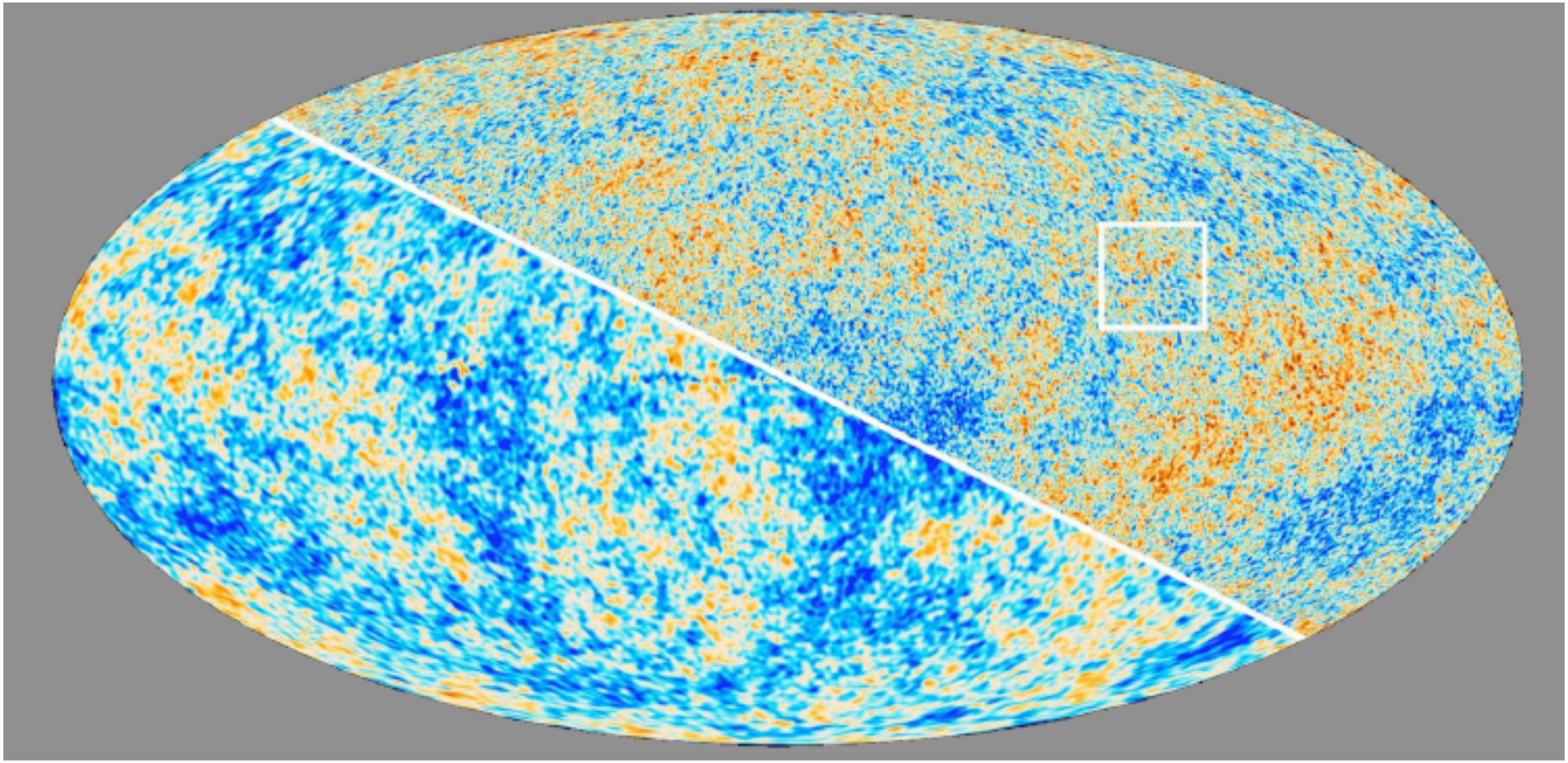
Resolution 3 x greater and detector noise 25 x smaller than WMAP :



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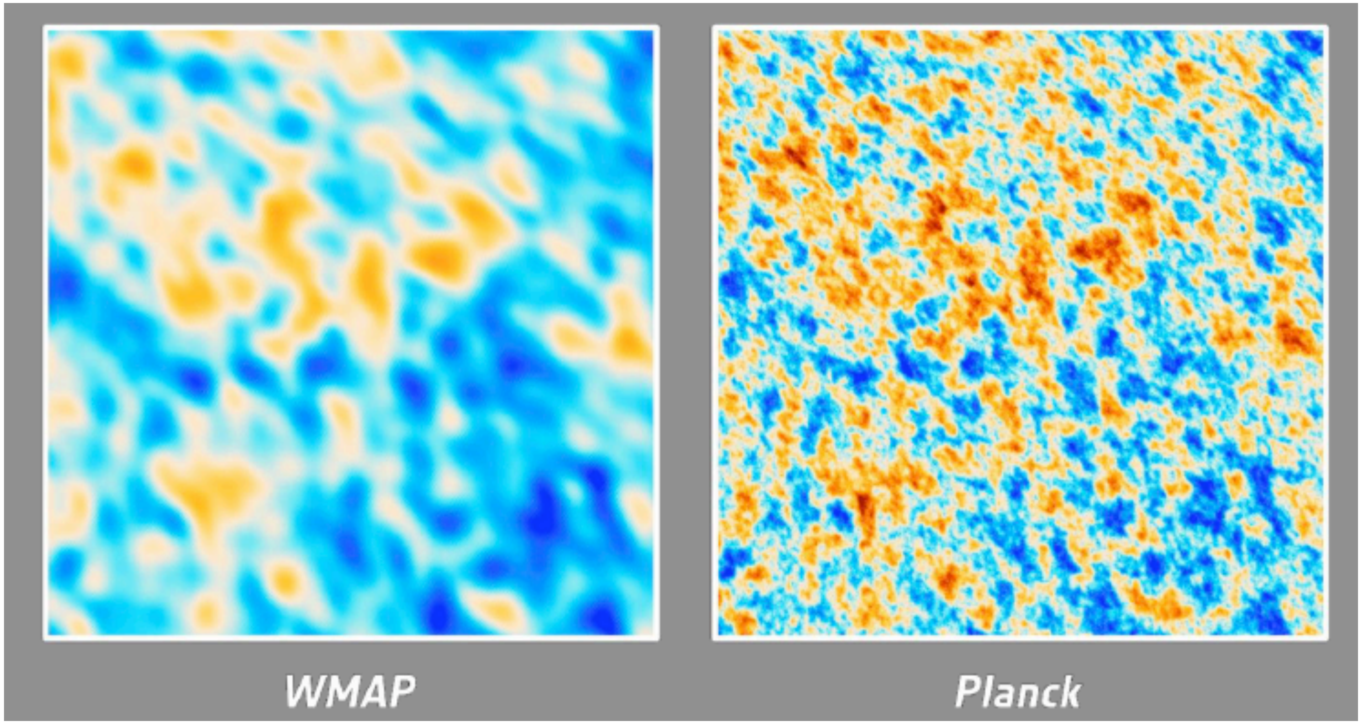
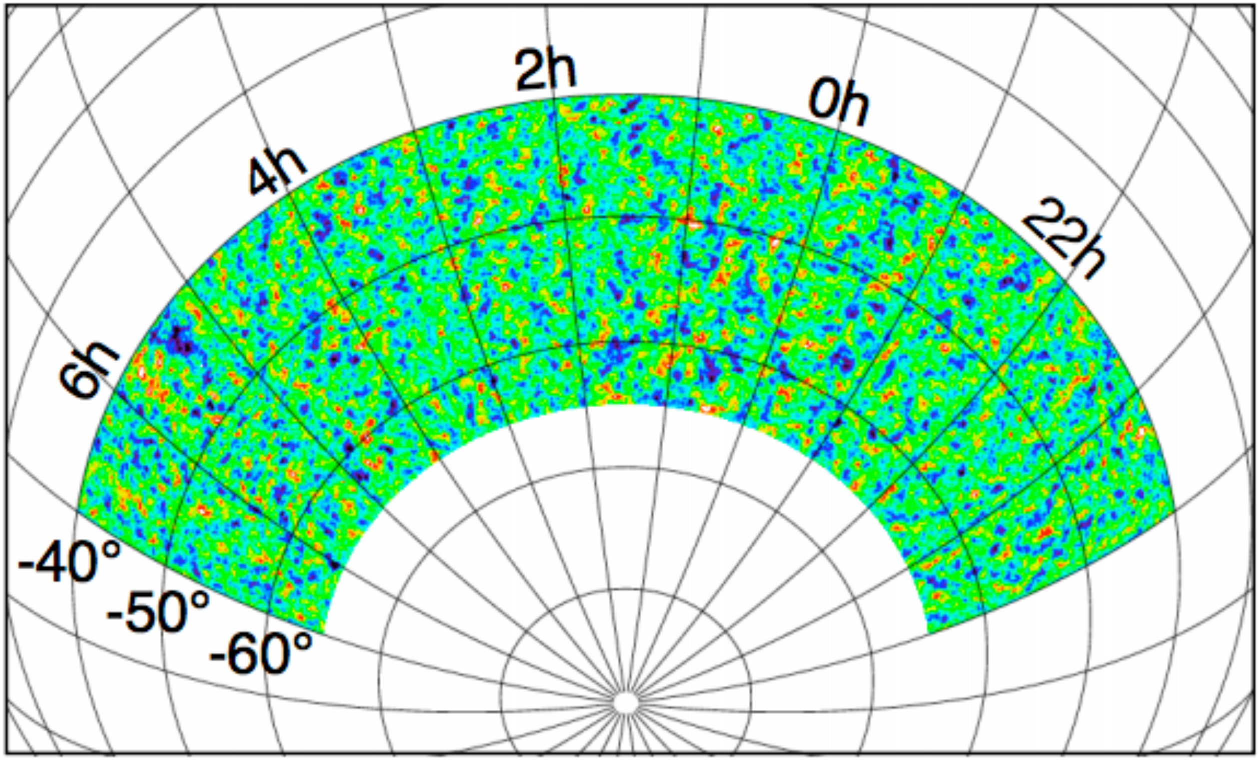


