The anomalous cosmic dipole :
Testing the cosmological principle

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IAP, Sorbonne Université, Paris, France

Théorie, Univers et Gravitation (TUG) meeting, LPENS, Paris 10-12 octobre

The Cosmological principle

The Universe is **homogeneous** and **isotropic**

Translation and Rotation invariance

Cosmological principle

The Universe is **homogeneous** and **isotropic**

$$ds^2 = -c^2 dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

FLRW

Cosmological principle

The Universe is **homogeneous** and **isotropic**

$$ds^2 = -c^2 dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$ FLRW

Homogeneous but anisotropic → Axis

Cosmological principle

The Universe is **homogeneous** and **isotropic**

$$ds^2 = -c^2 dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

FLRW

Homogeneous but anisotropic → Axis

$$ds^2 = -dt^2 + a_x(t)^2 dx^2 + a_y(t)^2 dy^2 + a_z(t)^2 dz^2,$$

Bianchi

Cosmological principle

The Universe is **homogeneous** and **isotropic**

$$ds^2 = -c^2dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

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Homogeneous but anisotropic → Axis

$$ds^2 = -dt^2 + a_x(t)^2 dx^2 + a_y(t)^2 dy^2 + a_z(t)^2 dz^2.$$

Bianchi

Inhomogeneous & isotropic → Centre

Cosmological principle

The Universe is **homogeneous** and **isotropic**

$$ds^2 = -c^2 dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

FLRW

Homogeneous but anisotropic → Axis

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a_x(t)^2 \mathrm{d}x^2 + a_y(t)^2 \mathrm{d}y^2 + a_z(t)^2 \mathrm{d}z^2.$$

Bianchi

Inhomogeneous & isotropic → Centre

$$ds^2 = -dt^2 + X^2(r,t)dr^2 + A^2(r,t)\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

LTB

Cosmological principle

The Universe is **homogeneous** and **isotropic**

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Homogeneous but anisotropic → Axis

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a_x(t)^2 \mathrm{d}x^2 + a_y(t)^2 \mathrm{d}y^2 + a_z(t)^2 \mathrm{d}z^2.$$

Bianchi

Inhomogeneous & isotropic → Centre

$$ds^2 = -dt^2 + X^2(r,t)dr^2 + A^2(r,t)\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

LTB

Inhomogeneous & anisotropic

$$ds^2 = dt^2 - A^2 dx^2 - B^2(dy^2 + dz^2)$$

$$\begin{aligned} ds^2 = dt^2 &- (A'^2_{\parallel}\sin^2\theta + A'^2_{\perp}\cos^2\theta)dr^2 \\ &- (A^2_{\parallel}\cos^2\theta + A^2_{\perp}\sin^2)d\theta^2 \\ &- (A^{2\prime}_{\parallel} - A^{2}_{\perp}{}') \sin\theta\cos\theta dr d\theta + -A^2_{\parallel}\sin^2\theta d\phi^2. \end{aligned}$$

(eg Szekeres models)

The Cosmological principle

1915

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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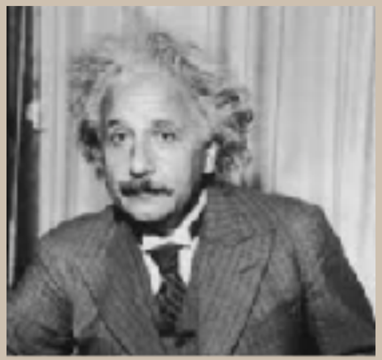
1917



The Cosmological principle

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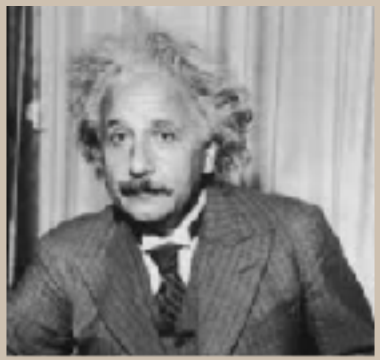

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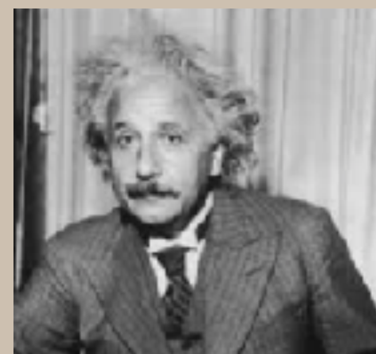
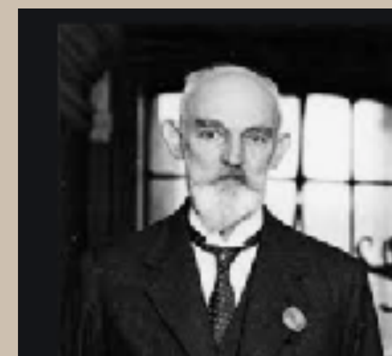
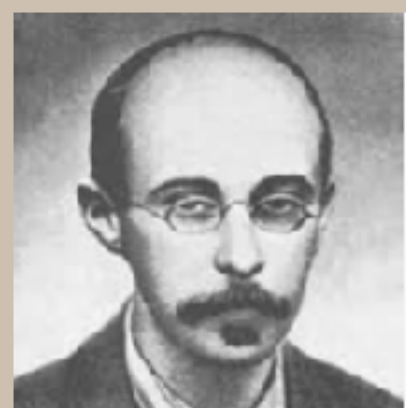



1922-1935

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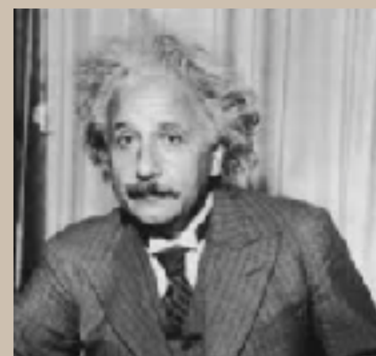
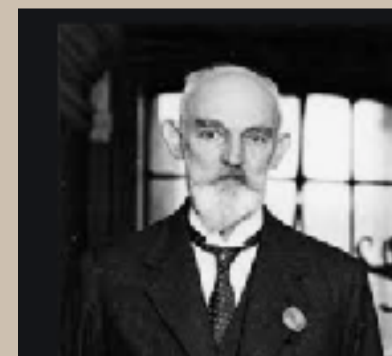
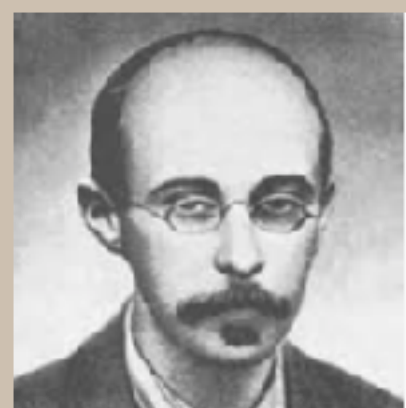



1922-1935



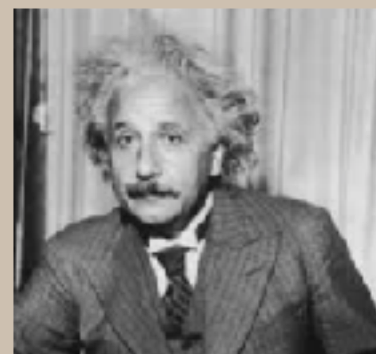

1932

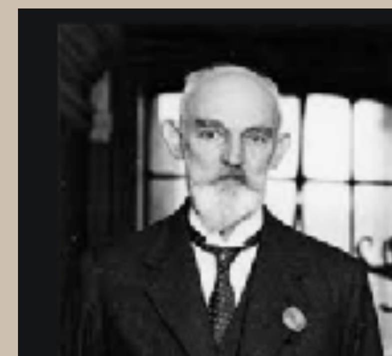
The Cosmological principle

1915

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

1917





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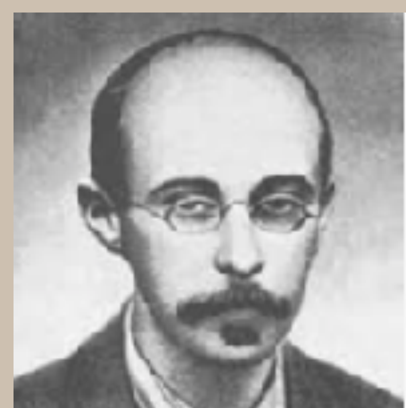


1932

1935

The Cosmological principle

Milne

A new basis for cosmology

By P. A. M. Dirac, F.R.S.
St John's College, Cambridge

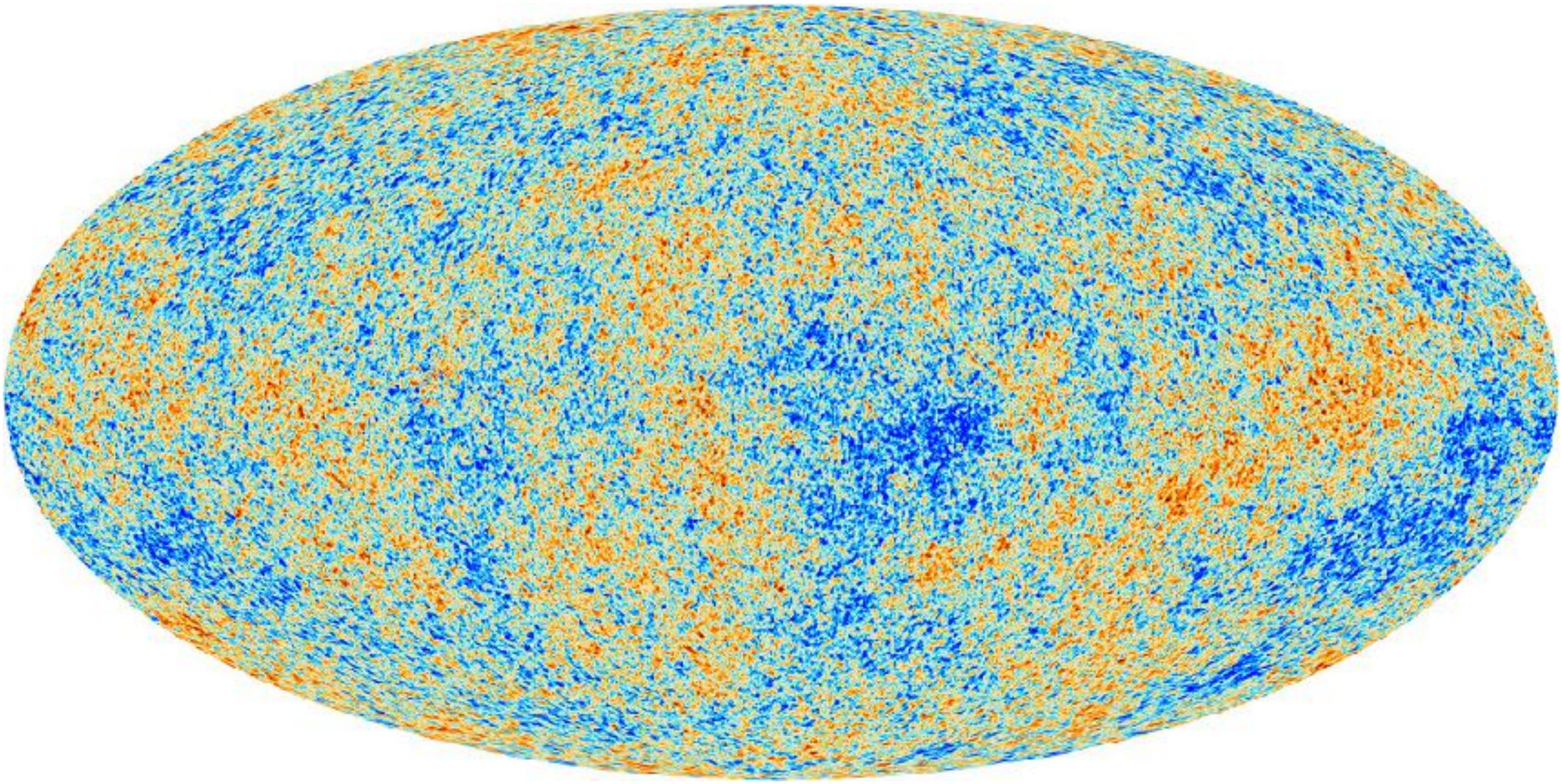
(*Received* 29 *December* 1937)

We now feel the need for some new assumptions on which to build up a theory of cosmology. This need is partially satisfied by the assumptions, which Milne calls the Cosmological Principle, that, apart from local irregularities, the universe is everywhere uniform and has spherical symmetry (in three dimensions)

these assumptions are fairly plausible and have a great simplifying effect on the subject, and until there is more definite evidence of their inadequacy it does not seem worth while to try more complicated schemes.

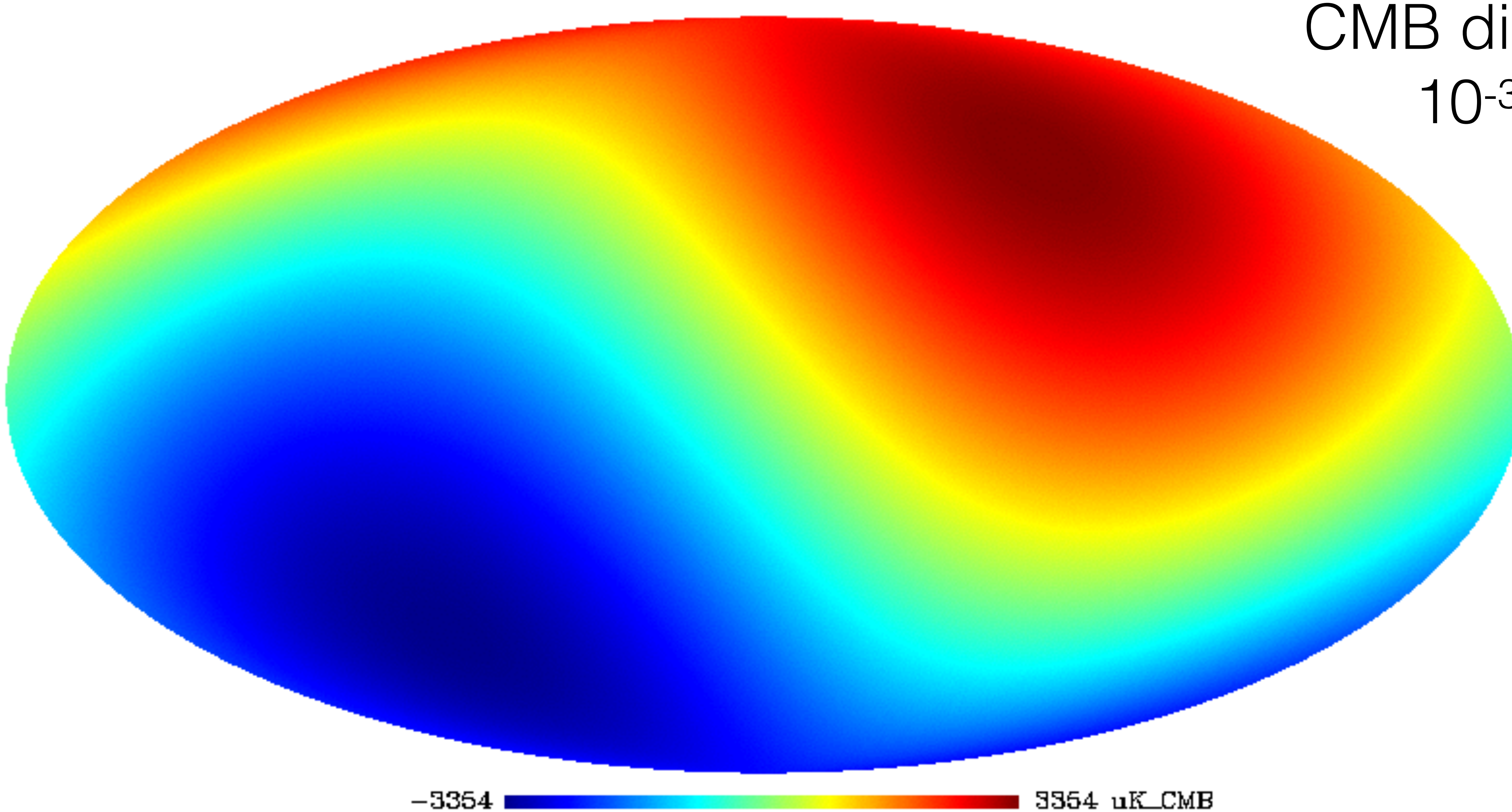
Observational evidence for the cosmological principle

Cosmic microwave background



Cosmic microwave background
Dipole —-Anisotropy

CMB dipole
10^{-3}

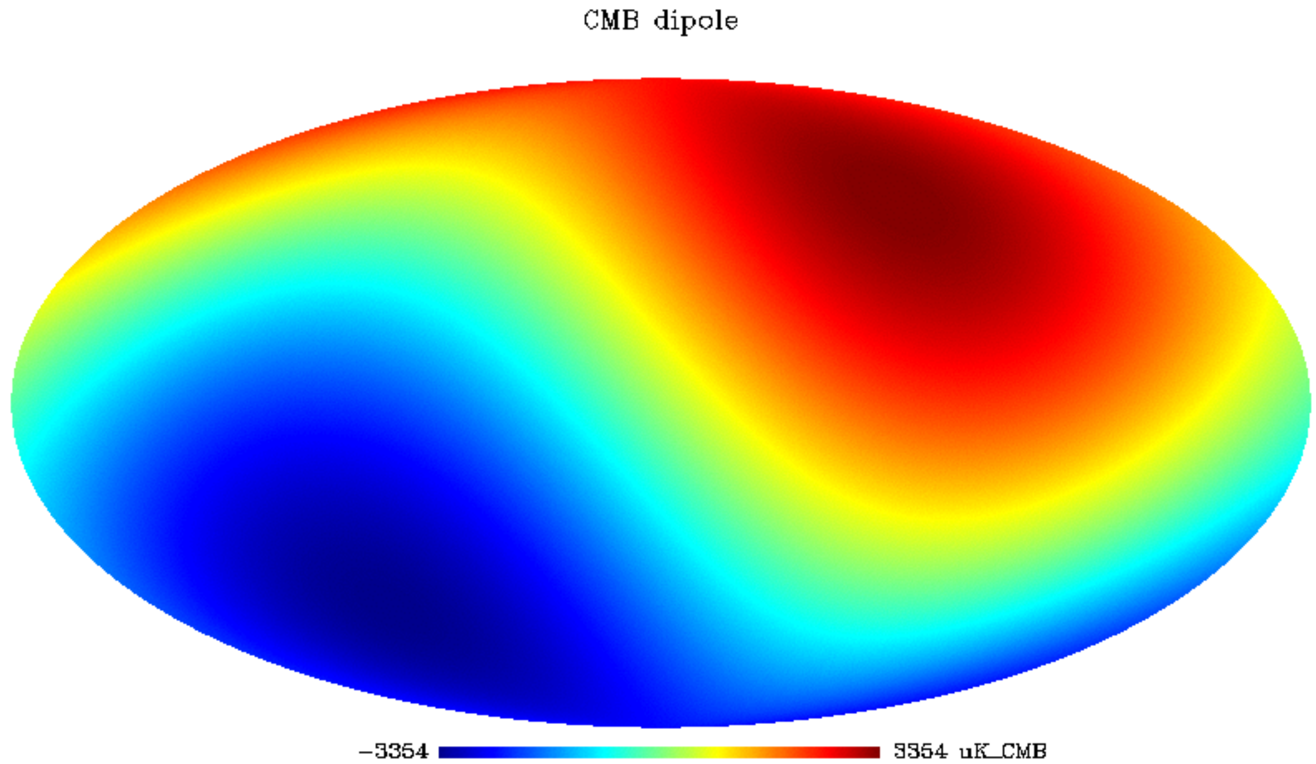


Comment on the Anisotropy of the Primeval Fireball*

P. J. E. Peebles† and David T. Wilkinson†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 17 June 1968)

$$\mathcal{T}'(\theta') = \mathcal{T}(1 - v^2/c^2)^{1/2}[1 - (v/c)\cos\theta']^{-1}$$

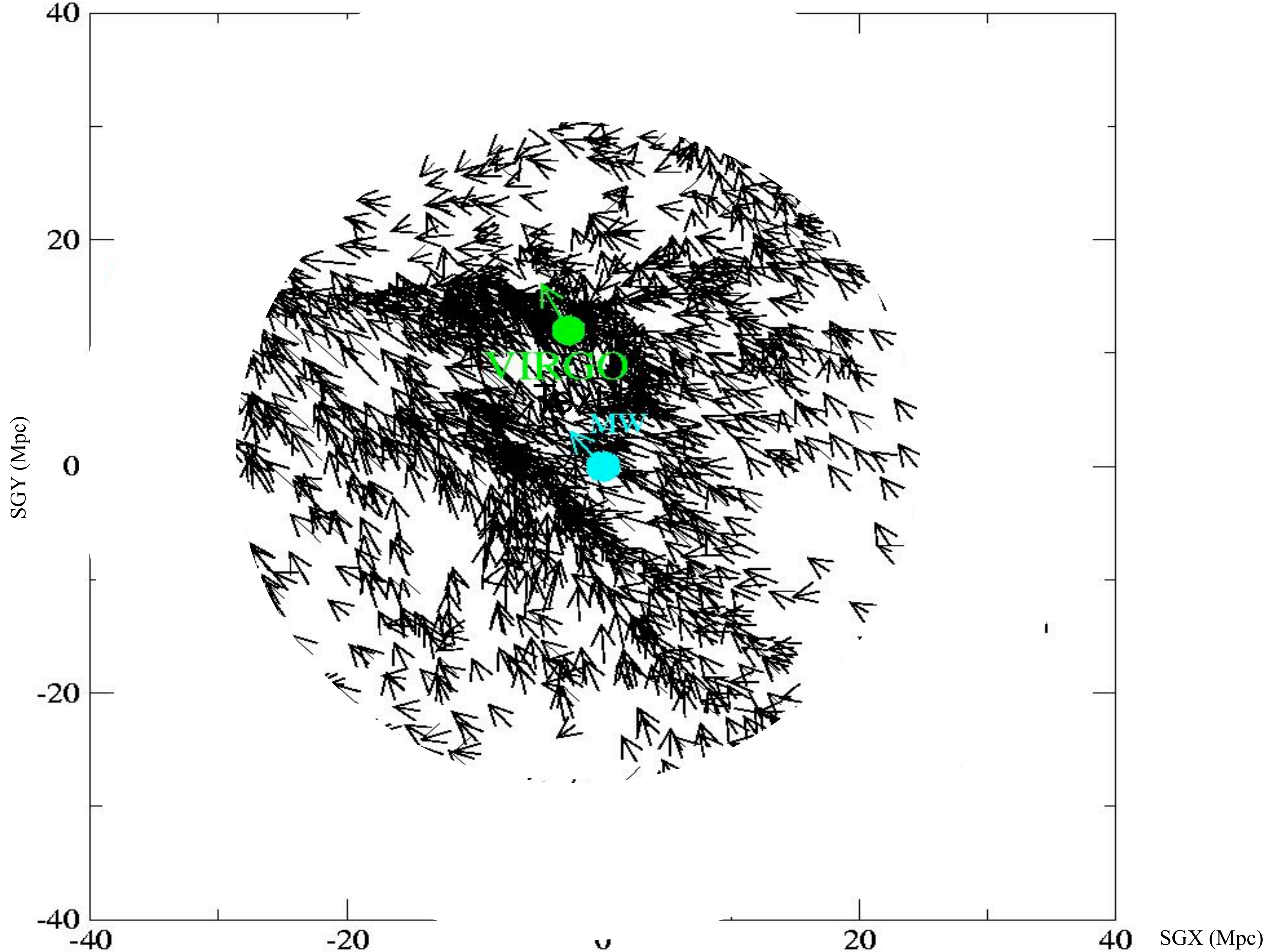
The origin of the CMB dipole ?



