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The CMB and our peculiar velocity

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CMB after COBE, WMAP, Planck, ...

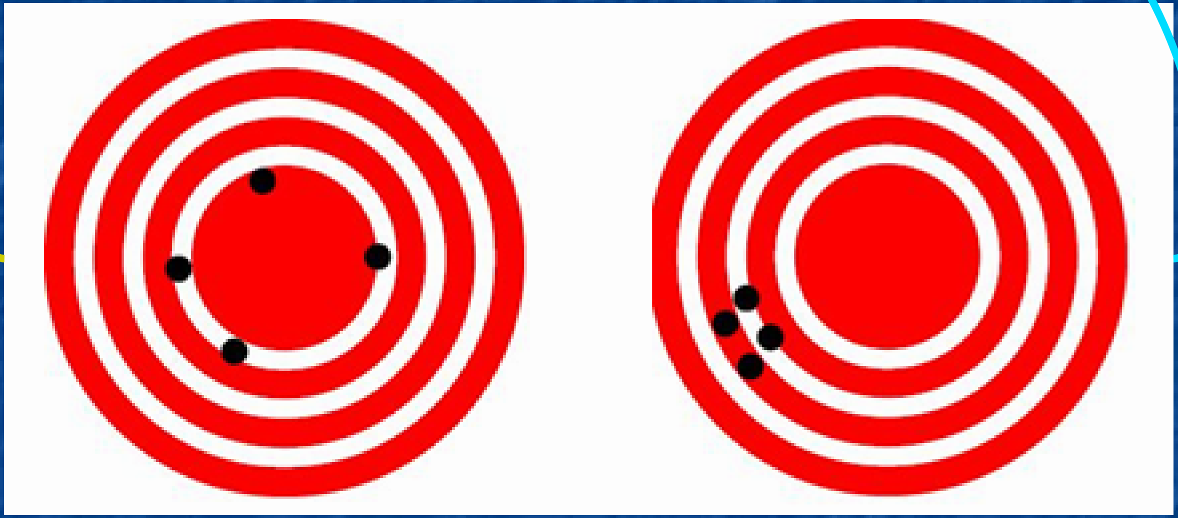
- The CMB is seen as one of the best confirmations of the Big-Bang model → *Nobel Prize 2006*
- A universe with only standard model particles + dark matter cannot explain its spectrum
- WMAP (and now Planck) established ΛCDM as the *de facto* standard cosmological model
  - ΛCDM + inflation explains 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

The Undying ΛCDM

- WMAP mission:
  - Observed the CMB for 9 years;
  - Reduction of the volume of the 6-dimensional ΛCDM parameter space (Ω_{b0}, Ω_{m0}, h, A, τ, n_s) by **~ 68,000**
    - The same model still works!
    - Non-trivial statistical result!
- This is still true, even with Planck, Atacama Cosmology Telescope (ACT) & South Pole Telescope (SPT)!

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:

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

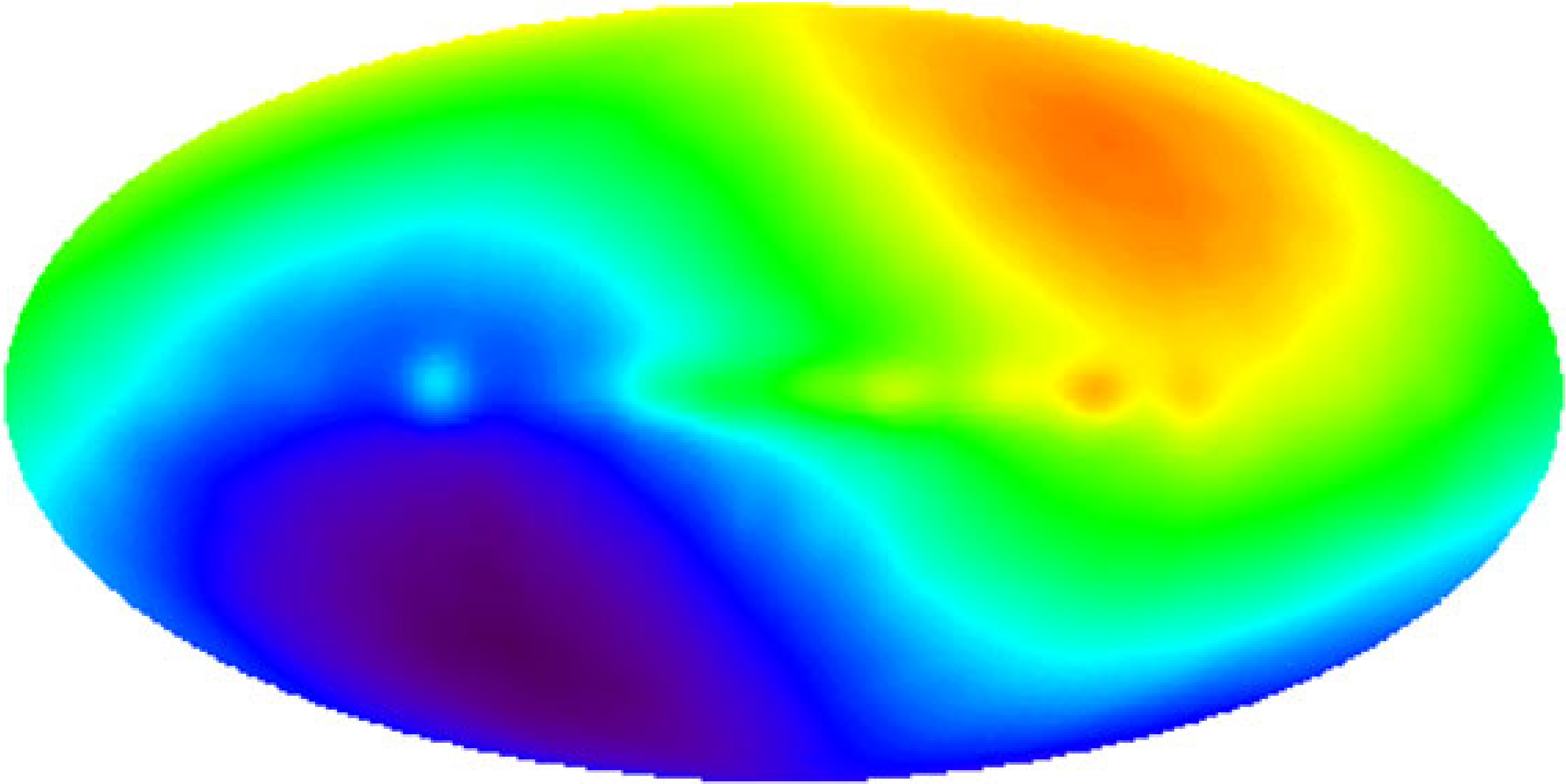
- $\ell = 0$ → monopole
- $\ell = 1$ → dipole: ~ 10^{-3}
- $\ell = 2$ → quadrupole: ~ 10^{-5}
- $\ell > 2$ → all ~ 10^{-5}

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}
  - $v_{CMB} \approx 369$ 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 (3) $\frac{\Delta T}{T} = 1.23 \times 10^{-3}$

- Assuming the whole dipole to be just Doppler, we find that the velocity should be $|\mathbf{v}| = 369$ km/s



Doppler & Aberration

- The CMB dipole ↔ Doppler effect
- But peculiar motion produces also aberration!

