# First constraints on the intrinsic CMB dipole and our velocity with Doppler and aberration

PHYSICAL REVIEW LETTERS

Accepted Paper

First constraints on the intrinsic CMB dipole and our velocity with Doppler and aberration

Phys. Rev. Lett.

Pedro da Silveira Ferreira and Miguel Quartin

**Accepted** 21 July 2021

https://arxiv.org/abs/2011.08385v2

PHYSICAL REVIEW D

*covering particles, fields, gravitation, and cosmology*

Accepted Paper

Disentangling Doppler modulation, aberration and the temperature dipole in the CMB

Phys. Rev. D

Pedro da Silveira Ferreira and Miguel Quartin

**Accepted** 21 July 2021

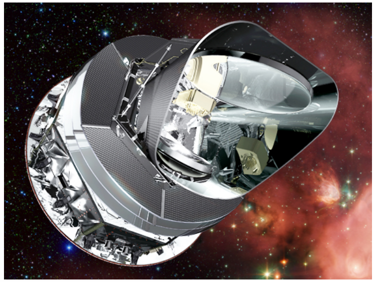
https://arxiv.org/abs/2107.10846

**Pedro da Silveira Ferreira**
**Ph.D. Student – Valongo Observatory (UFRJ)**
**Advisor: Miguel Quartin**
**25/08/2022 – COSMO22**

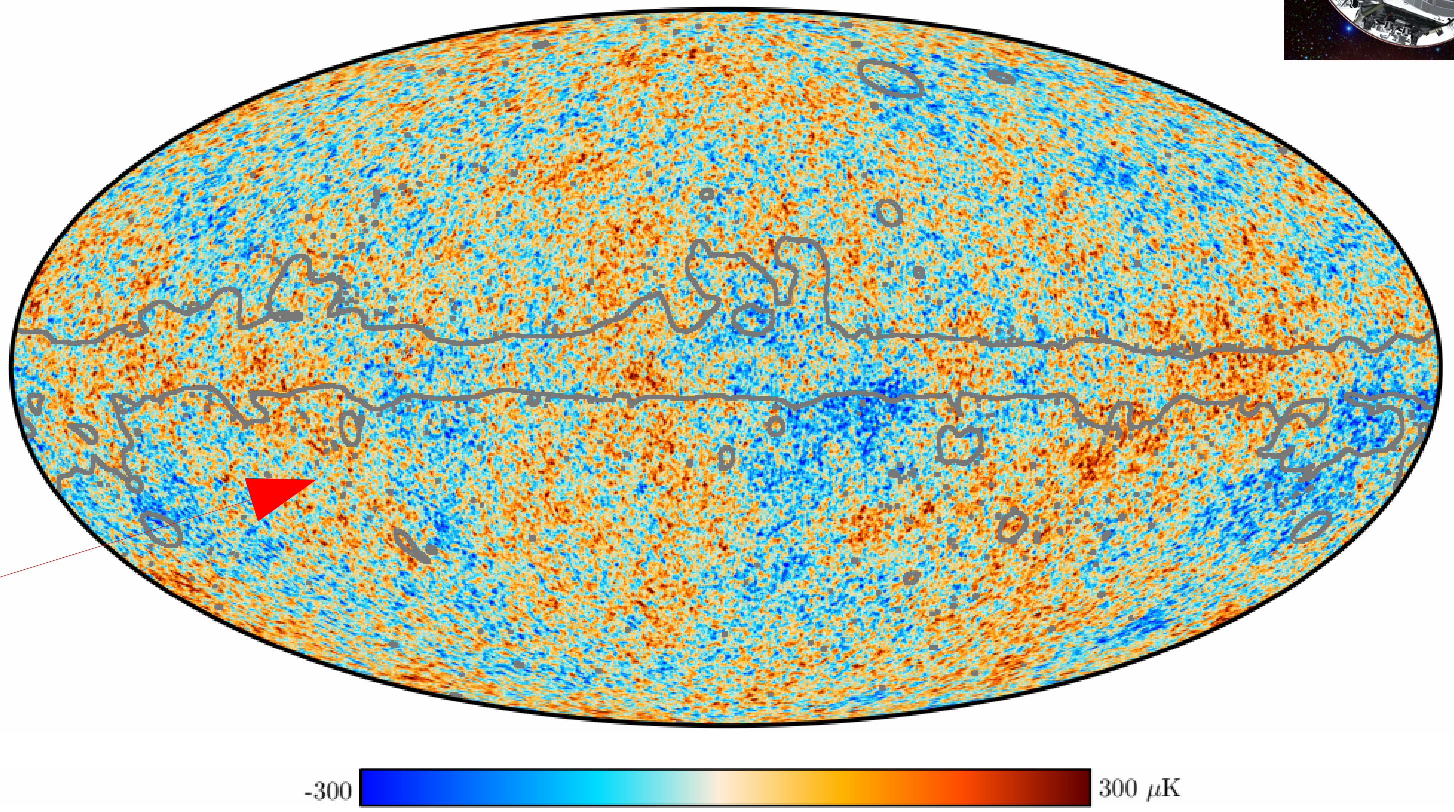
140 anos Observatório do Valongo

# Dipole and the Cosmological Principle

- The most **perfect Black Body** observed in nature.
- T=2.725K (after expansion, ~3000K on release)
- Very isotropic (**1/100000**) → **Evidence of cosmological principle**.



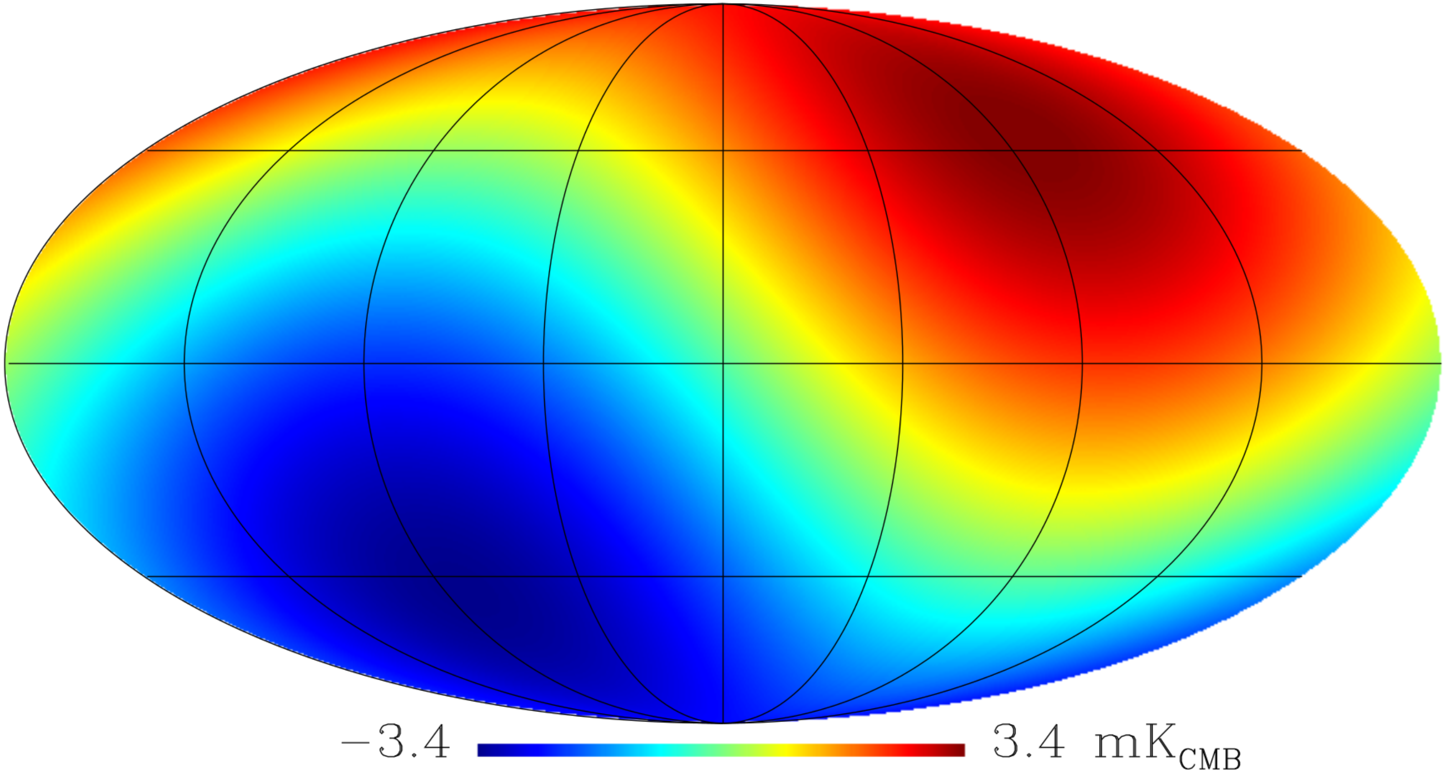
Planck - 2018




Hot and cold regions due to acoustic oscillations and SW effect

# Dipole and the Cosmological Principle

- The most **perfect Black Body** observed in nature.
- T=2.725K (after expansion, ~3000K on release)
- Very isotropic (**1/100000**) + Dipole (**1/1000**)
- This is **after remove the Dipole modulation** due to our peculiar velocity (assuming isotropy).



