Testing the cosmological principle

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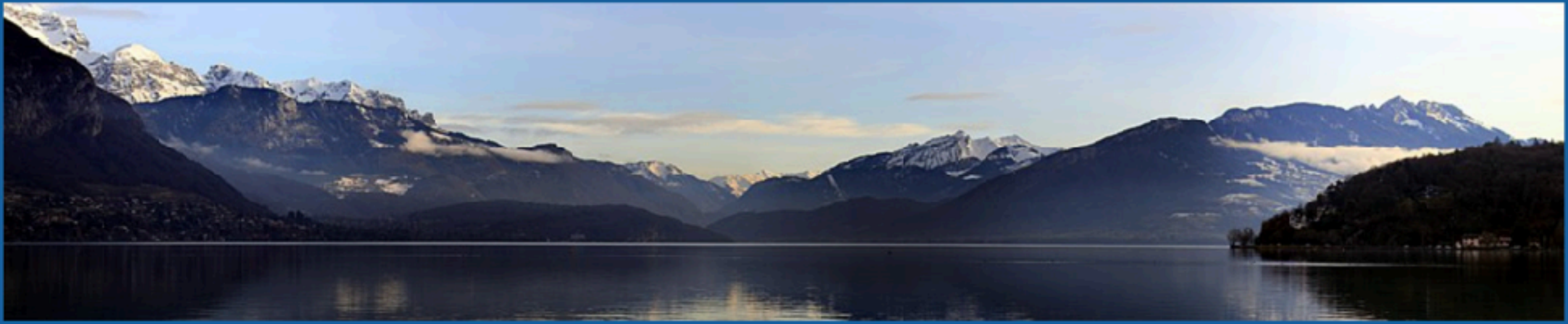
Nathan Secrest (Naval Observatory, USA)



Rubin-LSST France, Mai 2022

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

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FLRW

Homogeneous but anisotropic → Axis

Cosmological principle

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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

Cosmological principle

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Bianchi

Inhomogeneous & isotropic → Centre

Cosmological principle

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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**

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

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

Inhomogeneous & anisotropic

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

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

The Cosmological principle

1915

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

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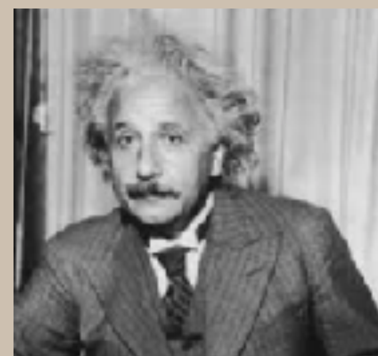
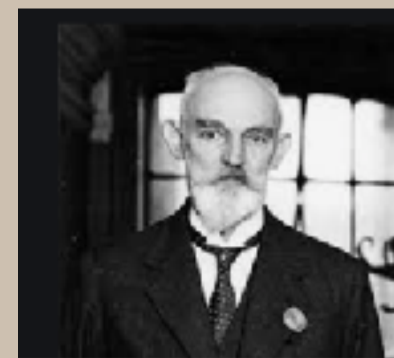
1917





The Cosmological principle

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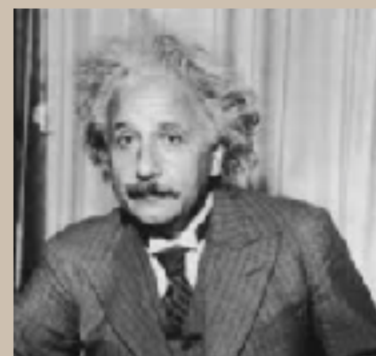
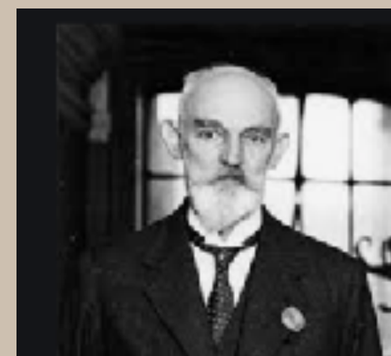
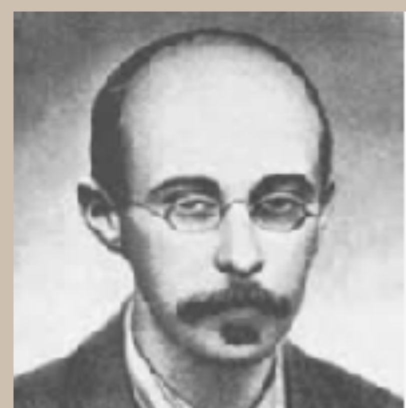



1922-1935




The Cosmological principle

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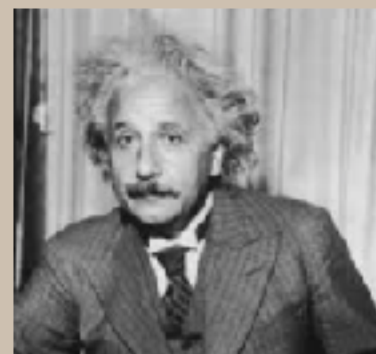
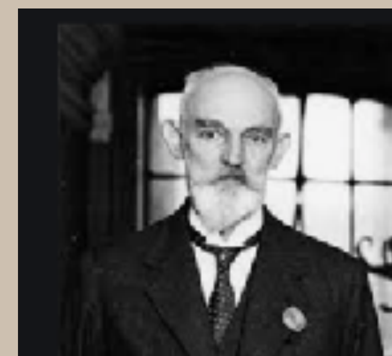
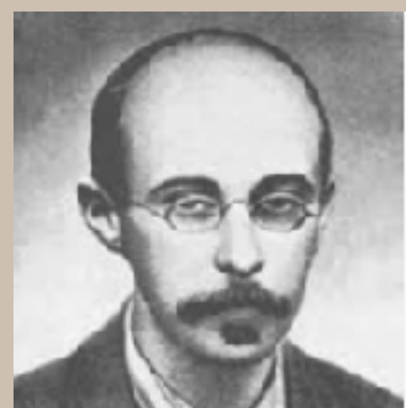
1917

1922-1935



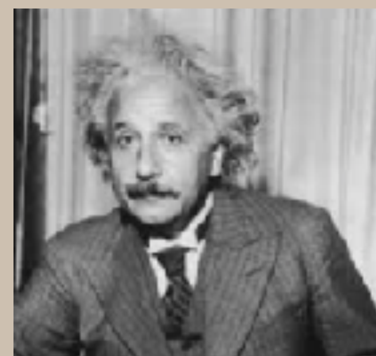
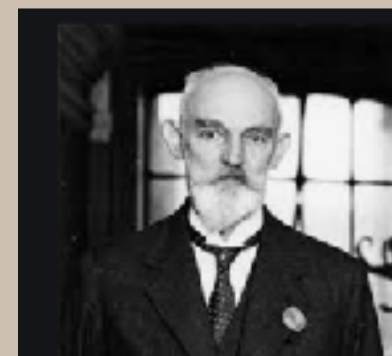

1932

The Cosmological principle

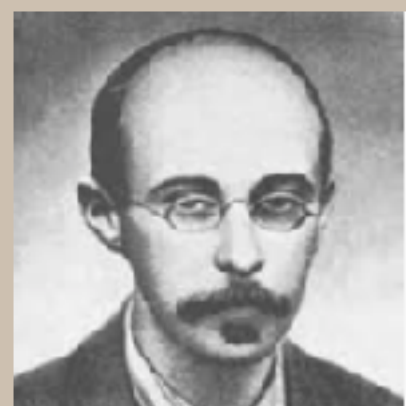
1915

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

1917

1922-1935




1932

1935

The Cosmological principle

Milne

A new basis for cosmology

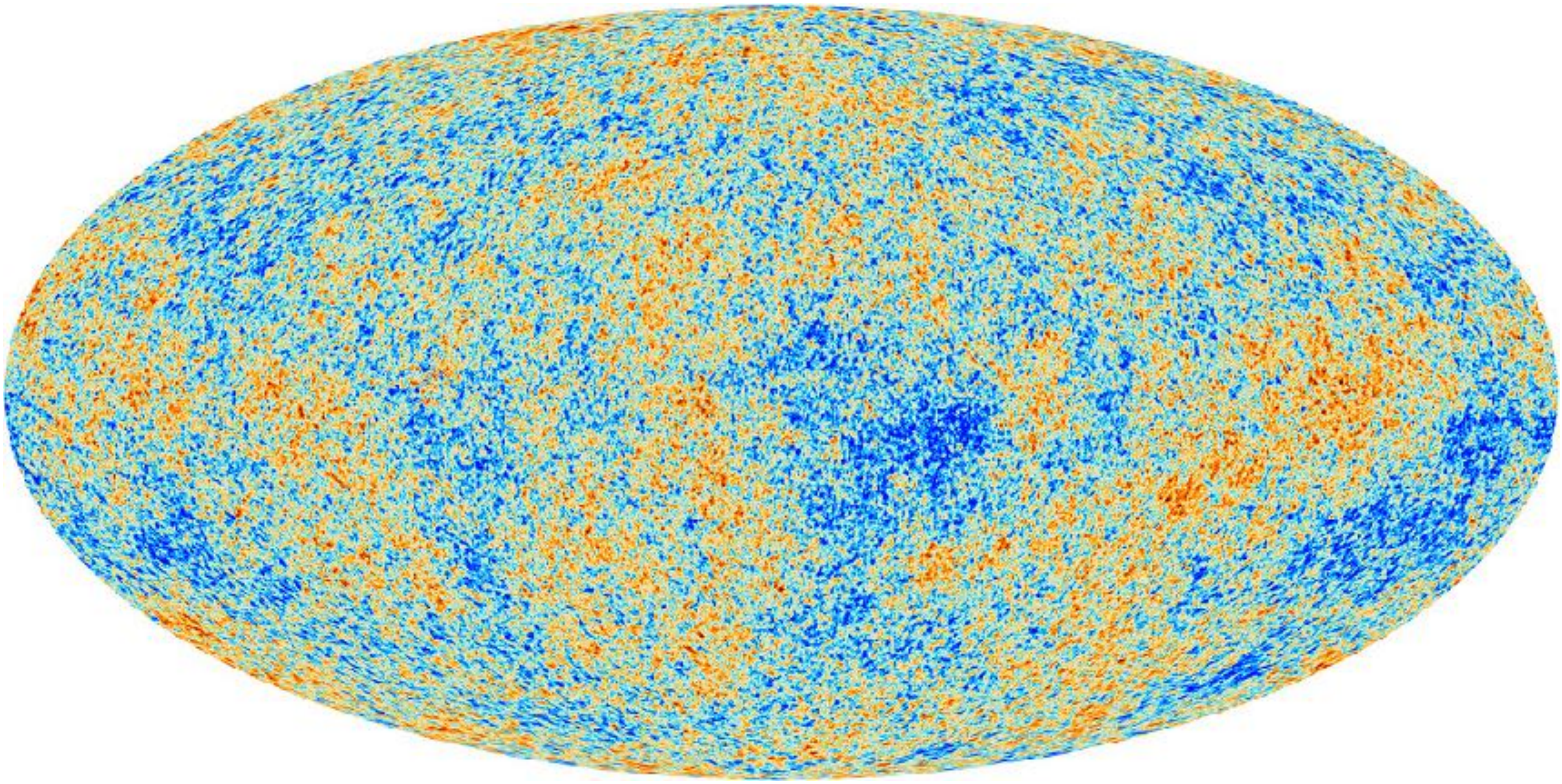
By P. A. M. Dirac, F.R.S.
St John's College, Cambridge

(*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) about every point, for an observer moving with the natural velocity at that point. 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.

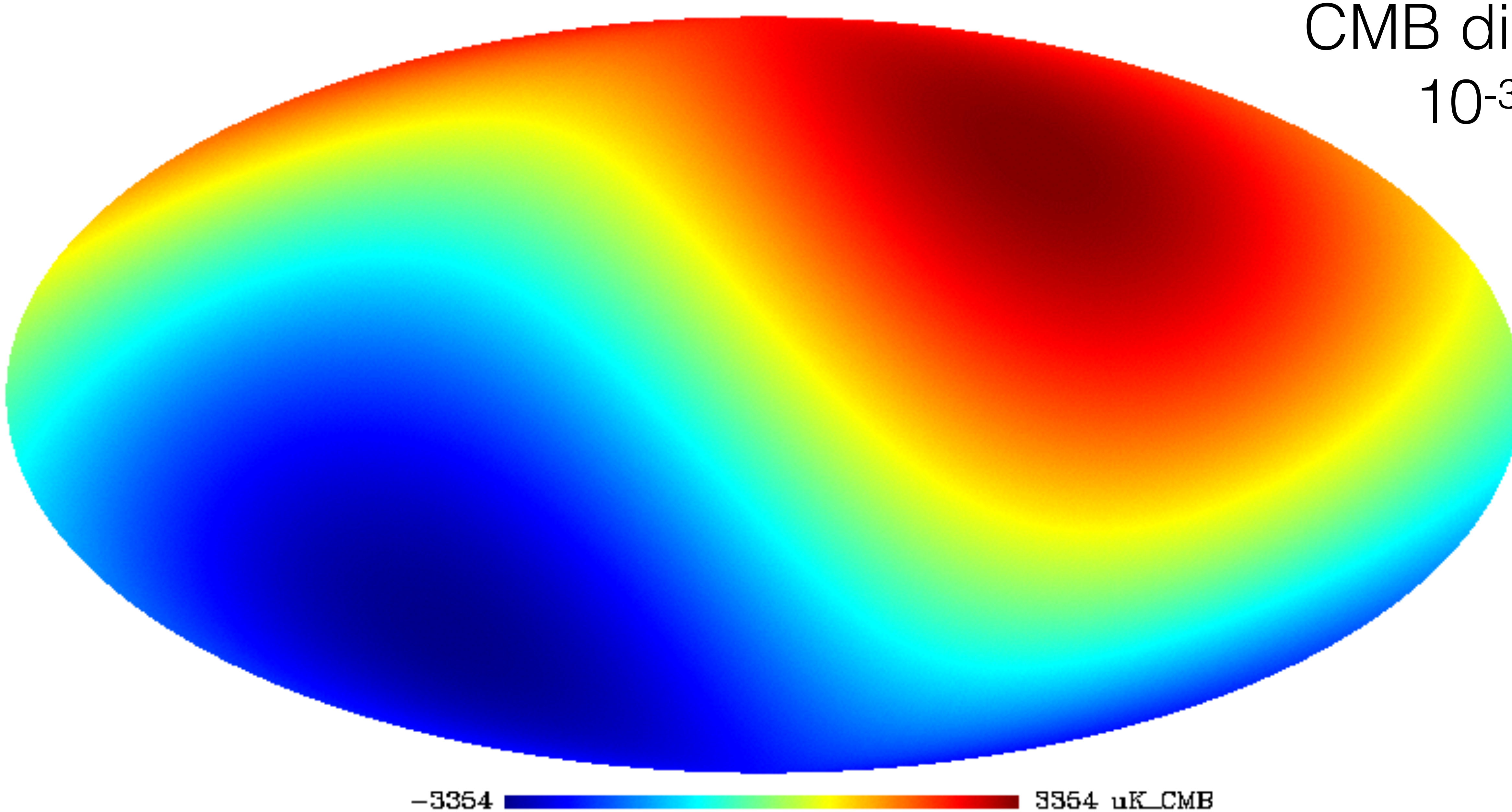
Observational evidence for the cosmological principle

Cosmic microwave background

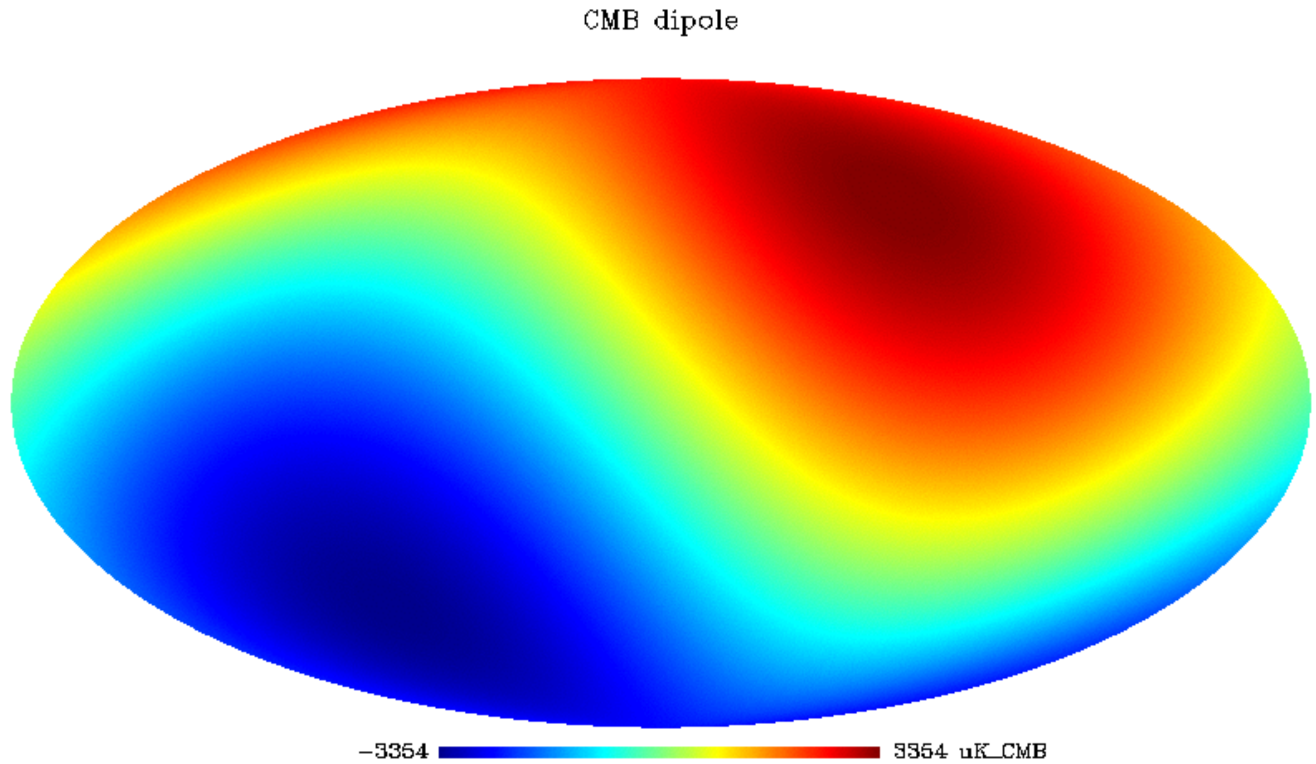


Cosmic microwave background
Dipole —-Anisotropy

CMB dipole
10^{-3}



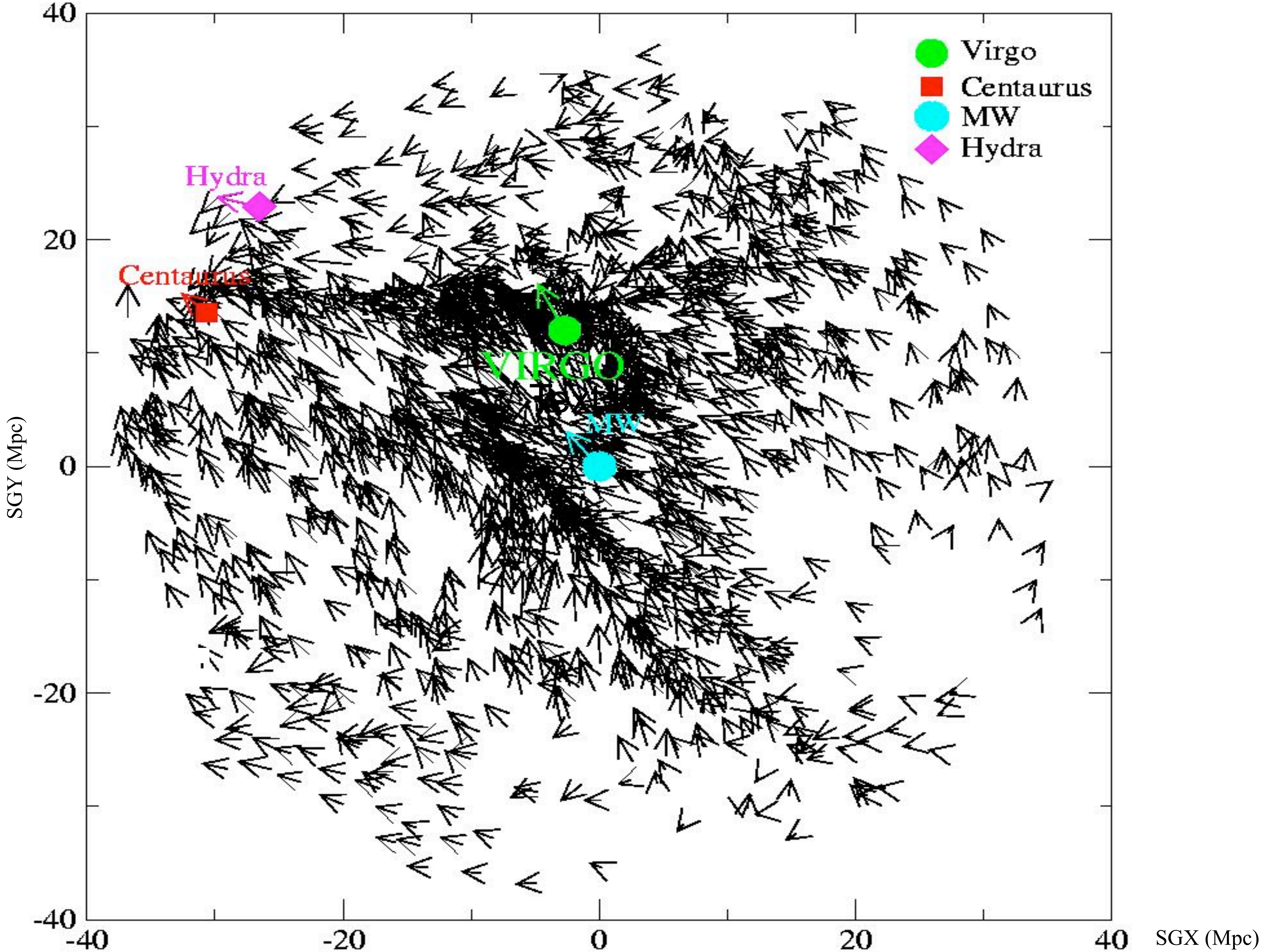
The origin of the CMB dipole ?