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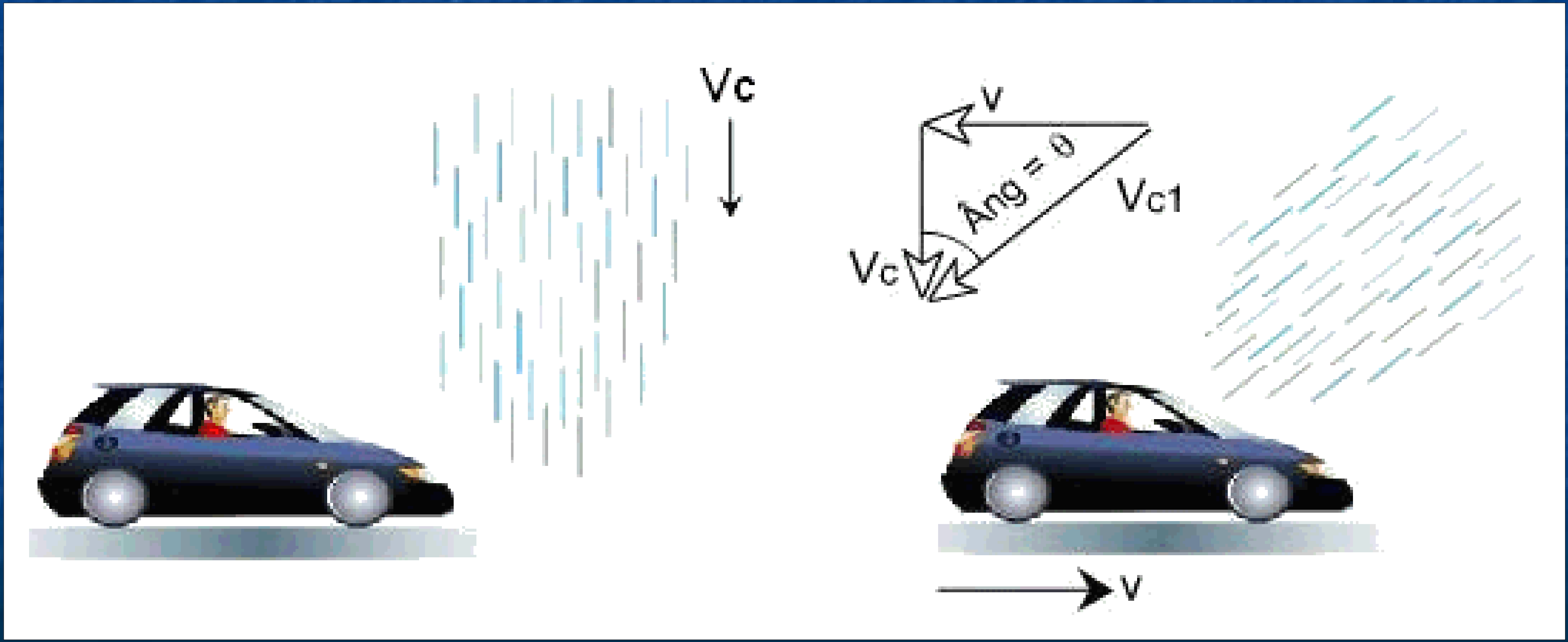