# The CMB Dipole

- The most **perfect Black Body** observed in nature.
- T=2.725K (after expansion, ~3000K on release)
- Very isotropic (**1/100000**) + Dipole (**1/1000**)
- This is after remove the Dipole modulation due to our peculiar velocity
  → **Just due to our movement?**

**If you expand in multipoles a temperature map with Doppler modulation:**

$$T(\theta)=T_0\frac{\sqrt{(1-\beta^2)}}{(1-\beta\cos\theta)}$$

$$T(\theta)=T_0\left(1+\boxed{\beta}\cos\theta+\frac{\beta^2\cos 2\theta}{2}+O(\beta^2)\right)$$

| Experiment | Amplitude [$\mu K_{CMB}$] | Velocity [Km/s] |
|---|---|---|
| COBE | $3358\pm24$ | $369,4\pm2,6$ |
| WMAP | $3355\pm8$ | $369,10\pm0.88$ |
| Planck 2015 | $3364.5\pm2.0$ | $370,09\pm0.22$ |
| **Planck 2018** | **$3362.08\pm0.99$** | **$369.82\pm0.11$** |

**Planck Collaboration, 2018** (Adapted)

# The CMB Dipole

## But part of the Dipole could be intrinsic!

We need another way to measure our $\beta$ (in relation to CMB), **independently from the dipole**. If it's different from Dipole we have a intrinsic Dipole.

## Anomalies and expected Dipole

The **standard cosmological model expect a $10^{-5}$ intrinsic dipole**.
However, the **CMB has some anomalies**, like:

- → **Cold spot**
- → **Low multipole alignments**
- → **Hemispherical & Parity Asymmetry**

CMB anomalies after Planck

Dominik J Schwarz[4,1], Craig J Copi[2], Dragan Huterer[3] and Glenn D Starkman[2]

Published 19 August 2016 • © 2016 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 33, Number 18

**Citation** Dominik J Schwarz *et al* 2016 *Class. Quantum Grav.* **33** 184001

**So, it's important to test it largest possible scale, the intrinsic dipole!**

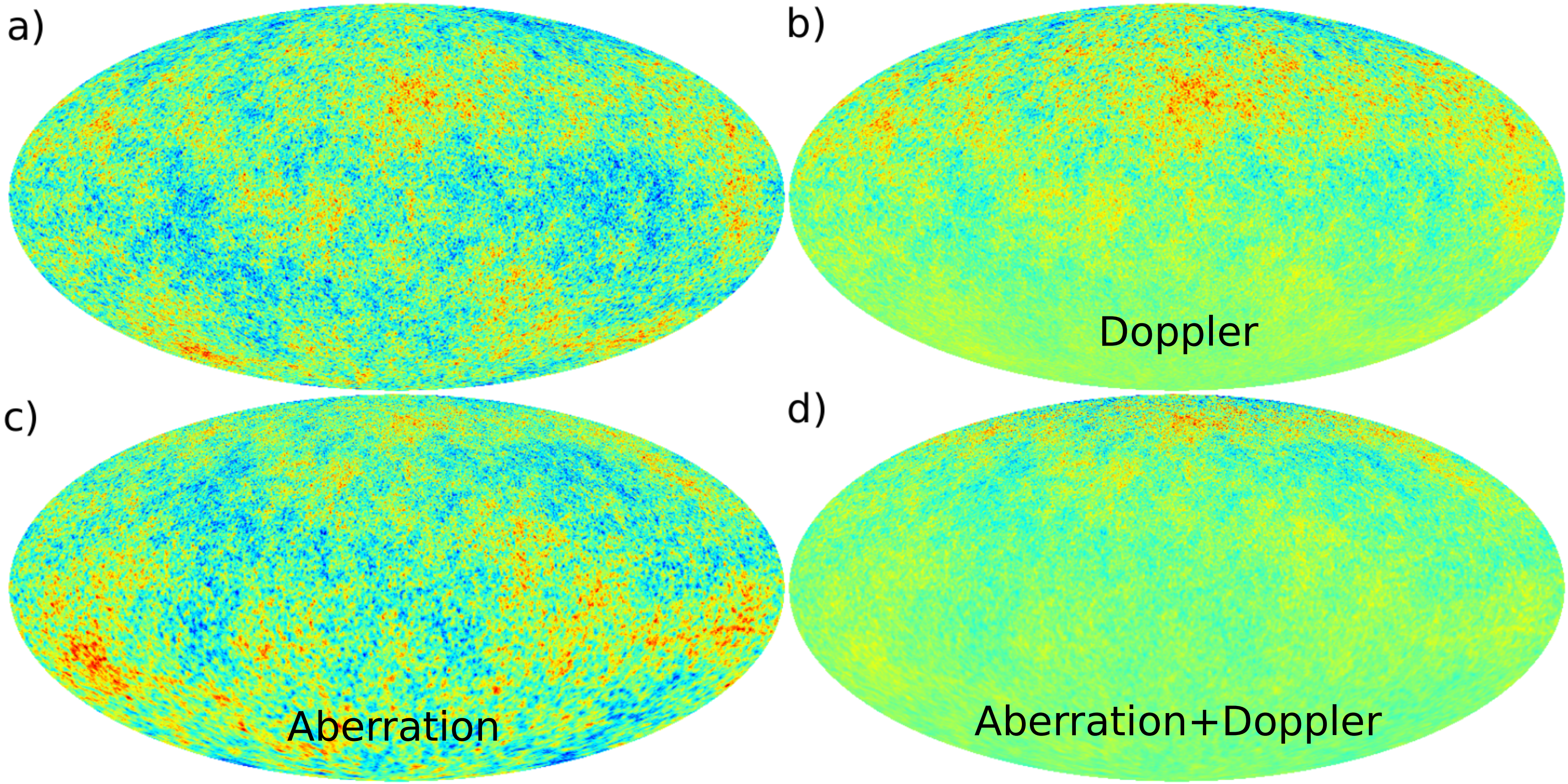
# The CMB intrinsic Dipole – Important feature

**An intrinsic Dipole could give important information about the very primordial universe and large structure.**

- Important test of the cosmological principle
- Large scale dipolar gravitational potential
- Privileged direction of universe
- Void effects
- Improve redshift measurements ($z^{Observed} \rightarrow z^{Cosmological}$)
- Comparison with other observables dipoles and velocities
- Tilted universe (Could occur if inflation takes ~10 e-foldings longer than required to solve the horizon problem and is related to superhorizon isocurvature perturbations. Leads to a cosmic “bulk flow” of galaxies and clusters)
- Primordial non-Gaussianity (by measuring Doppler modulation)

# Boosting the CMB – Different signatures of the effects

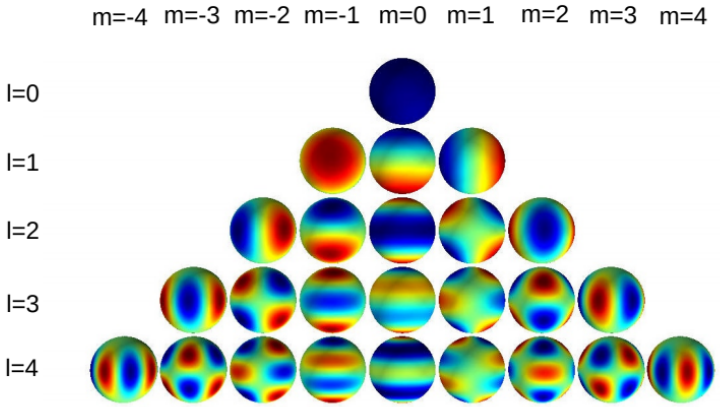
## Healpix Boost (modified version) – Signature on **Pixel space**