The Planck release of March 2013

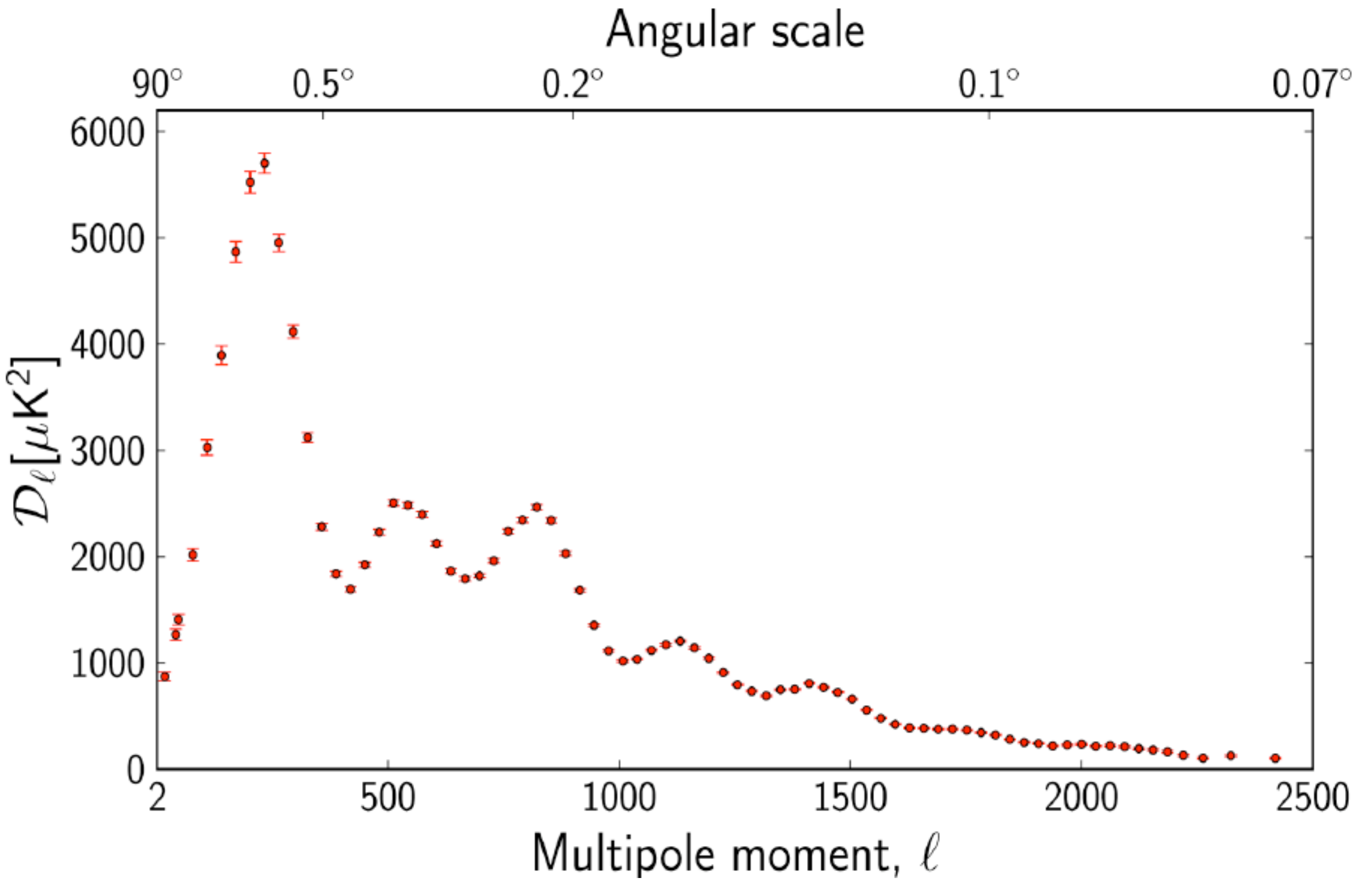
Resolution worse than SPT/ACT but much larger sky coverage :



SPT 2500 square degree field (6% of the sky)

The Planck release of March 2013

Large number of frequency channels, detectors per channel, redundant scans, allowed unprecedented amount of self-consistency checks



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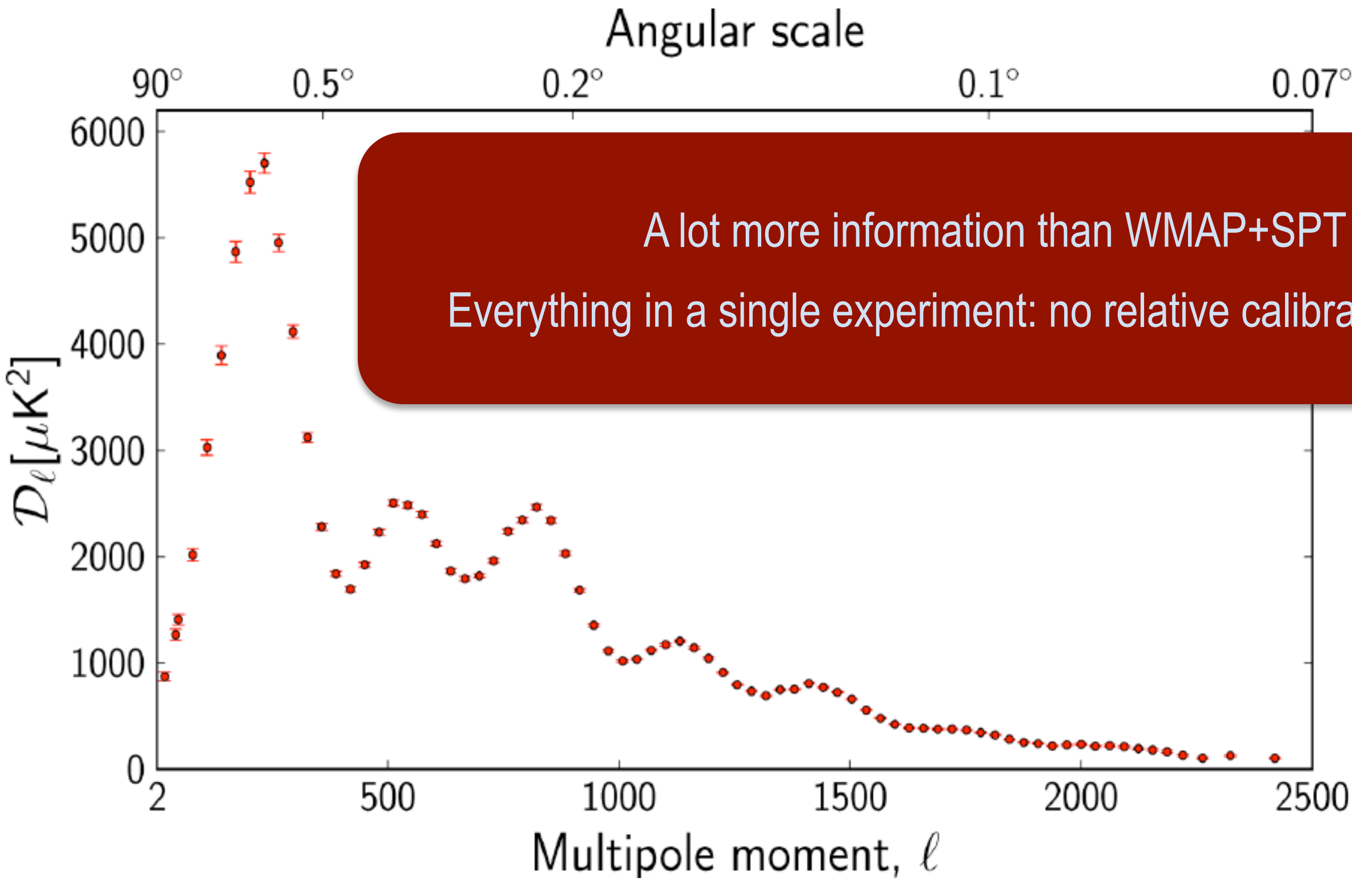

A lot more information than WMAP+SPT

Everything in a single experiment: no relative calibration issues

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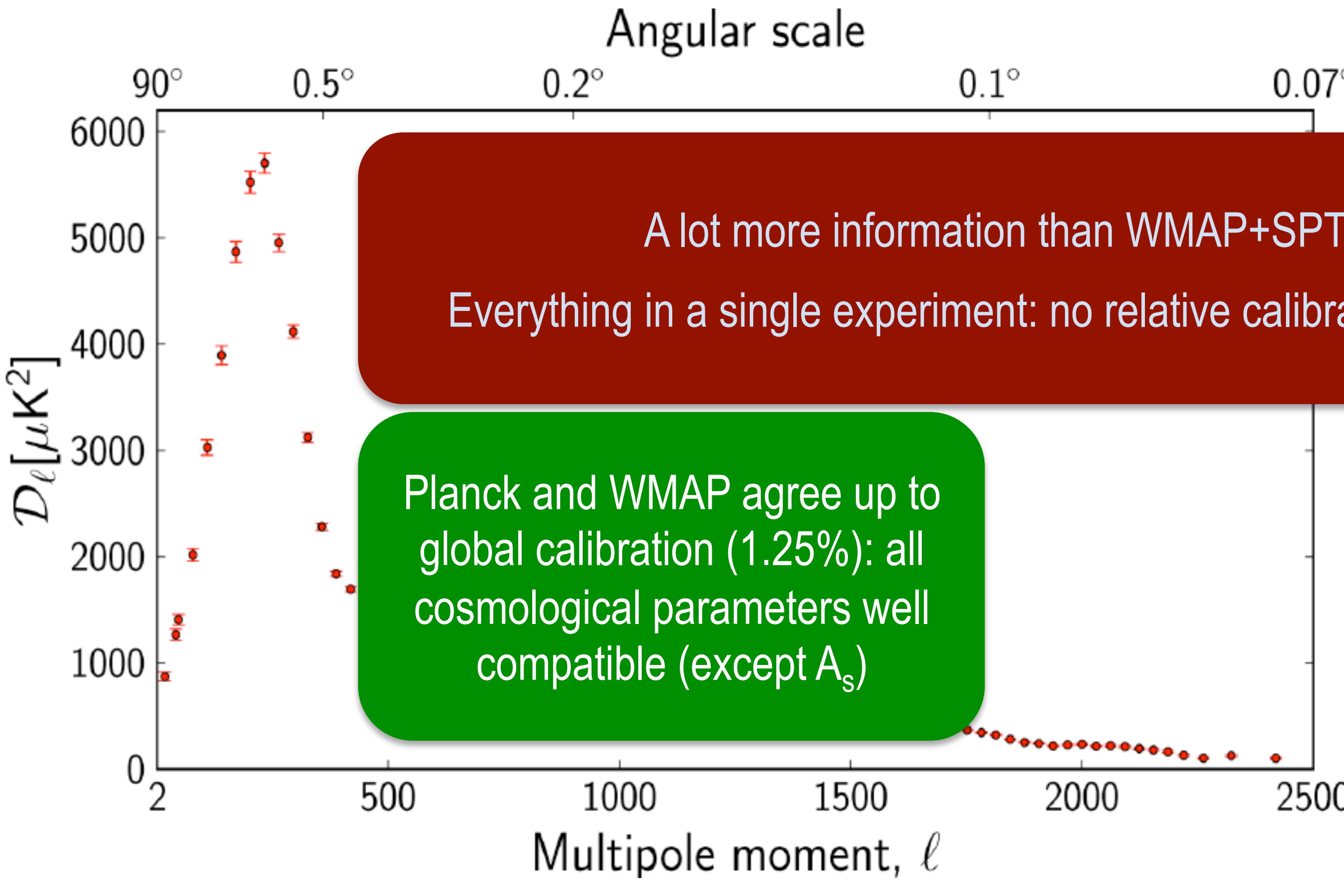

