The Ellis and Baldwin test and the cosmic dipole anomaly

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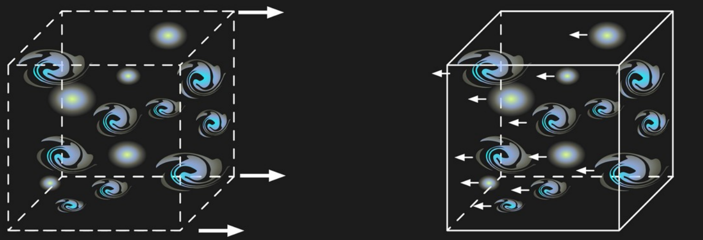
I. The Cosmological Principle

« There exist a cosmic rest frame **in which** the universe is, at sufficiently large scale, homogeneous and isotropic. »

(idea from Edward Milne, 1935)

The Cosmological Principle is only true within the CRF !



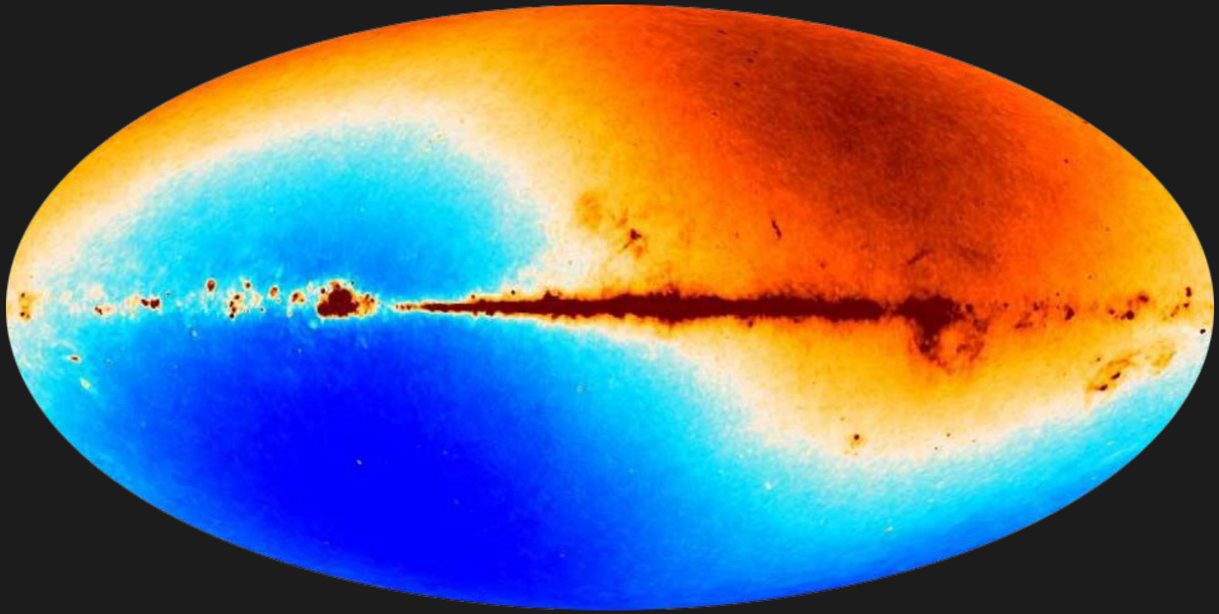
Rest frame

Moving frame
→ everything has a velocity
→ anisotropic

What is this Cosmological Rest Frame (CRF) ?

II. The CRF and the CMB

The CMB should be at rest in the CRF !