# Signature in the harmonic space - Spherical Harmonics (SH)

**Spherical Harmonics: like Fourier but over the sphere**

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




**Aberration and Doppler effects on harmonic space.**

$$a'_{\ell m} = a^{\rm Prim}_{\ell m} + a^{\rm A}_{\ell m} + a^{\rm D}_{\ell m}$$

**Non-diagonal correlations → independent from the dipole**

$$a^{\rm A}_{\ell m} = c^{\rm A,-}_{\ell m} a^{\rm Prim}_{\ell-1\,m} + c^{\rm A,+}_{\ell+1 m} a^{\rm Prim}_{\ell+1\,m},$$

$$a^{\rm D}_{\ell m} = c^{\rm D}_{\ell m} a^{\rm Prim}_{\ell-1\,m} + c^{\rm D}_{\ell+1 m} a^{\rm Prim}_{\ell+1\,m},$$

# Signature in the harmonic space - Spherical Harmonics (SH)

**Amendola et al., 2010**, find an estimator using non-diagonal correlations effect over the 2-point function:

$$a^*_{\ell\, m} a_{\ell+1\, m}$$

Expected 2-point correlation

Observed 2-point correlation

$$\hat{\beta}_z = \left( \sum_{\ell,m} \frac{f^{\rm obs}_{\ell m} \hat{f}^{\rm TH}_{\ell m}}{\mathfrak{C}_\ell \mathfrak{C}_{\ell+1}} \right) \left( \sum_{\ell,m} \frac{(\hat{f}^{\rm TH}_{\ell m})^2}{\mathfrak{C}_\ell \mathfrak{C}_{\ell+1}} \right)^{-1}$$

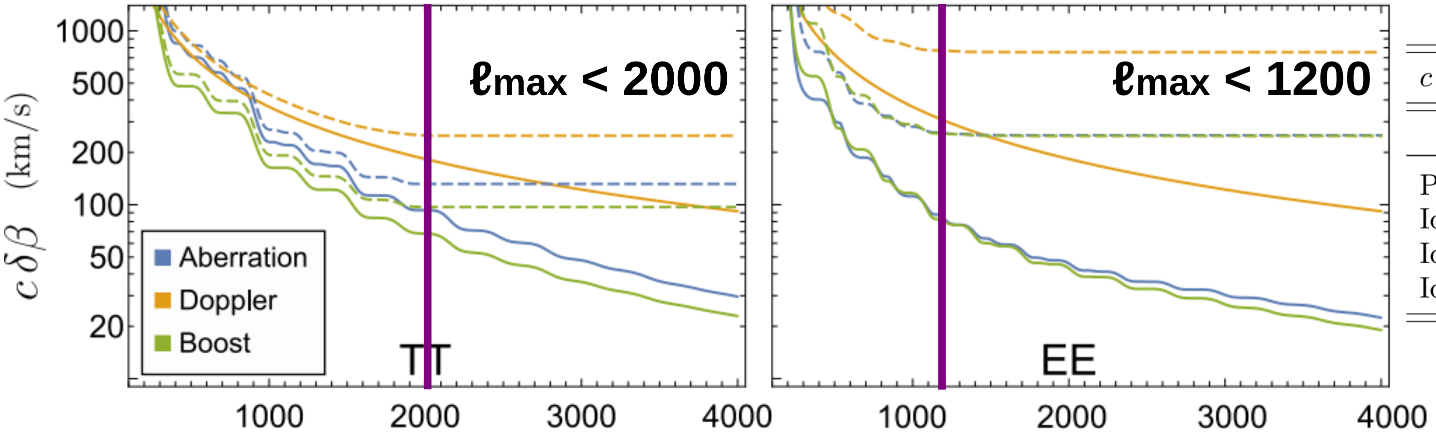
$$\mathfrak{C}_\ell \equiv (C_\ell + N_\ell)$$

Starting with ℓ > 2
To avoid dipole

**It works for temperature and polarization, and it's possible to measure aberration and Doppler independently.**

# Expected error – with Planck PR3-2018 data

## Statistical




| $c\,\delta\beta$ (km/s) | Aberration | Doppler | Boost |
|---|---|---|---|
| Planck 2018 | 97 | 230 | 80 |
| Ideal ($\ell_{\max} = 2000$) | 33 | 124 | 30 |
| Ideal ($\ell_{\max} = 3000$) | 22 | 83 | 19 |
| Ideal ($\ell_{\max} = 4000$) | 16 | 63 | 13 |

**TE+ET is hard to use due to difficulties in how to reproduce one systematic (DD) and has strong correlation between Ab and Dopp. Will be left for future works.**

## Systematical due to isotropic approximation ←

$$\mathfrak{C}_\ell \equiv (C_\ell + N_\ell)$$

Noise and mask (considering Master Matrix) is considered on the estimator as an **isotropic** effect→ **This will introduce bias that will be removed using mock simulations (including mask, realistic noise, realistic beaming and Planck systematical errors) training (simple linear bias by angular scale). Also, we remove the correlation between Ab. and Dopp. using such simulations.**

# Dipole Distortions (DD) – Systematical effects on data

CMB all-scale blackbody distortions induced by linearizing temperature

Alessio Notari and Miguel Quartin

Phys. Rev. D **94**, 043006 – Published 12 August 2016

$$I(\nu,\hat{\boldsymbol{n}}) = \frac{h}{c^2}\frac{2\nu^3}{e^{\frac{h\nu}{k_B T(\hat{\boldsymbol{n}})}}-1}\,. \qquad (14)$$

We Taylor expand around $T_0$ to first order, decomposing $T(\hat{\boldsymbol{n}}) = T_0 + \Delta T(\hat{\boldsymbol{n}})$, and get

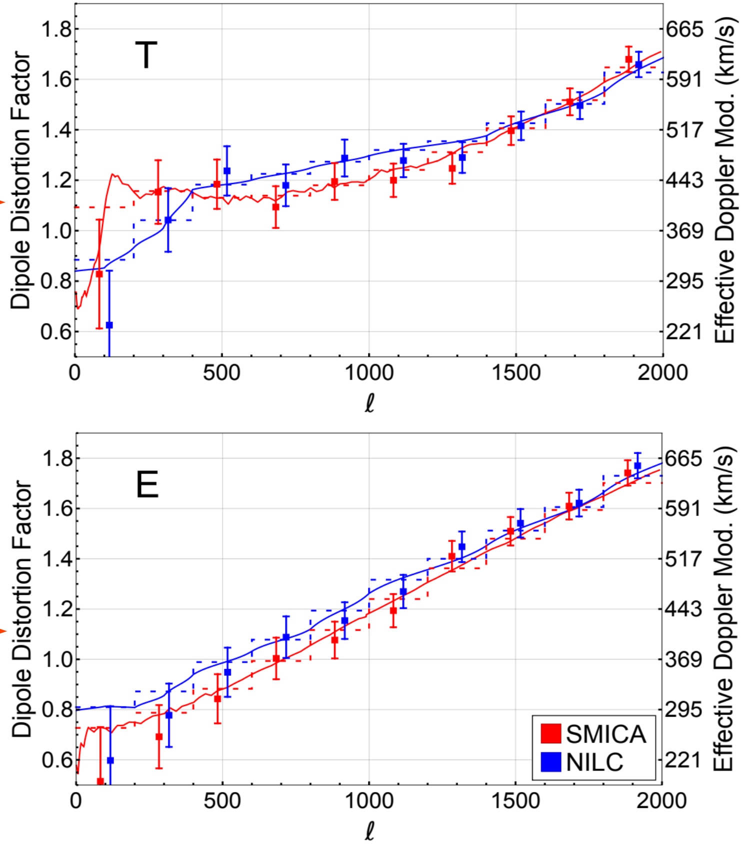
$$\delta I(\nu,\hat{\boldsymbol{n}}) \approx \frac{h}{c^2}\frac{2\nu^4 e^{\frac{\nu}{\nu_0}}}{T_0^2\left(e^{\frac{\nu}{\nu_0}}-1\right)^2}\delta T(\hat{\boldsymbol{n}}) \equiv K(\nu)\frac{\Delta T(\hat{\boldsymbol{n}})}{T_0}\,,$$

$$L(\hat{\boldsymbol{n}}) \equiv \delta I(\nu,\hat{\boldsymbol{n}})/K(\nu).$$

If we now extend the expansion to second order we get **for ℓ>2**

$$L(\nu',\hat{\boldsymbol{n}}') = \frac{\delta T(\hat{\boldsymbol{n}})}{T_0}\left[\boldsymbol{\beta}^{\rm D}\cdot\hat{\boldsymbol{n}} + 2\boldsymbol{\Delta}_1\cdot\hat{\boldsymbol{n}}(Q(\nu')-1)\right] + \frac{\delta T(\hat{\boldsymbol{n}})}{T_0} + \beta^{\rm A}\frac{\delta T_{ab}(\hat{\boldsymbol{n}})}{T_0} + \mathcal{O}(10^{-9})\,.$$

