On Planck CMB Anomalies, Alignments and Calibration

Alessio Notari [1]

June 2015, Santander, “Meeting on Fundamental Cosmology”

[1] In collaboration with M.Quartin and earlier work with R.Catena, L.Amendola, I.Masina, C.Quercellini.
arXiv:1504.04897
JCAP 032P 0415
JCAP 1501 (2015) 01, 008
JCAP 1403 (2014) 019
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?

  $(\beta = \frac{v}{c} = 10^{-3})$

CMB spectrum

More precisely

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

CMB spectrum

More precisely

- $T(\hat{n}) \to a_{\ell m} \equiv \int d\Omega\, Y^*_{\ell m}(\hat{n})\, T(\hat{n})$

CMB spectrum

More precisely

- $T(\hat{n}) \to a_{\ell m} \equiv \int d\Omega\, Y^*_{\ell m}(\hat{n}) T(\hat{n})$

Hypothesis of Gaussianity and Isotropy:

CMB spectrum

More precisely

- $T(\hat{n}) \to a_{\ell m} \equiv \int d\Omega\, Y^*_{\ell m}(\hat{n}) T(\hat{n})$

Hypothesis of Gaussianity and Isotropy:

- Physics fixes $C^{th}_\ell = \langle |a_{\ell m}|^2 \rangle$
- $a_{\ell m}$ random numbers from a Gaussian of width C^{th}_ℓ.
- 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

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

1. We can measure β with $\ell = 1$

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

1. We can measure β with $\ell = 1$ and $\ell > 1$![2]

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

1. We can measure β with $\ell = 1$ and $\ell > 1$![2]
2. Anomalies?

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

1. We can measure β with $\ell = 1$ and $\ell > 1$![2]
2. Anomalies?
3. Important for Alignments?

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

1. We can measure β with $\ell = 1$ and $\ell > 1$![2]
2. Anomalies?
3. Important for Alignments?
4. Important for Calibration??

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

CMB: Peculiar Velocity and Anomalies

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

  (not only $\ell = 1$!)

1. We can measure β with $\ell = 1$ and $\ell > 1$![2]
2. Anomalies?
3. Important for Alignments?
4. Important for Calibration??

[2] Kosowsky Kahniashvili, '2011, L. Amendola, Catena, Masina, A. N., Quartin'2011. Measured in Planck XXVII, 2013.

Effects of β

$T(\hat{n})$ (CMB Rest frame) $\Rightarrow$ $T'(\hat{n}')$ (Our frame)

Effects of β

$T(\hat{n})$ (CMB Rest frame) $\Rightarrow$ $T'(\hat{n}')$ (Our frame)

Preferred direction $\hat{\beta}$

Effects of β

$T(\hat{n})$ (CMB Rest frame) $\Rightarrow$ $T'(\hat{n}')$ (Our frame)

Preferred direction $\hat{\beta}$

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

Effects of β

$T(\hat{n})$ (CMB Rest frame) $\Rightarrow$ $T'(\hat{n}')$ (Our frame)

Preferred direction $\hat{\beta}$

- 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:

In multipole space

Mixing of neighbors:

$$a'_{\ell m} \simeq a_{\ell m} + \beta(c^{-}_{\ell m} a_{\ell-1\, m} + c^{+}_{\ell m} a_{\ell+1\, m}) + \mathcal{O}((\beta\ell)^2 \cdot a_{\ell\pm0,2})$$

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

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

In multipole space

Mixing of neighbors:

$$a'_{\ell m} \simeq a_{\ell m} + \beta(c^-_{\ell m} a_{\ell-1\, m} + c^+_{\ell m} a_{\ell+1\, m}) + \mathcal{O}((\beta\ell)^2 \cdot a_{\ell\pm 0,2})$$

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

In multipole space

Mixing of neighbors:

$$a'_{\ell m} \simeq a_{\ell m} + \beta(c^-_{\ell m} a_{\ell-1\, m} + c^+_{\ell m} a_{\ell+1\, m}) + \mathcal{O}((\beta\ell)^2 \cdot a_{\ell\pm 0,2})$$

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

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

In multipole space

Mixing of neighbors:

$$a'_{\ell m} \simeq a_{\ell m} + \beta(c^-_{\ell m} a_{\ell-1\, m} + c^+_{\ell m} a_{\ell+1\, m}) + \mathcal{O}((\beta\ell)^2 \cdot a_{\ell\pm0,2})$$