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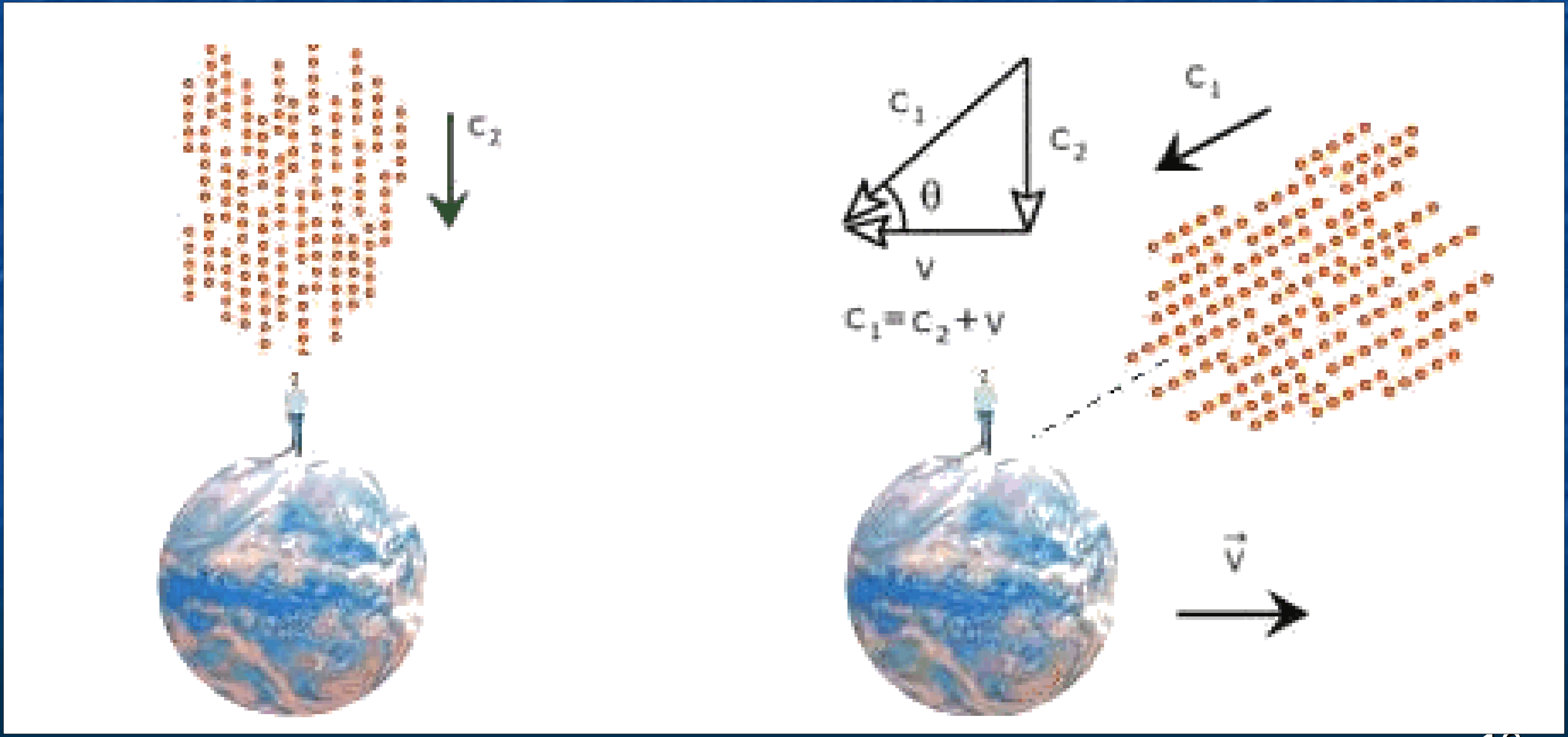
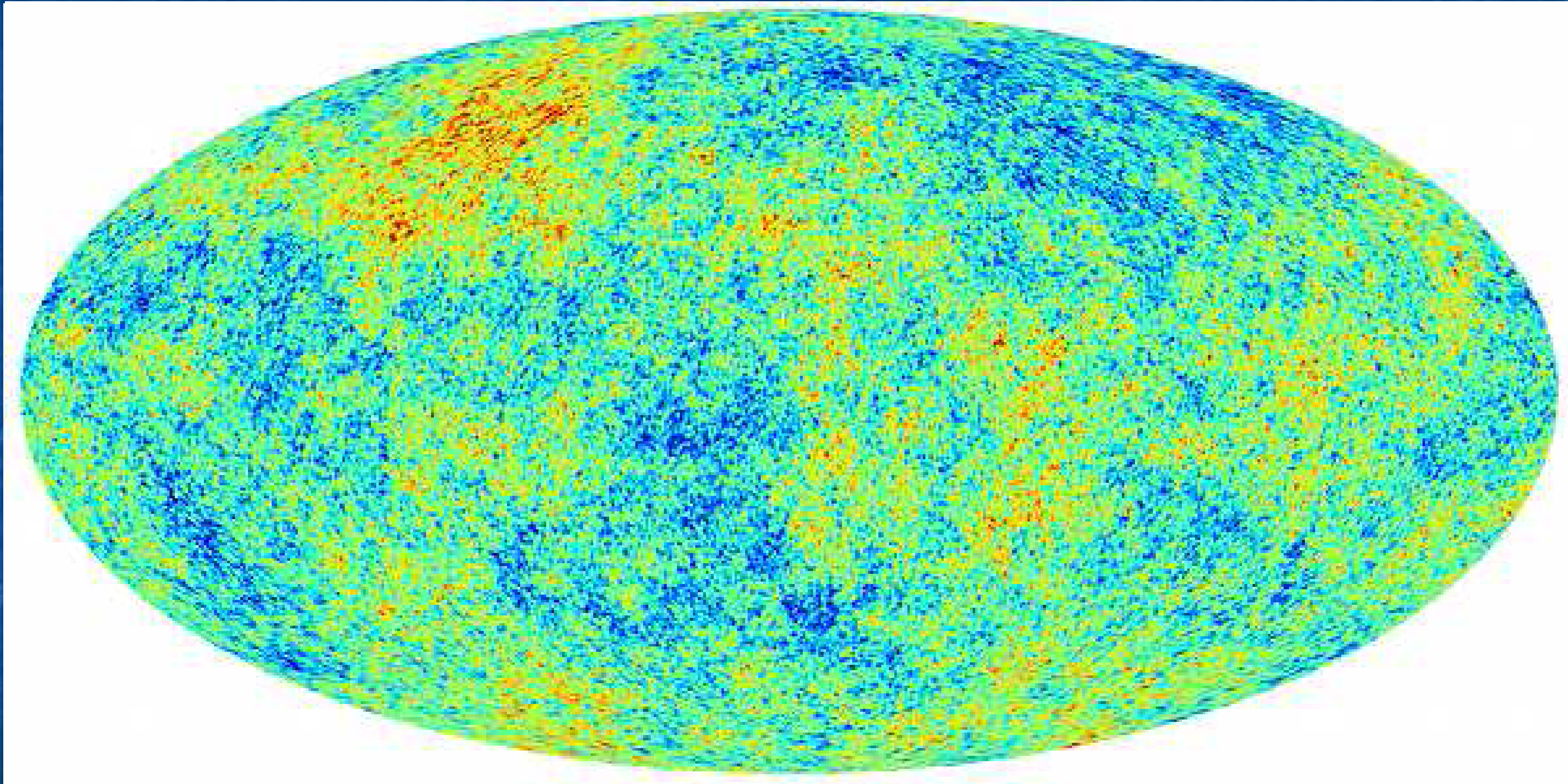
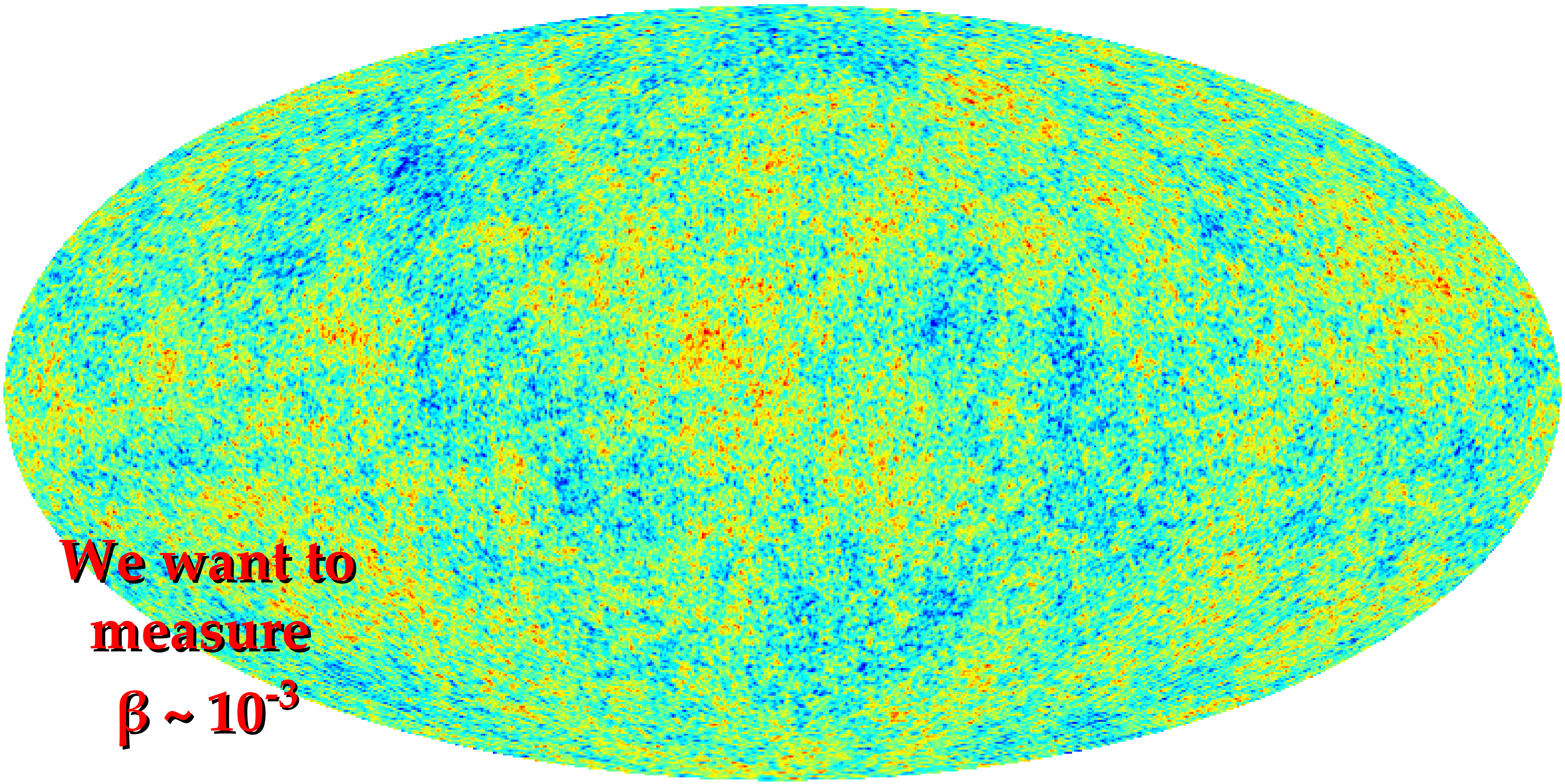


Doppler & Aberration



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

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 ℓ's

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

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

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_ℓ'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 ℓ's are affected: more ℓ 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): $\ell^{T}_{max} \sim 2000$; $\ell^{E,B}_{max} \sim 1600$