**Included on simulations and bias fitting, considering ℓ dependence.**




**Degenerate with Doppler but don't give any new information (only leakage of the dipole), should be removed.**

# Boost or intrinsic Dipole? - Degenerated effects

**Dipole vs off-diagonal couplings:**

Journal of Cosmology and Astroparticle Physics

Interpreting the CMB aberration and Doppler measurements: boost or intrinsic dipole?

Omar Roldan[1], Alessio Notari[2] and Miguel Quartin[1]

Published 10 June 2016

**Measuring Aberration and Doppler independently, and estimating $L_d$, we can solve this system and measure the intrinsic dipole!**

Non-Gaussianity factor

$$\boldsymbol{\Delta}_1 = \beta + \boldsymbol{\Delta}_{1,\mathrm{int}} \,,$$

$$\beta^{\mathrm{D}} = \beta + (1 + \alpha^{\mathrm{NG}})\boldsymbol{\Delta}_{1,\mathrm{int}} \,,$$

$$\beta^{\mathrm{A}} = \beta + \boldsymbol{L}_d \,,$$

**Without NG Doppler is completely degenerated with the Dipole!**

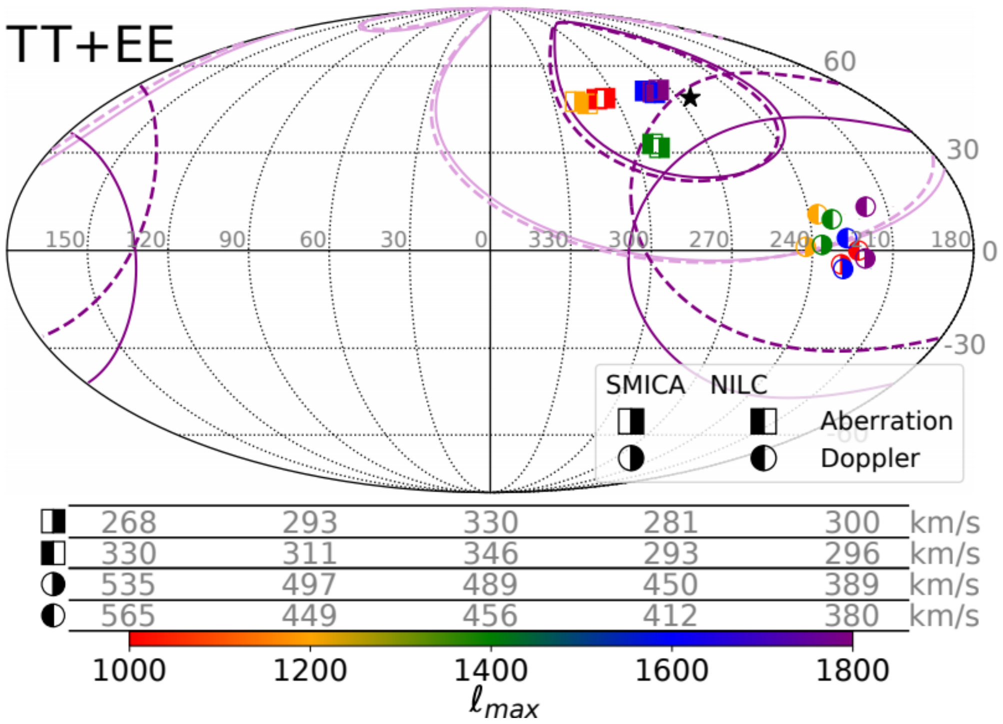
Lensing Dipole

**Absolute value can be estimated using Planck cosmological parameters (17% of Dipole value). Can be measured using large scale structure.**

The effects of lensing by local structures on the dipole of radio source cou

Calum Murray,[1]★ December 2021

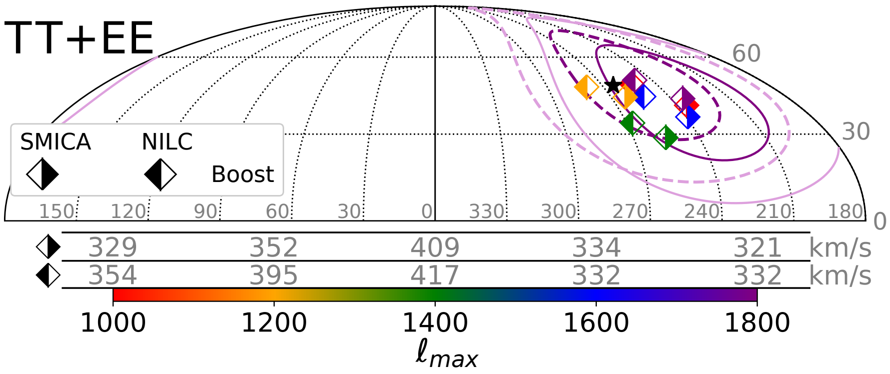
# Final combined TT+EE results




$$\boldsymbol{\Delta}_1 = \boldsymbol{\beta} + \boldsymbol{\Delta}_{1,\mathrm{int}} \,,$$

$$\boldsymbol{\beta}^{\mathrm{D}} = \boldsymbol{\beta} + (1+\alpha^{\mathrm{NG}})\boldsymbol{\Delta}_{1,\mathrm{int}} \,,$$

