A close look into CMB anisotropies
2014/2/05

A simple test for statistical homogeneity

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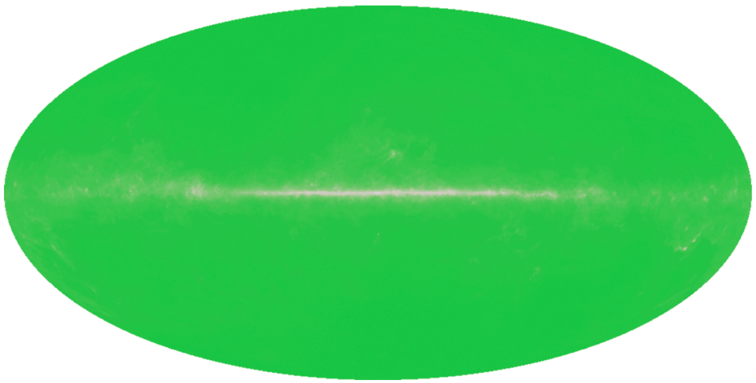
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

Contents

- A brief review for CMB (& PLANCK)
  - Cosmological parameters
  - Tensions between CMB & local universe
  - CMB on small scales
    - cluster cosmology in the PLANCK era
- the standard (concordant) cosmology 2013

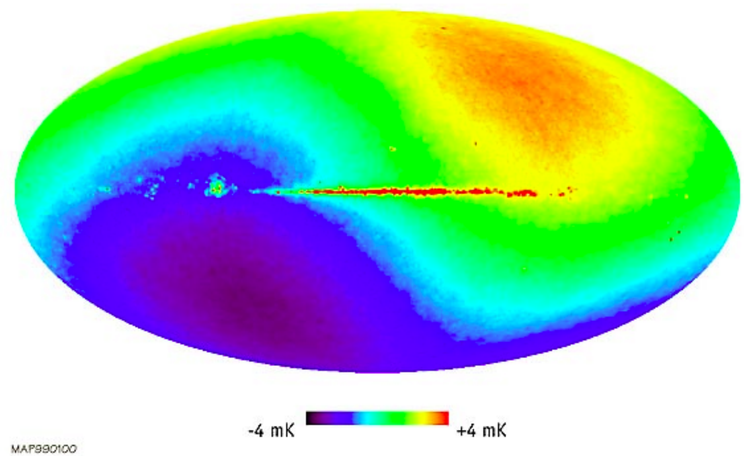
- A simple test for the statistical homogeneity

Cosmic Microwave Background (CMB)



Penzias and Wilson (1965)

$\sim 3\mathrm{K}$ (Relic of the Big-Bang, 3K black body)

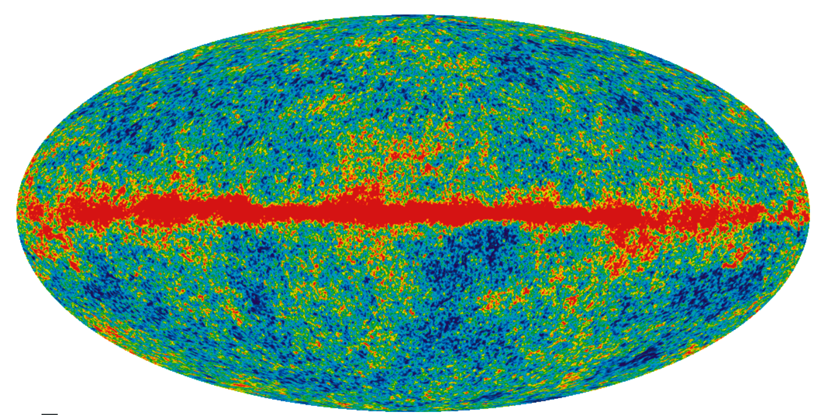


$\sim 3\mathrm{mK}$

(velocity relative to the CMB flame: ～620km/s)

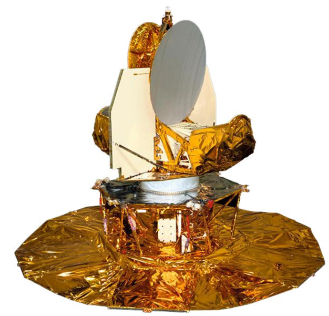
(primordial fluctuations +foregrounds)

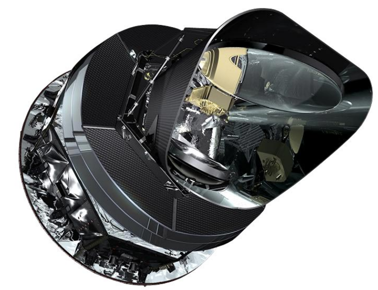
$\sim 30\mu\mathrm{K}$

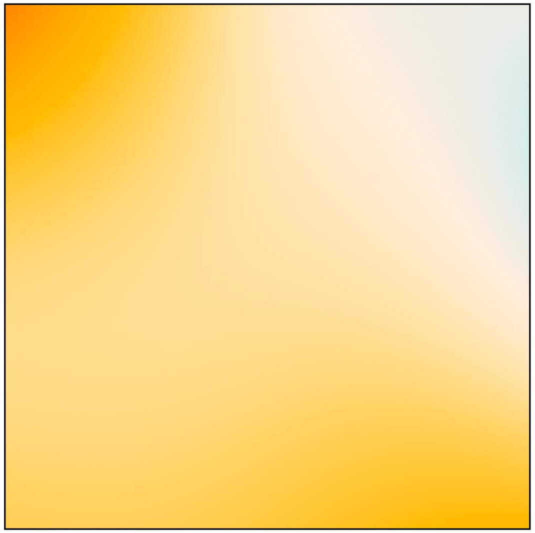


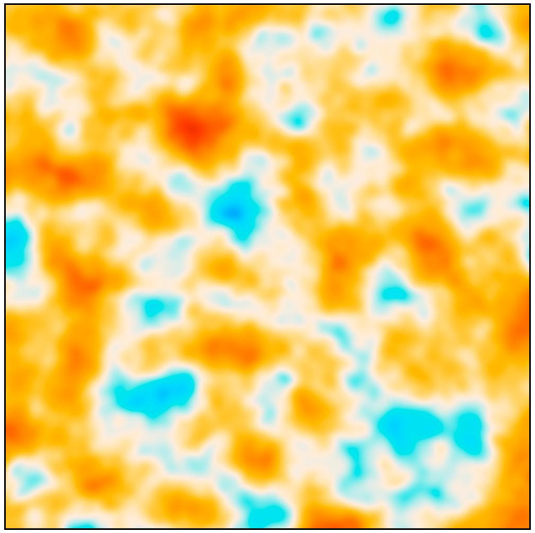
Credit: NASA / WMAP Science Team

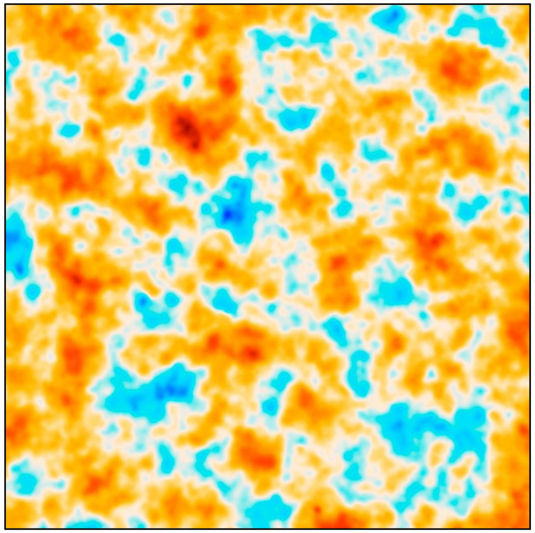
COBE-WMAP-PLANCK











COBE

1990s

WMAP

2000s

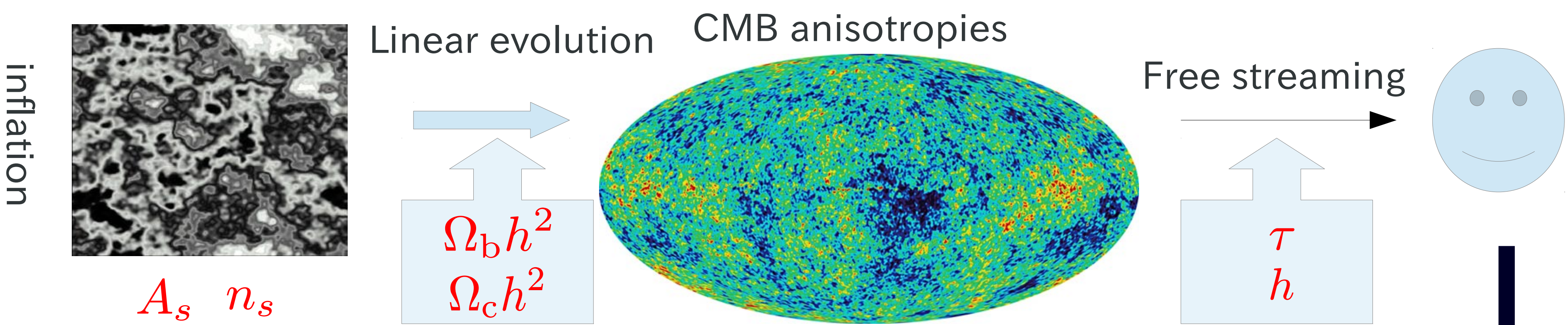
Planck

2010s

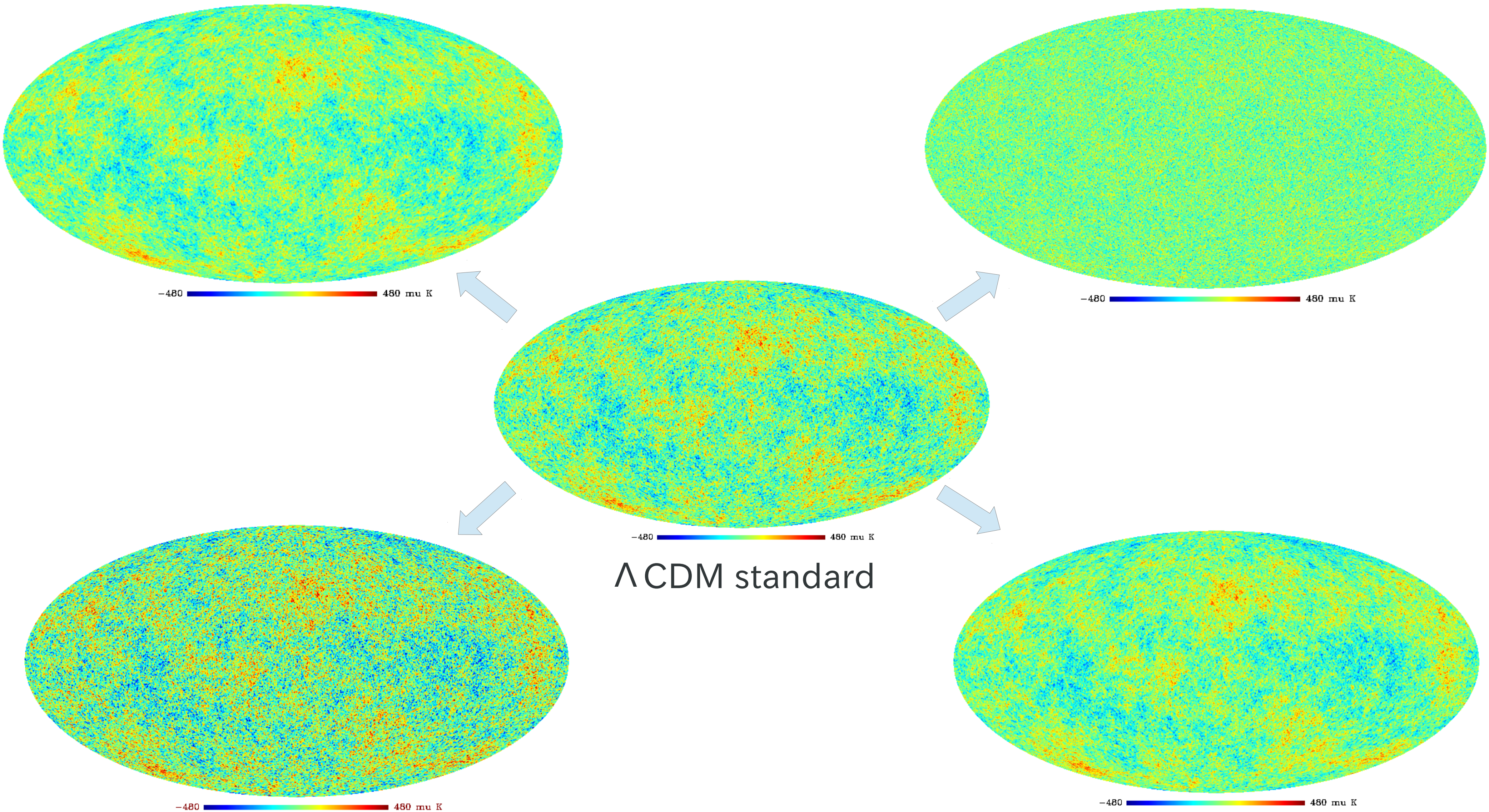
Planck's polarization data will come out 2014/06

"6 parameter standard model"

- Geometry of the universe
  - h hubble parameter,
- Initial conditions
  - matter densities… $\Omega_b h^2$ baryons, $\Omega_c h^2$ cold dark matter
  - fluctuations… $P_{\mathcal{R}} = A_s (k/k_0)^{n_s - 1}$ A_s amplitude, n_s spectral index
- astrophysics
  - τ optical depth to the last scattering surface

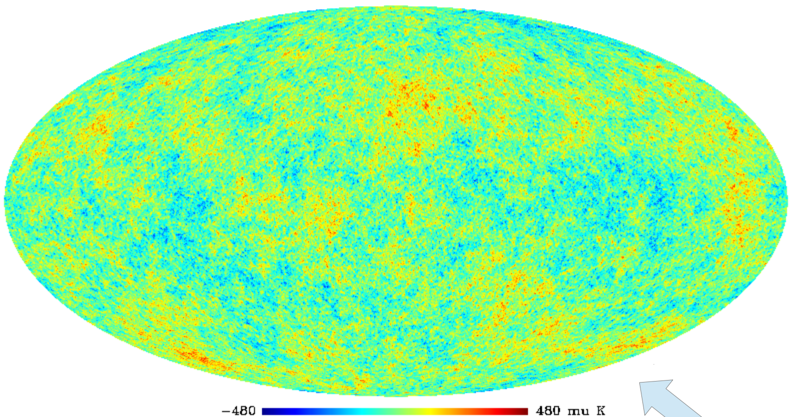


parameter dependence (real space)

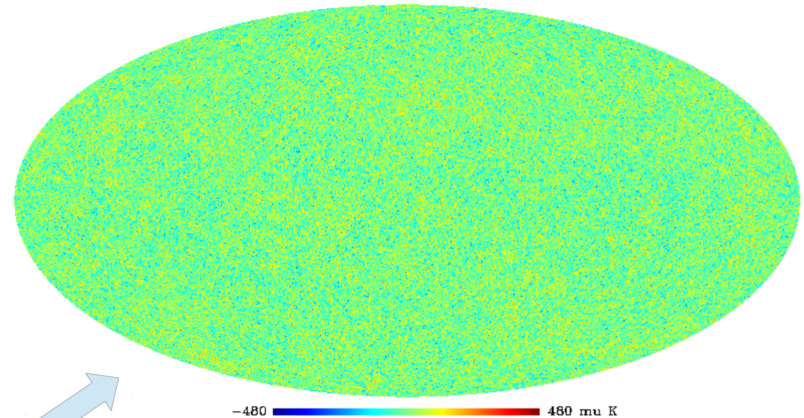


Which is which?：extra CDM, extra baryon, larger ns, larger τ

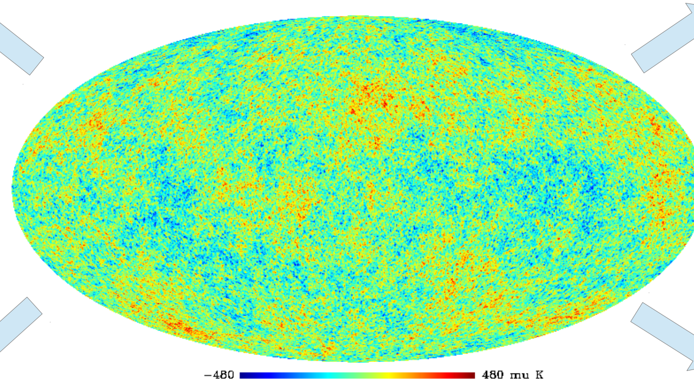
parameter dependence (real space)



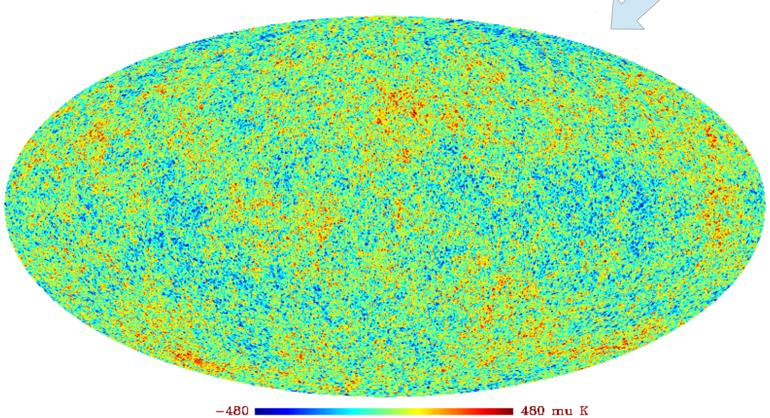
Extra CDM



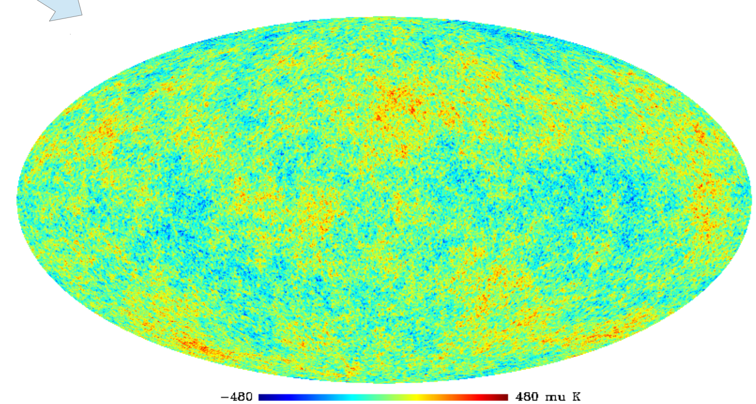
larger ns



ΛCDM standard



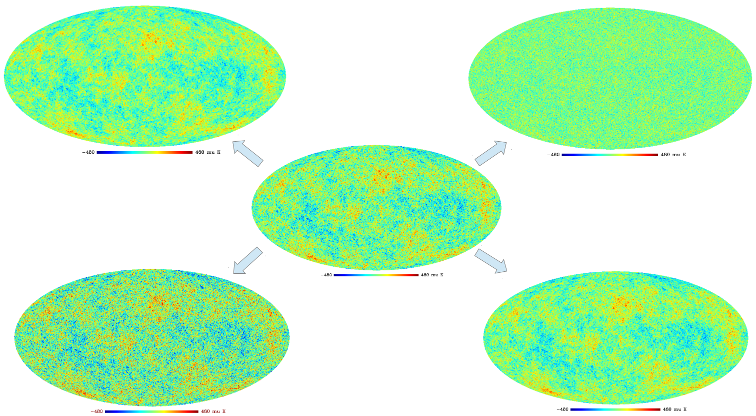
Extra baryon



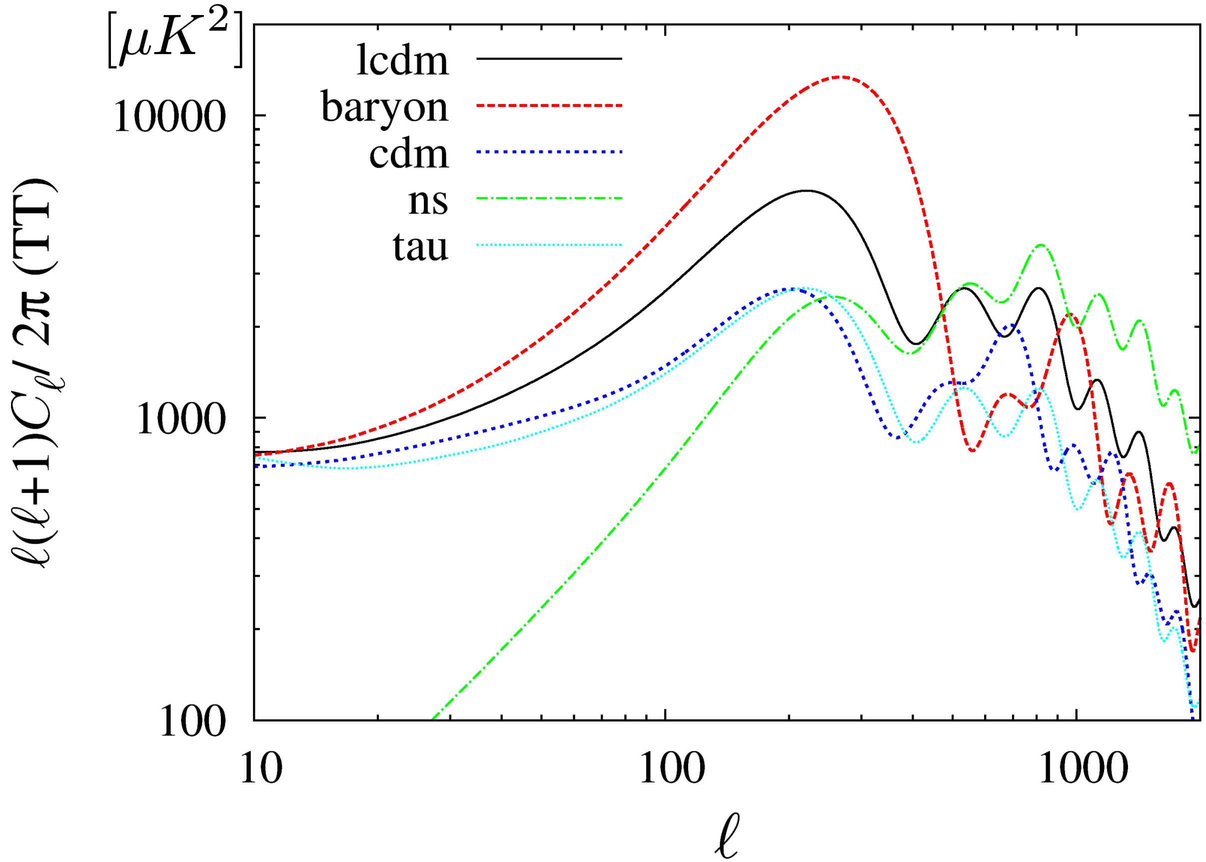
Larger τ

Which is which?：extra CDM, extra baryon, larger ns, larger τ

Parameter dependence (k-space)



take power spectra



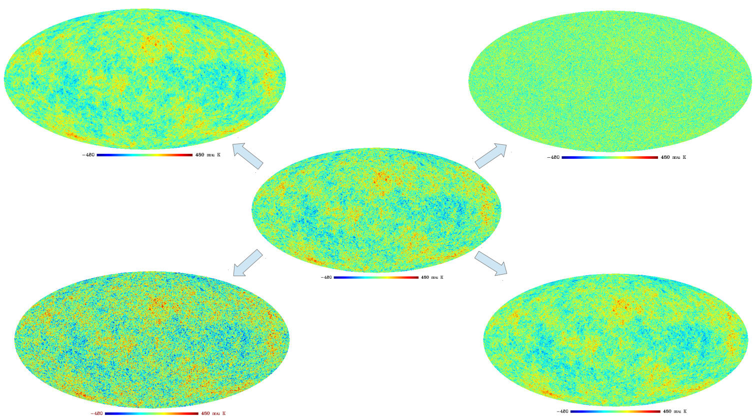
Observationally, positions of the peaks are most easily determined (0.1% precision)

$$\theta_{\rm acoustic} = 0.596724^\circ \pm 0.00038^\circ$$

$\theta_{\rm acoustic} \propto \Omega_m h^3$ (Percival et al., 2002)

