Tomographic study of Anomalous cosmic dipole with Rubin LSST

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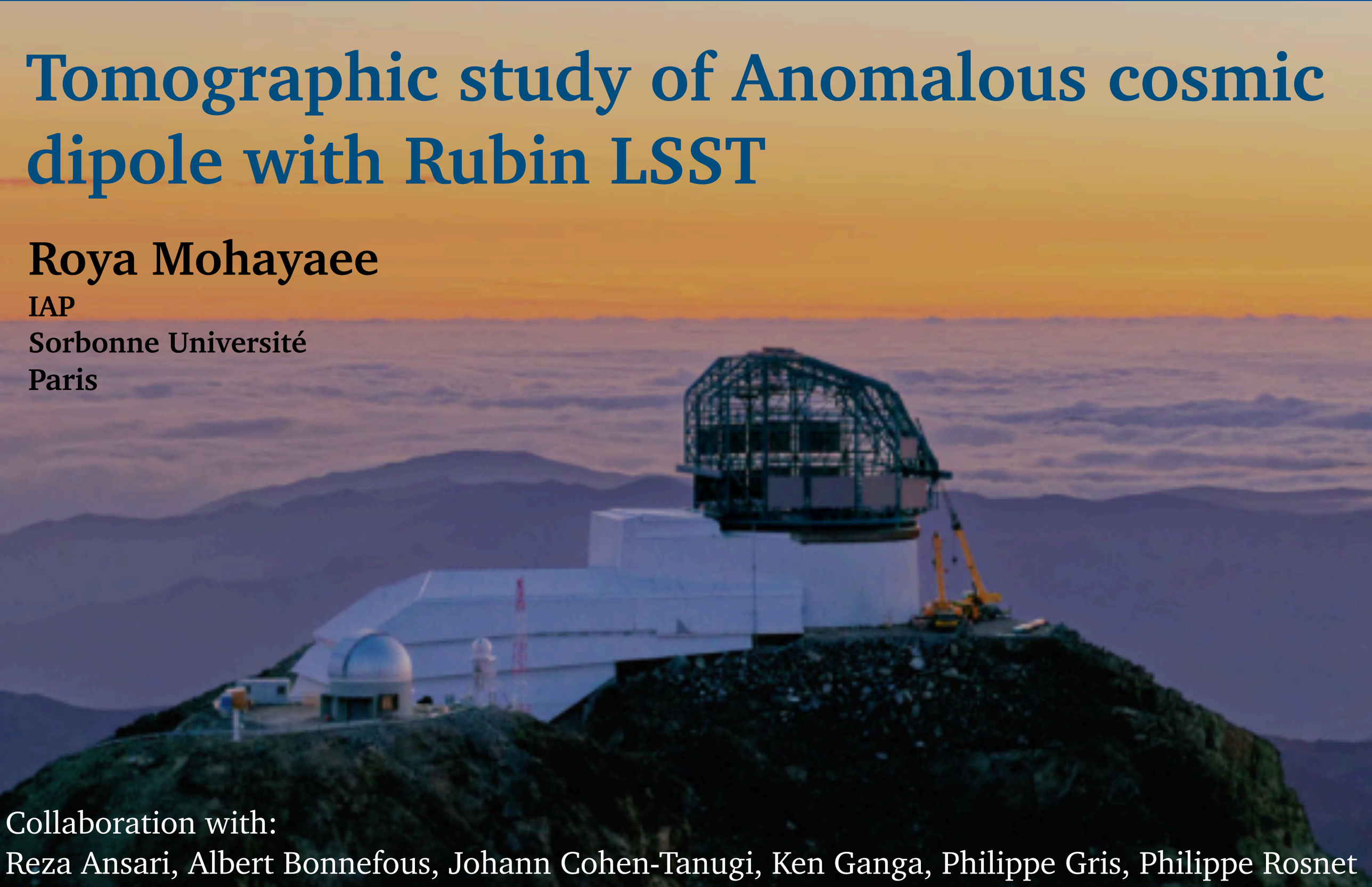


Collaboration with:
Reza Ansari, Albert Bonnefous, Johann Cohen-Tanugi, Ken Ganga, Philippe Gris, Philippe Rosnet

Rubin LSST-France APC 27-29 novembre 2024

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**

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

Homogeneous but anisotropic → Axis (Bianchi)

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

Inhomogeneous & isotropic → Centre (LTB)

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

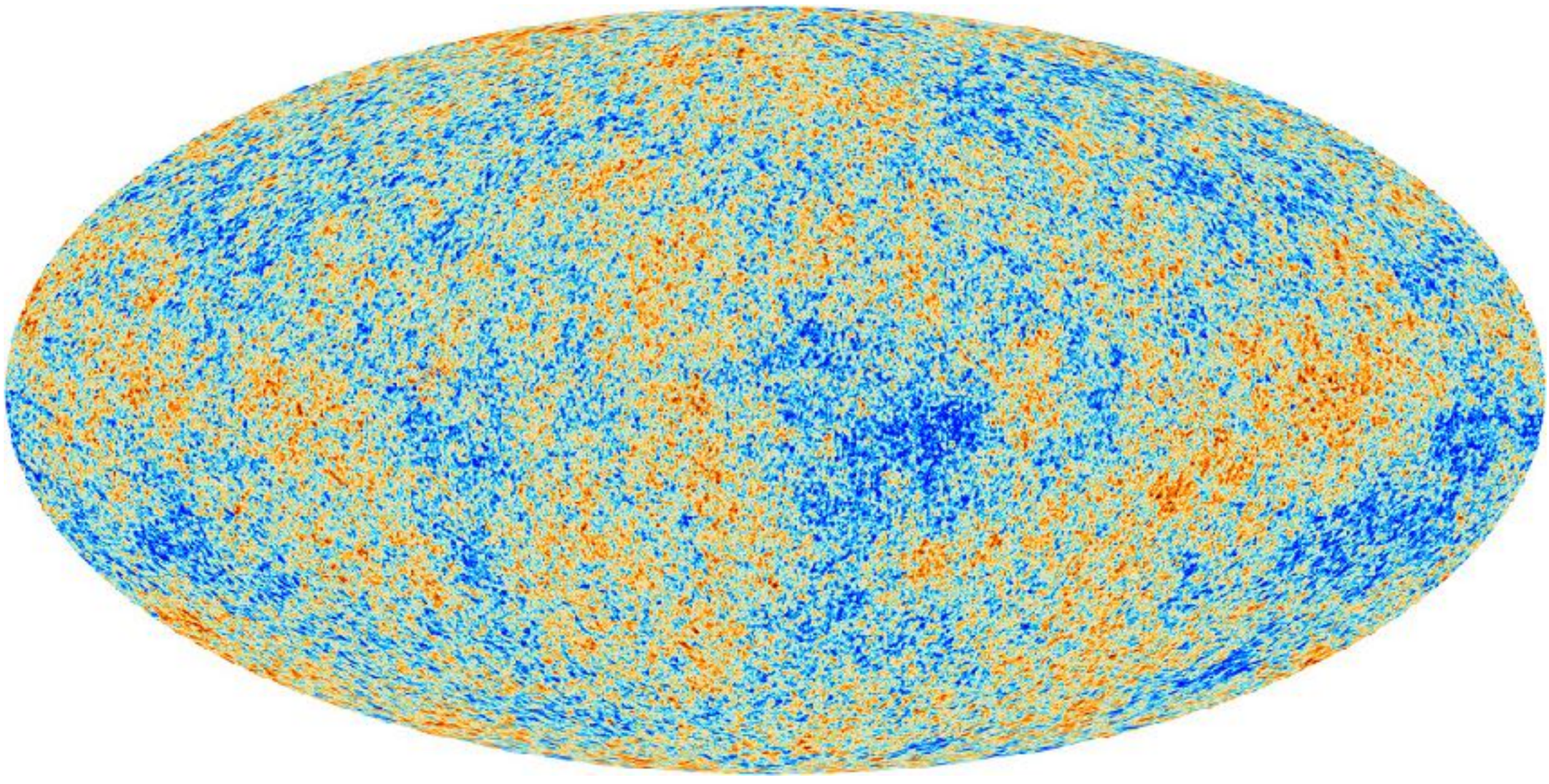
Inhomogeneous & anisotropic → Szekeres model

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

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

Observational evidence for **isotropy** of the Universe

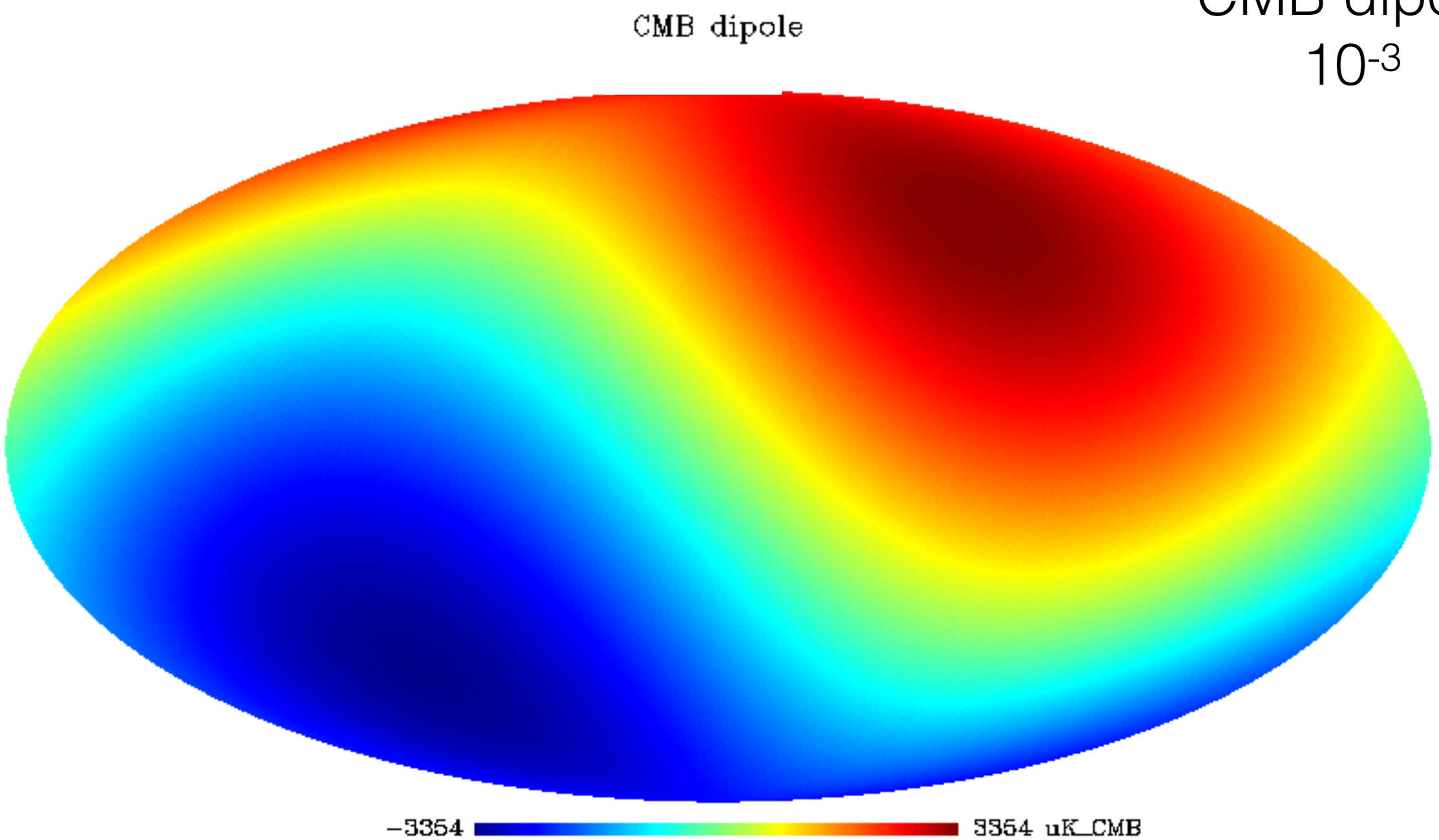
Cosmic microwave background



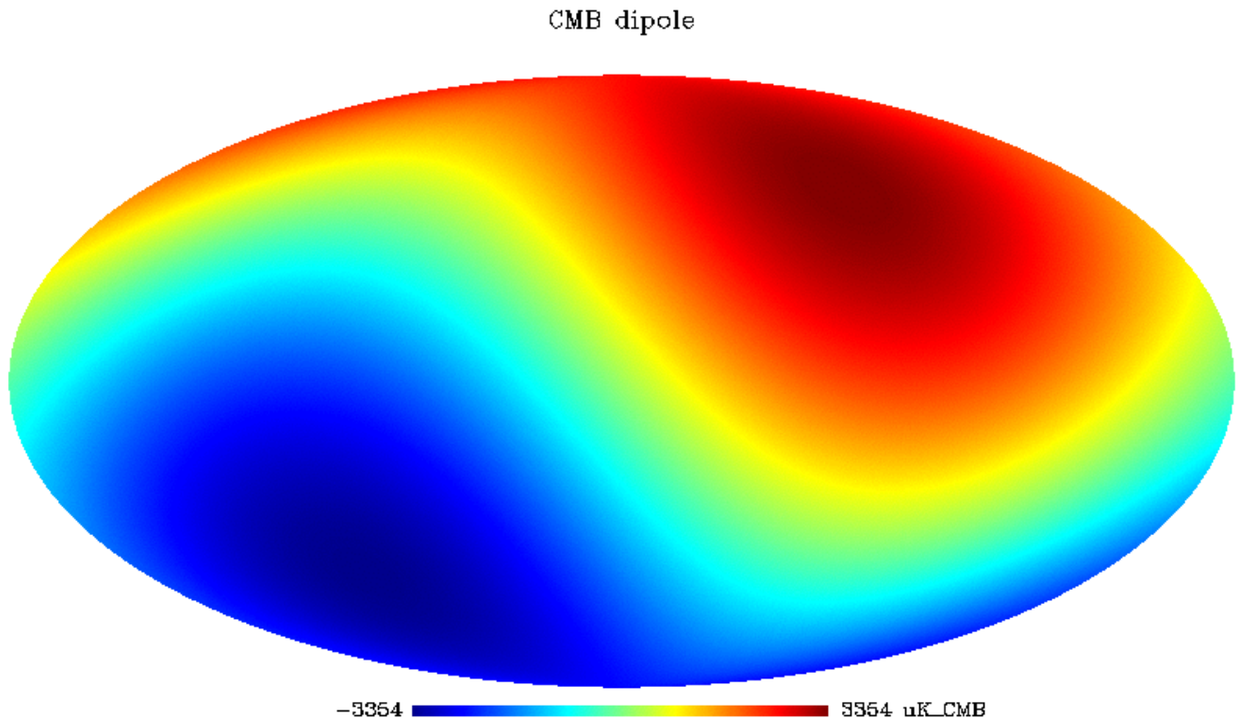
CMB restframe

Observational evidence for **anisotropy** of the Universe

CMB dipole
10^{-3}

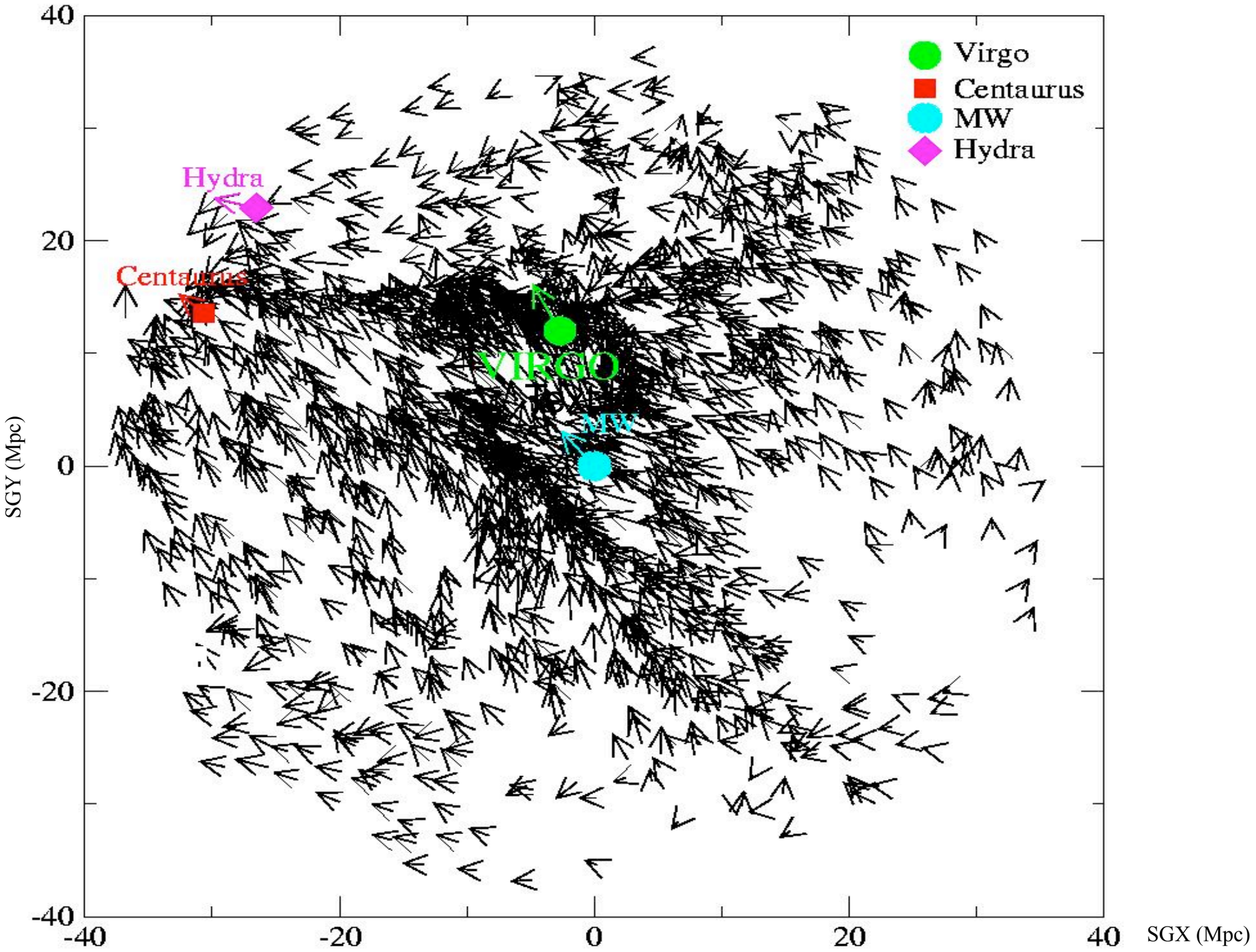


The origin of the CMB dipole ?



