In collaboration with Pedro S. Ferreira

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

Miguel Quartin
Instituto de Física
Univ. Fed. do Rio de Janeiro

First constraints on the intrinsic CMB dipole

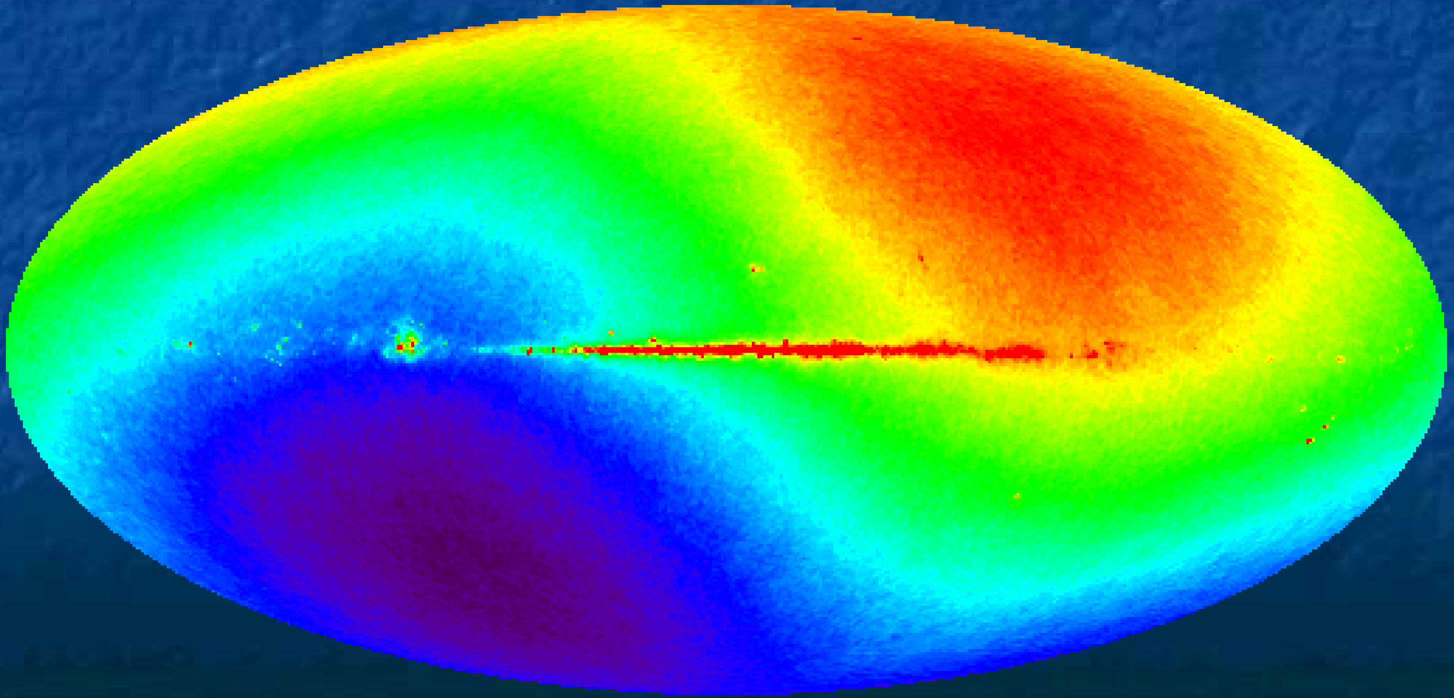
In collaboration with Pedro S. Ferreira

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

Miguel Quartin
Instituto de Física
Univ. Fed. do Rio de Janeiro

The CMB dipole

- CMB after Planck: cosmic variance limited measurements of all modes of the power spectrum up to $\ell \sim 1700$ for TT; Good measurements up to $\ell \sim 1200$ for EE
  - ACT and SPT get to even higher ℓ (but small fsky)
- But one important multipole is still missing: $\ell = 1$
  - CMB TT maps remove by hand the dipole

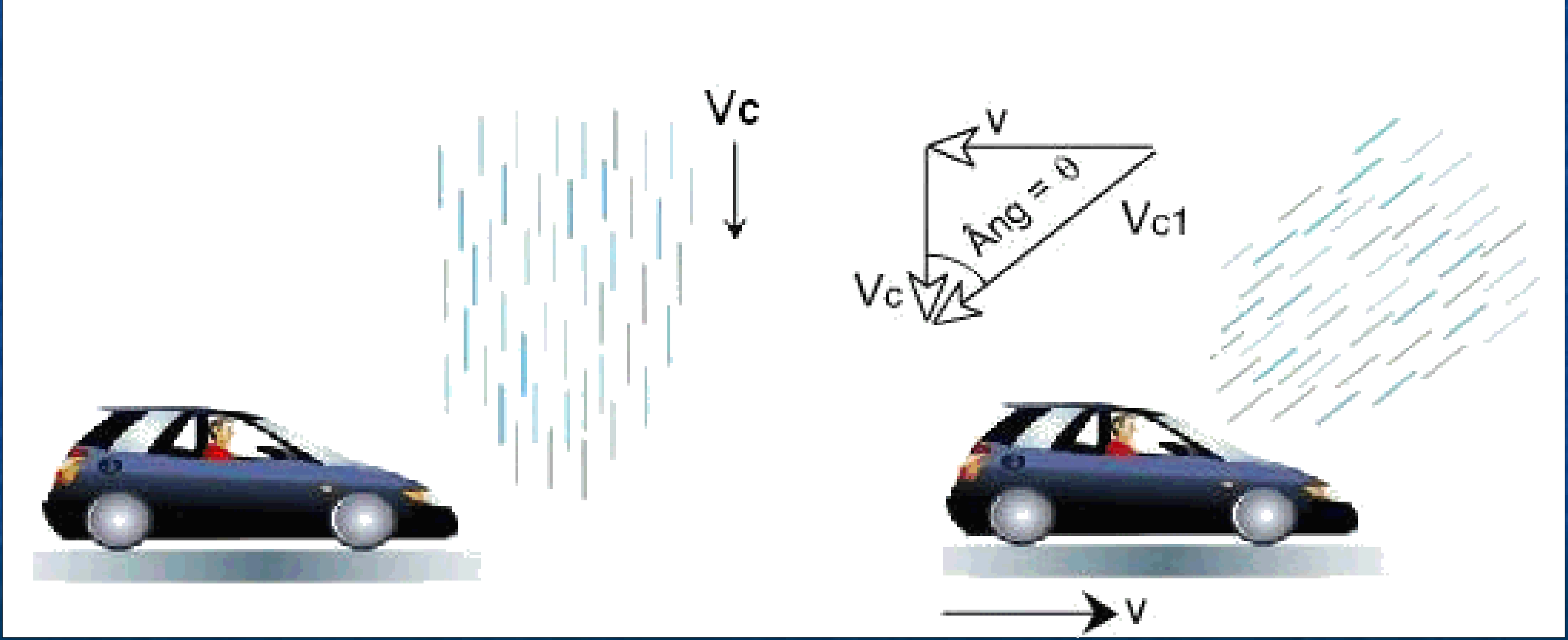


The CMB Dipole (2)

