COSMO 17 – Paris – Aug 2017

In collaboration with Alessio Notari, Omar Roldán
+ L. Amendola, R. Catena, I. Masina & C. Quercellini

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Towards a measurement of the primordial CMB dipole

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The CMB Dipole

- CMB Temperature: $T_{\mathrm{CMB}} \;=\; 2.7255\,K\left[1+\frac{\Delta T(\theta,\phi)}{T}\right]$

- Spherical Harmonics decomposition:

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

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- $\ell = 0$ → monopole
- $\ell = 1$ → dipole: ~ 10^{-3}
- $\ell = 2$ → quadrupole: ~ 10^{-5}
- $2 < \ell < 1000$ → 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}
  - $V_{\mathrm{CMB}} = 370.5$ km/s → $\beta \equiv v/c = 1.2345 \times 10^{-3}$
  - direction → $l = 264.00° \pm 0.03°$; $b = 48.24° \pm 0.02°$

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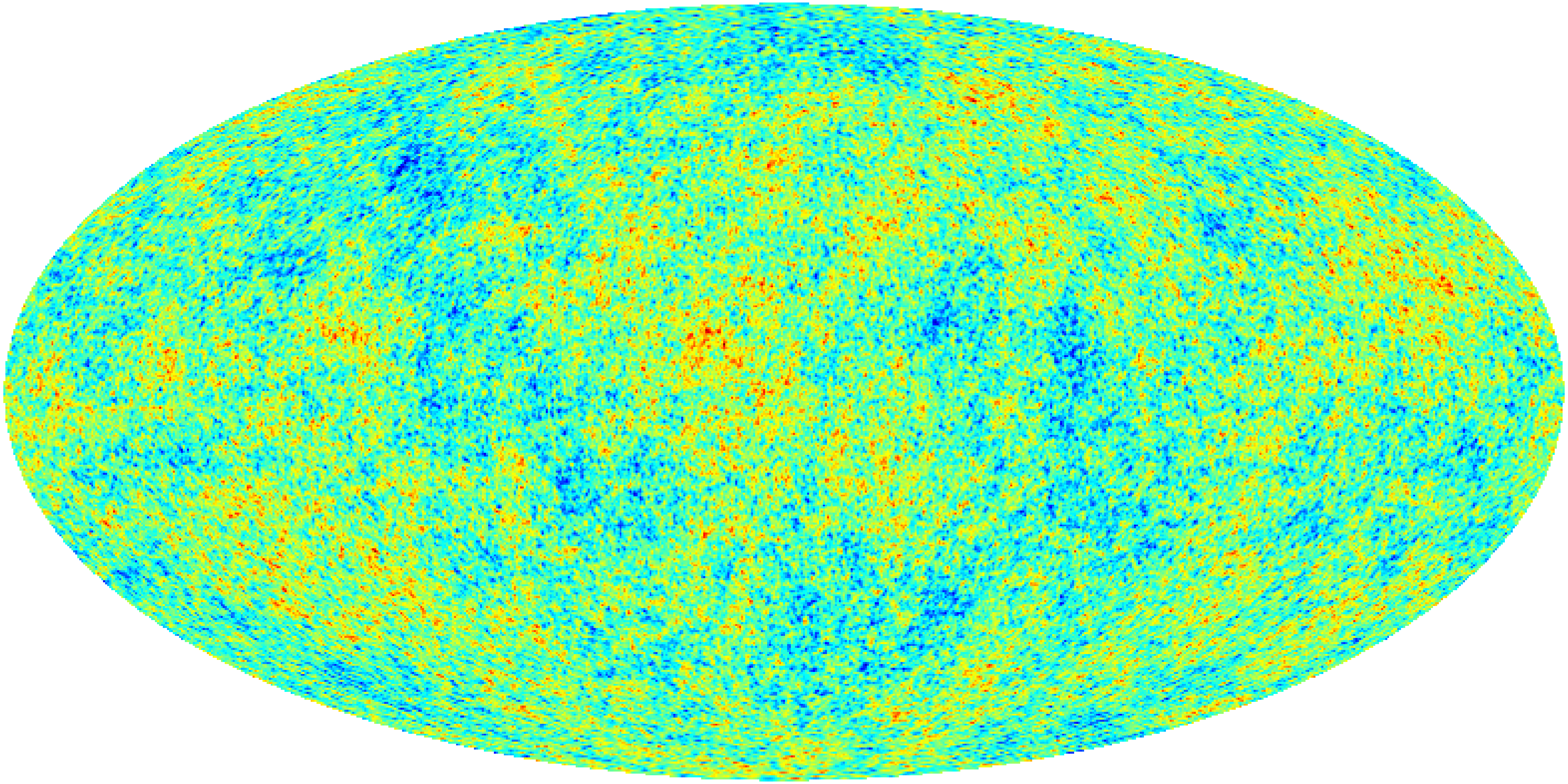
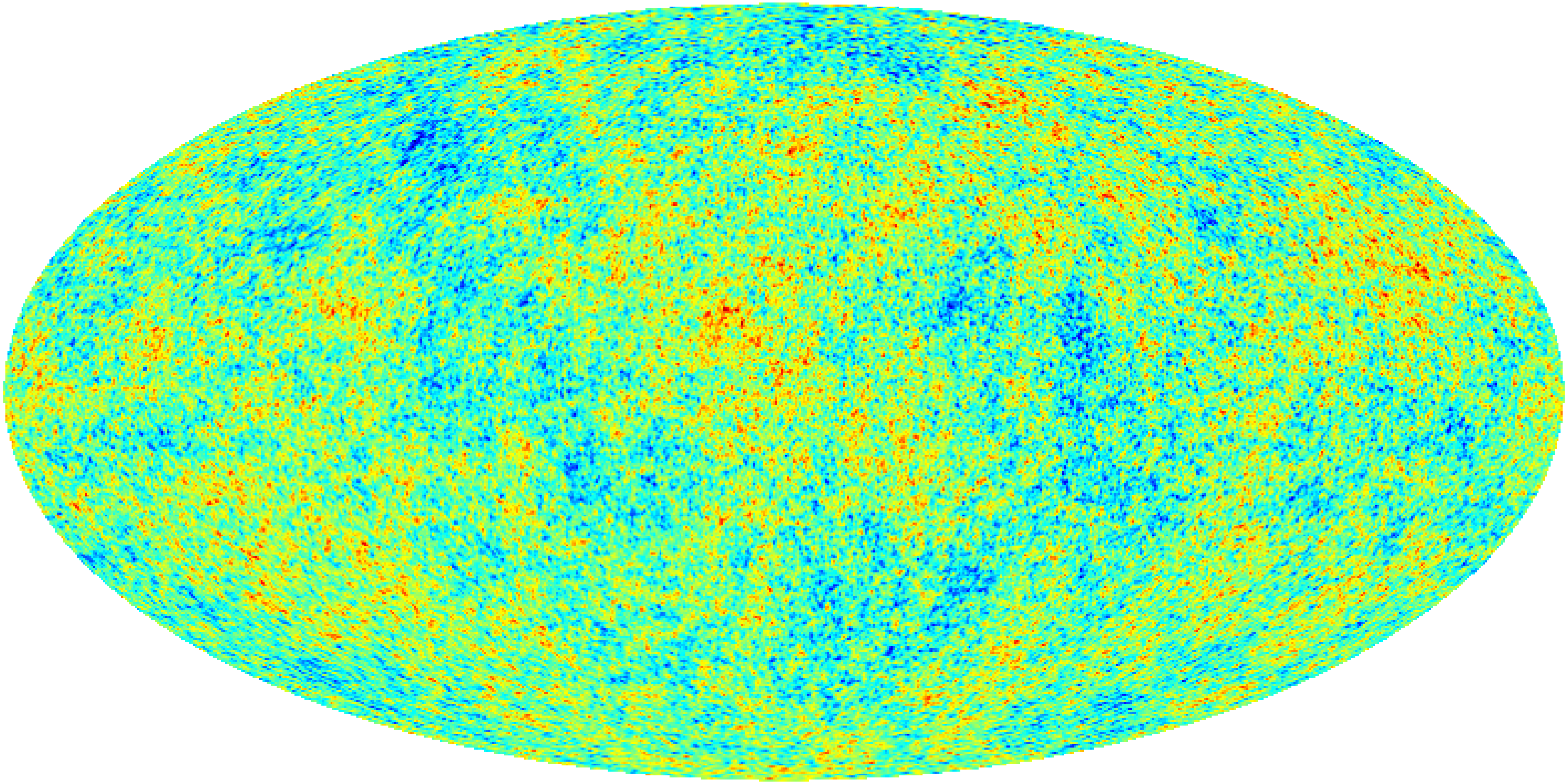
  - direction → l = 264.00° ± 0.03°; b = 48.24° ± 0.02°
- But there might be other contributions to the dipole:
  - Isocurvature CMB dipole; adiabatic CMB dipole, dipolar lensing; gradients of super-horizon modes etc.
- How to tell these contributions apart?