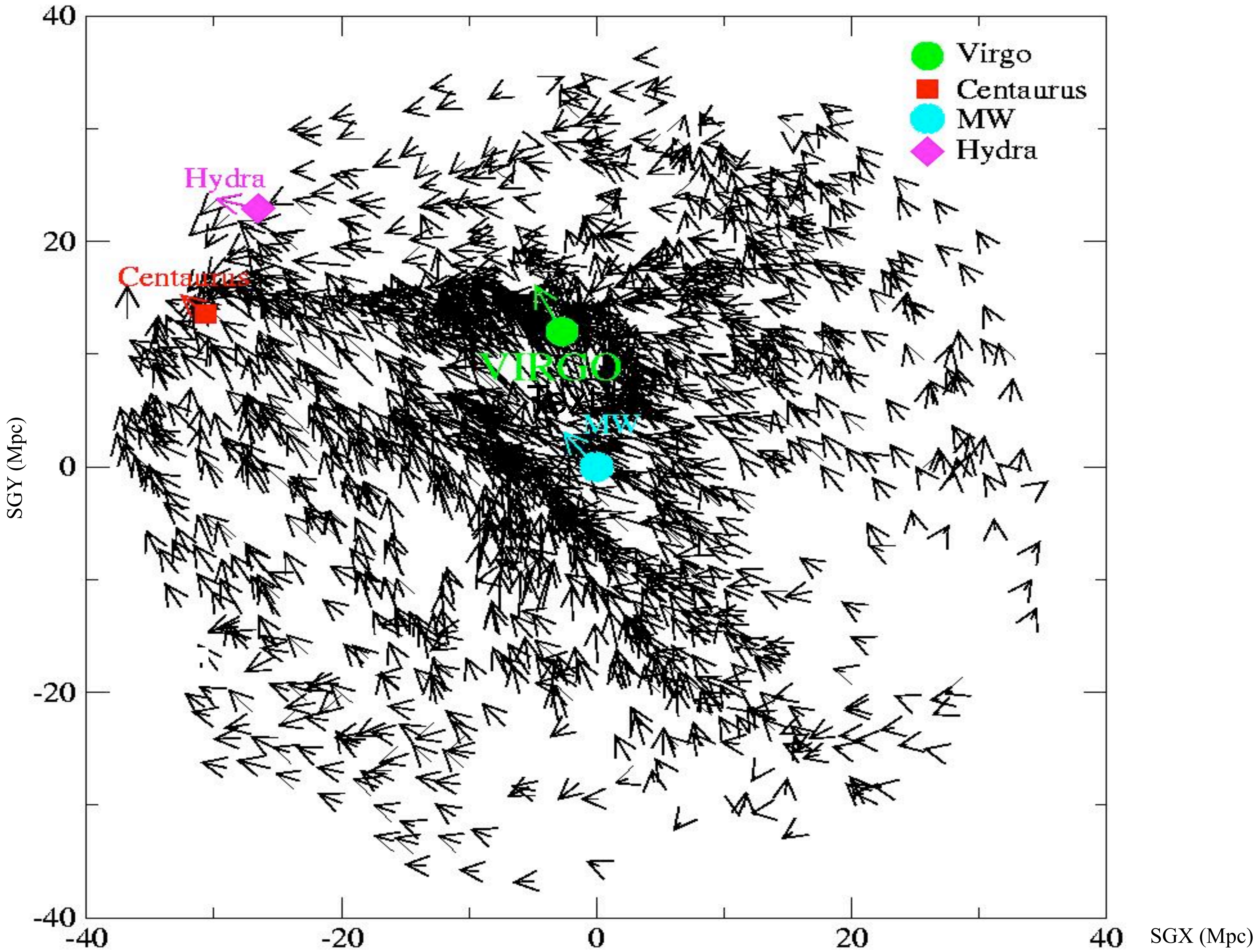
Dipole is purely Kinematic

Universe is anisotropic

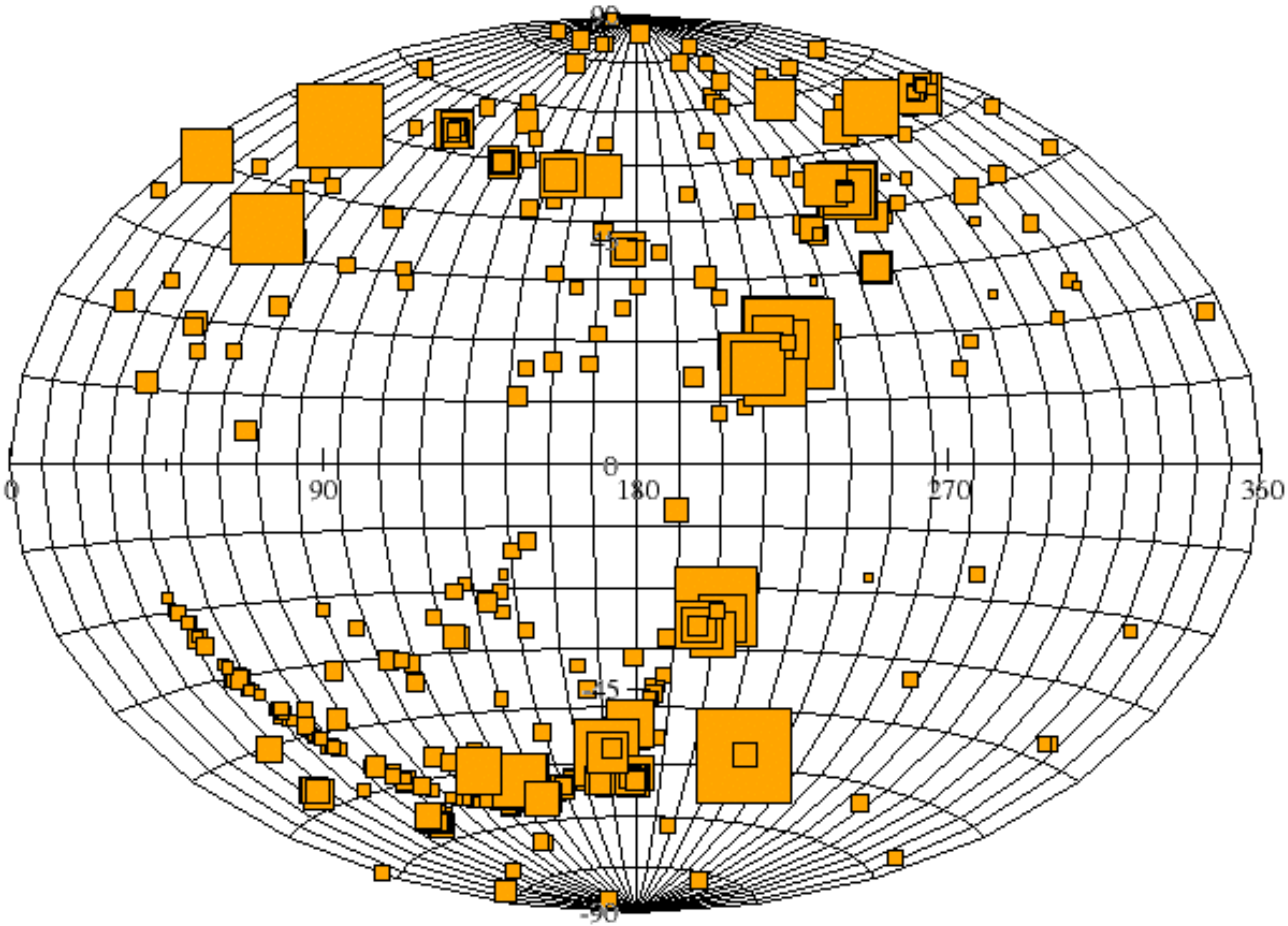
The origin of CMB dipole



Convergence to CMB dipole ?!

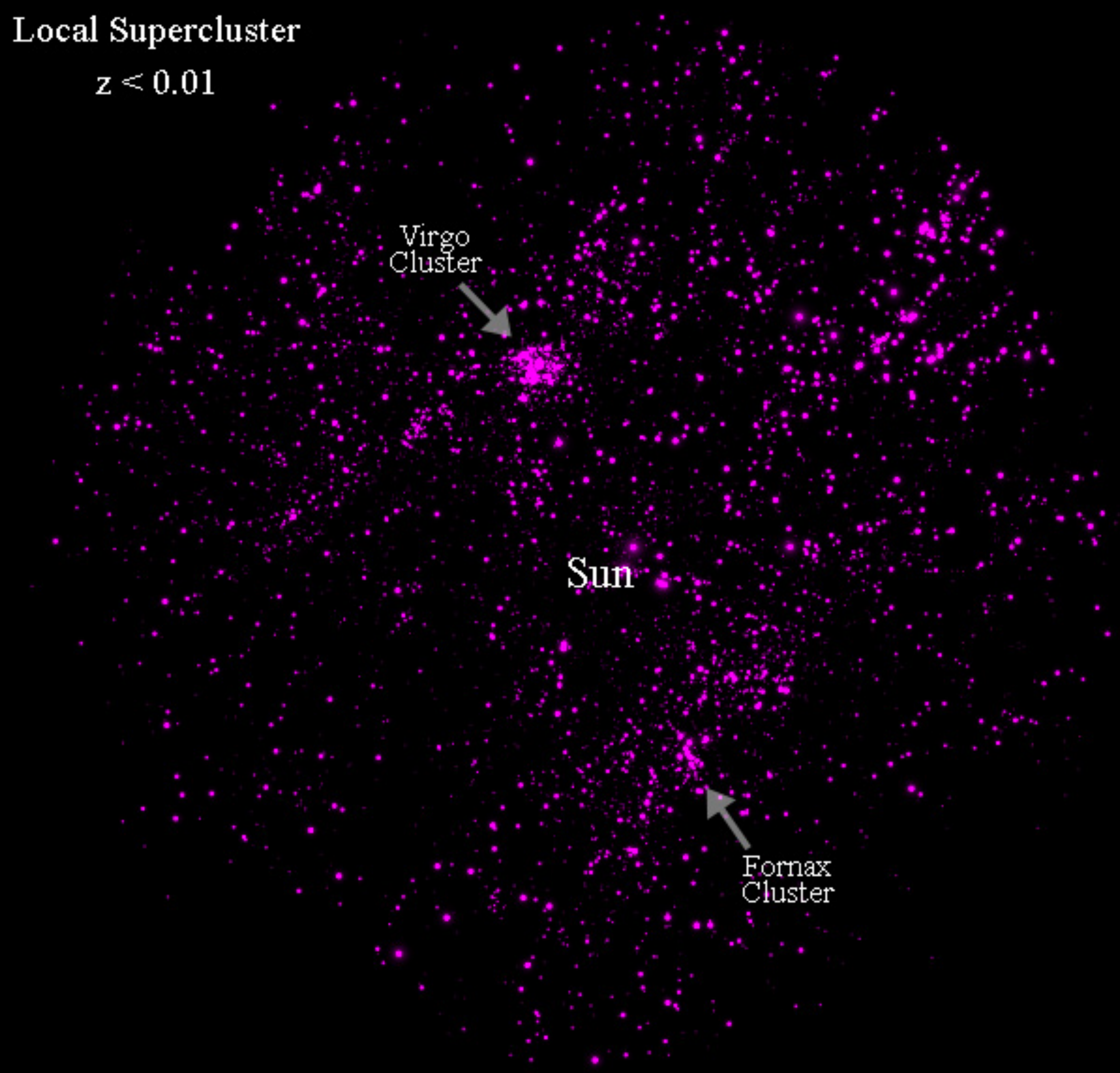


Velocities (distances) from SNe Ia
Union II compilation

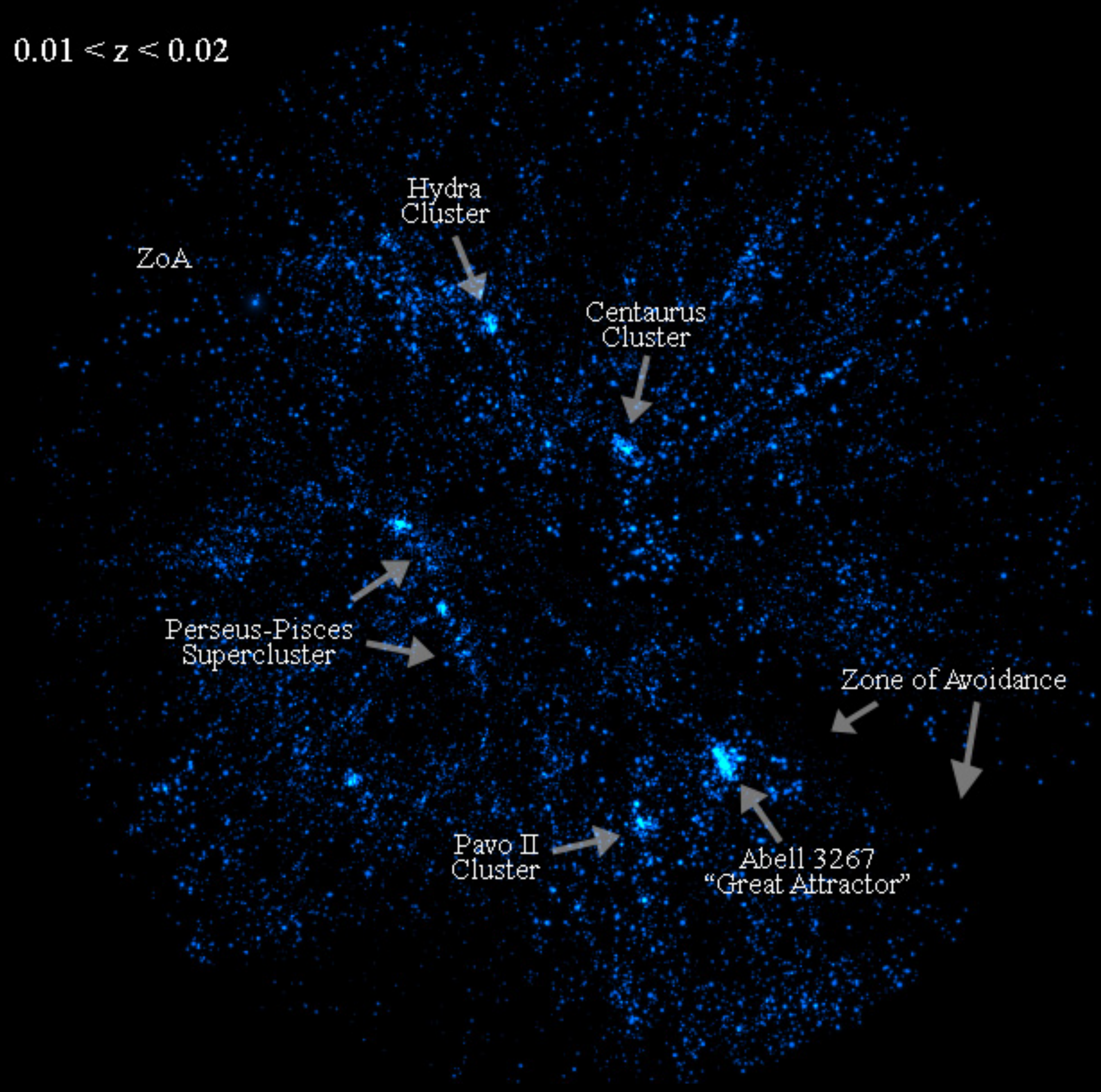


Colin, Mohayaee, Shafieloo, Sarkar, MNRAS 2012

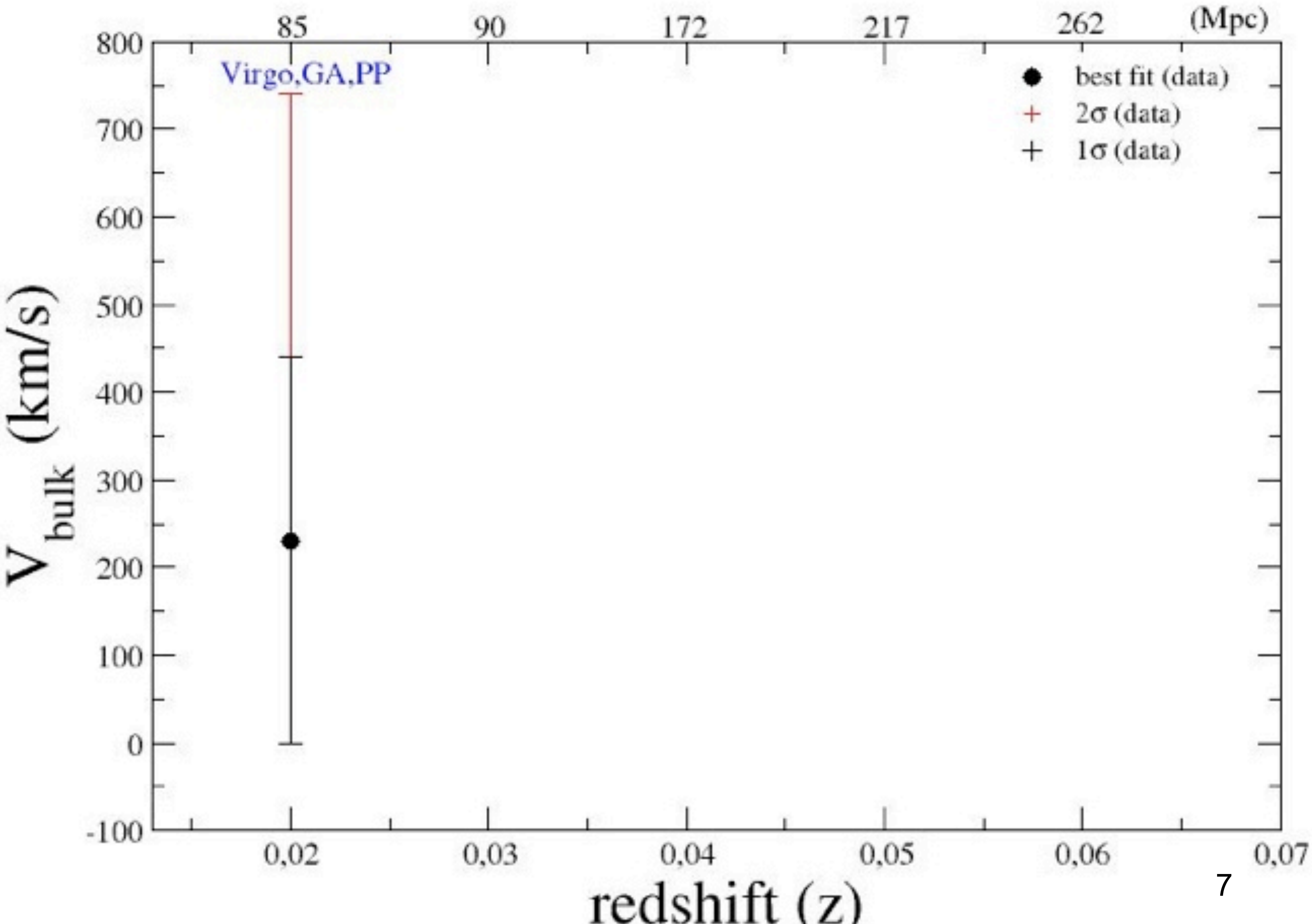
Bulk flow of increasingly volume: CMB rest frame ?



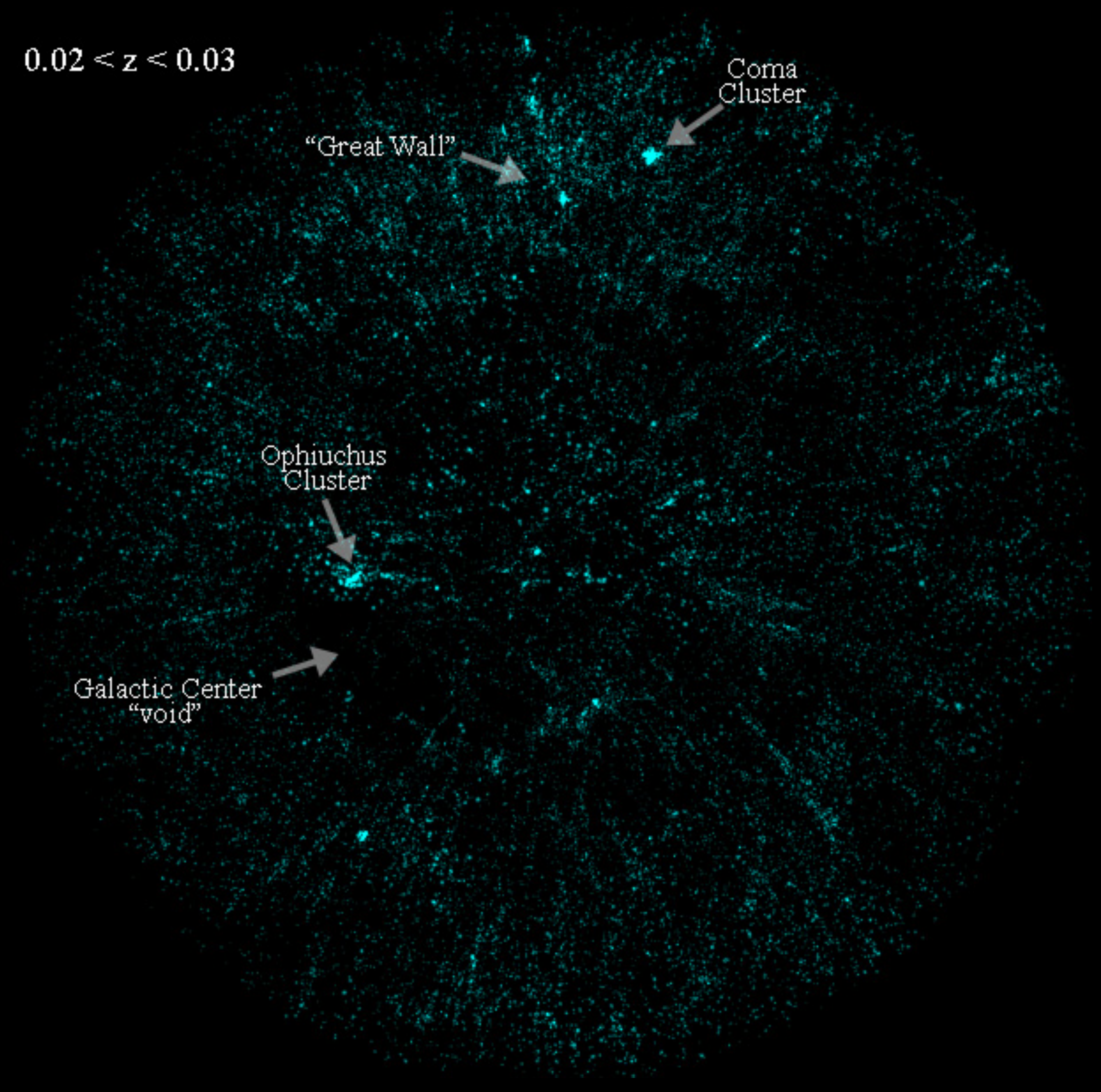
Bulk flow of increasingly larger volume: CMB rest frame ?



