Tomographic redshift dipole: Testing the cosmological principle

Universidade Federal do Espírito Santo

PPGCosmo

Pedro da Silveira Ferreira and Valerio Marra

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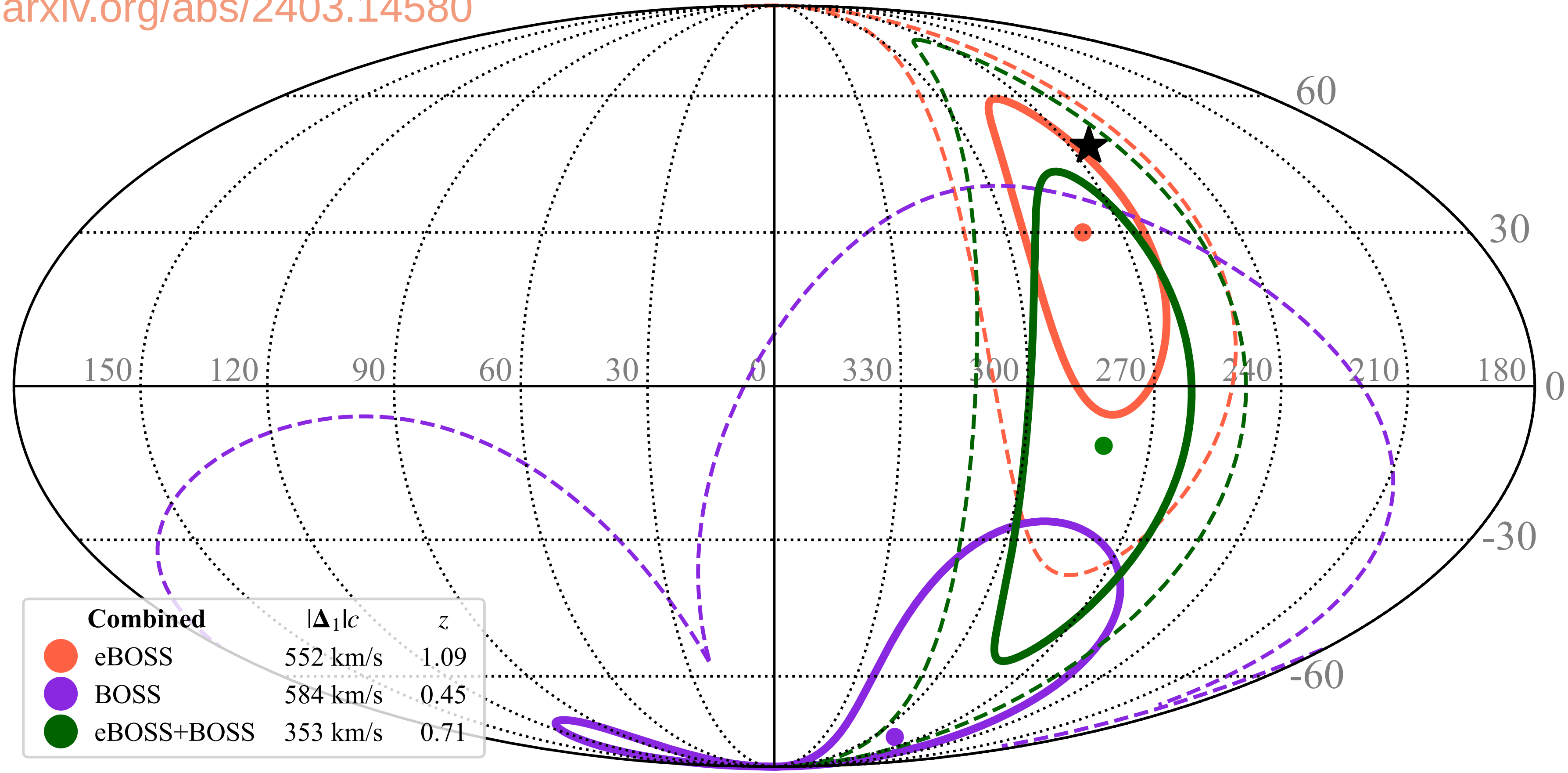
https://arxiv.org/abs/2403.14580



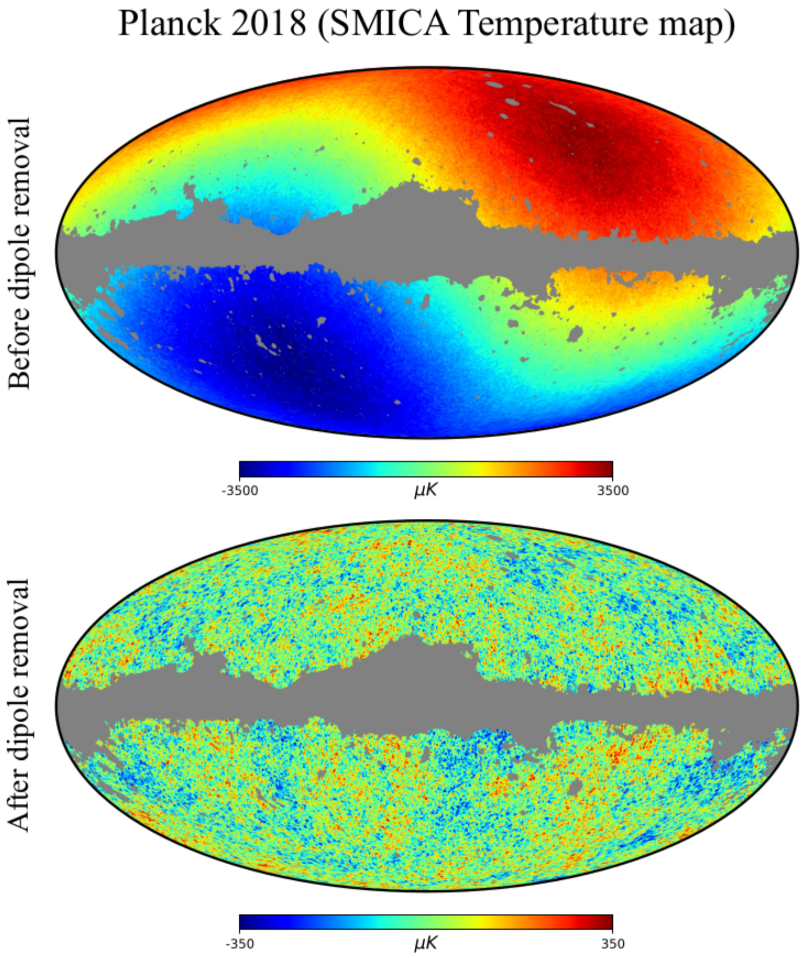
A challenge to the cosmological principle

Cosmology's standard model (ΛCDM), is founded on the cosmological principle, which asserts that **the universe is statistically homogeneous and isotropic on scales larger than approximately 100 Mpc**.

Consequently, the primary source of the dipole observed in distant objects should be attributed to our peculiar velocity.

This implies that velocity estimates derived from different sources, such as x-ray, radio galaxies (**RG**), quasars (**QSO**), supernovae Ia (**SNe**), and even gravitational waves, should agree.

However, over the past 25 years, several studies utilizing different RG and QSO catalogs have consistently found that, though the peculiar velocity is generally consistent in direction with the CMB dipole, its amplitude is in tension. This quarter-century-long puzzle poses a significant challenge to the standard model, with **the tension regarding the CMB dipole now reaching a** 5σ **level**.



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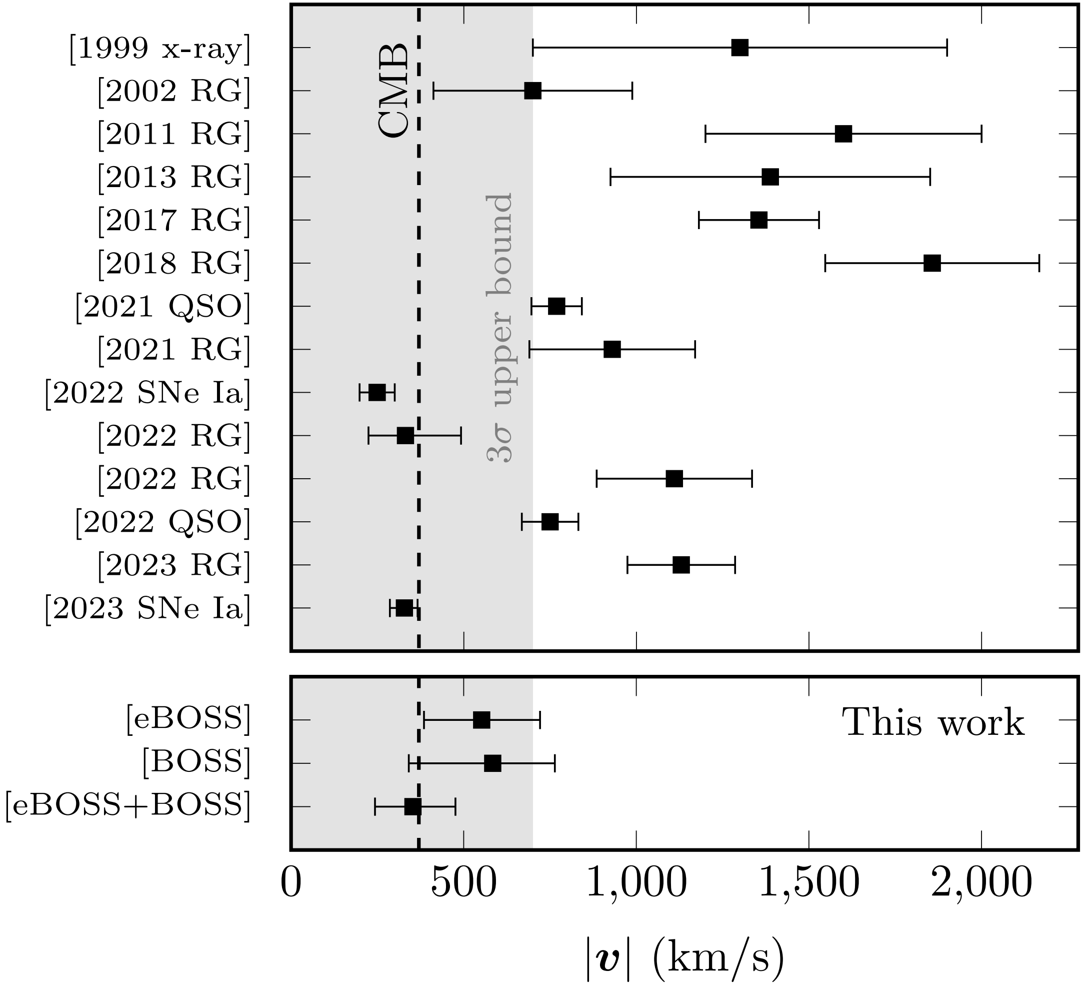

