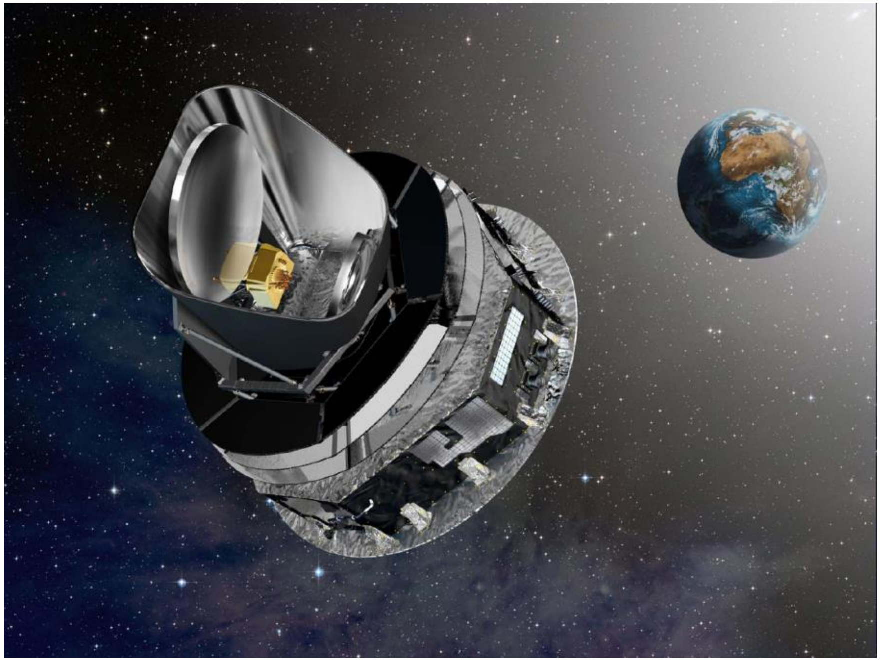
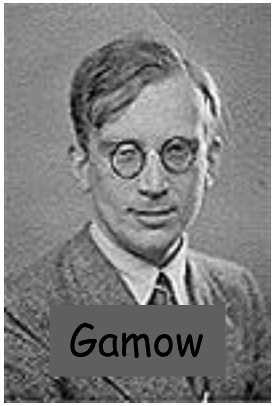


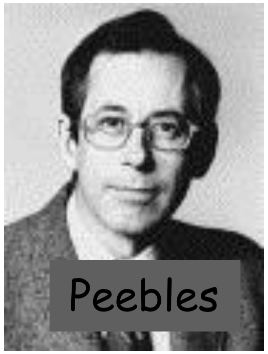
Planck implications for cosmology

CERN colloquium, 16.05.2013
J. Lesgourgues (EPFL, CERN, LAPTh)

The Cosmic Microwave Background

- … is the thermal radiation originating from the primordial plasma, predicted by Gamow, Zel'dovitch, Peebles, etc. (following theoretical arguments based on nucleosynthesis and the presence of hydrogen in the universe)





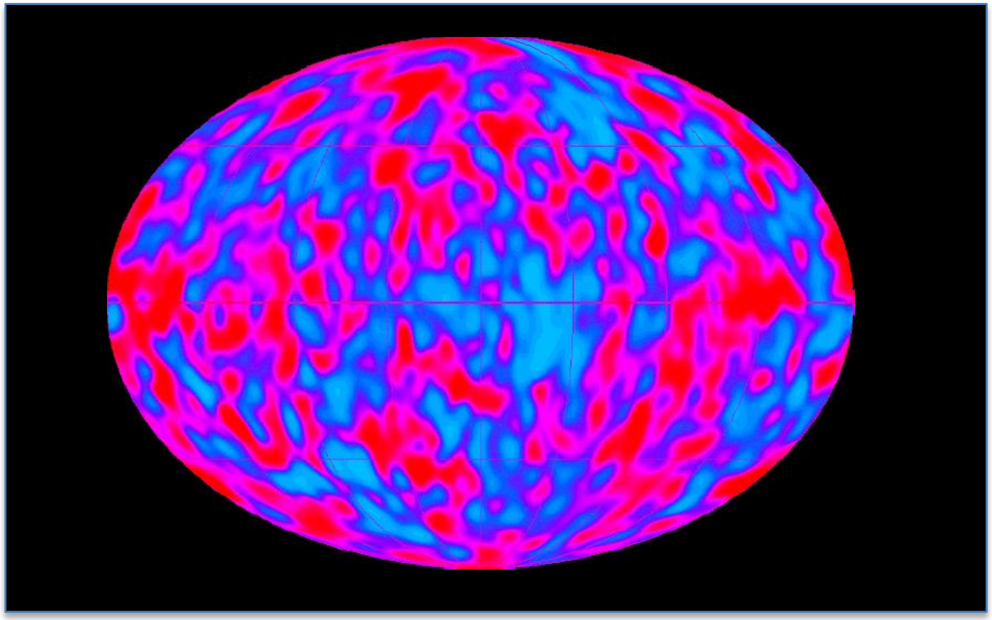
- … was emitted at photon decoupling, billions years ago, when T~eV

- … first observed by Penzias and Wilson in 1964

The Cosmic Microwave Background

- … should contain temperature/density inhomogeneities, that are the seeds of all large structures in the universe (formed by gravitational collapse), predicted by theorists in the 70's to be of order of $10^{-6} – 10^{-5}$

- … first observed on large angular scales by COBE in 1992 in the form of temperature anisotropies… and later by DASI as polarisation anisotropies …



The Cosmic Microwave Background

- … anisotropies should contain non-trivial spatial correlations telling us about the mechanism that generated them, and about electromagnetic + gravitational interactions the early universe.

- Detailed characteristics of these correlations predicted in the 70's (Silk, Yu, Peebles, Zel'dovitch, …)

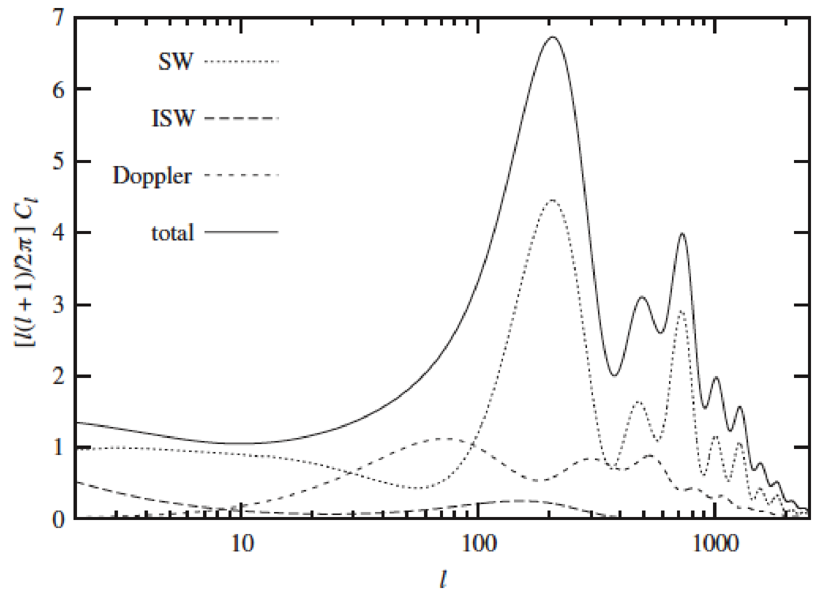
- Standard model for CMB anisotropies:

ingredients

  - General relativity, simple QED, assumption of homogeneous and isotropic Friedmann-Lemaître universe with at least photons, electrons, baryons, neutrinos, CDM, Λ
  - Primordial fluctuations from inflation induce temperature fluctuations in photon-baryon fluid
  - Acoustic waves due to photon pressure, modulated by baryon inertia and gravitational interactions
  - Photon-electron decoupling: diffusion processes inducing fluctuation damping and photon polarization

The Cosmic Microwave Background

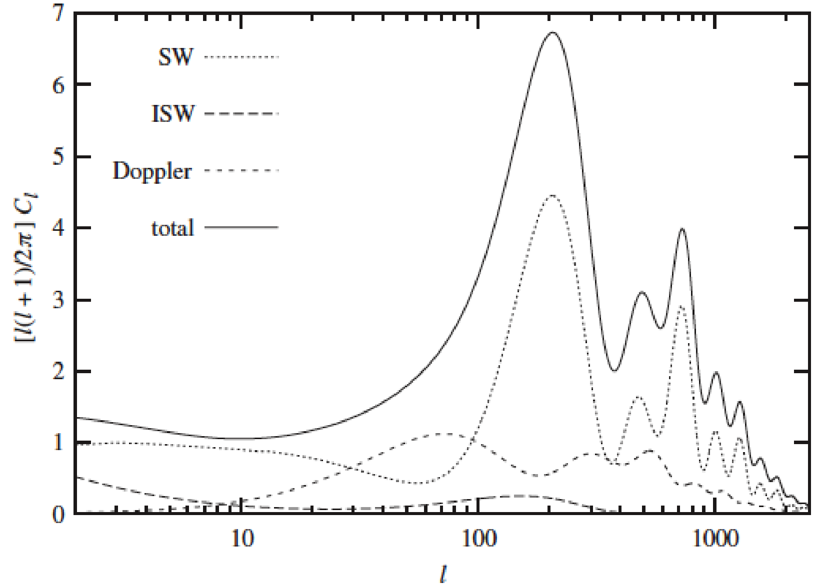
- Primary anisotropies: temperature 2-point function at decoupling features one correlation length = sound horizon at decoupling (real space), or peak series (multipole space)



- Secondary anisotropies:
  - Light deflection by gravitational lenses
  - Gravitational redshifting by structures along line of sight
  - Rescattering in reionized universe at low redshift

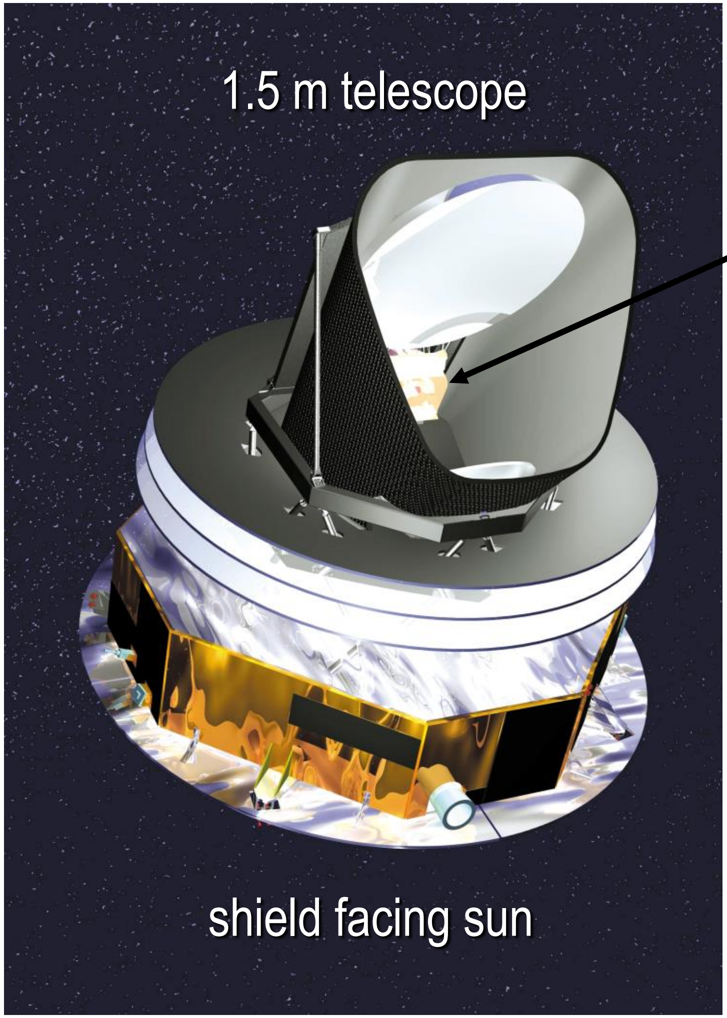
The Cosmic Microwave Background

- Theoretical predictions for C_l precise at 0.01% level (0.1% in Planck analysis) with CAMB (www.cosmologist.info) or CLASS (class-code.net)



- Peak structure first observed with good accuracy by Boomerang (2000), then many ground/balloon-based experiments, then WMAP, confirming standard model established in 1998 (= flat ΛCDM)