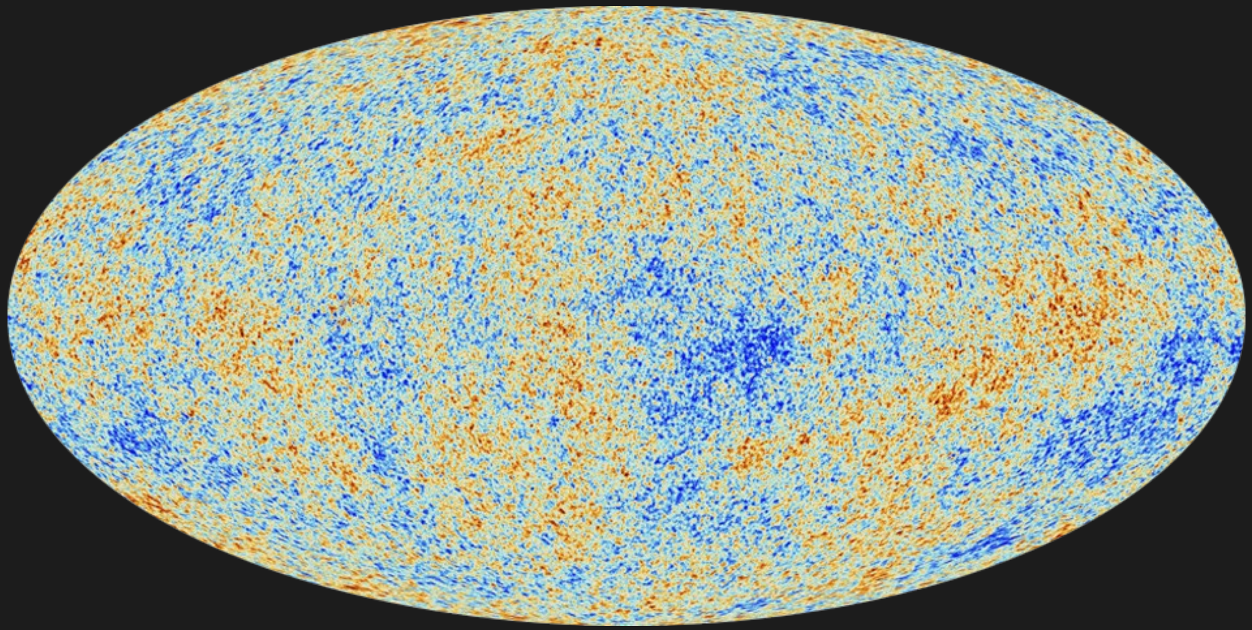


Main interpretation : CMB dipole is dominated by kinematic effects

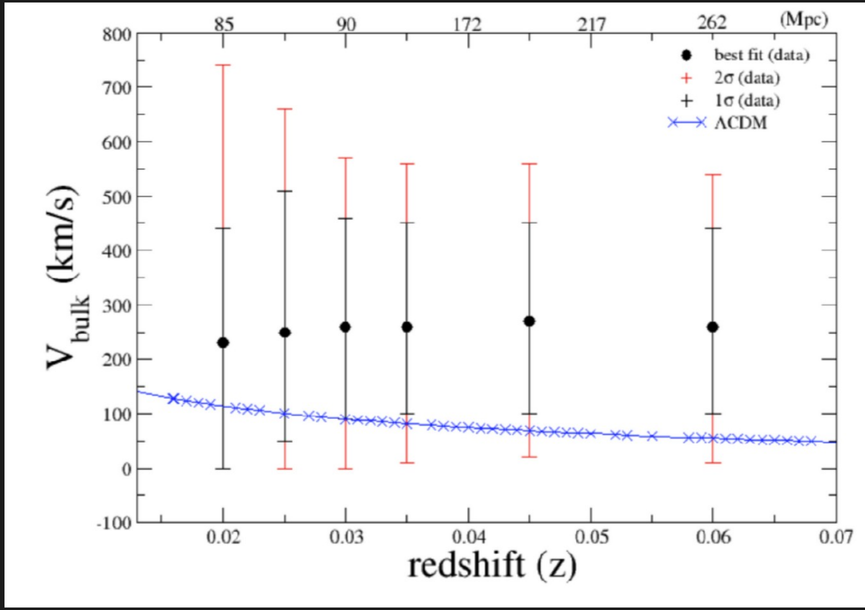
$v_{CMB} = 369.82 \pm 0.11\, km.s^{-1}$ toward the Virgo constellation