Why these shapes?
see, Hu, Sugiyama & Silk, Nature, 1996

Parameter dependence (k-space)



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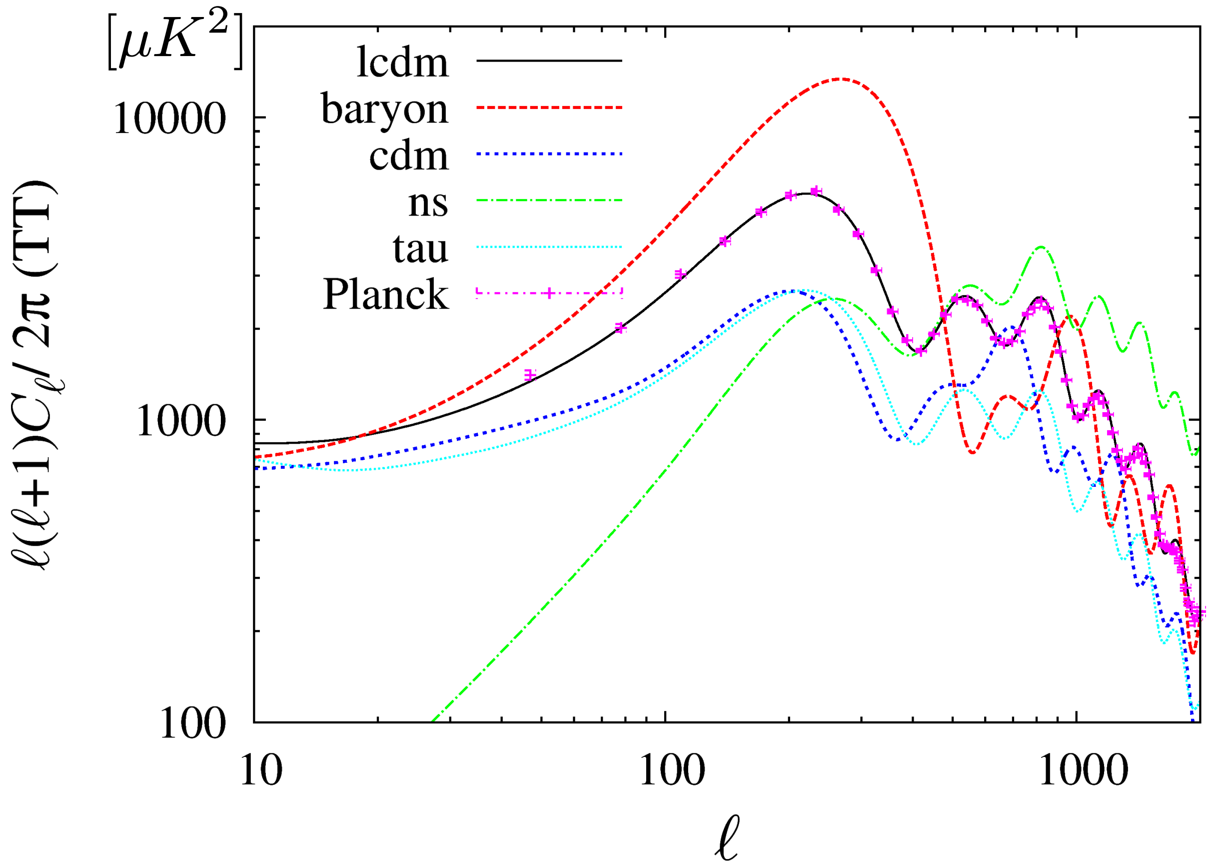

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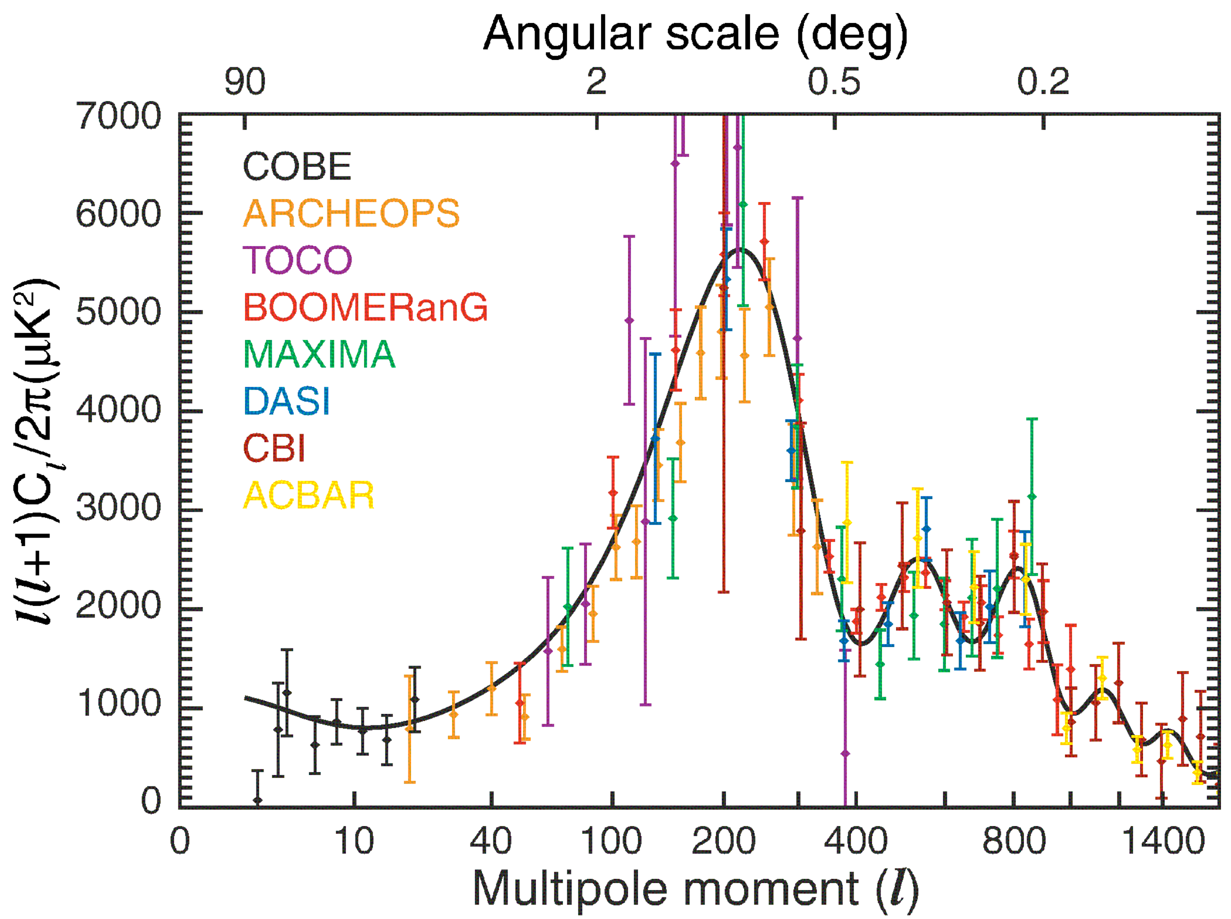
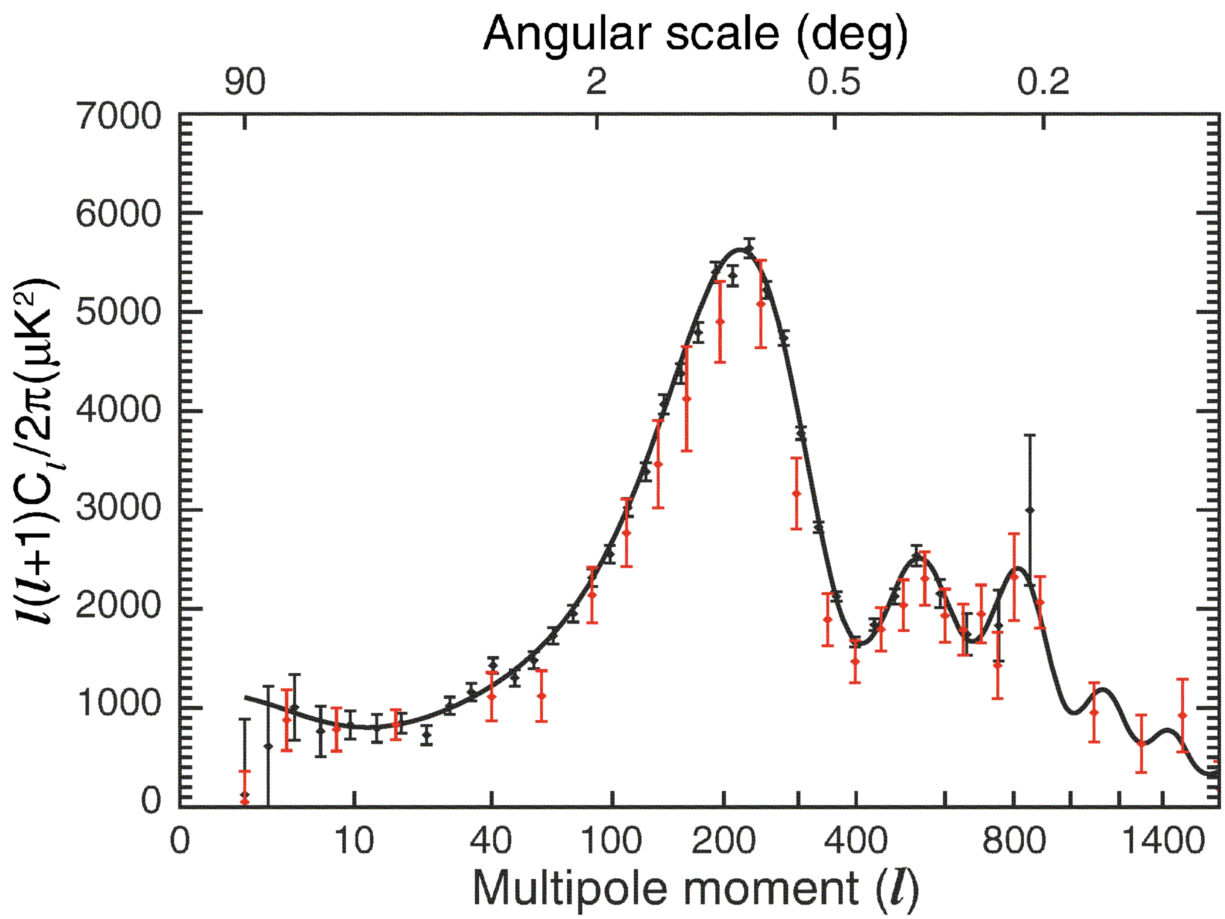
1996-2003



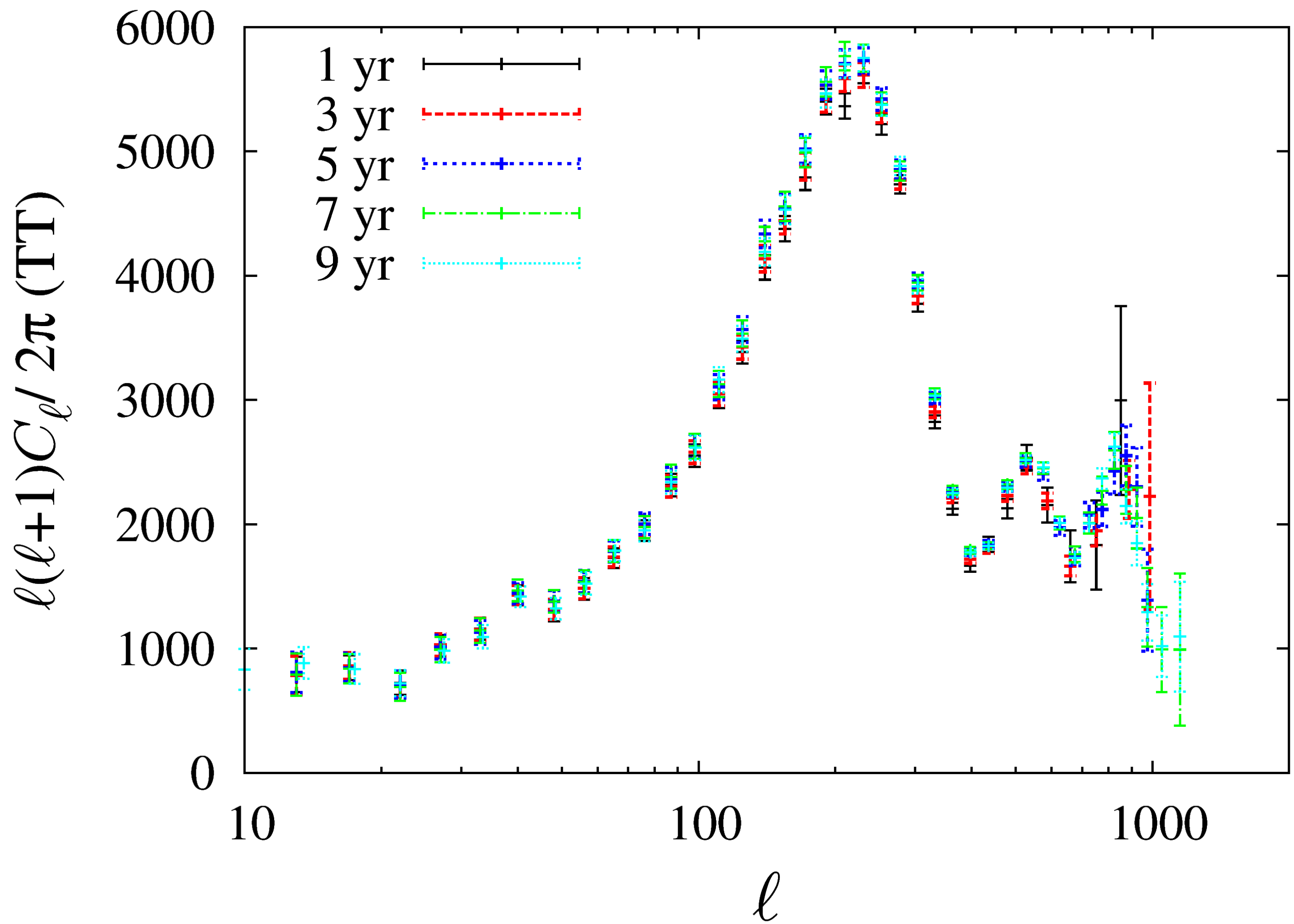
G. Hinshaw, et al., 2003, ApJS, 148, 135

2003 (WMAP1)

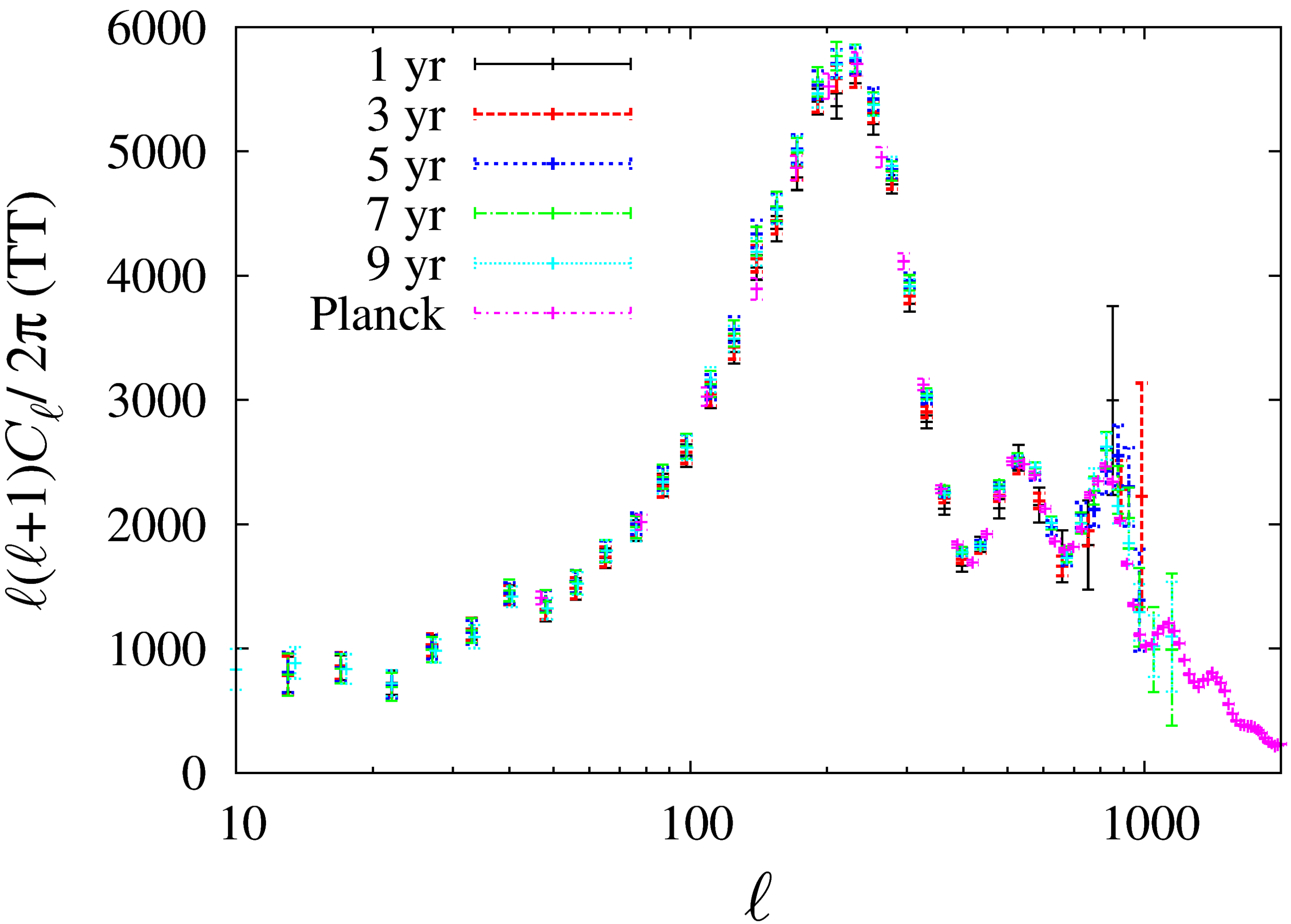


G. Hinshaw, et al., 2003, ApJS, 148, 135

WMAP final result (2013)

