II Escola J. Plínio Batista de Cosmologia – Mar 2014

# The CMB and our peculiar velocity

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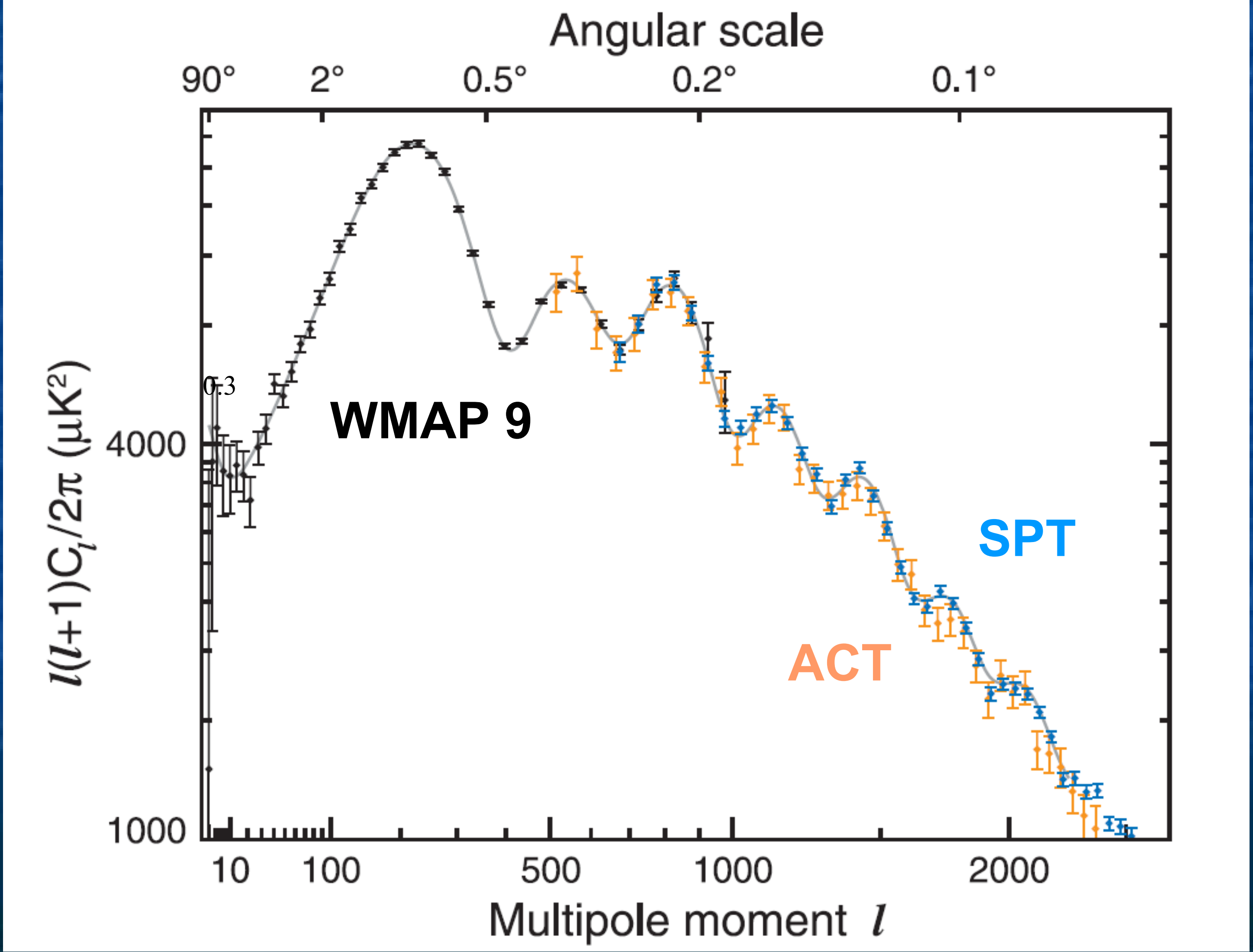
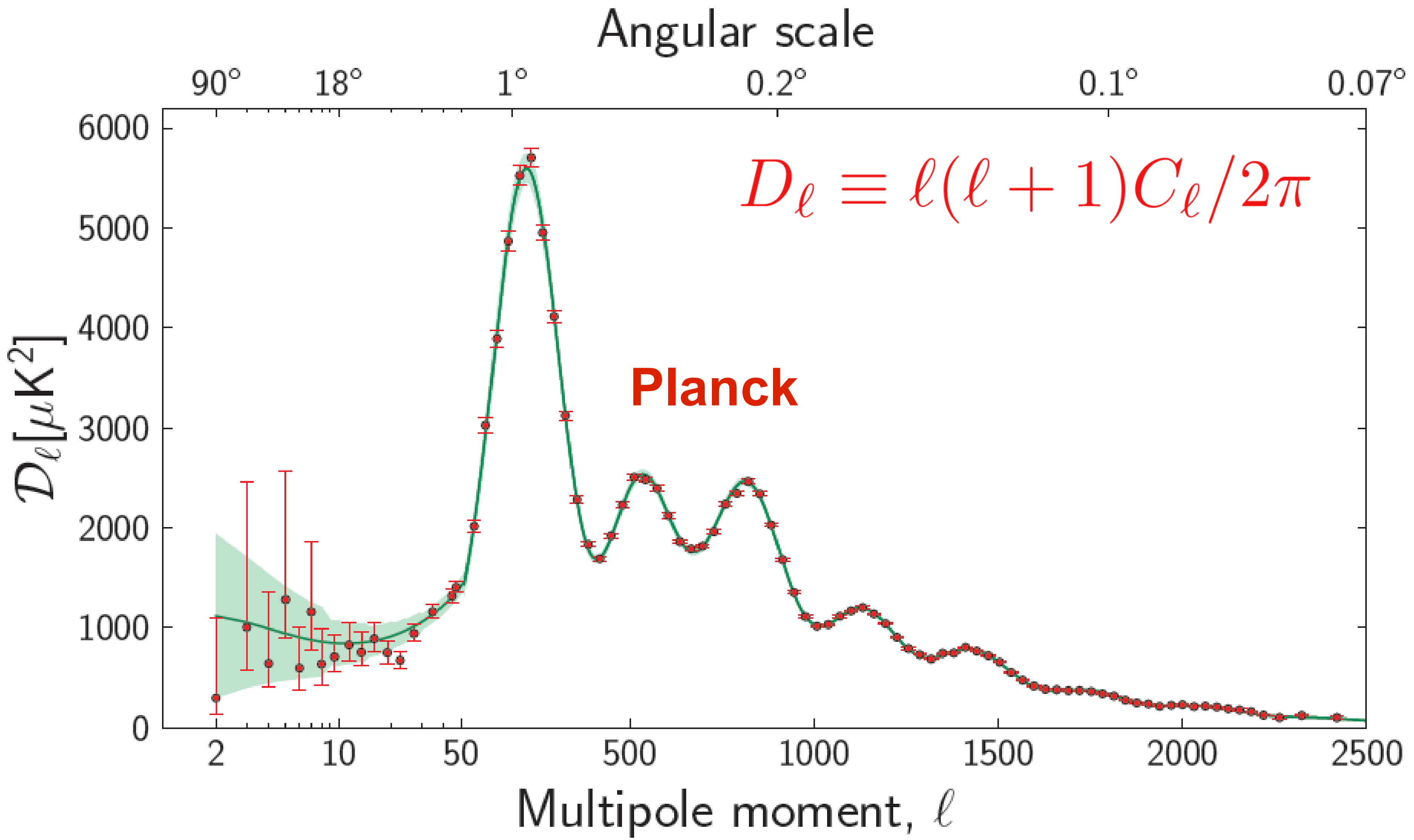
# CMB Power Spectrum

- Angular power spectrum

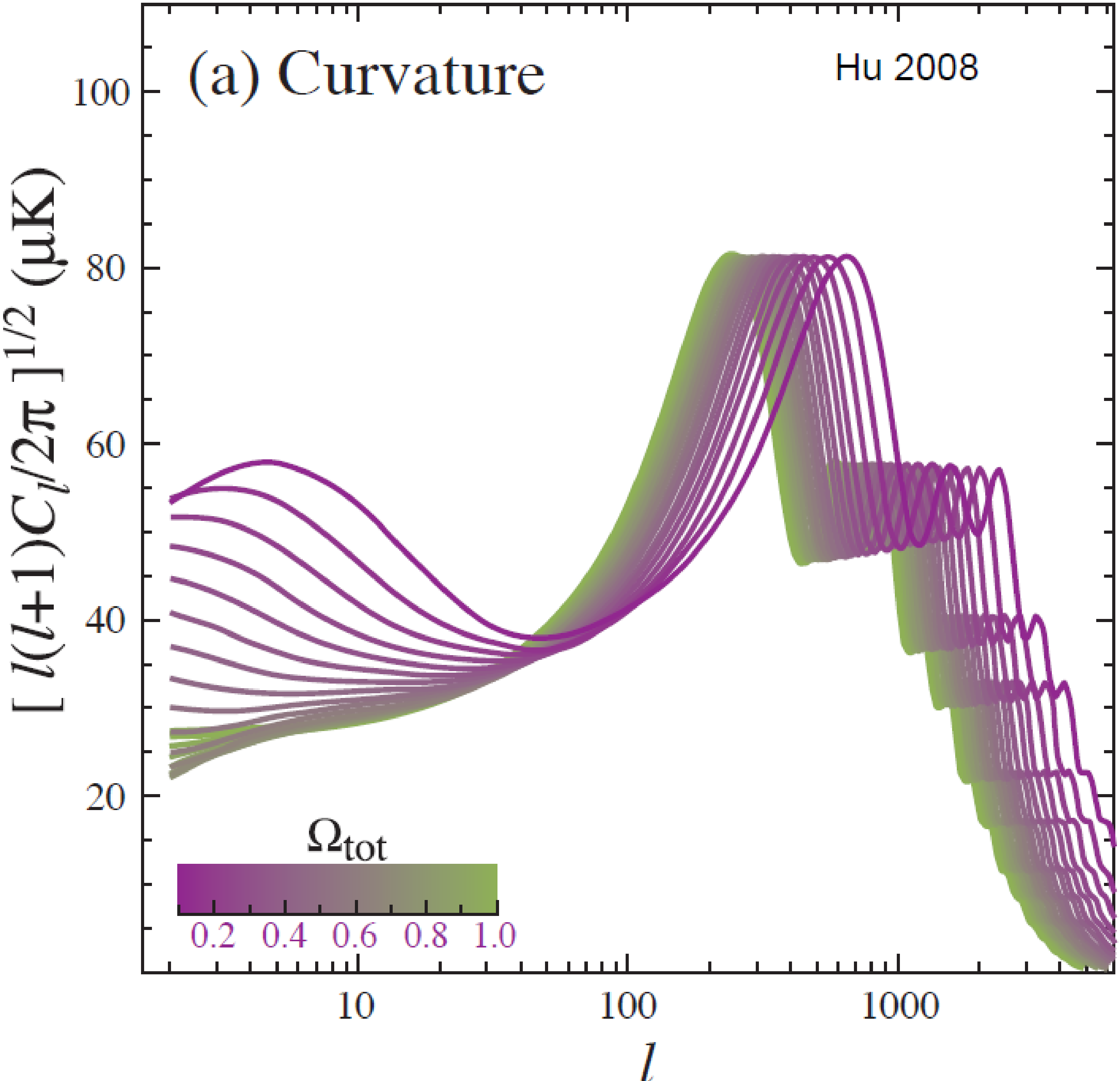


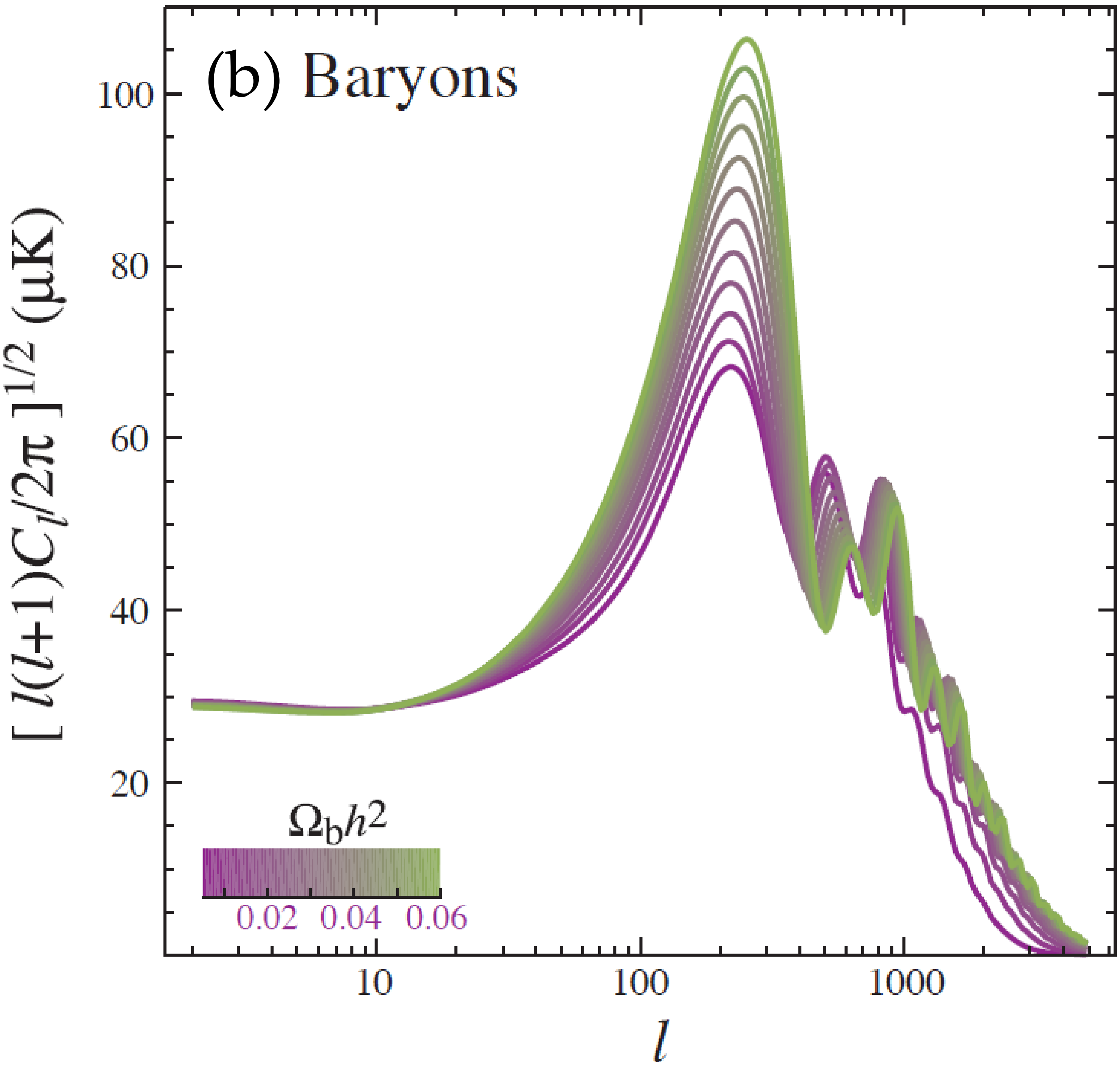
# CMB Power Spectrum (2)