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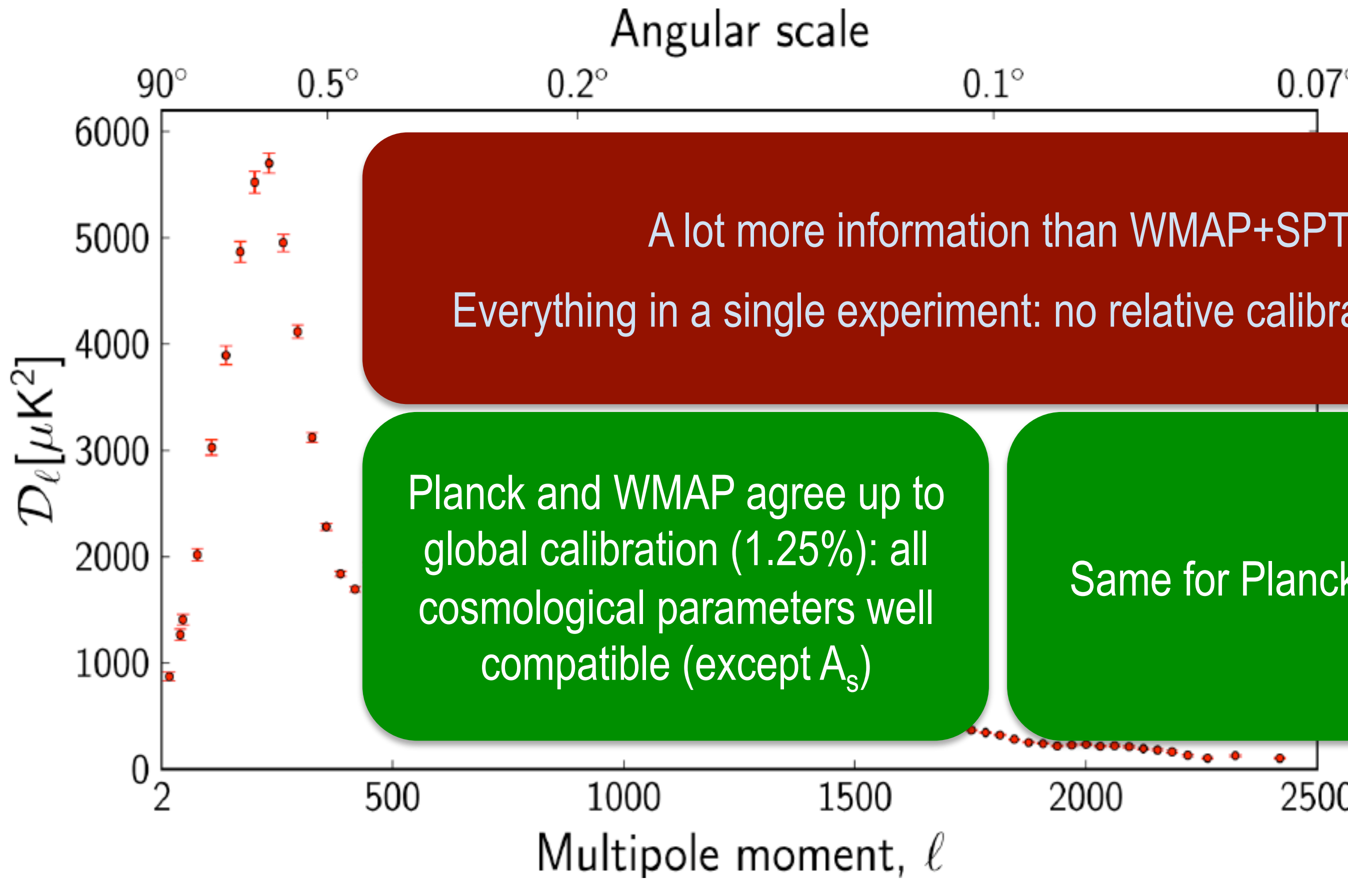

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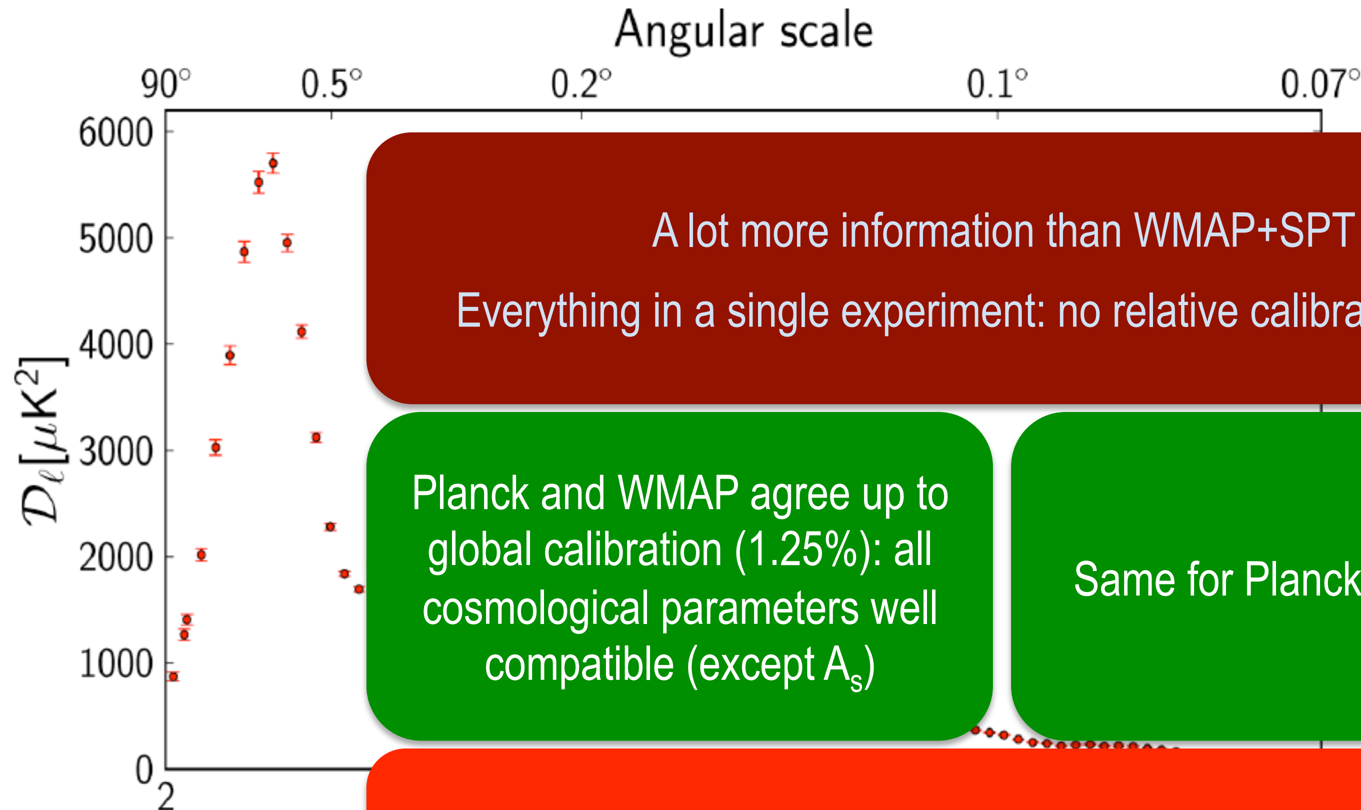

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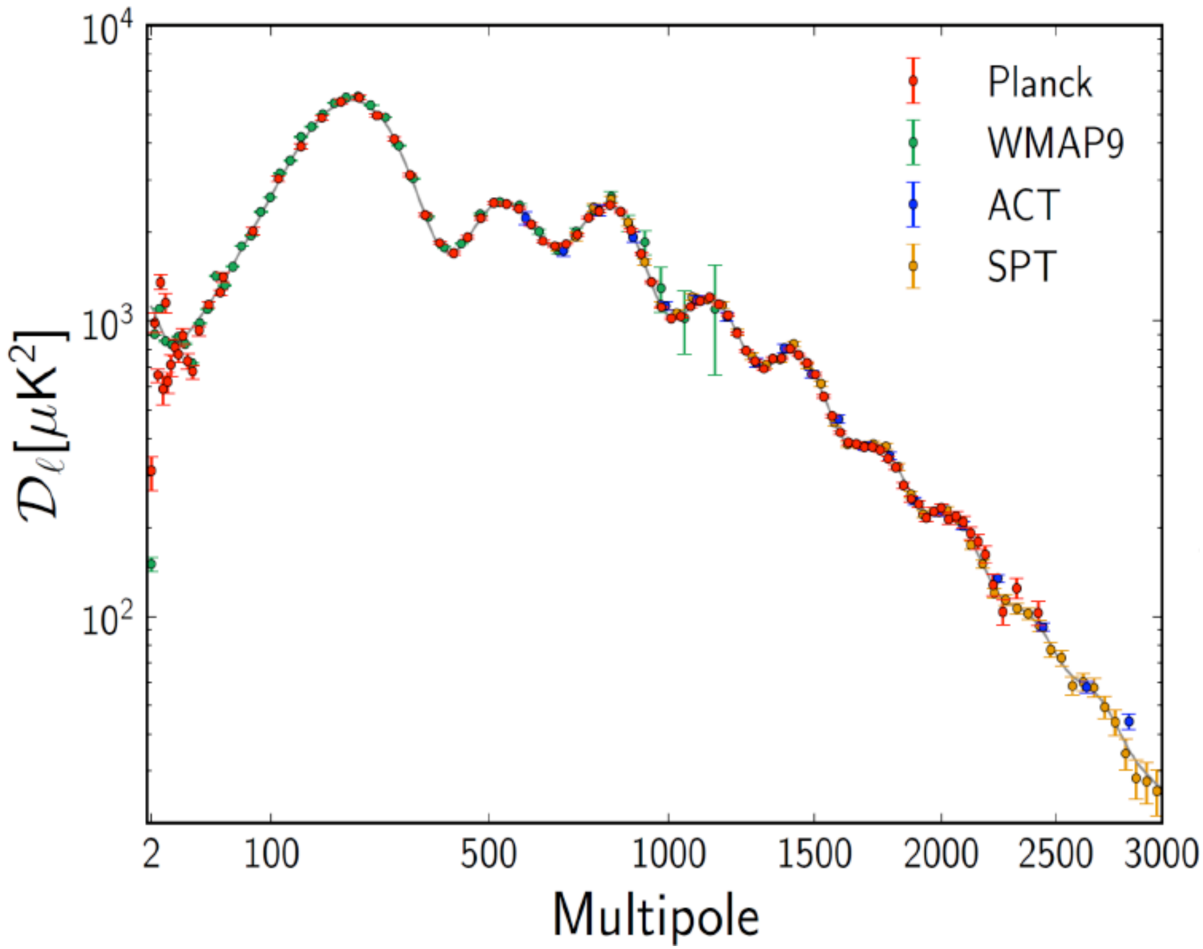
2012: problem with relative calibration of SPT12 w.r.t WMAP7: parameters in tension with Planck

The Planck release of March 2013

After recalibrating WMAP, ACT, SPT, spectra agree perfectly:



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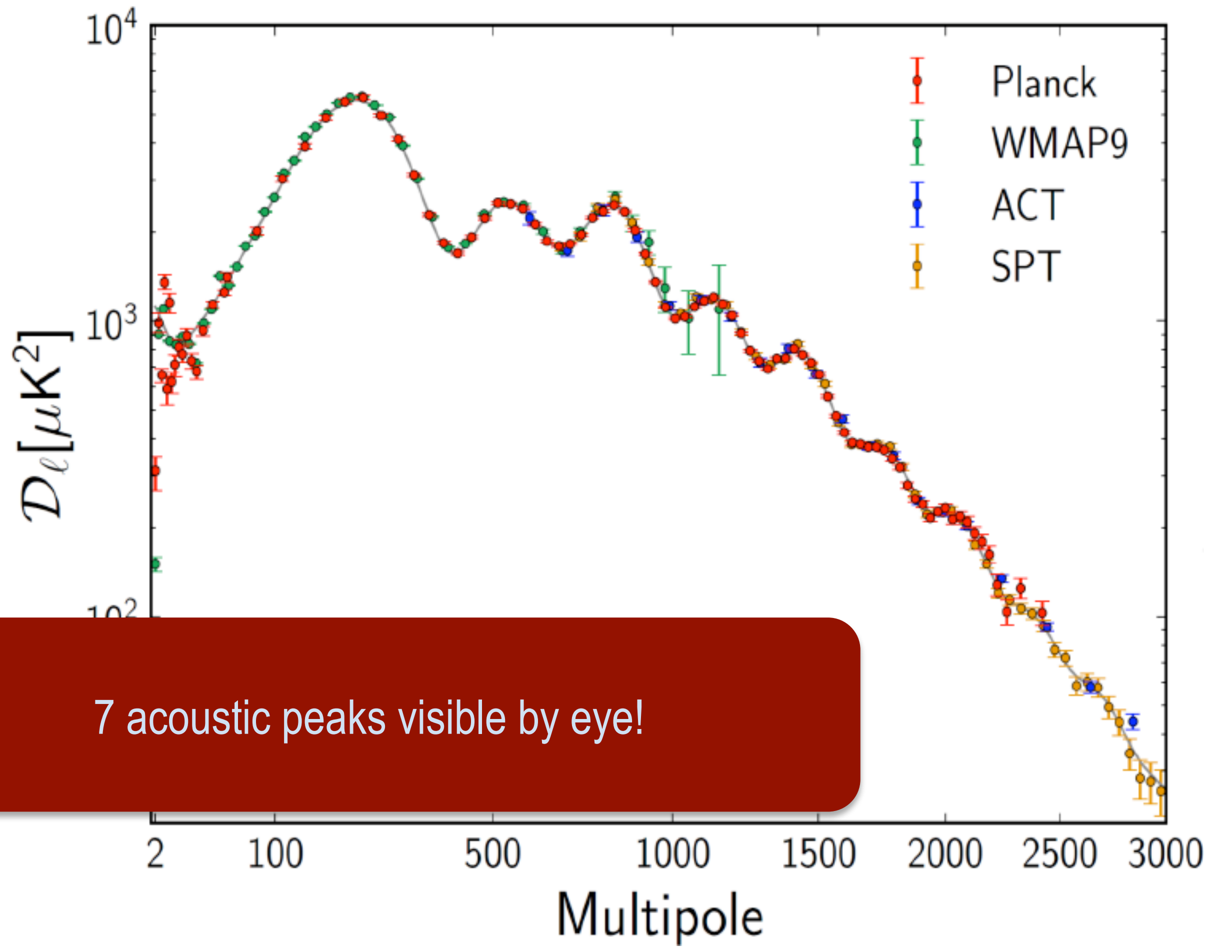

7 acoustic peaks visible by eye!

The Planck release of March 2013

Several beautiful products relevant for cosmology, beyond temperature power spectrum:

The Planck release of March 2013

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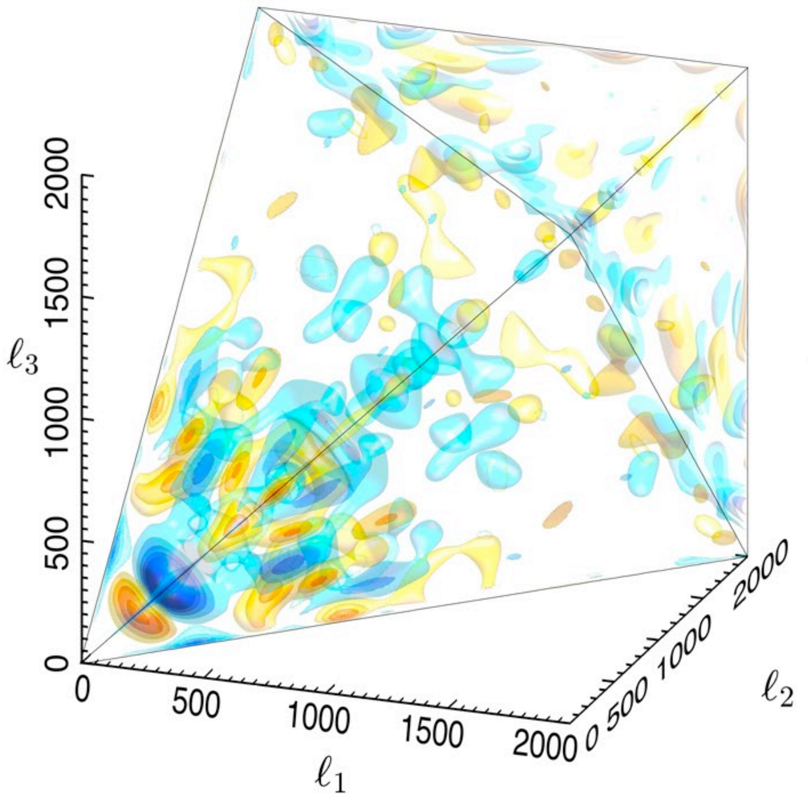
- Temperature bispectrum



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Several beautiful products relevant for cosmology, beyond temperature power spectrum:

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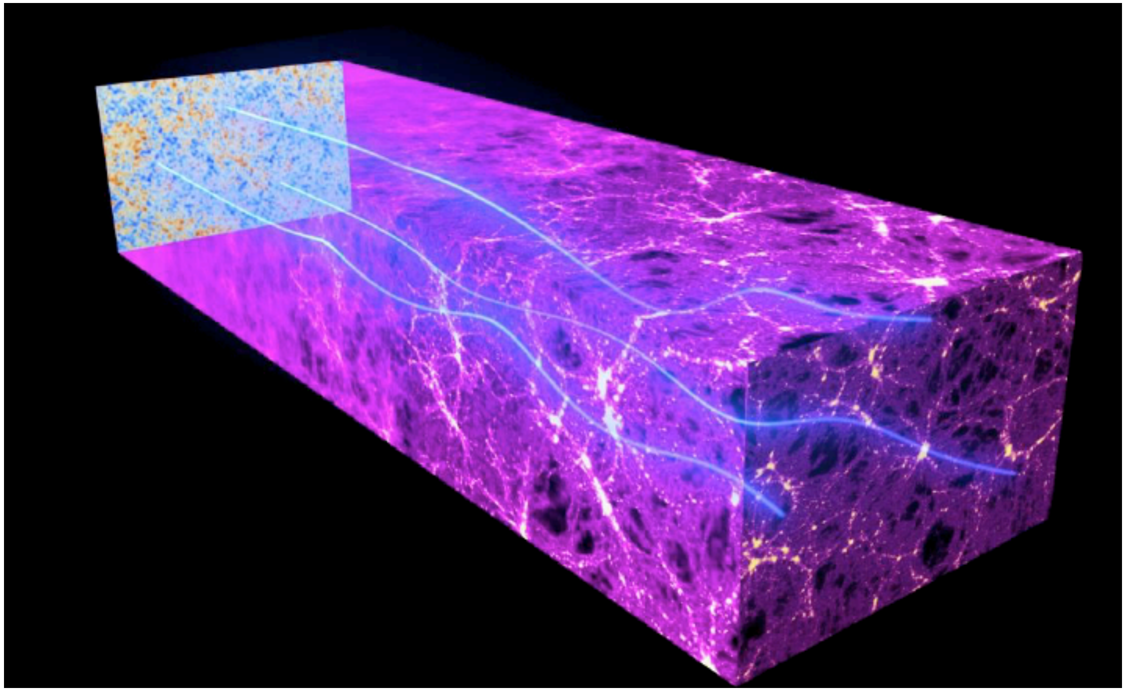
- Lensing potential map from temperature correlations



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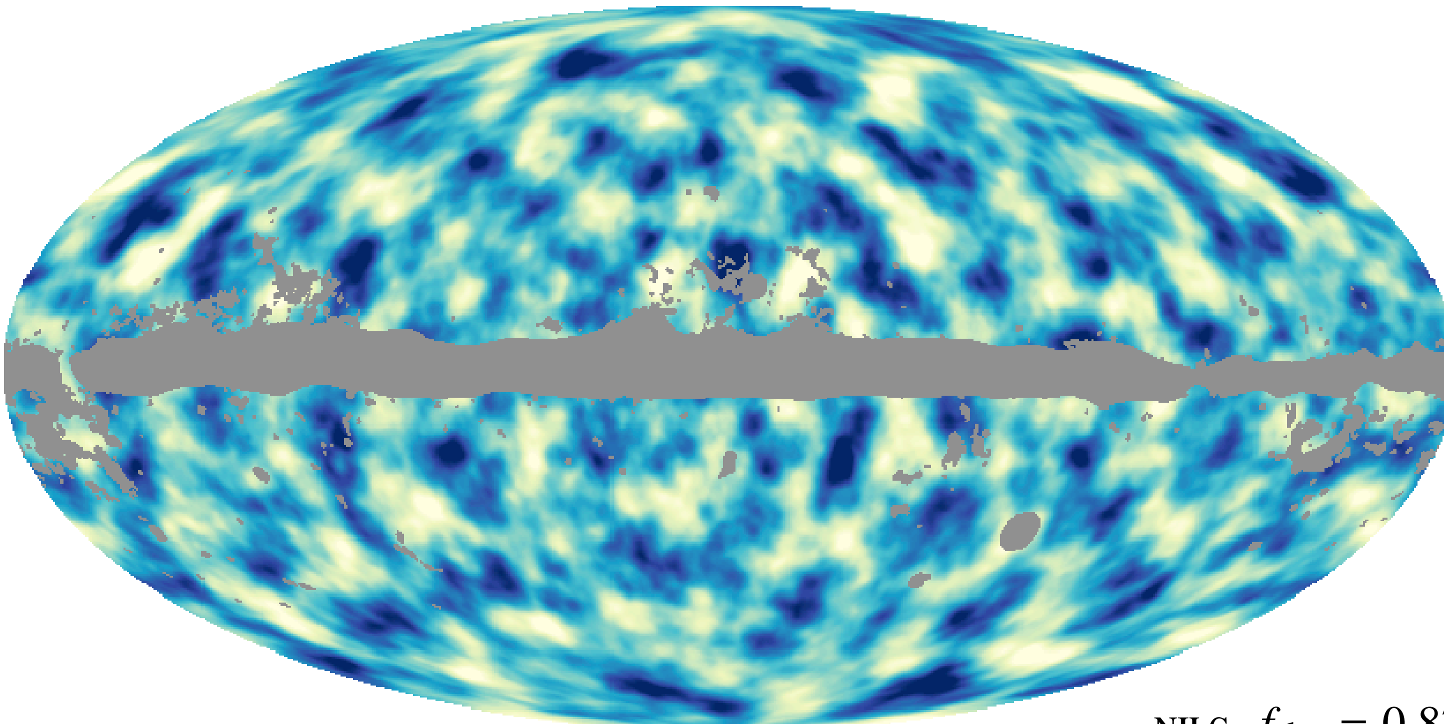

NILC, $f_{\rm sky} = 0.87$

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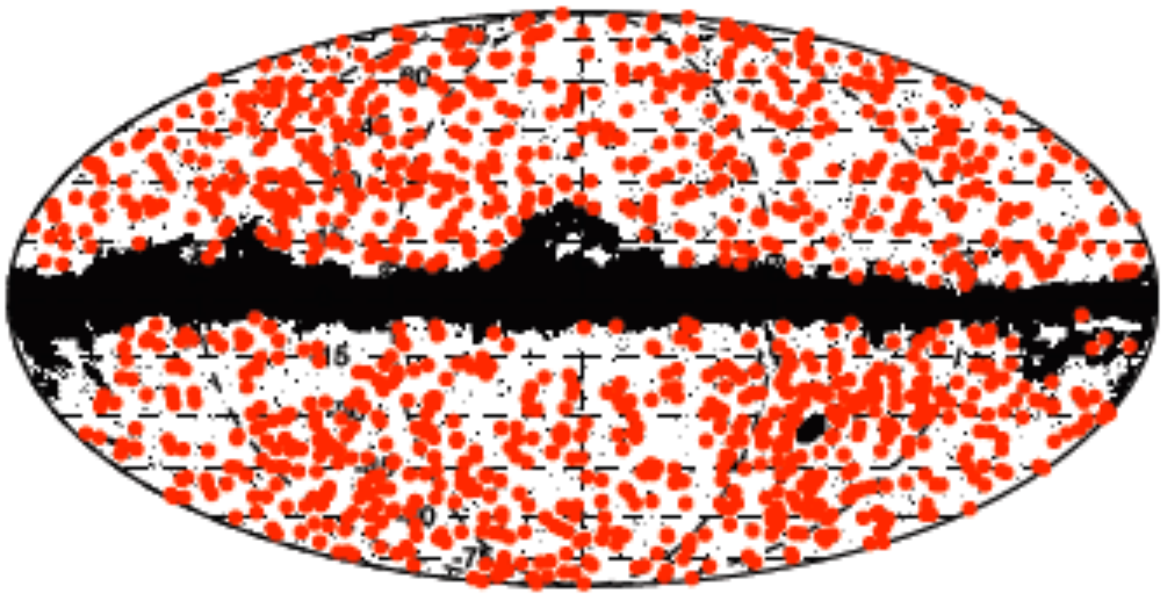

