My two cents on the cosmic dipole

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Outline

Motivation

- Our peculiar velocity wrt. the CMB has been measured not only as the CMB dipole but also via its modulation and aberration of the higher multipoles of the CMB temperature fluctuations.
  Within standard ΛCDM cosmology it should agree with our velocity wrt. the matter distribution on very large scales.

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- Other analyses agree with the CMB kinematic dipole (e.g. Lacy et al. [1907.01981]; Darling [2205.06880]; Cheng et al. [2309.02490])
- Analysing the Pantheon+ SN1a dataset one finds a roughly compatible amplitude but a different direction (Sorrenti et al. [2212.10328]).

Motivation

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 due to our motion wrt the different restframes.
2. The intrinsic dipole from fluctuations in the matter distribution is larger than the predictions from ΛCDM.

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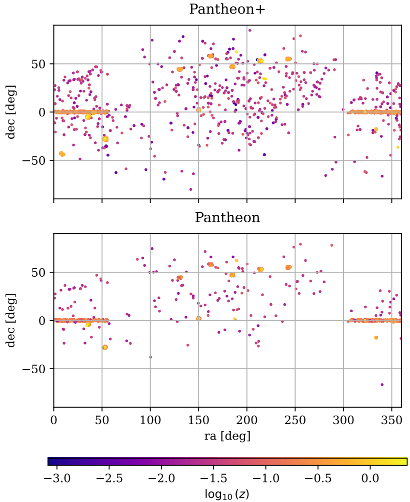
In this talk I first describe our findings for the Pantheon+ dipole (Sorrenti et al. [2212.10328]) .

Then I discuss a new method which allows to distinguish between the kinematic and an intrinsic dipole (Nadolny et al. [2106.05284]).

1701 lightcurves from 1550 type 1a SNe.



(Figure from Sorrenti et al.)

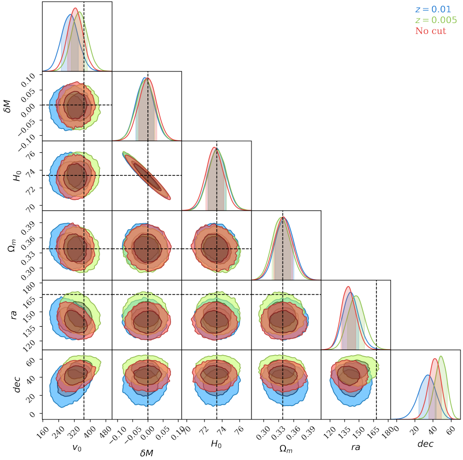
The Pantheon+ data: Method

$$D_L(\bar{z}) = \bar{D}_L(z - \delta z) = \bar{D}_L(z + \mathbf{n}\cdot\mathbf{v}) = \frac{1+\bar{z}}{H_0}\int_0^{\bar{z}} \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + 1 - \Omega_m}}$$
$$\simeq \bar{D}_L(z)\left(1 + \frac{1}{\mathcal{H}(z)r(z)}\mathbf{n}\cdot\mathbf{v}\right) \qquad (z \ll 1)\,.$$

We have fitted the data to this formula with the parameters H_0, Ω_m and the 3 components of the velocity $\mathbf{v}$ including only SNe above a redshift cut $z_{\rm cut}$ for different values of $z_{\rm cut}$.

We have determined the parameters inferred by the data with an MCMC routine.

The CMB dipole direction, (ra,dec) $= (167.942 \pm 0.007, 6.944 \pm 0.007)$ is excluded at more than 3σ .



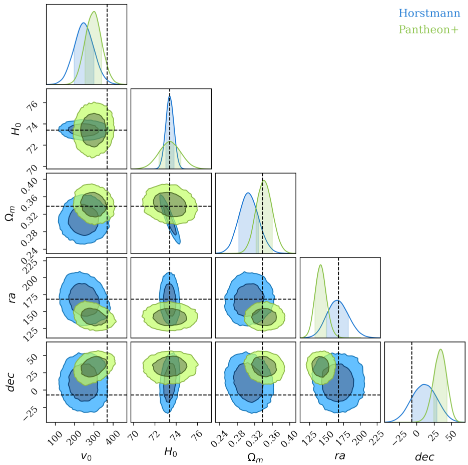
(Figure from Sorrenti et al.)