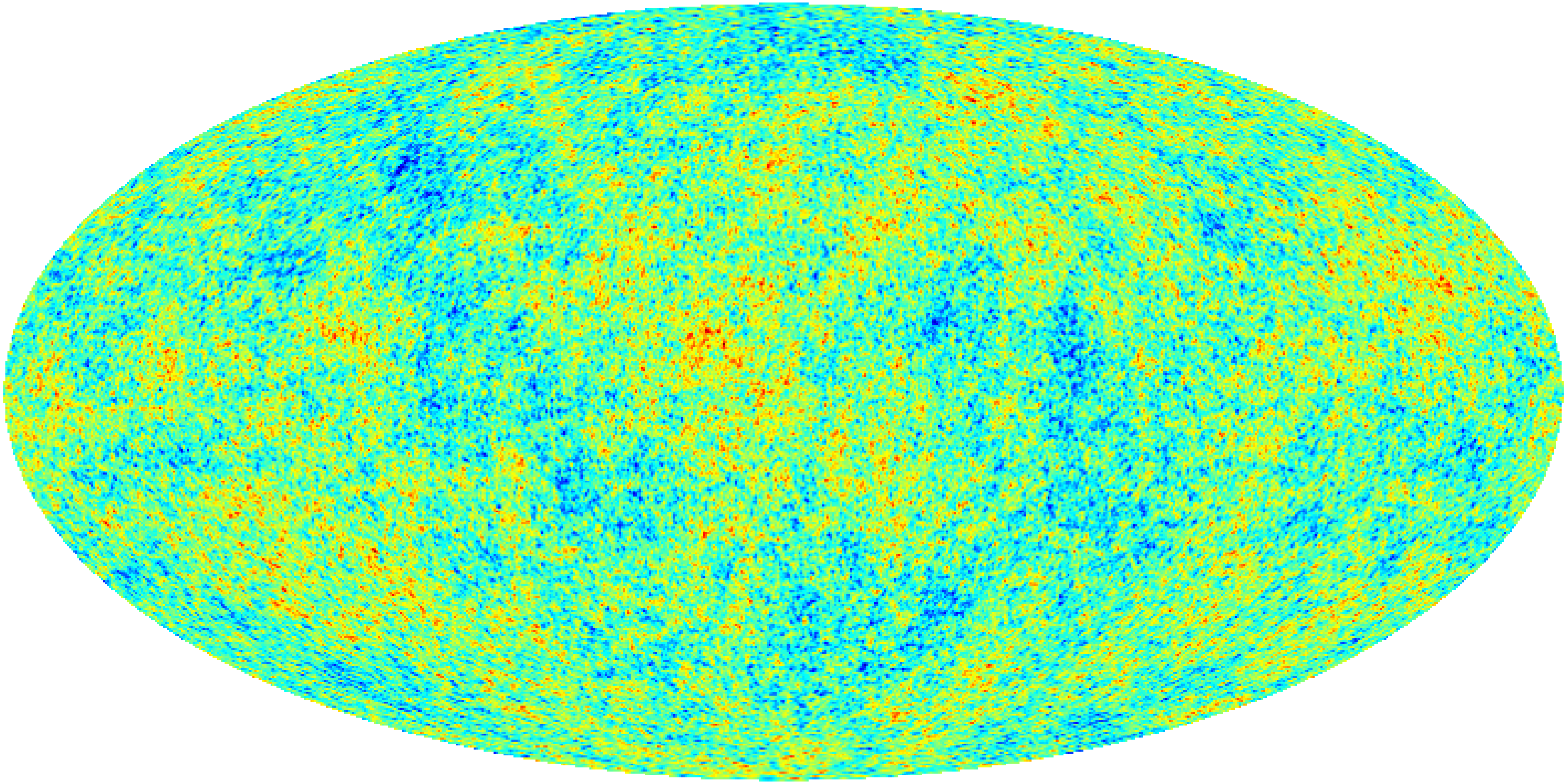
- If we assume no intrinsic dipole → measurement of v_{CMB}
  - v_{CMB} = 369.8 km/s → $\beta \equiv v/c = 1.234 \times 10^{-3}$
  - direction (gal. coord.) → l = 264.021° ± 0.005°; b = 48.25° ± 0.01°
- But there might be other contributions to the dipole:
  - Isocurvature or adiabatic grav. potential
  - Non-Gaussian grav. potential
  - dipolar lensing
  - gradients of super-horizon modes
- How to tell these contributions apart?

Doppler & Aberration

- The CMB dipole $\leftrightarrow$ Doppler effect
- But peculiar motion produces also aberration!