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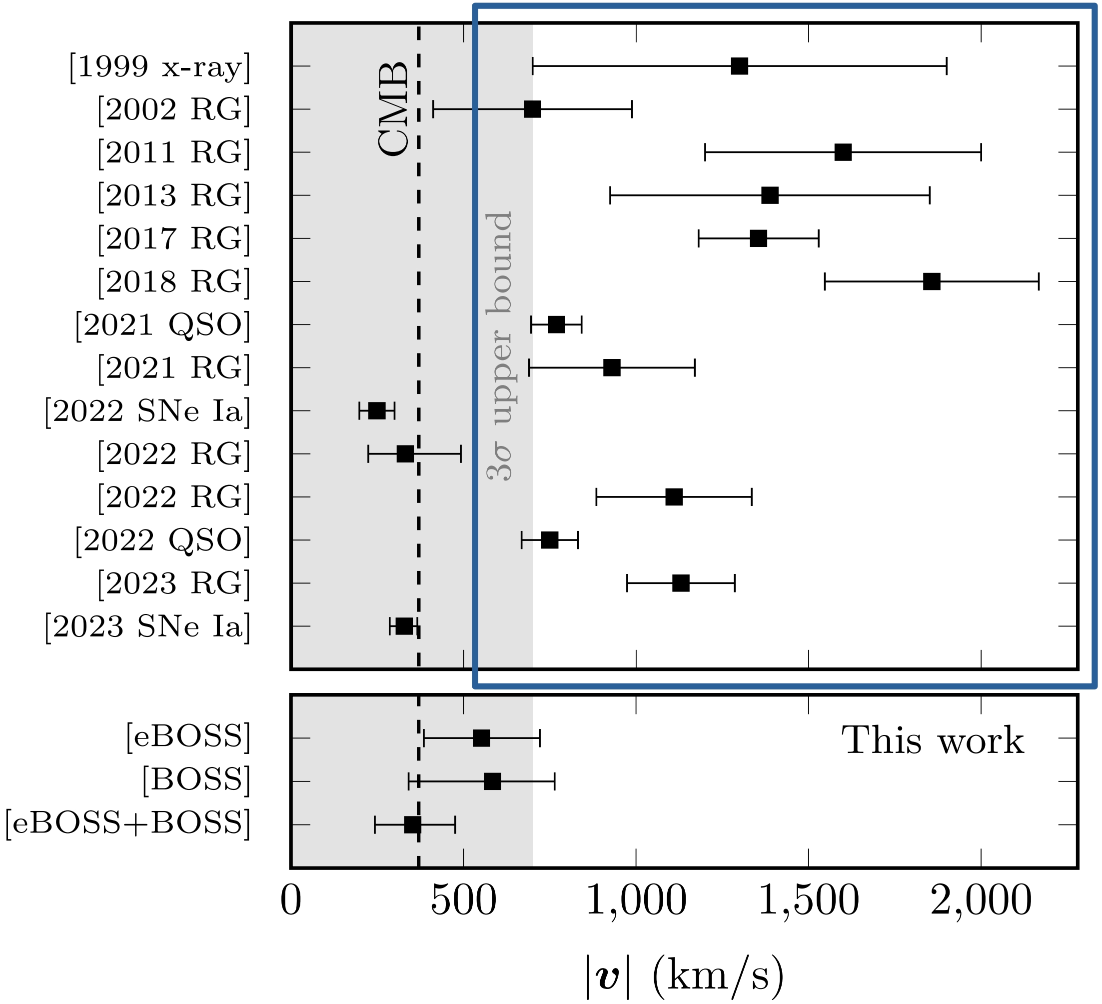

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PHYSICAL REVIEW LETTERS

Accepted Paper

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

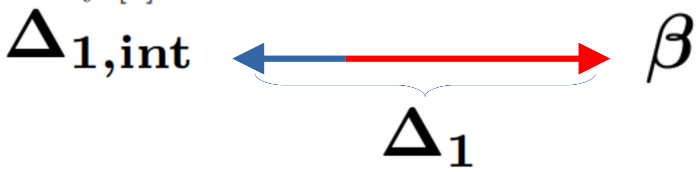
Phys. Rev. Lett.

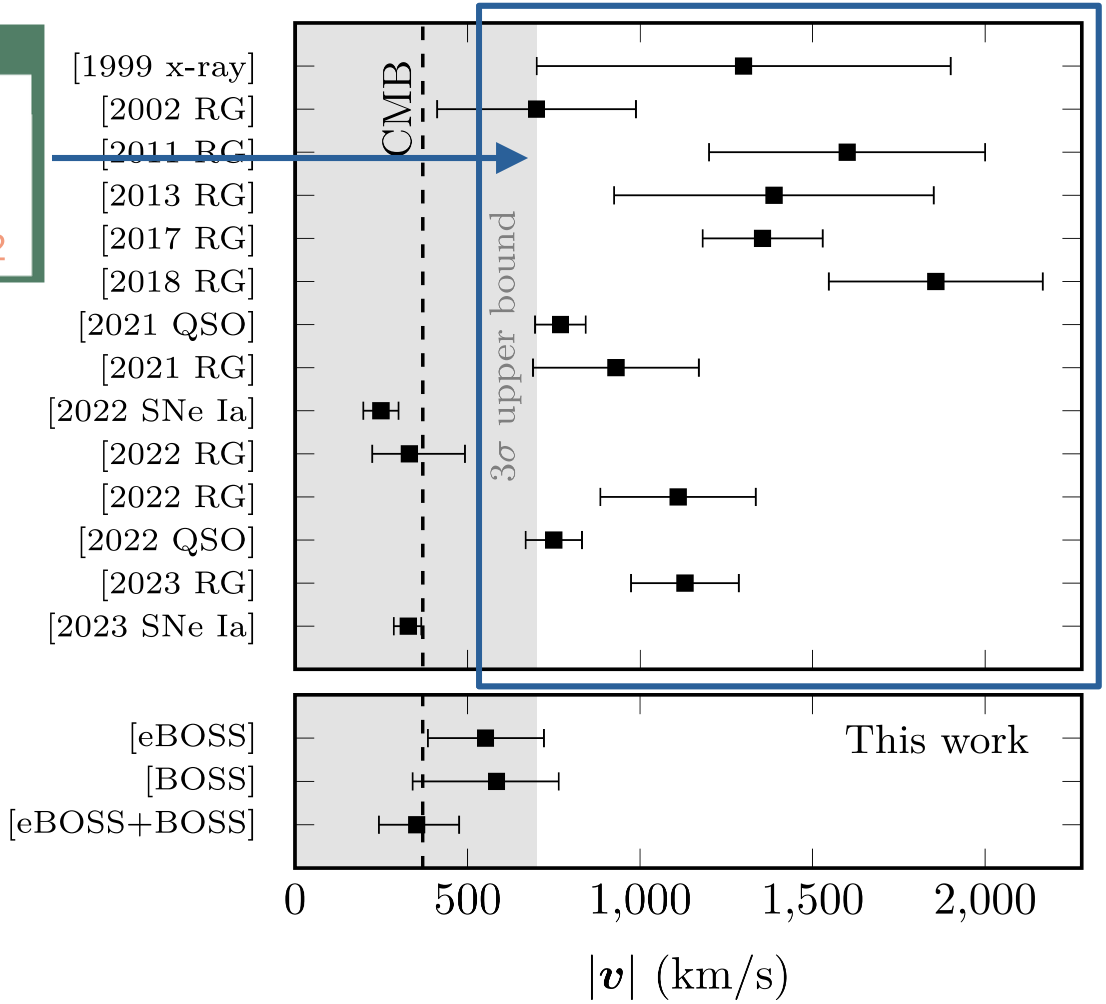
Pedro da Silveira Ferreira and Miguel Quartin

Accepted 21 July 2021

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

Nevertheless there exists the possibility that part of the dipolar effect could be due to primordial fluctuations in the surface of last-scattering (SLS). Concrete alternatives to the kinematic scenario were discussed as far back as 30 years ago by [2], which showed that a large local void could also explain the dipole. This particular scenario was further investigated by e.g. [3] and [4]. A "tilted universe scenario" composed of a superhorizon isocurvature perturbation was proposed in [5]. An inflationary model which produces similar results was proposed by [6]. This scenario can be tested as it leads to





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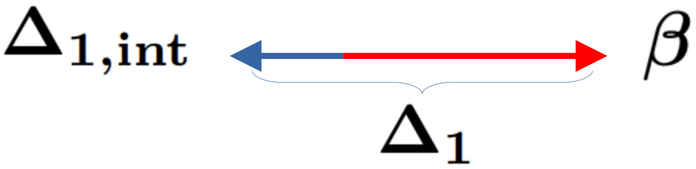
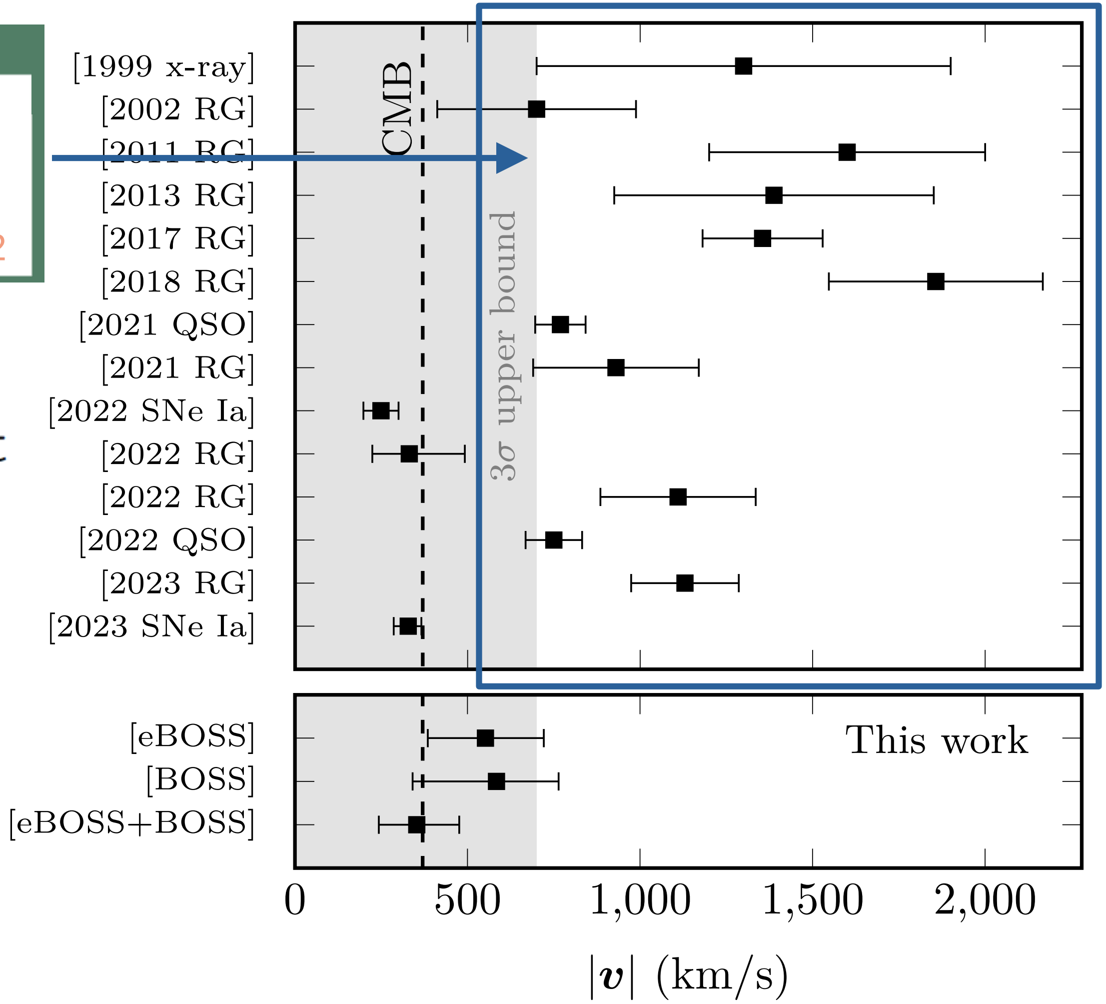
Interpreting the CMB aberration and Doppler measurements: boost or intrinsic dipole?