$$\boldsymbol{\beta}^{\mathrm{A}} = \boldsymbol{\beta} + \boldsymbol{L}_d \,,$$



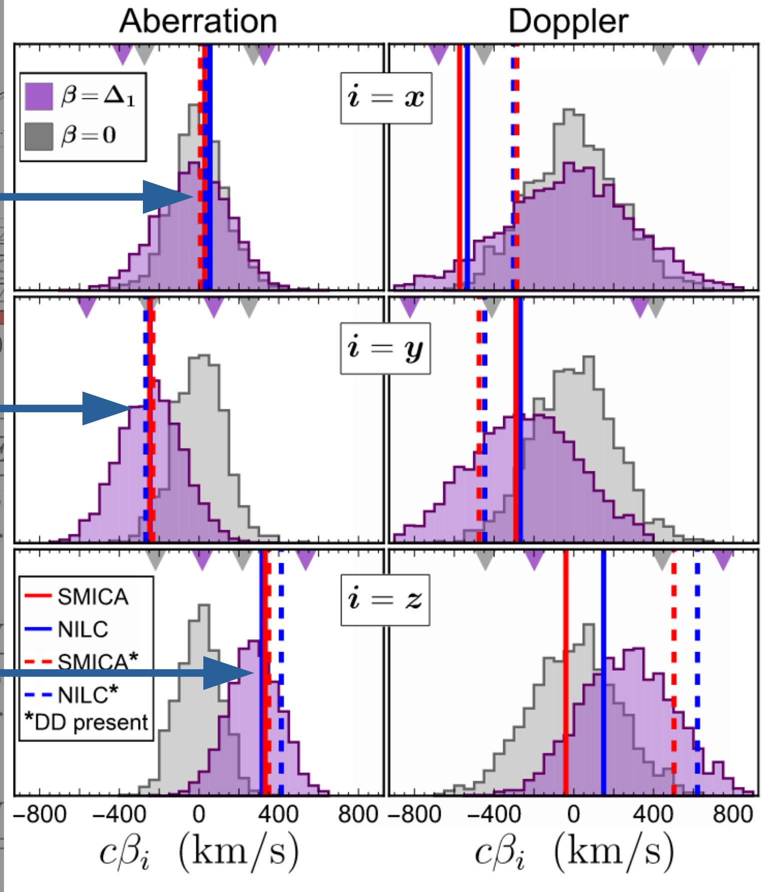

| | ***TT+EE*** | $\lvert \boldsymbol{v} \rvert$ [km/s] | $l(°)$ | $b(°)$ |
|---|---|---|---|---|
| SMICA | Aberration | $300 \pm 99 \pm 13$ | $276 \pm 32 \pm .1$ | $51 \pm 19 \pm .7$ |
| | Doppler | $390 \pm 140 \pm 13$ | $210 \pm 56 \pm 3$ | $-2 \pm 30 \pm .5$ |
| | Boost | $321 \pm 84 \pm 9$ | $234 \pm 21 \pm .1$ | $43 \pm 15 \pm .2$ |
| | Velocity | $300^{+111}_{-93} \pm 13$ | $276 \pm 33 \pm .1$ | $51 \pm 19 \pm .7$ |
| NILC | Aberration | $296 \pm 100 \pm 10$ | $280 \pm 32 \pm .3$ | $50 \pm 20 \pm .3$ |
| | Doppler | $380 \pm 140 \pm 10$ | $208 \pm 56 \pm 2$ | $13 \pm 30 \pm .2$ |
| | Boost | $332 \pm 83 \pm 9$ | $250 \pm 22 \pm 1$ | $50 \pm 15 \pm .1$ |
| | Velocity | $296^{+111}_{-88} \pm 10$ | $280 \pm 33 \pm .3$ | $50 \pm 20 \pm .3$ |

**Kinematic hypothesis v $\simeq$ 370km/s**

# Results

| *TT+EE* | | $\chi^2$ ($\beta = \boldsymbol{\Delta}_1$) | $\sigma$-value ($\beta = \boldsymbol{\Delta}_1$) | $\chi^2$ ($\beta = \mathrm{DD} = 0$) | $\sigma$-value ($\beta = \mathrm{DD} = 0$) |
|---|---|---|---|---|---|
| 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 |

**Strongly Favors kinematic hypothesis**



# The CMB Intrinsic Dipole

**Consistent with zero**, here is the absolute value upper bound. Not a very strong constraint, but **the first physical constraint**, and helps constraints results on **other sources like galaxies dipoles**.

| ***TT+EE*** | $\boldsymbol{\Delta}_{1,\mathrm{int}}$ | | $\alpha^{\mathrm{NG}}$ | |
|---|---|---|---|---|
| | amplitude | $\sigma$-value | [95% CI] | $\sigma$-value |
| SMICA | $< 3.6$ mK [95% CI] | 0.1 | $1.0^{+3.0}_{-3.9}$ | 0.7 |
| NILC | $< 3.7$ mK [95% CI] | 0.1 | $0.9^{+2.4}_{-3.3}$ | 0.9 |

$$\boldsymbol{\Delta}_1 = \beta + \boldsymbol{\Delta}_{1,\mathrm{int}}$$

| **Experiment** | Amplitude [$\mu K_{CMB}$] |
|---|---|
| Planck 2015 | 3364.5±2.0 |
| **Planck 2018** | **3362.08±0.99** |

# Comparing with dipole measurements on other observables

**Comparing with dipole measurements in other observables**

Using high-z data like radio galaxies, quasars, SNe, galaxies on optical... should give the same **v**. Some of the newest measurements using quasars and radio measure **v** in the **same direction but with absolute value of 800~1000 km/s.**

THE ASTROPHYSICAL JOURNAL LETTERS

A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]

Published 2021 February 25 • © 2021. The Author(s). Published by the American Astronomical Society.

The effects of lensing by local structures on the dipole of radio source counts

Calum Murray

*Monthly Notices of the Royal Astronomical Society*, Volume 510, Issue 2, February 2022,

**Comparing with CMB results we have ~5σ tension.**

A very fine tuned scenario where the intrinsic dipole is in the opposite direction and we have a higher velocity (compatible with radio and quasars results) summing a smaller total dipole (that would be wrongly interpreted as a incompatible velocity) is not more possible.

**Why this difference? Is it a systematical? Is it due somehow to universe evolution? Or a problem with the methodology? The mystery remains.**

# Perspectives

Both Doppler and aberration effects **should be present in all cosmological observables**.

- The **SKA** telescope is predicted to measure our velocity with **10% precision** [52].
- Both secular extragalactic parallax measurements using **GAIA** and **future CMB experiments** are expected to provide a similar precision (**10%**).
- Other proposed ways to measure the intrinsic CMB dipole includes the **spectral distortions of the monopole and quadrupole** in future spectrometric CMB instruments and the induced effect on the lensing of the CMB for **$\ell$>**3000.

**In the near future will be possible to exclude exotic scenarios with ~1 mK intrinsic dipole with this method.**

**~3x improvement on intrinsic dipole constraint and Boost measurement.**

| $c\,\delta\beta$ (km/s) | $TT+TE+ET+EE$ | | |
|---|---|---|---|
| | Aberration | Doppler | Boost |
| Planck 2018 | 97 | 230 | 80 |
| Simons Observatory | 47 | 163 | 40 |
| CMB-S4 | 29 | 111 | 25 |
| Ideal ($\ell_{\max}=2000$) | 33 | 124 | 30 |
| Ideal ($\ell_{\max}=3000$) | 22 | 83 | 19 |
| Ideal ($\ell_{\max}=4000$) | 16 | 63 | 13 |

**As very important feature of the universe we should try to measure it with several methods to avoid any bias or systematic and compare with different observables.**

# Conclusions

- For the first time we put an upper bound in the intrinsic dipole and measure aberration and Doppler independently from the dipole using **temperature and polarization** data, considering the **lensing dipole** and **non-gaussianity (degenerated with Aberration and Doppler)**.
- The results are **consistent with the peculiar velocity hypothesis** of the dipole.
- These findings **exclude for instance the possibility of a 800~1000 km/s** value (in the same direction) obtained in many **Cosmic Radio dipole** measurements. **Why this difference?**

# Questions are welcome!

pferreira@ov.ufrj.br
pdsf.ufrj@gmail.com

# Previous Measurements and our improvements

Not complete removal of DD, only boost (Doppler=Aberration), not complete treatment of degeneracy of aberration and Doppler with other effects, and only for temperature. Just consider velocity on dipole direction.

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

A&A 2013

*Planck* intermediate results

LVI. Detection of the CMB dipole through modulation of the thermal Sunyaev-Zeldovich effect: Eppur si muove II

A&A 2020

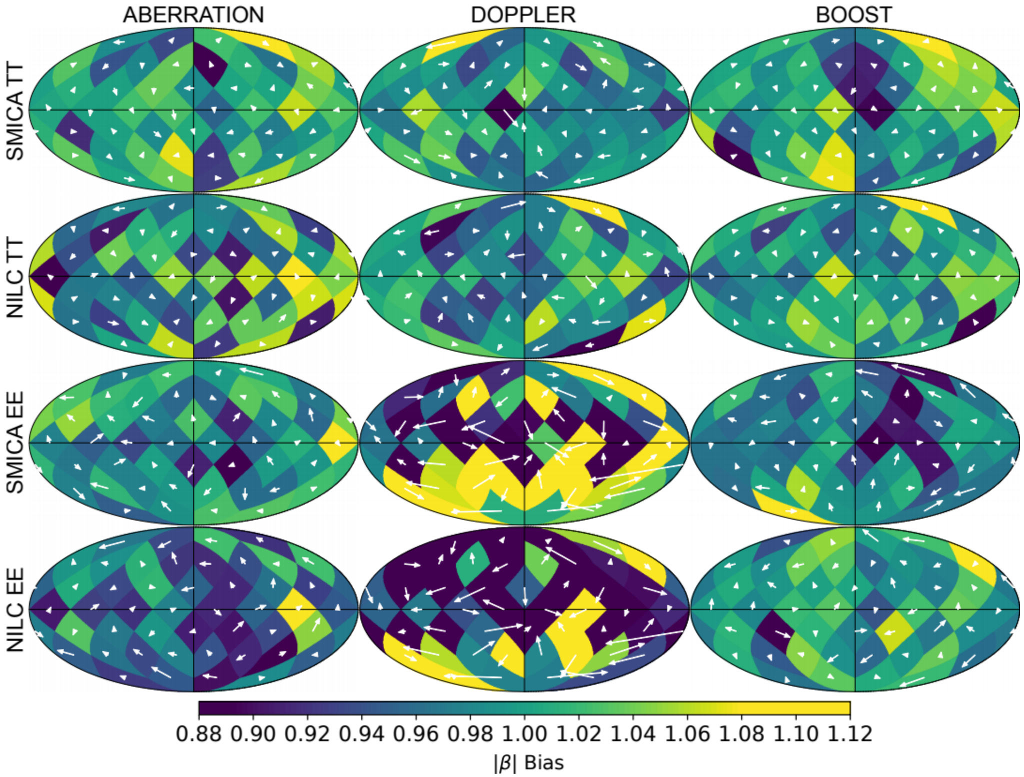
[Submitted on 14 Jun 2021]

