A new test of the Cosmological Principle: measuring our peculiar velocity and the large scale anisotropy independently

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Outline

Motivation

The dipole of the CMB has been measured very accurately. If interpreted as our peculiar velocity it yields (Planck, 2018):

$$v = (369.816 \pm 0.001) km/s, \qquad \ell = (264.021 \pm 0.008)^o \quad b = (48.253 \pm 0.004)^o$$

This is also consistent with modulation and aberration of the higher multipoles of the CMB temperature fluctuations as they are expected from peculiar velocities.

Within standard ΛCDM cosmology our velocity wrt. the CMB should agree with our velocity wrt. the galaxy (matter) distribution on very large scales.

But this seems not to be the case...

Motivation

People have tried to measure this velocity and, so far, it never agreed with the result from the CMB. Typically the direction is roughly compatible but the amplitude is a factor of 2 or more larger.

- 1994 (Lauer and Postman), Abell clusters
- 2013-20, radio surveys like NVSS and others [1301.5559], [1509.02532], [1710.08804], [1812.04739], [2010.08366]
- Quasars (Secrest et al. [2009.14826])

Combining quasars and radio galaxies Secrest et al. 2022 find a 5.2σ discrepancy from the CMB while the quasar and radio dipoles agree.

In all these analyses the following relation is being used (see later).

$$\beta = \frac{v}{c} = \frac{D}{2 + x(1 + \alpha)}$$

Here D is the dipole and x and α are phenomenological parameters which are measured and are assumed to be redshift independent. It has been shown that relaxing this assumption one can reconcile the observations with the CMB dipole (Dalang & Bonvin, 2021).

Apart from measurement/interpretation errors, there are two possible conclusions:

1. The restframe of the CMB does not agree with the one of matter (galaxies & quasars) $\Rightarrow$ we measure a different kinematic dipole, β.
2. The intrinsic dipole is larger than the predictions from ΛCDM.

In this talk I describe a new method to distinguish between the kinematic and an intrinsic dipole.

Introduction

- We expect the angular distribution of sources around us on very large scales and integrated over a considerable redshift range to exhibit a dipole due to our motion, we call it the kinematic dipole.
- But also clustering of sources will generically generate a dipole (number count dipole).
- There may even be an intrinsic dipole in our geometry if we live e.g. in a Bianchi model and not in a FL universe.
- We denote the geometric + clustering dipole the intrinsic dipole.

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In the CMB a dipole of amplitude $C_1 \simeq 2 \times 10^{-6}$ has been measured. As it is much larger than all higher multipoles, it has been attributed to our peculiar velocity leading to

$$\beta \simeq 1.2 \times 10^{-3} \quad \text{in direction} \quad (l, b) \simeq (264.02, 48.25)$$

Most probably it also contains an 'intrinsic' part but we expect this to be about 100 times smaller.

The kinematic dipole from number counts

If we count sources they are affected by our motion with respect, to their mean velocity (the 'background Universe'):

On the one hand, the observed solid angle in direction **n** is modified by $d\Omega \to (1 - 2\boldsymbol{\beta} \cdot \mathbf{n})d\Omega + \mathcal{O}(\beta^2)$ by a boost in direction **n**.

Furthermore, if the number density at the flux limit scales as F^{-x} and the flux behaves as $\nu^{-\alpha}$ in the vicinity of the observed frequency we obtain (Ellis & Baldwin 1984)

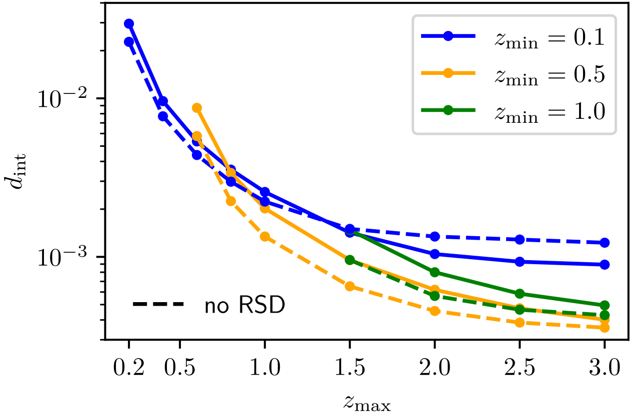
$$\frac{dN}{d\Omega}(> F_{\rm min}, \mathbf{n}) = \left(\frac{dN}{d\Omega}(> F_{\rm min}, \mathbf{n})\right)_{\rm rest} (1 + [2 + x(1+\alpha)]\boldsymbol{\beta} \cdot \mathbf{n}) + \mathcal{O}(\beta^2)\,.$$