Omar Roldan,[a] Alessio Notari[b] and Miguel Quartin[a]





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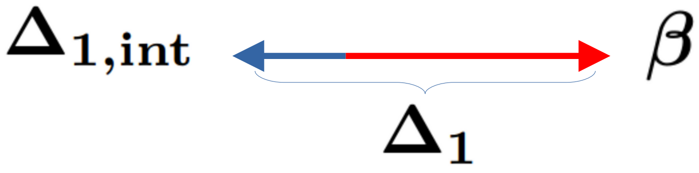
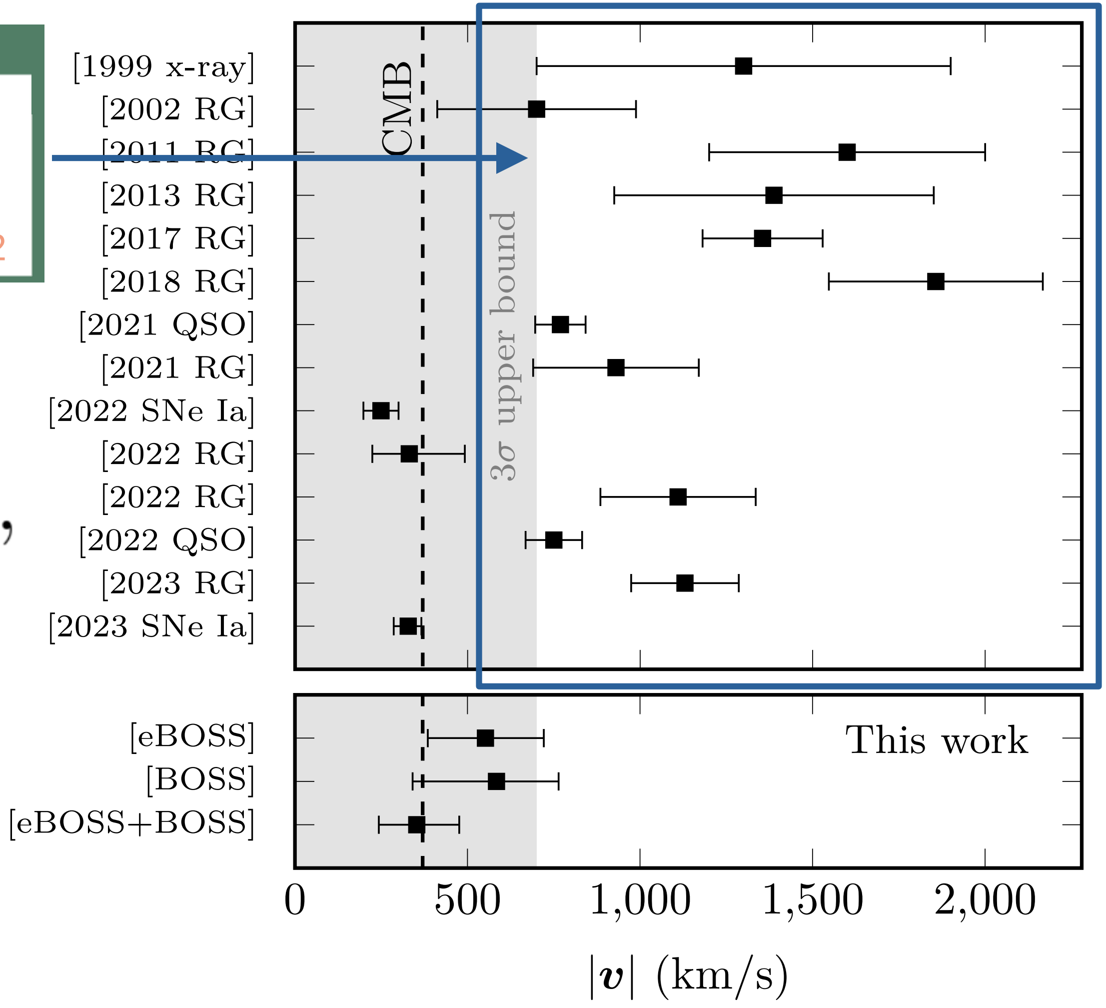
$$\boldsymbol{\Delta}_1 = \boldsymbol{\beta} + \boldsymbol{\Delta}_{1,\mathrm{int}} \,,$$

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

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





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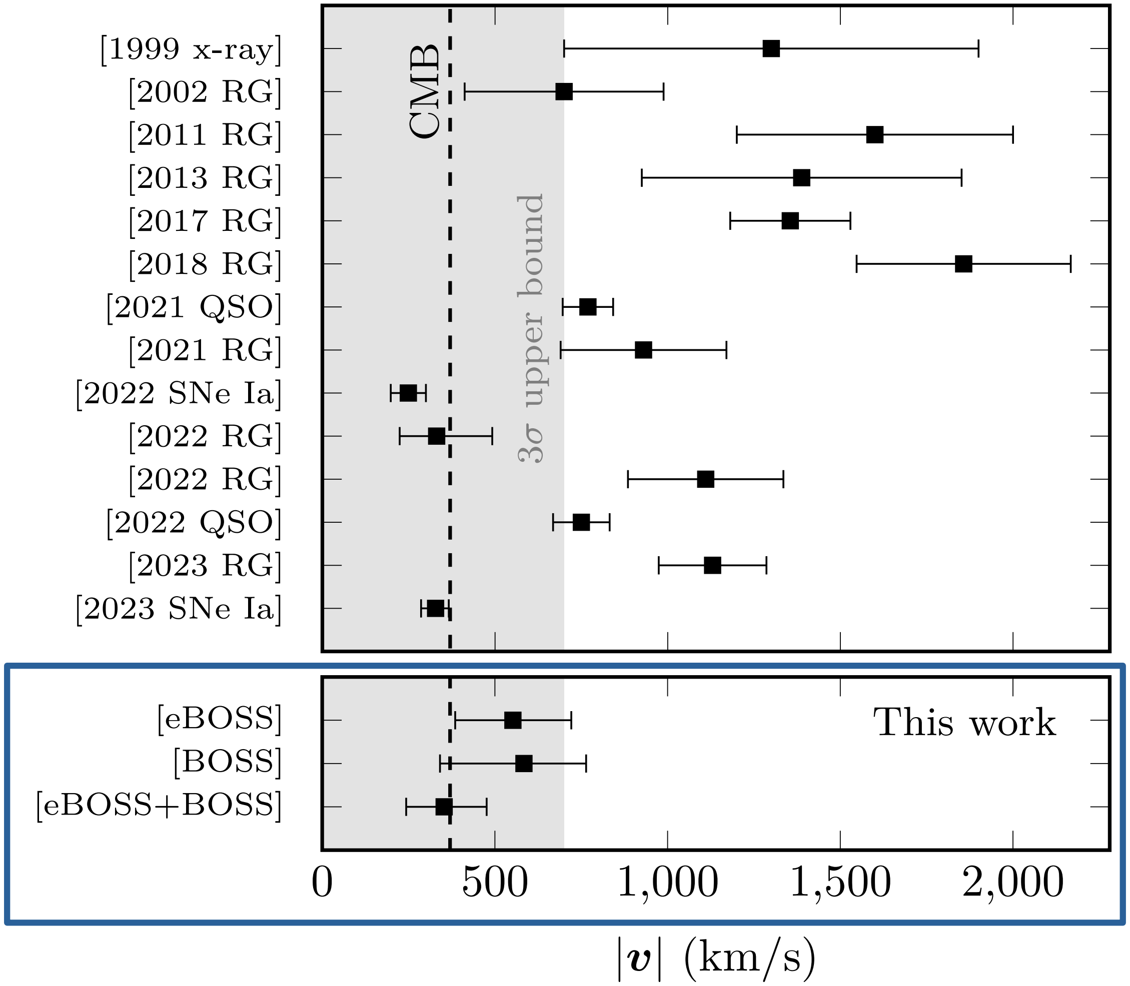


The redshift dipole

Doppler modulation

$$1 + z'(\hat{\boldsymbol{n}}') = (1 + z(\hat{\boldsymbol{n}}))\delta(\boldsymbol{\beta}, \hat{\boldsymbol{n}}')$$