II. The CRF and the CMB

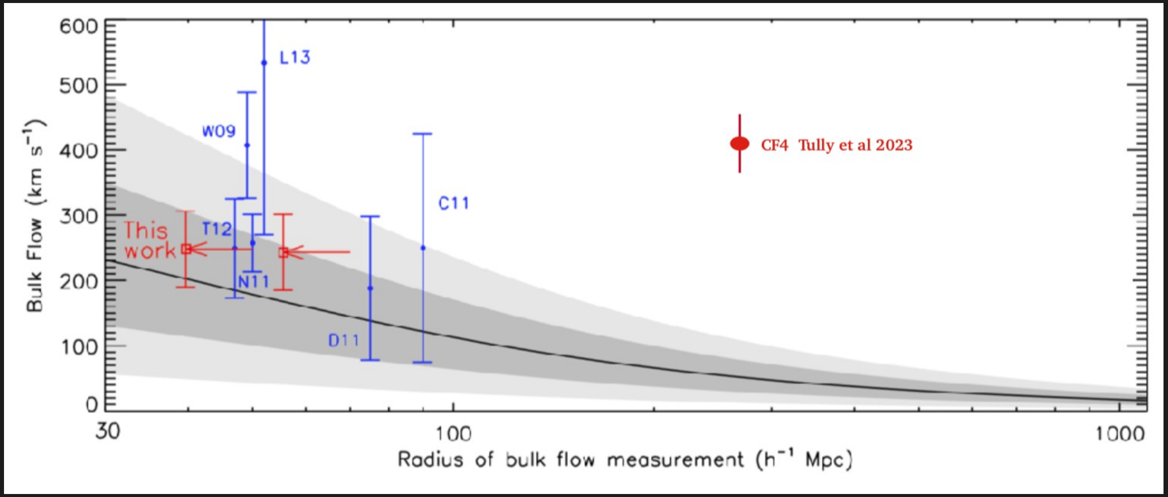
The CMB should be at rest in the CRF !



III. Is this CMB rest frame a Cosmological rest frame ?



Bulk velocity of SN Ia, with respect to the CMB [Colin et al. 2011]



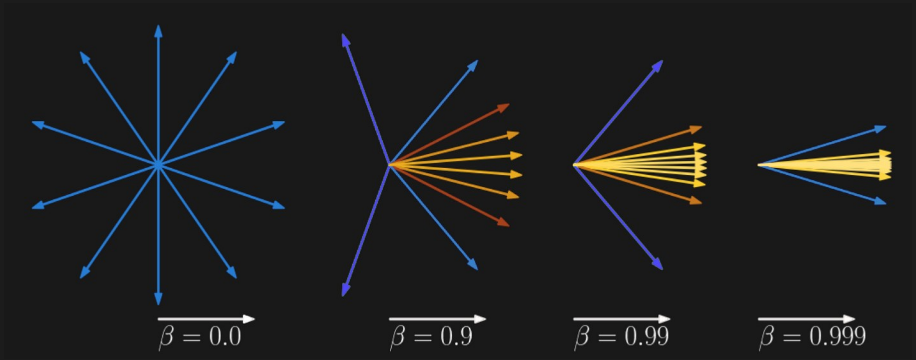
Summary of several measurement of the bulk flow velocity

It looks like the bulk-flow may be bigger than what we expect within LCDM, but it’s not that clear

III. The Ellis and Baldwin test

Our own velocity has an impact on our observations :

1) Relativistic aberrations : our field of view is distorted



$$\delta(\theta) = \gamma^{-1}(1-\beta\cos(\theta))^{-1}$$

$$d\Omega_{obs} = \delta(\theta)^2 d\Omega_{rest}$$

2) Doppler boosting : some sources go above/bellow the detection threshold

$$dN(>F_{min}) \propto F_{min}^{-x} \qquad F \propto \nu^{-\alpha} \qquad F_{obs} = \delta(\theta)^{1+\alpha} F_{rest}$$

⟶ we model our source spectra and luminosity distribution with power laws

There is an (intrinsic) anisotropy in our observations of the universe !