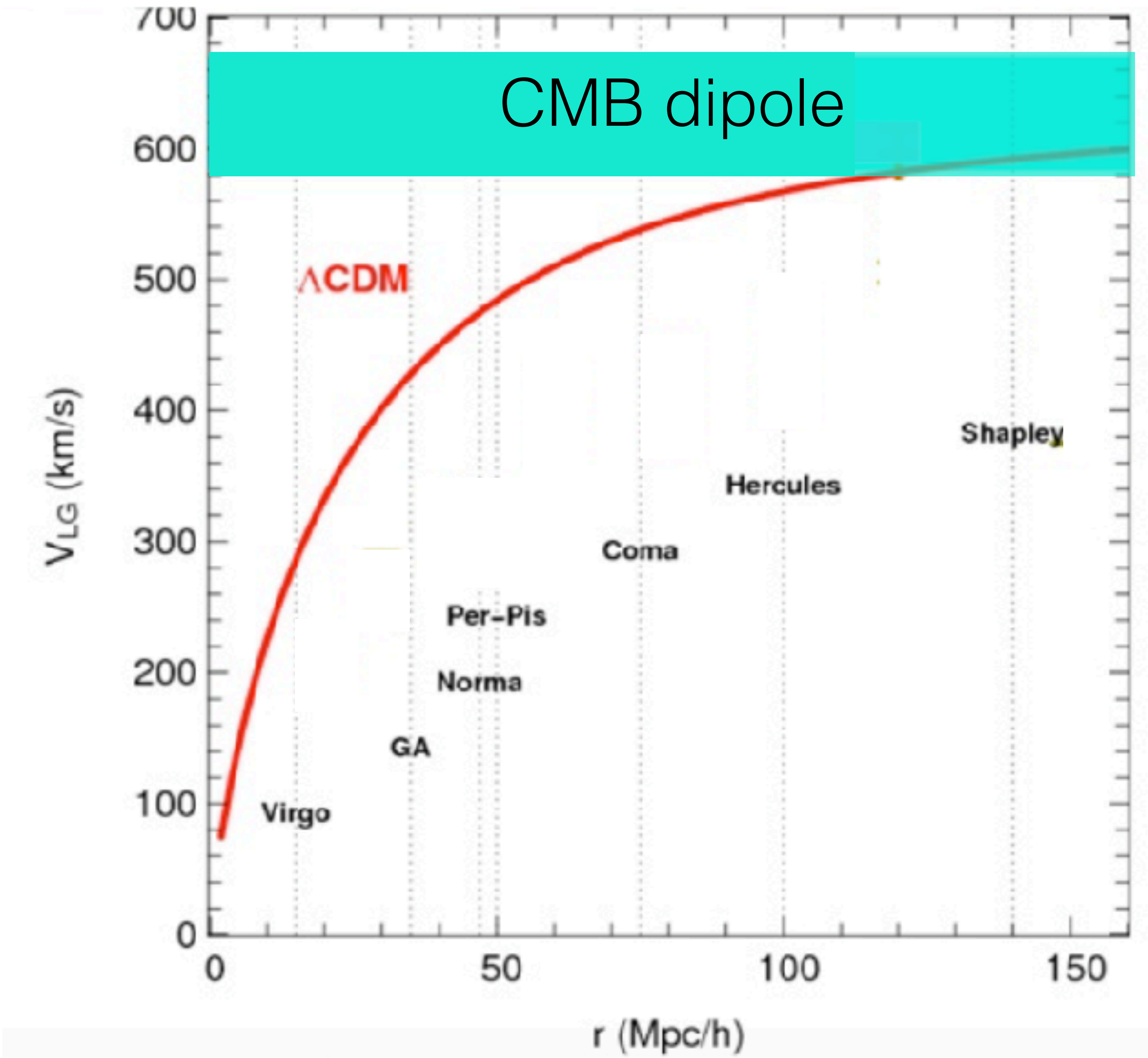
Dipole is purely Kinematic

Universe, at least up to a scale, must be anisotropic

Local Flow : origin of CMB dipôle



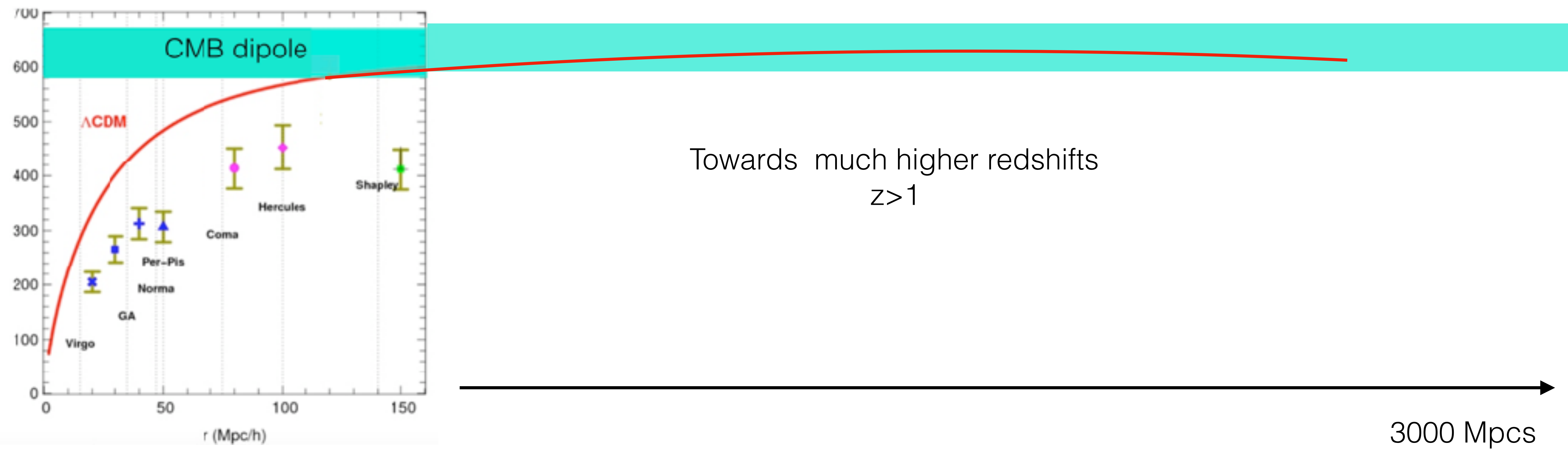
Test of cosmological principle : searching for CMB rest frame



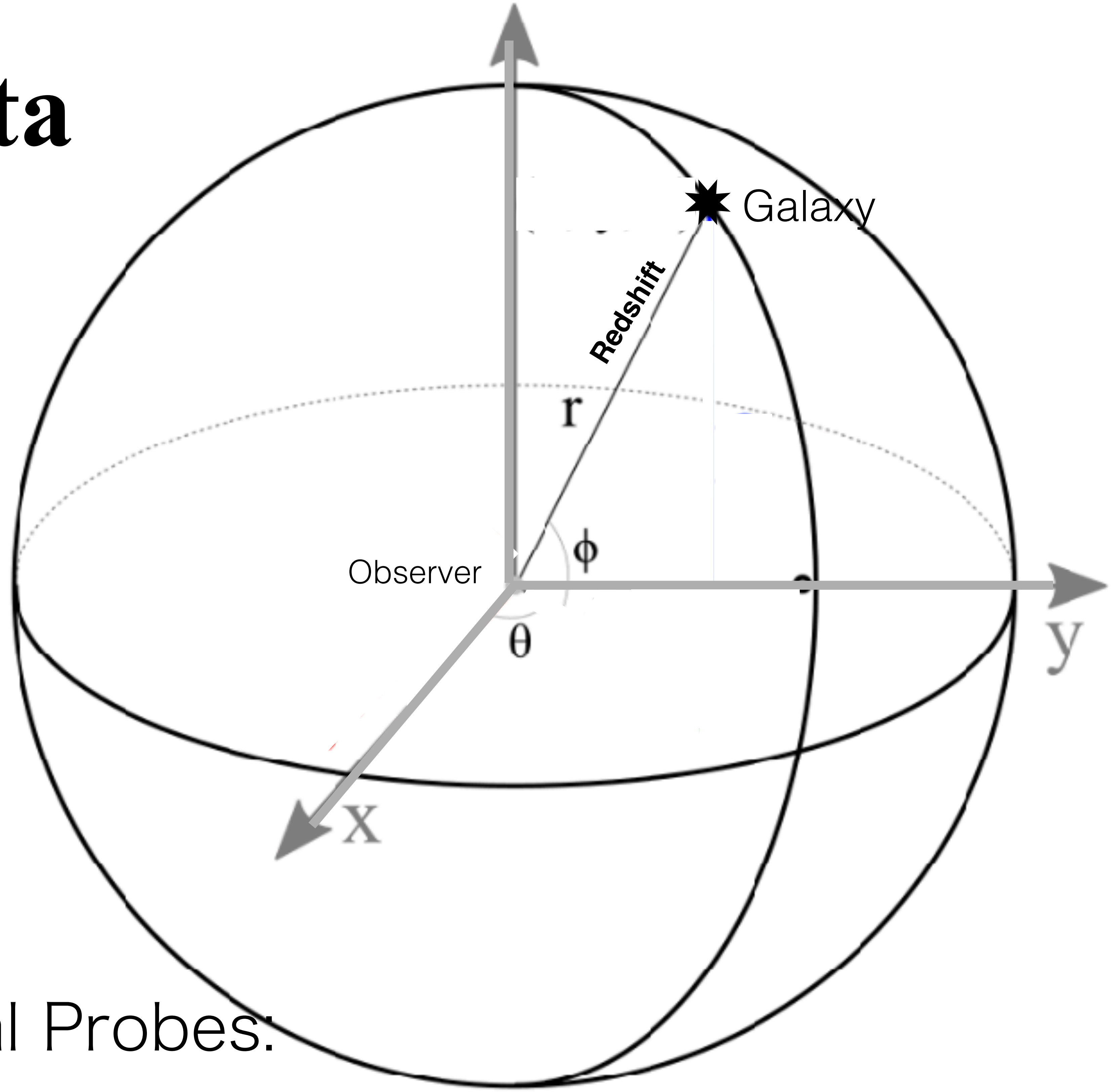
Dipole in the rest-frame of high redshift sources = Dipole in the CMB rest frame

Formulating the cosmological principle

The rest-frame of high redshift “sources” = Rest frame of CMB



Real Data



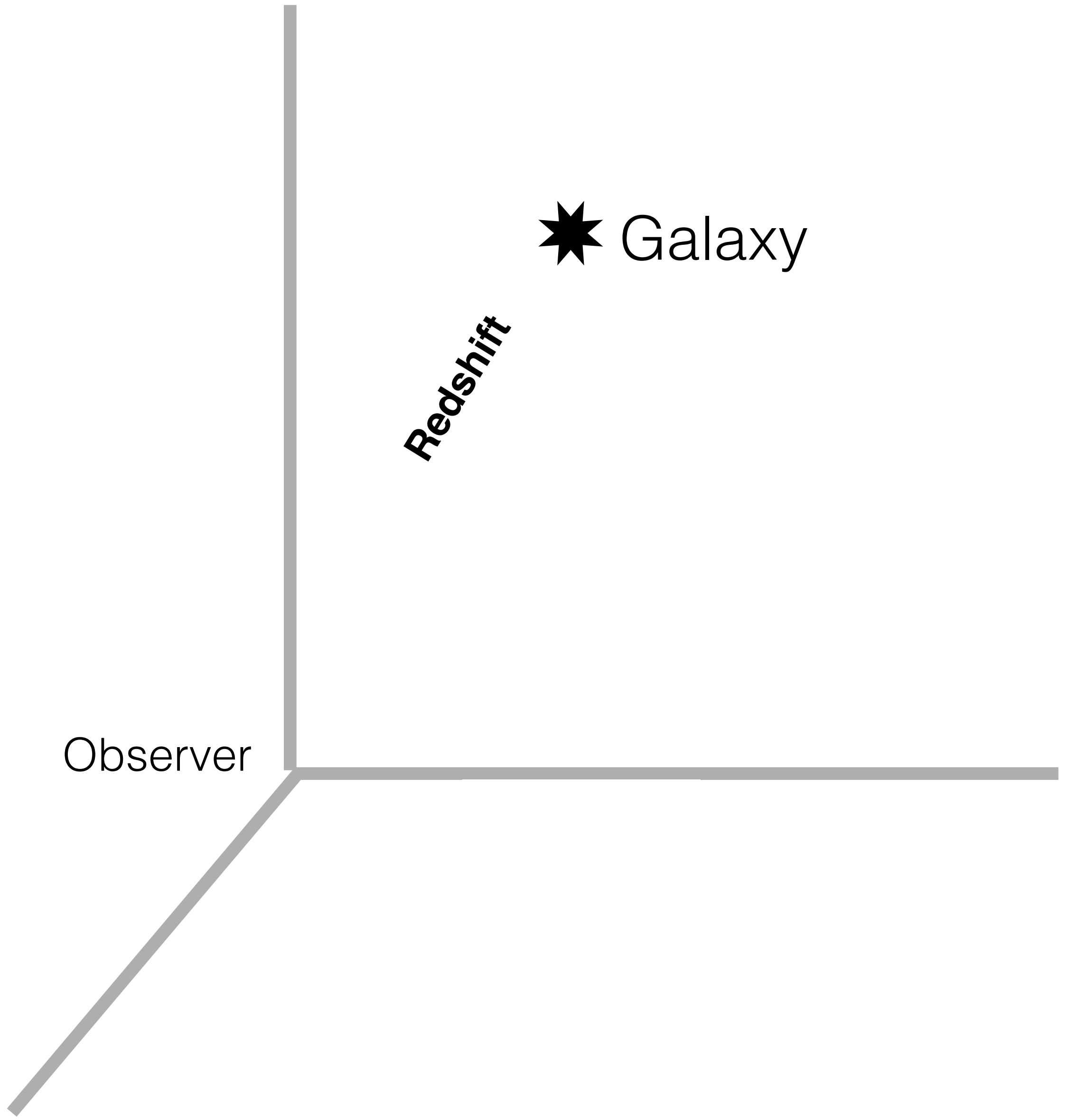
Observational Probes:

(I) Θ, φ, z, d (distance catalogues), Nearby

(II) Θ, φ, z (redshift surveys)

(III) Θ, φ (Imaging surveys), High redshift

Real Data



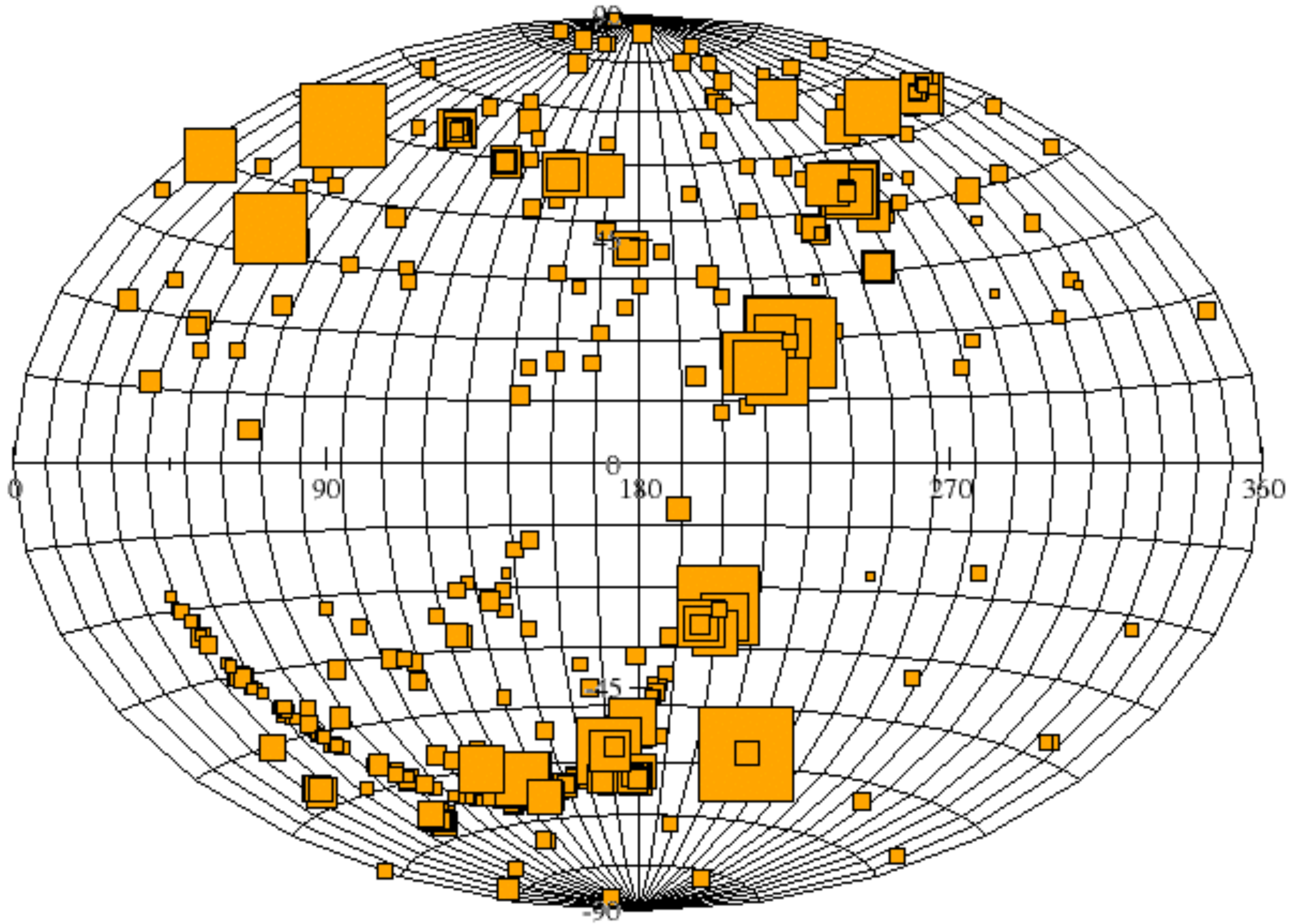
Observational Probes:

(I) Θ, φ, z, d (distance catalogues), Nearby

(II) Θ, φ, z (spectro surveys)

