CMB Distortions due to Peculiar Motion and Intrinsic Anomalies

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[1] In collaboration with M.Quartin, O.Roldan, and earlier work with R.Catena, M.Liguori, A.Renzi, L.Amendola, I.Masina, C.Quercellini.
JCAP 1606 (2016) no.06, 026, , arXiv:1510.08793,
JCAP 1509 (2015) 09, 050
JCAP 1506 (2015) 06, 047
JCAP 1501 (2015) 01, 008
JCAP 1403 (2014) 019
JCAP 1309 (2013) 036

JCAP 1202 (2012) 026; JCAP 1107 (2011) 027

CMB as a test of Global Isotropy

- Is the CMB statistically Isotropic?

- What is the impact of our peculiar velocity?

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- Can we disentangle them?

CMB spectrum

More precisely

- $T(\hat{n}) \rightarrow a_{\ell m}$

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Hypothesis of Gaussianity and Isotropy:

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Hypothesis of Gaussianity and Isotropy:

- $a_{\ell m}$ random numbers from a Gaussian of width C_ℓ^{th}.
- Physics fixes $C_\ell^{th} = \langle |a_{\ell m}|^2 \rangle$
- Uncorrelated: NO preferred direction

CMB: Peculiar Velocity and Anomalies

- Our velocity $\beta \equiv \frac{v}{c}$ breaks Isotropy introducing correlations in the CMB at *all* scales

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- Doppler:
  $T'(\hat{n}) = T(\hat{n})\gamma(1+\beta\cos\theta) \qquad (\cos(\theta) = \hat{n}\cdot\hat{\beta})$
- Aberration:
  $T'(\hat{n'}) = T(\hat{n})$
  with $\cos\theta - \cos\theta' = \beta\frac{\sin^2\theta}{1+\beta\cos\theta}$
  $\theta - \theta' \approx \beta\sin\theta$

Peebles & Wilkinson ’68, Challinor & van Leeuwen 2002, Burles & Rappaport 2006

In multipole space

Mixing of neighbors:

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$$a'_{\ell m} \simeq a_{\ell m} + \beta(c^-_{\ell m} a_{\ell-1\, m} + c^+_{\ell m} a_{\ell+1\, m}) + \mathcal{O}((\beta\ell)^2)$$

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- $c^+_{\ell m} = (\ell + 2 - 1)\sqrt{\frac{(\ell+1)^2 - m^2}{4(\ell+1)^2 - 1}}$
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- Doppler (constant), aberration grows with ℓ!

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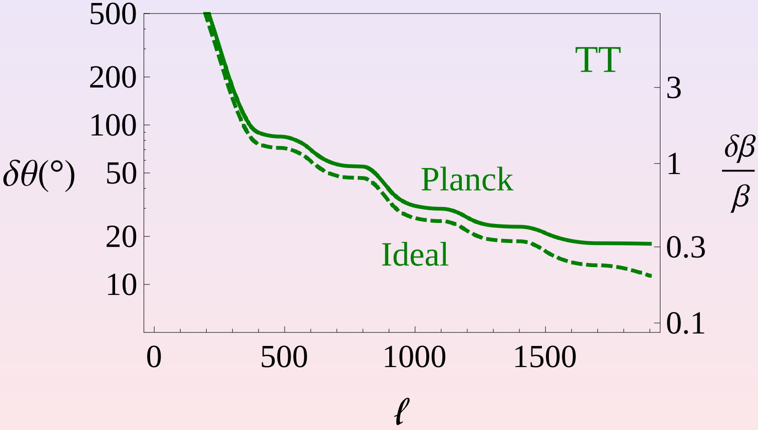
- Doppler (constant), aberration grows with ℓ!
- We can measure β through $\langle a_{\ell m} a_{\ell+1\, m}\rangle \neq 0$

  (Kosowsky & Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011, Planck XXVII, 2013.)