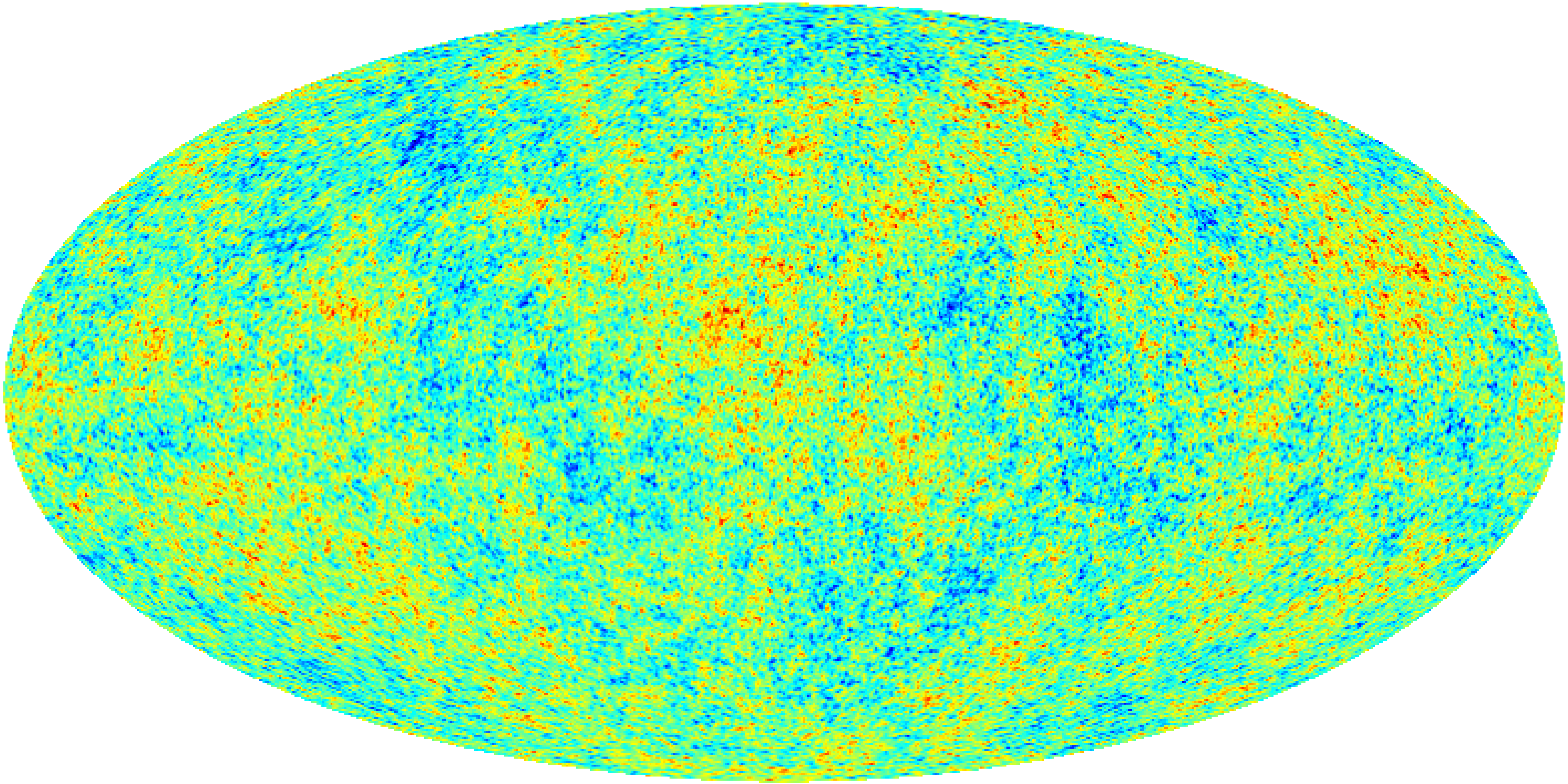


Doppler & Aberration



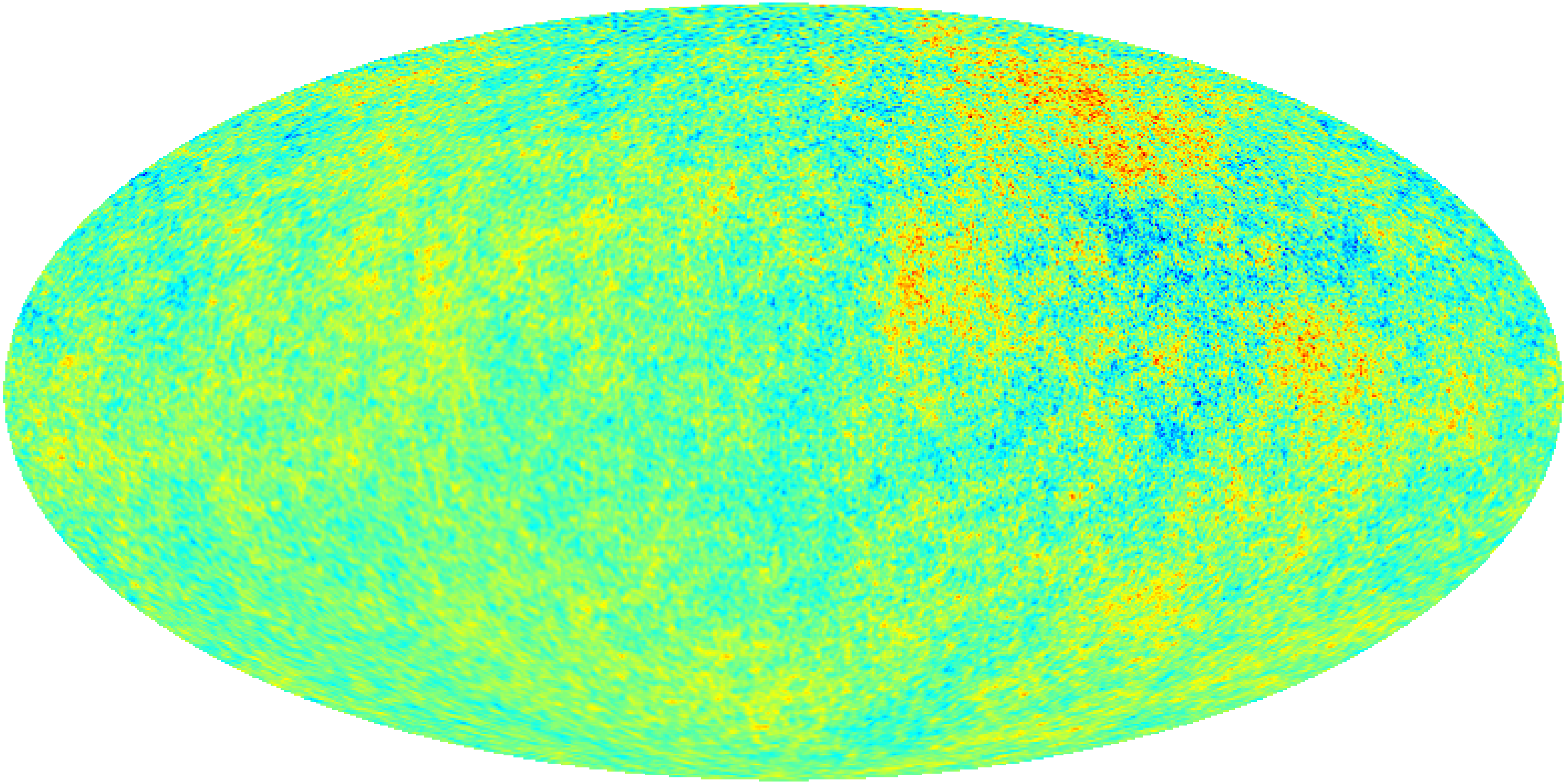
$$\beta = 0$$

Doppler & Aberration



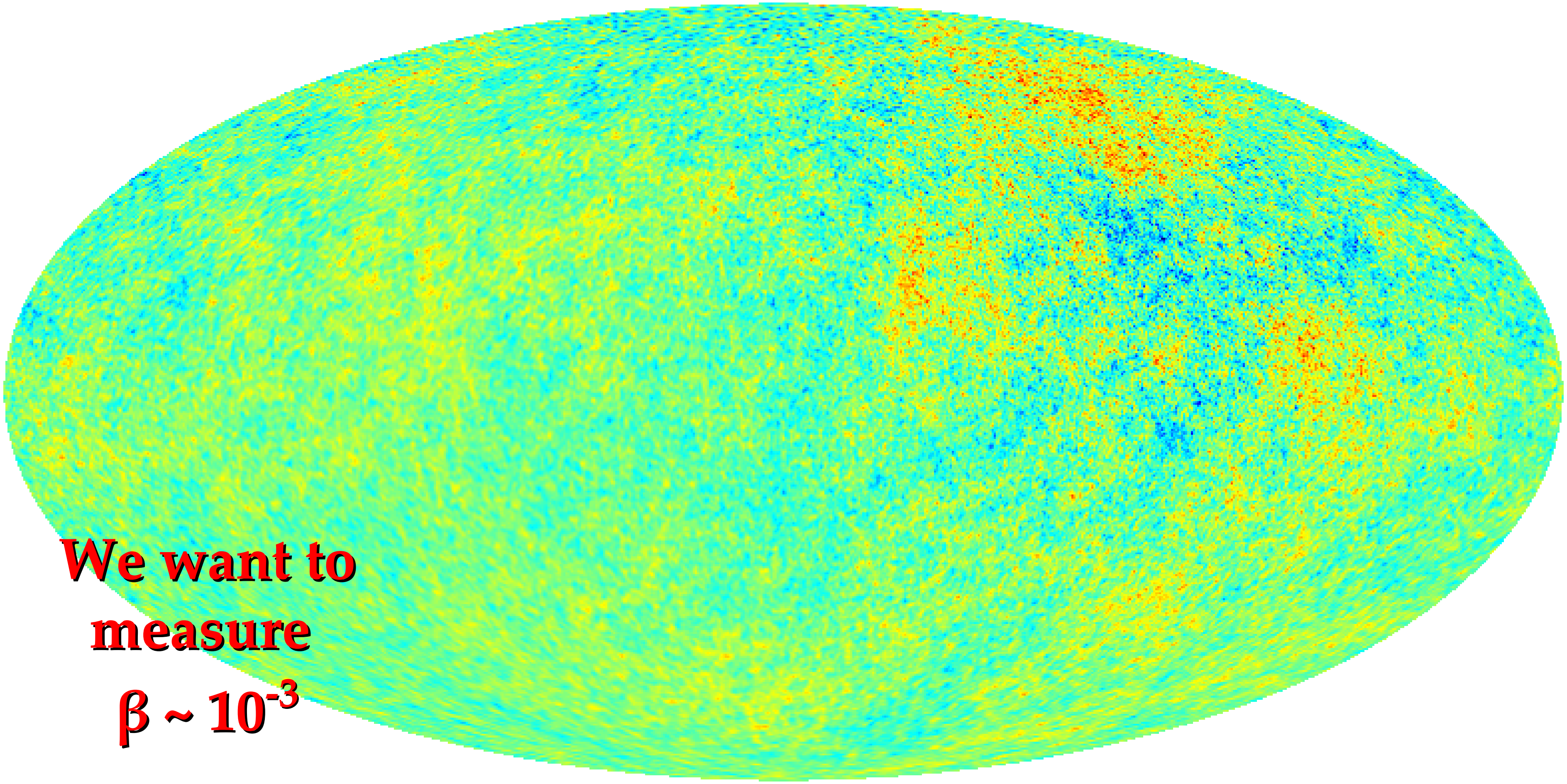
$\beta = 0.1$

Doppler & Aberration



$$\beta = 0.5$$

Doppler & Aberration



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

$$\beta = 0.5$$

$a_{\ell m}$ Correlations

- Aberration + Doppler effects on the alm's:

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

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

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

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

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

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

$a_{\ell m}$ Correlations

- Aberration + Doppler effects on the alm's:

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

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

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

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

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

a* = 1 *for aberration
d* = 1 *for Doppler

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

$a_{\ell m}$ 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
  - Planck 2018: $\ell^T_{max} \sim 1800$; $\ell^E_{max} \sim 1200$

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

Kosowski & Kahniashvili 1007.4539 (PRL)

S/N Forecasts (2011)

Notari & Quartin
1112.1400 (JCAP)

Experiment	$f_{\rm sky}$	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	80%	**12.8**
Ideal ($\ell \leq 3000$)	100%	**21**
Ideal ($\ell \leq 5000$)	100%	**38**

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

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

Caveat: an important subtlety

- CMB experiments measure intensity (or intensity differences, in the case of Planck)
  - Since at least WMAP the CMB temperature is defined based on a linearized blackbody spectrum relation
  - This definition, which we call the linearized temperature, introduces spurious second order effects on the CMB

$$I(\nu,\hat{\boldsymbol{n}}) = \frac{h}{c^2}\frac{2\nu^3}{e^{\frac{h\nu}{k_B T(\hat{\boldsymbol{n}})}}-1} \qquad \delta I(\nu,\hat{\boldsymbol{n}}) \approx \frac{h}{c^2}\frac{2\nu^4 e^{\frac{\nu}{\nu_0}}}{T_0^2\left(e^{\frac{\nu}{\nu_0}}-1\right)^2}\Delta T(\hat{\boldsymbol{n}})$$

$$L(\nu,\hat{\boldsymbol{n}}) = \frac{\Delta T(\hat{\boldsymbol{n}})}{T_0} + \left(\frac{\Delta T(\hat{\boldsymbol{n}})}{T_0}\right)^2 Q(\nu)$$

$$Q(\nu) \equiv \frac{\nu}{2\nu_0}\coth\left[\frac{\nu}{2\nu_0}\right]$$

Linearized temperature effects

- Spurious second order effects of linearized *T*:
  - It affects the measurements of the quadrupole, because it affects the Doppler quadrupole (which is 2^{nd} order)

    Notari & Quartin 1504.02076 (JCAP)

  - It can lead to small correction to the Planck overall calibration which is based on the orbital dipole

    Quartin & Notari 1504.04897 (JCAP)

  - It introduces a Dipole Distortion (DD): Doppler-like couplings proportional to the dipole and independent on the physical origin of the dipole

    Planck 2013 XXVII 1303.5087 (A&A)

    Quartin & Notari 1510.08793 (PRD)

Planck's Measurements of β

- These Dipole Distortions (DD) produce extra Doppler couplings → enhanced significance of the Doppler effect
  - Planck called this DD a boost factor, which is ~2.5 for Planck's maps (it depends on the frequencies used)
  - This extra signal however contains no new information (redundant with the dipole)
  - If not removed from the data → will bias the Doppler measurements towards the dipole!