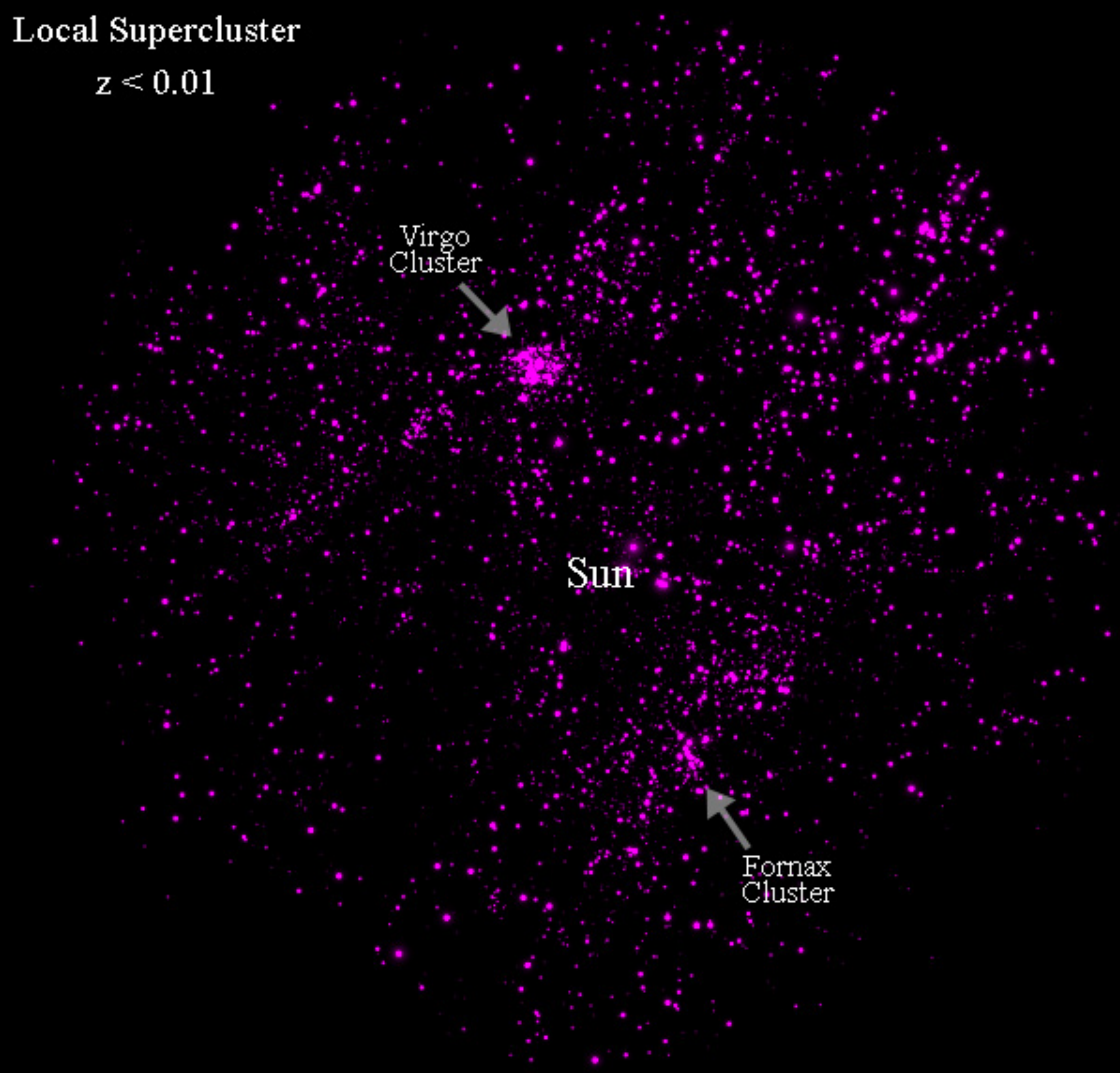
(III) Θ, φ (imaging surveys), High redshifts

Velocities (distances) from SNe Ia
Union II, JLA compilation

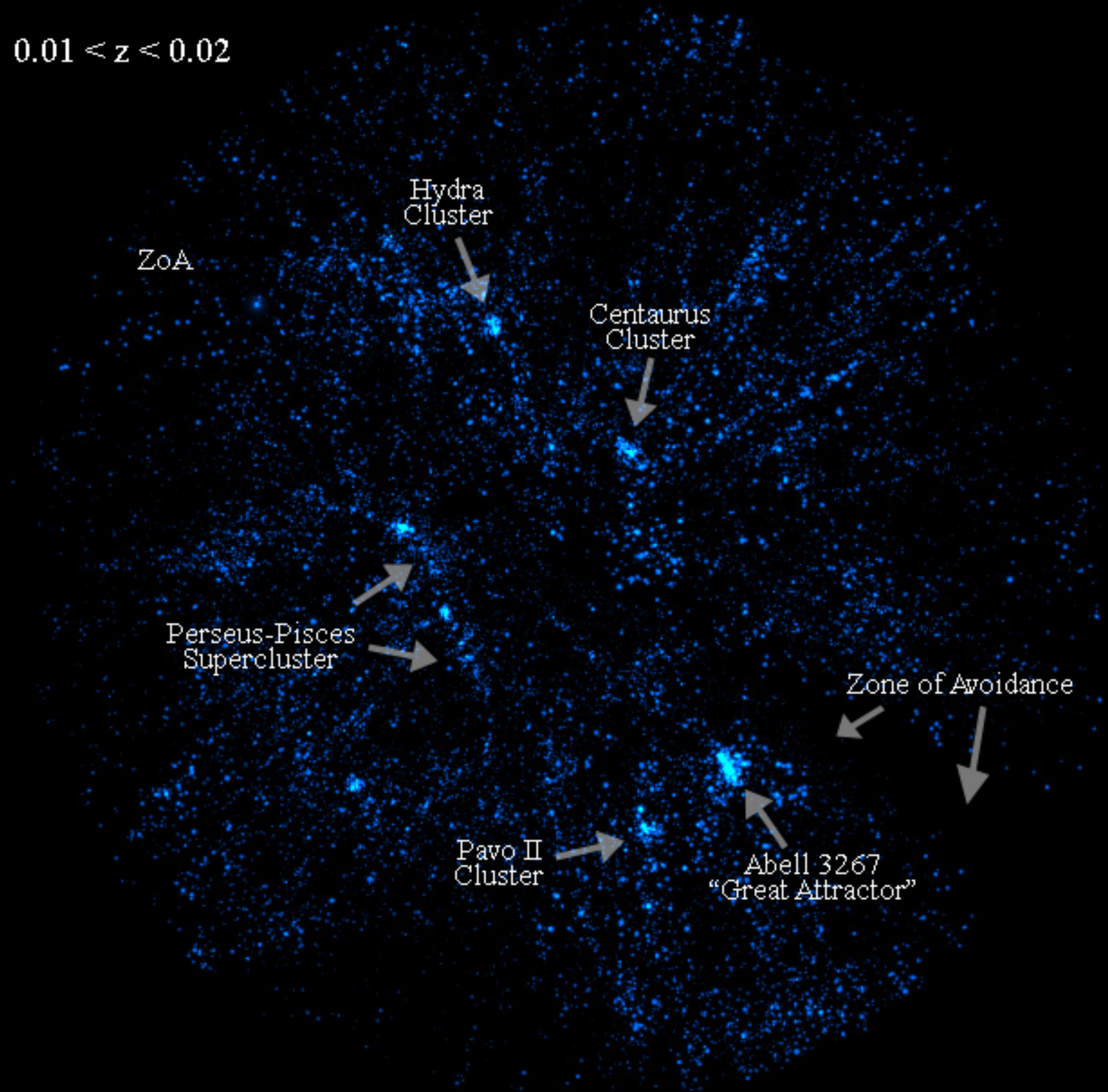


Colin, Mohayaee, Shafieloo, Sarkar, MNRAS 2012
Colin, Mohayaee, Rameez, Sarkar, A&A 2019

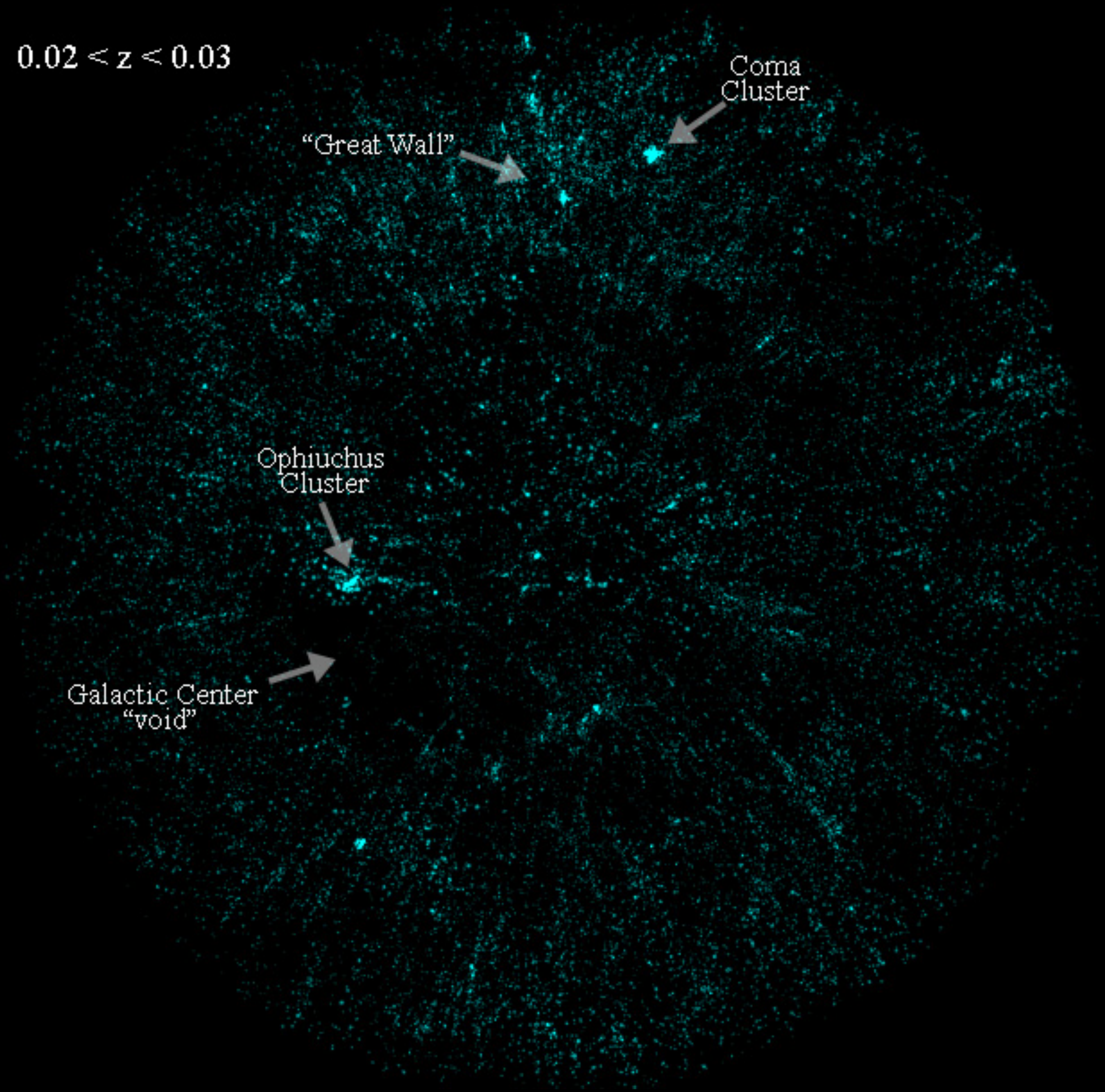
Bulk flow of increasingly volume: CMB rest frame ?



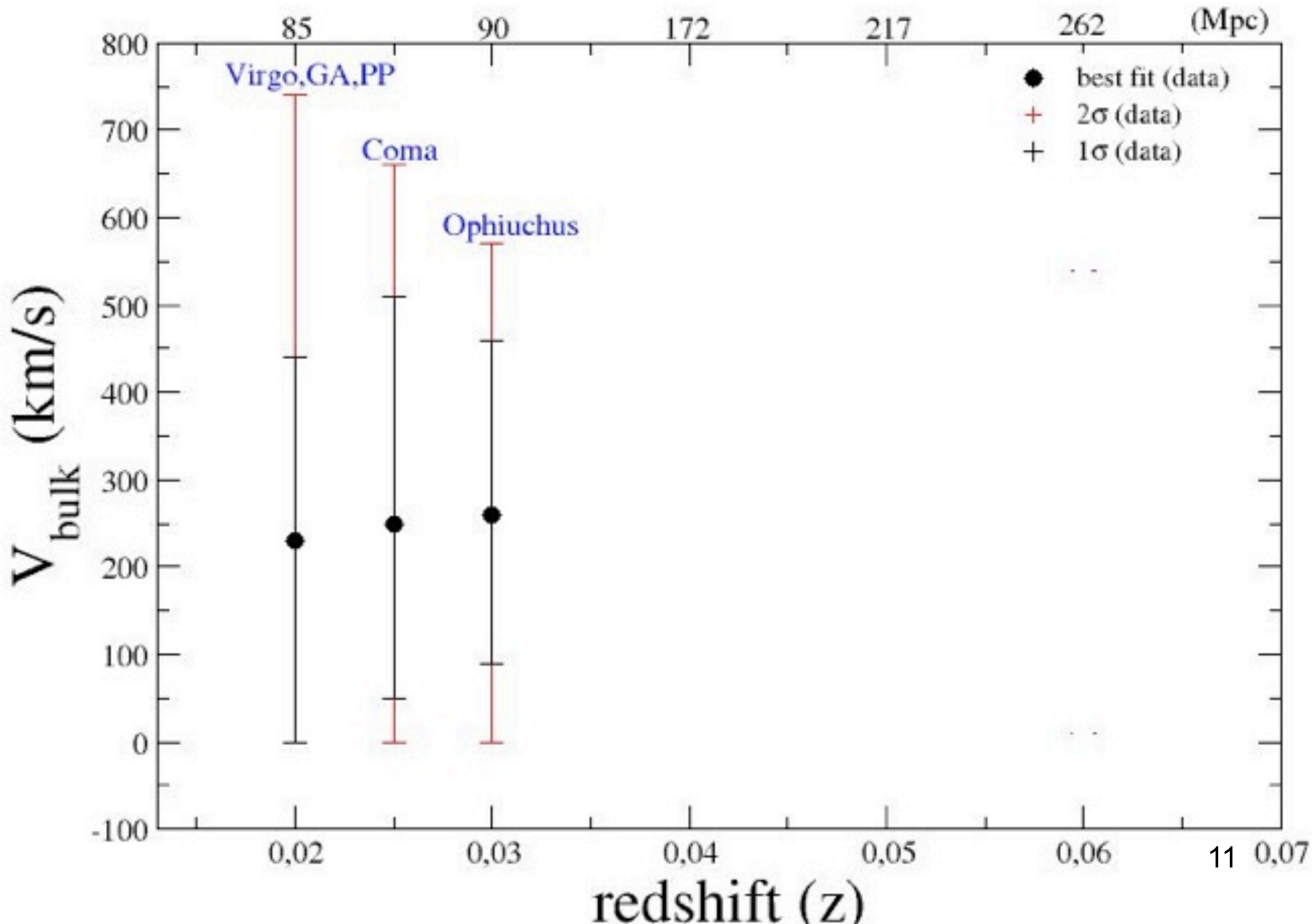
Bulk flow of increasingly larger volume: CMB rest frame ?

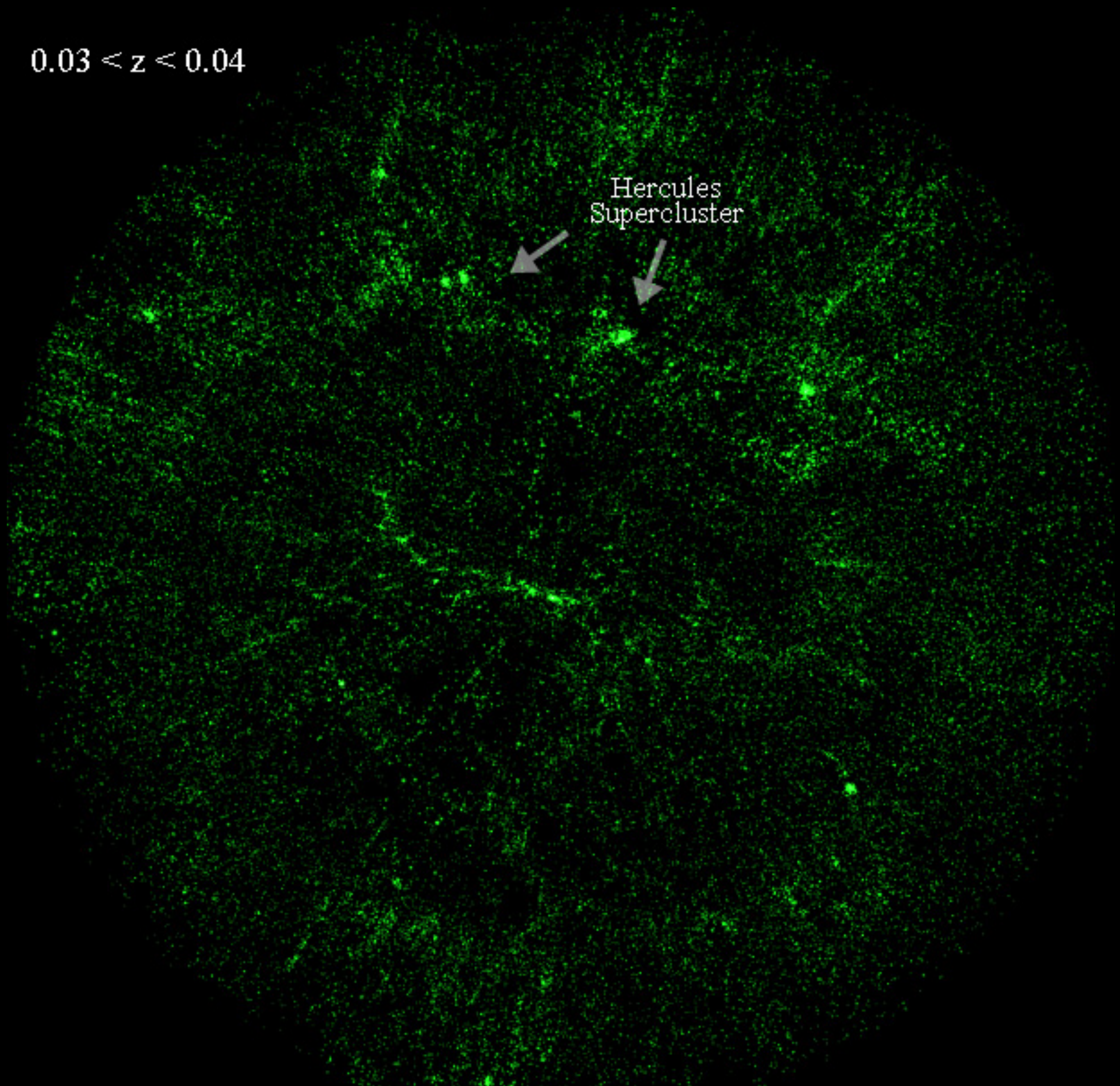


Bulk flow of increasingly larger volume: CMB rest frame ?