The Pantheon+ data: Significance

A simple χ^2–analysis yields :

$z_{\rm cut}$	$\chi^2_{\rm No-dip}$ - $\chi^2_{\rm best-fit}$	$\chi^2_{\rm Planck}$ - $\chi^2_{\rm best-fit}$	$\chi^2_{z_{HD}}$ - $\chi^2_{\rm best-fit}$
No cut	88.2	66.4	9.1
0.005	88.5	68.5	19.1
0.01	62.1	41.4	15.0
0.0175	53.6	42.6	14.4
0.025	41.7	19.2	-2.1
0.0375	22.3	5.3	1.3
0.05	8.7	0.9	-1.0
0.1	7.4	3.4	2.9

Comparing the Pantheon+ to the Pantheon analysis



(Figure from Sorrenti et al.)

The dipole analysis from the Pantheon data by Horstmann et al. (2021) 'agrees' with both, the Planck dipole and the best fit dipole from Pantheon+.

z_{cut}	Pantheon+	Pantheon
0.01	1576	1046

The velocity which generated the SN1a dipole is actually not just our velocity but

$$\mathbf{v} = \mathbf{v}_0 - \mathbf{v}_{\rm bulk} \, .$$

Hence a bulk velocity inside a ball of radius $\sim 150h^{-1}$Mpc with amplitude of about 300km/sec is needed to explain this result.

Interestingly, the direction of this bulk velocity is compatible with the one found in Watkins et al. [2302.02028] analysing the CosmicFlows-4 catalog Tully et al. 2022 and similar earlier papers by the same group.

The bulk velocity expected on this scale from ΛCDM is about 140km/sec. The probability to find more than 300km/sec is less than 1%.

Kinematic and intrinsic Dipole

- 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 (dipole of the source distribution).

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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

$$\beta \simeq 1.2 \times 10^{-3} \quad \text{in direction} \quad (l, b) \simeq (264, 48.25)$$

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

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)

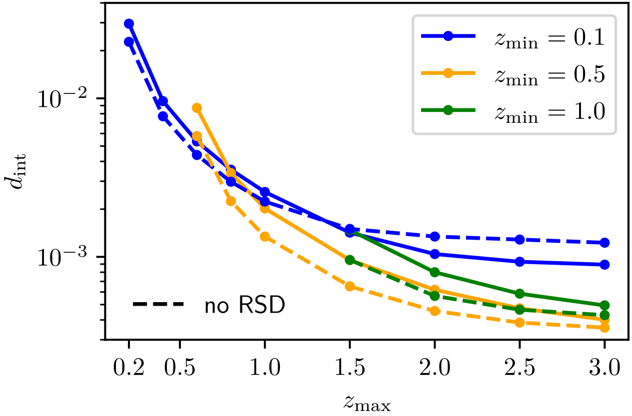
$$\frac{dN}{d\Omega}(> F_{\min}, \mathbf{n}) = \left(\frac{dN}{d\Omega}(> F_{\min}, \mathbf{n})\right)_{\rm rest} (1 + [2 + x(1 + \alpha)]\boldsymbol{\beta} \cdot \mathbf{n}) + \mathcal{O}(\beta^2) \, .$$

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

$$\mathbf{d}_{\rm kin} \sim 4.5 \times 10^{-3} \hat{\boldsymbol{\beta}}$$

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,

$$
\begin{aligned}
C_\ell^{SN} &= 1/\,\overline{N} \qquad \overline{N} = \frac{N_{\rm tot}}{4\pi f_{\rm sky}} \\
d_{SN} &= \sqrt{\frac{9C_1^{SN}}{4\pi}} = \frac{3}{\sqrt{N_{\rm tot}}} \qquad \text{for full sky coverage}\,.
\end{aligned}
$$

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 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 the source properties, the flux, F, redshift, z, angular size ϕ, ...

