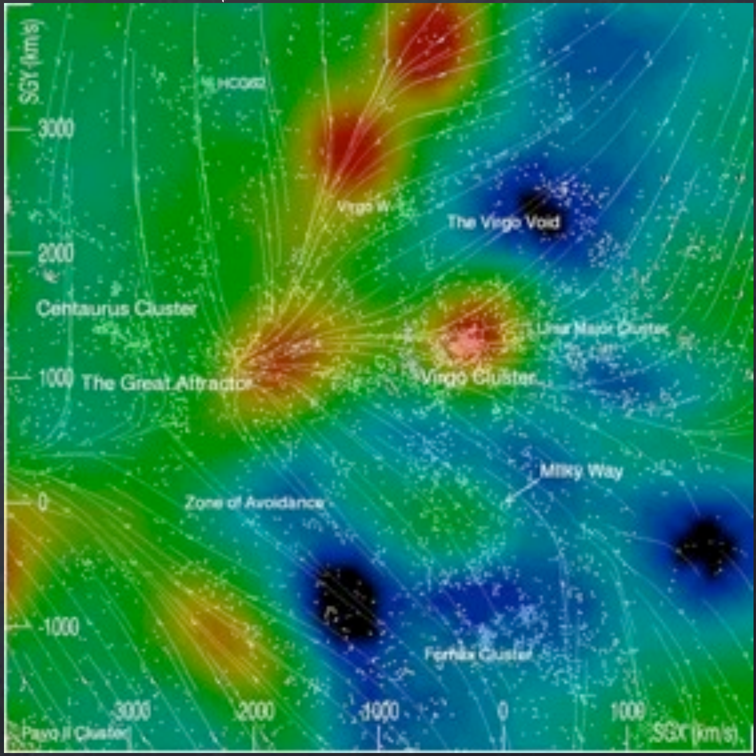
Estimating Scale Dependent Cosmic Bulkflows from Peculiar Velocity Surveys



Shankar Agarwal

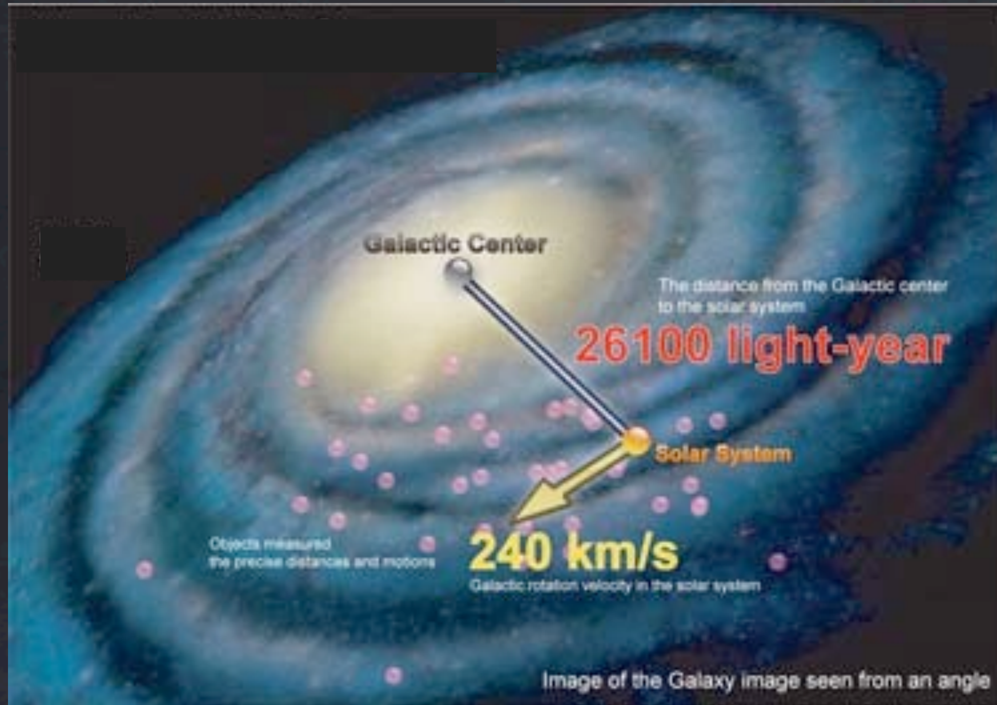
PhD, 2013 Univ. of Kansas, USA (w/ Hume Feldman)

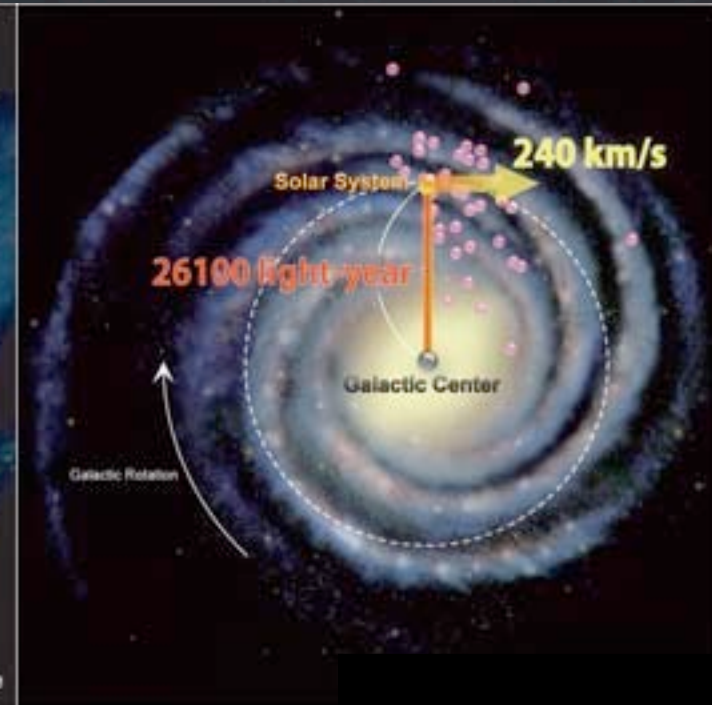
- Matter Power Spectrum Emulator
- Massive Neutrino simulations
- Large Scale Bulk Flows

PostDoc, LUTh, Meudon (w/ Pier-Stefano Corasaniti)

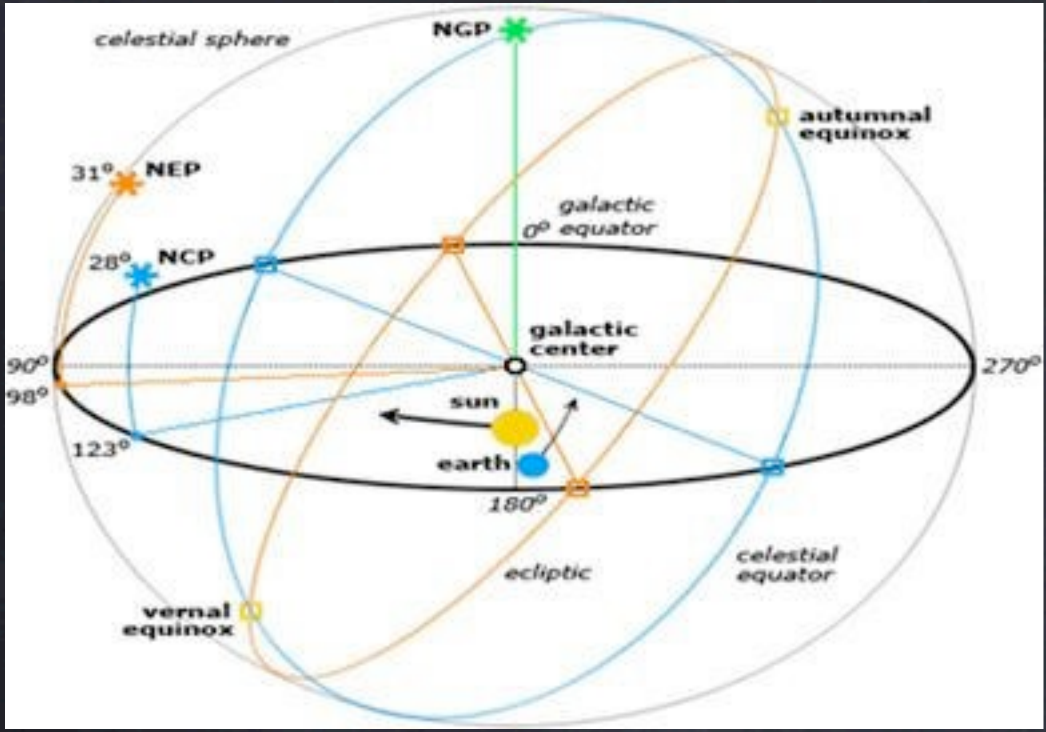
- Warm Dark Matter Cosmologies
- Clustered Dark Energy simulations

Agarwal, Feldman,, MNRAS 432, 307-317, (2013)
Macaulay, Feldman, Jaffe, Agarwal, Hudson, Watkins, MNRAS 425, 1709-1717 (2012)
Agarwal, Feldman, Watkins, MNRAS 424, 2667-2675, (2012)

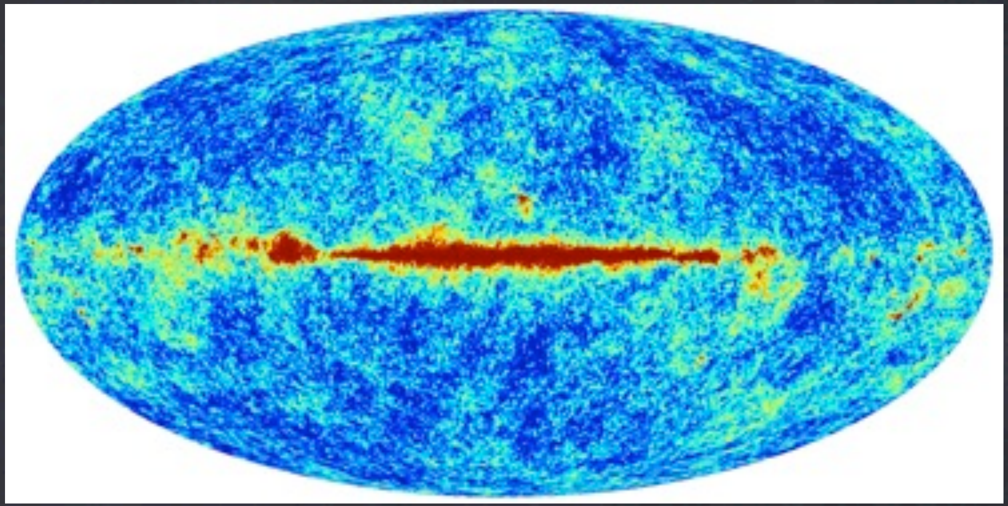

Galactic Center
The distance from the Galactic center
to the solar system
26100 light-year
Solar System
Objects measured
the precise distances and motions
240 km/s
Galactic rotation velocity in the solar system
Image of the Galaxy image seen from an angle


240 km/s
Solar System
26100 light-year
Galactic Center
Galactic Rotation

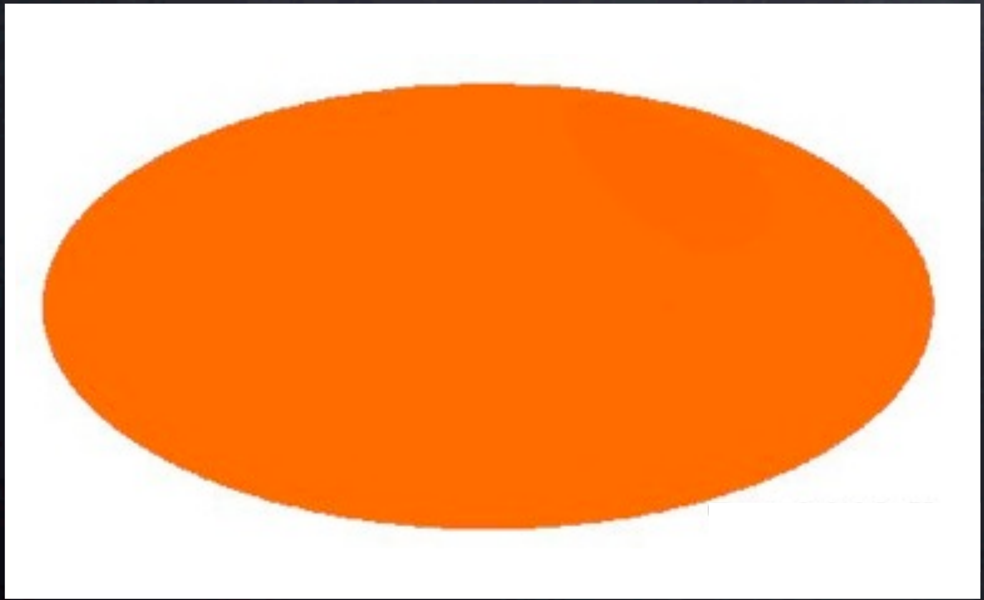

60°



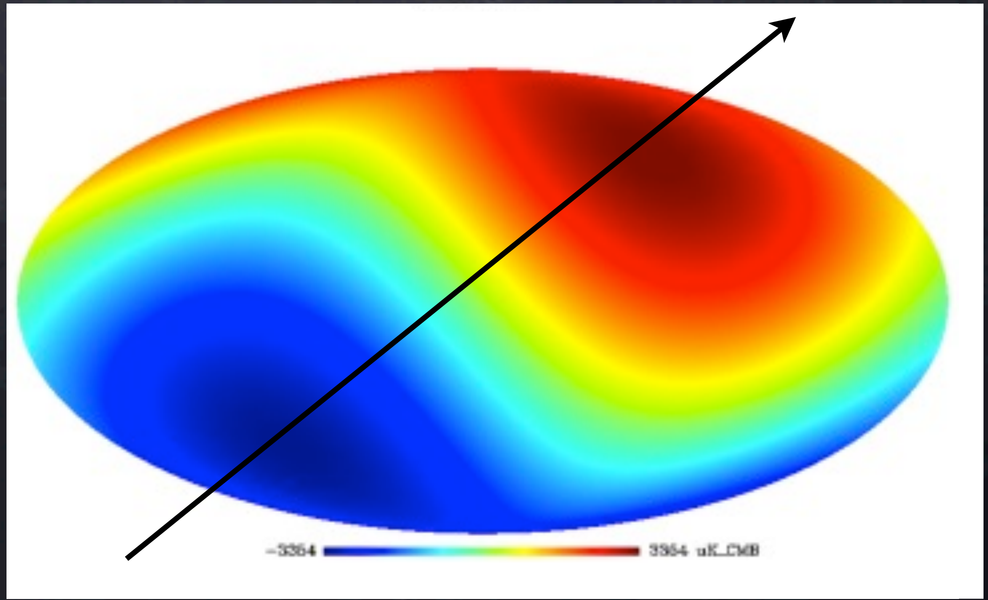
CMB



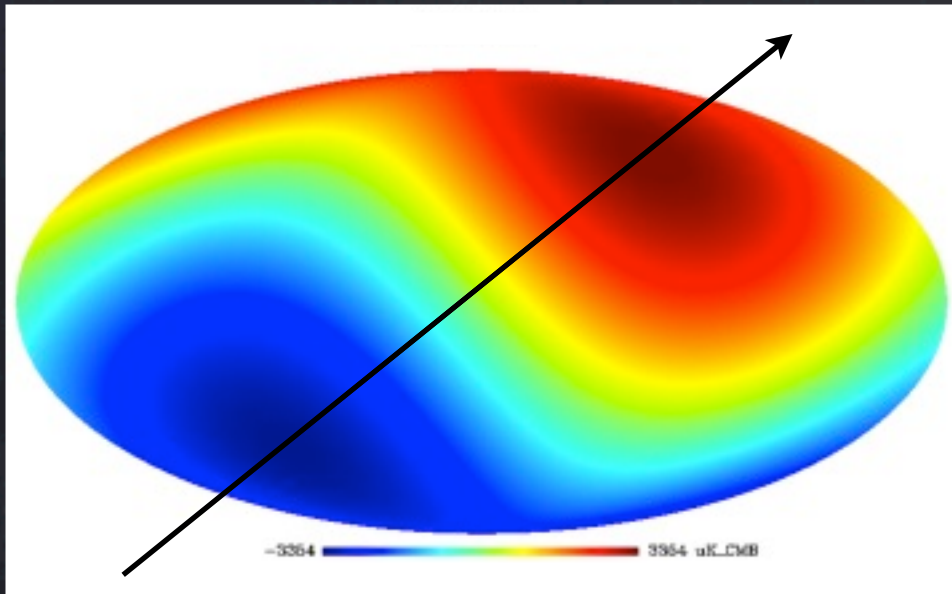
2.725 K



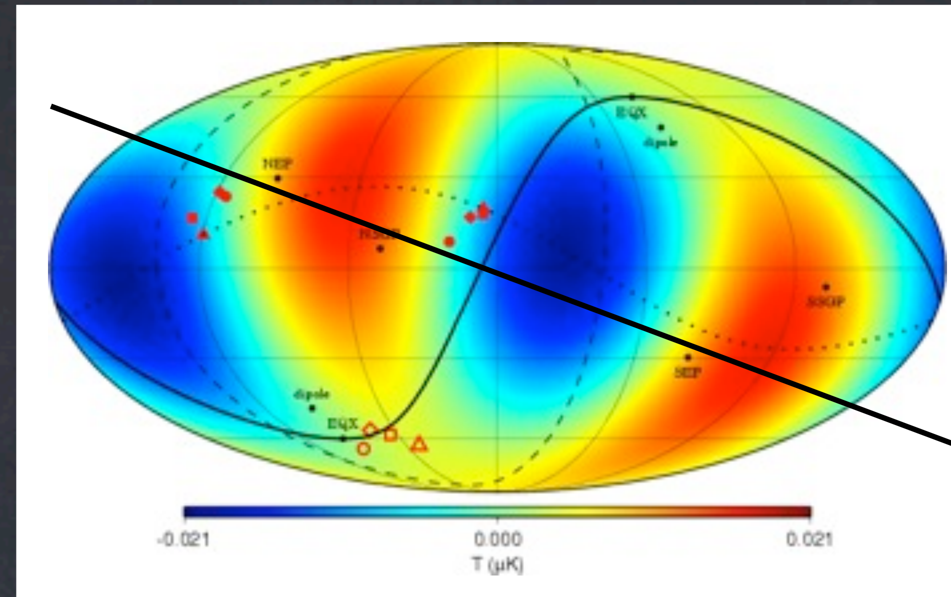
369km/s (264°,48°)



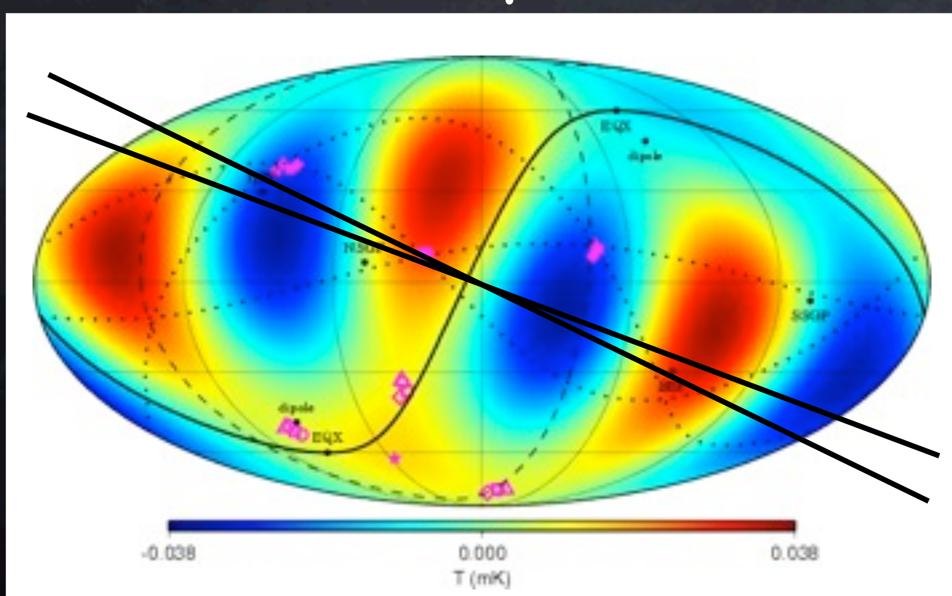
Dipole



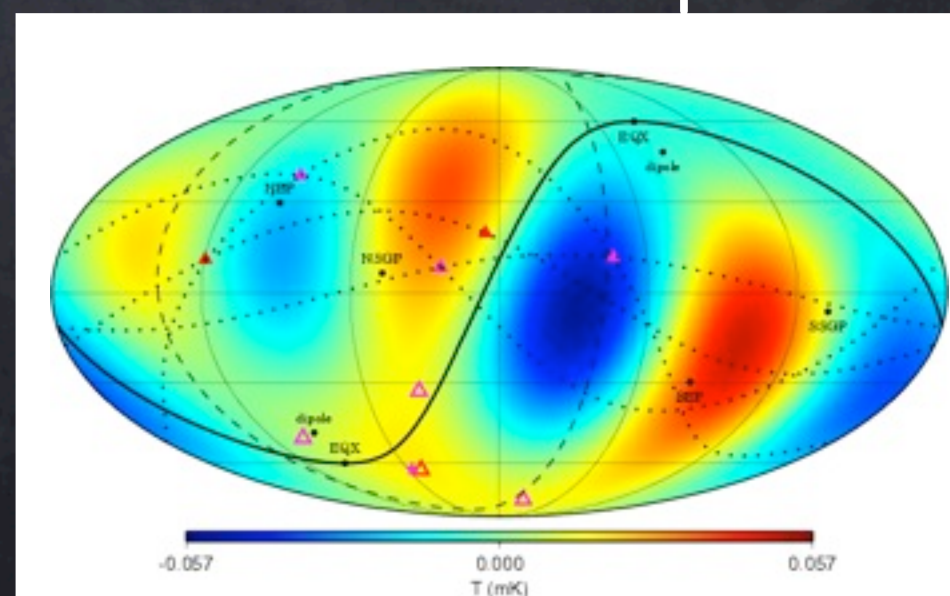
Quadrupole



Octupole



Quad + Octupole



Less than 0.1% probability of happening

Possible Explanations offered...