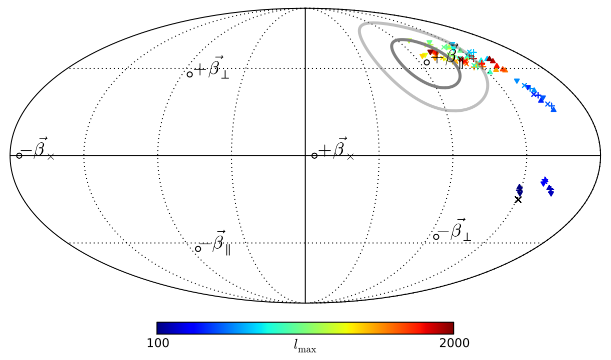
Expected sensitivity



L.Amendola, R.Catena, I.Masina, A.N., M.Quartin, C.Quercellini 2011

Planck Measurement

$$\beta = 384 km/s \pm 78 km/s \text{ (stat) } \pm 115 km/s \text{ (syst.)}$$



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

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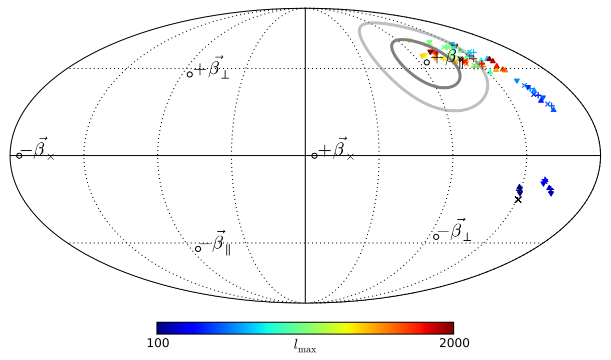

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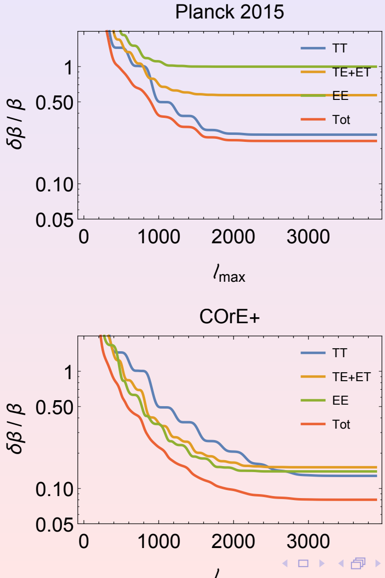
Found both Aberration and Doppler