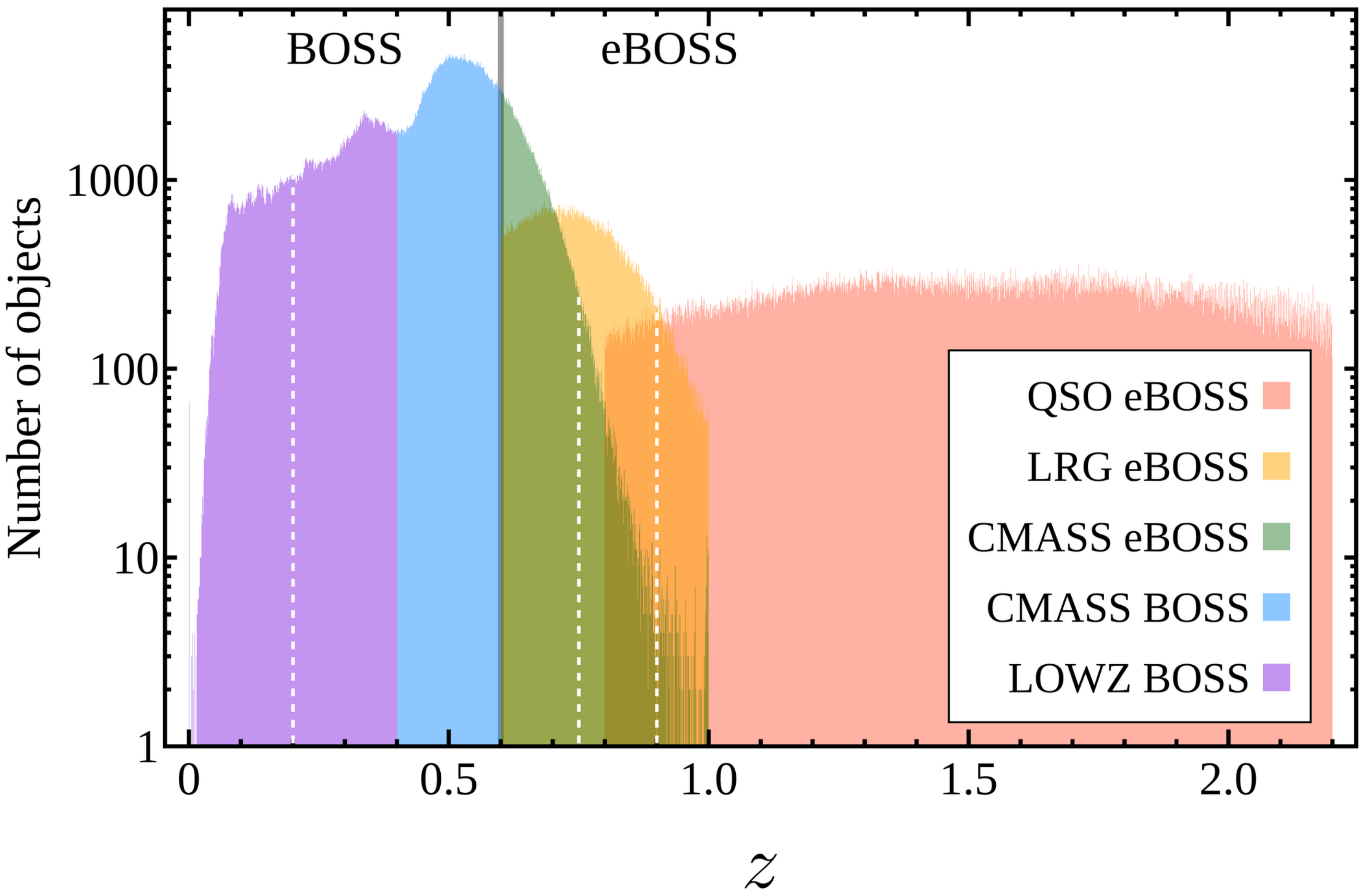
$$\delta(\boldsymbol{\beta}, \hat{\boldsymbol{n}}') = \frac{\sqrt{1-\beta^2}}{(1+\boldsymbol{\beta}\cdot\hat{\boldsymbol{n}}')}$$

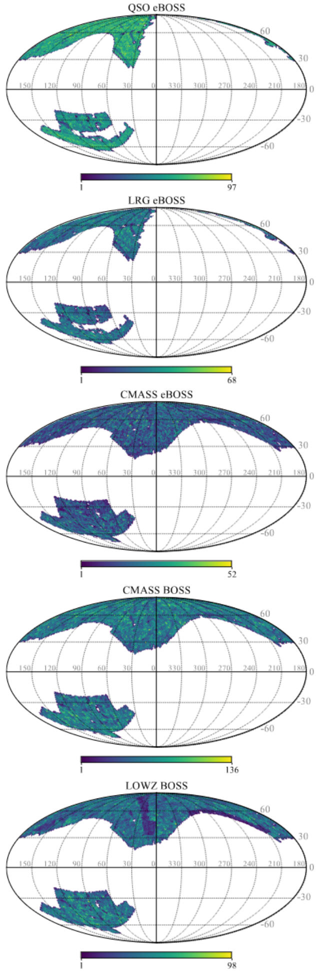
Relation between the dipole and the velocity

$$\boldsymbol{\Delta}_{\mathbf{1}} = -\boldsymbol{\beta} + \boldsymbol{\Delta}_{\mathbf{1,int}} + \mathcal{O}(\beta^2)$$

$\boldsymbol{\Delta}_{\mathbf{1,int}}$: <2% (0.2<z<2.2)

$$\boldsymbol{\Delta}_{\mathbf{1}} = -\boldsymbol{\beta}$$


BOSS
eBOSS
Number of objects
1000
100
10
1
0
0.5
1.0
1.5
2.0
z
QSO eBOSS
LRG eBOSS
CMASS eBOSS
CMASS BOSS
LOWZ BOSS


QSO eBOSS
LRG eBOSS
CMASS eBOSS
CMASS BOSS
LOWZ BOSS

Measuring the dipolar modulation

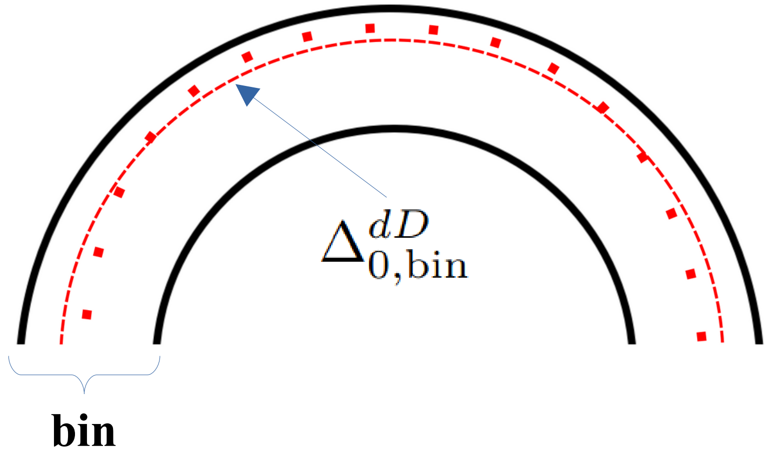
$$\chi^2_{\mathrm{bin}}(\boldsymbol{\Delta}_1) = \frac{\sum_i^N w_i^2 \left[1 + z_i - \Delta^{dD}_{0,\mathrm{bin}} \delta(-\boldsymbol{\Delta}_1, \hat{\boldsymbol{n}}'_i)\right]^2}{\sum_i^N w_i^2}$$

$$w_{i,\mathrm{eBOSS}} = w_{i,\mathrm{sys}} \cdot w_{i,\mathrm{noz}} \cdot w_{i,\mathrm{fc}} \,,$$

$$w_{i,\mathrm{BOSS}} = w_{i,\mathrm{sys}} \cdot (w_{i,\mathrm{noz}} + w_{i,\mathrm{fc}} - 1)$$

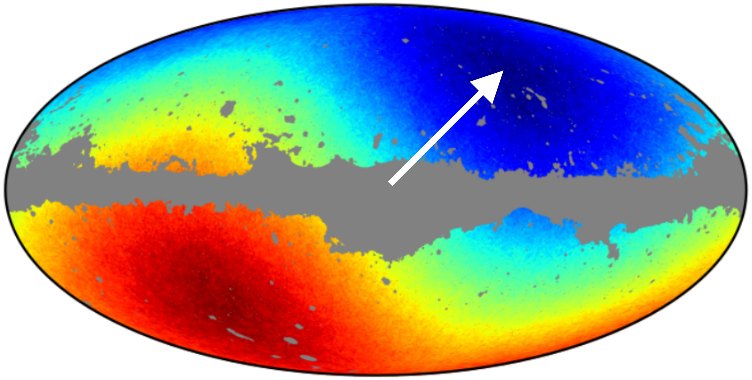
$$\Delta^{dD}_{0,\mathrm{bin}} = \sum_i^N w_i (1 + z_i) \delta(-\boldsymbol{\Delta}_1, \hat{\boldsymbol{n}}'_i)^{-1} \Big/ \sum_i^N w_i$$

$$\chi^2(\boldsymbol{\Delta}_1) = \sum_{\mathrm{bin}} \chi^2_{\mathrm{bin,NGC}}(\boldsymbol{\Delta}_1) + \sum_{\mathrm{bin}} \chi^2_{\mathrm{bin,SGC}}(\boldsymbol{\Delta}_1)$$



Measuring the dipolar modulation

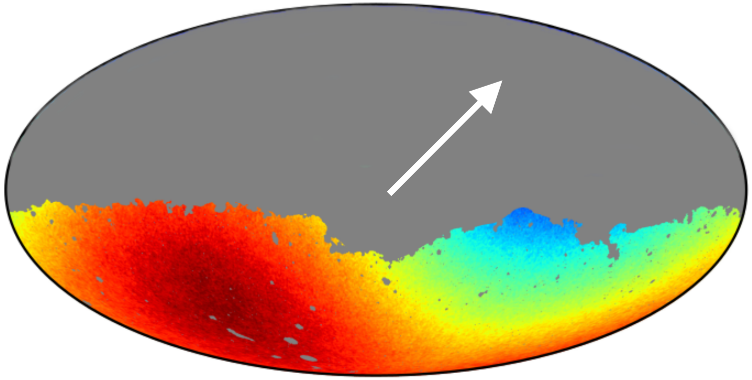
$$\chi^2_{\rm bin}(\boldsymbol{\Delta}_1) = \frac{\sum_i^N w_i^2 \left[1 + z_i - \Delta^{dD}_{0,\rm bin}\delta(-\boldsymbol{\Delta}_1, \hat{\boldsymbol{n}}'_i)\right]^2}{\sum_i^N w_i^2}$$



$$w_{i,\rm eBOSS} = w_{i,\rm sys} \cdot w_{i,\rm noz} \cdot w_{i,\rm fc}\ ,$$

$$w_{i,\rm BOSS} = w_{i,\rm sys} \cdot (w_{i,\rm noz} + w_{i,\rm fc} - 1)$$

$$\Delta^{dD}_{0,\rm bin} = \sum_i^N w_i(1 + z_i)\delta(-\boldsymbol{\Delta}_1, \hat{\boldsymbol{n}}'_i)^{-1} \Big/ \sum_i^N w_i$$



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Measuring the dipolar modulation

$$\chi^2_{\text{bin}}(\mathbf{\Delta}_1) = \frac{\sum_i^N w_i^2 \left[1 + z_i - \Delta^{dD}_{0,\text{bin}} \delta(-\mathbf{\Delta}_1, \hat{\boldsymbol{n}}'_i)\right]^2}{\sum_i^N w_i^2}$$

$$w_{i,\text{eBOSS}} = w_{i,\text{sys}} \cdot w_{i,\text{noz}} \cdot w_{i,\text{fc}} \,,$$