1. Compact Universe prevent matter sloshing.

Zeldovich 1984

Stevens, Scott, Silk 1993

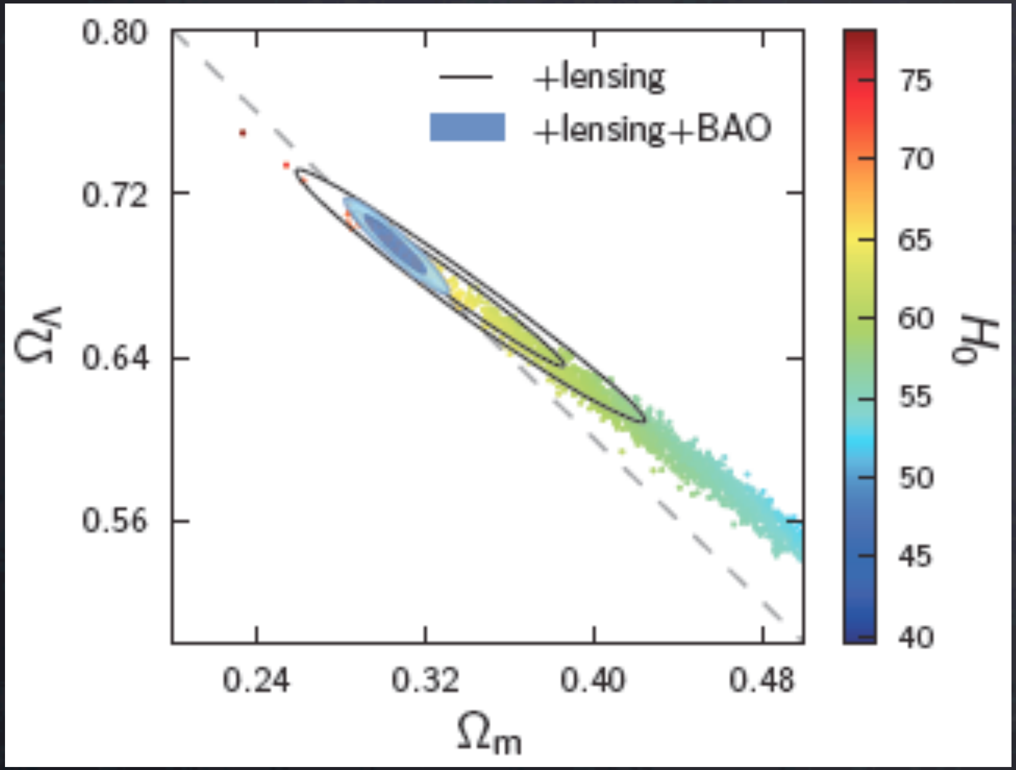
Tegmark, Costa, Hamilton 2013

Max Tegmark: "There's a hint in the data that if you traveled far and fast in the direction of the constellation Virgo, you'd return to Earth from the opposite direction,"

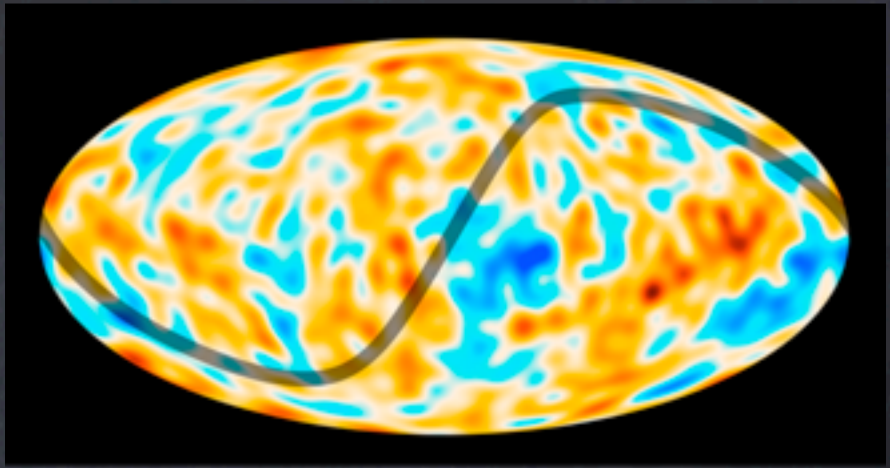
Possible Explanations offered...

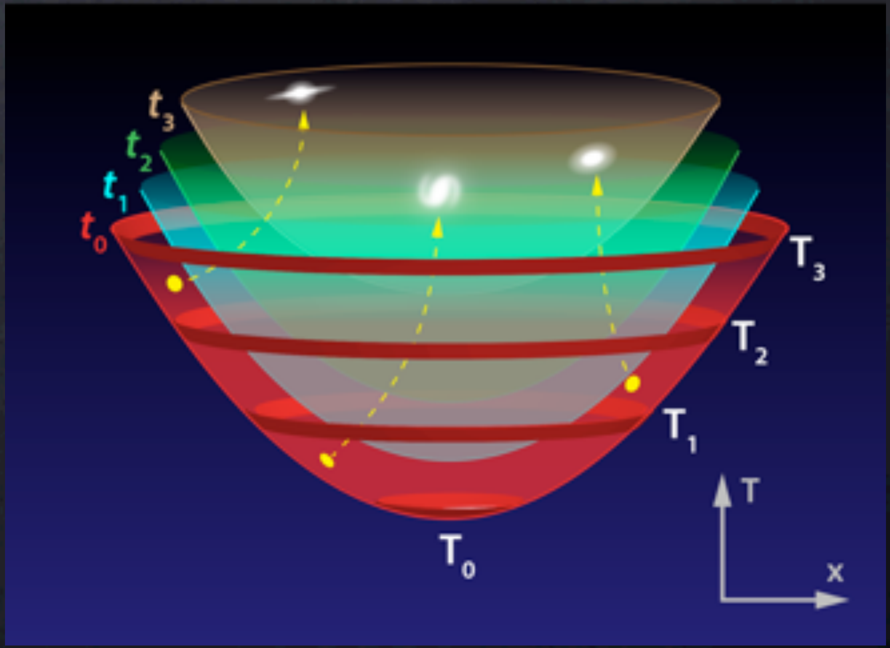
3. Open Universe Liddle, Cortes 2013

Universe arose from decay of a metastable false vacuum state via bubble nucleation.



Planck 2013

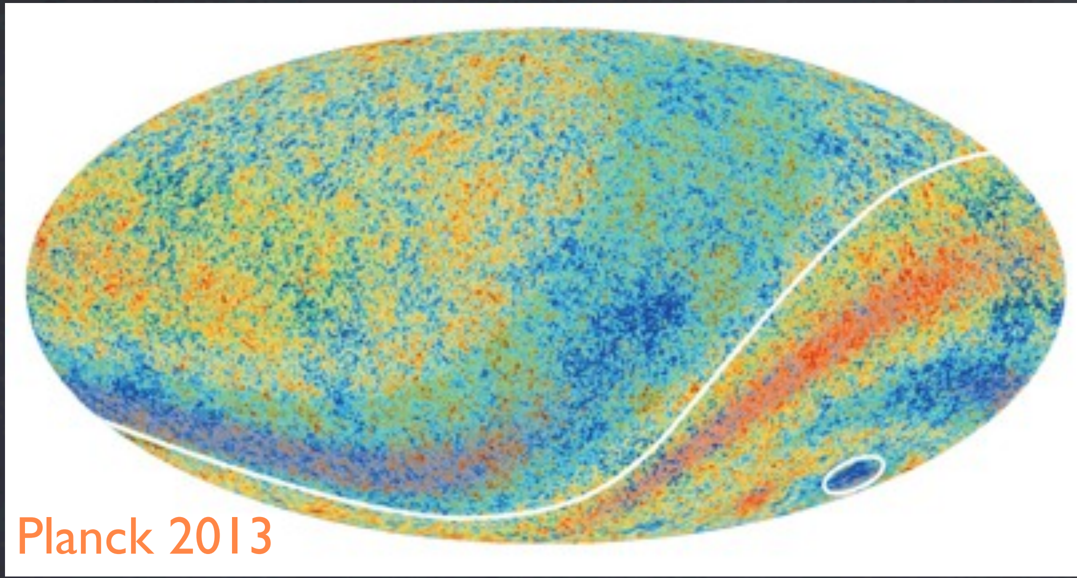




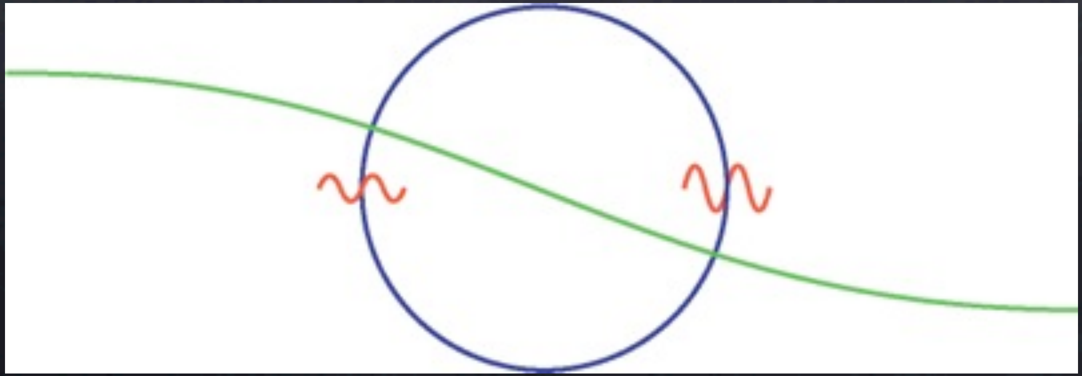
$\Omega_k = 0$ to within 1%

Possible Explanations offered...

3. Lopsided Universe


Planck 2013

A Hemispherical Power Asymmetry from Inflation

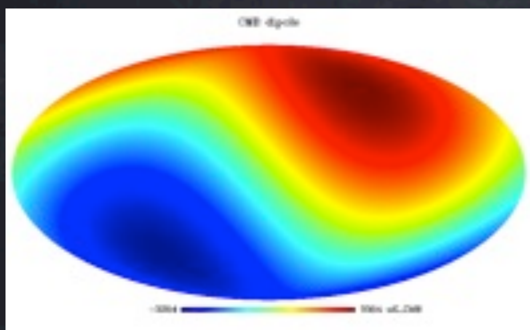


Erickcek, Kamionkowski, Carroll 2008

Possible Explanations offered...

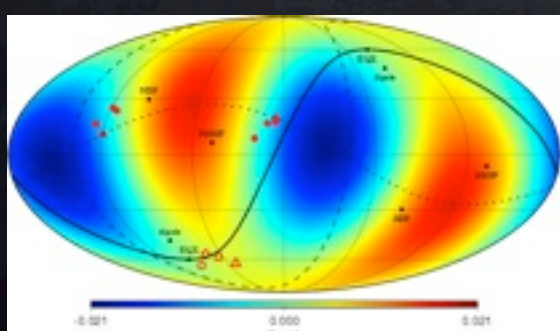
4. Weak Gravitational Lensing of the CMB   Vale 2005

Weak gravitational lensing by local large scale structures will coherently deform the initially perfect dipole, causing a leakage of power at the sub-percent level into other low- ℓ moments.