$$\frac{dN}{d\Omega_{obs}}(>F_{min},\hat{n}) = \frac{dN}{d\Omega_{rest}}(>F_{min},\hat{n})\delta(\theta)^{2+x(1+\alpha)}$$
$$= \overline{N}(1+d_{kin}\cdot\hat{n})$$

$$d_{kin}=(2+x(1+\alpha))\beta$$

(Ellis and Baldwin 1984)

Model independant way to test the cosmological principle !

$$d_{kin} = \left(2 + x\left(1 + \alpha\right)\right)\beta$$

[Ellis and Baldwin 1984]

Model independant way to test the cosmological principle !

Only need :

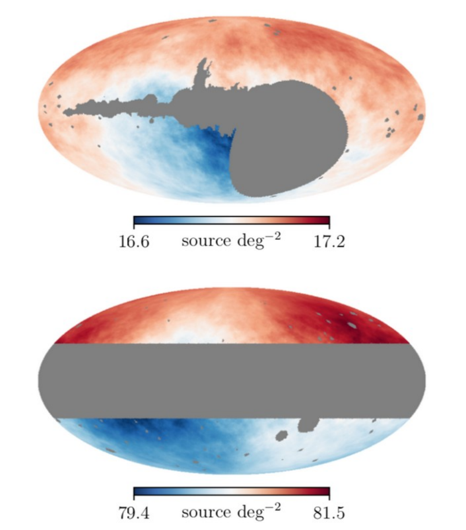
- (almost) full-sky survey → good dipole fit + prevent leakage
- *sufficiently* far-away sources → no clustering/LSS
- *minimal* knowledge of spectra/luminosity distribution → to have x, α
- above 10^5 sources → prevent shot noise
- consistent scanning pattern

Quite a lot of constraints actually….

IV. What are the results for now ?

It doesn't coincide with the CMB rest frame…

- Measurement of the dipole in NVSS since 2002 [Blake and Wall 2002]
- Coherent results with other radio surveys (*e.g* TGSS, SUMSS, WENSS)
  (for ex. [Rubart Schwarz 2013], [Colin et al. 2017], etc.)
- [Secrest et al. 2022] study of both CatWISE quasars and NVSS radio sources, 5σ anomaly



NVSS radio galaxies :

(5.0×10^5 sources)

$$v_{NVSS} = 1100 \pm 200\, km.s^{-1}$$

CatWISE quasars :

(1.6×10^6 sources)

$$v_{WISE} = 750 \pm 80\, km.s^{-1}$$

The number count dipole amplitude is far too big for both (independant) catalogue !
+ there is a ~40° difference in the direction between the CMB and the matter dipole

V. Is there something not taken into account in the EB formula ?

- Real number count : [Friedman-Shaw et al. 2024]

$$\Delta_g = \left\{ b_1\delta_m + \mathcal{H}^{-1}\partial_r v_{\|} \right\} + \left\{ \frac{5s-2}{2} \int_0^{\chi} d\chi' \frac{\chi - \chi'}{\chi\chi'} \Delta_\Omega (\Psi + \Phi) \right\}$$
$$+ \left\{ \mathcal{R}_v (v_{\|} - v_{\|,o}) - (2-5s) v_{\|,o} \right\}$$
$$+ \left\{ \left(\mathcal{R}_v - \frac{2-5s}{\mathcal{H}_0 \chi} \right) \mathcal{H}_0 V_o + (\mathcal{R}_v + 1)\Psi - \mathcal{R}_v \Psi_o + (5s-2)\Phi + \dot{\Phi}\mathcal{H}^{-1} + (b_e - 3)\mathcal{H}V \right\}$$
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Real matter distribution

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Kinematic effects

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Real matter distribution

Redshift-space distortion

$$\Delta_g = \left\{ b_1 \delta_m + \mathcal{H}^{-1} \partial_r v_{\parallel} \right\} + \left\{ \frac{5s-2}{2} \int_0^{\chi} d\chi' \frac{\chi - \chi'}{\chi \chi'} \Delta_\Omega (\Psi + \Phi) \right\}$$
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Redshift-space distortion

Weak-lensing

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Kinematic effects

GR

1) The dominant effect here should be the **clustering**

= the intrinsic anisotropy of the matter distribution, due to LSS

How can we constrain it ?