Doppler & Aberration



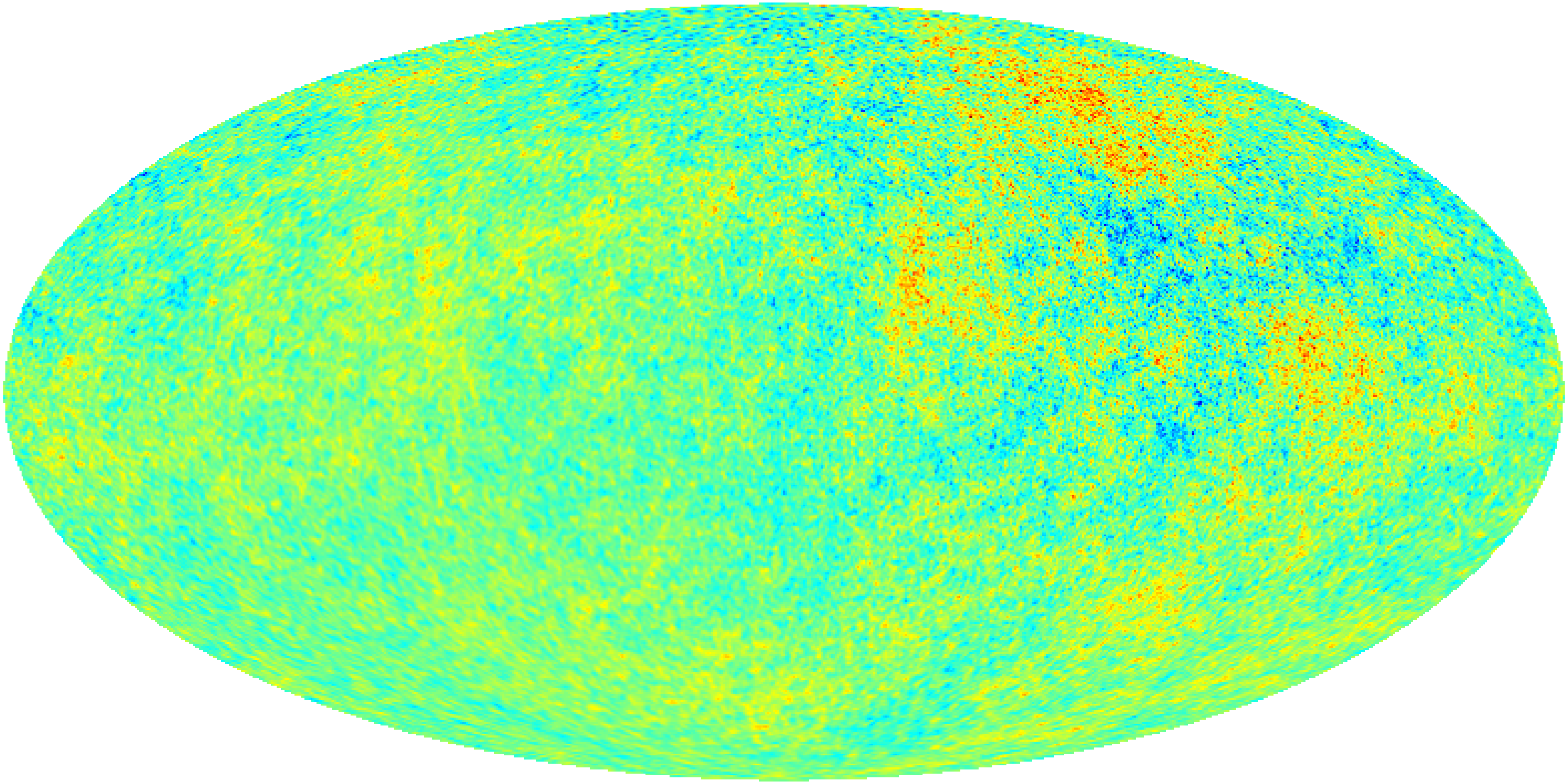
$\beta = 0$

Doppler & Aberration



$\beta = 0.1$

Doppler & Aberration



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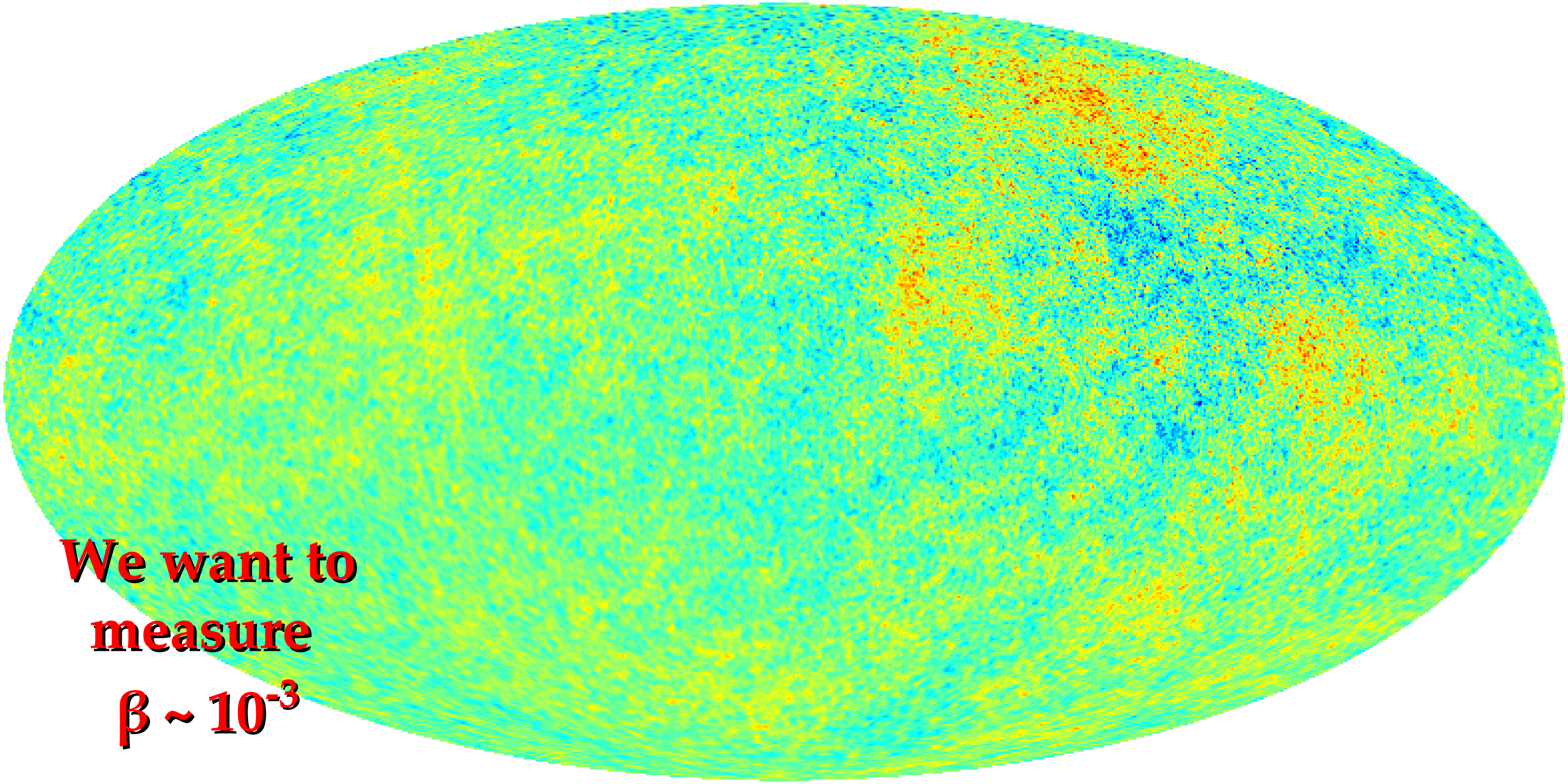
Doppler & Aberration



$\beta = 0.5$

$a_{\ell m}$ Correlations

- Aberration + Doppler effects on the alm's:

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

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

$$a_{\ell\,m}^{[\text{boost}]} \simeq a_{\ell\,m}^{[\text{Prim}]} + c^-_{\ell m} a_{\ell-1\,m}^{[\text{Prim}]} + c^+_{\ell m} a_{\ell+1\,m}^{[\text{Prim}]}$$

$$c^+_{\ell m} = \beta\left[a(\ell+2) - d\right]\sqrt{\frac{(\ell+1)^2 - m^2}{4(\ell+1)^2 - 1}}$$

$$c^-_{\ell m} = -\beta\left[a(\ell-1) + d\right]\sqrt{\frac{\ell^2 - m^2}{4\ell^2 - 1}}$$

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

S/N Forecasts (2011)

Notari & Quartin 1112.1400 (JCAP)

Experiment	f_{sky}	S/N
WMAP (9 years)	78%	**0.7**
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**
Ideal ($\ell \leq 3000$)	100%	**21**
Ideal ($\ell \leq 5000$)	100%	**38**

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Burigana et al. (CORE col.), (1704.05764)

Planck Measured Aberration (2013)