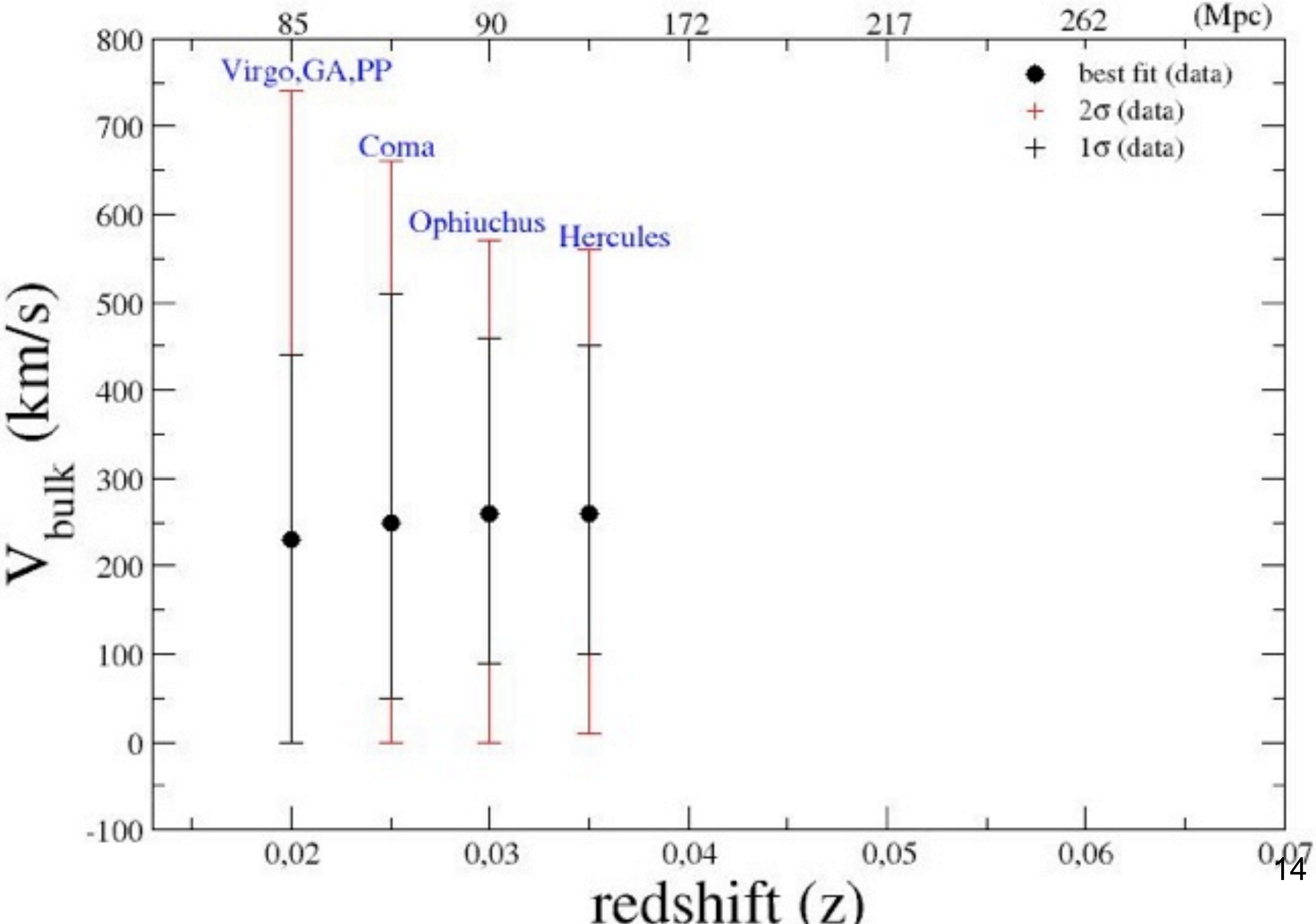


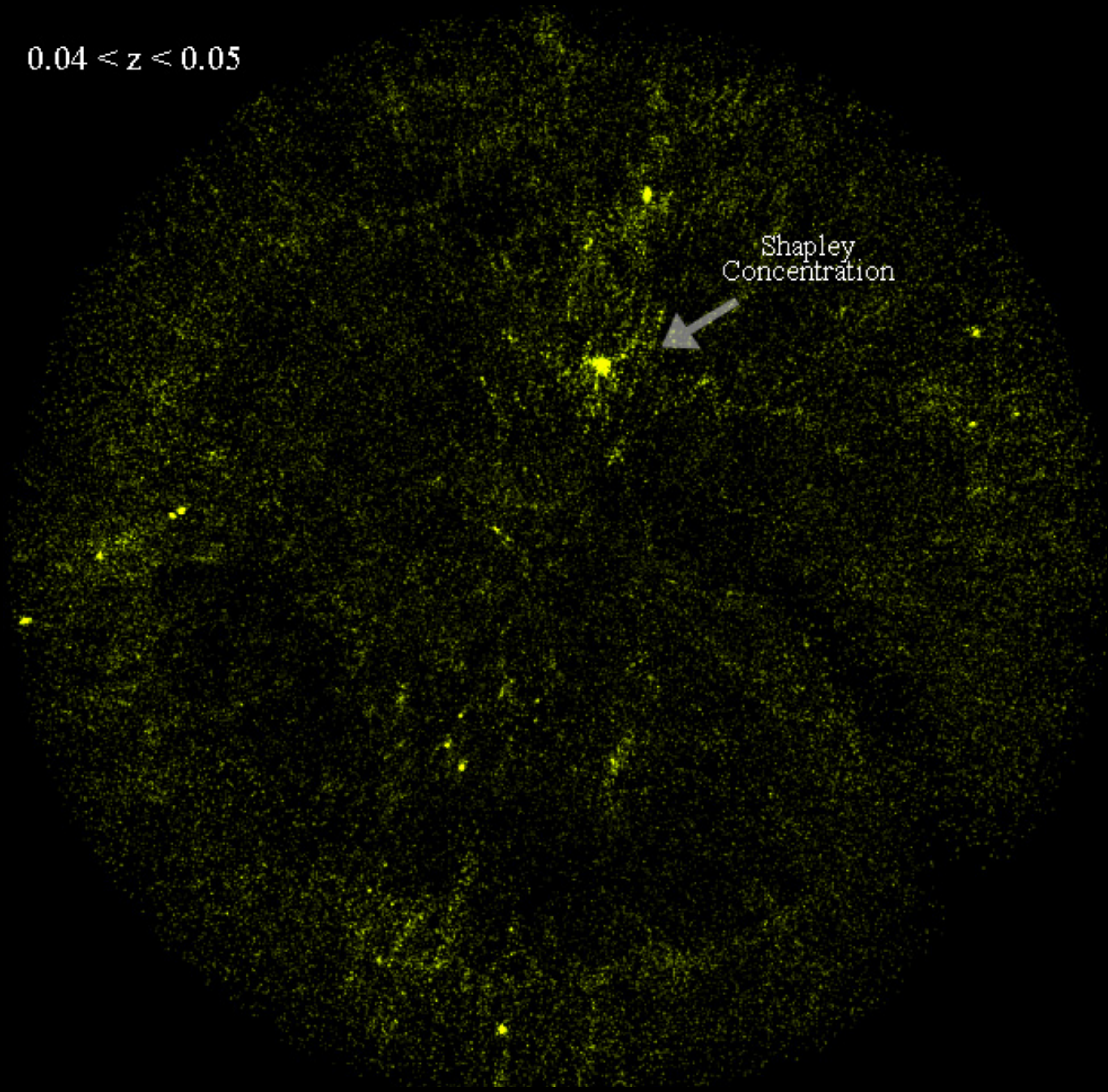
Bulk flow from SNe Ia data



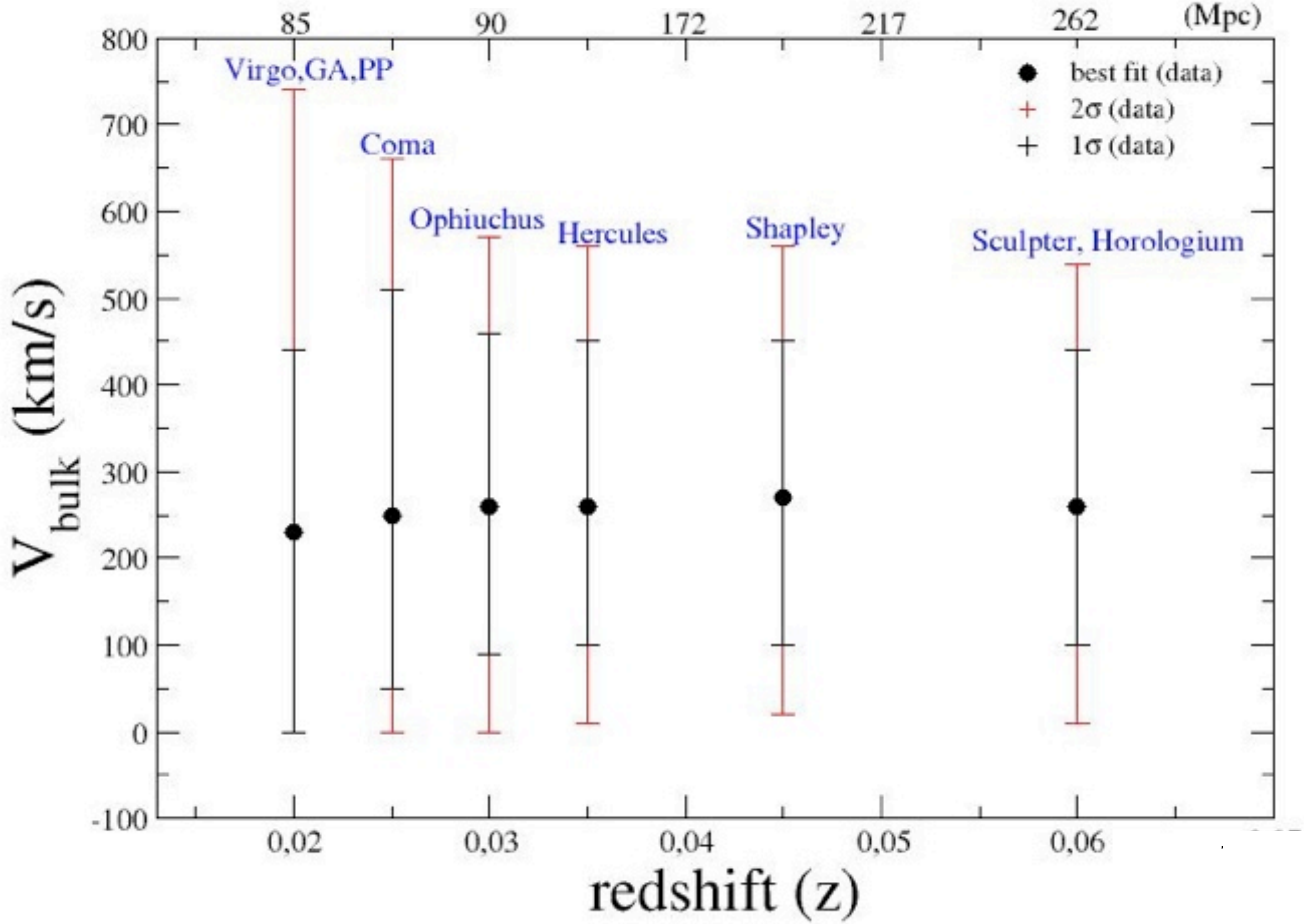

0.03 < z < 0.04
Hercules
Supercluster

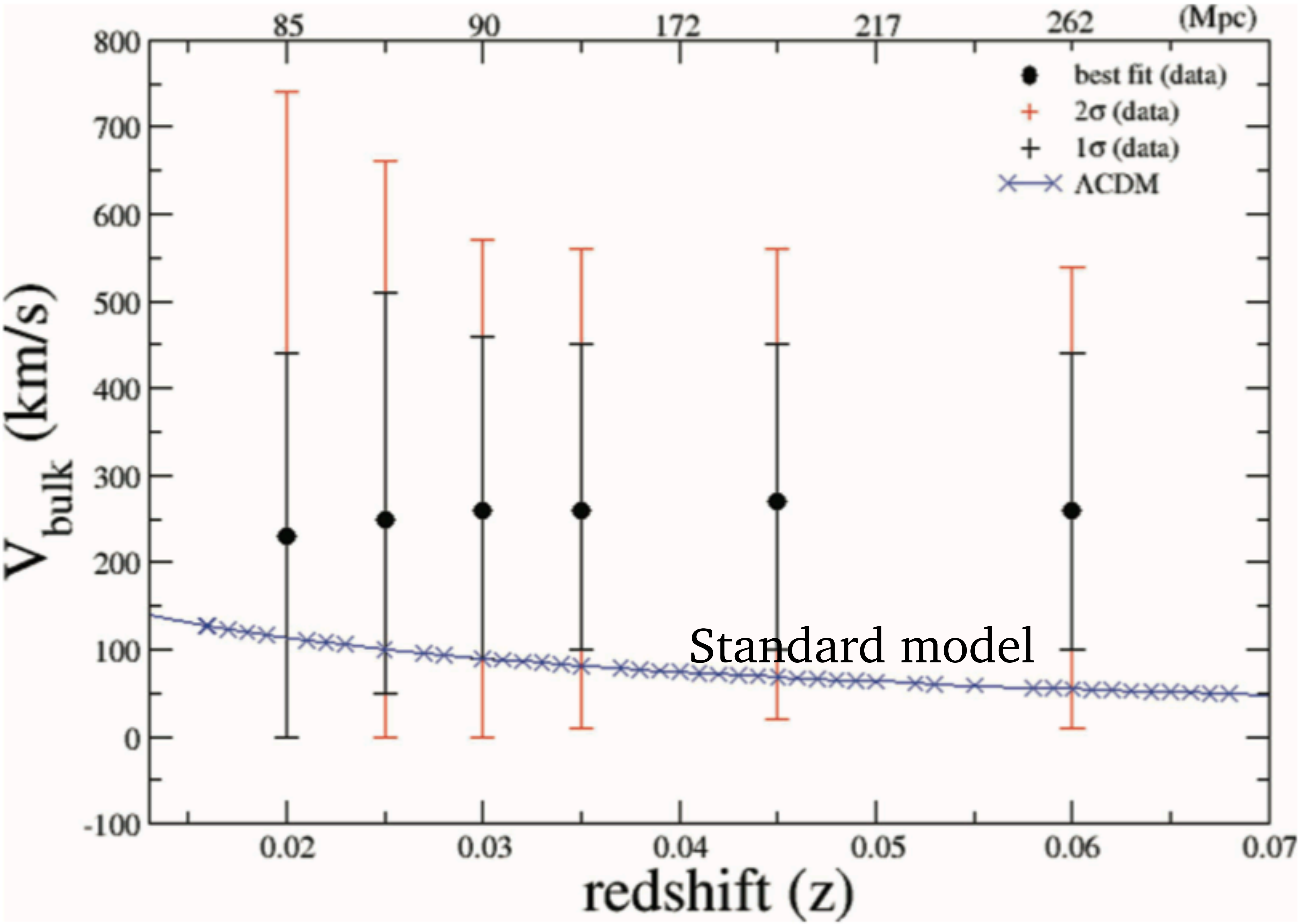
Bulk flow from SNe Ia data




0.04 < z < 0.05
Shapley
Concentration

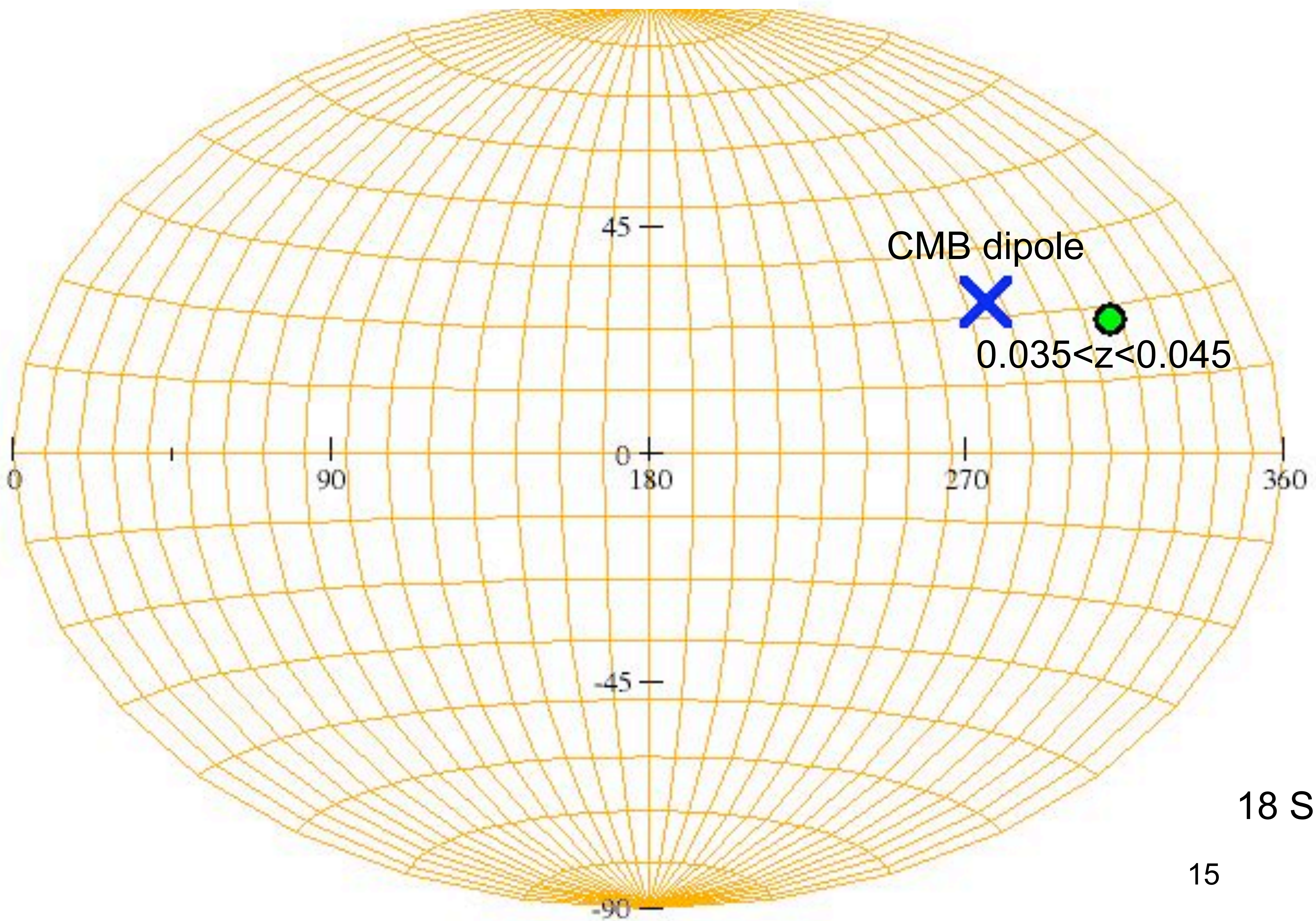
Bulk flow from SNe Ia data





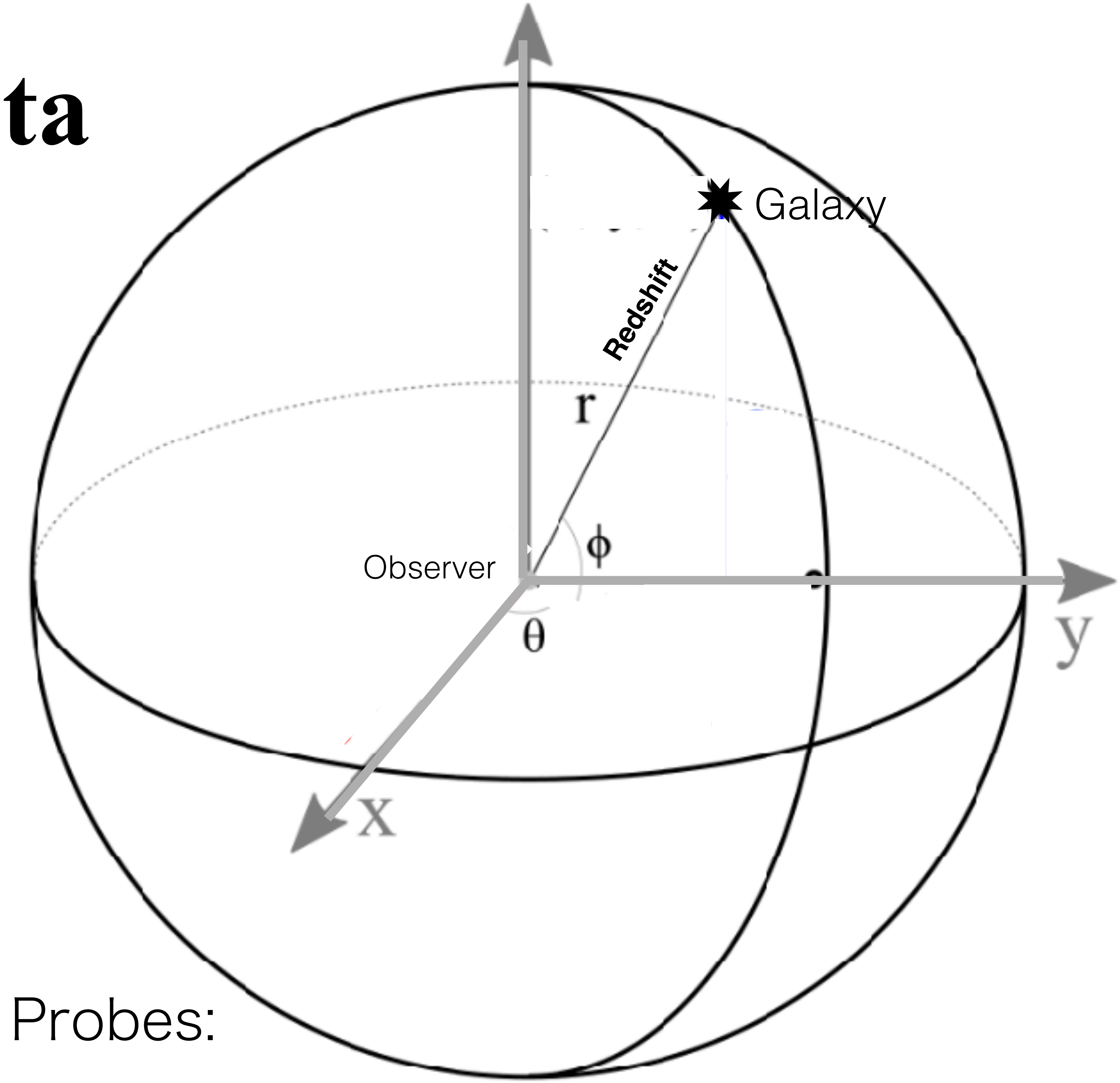
85
90
172
217
262
(Mpc)
800
700
600
500
400
300
200
100
0
-100
V_{bulk} (km/s)
best fit (data)
2σ (data)
1σ (data)
ΛCDM
Standard model
0.02
0.03
0.04
0.05
0.06
0.07
redshift (z)

Bulk flow direction from data



18 SNe

Real Data



Observational Probes:

(I) Θ, φ, z, d (SNe Ia ··· catalogues), Nearby

(II) Θ, φ, z (redshift catalogues)