CMB Missions

SPT / SPTPol

Planck

EBEX

ACT / ACTPol

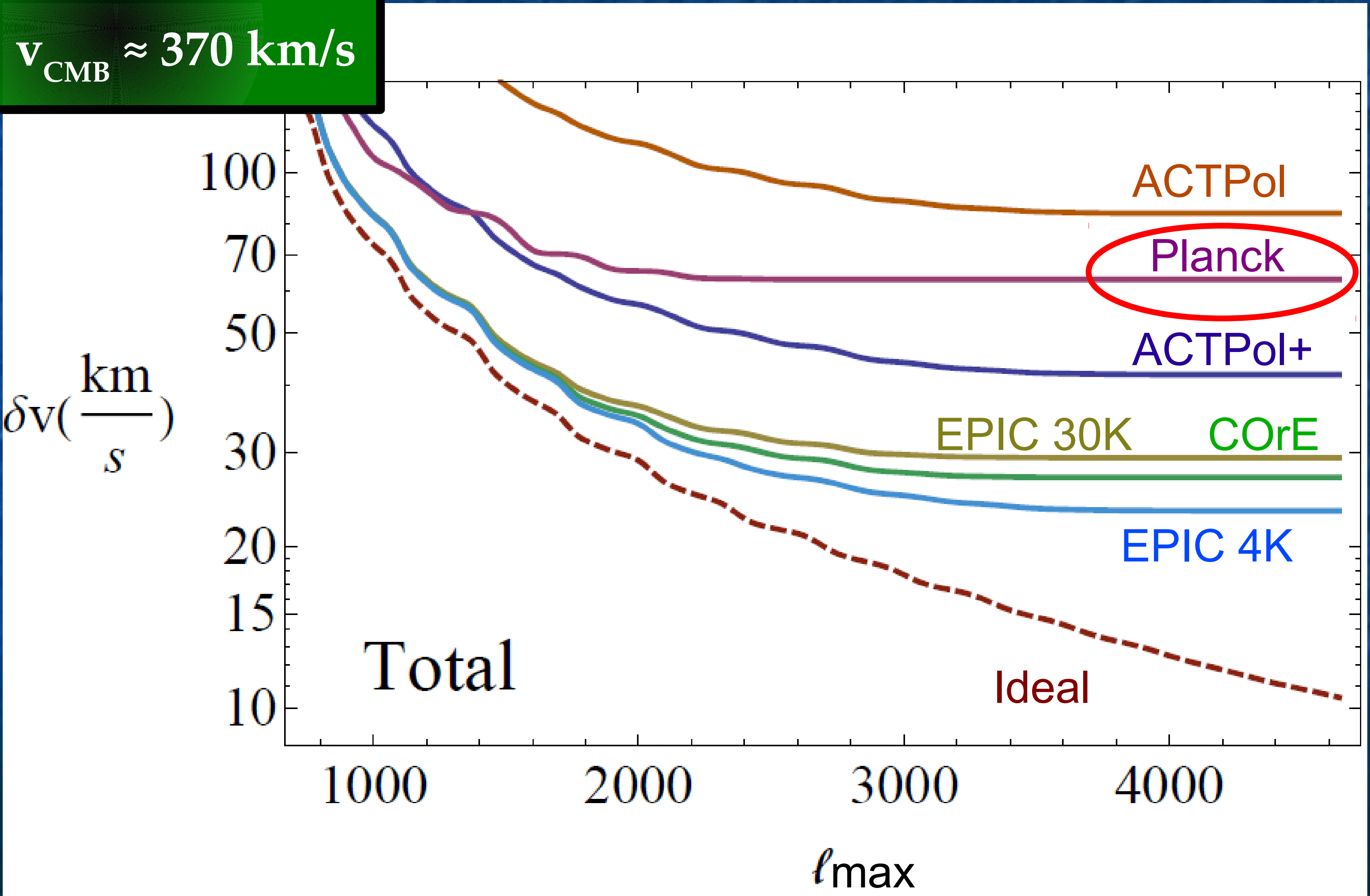
Results: S/N

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 β 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 spherical void models (“LTB”)?
  - 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)*
  - Except in partial-sky surveys. E.g.: 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 ℓ's
  - No change for the low-ℓ anomalies → WMAP was already limited by cosmic variance for $\ell < 600$.
  - The statistical significance of these is around 3σ.
- 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-ℓ ($2 < \ell < 40$), the power spectrum in antipodal hemispheres differ considerably
    - Effect is maximized when 1 hemisphere is centered around $b = -20^o$, $l = 237^o$

      Eriksen et al., astro-ph/0307507 (ApJ)
    - Planck name: *Hemispherical Asymmetry*
  - At all ℓ'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

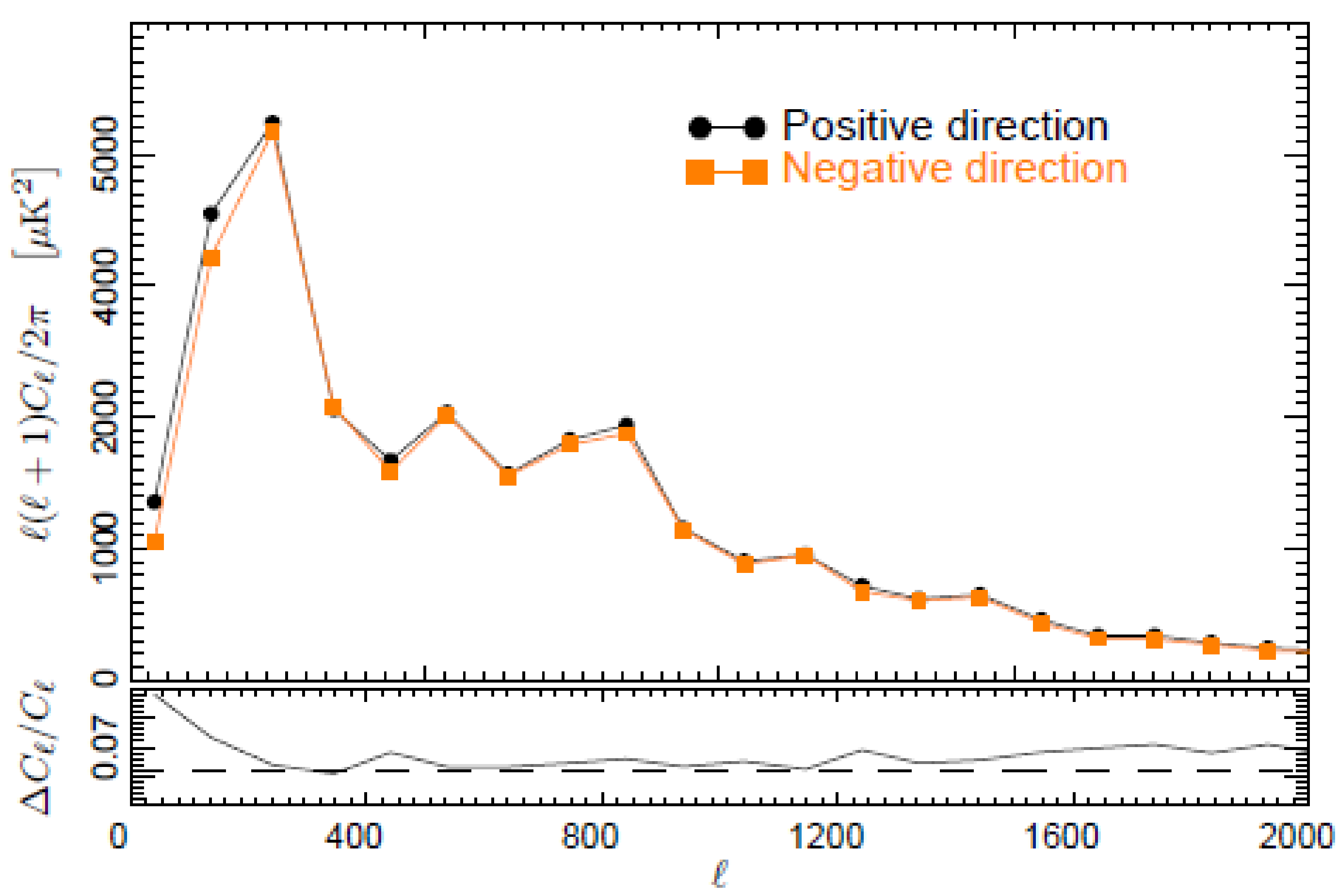
- WMAP measured the power asymmetry up to $\ell = 600$