- $c^+_{\ell m} = (\ell + 2 - 1)\sqrt{\frac{(\ell+1)^2 - m^2}{4(\ell+1)^2 - 1}}$
  $c^-_{\ell m} = -(\ell - 1 + 1)\sqrt{\frac{\ell^2 - m^2}{4\ell^2 - 1}}$
- Doppler (constant), aberration grows with ℓ!
- For $\ell > 1/\beta \approx 800$ more neighbors are coupled

$$a'_{\ell m} = \sum_{\ell'} K_{\ell\ell' m} a_{\ell' m}$$

Doppler Dipole and Quadrupole

A monopole leaks into

- a dipole ($\beta \approx 10^{-3}$)

Doppler Dipole and Quadrupole

A monopole leaks into

- a dipole ($\beta \approx 10^{-3}$)
- a quadrupole ($\beta^2 \approx 10^{-6}$):

$$T'(\hat{\boldsymbol{n}}') \propto T_0 + (\boldsymbol{\beta} \cdot \hat{\boldsymbol{n}}) + (\boldsymbol{\beta} \cdot \hat{\boldsymbol{n}})^2 - \frac{1}{2}\beta^2 + \dots,$$

WMAP/Planck Quadrupole-Octupole alignments

A possible anomaly:

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

WMAP/Planck Quadrupole-Octupole alignments

A possible anomaly:

- From a_{2m} and a_{3m} $\rightarrow$ Multipole vectors $\rightarrow$ $\hat{n}_2, \hat{n}_3$.
- $\hat{n}_2 \cdot \hat{n}_3 \approx 0.99$

WMAP/Planck Quadrupole-Octupole alignments

A possible anomaly:

- From a_{2m} and a_{3m} $\to$ Multipole vectors $\to$ $\hat{n}_2, \hat{n}_3$.
- $\hat{n}_2 \cdot \hat{n}_3 \approx 0.99$
- 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 shows less alignment than WMAP: 2.3σ for $\hat{n}_1 \cdot \hat{n}_2$ (SMICA 2013)

[3] Copi et al. '13

Removing Doppler quadrupole

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

[3] Copi et al. '13

Removing Doppler quadrupole

- Planck data shows less alignment than WMAP: 2.3σ for $\hat{n}_1 \cdot \hat{n}_2$ (SMICA 2013)
- After removing Doppler $\rightarrow 2.9\sigma$ [3] (agreement with WMAP)

[3] Copi et al. '13

Frequency dependence!

- The Dopper Quadrupole in Intensity is frequency dependent: [4]

$$\delta I'(\nu') \propto \frac{\delta T(\hat{\boldsymbol{n}})}{T_0} + (\boldsymbol{\beta} \cdot \hat{\boldsymbol{n}}) + Q(\nu)(\boldsymbol{\beta} \cdot \hat{\boldsymbol{n}})^2 - \frac{1}{2}\beta^2 + \ldots,$$

where

$$Q(\nu') = \frac{\nu'}{2T_0} \coth\left(\frac{\nu'}{2T_0}\right).$$

[4] Sazonov & Sunyaev '99, Kamionkowski & L. Knox '04, Chluba & Sunyaev '04

Frequency dependence!

- The Dopper Quadrupole in Intensity is frequency dependent: [4]

$$\delta I'(\nu') \propto \frac{\delta T(\hat{\boldsymbol{n}})}{T_0} + (\boldsymbol{\beta} \cdot \hat{\boldsymbol{n}}) + Q(\nu)(\boldsymbol{\beta} \cdot \hat{\boldsymbol{n}})^2 - \frac{1}{2}\beta^2 + \ldots ,$$

where

$$Q(\nu') = \frac{\nu'}{2T_0} \coth\left(\frac{\nu'}{2T_0}\right) .$$

- Using $Q_{\rm eff} \approx 1.7$ (SMICA 2013)

$\rightarrow 3.3\sigma$ for $\hat{n}_1 \cdot \hat{n}_2$ (A.N. & M.Quartin, JCAP 2015)

[4] Sazonov & Sunyaev '99, Kamionkowski & L. Knox '04, Chluba & Sunyaev '04

Frequency dependence!