Expected power spectrum within LCDM, for a source distribution $n_s(r)$:

$$\langle C_l^{cl} \rangle = \frac{2}{\pi} \int dk\, k^2 P(k, z=0) W_l^{cl}(k)^2$$

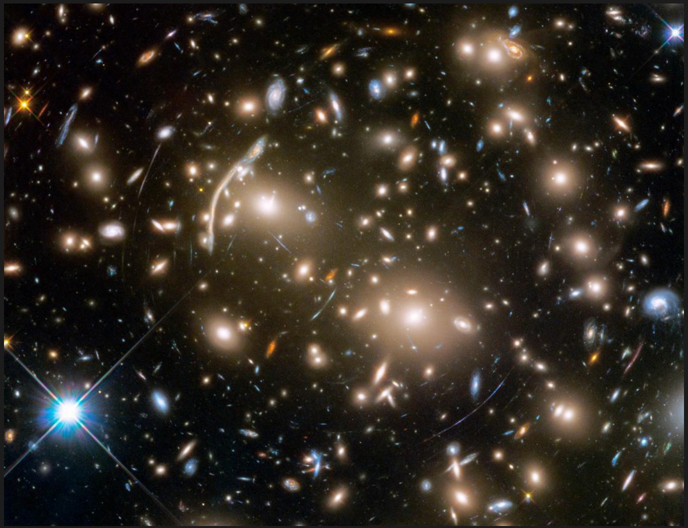
$$W_l^{cl}(k) = \int_0^{r_{max}} dr\, n_s(r) b_s(r) D_+(r) j_l(kr)$$

$$\langle d_{cl}^2 \rangle = \frac{9 \langle C_1^{\kappa} \rangle}{4\pi}$$

At far enough redshift, this clustering dipole can be as small as we want, but dominates at close distance.

In CatWISE $d_{cl} \approx 2.4 \times 10^{-4}$ compared to $d_N \approx 1.5 \times 10^{-2}$

2) What about **Weak-lensing** ?



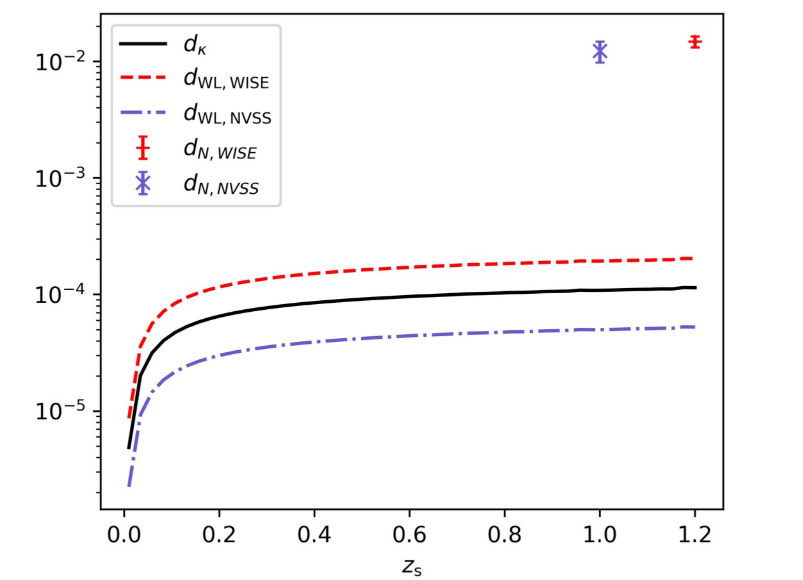
The local universe deforms observations along the line of sight, through the convergence field :

$$\kappa(r_s,\hat{n}) = \frac{3 H_0 \Omega_m}{2 c^2} \int_0^{r_s} dr \, \frac{r(r_s - r)}{r_s a(r)} \delta_m(r,\hat{n})$$

- WL impact should be *stronger* in the same direction as the dipole
- Should be stronger at large redshift
- Impact of the convergence dipole on the number count dipole

$$d_{WL} = 2(x-1) d_\kappa$$

[Mohayaee and Bonnefous 2026] → Its also negligible !