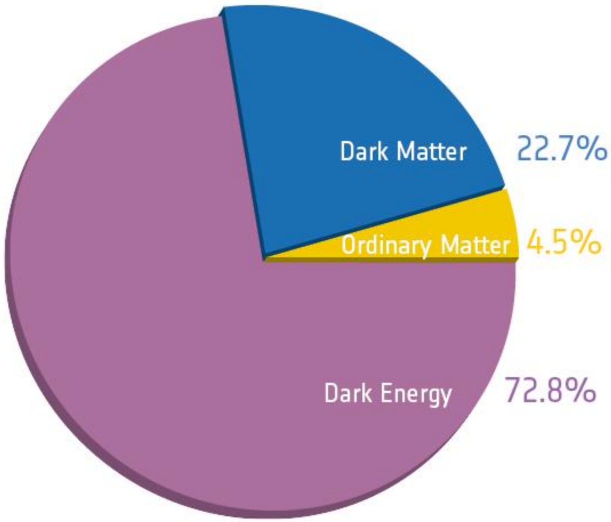


Planck (2013)

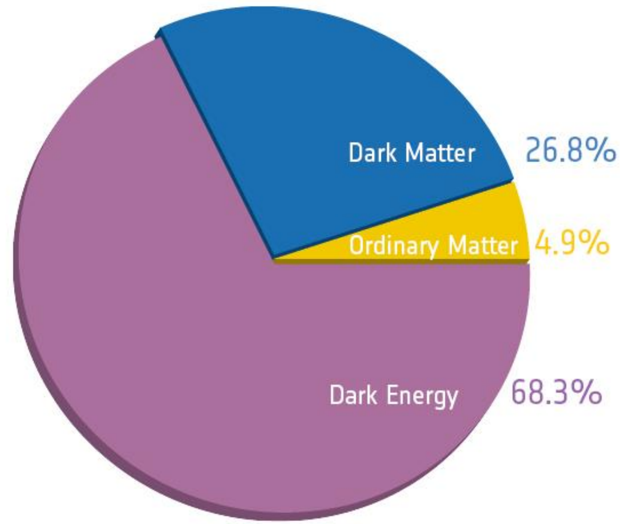


1 yr
3 yr
5 yr
7 yr
9 yr
Planck
6000
5000
4000
3000
2000
1000
0
10
100
1000
$\ell(\ell+1)C_\ell / 2\pi$ (TT)
ℓ

Before PLANCK



After



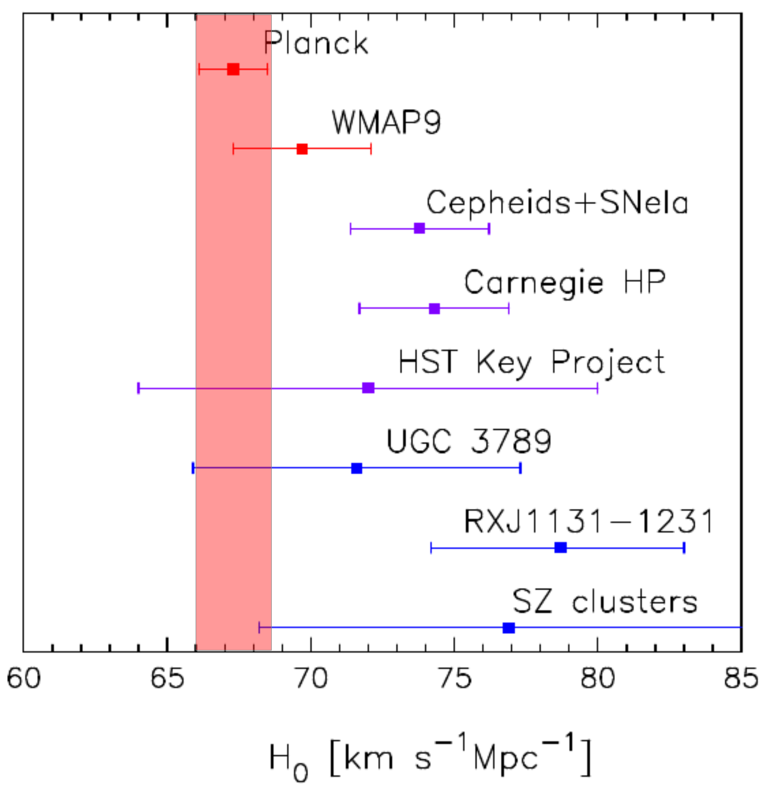
Age of the universe

13.7Gyr

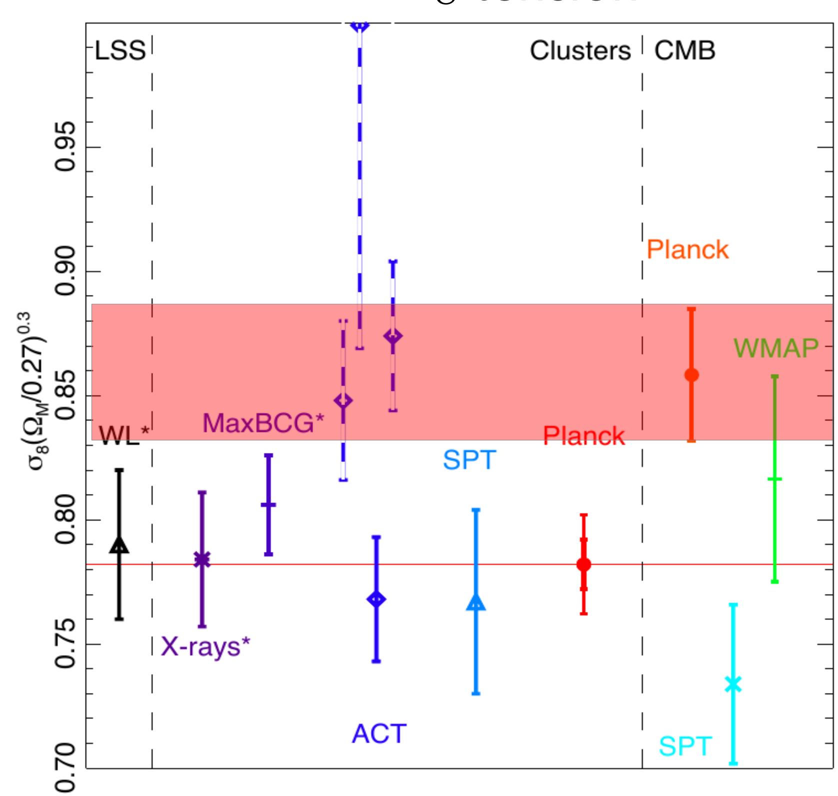
↓

13.8Gyr

H0 tension



σ_8 tension

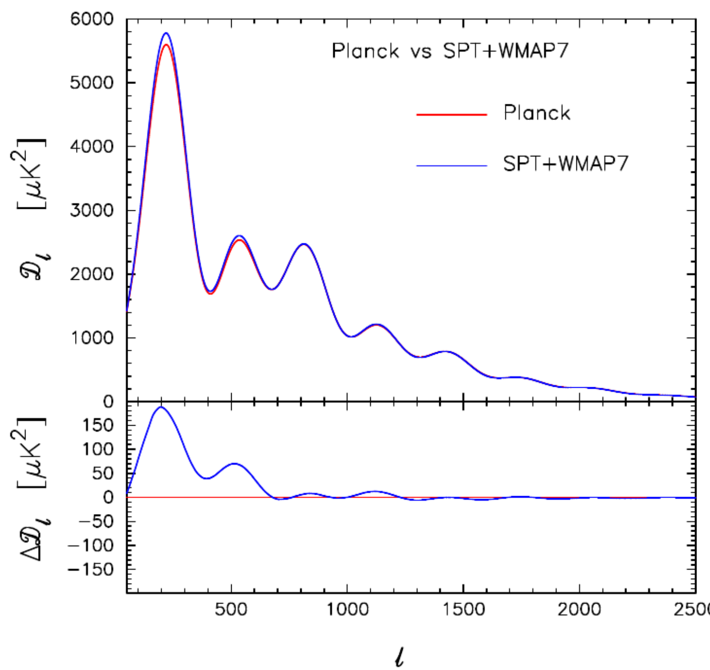


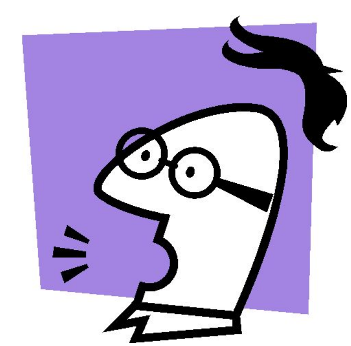
Why Large Ω_M ?

Planck & SPT(another CMB experiment) are consistent, but WMAP data show 2.6% larger amplitude in the power spectrum.

That leads larger (2.6 σ) $\Omega_c h^2$ than WMAP+SPT, and consequently different $\Omega_\Lambda,\ H_0$ values (3.2 σ , 2.7 σ).

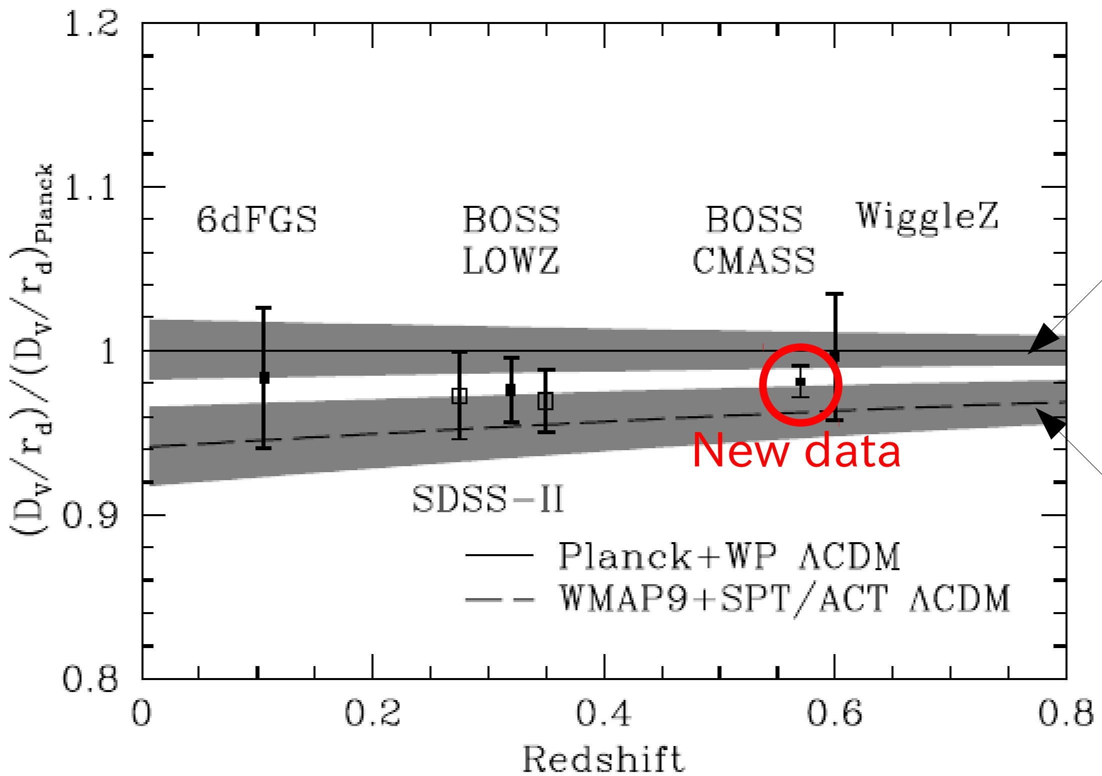
Planck team says the result from WMAP +SPT is not consistent with BOSS's BAO data.





Latest result from BOSS

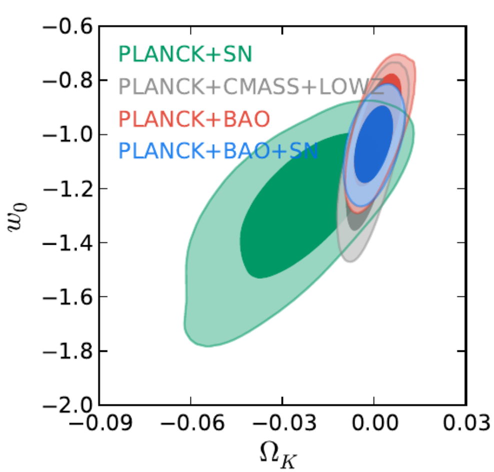
(Anderson+,1312.4877)

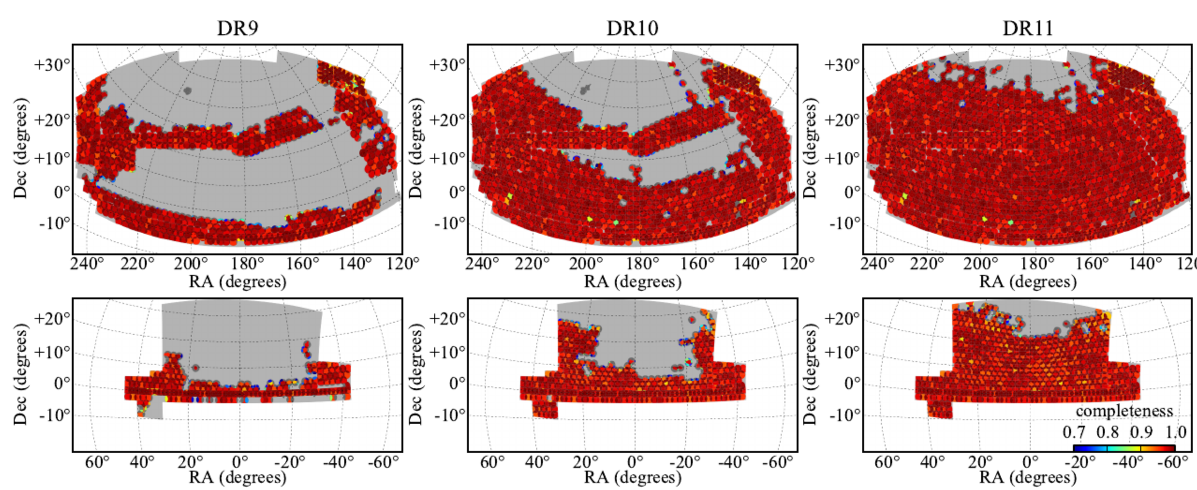


PLANCK prediction

BOSS is in between

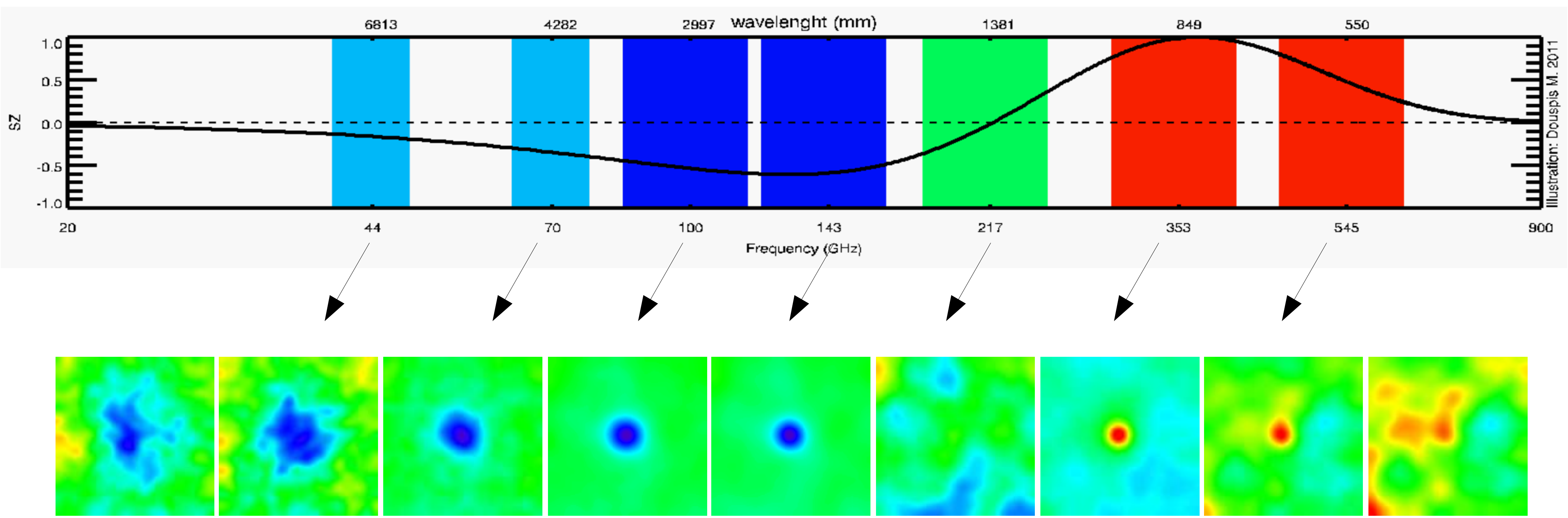
WMAP prediction





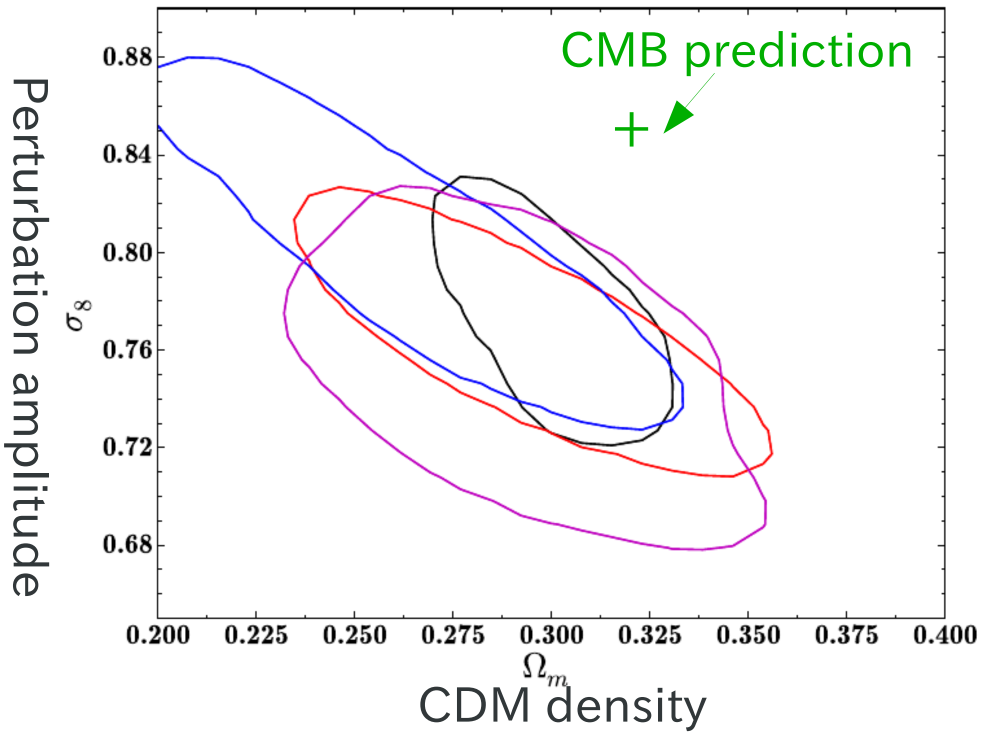
SZ signal from Planck

- Some CMB photons are Compton-scattered by hot electrons in clusters of galaxies, leading to a distortion of the Blackbody
- Total thermal energy → unbiased mass-limited selection
- Number of clusters highly depends on the fluctuation amplitude
- All-sky survey → rarest clusters → cosmology (DE, ν-mass)
- Can probe high-z clusters