The Planck satellite



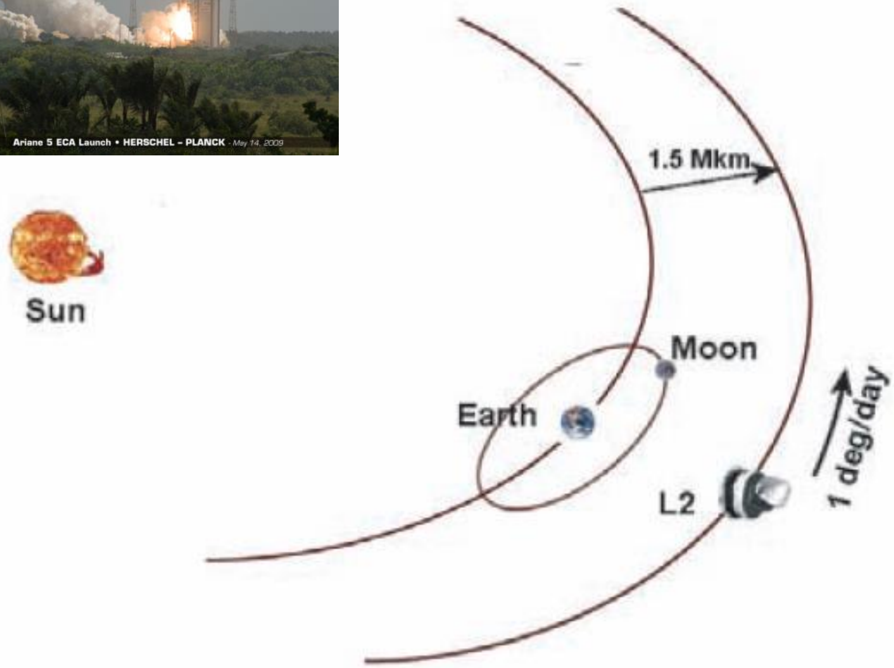
2 instruments:

- LFI (led by Italy)
  - HEMTs (transitors)
  - cooled at 20K
  - sensitive to 30-100 GHz

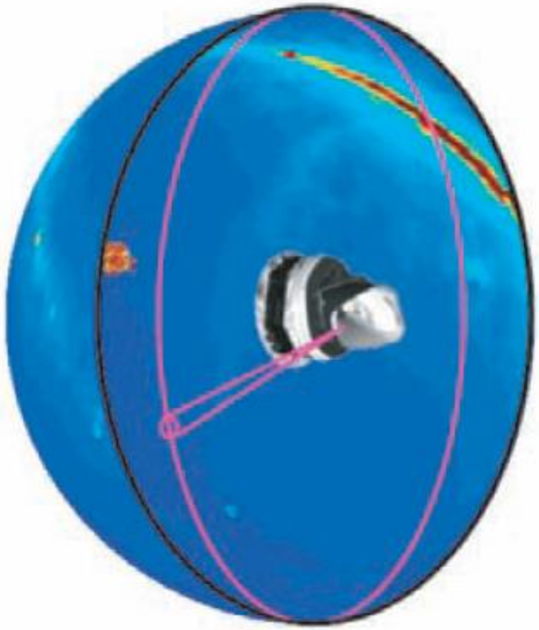
- HFI (led by France/UK)
  - bolometer array
  - cooled at 0.1K
  - sensitive to 100-857 GHz

The Planck satellite

- Launched by ESA and placed in L2 orbit in 2009. Full scan every 6 month.



1 rotation per minute



10% of time for tiny manoeuvres
(data not used)

- Cost: 5 cents/european/yr (700ME), 400-650 scientists
- 2 tons, 4.2m diameter, 36’000 l of ^{4}He, 12’000 l of ^{3}He

The Planck satellite

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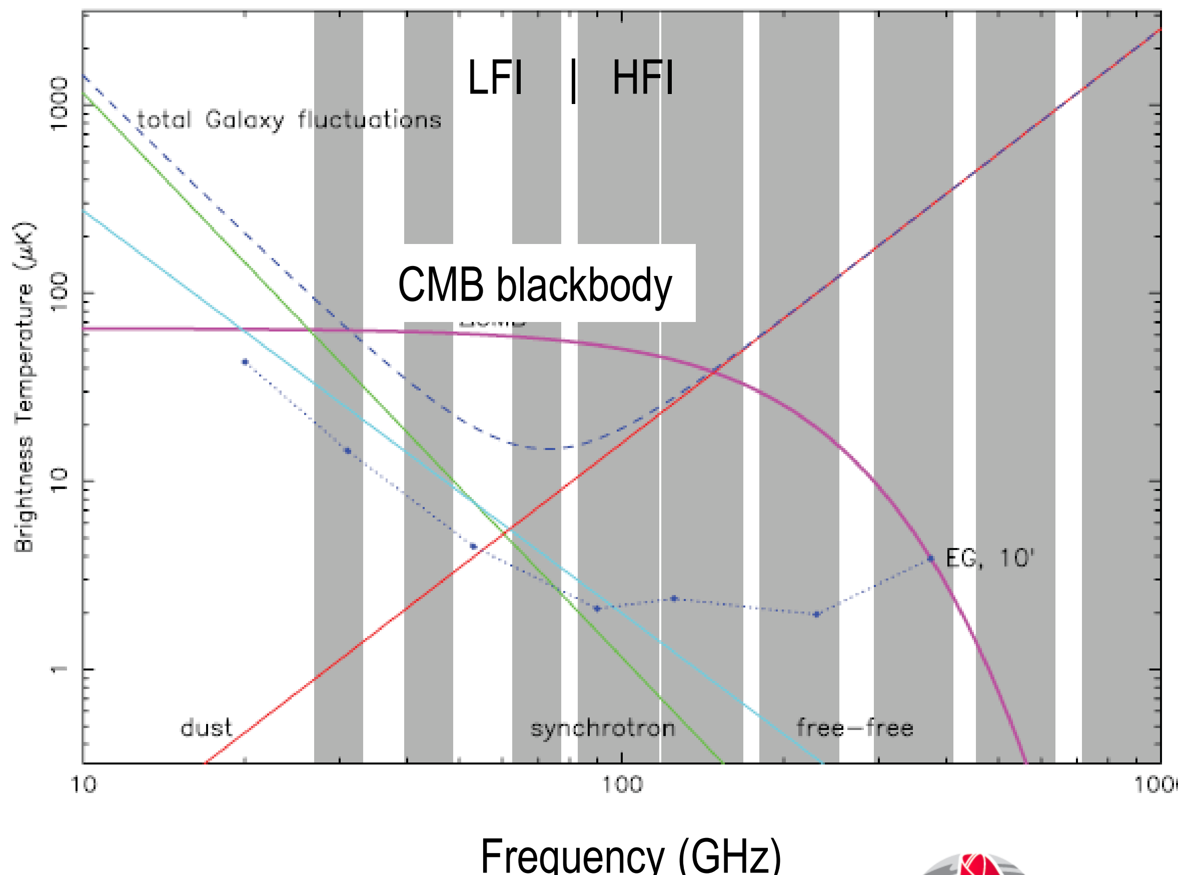
- 75 detectors cover 9 frequency channels

detectors:



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- Planck strengths: large and redundant sky coverage, number of channels & detectors, low detector noise (25 x better than WMAP). Resolution intermediate between WMAP (3 x better) and ACT, SPT.

The Planck satellite

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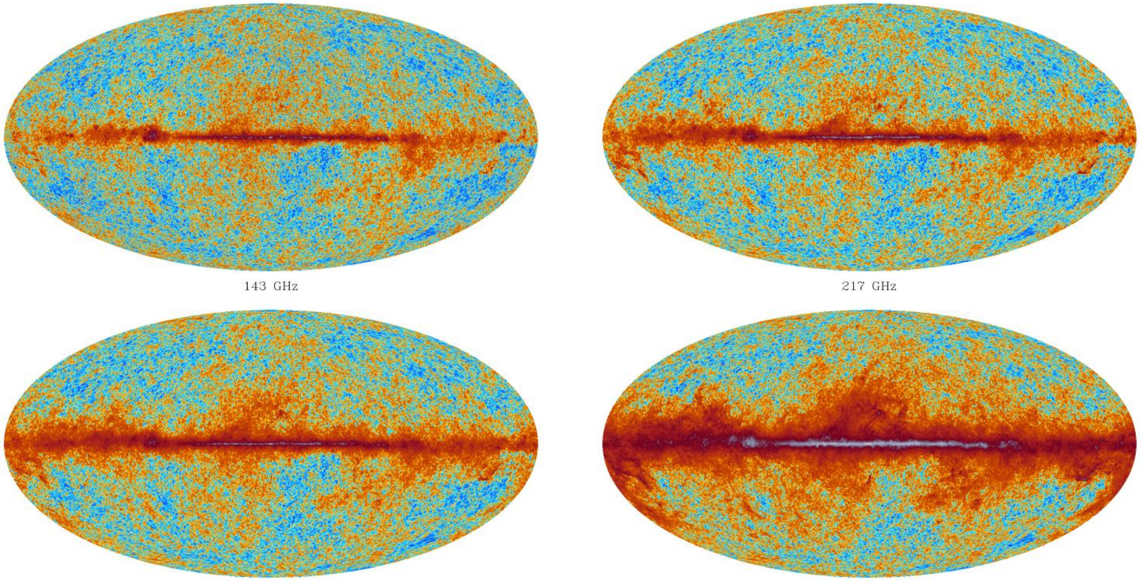
- HFI requires complex cryogenic cooling at 0.1K (dilution of ^{3}He in ^{4}He). Designed for > 2 scans, achieved 5. Turned off in Jan 2012 (due to ^{3}He level).
- LFI requires cooling at 20K with ^{4}He only and proceeds until autumn 2013 (8 scans).

- This release is restricted to "nominal mission", 15 months, > 2 scans.

From time-ordered data to maps

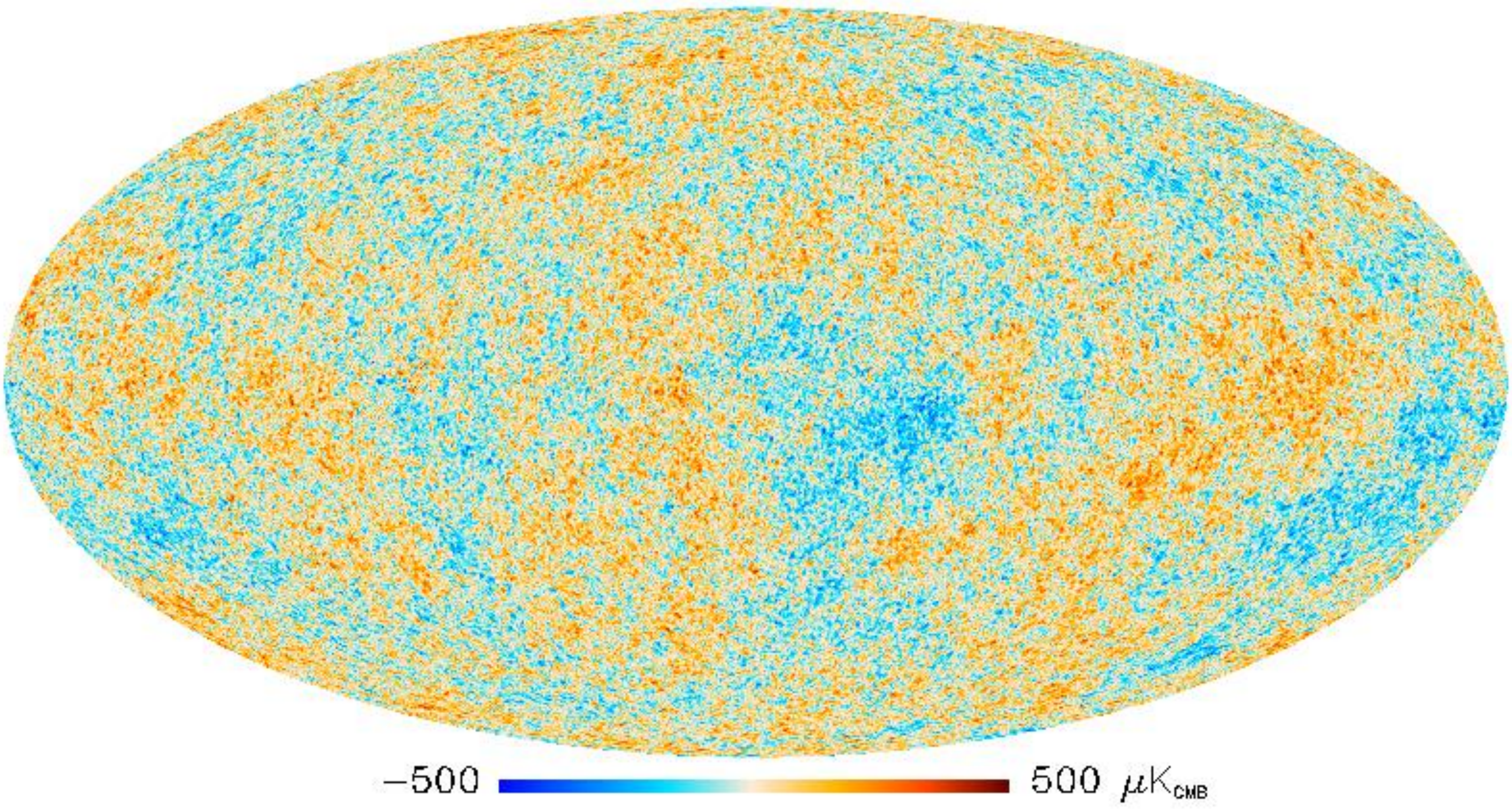
- Sophisticated algorithms correct for systematics (detector noise and response, small cooling instabilities and seasonal effects, cosmic rays, pointing errors, beam shape …) and reduce data to nine temperature maps, or to a set of combined component-separated map