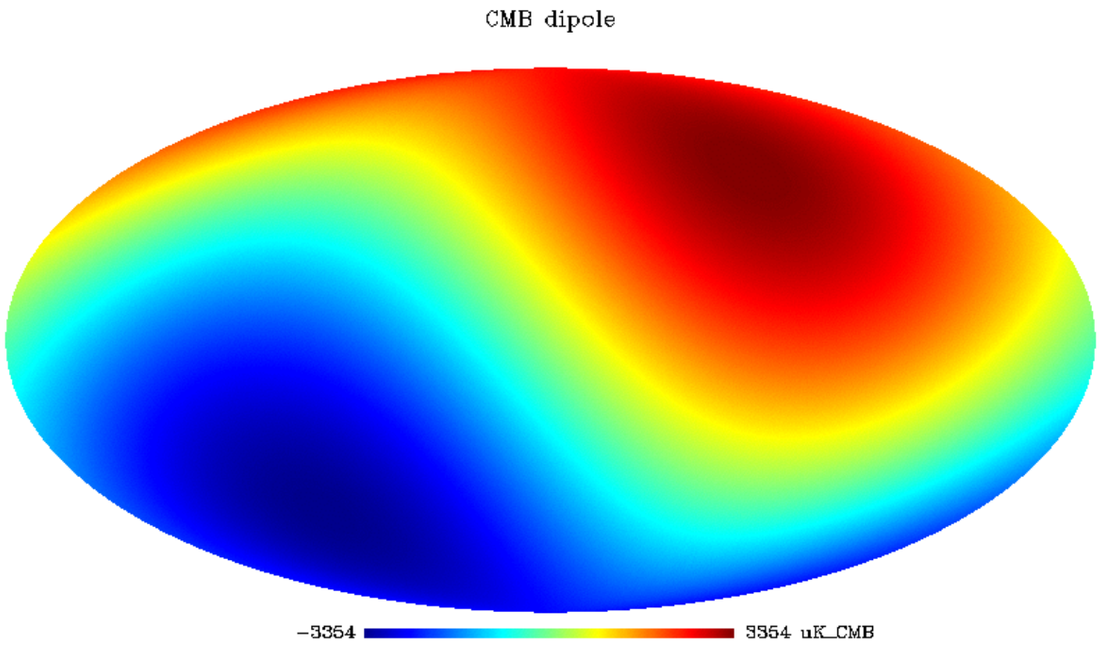
Dipole is purely Kinematic
Universe, at least up to a scale, must be anisotropic

The origin of CMB dipole
Local anisotropy

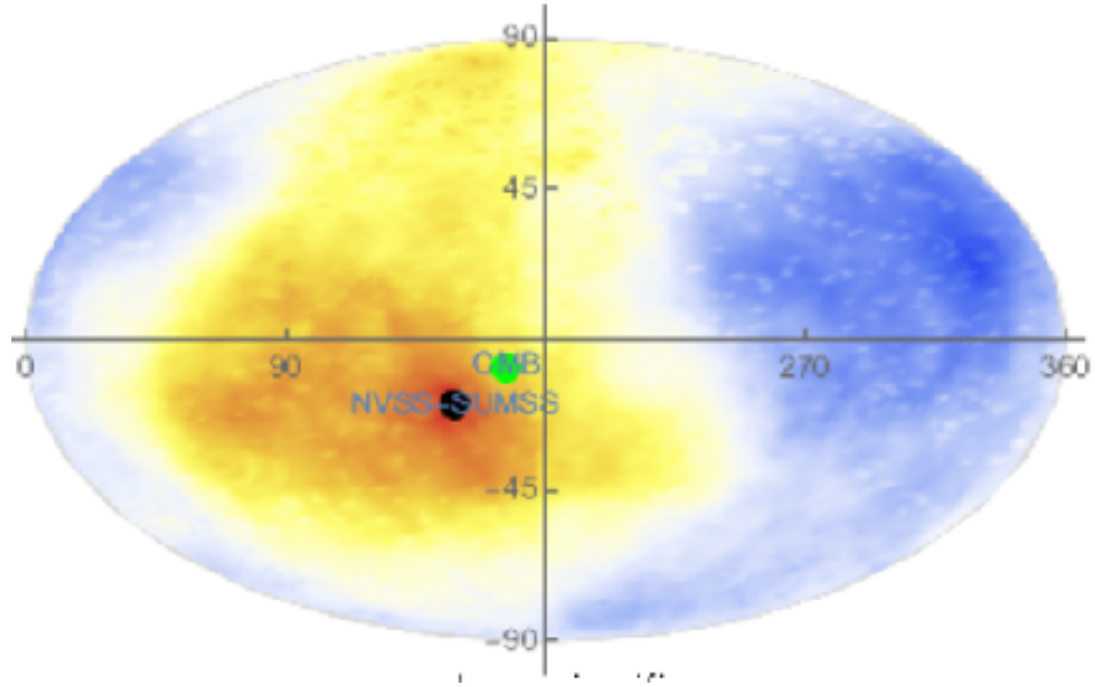


Question we wish to answer with Rubin LSST

Is our velocity in the rest frame of CMB equal to our velocity in the rest frame of **distant** sources ?

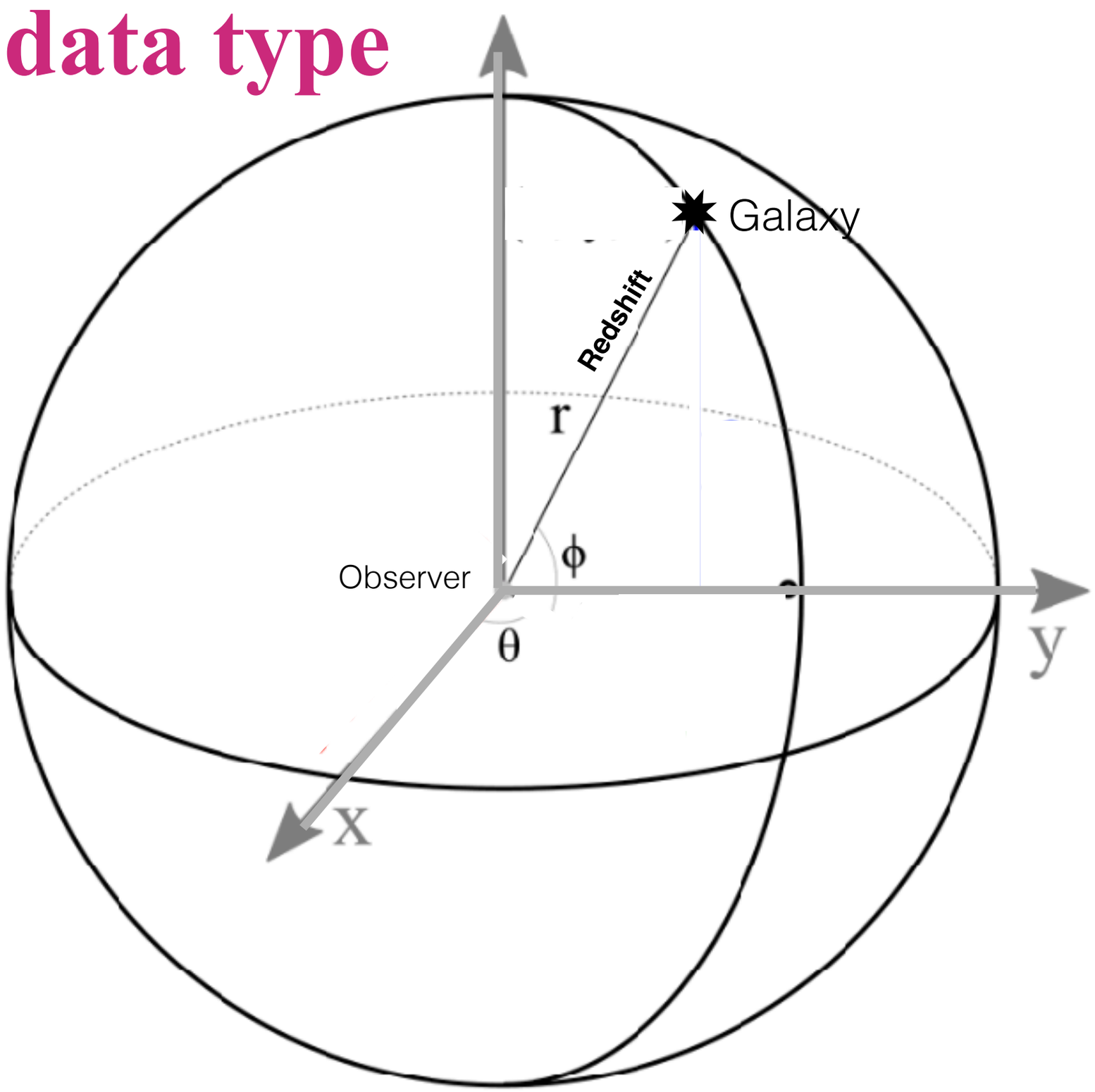


Radiation dipole



Matter dipole

probes: data type

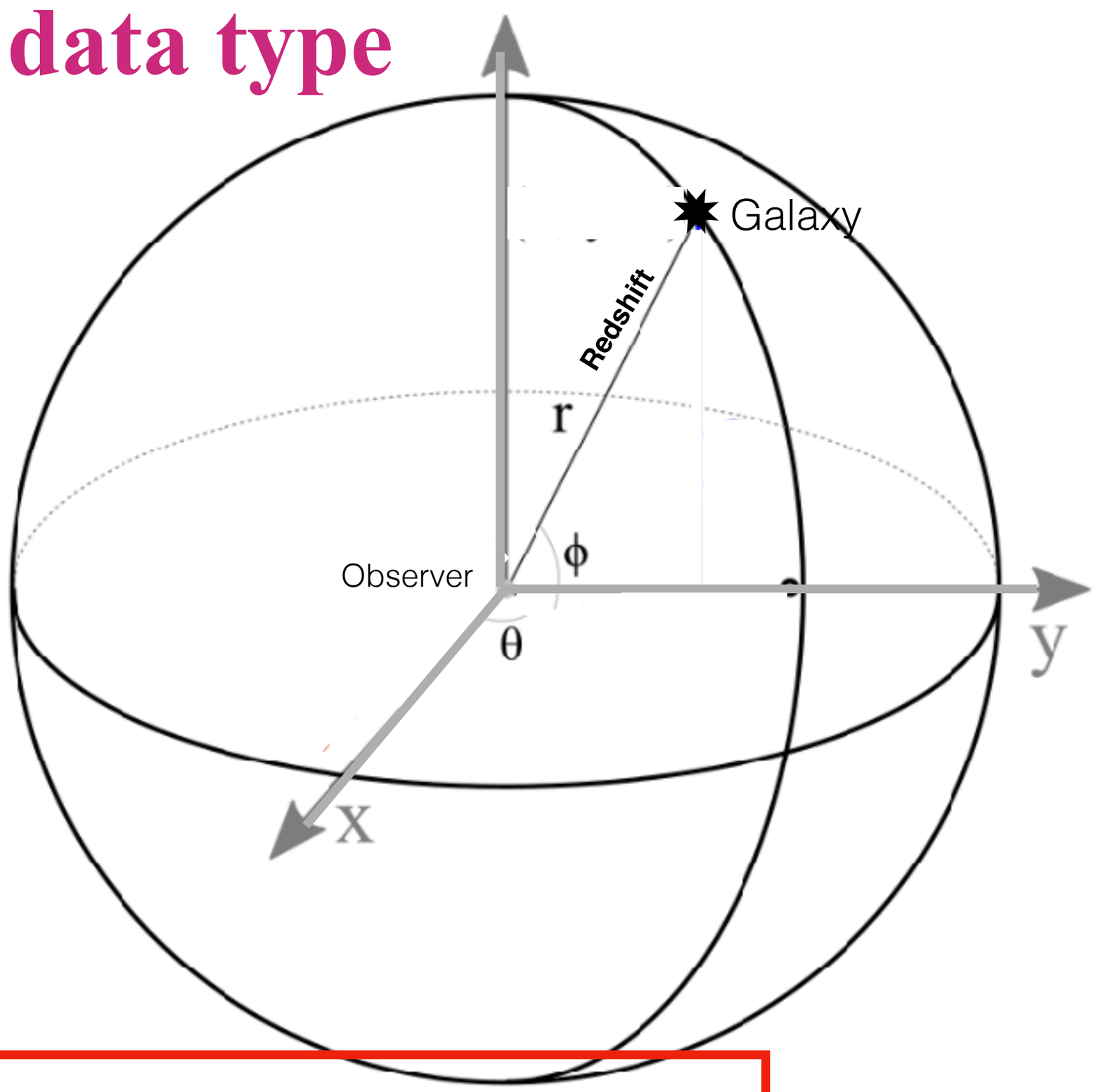


(I) Θ, φ, z, d (distance catalogues, SNe IA, nearby)

(II) Θ, φ, z (redshift surveys, medium redshifts + theoretical modelling)