Expected convergence dipole in LCDM, compared with the anomalous dipole in NVSS and WISE

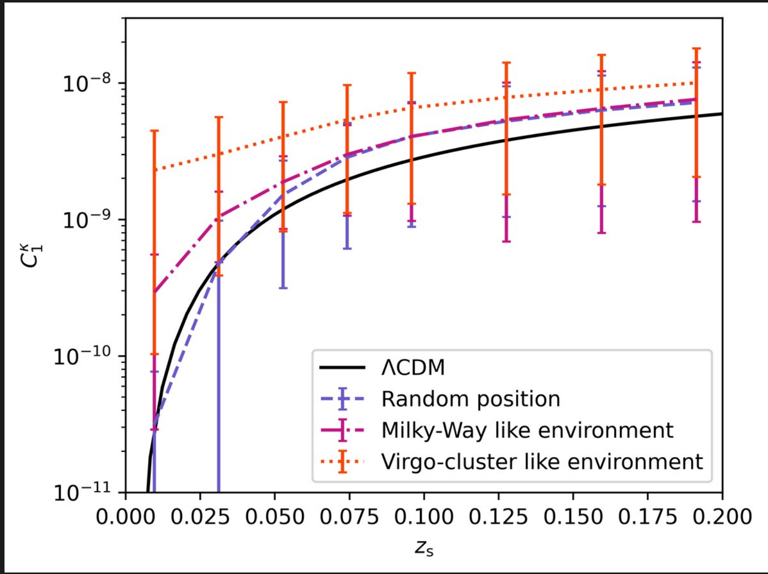
$$\langle C_l^\kappa \rangle = \frac{2}{\pi} \int dk\, k^2 P(k, z=0)\, W_l^\kappa(k)^2$$

$$W_l^{cl}(k) = \frac{3 H_0^2 \Omega_m}{2 c^2} \int_0^{r_{max}} dr\, \frac{r(r_{max}-r)}{r_{max}\, a(r)} D_+(r)\, j_l(kr)$$

- Same as clustering, we can obtain expected LCDM convergence dipole

- How much that expectation is impacted by the local matter distribution ?

- Using simulation from the Quijote suite [F. Villaescusa-Navarro et al. 2020], to account for the particular position of the MW, we can constrain the value of the convergence dipole



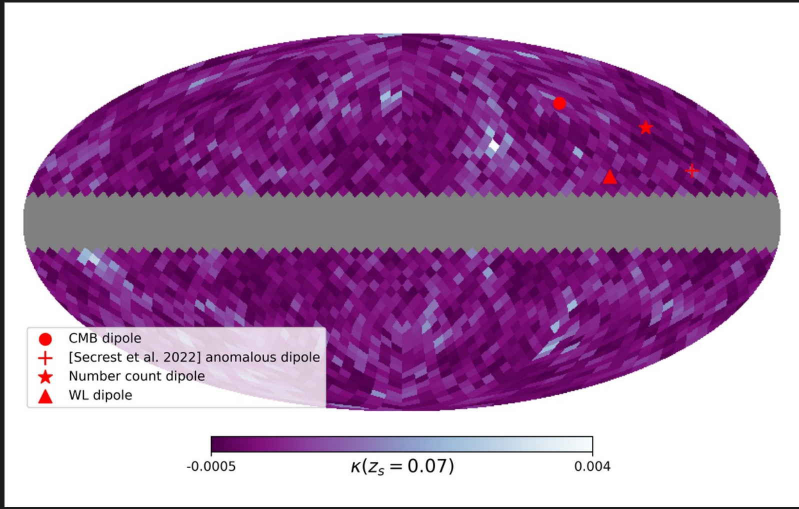
l=1 angular power spectrum of the convergence field in a Quijote simulation for different types of observer