Temperature maps at 70, 100, 143, 217 GHz

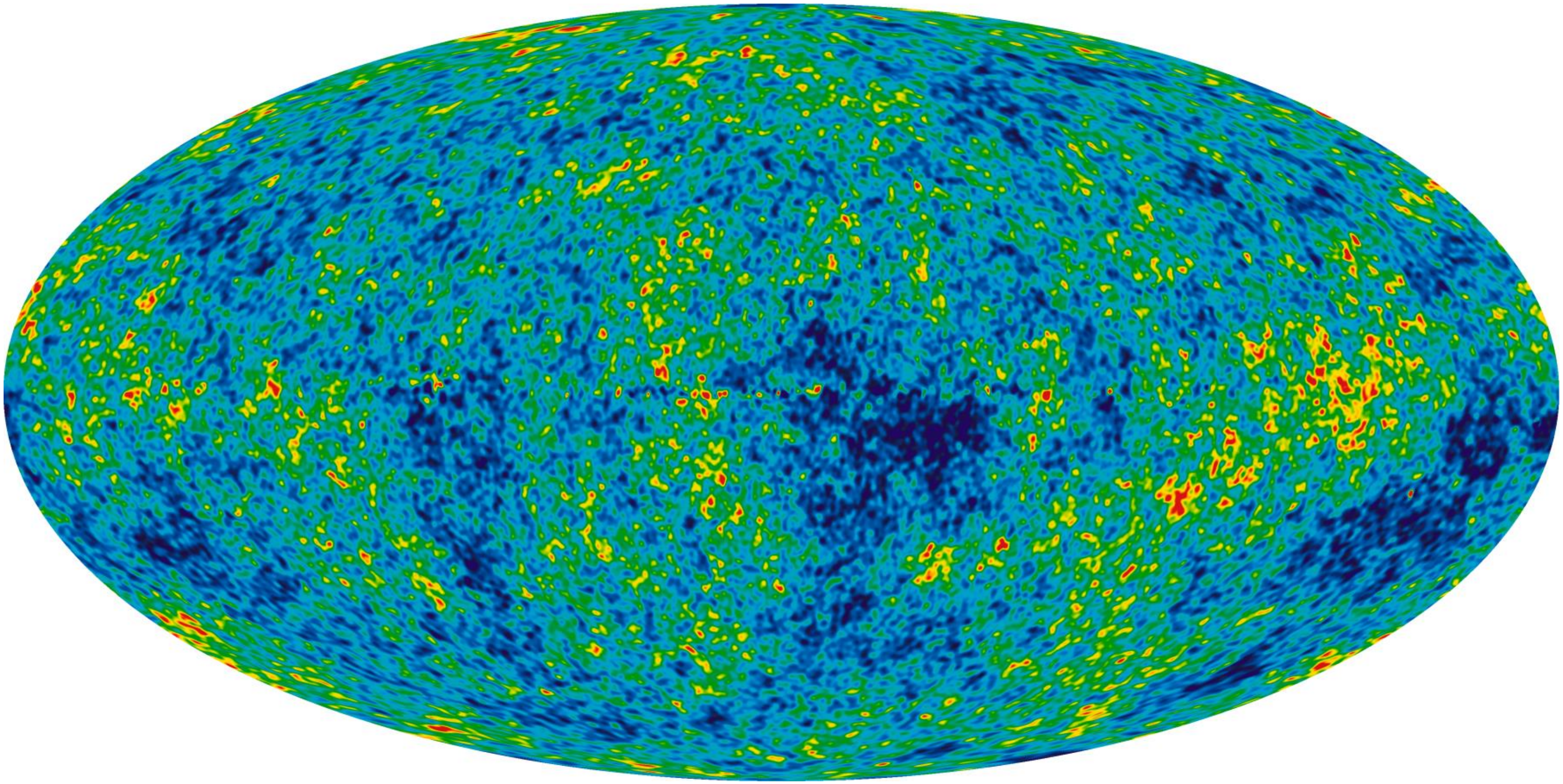
- Polarization maps differed to 2014: analysis not yet mature

From time-ordered data to maps



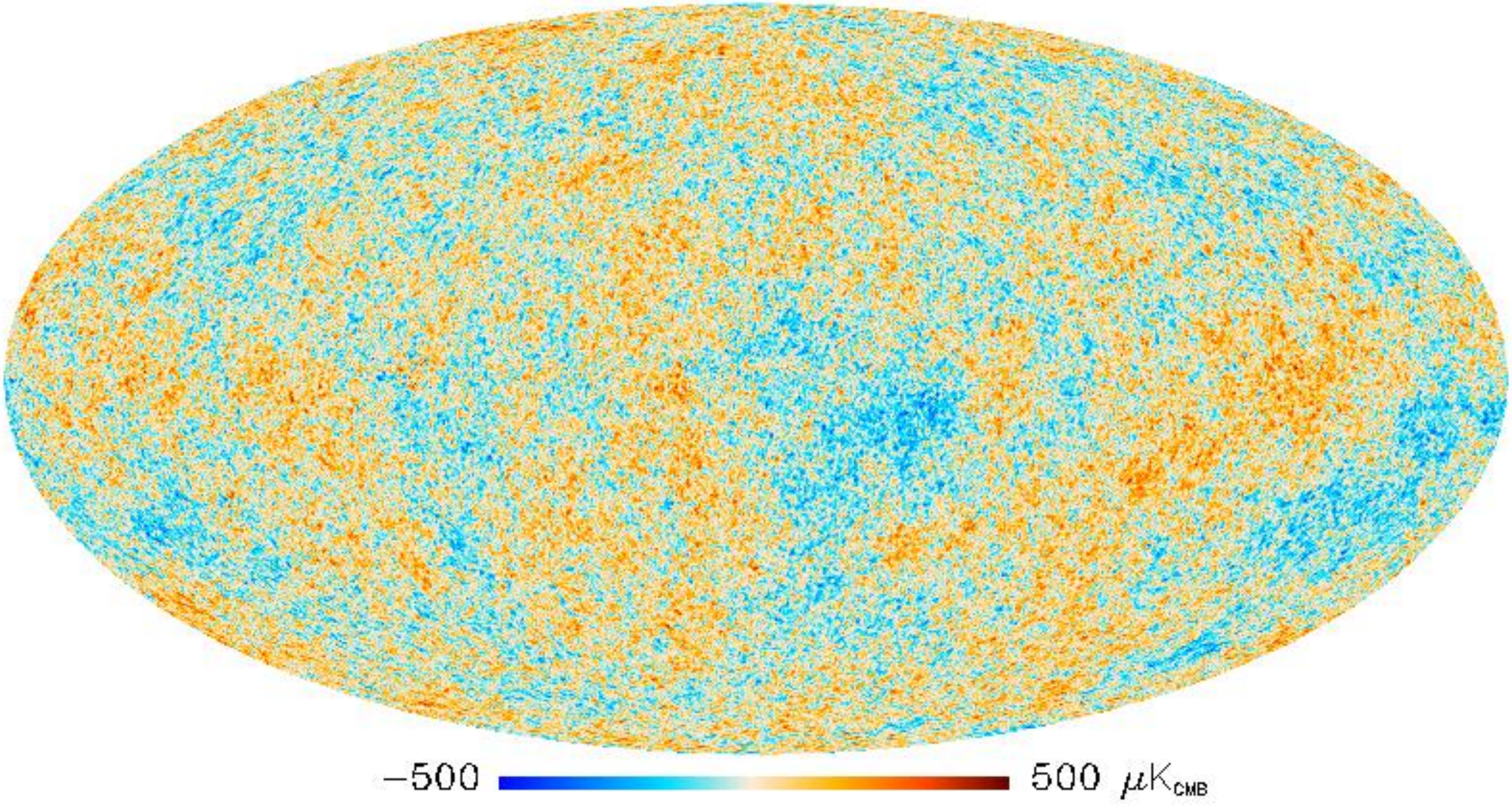
Combined CMB map

From time-ordered data to maps



CMB map from WMAP (different color scale)

From time-ordered data to maps

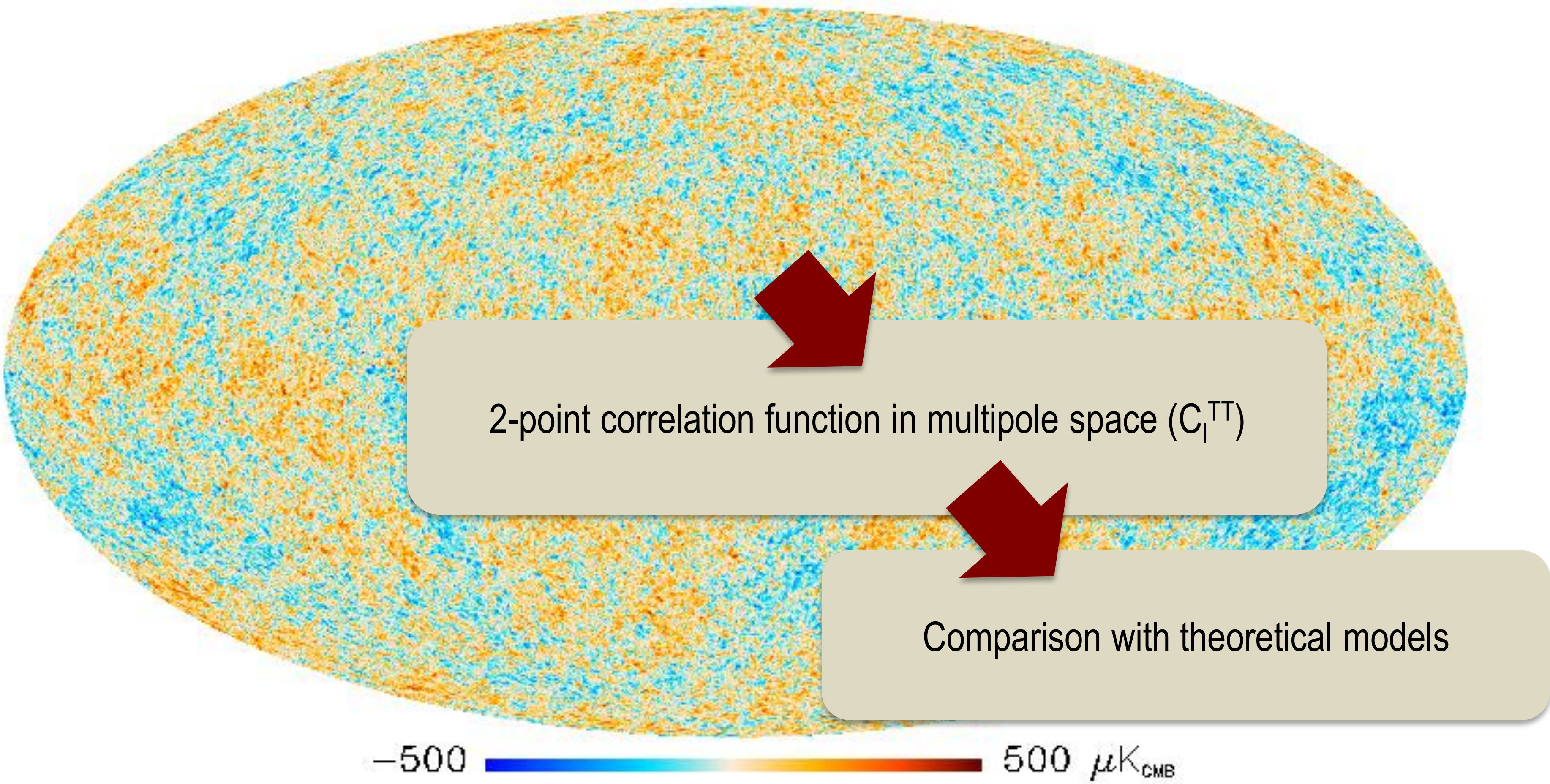


Combined CMB map

From maps to power spectrum

2-point correlation function in multipole space (C_l^{TT})