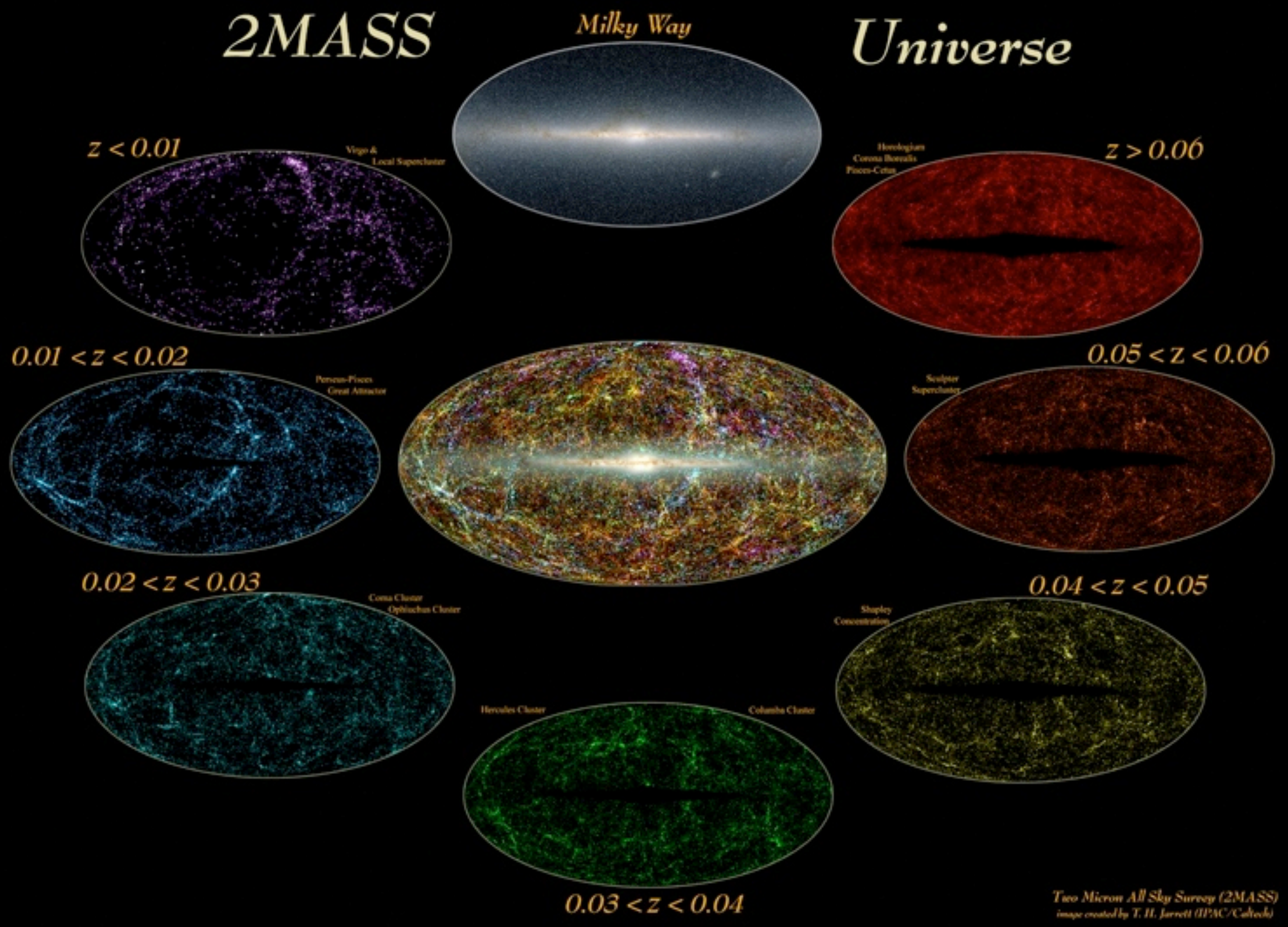
(III) Θ, φ (photometric catalogues), High redshift

2MRS redshift survey

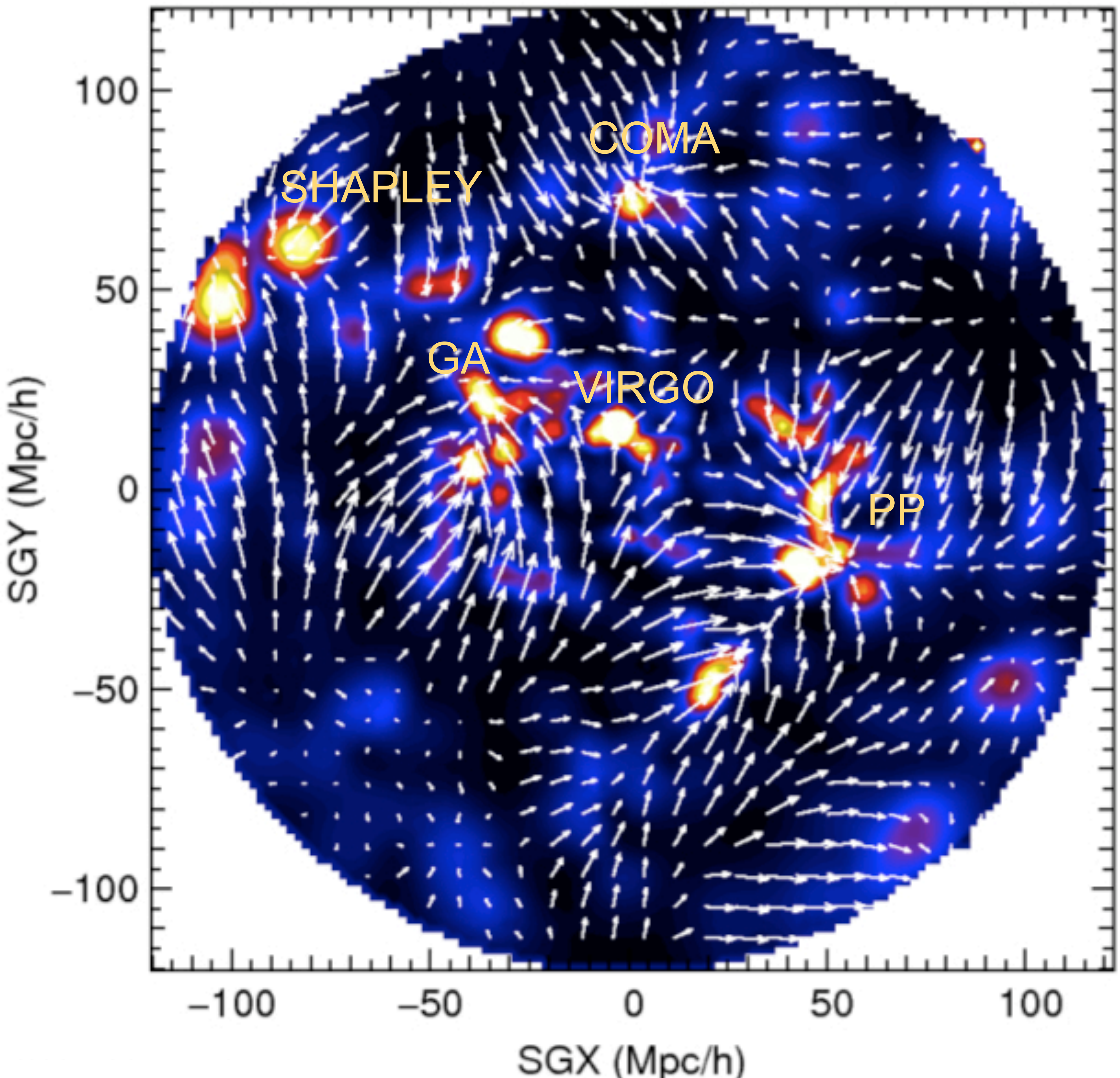
(Huchra etal 2005,...)

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)

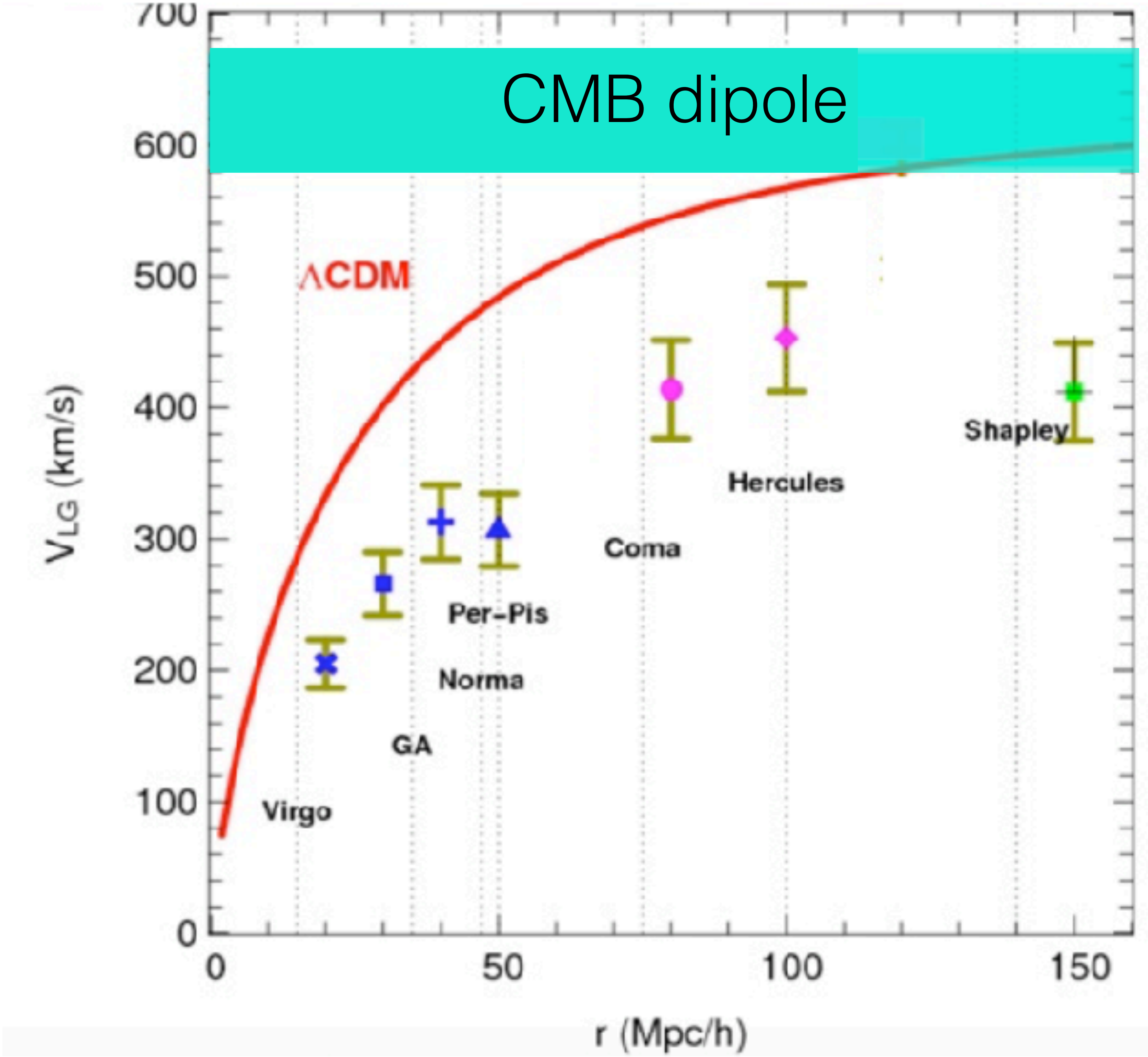


Velocity field of 2MRS: from great attractor to Shapley infall



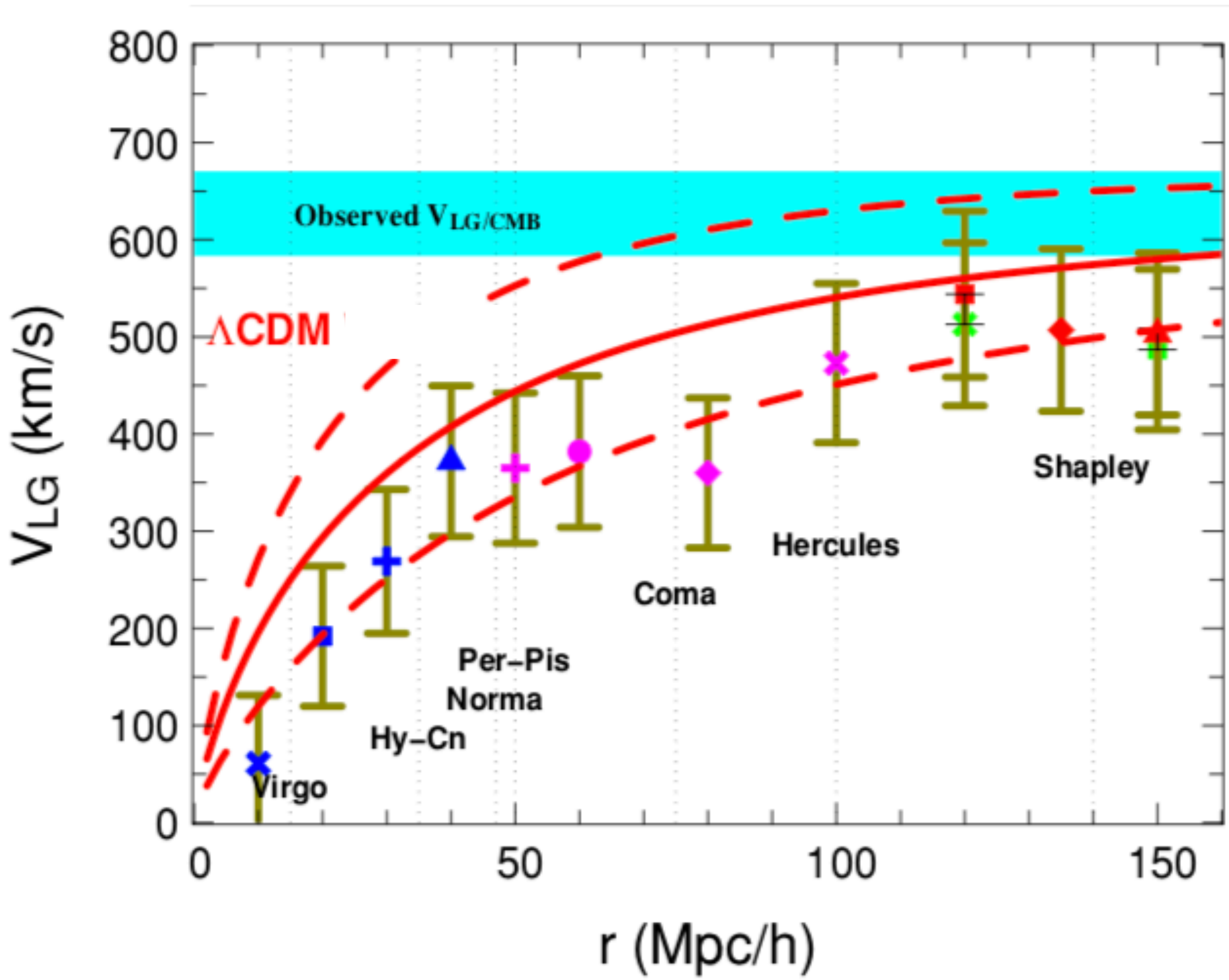
Reconstruction uses Optimal Transport techniques

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



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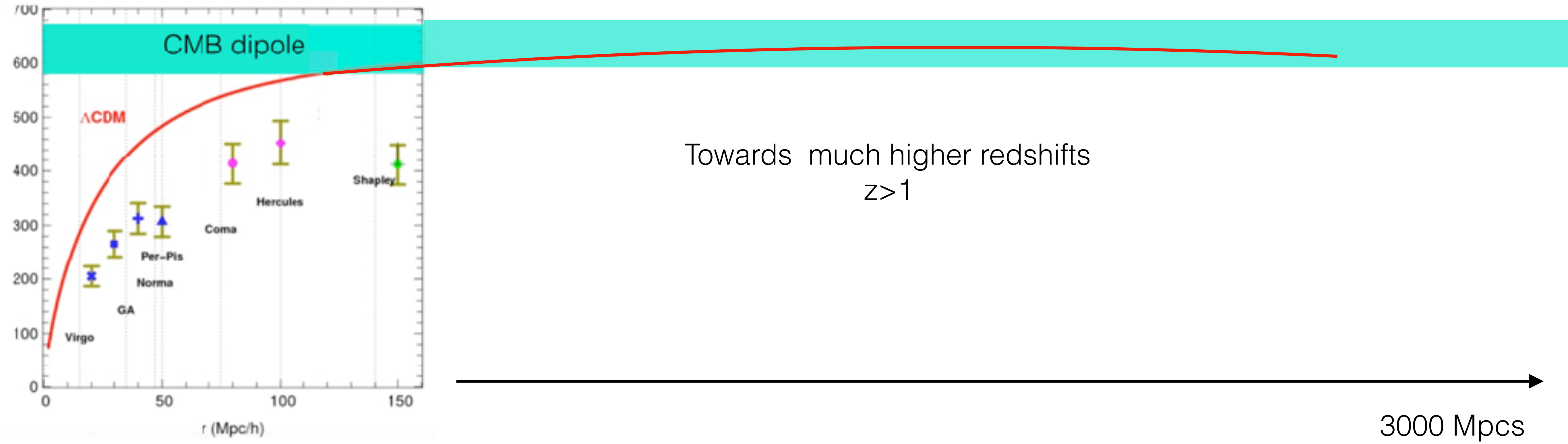
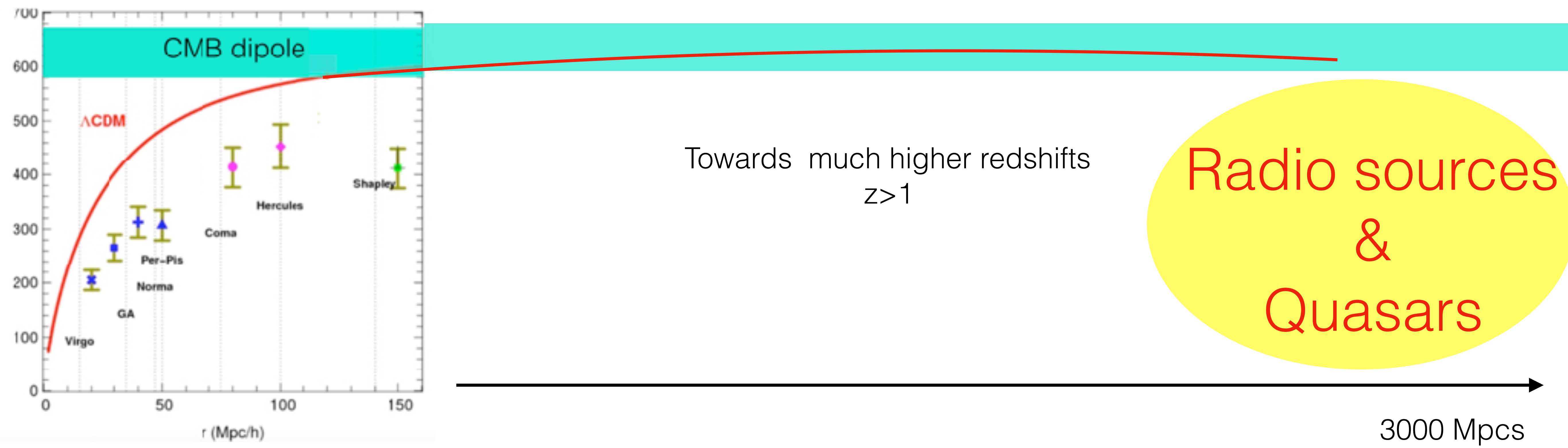


