Peculiar velocity effects and CMB anomalies

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[1] In collaboration with: M.Quartin, O.Roldan, earlier work with R.Catena, M.Liguori, A.Renzi, L.Amendola, I.Masina, C.Quercellini

JCAP 1606 (2016) no.06, 026, Phys.Rev. D94 (2016) no.4, 043006 ,
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
and “Exploring cosmic origins with CORE: effects of observer peculiar motion",
CORE Collaboration, JCAP 1804 (2018) no.04, 021

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

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Hypothesis of Gaussianity and Isotropy:

- $a_{\ell m}$ random numbers from a Gaussian of width C^{th}_ℓ.
- Physics fixes $C^{th}_\ell = \langle |a_{\ell m}|^2 \rangle$
- 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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  $T'(\hat{n}) = T(\hat{n})\gamma(1 + \beta\cos\theta)$ $\quad$ $(\cos(\theta) = \hat{n}\cdot\hat{\beta})$

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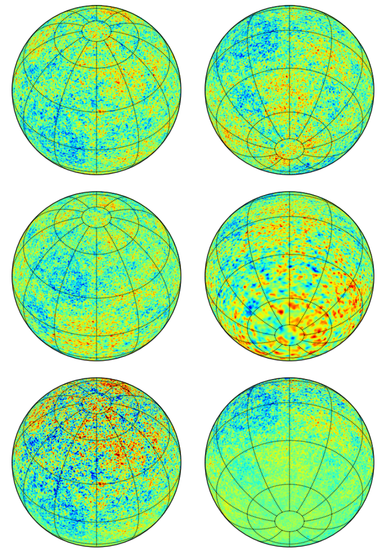
- Doppler:
  $T'(\hat{n}) = T(\hat{n})\gamma(1 + \beta \cos\theta) \qquad (\cos(\theta) = \hat{n} \cdot \hat{\beta})$
- Aberration:
  $T'(\hat{n}') = T(\hat{n})$
  $\theta - \theta' \approx \beta \sin\theta$

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

Aberration & Doppler



In multipole space

Mixing of neighbors:

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Mixing of neighbors:

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

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- $c^+_{\ell m} = (\ell + 2 - 1)\sqrt{\frac{(\ell+1)^2 - m^2}{4(\ell+1)^2 - 1}}$

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

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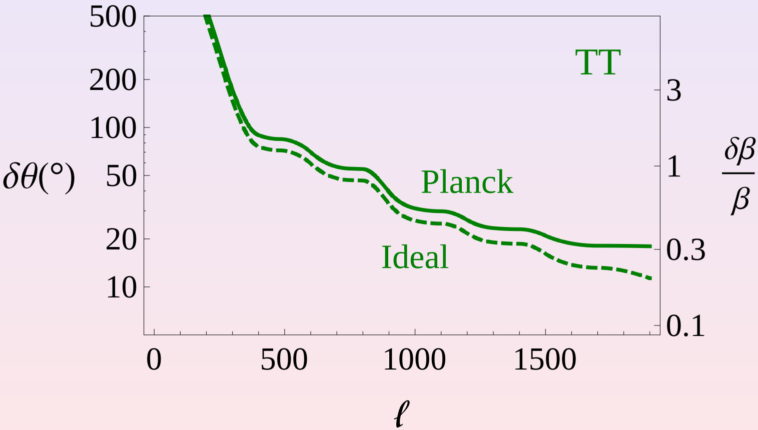
- Doppler (constant), aberration grows with ℓ!
- We can measure β (Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011, Planck XXVII, 2013.)