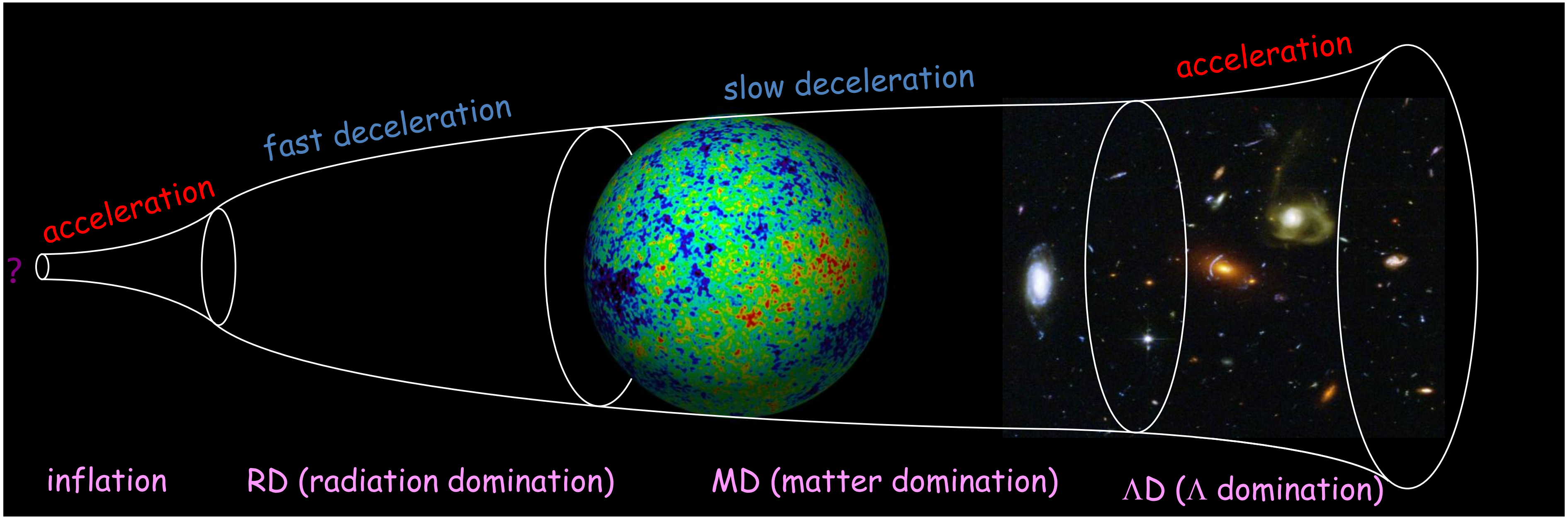
Comparison with theoretical models



Combined CMB map

Fitting the minimal model

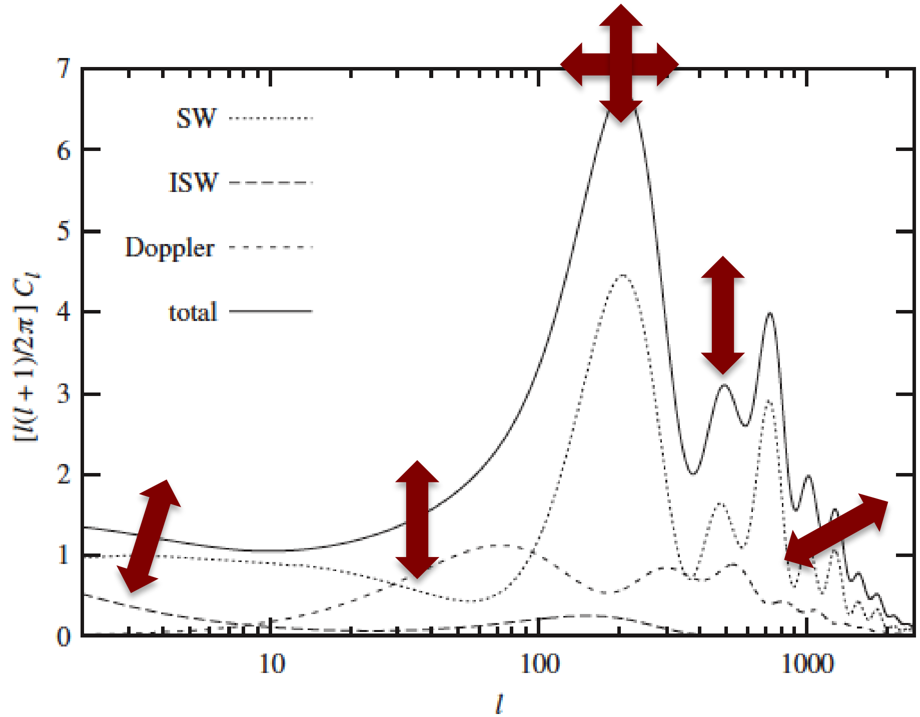
- Minimal ΛCDM model relies on assumption of flat, homogeneous universe with 5 components (photons, baryons, CDM, neutrinos, Λ) and 4 stages :



- 6 free parameters (abundance of baryons, CDM, Λ ; amplitude and spectral index of primordial fluctuations ; epoch of reionisation due to star formation)

Fitting the minimal model

- In minimal model, CMB spectrum affected by 8 physical effects



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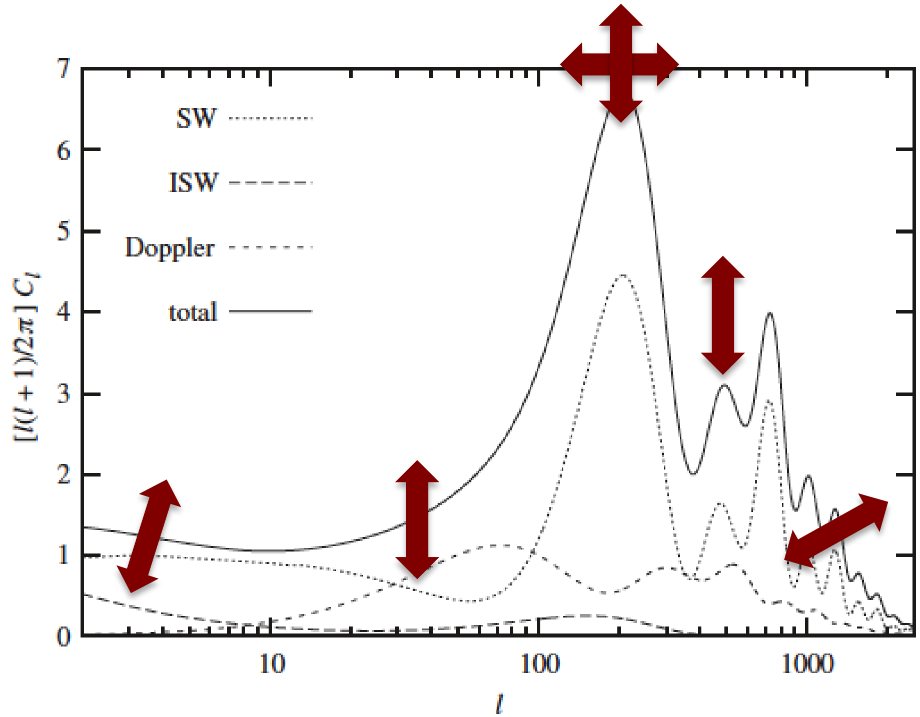

- Minimal ΛCDM: 8 effects controlled by 6 parameters
- Some easy to detect, some are more difficult (cosmic variance): degeneracies

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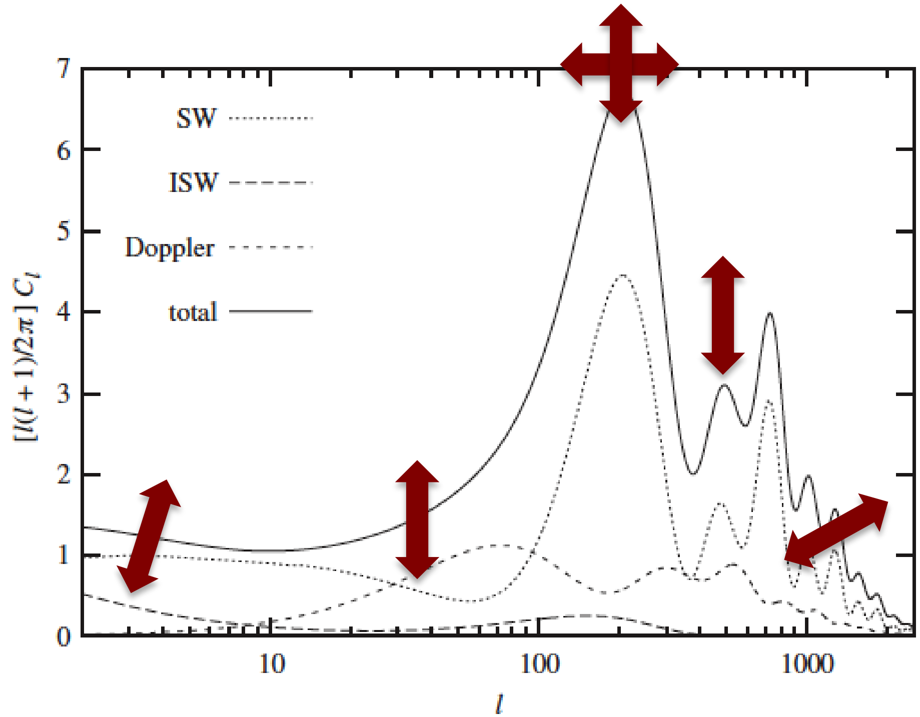

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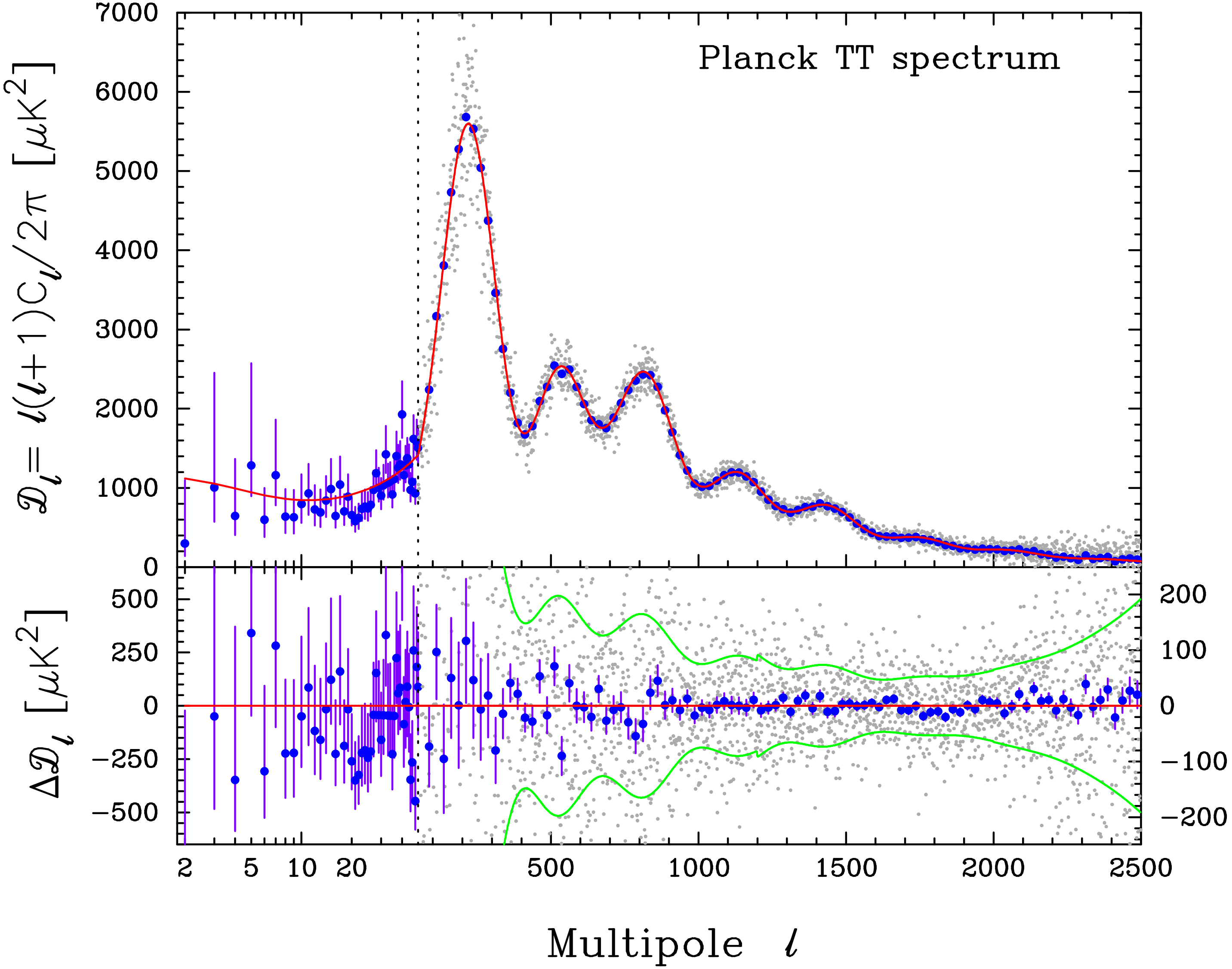
- Some easy to detect, some are more difficult (cosmic variance): degeneracies

- Extended models: some extensions bring more independent effects, some not

ΛCDM is a very good fit



ΛCDM is a very good fit

Using Planck + WP (= EE +TE from WMAP for $l \leq 23$), at 1-sigma:

Peak scale	0.060%
Baryon density	1.3%
CDM density	2.3%
Primordial amplitude	2.5%
Primordial spectral index	0.76%
Reionization optical depth	0.13%

Derived (model-dependent) parameters:

- Hubble parameter
- Λ fractional density

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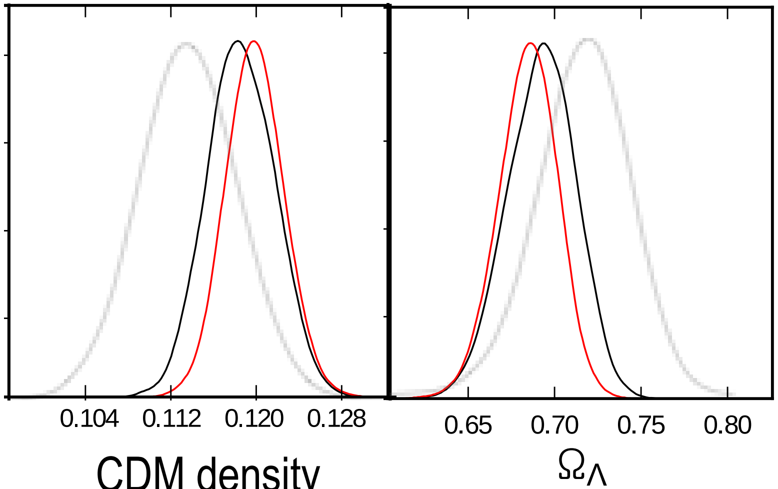
Consistency with WMAP alone

preference for high CDM density, small H_0, small Ω_Λ



(H_0 related)

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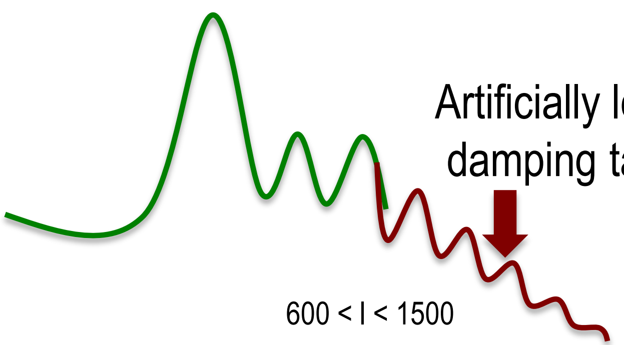
tension with WMAP+SPT

explained as WMAP/SPT relative calibration error



high H_0 plus, if possible, new physics: N_{eff} , negative running…

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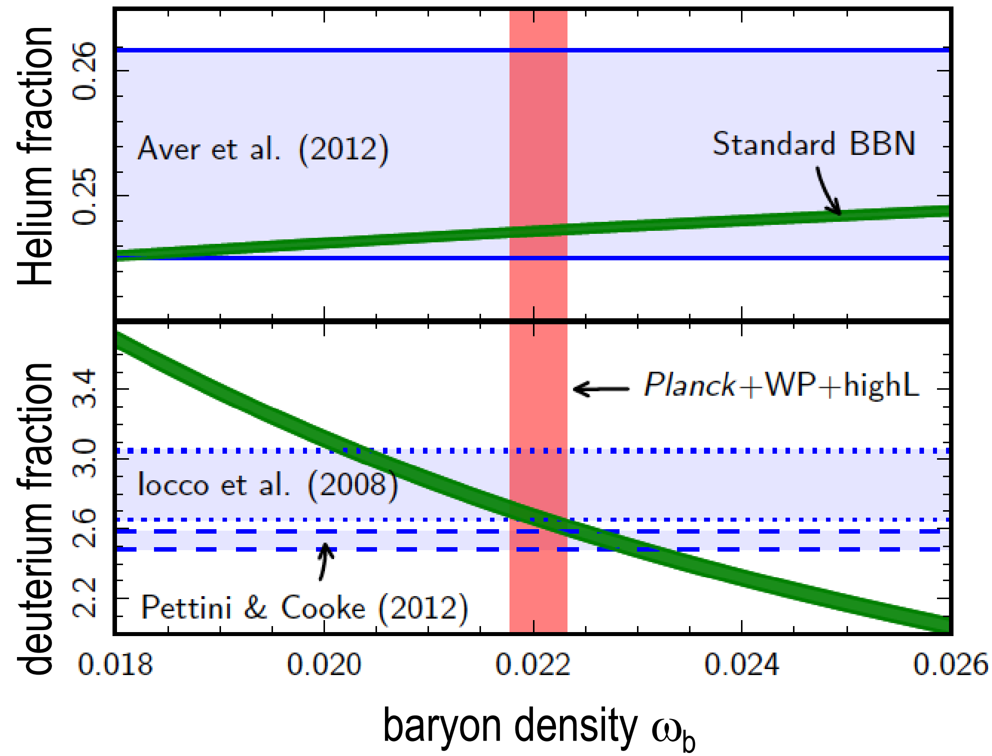
consistency with theory of Nucleosynthesis and measurement of primordial D, He



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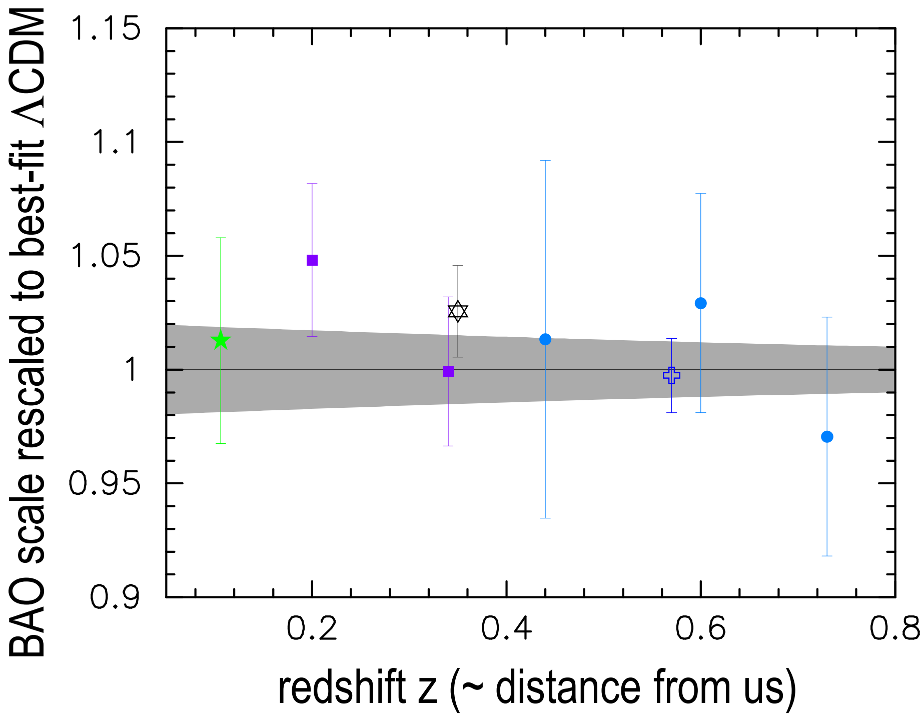
consistency with
Baryon Acoustic Oscillations



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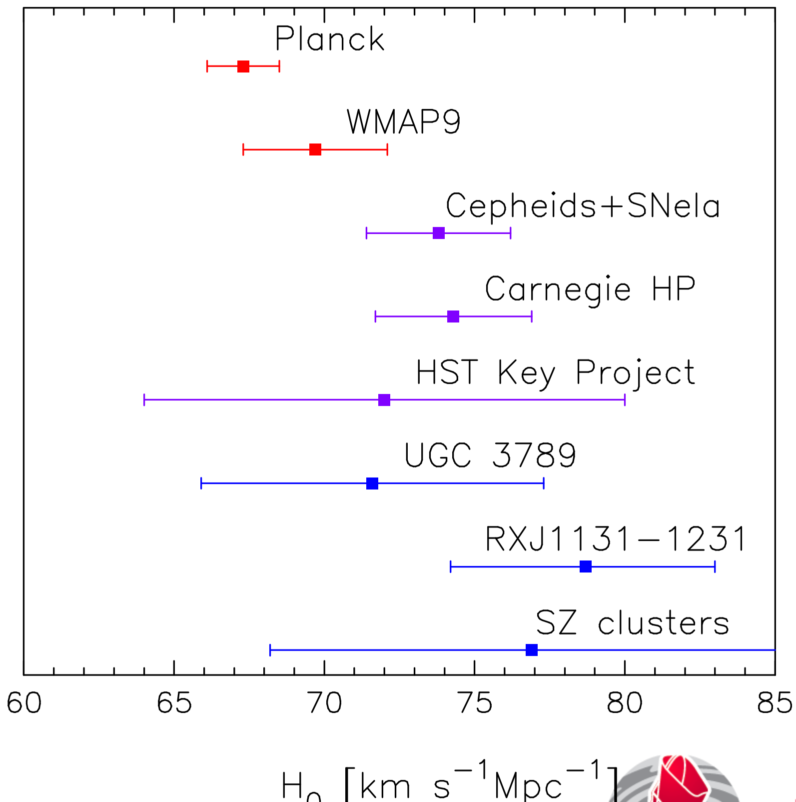
tension with direct H_0 measurements



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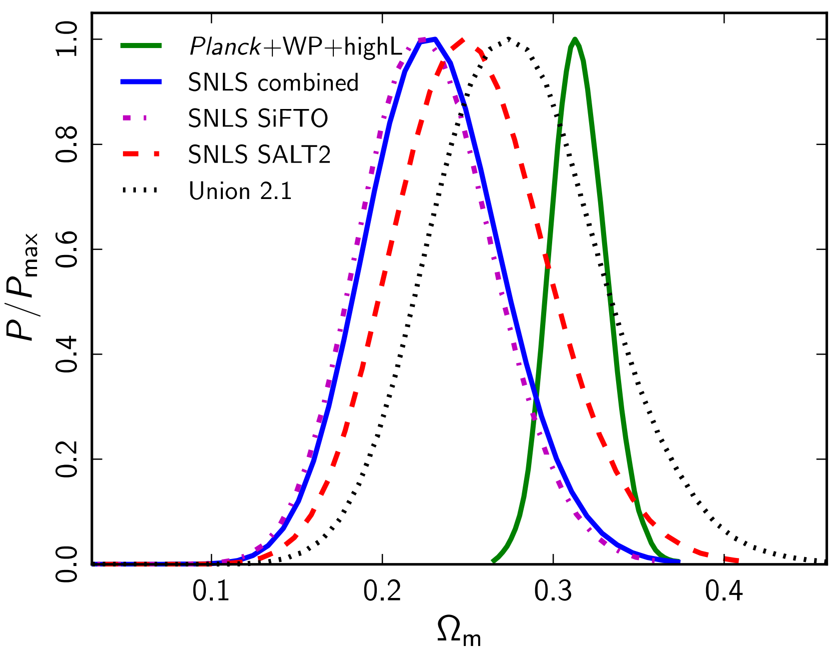
consistency with supernovae (SNIa) luminosity



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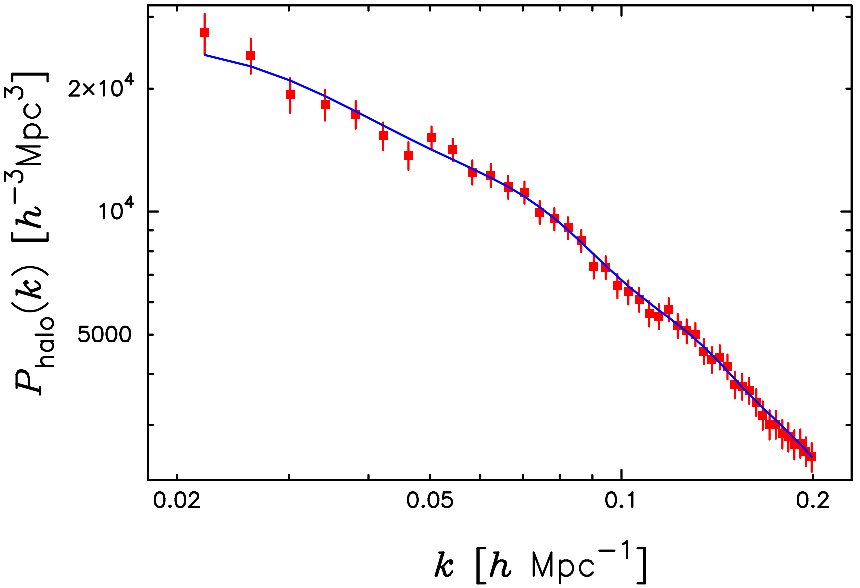
consistency with galaxy 2-pt correlation