- The Dopper Quadrupole in Intensity is frequency dependent: [4]

$$\delta I'(\nu') \propto \frac{\delta T(\hat{\boldsymbol{n}})}{T_0} + (\boldsymbol{\beta}\cdot\hat{\boldsymbol{n}}) + Q(\nu)(\boldsymbol{\beta}\cdot\hat{\boldsymbol{n}})^2 - \frac{1}{2}\beta^2 + \ldots,$$

where

$$Q(\nu') = \frac{\nu'}{2T_0}\coth\left(\frac{\nu'}{2T_0}\right).$$

- Using $Q_{\rm eff} \approx 1.7$ (SMICA 2013)

$\rightarrow$ 3.3σ for $\hat{n}_1 \cdot \hat{n}_2$ (A.N. & M.Quartin, JCAP 2015)

- $Q(\nu)$ weighted average in the range $1 - 5$ (HFI)

[4] Sazonov & Sunyaev '99, Kamionkowski & L. Knox '04, Chluba & Sunyaev '04

Planck Calibration?

- Doppler effect is used to calibrate the detectors!

Planck Calibration?

- Doppler effect is used to calibrate the detectors!

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

Planck Calibration?

- Splitting $\boldsymbol{\beta}_{\boldsymbol{TOT}} = \boldsymbol{\beta}_{\boldsymbol{S}} + \boldsymbol{\beta}_{\boldsymbol{O}}$ (A.N. & M.Quartin '2015) :

$$\delta I_\nu = \frac{\delta T}{T_0} + \boldsymbol{\beta}_{\boldsymbol{S}} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta}_{\boldsymbol{S}} \cdot \hat{\mathbf{n}})^2 + \boldsymbol{\beta}_{\boldsymbol{O}} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta}_{\boldsymbol{O}} \cdot \hat{\mathbf{n}})^2$$

$$+ 2\, Q(\nu)(\boldsymbol{\beta}_{\boldsymbol{S}} \cdot \hat{\mathbf{n}})(\boldsymbol{\beta}_{\boldsymbol{O}} \cdot \hat{\mathbf{n}}) - \beta_S \beta_O - \frac{1}{2}\beta_S^2 - \frac{1}{2}\beta_O^2 .$$

Planck Calibration?

- Splitting $\boldsymbol{\beta_{TOT}} = \boldsymbol{\beta_S} + \boldsymbol{\beta_O}$ (A.N. & M.Quartin '2015) :

$$\delta I_\nu = \frac{\delta T}{T_0} + \boldsymbol{\beta_S} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta_S} \cdot \hat{\mathbf{n}})^2 + \boldsymbol{\beta_O} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}})^2$$
$$+ 2\, Q(\nu)(\boldsymbol{\beta_S} \cdot \hat{\mathbf{n}})(\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}}) - \beta_S \beta_O - \frac{1}{2}\beta_S^2 - \frac{1}{2}\beta_O^2 .$$

- Leading $\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}} \approx 10^{-4}$

Planck Calibration?

- Splitting $\boldsymbol{\beta_{TOT}} = \boldsymbol{\beta_S} + \boldsymbol{\beta_O}$ (A.N. & M.Quartin '2015) :

$$\delta I_\nu = \frac{\delta T}{T_0} + \boldsymbol{\beta_S} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta_S} \cdot \hat{\mathbf{n}})^2 + \boldsymbol{\beta_O} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}})^2$$
$$+ 2\,Q(\nu)(\boldsymbol{\beta_S} \cdot \hat{\mathbf{n}})(\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}}) - \beta_S \beta_O - \frac{1}{2}\beta_S^2 - \frac{1}{2}\beta_O^2 \,.$$

- Leading $\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}} \approx 10^{-4}$
- Subleading $\approx 10^{-6}$

$Q(\nu) \approx (1.25, 1.5, 2.0, 3.1)$ for HFI!

Planck Calibration?