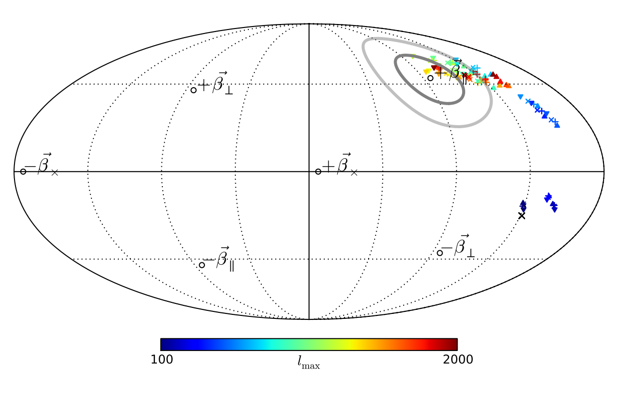
Expected sensitivity



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

Planck Measurement

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



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

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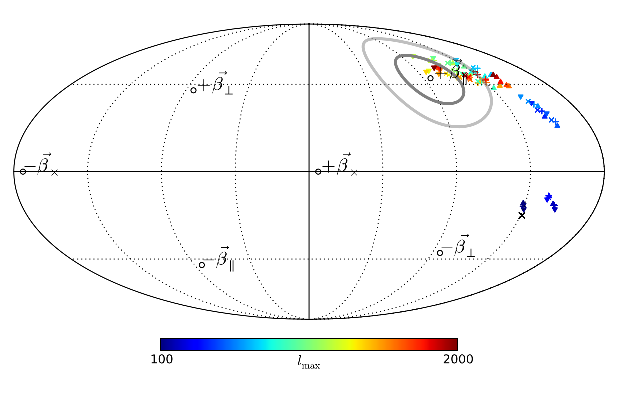

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Found both Aberration and Doppler

Different frequencies

- $\beta = 384 km/s \pm 78 km/s$ (stat) $\pm 115 km/s$ (syst.)
- Systematics are present (discrepancy between different frequency maps for Aberration)

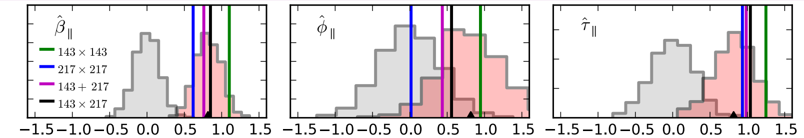

Figure: Total: β. Aberration: ϕ. Doppler: τ.

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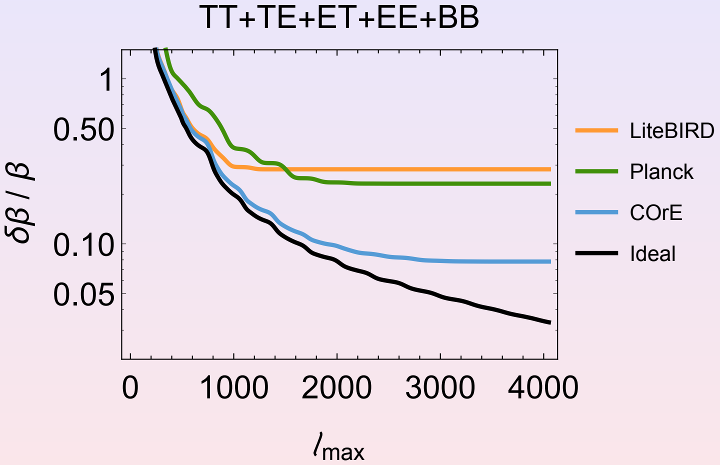
Forecasts



“Exploring cosmic origins with CORE: effects of observer peculiar motion", CORE Collaboration, JCAP 2018

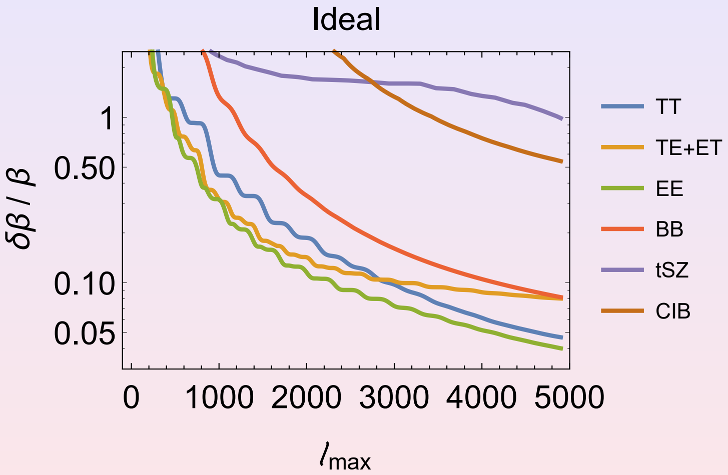
Forecasts: Other Sources

CMB

CMB & Proper motion

Anomalies

Frequency dependence



CIB and tSZ maps

“Exploring cosmic origins with CORE: effects of observer peculiar motion", CORE Collaboration, JCAP 2018