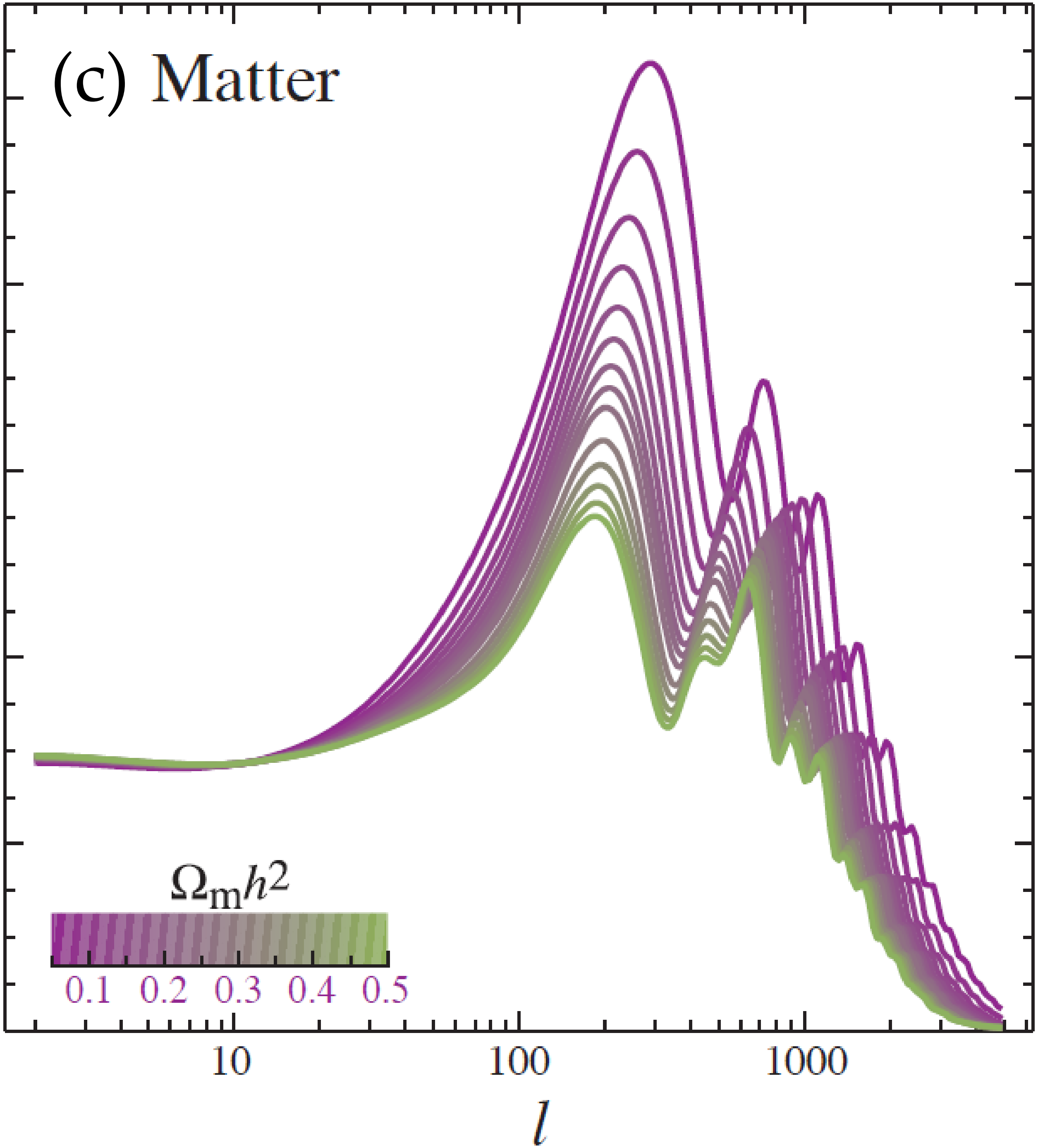


# The Undying ΛCDM

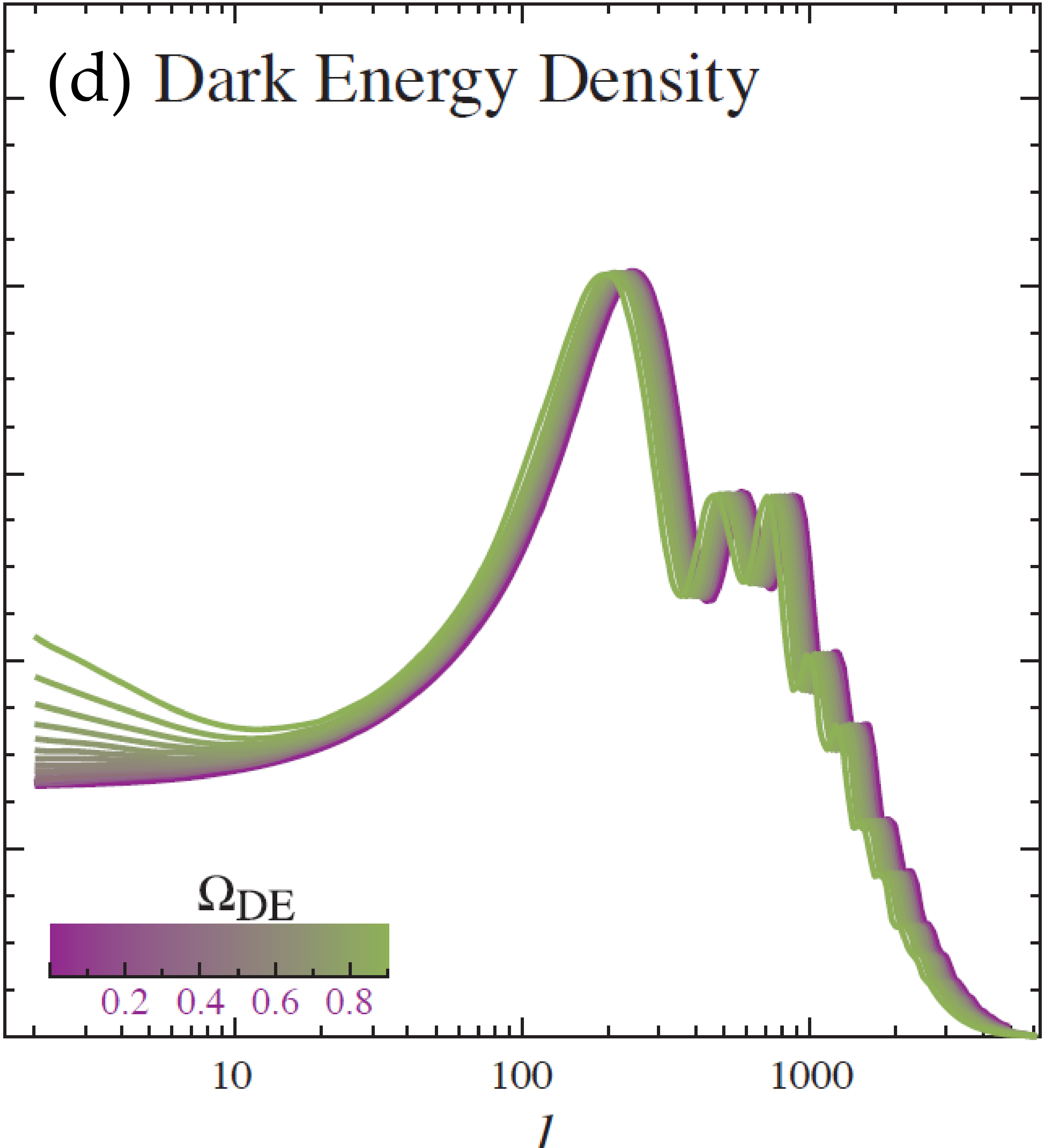
- WMAP mission:
  - Observed the CMB for 9 years;
  - Reduction of the volume of the 6-dimensional ΛCDM parameter space ($\Omega_{b0}$, $\Omega_{m0}$, h, A, $\tau$, $n_s$) by **~ 68,000**
    - The same model still works!
    - Non-trivial statistical result!
- Will this still be true after the final analysis of Planck, Atacama Cosmology Telescope (ACT) & South Pole Telescope (SPT)?


(a) Curvature
Hu 2008
$[\,l(l+1)C_l/2\pi\,]^{1/2}$ (μK)
100
80
60
40
20
$\Omega_{tot}$
0.2 0.4 0.6 0.8 1.0
10
100
1000
$l$

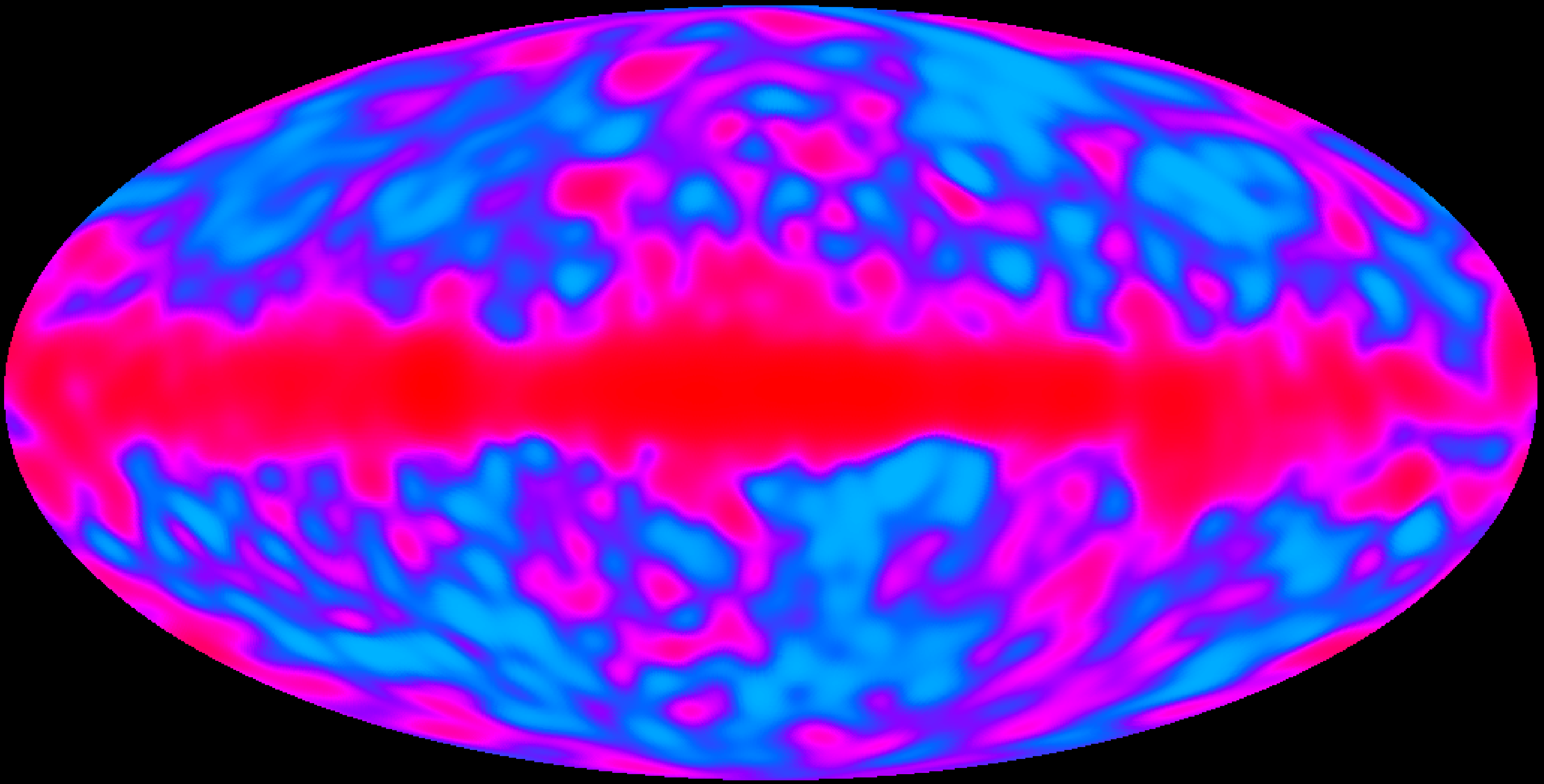

(b) Baryons
100
80
60
40
20
$[\, l(l+1)C_l/2\pi \,]^{1/2}$ (μK)
$\Omega_b h^2$
0.02 0.04 0.06
10
100
1000
$l$



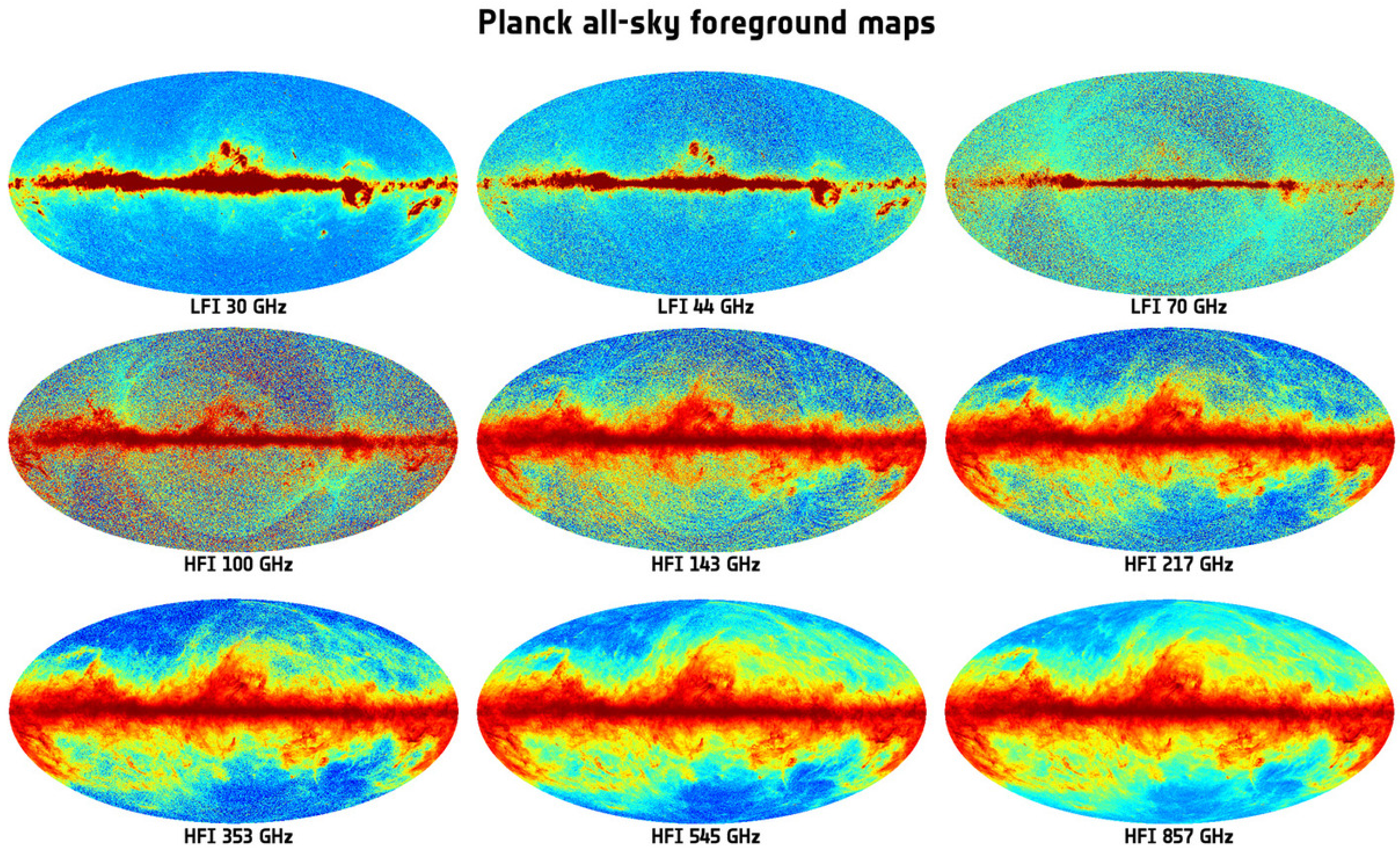
(c) Matter
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
10
100
1000
$l$