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

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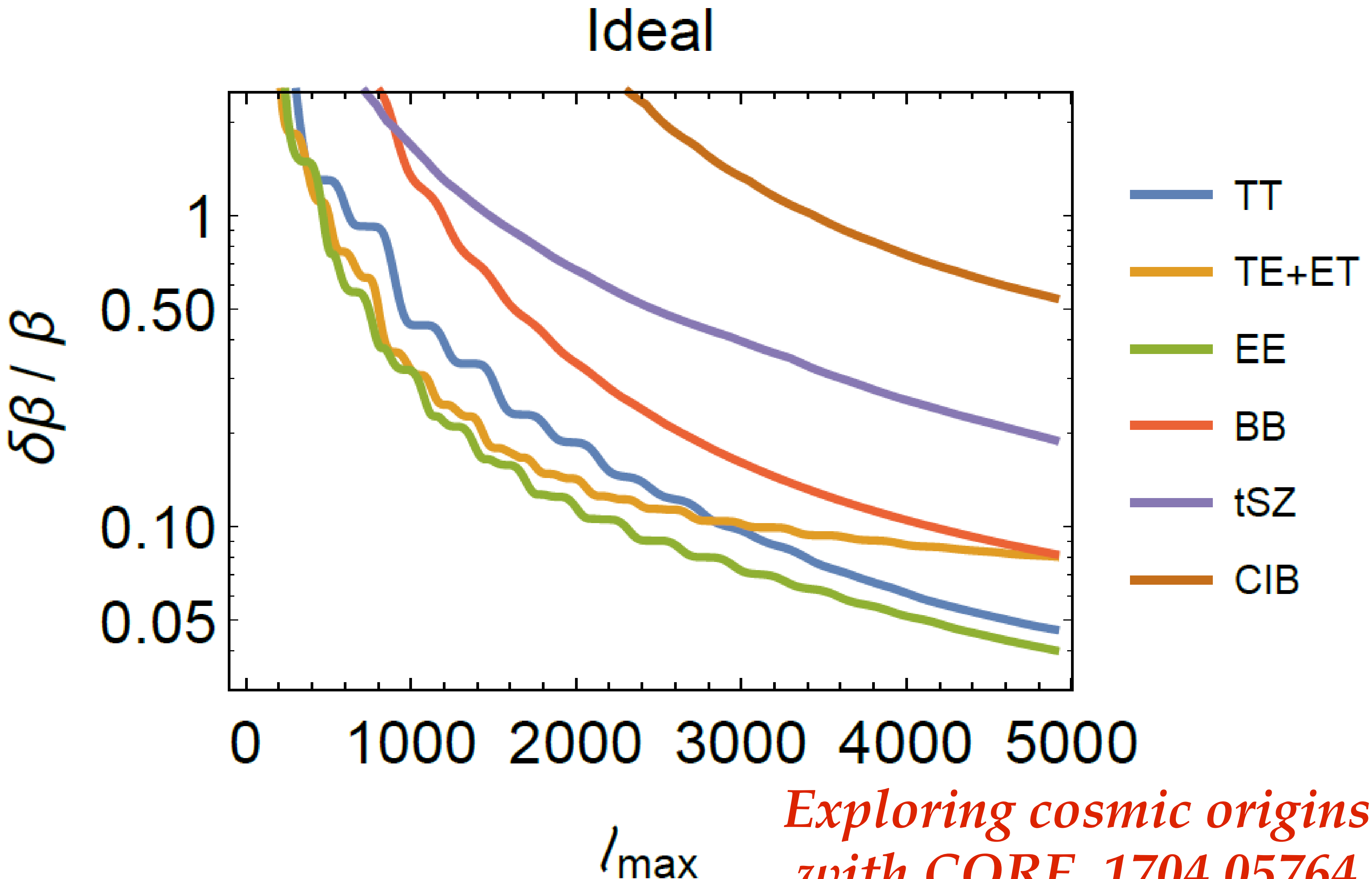
Future of Aberration Measurements

- Aberration and Doppler measurement → basically limited by:
  - The number of independent maps
  - The number of measured modes (multipoles) in each map
- In the CMB: aberration signal > Doppler signal
  - Doppler signal is the same in most CMB maps
  - Aberration signal depends on the derivatives of the C_ℓ's
    - Steeper or wiggly spectra → more signal
      - Thermal SZ and Cosmic Infrared Bkg (CIB) → low signal

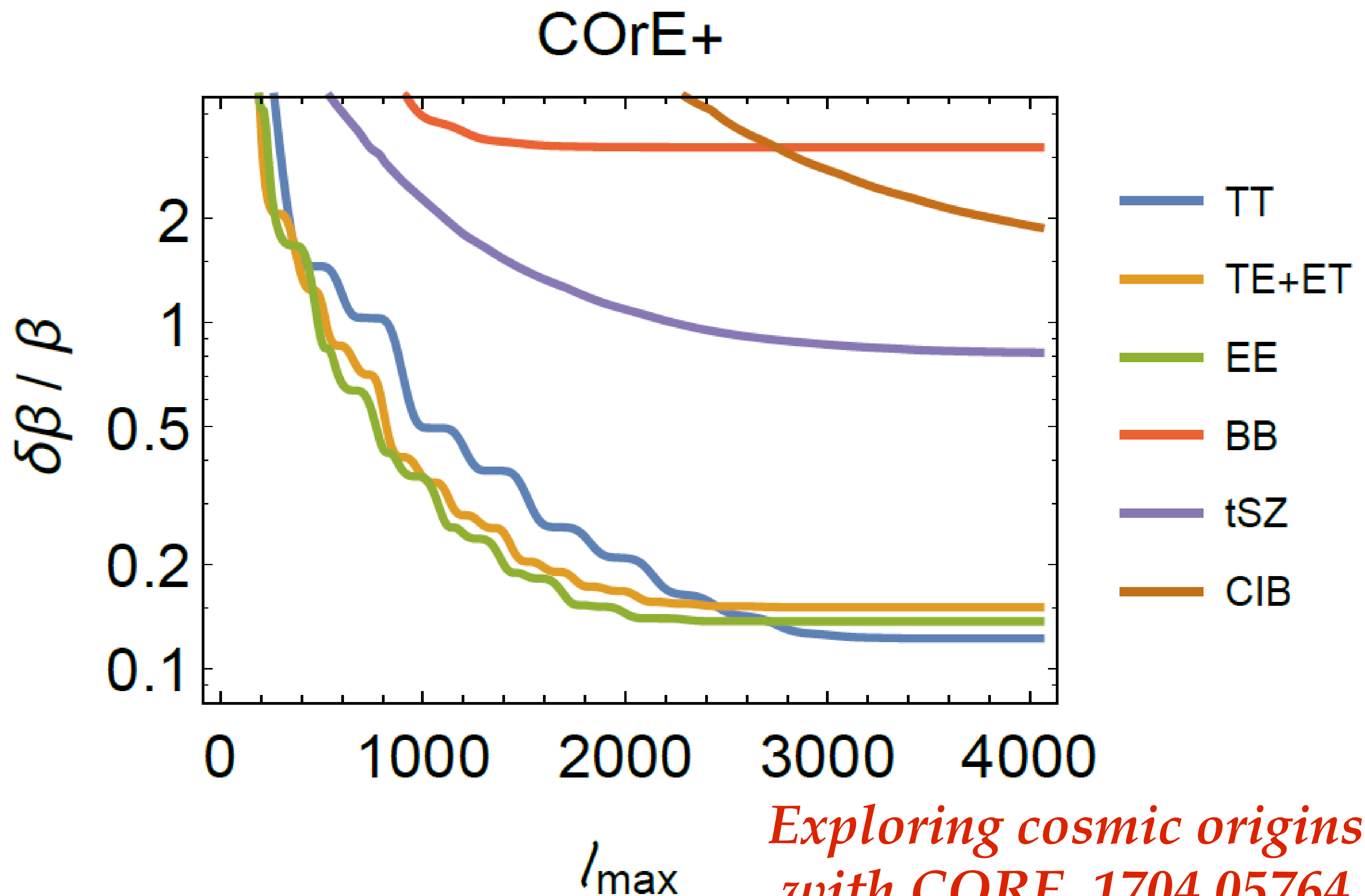
Burigana et al. (CORE col.), (1704.05764)