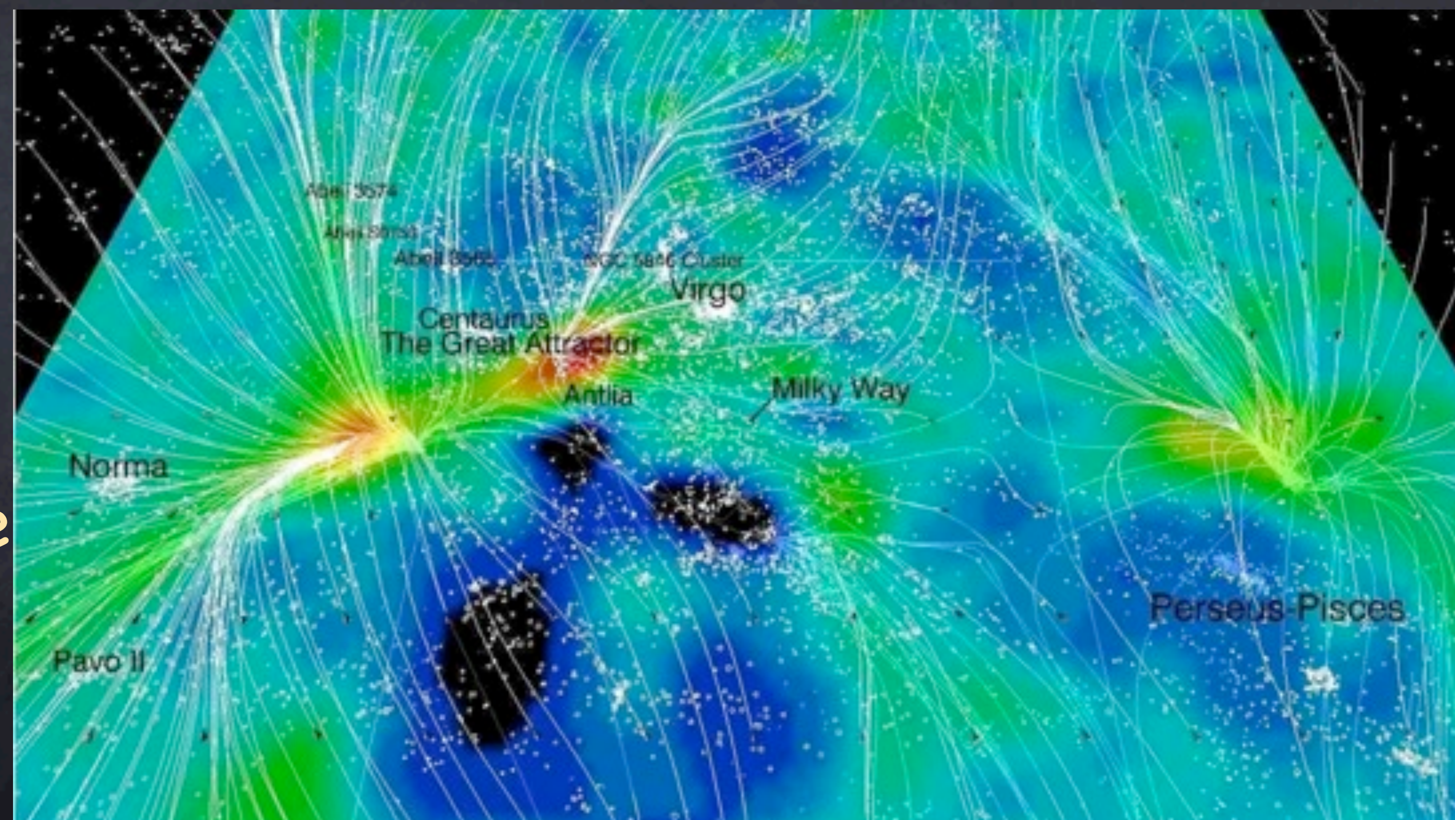


3.5 mK

Power leakage

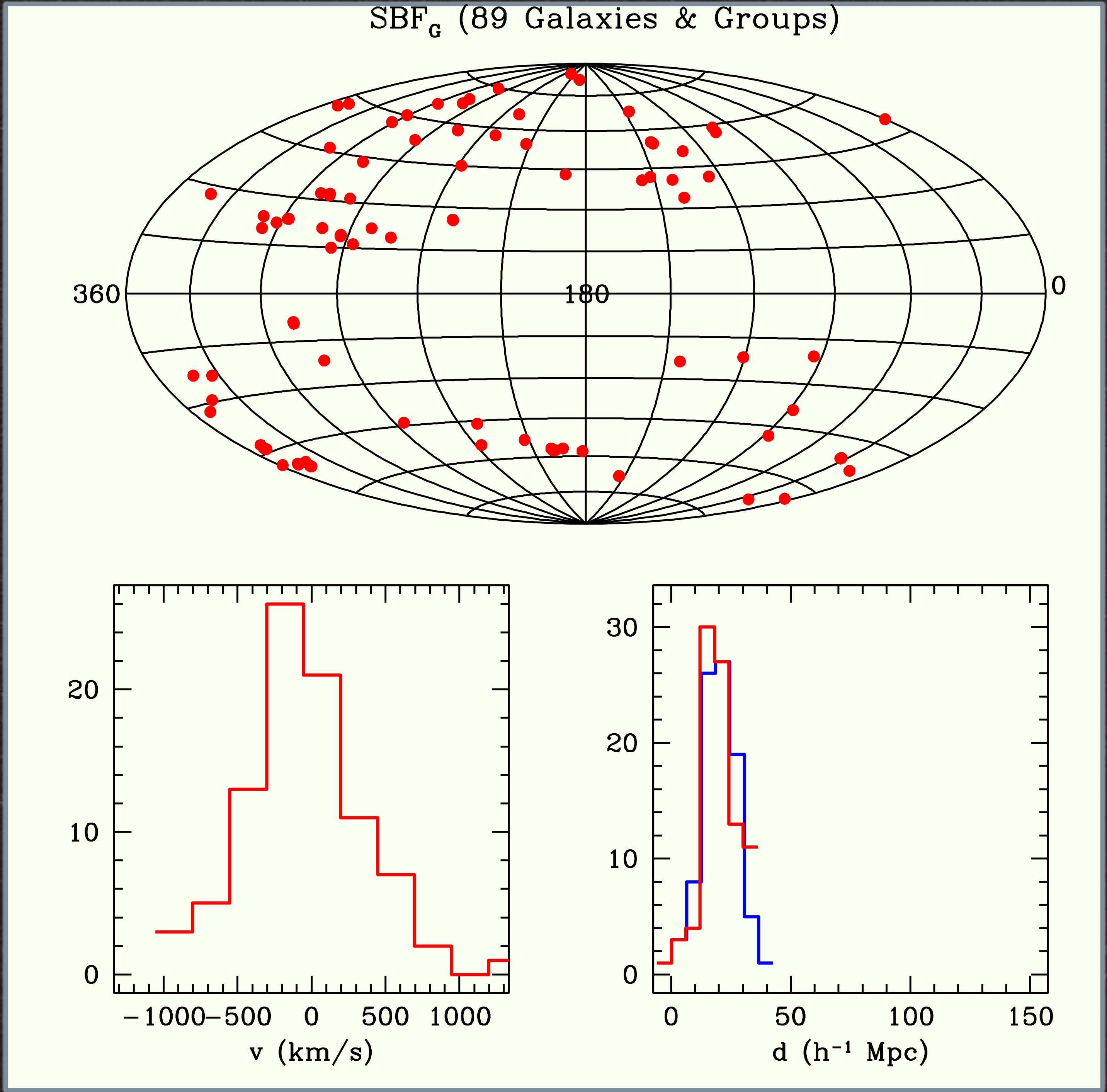


.035 mK

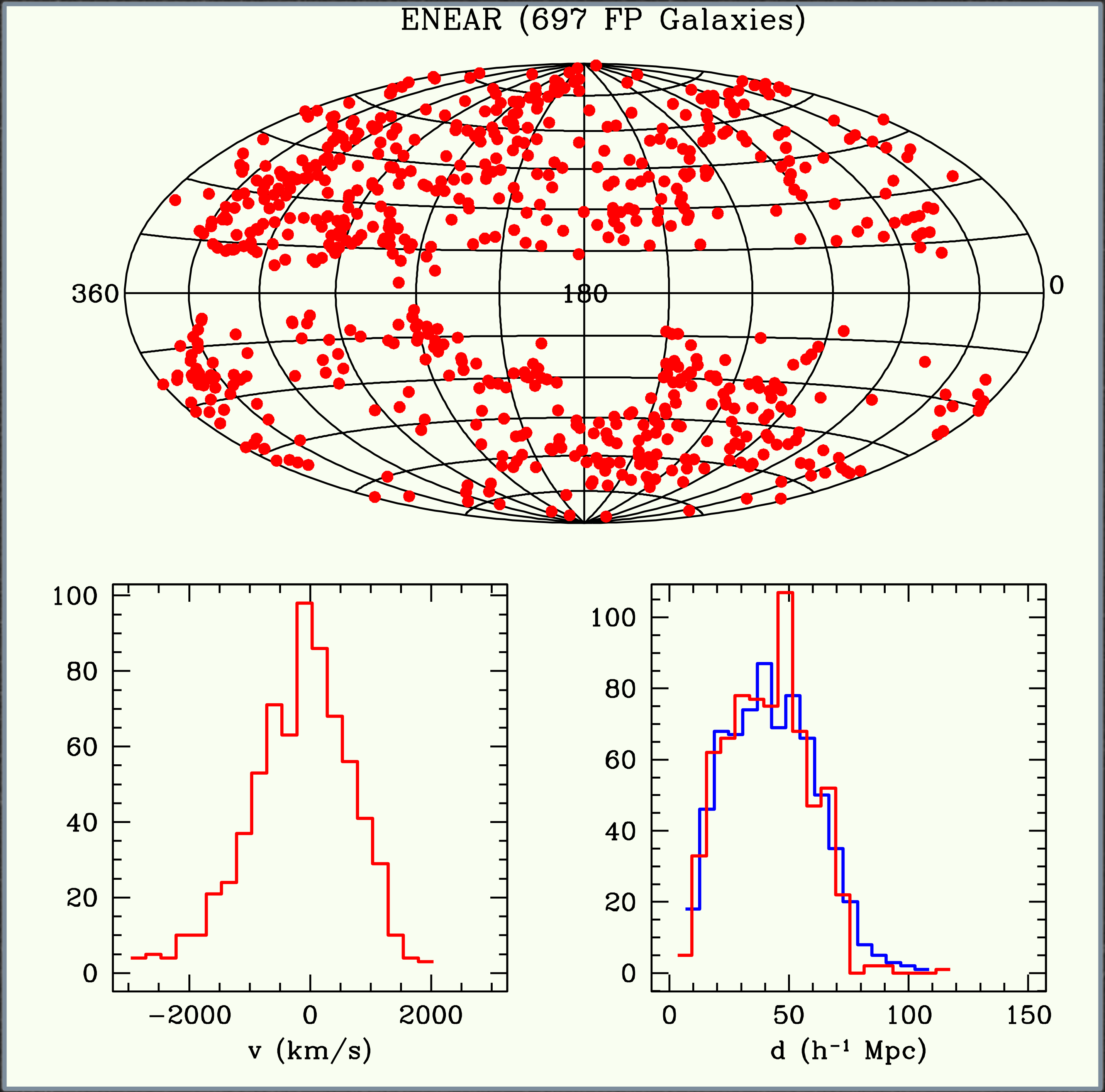


map the local density field ...