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

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

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

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

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 (-) direction we obtain the $N_W^\pm$,

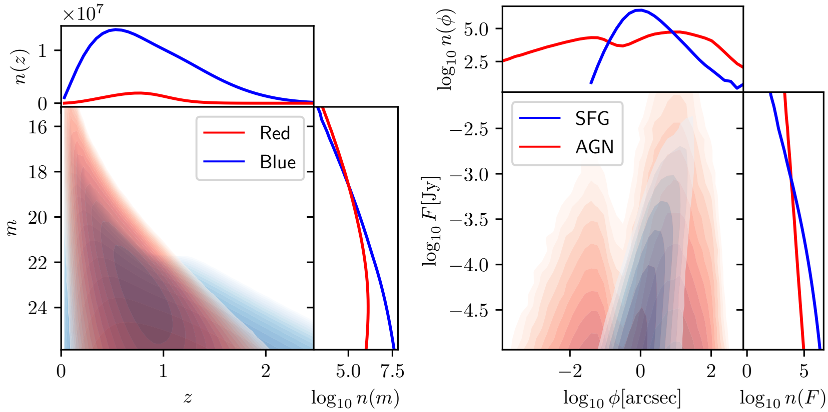
$$\frac{dN_W^\pm}{d\Omega}(\mathbf{n}) = \sum_{i\in{\rm cut}} W_i(F_i + \delta^\pm_{F_i}, z_i + \delta^\pm_{z_i}, \phi_i + \delta^\pm_{\phi_i}, \cdots)$$

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

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

Forecasting two examples

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



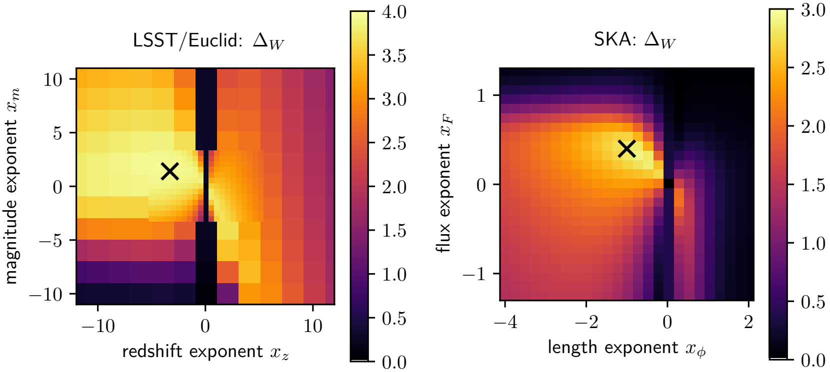
(from Nadolny et al. 2021)

- Calculating the number count fluctuation $\Delta(\mathbf{n}, z)$ with CLASS (halofit) using $b(z)$ $f_{\rm evo}$, $s(z)$ 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.

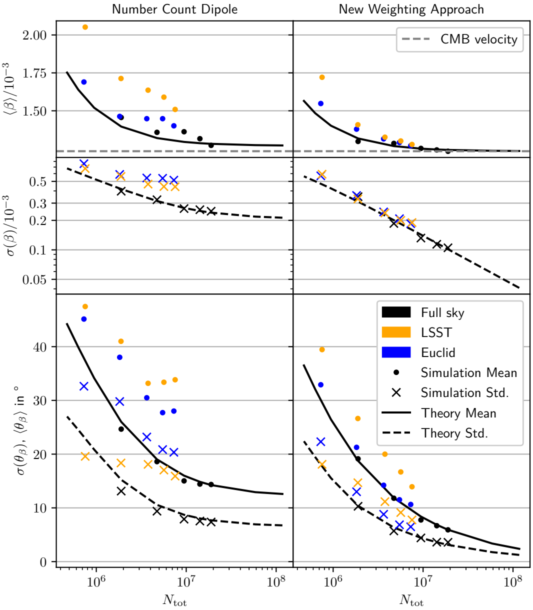
Optima weights

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 $(x_F, x_\phi) = (0.4, -1)$.
(from Nadolny et al. 2021).