- Splitting $\boldsymbol{\beta_{TOT}} = \boldsymbol{\beta_S} + \boldsymbol{\beta_O}$ (A.N. & M.Quartin '2015) :

$$\delta I_\nu = \frac{\delta T}{T_0} + \boldsymbol{\beta_S} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta_S} \cdot \hat{\mathbf{n}})^2 + \boldsymbol{\beta_O} \cdot \hat{\mathbf{n}} + Q(\nu)(\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}})^2 + 2\,Q(\nu)(\boldsymbol{\beta_S} \cdot \hat{\mathbf{n}})(\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}}) - \beta_S \beta_O - \frac{1}{2}\beta_S^2 - \frac{1}{2}\beta_O^2 .$$

- Leading $\boldsymbol{\beta_O} \cdot \hat{\mathbf{n}} \approx 10^{-4}$
- Subleading $\approx 10^{-6}$

  $Q(\nu) \approx (1.25, 1.5, 2.0, 3.1)$ for HFI!

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

Planck Calibration?

- Splitting $\boldsymbol{\beta_{TOT}} = \boldsymbol{\beta_S} + \boldsymbol{\beta_O}$ (A.N. & M.Quartin '2015) :

$$\delta I_\nu = \frac{\delta T}{T_0} + \boldsymbol{\beta_S}\cdot\hat{\boldsymbol{n}} + Q(\nu)(\boldsymbol{\beta_S}\cdot\hat{\boldsymbol{n}})^2 + \boldsymbol{\beta_O}\cdot\hat{\boldsymbol{n}} + Q(\nu)(\boldsymbol{\beta_O}\cdot\hat{\boldsymbol{n}})^2 + 2\,Q(\nu)(\boldsymbol{\beta_S}\cdot\hat{\boldsymbol{n}})(\boldsymbol{\beta_O}\cdot\hat{\boldsymbol{n}}) - \beta_S\beta_O - \frac{1}{2}\beta_S^2 - \frac{1}{2}\beta_O^2 .$$

- Leading $\boldsymbol{\beta_O}\cdot\hat{\boldsymbol{n}} \approx 10^{-4}$
- Subleading $\approx 10^{-6}$

  $Q(\nu) \approx (1.25, 1.5, 2.0, 3.1)$ for HFI!
- The $Q(\nu)$ corrections should be included in Planck Calibration: might represent $\mathcal{O}(1\%)$ systematics
  - Spurious quadrupole?
  - Leakage on the Dipole?

Testing Isotropy

- Given a map $T(\hat{n})$ we can mask a part of the sky: $\tilde{T}(\hat{n}) = M(\hat{n})T(\hat{n})$
- We compute $\tilde{a}_{\ell m} \rightarrow \tilde{C}_{\ell}^{M}$

Testing Isotropy

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

Testing Isotropy

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

Testing Isotropy

- Given a map $T(\hat{n})$ we can mask a part of the sky: $\tilde{T}(\hat{n}) = M(\hat{n})T(\hat{n})$
- We compute $\tilde{a}_{\ell m} \rightarrow \tilde{C}_\ell^M$
- And compare two opposite halves $\tilde{C}_\ell^N$ and $\tilde{C}_\ell^S$
- Note: The $\tilde{C}_\ell$ are a *biased* estimator of C_ℓ but can be reconstructed as $C_\ell = \sum_{\ell'} \mathcal{M}_{\ell\ell'} \tilde{C}'_\ell$
- Roughly $\tilde{C}_\ell \approx C_\ell \cdot f_{sky}$

Hemispherical asymmetry?

- 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

Hemispherical asymmetry?

- 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

Hemispherical asymmetry?

- 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 2013, XIII. Isotropy and Statistics.

Planck asymmetry

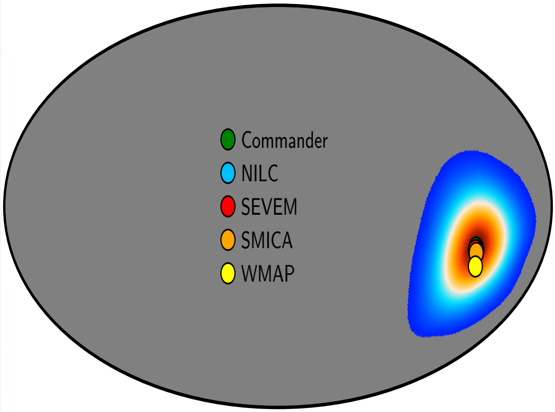
- 7% asymmetry

Planck asymmetry

- 7% asymmetry
- at scales $\gtrsim 4^\circ$

Planck asymmetry

- 7% asymmetry
- at scales $\gtrsim 4^\circ$
- Same as in WMAP



Hemispherical Asymmetry at high ℓ?