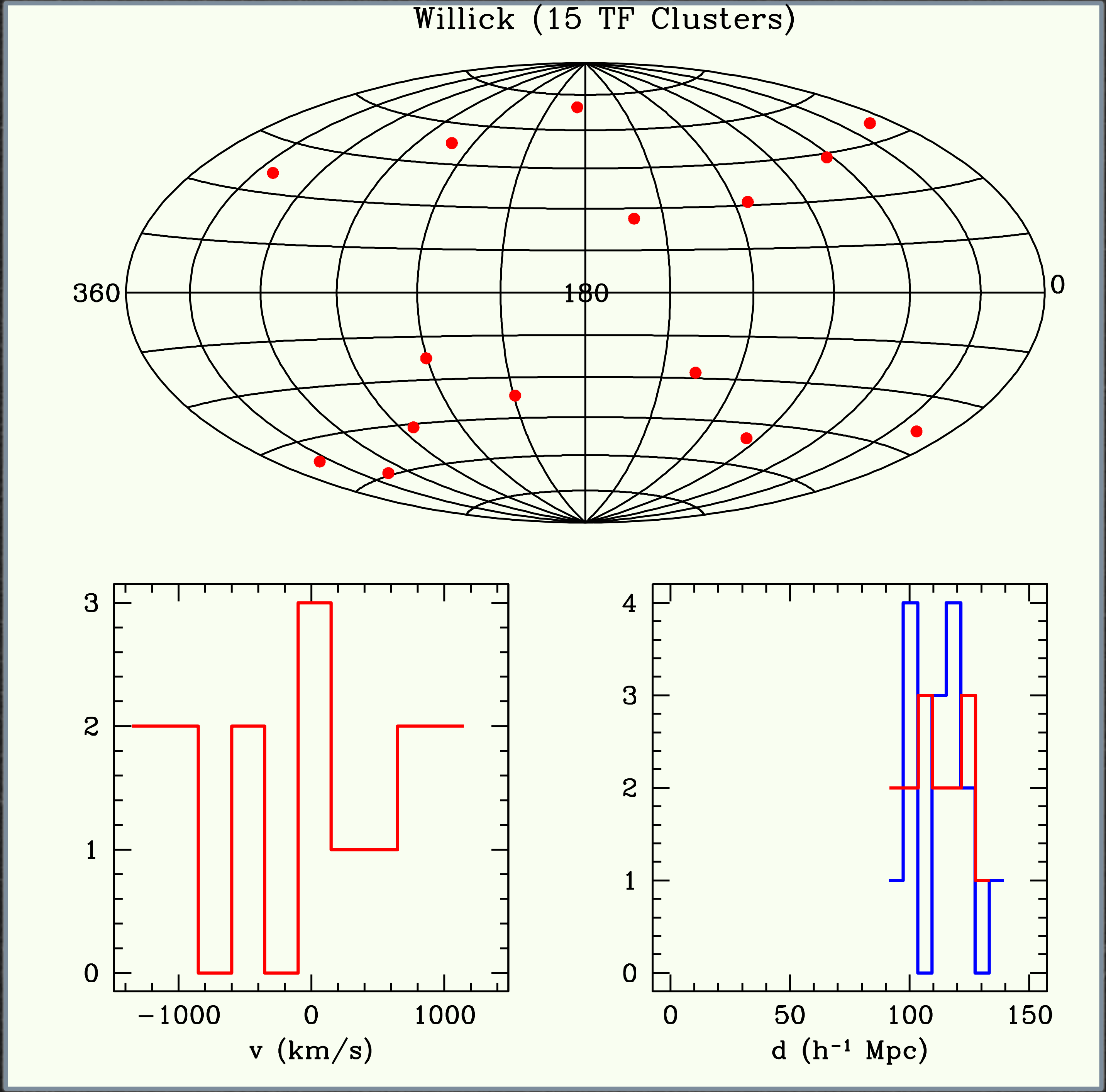
Peculiar Velocity Surveys



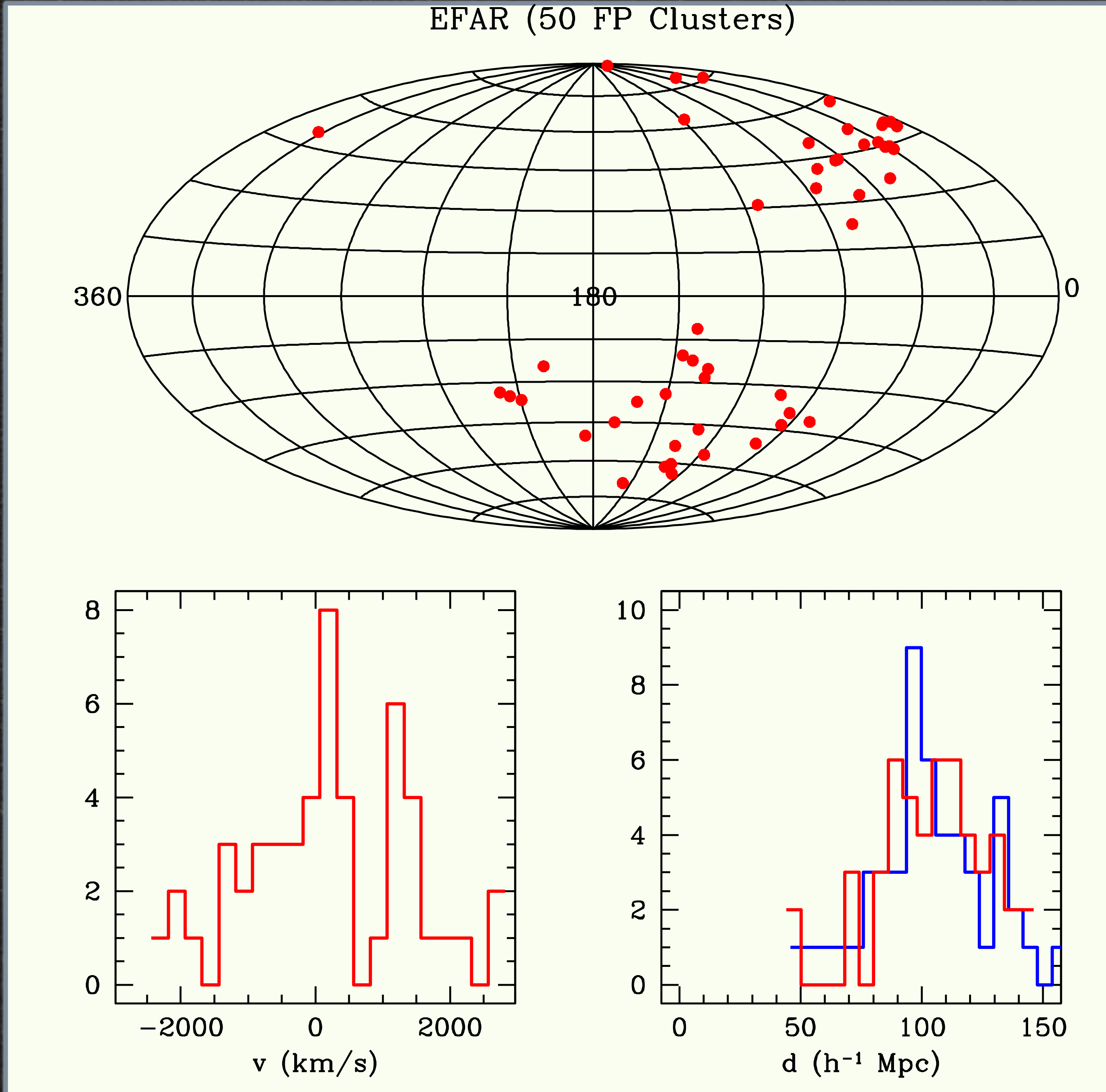
Peculiar Velocity Surveys



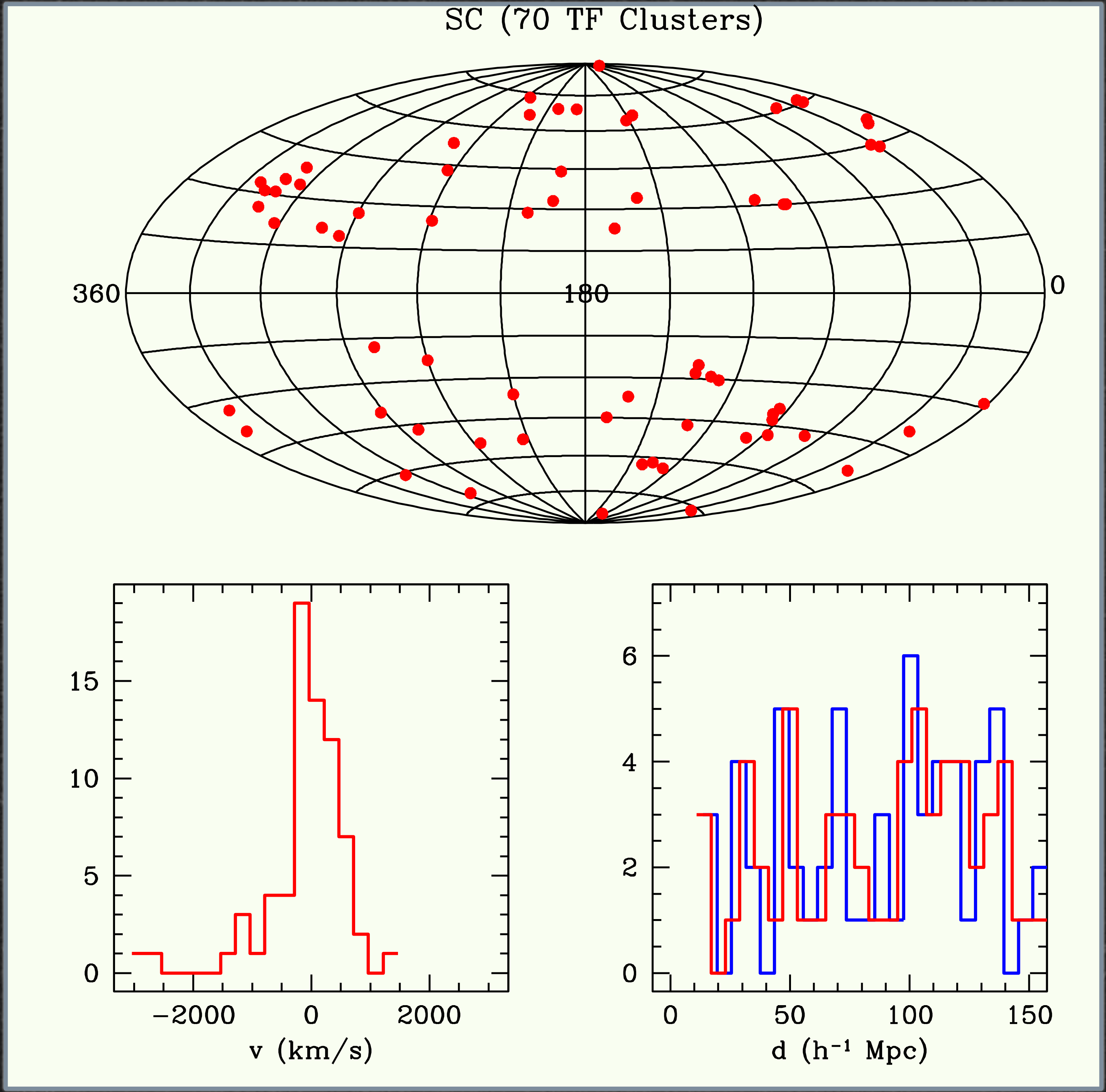
Peculiar Velocity Surveys



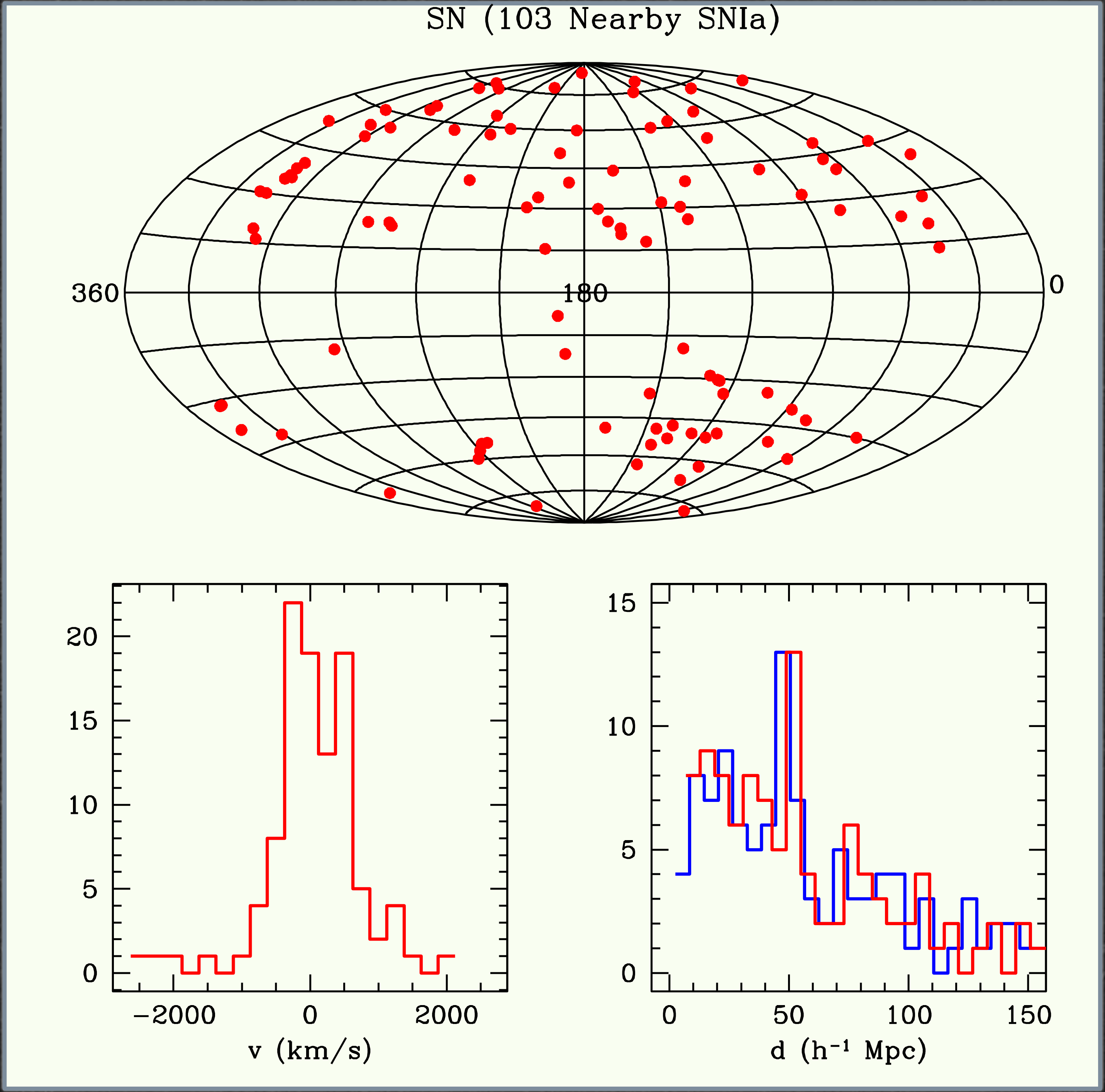
Peculiar Velocity Surveys



Peculiar Velocity Surveys



Peculiar Velocity Surveys



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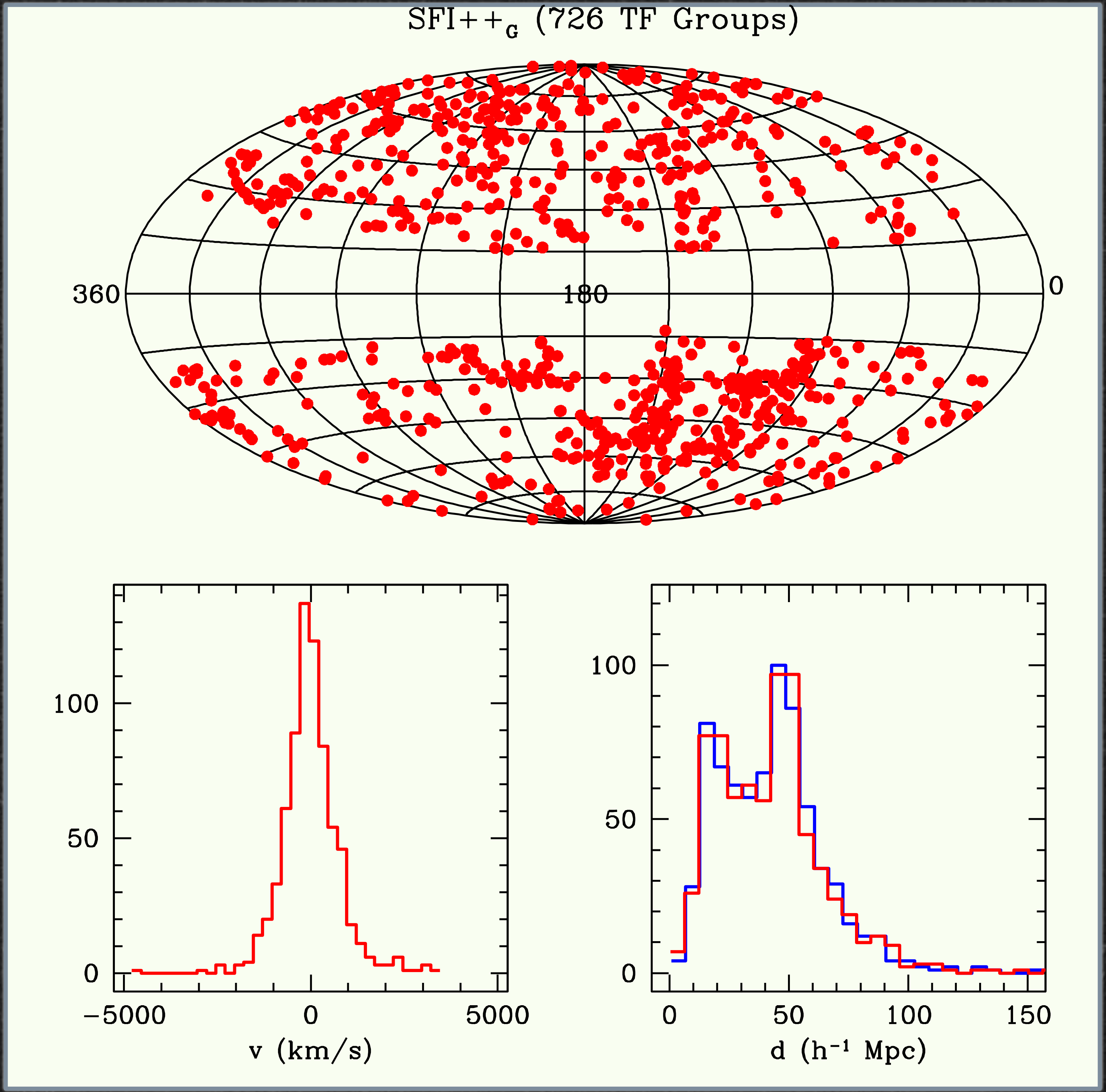
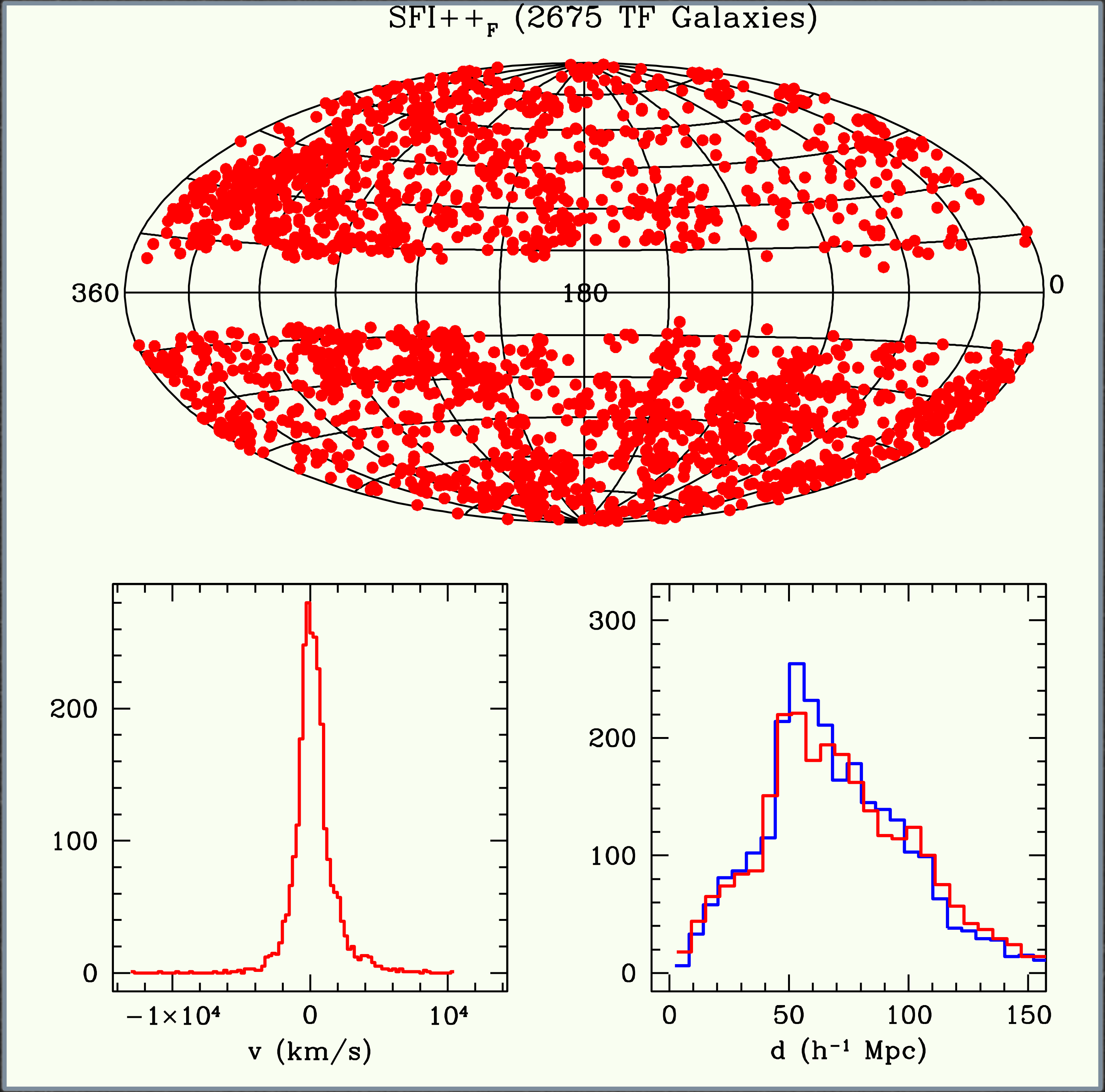
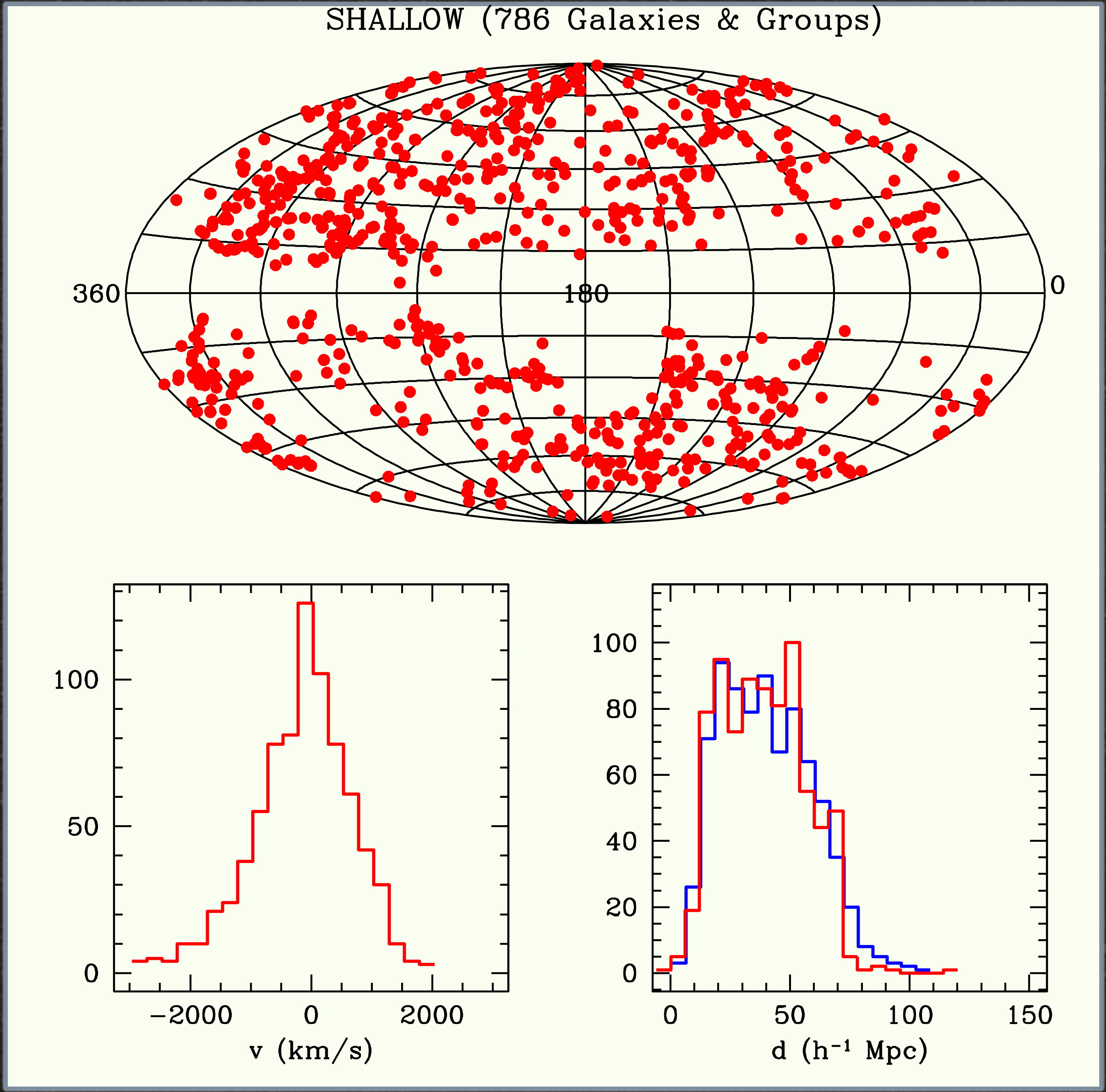