- Planck 2013 did not remove the DD
  - So their values are not independent from the dipole

Notari & Quartin 1510.08793 (PRD)

Planck's Measurements of β

- The DD also leaks a Doppler signal into the tSZ maps
  - Low significance on the tSZ maps, but can be measured by cross-correlating tSZ and T maps.
  - We estimated it could be measured in this way with Planck at high significance (~10σ), but serves only as a cross-check (no new information)
  - Also be a contaminant for future tSZ measurements (it is below the noise level of Planck, but above the noise levels of CORE or CMB Stage 4)

Notari & Quartin 1510.08793 (PRD)

  - Planck measured these tSZ – T correlations in 2020 at ~6σ using two different pipelines

Planck intermediate results. LVI 2003.12646

Primordial CMB dipole?

- Can a 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 $\ell \leftrightarrow \ell+1$)?
- Primordial vs kinematic separation: not straightforward
  - For adiabatic perturbations there is a degeneracy between the Doppler effect and the primordial perturbations
- Clear answer → needs careful 2nd order perturb. Analysis
  - We found that Doppler-couplings are generated naturally in single-field slow-roll inflation (due to a dip. grav. potential) just like a regular boost
  - Different couplings → other inflation model!

Omar Roldán (former PhD stud.)

Primordial CMB dipole? (2)

- Aberration-couplings are in general NOT degenerate, 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!
- Combining dipole + Doppler + aberration → measure of our peculiar velocity and the intrinsic CMB dipole

	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)

Primordial CMB dipole? (3)

- Conclusion: it is possible to measure the primordial dipole with aberration + Doppler couplings!
- Since the velocity is ~100 times larger than the expected dipole, we need to measure both with ~100σ
  - With the CMB we would need to reach ℓ ~ 10000
    - At very high ℓ → tiny signal due to Silk Damping; foregrounds much larger
  - So it will be very hard to go beyond ~30σ with the CMB

- But with the many claims of anomalies on large scales even we may still rule out exotic primordial models by measuring the intrinsic dipole

Aberration & Doppler estimators

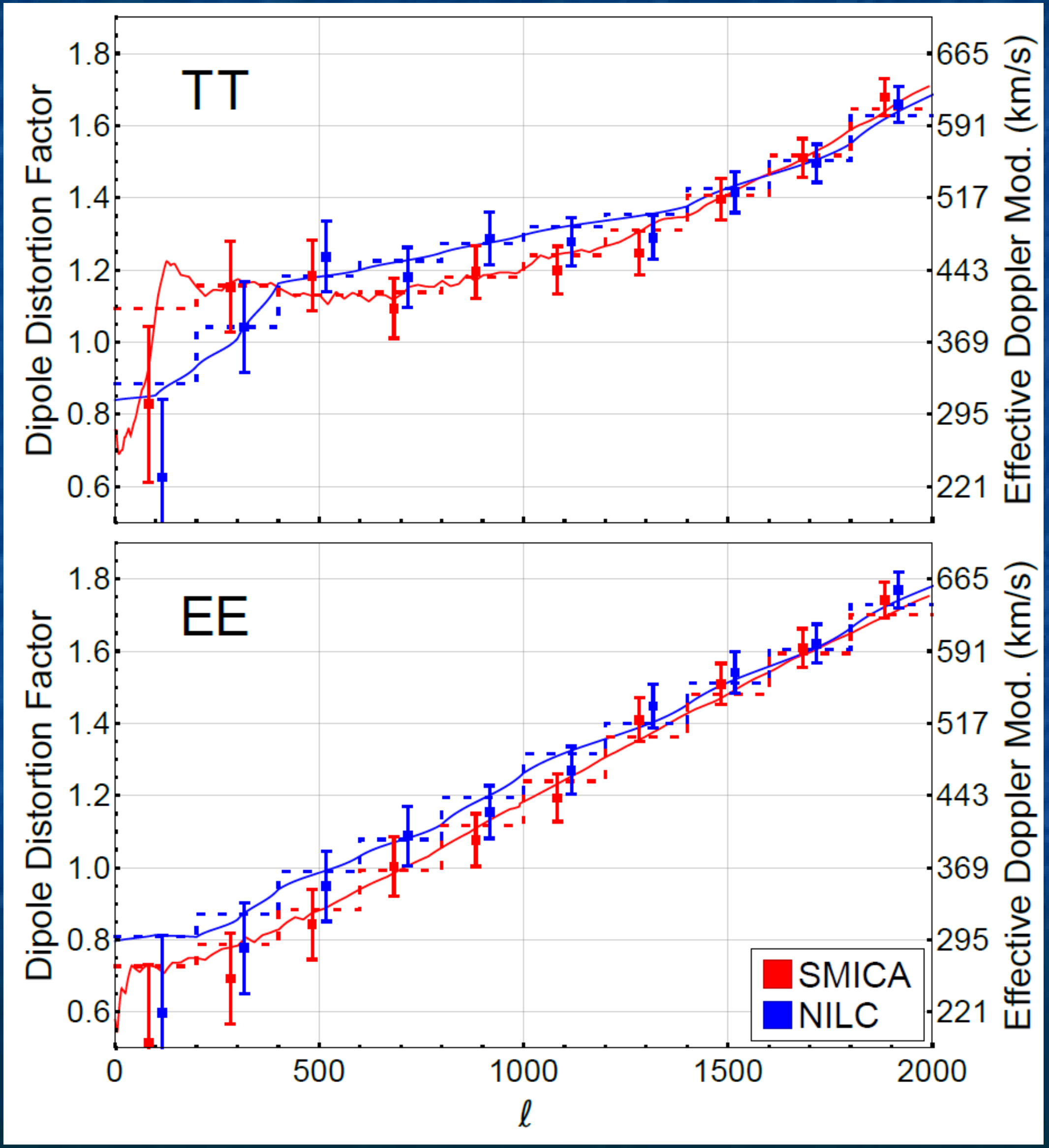
- In order to better constrain an intrinsic CMB dipole we should measure aberration and Doppler independently

- Our estimators recover all 3 components of both aberration and Doppler separately
  - Need to account for masking and anisotropic noise biases
  - Aber. & Doppler are both (ℓ, ℓ+1) effects so they correlate

- We correct these biases by brute-force: we performed 3 * 3072 HEALPix simulations using our HEALPix-Boost code including either aberration, Doppler or a Boost
  - "Boost" assumes aber. & Doppler have the same direction
  - These simulations include mask and 300 anisotropic noise simulations for each SMICA and NILC maps

Removing the spurious DD

- The Dipole Distortions depend on the weights in each frequency band used to build the CMB map
  - It also depends on the multipole!
- We estimated it only for SMICA and NILC
  - The effect on Commander and SEVEM is much more complicated



Main results: measured values

- Results after removing the DD, mask and noise bias, and removing the aber ↔ Doppler correlations

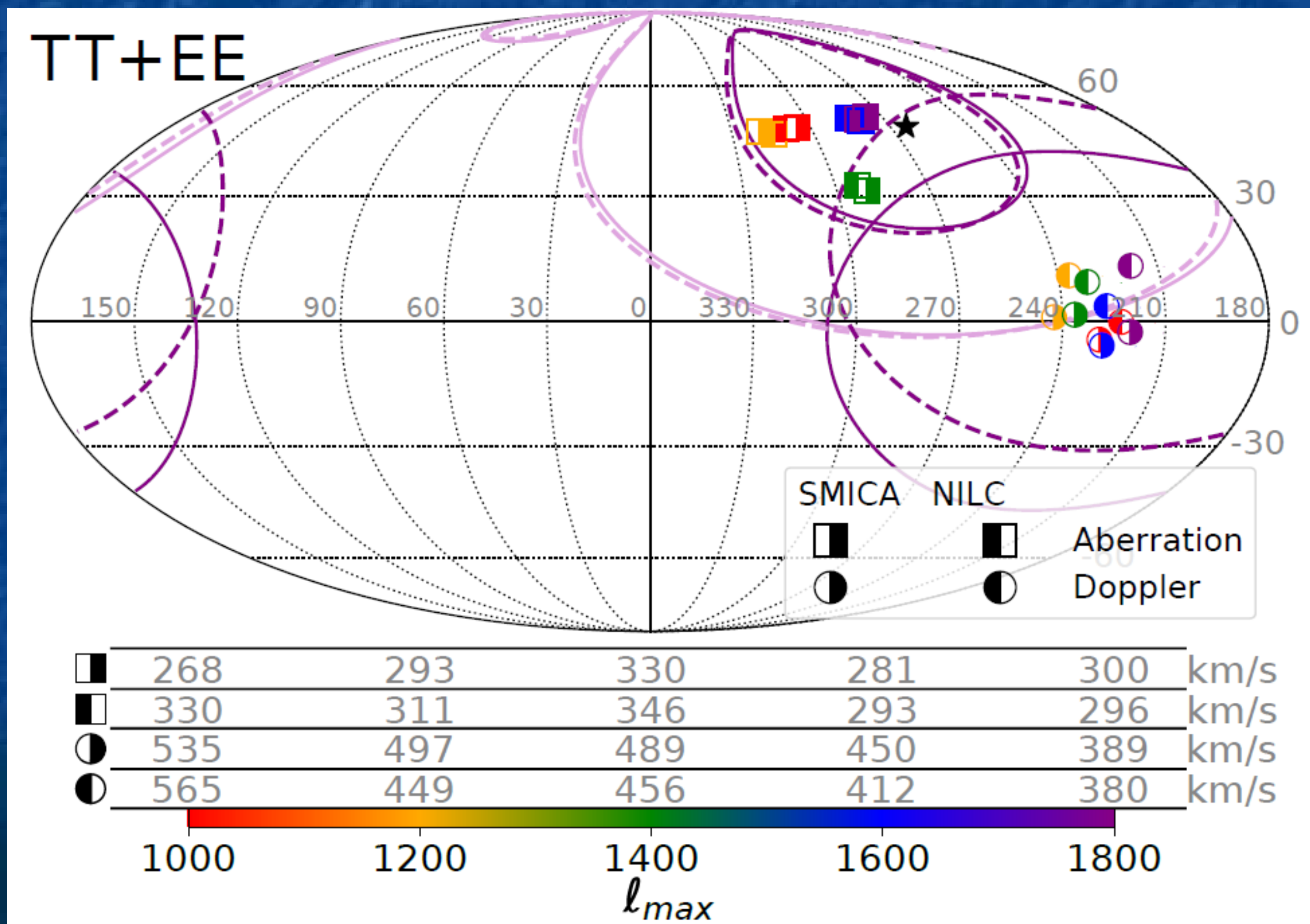
	TT+EE	$\lvert v \rvert$ [km/s]	$l(^\circ)$	$b(^\circ)$
SMICA	Aberration	$300 \pm 99 \pm 13$	$276 \pm 32 \pm .1$	$51 \pm 19 \pm .7$
SMICA	Doppler	$390 \pm 140 \pm 13$	$210 \pm 56 \pm 3$	$-2 \pm 30 \pm .5$
SMICA	Boost	$321 \pm 84 \pm 9$	$234 \pm 21 \pm .1$	$43 \pm 15 \pm .2$
NILC	Aberration	$300 \pm 100 \pm 10$	$280 \pm 32 \pm .3$	$50 \pm 20 \pm .3$
NILC	Doppler	$380 \pm 140 \pm 10$	$208 \pm 56 \pm 2$	$13 \pm 30 \pm .2$
NILC	Boost	$332 \pm 83 \pm 9$	$250 \pm 22 \pm 1$	$50 \pm 15 \pm .1$