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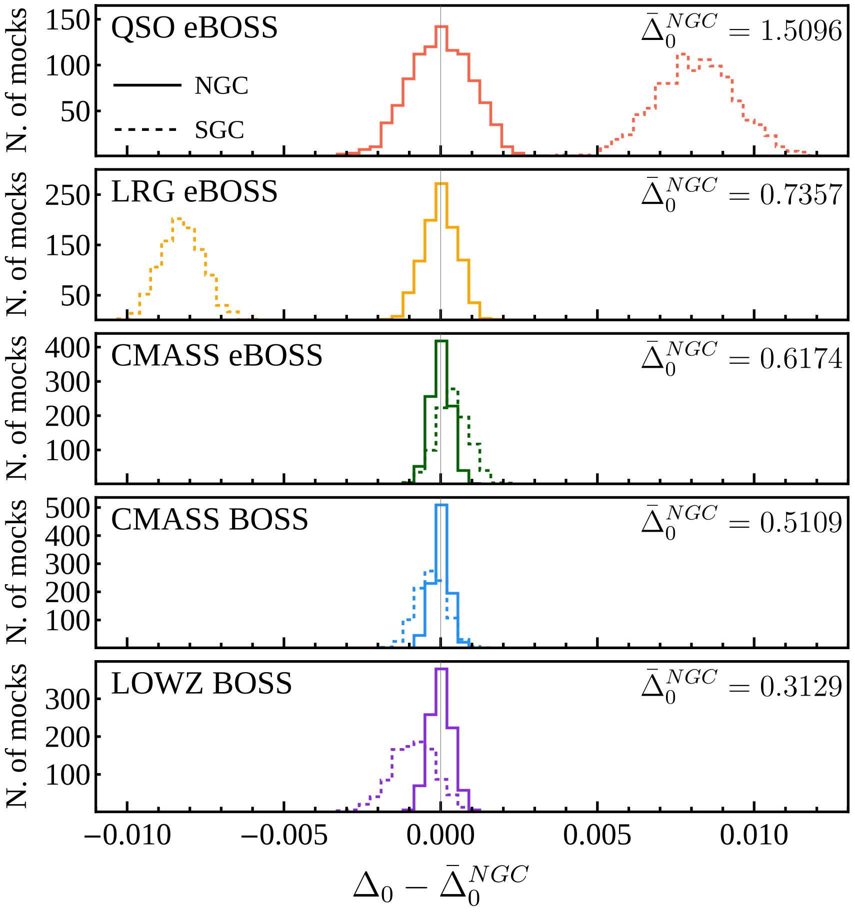
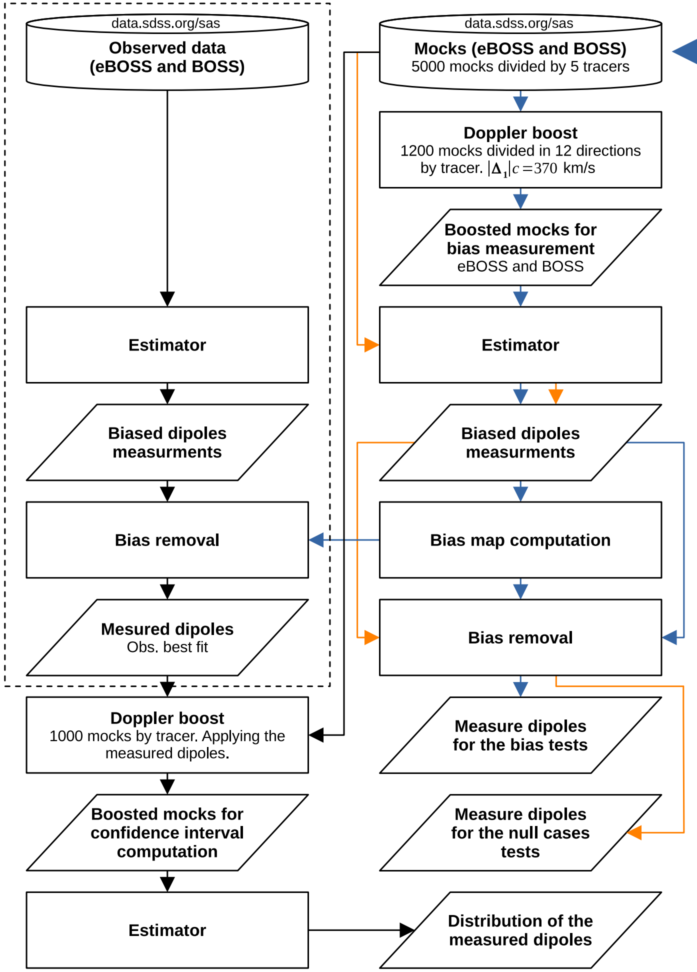


Pedro da S. Ferreira – dasferreira.pedro@gmail.com

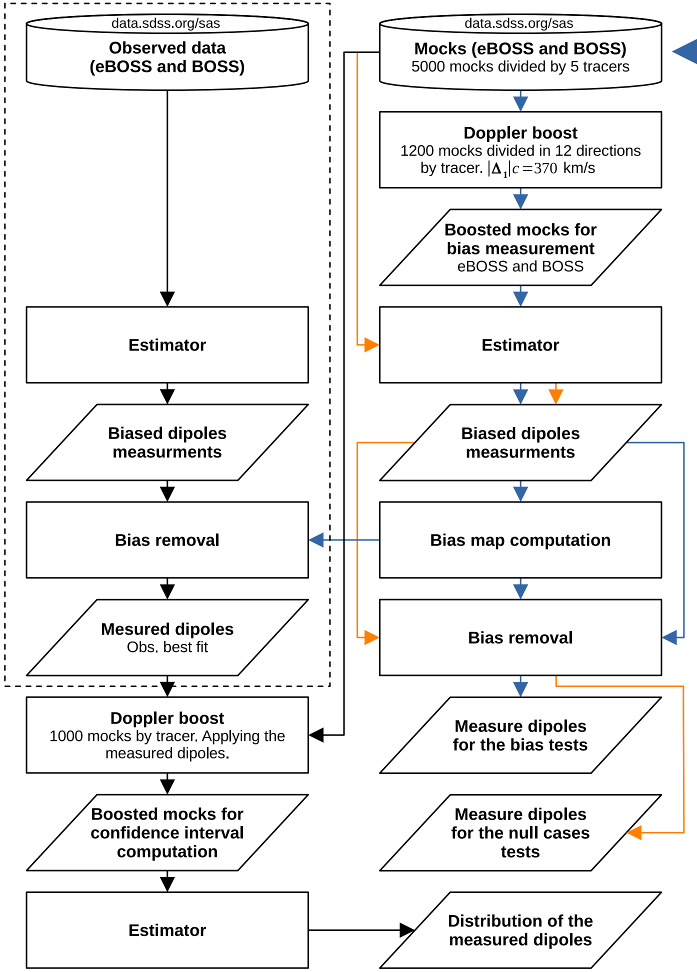
Measuring the dipolar modulation

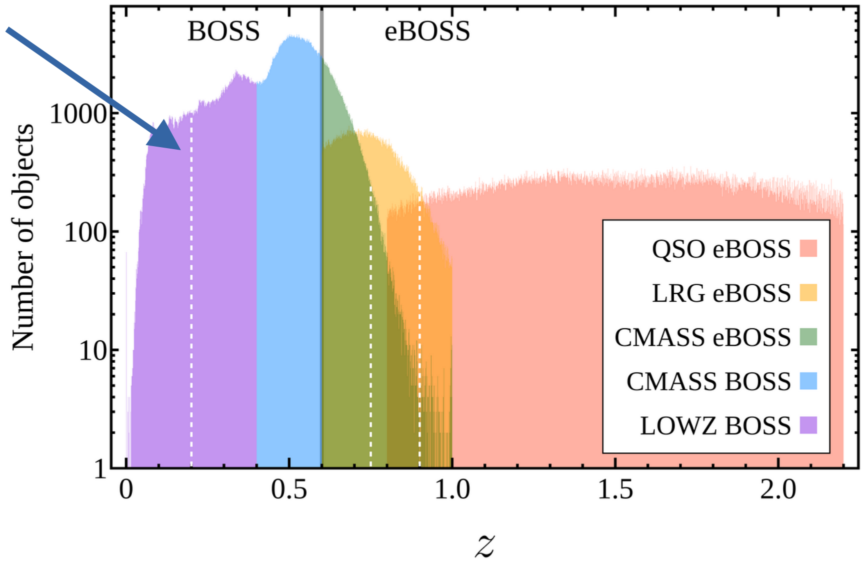


Realistic error bars: Survey systematics, including observational strategies, footprint inhomogeneities, and variations in sky and telescope conditions, will affect the errors and could introduce measurement bias. To assess and then adjust for this bias, we developed a series of mock catalogs from **eBOSS's EZmock** sample and **BOSS's MultiDark-Patchy mocks**. Notably, we utilized the realistic version of EZmock, which incorporates observational systematics, unlike the MultiDark-Patchy mocks that lack this aspect.

Mocks: <u>Include effects of clustering, survey geometry, redshift evolution, sample selection biases, and all systematic effects</u> (except BOSS).