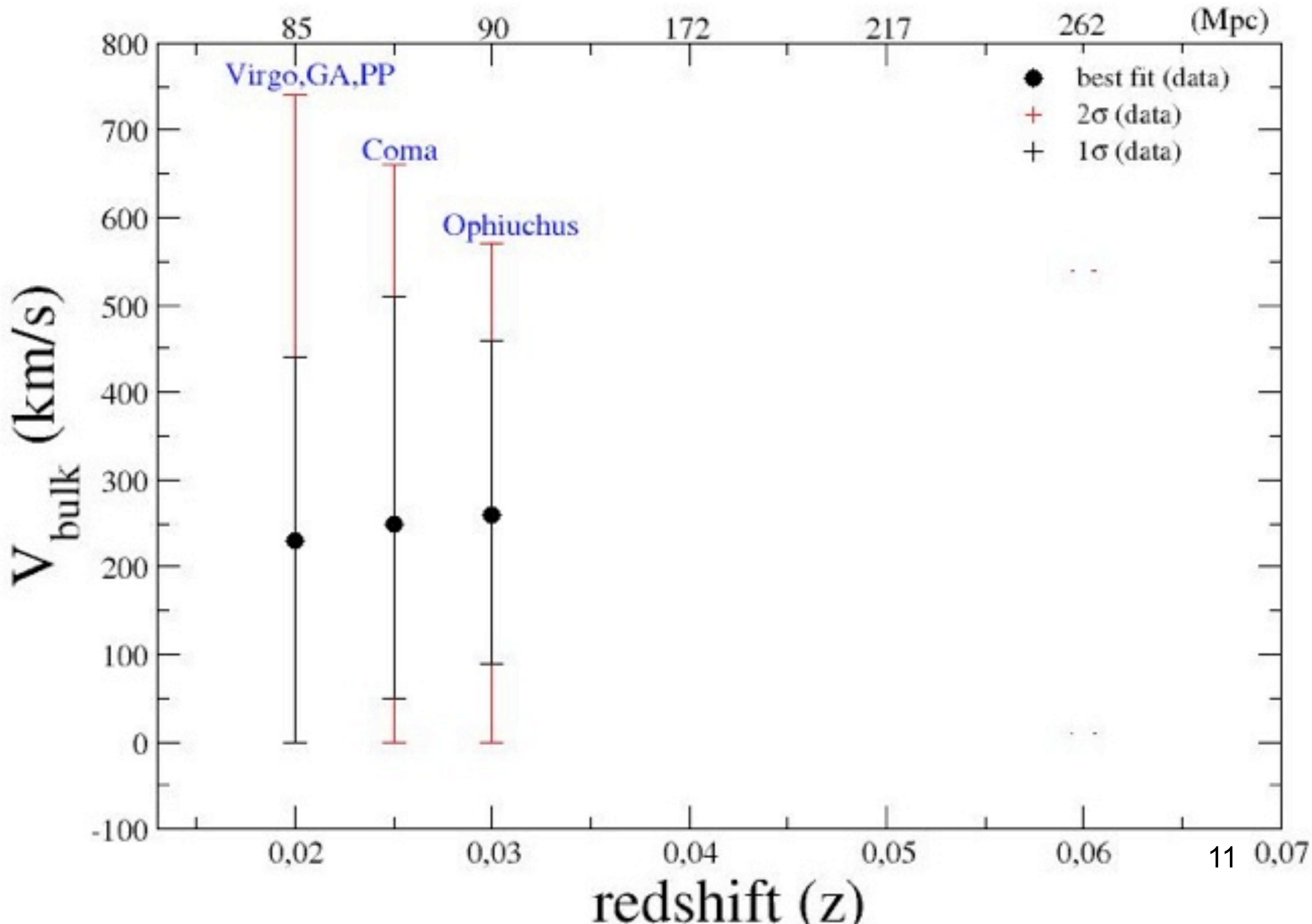
|Bulk flow| from SNe Ia data

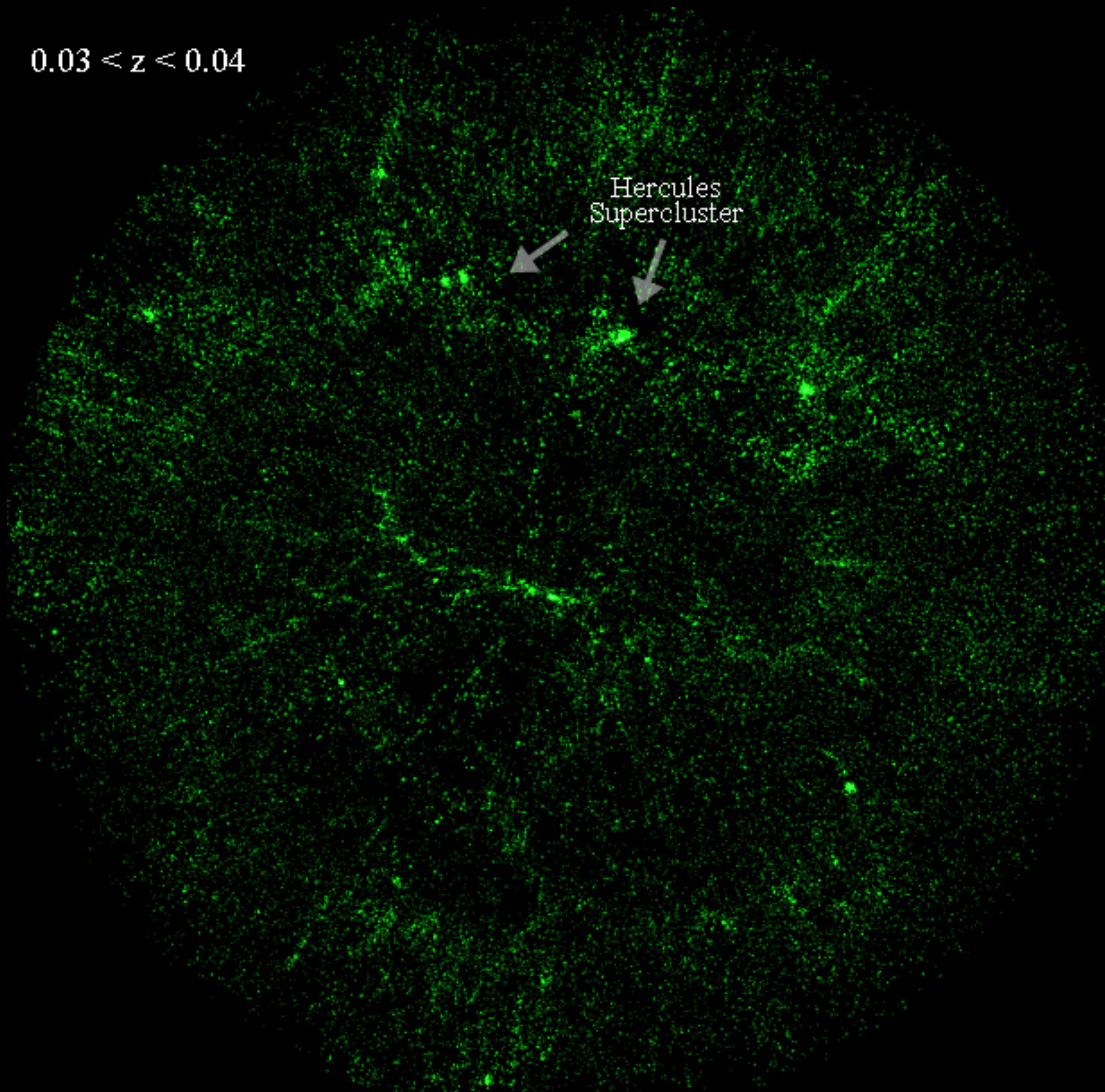


Bulk flow of increasingly larger volume: CMB rest frame ?