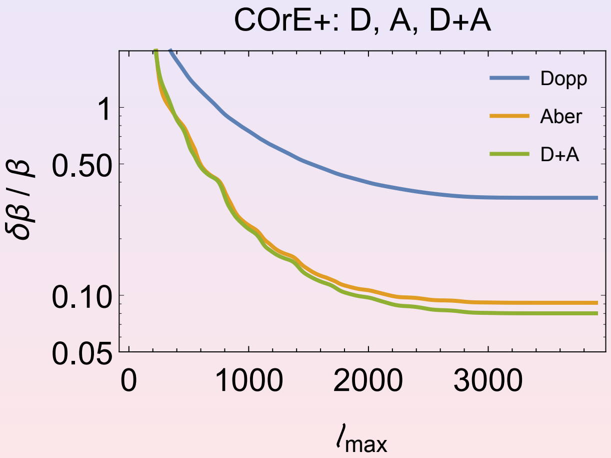
Forecasts

Experiment	# ν bands	$10^6\sigma_T(\frac{\mu K}{K})$	$10^6\sigma_P\,(\frac{\mu K}{K})$	$\theta_{\rm fwhm}$	$f_{\rm sky}$	S/N
ACBAR '08 [26]	1	0.9	–	$4.8'$	1.7%	1.0
WMAP (9 years) [27, 28]	5	14	20	$13.2' - 52.8'$	78%	0.7
EBEX [29]	3	0.33	0.48	$8'$	1%	0.9
BICEP2 (2 years) [30, 31]	1	3.2	4.6	$0.6'$	2%	2.5
Planck (30 months) [28, 32]	7	1.0 – 8.4	1.7 – 14.5	$4.7' - 32.7'$	80%	5.9
SPT SZ [33, 34]	3	5.7 – 30	–	$1.0' - 1.6'$	6%	2.0
SPTPol (3 years) [35]	2	1.3 – 1.5	1.9 – 2.1	$1.0' - 1.6'$	1.6%	2.5
SPTPol Wider (6 years)	2	2.4 – 2.6	3.3 – 3.7	$1.0' - 1.6'$	10%	5.2
ACTPol Deep (1 year) [36]	2	0.5 – 2.2	0.7 – 3.1	$1.0' - 1.4'$	0.36%	1.4
ACTPol Wide (1 year) [36]	2	2.5 – 11	3.5 – 16	$1.0' - 1.4'$	10%	4.4
ACTPol Wider (4 years)	2	2.5 – 11	3.5 – 16	$1.0' - 1.4'$	40%	8.8
COrE (4 years) [28]	15	0.07 – 9.0	0.12 – 15.6	$2.8' - 23.3'$	80%	14
EPIC 4K [37]	9	0.08 – 0.82	0.11 – 1.2	$2.5' - 28'$	80%	16
EPIC 30K [37]	9	0.20 – 4.4	0.28 – 6.2	$2.5' - 28'$	80%	13
Ideal Exp. (up to $\ell = 6000$)	Any	0	0	$0'$	100%	44

Expected sensitivity



Separating Doppler and Aberration



Aberration grows at high ℓ

Is β degenerate with an Intrinsic Dipole?[3]

- A dipolar large scale potential: $\Phi_D = \cos(\theta)\phi(r)$
  $\Phi_{TOT} = \Phi + \Phi_D$

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- Produces a CMB dipole $T_D = \frac{1}{3}\cos(\theta)\phi(r_{LSS})$
- It also produces couplings at 2nd order $\mathcal{O}(\Phi\,\Phi_D)$: degenerate with a boost?

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- A mismatch between $\beta_{\ell=1}$ and Doppler couplings would have 2 implications:
    - Unexpected large intrinsic dipole
    - Non-Gaussianity

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- Measuring agreement between $\beta_{\ell=1}$ and Aberration-couplings → boost.

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Is β degenerate with an Intrinsic Dipole?[6]

	10^{-3} dipole	10^{-8} Doppler-like couplings	10^{-8} aberration-like couplings
Peculiar velocity	yes	yes	yes
Dipolar Φ	yes	yes*	only with fine-tuning
Non-Gauss. dipolar Φ	yes	different	only with fine-tuning

* Reminder: we have only been able to prove the corresponding result on large scales.

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[6] O.Roldan, A.N., M.Quartin 2016

Testing Isotropy

- Given a map $T(\hat{n})$: mask half of the sky: $\tilde{T}(\hat{n}) = M(\hat{n})T(\hat{n})$
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- And compare two opposite halves $\tilde{C}_\ell^N$ and $\tilde{C}_\ell^S$

Hemispherical asymmetry?

- In several papers: significant (about 3σ) hemispherical asymmetry of Amplitude $A \sim 7\%$ at $\ell < \mathcal{O}(60)$

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- And also to the Planck data! (Up to which ℓ?)

  Planck Collaboration 2013, XIII. Isotropy and Statistics.

Planck asymmetry

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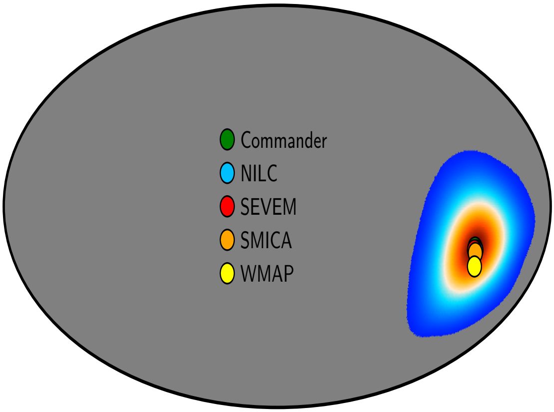

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A.N., M.Quartin & R.Catena, JCAP Apr. ’13

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- We find (A.N., M.Quartin & JCAP '14, Planck Collaboration 2013, XIII. Isotropy and Statistics)
  - $2.5 - 3\sigma$ anomaly only at $\ell \lesssim 600$
  - With decreasing Amplitude (from 7% to 1%)

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- Use Planck data up to $\ell = 2000$ (M. Quartin & A.N. '14)