(d) Dark Energy Density
$\Omega_{DE}$
0.2 0.4 0.6 0.8
10
100
1000
l

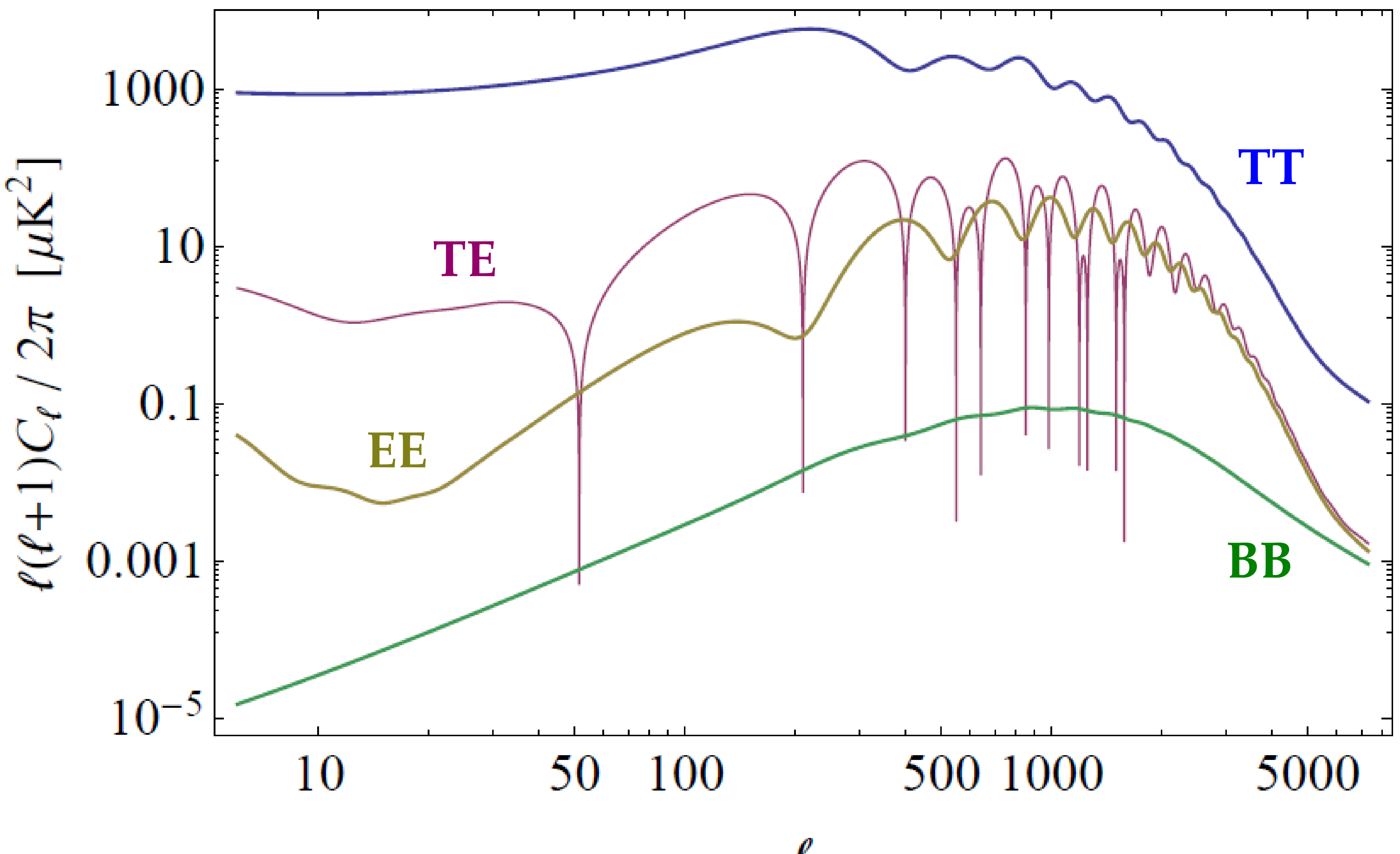
# CMB Satellites: COBE (1989 –1993)



# CMB Satellites: Planck (2009 –2012)



# Theoretical Spectra

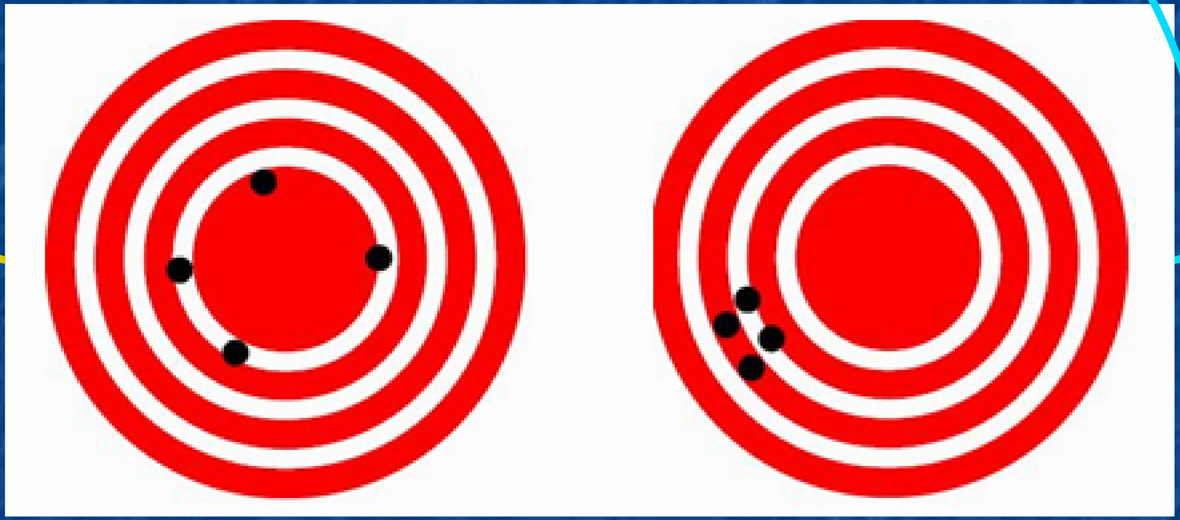


# CMB after COBE, WMAP, Planck, ...

- The CMB is seen as one of the best confirmations of the Big-Bang model → *Nobel Prize 2006*
- A universe with only standard model particles + dark matter cannot explain its spectrum
- WMAP (and now Planck) established ΛCDM as the *de facto* standard cosmological model
  - ΛCDM + inflation explains almost all CMB observations
  - Some small deviations ("anomalies") were detected by WMAP and confirmed by Planck (currently at ~3σ).
  - Planck detected no new anomalies OR non-gaussianity

***Planck XXIII – 1303.5083***

# Precision Cosmology vs. Accuracy Cosmology



- Precise parameter estimation in ΛCDM not enough
  - Very important to cross-check observations
    - Rule-out systematics
  - Very important to cross-check theoretical assumptions
    - e.g.: homogeneity, isotropy

# The CMB Dipole

- CMB Temperature: $T_{\rm CMB} = 2.725\,K \left[1 + \frac{\Delta T(\theta,\phi)}{T}\right]$
- Spherical Harmonics decomposition:

$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{\ell} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}$$

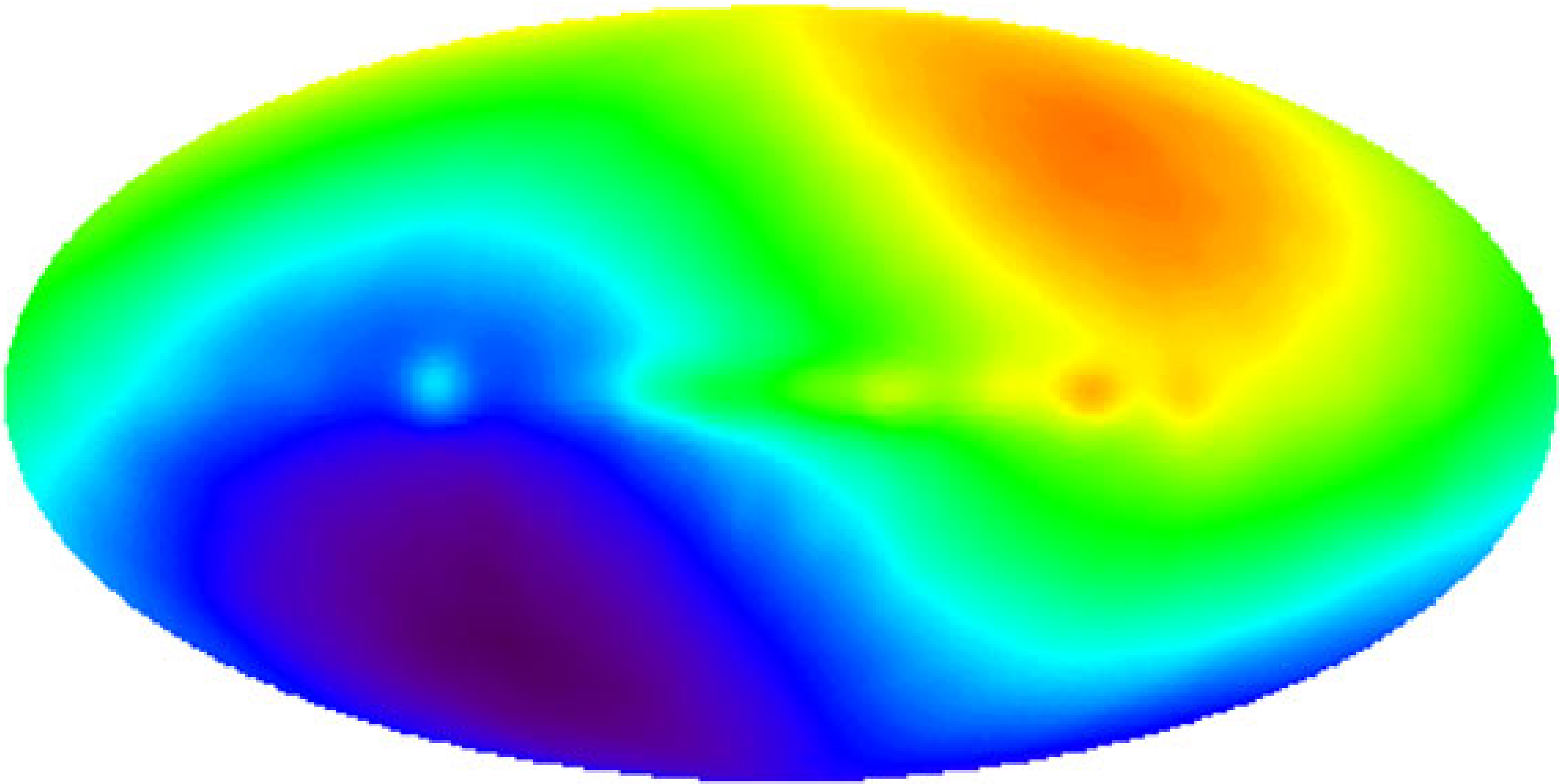
- $\ell = 0 \rightarrow$ monopole
- $\ell = 1 \rightarrow$ dipole: $\sim 10^{-3}$
- $\ell = 2 \rightarrow$ quadrupole: $\sim 10^{-5}$
- $\ell > 2 \rightarrow$ all $\sim 10^{-5}$

# The CMB Dipole (2)

- The CMB dipole ~ 100 times larger than other multipoles
  - Reason: Doppler effect due to our peculiar motion
- CMB dipole → measurement of $v_{CMB}$
  - $v_{CMB} \approx 370$ km/s → $\beta \equiv v/c = 1.231 \times 10^{-3}$
  - direction → $l = 263.99° \pm 0.14°$; $b = 48.26° \pm 0.03°$
- But there might be other contributions to the dipole:
  - Isocurvature CMB dipole; dipolar lensing; gradients of super-horizon modes etc.
- How to tell these contributions apart?