**Bayesian estimation of our local motion from the Planck-2018 CMB temperature map**

Sayan Saha, Shabbir Shaikh, Suvodip Mukherjee, Tarun Souradeep, Benjamin D. Wandelt

# Bias and Correlation

$$\chi^2 = \sum_n \left( \frac{\tilde{\beta}^{\mathrm{SIM,M}}_{nXYi,\mathrm{bin}} - \lambda^{\mathrm{M}}_{Xi,\mathrm{bin}} \beta^{\mathrm{FID}}_{nXYi} - \mu^{\mathrm{M}}_{Xi,\mathrm{bin}}}{\tilde{\sigma}^{\mathrm{SIM,M}}_{XYi,\mathrm{bin}}} \right)^2$$



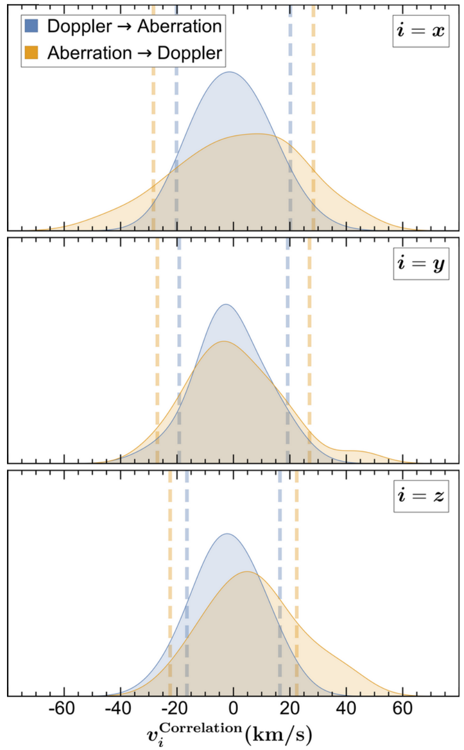

$$\beta_{A,i} \equiv \beta^{[c]}_{A,i} - R_i \beta_{D,i} \,,$$
$$\beta_{D,i} \equiv \beta^{[c]}_{D,i} - S_i \beta_{A,i} \,.$$

Correlated vectors calculated using the sum of the unbiased bins.

$$\beta^{\mathrm{SIM,M}}_{nXYi,\mathrm{bin}} = \frac{\tilde{\beta}^{\mathrm{SIM,M}}_{nXYi,\mathrm{bin}} - \mu^{\mathrm{M}}_{Xi,\mathrm{bin}}}{\lambda^{\mathrm{M}}_{Xi,\mathrm{bin}}}$$

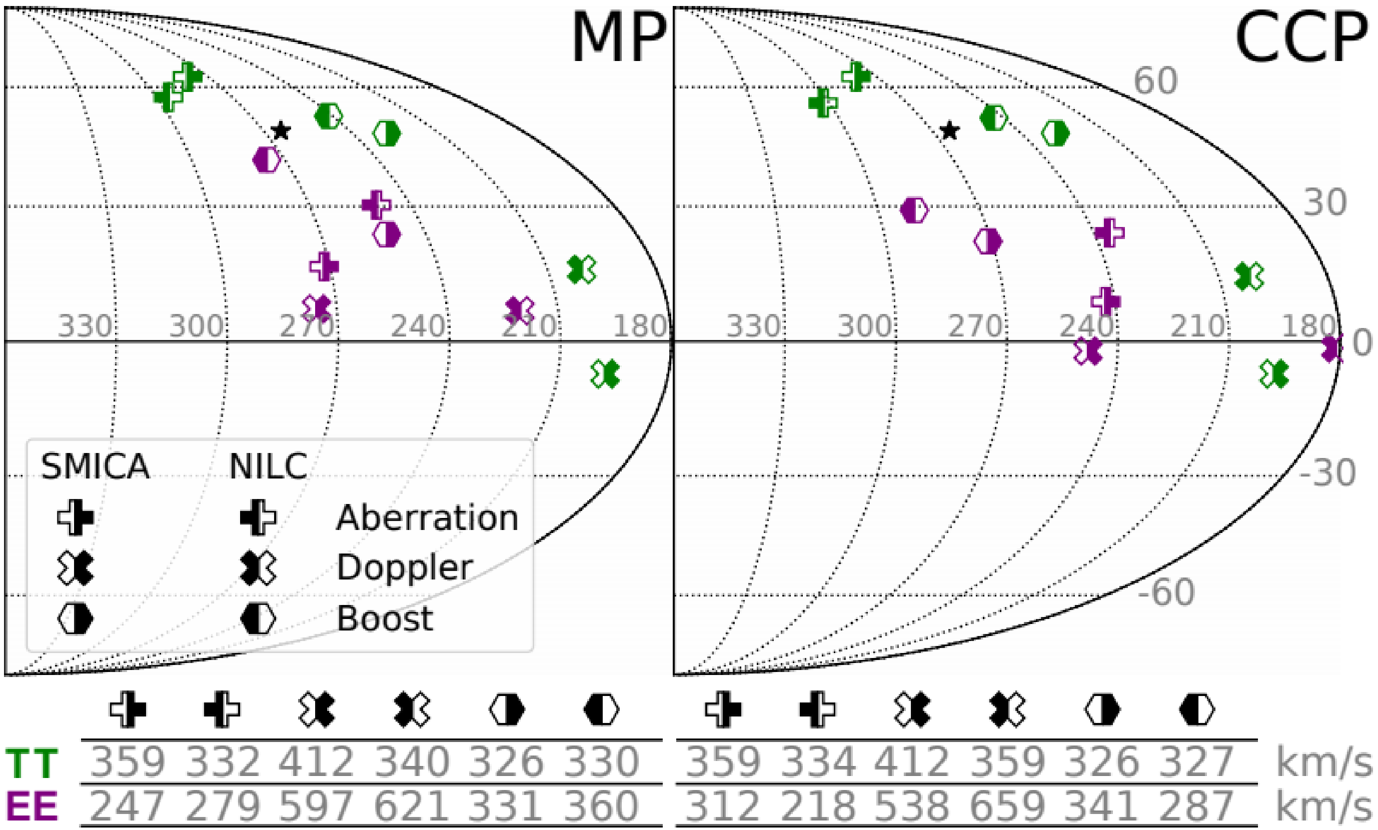
multipole bin of $\Delta\ell = 10$

$$\chi^2_S = \sum_n \left( \frac{\beta^{[c]}_{nA\,Di} - \beta^{\mathrm{FID}}_{nA\,Ai} S_i}{\sigma_{Di}} \right)^2 + \sum_n \left( \frac{\beta^{[c]}_{nB\,Di} - \beta^{\mathrm{FID}}_{nB\,Bi}(S_i + 1)}{\sigma_{Di}} \right)^2 ,$$