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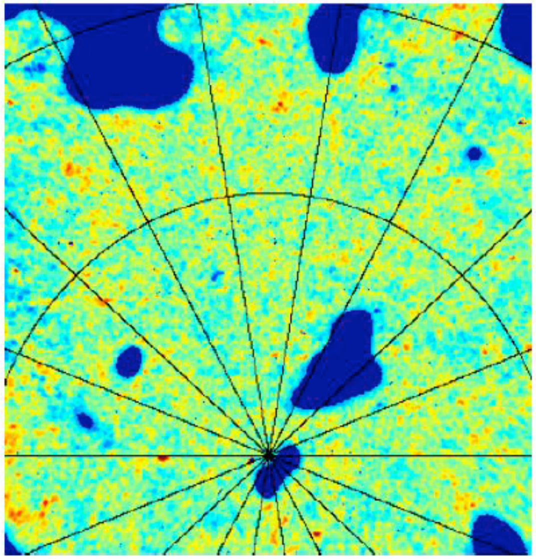

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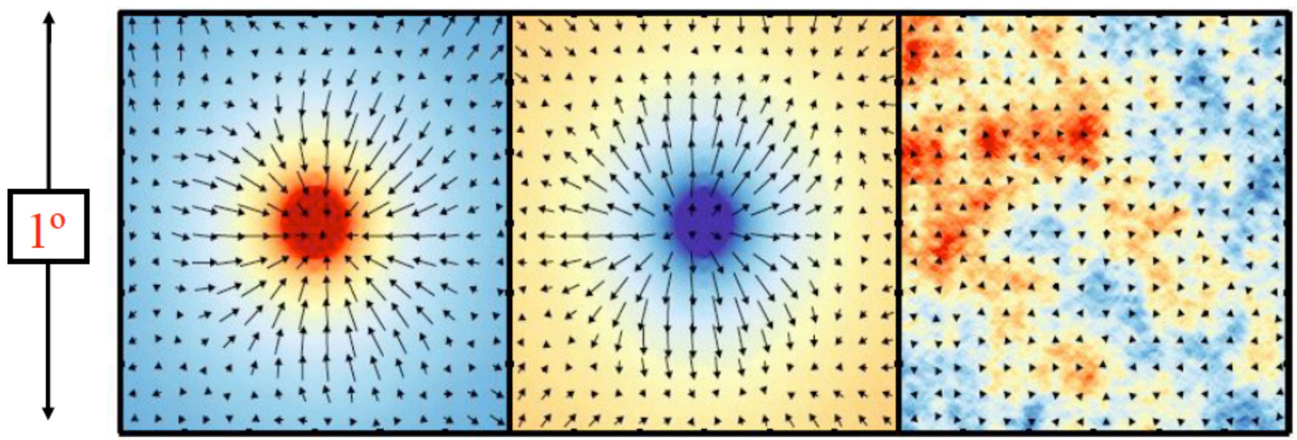
and correlations between them!

e.g. 42σ detection of lensing x CIB correlation



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- Temperature bispectrum
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- Cluster map from Sunayev-Zel'dovitch effect
- Dusty star-forming galaxy map from Cosmic Infrared Background
- Motion of solar system w.r.t. cosmic frame from temperature trispectrum (Doppler boost, independent of dipole anisotropy)

$v = 384\ km.s^{-1} \pm 78\ km.s^{-1}$ (stat) $\pm 115\ km.s^{-1}$(sys)

compatible with observed dipole: $369\ km.s^{-1}$

What should we remember from the data analysis?

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Striking consistency …

… with other experiments, bringing ever stronger evidence for flatness, simplest models of inflation, cosmological constant, etc.

… or marginal inconsistencies …

… questionning number of relativistic degrees of freedom, neutrino masses, large-scale isotropy, etc.

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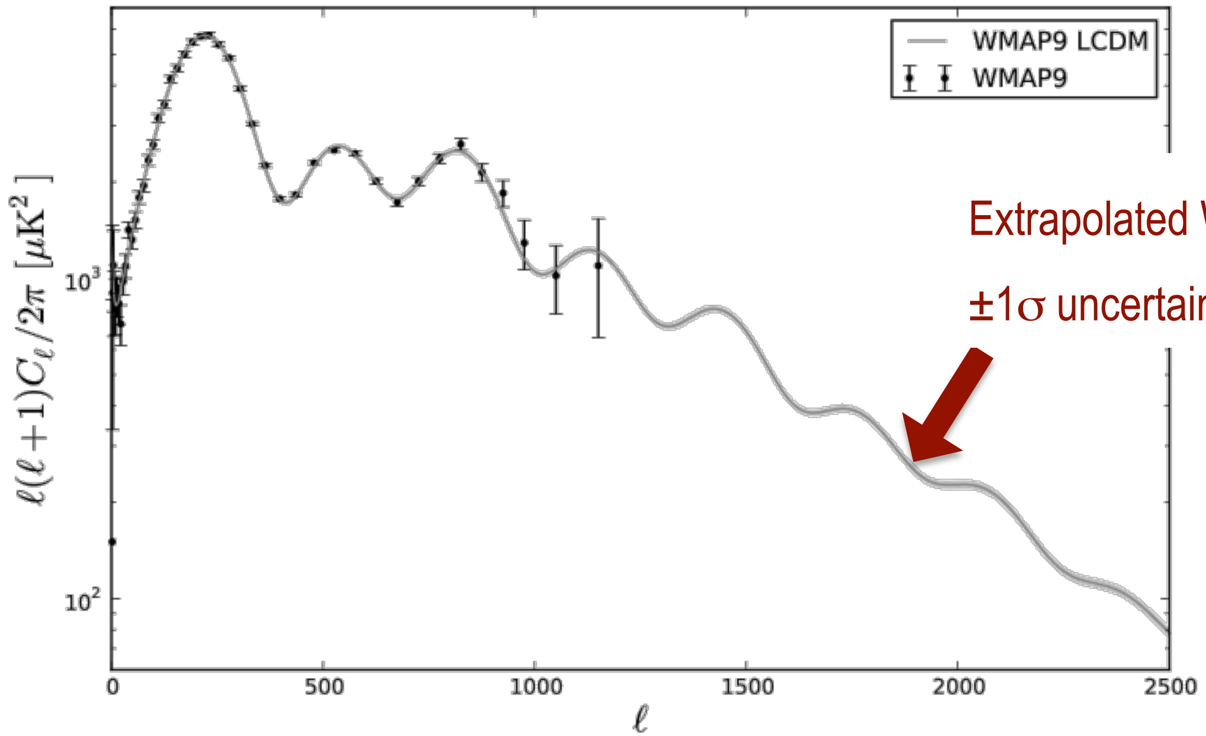
(2) … or marginal inconsistencies …

… questionning number of relativistic degrees of freedom, neutrino masses, large-scale isotropy, etc.

Consistency between Planck and other experiments within ΛCDM model

- WMAP data + LCDM model make very precise prediction on small scales:



Extrapolated WMAP9 best-fit

±1σ uncertainty assuming ΛCDM

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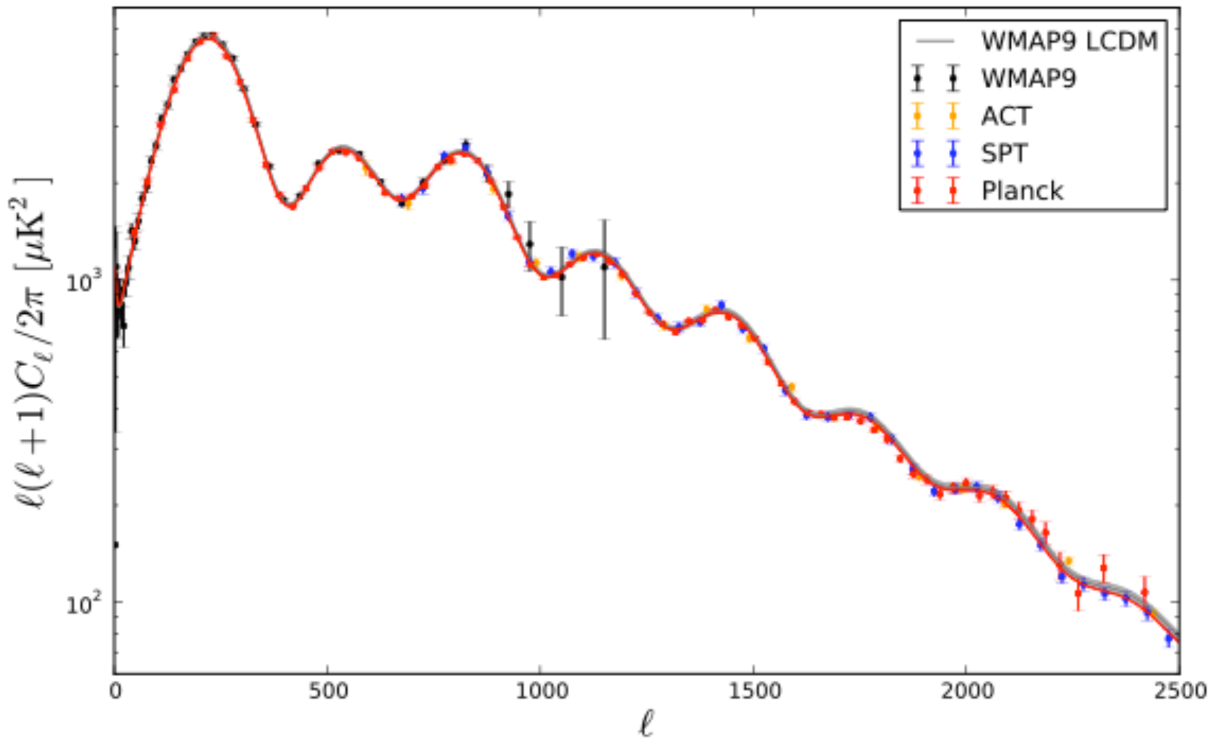

… in extraordinary agreement with Planck data / best-fit : no WMAP-Planck tension

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Also beautiful agreement between Planck best-fit and :