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

probes: data type



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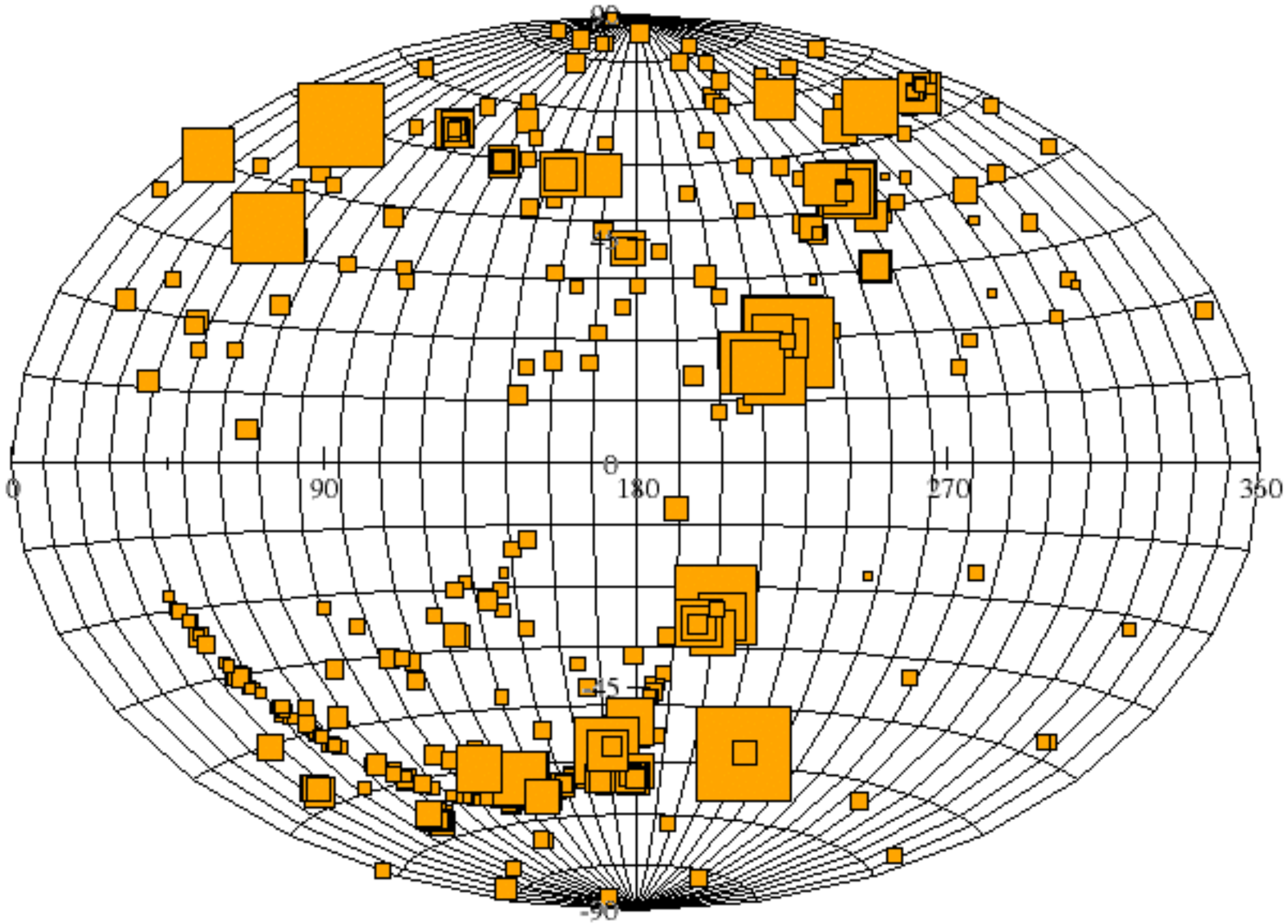
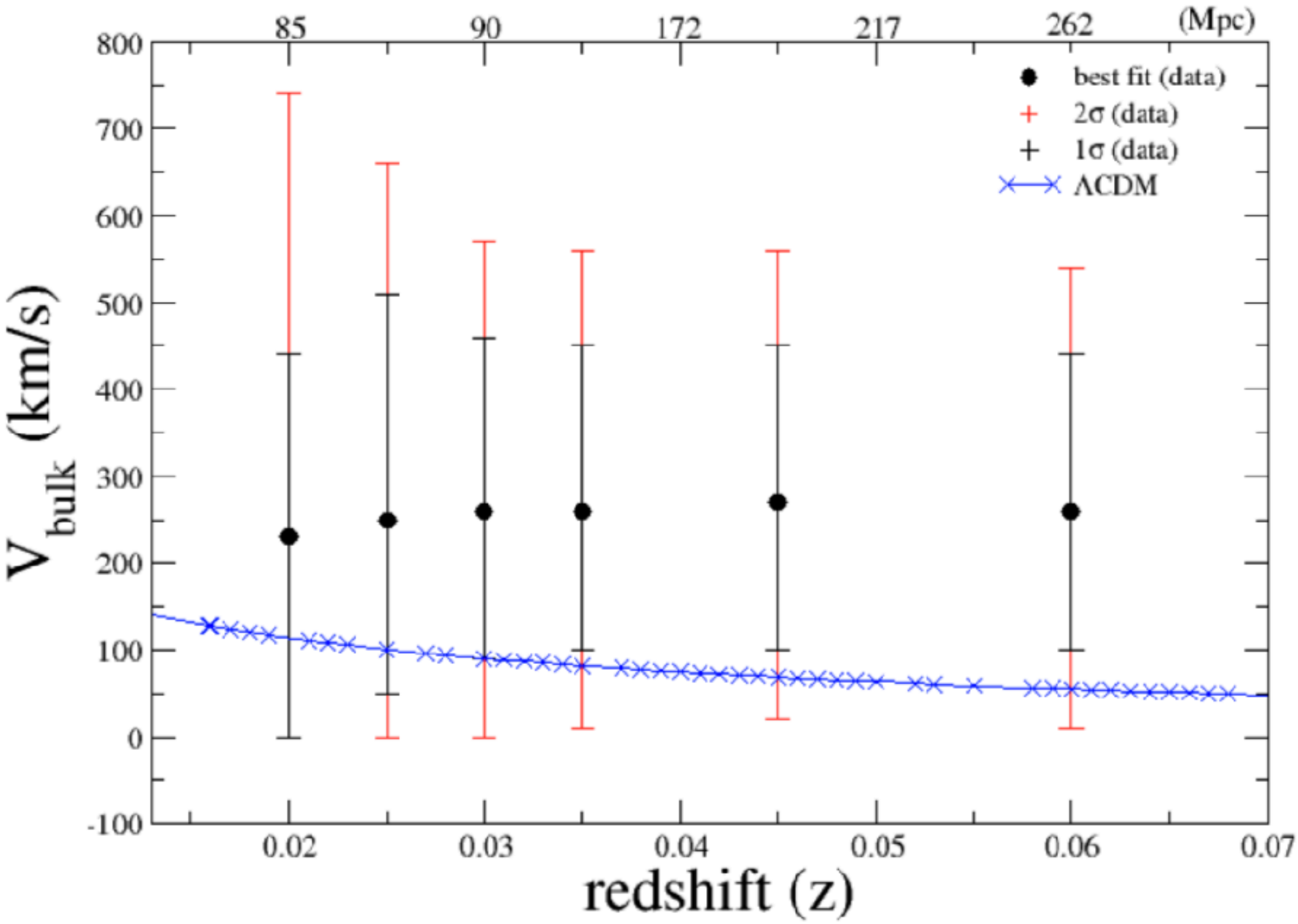
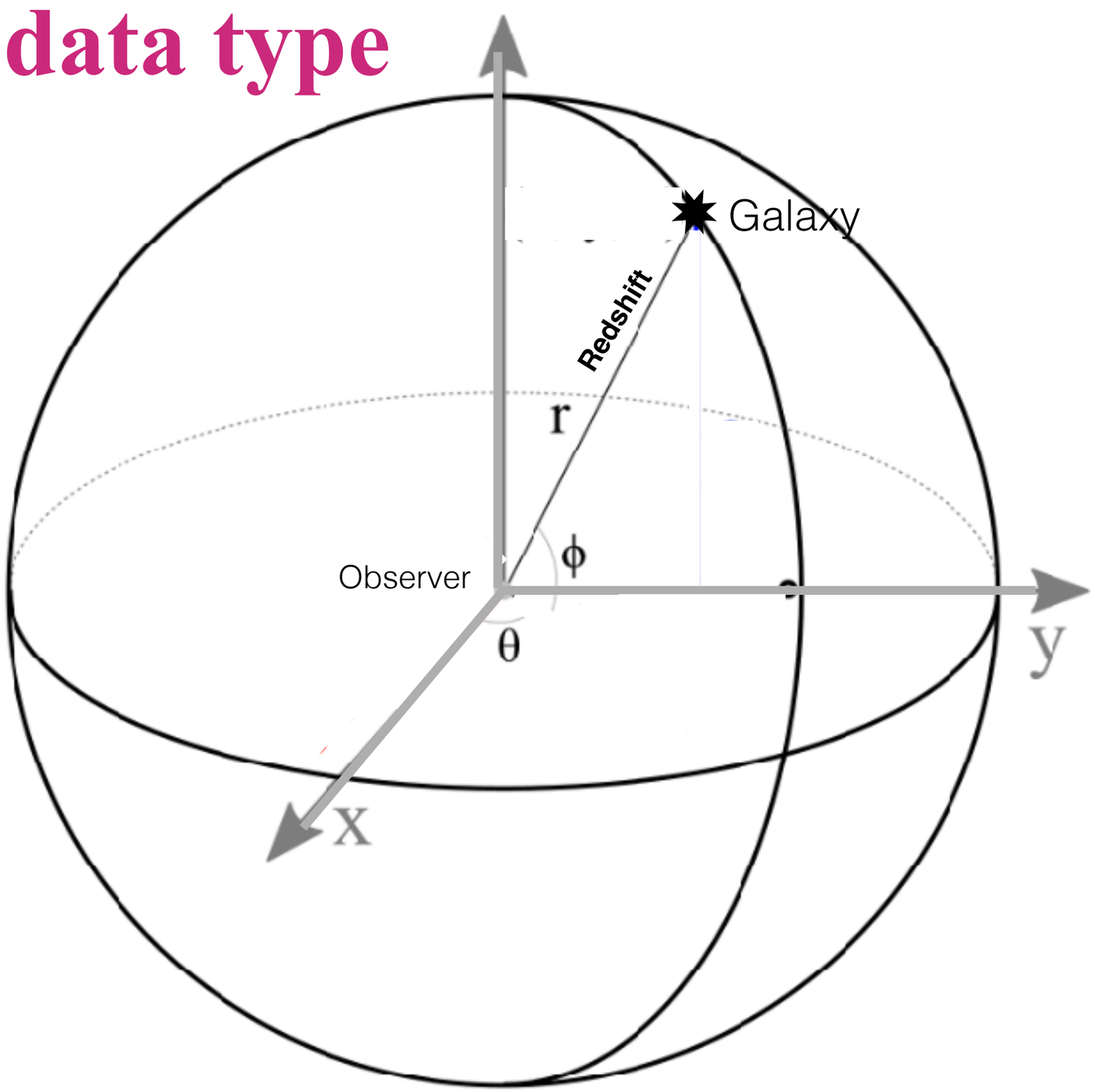
Study of anisotropy with SNe Ia
Union II compilation
Standard candles



Colin, Mohayaee, Shafieloo, Sarkar, MNRAS 2012


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
0.02
0.03
0.04
0.05
0.06
0.07
redshift (z)

probes: data type



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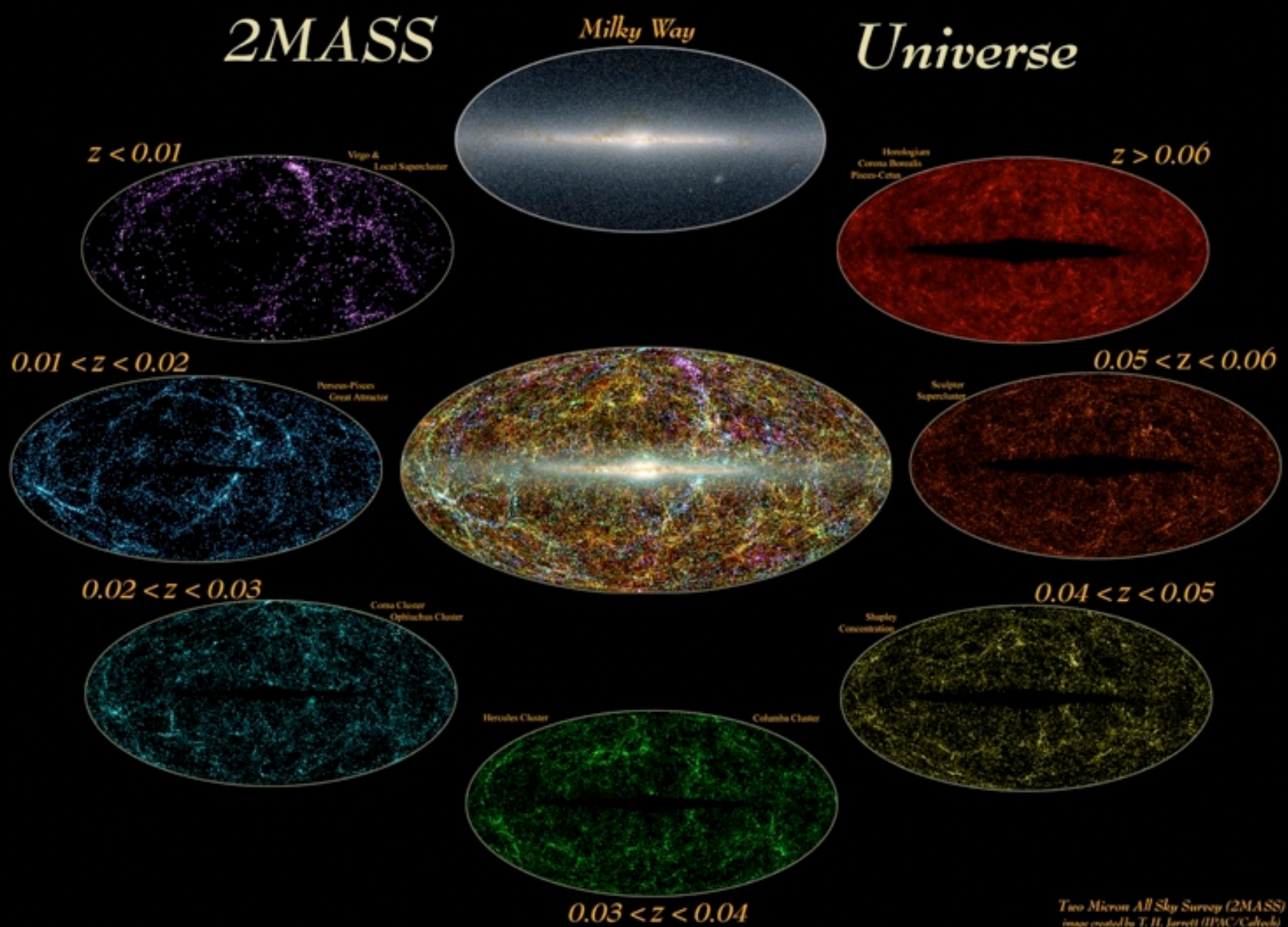
2MRS redshift survey

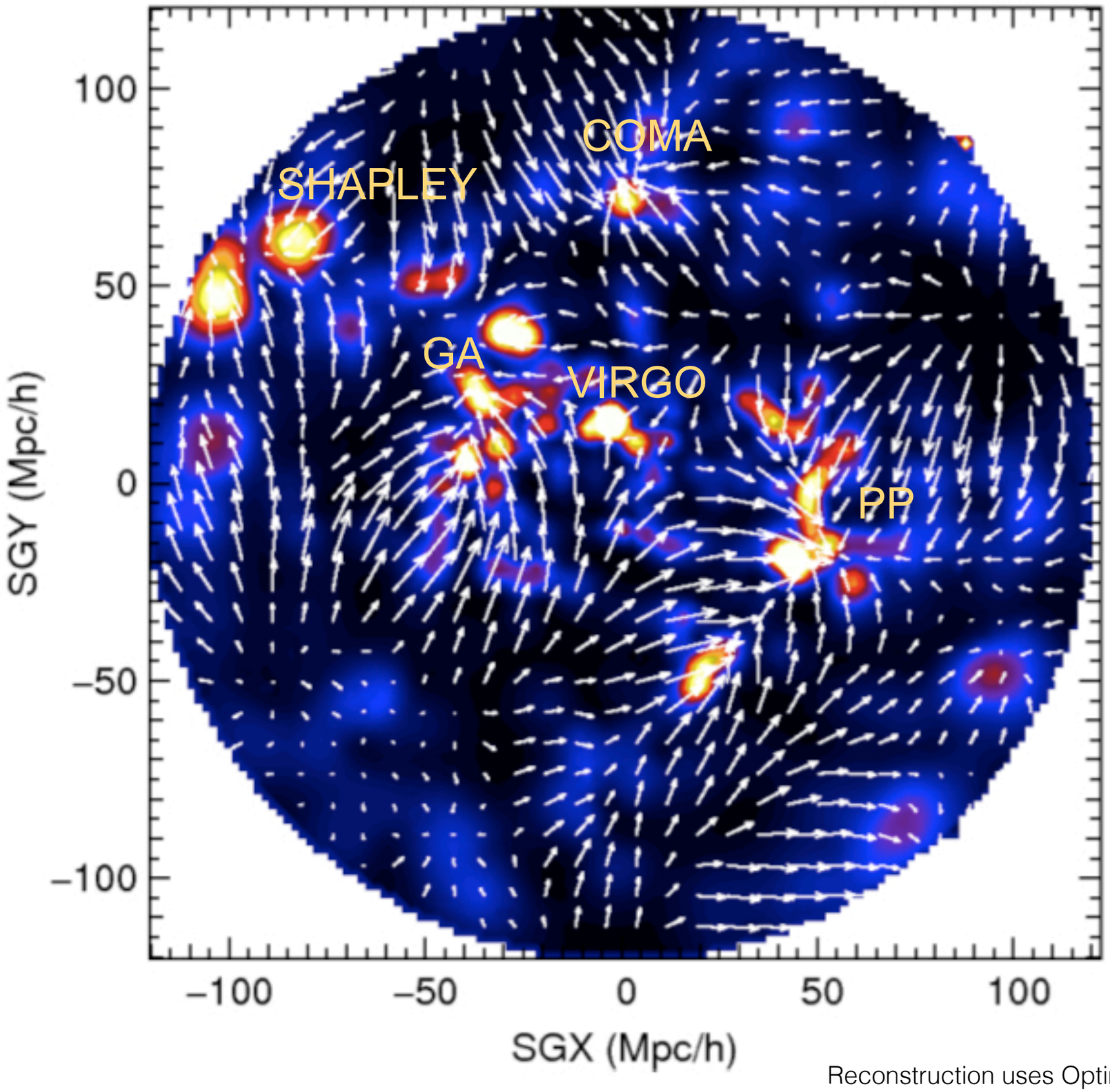
(Huchra etal 2005,...)

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)