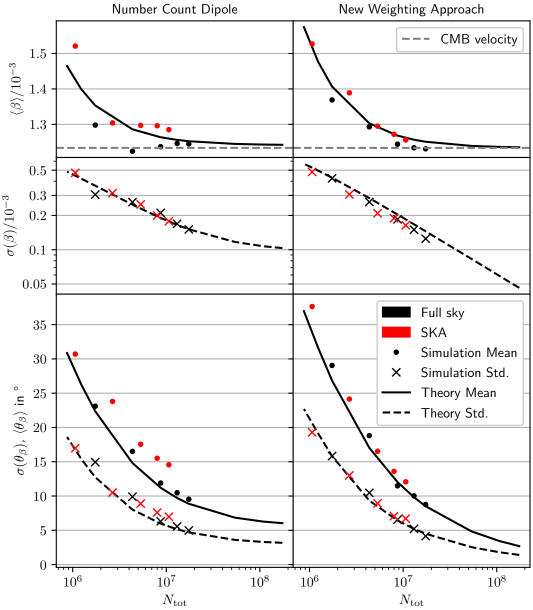
Accuracy of β from LSST/Euclid



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

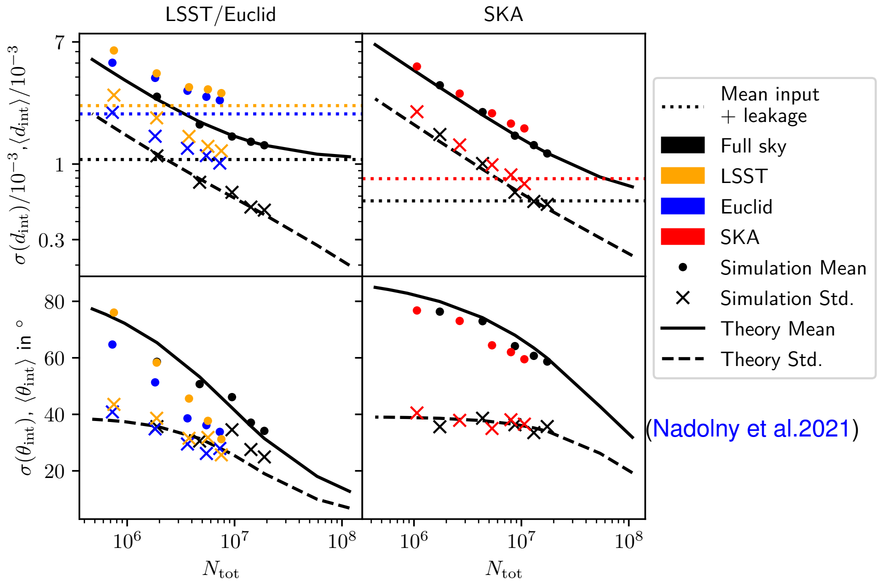
(Nadolny et al. 2021).

Accuracy of β from SKA



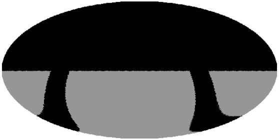
(Nadolny et al. 2021).

Intrinsic dipole



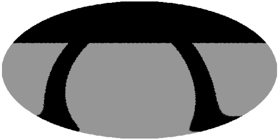
(Nadolny et al.2021)

Sky covergae



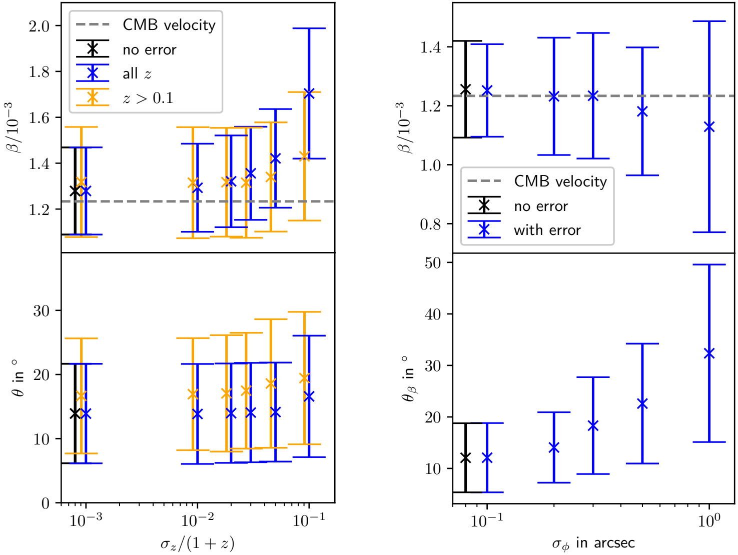
LSST

Euclid



SKA

Measurement errors



$N_{\text{tot}} = 0.75 \times 10^7$ $N_{\text{tot}} = 1.1 \times 10^7$

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 $z \sim 4$. (SKA)
- 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).
- It might be interesting to apply this weighting technique to higher multipoles of the number counts.

Happy birthday Subir !