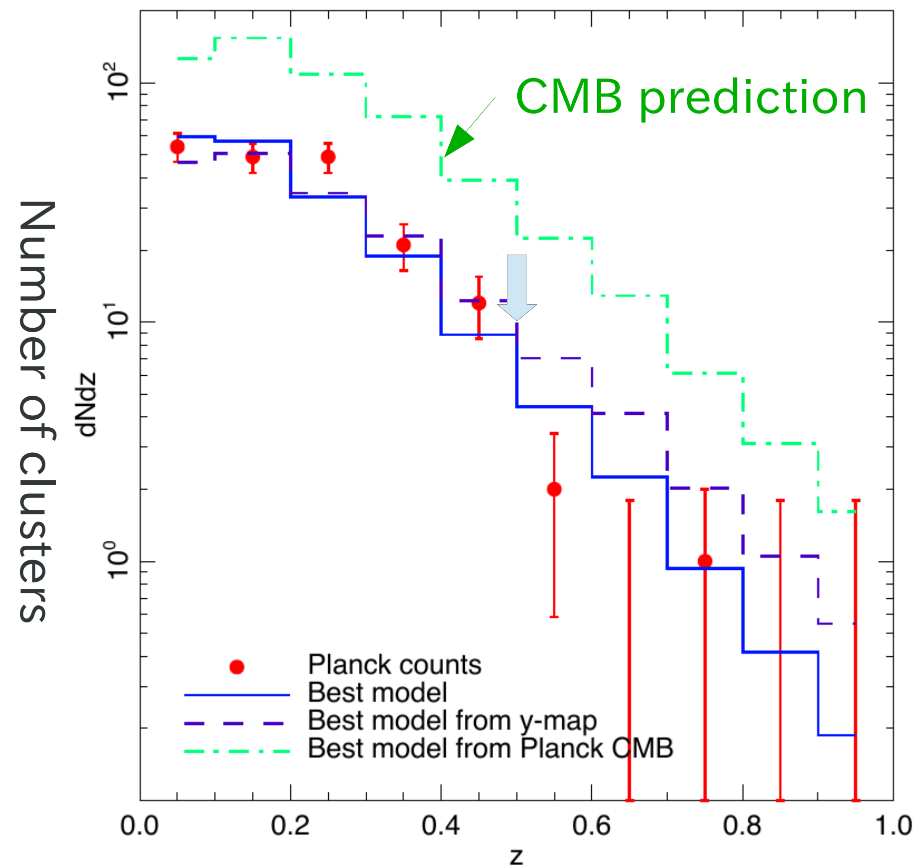


Stacked signal from PLANCK

Planck 2013 cluster results



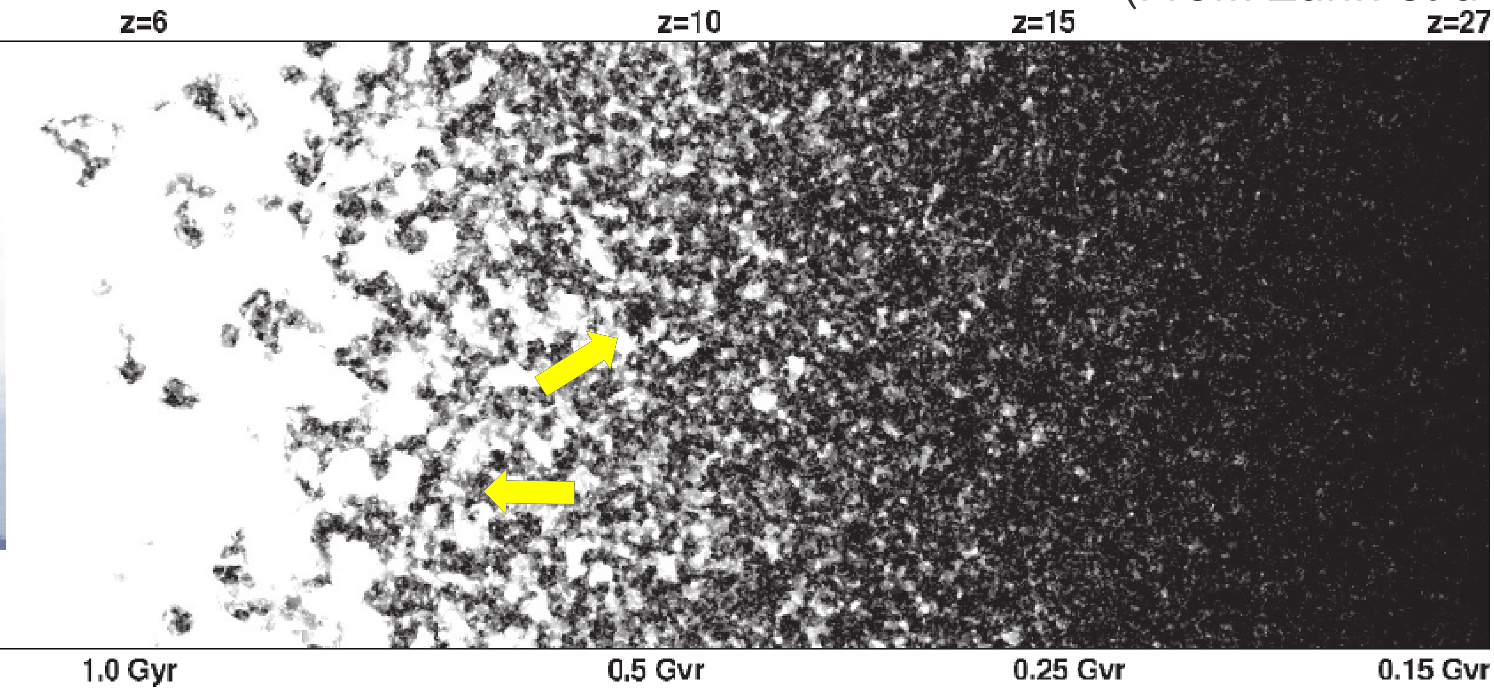
(different colors take into account different possible systematics)

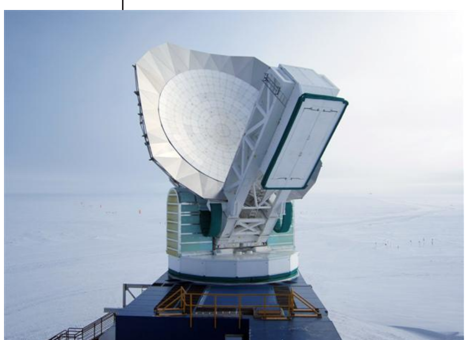


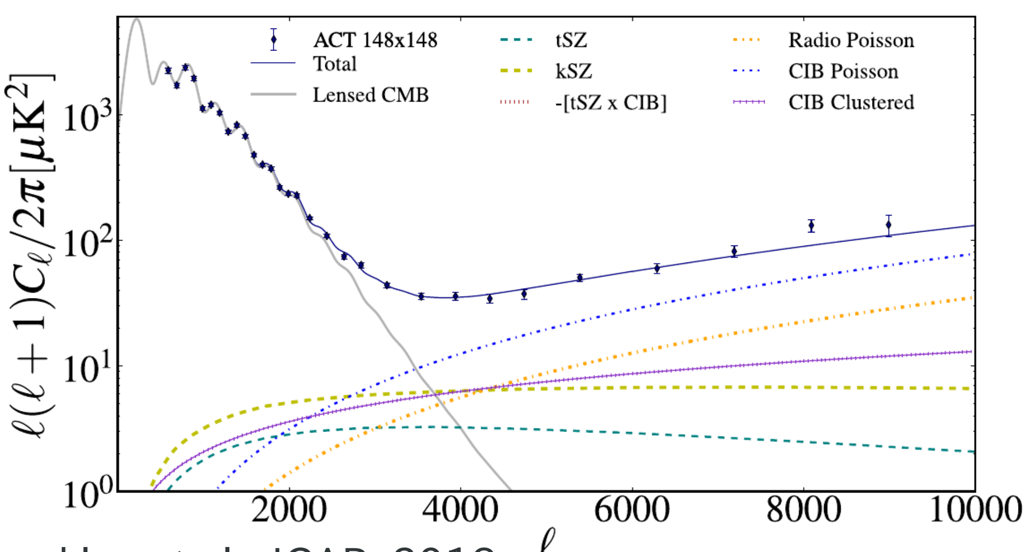
(CMB anisotropies) + (6 parameter model) suggest more clusters than observed

kSZ as a probe of EoR

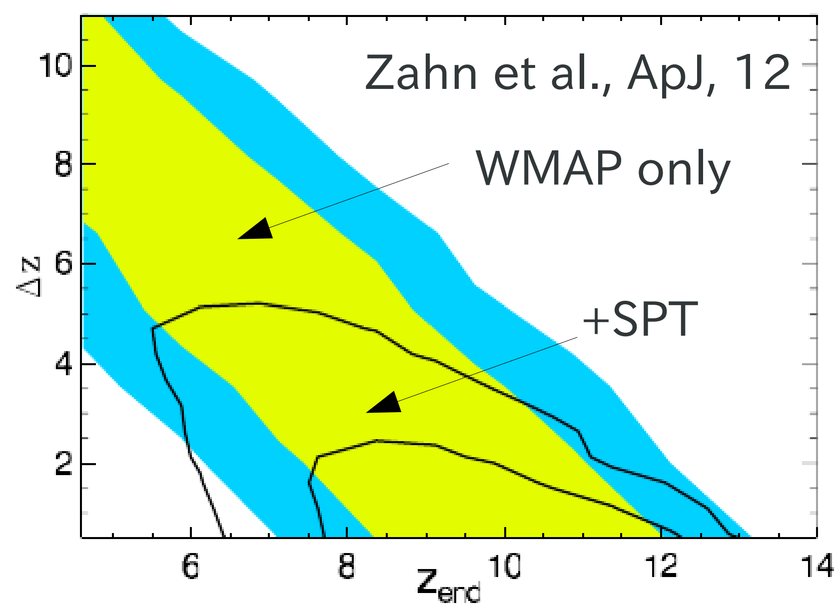
(From Zahn et al., 12)



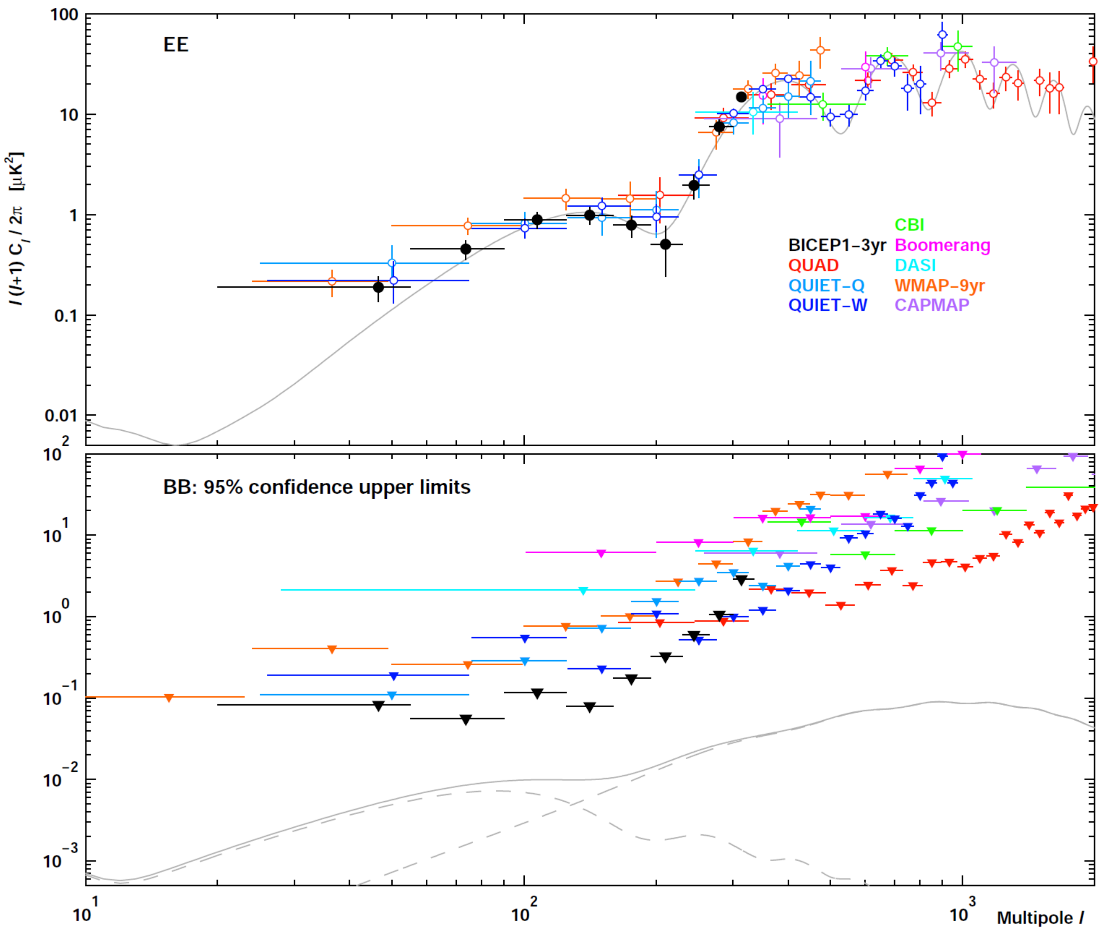




Dunkley et al., JCAP, 2013



Polarization measurements



BICEP collaboration arxiv: 1310.1422

E-mode has been already measured

Polarization due to the Density fluctuations

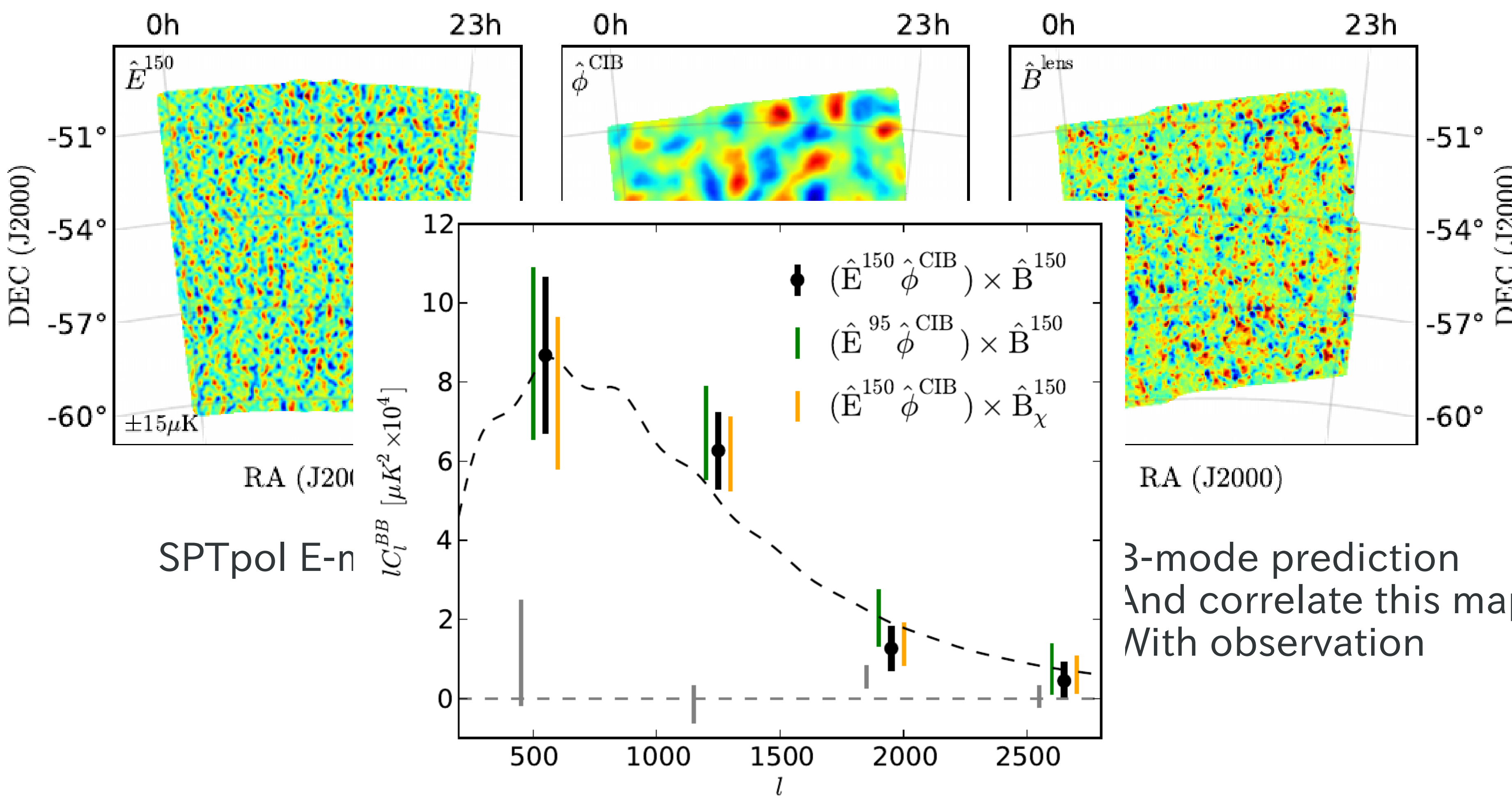
B-mode upper bounds

Polarization due to the Inflationary GWs

B-mode indirect detection --- SPTPol

arxiv:1307.5830

$$B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi), \quad (1$$



SPTpol E-n

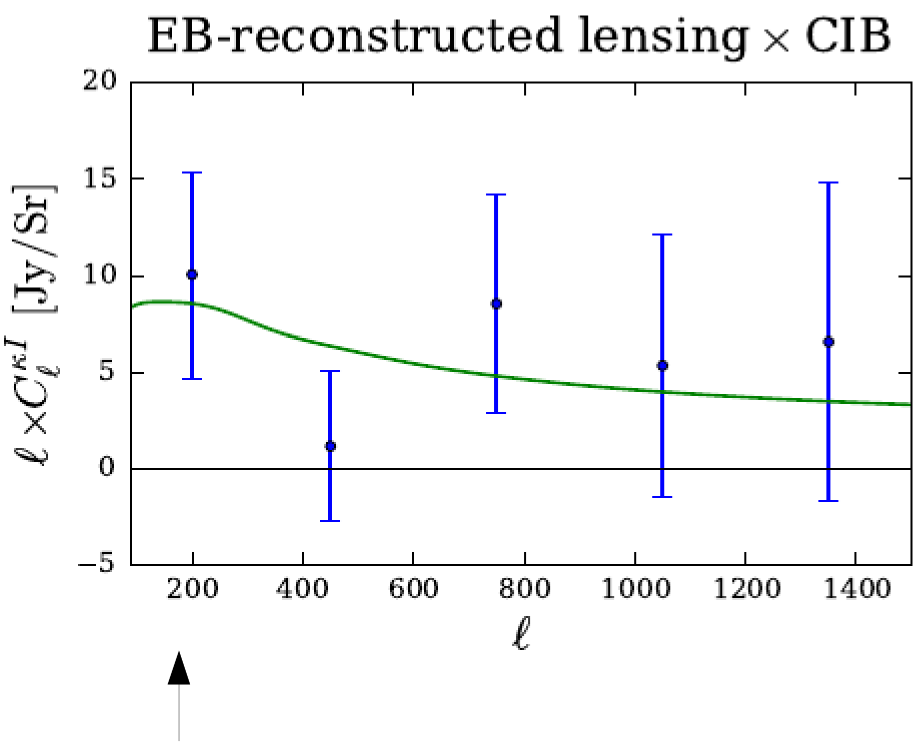
B-mode prediction
And correlate this map
With observation

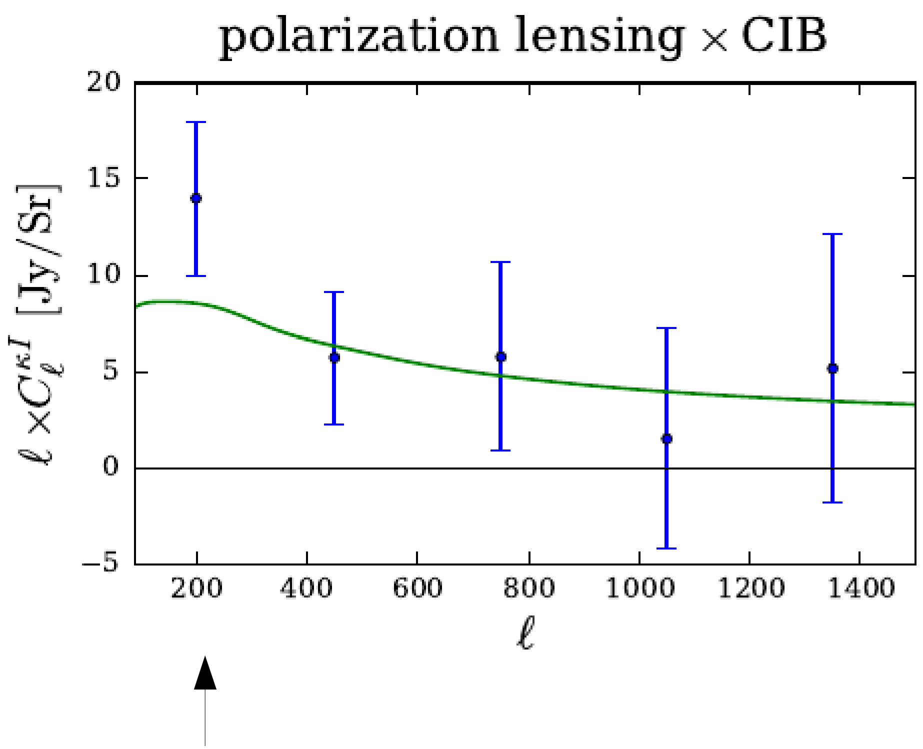
7.7σ detection

Polarbear results

Arxiv:1312.6645

Cross correlation between reconstructed lensing and Herschel CIB





B-mode polarization map contains
Lensing information (2.3 sigma)

EE and BE estimators combined (4.0 sigma)

Concordant cosmology 2013

- The results of PLANCK have indicated two possible tensions:
  - 1) matter fluctuation amplitude today
    - Extrapolation from CMB suggests larger amplitude of matter fluctuation σ_8 than measured in the local universe
  - 2) Hubble parameter today
    - Extrapolation from CMB suggests smaller H_0 than measured in the local universe

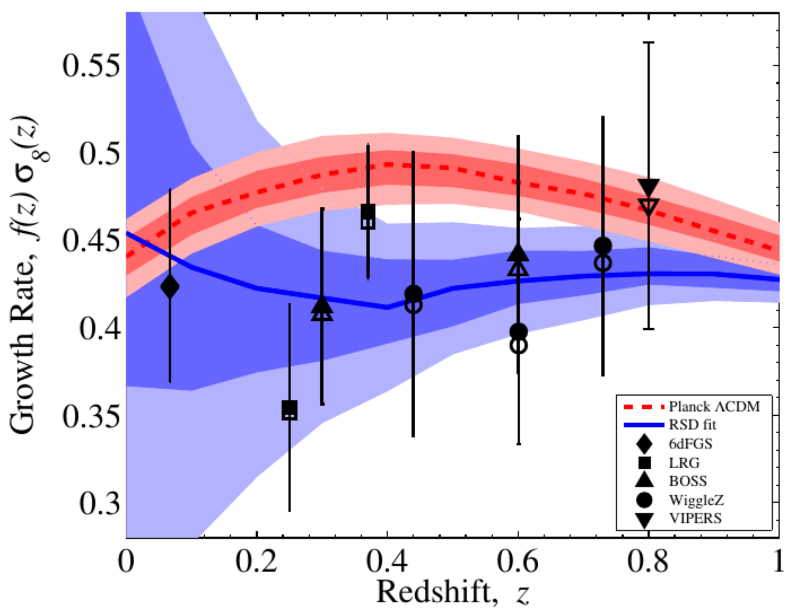
やること決まった!

http://www.pixiv.net

How do you reconcile the tension?