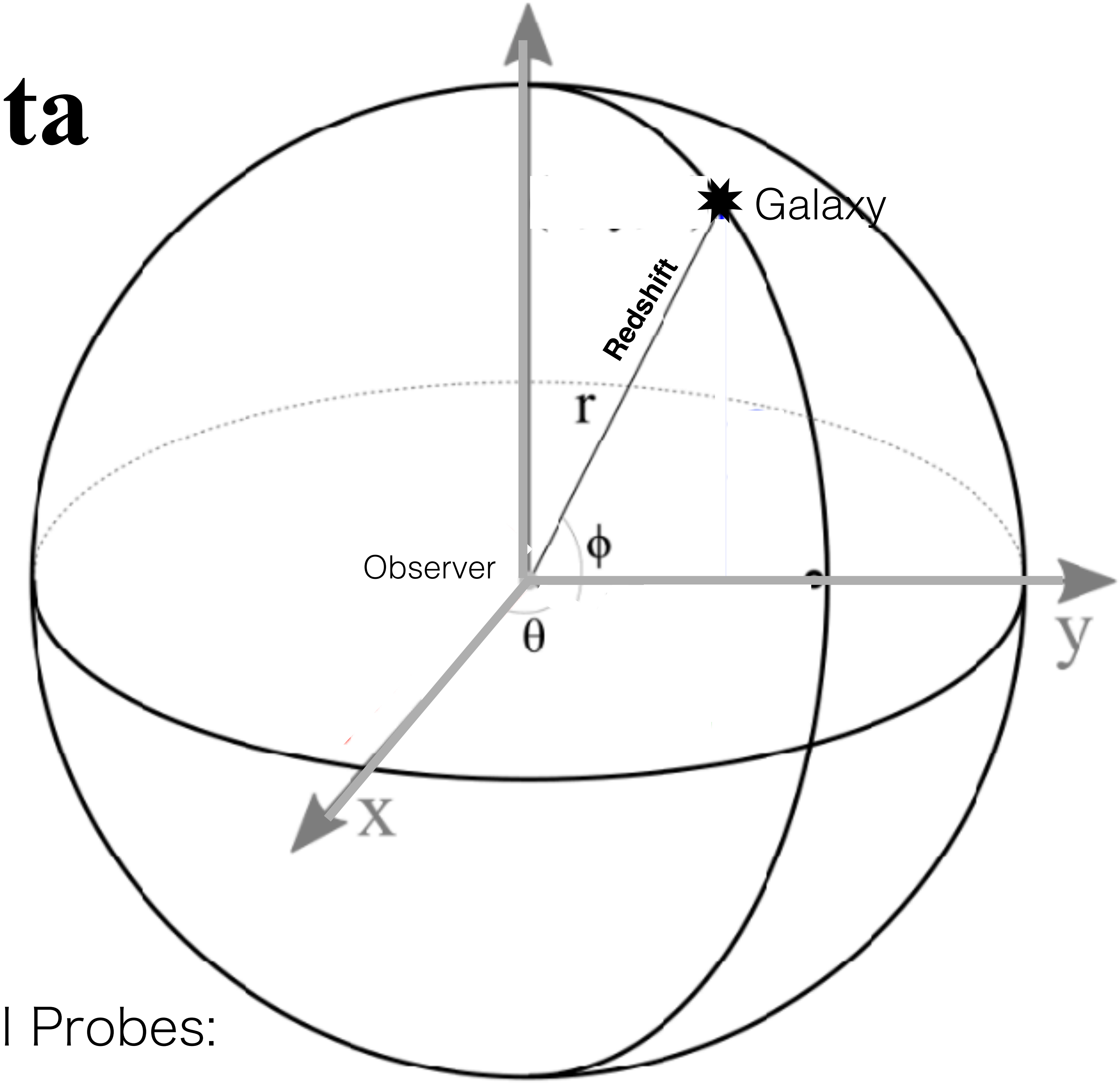
Cosmological principle:
rest-frame of high redshift “sources” = CMB rest frame

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), Nearby

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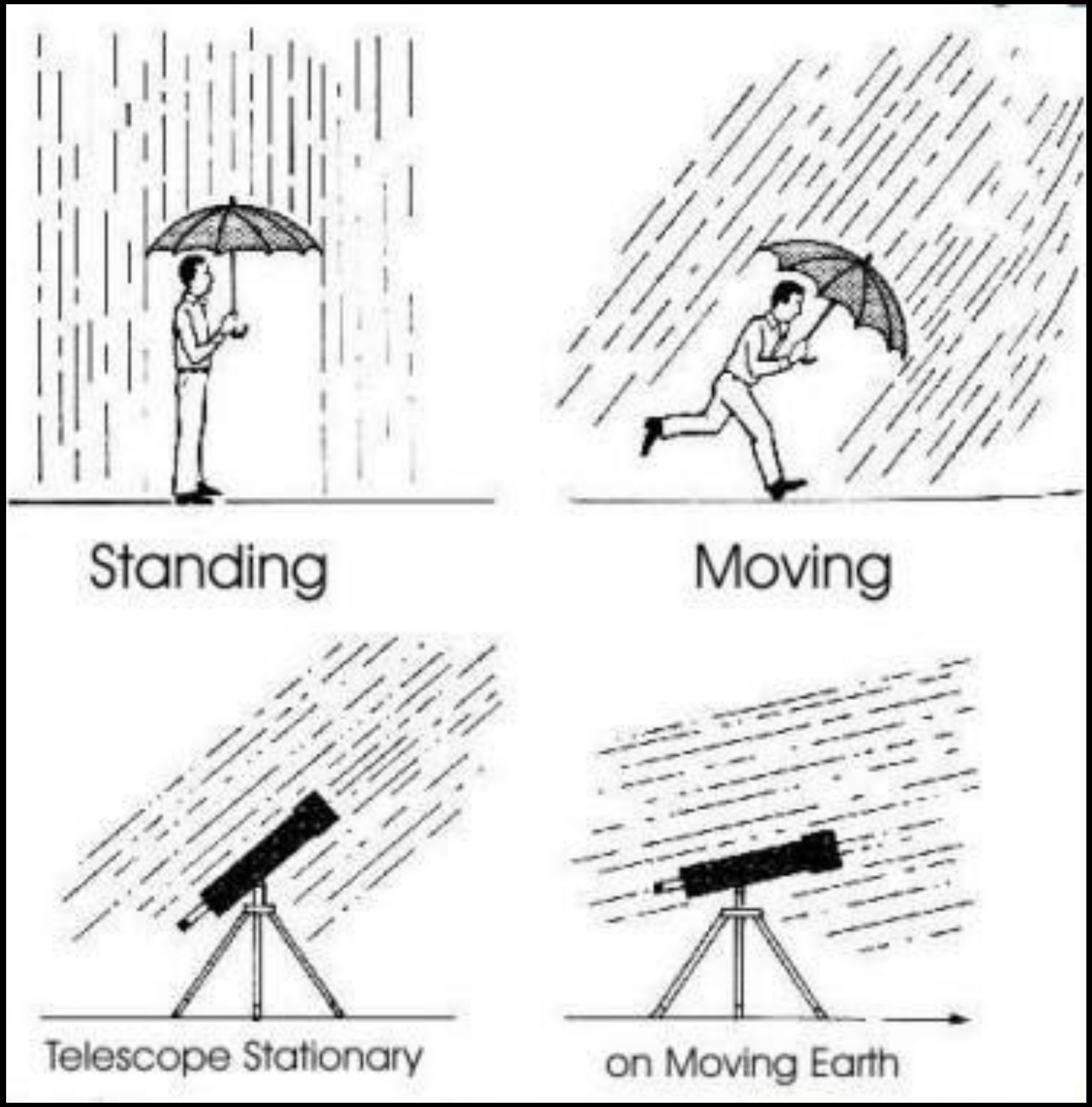
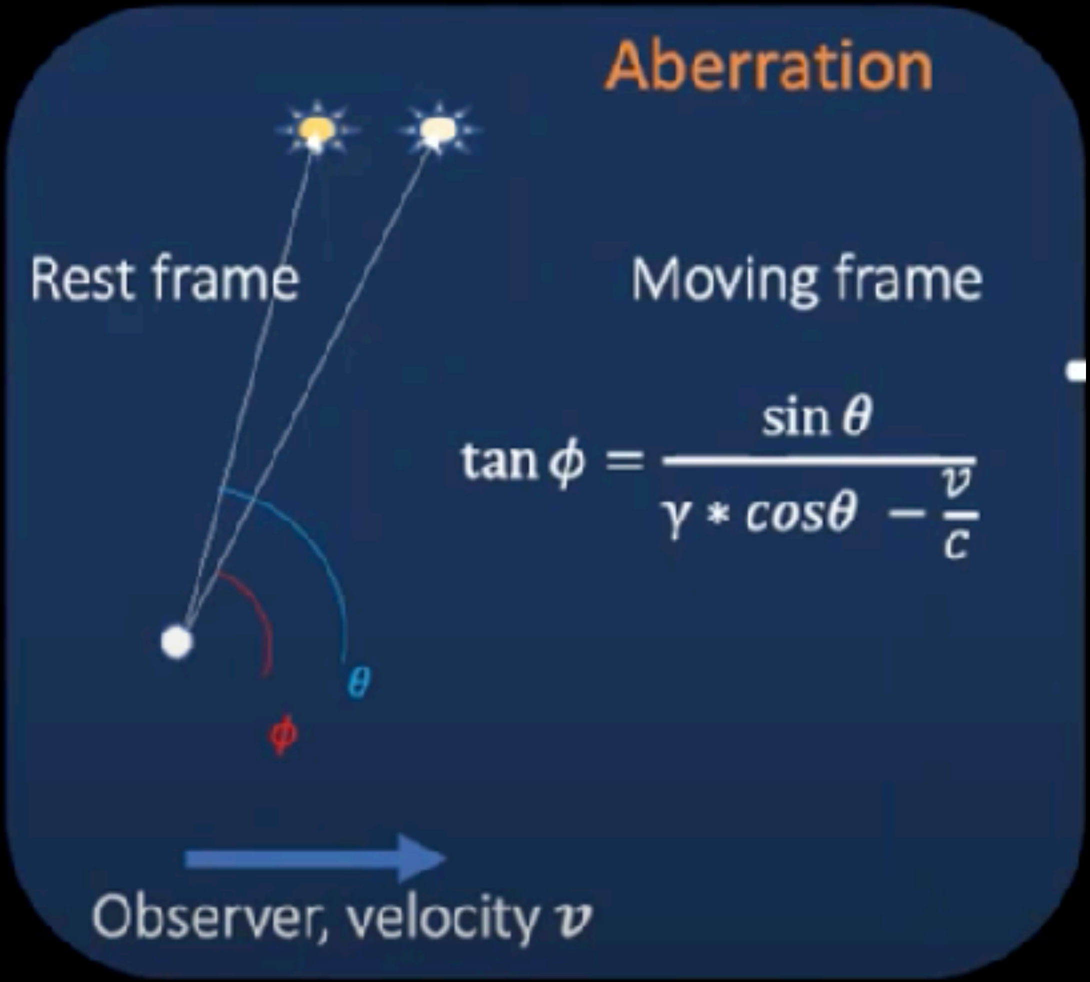
(III) Θ, φ (Imaging surveys), high redshift

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



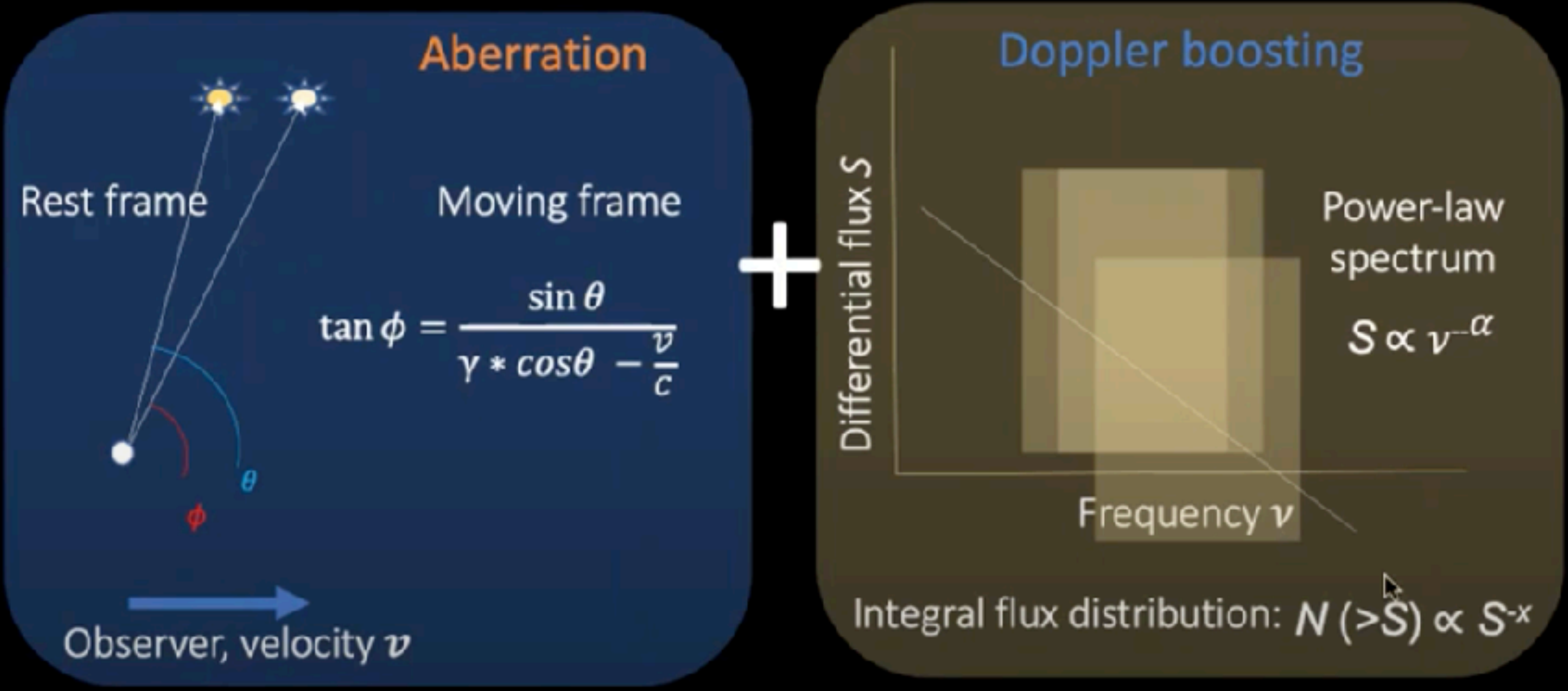
Colin, Mohayaee, Rameez,Sarkar, MNRAS 2017
Rameez, Mohayaee, Sarkar,Colin, MNRAS 2018
Colin, Mohayaee, Rameez,Sarkar, MNRAS 2019
Mohayaee, Rameez, Sarkar, 2020
Secrest, von Hausegger, Rameez, Mohayaee, Sarkar, Colin …, 2021

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

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

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

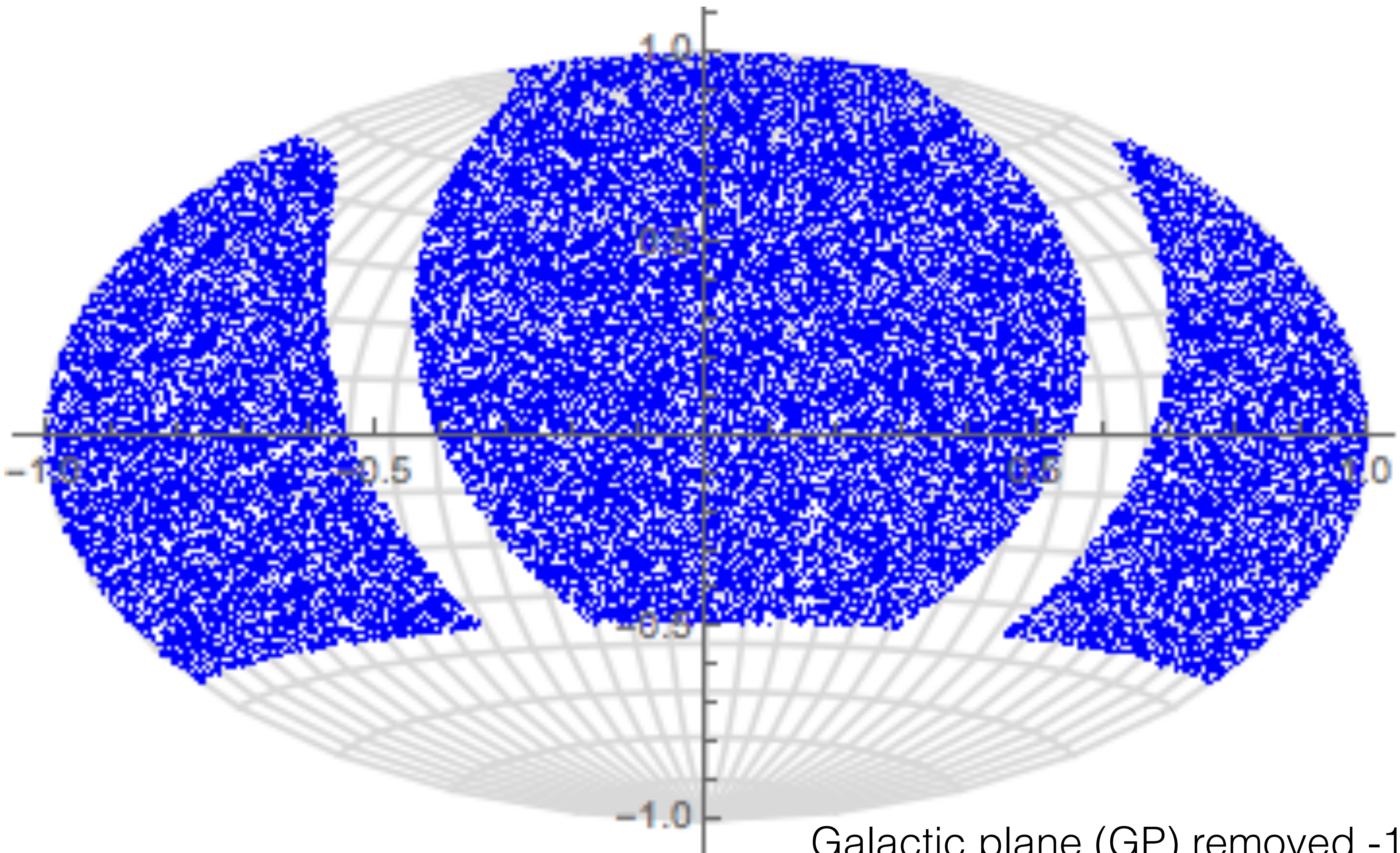
$$S_\nu \propto \nu^{-\alpha}$$

Independent of distance to the source

DATA: NRAO VLA Sky Survey Catalogue (NVSS)

1773488 Radio galaxies

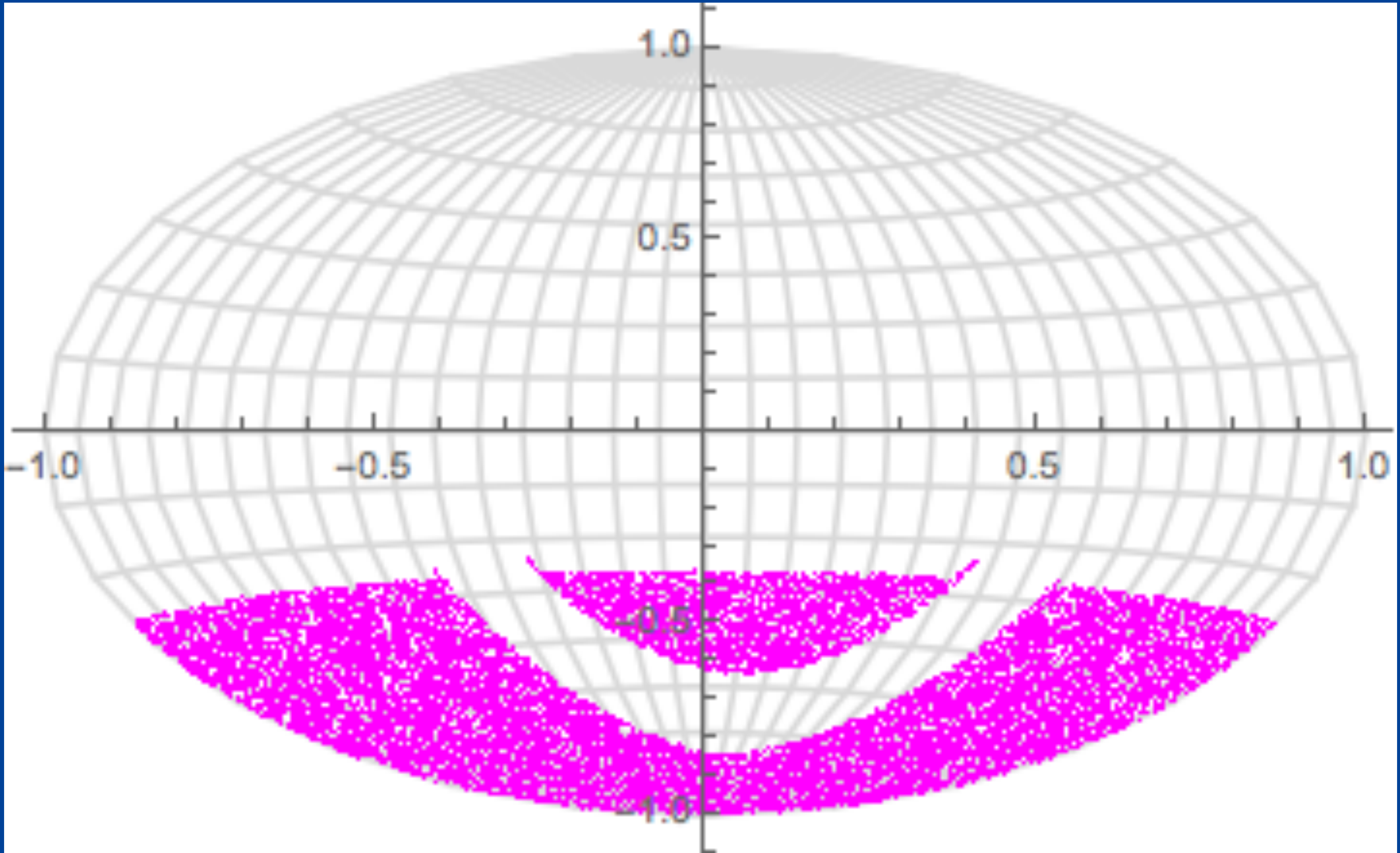
583587 Radio galaxies in 10 mjy <Flux< 1000 mjy