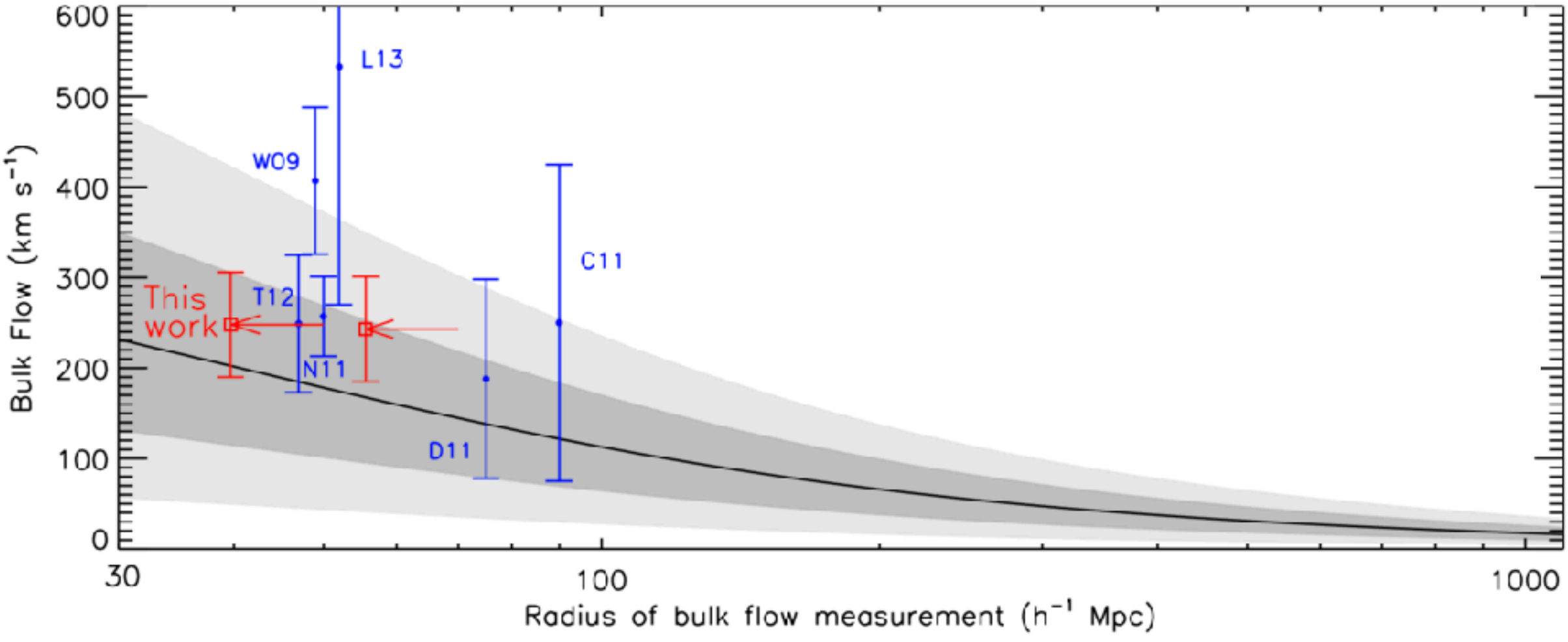


Local Anisotropy
Distance reconstruction

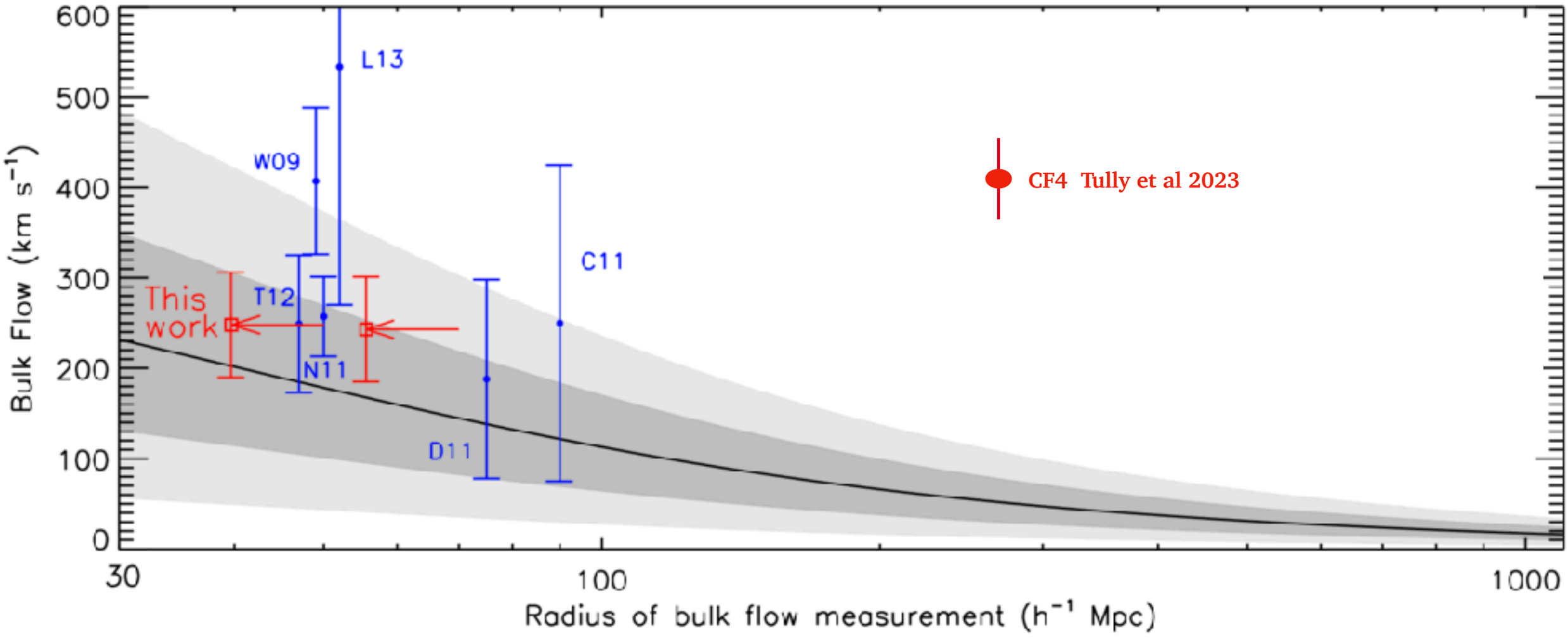


Reconstruction uses Optimal Transport techniques

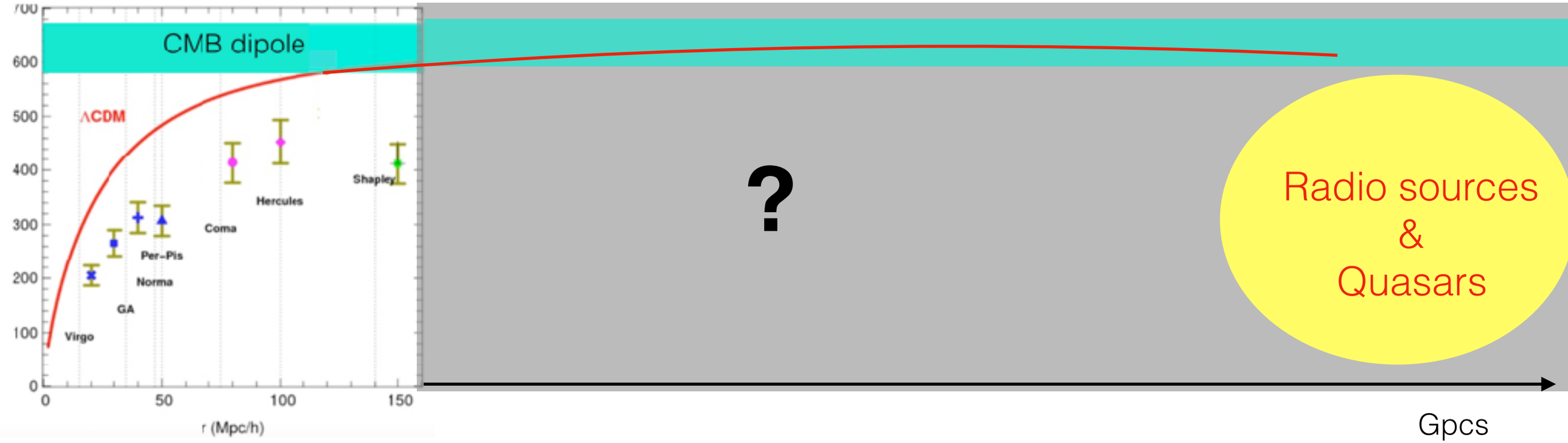
Convergence to the CMB rest frame



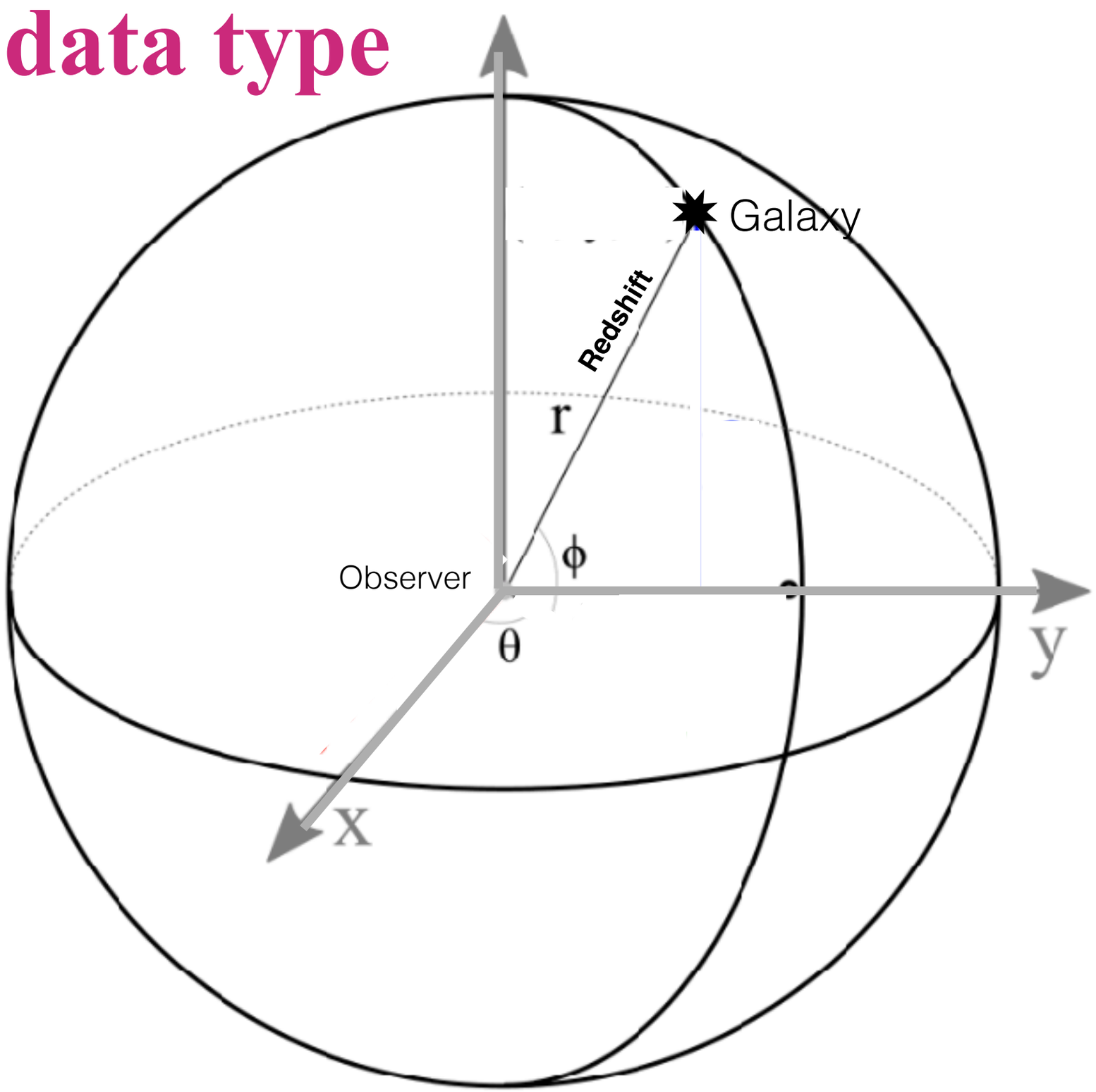
Convergece to the CMB restframe



A tomographic study : searching for the CMB rest frame



probes: data type



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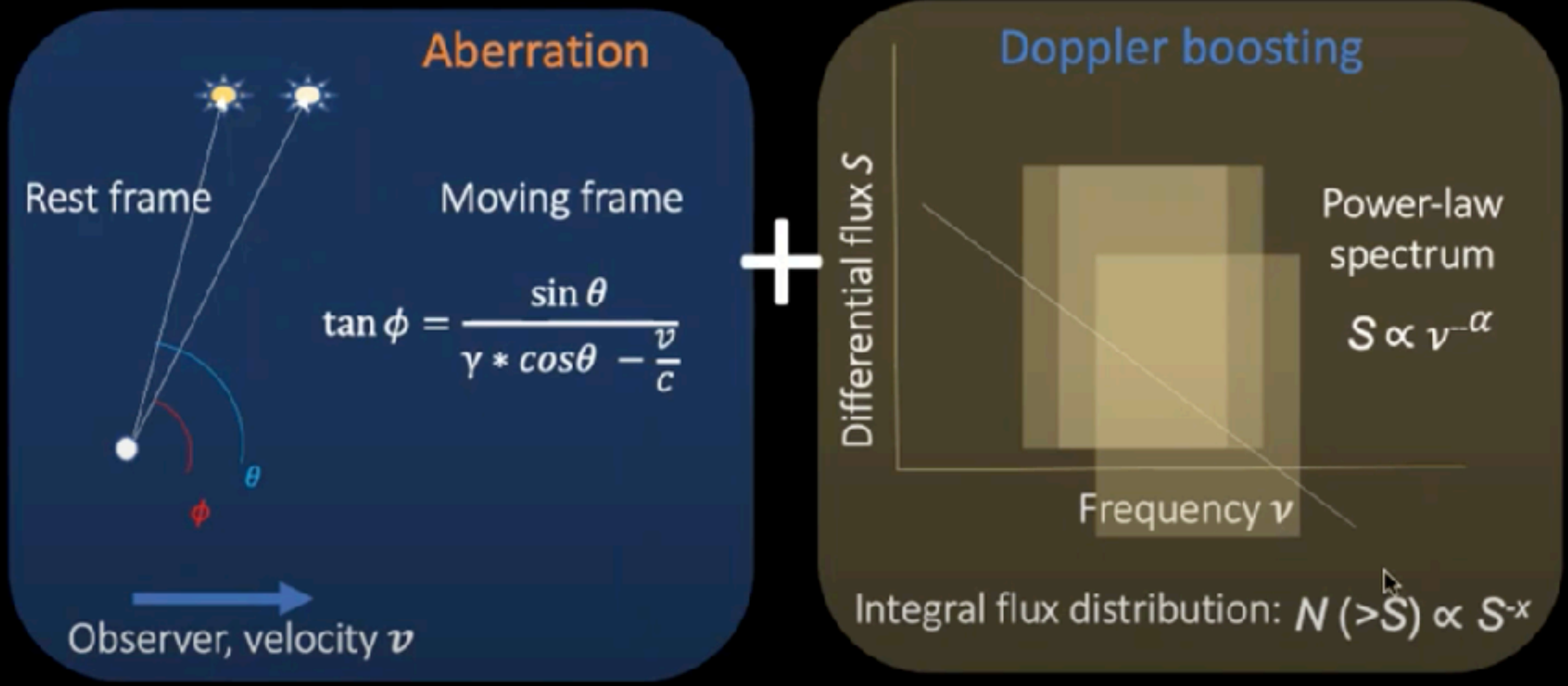
Probe 3 : Aberration and Doppler boosting



Ellis & Baldwin,
MNRAS 206:377,1984

Ellis and Baldwin 1984

Anisotropy in source distribution → observer's velocity

Aberration and Doppler boosting

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

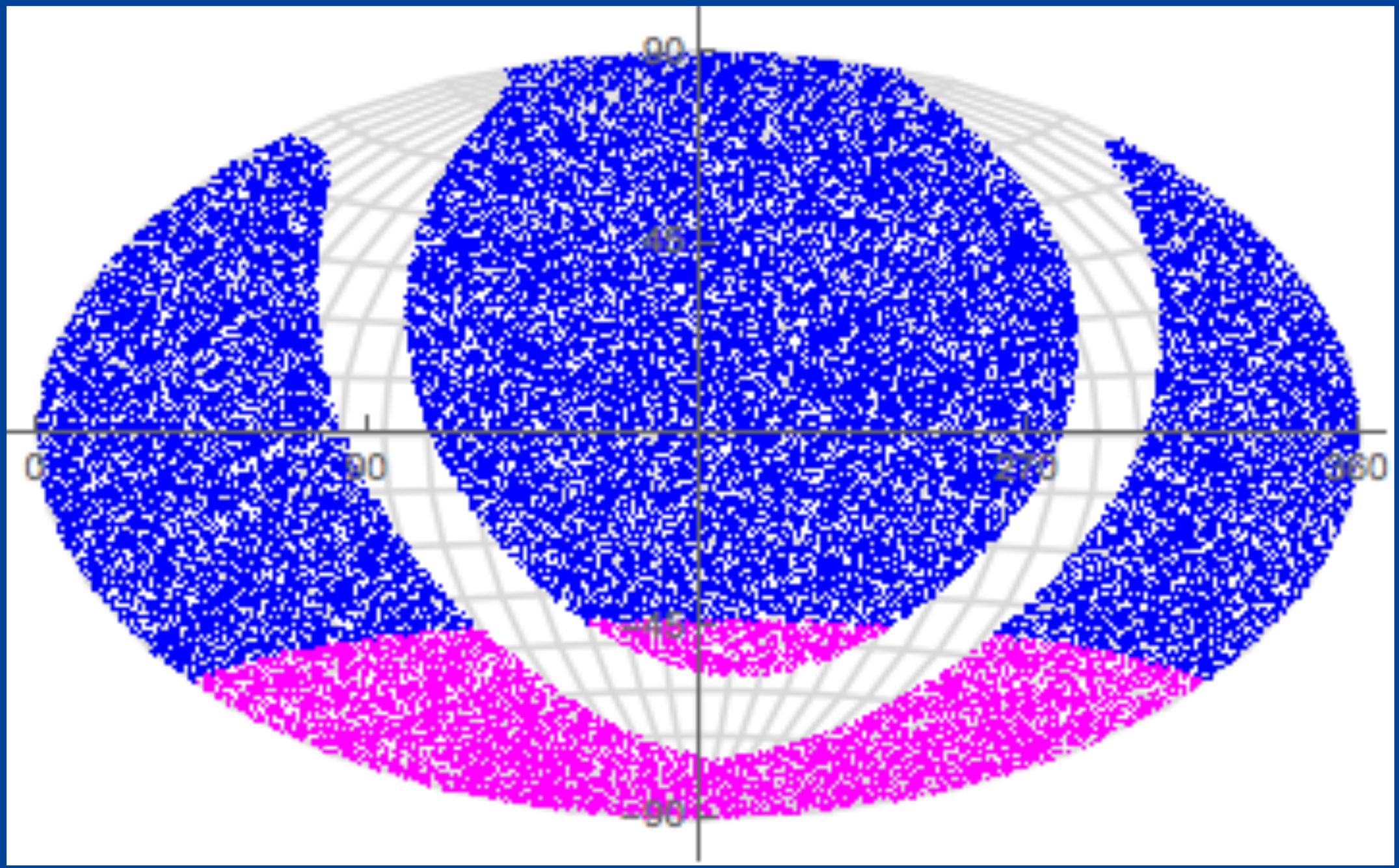
$dN/d\Omega(>S_\nu) \propto S_\nu^{-x}$

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

Independent of distance to the source

DATA: NVSS+SUMSS

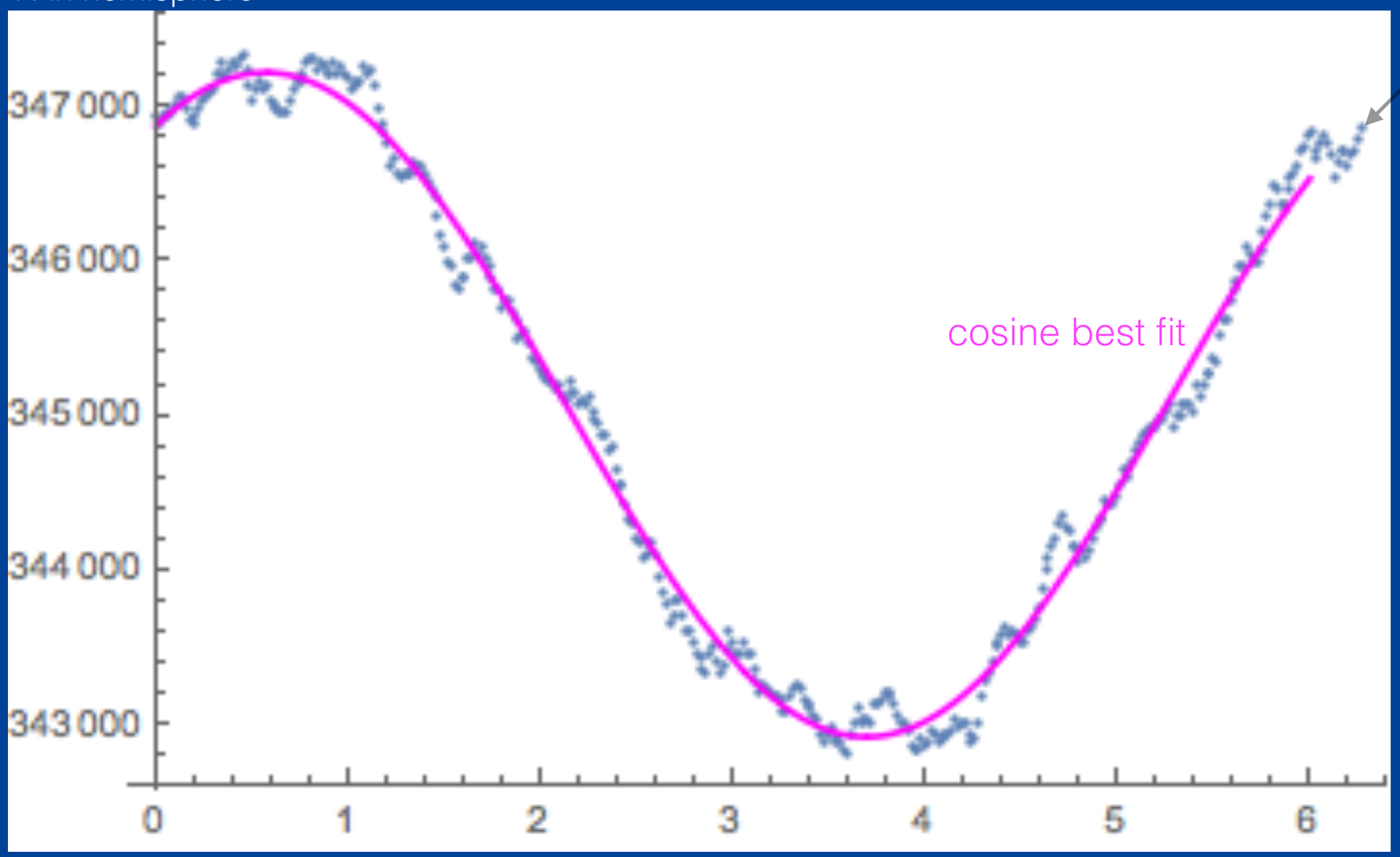
576461 Radio galaxies in 10 mjy <Flux< 1000 mjy