- SMICA and NILC provide very consistent results → sign of low systematics

*da S. Ferreira & Quartin **2011.08385***

Main results: measured values

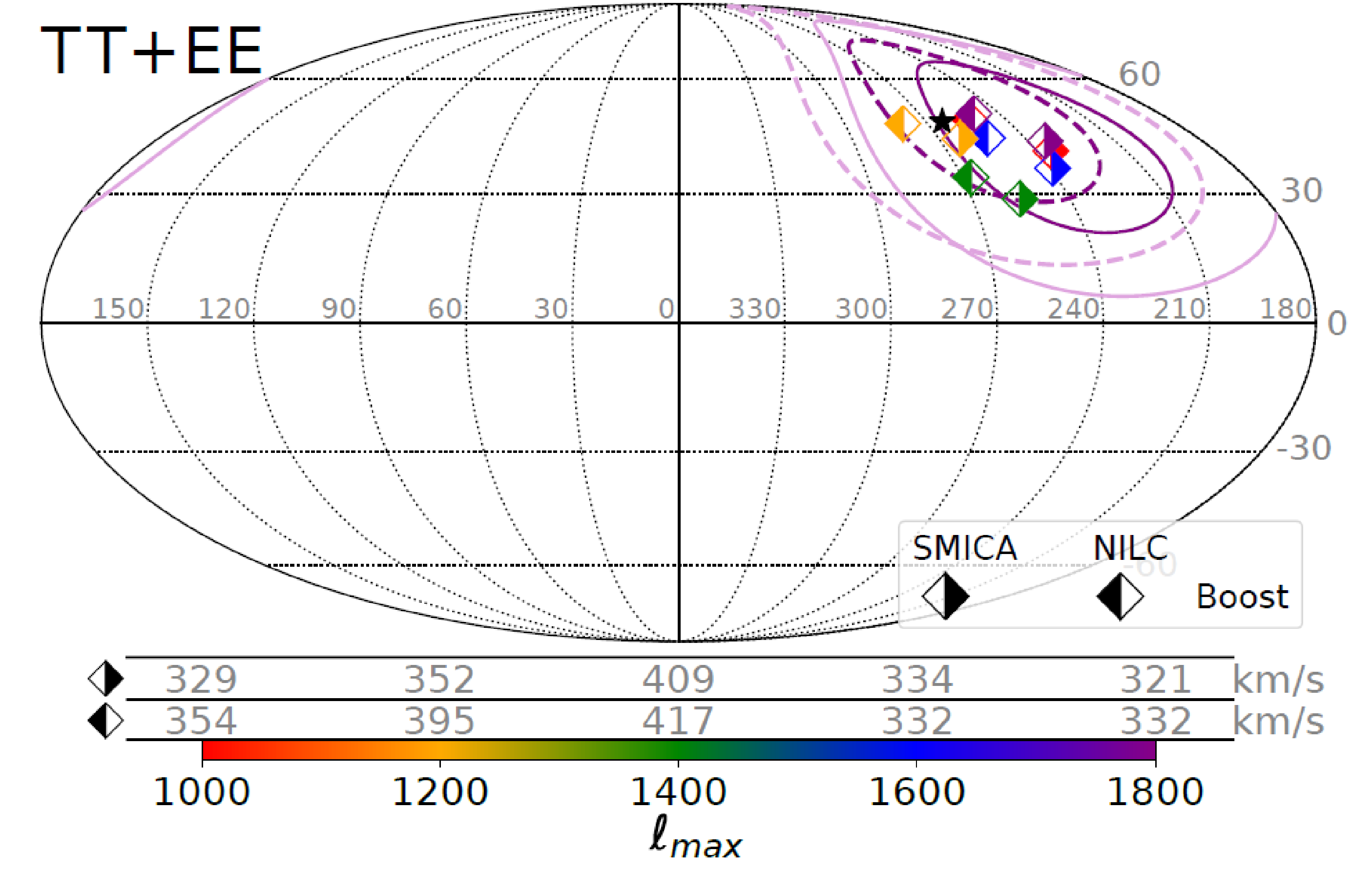
TT has more signal than EE (because each E mode in Planck has lowish S/N), but TT+EE is slightly more precise



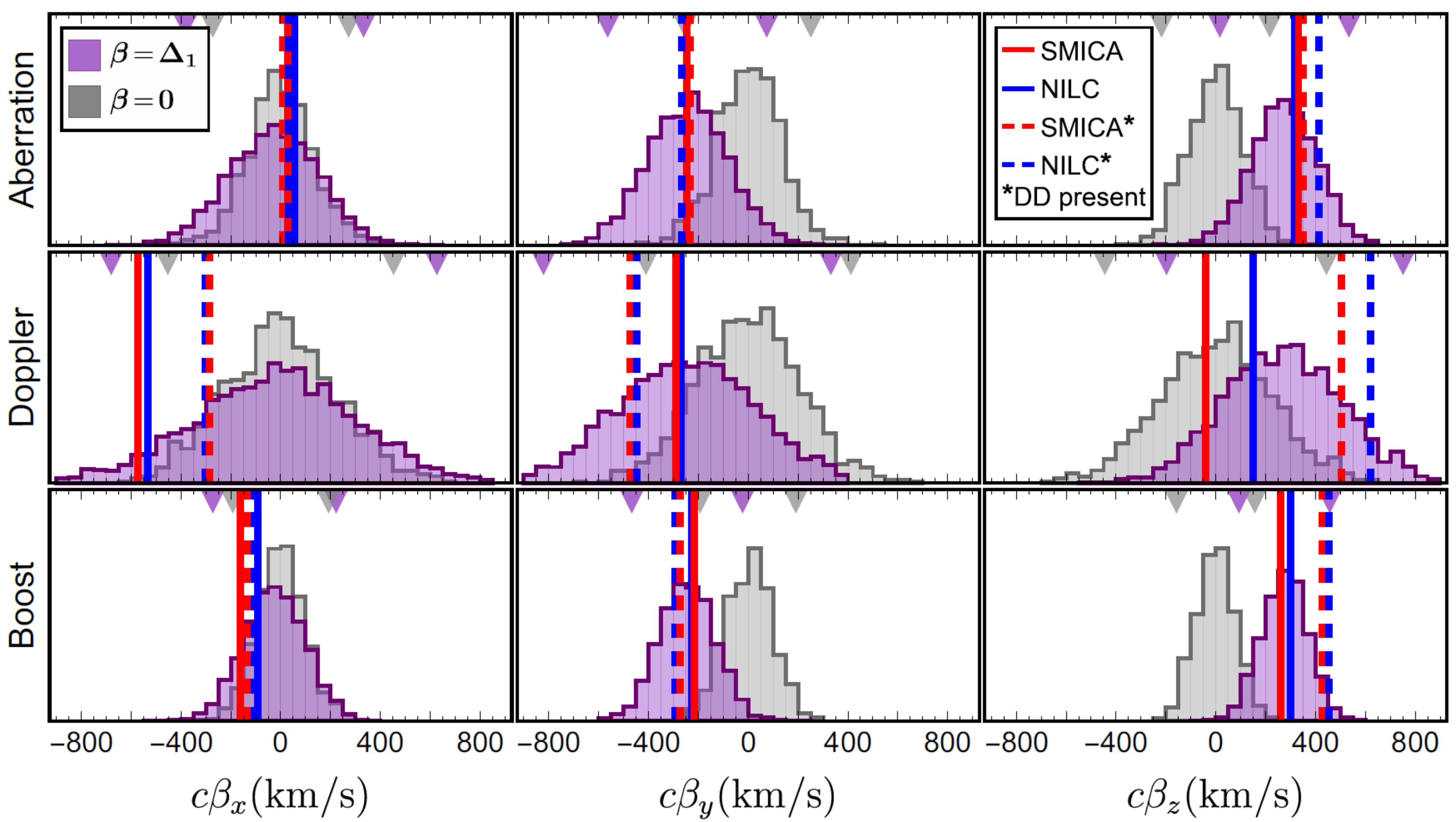
◨	268	293	330	281	300	km/s
◧	330	311	346	293	296	km/s
◑	535	497	489	450	389	km/s
◐	565	449	456	412	380	km/s