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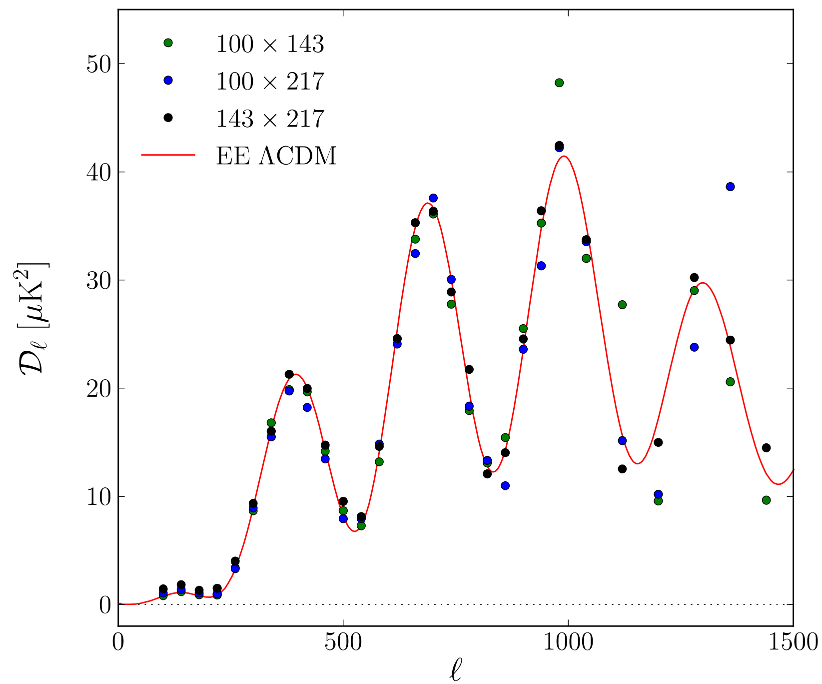
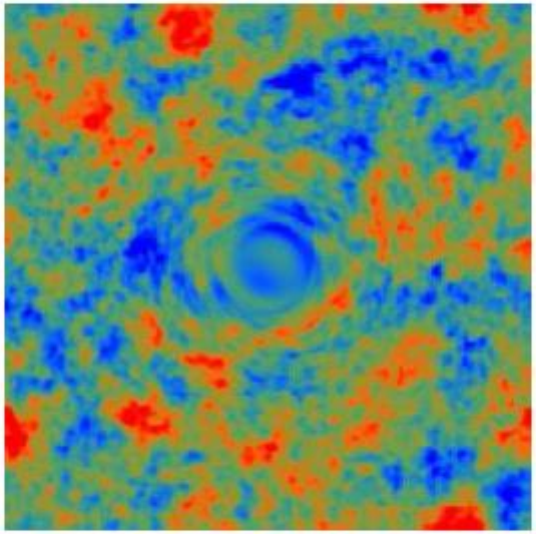
consistency with preliminary (raw) polarization spectrum



Lensing extraction

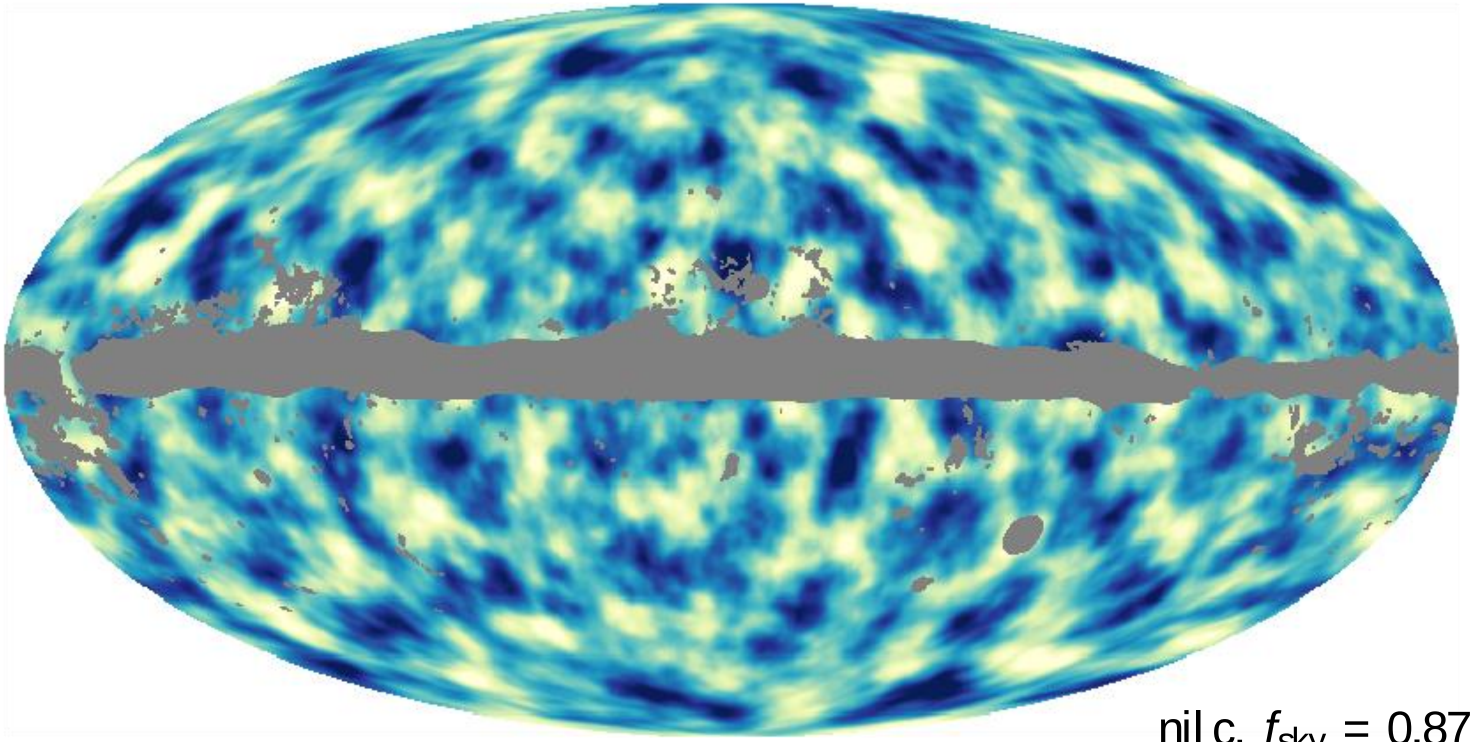
- exaggerated effect of a huge cluster:



- In fact, only 2’-3’ deflections, coherent over large scales: invisible by eye
- Lensing potential = projected gravitational field (with some kernel: sensitive to structures at z~1-3)
- Induces non-gaussianity with very specific correlations (between different angular scales). Can be extracted with specific “quadratic estimator”
- Proposed by Hu & Okamoto (2001)
  First success in 2012 (SPT-ACT)

Lensing extraction

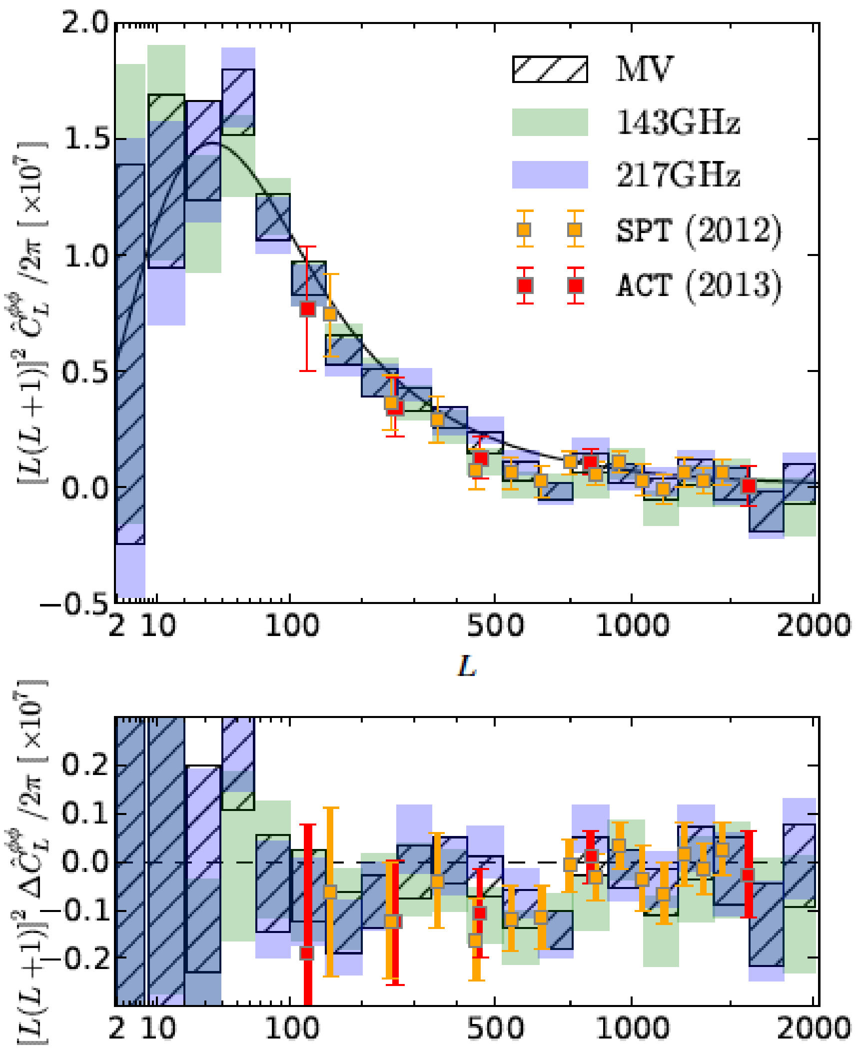
Lensing potential map:



Low signal-to-noise, but correlates at high level with different tracers of LSS (20 sigma with NVSS quasars, 10 sigma with SDSS LRG, 42 sigma with Planck's CIB)

Lensing extraction

- Lensing power spectrum consistent with ΛCDM
- Helps removing degeneracies and measuring extended model parameters with Planck alone



Beyond minimal ΛCDM

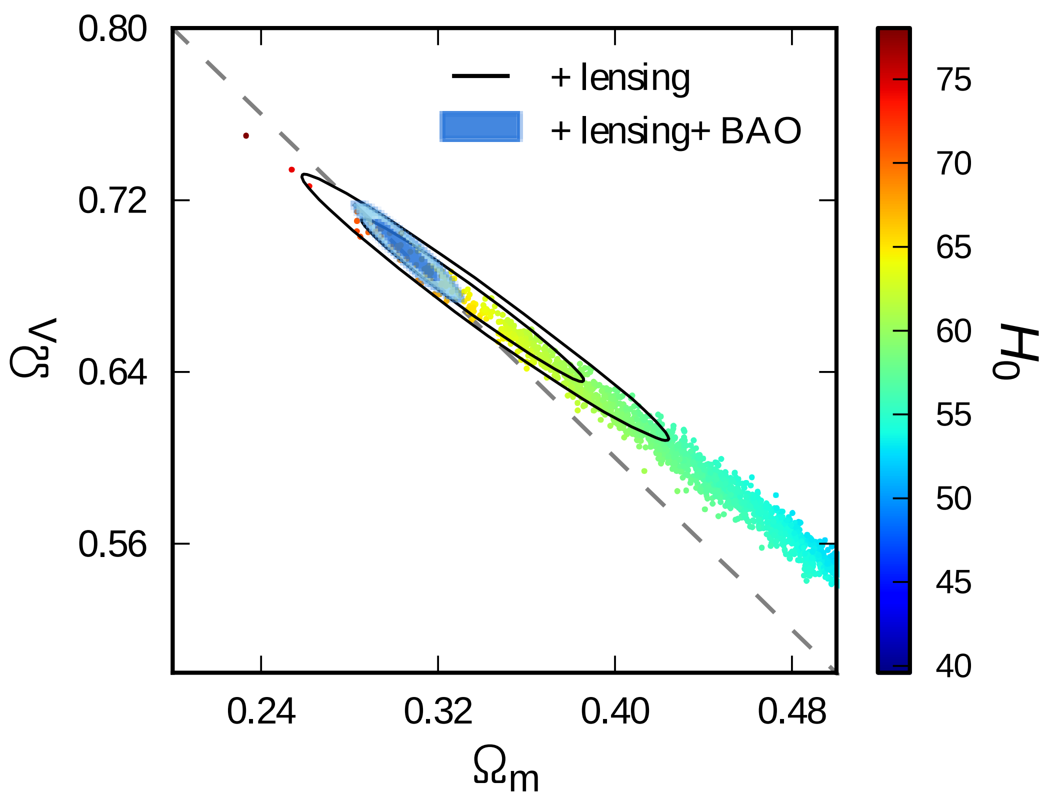
Curvature

CMB alone (Planck+WP+HighL), despite geometrical degeneracy:

$100\Omega_k = -4.2 \pm 4.5$ (95%CL)

With lensing and BAO:

$100\Omega_k = -0.10 \pm 0.63$ (95%CL)



Relativistic d.o.f. (N_{eff})

- In minimal ΛCDM model $N_{eff} \approx 3$ (relic background of 3 flavor neutrinos); could have $N_{eff}>3$ due to lepton asymmetry, sterile neutrinos, other very light relics (gravitinos, axions, …)

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  - now, CMB alone (Planck+WP+HighL)

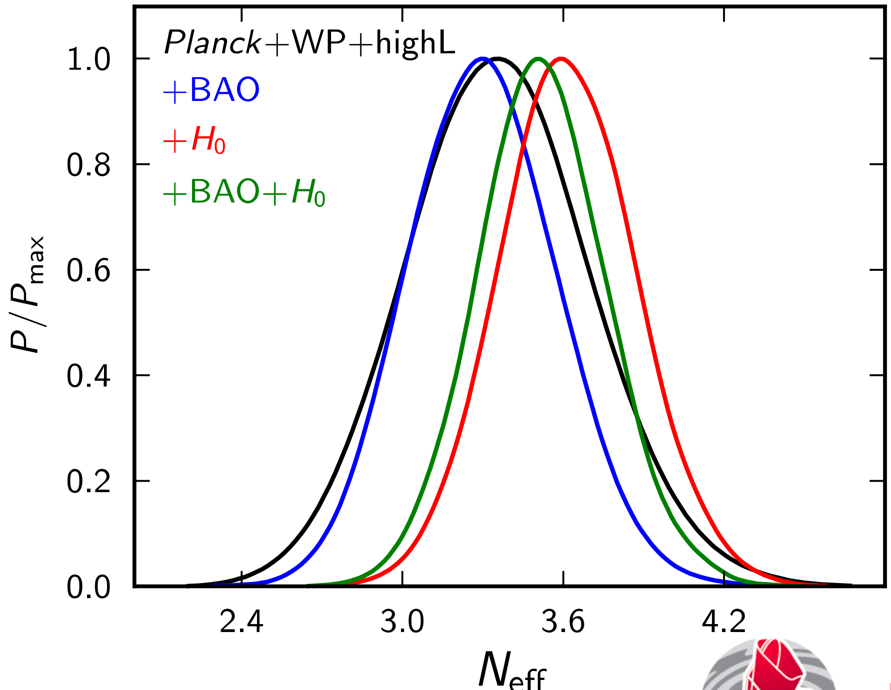
    $N_{eff} = 3.36 \pm 0.66$ (95%CL)