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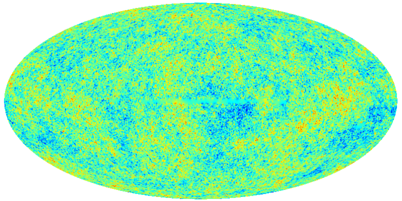

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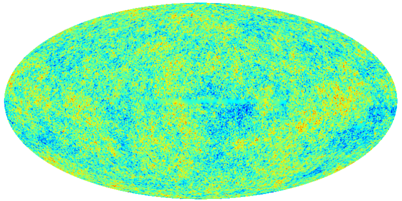
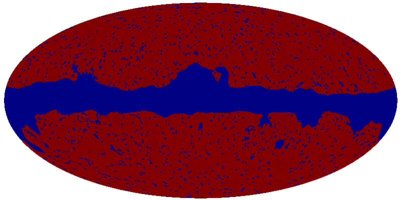


- Before this, we mask Galaxy and point sources!



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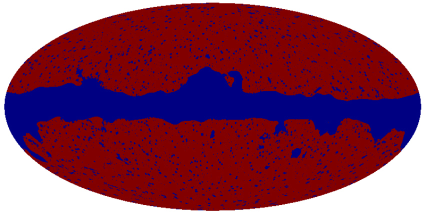

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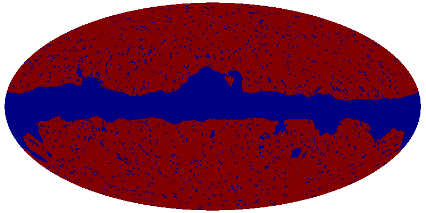
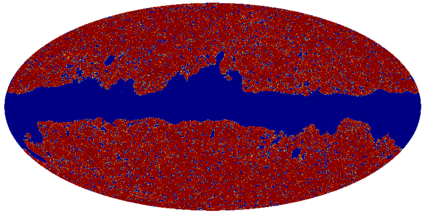


- We produced a Symmetrized U73 (M. Quartin & A.N. '14)



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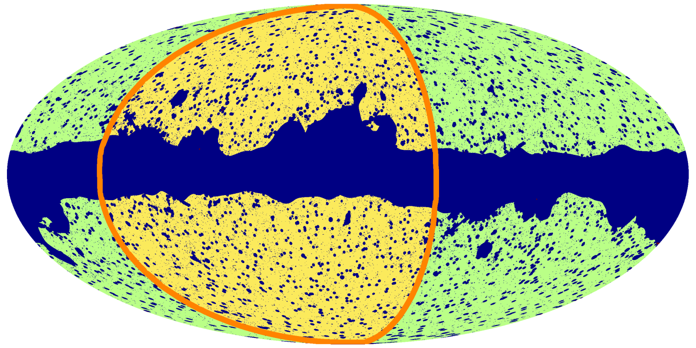
- We mask Planck (symmetrized mask)
- And then we cut the sky into two parts (N vs. S)



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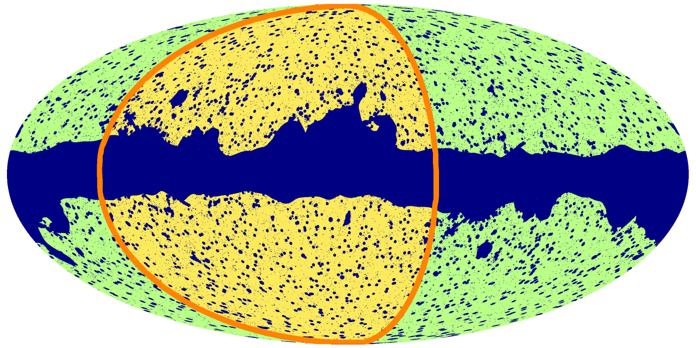
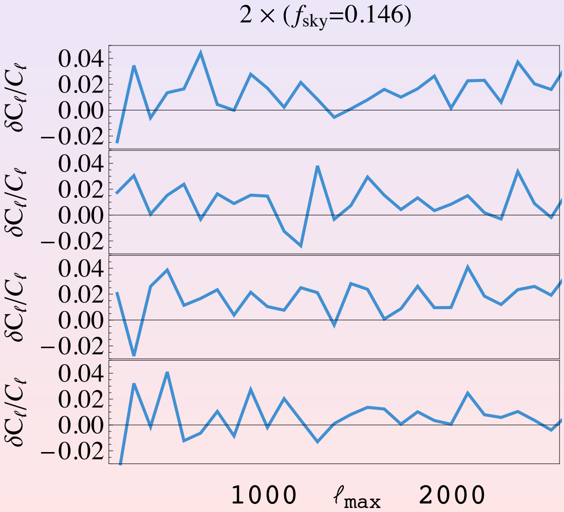