For typical radio galaxies with $x \sim 1$ and $\alpha \sim 0.75$, this gives a kinematical dipole of

$$\mathbf{d}_{\rm kin} \sim 4.6 \times 10^{-3}\hat{\boldsymbol{\beta}}$$

when inserting the CMB velocity.

Using CLASS we have also calculated the intrinsic clustering dipole in a typical ΛCDM cosmology:



The intrinsic Dipole (from Nadolny et al. 2021).

The shot noise dipole from number counts

Shot noise induces an angular power spectrum given by the inverse of the source density. For N_{tot} sources on a fraction $f_{\rm sky}$ of the sky,

$$C_\ell^{SN} = 1/\,\overline{N} \qquad \overline{N} = \frac{N_{\rm tot}}{4\pi f_{\rm sky}}$$

$$d_{SN} = \sqrt{\frac{9C_1^{SN}}{4\pi}} = \frac{3}{\sqrt{N_{\rm tot}}} \qquad \text{(for full sky coverage)}$$

Hence with $N_{\rm tot} \simeq 10^6$ shot noise is comparable to the kinematic dipole.

(For partial sky coverage leakage from higher multipoles increases this dipole roughly by a factor $1/f_{\rm sky}$ so that the above formula remains actually roughly valid.)

The dipole from weighted number counts

The total dipole from the number counts is

$$\mathbf{d}^N_{tot} = \mathbf{d}^N_{\rm kin} + \mathbf{d}_{\rm int} + \mathbf{d}^N_{SN}$$

$$\frac{dN}{d\Omega}(\mathbf{n}) = \sum_{i\in{\rm cut}} \delta(\mathbf{n}_i - \mathbf{n}) = \overline{N}(1 + \mathbf{n}\cdot\mathbf{d}^N_{tot} + \mathcal{O}(n_j^2))$$

We can weight the number count with a function of measured source properties : flux, F, redshift, z, angular size ϕ, ...

Instead of simply N, we can determine the dipole of some weighted number count,

$$\frac{dN^W}{d\Omega}(\mathbf{n}) = \sum_{i\in{\rm cut}} W(F_i, z_i, \phi_i, \cdots)\delta(\mathbf{n}_i - \mathbf{n})$$

As F, z and ϕ are affected in a well defined way by peculiar velocities, we obtain a weighted dipole

$$\mathbf{d}^W_{tot} = \mathbf{d}^W_{\rm kin} + \mathbf{d}_{\rm int} + \mathbf{d}^W_{SN}$$

Consider $\mathbf{d}^W_{\rm kin} = B^W\boldsymbol{\beta}$ while $\mathbf{d}^N_{\rm kin} = B^N\boldsymbol{\beta}$.

In the observable $N - N^W$ the intrinsic dipole drops out while in $B^W N - B^N N^W$ then the kinematic dipole drops out. More precisely

$$\boldsymbol{\beta}^{\rm est} = \frac{\mathbf{d}^W_{\rm est} - \mathbf{d}^N_{\rm est}}{B^W - B^N}, \qquad \mathbf{d}^{\rm est}_{\rm int} = \frac{B^W\mathbf{d}^N_{\rm est} - B^N b d^W_{\rm est}}{B^W - B^N}.$$

B^W and B^N

The weighting factors B^W and also B^N can in principle be determined directly from the data: We can boost each data point e.g. with measured angular size and measured frequency dependence or flux, knowing the change of angular size and frequency under boosts.