  - With lensing and BAO:

    $N_{eff} = 3.30 \pm 0.52$ (95%CL)

  - With H_0 and BAO:

    $N_{eff} = 3.53 \pm 0.46$ (95%CL)



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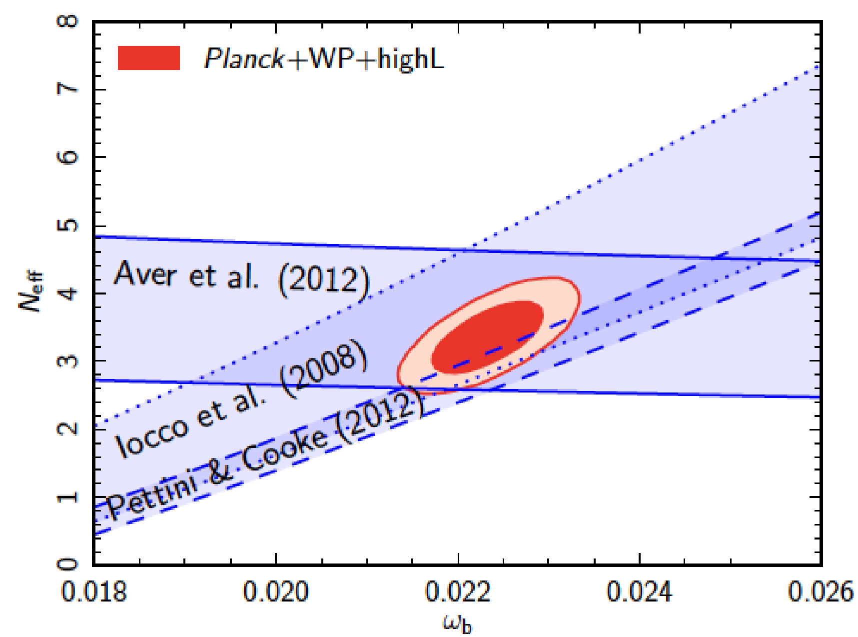
Consistency with Nucleosynthesis (with free N_{eff})



Neutrino mass

- CMB sensitive to Σm_ν (sum over all families) : specific effects mainly on secondary anisotropies (early integrated Sachs-Wolfe and lensing)

- Neutrino oscillations imply $\Sigma m_\nu > 0.06$ (0.1) eV for Normal (Inverted) hierarchy

- Loose upper bound from beta decay experiments (KATRIN could find Σm_ν<1.2eV (95%CL)

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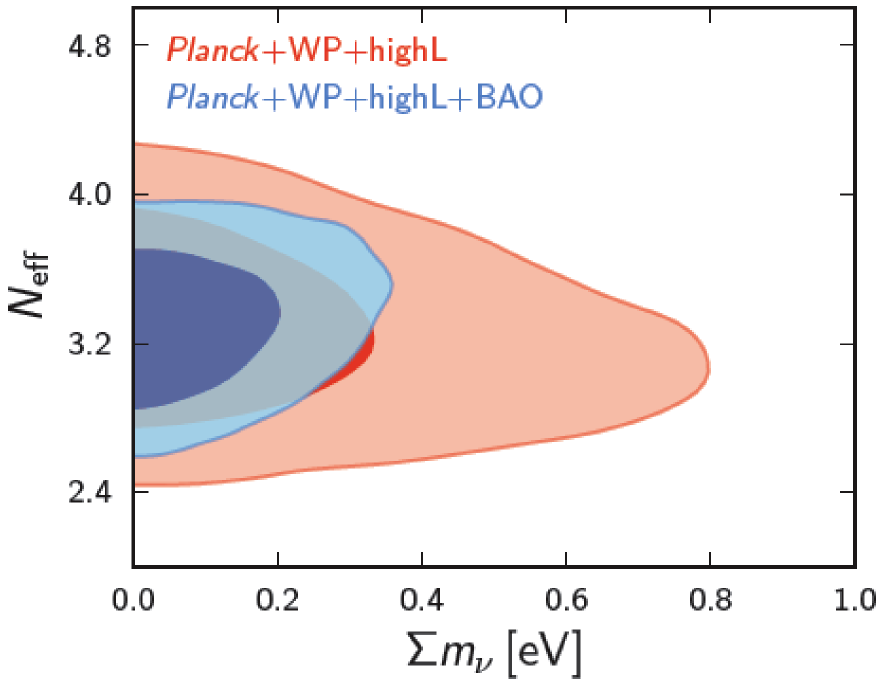
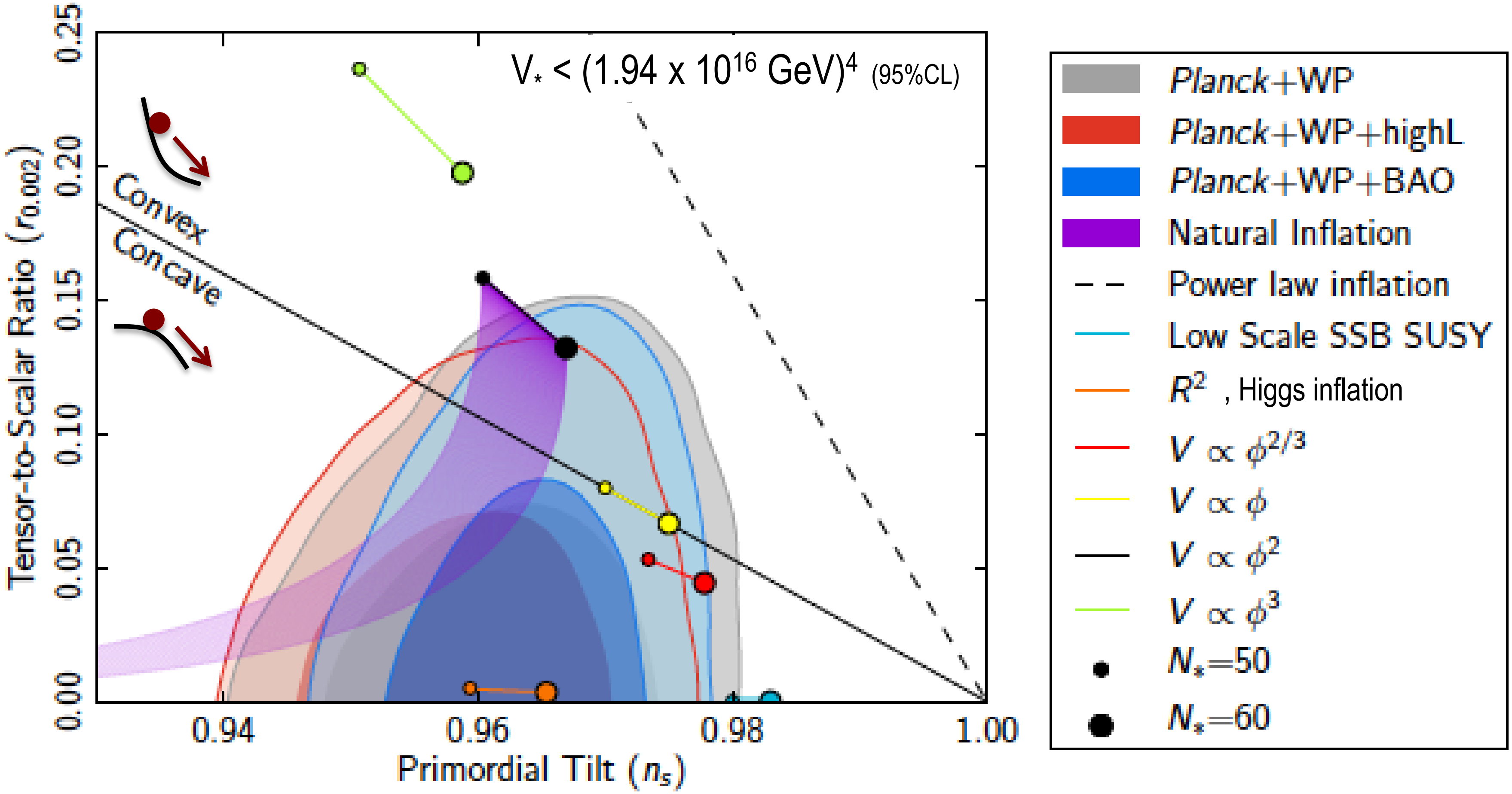
- CMB alone : $\Sigma m_\nu < 0.66$eV (95%CL)
- With BAO : $\Sigma m_\nu < 0.23$eV (95%CL)
- With lensing: $\Sigma m_\nu < 0.85$eV (95%CL)



Lensing spectrum likes small neutrino mass, temperature dislikes it (latter connected with low l region…)

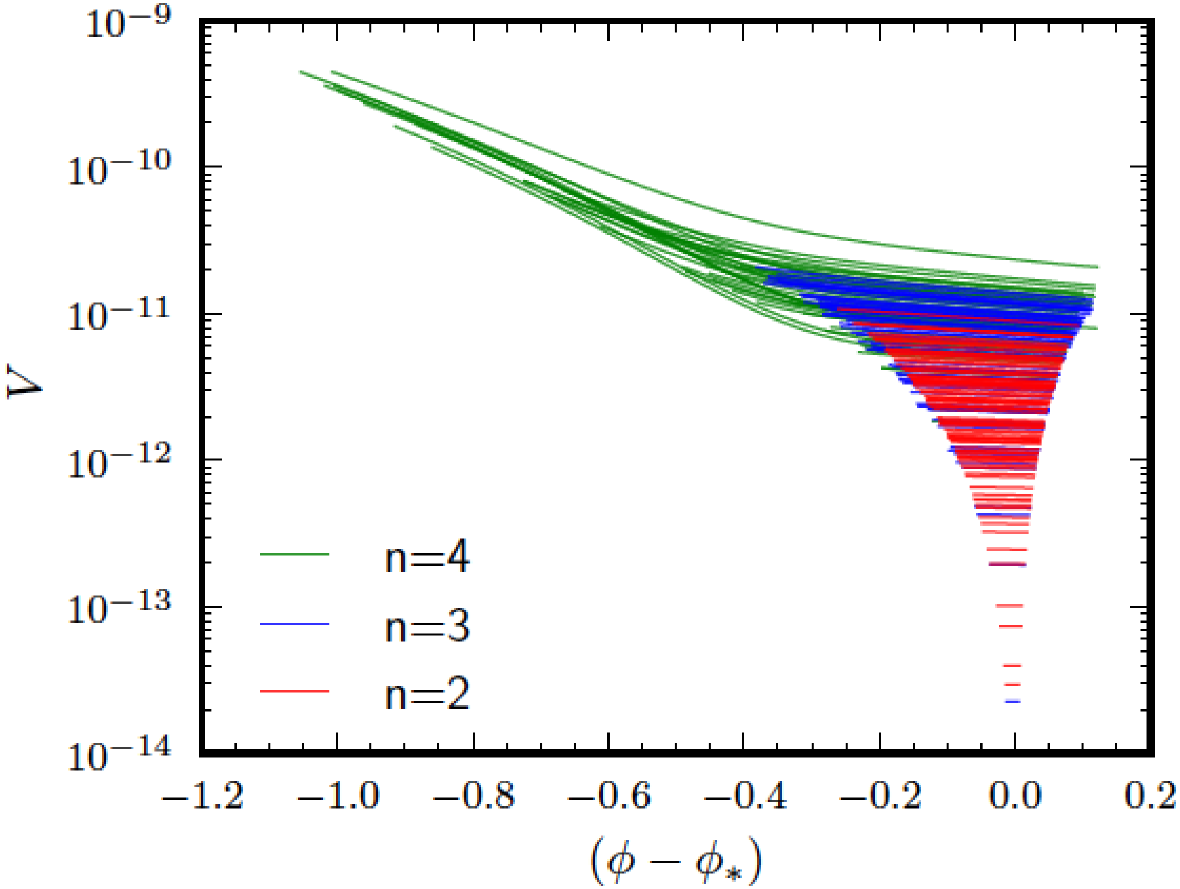
Robust w.r.t cosmological extensions (excepted for curvature: 50% weakening)