- Smoothing the cut!

Hemispherical Asymmetry due to Velocity

$\beta = 1.23 \times 10^{-3}$



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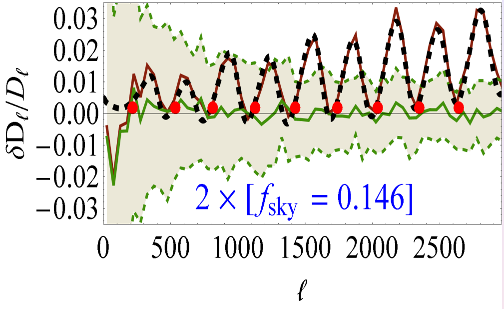

Figure: Discs along the Dipole direction

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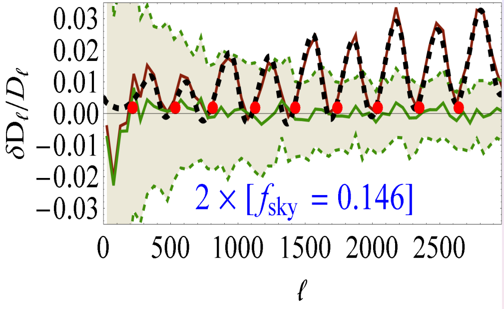

Figure: Discs along the Dipole direction

For a small disc:

$$\frac{\delta C_\ell}{C_\ell} \simeq 4\beta + 2\beta\ell C'_\ell$$

A.N., M.Quartin, R.Catena 2013

“Dipolar modulation"?

- Several authors have studied the ansatz

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- 3-σ detection of A_{mod} along max. asymm. direction (For $\ell < 60$ or $\ell < 600$)

- $A_{\rm mod}$ 60 times bigger than β! (at $\ell < 60$)

Our Results on A

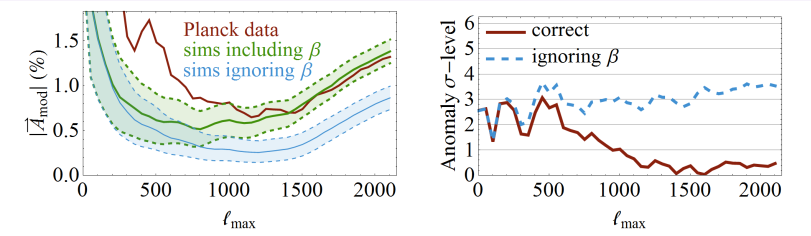

Figure: All simulations include Planck noise asymmetry.

A.N. & M.Quartin, 2014

Dipolar modulation on Large Scales?

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- Polarization maps! (LiteBIRD, COrE) Assuming some model
- Large Scale Structure?

Frequency dependence??

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- But, consider Intensity:

$$I(\nu) = \frac{2\nu^3}{e^{\frac{\nu}{T(\hat{\boldsymbol{n}})}} - 1} .$$

- Linearizing Intensity we get (WMAP, PLANCK...)

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

Frequency dependence??

- At second order:

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

where $Q(\nu) \equiv \nu/(2\nu_0)\coth[\nu/(2\nu_0)]$.

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- Spurious *y*-distortion
- Degenerate with tSZ and primordial *y*-distortion
- Any *T* fluctuation produces this

Frequency dependence??