- Planck extended this to $\ell = 1500$
  - They could go even higher, to $\ell = \sim 1900$

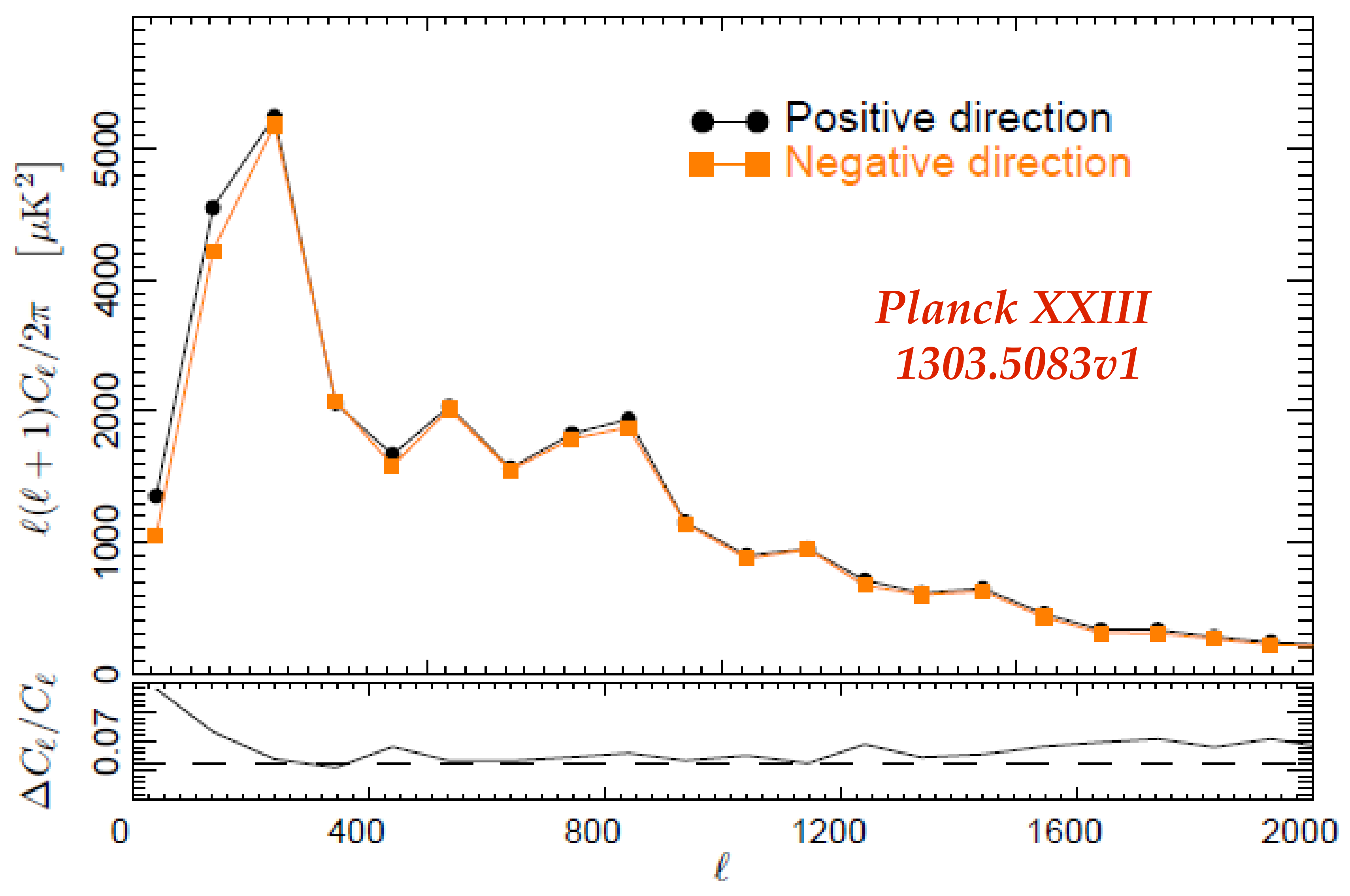
Hemispherical Asymmetry

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

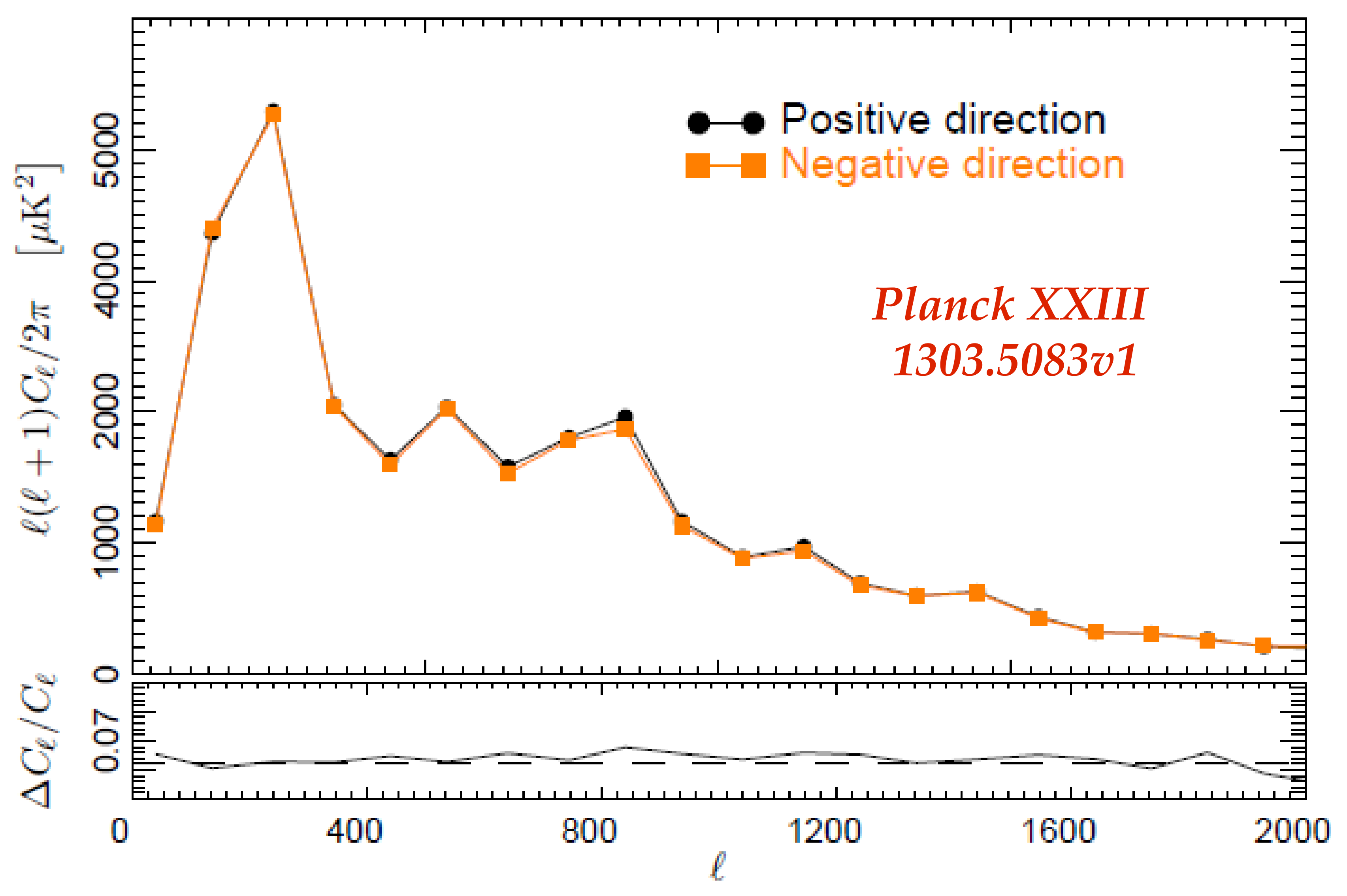
Planck XXIII
1303.5083v1



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 χ^2 to find the best fit A on simulated data using HEALPix (modified to allow Doppler + aberration)
- It turns out aberration adds an important contribution to the power asymmetries