- Defined 3 types of observer (Random, Virgo-cluster-like, MW-like)
  → defined according to halo mass, distance to cluster and velocity
- For each type, take 50 of them
- Reconstruct the convergence field and extract low multipoles

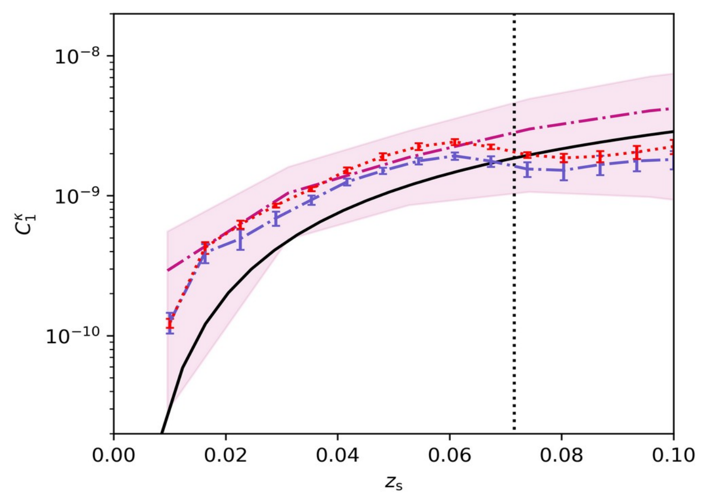
Local universe has a huge impact on the convergence field !

→ Only at low redshift (up to z~0.1)

- Using 2MRS, we can reconstruct the (local) matter density field, then the local convergence field (up to z~0.07)



Reconstructed convergence field using 2MRS



Reconstructed dipole of the convergence field at different redshift compared with the LCDM expectation

→ align with the CMB !

Conclusion : For now, not the beginning of an explanation from the cosmological perspective within LCDM model

3) What if we don’t have a perfect power law ?

[Bonnefous 2026]

→ it doesn’t change anything, we just have to redefine the coefficients

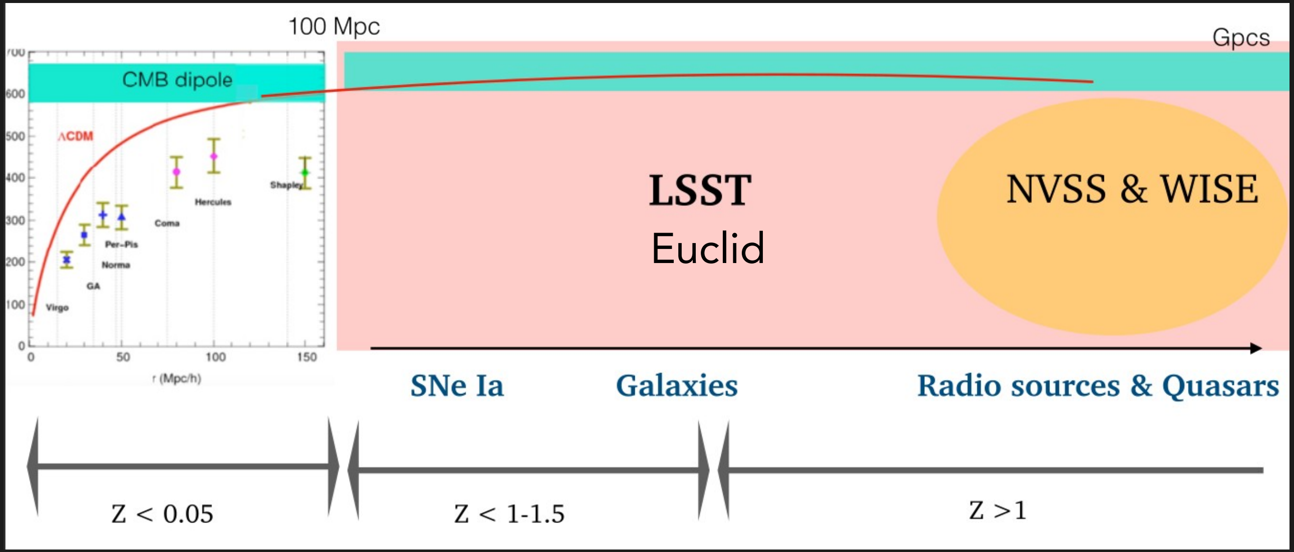
$$\alpha_{eff} = \frac{\int d\nu\, T_X(\nu)\, \nu \frac{\partial S_\nu}{\partial \nu}}{\int d\nu\, T_X(\nu)\, S_\nu} \qquad x_{eff} = \frac{-\partial \log N}{\partial \log L}$$