Future of Aberration: Ideal Exp.



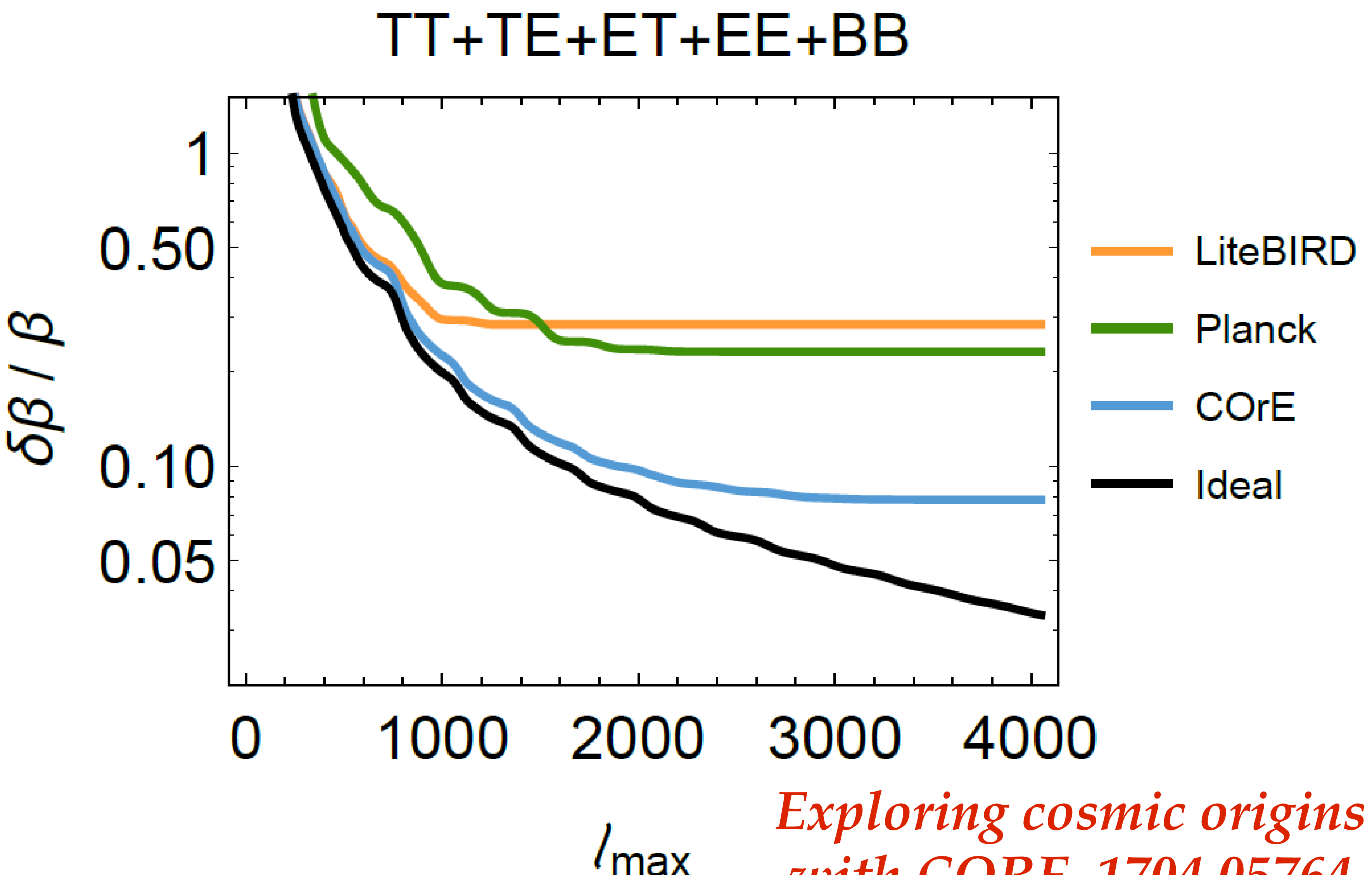
Exploring cosmic origins with CORE 1704.05764

Future of Aberration: COrE



Exploring cosmic origins with CORE 1704.05764

Future of Aberration: comparison



Exploring cosmic origins with CORE 1704.05764

Primordial CMB dipole?