Main results: assuming just a Boost

- If we ignore the possibility of an intrinsic dipole, we can measure aberration and Doppler with more precision
  - Assume they are collinear



Sims vs. data: fiducial & null hypothesis



Statistical significance

- The null hypothesis (no aberration, Doppler or DD signals in the data) is excluded at over 6σ!
- Aberration and Doppler measurements are consistent with the peculiar velocity hypothesis of the dipole (i.e., no intrinsic dipole)

TT+EE		$\boldsymbol{\beta} = \boldsymbol{\Delta}_1$		$\beta = \mathrm{DD} = 0$	
		χ^2	σ-value	χ^2	σ-value
SMICA	Aberration	0.3	0.1	18	3.5
	Doppler	4.6	1.3	12	2.6
	Boost	1.3	0.3	45	6.1
	Aber. & Dopp.	4.9	0.6	30	4.1
NILC	Aberration	0.3	0.1	21	3.9
	Doppler	2.7	0.8	13	2.9
	Boost	0.4	0.1	49	6.4
	Aber. & Dopp.	3.0	0.2	34	4.6

Pedro S. Ferreira (PhD stud.)

The intrinsic dipole

- We decompose the intrinsic dipole into 2 possible sources: a Gaussian and a non-Gaussian potential
  - A Gaussian potential produces the same Doppler effects as a velocity. A NG potential does not.
  - For a given specific intrinsic dipole model → one works out the exact Doppler & aberration (dip. lensing) contributions
  - It is convenient to define 3 coefficients α:

$$\Delta_{1,\mathrm{int}} \equiv \Delta_{1,\mathrm{int}}^{\mathrm{Tot}} \equiv \Delta_{1,\mathrm{int}}^{\mathrm{G}} + \Delta_{1,\mathrm{int}}^{\mathrm{NG}}$$

$$\Delta_1 = \beta + \Delta_{1,\mathrm{int}}^{\mathrm{G}} + \Delta_{1,\mathrm{int}}^{\mathrm{NG}}$$

$$\beta^{\mathrm{D}} = \beta + \Delta_{1,\mathrm{int}}^{\mathrm{G}} + \alpha_1 \Delta_{1,\mathrm{int}}^{\mathrm{NG}}$$

$$\beta^{\mathrm{A}} = \beta + \alpha_2 \Delta_{1,\mathrm{int}}^{\mathrm{G}} + \alpha_3 \Delta_{1,\mathrm{int}}^{\mathrm{NG}}$$

The intrinsic dipole

$$\Delta_1 = \beta + \Delta^{\rm G}_{1,\rm int} + \Delta^{\rm NG}_{1,\rm int}$$
$$\beta^{\rm D} = \beta + \Delta^{\rm G}_{1,\rm int} + \alpha_1 \Delta^{\rm NG}_{1,\rm int}$$
$$\beta^{\rm A} = \beta + \alpha_2 \Delta^{\rm G}_{1,\rm int} + \alpha_3 \Delta^{\rm NG}_{1,\rm int}$$

- If we neglect dipolar lensing effects (α_2, $\alpha_3 << 1$) the total intrinsic dipole is given directly by: $\Delta^{\rm Tot}_{1,\rm int} \simeq \Delta_1 - \beta^{\rm A}$
- If we also neglect Doppler couplings arising from a NG potential ($\alpha_1 << 1$) we can also measure

$$\Delta^{\rm G}_{1,\rm int} \simeq \beta^{\rm D} - \beta^{\rm A} \qquad \Delta^{\rm NG}_{1,\rm int} \simeq \Delta_1 - \beta^{\rm D}$$

- Since our measurements are consistent w/ no intrinsic dipole, we can only put upper bounds

TT+EE	Intrinsic dipole	σ-value	95% max [mK]
SMICA	$\Delta^{\rm G}_{1,\rm int}$	1.2	8.0
	$\Delta^{\rm NG}_{1,\rm int}$	1.3	7.2
	$\Delta^{\rm Tot}_{1,\rm int}$	0.1	3.5
NILC	$\Delta^{\rm G}_{1,\rm int}$	0.8	7.6
	$\Delta^{\rm NG}_{1,\rm int}$	0.8	6.7
	$\Delta^{\rm Tot}_{1,\rm int}$	0.1	3.5

Peculiar Velocity in other sources

- Another way to test the peculiar velocity hypothesis of the CMB dipole: measure our peculiar velocity wrt other distant sources
  - The radio galaxies dipole has been measured many times in the last 20 years
    - Results are mostly inconsistent, and the inferred velocity is very high (usually > 1000 km/s)

See e.g. Siewert, Schmidt-Rubart, Schwarz (2010.08366)

Peculiar Velocity in other sources

- Another way to test the peculiar velocity hypothesis of the CMB dipole: measure our peculiar velocity wrt other distant sources
  - The radio galaxies dipole has been measured many times in the last 20 years
    - Results are mostly inconsistent, and the inferred velocity is very high (usually > 1000 km/s)

See e.g. Siewert, Schmidt-Rubart, Schwarz (2010.08366)

  - Peculiar velocity surveys in nearby galaxies (<~150 Mpc) are more consistent with the expected values,
    - subject to many systematics & empirical power-laws
    - precision also not very large
  - Future radio continuum measurements with SKA and secular parallax with Gaia may reach 10% precision

Peculiar Velocity in other sources

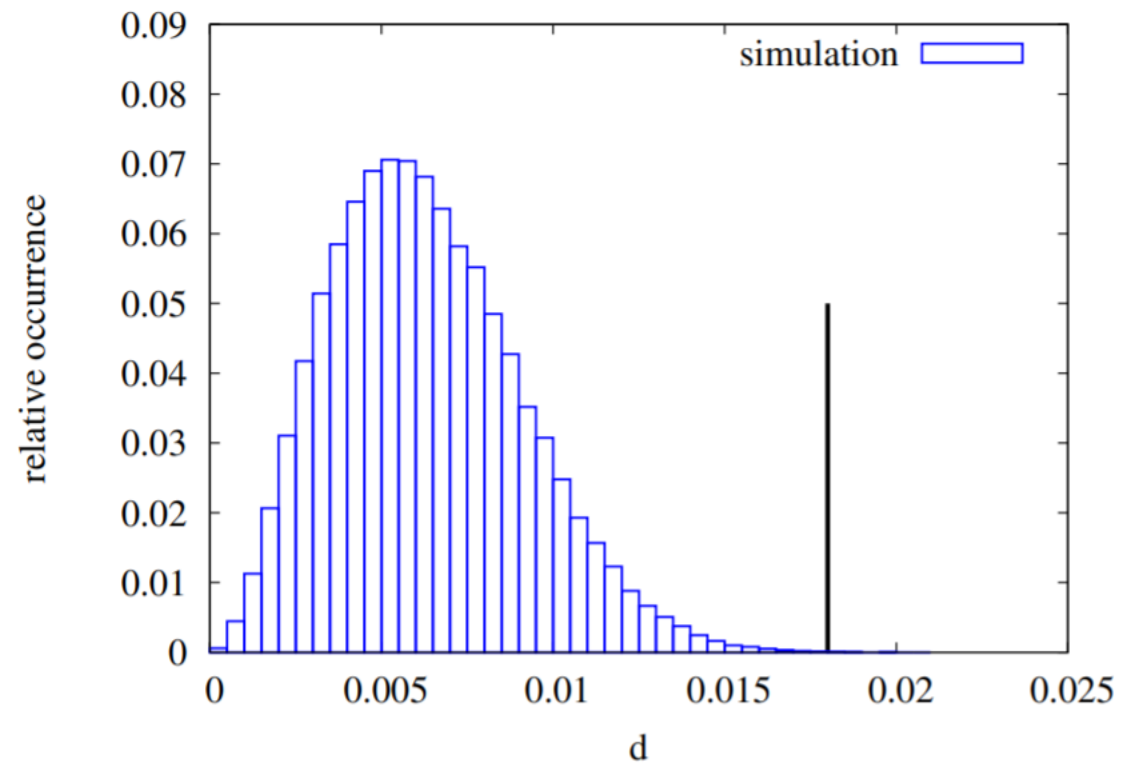
- The radio galaxy dipole is measured to be a few times larger than expected from the CMB
  - Measured radio flux follows a power law
  - Number density of radio sources → also assumed to follow a power law

$$S \propto v^{-\alpha}$$

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(>S) \propto S^{-x}$$

$$d \equiv \left[2 + x(1+\alpha)\right]\beta$$

$$d_{\mathrm{CMB}} = 0.0046$$



Rubart, Schwarz 1301.5559 (A&A)