- Dominated by dipole $\Delta_1 = \beta + \text{intrinsic dipole}$ [7]

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[7] Knox,Kamionkowski '04, Chluba, Sunyaev '04, Planck 2013 results. XXVII., A.N. & Quartin '16

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$$L(\nu, \hat{\boldsymbol{n}}) = \mu\Delta_1 + \frac{\delta T}{T_0} - \tilde{\beta}\mu\frac{\delta T}{T_0} + \tilde{\beta}\left(\frac{\delta T_{ab}}{T_0}\right) + \\ + \left[\left(\mu^2 - \frac{1}{3}\right)\Delta_1^2 + \frac{1}{3}\Delta_1^2 + 2\Delta_1\mu\frac{\delta T}{T_0}\right]Q(\nu)\,.$$

- Quadrupole (10^{-7})
- Monopole (10^{-7})
- Couplings (10^{-8})

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- Quadrupole (10^{-7})
- Monopole (10^{-7})
- Couplings (10^{-8})

- "Spurious" spectral *y*-distortions : degenerate with primordial *y*-distortions, and tSZ

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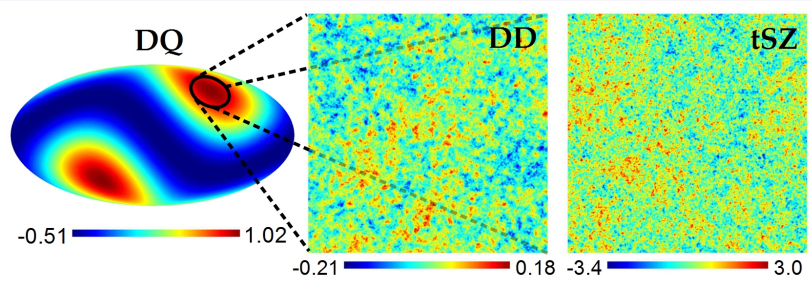
Spurious y signal



A.N. & M.Quartin, 2016

Planck Calibration?

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- WMAP calibrated using $\beta_{ORBITAL}$ ($\approx 10^{-4}$)
- Planck 2013 on β_{SUN} (using WMAP!)
- Planck 2015 calibrated on $\beta_{ORBITAL}$

Planck Calibration?

- Splitting $\beta_{\boldsymbol{TOT}} = \beta_{\boldsymbol{S}} + \beta_{\boldsymbol{O}}$:

$$
\begin{aligned}
\delta I_\nu &= \frac{\delta T}{T_0} + \beta_{\boldsymbol{S}} \cdot \hat{\boldsymbol{n}} + \beta_{\boldsymbol{O}} \cdot \hat{\boldsymbol{n}} + \\
&+ Q(\nu)\left[(\beta_{\boldsymbol{S}} \cdot \hat{\boldsymbol{n}})^2 + (\beta_{\boldsymbol{O}} \cdot \hat{\boldsymbol{n}})^2 + 2(\beta_{\boldsymbol{S}} \cdot \hat{\boldsymbol{n}})(\beta_{\boldsymbol{O}} \cdot \hat{\boldsymbol{n}})\right]
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- Subleading $\approx 10^{-6}$, 1-year or 6-months periodicity

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- $Q(\nu)$ corrections should be included in Planck Calibration: might represent up to $\mathcal{O}(1\%)$ systematics

(A.N. & M.Quartin '2015)

WMAP/Planck Quadrupole-Octupole alignments

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- From a_{2m} and a_{3m} → Multipole vectors → $\hat{n}_2, \hat{n}_3$.

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Another anomaly:

- From a_{2m} and a_{3m} → Multipole vectors → $\hat{n}_2, \hat{n}_3$.
- $\hat{n}_2 \cdot \hat{n}_3 \approx 0.99$
- And also Dipole-Quadrupole-Octupole $(\hat{n}_1, \hat{n}_2, \hat{n}_3)$ aligned (*e.g.*Copi et al. '13)

Removing Doppler quadrupole

- Planck data initially showed less alignment than WMAP: 2.3σ for $\hat{n}_1 \cdot \hat{n}_2$ (SMICA 2013)

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- Using $Q_{\rm eff} \approx 1.7$ on SMICA 2013, (A.N. & M.Quartin, JCAP 2015)

  $\rightarrow 3.3\sigma$ for $\hat{n}_1 \cdot \hat{n}_2$