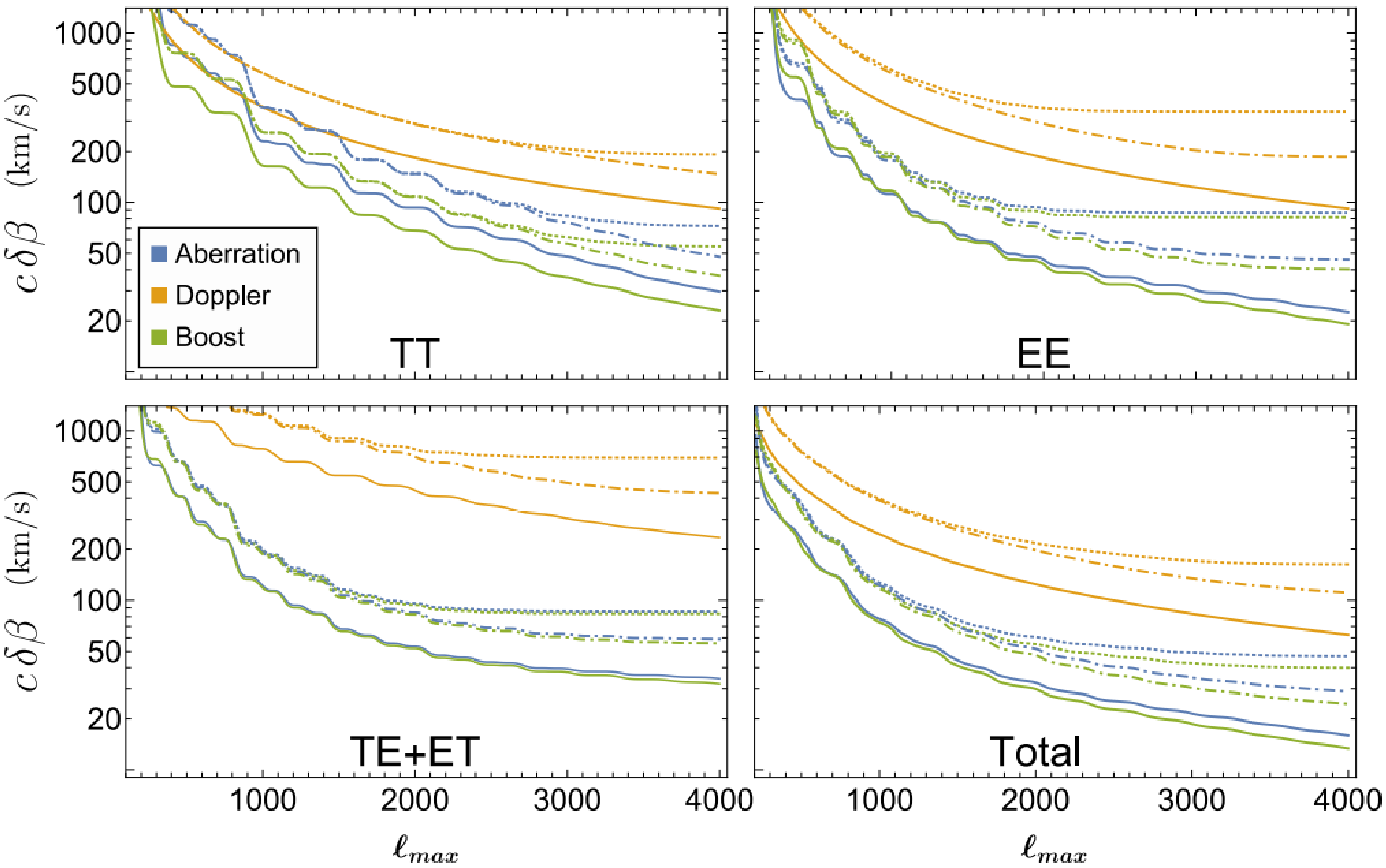


# Comparision between pipelines

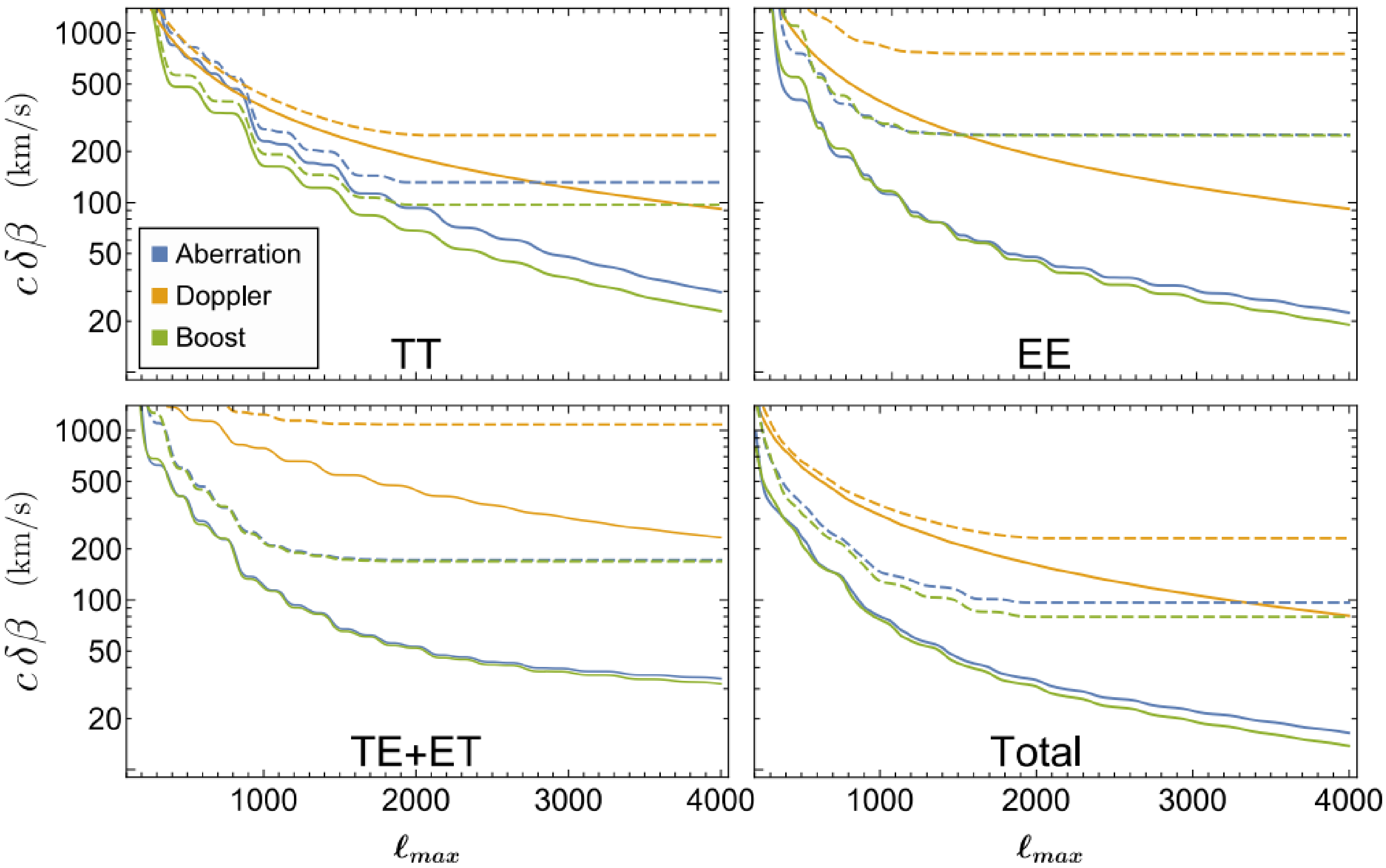
## Very robust



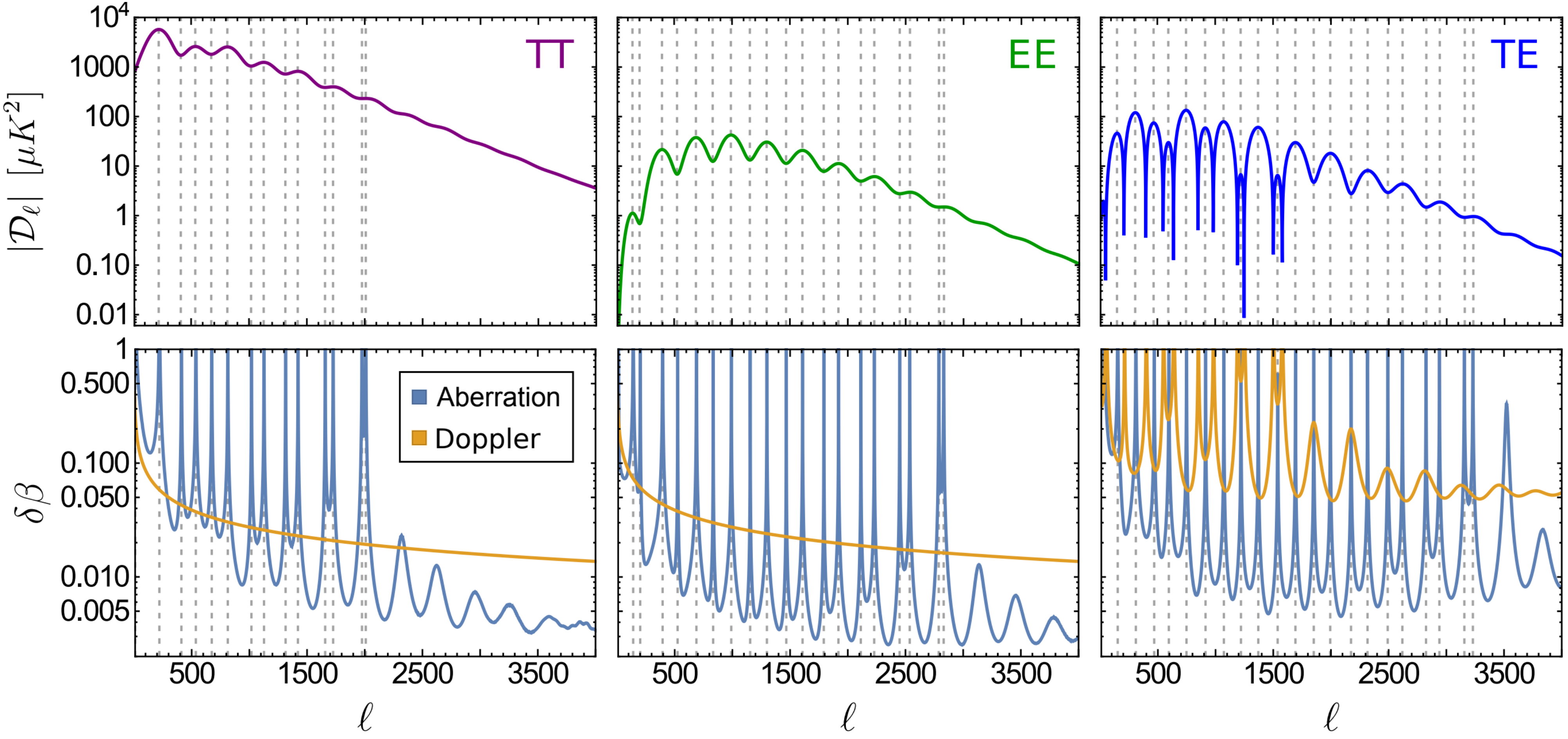
# Forecasts - Statistical error (Simons, CMB-S4 vs Ideal)



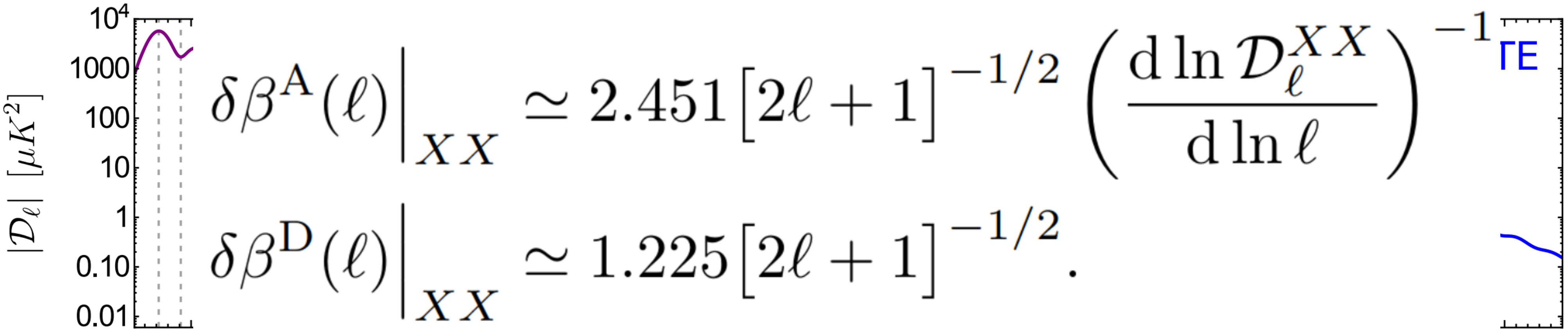
# Statistical error (Planck vs. Ideal)



# Expected error by ℓ

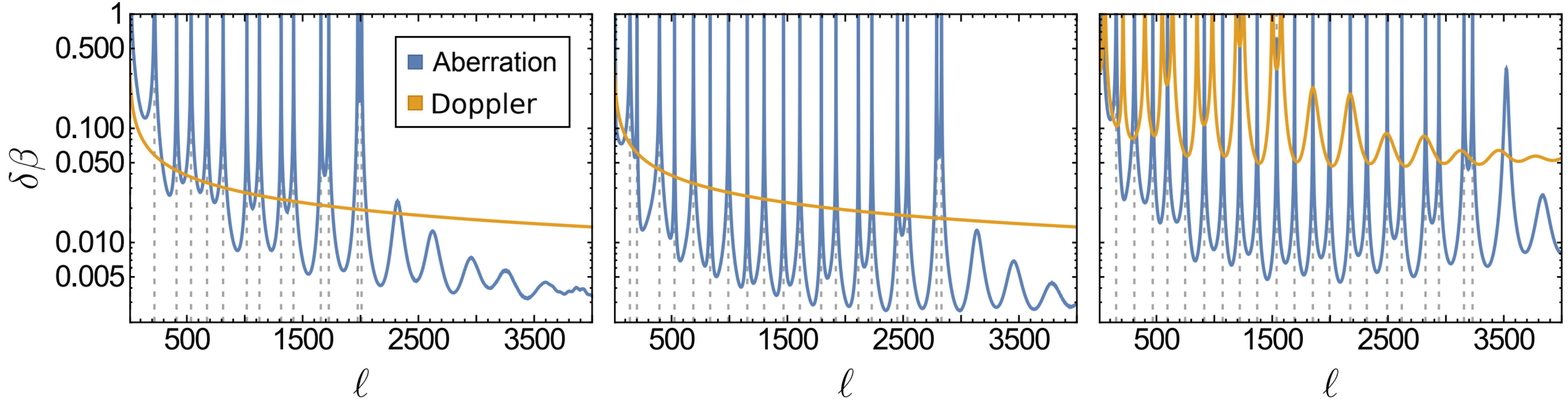


# Expected error by ℓ




$$\delta\beta^{\mathrm{A}}(\ell)\Big|_{XX} \simeq 2.451\,[2\ell+1]^{-1/2}\left(\frac{\mathrm{d}\ln\mathcal{D}_\ell^{XX}}{\mathrm{d}\ln\ell}\right)^{-1}$$

$$\delta\beta^{\mathrm{D}}(\ell)\Big|_{XX} \simeq 1.225\,[2\ell+1]^{-1/2}.$$