# CMB Dipole $\frac{\Delta T}{T} = 1.23 \times 10^{-3}$

- Assuming the whole dipole to be just Doppler, we find that the velocity should be $|\mathbf{v}| = 370$ km/s



# Doppler & Aberration

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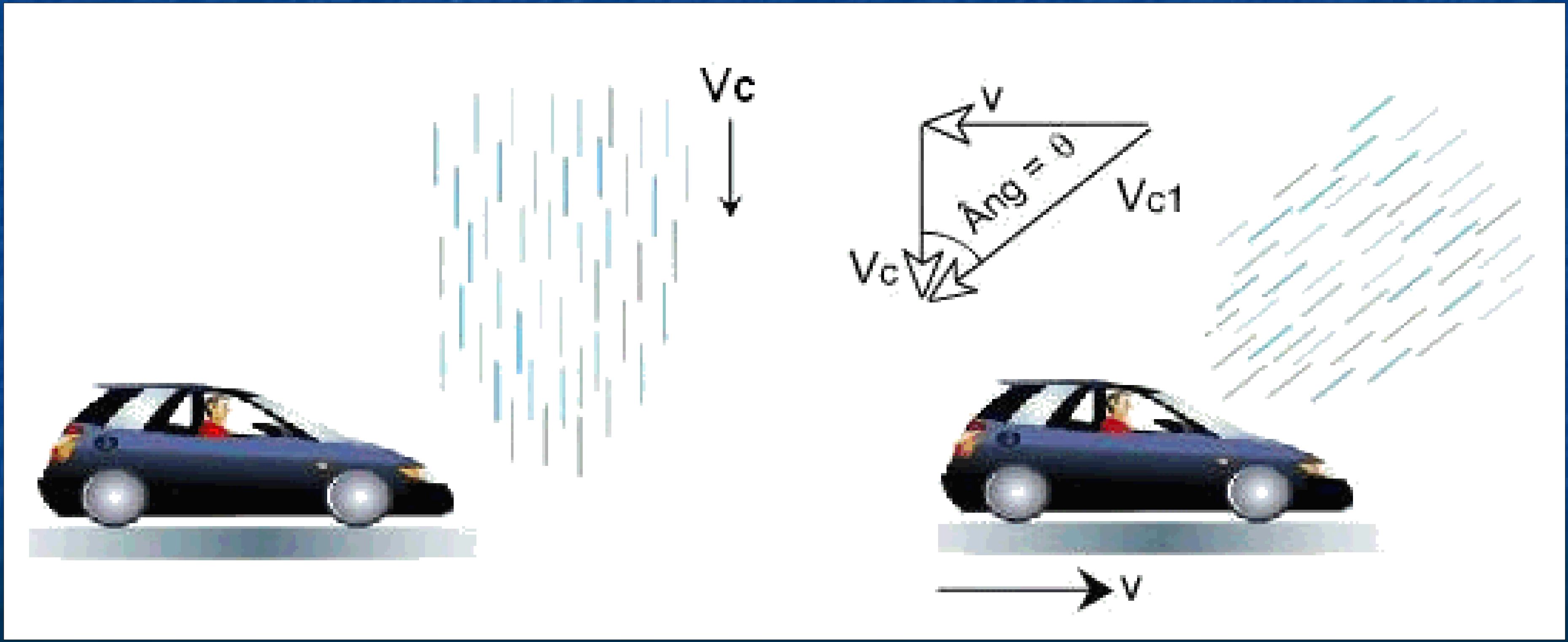

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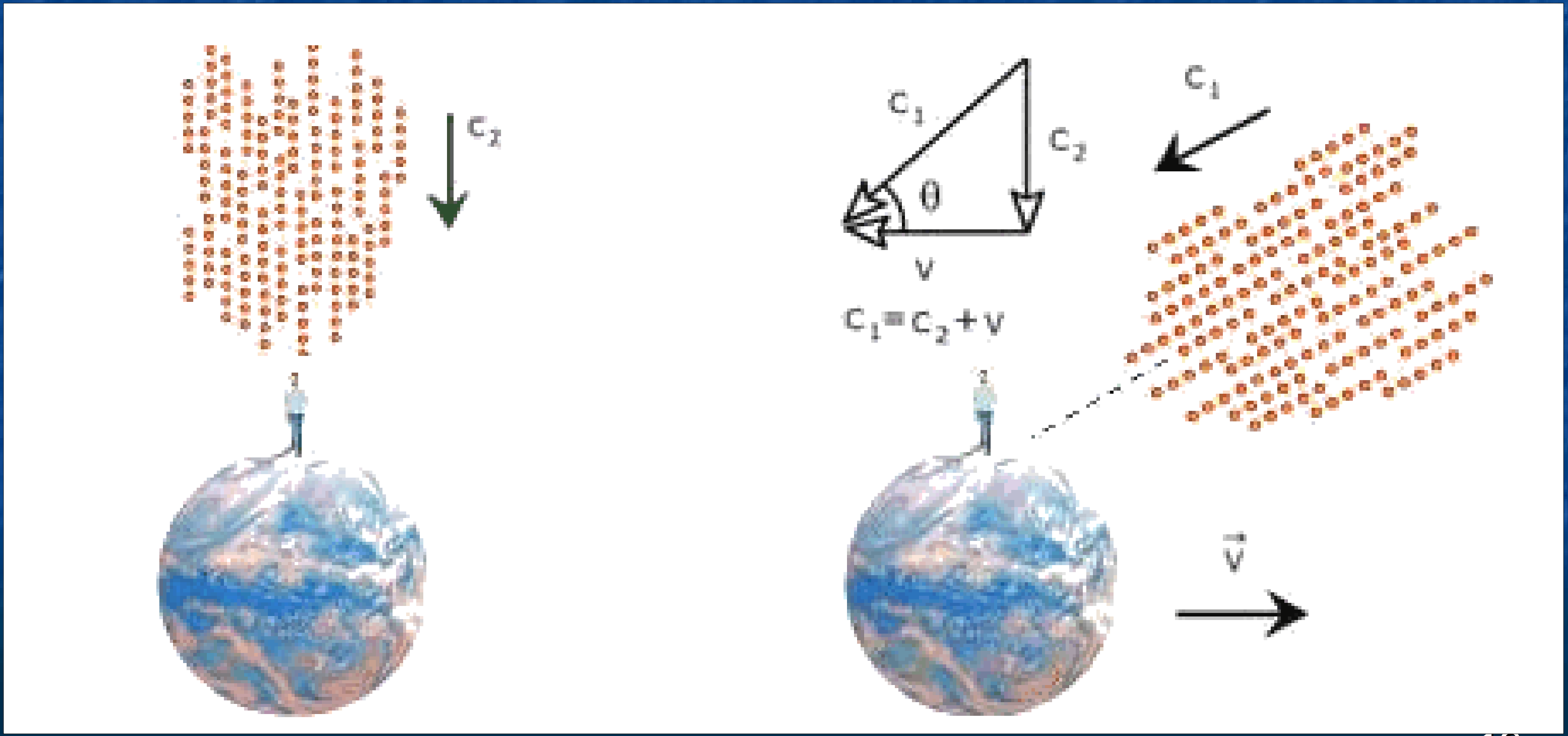

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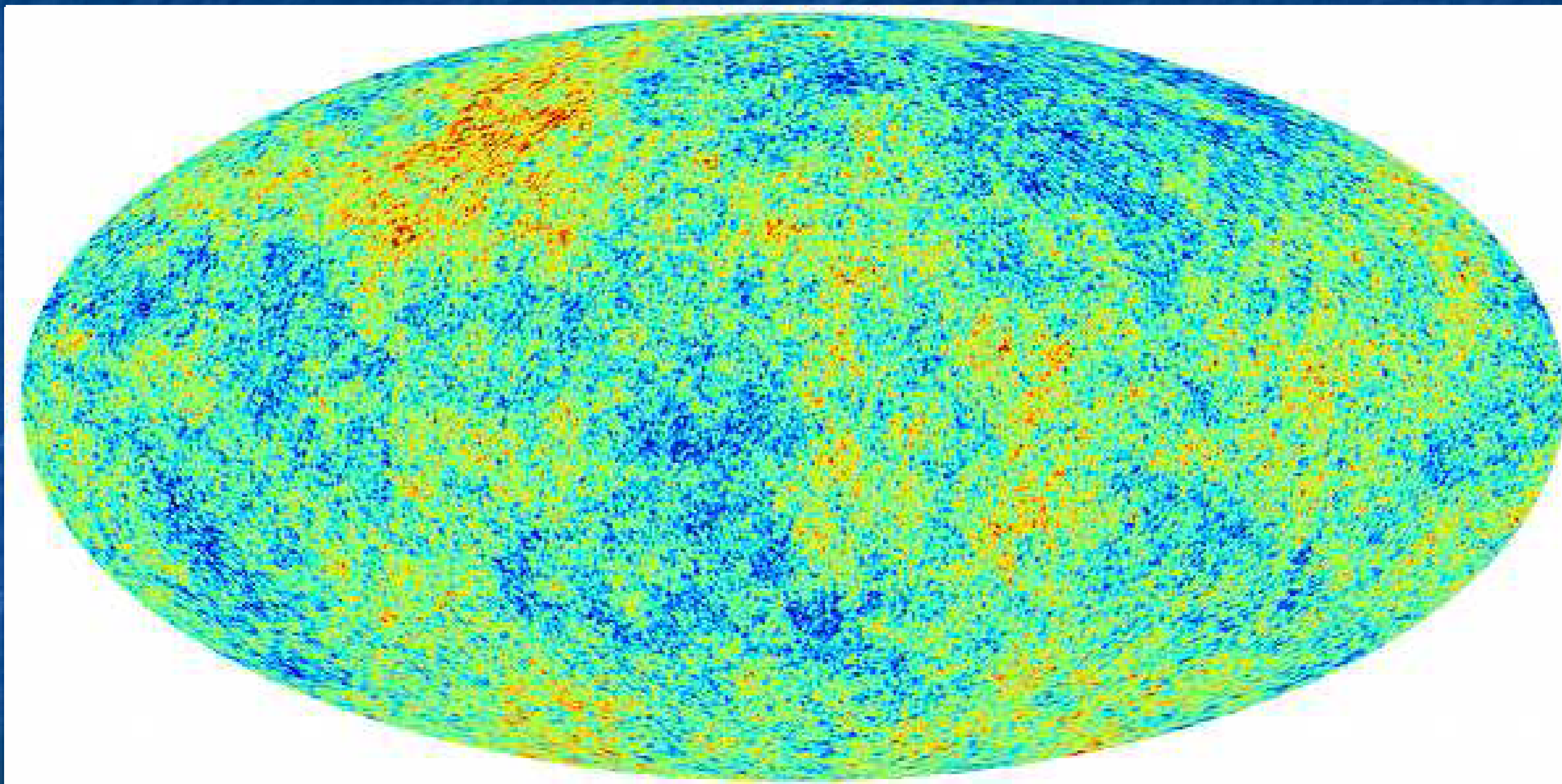
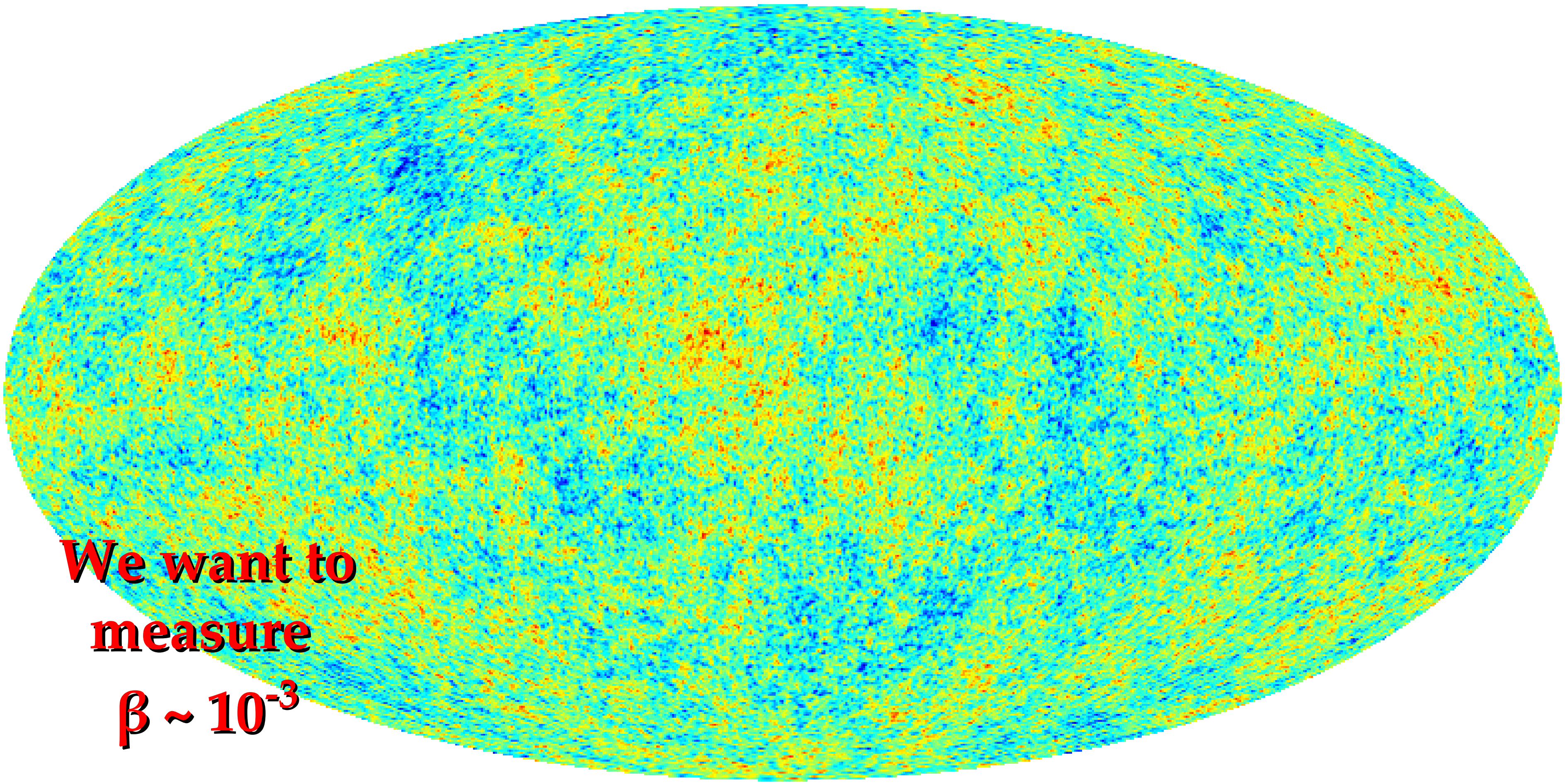


$\beta = 0$ $\beta = 0.5$ $\beta = 0.9$

# Doppler & Aberration



**We want to measure $\beta \sim 10^{-3}$**

$\beta = 0$ $\beta = 0.1$ $\beta = 0.5$

# $a_{\ell m}$ Correlations

Aberration → $a_{\ell m}$ correlations between different $\ell$'s

$$a_{\ell m}^{X\,[\text{Aberrated}]} = \sum_{\ell'=0}^{\infty} K^{X}_{\ell'\,\ell\,m}\, a_{\ell' m}^{X\,[\text{Primordial}]}$$

$$K^{T}_{\ell'\,\ell\,m} = \int_{-1}^{1} \frac{\mathrm{d}x}{\gamma\,(1-\beta x)}\, \tilde{P}_{\ell'}^{m}(x)\, \tilde{P}_{\ell}^{m}\left(\frac{x-\beta}{1-\beta x}\right)$$

Assoc. Legendre Polin.

- For E and B polarization the integrals are similar
- These integrals present a numerical challenge!

*Chluba 1102.3415 (MNRAS)*

# $a_{\ell m}$ Correlations (2)

- These predicted correlations
  - Do not affect the angular power spectrum (the $C_\ell$'s)
  - Break statistical isotropy of the CMB

$$\langle a_{\ell m}\, a_{\ell' m'} \rangle \neq C_\ell \, \delta_{\ell\ell'} \, \delta_{mm'}$$

- We can build an estimator for β
  - Since all $\ell$'s are affected: more $\ell$ measured → better S/N
  - Measuring **EE**, **ET**, **TE** and **BB** power spectra → better S/N
  - Better S/N ↔ more accurate measurement of β
  - Planck (30 months): $\ell^T_{max} \sim 2500$ ; $\ell^{E,B}_{max} \sim 1700$

# Curiosity

- Non-Gaussianity is generated and Statistical isotropy is broken BUT
  - There are no imaginary (oops, complex) fields hypothetically increasing the size of the universe by 100000000000000000000000000000000000000000000000000 0000000000 +/- ???
  - There are no extra-dimensions
  - There are no unknown potentials
    - Using the dipole as a measurement of the velocity, there are not even free-parameters
- This must be the reason inflationary cosmologist call it an ABERRATION!