Notari, Quartin & Catena 1304.3506 (JCAP)

Aberration Power Asymmetry (2)

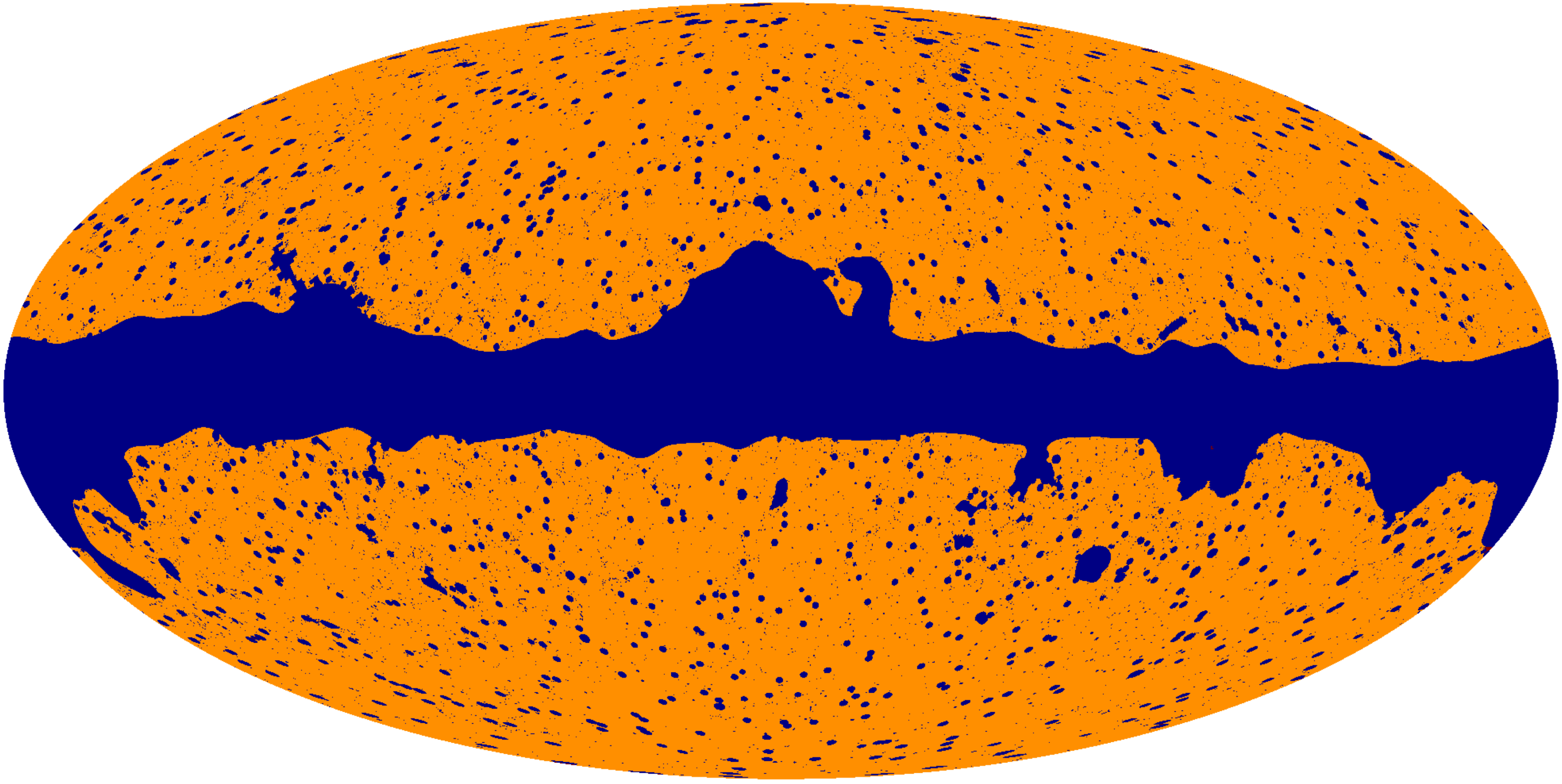
- There seems to be nevertheless some other source of anomalies at low ℓ
- Steps to properly assess CMB power anomalies:
  - Smooth (apodize) mask to reduce edge effects

    Flender & Hotchkiss 1307.6069
  - Deboost the CMB (or boost simulations)
  - Note that Planck noise is also asymmetric
    - This is due to the non-isotropic sky-scan
  - Use an antipodally symmetric mask
    - If a pixel is masked, mask also the antipodal pixel