- Can a precise (ideally ~100σ) measurement of the velocity allow us to measure the primordial CMB dipole?
  - Or does a primordial dipole also produce the same aberr. and Doppler signature (*i.e.* couplings between $\ell \leftrightarrow \ell+1$)?
- Clear answer → needs careful 2nd order perturb. analysis

$$a_{\ell m}^{\text{[Boosted]}} = \sum_{\ell'=0}^{\infty} \left(K_{\ell' \ell m}^{\text{Dopp}} + K_{\ell' \ell m}^{\text{aber}}\right) a_{\ell' m}^{X\,\text{[Primordial]}}$$

- We found that:
  - Doppler-couplings are generated naturally in single-field slow-roll inflation (due to a dipolar grav potential)
    - Measuring different couplings → other type of inflation!

Roldan, Notari & Quartin 1603.02664 (JCAP)

Primordial CMB dipole? (2)

- Aberration-couplings are in general NOT produced, unless we fine-tune the radial profile of the grav potential (due to an induced dipolar lensing effect).
  - If the dipole is isocurvature, we also need to fine-tune the distance to the LSS!

	10^{-3} dipole	10^{-8} Doppler-like couplings	10^{-8} aberration-like couplings
Peculiar velocity	yes	yes	yes
Adiab. dipolar potential	yes	yes*	only with fine-tuning
Isocur. dipolar potential	yes	yes*	only w/ *even more* fine-tun.
Non-Gauss. dipolar pot.	yes	different	only with fine-tuning

Roldan, Notari & Quartin 1603.02664 (JCAP)

Future of Aberration: 21cm

- 21cm intensity mapping is also a very promising candidate
  - Tomography + no Silk damping → many more modes
  - 21cm can go to high z
    - Epoch of Reionization ($7 < z < 13$)
    - Dark ages ($20 < z < 200$)
  - Each z slice → like a new CMB map, with potentially even more modes (higher ℓ)
  - Depending on instrumental noise and ability to subtract foregrounds...

Quartin, Muñoz, Notari & Raccanelli (in prep)

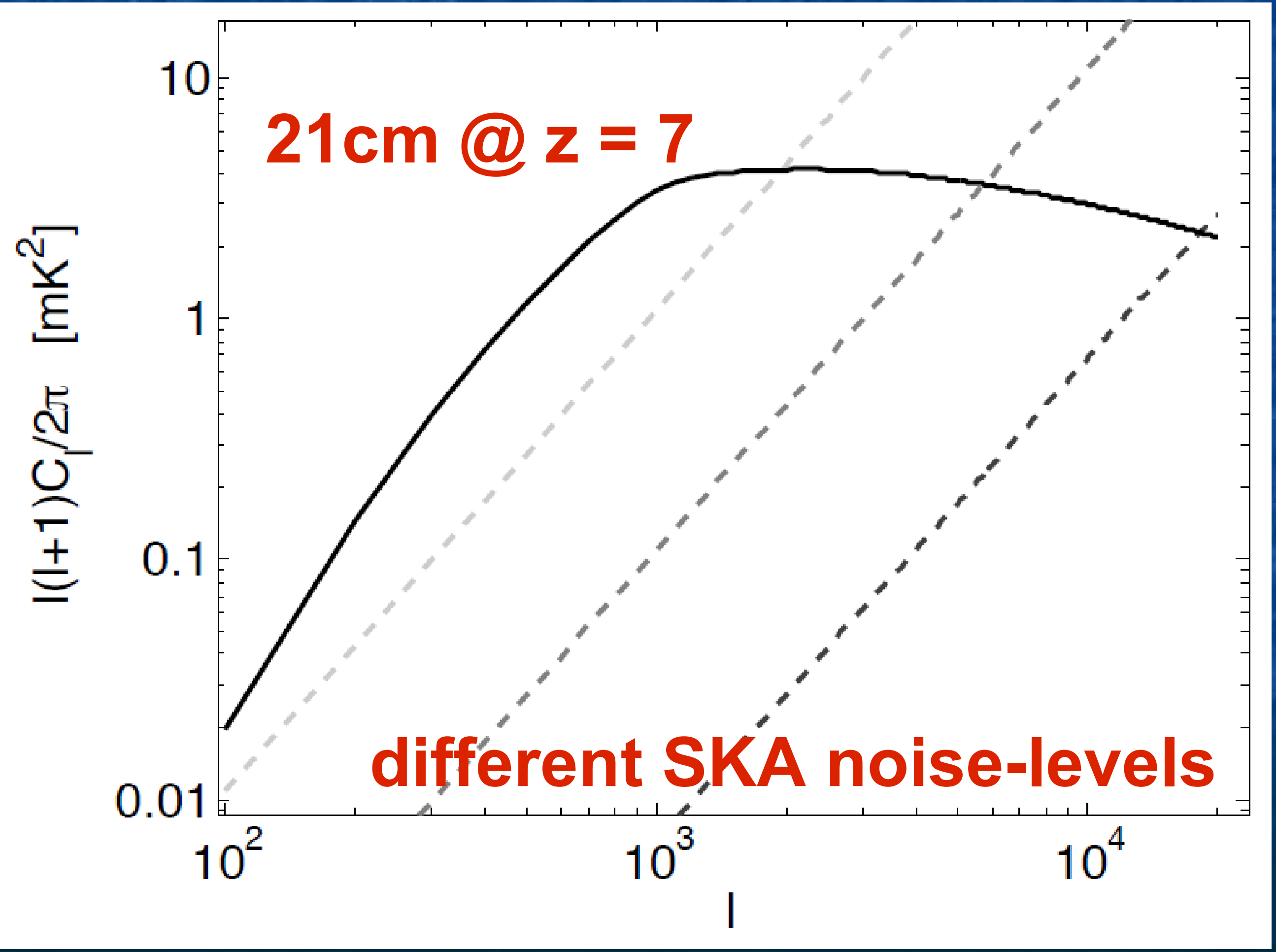
Future of Aberration: 21cm

- 21cm tomography: each z slice → like a new CMB map, with potentially even more modes (higher ℓ)
- Trade-off in the frequency (redshift) binning $\Delta\nu$
  - Large $\Delta\nu$ → less correlations between bins + less noise
  - Small $\Delta\nu$ → more modes → potentially higher S/N
- Assuming $\Delta\nu$ = 1 MHz (a bit conservative)
  - Epoch of Reion. → 75 redshift bins
  - Dark Ages → 40 redshift bins
- Dark ages physics more linear → much simpler
  - But not acessible to SKA. May need a moon-based exp.!