- Interestingly, other cosmological measurements seem to indicate the same tendency

Redshift space distortions

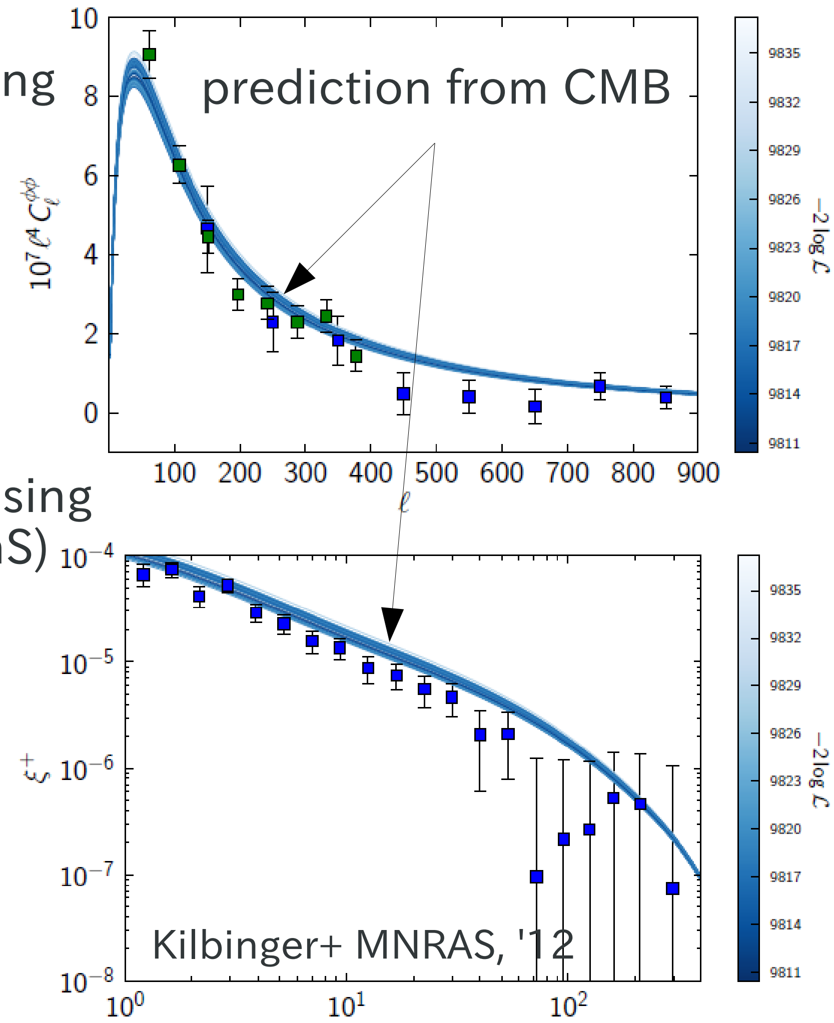


Macaulay, PRL, 2013

(Taruya-san & Yamamoto-san's talks)

CMB lensing (PLANCK)

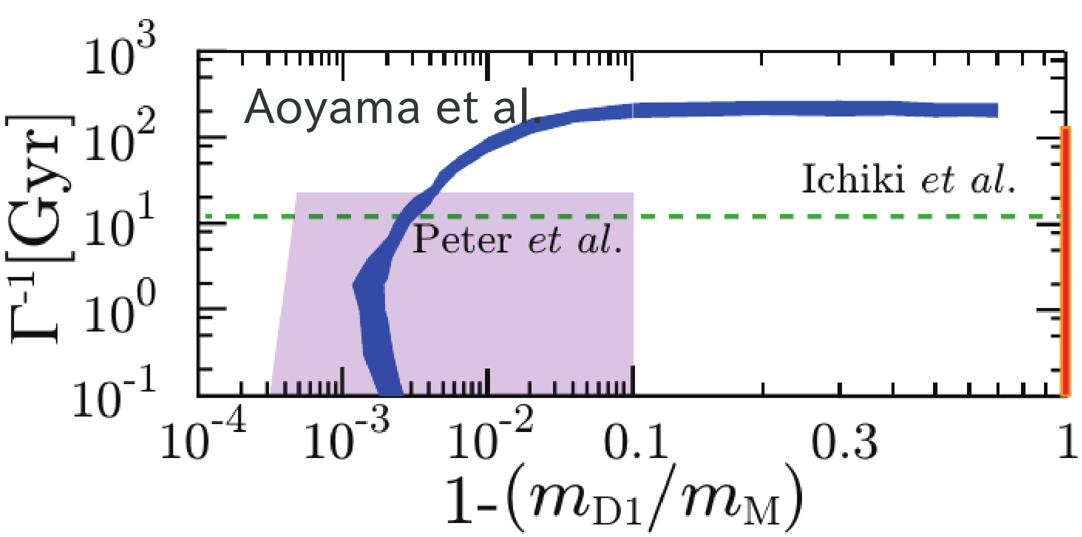
galaxy lensing (CFHTLenS)



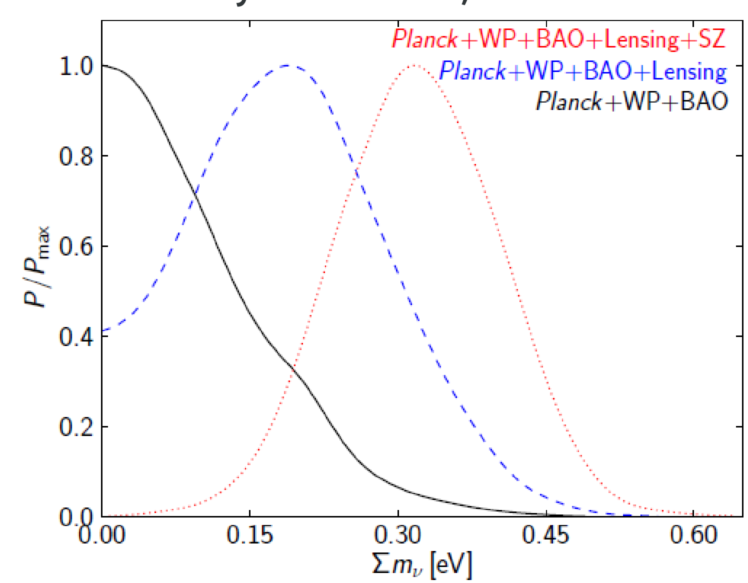
(from 1308.5870)

How do you reconcile the tension?

- How do you reconcile the σ_8 tension?
  - Planck CMB measurement is wrong by 15% (Spergel+, 1312.3313)
  - Sys. Error in the cluster mass estimates by 45% (not likely)
  - 2/3 of clusters are missing (never happens)
  - massive neutrinos with 0.2-0.3 eV (Wyman+1307.7715; Battye+1308.5870)
  - Decaying dark matter with lifetime 200Gyr (Aoyama, KI+, submitted)
  - Local underdensity (Marra+, PRL 13; Lee, 1308.3869)



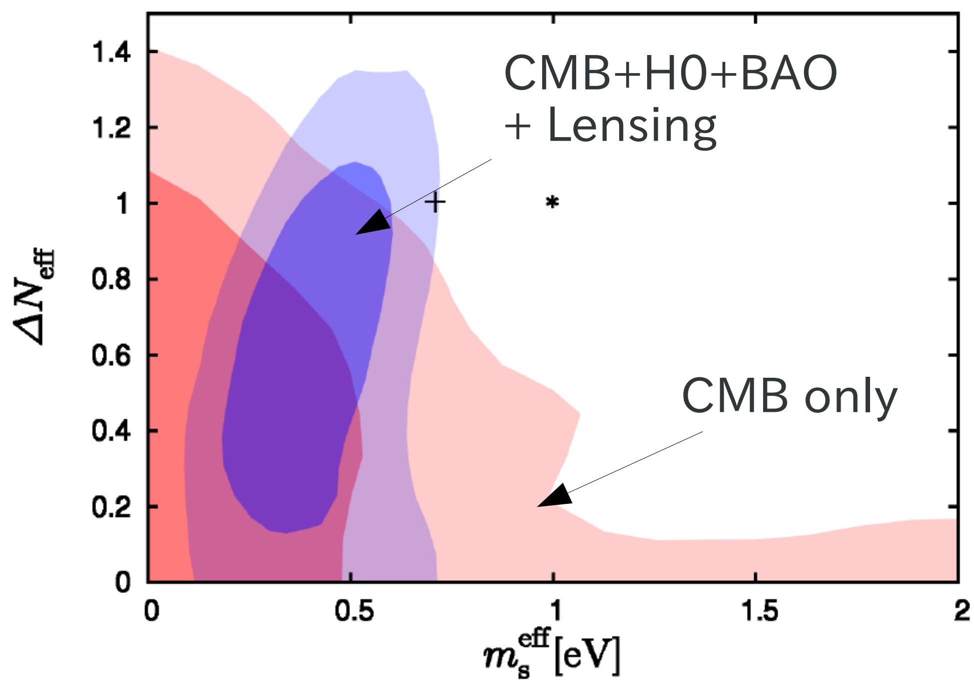
Battye & Moss, 1308.5870



Extra-radiation components?

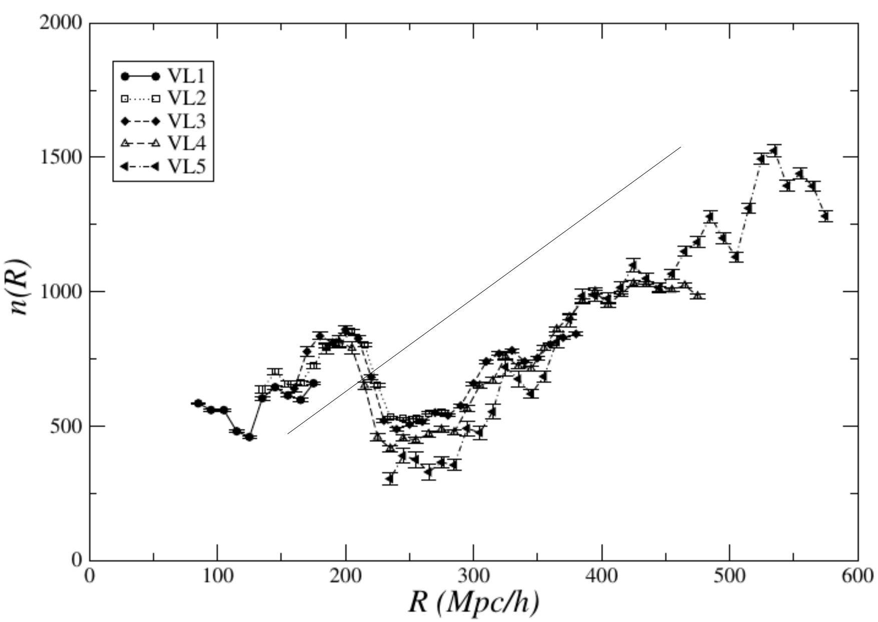
- The tension in H0 can be reconciled with extra radiation component --- Why?
  - Larger N_eff → Expansion faster → smaller acoustic scale → we need shorter distance to CMB (to keep the position of the peaks fixed) → Larger H0 !
- A global solution
  - One sterile neutrino with mass ~eV

    (Hamann+, 1308.3255)

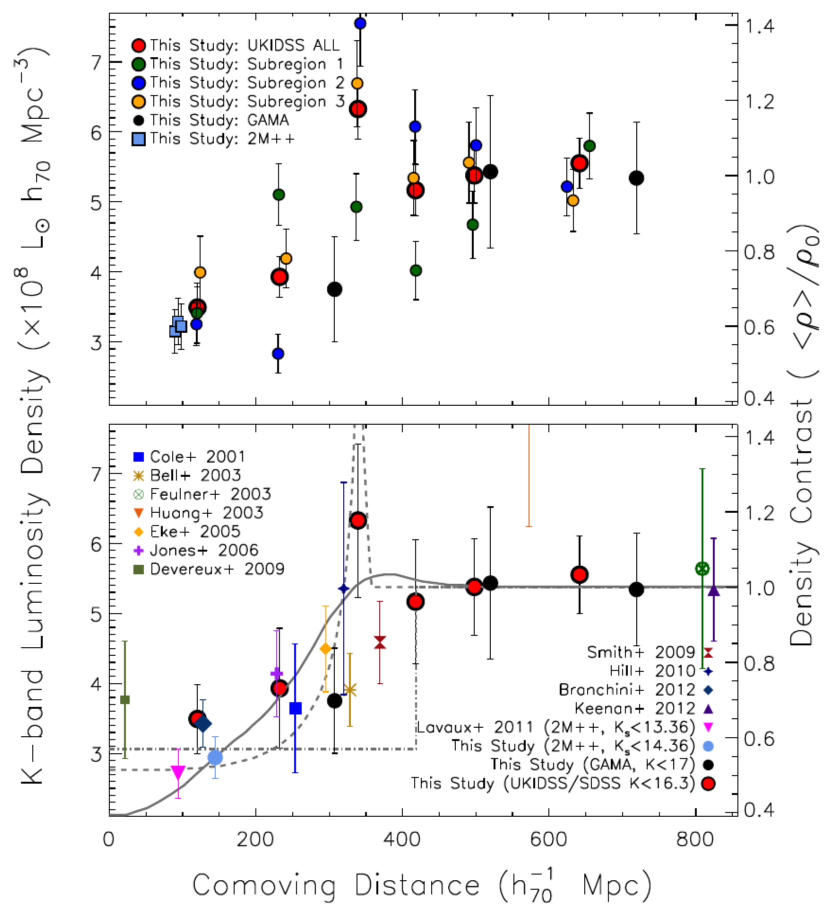


Local structure ?

- Evidence for a local void ?
  - smaller σ_8 (Lee, 1308.3869; Ichiki,Yoo,Oguri, in prep)
  - larger H_0 (Marra+, PRL, 2013)



Sylos Labini, CQG. 28, (2011) 164003



(Keenan et al., ApJ, 2013)

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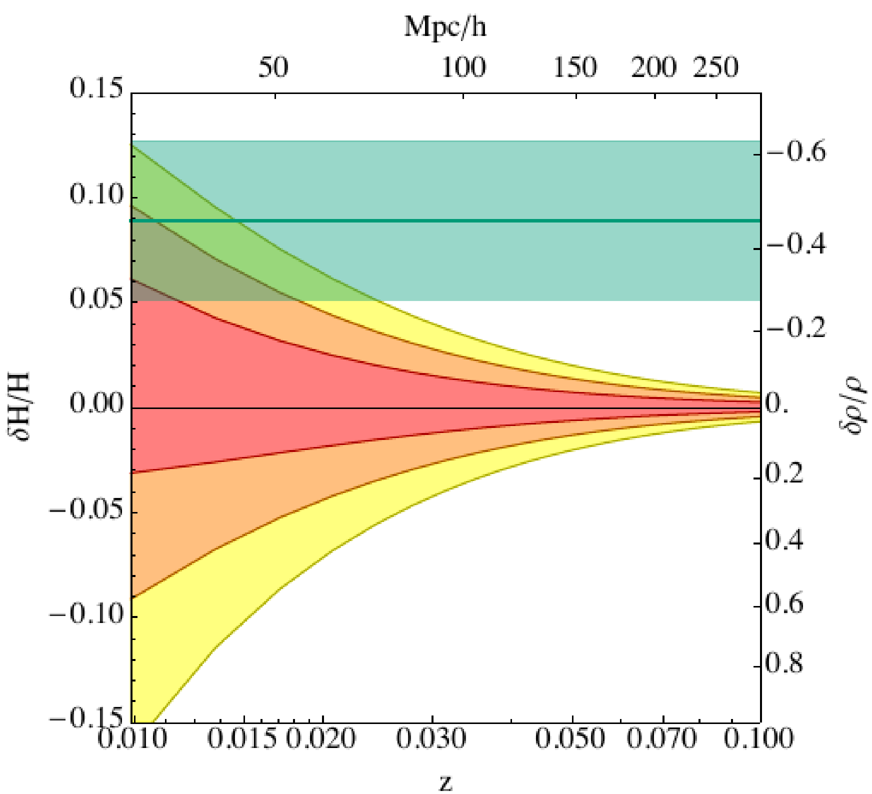
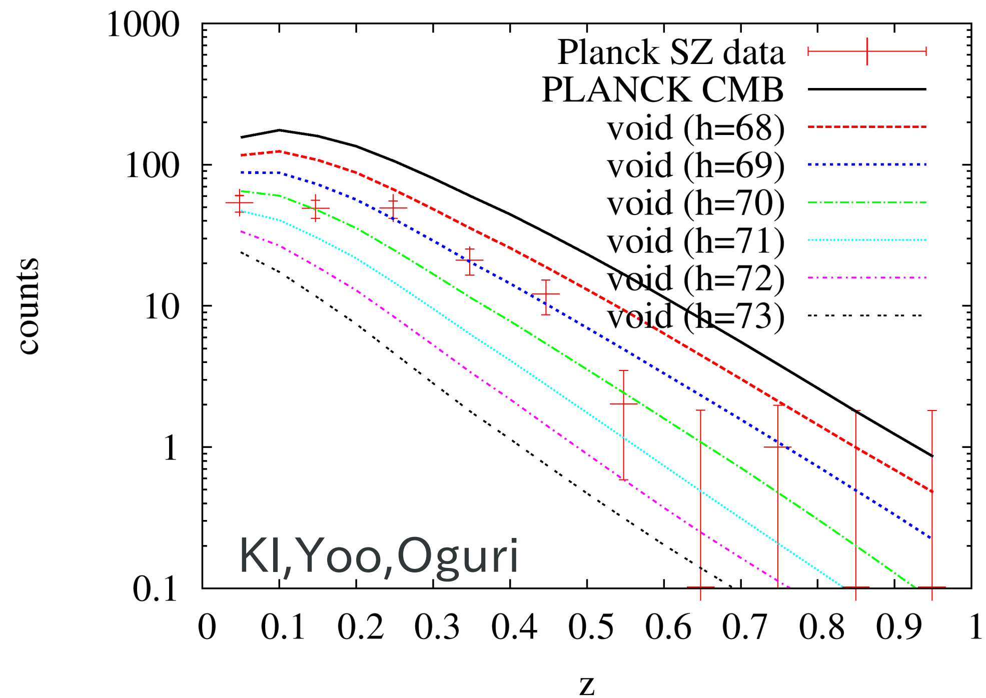


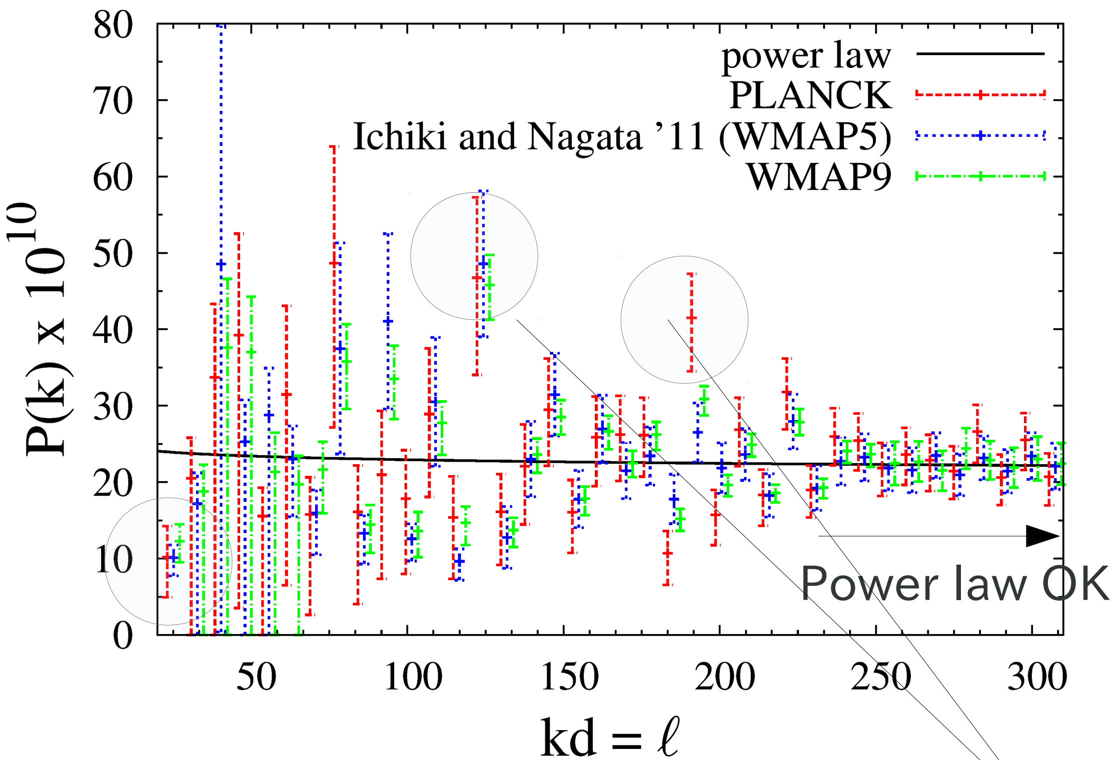


Cosmic variance ⇔ New systematics?

global local structure

- Cosmic Variance ⇔ New systematics

KI & Yokoyama, to be submitted



$$\Omega_b h^2 = 0.02205 \pm 0.00028 \pm 0.0002$$

$$n_s = 0.9603 \pm 0.0073 \pm 0.002$$

We need an *accurate* model, P(k), to derive *correct* value of baryon density, from *precise* data

An error inherent to the fact that we have only one observable universe

Precise vs. Accurate?