Conclusions

- By removing the DD → measure aber. & Doppler independently from each other & from the dipole
- Null hypothesis (no aber., Dopp. & DD) excluded at $> 6\sigma$
- Aberration and Doppler measurements are consistent with the dipole
  - Consistent with no intrinsic dipole
  - First upper bound on its amplitude: 3.5 mK
  - The specific bound depends on the intrinsic dipole model, but for any given model, the 3 independent observables (A, D and dipole) can put meaningful constraints
- Hints at systematic origins for radio dipole measurements > 1000 km/s

Conclusions

- By removing the DD → measure aber. & Doppler independently from each other & from the dipole
- Null hypothesis (no aber., Dopp. & DD) excluded at $> 6\sigma$
- Aberration and Doppler measurements are consistent with the dipole
  - Consistent with no intrinsic dipole
  - First upper bound on its amplitude: 3.5 mK
  - The specific bound depends on the intrinsic dipole model, but for any given model, the 3 independent observables (A, D and dipole) can put meaningful constraints
- Hints at systematic origins for radio dipole measurements > 1000 km/s

Obrigado!

Extra

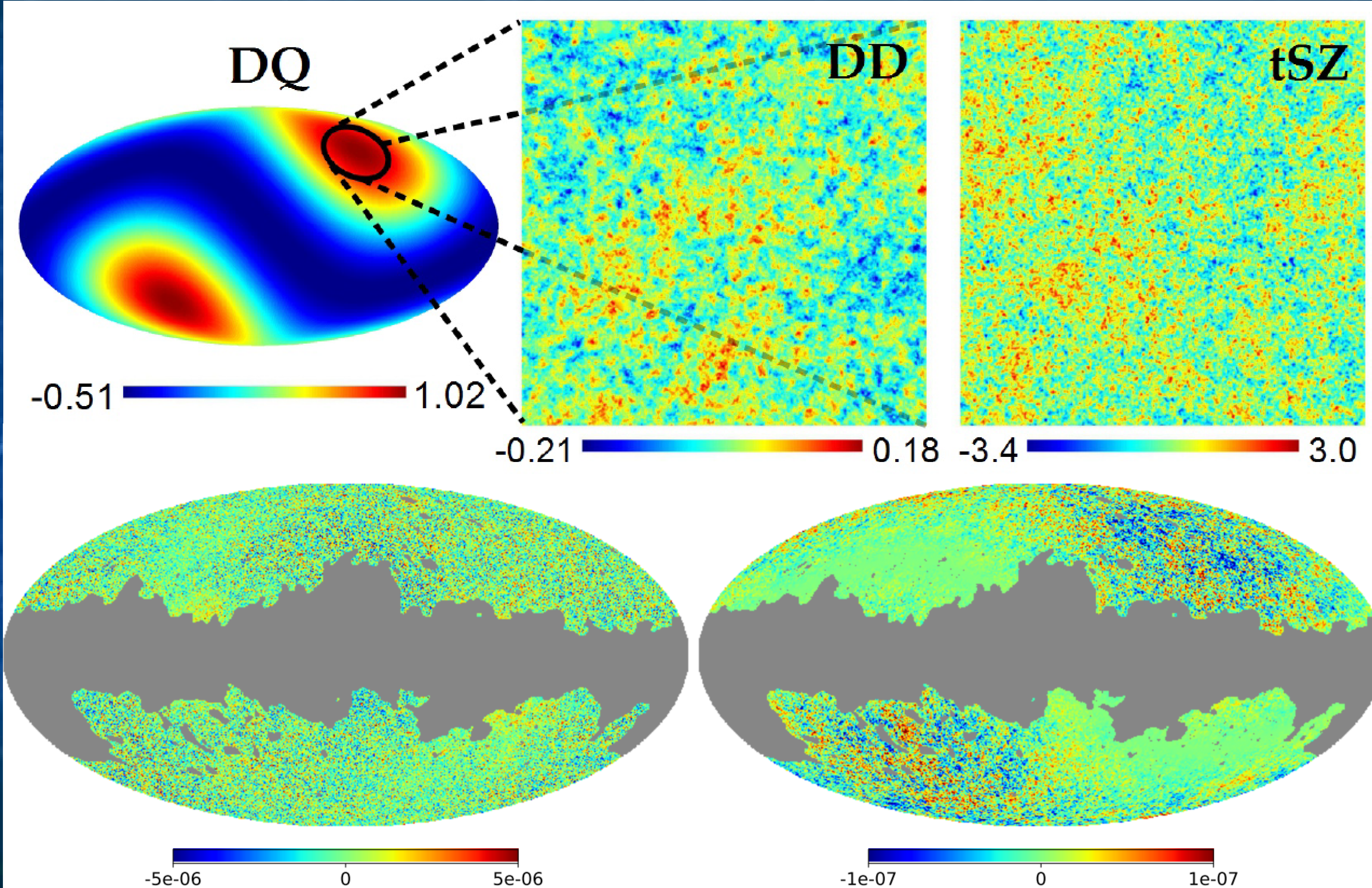
Slides

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

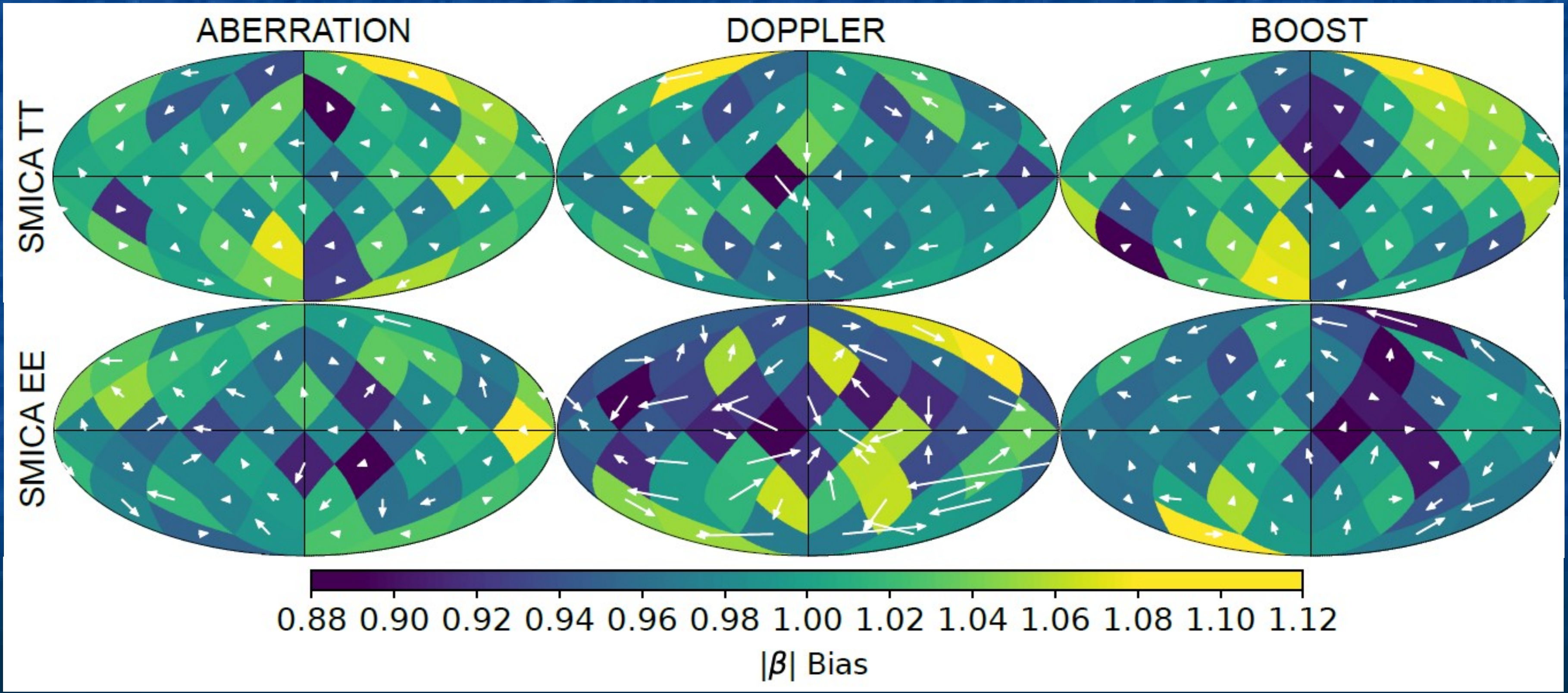
Burigana et al. (CORE col.), (1704.05764)