Quartin, Muñoz, Notari & Raccanelli (in prep)

Future of Aberration: 21cm

- Kovetz & Kamionkowsky: 1210.3041 (PRD)



Far Future of Aberration: 21cm

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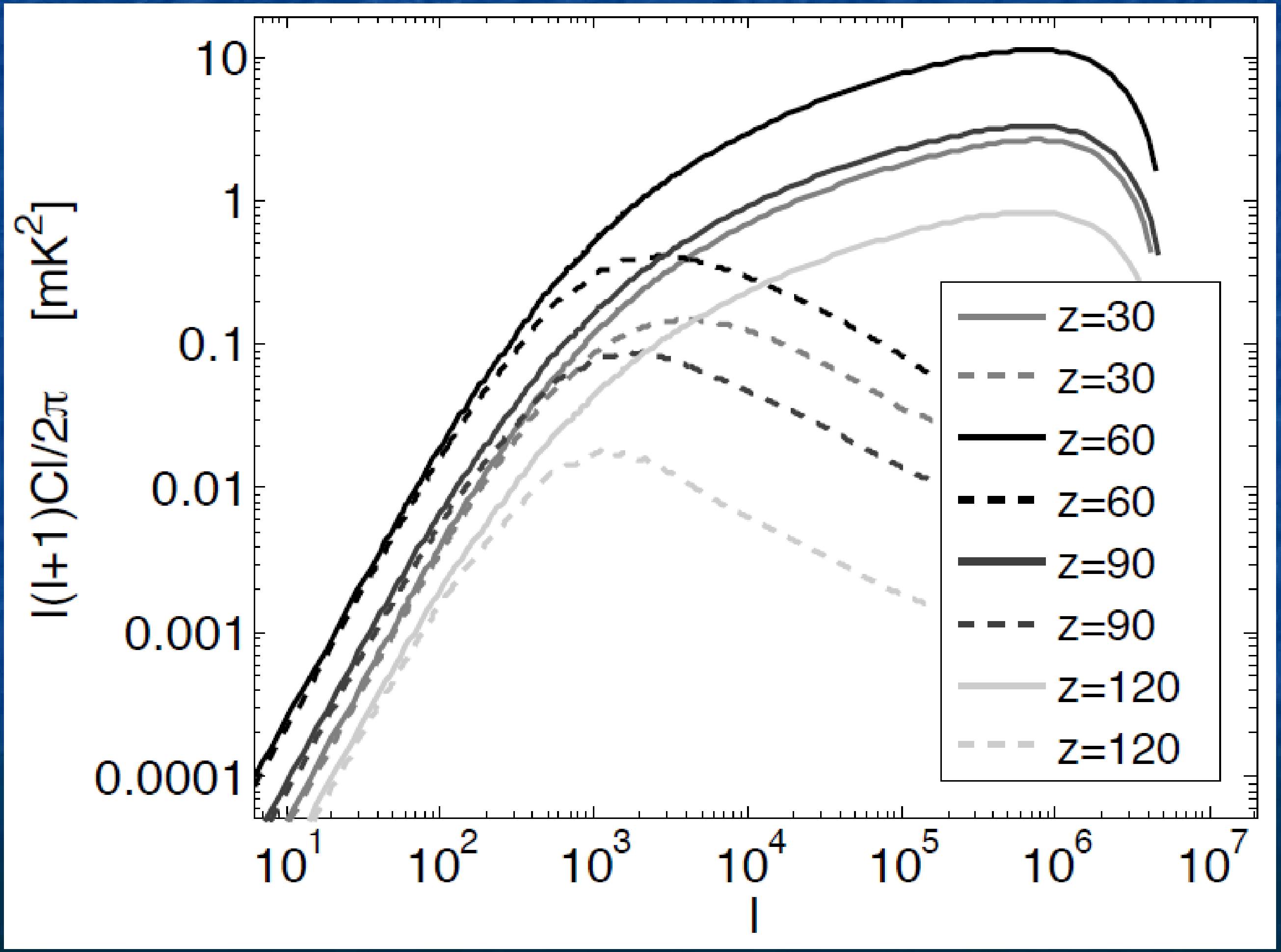
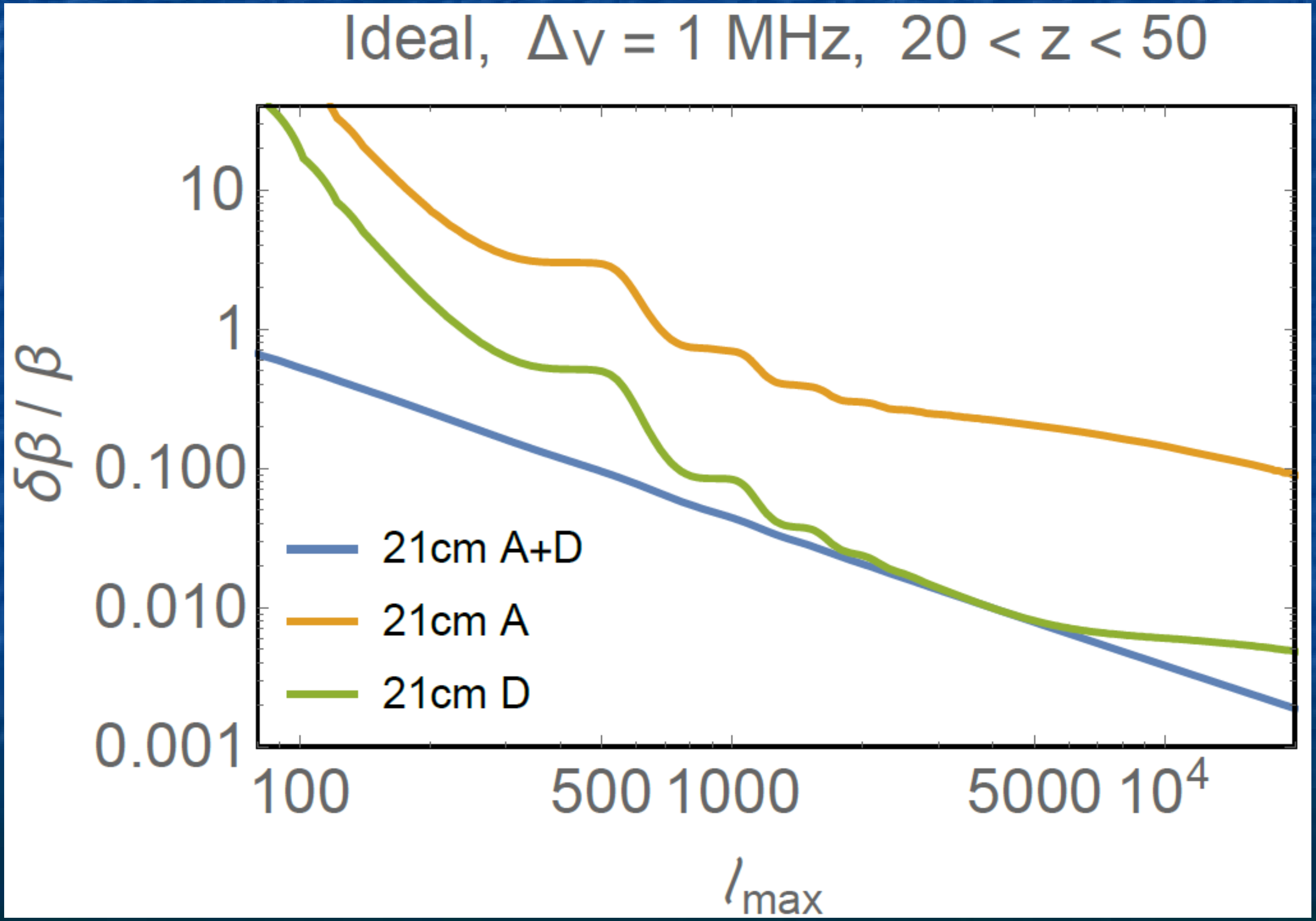