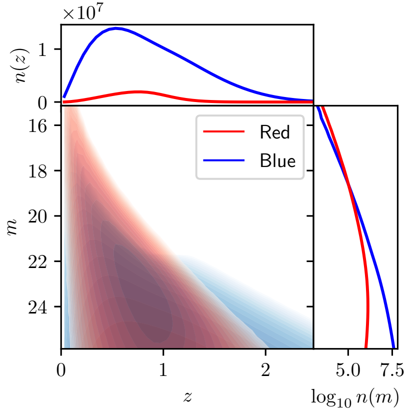
Boosting the data with $\beta_{\rm test}$ in forward (+) and backward (-) directionwe obtain the $N_W^\pm$,

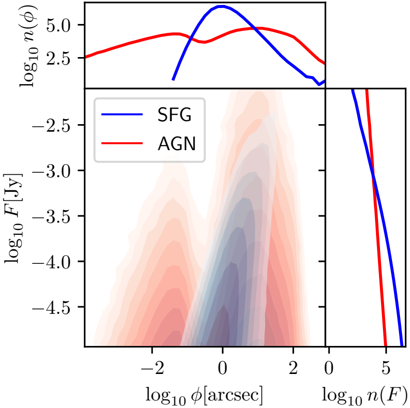
$$\frac{dN_W^\pm}{d\Omega}(\mathbf{n}) = \sum_{i\in{\rm cut}} W_i(F_i + \delta^\pm_{F_i}, z_i + \delta^\pm_{z_i}, \phi_i + \delta^\pm_{\phi_i}, \cdots)$$

$$B^W = 2 + \frac{N_W^+ - N_W^-}{N_W^+ - N_W^-}\beta_{\rm test}^{-1}$$

(The '2' in front comes from the change in the solid angle $d\Omega$.)

We considered $W(m,z) = m^{x_m} z^{x_z}$ for LSST and Euclid photometric surveys and $W(F,\phi) = F^{x_F}\phi^{x_\phi}$ for SKA



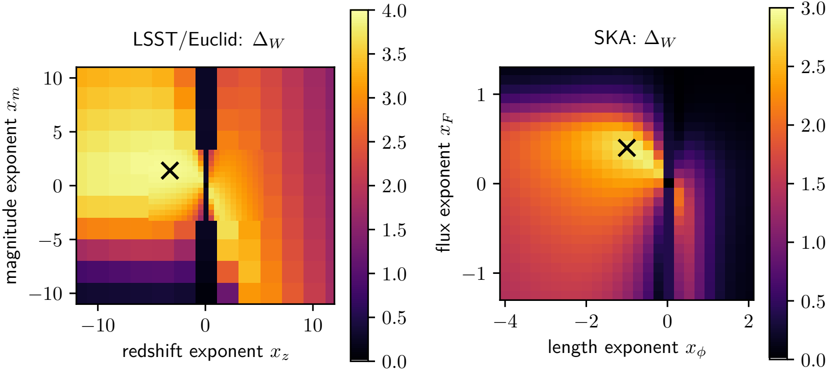


Realization

- Calculating the number count fluctuation $\Delta(\mathbf{n}, z)$ with CLASS (halofit) using $b(z)$ $f_{\rm evo}(z)$, $s(z)$ from Alonso et al. (2015).
- Producing a Gaussian realization in the sky using the sky coverage of the experiment and full sky.
- Poissons sampling with $n(m, z)$ or $n(F, \phi)$ and fixed $N_{\rm tot}$.
- Applying a boost with $\beta_{\rm CMB}$ on n, m, z, F and ϕ.
- Calculating S/N for β for different weighting exponents, $x_m, \cdots x_\phi$ in order to determine the best weights.
- Analyzing the resulting maps for the best weights, e.g. calculating its dipole for N and N^W.