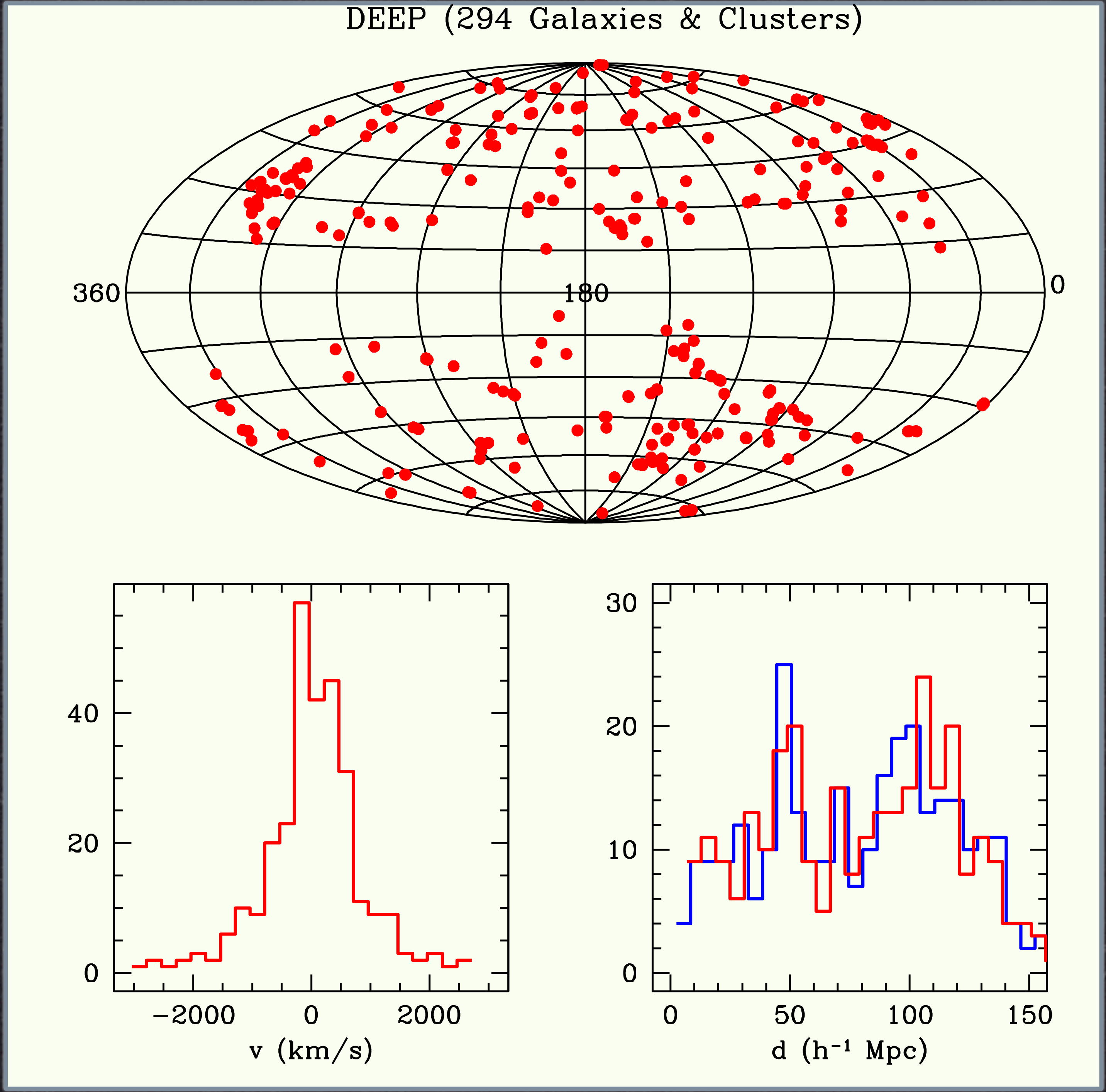
Peculiar Velocity Surveys



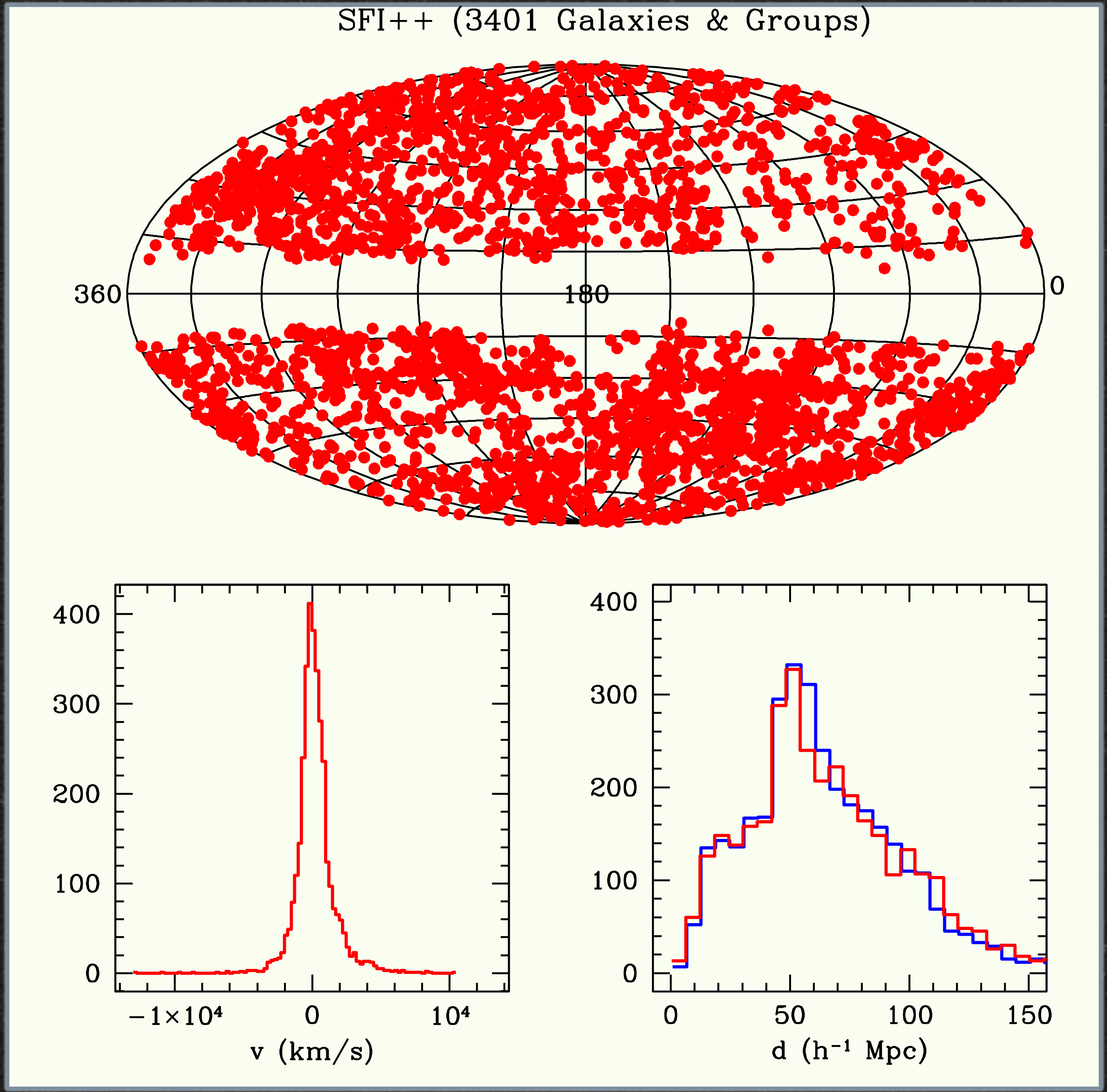
Peculiar Velocity Surveys



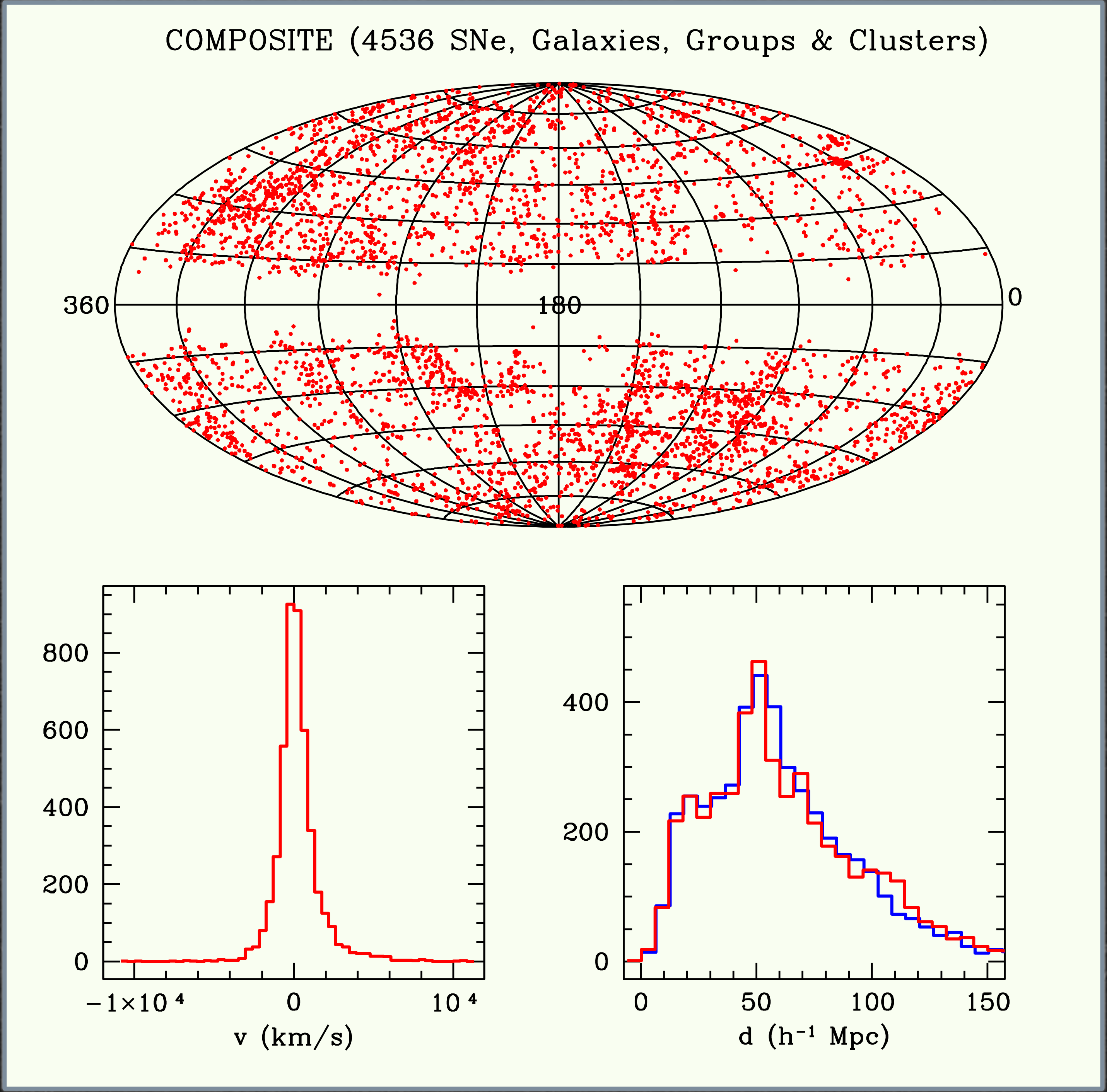
Peculiar Velocity Surveys



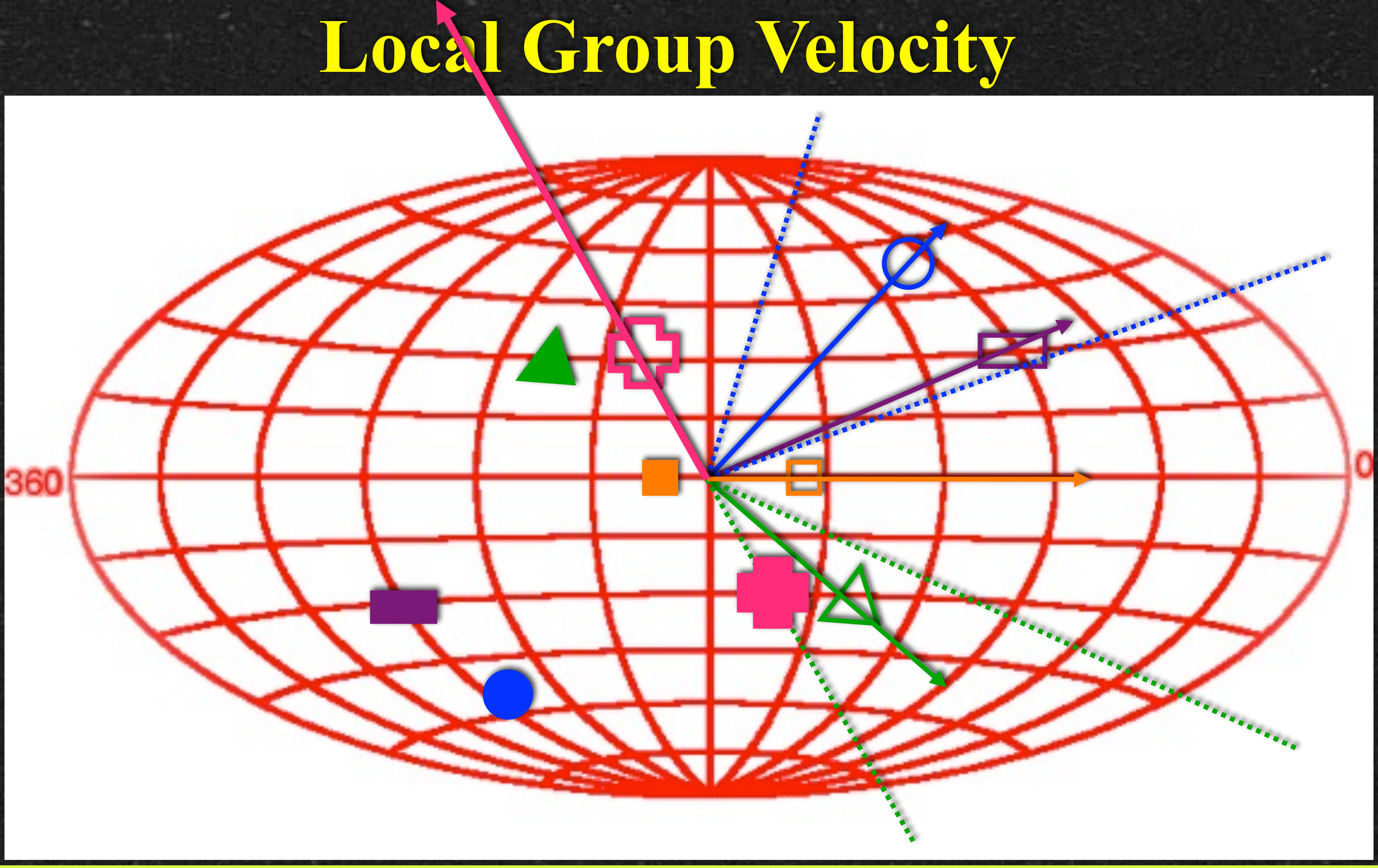
Peculiar Velocity Surveys



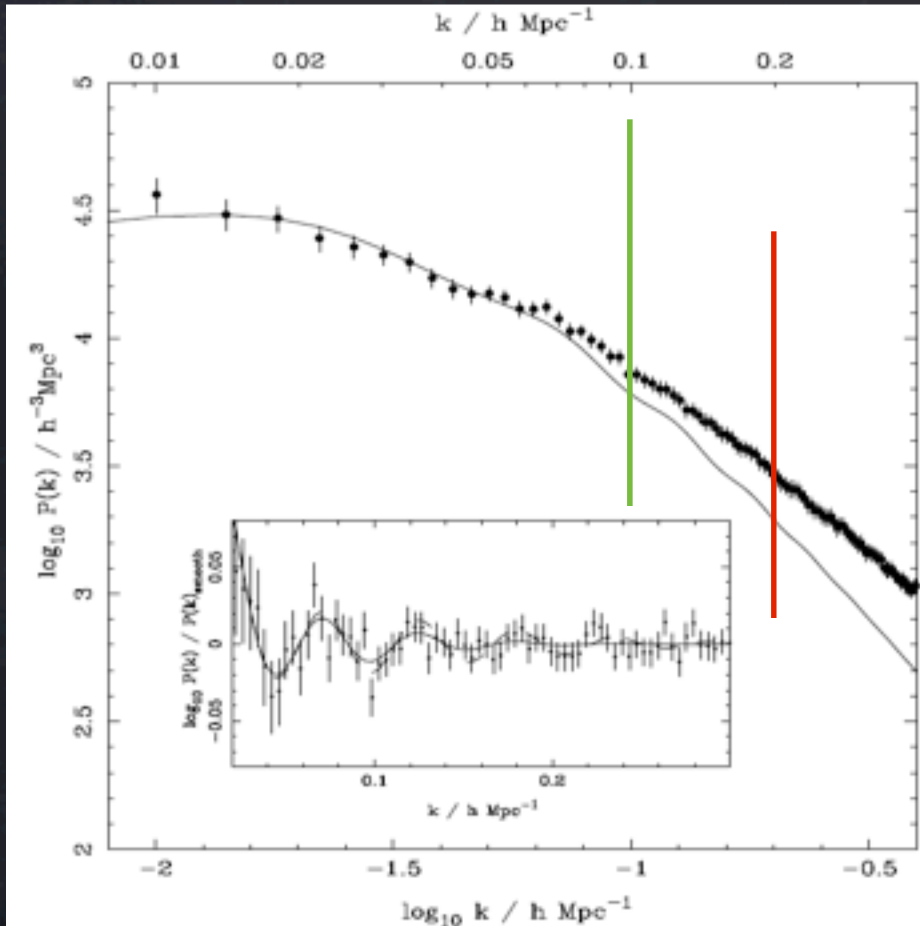
Peculiar Velocity Surveys



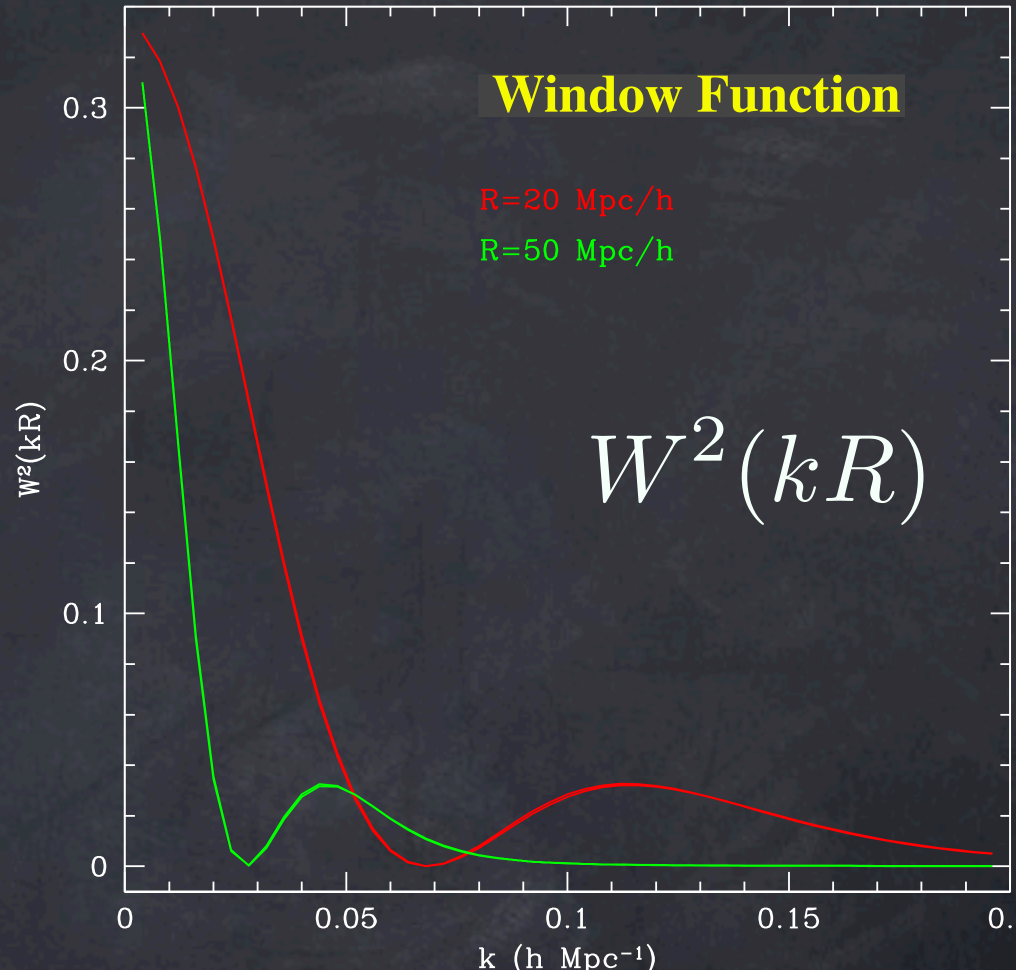
Local Group Velocity

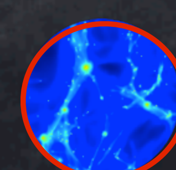


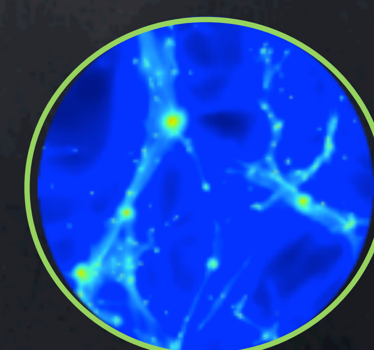
V_{CMB} :	271°	+29°	620 km / s
V_{LP} :	220°	–28°	561 ± 284 km / s
V_{RPK} :	260°	+54°	600 ± 350 km / s
V_{SMAC} :	195°	0°	700 ± 250 km / s
V_{LP10k} :	173°	+63°	1000 ± 500 km / s
V_{SC} :	180°	0°	100 ± 150 km / s



Matter Power Spectrum



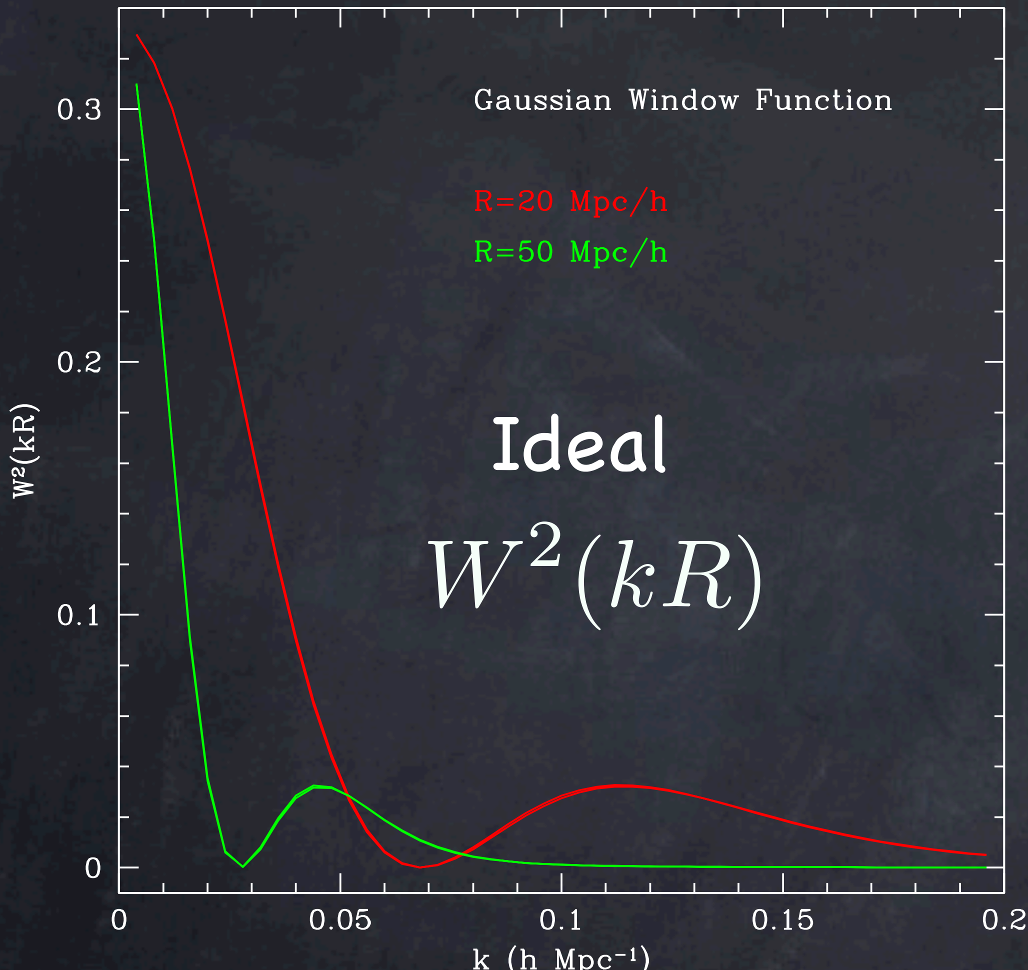




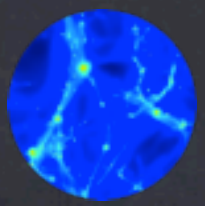
RMS Bulk Flow:

$$\sigma_v^2(R) = \frac{(H_o\Omega_m^{0.6})^2}{2\pi^2}\int \mathrm{d}k\ P(k)W^2(kR)$$

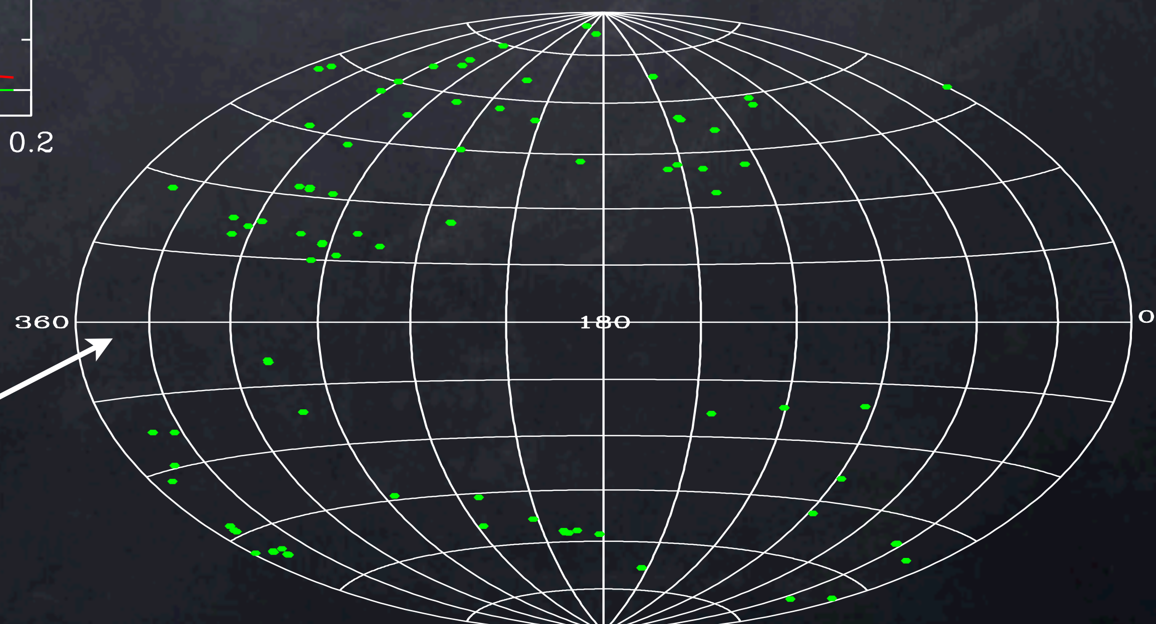
Window Functions



Ideal Survey
(Dense, Isotropic)