Searching for dipole

Example of hemispherical counting:

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

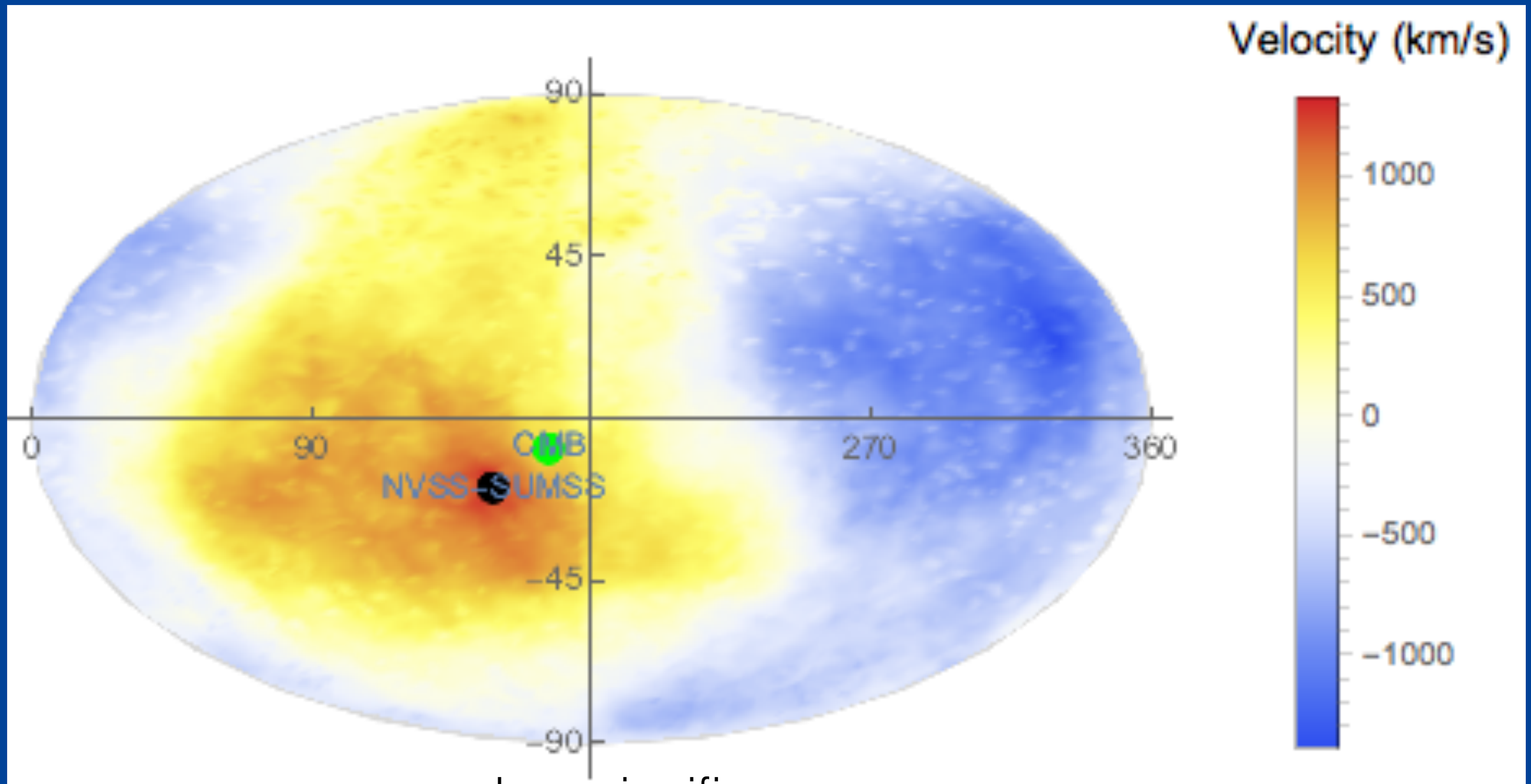


Dipole

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

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

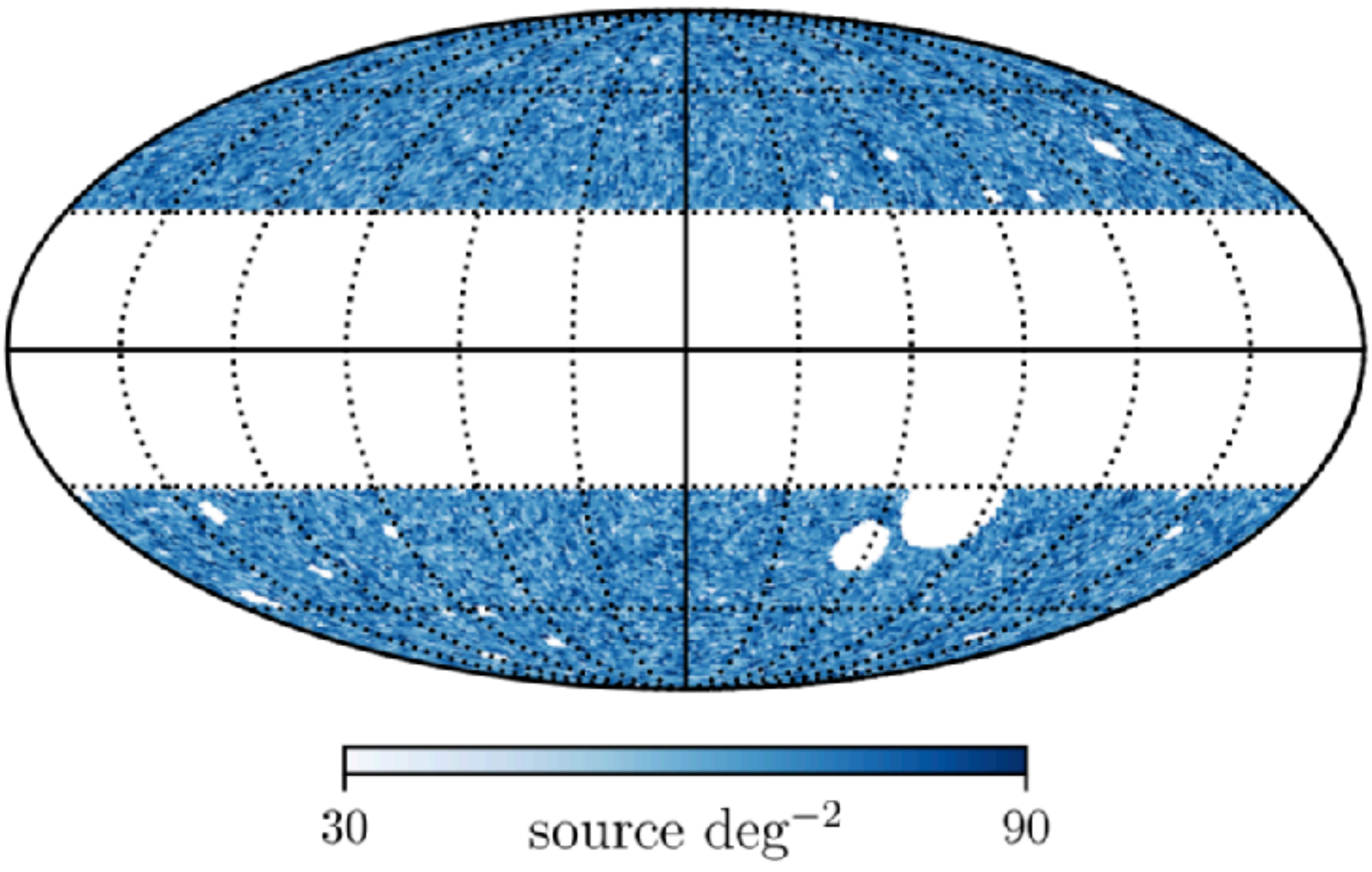
WISE :(Wright et al. 2010) & NEOWISE (Mainzer et al. 2011)

CatWISE : Eisenhardt et al 2020

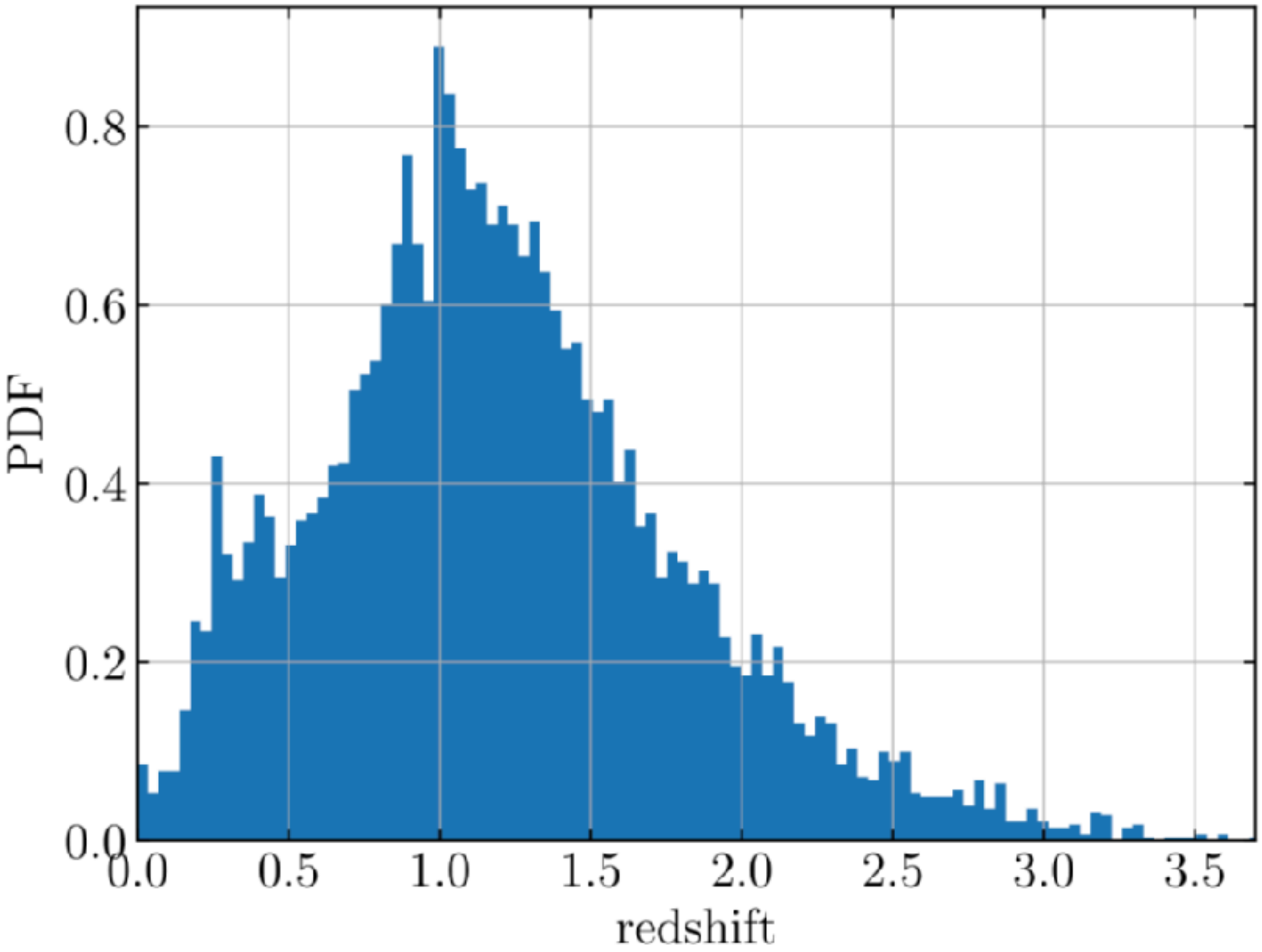
positions and the four-band photometry for 747,634,026 objects

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

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



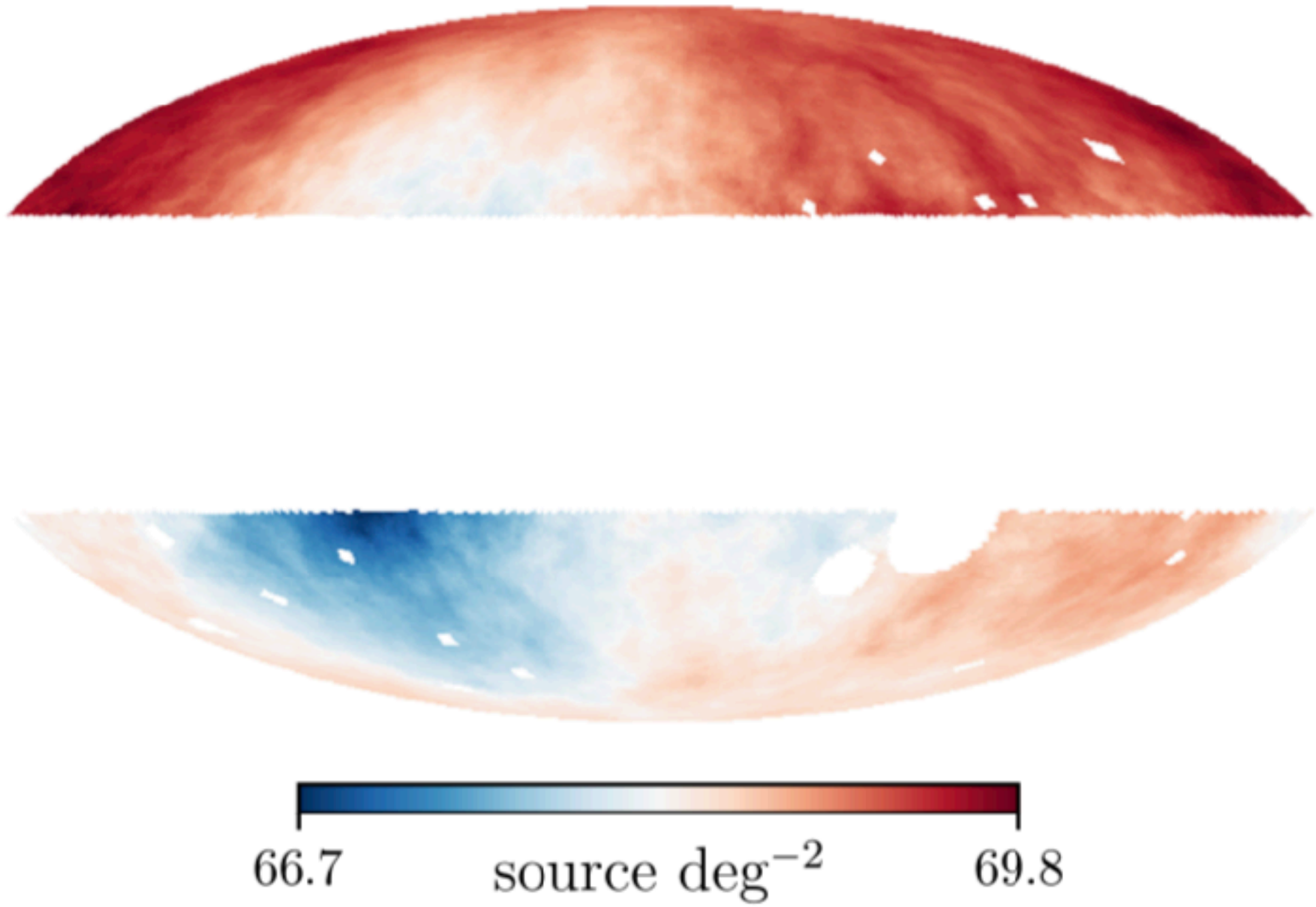
Redshift distribution



The Dipole

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

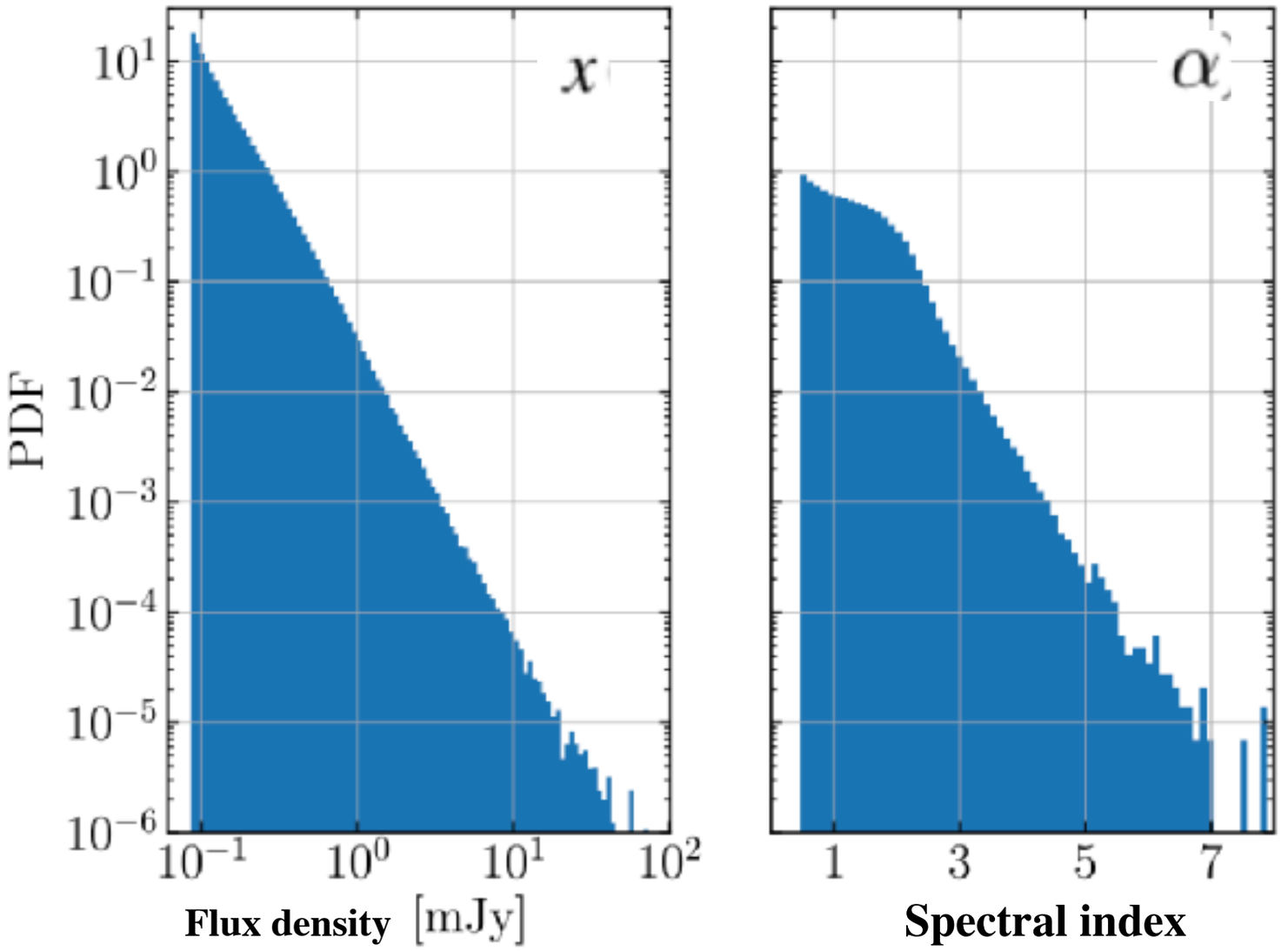
CMB dipole. = 0.007 , (l, b) = (276°, 30°)