We can generalize the EB test to (pretty much) any large scale survey !

→ especially NIR/visible galactic survey

VI. Future application of this test

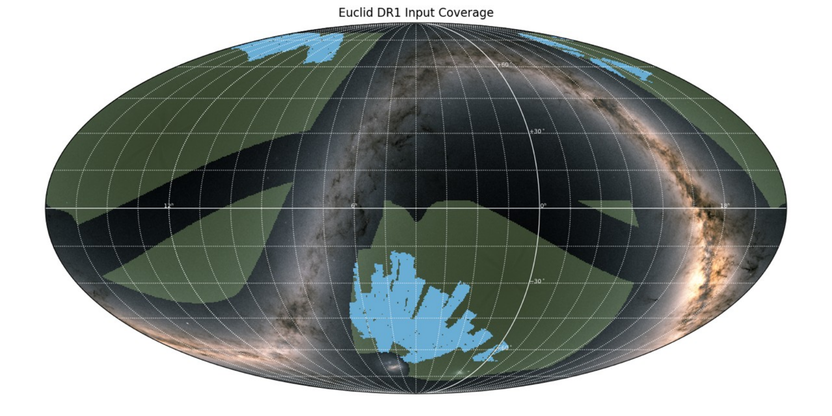
Future large scale surveys : LSST, Euclid, SPHEREx
Goal : bridging the local universe to the distant radio sources and quasars



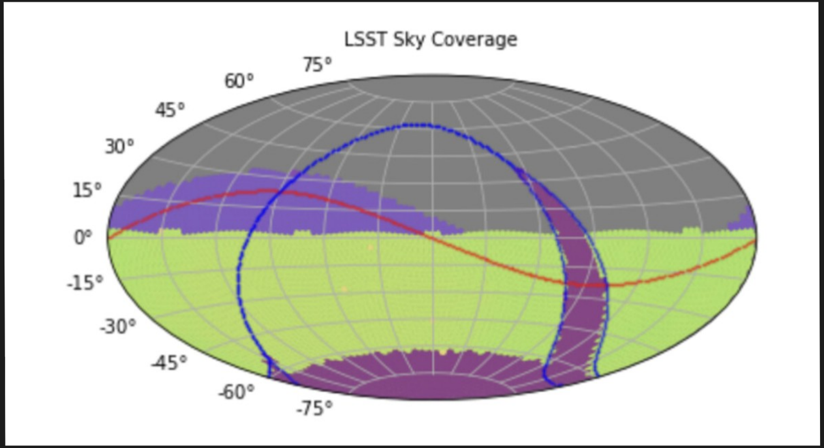
VI. Future application of this test

Completely new challenges :

- Smaller cover = more leakage
- Visible/NIR galaxies = no power laws, obtaining α is tricky
- REDENNING, extinction



Euclid sky coverage (in blue : DR1)



LSST sky coverage

VI. Conclusion :

- There is a 5σ discrepency between the CMB kin. dipole, and the matter dipole
- Weak lensing is a too weak effect to have to be taken into account, still no explanation of this anomaly **within** LCDM
- We can generalize the EB test to any spectral profile/any magnitude distribution !
- We're working with LSST, Euclid (and SPHEREx ?), to apply this test to new sets of data
- Current work :

  1) Creating mock catalogue

  2) Obtaining α for galaxies in the visible/NIR