Measuring the dipolar modulation





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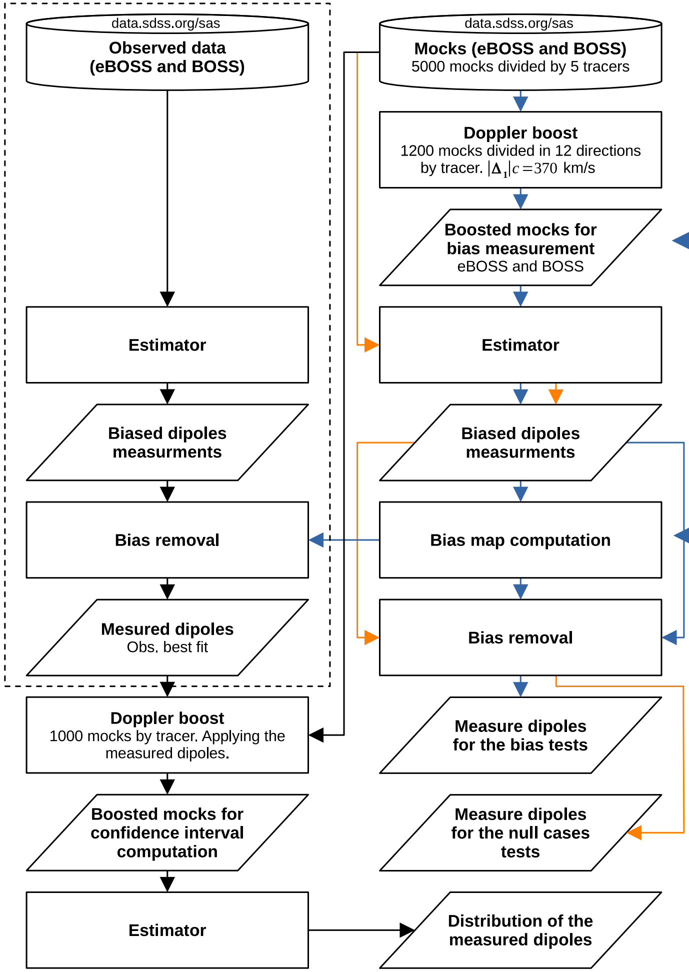
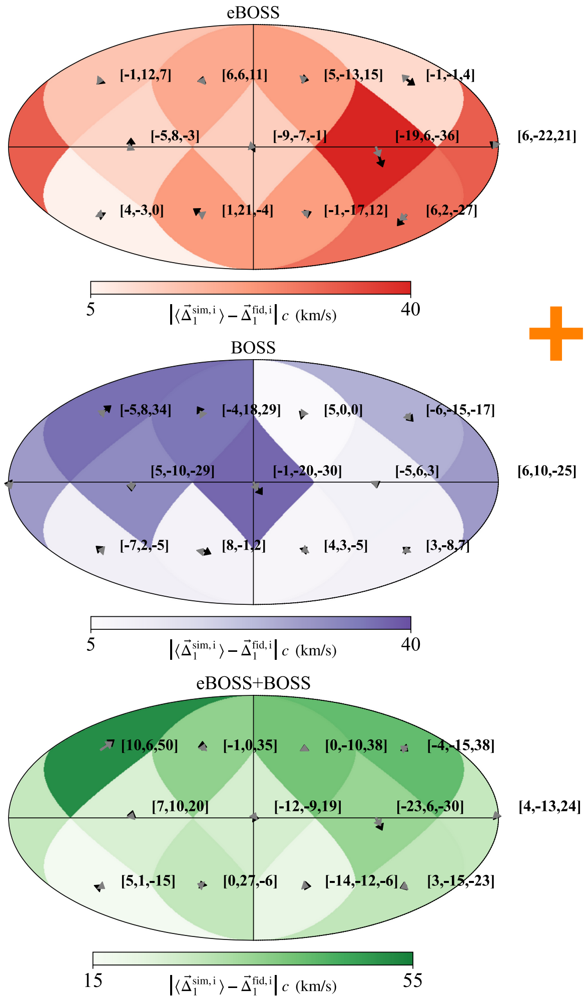
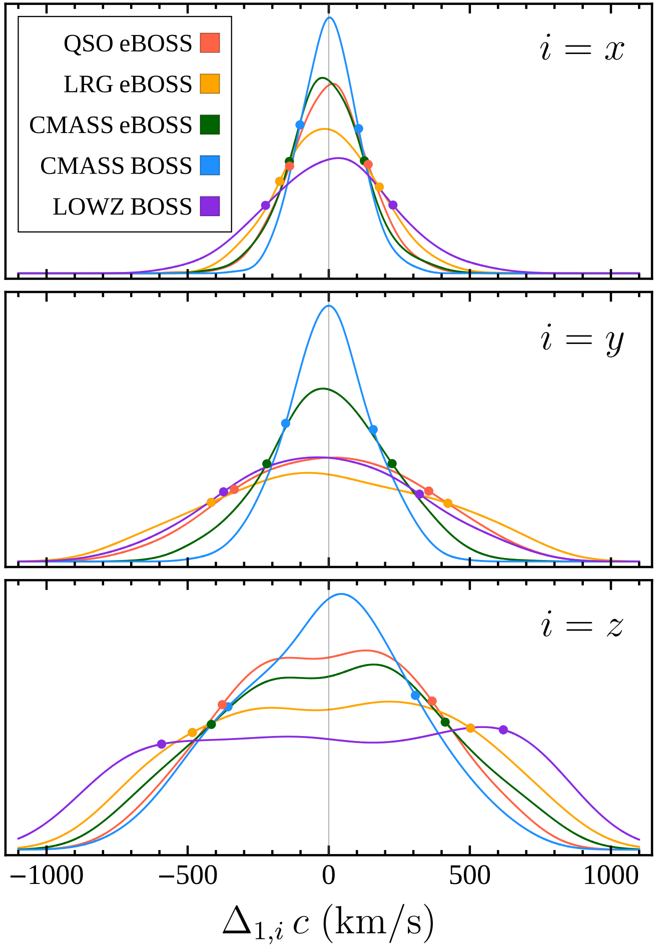
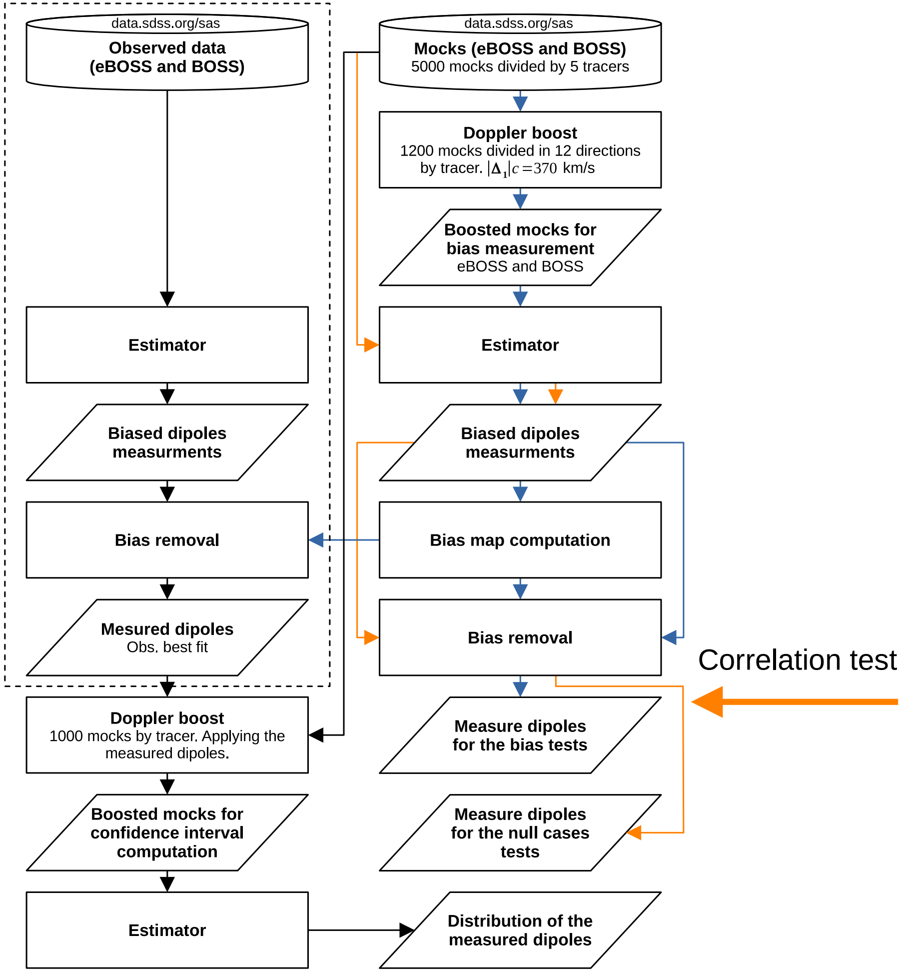
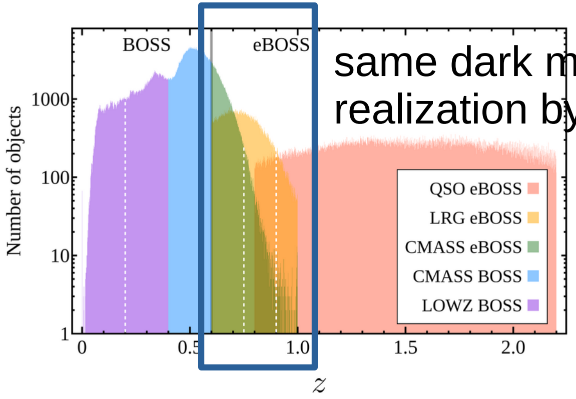






Measuring the dipolar modulation

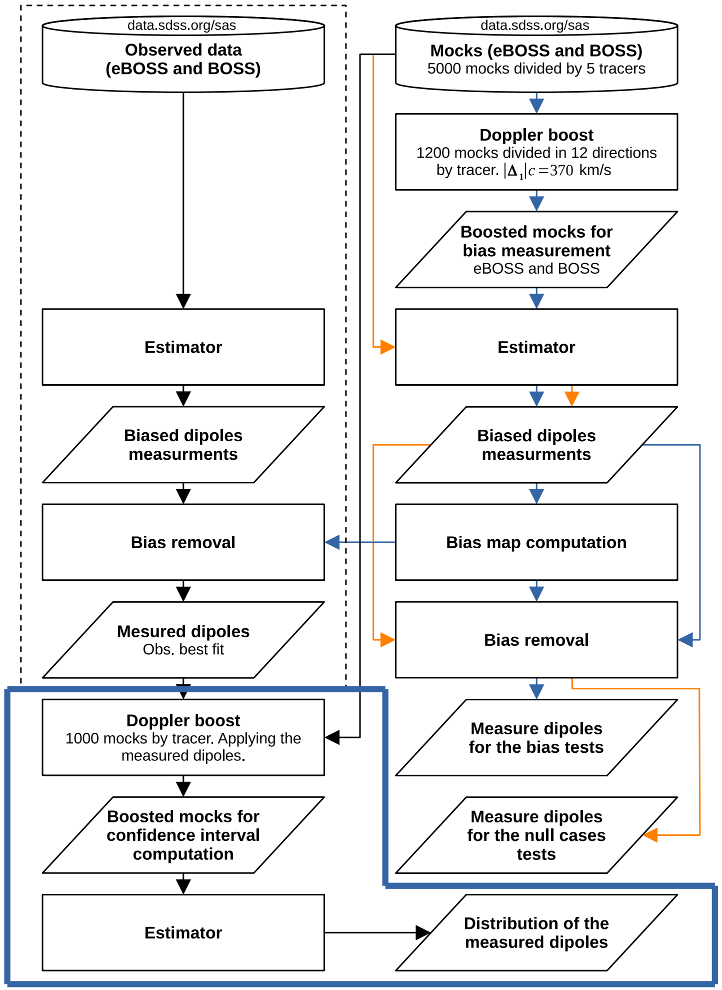




same dark matter realization by id

$$\mathbf{\Delta_1} = -\beta + \boxed{\mathbf{\Delta_{1,int}}} + \mathcal{O}(\beta^2)$$

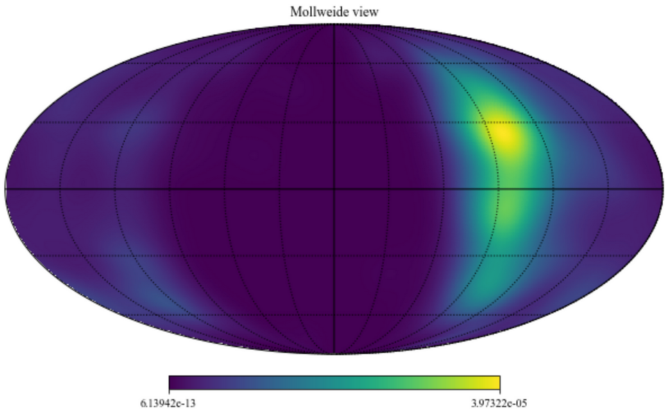
Measuring the dipolar modulation



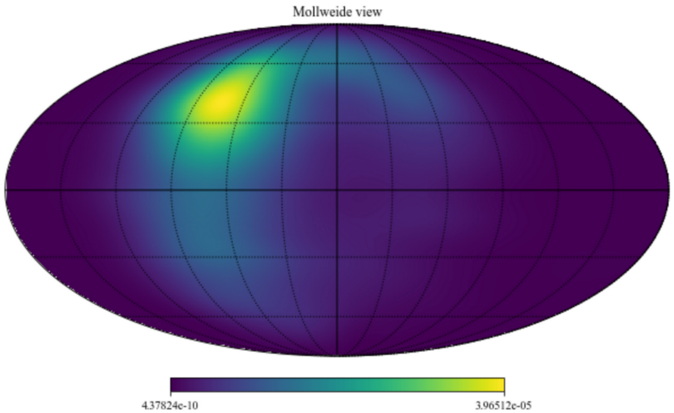
Obtaining the distribution of measured dipoles