*__ac·cu·ra·cy__ /ǽkjurəsi/ 名 (形 áccurate; 反 inaccuracy) U 正確さ, 精密さ, 的確さ; 正確に行なえる能力. **for áccuracy's sàke** [副] 正確を期するために. **with áccuracy** [副] 正確に (accurately).

*__ac·cu·rate__ /ǽkjurət/ 形 (名 áccuracy; 反 inaccurate) 1 (情報·報告などが)正確な[で]; (計器などが)精密な (☞ correct 類義語; cure 単語の記憶): a fairly ~ calculation かなり正確な計算 / John is ~ *with* figures. <A+*with*+名·代> ジョンは計算が正確です / My sister is always ~ *in* her statements. <A+*in*+名·代> 妹はいつも言うことが正確だ / a clock ~ *to* ... 誤差が1/1000秒

*__pre·cise__ /prɪsáɪs/ 形 (名 precision; 反 imprecise) 1 (きわめて)正確な, 精密な (☞ correct 類義語); 明確な: ~ measurements 正確な寸法 / His translation is very ~. 彼の翻訳は非常に正確だ. 2 A まさにその: at that ~ moment まさにその瞬間 に. 3 [時に軽蔑] (性格などが)きちょうめんな; しゃくし定規の. **to be precise** [副] 文修飾語 厳密に言えば

*__pre·cise·ly__ /prɪsáɪsli/ 副 1 正確に (exactly); ちょうど, まさに, はっきりと: It is ~ as you said. 全く君の言ったとおりだ / The plane took off at twelve ~. 飛行機は12時きっかりに離陸した / I can't tell ~ how it began. それがどの様に始まったかはっきりとはわからない. 2 S まさにそのとおり (quite so) (返事などに用いる): "Was it like this?" "P~." 「それはこんなふうでしたか」「そのとおりです」

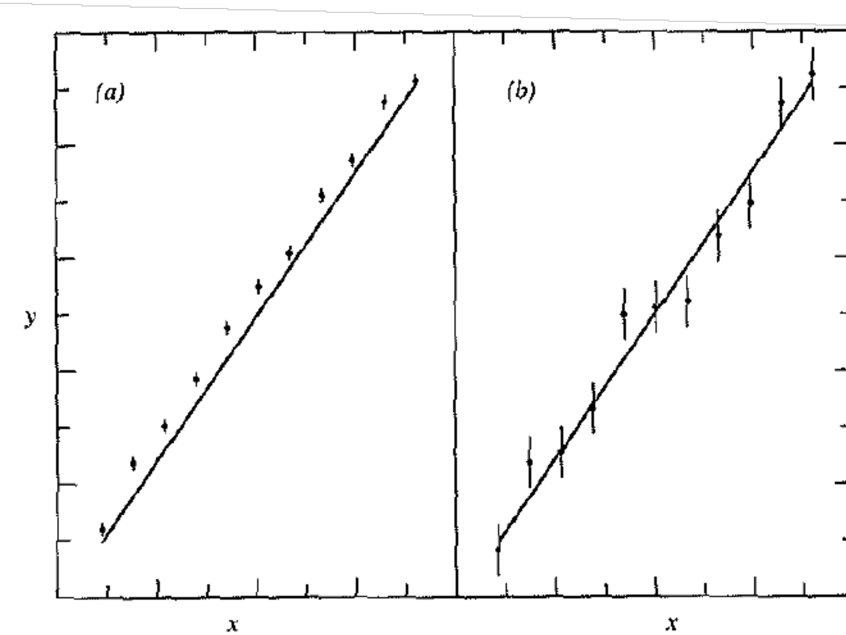


FIGURE 1.1
Illustration of the difference between precision and accuracy. (*a*) Precise but inaccurate data. (*b*) Accurate but imprecise data. True values are represented by the straight lines.

Data Reduction and Error Analysis
For the Physical Sciences,
Bevington&Robinson, McGraw-Hill

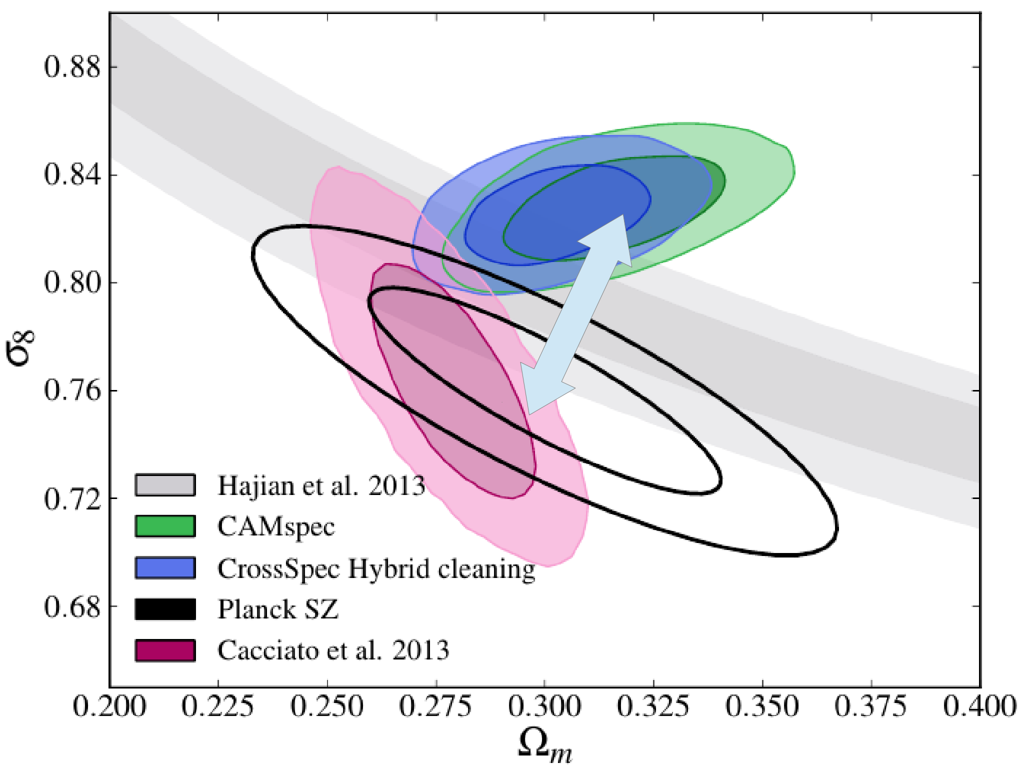
Error in Planck? Spergel et al. 1312.3313

TABLE 1
PLANCK VERSUS PRE-PLANCK ΛCDM COSMOLOGICAL PARAMETERS

	Planck Analysis	No 217 × 217	WMAP9+ACT
$10\ \Omega_c h^2$	1.199±0.026	1.181± 0.027	1.146±0.043
n_s	0.9603±0.0073	0.9661±0.0077	0.973 ± 0.011
H_0	67.3±1.2	68.1±1.2	69.7 ± 2.0
$100\ \Omega_b h^2$	2.205± 0.028	2.226 ±0.029	2.260 ±0.041
Ω_m	0.315± 0.016	0.305 ±0.016	0.284 ±0.024

・Spergel et al. find a possible systematics Planck's 217GHz band

Strange signal comes from pixels observed once



・That reconcilse a part of the tension, But not entirely

CMB future experiments (3 directions)

- B-mode polarization measurements
  - Spider(2013-), EVEX(2013-), QUIET, PolarBeaR, QUBIC(2014-), QUIJOTE(2014-), PLANCK(-2014) LiteBird, COrE, EPIC, ⋯ and more!
- spectroscopy
  - PRISM, PIXIE (O(100) band detectors!)
  - Small distortion from black body, detect all clusters
- Toward lower frequency (21cm cosmology)
  - LOFAR,MWA,HERA,SKA
  - Vast information 10^7 modes (2D) ⇨ 10^{18} modes (3D)

summary

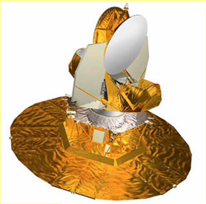
- PLANCK determined cosmological parameters precisely
  - upto l=2500, basically consistent with ΛCDM
- B-mode measurements have just begun!
  - Lensing x CIB cross correlations
- Planck's CMB and local measurements indicate some tensions (3 sigma)
  - Neutrino mass, local void, extra-radiation, … any idea?
  - Need ACCURATE models to compare with PRECISE measurements
- Bright future
  - B-mode polarization（GWs）, spectrometry, 21cm

Contents

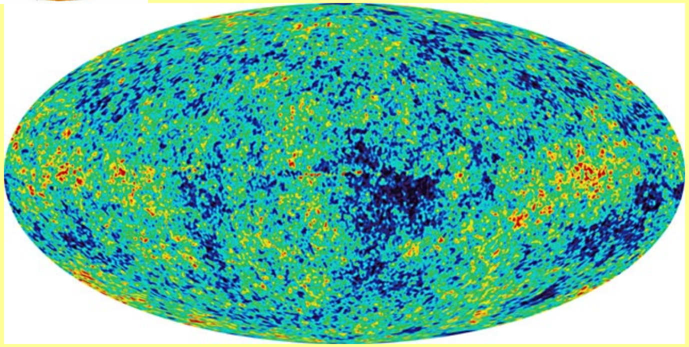
- A brief review for CMB (& PLANCK)
  - Cosmological parameters
  - Tensions between CMB & local universe
  - CMB on small scales
    - cluster cosmology in the PLANCK era
- the standard (concordant) cosmology 2013

- A simple test for the statistical homogeneity

CMB anisotropies



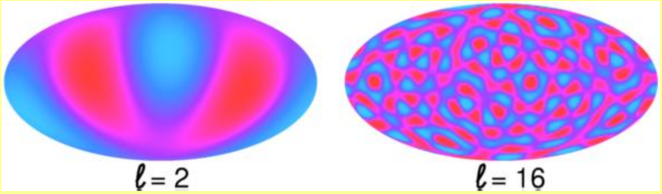
Microwave sky: $\dfrac{\Delta T(\hat{n})}{T_0}$



CMB: Density fluctuations
380,000 yr after the big-bang

Expand with the spherical harmonics

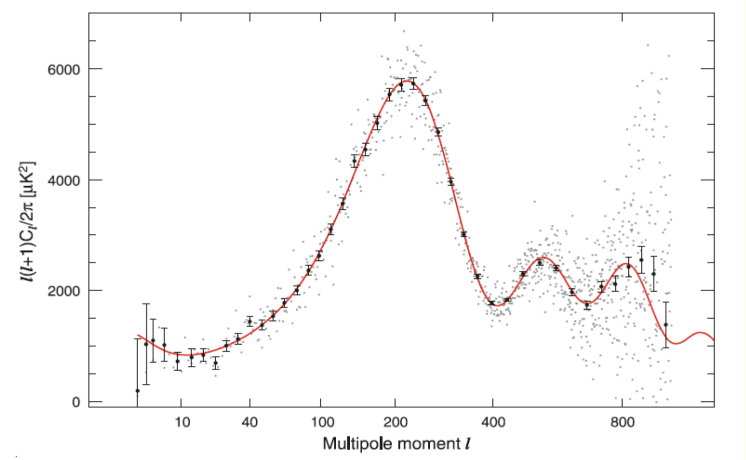
$$\frac{\Delta T(\hat{n})}{T_0} = \sum_{\ell m} a_{\ell m} Y_{\ell m}$$



Power spectrum: Calc the variance of the expanded coefficients

$$C_\ell = \langle a^*_{\ell m} a_{\ell m} \rangle$$
$$= \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

WMAP power spectrum



Today's question

- The variance (C_ℓ) contains most of the cosmological information

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

- Why should we divide the squares by $(2\ell+1)$, and not by 2ℓ? (textbooks say we should divide by (d.o.f -1) to get an unbiased estimate)
- **This is because we have *implicitly* assumed that the mean of $a_{\ell m}$ is zero.**

condition for the zero-mean

- We believe that, according to the cosmological principle, we can write any perturbation variables as

$$\phi(t,x) = \phi_0(t) + \delta\phi(t,x)$$

$$\langle \delta\phi(t,x) \rangle = 0$$ Independent of position (x)

- This is possible when $\phi(t,x)$ is statistically homogeneous:

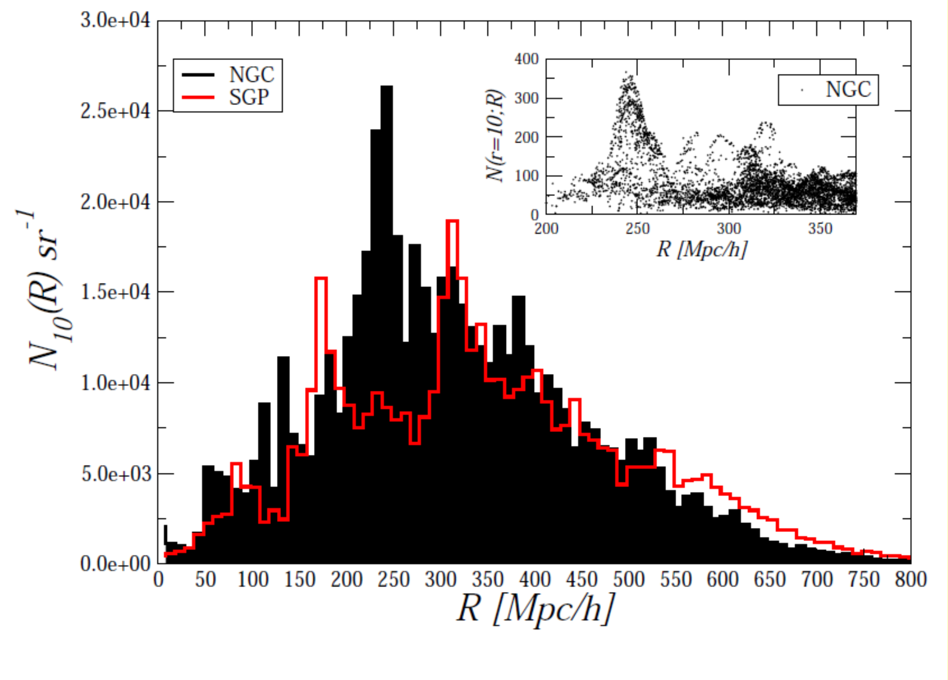
$$\langle \phi(\vec{x}) \rangle = \left\langle \phi(\vec{x} + \vec{T}) \right\rangle$$ $\vec{T}$: arbitrary vector

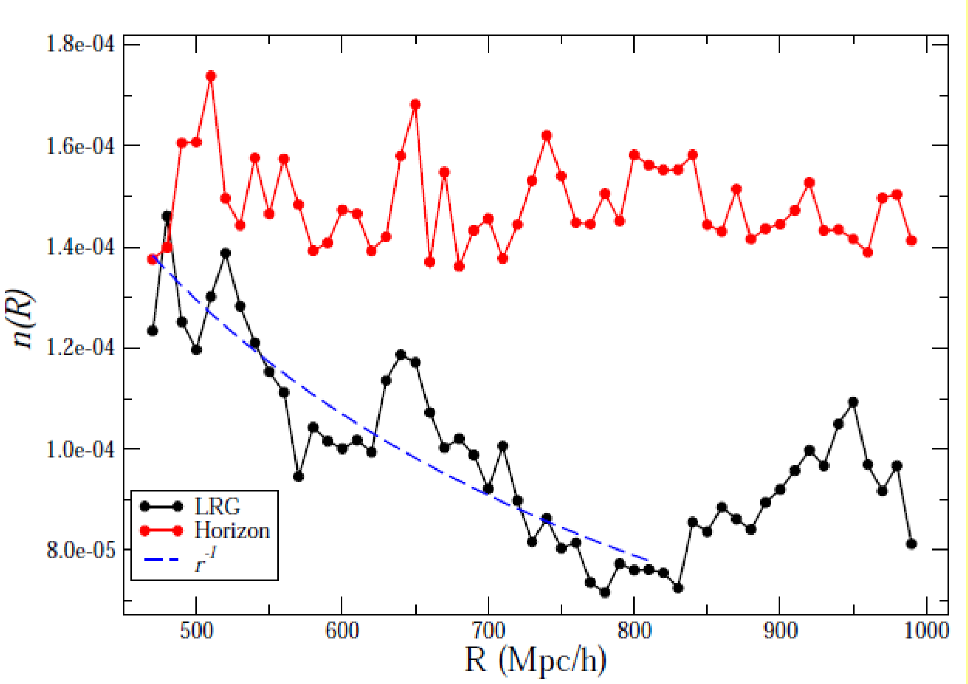
- **The condition should be tested by observations!**

Another motivation

- In the analysis of CMB anisotropies, **zero mean is usually assumed implicitly.**
  - Any higher order statistics, such as variance, skewness, kurtosis etc... are affected by this assumption.
  - Non-zero mean have been indicated by LSS (e.g., Sylos Labini, QCG '11)
    - However, LSS suffers from bias, selection rules, galaxy evolution,...

Let's look for in the CMB anisotropies !





Sylos Labini, CQG. 28, (2011) 164003

Mean of CMB anisotrpies (1)

- CMB fluctuations $\delta T(x,\hat{n})$ are related with the primordial fluctuations (random variable) $\phi(\vec{k})$ through transfer function $\mathcal{T}(\vec{k},\hat{n})$ as

$$\delta T(x,\hat{n}) = \int \frac{d^3k}{(2\pi)^3}\mathcal{T}(\vec{k},\hat{n})\phi(\vec{k})e^{i\vec{k}\cdot\vec{x}}$$

- Expanded coefficients of CMB fluctuations:

$$a_{\ell m} = \int d^2\hat{n}\delta T(\hat{n})Y_{\ell m}(\hat{n})$$
$$= 4\pi(-i)^\ell \int \frac{d^3k}{(2\pi)^3}\mathcal{T}_\ell(k)\phi(\vec{k})Y_{\ell m}(\hat{k})$$

Legendre coefficients of the transfer function

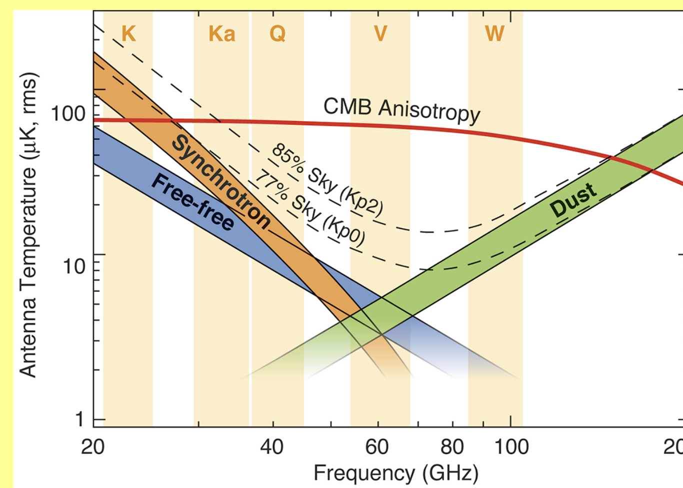
- Therefore, $\langle\phi\rangle = 0 \rightarrow \langle a_{\ell m}\rangle = 0$

- Furthermore, if $\phi(\vec{k})$ are Gaussian, so are $a_{\ell m}$

Difficulty…Foreground,Noise,Mask

- Some of the CMB photons are not primordial origin
  - Dust emission, synchrotron, free-free…
  - They have non-Gaussian dist., **non-zero mean**
- Cleaning should not be perfect
  - masking the galactic disk
  - **induces unwanted correlations**
- Instrumental noises
  - they have zero-mean

Bennett et al., 2003



Beating the mask

- Mask introduces unwanted correlations between the sample $a_{\ell m}$s

$$a_{\ell m}^{\text{mask}} = \sum M_{\ell m;\ell' m'} a_{\ell' m'} \qquad \text{or} \quad \vec{a}_m^{\text{mask}} = M \cdot \vec{a}_m$$

- Simple statistical tests rely on the independence... what would you do?
  - Do a test including the correlations
    - Monte Carlo simulation (Kashino, KI, Takeuchi, PRD '12)
  - Construct a de-correlated variable
    - V-vector method (Armendariz-Picon, JCAP '11, KI in prep.)
    - Principal component analysis

v-vector method (Armendariz-Picon, JCAP, '11)