MC simulations: Statistical significance

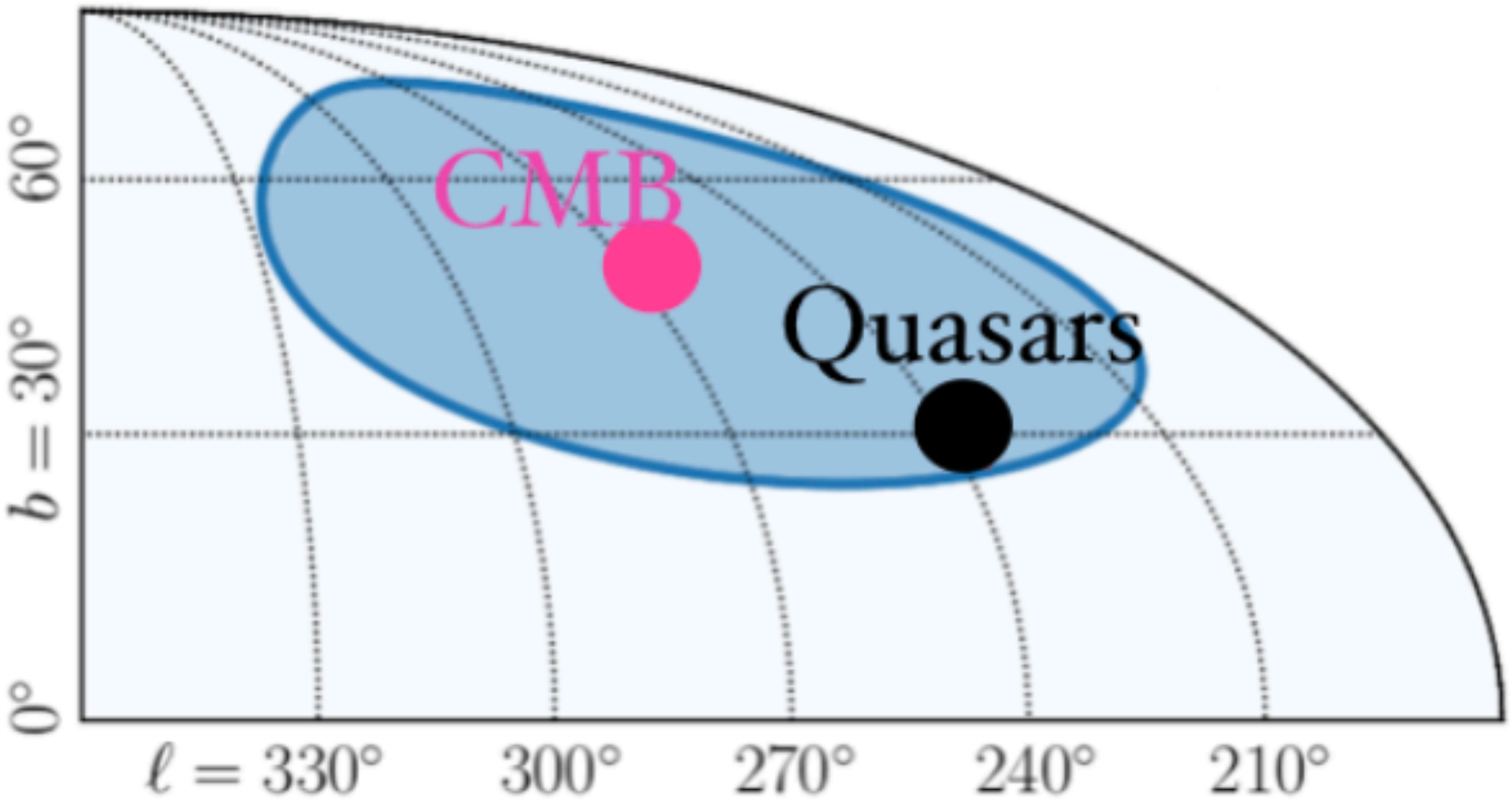
10^7 random sky
mimicking CatWISE
same masks,
estimator, flux….

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}

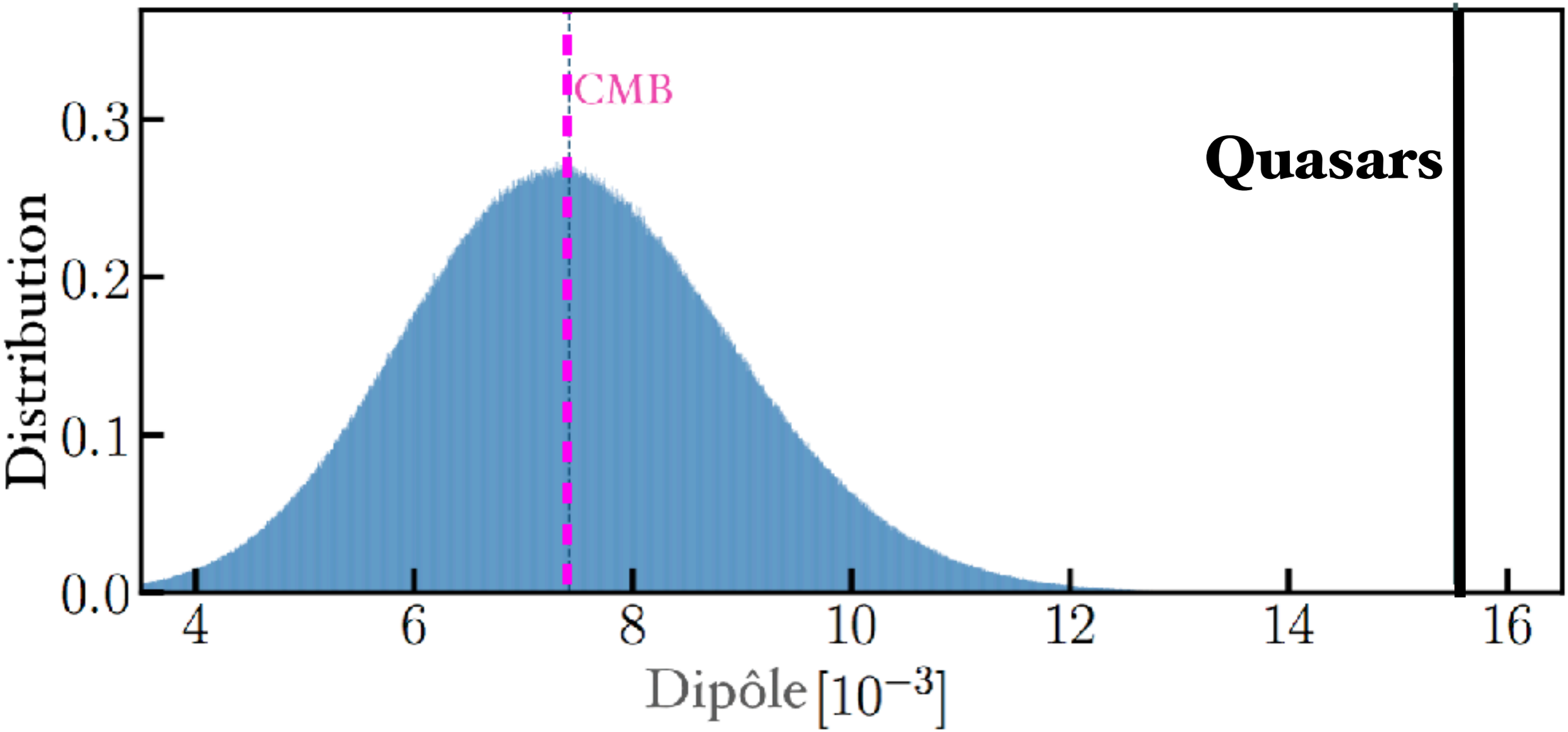
5/10000000 MC simulations



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)



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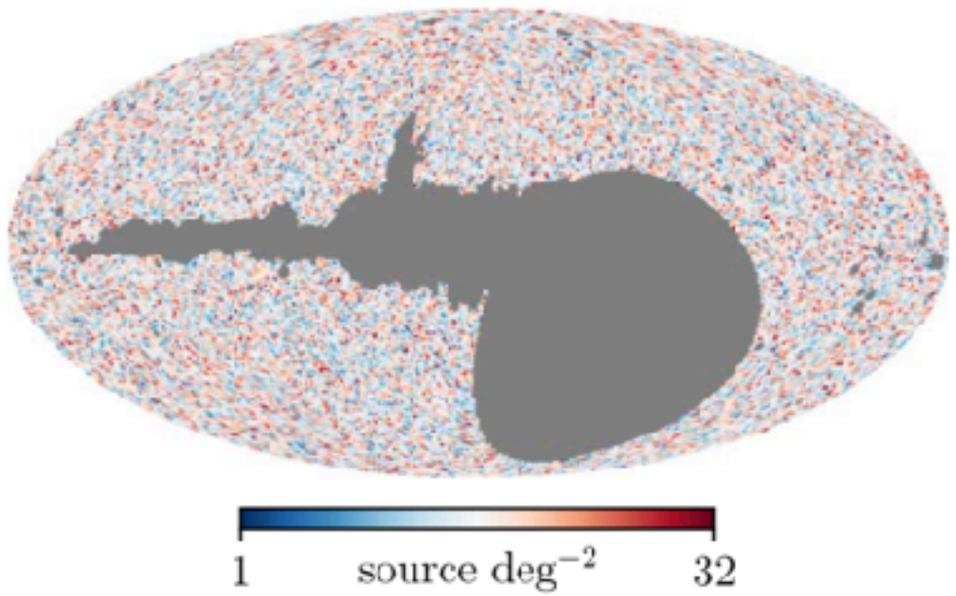
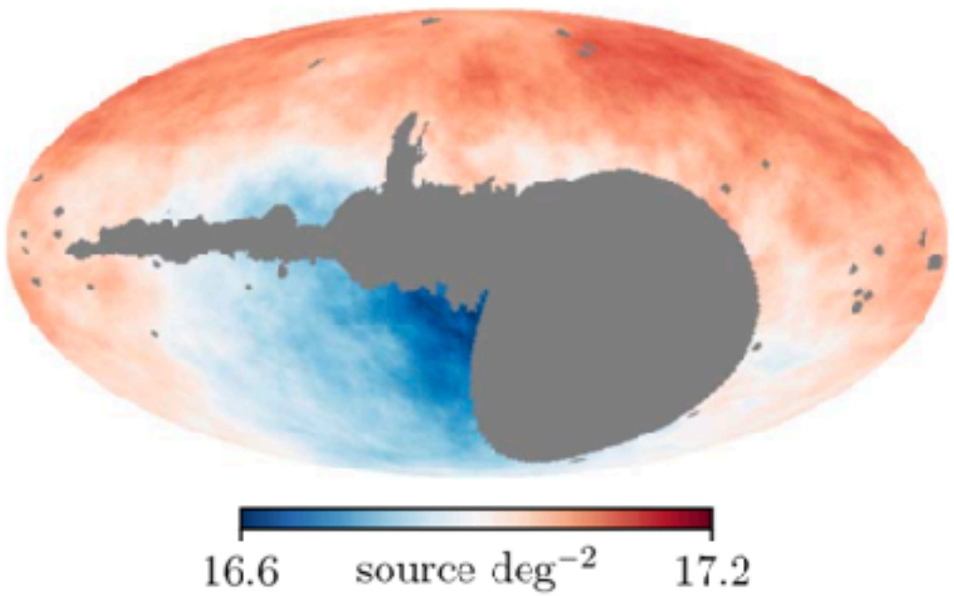
10^7 random sky
mimicking CatWISE
same masks,
estimator, flux….

ApJLetters 2021, 2022, Nature 2024

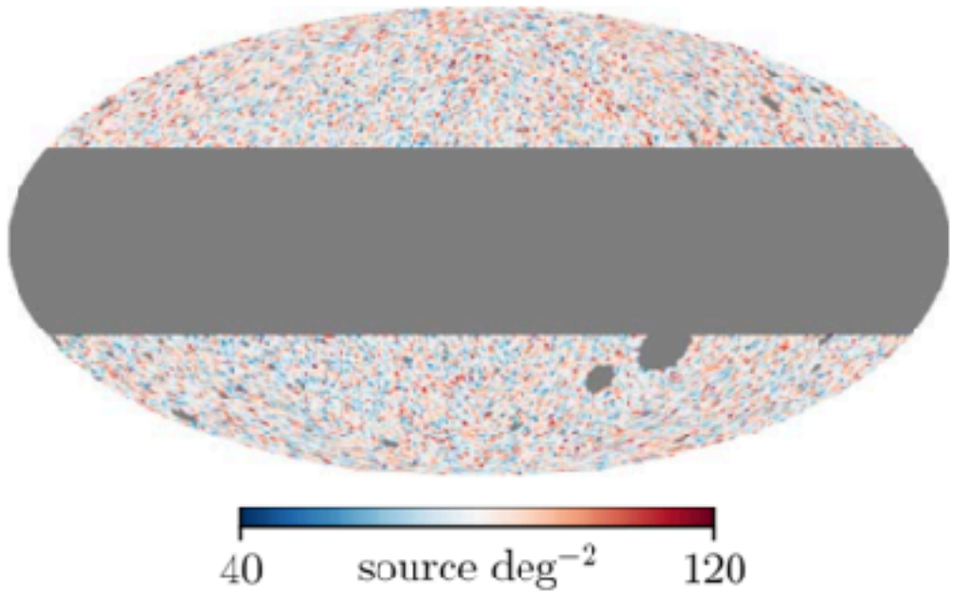
Do the Radio and the Infrared data agree ?