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

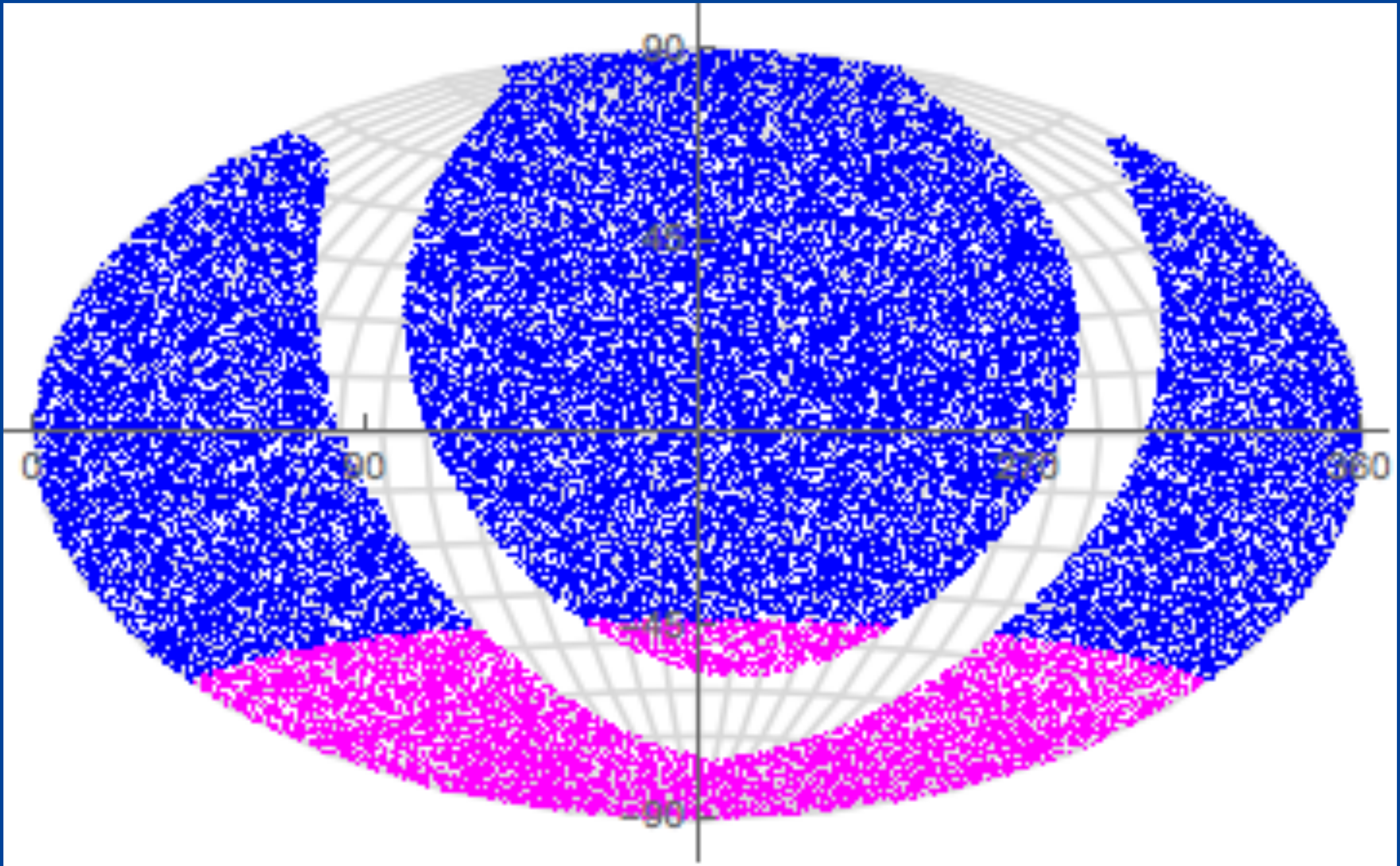
DATA: The Sydney University Molonglo Sky Survey SUMSS

211050 Radio galaxies
183720 Radio galaxies in 10 mjy <Flux< 1000 mjy



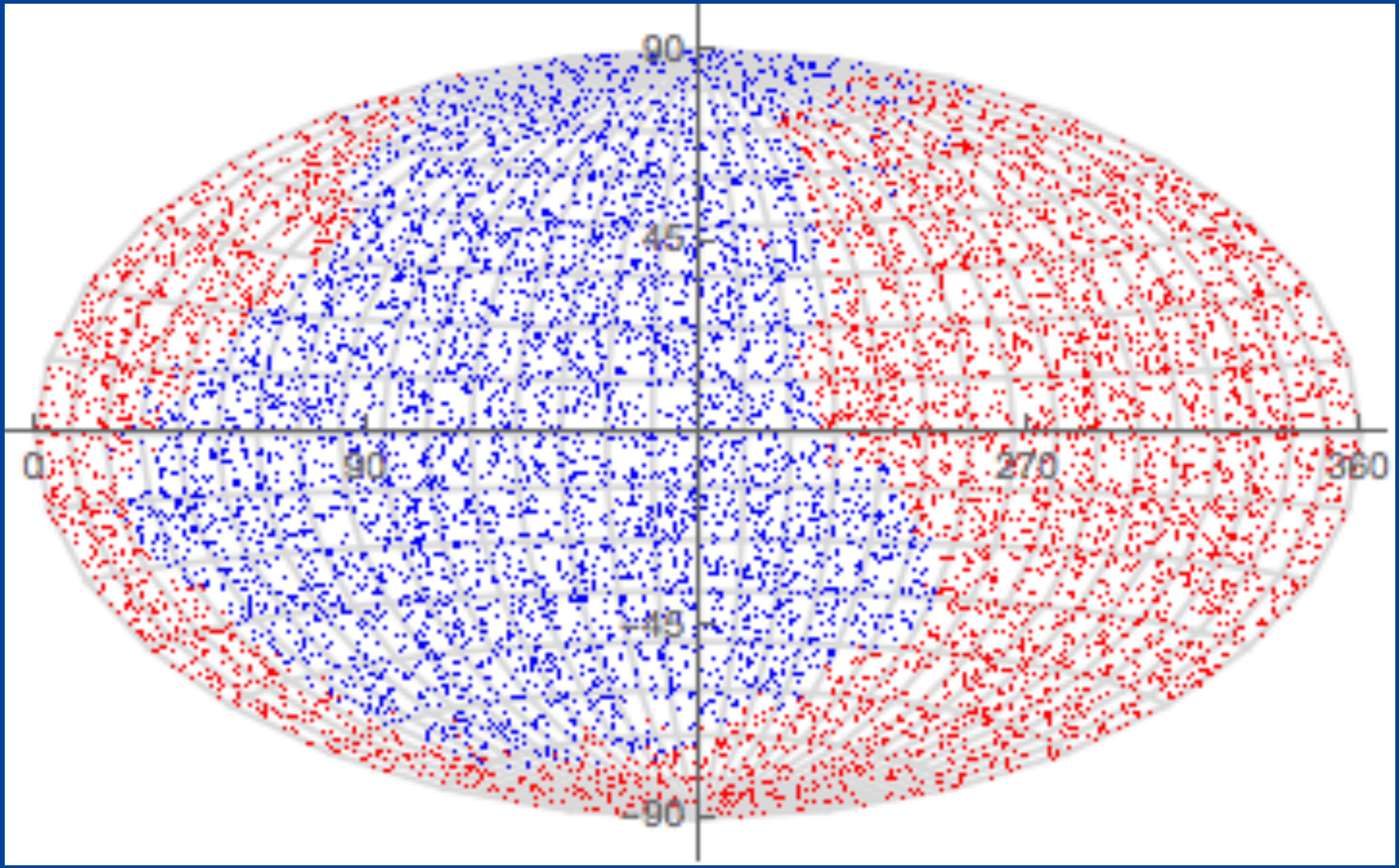
DATA: NVSS+SUMSS

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

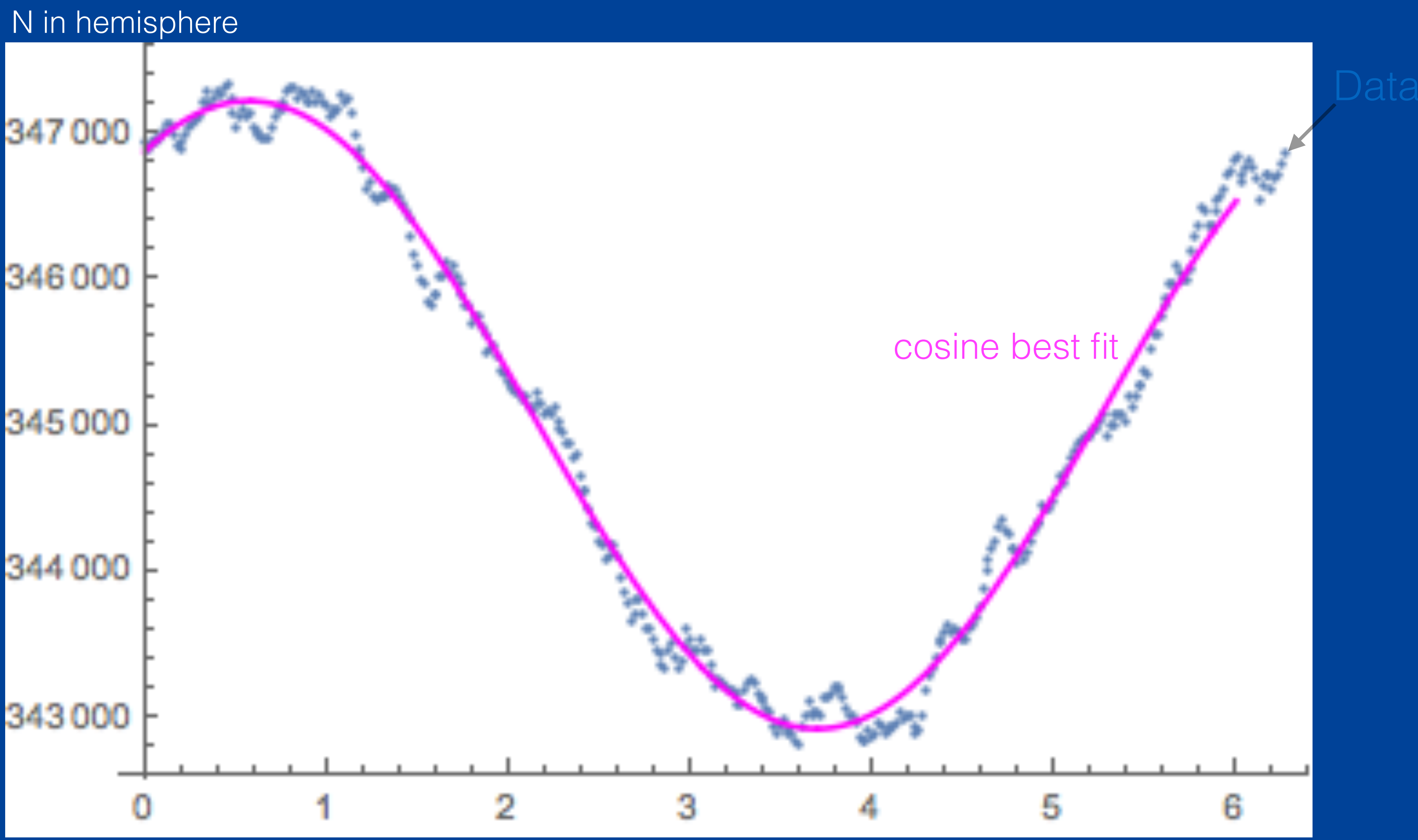
Red: hemispheres containing LESS galaxies than the mean

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

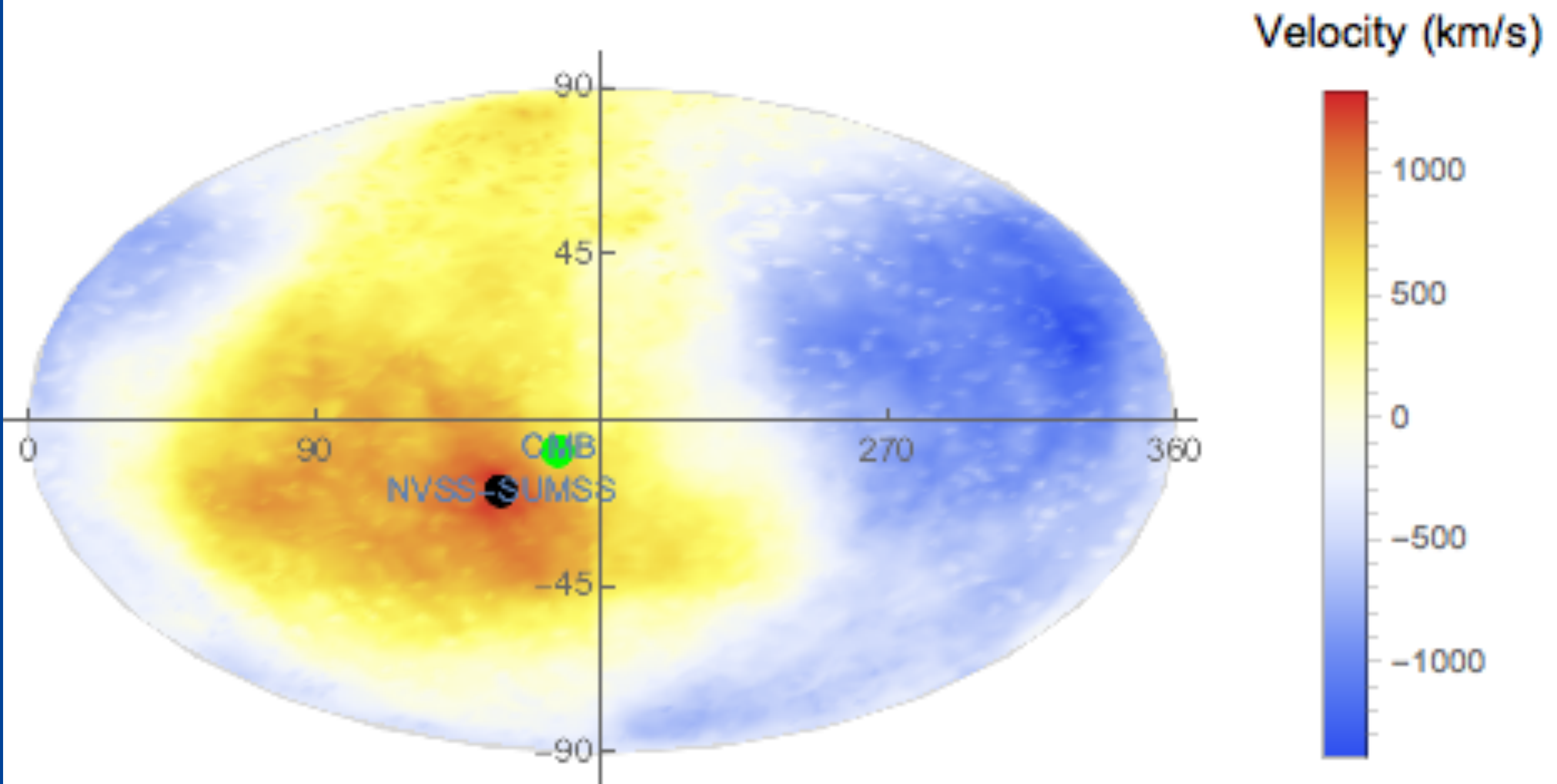


φ (Radians)

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

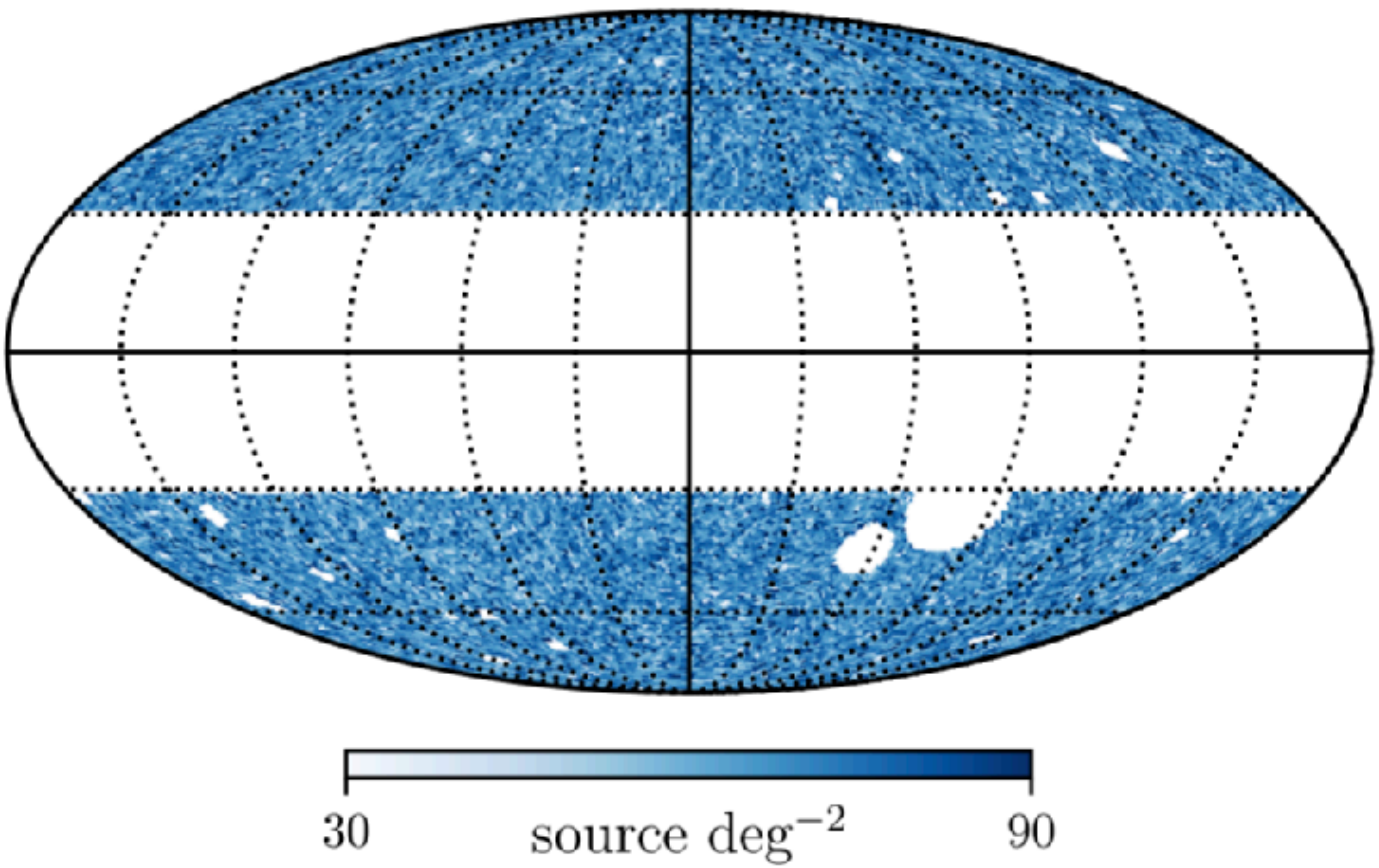
WISE :(Wright et al. 2010) & NEOWISE (Mainzer et al. 2011)