Measuring the dipolar modulation

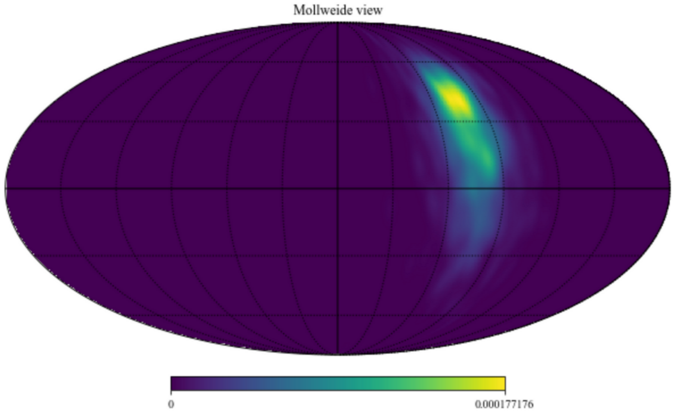
QSO



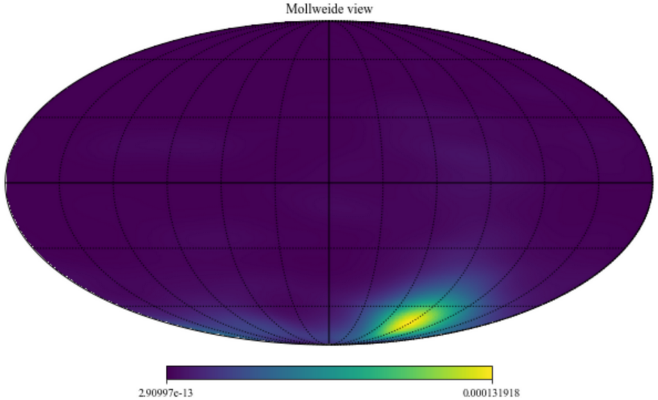
LRG



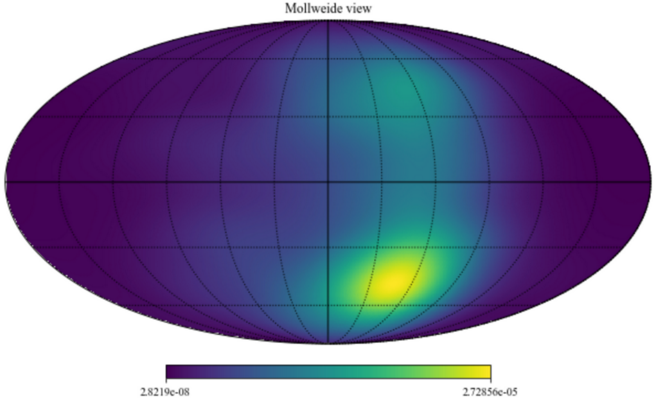
CMASS



CMASS BOSS



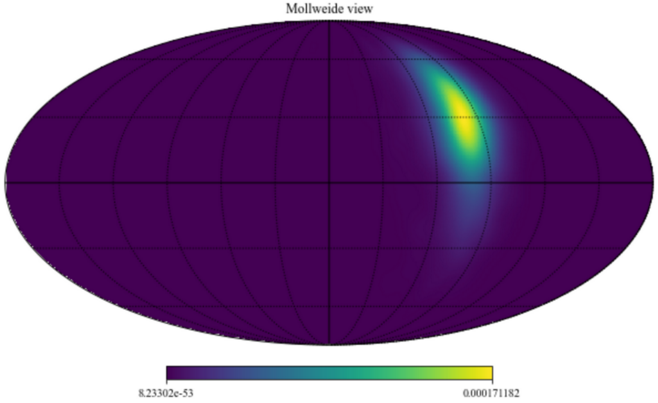
LOWZ BOSS



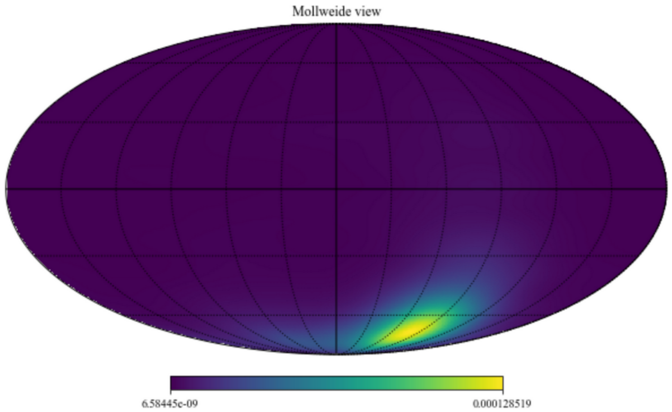
https://lscsoft.docs.ligo.org/ligo.skymap/