DD modulation of tSZ maps



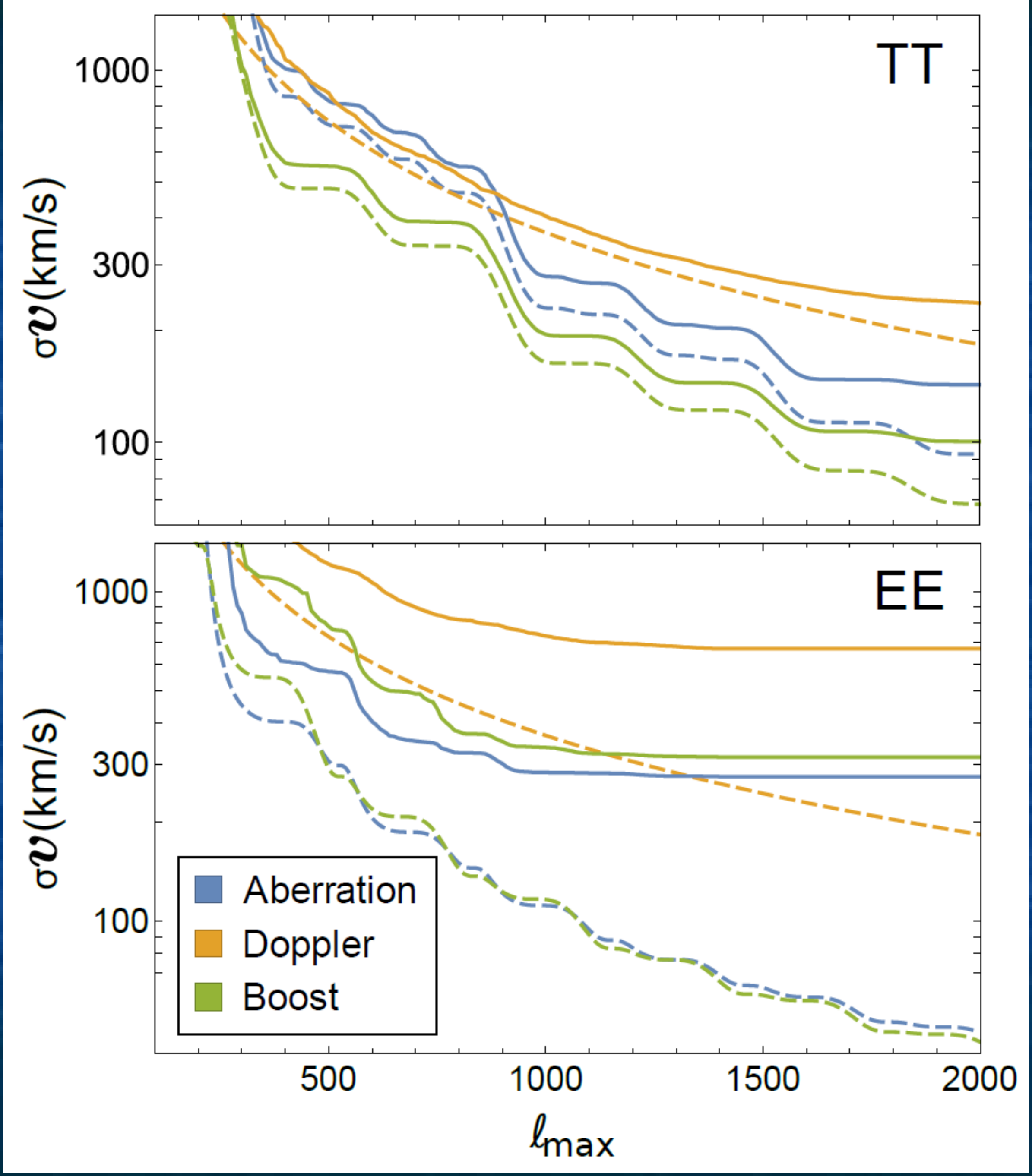
Mask and noise bias removal

- Final results of recovering a given input signal
  - Arrows start at fiducial signal position and end at recovered values

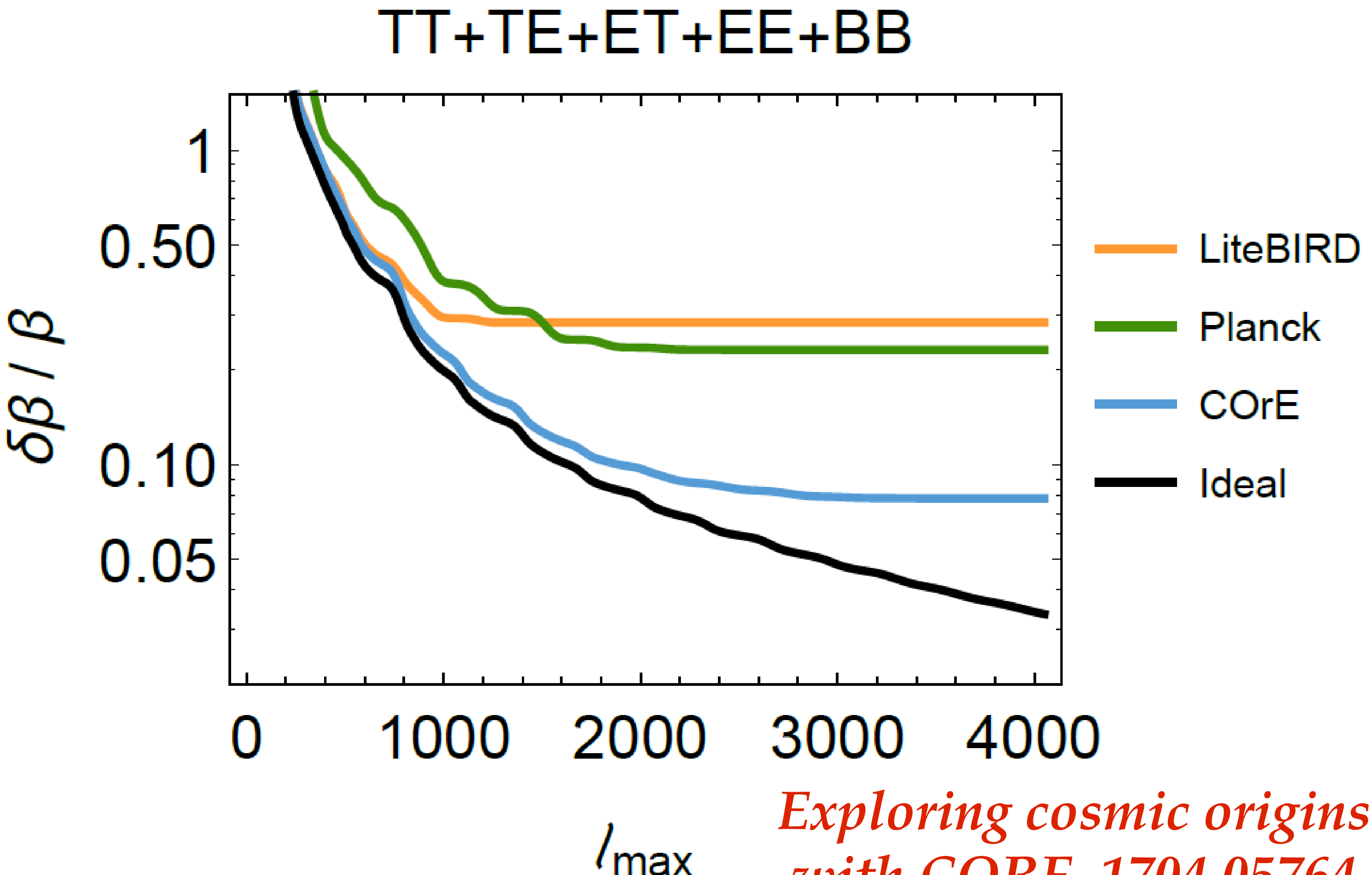


Expected uncertainties

- Better S/N in the EE maps would increase our precision



Future of Aberration: comparison



Exploring cosmic origins with CORE 1704.05764

Results after removing leakages between Aber. & Doppler

$$\mathrm{DD}_\ell^{\mathrm{M}} \equiv \sum_\nu 2X_{\ell,\nu}^{\mathrm{M}}\left[Q(\nu)-1\right]$$