Forecasts

Experiment	Channel [GHz]	θ_{FWHM} [arcmin]	σ^T [μK.arcmin]	S/N TT	S/N $TE+ET$	S/N EE	S/N Total
Planck	(all)	$\simeq 5.5$	$\simeq 13$	3.8	1.7	1.0	4.3
LiteBIRD	(all)	$\simeq 19$	$\simeq 1.7$	2.0	1.8	1.8	3.3
CORE	60	17.87	7.5	2.1	1.9	1.8	3.4
	70	15.39	7.1	2.5	2.4	2.2	4.1
	80	13.52	6.8	2.8	2.8	2.6	4.8
	90	12.08	5.1	3.5	3.4	3.3	5.9
	100	10.92	5	3.9	3.7	3.7	6.5
	115	9.56	5	4.3	4.2	4.2	7.3
	130	8.51	3.9	5.1	4.9	5.	8.6
	145	7.68	3.6	5.7	5.3	5.5	9.5
	160	7.01	3.7	6.1	5.6	5.8	10.1
	175	6.45	3.6	6.5	5.8	6.1	10.7
	195	5.84	3.5	7.1	6.1	6.5	11.4
	220	5.23	3.8	7.5	6.3	6.7	11.9
	255	4.57	5.6	7.5	5.9	6.2	11.4
	295	3.99	7.4	7.5	5.7	5.8	11.
	340	3.49	11.1	7.	5.1	4.9	9.9
	390	3.06	22	5.8	3.8	3.1	7.6
	450	2.65	45.9	4.5	2.3	1.4	5.3
	520	2.29	116.6	2.9	1.	0.3	3.1
	600	1.98	358.3	1.4	0.3	0.	1.4
	(all)	$\simeq 4.5$	$\simeq 1.4$	8.2	6.6	7.3	12.8
Ideal ($\ell_{\max} = 2000$)	(all)	0	0	5.3	7.1	8.7	12.7
Ideal ($\ell_{\max} = 3000$)	(all)	0	0	10	9.8	14	21
Ideal ($\ell_{\max} = 4000$)	(all)	0	0	16	11.4	19	29
Ideal ($\ell_{\max} = 5000$)	(all)	0	0	22	12.6	26	38

Is β degenerate with an Intrinsic Dipole?

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

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- A dipolar large scale potential: $\Phi_L = \cos(\theta) f(r)$
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- Φ_L produces dipolar Lensing = Aberration ?
- Yes, but coefficient: generically depends on $f(r)$:
- $\Longrightarrow$ non-degenerate with Aberration ($f(r) \propto r^2$)

[3] 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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Hemispherical asymmetry?

- In several papers: significant (about 3σ) hemispherical asymmetry at $\ell < \mathcal{O}(60)$

  Eriksen et al. ’04, ’07, Hansen et al. ’04, ’09, Hoftuft et al. ’09, Bernui ’08, Paci et al. ’13

- The claim extends also to $\ell \leq 600$ (WMAP)

  Hansen et al. ’09

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

  Planck Collaboration, XIII. Isotropy and Statistics.

Planck asymmetry

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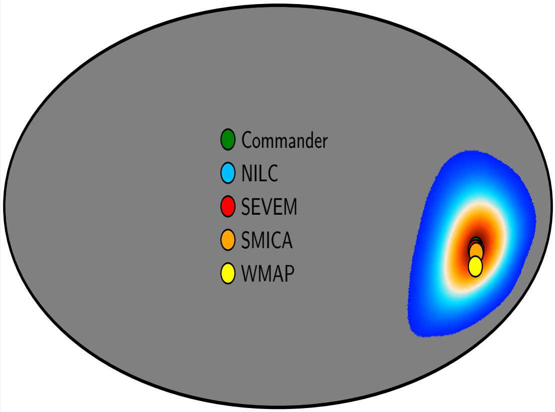
- Same as in WMAP



Hemispherical Asymmetry at high ℓ?