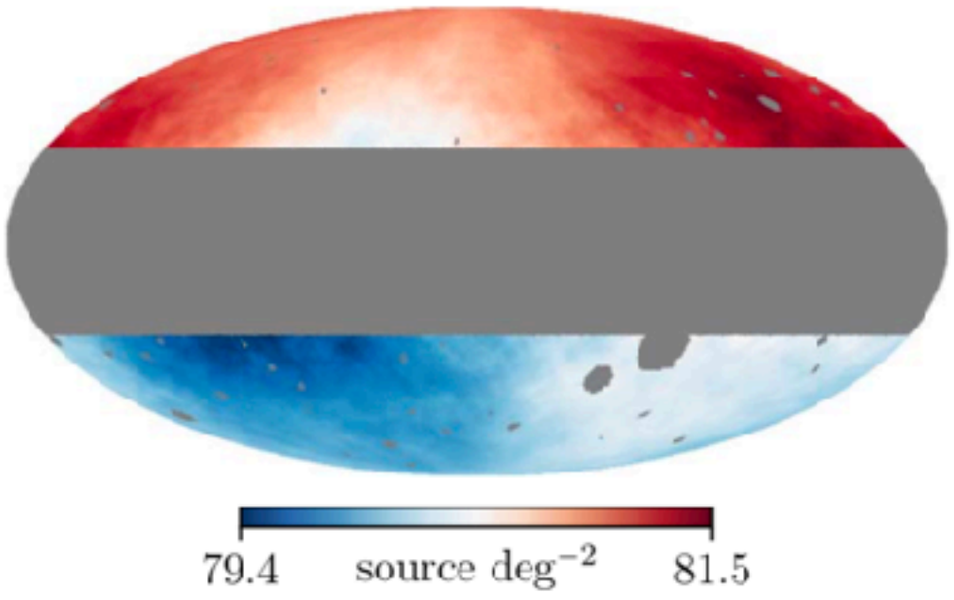
NVSS



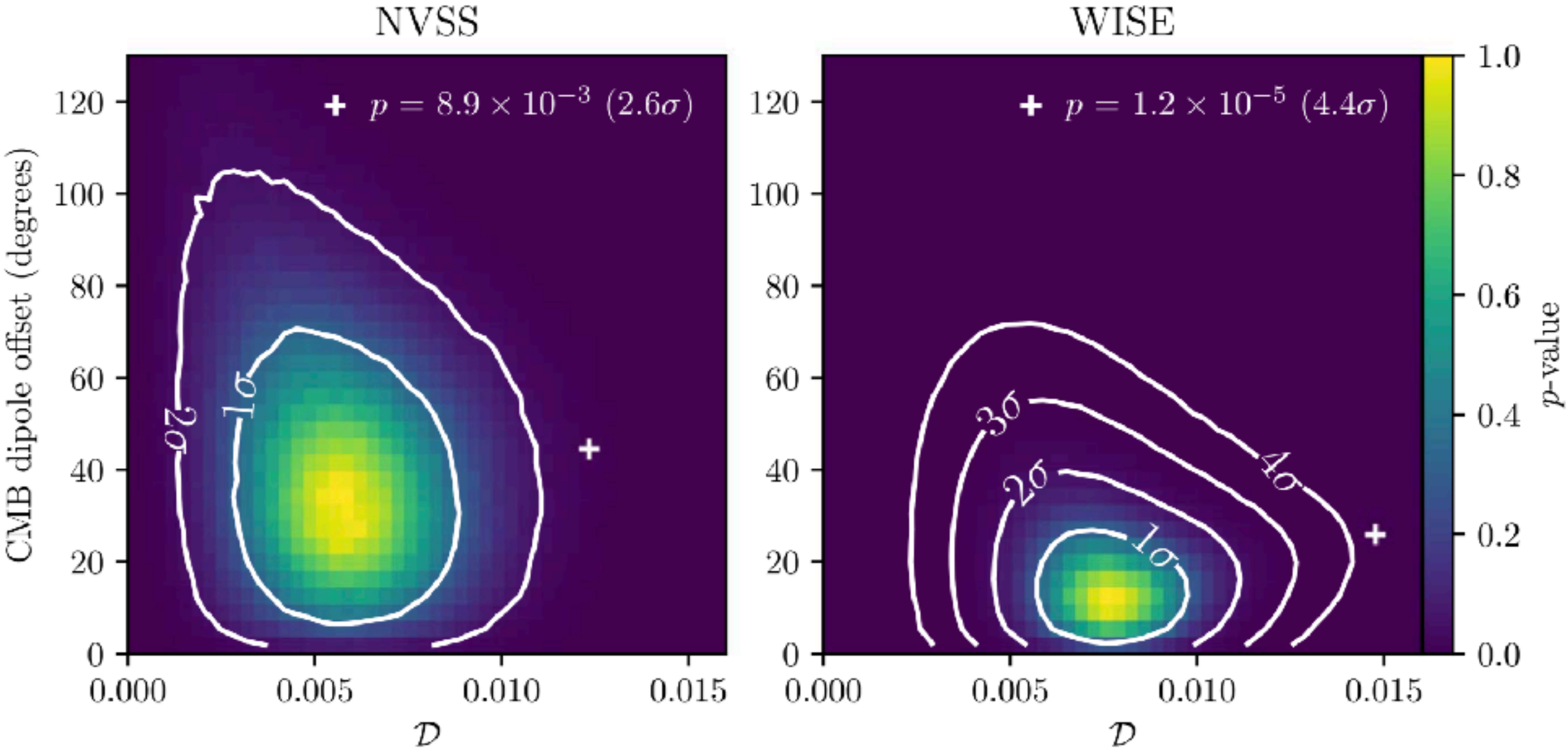


WISE





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



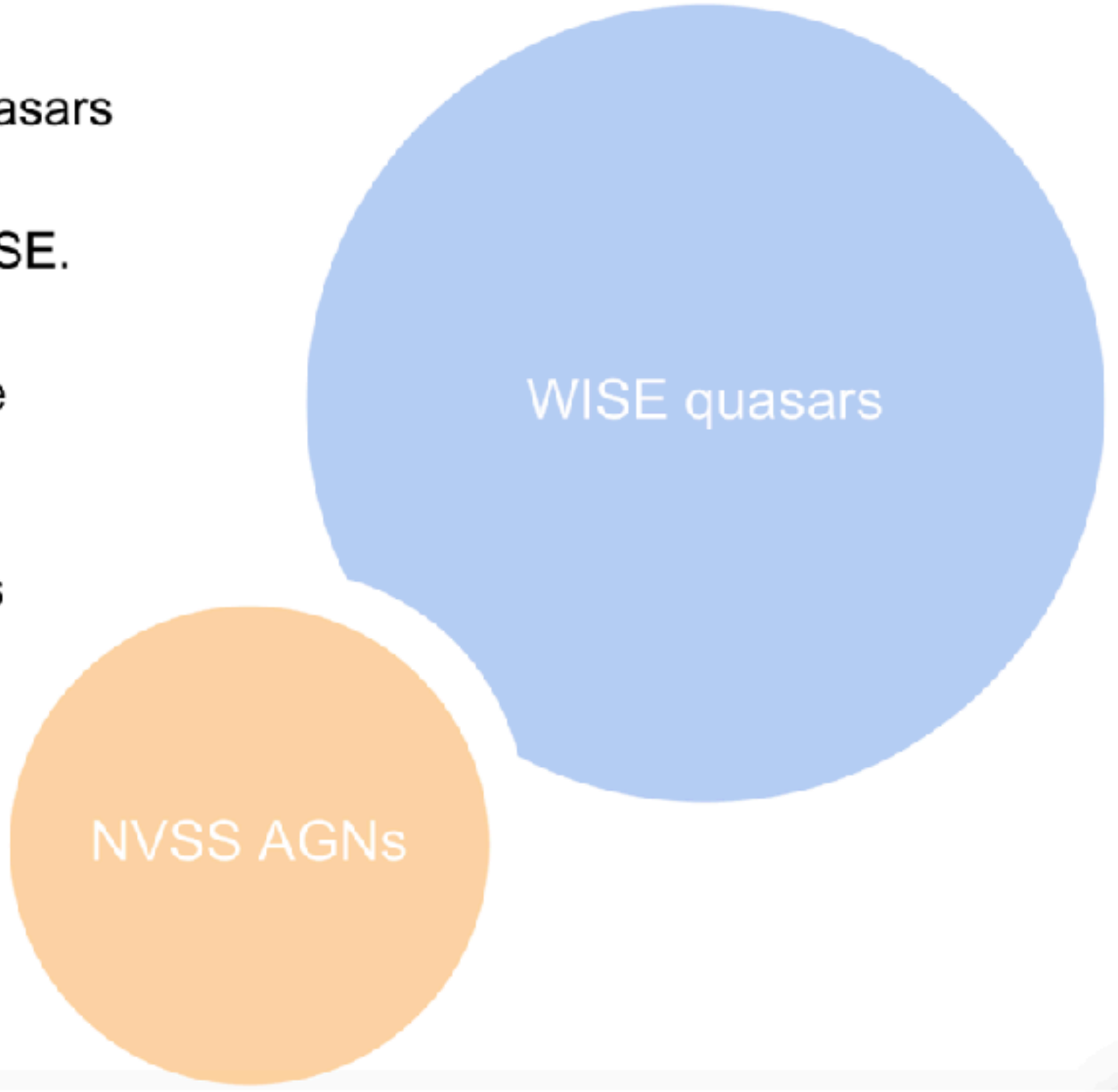
Shared sources: 1.4% of WISE quasars

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.**



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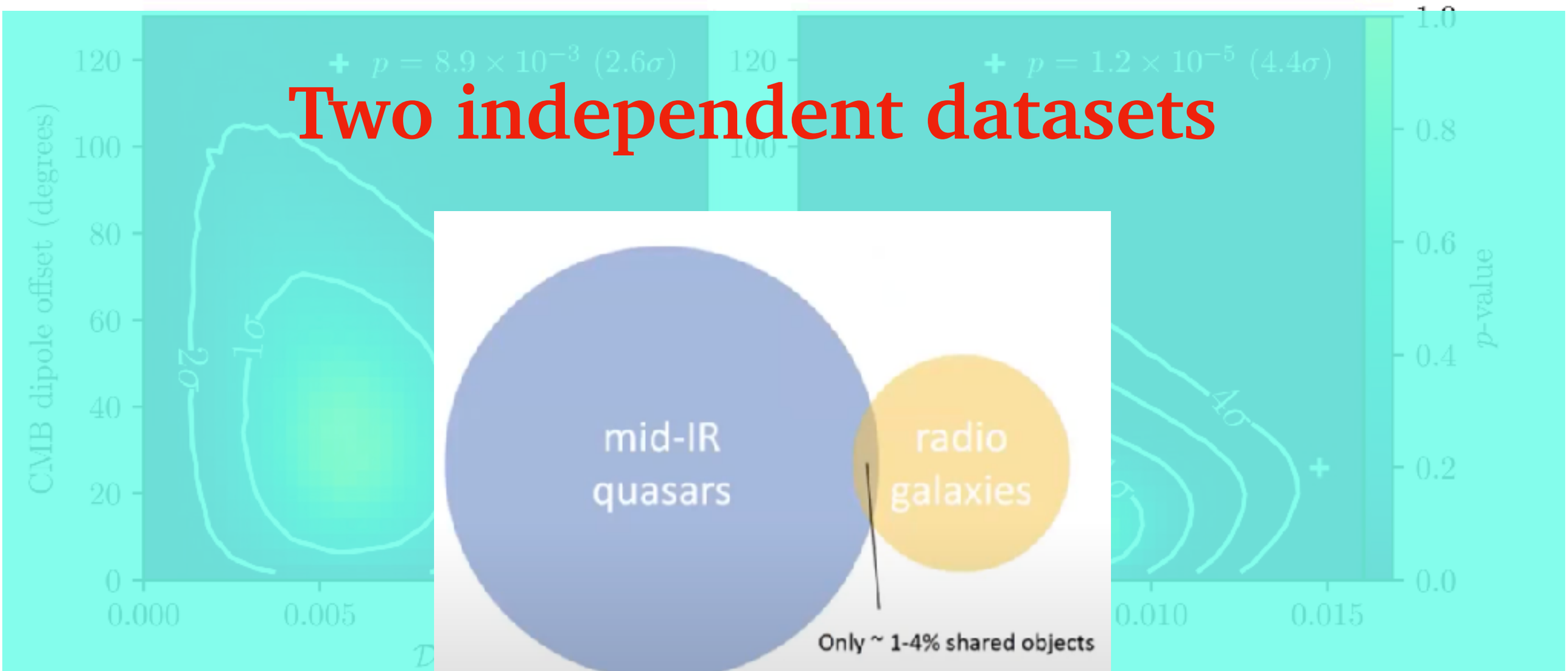
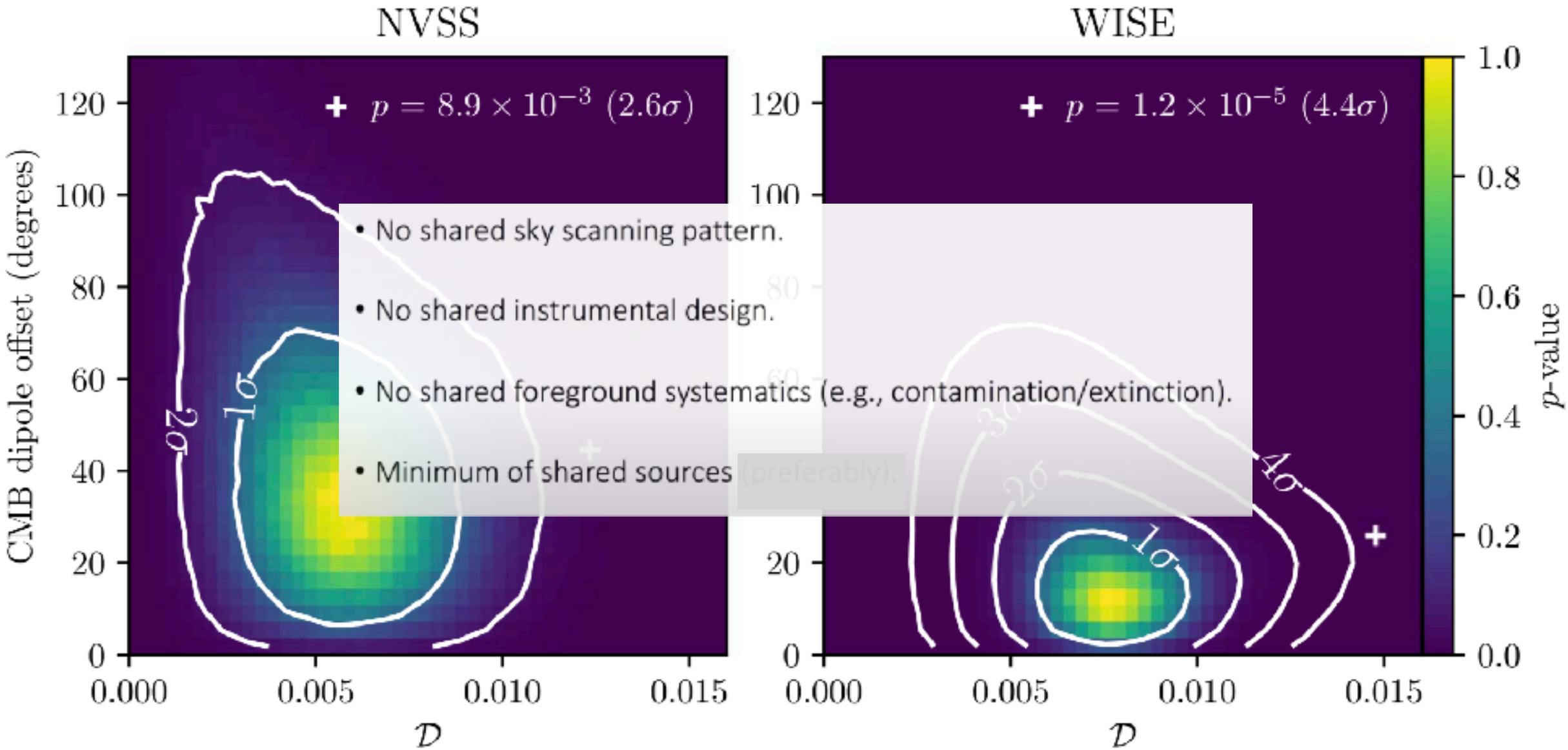