- A correct analysis has to include Doppler and Aberration (in simulations: important at high $\ell \simeq 1000$)

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

Hemispherical Asymmetry at high ℓ?

- A correct analysis has to include Doppler and Aberration (in simulations: important at high $\ell \simeq 1000$)

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

Hemispherical Asymmetry at high ℓ?

- A correct analysis has to include Doppler and Aberration (in simulations: important at high $\ell \simeq 1000$)

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

- Revised Planck 2013 paper corrects previous claim at $\ell \approx 1500$ and now only $\ell < 600$ anomalous (about 3σ).

  Planck Collaboration 2013, XIII. Isotropy and Statistics, v2, Dec 2013.

Hemispherical Asymmetry at high ℓ?

- A correct analysis has to include Doppler and Aberration (in simulations: important at high $\ell \simeq 1000$)

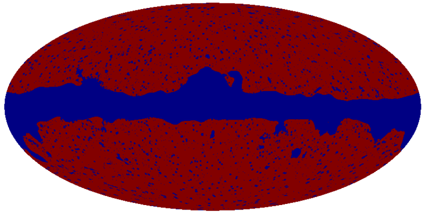
  A.N., M.Quartin & R.Catena, JCAP Apr. '13

- Revised Planck 2013 paper corrects previous claim at $\ell \approx 1500$ and now only $\ell < 600$ anomalous (about 3σ).

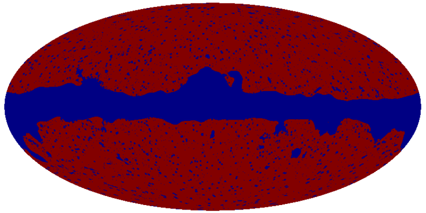
  Planck Collaboration 2013, XIII. Isotropy and Statistics, v2, Dec 2013.

- We find between $2 - 3\sigma$ anomaly at $\ell \lesssim 600$ (A.N., M.Quartin & JCAP '14)

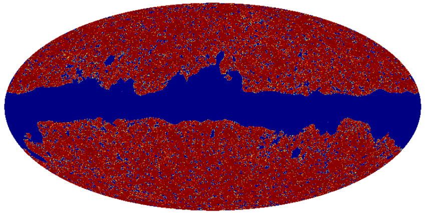
Planck Mask (U73)



Planck Mask (U73)

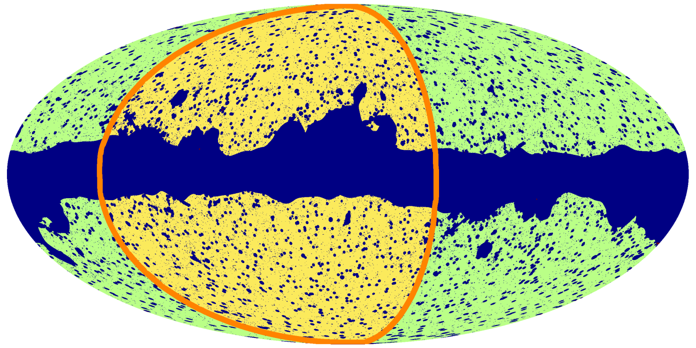


- We produced a Symmetrized U73 (M. Quartin & A.N. '14)



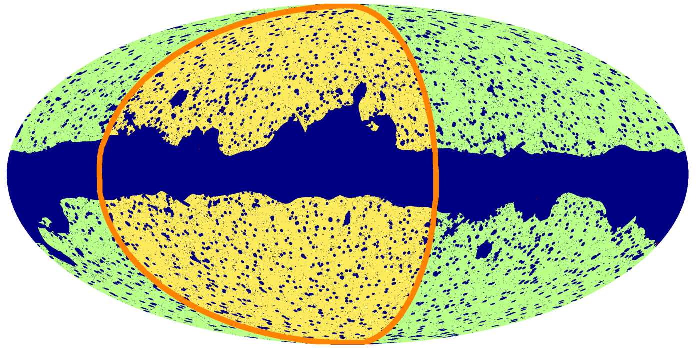
Planck Mask (Symmetrized)

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



Planck Mask (Symmetrized)

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



- Smoothing the cut!