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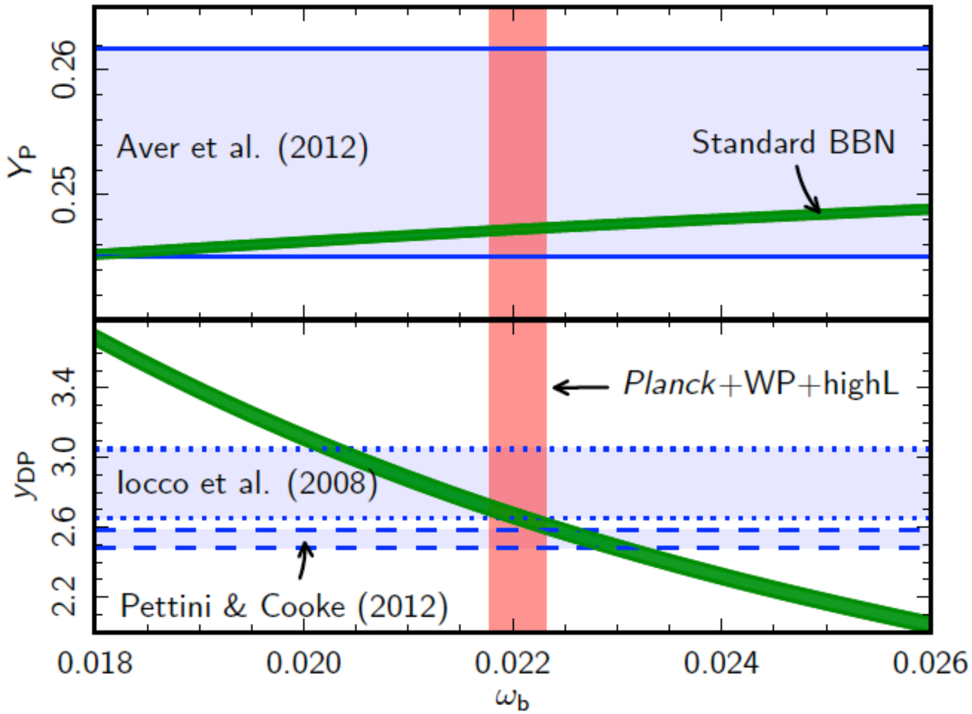

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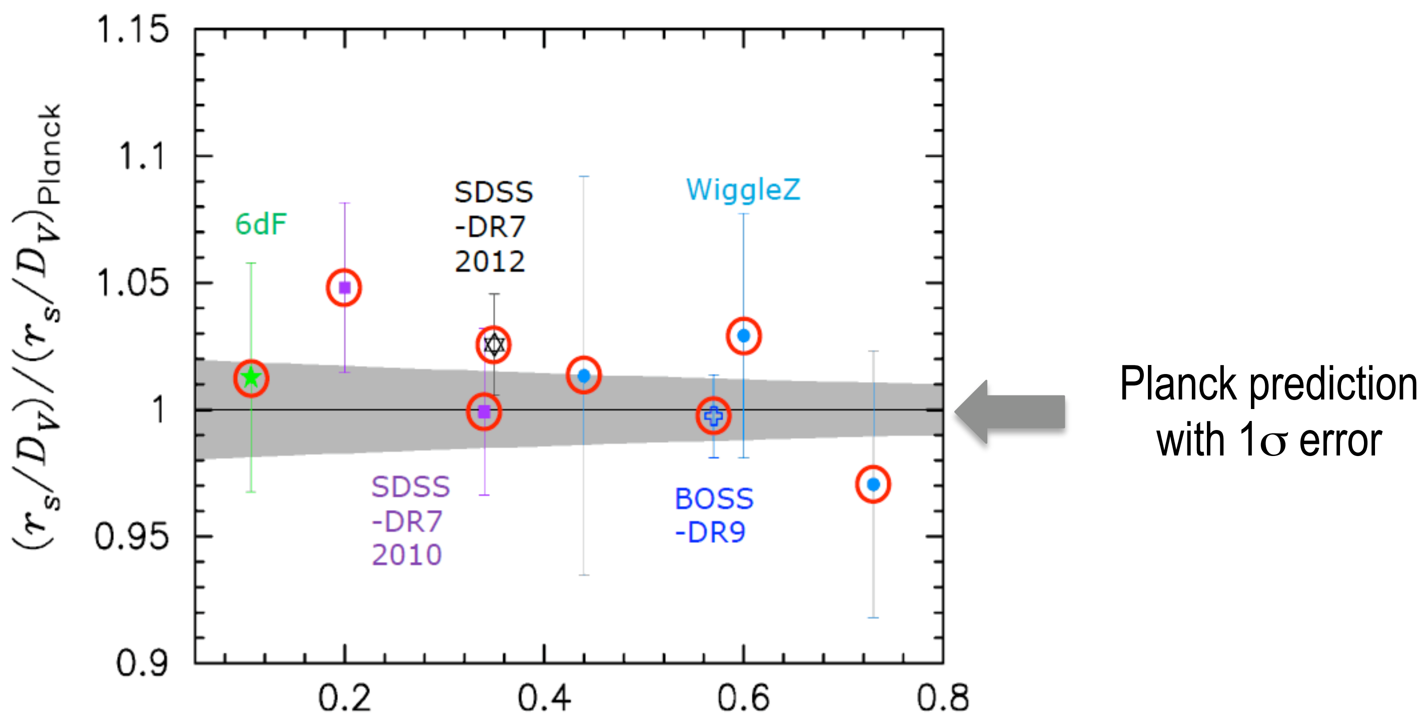

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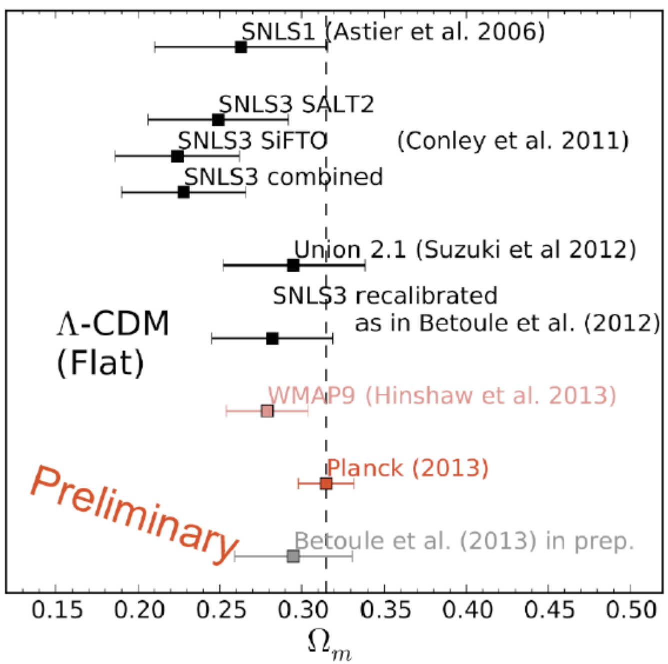
- BBN data
- BAO scale measurements at various redshifts
- SNIA luminosity
  - Excellent with Union 2.1, marginal with SNLS3 2011, excellent with SNLS3 2012-2013



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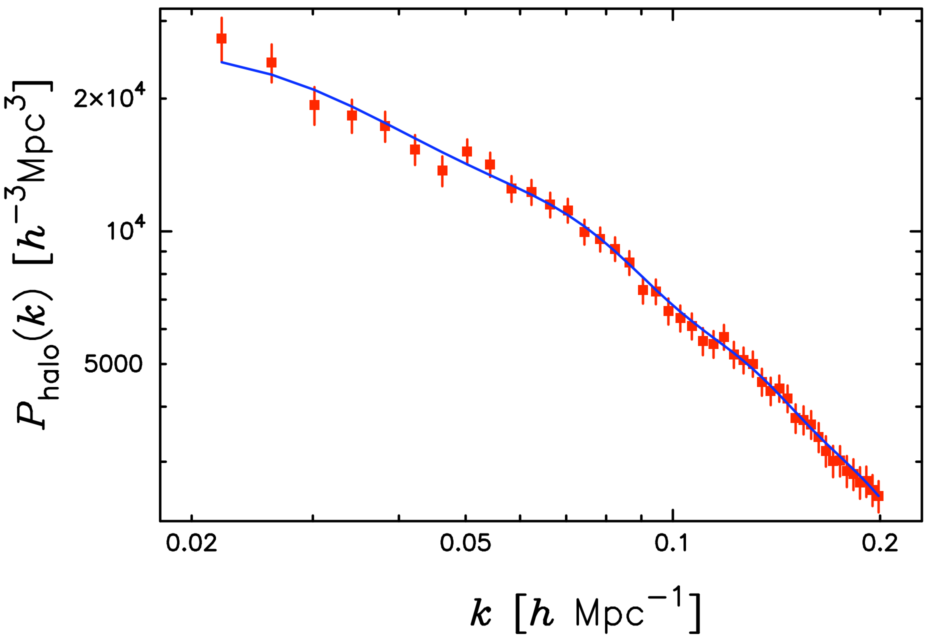
- Shape of galaxy correlation function (here SDSS LRG)



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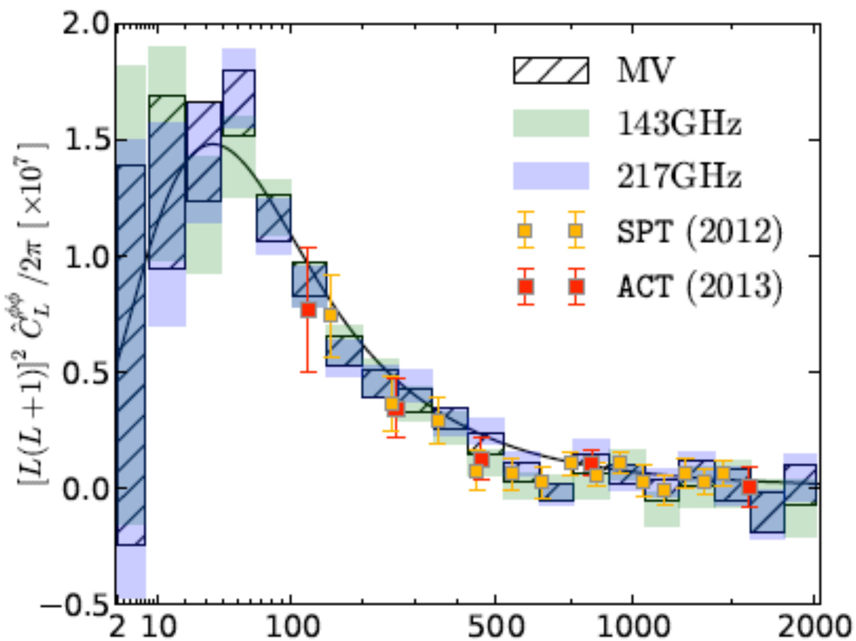

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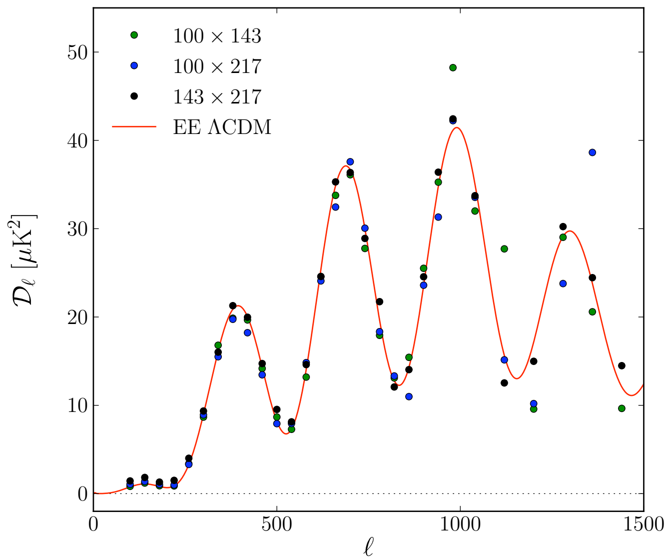
- Preliminary Planck polarisation data