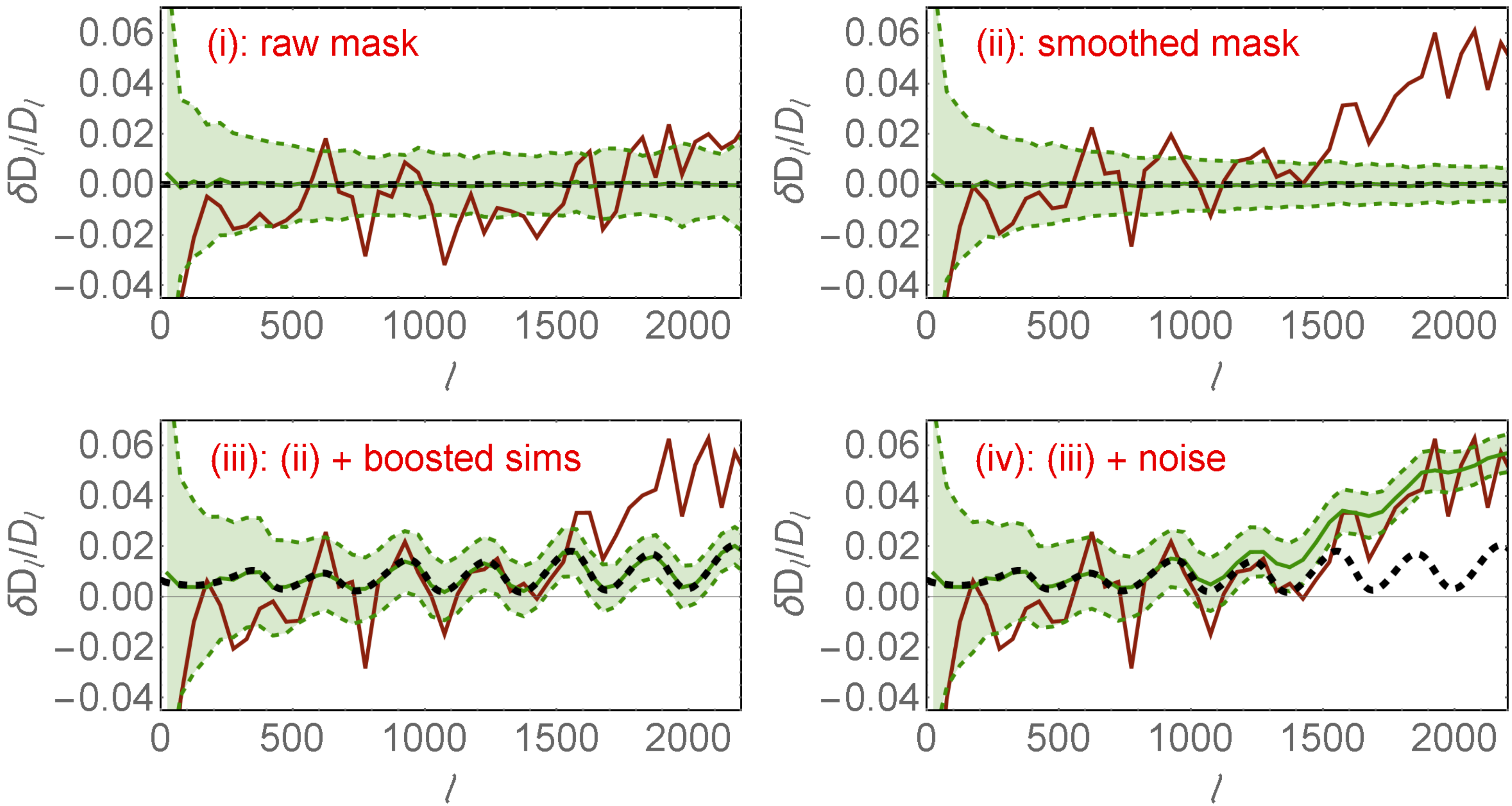
Quartin & Notari 1308.5792

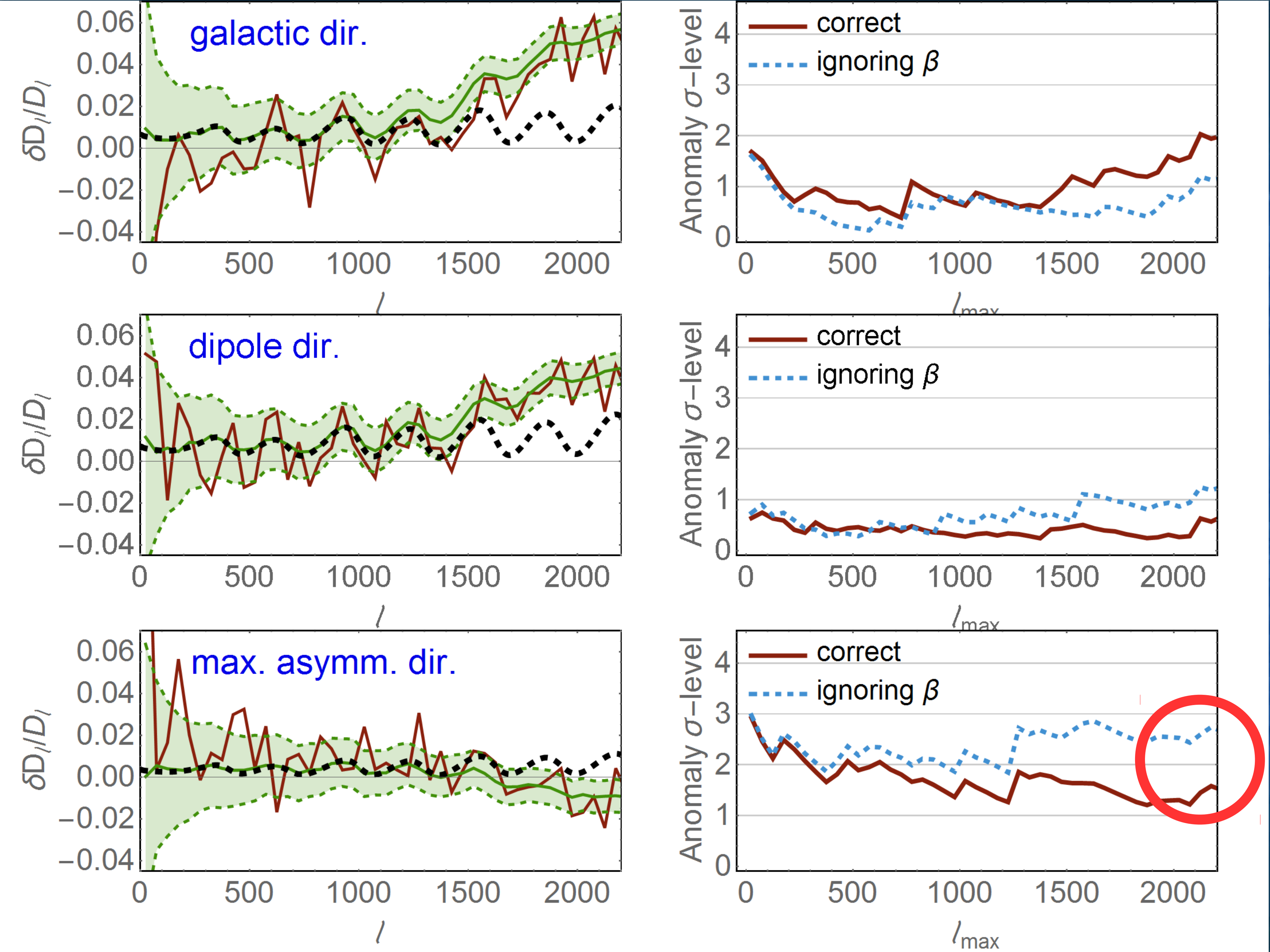
Aberration Power Asymmetry (8)

- A symmetrized U73



Step-by-step


(i): raw mask
(ii): smoothed mask
(iii): (ii) + boosted sims
(iv): (iii) + noise
0.06
0.04
0.02
0.00
−0.02
−0.04
0
500
1000
1500
2000
$\delta D_l/D_l$
l


galactic dir.
dipole dir.
max. asymm. dir.
$\delta D_l/D_l$
l
correct
ignoring β
Anomaly σ−level
l_{max}

Dipolar Modulation of Power?

- Some authors have suggested the CMB power spectrum amplitude is modulated by a cosine