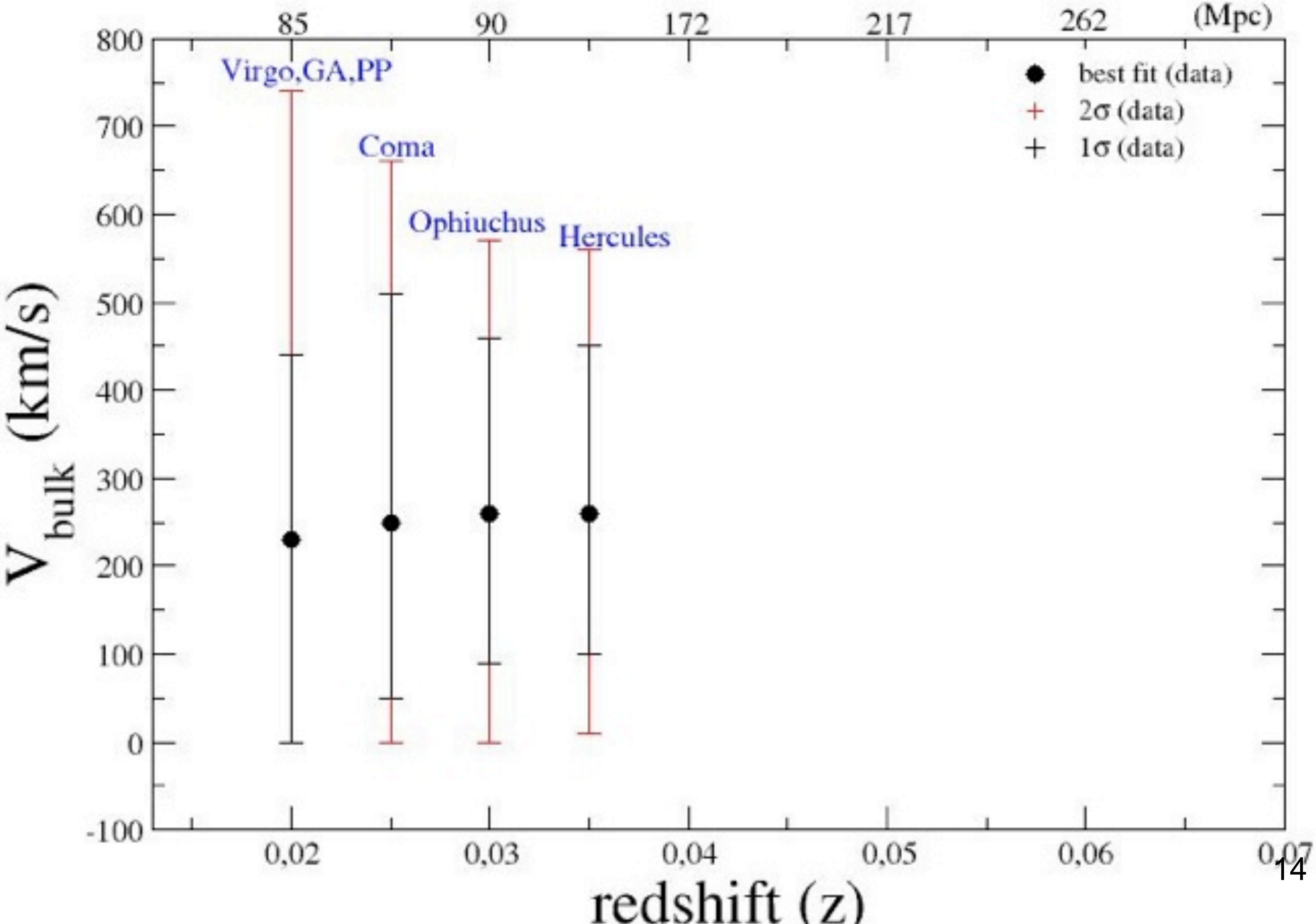


|Bulk flow| from SNe Ia data

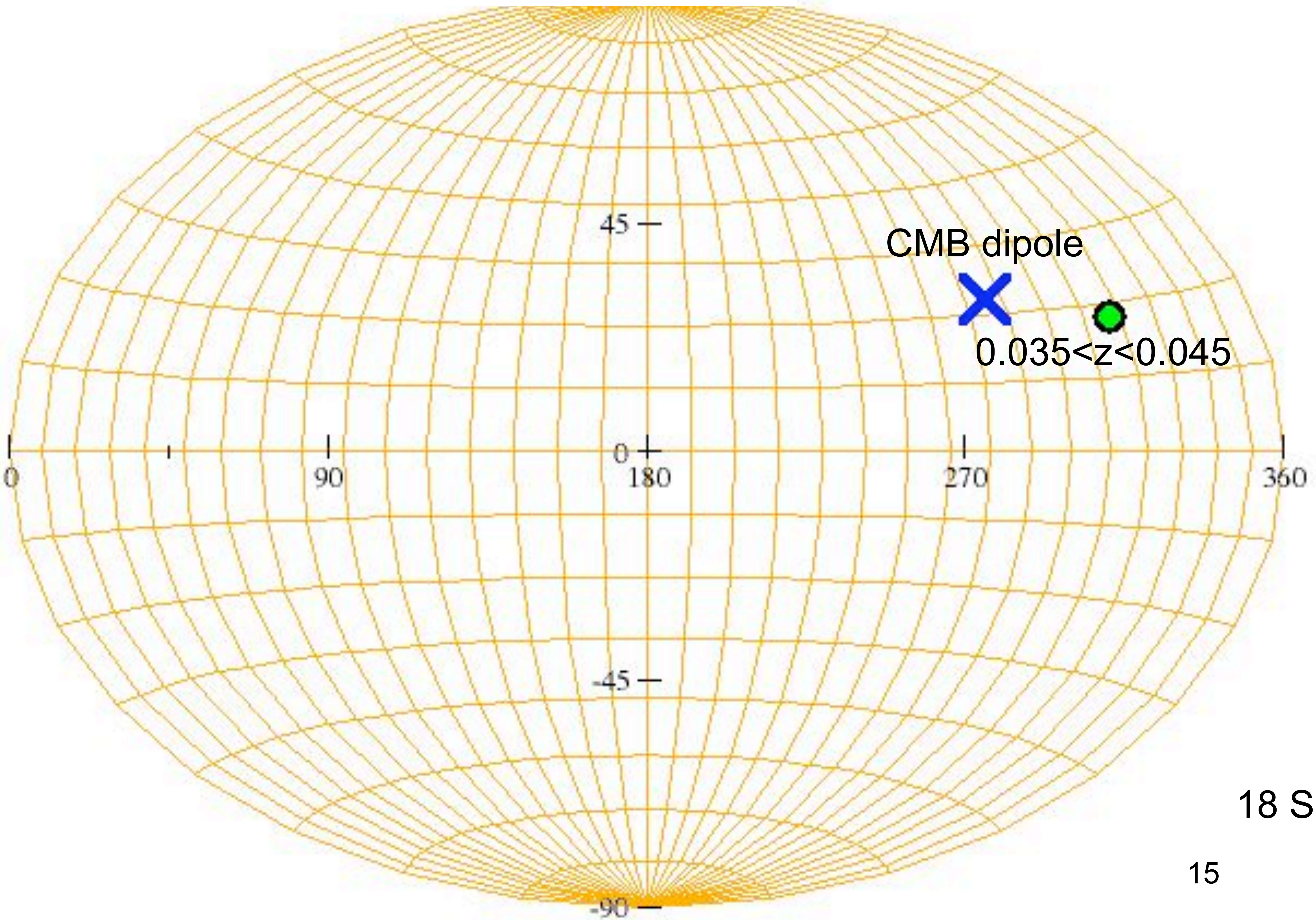



0.03 < z < 0.04
Hercules
Supercluster

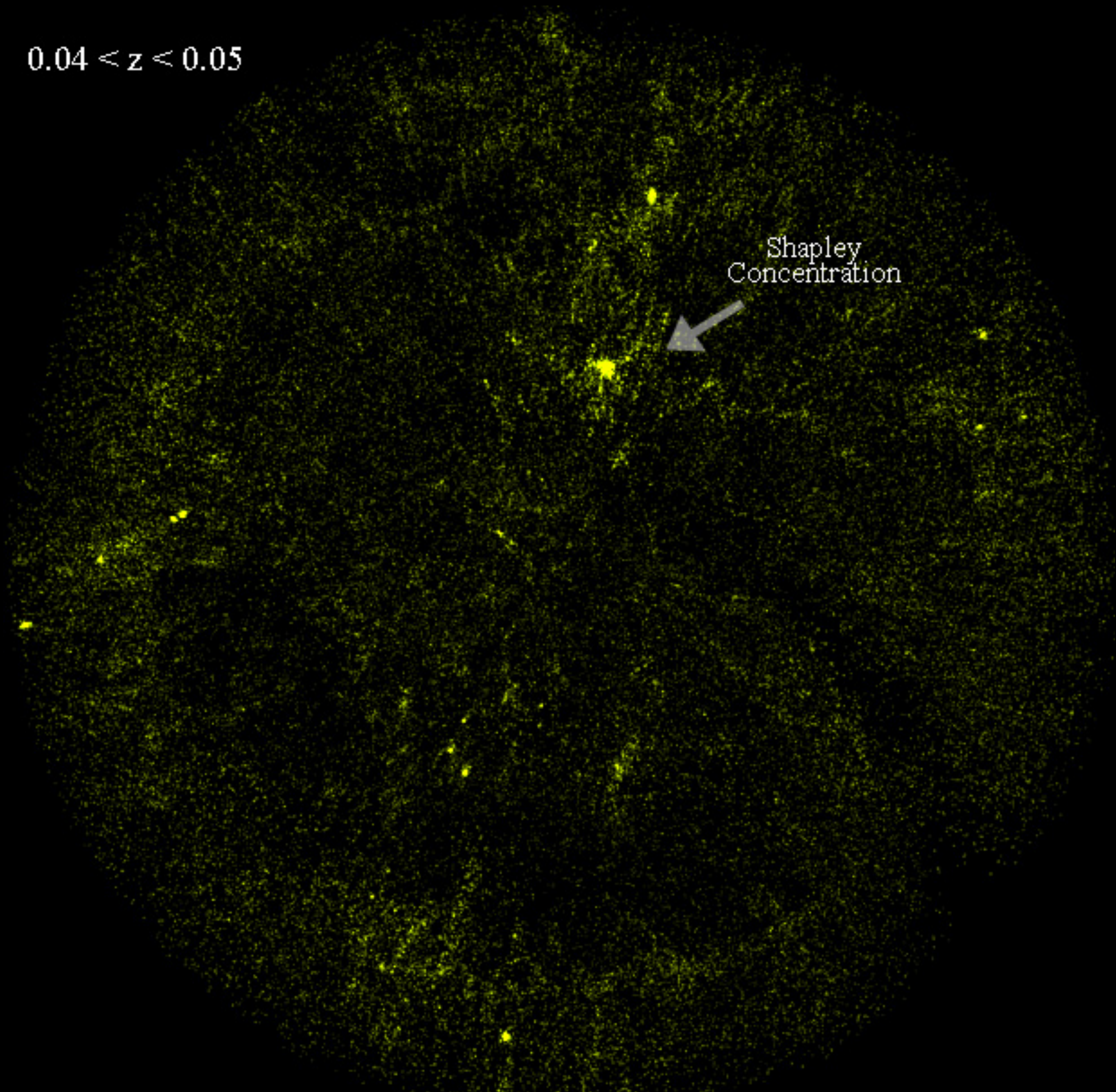
|Bulk flow| from SNe Ia data



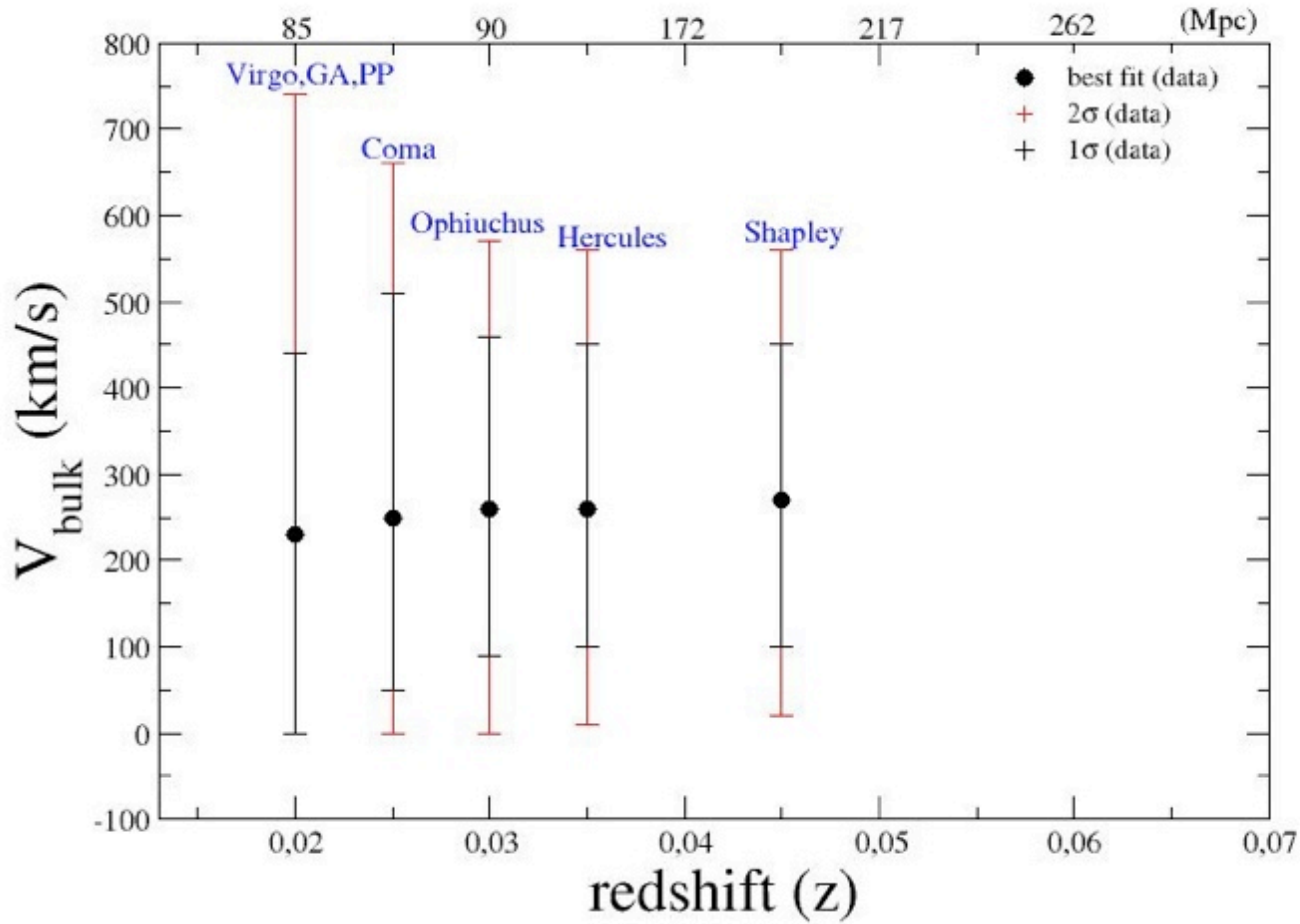
Bulk flow direction from data



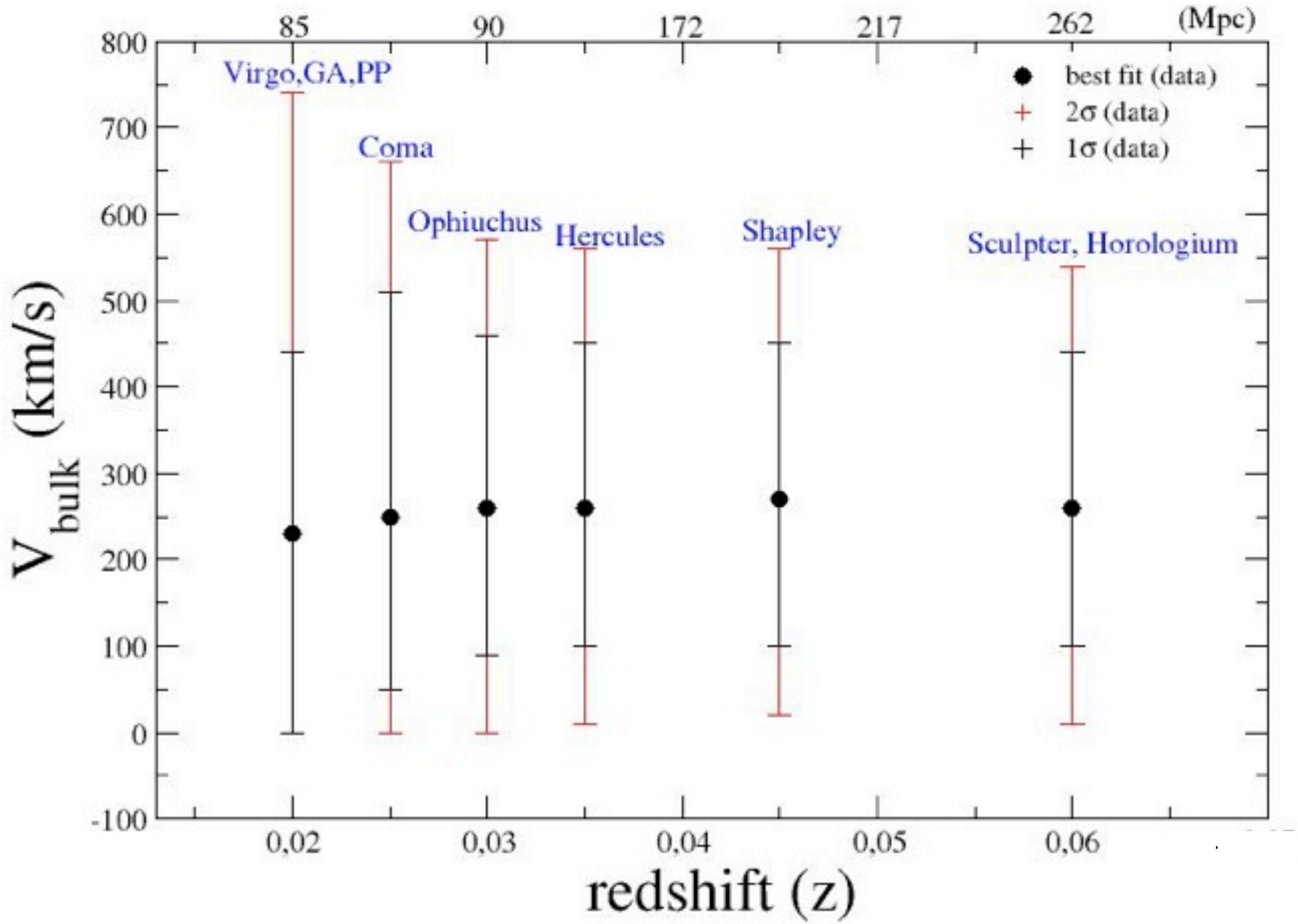
18 SNe

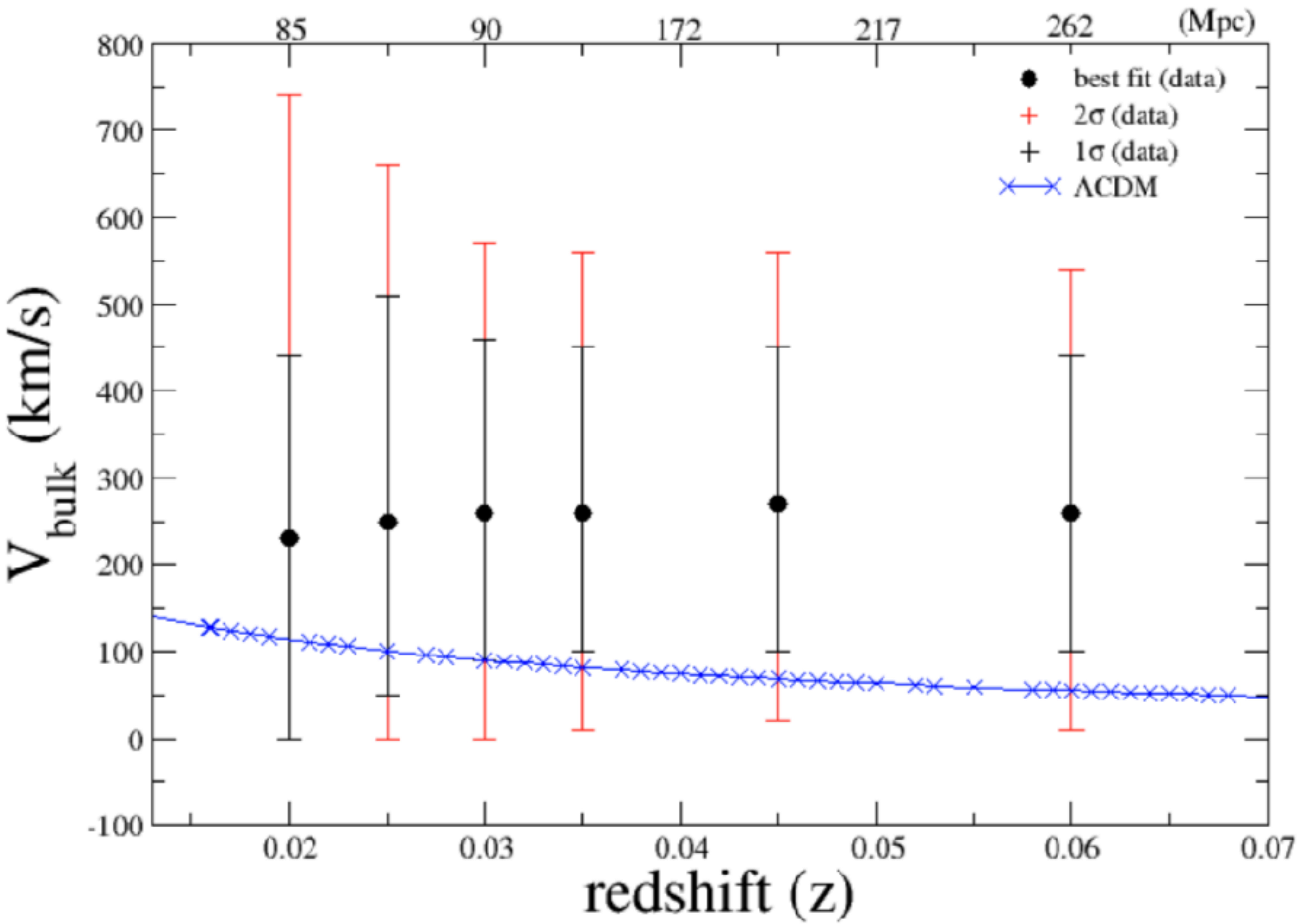

0.04 < z < 0.05
Shapley
Concentration

|Bulk flow| from SNe Ia data



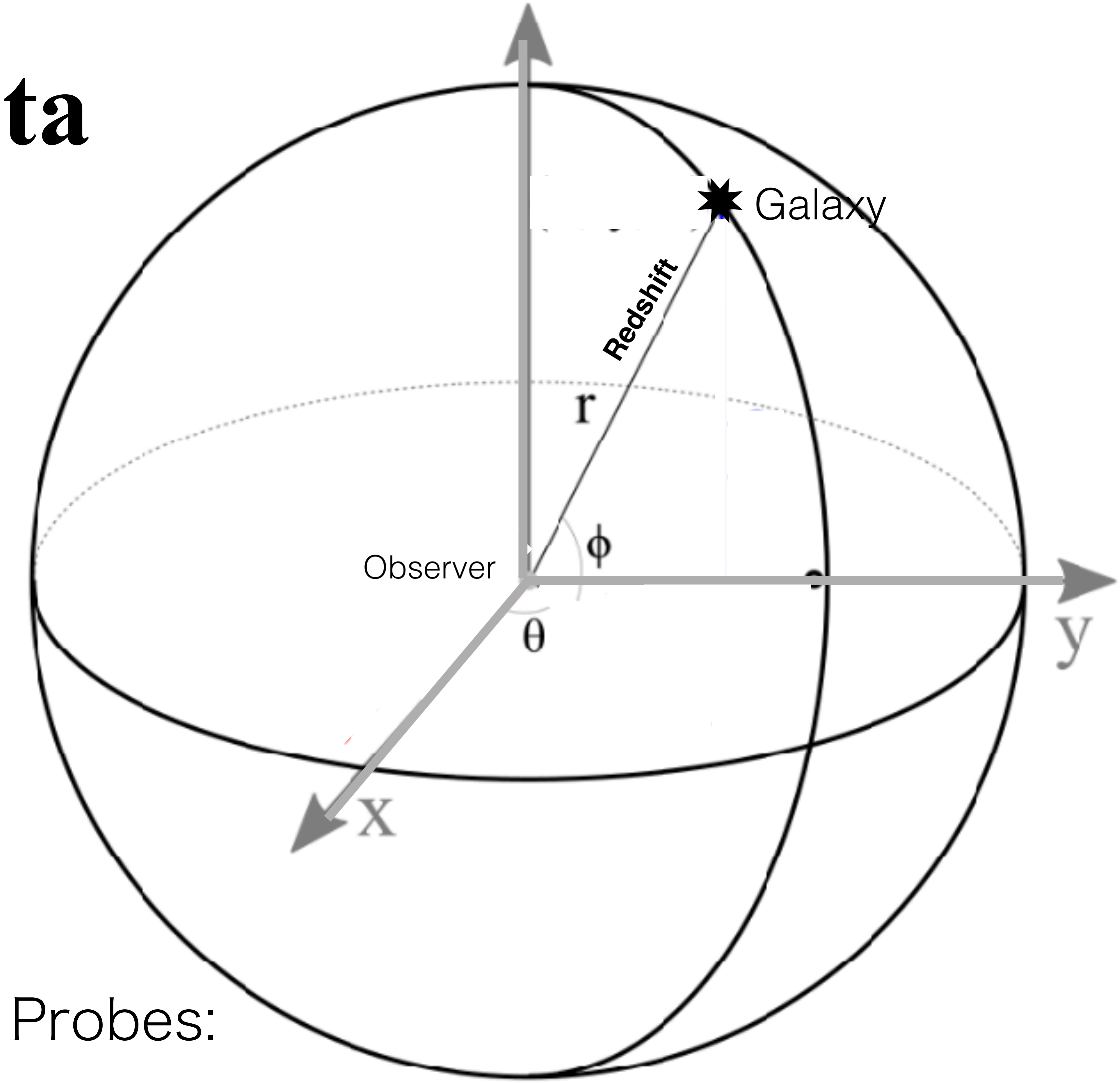
|Bulk flow| from SNe Ia data





85
90
172
217
262
(Mpc)
800
700
600
500
400
300
200
100
0
-100
best fit (data)
2σ (data)
1σ (data)
ΛCDM
V bulk (km/s)
0.02
0.03
0.04
0.05
0.06
0.07
redshift (z)

Real Data



Observational Probes:

(I) Θ, φ, z, d (SNe Ia … catalogues)

(II) Θ, φ, z (redshift catalogues)

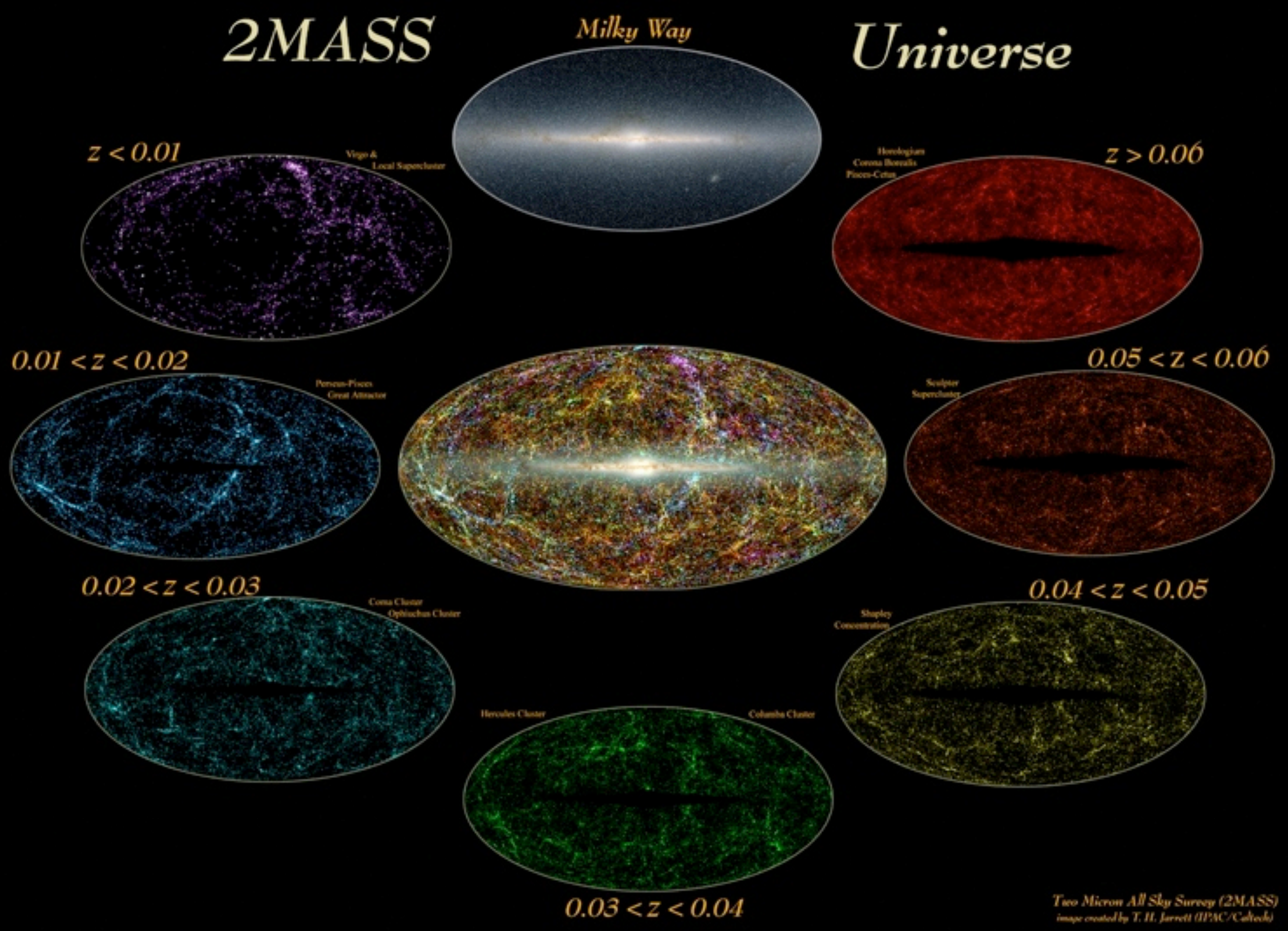
(III) Θ, φ (photometric catalogues)

2MRS redshift survey

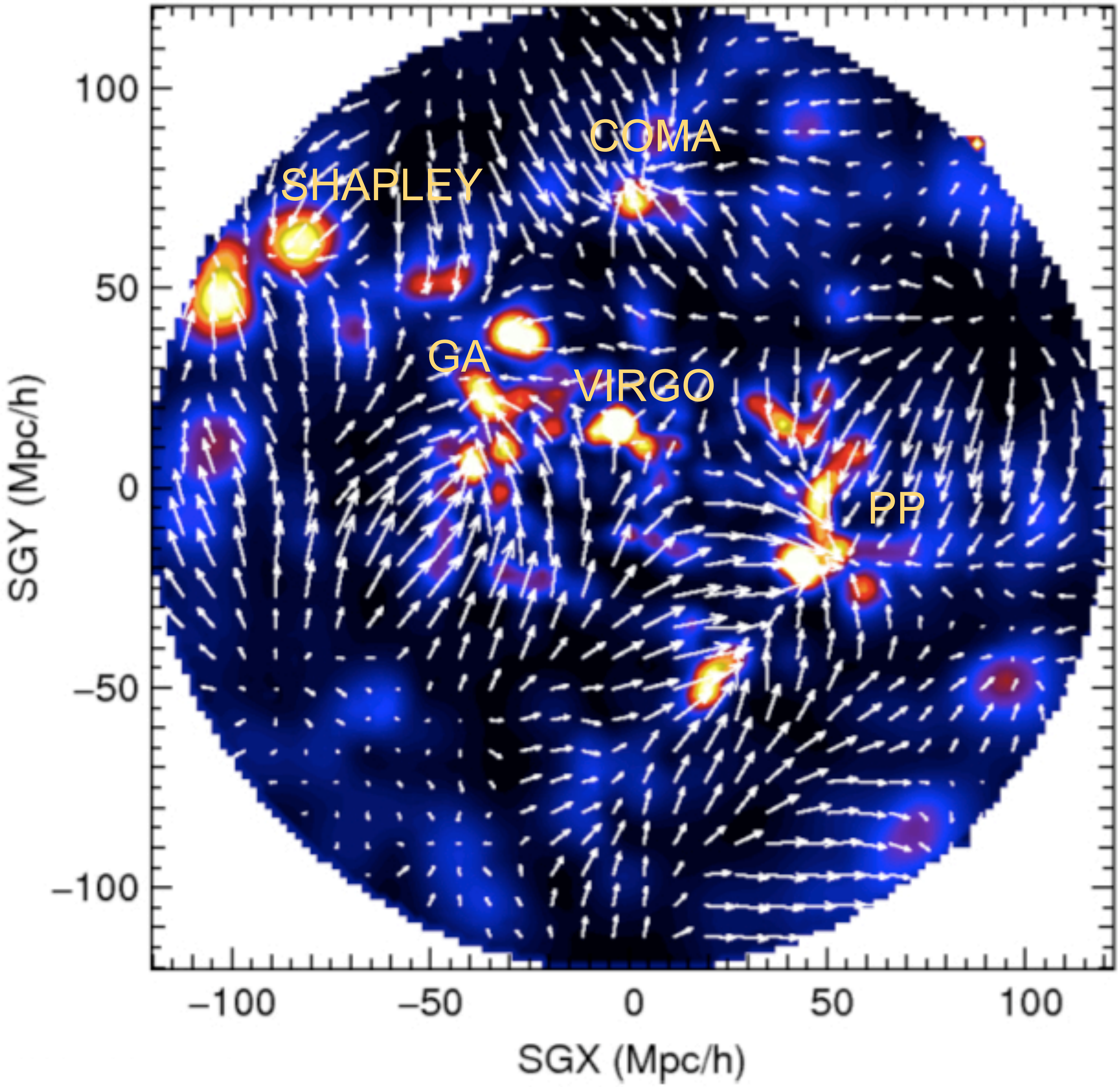
(Huchra etal 2005,...)

Based upon the 2MASS photometric galaxy catalog , Full sky
~25000 galaxies, selected with K_s<11.25

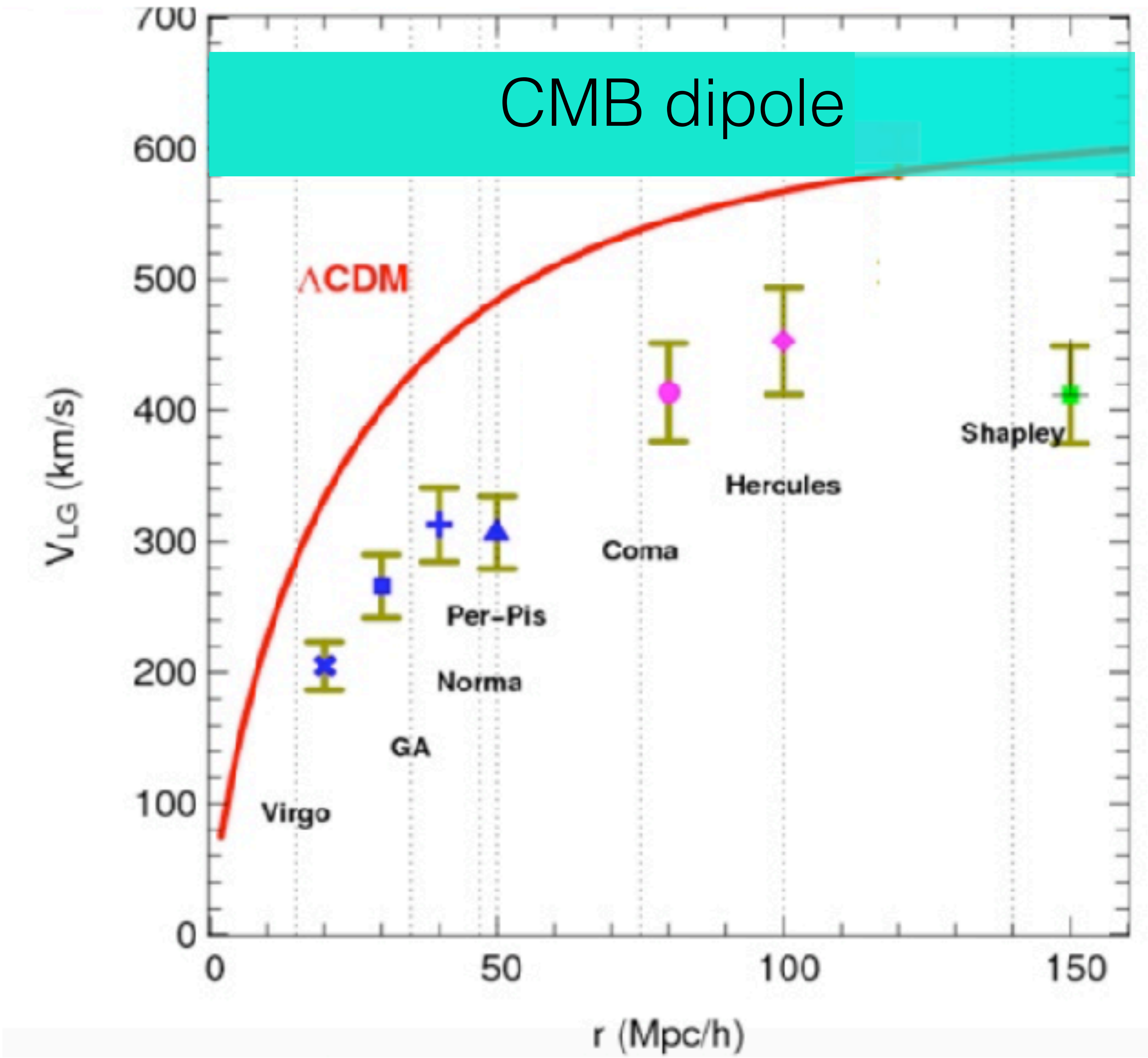
~250 Mpc/h (z~0.08) deep , Distribution peaks at ~90 Mpc/h (z~0.03)