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

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- We find between $2.5 - 3\sigma$ anomaly only at $\ell \lesssim 600$

  (A.N., M.Quartin & JCAP '14, Planck Collaboration 2013, XIII. Isotropy and Statistics)

Hemispherical Asymmetry due to Velocity

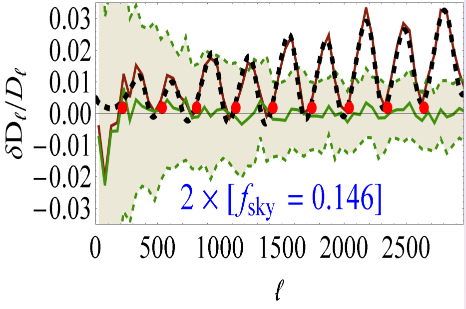

Figure: Discs along the Dipole direction

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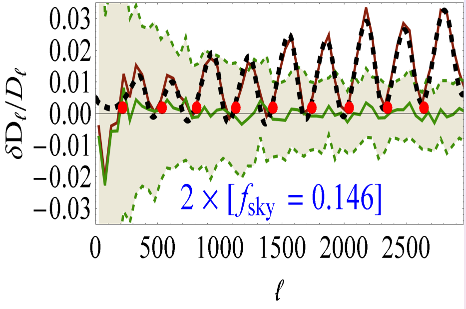

Figure: Discs along the Dipole direction

- For a small disc (along Dipole direction):

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

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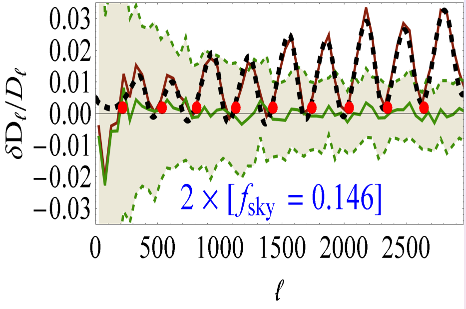

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- Small area experiments bias (*i.e.* CMB peaks position shifts of 0.5% in ACT) A.N., M.Quartin, R.Catena 2013

“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_{mod} 60 times bigger than β! (at $\ell < 60$)

Our Results on A

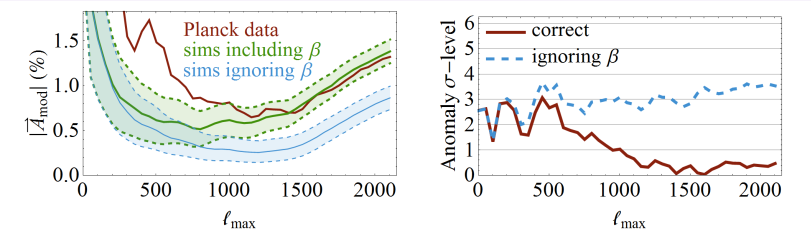

Figure: All simulations include Planck noise asymmetry.

A.N. & M.Quartin, 2014

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

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- Linearize Intensity: (WMAP, PLANCK...):
- Using $T \equiv T_0 + \Delta T(\hat{n})$, $I \equiv I_0 + \Delta I(\hat{n})$, we get

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

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 Δ_1 [4]

[4] Knox,Kamionkowski '04, Chluba, Sunyaev '04, Planck , 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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- Caveat : $\Delta_1 = \beta + \text{intrinsic dipole}$

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WMAP/Planck Quadrupole-Octupole alignments

Another anomaly:

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- $\hat{n}_2 \cdot \hat{n}_3 \approx 0.99$

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Another anomaly:

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

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- Using $Q_{\text{eff}} \approx 1.7$ on SMICA 2013, (A.N. & M.Quartin, JCAP 2015) $\Longrightarrow \boxed{3.3\sigma}$ for $\hat{n}_1 \cdot \hat{n}_2$
- ...and agreement among different maps!

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Planck Calibration?

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4. Never use linearized temperature $\Delta I(\hat{n}) = H \Delta T(\hat{n})$, to avoid spurious frequency dependence (calibration, maps...)