Many extensions of LCDM not favored and bounded…

- Spatial curvature
- Dark energy with
  - $w \neq -1$
  - $w_0 + a\, w_a \neq -1$
- Large DM annihilation (smooth background)
- Variation of the fine-structure constant
- Running of the primordial spectral index
- Features in the primodial spectrum
  - Binning method
  - Parametric search
- Primordial magnetic fields (neglect Faraday; non-helical case; vectors and scalars)
- Isocurvature modes
  - General correlated CDM, neutrino density/velocity
  - Axion-like (CDM, uncorrelated)
  - Curvaton-like (CDM, maximally correlated)
- Primordial non-gaussianity
- Topological defects contribution
- Non-trivial topology
- Several inhomogeneous background models (Bianchi…)

Maximal likelihood does not increase, or increases marginally w.r.t number of extra parameters

(can be expressed in terms of Bayesian evidence ratio)

Simplest inflationary models established as leading mechanism for primordial perturbations…

- Flatness
- Gaussian primordial perturbations
- Adiabatic primordial perturbations
- Power-law primordial spectrum
- No detectable signatures of topological defects, curvaton, …

Newest statement

- Primordial GW and inflationary energy scale yet to be discovered,

$V_* < (1.94 \times 10^{16}\ \mathrm{GeV})^4$ (95%CL)

- Preference for concave potentials (includes hilltop, R^2, Higgs inflation…)

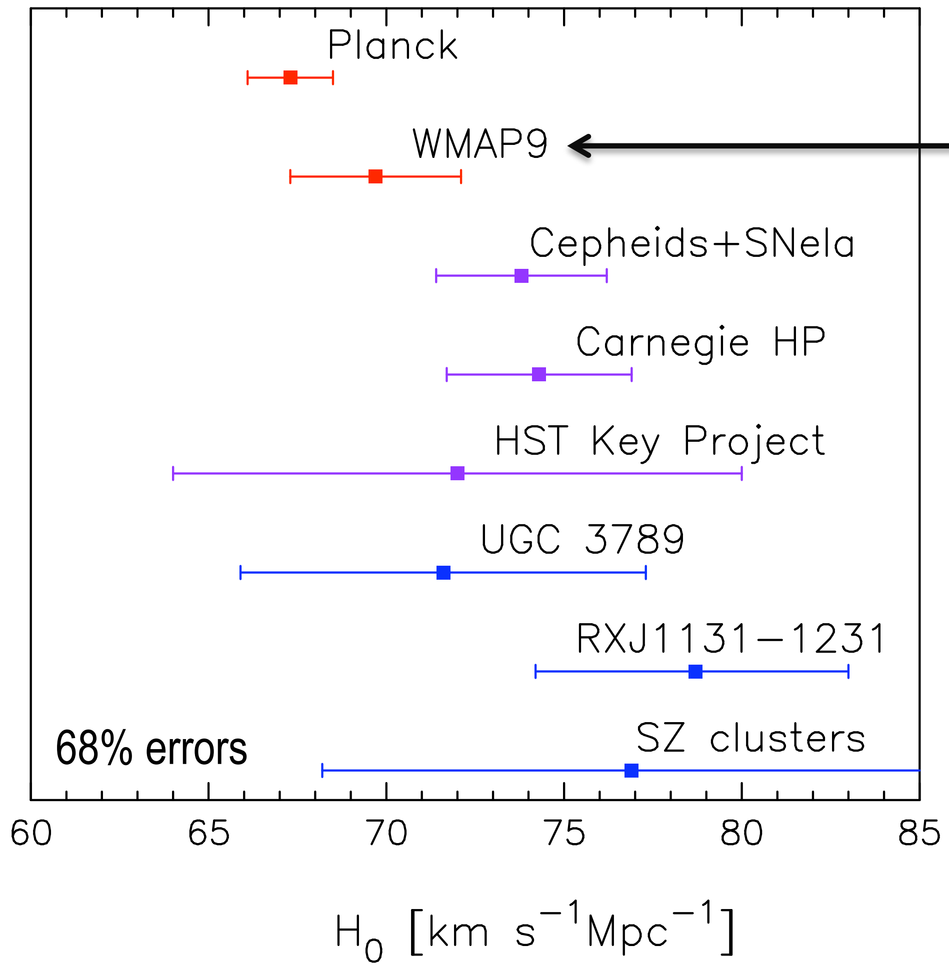
Marginal inconsistencies…

If you believe that 2σ (or at most 3σ) tensions should not even be mentioned/ discussed…

STOP LISTENNING

If you wish to be aware of them, since they could be some preliminary hints of future discrepancies/discoveries…

Planck versus direct H_0 measurements (assuming ΛCDM)

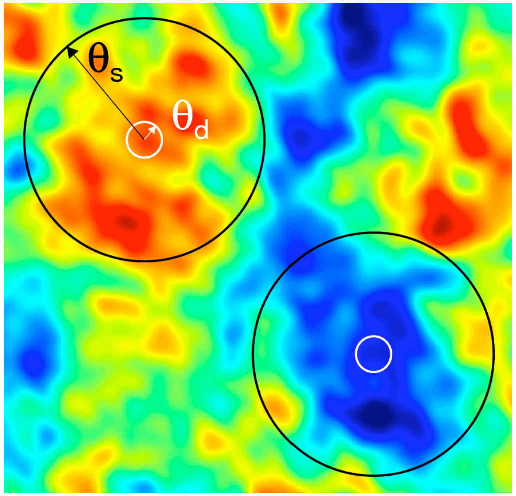


WMAP9 agrees with both (while WMAP7 + SPT12 in tension with Planck, due to relative calibration issue)

Planck versus direct H_0 measurements (assuming ΛCDM)

How does the CMB probes H_0 within ΛCDM?

- Angular scale of diffusion damping relative to angular scale of sound horizon:



- In harmonic space : scale of damping tail relative to scale of acoustic peaks

Larger H_0 = for fixed peak location, smaller tail (stronger damping)

Planck – direct H_0 tension (assuming ΛCDM)

Previous CMB constraints on H_0 within ΛCDM:

- WMAP alone: no damping tail measurement, large error bar on H_0 (fixed indirectly by other effects)
- WMAP+SPT12: relative calibration issue: artificially low damping tail, large H_0
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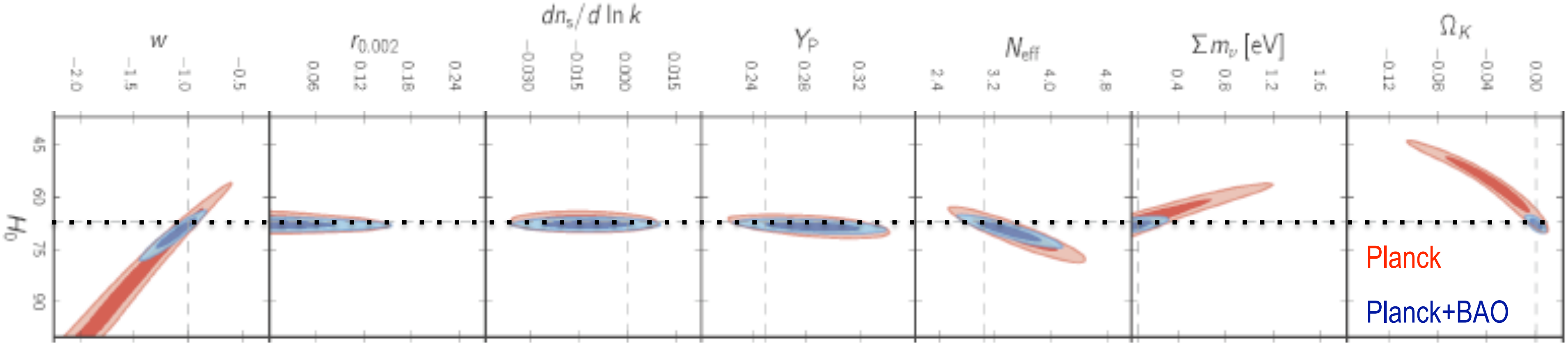
We can:

- Ignore this 2.5σ tension
- Blame Planck (Beams? Foregrounds? Has been tested, very unlikely)
- Blame direct H_0 measurements (Calibration issues? Selection effects? Has also been tested)
- Argue that observables are different (local/global H_0): not sufficient — Marra et al. 2013
- Go beyond ΛCDM

Planck – direct H_0 tension (assuming ΛCDM)

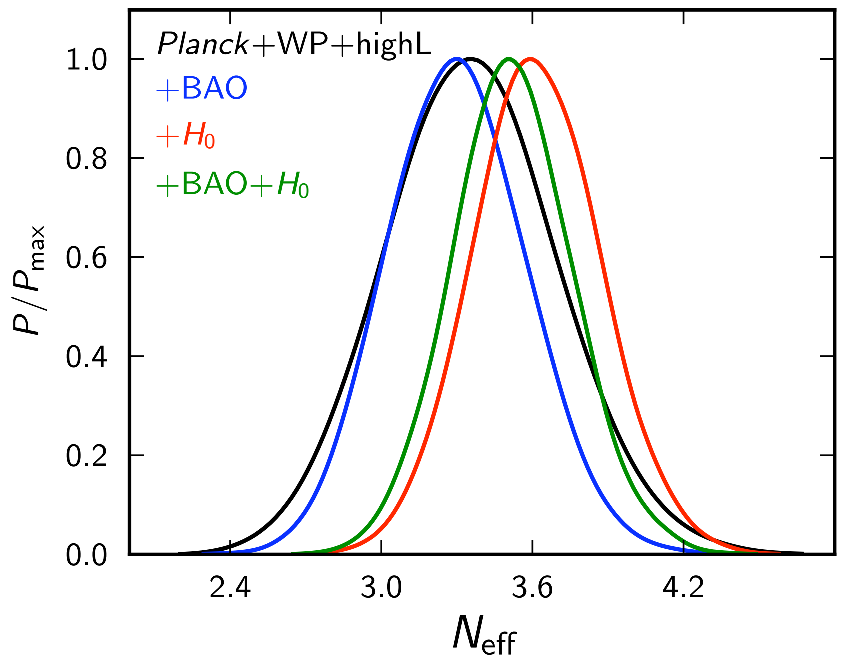
How can we reduce the tension between Planck and H_0 without introducing tension with BAO?