Velocity field of 2MRS: from great attractor to Shapley infall

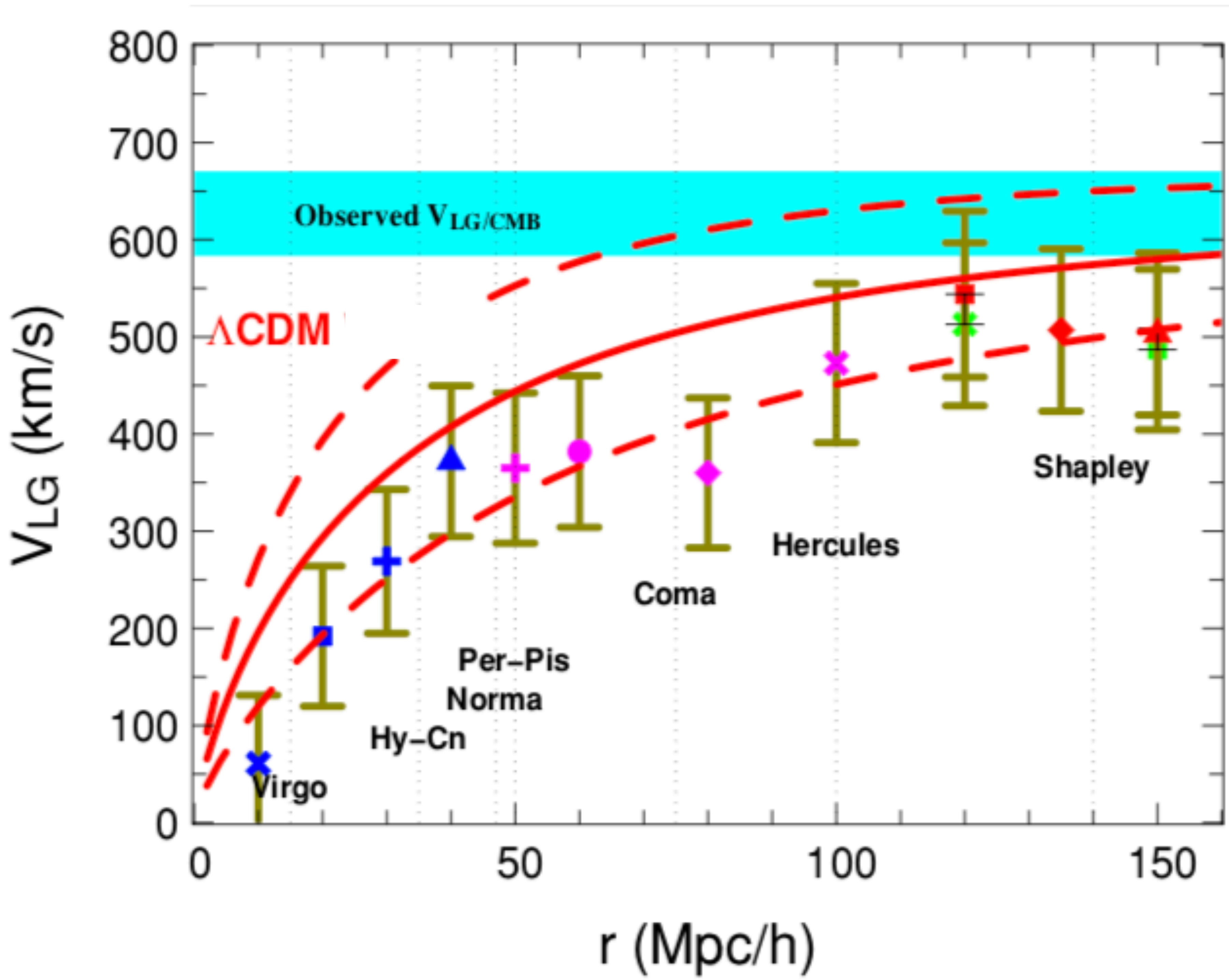


Test of cosmological principle : CMB rest frame



Cosmological principle:
rest-frame of high redshift “sources” = CMB rest frame

Test of cosmological principle : CMB rest frame



Cosmological principle:
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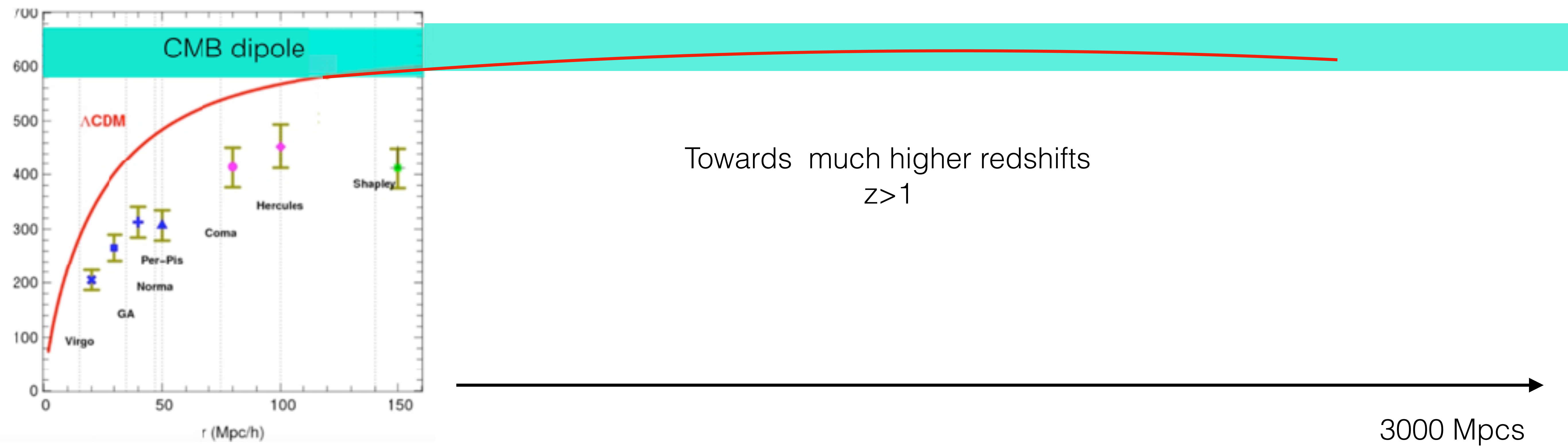
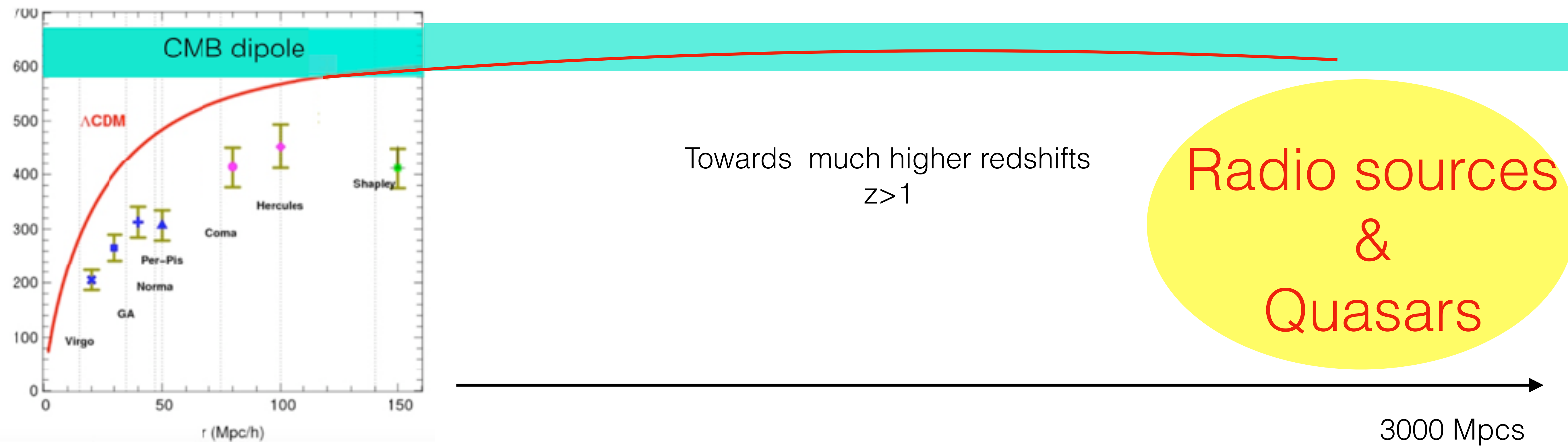
Test of cosmological principle : CMB rest frame



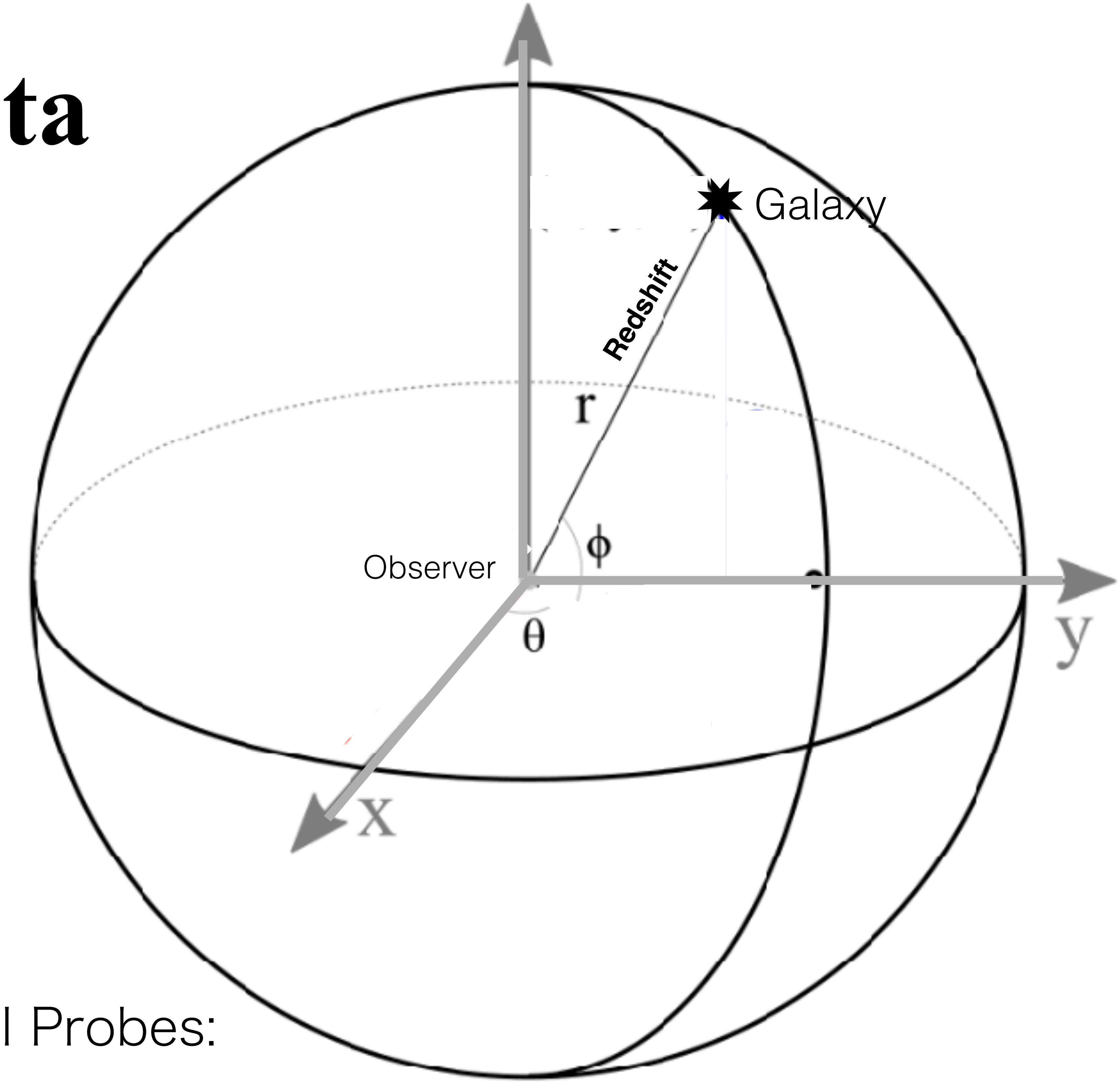
Cosmological principle:
rest-frame of high redshift “sources” = CMB rest frame

Test of cosmological principle : searching for CMB rest frame



Dipole in the rest-frame of high redshift sources = Dipole in the CMB rest frame

Real Data



Observational Probes:

(I) Θ, φ, z, d (distance catalogues)

(II) Θ, φ, z (redshift surveys)

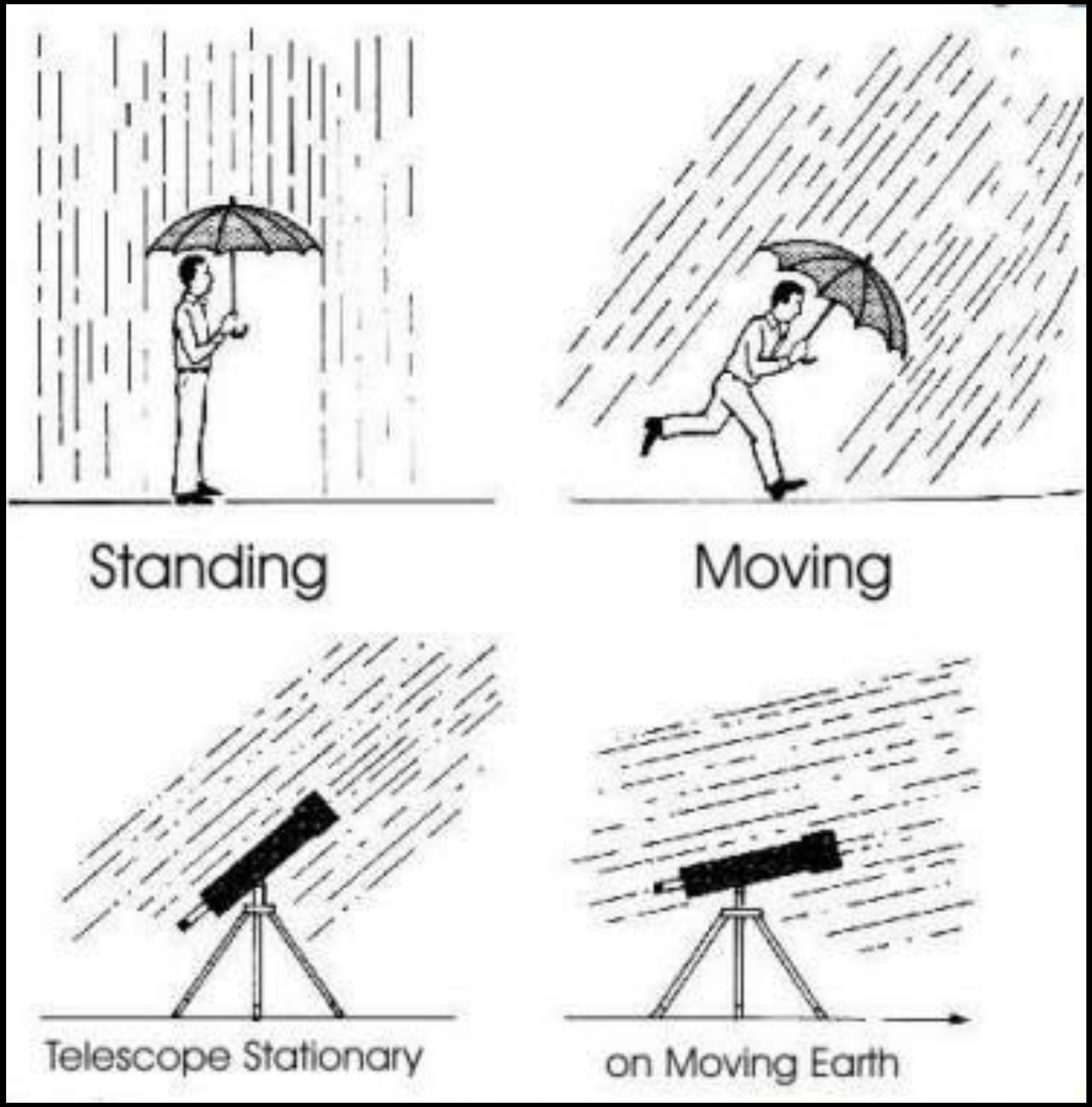
(III) Θ, φ (Imaging surveys)

Aberration

IV. *A Letter from the Reverend Mr.* James Bradley *Savilian Profeſſor of Aſtronomy at* Oxford, *and F.R.S. to Dr.*Edmond Halley Aſtronom. Reg. &c. *giving an Account of a new diſcovered Motion of the* Fix'd Stars.

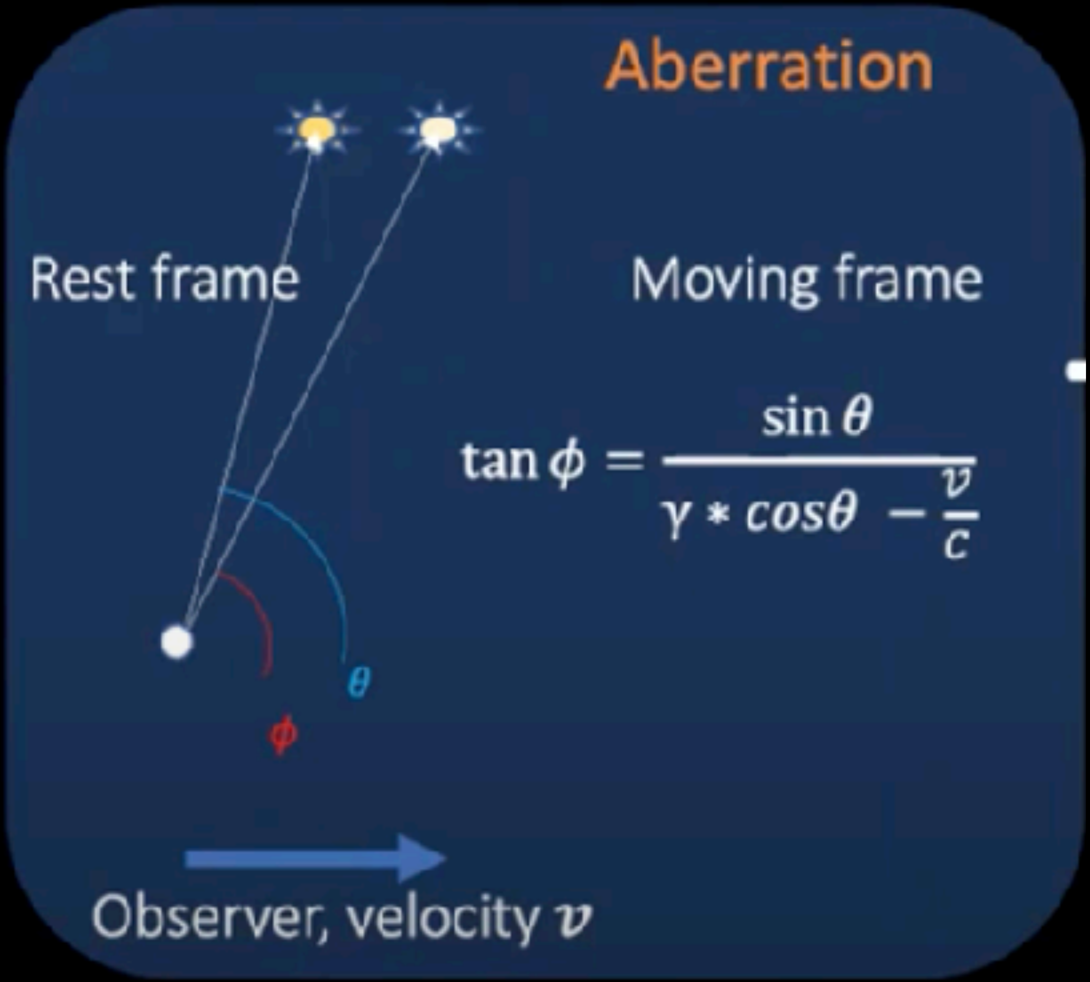
1727.	d.	The Difference of Declination by Obſervation. "	The Difference of Declination by the Hypotheſis. "	1728.	d.	The Difference of Declination by Obſervation. "	The Difference of Declination by the Hypotheſis. "
September -	14	29½	28½	*April* - -	16	18½	18
- - -	24	24½	25½	*May* - -	5	24½	23½
October - -	16	19½	19½	*June* - -	5	32	31½
November -	11	11½	10½	- - -	25	35	34½
December -	14	4	3	*July* - -	17	36	36
1728							
February -	17	2	3	*Auguſt* -	2	35	35½
March - -	21	11½	10½	*September* -	20	26½	26½

Probe 3 : Imaging surveys
Θ, ϕ
Aberration and Doppler boosting



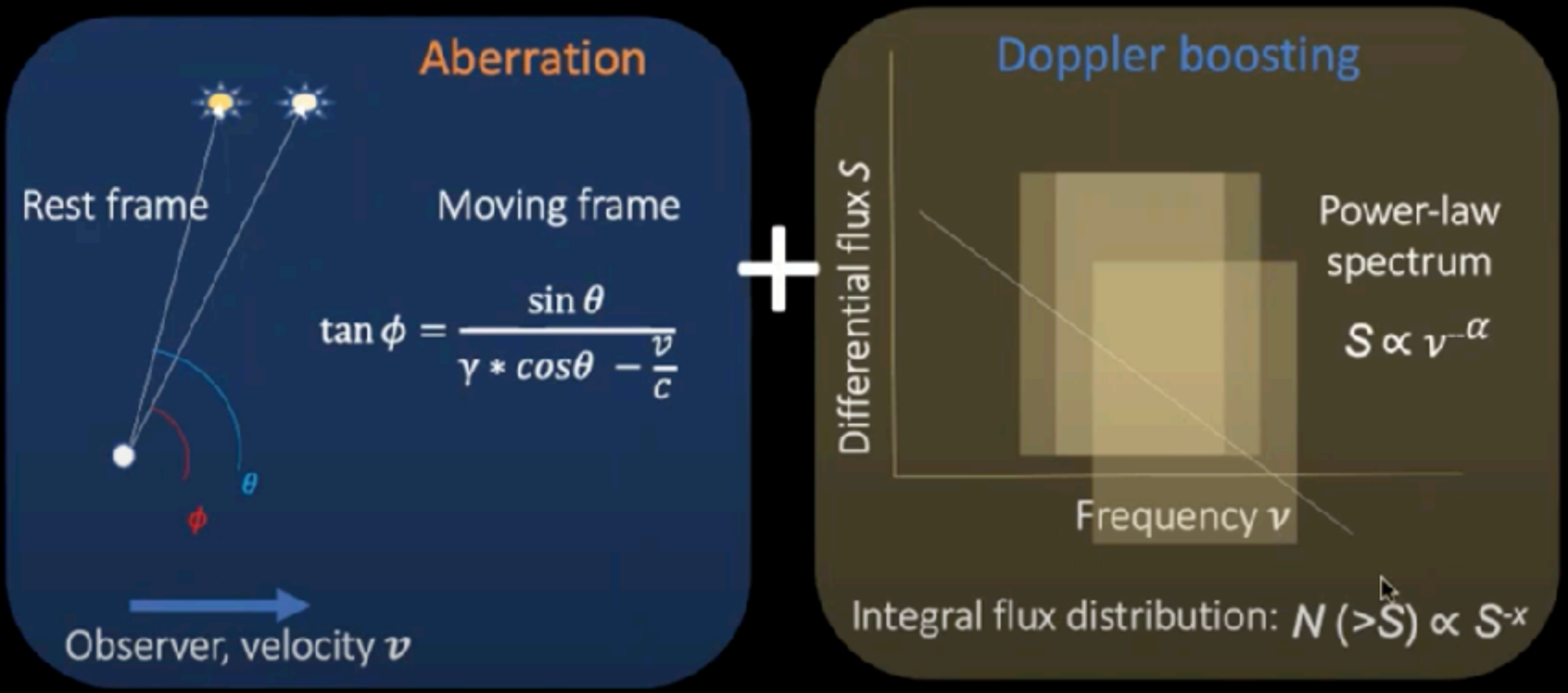
Colin, Mohayaee, Rameez,Sarkar, MNRAS 2017
Rameez, Mohayaee, Sarkar,Colin, MNRAS 2018
Colin, Mohayaee, Rameez,Sarkar, MNRAS 2019
Mohayaee, Rameez, Sarkar, 2020
Secrest, von Hausegger, Rameez, Mohayaee, Sarkar, Colin …, 2021, 2022

Probe 3 : Imaging surveys
Θ, ϕ
Aberration and Doppler boosting



Ellis & Baldwin,
MNRAS 206:377,1984

Probe 3 : Imaging surveys
Θ, ϕ
Aberration and Doppler boosting



Ellis & Baldwin, MNRAS 206:377,1984

Aberration

Ellis and Baldwin 1984

Anisotropy in source distribution → observer's velocity

Aberration and Doppler boosting

$$\textbf{Dipole} = [2 + x(1 + \alpha)]v/c.$$

$$dN/d\Omega(>S_\nu) \propto S_\nu^{-x}$$

$$S_\nu \propto \nu^{-\alpha}$$

Independent of distance to the source

Mon. Not. R. astr. Soc. (1984) **206**, 377–381

On the expected anisotropy of radio source counts

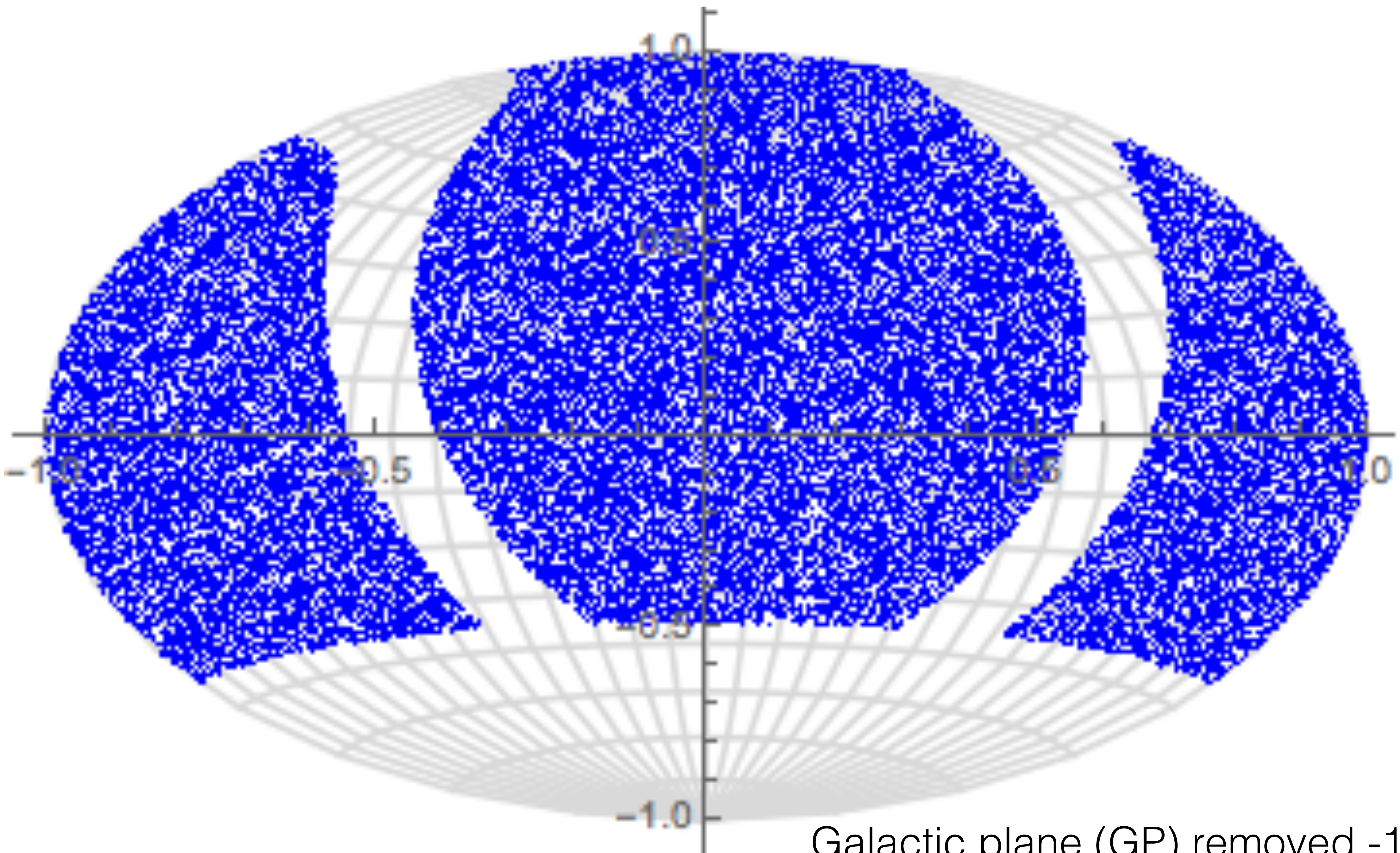
G. F. R. Ellis* and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

Thus existence of such an observed anisotropy is a test of the isotropy of the source counts in their rest frame. The great power of this test is that the measurements can be made (and the result must hold) for any source counts, whether in a wide or a narrow solid angle, for flat or steep source spectra, etc, irrespective of selection effects or source evolution, as long as the forward and backward measurements are done in the identical manner.