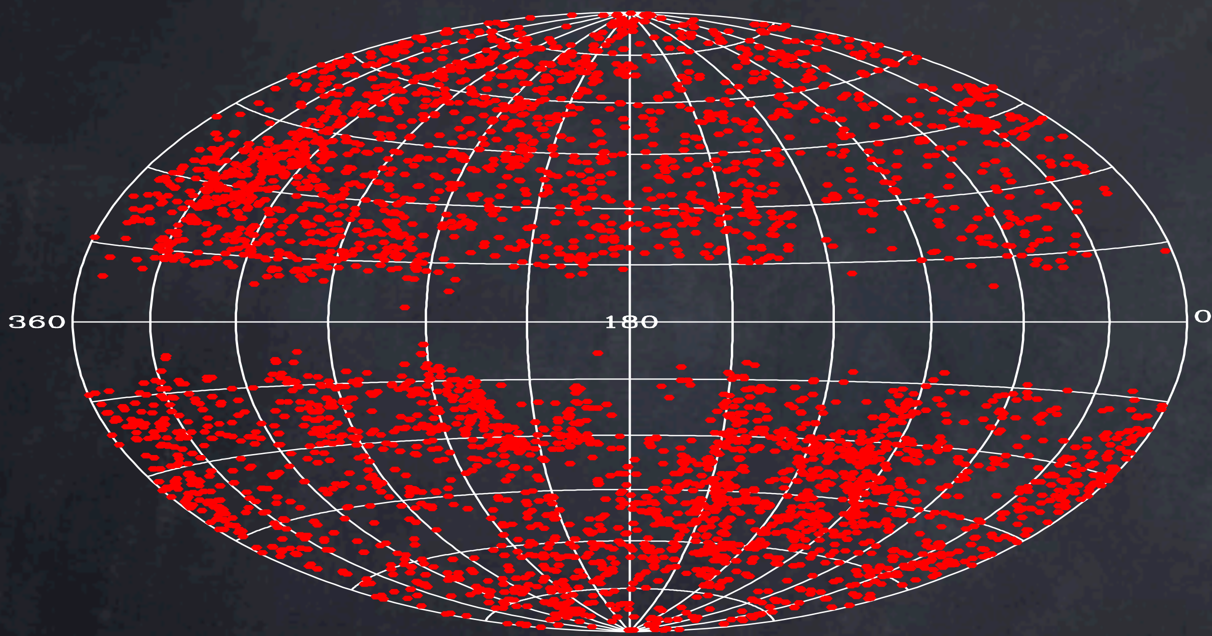
Real Survey
(Sparse, anisotropic, noisy)



Galactic plane

Maximum Likelihood Estimate of Bulk Flow Components

$$L[\{U_i\}/\{S_n\}] = \prod_n \frac{1}{\sqrt{\sigma_n^2+\sigma_*^2}} \exp\left[-\frac{1}{2}\frac{(S_n - \hat{r}_n\cdot\vec{U})^2}{\sigma_n^2+\sigma_*^2}\right]$$



Measured line-of-sight velocity

$$S = cz - H_0 d$$

$$\delta d \approx 10\%$$

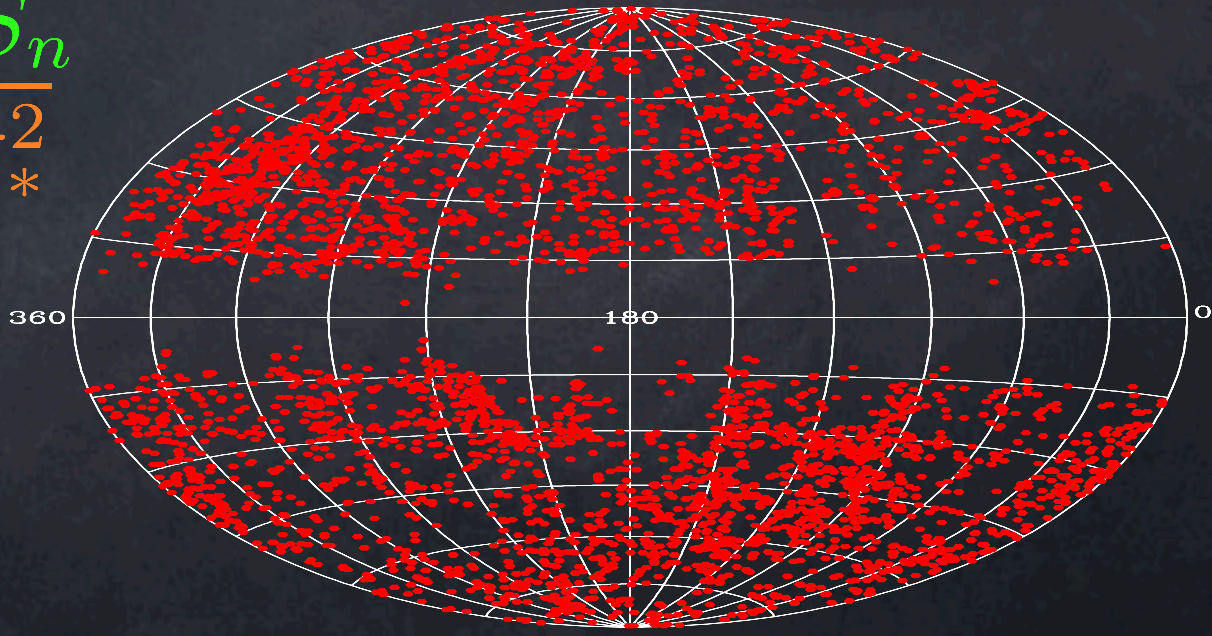
Maximize the likelihood L w.r.t U_i

$$U_i = \left(\sum_m \frac{\hat{r}_{m,i}\hat{r}_{m,j}}{\sigma_m^2+\sigma_*^2}\right)^{-1} \sum_n \frac{\hat{r}_{n,j}S_n}{\sigma_n^2+\sigma_*^2}$$

Maximum Likelihood Estimate of Bulk Flow Components

$$U_i = \left(\sum_m \frac{\hat{r}_{m,i}\hat{r}_{m,j}}{\sigma_m^2 + \sigma_*^2} \right)^{-1} \sum_n \frac{\hat{r}_{n,j} S_n}{\sigma_n^2 + \sigma_*^2}$$

$$U_i = A_{ij}^{-1} \sum_n \frac{\hat{r}_{n,j} S_n}{\sigma_n^2 + \sigma_*^2}$$

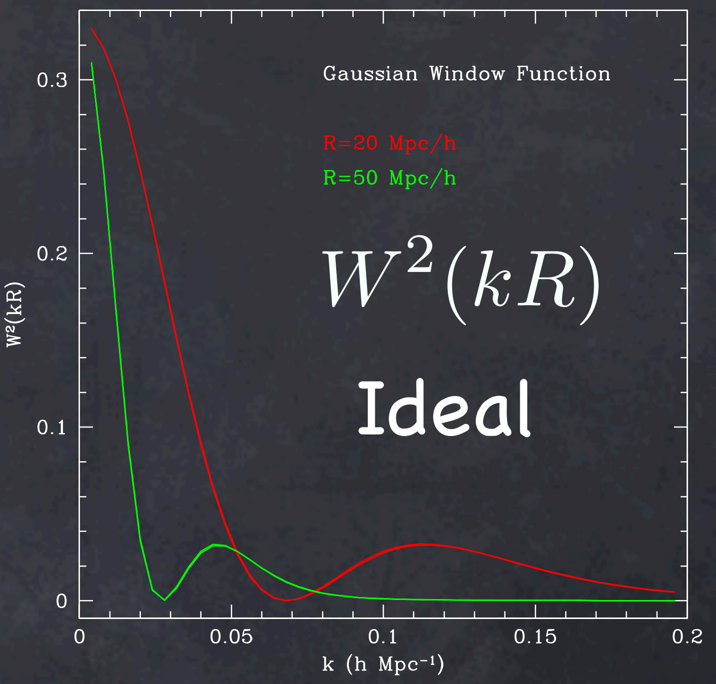


$$U_i = \sum_n w_{i,n} S_n$$

MLE weights

Survey Window Functions

$$\sigma_v^2(R) = \frac{(H_o\Omega_m^{0.6})^2}{2\pi^2}\int \mathrm{d}k\; P(k)W^2(kR)$$



W^2_{ij} indicates which scales a survey probes, thereby contributing to the bulk flow.

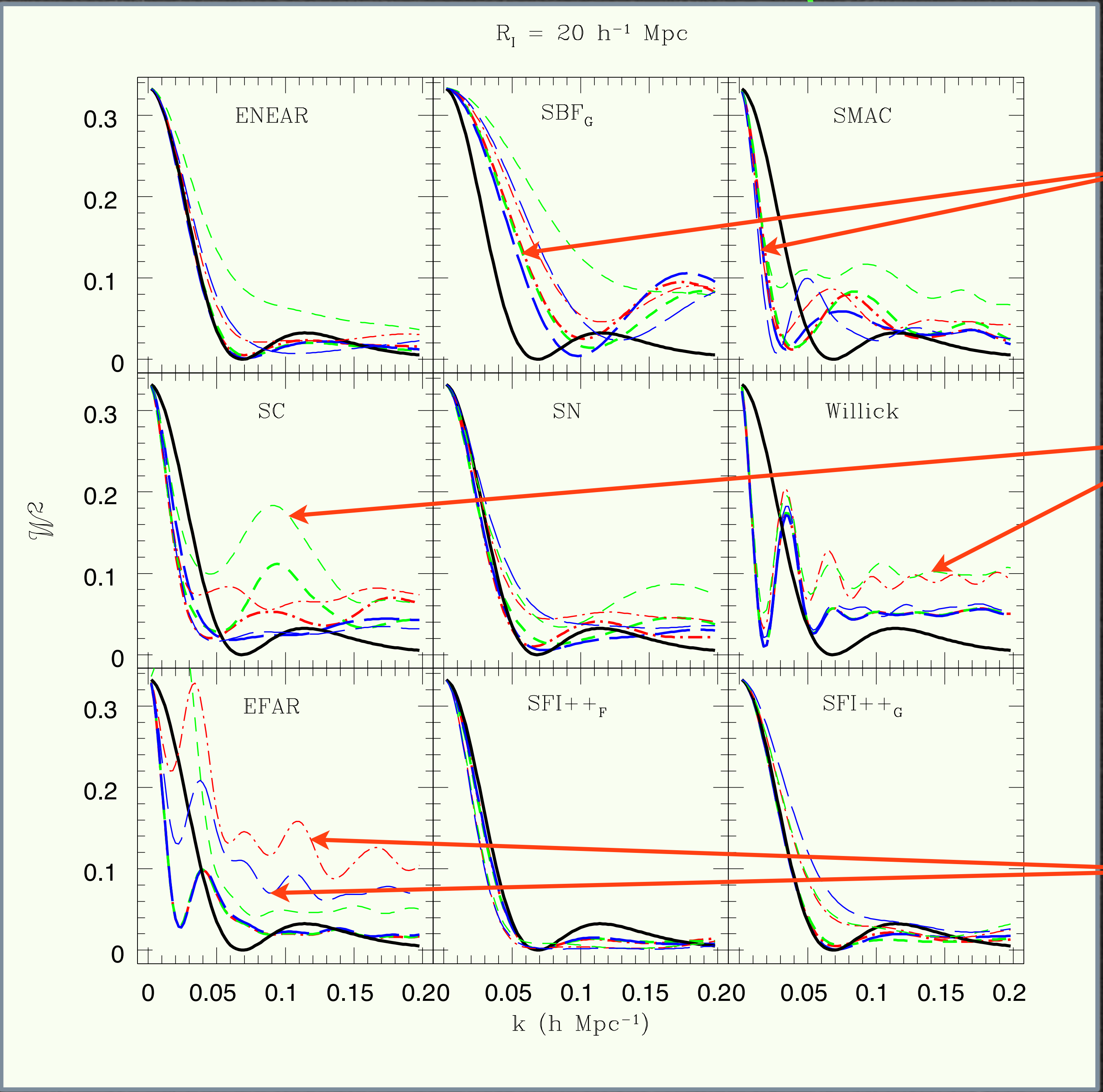
$$W^2_{ij}(k) = \sum_{m,n} w_{i,m} w_{j,n} f_{mn}$$

depends on the geometry of survey

$$f_{mn} = \int \frac{d^2\hat{k}}{4\pi}\left(\hat{\mathbf{r}}_m\cdot\hat{\mathbf{k}}\;\;\hat{\mathbf{r}}_n\cdot\hat{\mathbf{k}}\right)\exp\left(i\mathbf{k}\cdot(\mathbf{r}_m-\mathbf{r}_n)\right)$$

Compare survey window functions to the ideal one.

window functions



Scales:

Surveys probe different scales

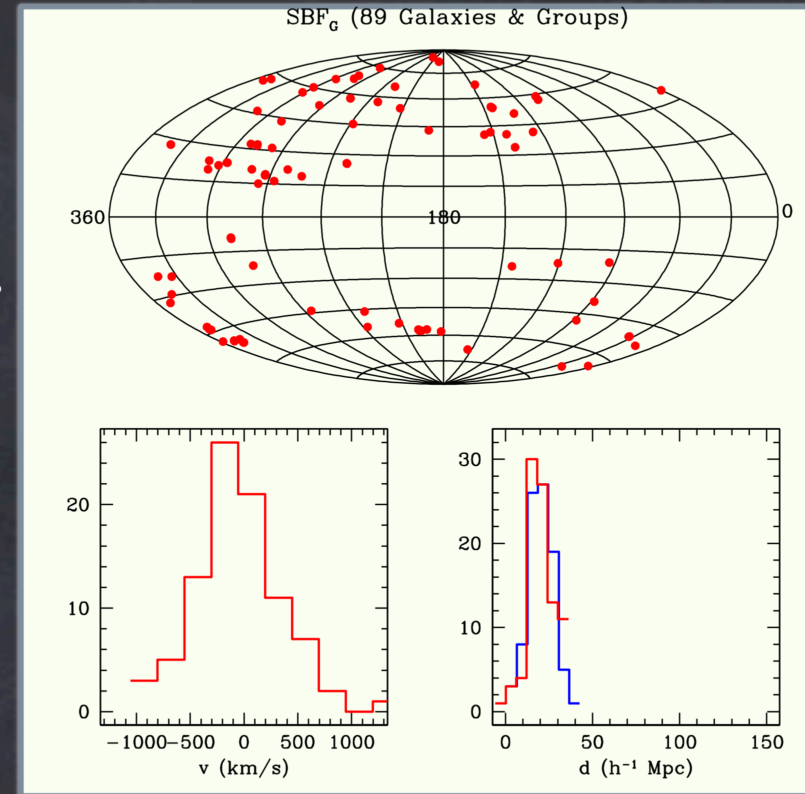
Aliasing:

Surveys probe small scales differently

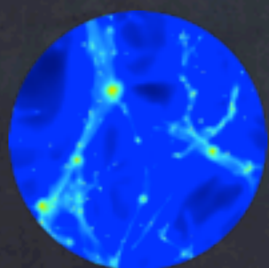
Isotropy:

Surveys are rarely isotropic (or homogeneous)

Real Surveys measure the average flow of the specific survey



... which is not the same as measuring the bulk flow of an ideal survey.



Linear Theory :

$$\sigma_v^2(R) = \frac{(H_o \Omega_m^{0.6})^2}{2\pi^2} \int \mathrm{d}k \; P(k) W^2(kR)$$

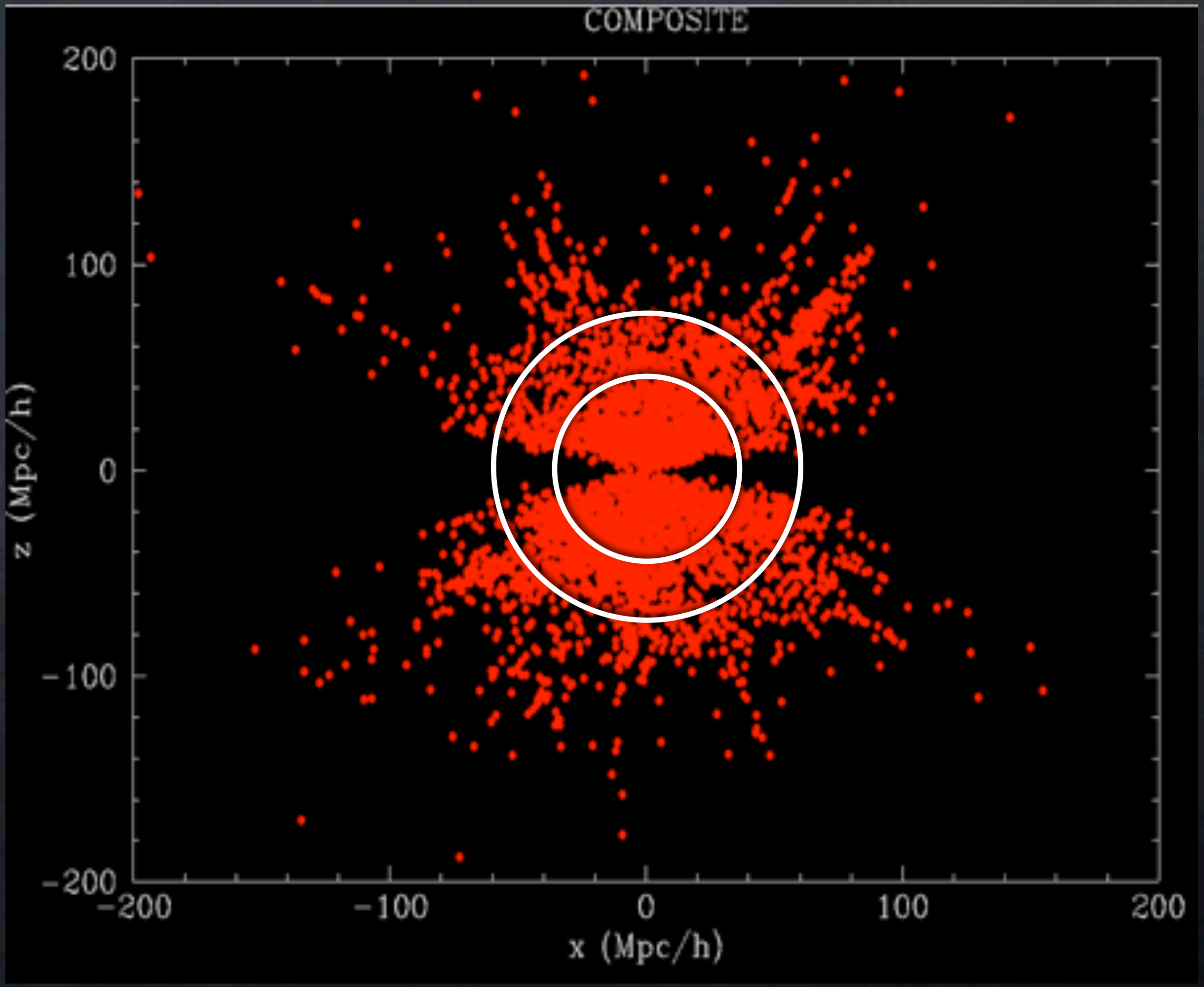
Blindly Comparing Survey results to linear theory is misleading