Hemispherical Asymmetry due to Velocity

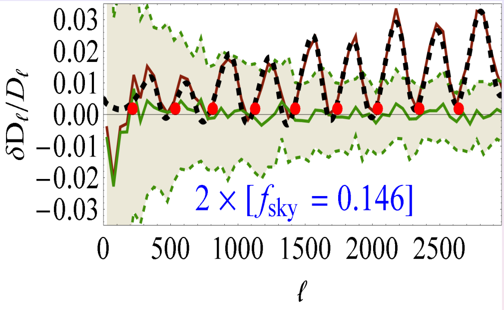


Figure : Discs along the Dipole direction

Hemispherical Asymmetry due to Velocity

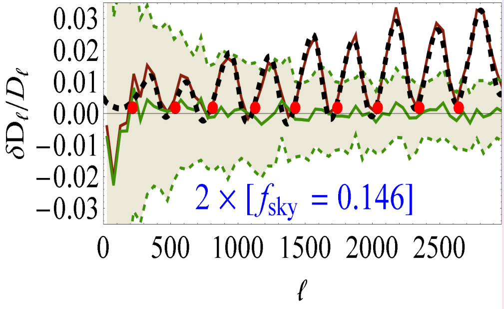


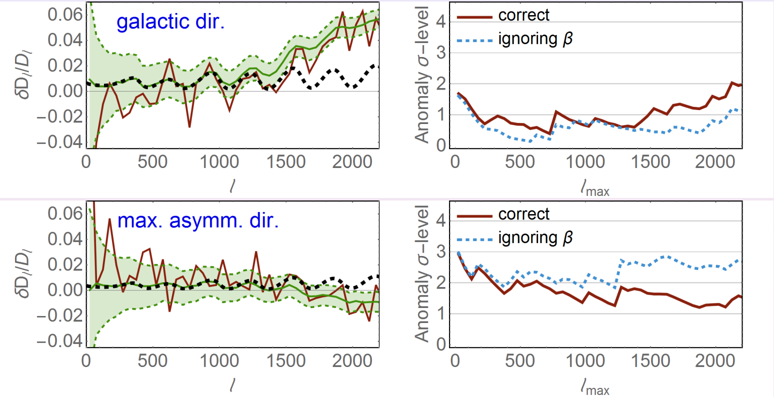
Figure : Discs along the Dipole direction

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

Significance: Results



Simulations include Noise and Doppler+Aberration.

(A.N., M.Quartin 2014)

“Dipolar modulation"?

- Several authors have studied the ansatz

$$T = T_{\rm isotropic}\left(1 + \boldsymbol{A}_{\rm mod} \cdot n\right),$$

“Dipolar modulation"?

- Several authors have studied the ansatz

$$T \;=\; T_{\rm isotropic}\left(1 + \boldsymbol{A}_{\rm mod}\cdot n\right)\,,$$

- 3-σ detection of A_{mod} along max. asymm. direction (For $\ell < 64$ or $\ell < 600$)

“Dipolar modulation"?

- Several authors have studied the ansatz

$$T = T_{\rm isotropic}\left(1 + \boldsymbol{A}_{\rm mod} \cdot \boldsymbol{n}\right) ,$$

- 3-σ detection of A_{mod} along max. asymm. direction (For $\ell < 64$ or $\ell < 600$)

- $A_{\rm mod}$ 60 times bigger than β!

Our Results on A

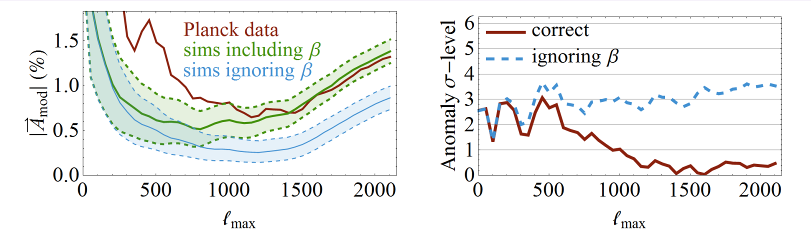


Figure : All simulations include Planck noise asymmetry.

A.N. & M.Quartin, 2014