- Goal: to remove the effect of the mask from the observed spherical harmonic coefficients

$$a_{\ell m}^{\text{mask}} = \sum M_{\ell m;\ell' m'} a_{\ell' m'}$$

observed ↗ ↖ signal

- Let us use a vector notation:

$$\vec{a}_m^{\text{mask}} = M \cdot \vec{a}_m$$

- Find m-independent v-vectors (by SVD) that satisfy

$$\vec{v}^{\ \text{t}} = \vec{v}^{\ t} M$$

$$v_{\ell m} = \begin{cases} v_\ell & \text{for } |m| \le m_{\max} \text{ and } m_{\max} \le \ell \le \ell_{\max} \\ 0 & \text{(otherwise)} \end{cases}$$

binning

- Construct d_m as a dot product of $\vec{v}$ and $\vec{c}_m$

$$d_m \equiv \vec{v} \cdot \vec{a}_m^{\text{mask}} = \sum_\ell v_{\ell m} a_{\ell m}^{\text{mask}} = \vec{v} \cdot (M \vec{a}_m) = \vec{v} \cdot \vec{a}_m$$

$$\text{for} \quad (|m| \le m_{\max})$$

v-vector method (Armendariz-Picon, JCAP, '11)

- Find m-independent v-vectors (by SVD) that satisfy

$$\vec{v}^{\,\mathrm{t}} = \vec{v}^{\,t} M$$

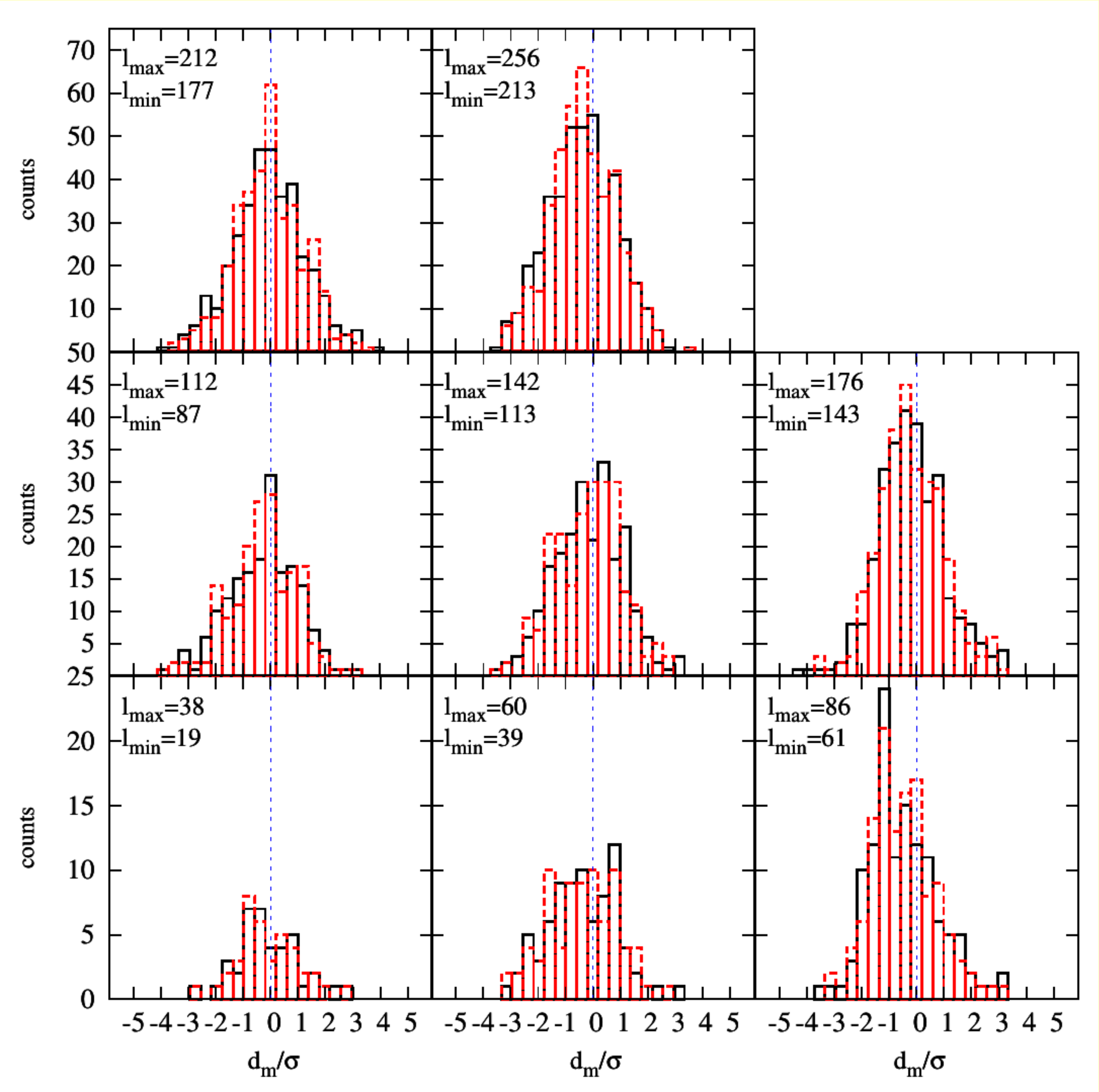
- Construct d_m as a dot product of $\vec{v}$ and $\vec{a}_m^{\mathrm{mask}}$

$$d_m \equiv \vec{v} \cdot \vec{a}_m^{\mathrm{mask}} = \vec{v} \cdot (M\vec{a}_m) = \vec{v} \cdot \vec{a}_m$$

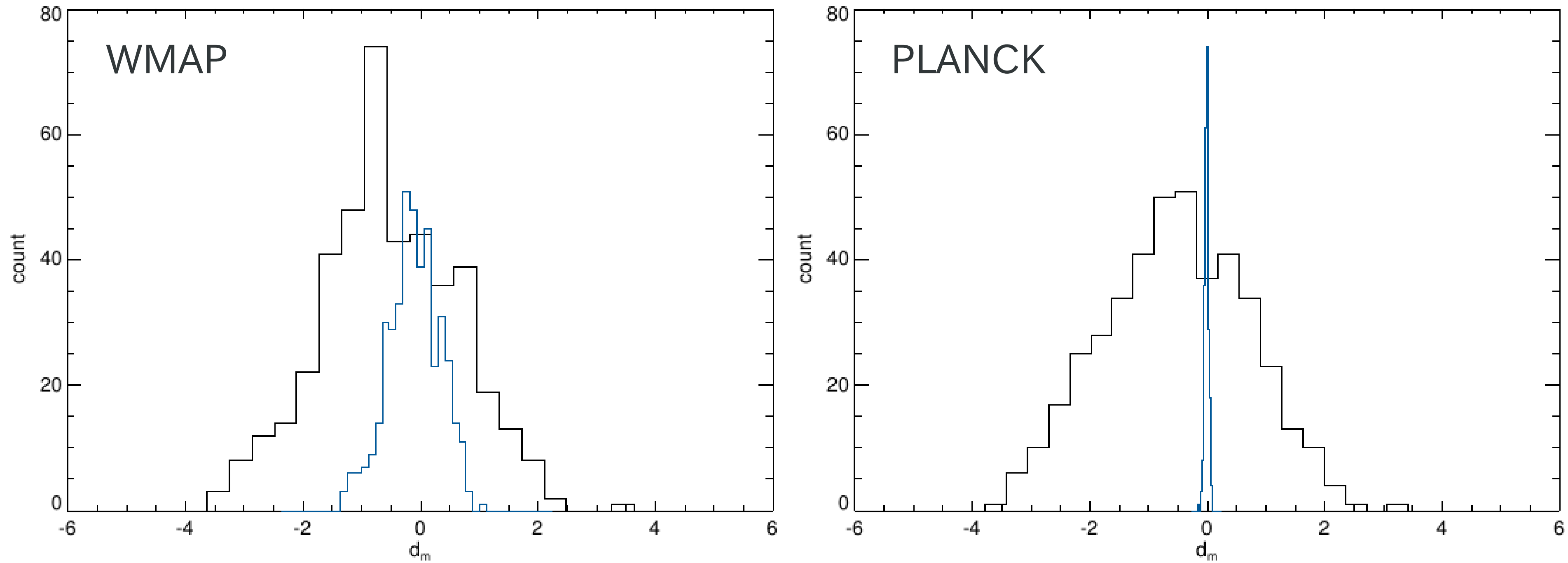
- The new stochastic variable d_m have following properties:
  - Foreground insensitive (because we work on $a_{\ell m}^{\mathrm{mask}}$)
  - Statistically independent samples (because $\vec{v}$ is constant)
  - zero-mean Gaussian if $a_{\ell m}$ are zero mean Gaussian
  - have m-independent variance

RESULTS

Distribution of the stochastic variable from PLANCK and CMB

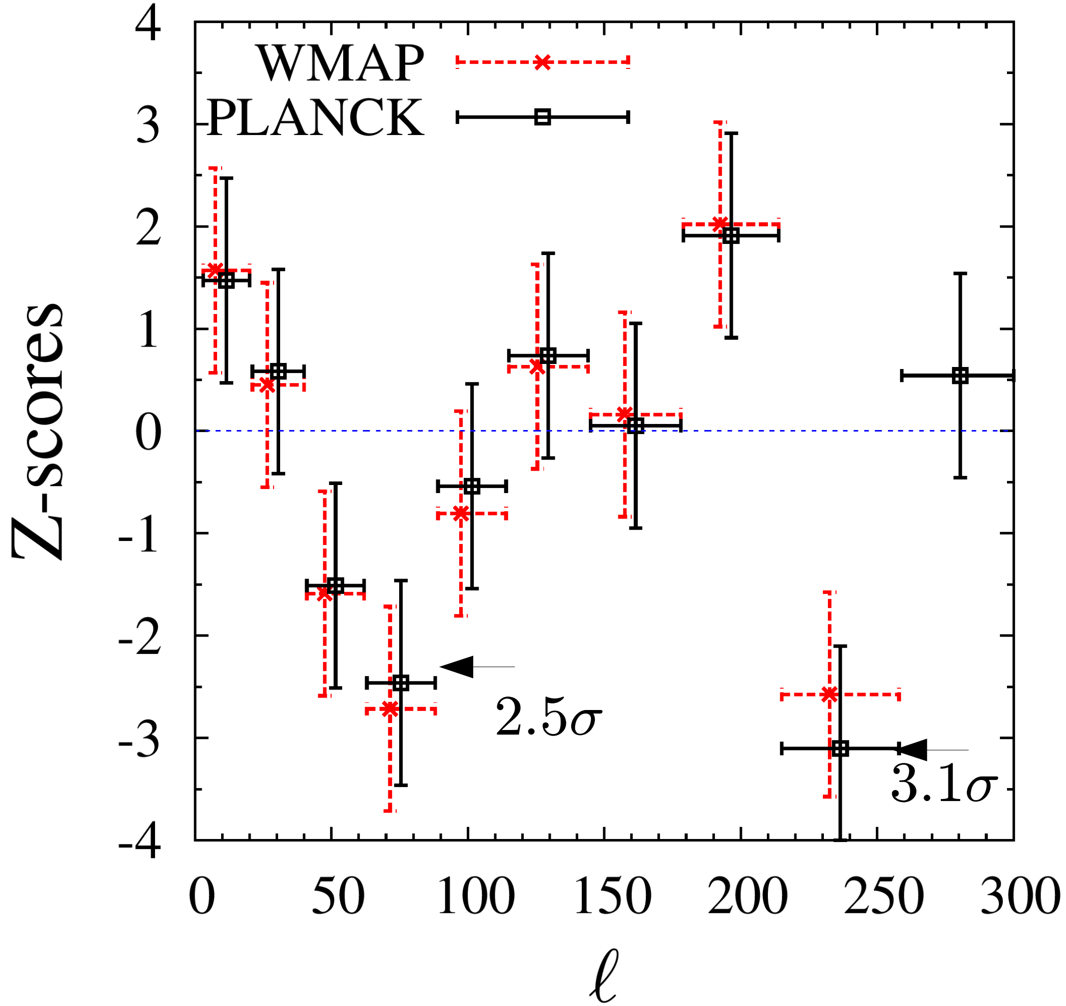


Noise levels



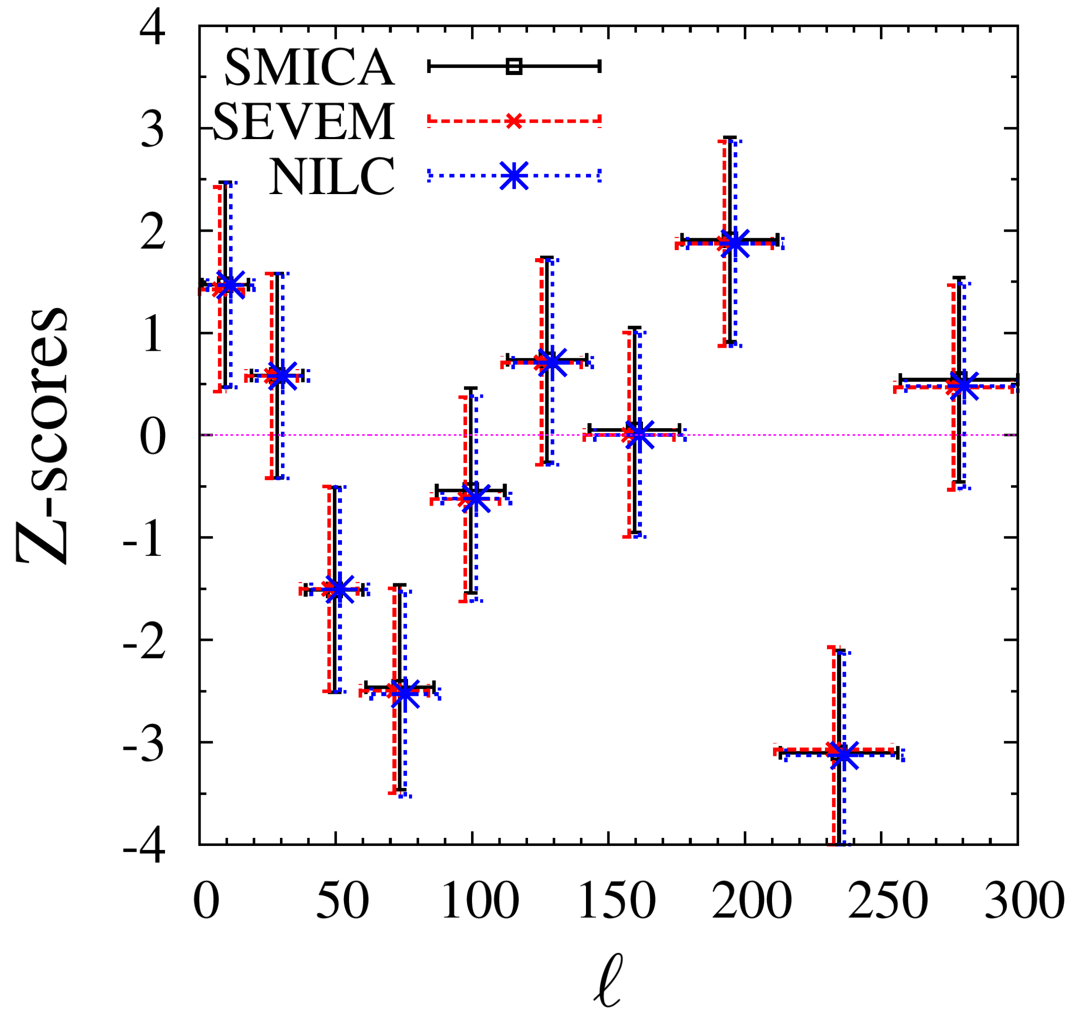
- black – signal, blue – noise
- noise becomes significant on smaller angular scales
- noise contributes upto 40 % for WMAP @ lmax=256

Result



KI, to be submitted

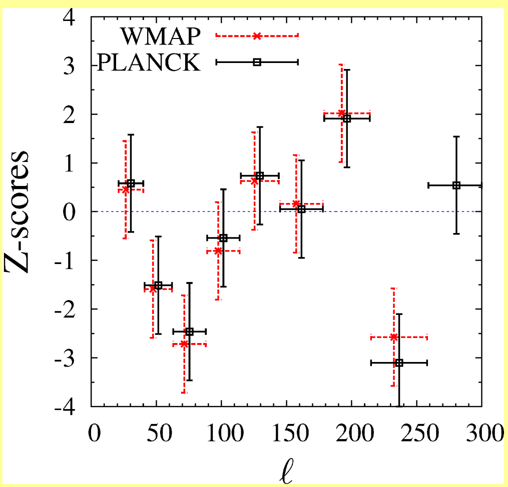
Result (2)

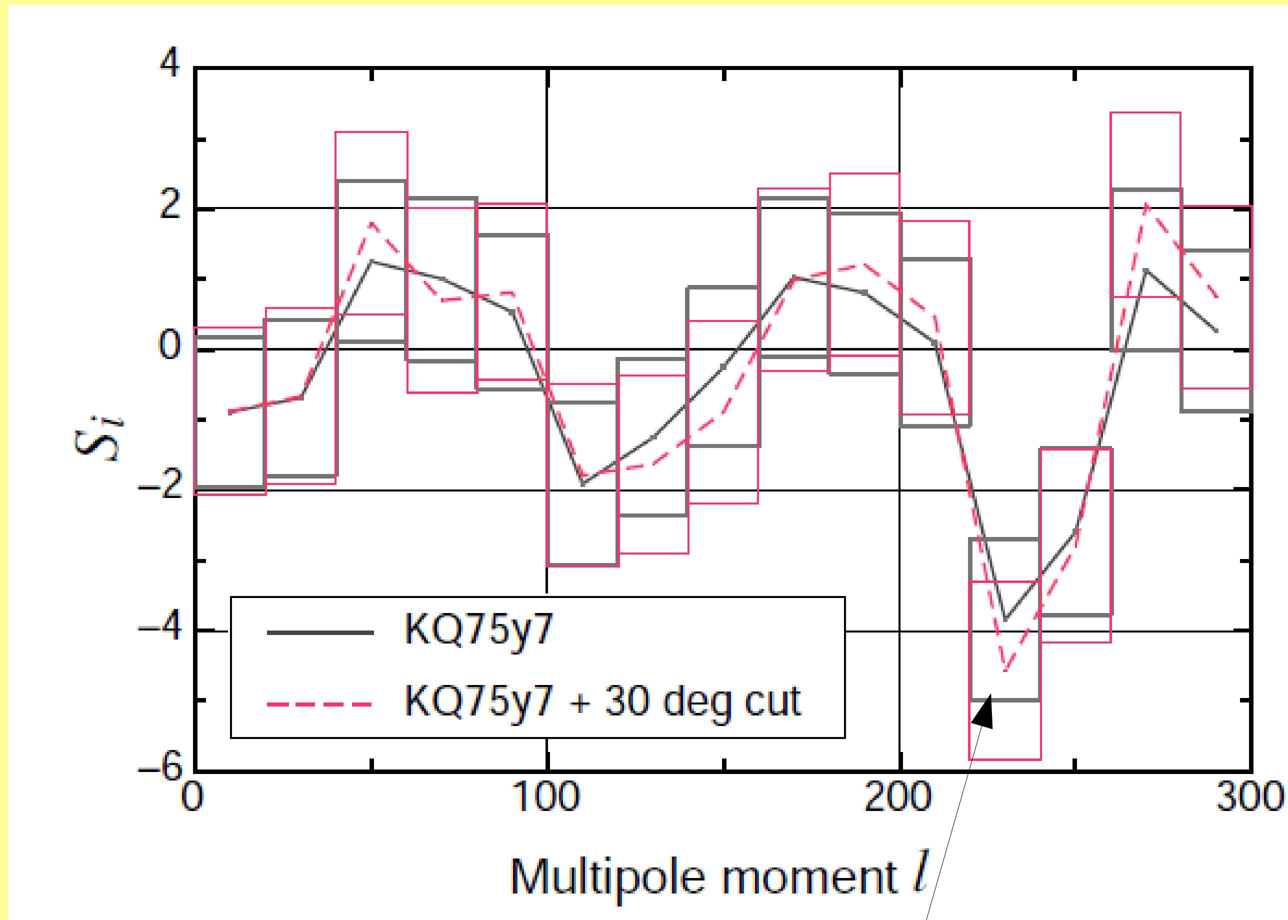


Independent of the foreground cleaning methods

Monte-Carlo simulation results

Kashino, KI, Takeuchi, PRD, '12





We found the same tendency! 99.93% anomaly

Looking elsewhere effect: Stouffer's weighted Z test

- Combining the results of multiple, independent tests of a hypothesis → Stouffer's weighted Z