Tensors, spectral index and inflation



- Also OK: Hill-top with p=2 or p≥4; also disfavored: inverse power-law

Inflation potential reconstruction



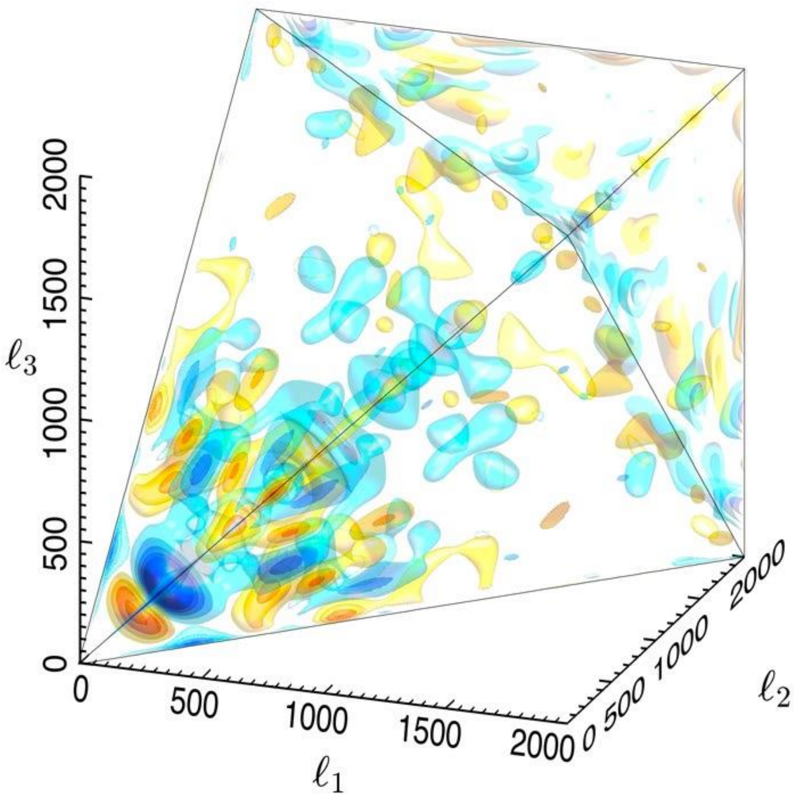
“observable window” of the inflaton potential, assuming that it can be Taylor-expanded inside this region at order n = 2, 3, 4 (units of true m_P)

Other investigated extensions

Significant detection ?

- Light sterile neutrino (thermal or non-thermal, m < 10 eV) ☒
- Dark energy with
  - $w \neq -1$ ☒
  - $w_0 + a\, w_a \neq -1$ ☒
- 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 ☒

Primordial non-gaussianity



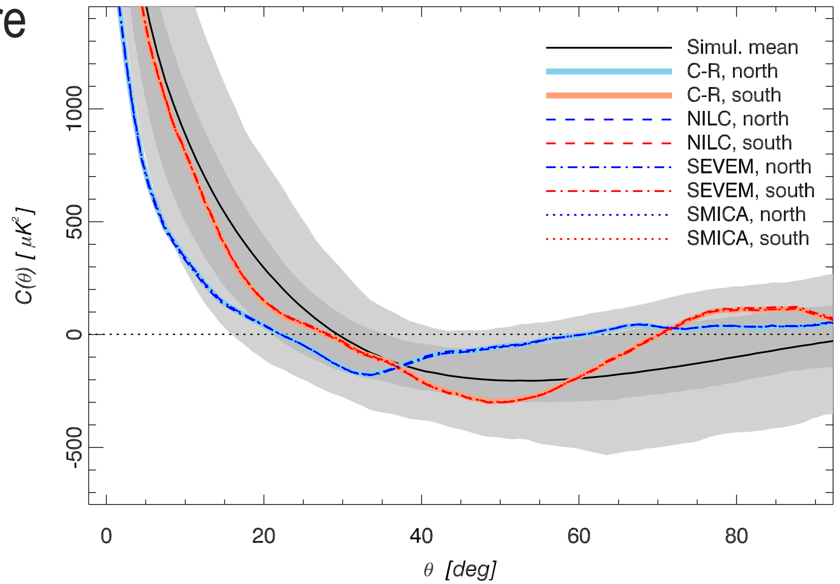
Temperature bispectrum (3-point function) after foreground cleaning

- Amplitude of specific bispectrum shapes: *(WMAP9)*
  - $f_{NL}^{local} = 2.7 \pm 5.8$ (68%CL) *37 ± 20*
  - $f_{NL}^{equi} = -42 \pm 75$ (68%CL) *51 ± 136*
  - $f_{NL}^{ortho} = -25 \pm 39$ (68%CL) *-245 ± 100*
- For trispectrum (4-point function):
  - $\tau_{NL}^{local} < 2500$ (95%CL)
- Compatible with very small NG level predicted by canonical single-field inflationary models

Isotropy

- 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

- Gone away:
  - Low quadrupole
  - Quadrupole-octopole alignement

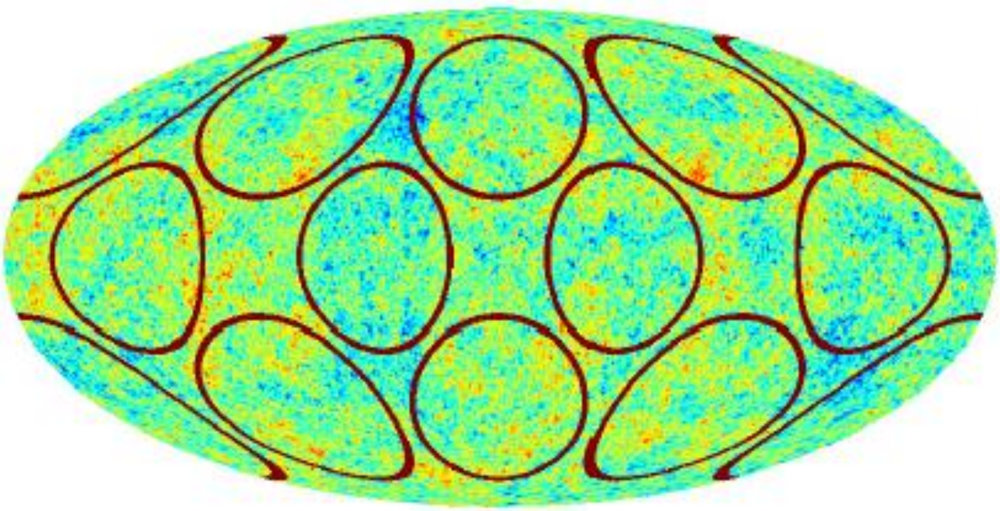


2-point correlation function in real (angular) space

Galactic foregrounds? Solar emission? Local universe?
Primordial fluctuations? Topology? Magnetic fields?

Topology

- Search for matching circles
- Search for specific patterns for flat spaces with cubic toroidal (T3), equal-sided chimney (T2) and slab (T1) topologies, three multi-connected spaces of constant positive curvature (dodecahedral, truncated cube and octahedral) and two compact negative-curvature spaces
- Search for Bianchi VII_h cosmology

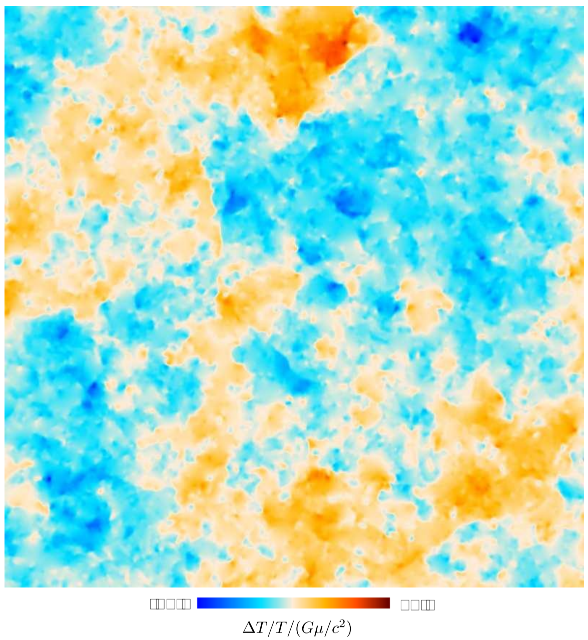


simulated maps with matching circles at 24°

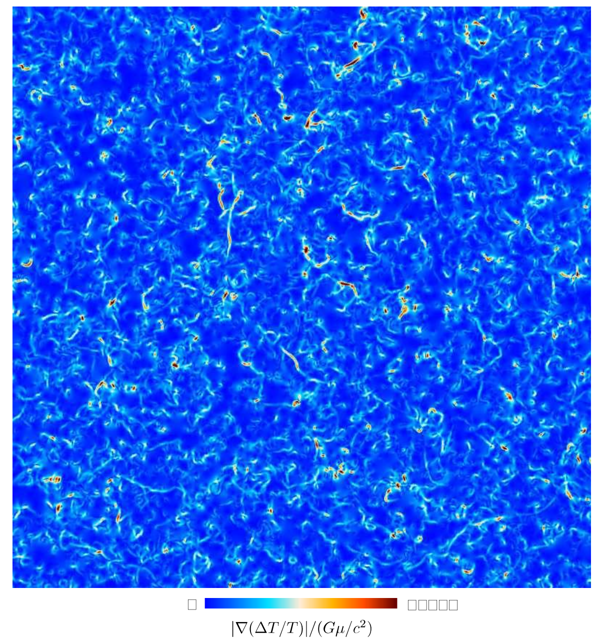
Defects

- Simulation of CMB distorted by cosmic strings:

temperature:



spherical gradient:



Search through power spectrum distortions and specific types of non-gaussianity: no evidence ($G\mu/c^2 < 10^{-7}$)

CMB Dipole

- Newtonian gravity: motion of observer gives dipole from Doppler effect

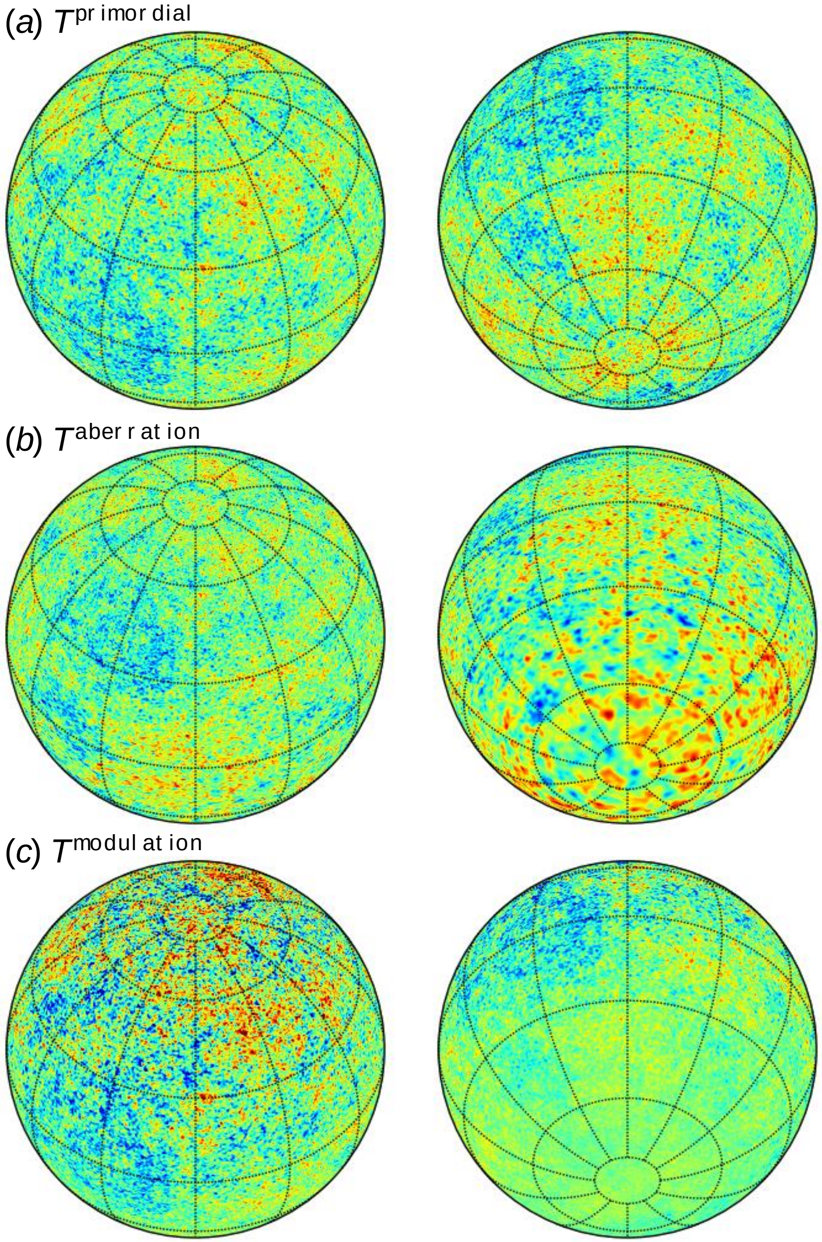
- GR: Doppler *boost* affects all multipoles at 10^{-5} level. Aberration (similar to coherent lensing) and modulation.

- First detection of this effect:

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

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

- No evidence for anomalous primordial dipole



Conclusions

- 23 papers fro March contain thousand times more information…
- fascinating that simplistic minimal 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