# $a_{\ell m}$ Correlations (3)

- Previous solution for computing $K_{\ell' \ell m}$ → Taylor expansion in $\beta$ → becomes effectively exp. in $\beta\ell$
  - $a_{\ell m}$ correlations between $\ell$ and $\ell+n$ are $O(\beta\ell)^n$
  - Expansion breaks down for $\ell > \sim 800$ !

*Kosowski & Kahniashvili 1007.4539 (PRL)*

*Amendola, Catena, Masina, Notari, Quartin, Quercellini 1008.1183 (JCAP)*

- We proposed 2 better solutions:
  - Very accurate approx. solutions for $K_{\ell' \ell m}$
  - An altogether new approach: *pre-deboost* the CMB

*Notari, Quartin 1112.1400 (JCAP)*

# Approximate Solutions ("Fits")
# (typical accuracy error < 0.5%)

$$K^X_{\ell-n\,\ell\,m} \;\simeq\; J_n\left(-2\,\beta\left[\prod_{k=0}^{n-1}\left[(\ell-k)\;{}_sG_{\ell-k\,m}\right]\right]^{1/n}\right)$$

$$K^X_{\ell+n\,\ell\,m} \;\simeq\; J_n\left(2\,\beta\left[\prod_{k=1}^{n}\left[(\ell+k)\;{}_sG_{\ell+k\,m}\right]\right]^{1/n}\right)$$

$${}_sG_{\ell\,m} \;\equiv\; \sqrt{\frac{\ell^2-m^2}{4\ell^2-1}\left[1-\frac{s^2}{\ell^2}\right]}$$

# The Pre-deboost Technique

- Taylor expansion in $\beta$ $\rightarrow$ becomes an effective exp. in $\beta\ell$
  - $\beta \approx 1/800 \rightarrow$ expansion breaks down for $\ell > \sim 800$ !
  - If $\beta$ happened to be $\sim 10^{-4} \rightarrow$ expansion OK until $\ell \sim 10000$
  - There IS a trick to get $\beta_{eff} <\sim 10^{-4}$ !
- Here is the trick:
  - Perturbation theory $\rightarrow$ intrinsic CMB dipole $\sim 10^{-5}$
  - One can therefore deboost the CMB using $\beta$ from the measured dipole
    - Should be done in the TOD (before any harmonic analysis)
  - Residual $\beta$ should be $\sim 10^{-5}$ $\rightarrow$ Taylor expand in residual $\beta$!

*Notari & Quartin 1112.1400 (JCAP)*

# The Pre-deboost Technique (2)

- One can therefore deboost the CMB using β from the measured dipole

$$\hat{\boldsymbol{n}}' = \frac{\hat{\boldsymbol{n}} + \left[\gamma\,\beta + (\gamma - 1)(\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{\beta}})\right]\hat{\boldsymbol{\beta}}}{\gamma(1 + \boldsymbol{\beta} \cdot \hat{\boldsymbol{n}})}$$

$$\nu' = \nu\,\gamma\,(1 + \boldsymbol{\beta} \cdot \hat{\boldsymbol{n}})$$

$$T(\hat{\boldsymbol{n}})_{\text{deboosted}} = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1 + \boldsymbol{\beta}^{\text{fit}}_{\text{dip}} \cdot \hat{\boldsymbol{n}})}$$

# Corrections to Previous Results

- Using exact coefficients (integrating for fixed $\ell$ & m)
  - There is **less** bias to the normal power spectrum
    - Before: claims of $\mathcal{O}(\beta^2)$ bias
  - There is **less** conversion of E modes into B modes
    - Before: claims of sub-dominant correlations $\mathcal{O}(\beta/\ell)$
- $\ell \rightarrow \ell + 1$ correlations always relevant
- The 1st order expansion "miraculously" works for $\beta > 800$
  - Errors are $< 5\%$ for $\ell <\sim 4000$

# $a_{\ell m}$ Correlations (4)

$$a_{\ell m}^{X\,[\mathrm{Aberrated}]} = \sum_{\ell'=0}^{\infty} K^{X}_{\ell'\,\ell\,m}\, a_{\ell' m}^{X\,[\mathrm{Primordial}]}$$

- Most important correlation: $\ell \rightarrow \ell + 1$

$$a_{\ell\,m}^{[\mathrm{Aber}]} \simeq c_{\ell m}^{-} a_{\ell-1\,m}^{[\mathrm{Prim}]} + c_{\ell m}^{+} a_{\ell+1\,m}^{[\mathrm{Prim}]}$$

$$c_{\ell m}^{+} = \beta\,(\ell+1)\sqrt{\frac{(\ell+1)^2 - m^2}{4(\ell+1)^2 - 1}}$$

$$c_{\ell m}^{-} = -\beta\,\ell\sqrt{\frac{\ell^2 - m^2}{4\ell^2 - 1}}$$

# $a_{\ell m}$ Correlations (5)

- We can now build an estimator for β
  - Let's define the complex matrix $F_{\ell m} \equiv a^*_{\ell\, m} a_{\ell+1\, m}$

$$F_{\ell m} = a^{[P]\,*}_{\ell\, m} a^{[P]}_{\ell+1\, m} + c^-_{\ell+1 m} a^{[P]\,*}_{\ell\, m} a^{[P]}_{\ell\, m} + c^+_{\ell m} a^{[P]*}_{\ell+1\, m} a^{[P]}_{\ell+1\, m} + c^-_{\ell m} a^{[P]\,*}_{\ell-1\, m} a^{[P]}_{\ell+1\, m} + c^+_{\ell+1 m} a^{[P]*}_{\ell\, m} a^{[P]}_{\ell+2\, m}$$

- Its expectation value is REAL and proportional to β

$$\langle F_{\ell m} \rangle \;=\; c^-_{\ell+1 m} C_\ell + c^+_{\ell m} C_{\ell+1} \;=\; \beta(\ldots)$$

  - Let's define the real part of Flm as another matrix

$$\frac{1}{2}(F_{\ell m} + F_{\ell -m}) \equiv f_{\ell m}$$

# $a_{\ell m}$ Correlations (6)

- Since flm is proportional to β, we can build a $\chi^2$

$$\chi^2(\beta) = \sum_{\ell,m} \frac{\left[f_{\ell m}^{\rm obs} - \beta \hat{f}_{\ell m}^{TH}\right]^2}{\langle f_{\ell m} f_{\ell m}\rangle} = \cdots = \sum_{\ell,m} \frac{\left[f_{\ell m}^{\rm obs} - \beta \hat{f}_{\ell m}^{TH}\right]^2}{C_\ell C_{\ell+1}}$$

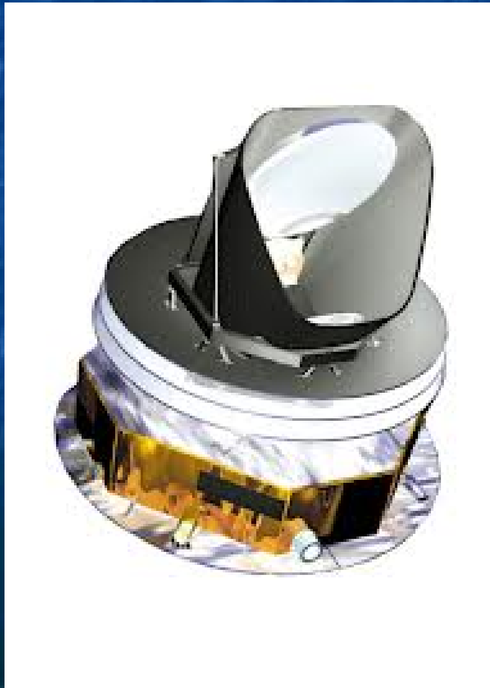
- Once we have a $\chi^2$ it is trivial to estimate β and its error bar
  - We proceeded to estimate it for future (at the time) experiments

# CMB Missions

**SPT / SPTPol**

**EBEX**

**Planck**



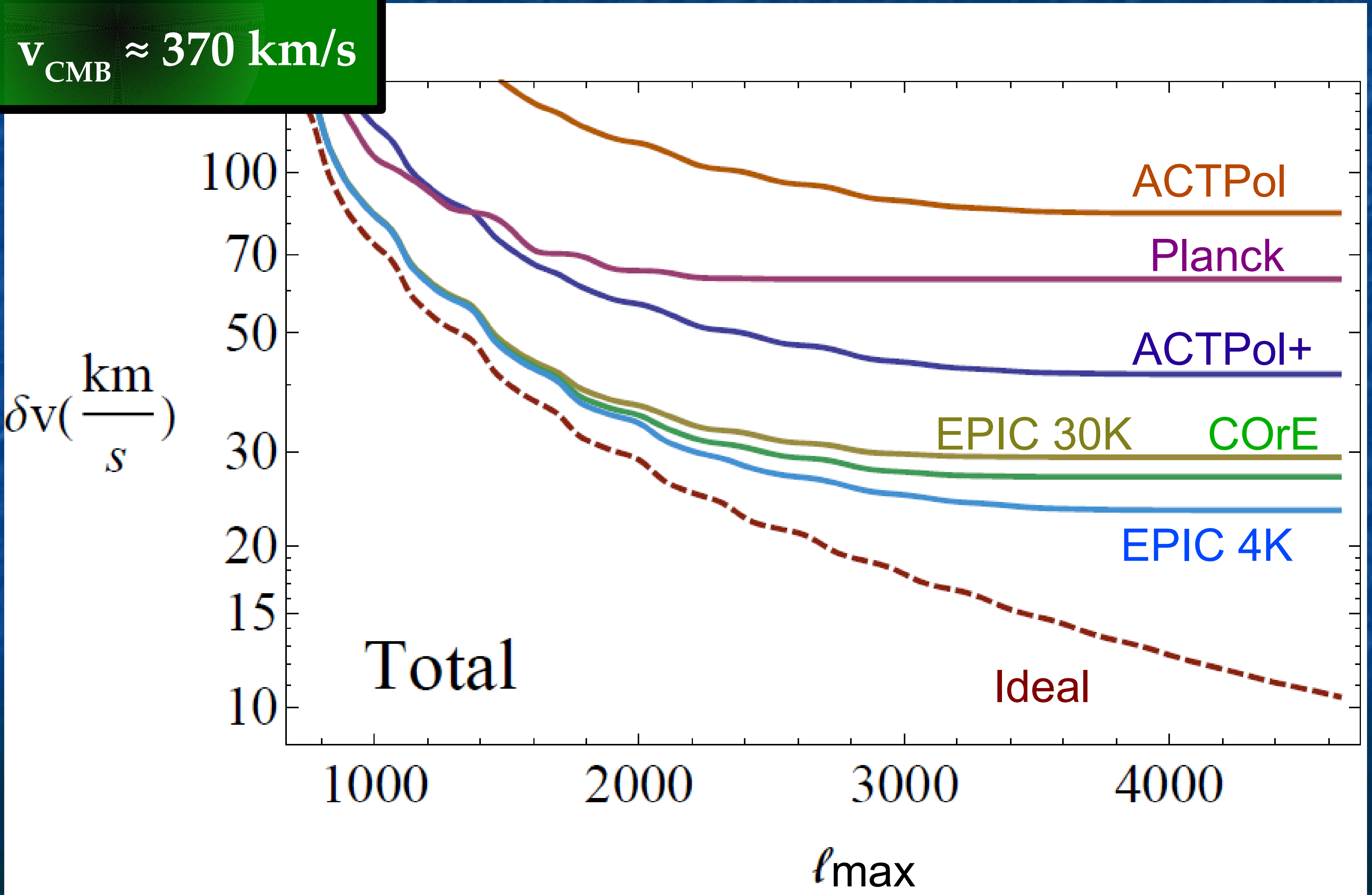
# Results: S/N

*Notari & Quartin 1112.1400 (JCAP)*

| *Experiment* | $f_{\rm sky}$ | $S/N$ |
|---|---|---|
| WMAP (9 years) | 78% | **0.7** |
| EBEX | 1% | **0.9** |
| *Planck* (2.5 years) | 80% | **5.9** |
| SPT SZ | 6% | **2.0** |
| SPTPol (3 years) | 1.6% | **2.5** |
| ACTPol (1 year) | 10% | **4.4** |
| ACTPol + (4 years) | 40% | **8.8** |
| COrE (4 years) | 80% | **14** |
| EPIC 4K | 80% | **16** |
| EPIC 30K | 80% | **13** |
| Ideal ($\ell \leq 6000$) | 100% | **44** |

# Results: Measuring β

**$v_{CMB} \approx 370$ km/s**



# Planck Measured Aberration!

## *Planck* 2013 results. XXVII. Doppler boosting of the CMB: Eppur si muove*


**ABSTRACT**

Our velocity relative to the rest frame of the cosmic microwave background (CMB) generates a dipole temperature anisotropy on the sky which has been well measured for more than 30 years, and has an accepted amplitude of $v/c = 1.23 \times 10^{-3}$, or $v = 369\,\mathrm{km\,s^{-1}}$. In addition to this signal generated by Doppler boosting of the CMB monopole, our motion also modulates and aberrates the CMB temperature fluctuations (as well as every other source of radiation at cosmological distances). This is an order $10^{-3}$ effect applied to fluctuations which are already one part in roughly $10^{-5}$, so it is quite small. Nevertheless, it becomes detectable with the all-sky coverage, high angular resolution, and low noise levels of the *Planck* satellite. Here we report a first measurement of this velocity signature using the aberration and modulation effects on the CMB temperature anisotropies, finding a component in the known dipole direction, $(l, b) = (264°, 48°)$, of $384\,\mathrm{km\,s^{-1}} \pm 78\,\mathrm{km\,s^{-1}}$ (stat.) $\pm 115\,\mathrm{km\,s^{-1}}$ (syst.). This is a significant confirmation of the expected velocity.



**Key words.** Cosmology: observations – cosmic background radiation – Reference systems – Relativistic processes


$384\,\mathrm{km\,s^{-1}} \pm 78\,\mathrm{km\,s^{-1}}$ (stat.) $\pm 115\,\mathrm{km\,s^{-1}}$ (syst.)

# What are we measuring?

- Doppler & aberration → in principle independent effects;
- What $\beta$ are we measuring?
- Standard picture: adiabatic perturbation
  - Doppler & aberration with same magnitude
- What about an isocurvature dipole?
  - Superhorizon isocurvature perturb. → large bulk flows
    - Are large bulk flows real?
- Other sources of dipole:
  - off-center LTB (spherical) void models
  - Metrics with vorticity?
  - … ?