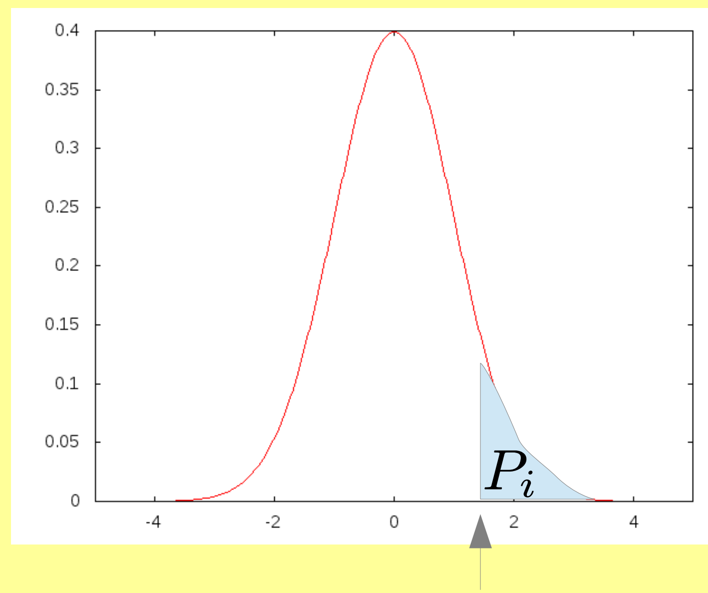
(Stouffer+,The American soldier 1949)

$$Z \equiv \frac{\sum_1^n w_i Z_i}{\sqrt{\sum_1^n w_i^2}}$$

Normal distribution

w_i is taken to be the number of degree of freedom for each bin

$$w_i = 2m_{\max}^{(i)}$$



Z_i

Result: $Z = 2.38(\mathrm{WMAP})$ $Z = 1.74(\mathrm{PLANCK})$

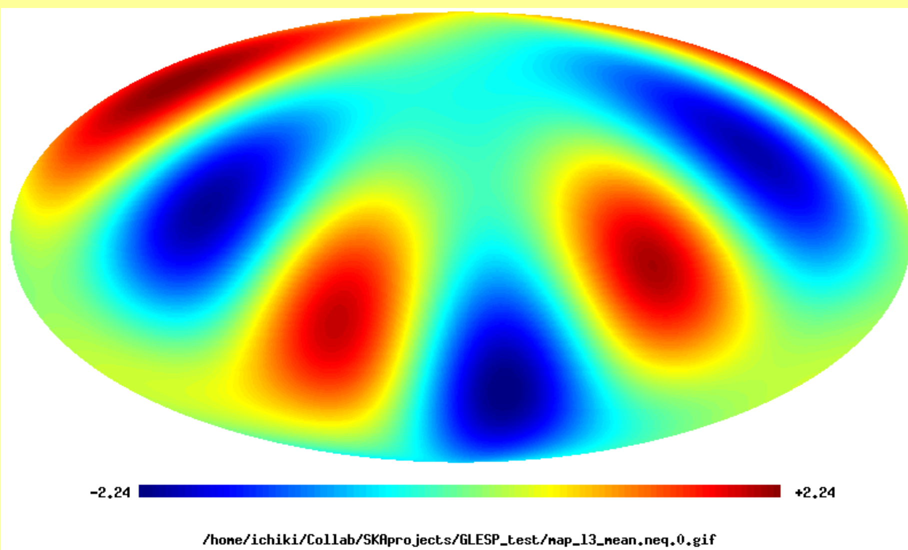
summary

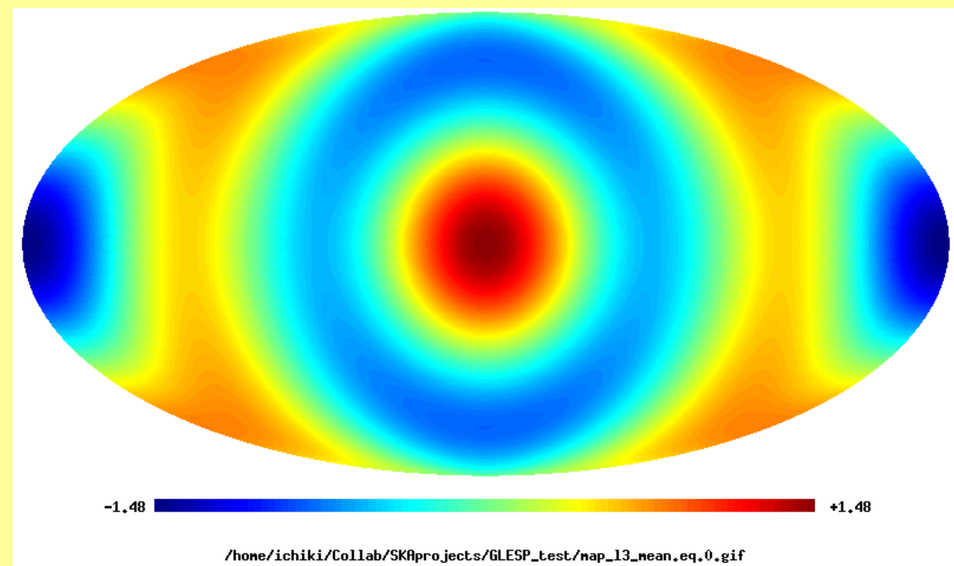
- In the analysis of CMB anisotropies, “zero mean” has been assumed implicitly (or by the Cosmo. Principle)
  - Zero mean should be confirmed using observation data themselves!
- We test this hypothesis using recent WMAP and PLANCK temperature anisotropies maps
- We find a hint of deviation (3 σ) from the zero-mean hypothesis at $\ell \approx 230$ in both WMAP and PLANCK
  - Stouffer's z → 2.3 σ (WMAP) 1.7 σ (PLANCK)
- How does the non zero mean sky look like in terms of non-Gaussianity?

Meaning of the zero mean

Fluctuations such that $\int d\hat{n}\frac{\Delta T(\hat{n})}{T} = \sum_{\ell m} \int d\hat{n} a_{\ell m} Y_{\ell m}(\hat{n}) = 0$

do not necessarily mean $\langle a_{\ell m} \rangle = 0$





$a_{3m} = (1,1)$ for $m \geq 0$

$a_{31} = (1,0),\ a_{3,3} = (-1,0)$
$a_{30},\ a_{3,2} = (0,0)$

CMB MAP in practice

- Putting the mask $M(\hat{n})$

$$\delta T(\hat{n})_{\rm obs} \equiv M(\hat{n})\delta T_{\rm CMB}(\hat{n})$$

Going to the spherical harmonic space

$$(\delta T_{\rm obs})_{\ell m} \equiv a_{\ell m}^{\rm mask} = \sum M_{\ell m;\ell' m'}(a_{\ell' m'} + N_{\ell' m'})$$

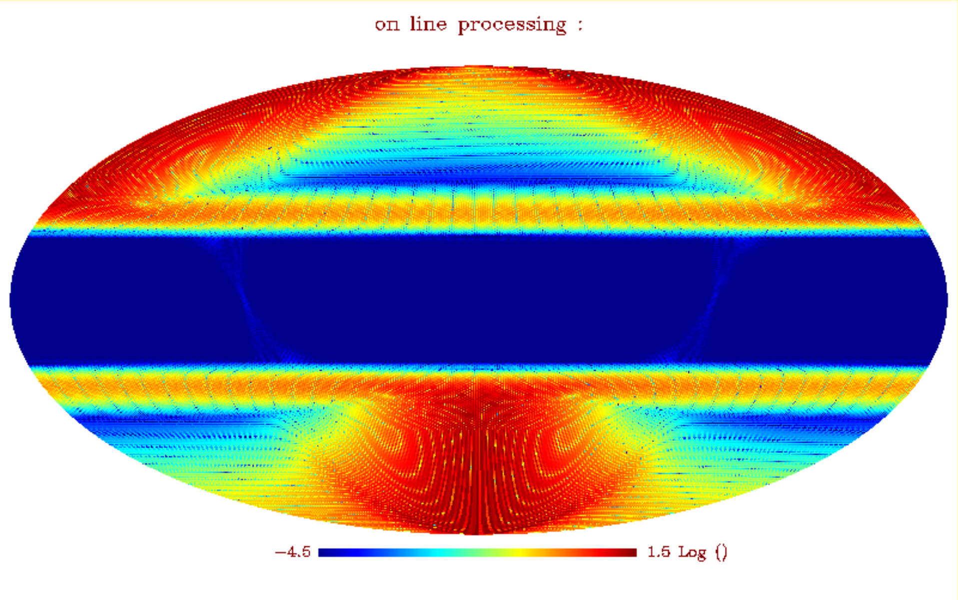
observed

signal

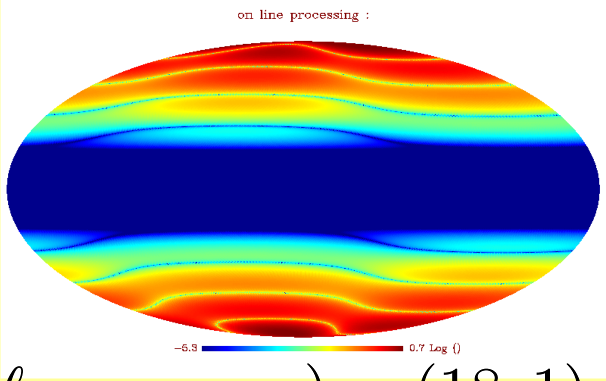
· Zero mean still holds true if $\langle N_{\ell m}\rangle = 0$, however $a_{\ell m}^{\rm mask}$ and $a_{\ell' m'}^{\rm mask}$ are *not independent* due to the coupling

We cannot use a simple statistical test
(such as the student's t-test)

Visualization of v-vectors



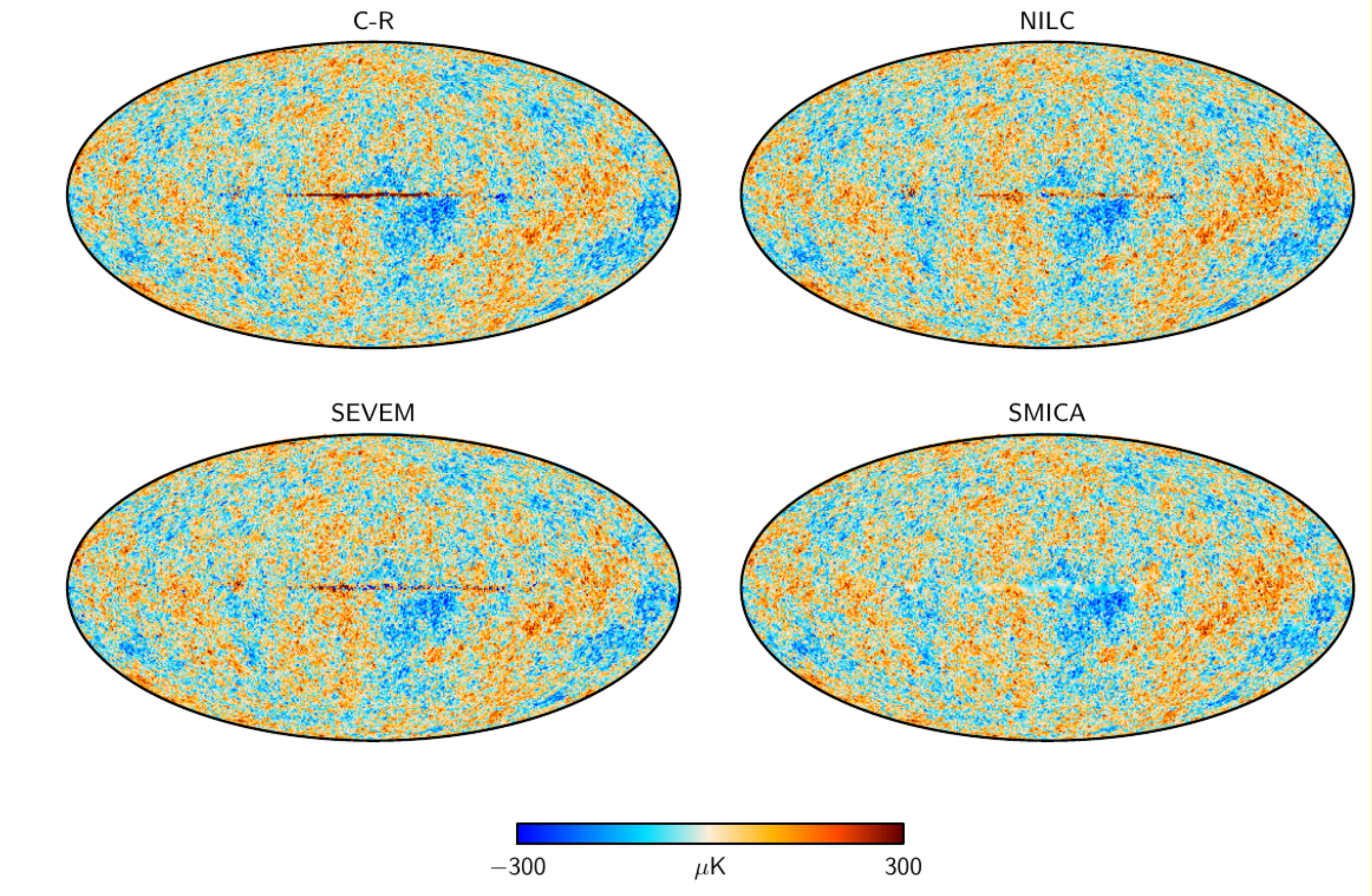
$$(\ell_{\max}, m_{\max}) = (212, 177)$$



$$(\ell_{\max}, m_{\max}) = (18, 1)$$

銀河面が除かれた重み付けがなされる。

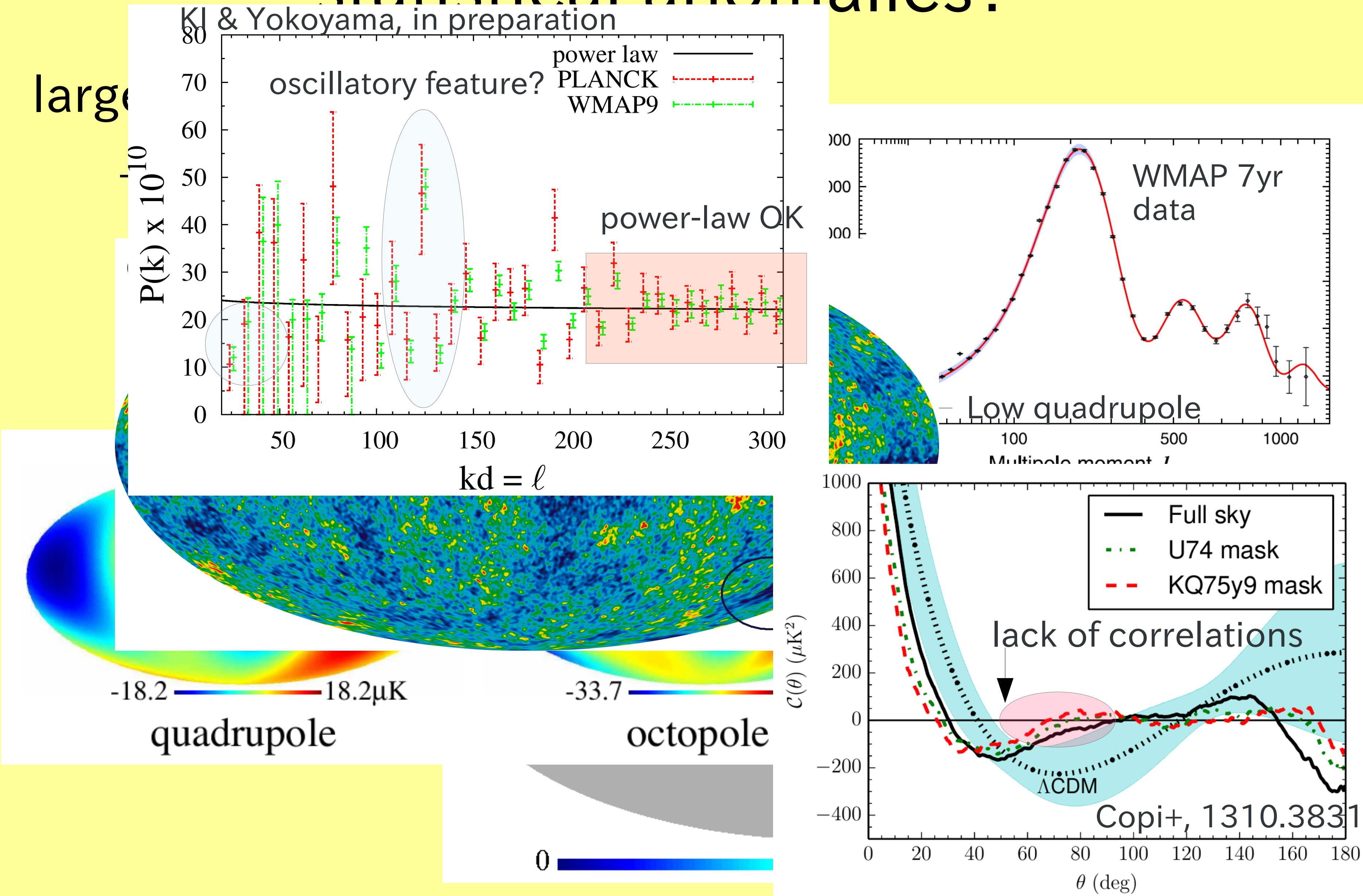
PLANCK foreground reduced maps

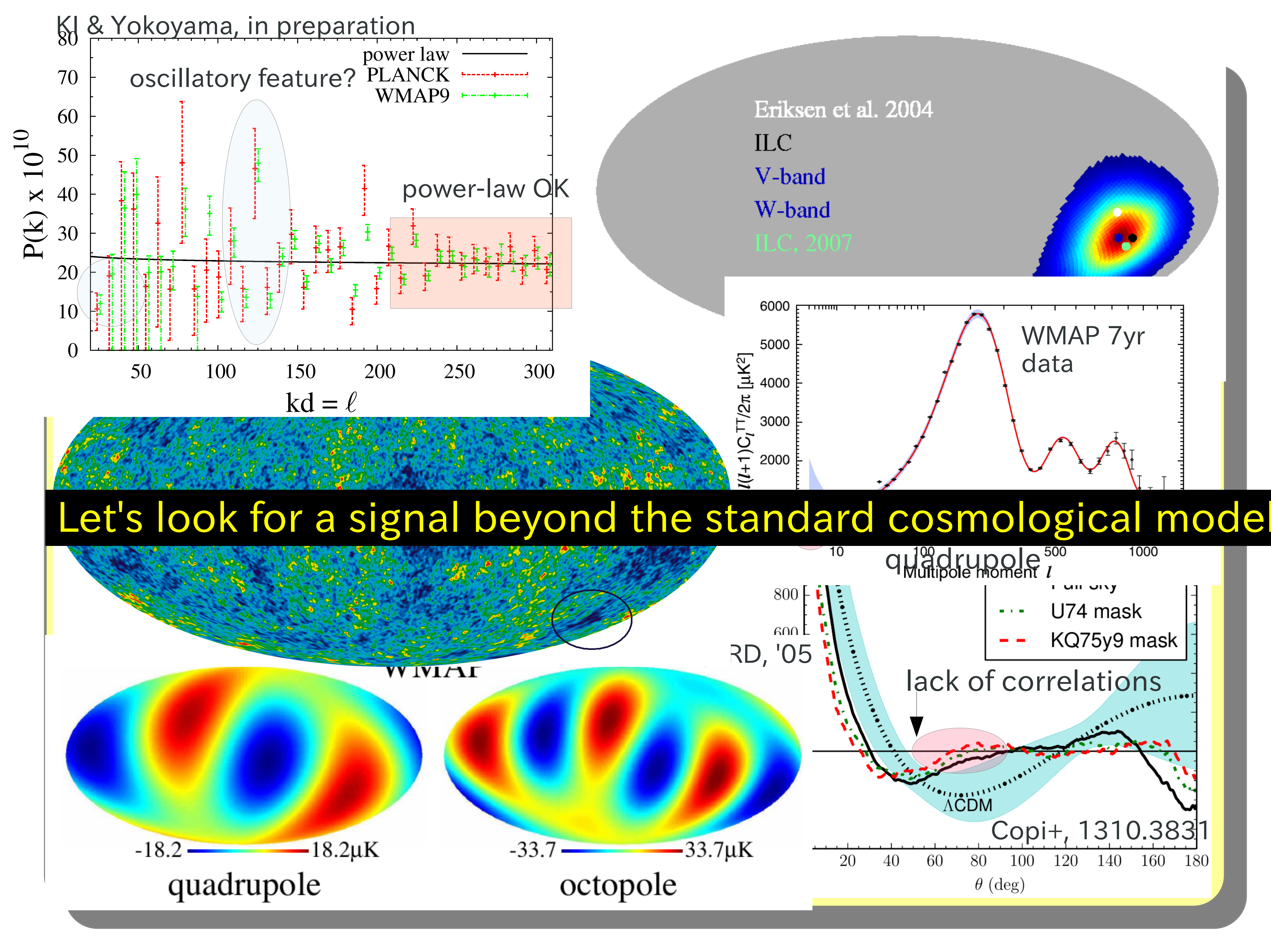


- SMICA (spectral matching ICA)
  - Internal linear combination in harmonic space giving minimum variance
- SEVEM
  - Internal template fitting
- Commander-Ruler
  - Pixel based, foreground model parameters are fitted using mcmc
- NILC
  - Internal linear combination in needlet space

statistical anomalies?

- large





Let's look for a signal beyond the standard cosmological model

Scaling relation

・fitting to the XMM Newton 71 clusters

$$E^{-2/3}(z)\left[\frac{D_A^2 Y_{500}}{10^{-4}\mathrm{Mpc}^2}\right] = 10^{-0.19\pm0.01}\left(\frac{M_{500}^{\mathrm{Yx}}}{6\times10^{14}M_{\odot}}\right)^{1.79\pm0.06}$$