- Phantom DE (w ~ -1.2)
- Huge primordial Helium fraction (in clear conflict with BBN)
- N_{eff} ~ 4 : increasing N_{eff} with fixed z_{eq} leads to larger H_0 (and stronger damping)
- Probably some less economic explanations…

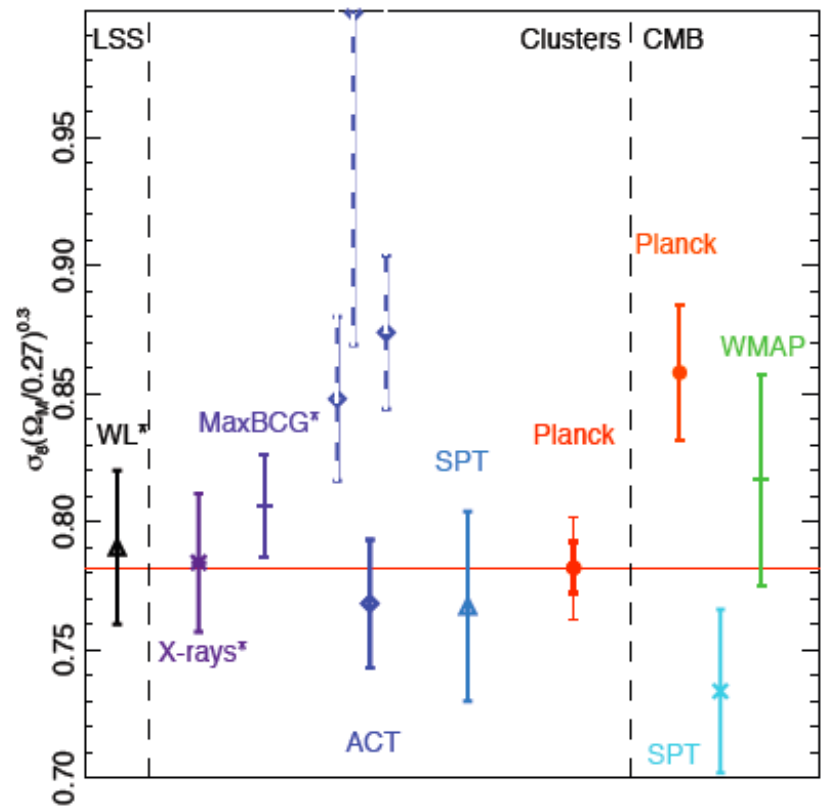
Status of N_{eff} constraint

- Before Planck: $N_{eff} > 3$ preferred by CMB (WMAP7 + SPT12, WMAP +ACT) due to artificially low damping tail
- After Planck: $N_{eff} = 3.046$ well compatible with Planck+BAO, but $N_{eff} > 3$ relaxes tension with H_0 (always with small significance, ~ 2.3σ)



σ8 tension

- σ8 = amplitude of large scale structure power spectrum on inter-galactic scale
- Probed by galaxy redshift surveys, cosmic shear surveys, cluster count, Lyman-alpha forest in quasars



- Value extrapolated from Planck temperature higher than most LSS results
- Does tension between the two favor a non-minimal neutrino mass *(or some supression of LSS growth due to modified gravity)* ?

Status of M_ν bound

- CMB temperature (primary anisotropy contribution): Early ISW
  - High mass creates depletion for $50<l<100$
- CMB temperature (secondary anisotropy contribution): lensing smoothing
  - High mass leads to less smoothing of acoustic oscillations

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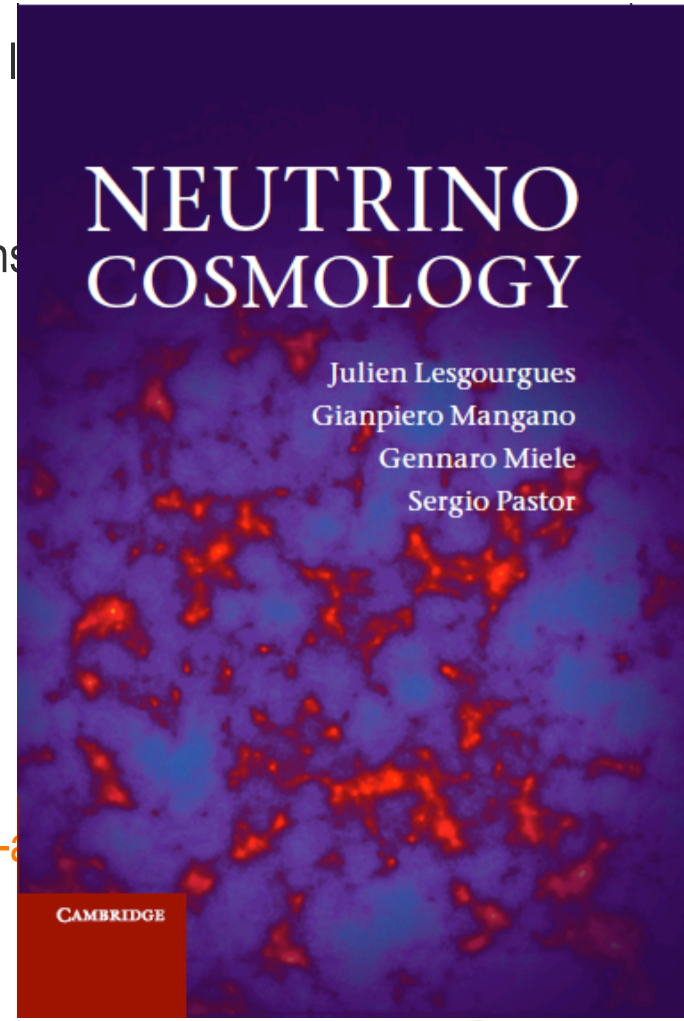

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→ Better fitted with zero/minimal mass

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→ Better fitted with small mass (Σm_ν~0.3-0.8eV)

- Other matter power spectrum estimates (galaxies, Lyman-alpha)
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→ Depends on data

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Better fitted with

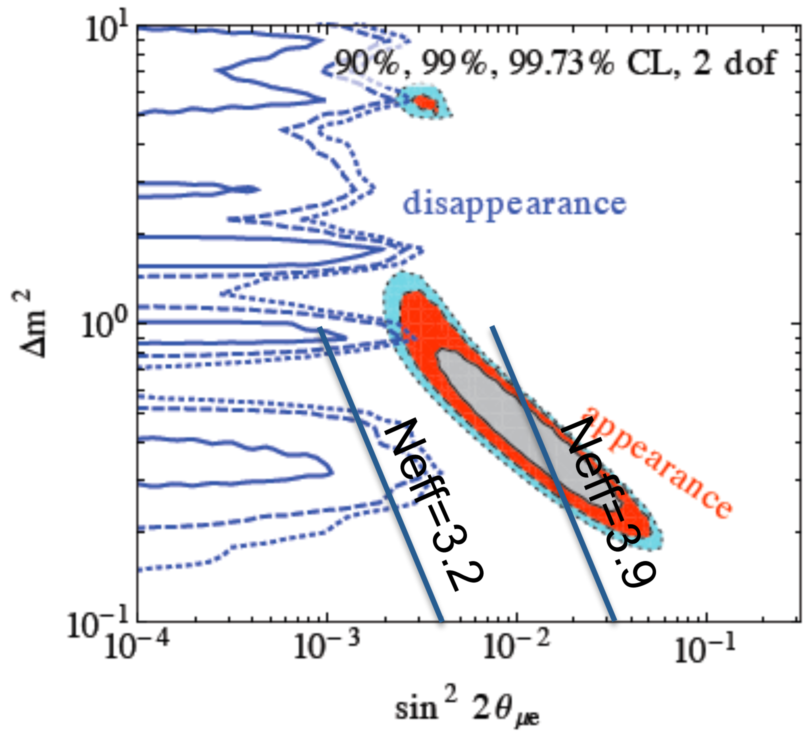
Probably the most robust probe (not affected by bias issues)

Then most reliable bound = Planck + BAO : $\Sigma m_\nu < 0.23$ eV (95%)

Light sterile neutrinos

Motivations: anomalies in short-baseline neutrino oscillation experiments

3+1 analysis in
Kopp et al. 2013



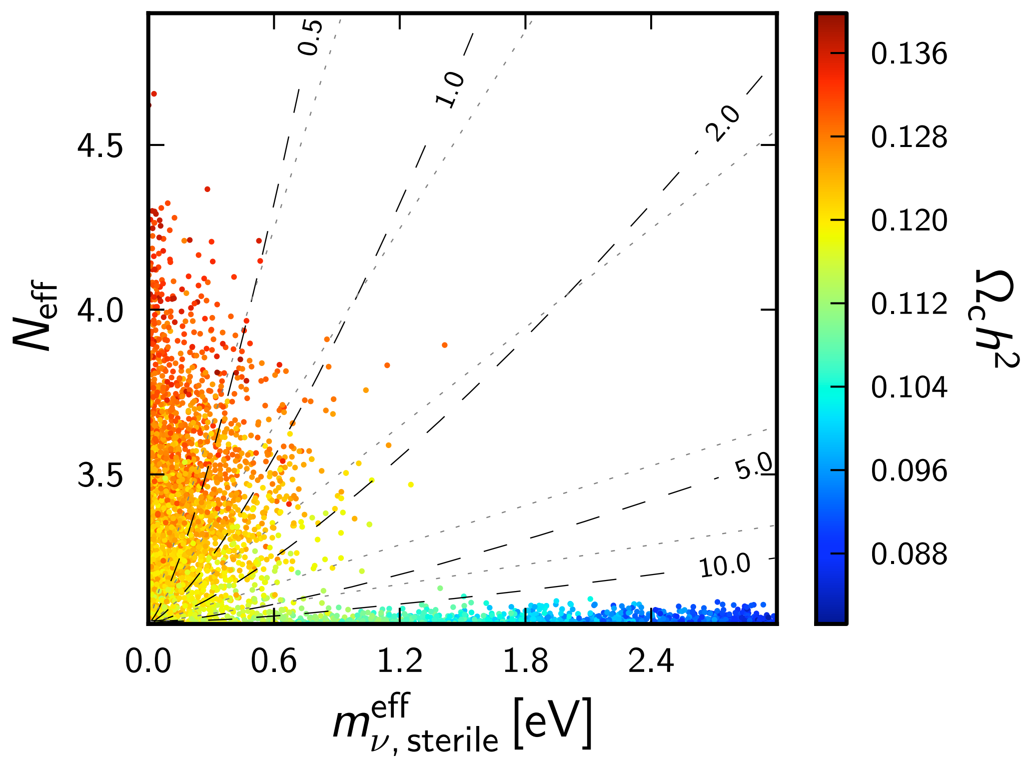
Appearance: LSND, MiniBoone, NOMAD, KARMEN, ICARUS, E776

Disappearance: atmospheric, solar, reactor, Gallium, MiniBoone, CDHS, Minos, KARMEN

Light sterile neutrinos

CMB only (Planck + WP + highL) analysis for 3+1 case:

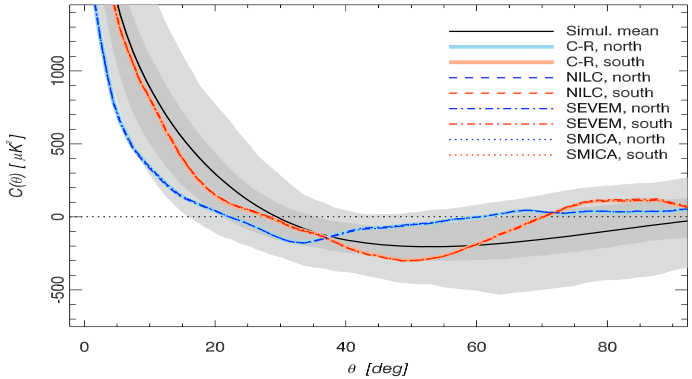
Total neutrino density in early universe



Sterile neutrino density today $\omega_{\nu s}$

Isotropy and large scale anomalies

- Confirmation of small perturbation variance on large angular scales
- Less variance in nothern ecliptic hemisphere on all scales (up to l~1500)
- [Even multipoles supressed till l~25]
- Cold spot
- Low quadrupole
- Quadrupole-octopole alignement



2-point correlation function in real (angular) space

Galactic foregrounds? Solar emission? Peculiarity of local universe?
Lrge-scale inhomogeneity? Primordial fluctuations? Topology? Magnetic fields?

Depends a lot on galactic cut and foreground removal…

Conclusions

- 23 papers fro March 2013 contain thousand times more information…
- fascinating that simplistic minimal comsological model of 1998 is still a good fit, despite reduction of allowed parameter space volume by ~10^5
- Maximally Boring Universe or Maximally Elegant Model ?
  - Actually none of them if anomalies are taken seriously !!
- Potential of improvement for next year's release:
  - From nominal survey to full survey data
  - Polarization
  - Possible improvement of foreground modeling, mask reduction, manoeuvres inclusion