# Aberration as a Nuisance

- Aberration is not currently corrected for in the data → this can lead to biases and/or anomalies
  - Cosmological parameter bias was shown to be negligible
    - See *Catena & Notari 1210.2731 (JCAP)*
  - Exception: sound-horizon size
    - See *Jeong et al. 1309.2285*
  - It also adds no significant KSW non-Gaussianity
    - See *Catena, Liguori, Notari & Renzi 1301.3777 (JCAP)*
- But Aberration induces a Hemispherical Asymmetry
  - It cannot explain all Hemisf. Asymmetry, but neither can be neglected

*Notari, Quartin & Catena 1304.3506*

# CMB Anomalies

***Planck* 2013 results. XXIII. Isotropy and statistics of the CMB**

- Planck has confirmed the anomalies observed in WMAP
  - Some of them were *initially* claimed to extend to higher $\ell$'s
  - No change for the low-$\ell$ anomalies → WMAP was already limited by cosmic variance for $\ell < 600$.
  - The statistical significance of these is around $3\sigma$.
- These anomalies are so-called because, if real, they violate very one of 2 basic hypothesis: initial fluctuations are statistically isotropic and Gaussian
- In a nutshell Planck sees no significant non-Gaussianity
  - Apart from well-understood ISW-lensing effect

# CMB large-angle Anomalies

- The anomalies present in large angular scales are (according to Planck)
  - Quadrupole-octopole alignment
  - The low variance
  - Phase corrections
  - Hemispherical asymmetry
  - Dipolar power modulation
  - Generalized power modulation
  - Parity asymmetry
  - The Cold Spot

***Planck XXIII***
***1303.5083***

# Hemispherical asymmetries

- There are 2 anomalies which can be called hemispherical
  - For low-$\ell$ ($2 < \ell < 40$), the power spectrum in antipodal hemispheres differ considerably
    - Effect is maximized when 1 hemisphere is centered around galactic co-latitude $110^o$ & longitude $237^o$
    - See Eriksen et al. 2004
    - Planck name: Hemispherical Asymmetry
  - At all $\ell$'s, there appears to be more power in the north sky than in the south sky
    - Sometimes it is assumed that the power may be modulated along the sky by a dipole term
    - Planck name: Dipolar Asymmetry

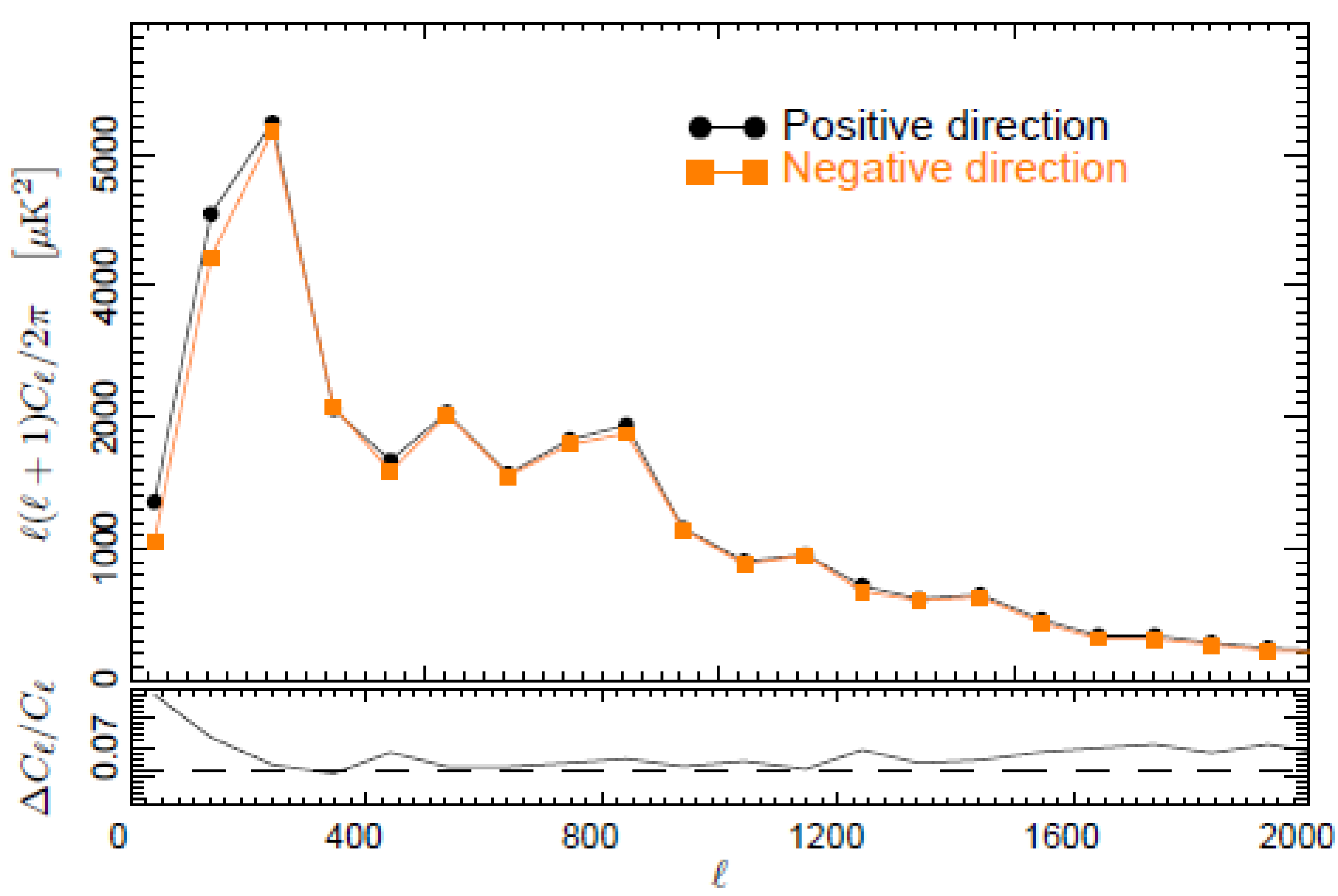
# Hemispherical asymmetries (2)

- An obvious candidate for a dipolar modulation is a boost!
  - Problem: the dipolar modulation appears to be maximal not along the peculiar velocity direction but instead along the galactic plane
- WMAP measured the power asymmetry up to $\ell = 600$
- Planck extended this to $\ell = 1500$
  - They should be able to go even higher, to $\ell = 2000$...

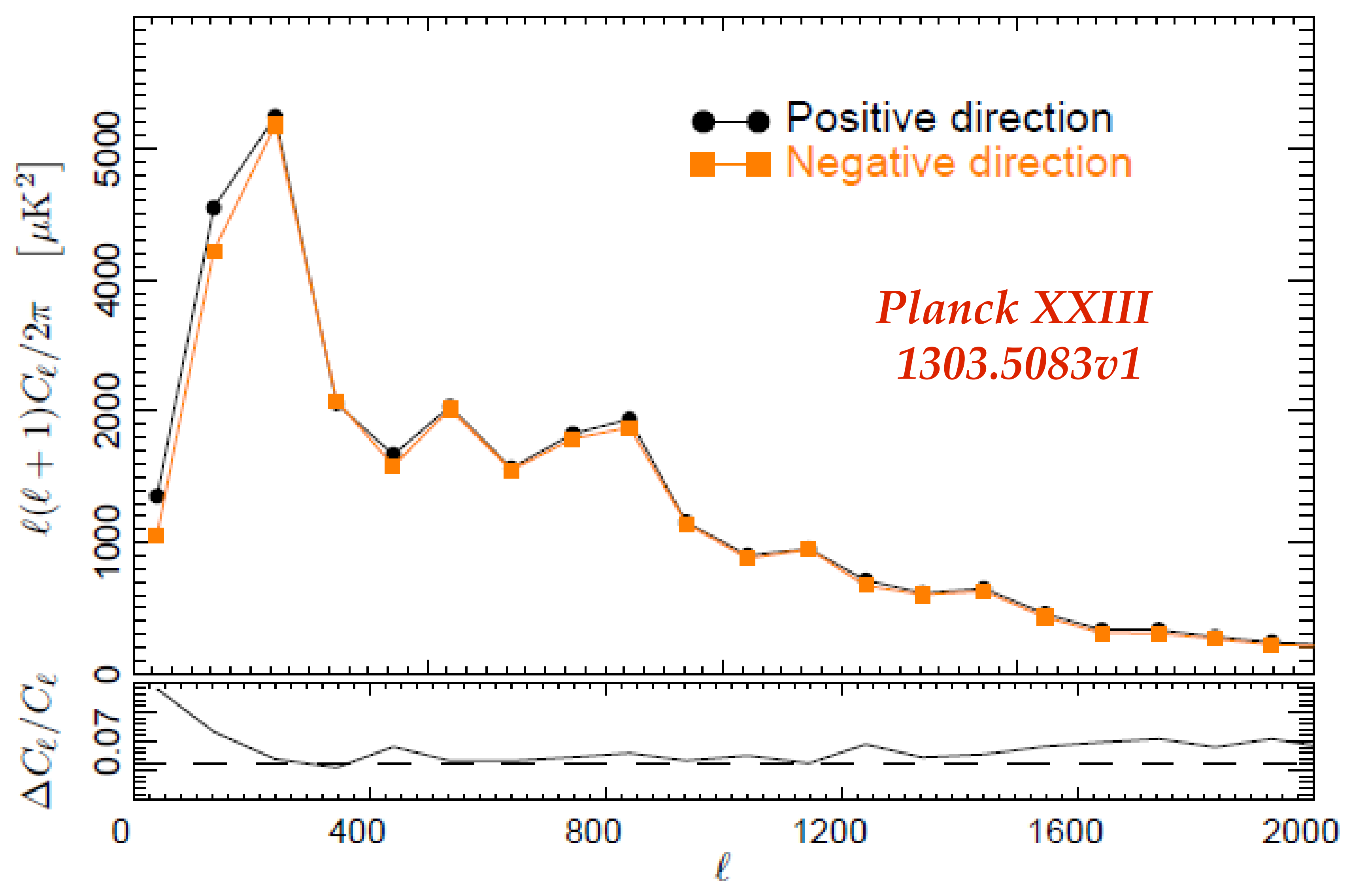
# Hemispherical Asymmetry

- Hemispherical Asymmetry (or "North-South" asymmetry) is an overall difference in power between 2 hemispheres of the sky

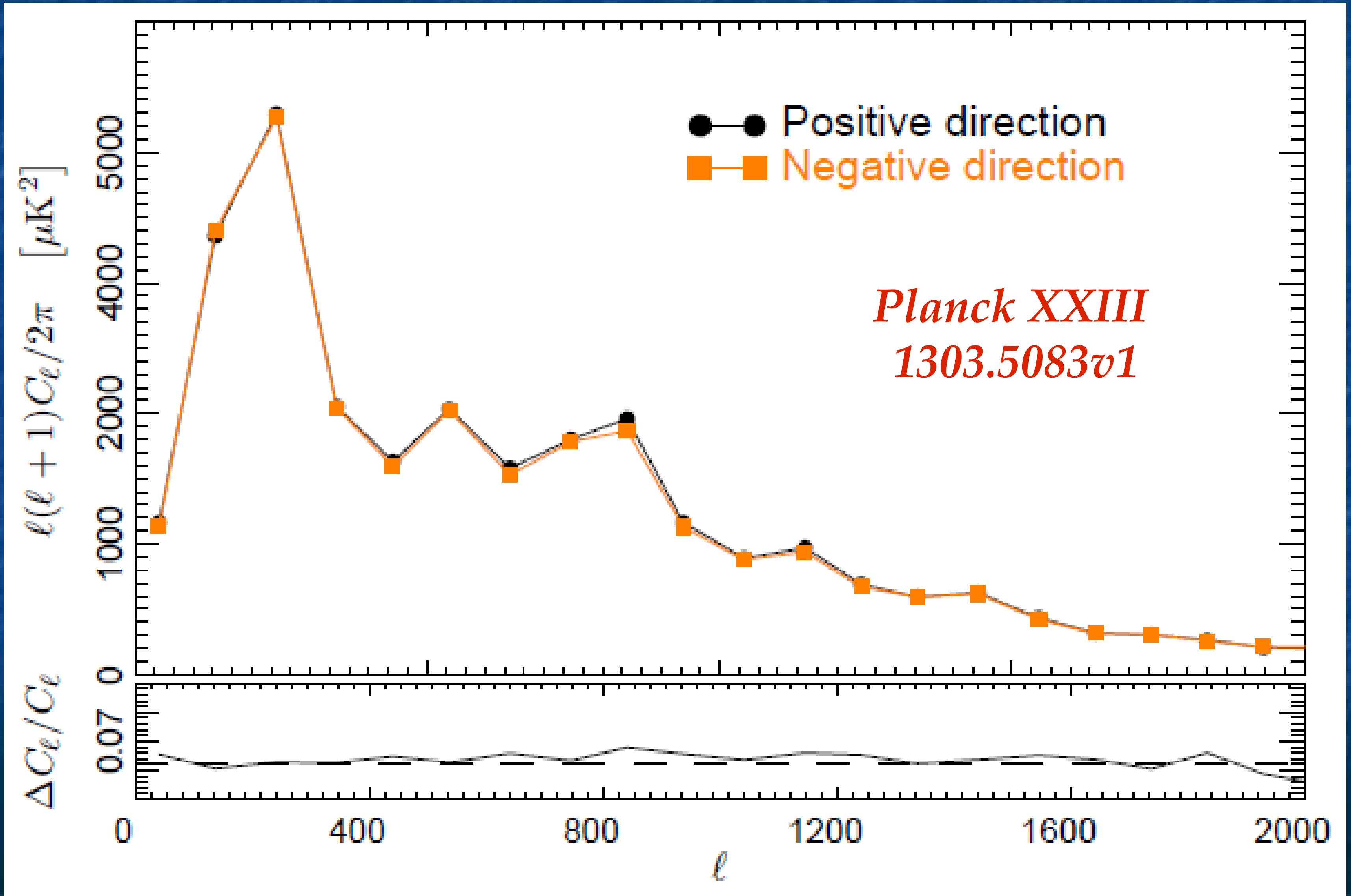
*Planck XXIII*
*1303.5083v1*



# Direction of maximal power asymmetry



# Power asymmetry along the dipole direction



# Aberration Power Asymmetry

- Aberration induces a power asymmetry!
  - Even if the asymmetry is not maximal along the dipole we must understand and subtract the aberration contribution
- We can compute the aberration asymmetry this way:
  - The overall power is a multiplicative parameter A
  - We construct a simple $\chi^2$ to find the best fit A on simulated data using HEALPix (modified to allow aberration)

$$\chi^2(A) = \sum_\ell \frac{(D_\ell^{\rm exp} - A\hat{D}_\ell^{\rm th})^2}{\sigma_\ell^2} \qquad A_{\rm bf} = \sum_\ell \frac{D_\ell^{\rm exp}\hat{D}_\ell^{\rm th}}{\sigma_\ell^2} \Big/ \sum_\ell \frac{(\hat{D}^{\rm th})^2}{\sigma_\ell^2}$$

$$\left\langle \frac{\delta A}{A} \right\rangle \equiv 2\frac{A_{\rm bf}^N - A_{\rm bf}^S}{A_{\rm bf}^N + A_{\rm bf}^S} \simeq \frac{\sum_\ell (2\ell+1)\delta D_\ell / D_\ell}{\sum_\ell (2\ell+1)}$$