DATA: NRAO VLA Sky Survey Catalogue (NVSS)

1773488 Radio galaxies

583587 Radio galaxies in 10 mjy <Flux< 1000 mjy

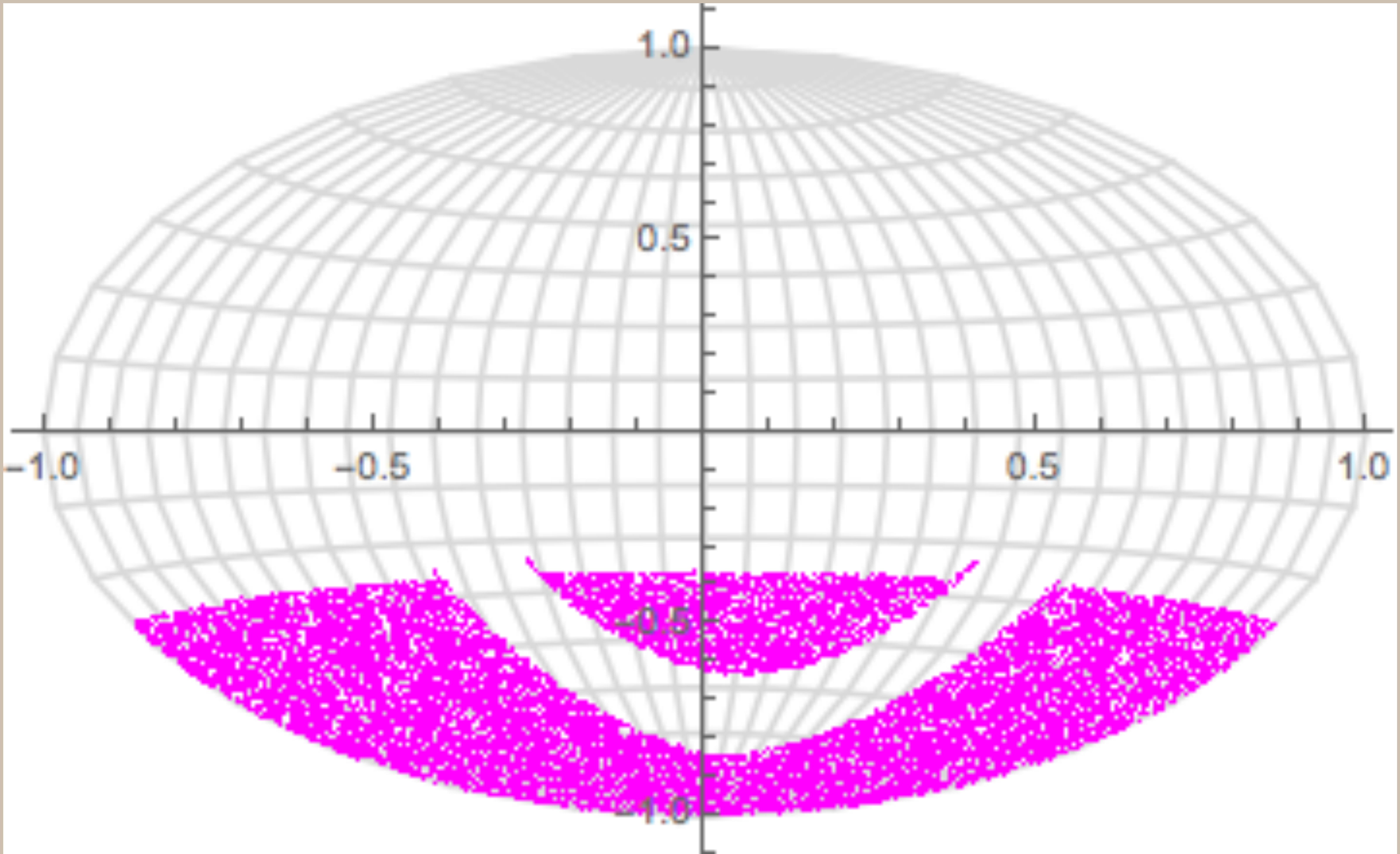


Galactic plane (GP) removed $-10^o<b<10^o$

DATA: The Sydney University Molonglo Sky Survey SUMSS

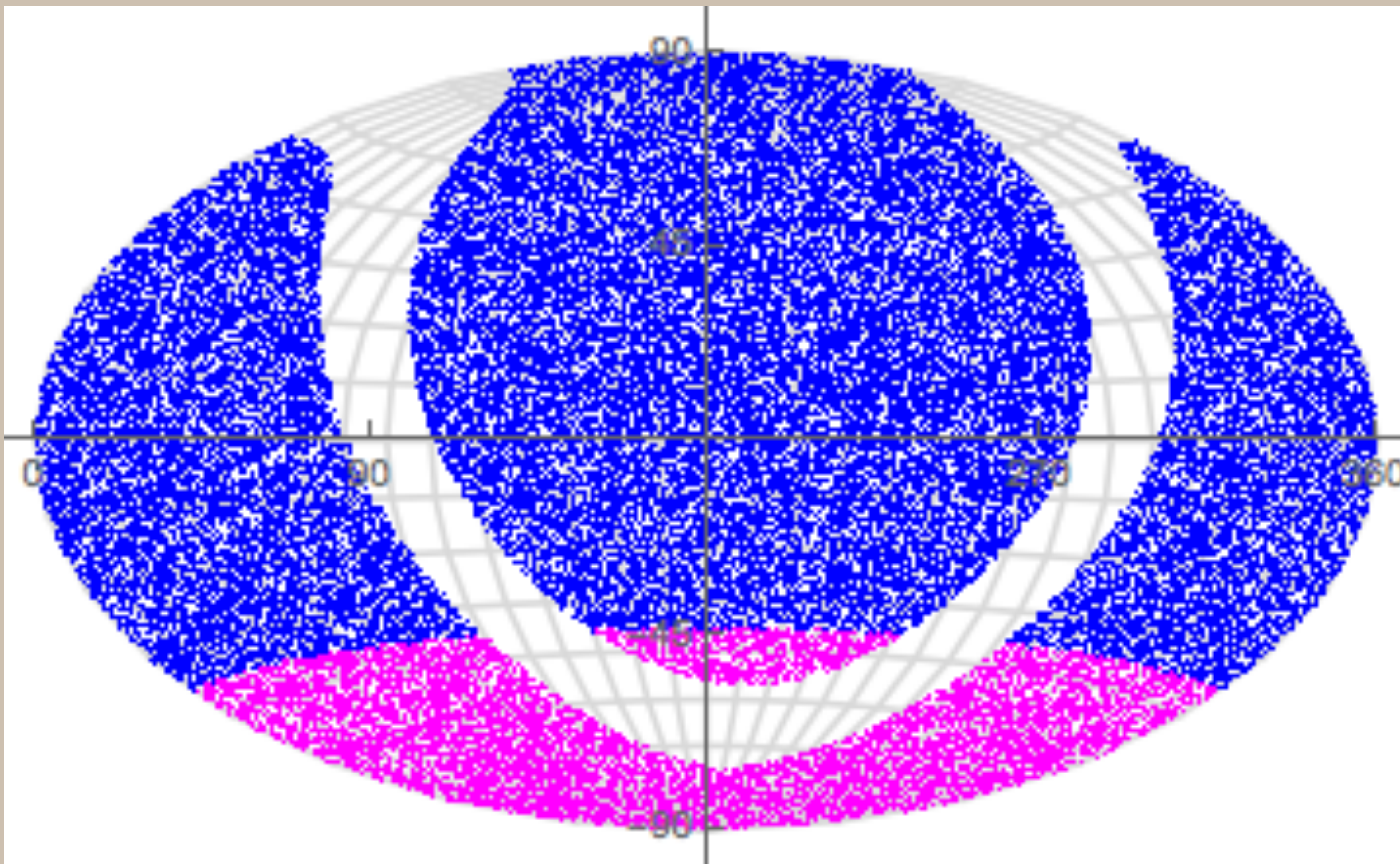
211050 Radio galaxies

183720 Radio galaxies in 10 mjy <Flux< 1000 mjy



DATA: NVSS+SUMSS

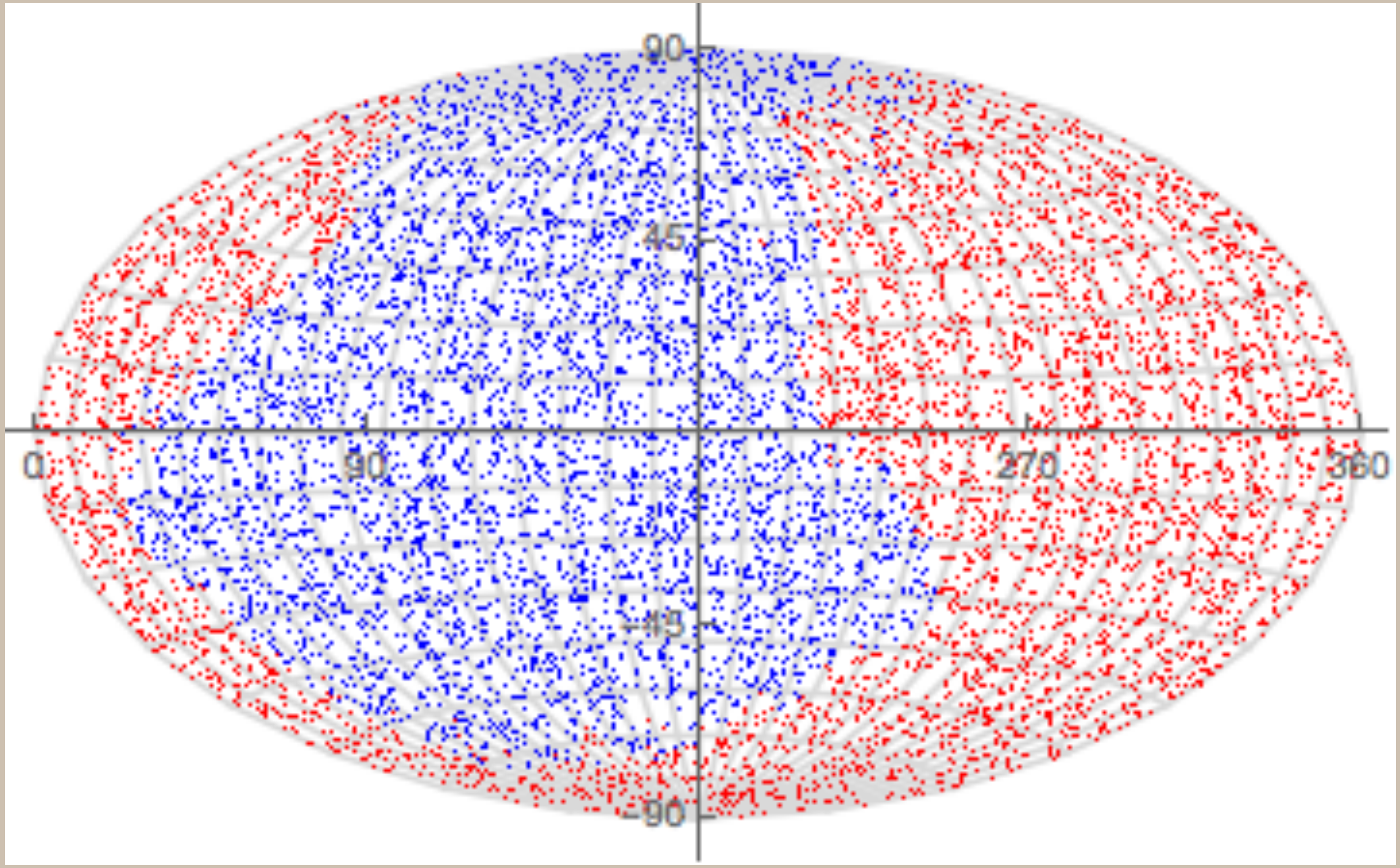
576461 Radio galaxies in 10 mjy <Flux< 1000 mjy



Searching for dipole

We randomly select a direction ($\theta=\{-\pi/2,\pi/2\}$ and $\varphi=\{0,2\pi\}$

and count Number of galaxies in each hemisphere



Mean number of galaxies in each hemisphere: 345192., Max difference between two hemispheres: 5185 galaxies

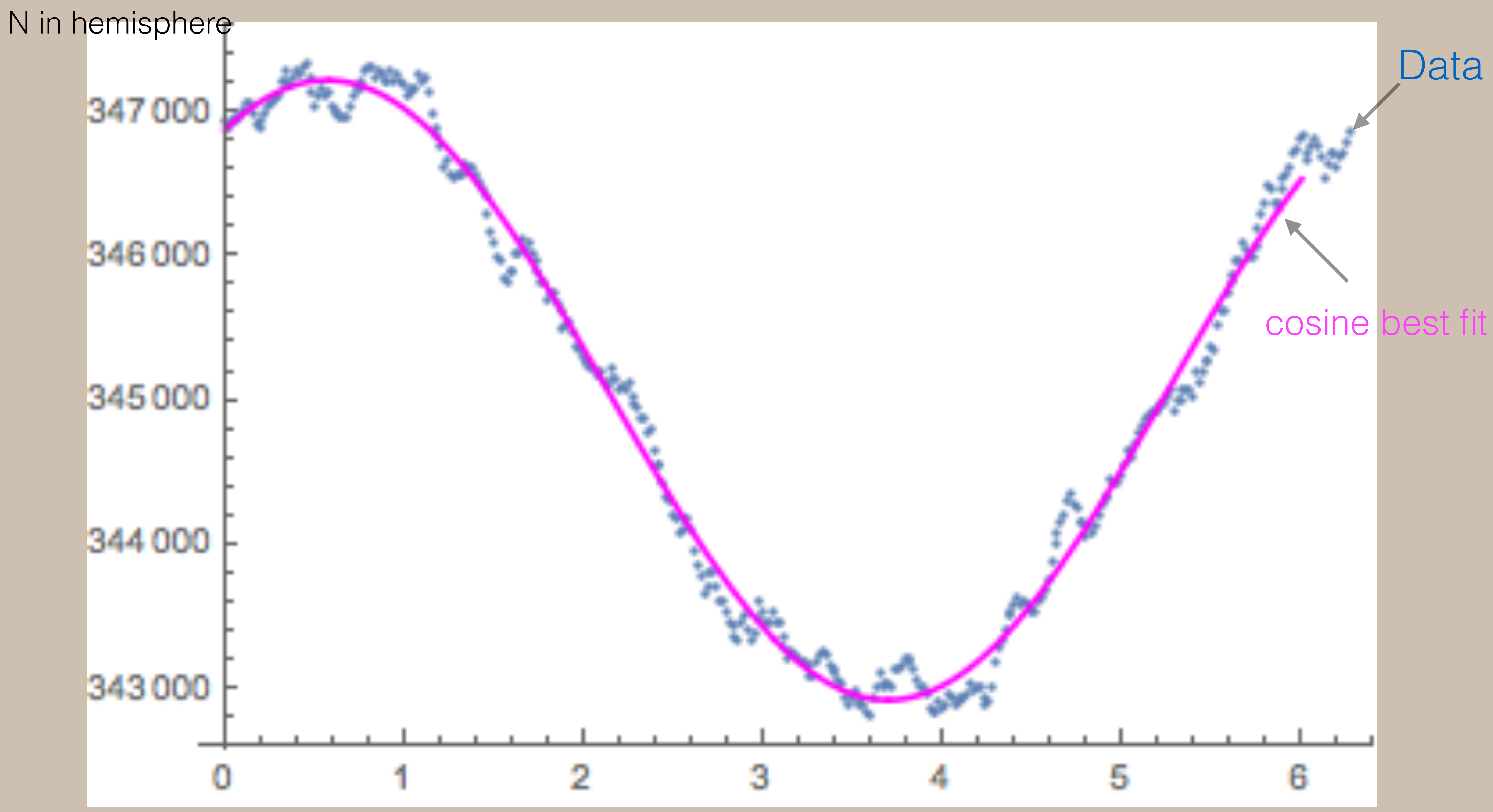
Red: hemispheres containing LESS galaxies than the mean

Blue: Hemispheres containing MORE galaxies than the mean

Searching for dipole

Example of hemispherical counting:

Here we fix the axis $\theta=\{0,90\}$ and turn φ every one degree

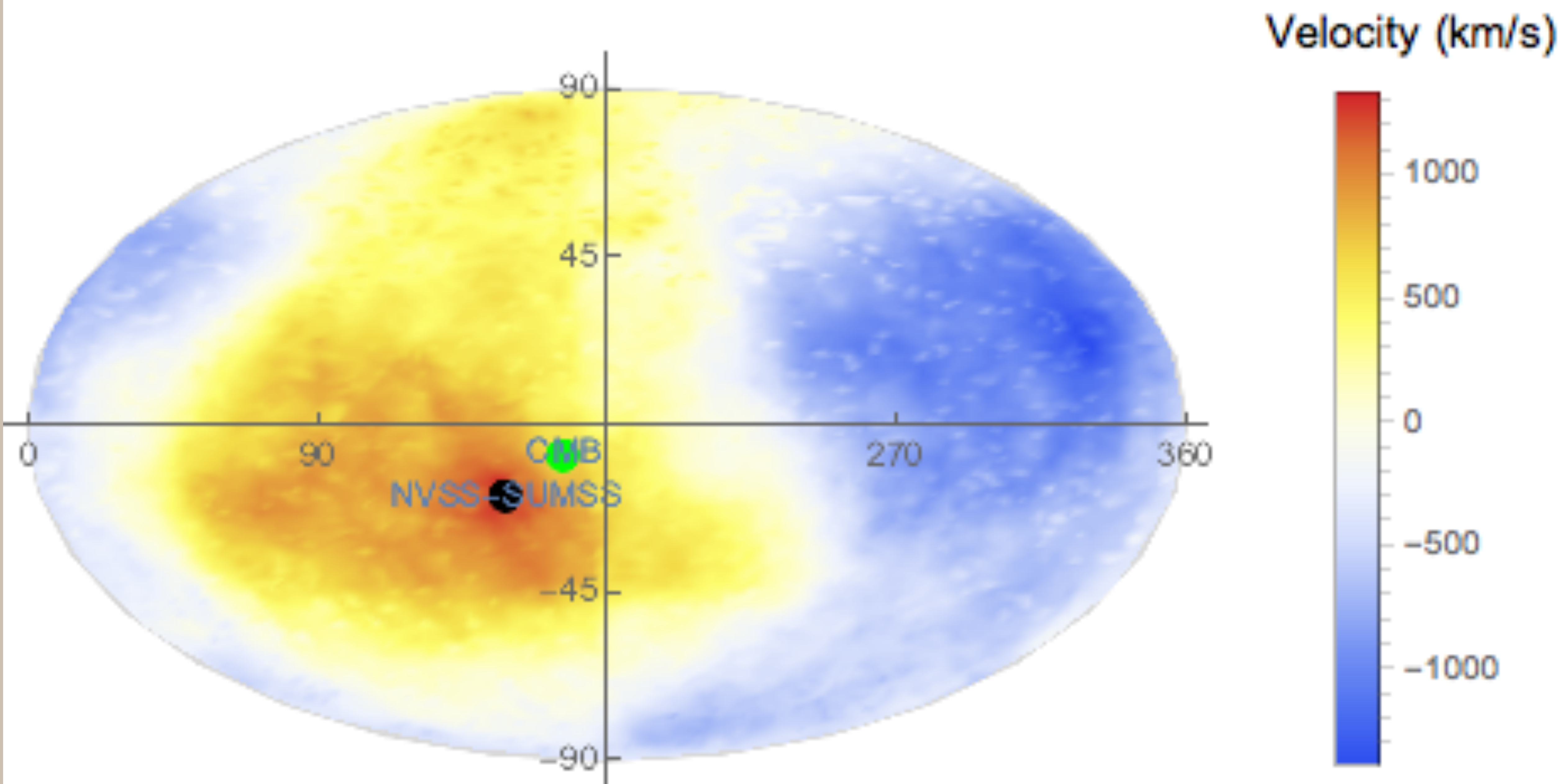


φ (Radians)

Dipole

Dipole direction: {RA=156°, DEC=-17°} compare to CMB DIpole {RA=168° , DEC=-7°}

Dipole Amplitude : velocity of barycentre of solar system w.r.t. Radio galaxies restframe = 1097 km/s
velocity of barycentre of solar system w.r.t. CMB restframe = 369 km/s