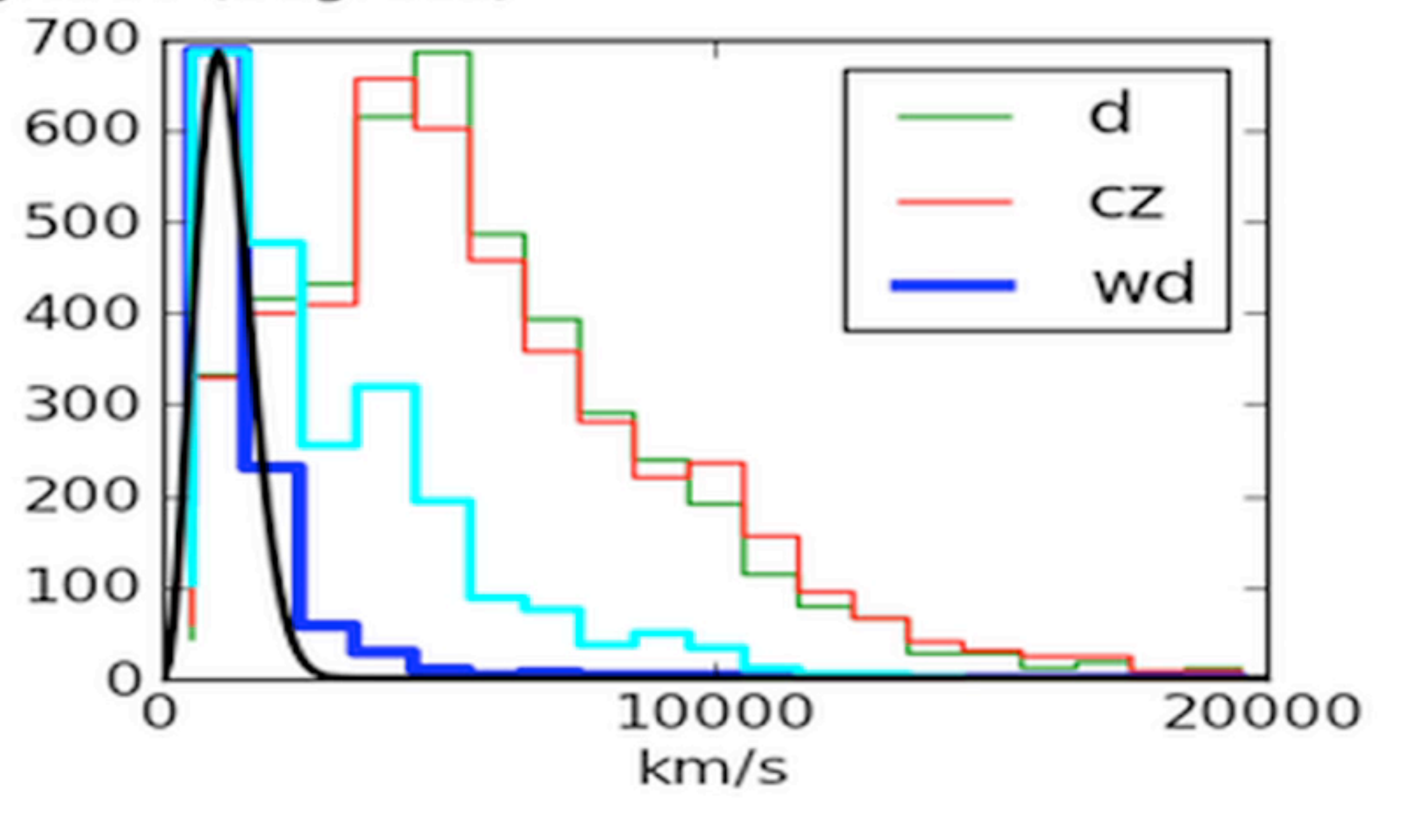
New Method

Minimum Variance Method

Survey → Re-design Window Function → Bulk Flow

Give weights to galaxies such that a real survey turns into a near-ideal one of size R.



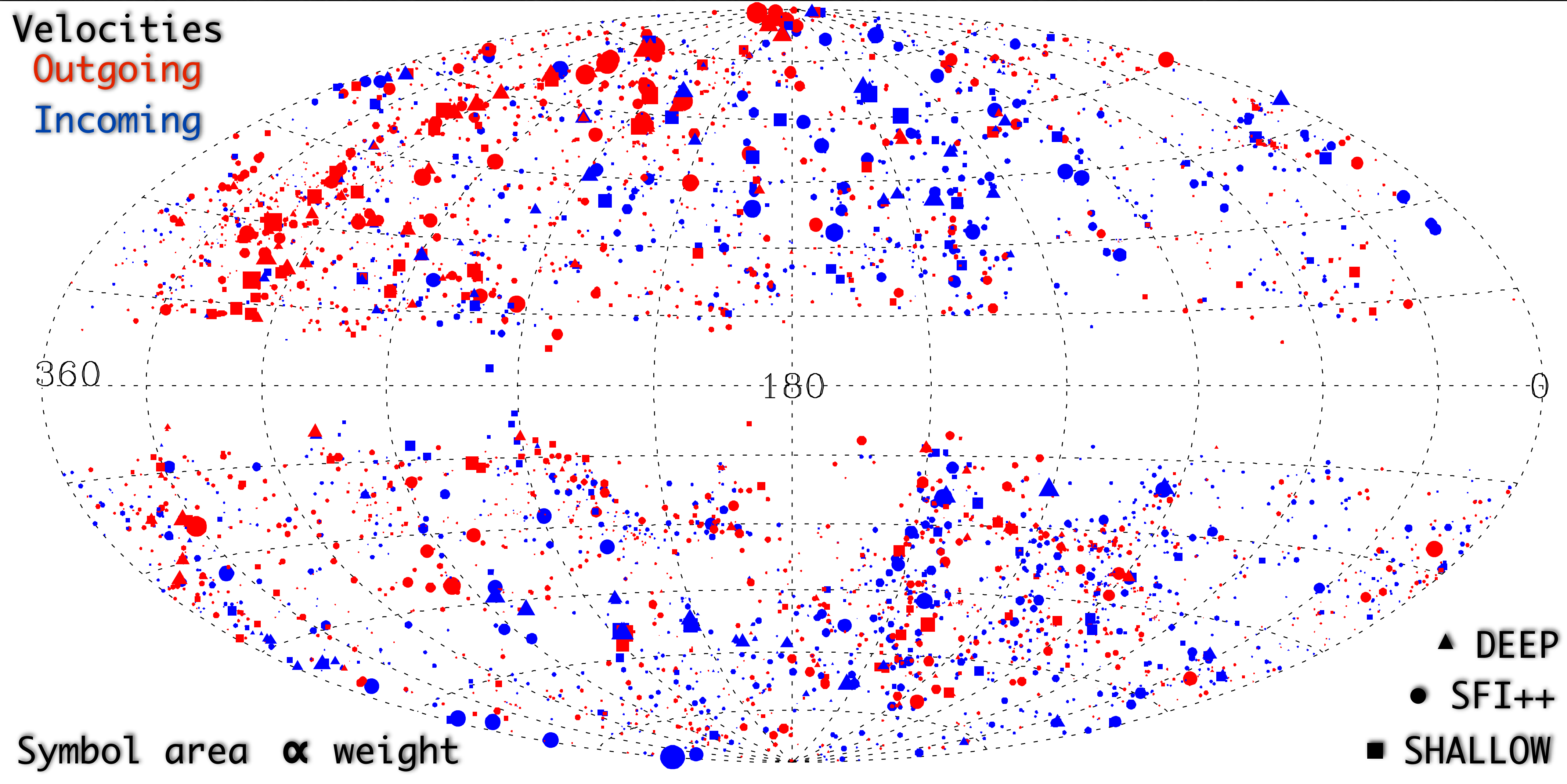


Survey (real space)

Weighted Survey

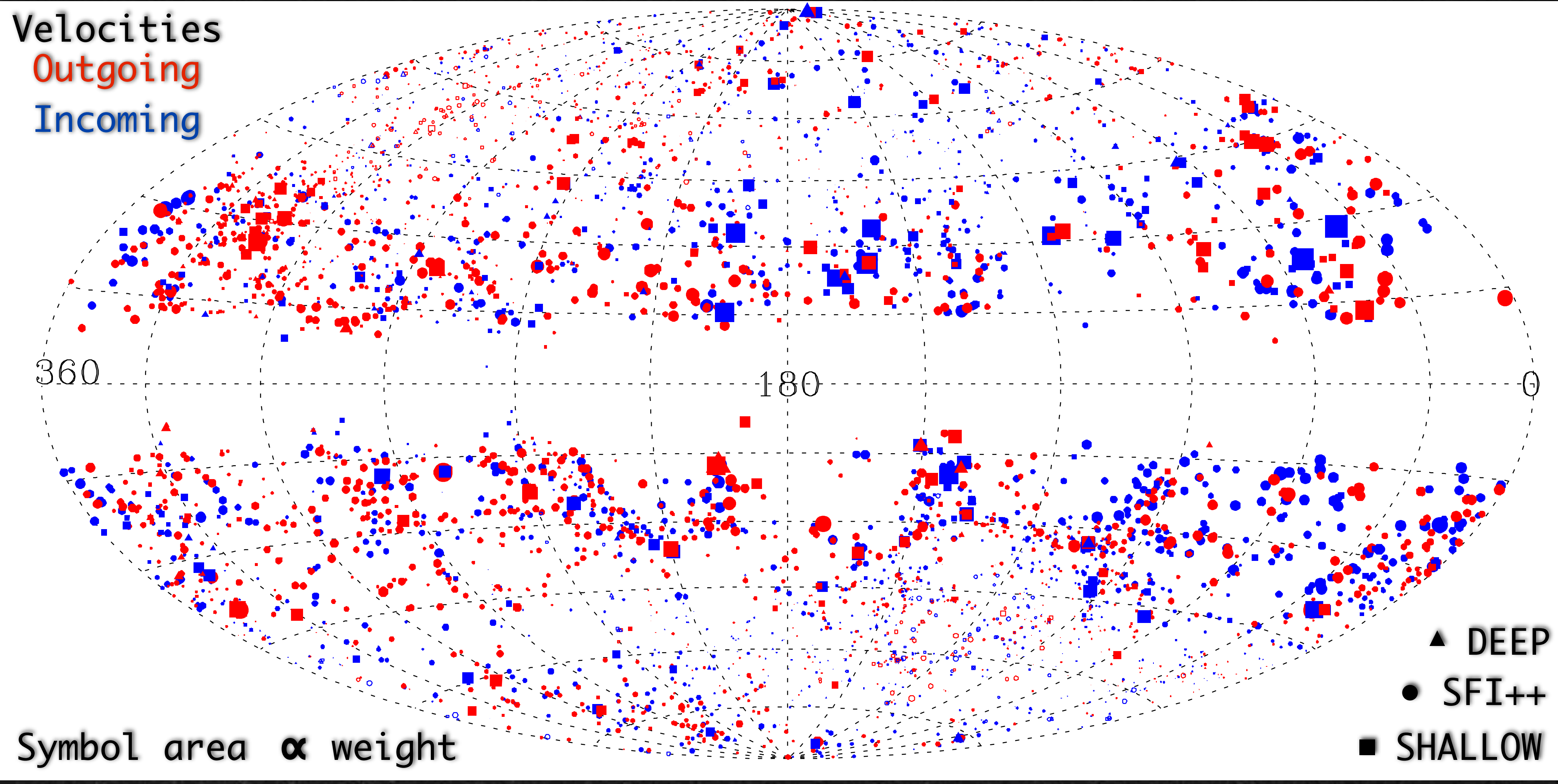
Survey (redshift space)

Surveys

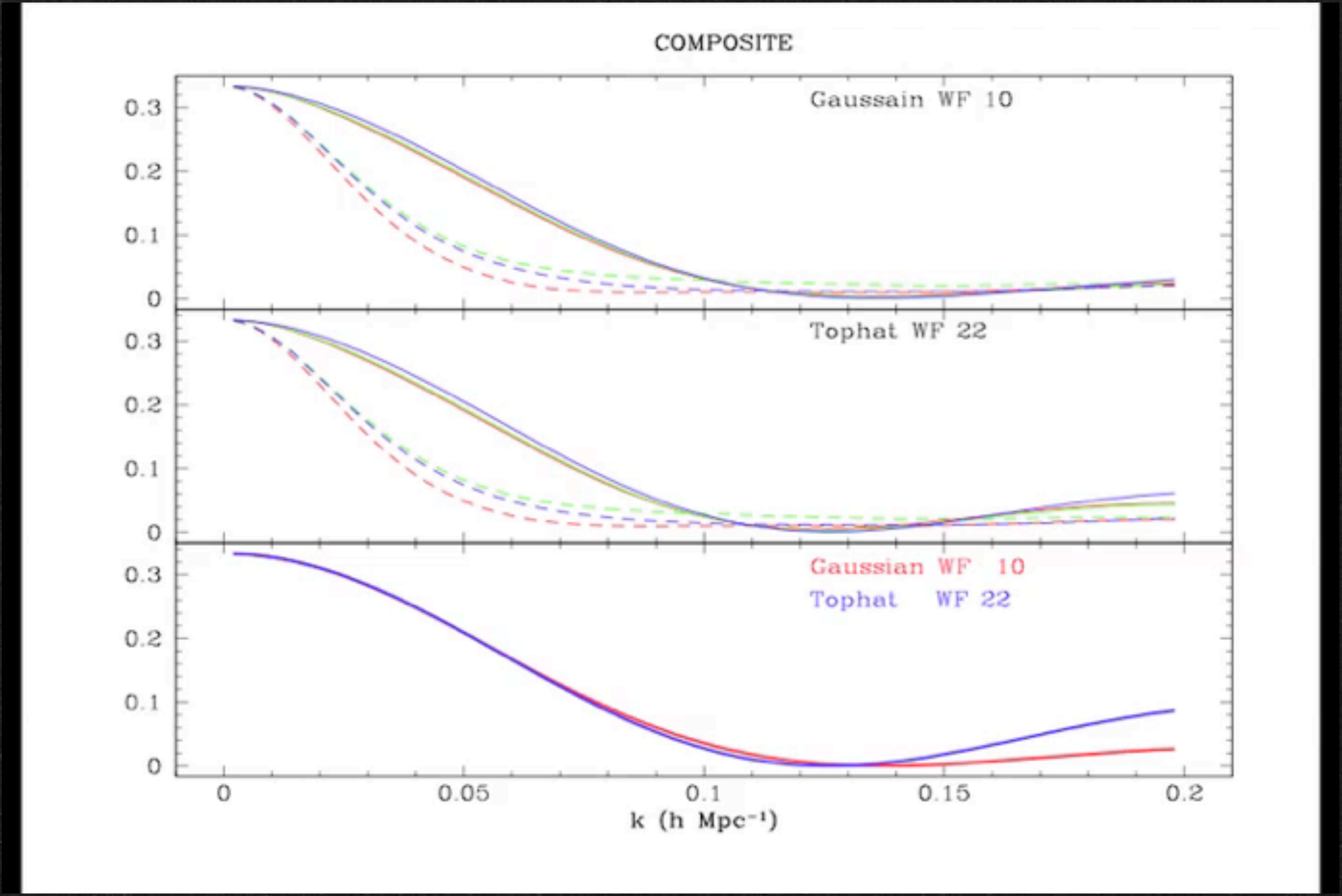


Velocities
Outgoing
Incoming
360
180
0
DEEP
SFI++
SHALLOW
Symbol area ∝ weight

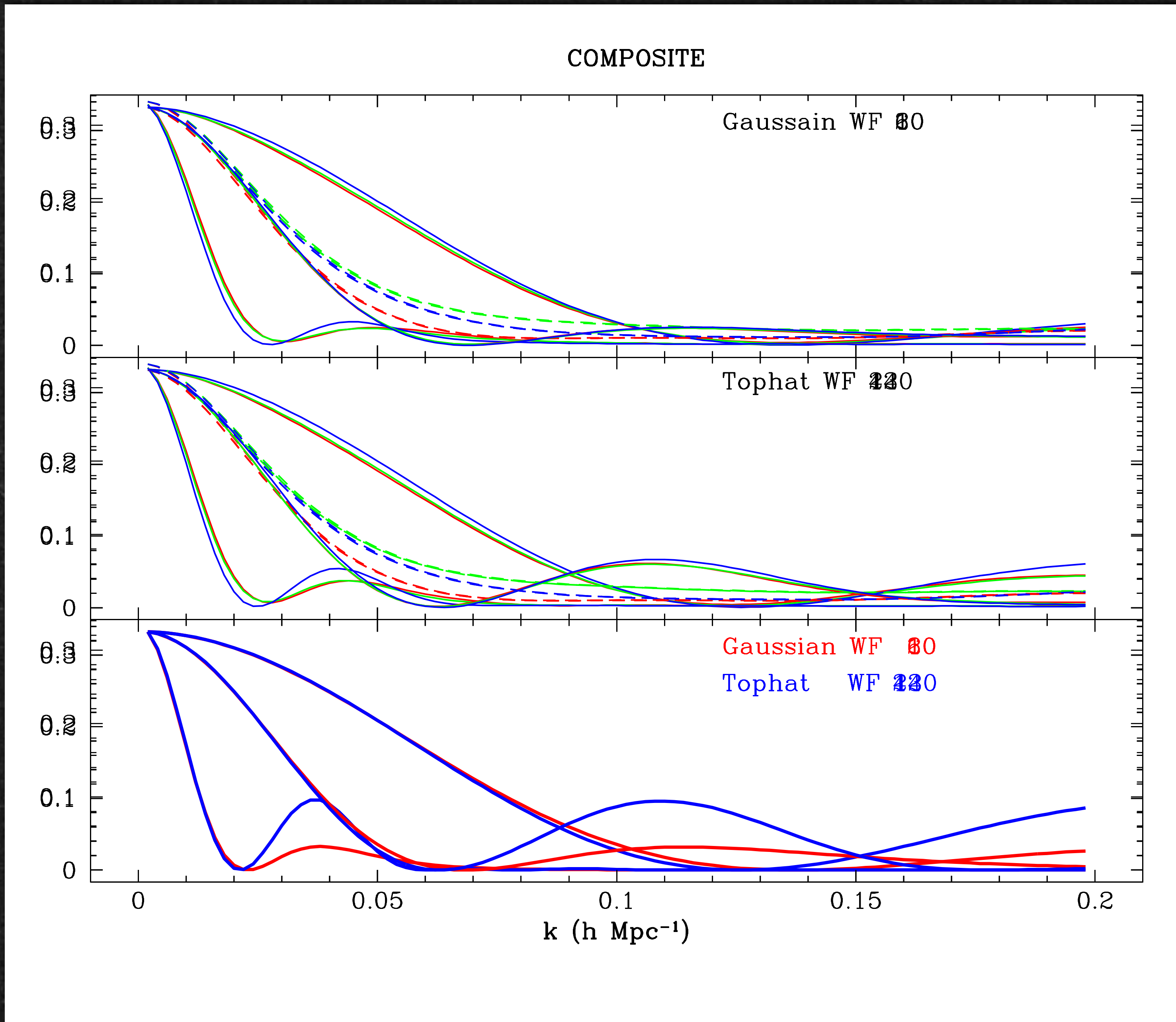
Minimum Variance Moments (MV)