# Dipole Distortions (DD)

$$X^{\mathrm{SMICA}\,T}_{\ell\nu} = \frac{W^{\mathrm{Full},T}_{\ell\nu}}{b_{\ell\nu}c_{\nu}} + \mathcal{P}(\ell)\left[\frac{W^{\mathrm{High},T}_{\ell\nu}}{b_{\ell\nu}} - \frac{W^{\mathrm{Full},T}_{\ell\nu}}{b_{\ell\nu}c_{\nu}}\right], \quad (23)$$

$$X^{\mathrm{NILC}\,T}_{\ell\nu} = \frac{\sum_{\mathrm{band}} W^{\mathrm{NMW},T,\mathrm{band}}_{\nu} h^{\mathrm{band}}_{\ell}}{\sum_{\mathrm{band}} h^{\mathrm{band}}_{\ell}} . \quad (24)$$

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

$$\mathrm{DD}^{\mathrm{M}}_{\mathrm{bin}} \equiv \frac{\sum_{\ell=200(\mathrm{bin}-1)+2}^{200\mathrm{bin}+1} (2\ell+1)\mathrm{DD}^{\mathrm{M}}(\ell)}{\sum_{\ell=200(\mathrm{bin}-1)+2}^{200\mathrm{bin}+1} (2\ell+1)}$$