Low significance

Wide-field Infrared Survey Explorer

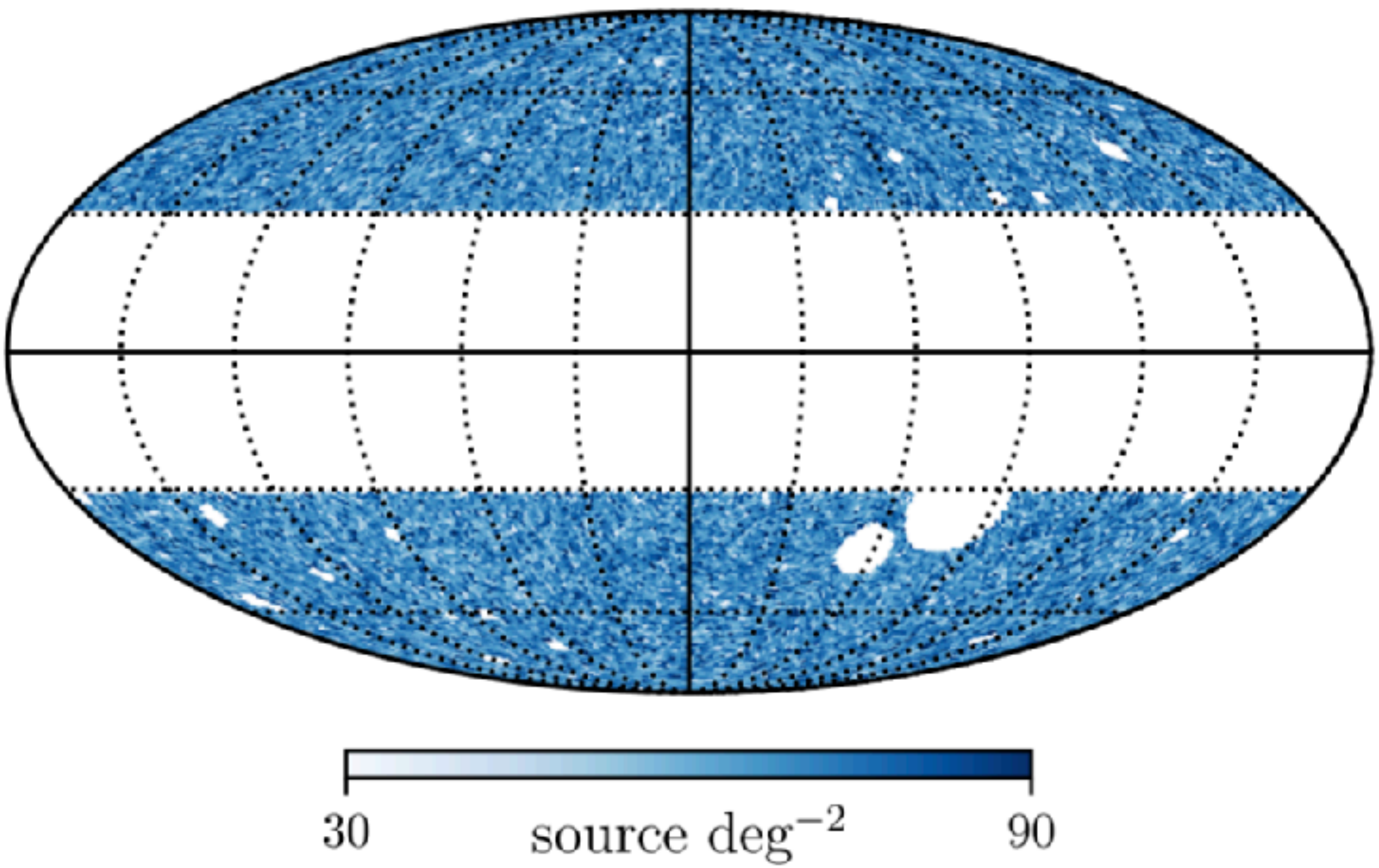
WISE :(Wright et al. 2010) & NEOWISE (Mainzer et al. 2011)

CatWISE : Eisenhardt et al 2020

positions and the four-band photometry for 747,634,026 objects

Full-sky **mid-infrared** survey in:

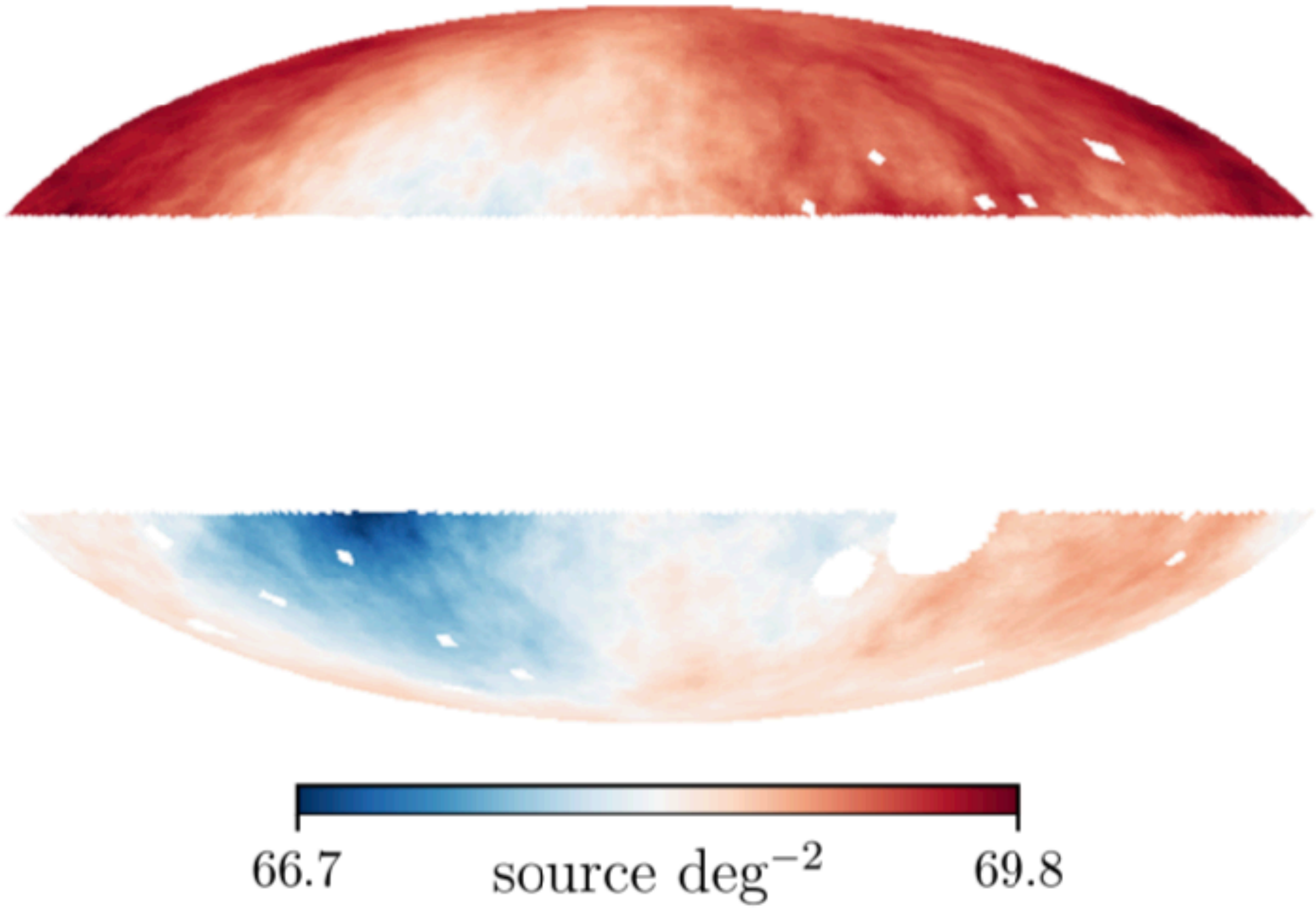
3.4um (W1)	(2009 – present)
4.6um (W2)	(2009 – present)
12um (W3)	(2009 – 2010)
22um (W4)	(2009 – 2010)



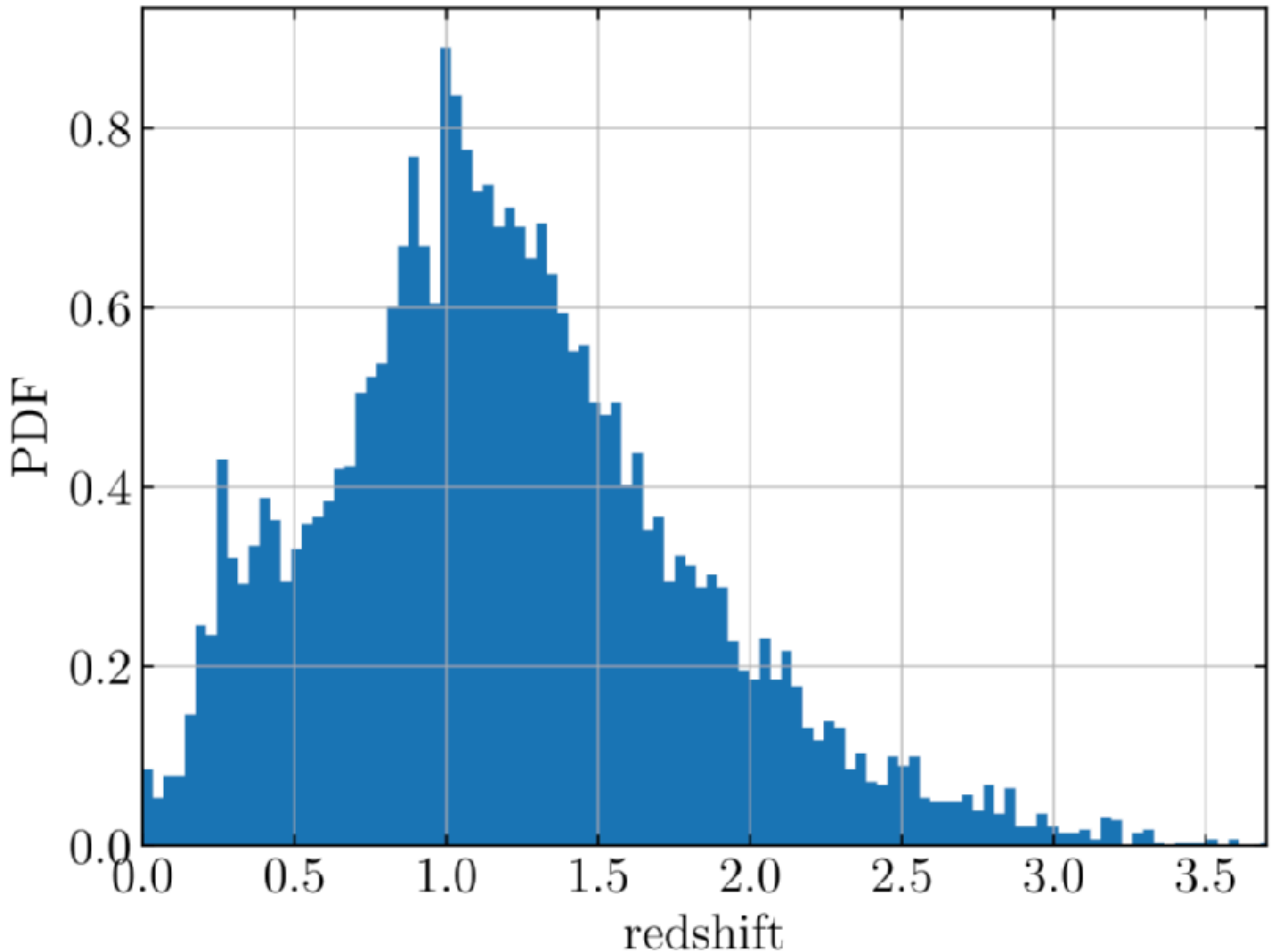
The Dipole

Quasar Dipole = 0.01554, (l, b) = (238°. 2, 28°.8).

CMB dipole. = 0.007 , (l, b) = (276°, 30°)



Redshift distribution

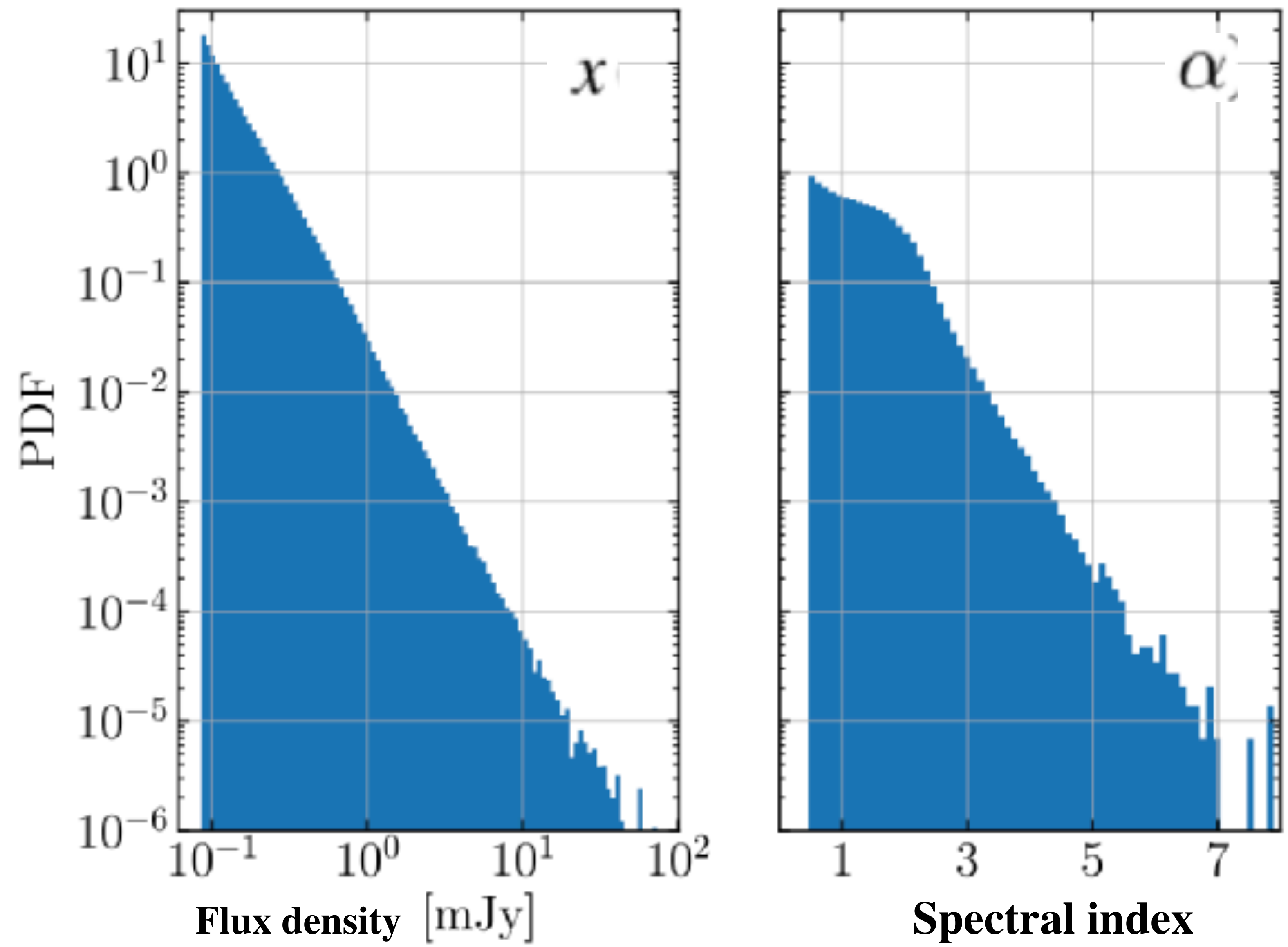


Statistical significance

10^7 random sky

mimicking CatWISE
same masks,
estimator, flux….

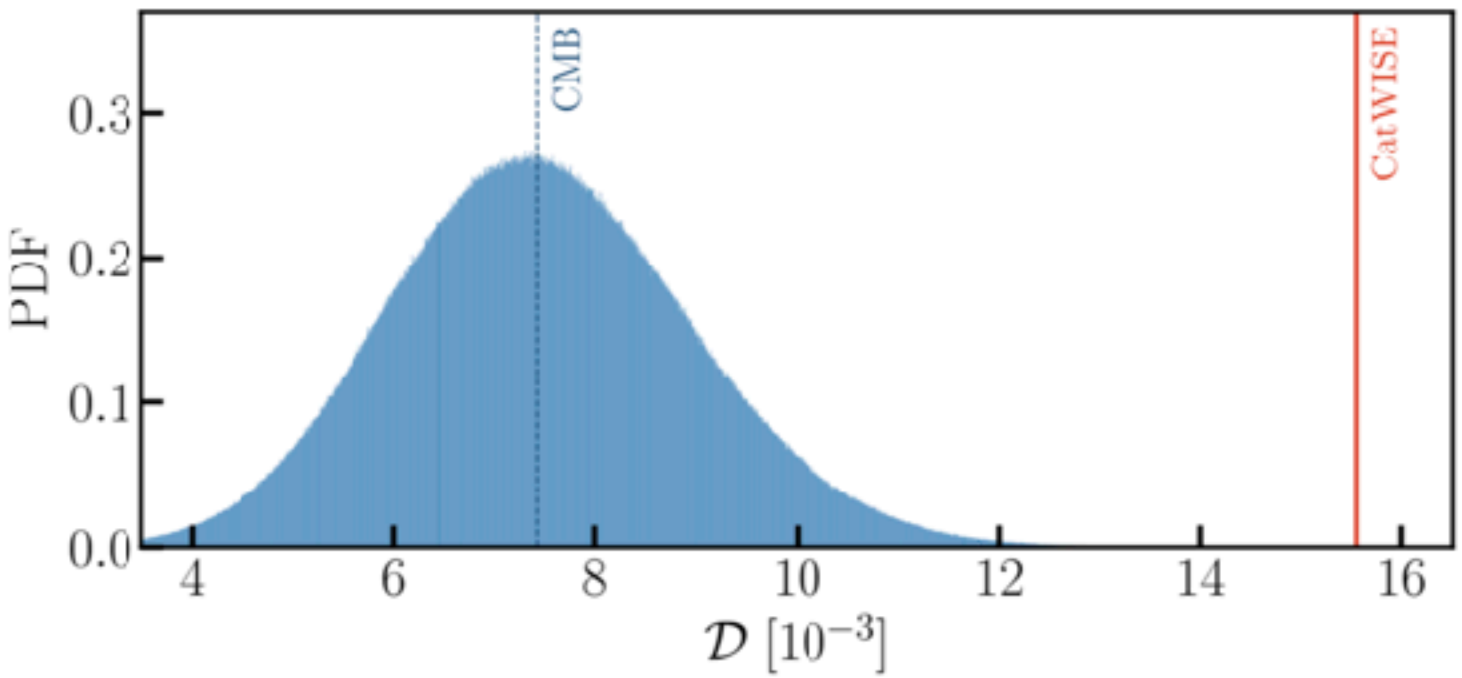
Dipole $= [2 + x(1 + \alpha)]v/c.$

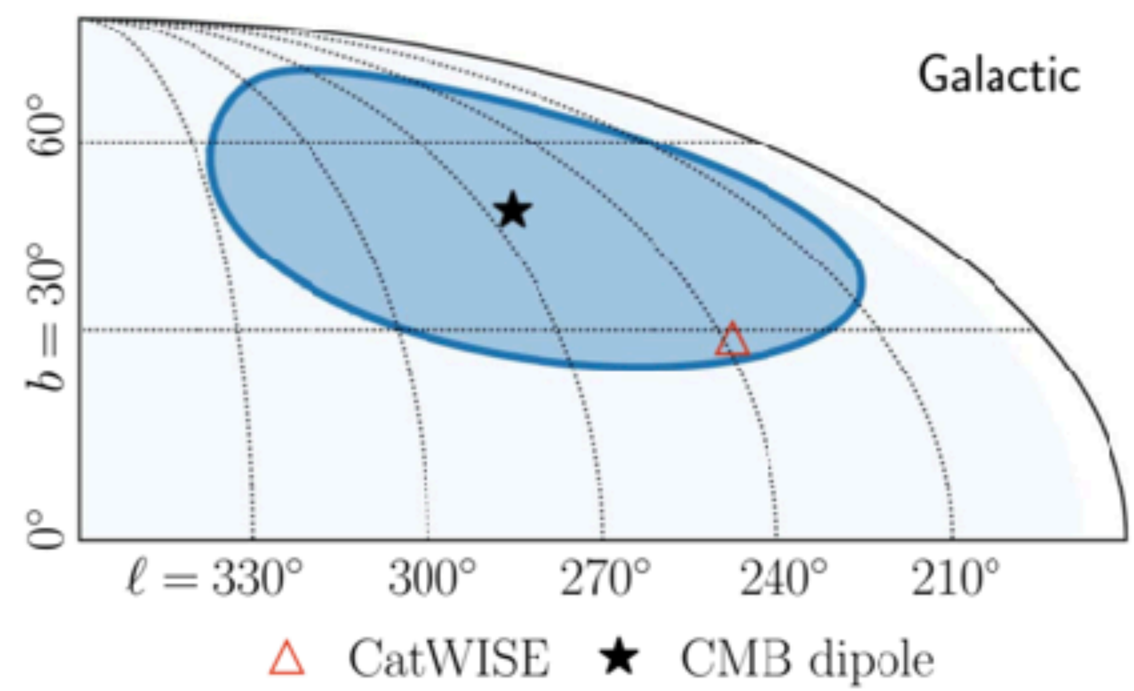


The null Hypothesis:
An observer moving with a velocity of 369.82 km/s (CMB expectation) can see a dipole twice that of CMB" !
Rejected : p value of $5\text{x}10^{-7}$

Statistical significance

4.9 sigma





Is quasar data consistent with radio data ?

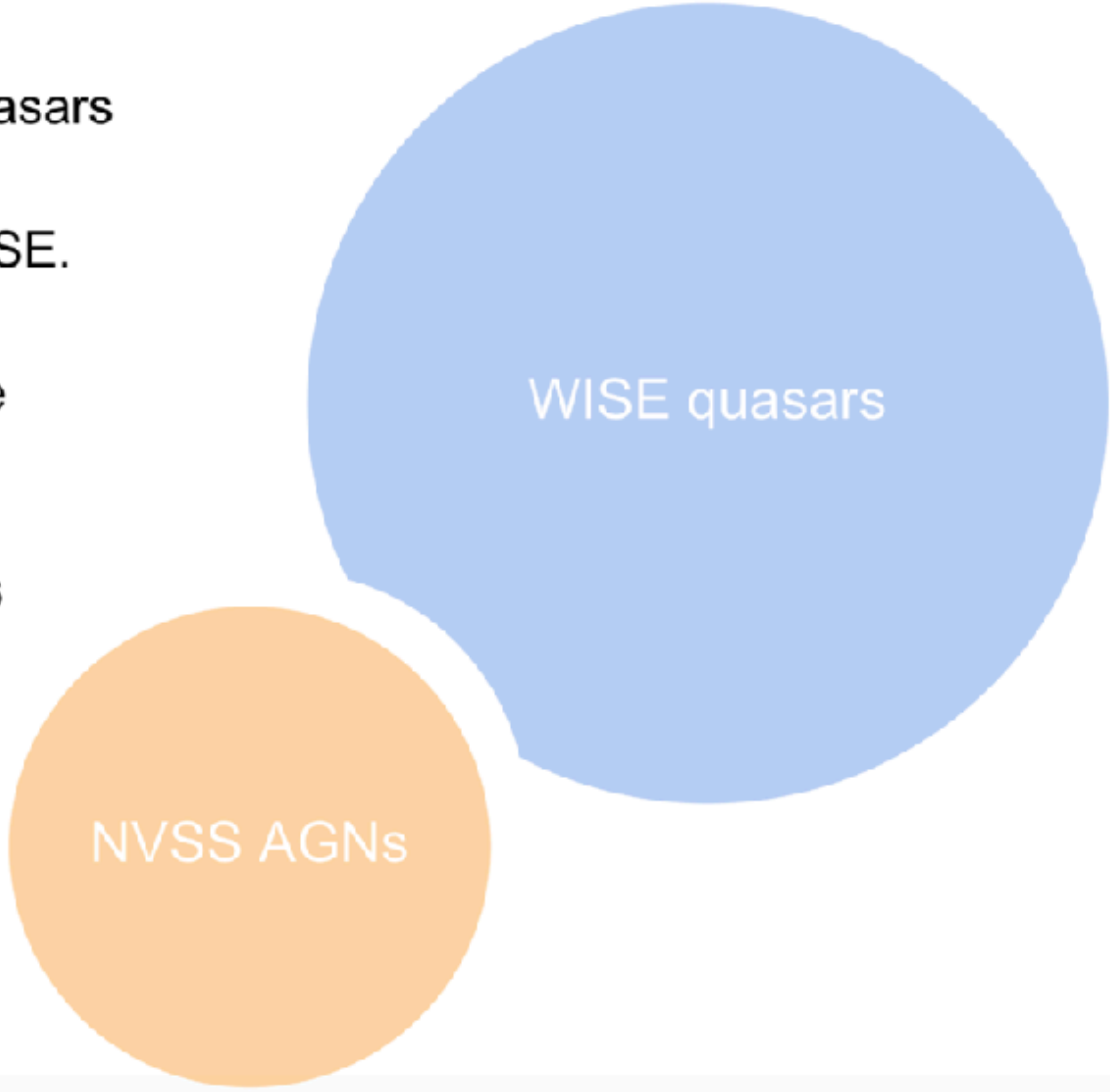
Shared sources: 1.4% of WISE quasars

Removed shared sources from WISE.

Kept sources in NVSS to maximize sources in smaller catalog.

WISE quasars in unshared regions removed randomly to preserve uniformity.