CatWISE : Eisenhardt et al 2020

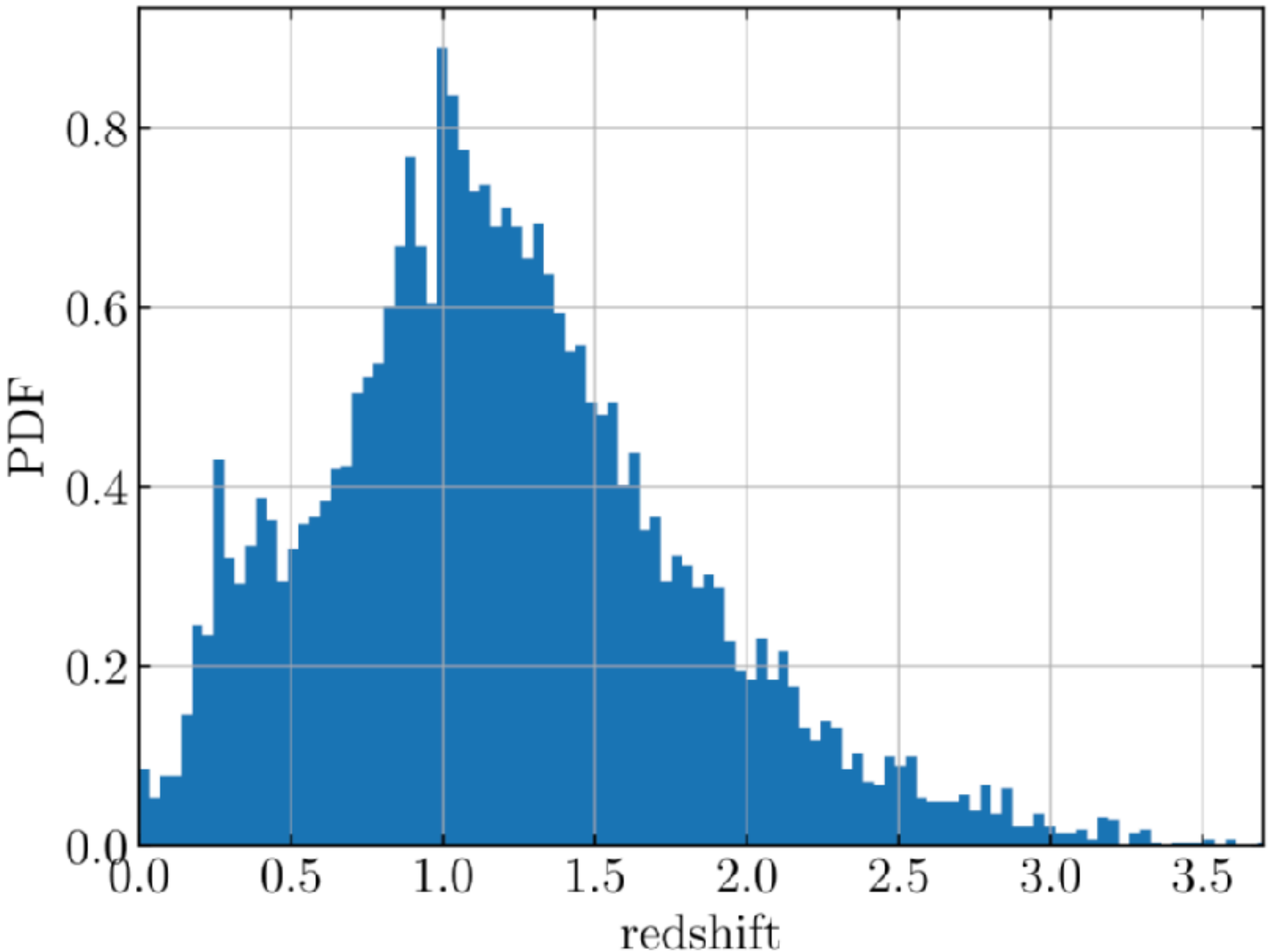
positions and the four-band photometry for 747,634,026 objects

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

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



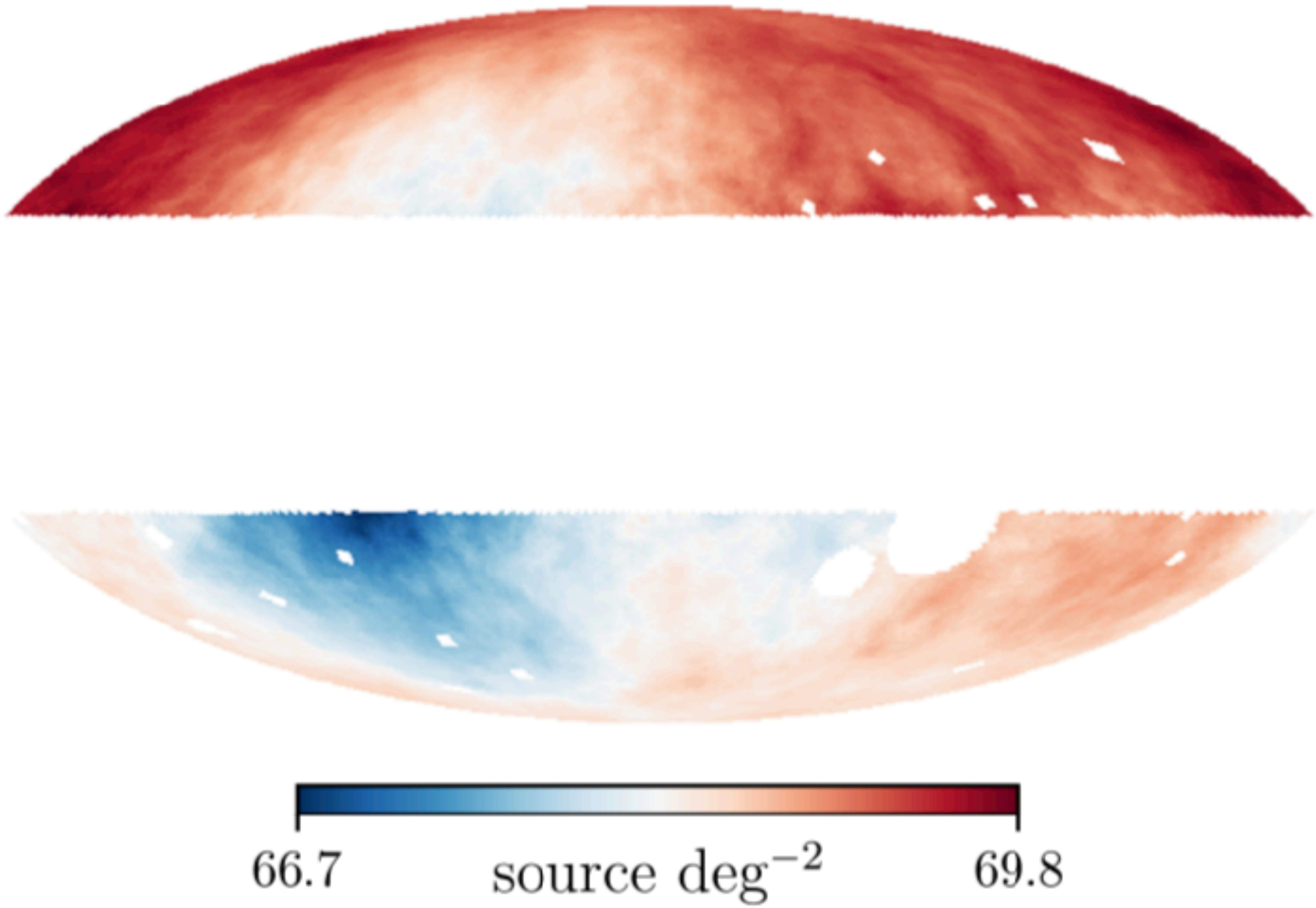
Redshift distribution



The Dipole

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

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

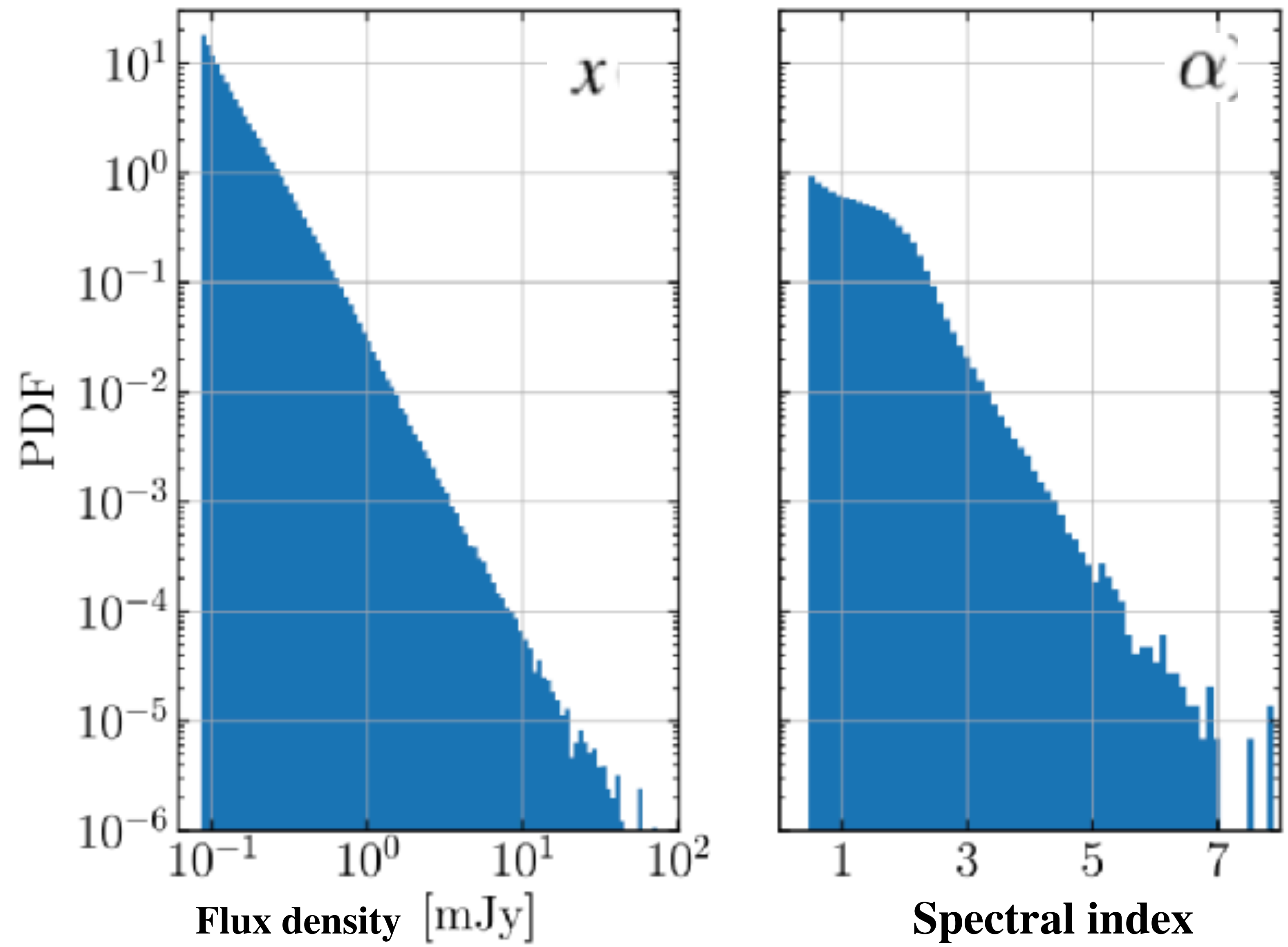


Statistical significance

10^7 random sky

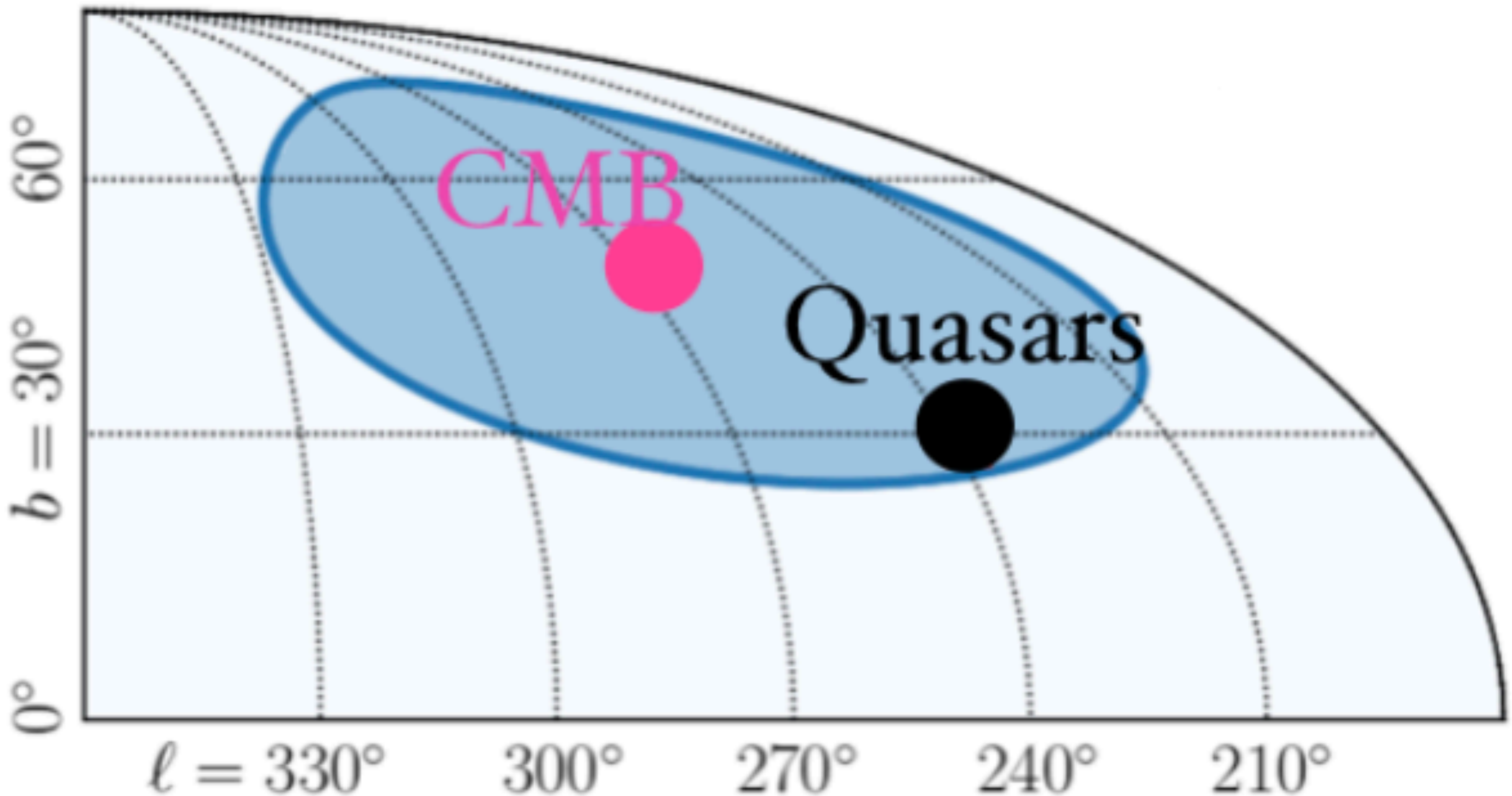
mimicking CatWISE
same masks,
estimator, flux….

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 5×10^{-7}

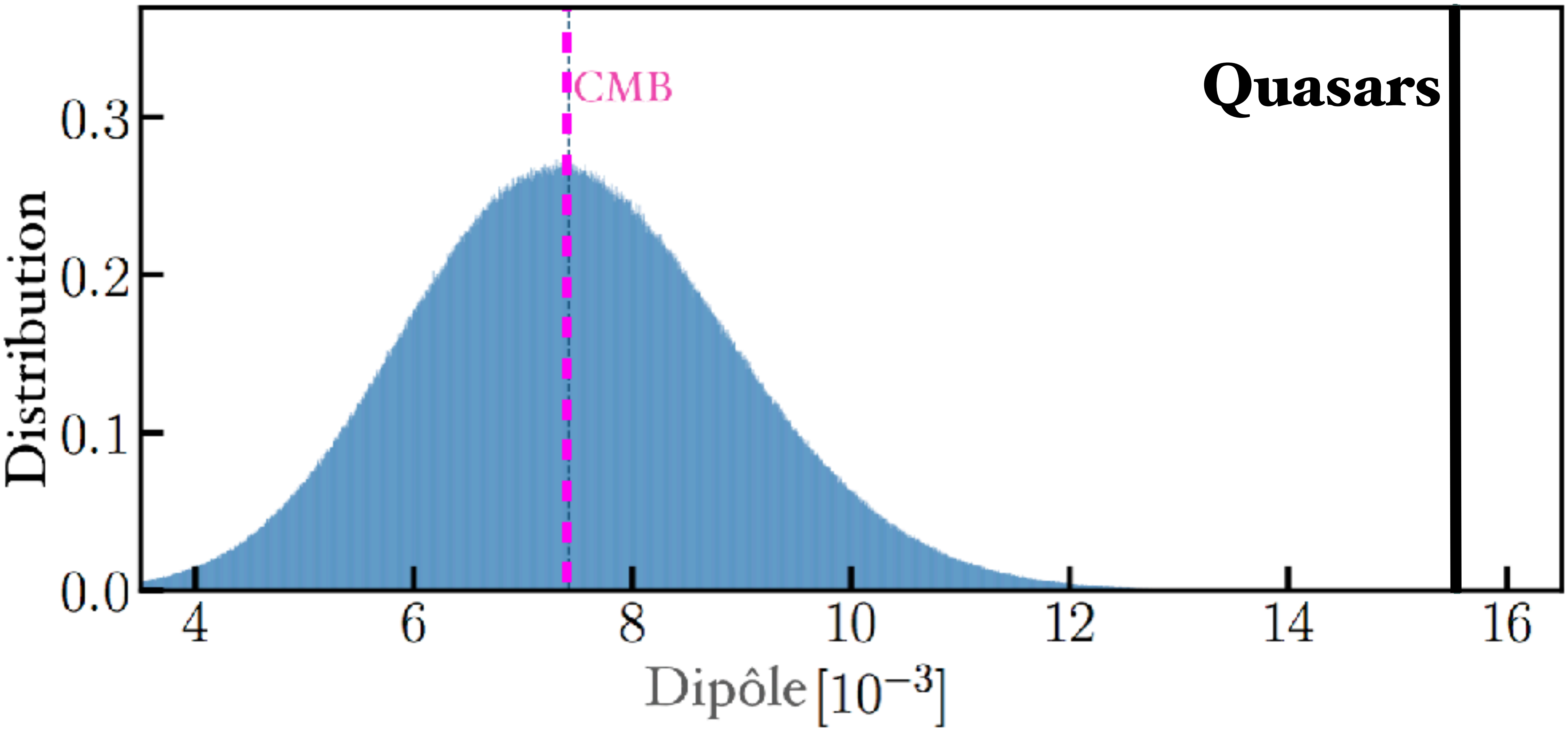
5/10000000 MC simulations



Catalogues, Codes et Simulations pour l'analyse statistique à la disposition de la communauté
Github :
https://doi.org/10.5281/zenodo.4431089

ApJLetters 2021

(5/10 000 000 simulations = 4.9 sigma)



Catalogues, data & Codes *Open access* for the community

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

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

ApJLetters 2021

Testing the cosmological principle with Rubin/LSST

Billions of sources, many at high redshifts, "homogeneous" coverage, …..

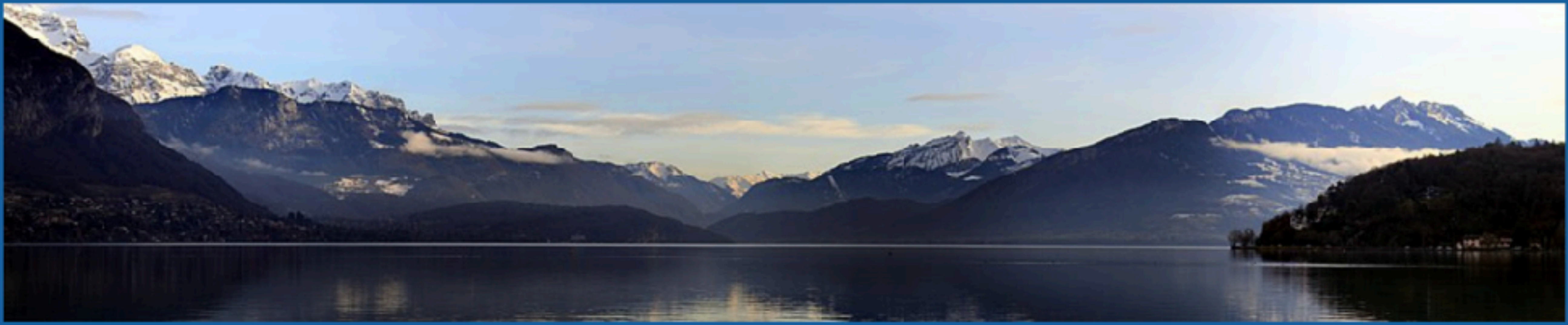
Improving Physical Cosmology: An Empiricist's Assessment

P. J. E. Peebles

June 4, 2021

This broad variety of ways to look at the universe adds up to a compelling empirical case for the ΛCDM theory as an impressively good **approximation to reality.**

Maybe more tensions will be found as the constraints improve. If so then I expect the case for ΛCDM as a useful approximation will remain compelling, and there will be more clues to a **still better theory.**



Rubin-LSST France, Mai 2022

FIN