# Aberration Power Asymmetry (2)

- Aberration induces a power asymmetry
  - For antipodal half sky cuts (– galactic mask) we estimate an asymmetry:
    - at $1 < \ell < 1500$ of $0.36\% \pm 0.17\%$
    - at $1 < \ell < 2500$ of $0.58\% \pm 0.10\%$
  - For antipodal $90^o$ disks at $1 < \ell < 1500$, of $0.7\% \pm 0.3\%$
    - The error bars were obtained through Monte Carlo analysis → different random seeds
      - Keep in mind: real data is one particular realization!
    - This is statistically significant and accounts for an important fraction of the asymmetry in Planck

*Notari, Quartin & Catena 1304.3506 (JCAP)*

# Aberration Power Asymmetry (4)

- We modified HEALPix to include the possibility of "boosts" (Doppler + aberration)
- It turns out a simple analytical estimate works well. For 2 small antipodal discs around the dipole:
  - Doppler: produces a $\pm\beta$ discrepancy → $\Delta T = 2\beta$
    - For the C_ℓ, this amounts to a $4\beta$ difference in N and S
  - Aberration: $\ell \rightarrow \ell\,(1 \pm \beta)$ In other words: $\Delta\ell = \beta\ell$

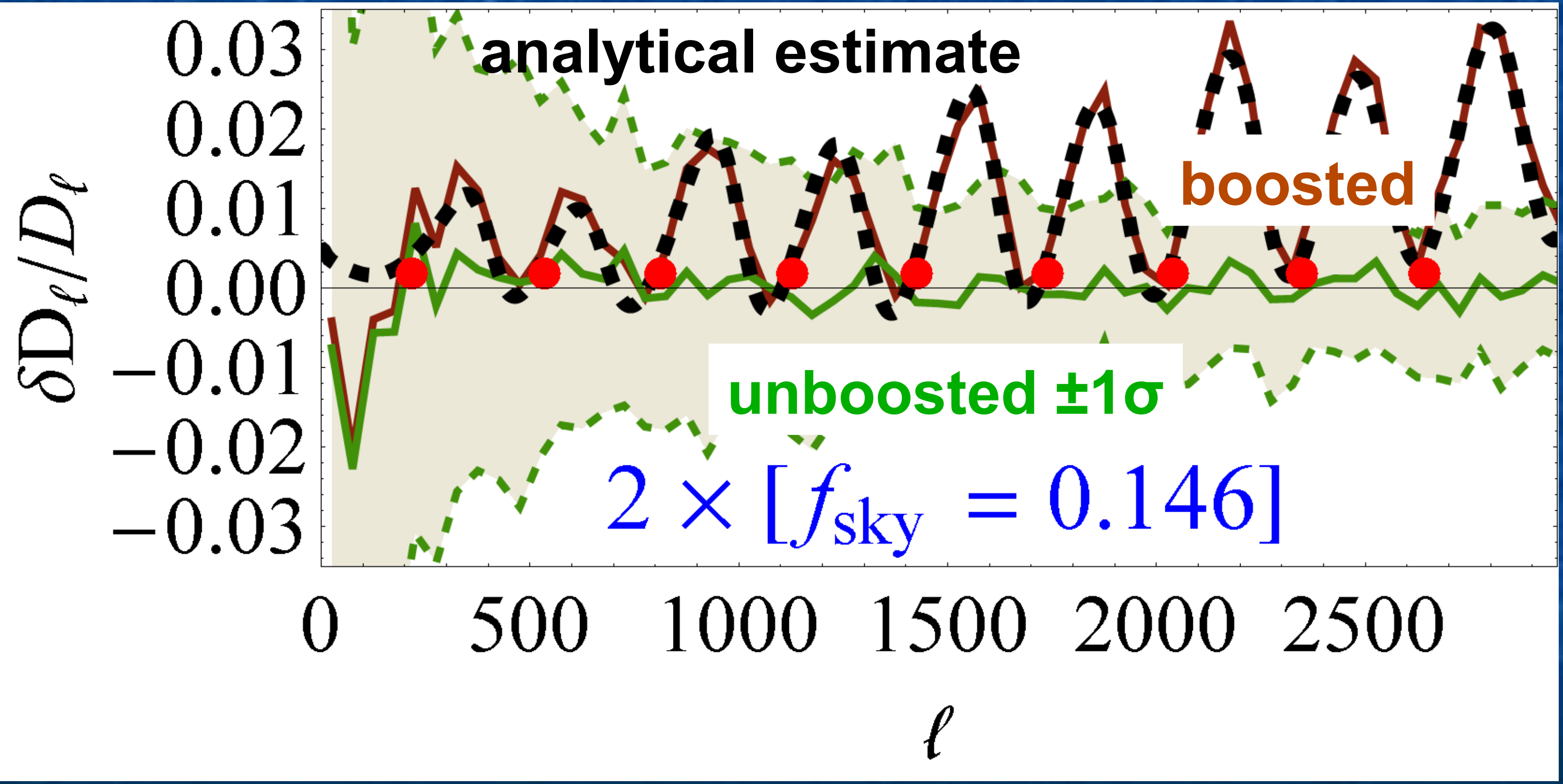
$$\Delta C_\ell = (dC_\ell/d\ell)\,\Delta\ell \sim \pm(C_{\ell+1} - C_\ell)\Delta\ell$$

$$\delta C_\ell/C_\ell \sim 4\overline{\beta} + 2\overline{\beta}\,\ell\,(1 - C^{\rm th}_{\ell+1}/C^{\rm th}_\ell)$$

$$\overline{\beta} = \beta\,\frac{\int_R d\Omega\cos(\gamma)}{\int_R d\Omega}$$

# Aberration Power Asymmetry (5)

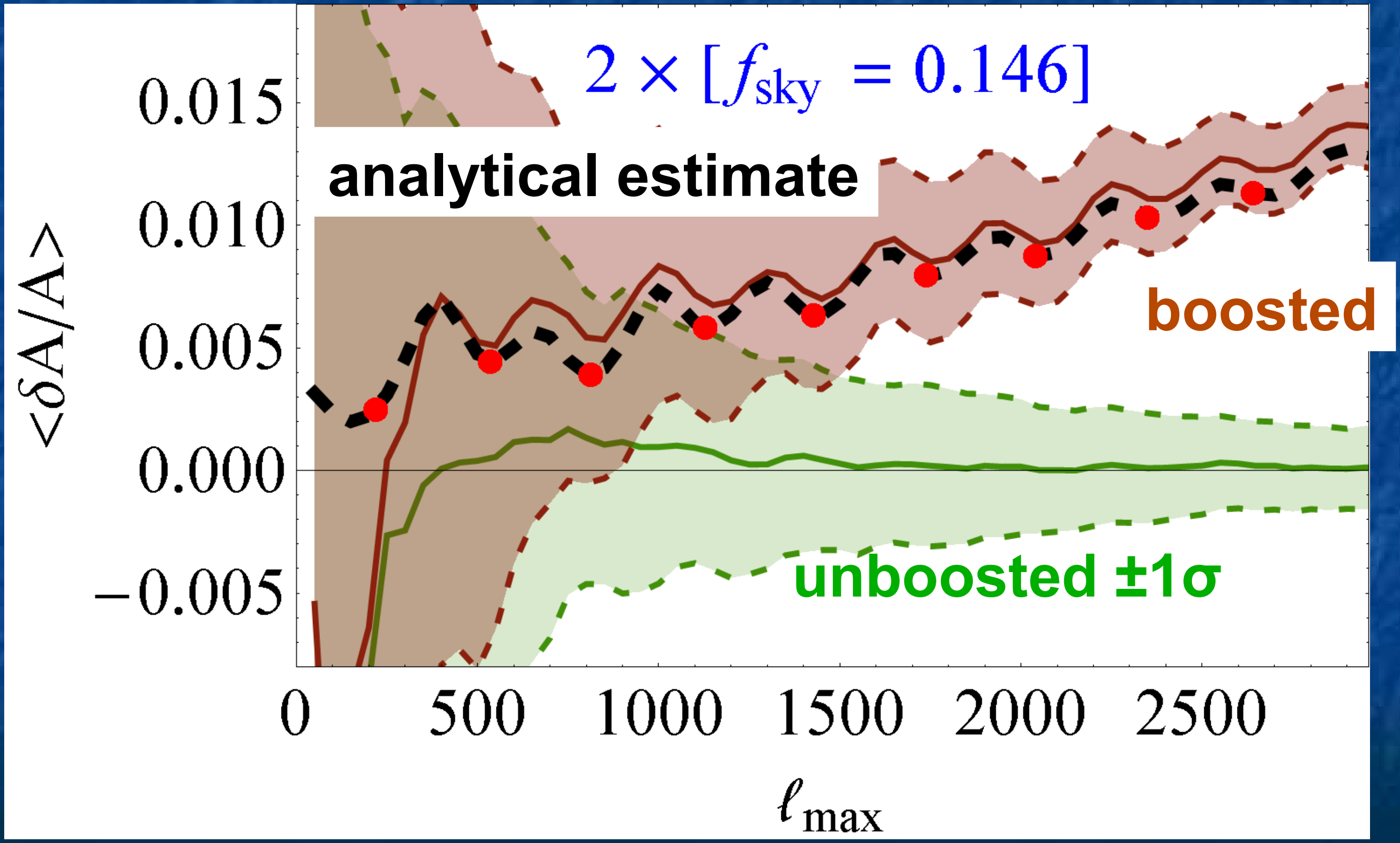
- Hemispherical Asymmetry due to aberration:



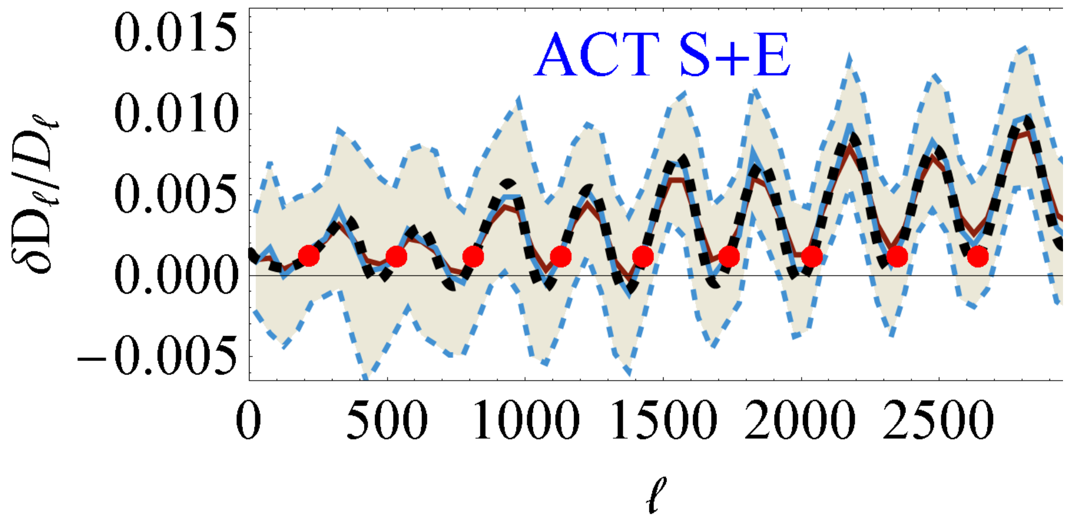

*Notari, Quartin & Catena 1304.3506 (JCAP)*

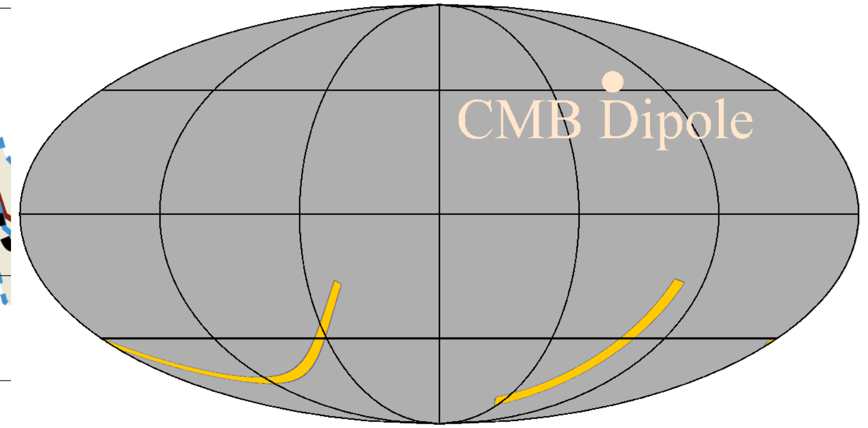
# Aberration Power Asymmetry (6)

- Hemispherical Asymmetry due to aberration:

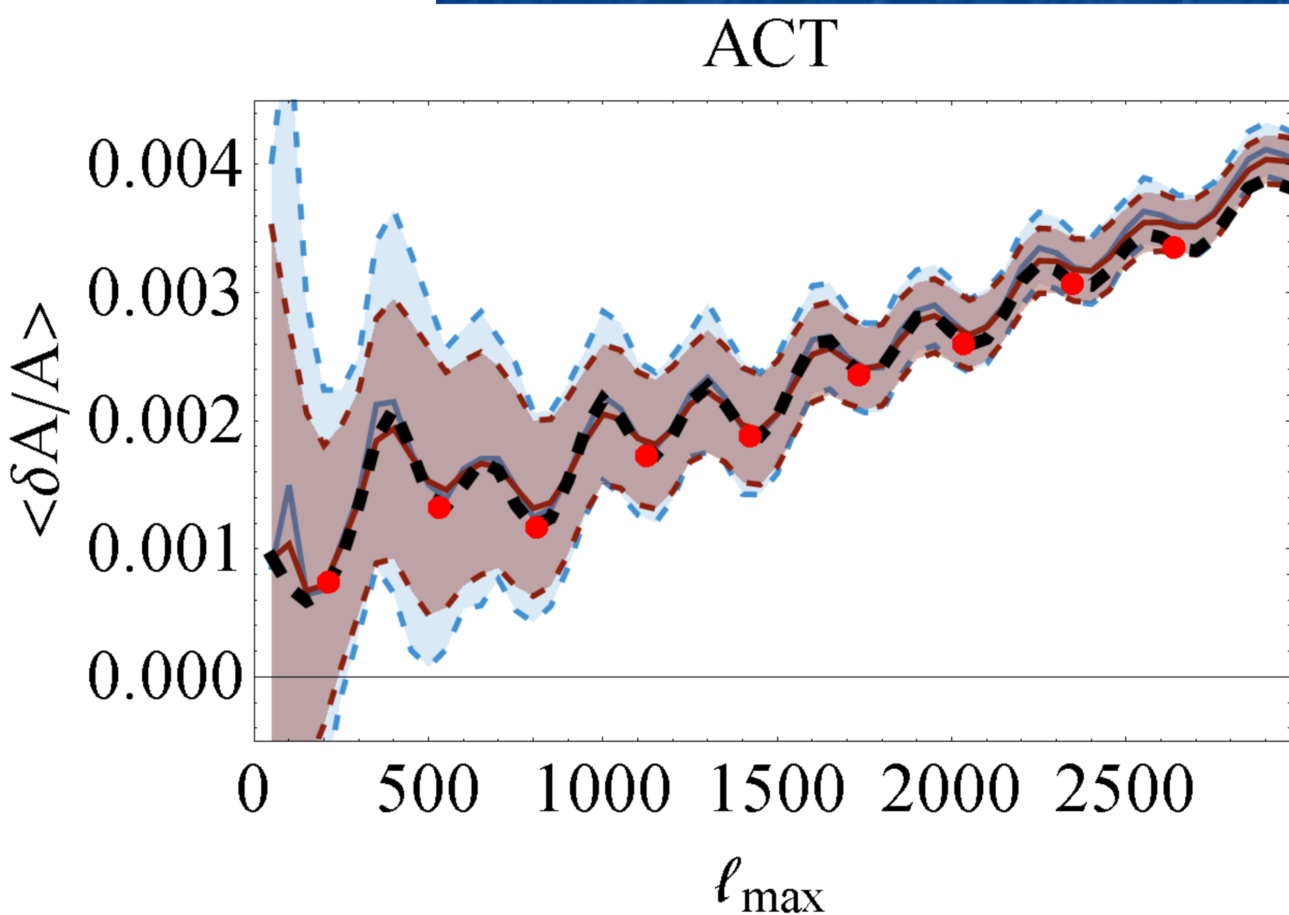



*Notari, Quartin & Catena 1304.3506 (JCAP)*




# ACT estimates

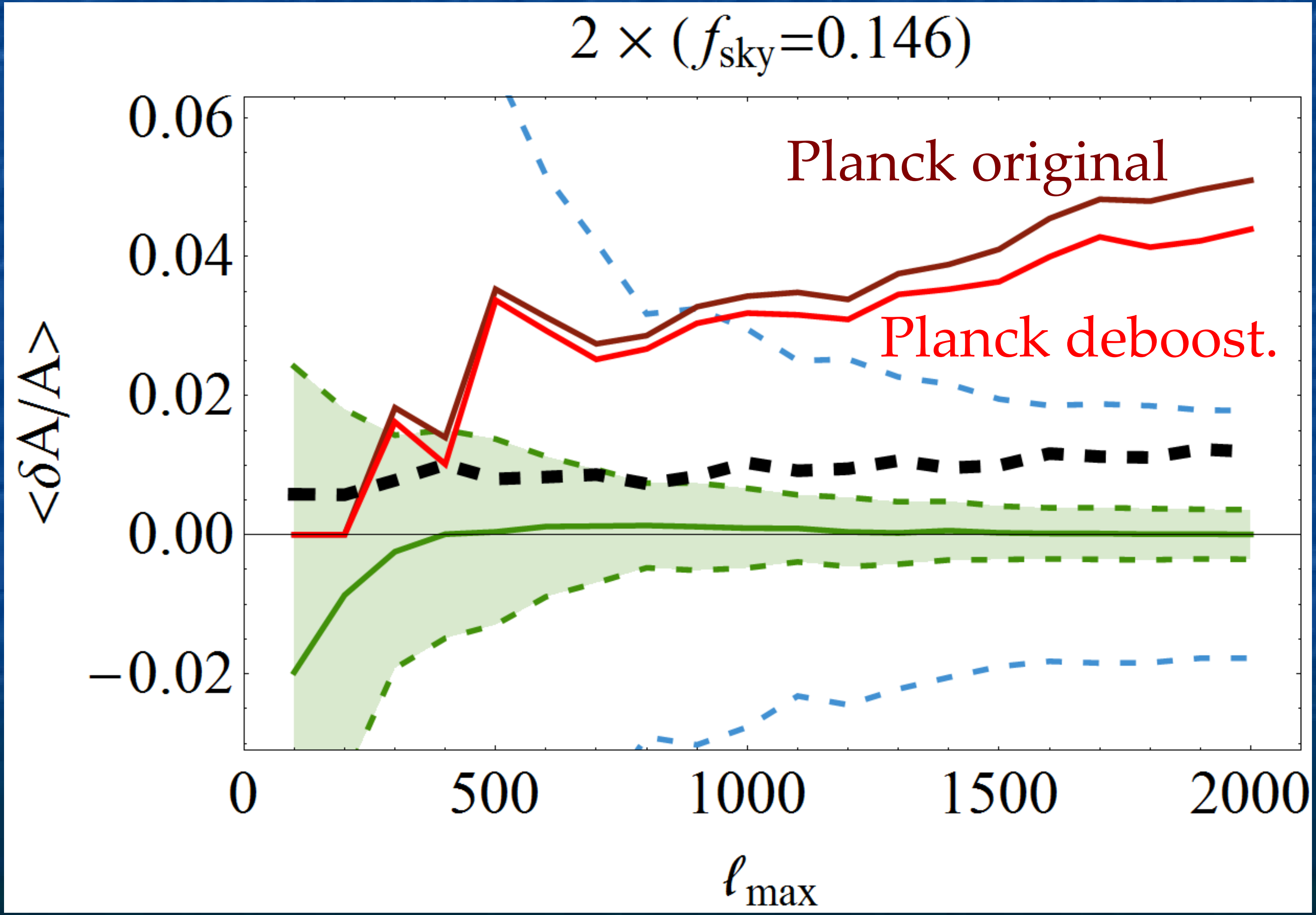


# Aberration Power Asymmetry (7)

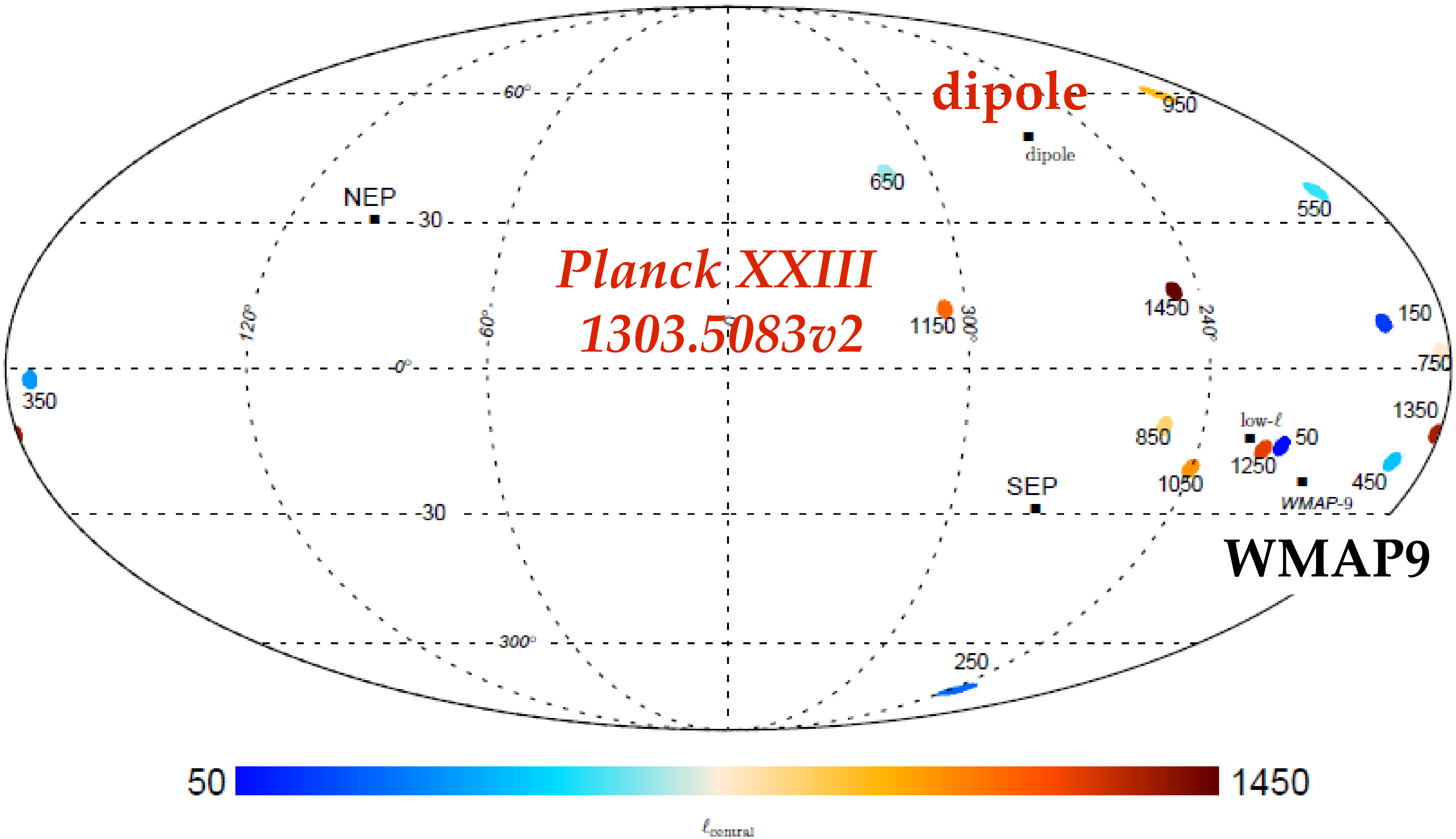
- There seems to be nevertheless some other source of anomalies at low $\ell$
- But de-boosting the CMB will alleviate the power anomaly!
  - Currently $3\sigma$. If it gets down to $2\sigma \rightarrow$ problem solved!
  - Need to look at $\ell > 1500$. We predict the maximum asymmetry direction should drift towards the direction of the dipole.
- It was recently also shown that edge effects from the mask + inter-scale correlation are sources of this asymmetry *Flender & Hotchkiss 1307.6069*

# Aberration Power Asymmetry (8)

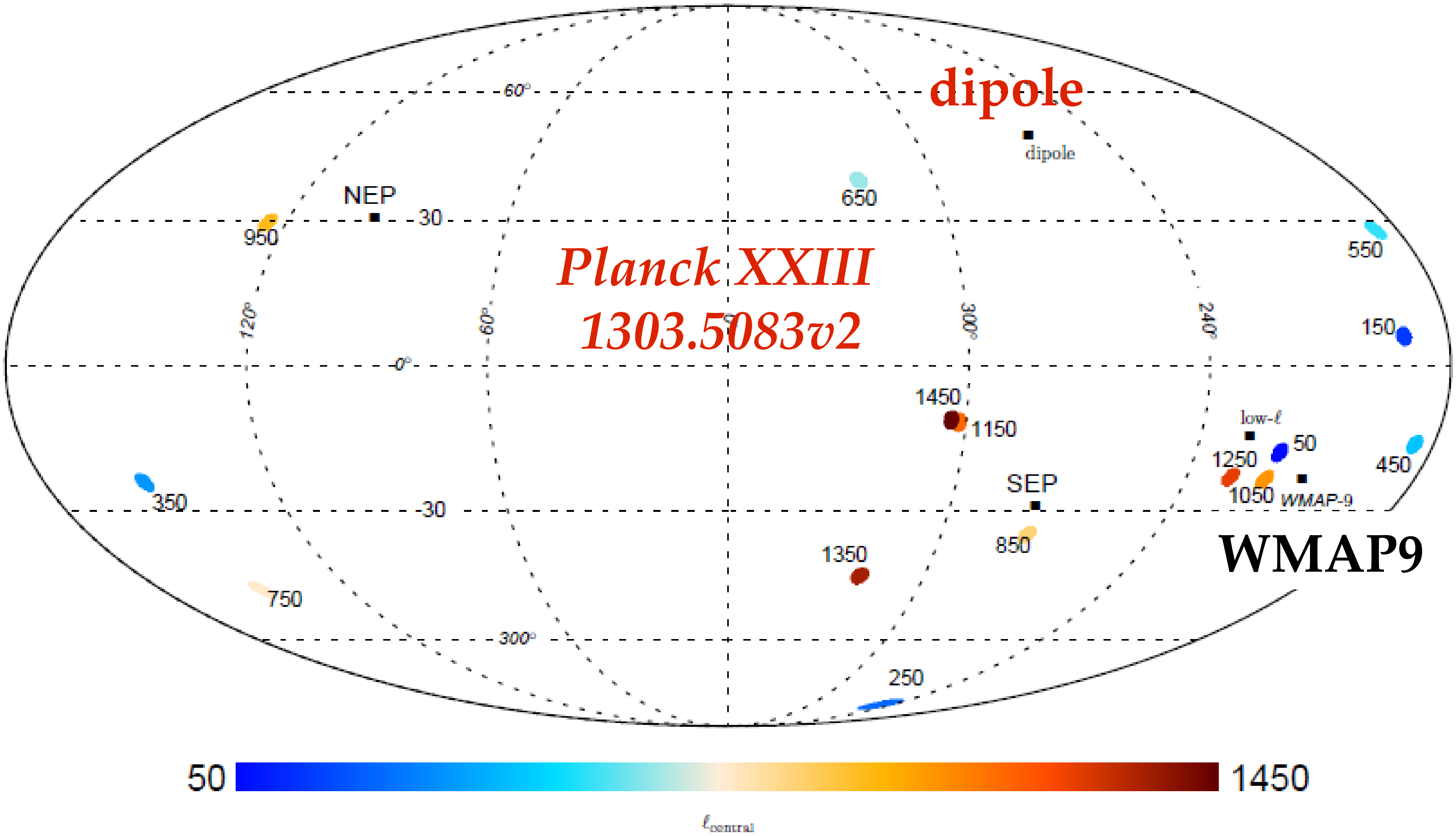
- Deboosting Planck real data [PRELIMINARY]:



# Planck's Hem. Asymmetry



# Planck's Hem. Asymmetry – deboosted

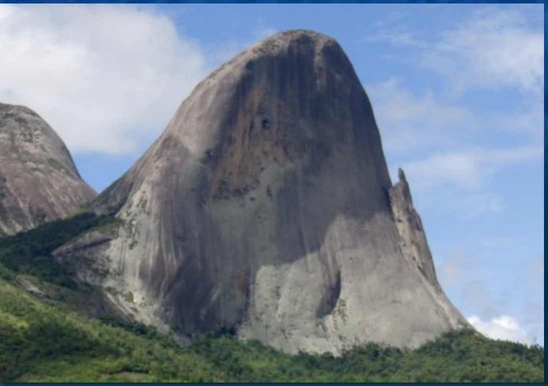


# Conclusions

- Aberration has been CONFIRMED by Planck
- Statistical isotropy broken
  - BUT no non-gaussianity OR grav. lensing
- 2 new techniques allow full analysis of the correlations
  - Nonlinear fitting functions
  - Pre-deboost
- Our predictions were also quantitatively confirmed
  - Future: ACTPol with $f_{sky} = 0.4$ (4 years)
    - S/N ~ 9; $\delta$(direction) < 7$^o$; $\delta v / v_{CMB} < 13\%$

# Conclusions (2)

- Measurement of aberration breaks the degeneracy between intrinsic dipole and peculiar velocity
- Window to measure primordial dipole? Bulk flows?
- Cross-check against more exotic models:
  - anisotropic models, Hubble scale magnetic fields? $P(\vec{k})$?
- Introduces systematics if not corrected for
  - Planck now acknowledges this for its Hemispherical Asymmetry estimates



**Obrigado!**