Measuring the dipolar modulation

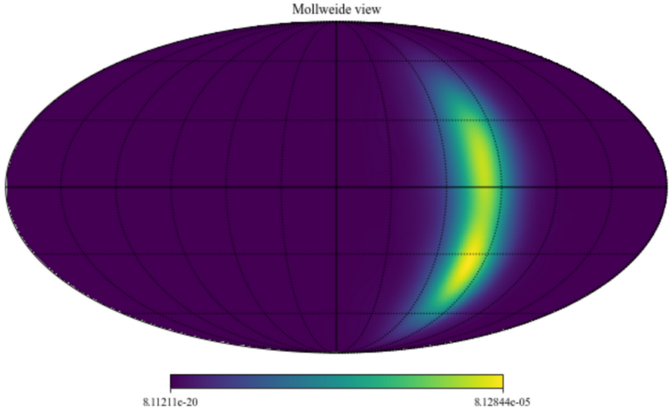
eBOSS



BOSS



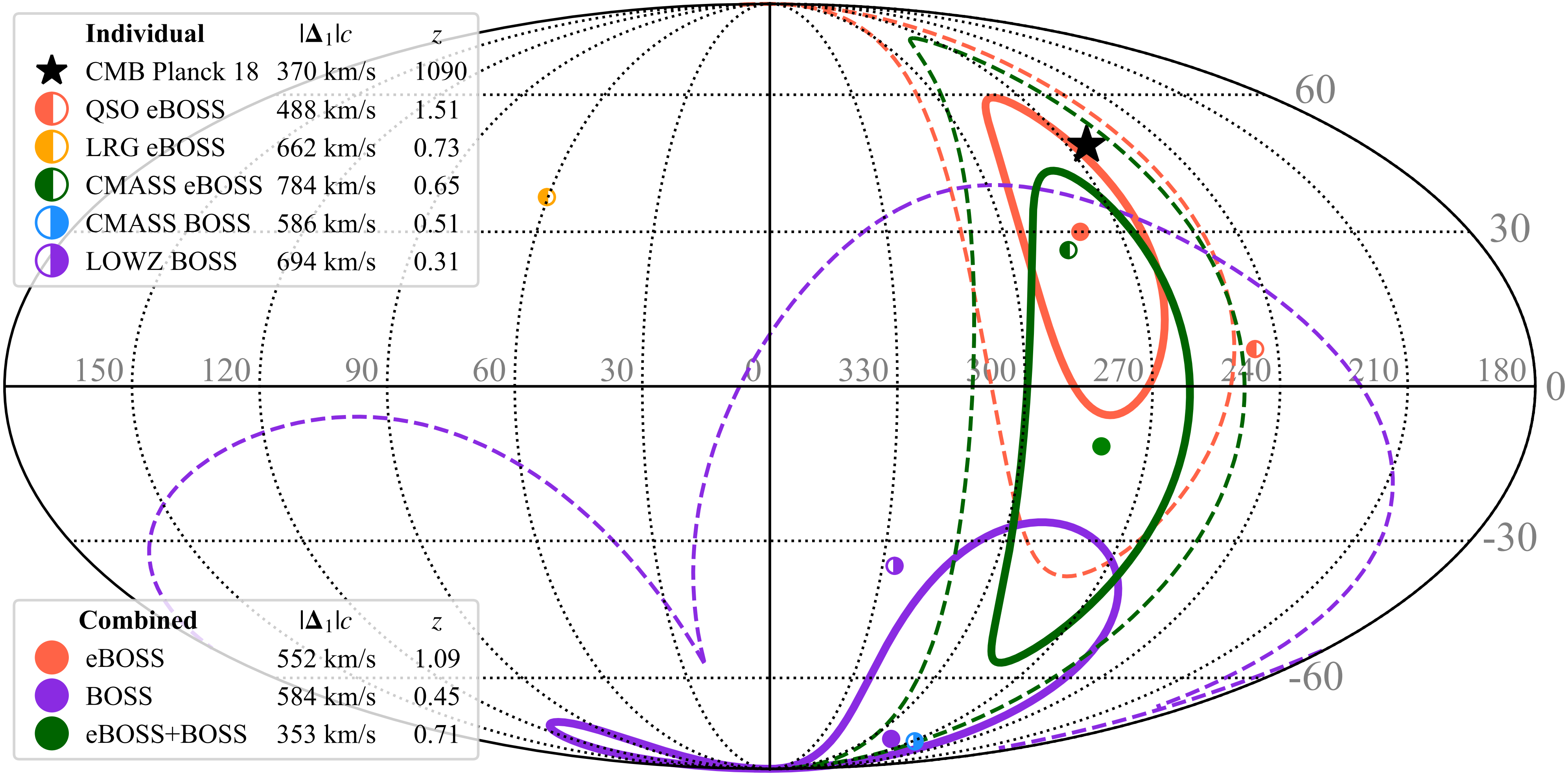
eBOSS+BOSS



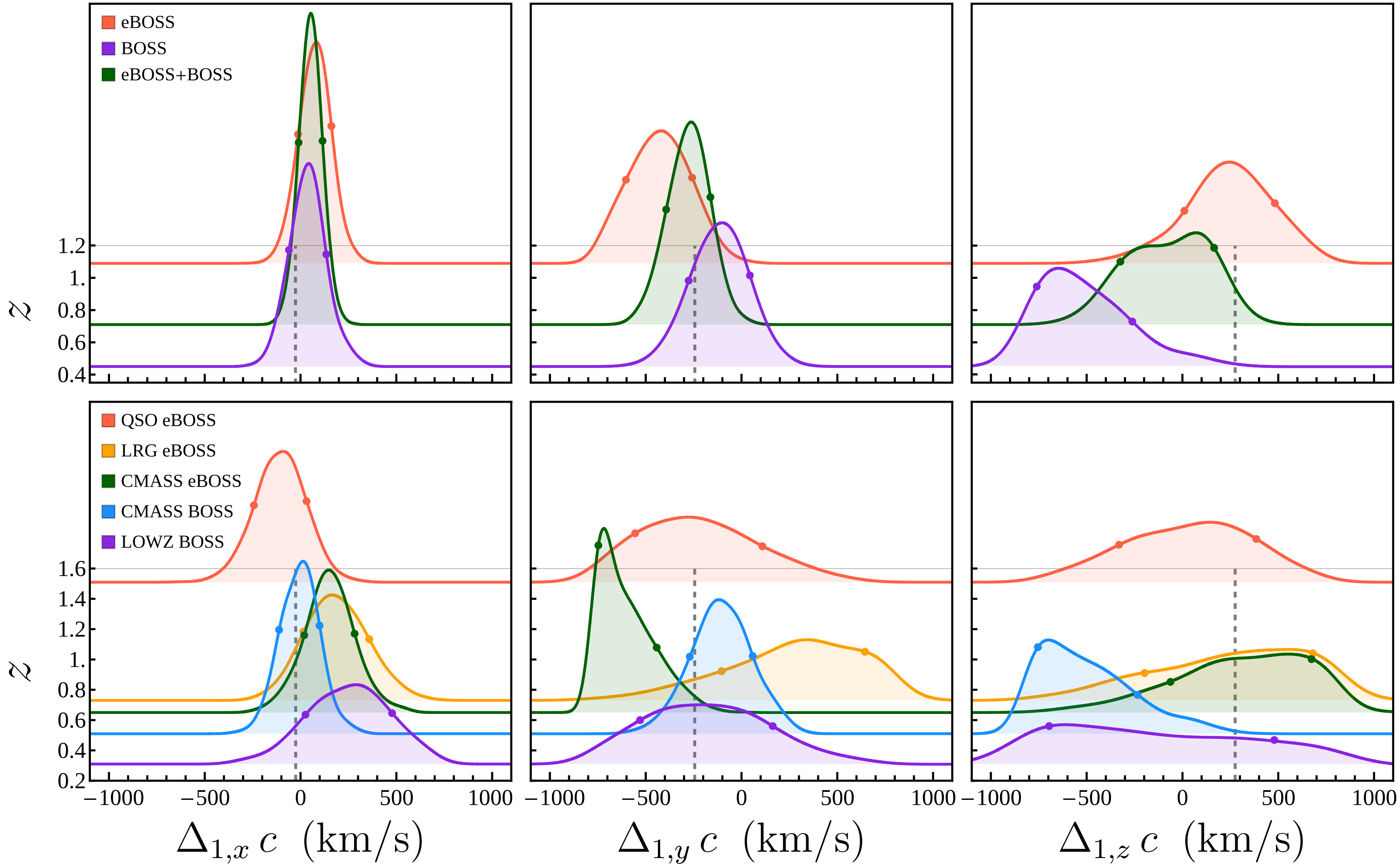
$$P_x^{\mathrm{BOSS}} = P_x^{\mathrm{CMASS\ BOSS}} \times P_x^{\mathrm{LOWZ\ BOSS}}$$
$$P_x^{\mathrm{eBOSS}} = P_x^{\mathrm{QSO\ eBOSS}} \times P_x^{\mathrm{LRG\ eBOSS}} \times P_x^{\mathrm{CMASS\ eBOSS}}$$
$$P_x^{\mathrm{eBOSS+BOSS}} = P_x^{\mathrm{eBOSS}} \times P_x^{\mathrm{BOSS}}\,, \qquad (11)$$

https://lscsoft.docs.ligo.org/ligo.skymap/

Results


Individual | $|\Delta_1|c$ | z
CMB Planck 18 | 370 km/s | 1090
QSO eBOSS | 488 km/s | 1.51
LRG eBOSS | 662 km/s | 0.73
CMASS eBOSS | 784 km/s | 0.65
CMASS BOSS | 586 km/s | 0.51
LOWZ BOSS | 694 km/s | 0.31
Combined | $|\Delta_1|c$ | z
eBOSS | 552 km/s | 1.09
BOSS | 584 km/s | 0.45
eBOSS+BOSS | 353 km/s | 0.71
150 120 90 60 30 0 330 300 270 240 210 180
60
30
0
-30
-60

Results



eBOSS
BOSS
eBOSS+BOSS
QSO eBOSS
LRG eBOSS
CMASS eBOSS
CMASS BOSS
LOWZ BOSS
z
1.2
1.
0.8
0.6
0.4
1.6
1.4
0.2
−1000
−500
0
500
1000
$\Delta_{1,x}\, c$ (km/s)
$\Delta_{1,y}\, c$ (km/s)
$\Delta_{1,z}\, c$ (km/s)

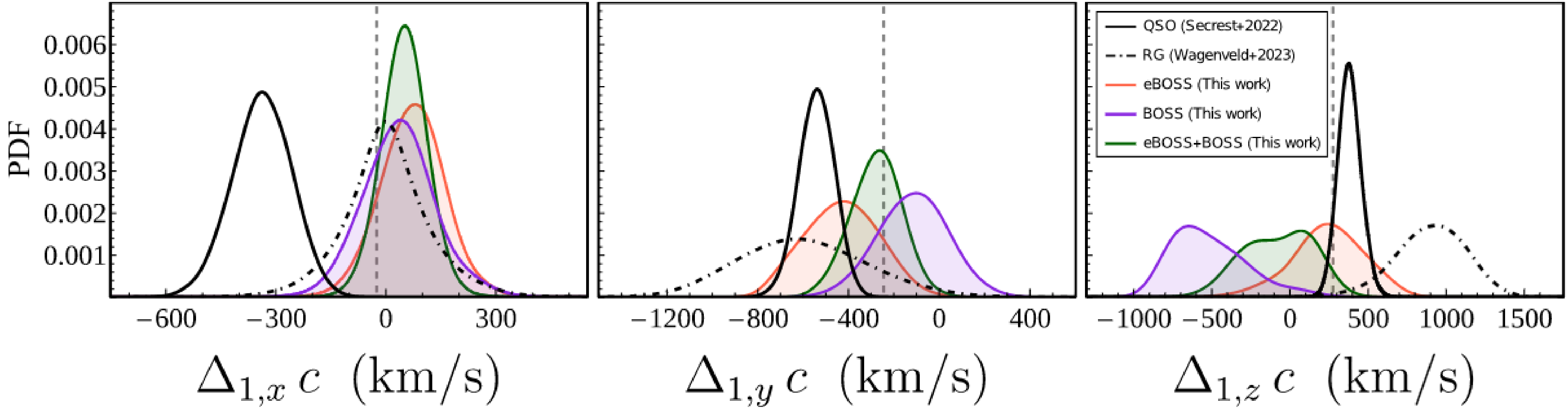
Results

Table 1 | Dipole measurements with 1σ uncertainties and significance of tension against the CMB dipole.

	Case	z	Dipole Δ_1 $\lvert v \rvert$ (km/s)	Dipole Δ_1 $l(°)$	Dipole Δ_1 $b(°)$	Significance of tension KDE	Significance of tension Distfit
	CMB	1090	$369.8^{+0.1}_{-0.1}$	$264.02^{+0.01}_{-0.01}$	$48.253^{+0.005}_{-0.005}$	–	–
Combined	eBOSS	1.09	552^{+169}_{-167}	280^{+12}_{-12}	30^{+15}_{-27}	0.8σ	0.8σ
Combined	BOSS	0.45	584^{+180}_{-243}	286^{+25}_{-146}	-77^{+52}_{-4}	2.1σ	1.9σ
Combined	eBOSS+BOSS	0.71	353^{+123}_{-111}	281^{+14}_{-14}	-11^{+39}_{-30}	1.4σ	1.3σ
Individual	QSO eBOSS	1.51	488^{+207}_{-187}	245^{+30}_{-89}	7^{+33}_{-44}	0.2σ	0.2σ
Individual	LRG eBOSS	0.73	662^{+200}_{-240}	60^{+232}_{-22}	37^{+14}_{-58}	1.0σ	1.0σ
Individual	CMASS eBOSS	0.65	784^{+150}_{-160}	285^{+10}_{-13}	26^{+18}_{-33}	1.6σ	1.2σ
Individual	CMASS BOSS	0.51	586^{+196}_{-251}	269^{+34}_{-143}	-78^{+62}_{-4}	2.1σ	1.6σ
Individual	LOWZ BOSS	0.31	694^{+198}_{-247}	327^{+6}_{-284}	-35^{+73}_{-16}	0.6σ	0.6σ

To evaluate the two-tailed significance, we compare the dipoles to the CMB value in Cartesian coordinates using two methods: a non-parametric Kernel Density Estimation (KDE) with a Gaussian kernel and a parametric best-fit distribution analysis conducted using the `Distfit` Python module[39]. The table additionally lists the effective redshift for each scenario. For BOSS and eBOSS data, this corresponds to the weighted average redshift, which is equivalent to the monopole.

Comparing



Extended Data Fig. 6 | Comparison of dipole measurements in Cartesian coordinates with previous estimates. The distributions for eBOSS, BOSS, eBOSS+BOSS analyses correspond to those presented in Fig. 5.

Conclusions

Our redshift dipole measurements show agreement with the CMB dipole, exhibiting a tension of 0.8σ for eBOSS data ($0.6 < z < 2.2$), 2.1σ for BOSS data ($0.2 < z < 0.6$), and 1.4σ for combined eBOSS+BOSS data ($0.2 < z < 2.2$). The most notable, albeit moderate, tension with the anticipated dipole arises from BOSS data within the redshift range $0.2 < z < 0.6$, where our findings suggest a deviation towards the southern hemisphere, despite the dipole's magnitude closely matching expectations.

These results reveals that our motion with respect to distant galaxies and quasars is in close agreement with that suggested by the CMB dipole, as illustrated in Fig. 3 in both Galactic and Cartesian coordinates. This concordance implies that matter at cosmological distances of 1–5 Gpc shares the same rest frame as the CMB, located approximately 14 Gpc away, offering substantial support to the cosmological principle, which advocates for large-scale homogeneity and isotropy. Moreover, our results suggest that previous assertions of discrepancies with the CMB dipoles might stem from overlooked systematic influences, such as the redshift evolution modeling of observables, biases in the estimators or the underestimation of uncertainties

Update: V3 coming (1~2 weeks) + Perspectives

- 3 typos in equations.
- Absolute values are a bit biased due to small inconsistency during analysis, they are smaller than presented in V2. Conclusions will remain the same. Still compatible with the CMB dipole and in tension with previous number count dipoles. It seems that LOWZ was only noise (estimator does not minimized).

Pedro da S. Ferreira – dasferreira.pedro@gmail.com

Thanks for your attention!