Far Future of Aberration: 21cm

- S/N lowish for aberration; high for Doppler *[preliminary]*



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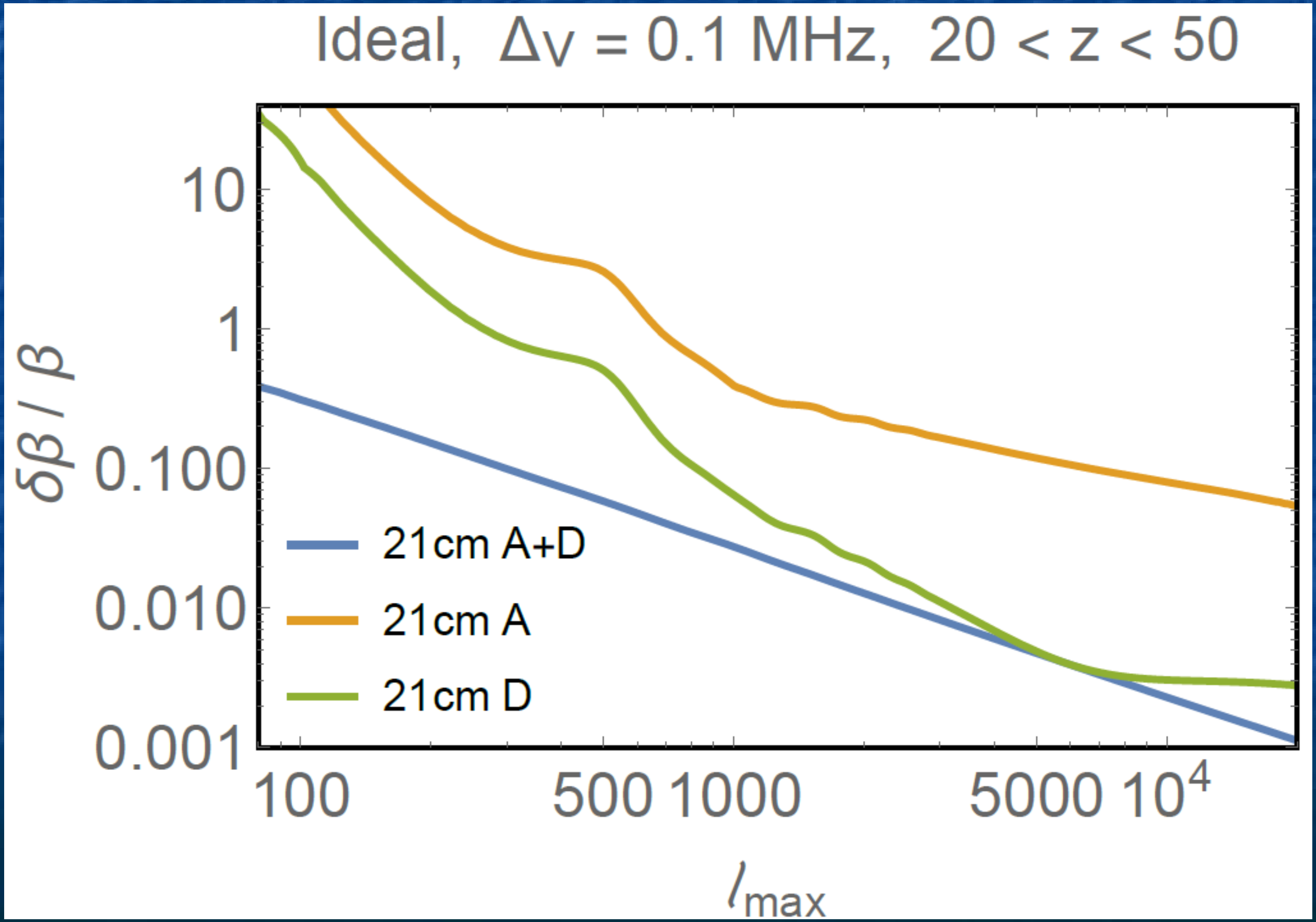

Conclusions

- Aberration & Doppler have been measured by Planck @ over 4σ (or 3σ considering unknown systematics)
  - Exactly as predicted in *Notari & Quartin 1112.1400 (JCAP)*
- Aberration couplings → measures our peculiar velocity
- Doppler coupl. → measures primordial non-Gaussianity
  - DC S/N in futuristic 21cm can be > 100
- Can constrain properties of the intrinsic dipole
- It is a systematic if not removed
  - Affects: instrument calibration and CMB anomalies

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Merci!