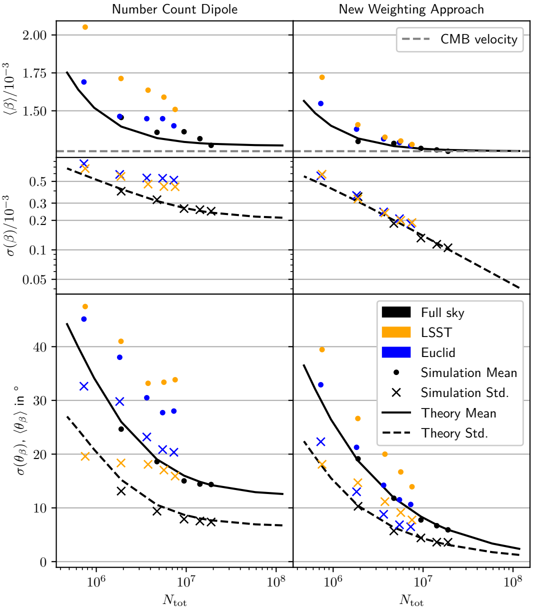
In real data the pre-factors B_N and B_W can be determined by boosting a random sky distribution with the properties $n(m, z)$ or $n(F, \phi)$ of the data with a large velocity.

We simulated this distributions and determined the $S/N = \beta\Delta_W\sqrt{N_{\rm tot}}/3$,
$\Delta_W = |B_W - B_N|\overline{W}/\sigma_W$
as function of the exponents (x_m, z_m) and (x_F, x_ϕ).



The S/N maxima are at $(x_m, z_m) = (1.4, -3.3)$ and $(x_F, x_\phi) = (0.4, -1)$.

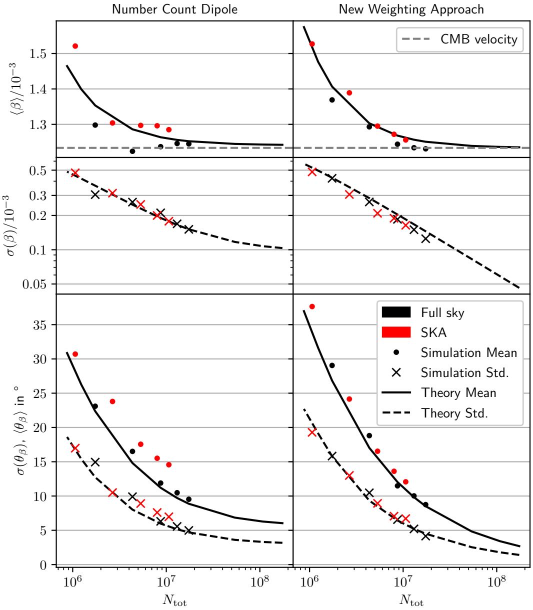
Accuracy of β from LSST/Euclid



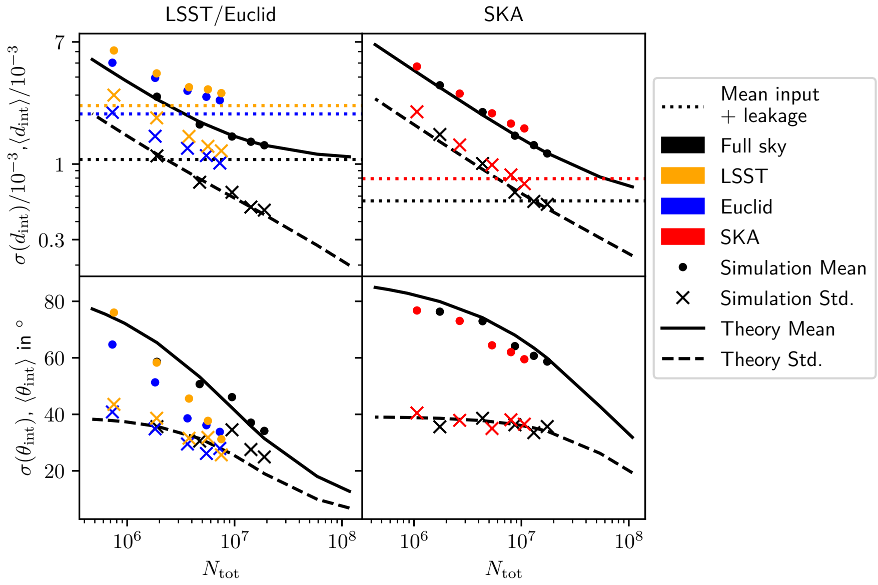
$$\mathbf{d}_{\rm tot} = \mathbf{d}_{\rm kin} + \mathbf{d}_{\rm else}$$

$$\langle \mathbf{d}^2_{\rm tot} \rangle = \langle \mathbf{d}^2_{\rm kin} \rangle + \langle \mathbf{d}^2_{\rm else} \rangle$$