→ **Totally orthogonal catalogs.**



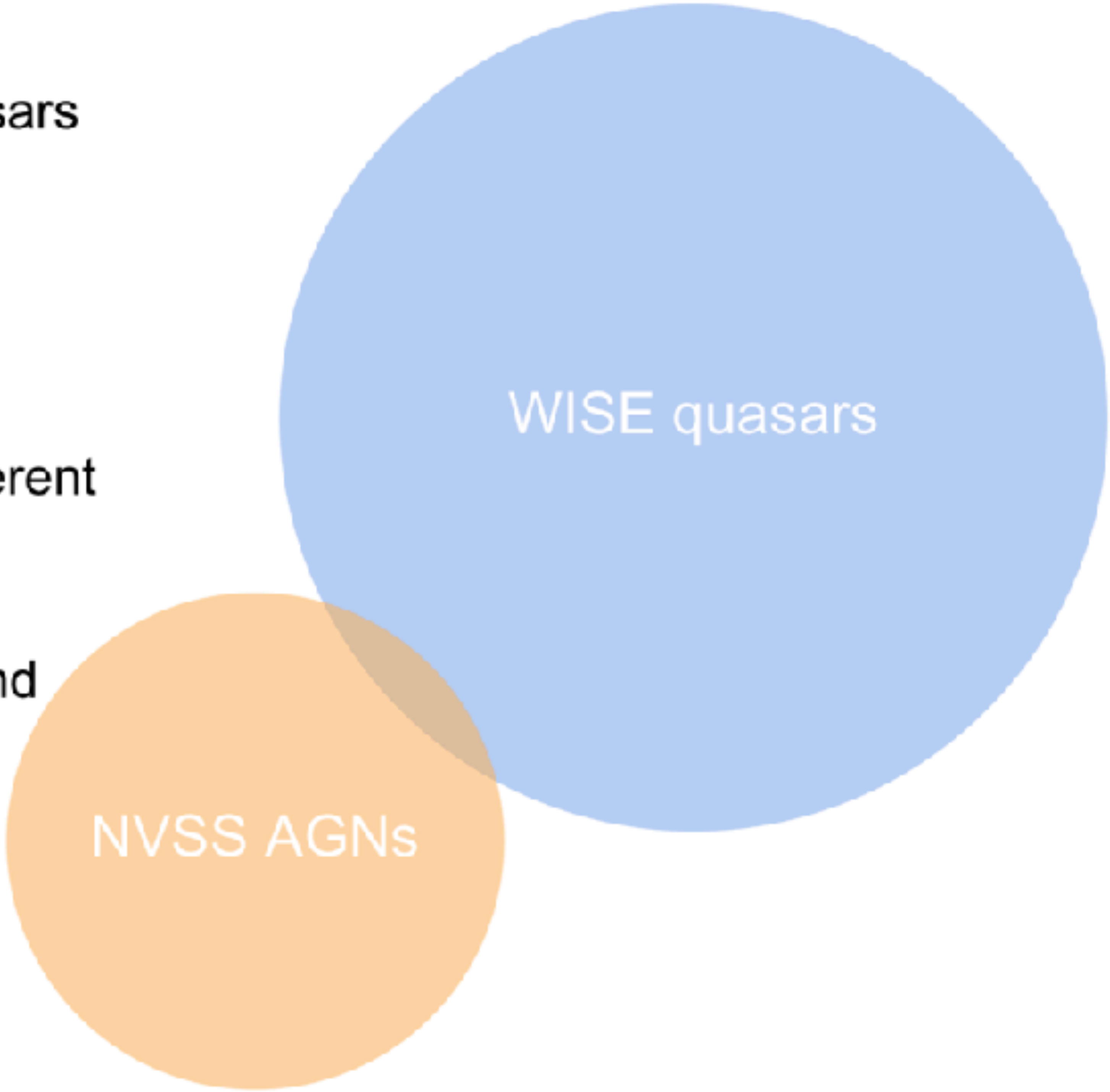
Is quasar data consistent with radio data ?

Shared sources: **1.4%** of WISE quasars

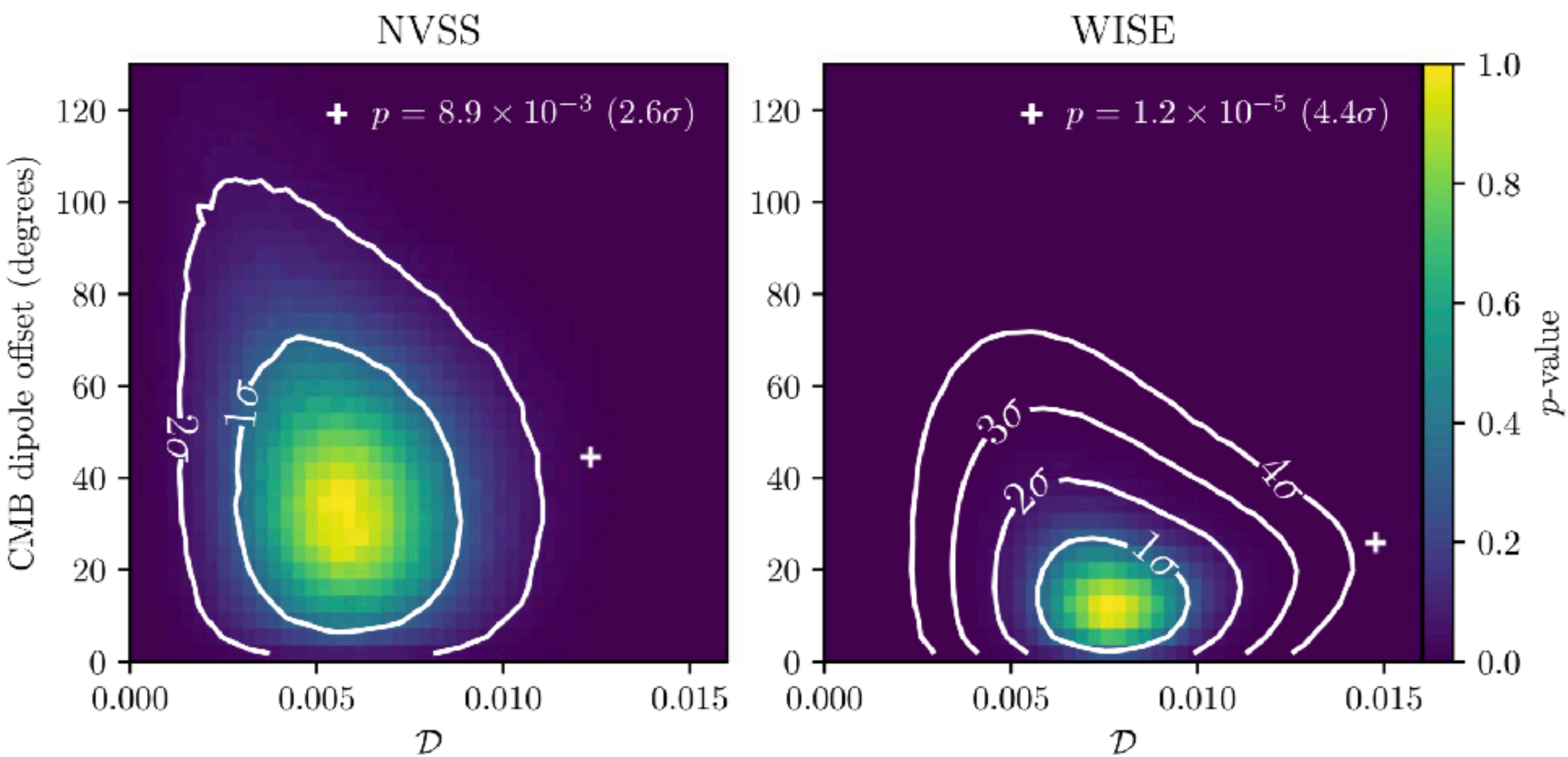
Why?

Radio galaxies and quasars are different kinds of object!

- Radio galaxies: evolved, “red and dead” massive ellipticals
- Quasars: bluer, gas-rich disk galaxies



Joint Analysis: Infrared (Wise) and radio sources (NVSS)
Statistical significance: 5.1 sigma



ApJLetter, 2022

All data and codes made public:

Code and data → https://doi.org/10.5281/zenodo.4431089

Our paper (open access):
https://ui.adsabs.harvard.edu/abs/2021ApJ...908L..51S/abstract

George Ellis and Baldwin

MNRAS, 1984

vations of the microwave background radiation. If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon either

(a) the idea that the radio sources are at cosmological distances, or

(b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or

(c) the standard FRW Universe models.

Anomalies in Physical Cosmology

P. J. E. Peebles

Nobel laureate 2019

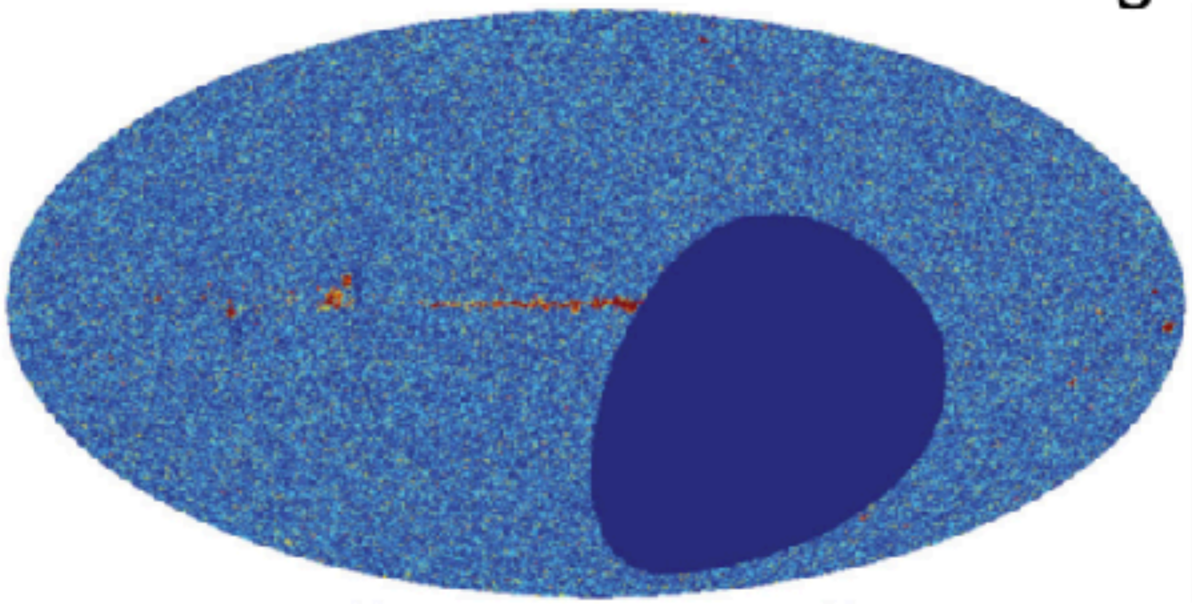
Annals of Physics **2022**

The ΛCDM cosmology passes demanding tests that establish it as a good approximation to reality. The theory is incomplete, of course, and open issues are being examined in active research programs.

The dipole anisotropy in the distribution of objects at distances comparable to the Hubble length is about in the direction expected from the kinematic effect if the dipole anisotropy in the CMB is due to our motion relative to the rest frame defined by the mean mass distribution, but the dipole amplitude is at least twice the prediction. This anomaly is about as well established as the Hubble Tension, yet the literature on the kinematic effect is much smaller than the 344 papers with the phrase “Hubble Tension” in the abstract in the SAO/NASA Astrophysics Data System. (I expect the difference is an inevitable consequence of the way we behave.)

Merci !

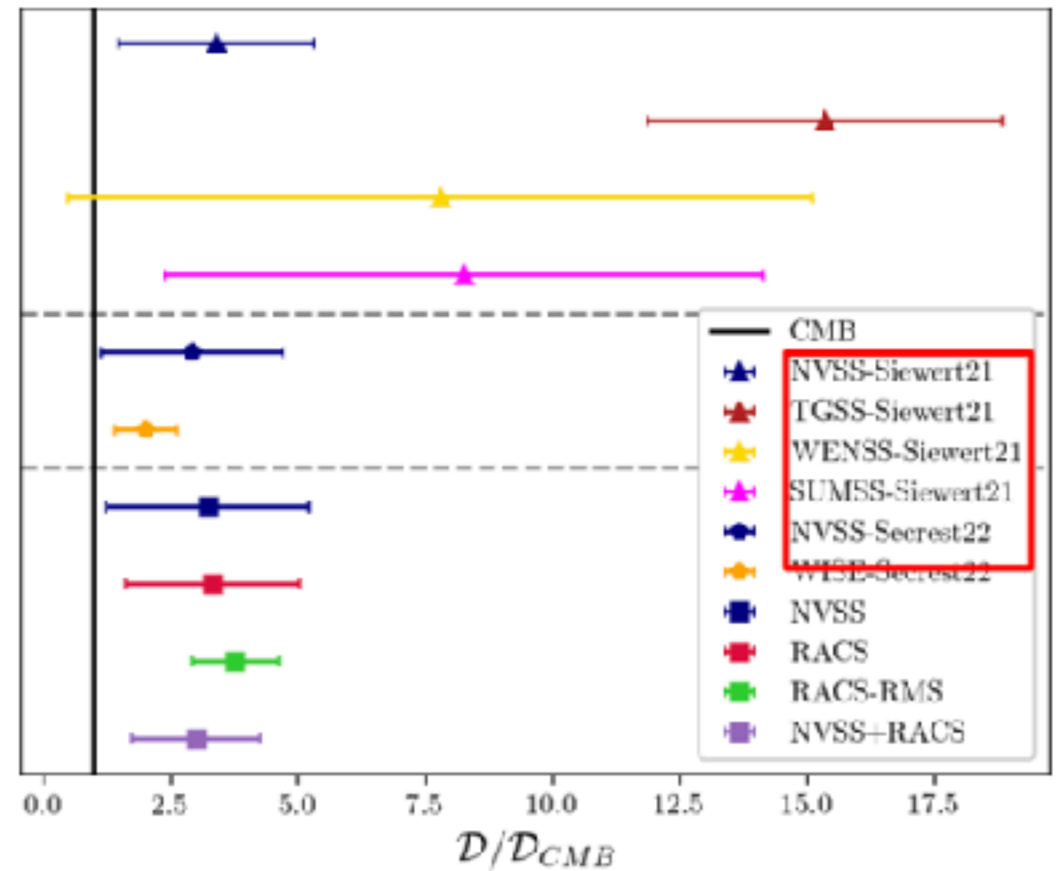
The NRAO VLA Sky Survey (NVSS; 1998): first constraints with ~0.5 million radio galaxies



Gibelyou & Huterer (2012)

(Except Blake & Wall 2002), Singal (2011), Gibelyou & Huterer (2012), Rubart & Schwarz (2013), Tiwari et al. (2015), Tiwari & Nusser (2016), Colin et al. (2017), Bengaly et al. (2018), Siewert et al. (2021):

→ ~3σ tension with kinematic expectation!



Radio results with 3σ error bars from Wagenveld et al. (2023) with some earlier radio results highlighted

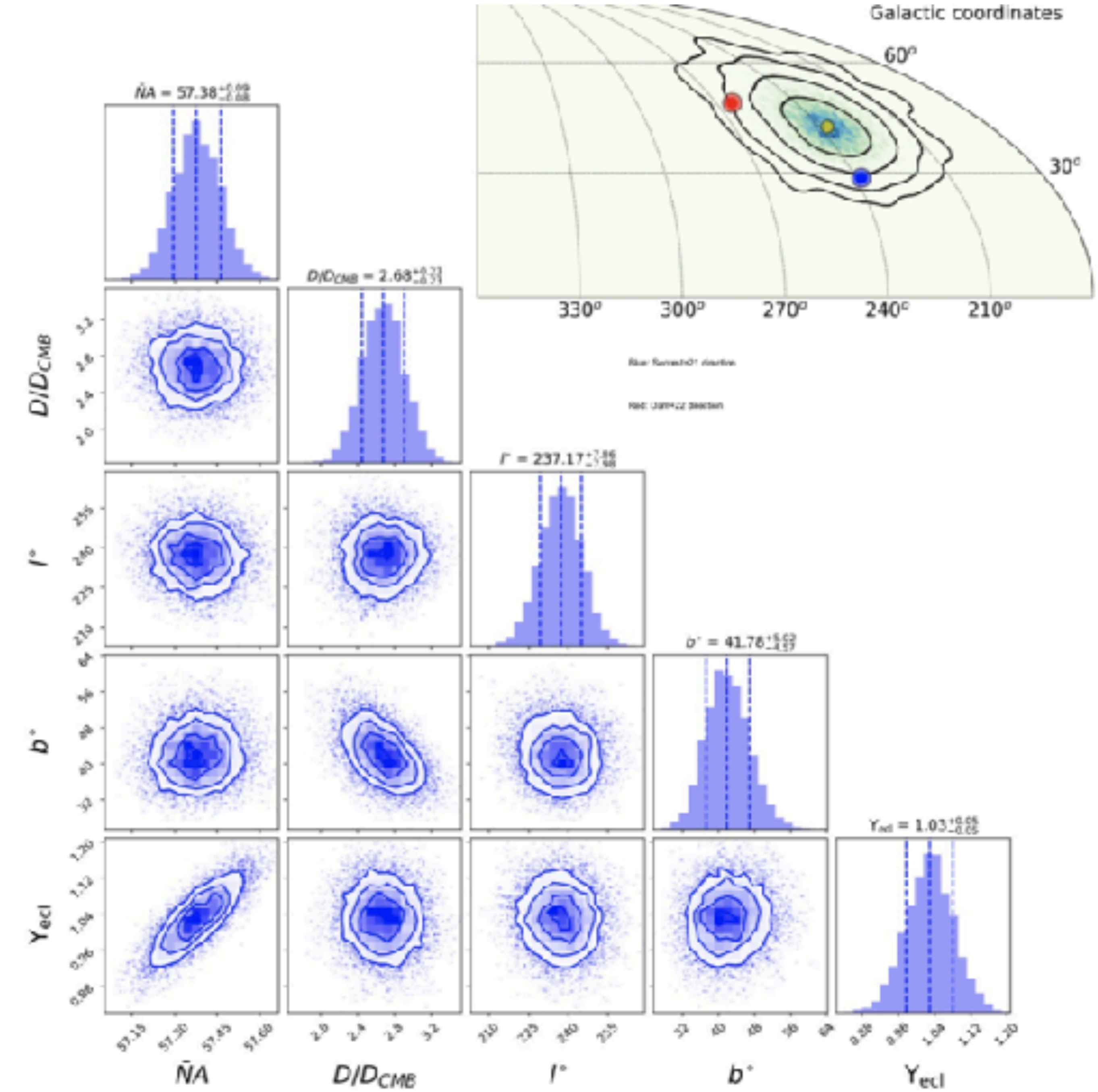
Okay, Bayesian…

Dam+23 performed a Bayesian analysis of the WISE quasar catalog from Secrest+21

- Poissonian likelihood
- Uniform priors

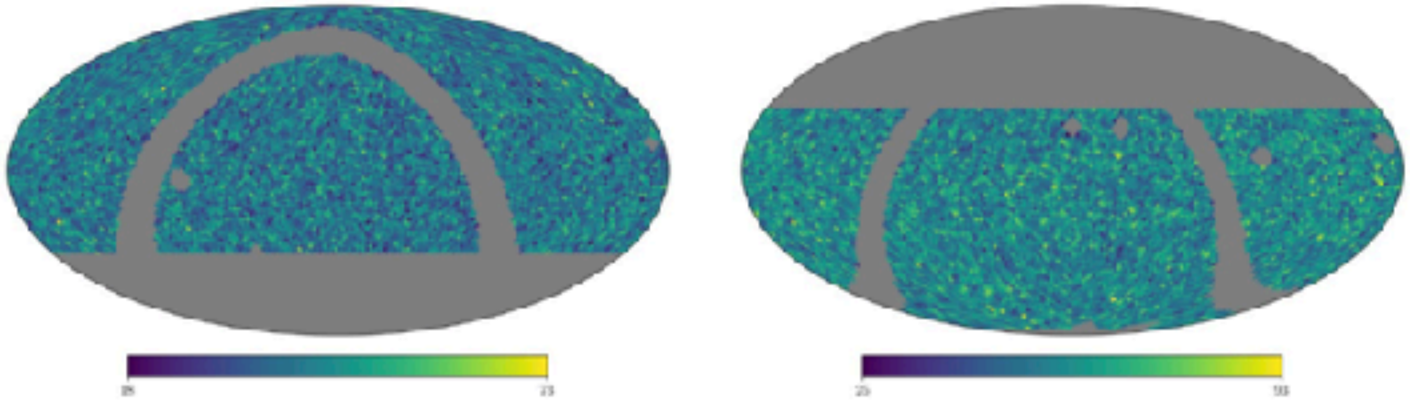
→ Found $D/D_{CMB} = 2.7$

Marginalizing over all other parameters, CMB dipole amplitude rejected at **5.7σ** level



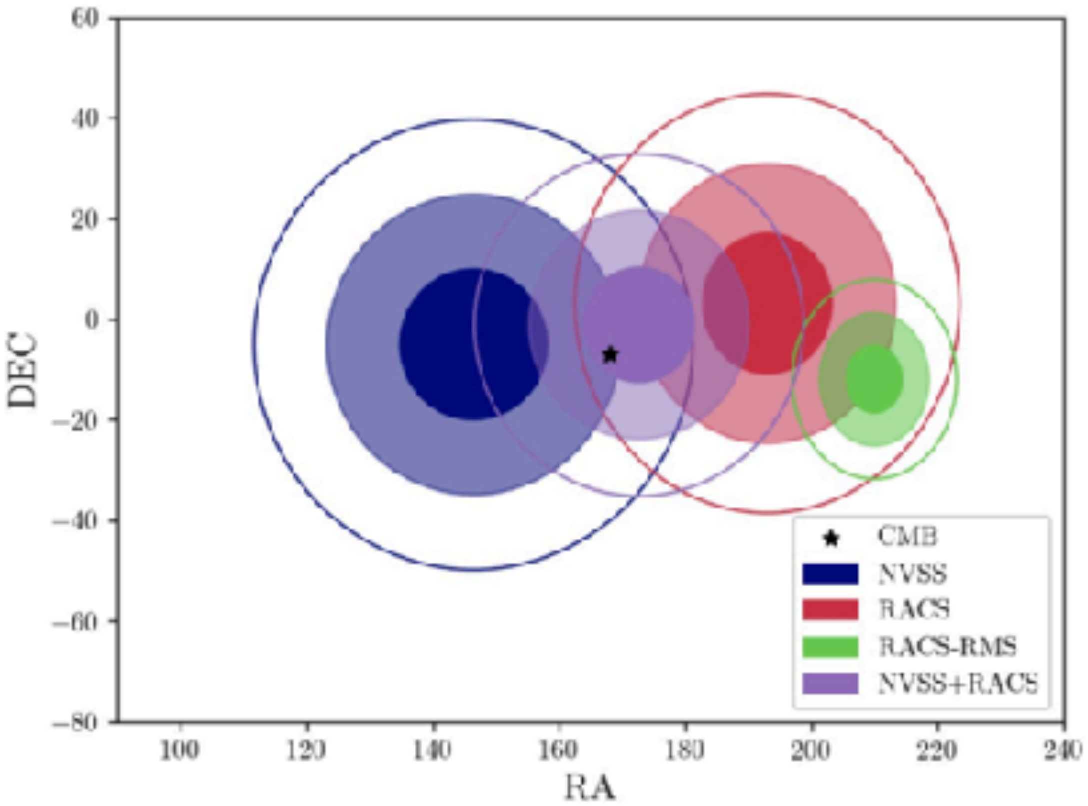
NA = mean count per sky pixel; Y_{ecl} = fractional offset of ecliptic latitude bias from value found by Secrest+21

Okay, Bayesian…



Wagenveld+23

- Used multi-Poisson MLE with novel term to account for survey non-uniformity to maximize source counts in estimator.



Reject CMB dipole at **4.8σ** level, ***the highest using <u>only</u> radio data.***

<u>My view:</u> Orthogonality of radio galaxies and quasars suggests joint significance of cosmic dipole problem exceeding 6σ!