Two independent datasets

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



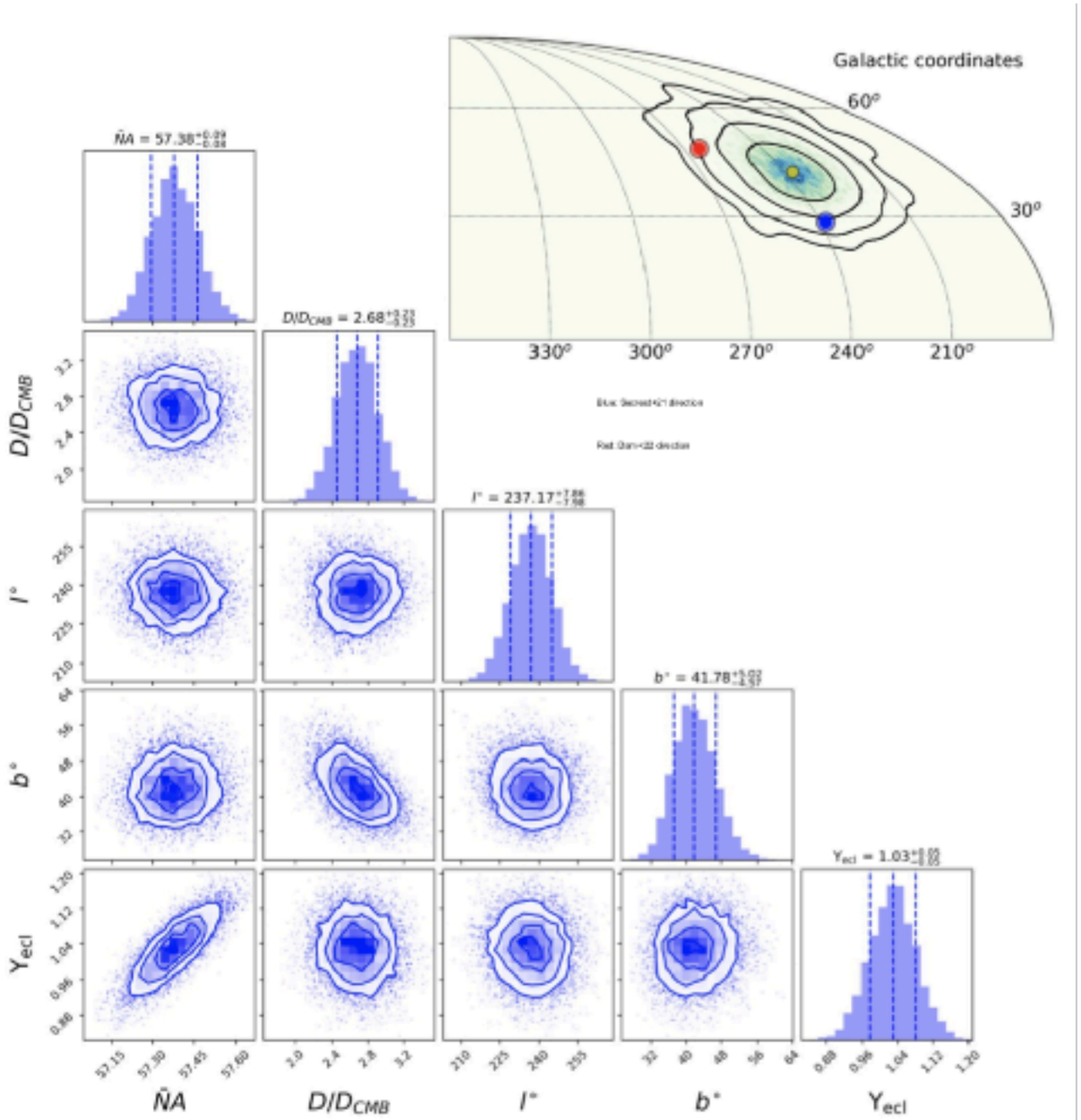
Results confirmed by Bayesian analysis

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

- Poissonian likelihood
- Uniform priors

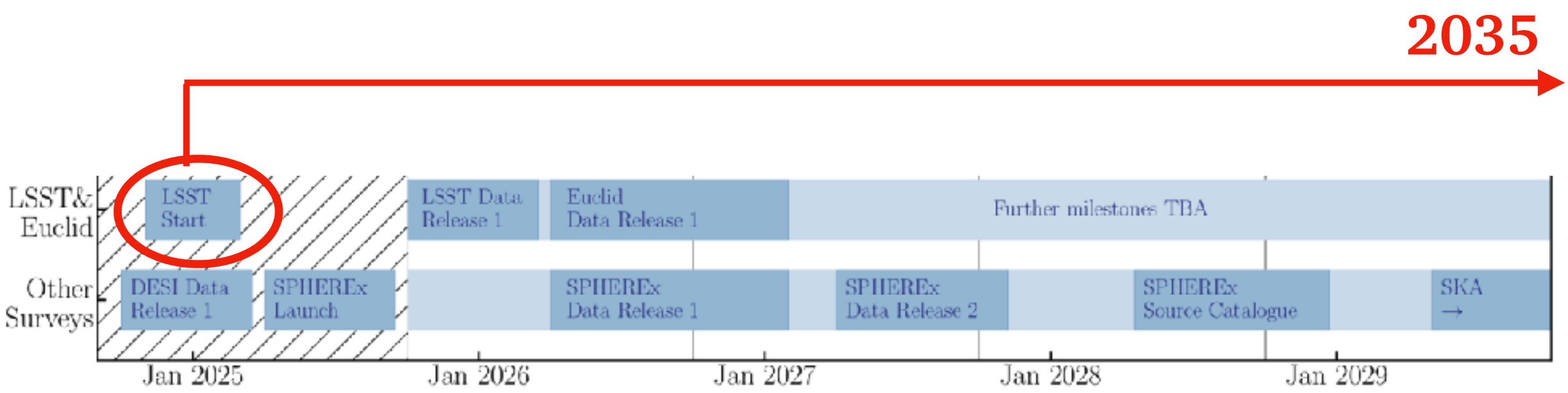
→ Found $D/D_{CMB} = 2.7$

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



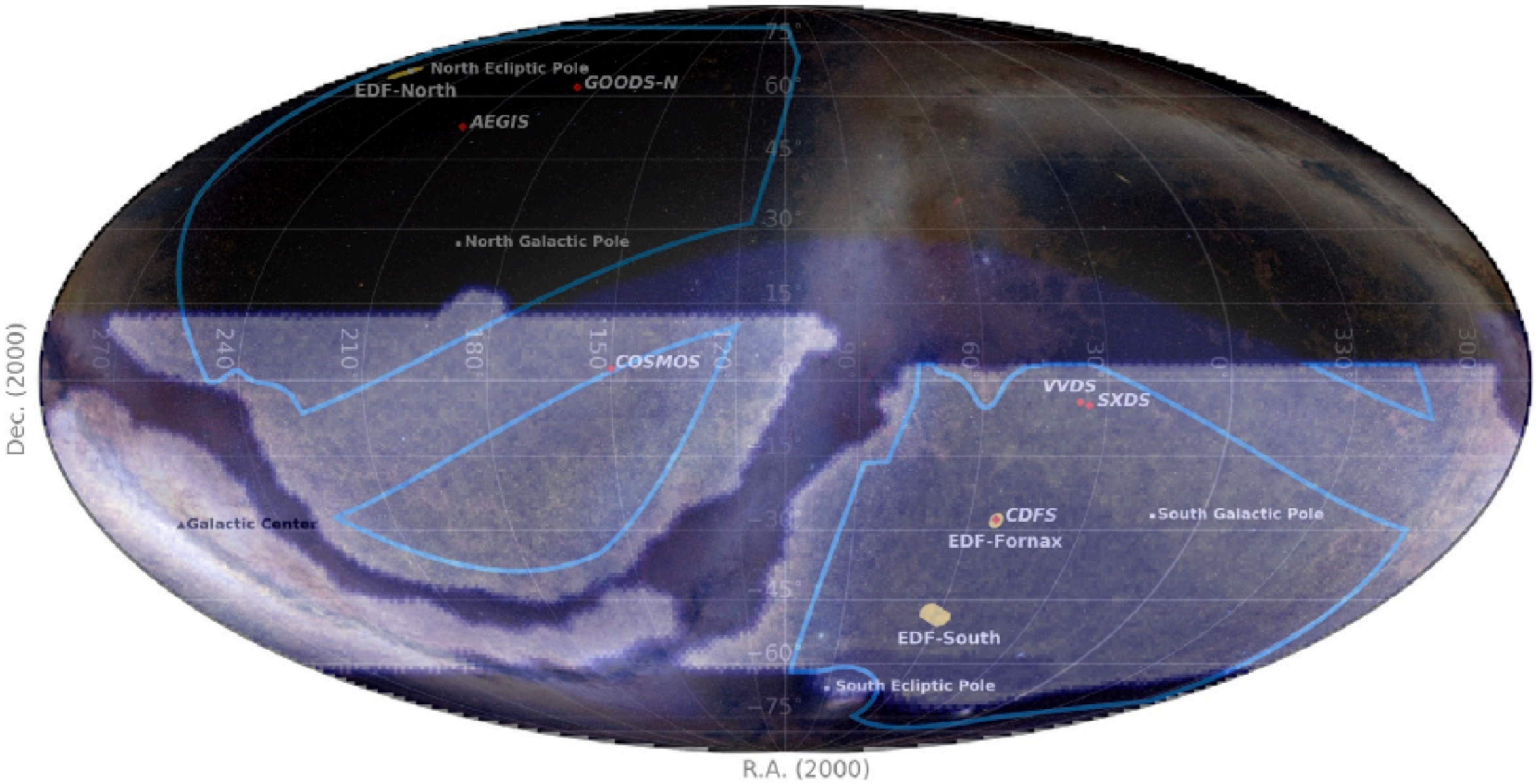
NA = mean count per sky pixel; Y_{ecl} = fractional offset of ecliptic latitude bias from value found by Secrest+21

Rubin LSST



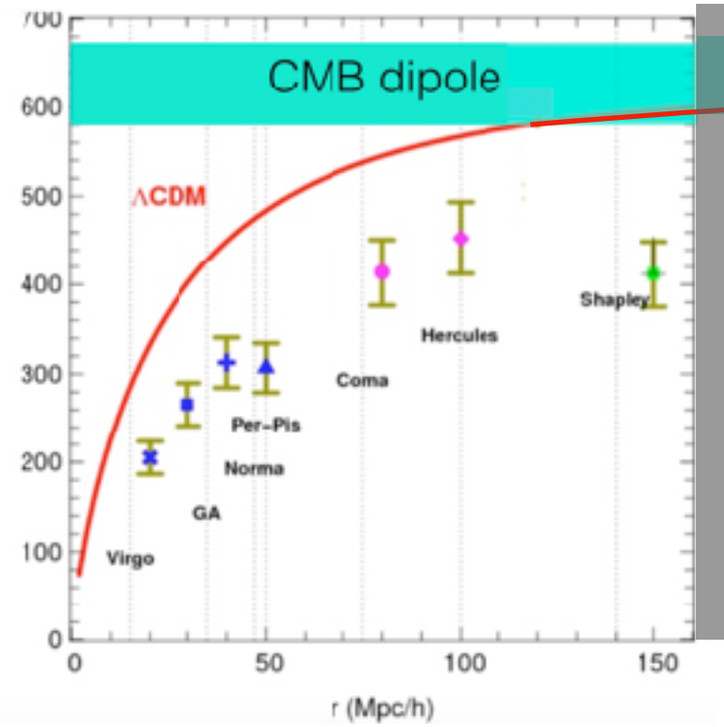
— systematic scan for 10 years
— One million SNe Ia , distances !
— 20 billions galaxies
— Photometric Redshift

Rubin LSST



Courtesy: Reza Ansari

A tomographic study : searching for CMB rest frame

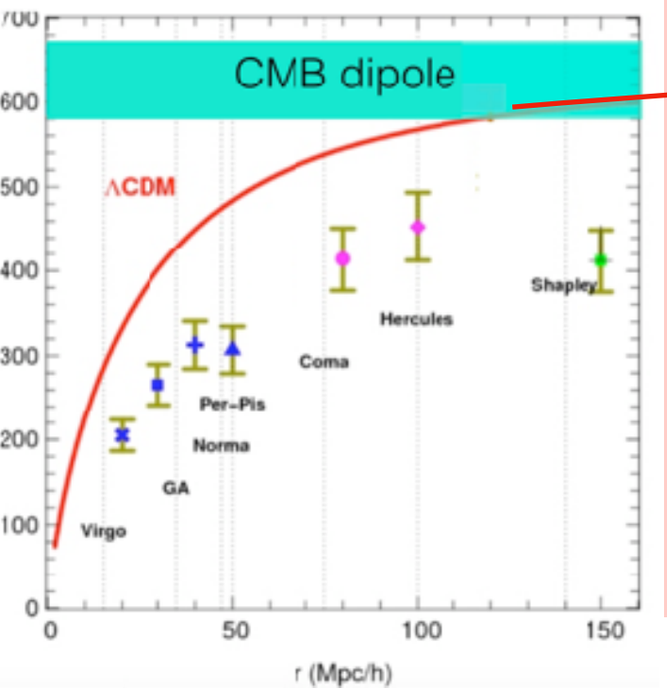


Towards much higher redshifts
z>1

Radio sources
&
Quasars

3000 Mpcs

A tomographic study : searching for CMB rest frame



100 Mpc

Gpcs

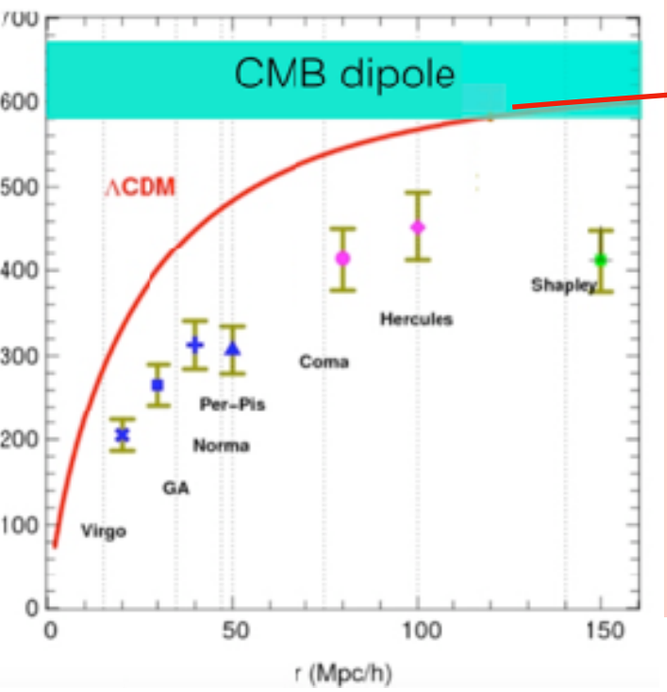
LSST

NVSS & WISE

SNe Ia **Galaxies** **Radio sources & Quasars**

$Z < 0.05$ $Z < 1\text{-}1.5$ $Z > 1$

A tomographic study : searching for CMB rest frame



100 Mpc

Gpcs

LSST

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SNe Ia **Galaxies** **Radio sources & Quasars**

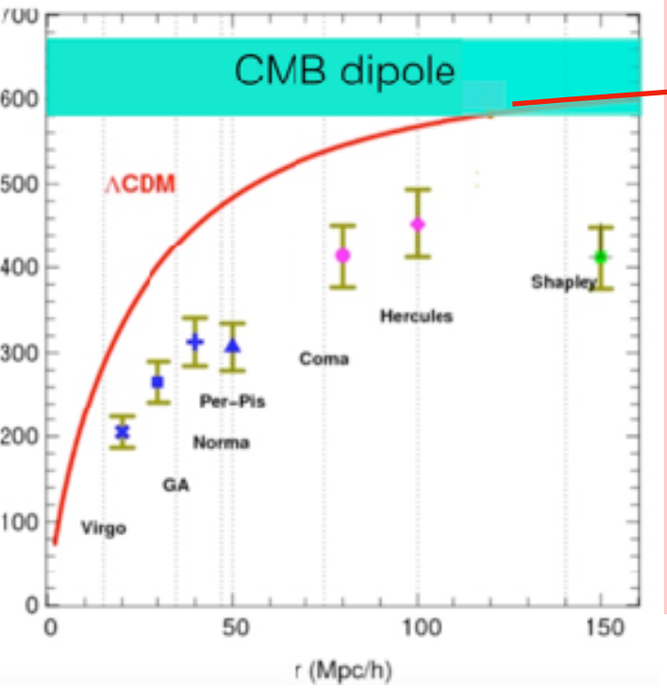
Z < 0.05

Z < 1-1.5

Z >1

intrinsic/clustering dipole

A tomographic study : searching for CMB rest frame



100 Mpc

Gpcs

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SNe Ia

Galaxies

Radio sources & Quasars

Z < 0.05

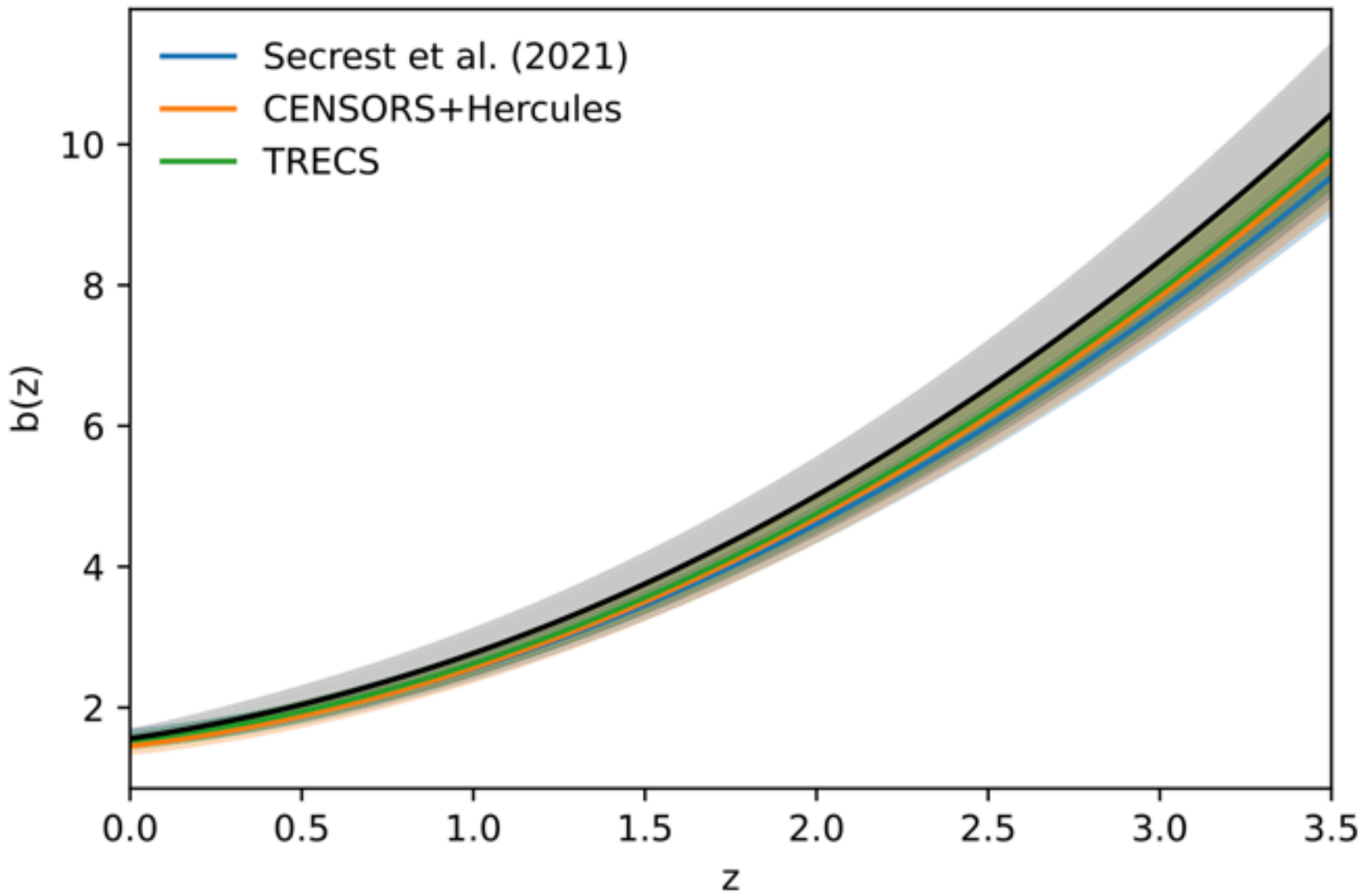
Z < 1-1.5

Z >1

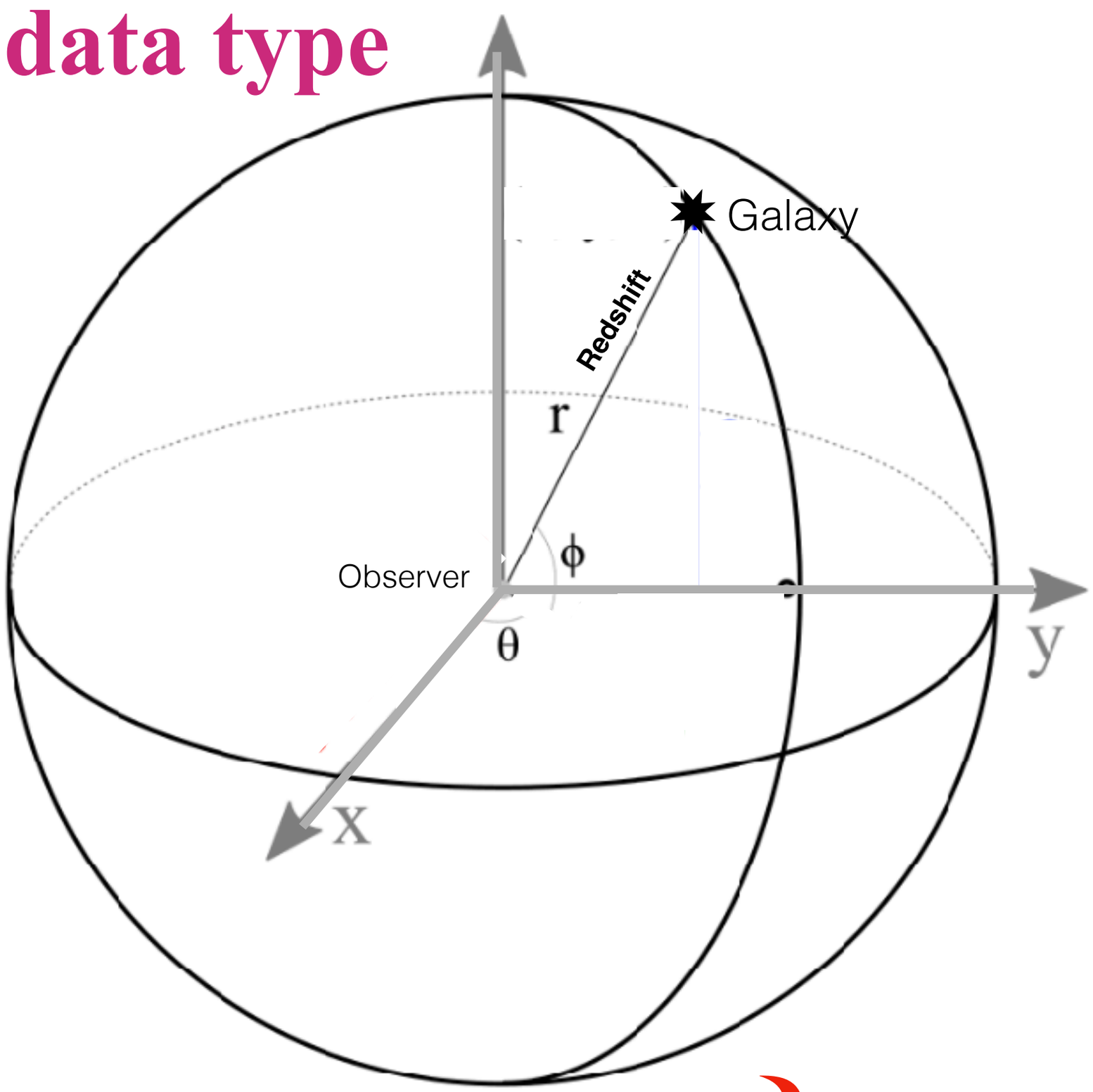
intrinsic/clustering dipole

Biasing

Biasing


Secrest et al. (2021)
CENSORS+Hercules
TRECS
b(z)
10
8
6
4
2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z

probes: data type



(I) Θ, φ, z, d (distance catalogues, SNe IA, nearby)

(II) Θ, φ, z (redshift surveys, medium redshifts)

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

} With Rubin LSST

FIN