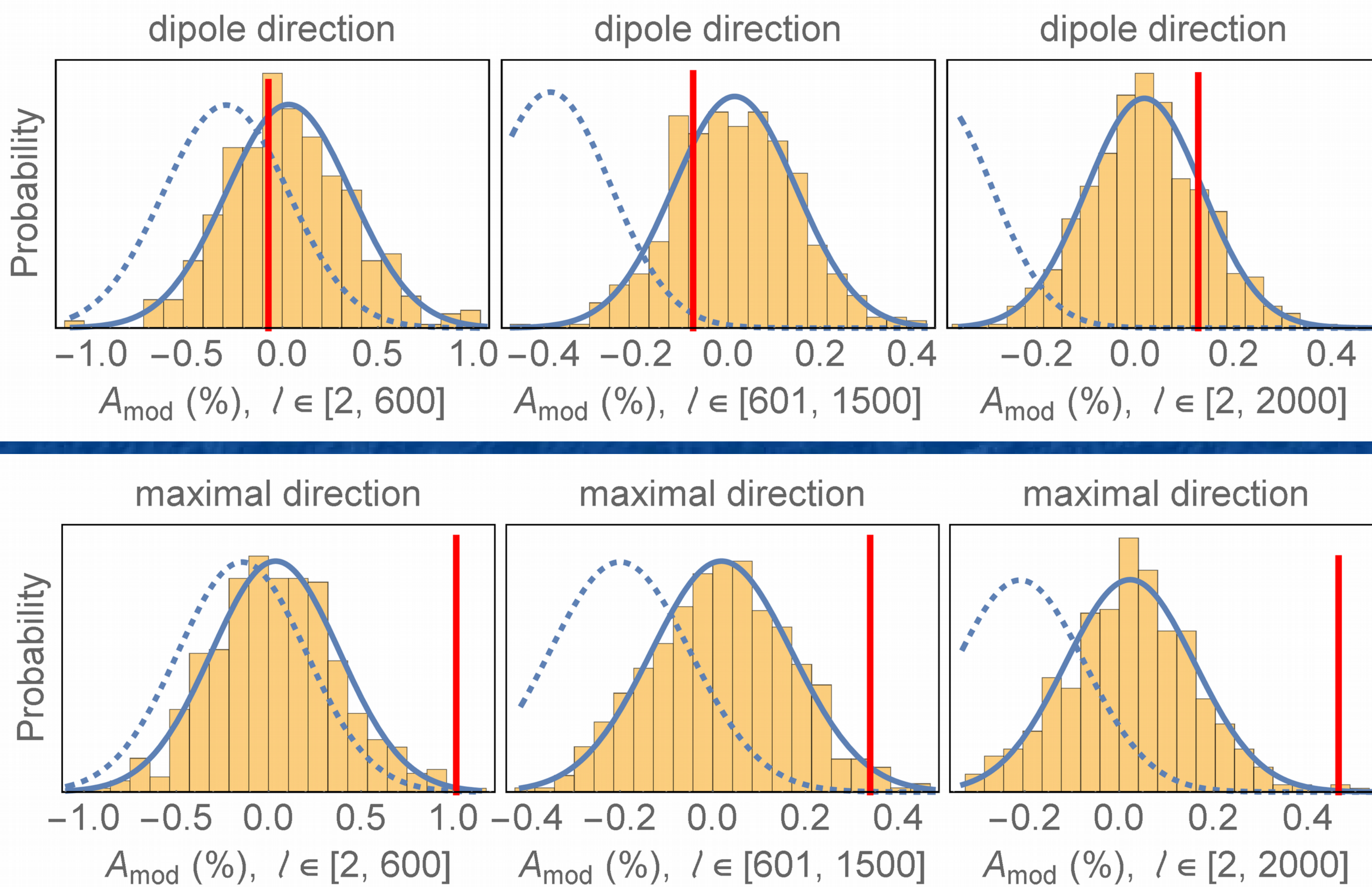
$$T = T_{\mathrm{isotropic}}\left(1 + A_{\mathrm{mod}} \cos\alpha\right)$$

$$\chi^2(A_{\mathrm{mod}}) = \sum_{\ell} \sum_{i,j} \mathcal{I}_{\ell}^{ij} \left(D_{\ell}^{i} - \overline{D}_{\ell}^{i}\right)\left(D_{\ell}^{j} - \overline{D}_{\ell}^{j}\right)$$

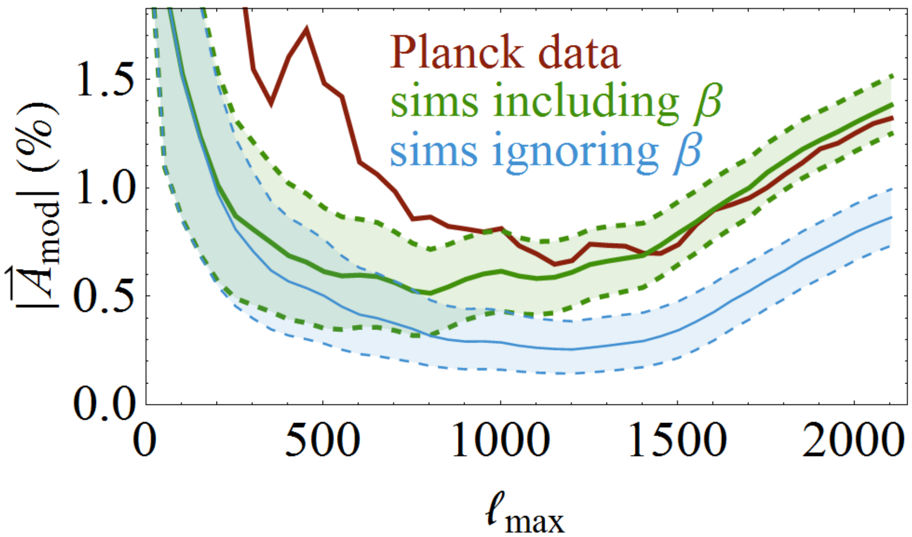
$$\overline{D}_{\ell}^{N,S} = (\overline{D}_{\ell}^{\mathrm{gauss}} \pm \delta D_{\ell}^{\beta})(1 \pm 2\langle\cos\alpha\rangle A_{\mathrm{mod}}) + N_{\ell}^{N,S}$$

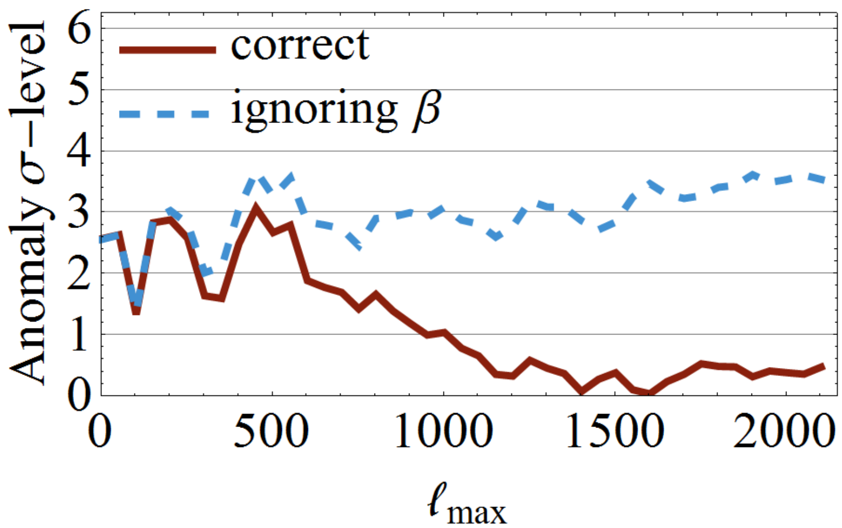
- We can now properly measure this parameter

Dipolar Modulation of Power?



Dipolar Modulation of Power? (2)





Conclusions

- Aberration has been CONFIRMED by Planck
- Statistical isotropy broken
  - BUT no non-Gaussianity OR grav. lensing
- Our predictions were also quantitatively confirmed
  - Future: ACTPol with $f_{sky} = 0.4$ (4 years)
    - S/N ~ 9; δ(direction) < 7^o; $\delta v / v_{CMB} < 13\%$
- Measurement of aberration breaks the degeneracy between intrinsic dipole and peculiar velocity
- Window to measure primordial dipole?

Conclusions (2)

- Cross-check against more exotic models;
- Introduces systematics if not corrected for
- Hemispherical asymmetry reduced from 2.8 to 1.6σ
- No evidence for dipolar modulation: < 1σ (instead of 3 to 5σ if we ignore the boost)

- We should always work on the CMB rest frame!

Thanks!