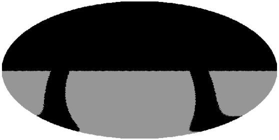
Accuracy of β from SKA



Intrinsic dipole

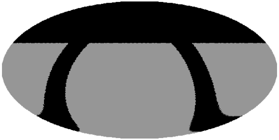


Sky covergae



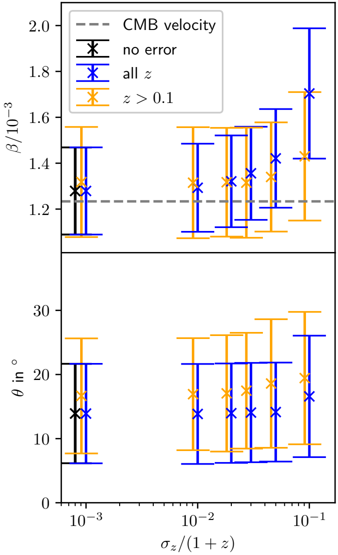
LSST

Euclid

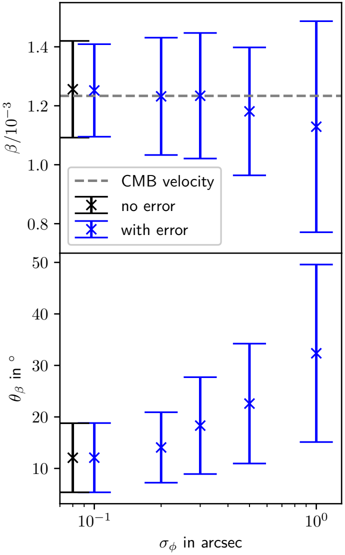


SKA

Measurement errors



$N_{\rm tot} = 0.75 \times 10^7$



$N_{\rm tot} = 1.1 \times 10^7$

Final results

	LSST	Euclid	SKA (realistic)	SKA (high resolution)
$N_{\rm tot}$	10^9	10^9	10^8	3.3×10^8
$\sigma_z/(1+z)$ and σ_ϕ	5%	5%	0.1arcsec	0
$z_{\rm min}$ and $\phi_{\rm min}$	0.2	0.2	0.3 arcsec	0
$f_{\rm sky}$	40%	38%	61%	61%
$\sigma(\beta)/\beta$	1.4%	1.3%	4.5%	2.5%
$\langle\theta_\beta\rangle$	1.2^o	0.9^o	3.9^o	2.2^o
$\sigma(d_{\rm int})/d^{\rm t}_{\rm int}$	4.6%	4%	39%	23%
$\langle\theta_{\rm int}\rangle$	3.1^o	2.7^o	24^o	13^o

Expected observational parameters for LSST, Euclid, and the SKA, respectively.

Amplitude and direction of our velocity and the intrinsic dipole obtained by extrapolating the simulation results of the Figures to larger $N_{\rm tot}$.

Systematic uncertainty of $\approx 2\%$ in β and $d^t_{\rm int}$ (intrinsic dipole + leakage) not reflected in the errors reported here.

Conclusions

- The intrinsic dipole from LSS clustering is typically $\simeq 10^{-3}$ and not $\simeq 10^{-5}$, even for a survey from $z \sim 1$ to $z \sim 3$.
- By combining two (or more?) observables it is possible to isolate both, the kinematic and the intrinsic dipole.
- To extract the intrinsic dipole, a good sky coverage is very important.
- A large $N_{\rm tot} \gtrsim 10^8$ is required for a measurement with 10% accuracy.
- With LSST/Euclid we will be able to measure the kinematic and the intrinsic dipole (including leakage) to a few % accuracy in amplitude and a few degrees in direction.
- For SKA the prospects for the kinematic dipole are similar but the intrinsic dipole will be less well measured (it is somewhat more than a factor 2 smaller).
- What about applying this weighting technique to higher multipoles of the number counts?