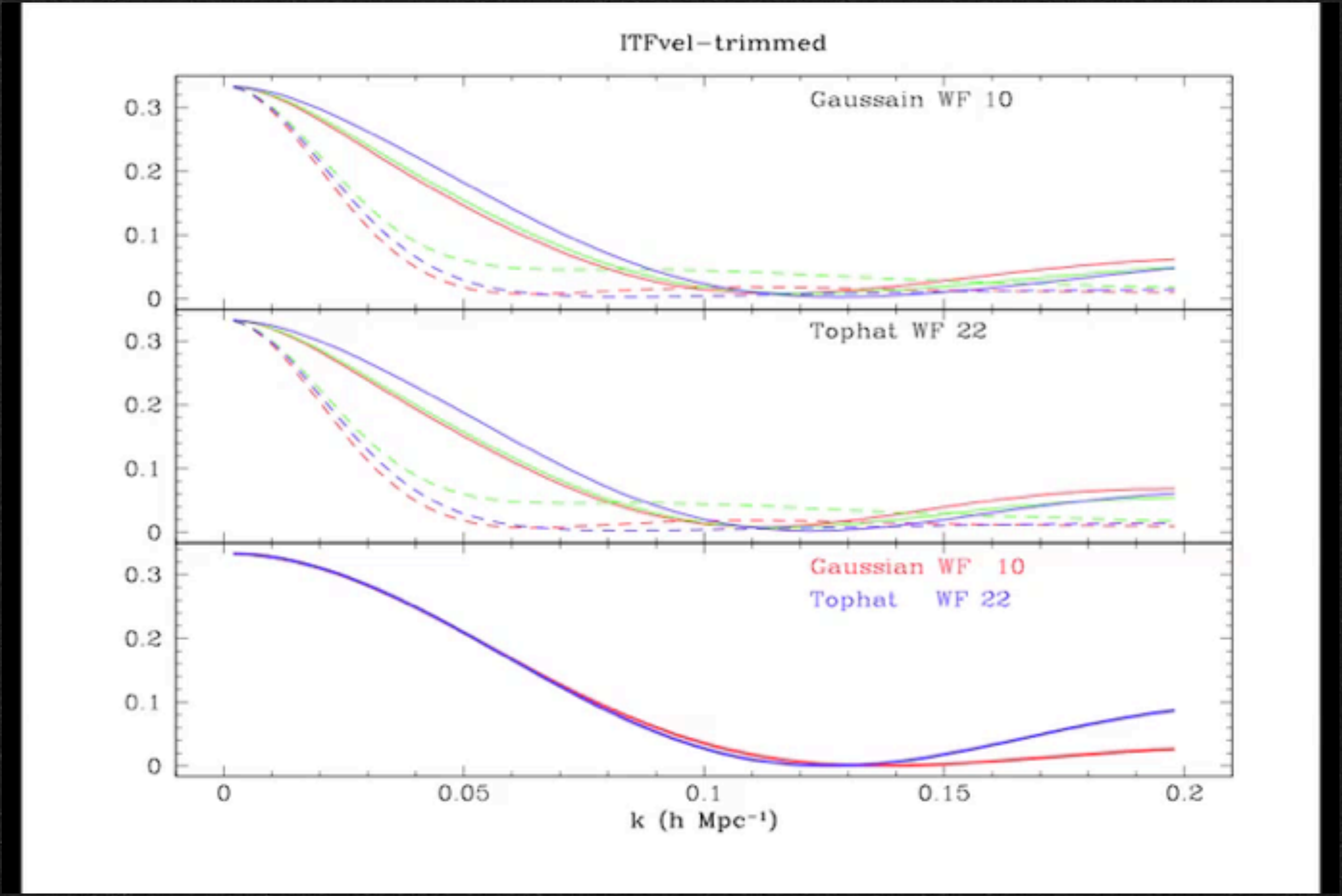
window function design



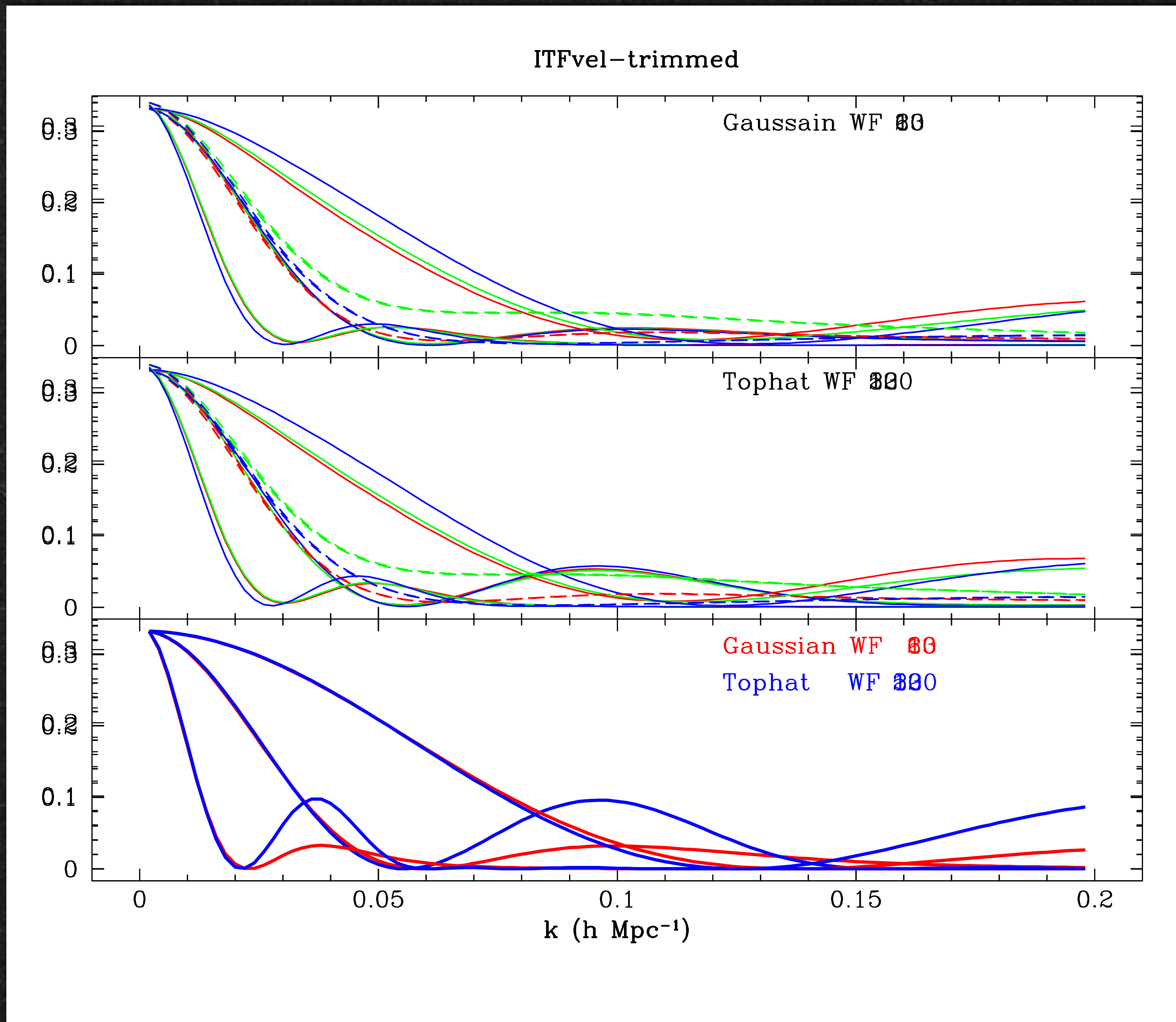
window function design



window function design

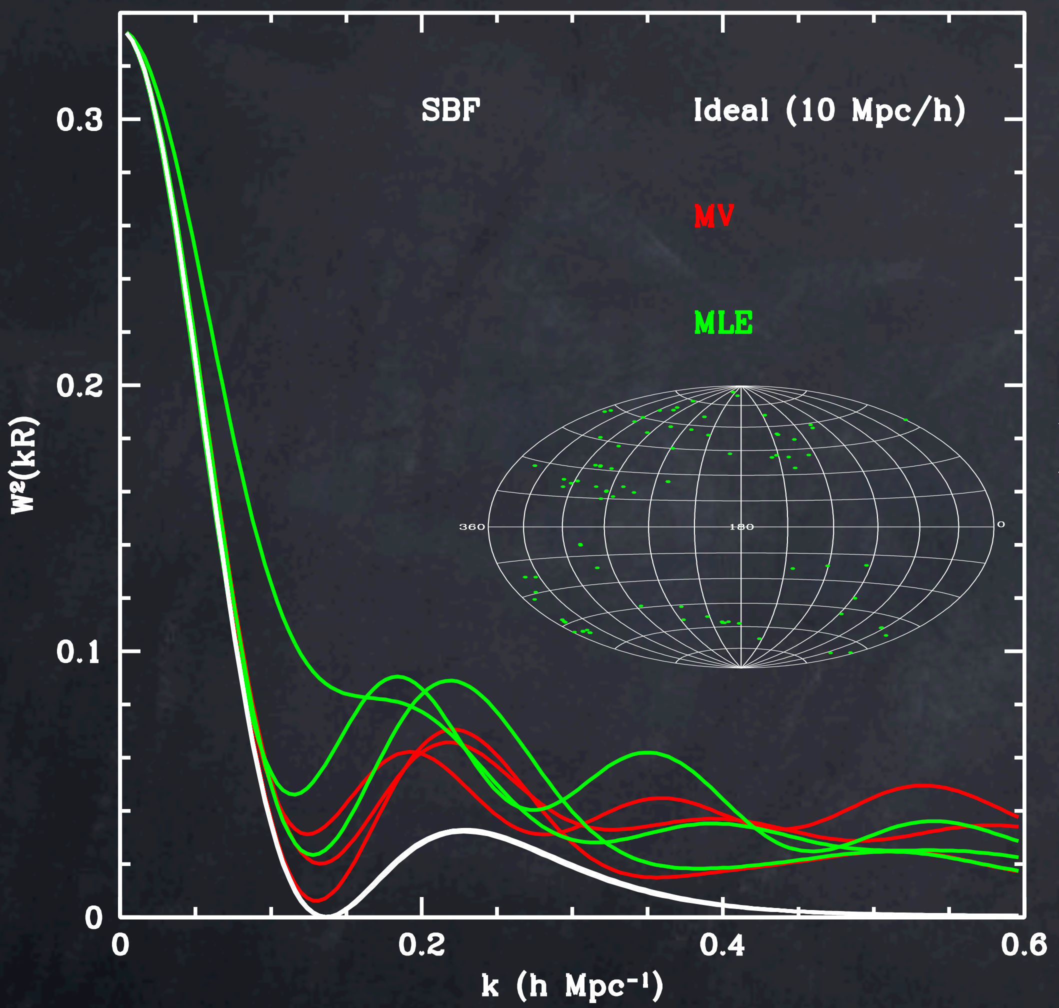


window function design

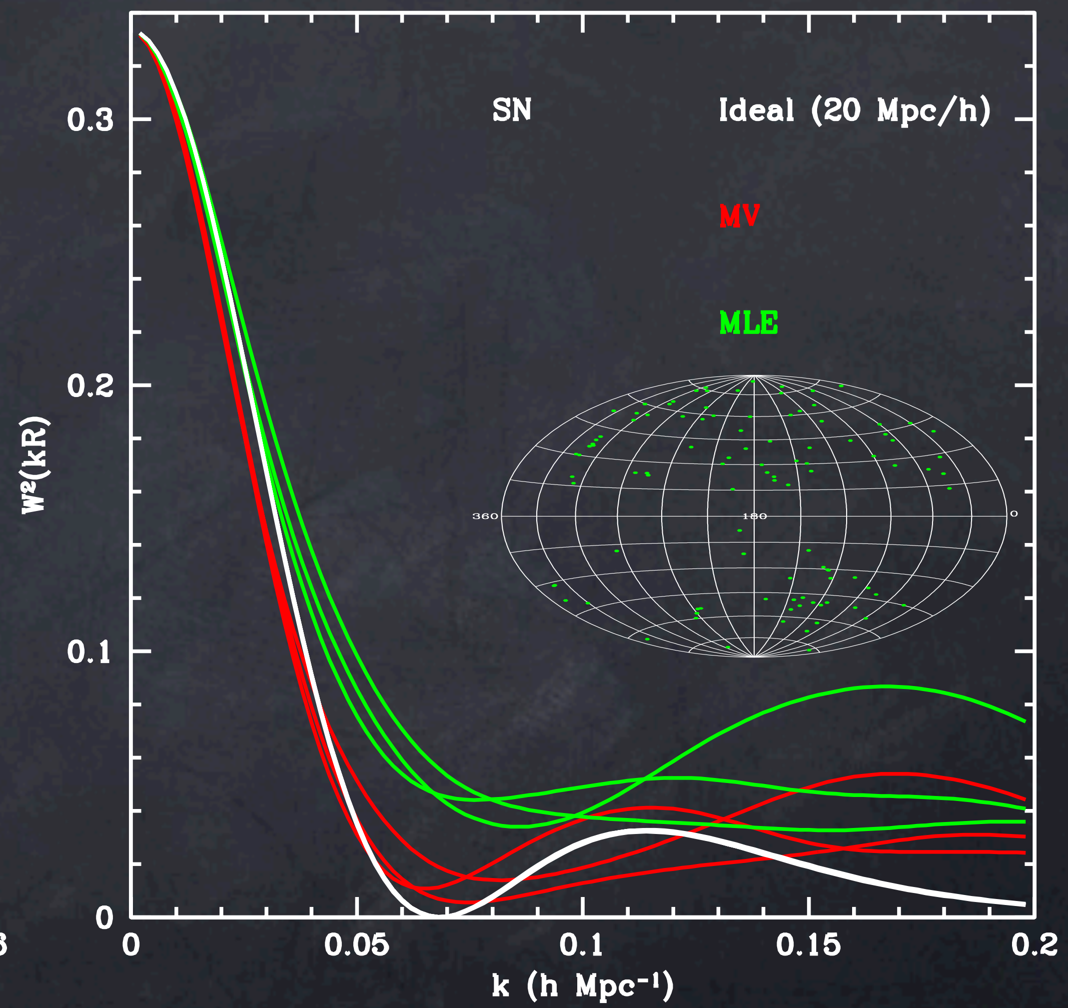


Survey Window Functions

SBF (89)



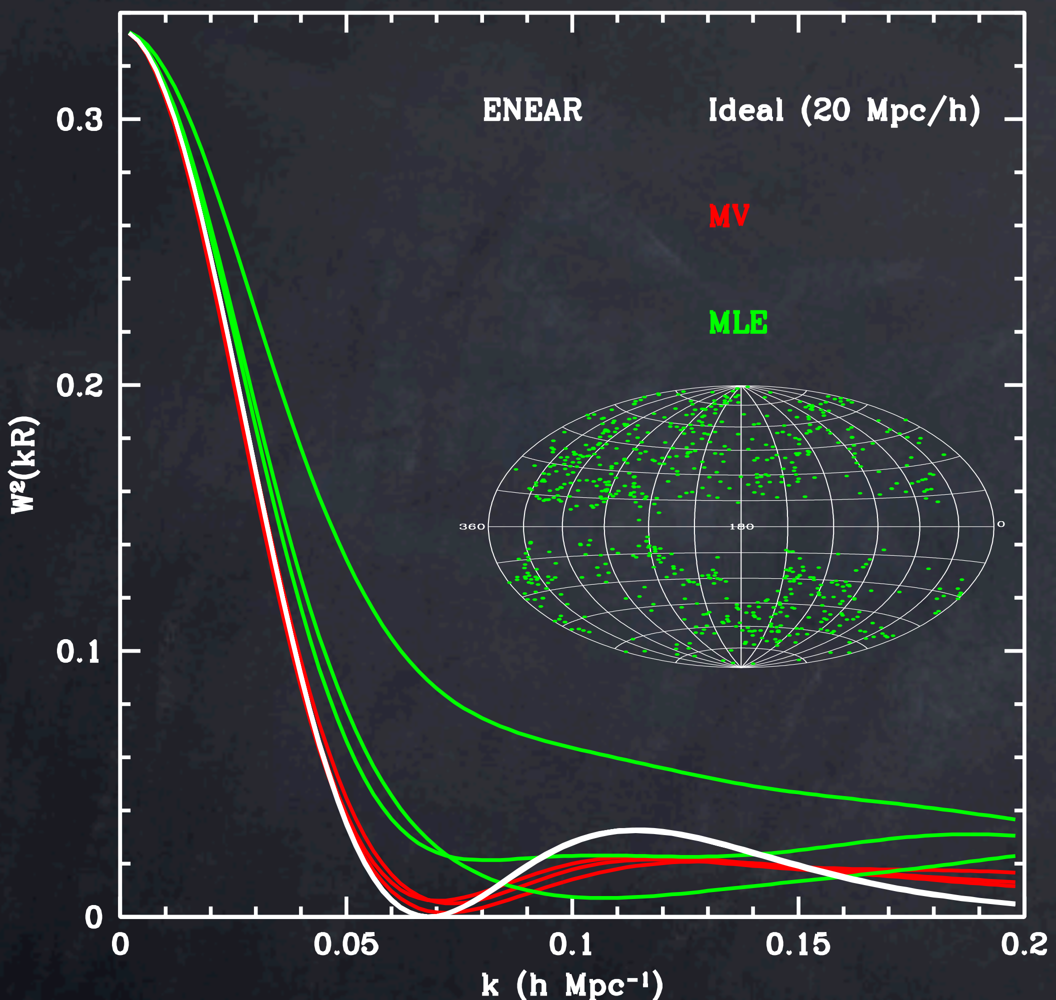
SNe Ia (103)



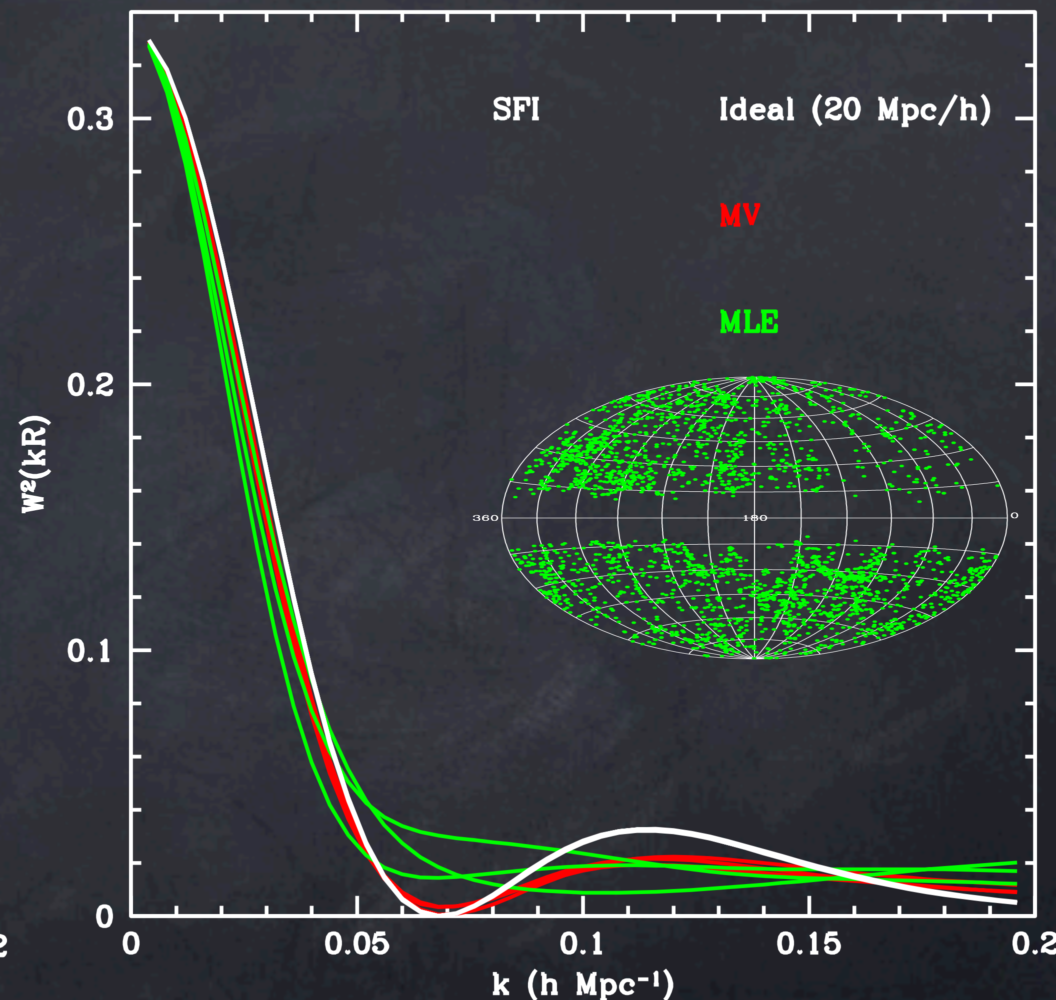
MV window functions are marginally better than MLE window functions

Survey Window Functions

ENEAR (697)

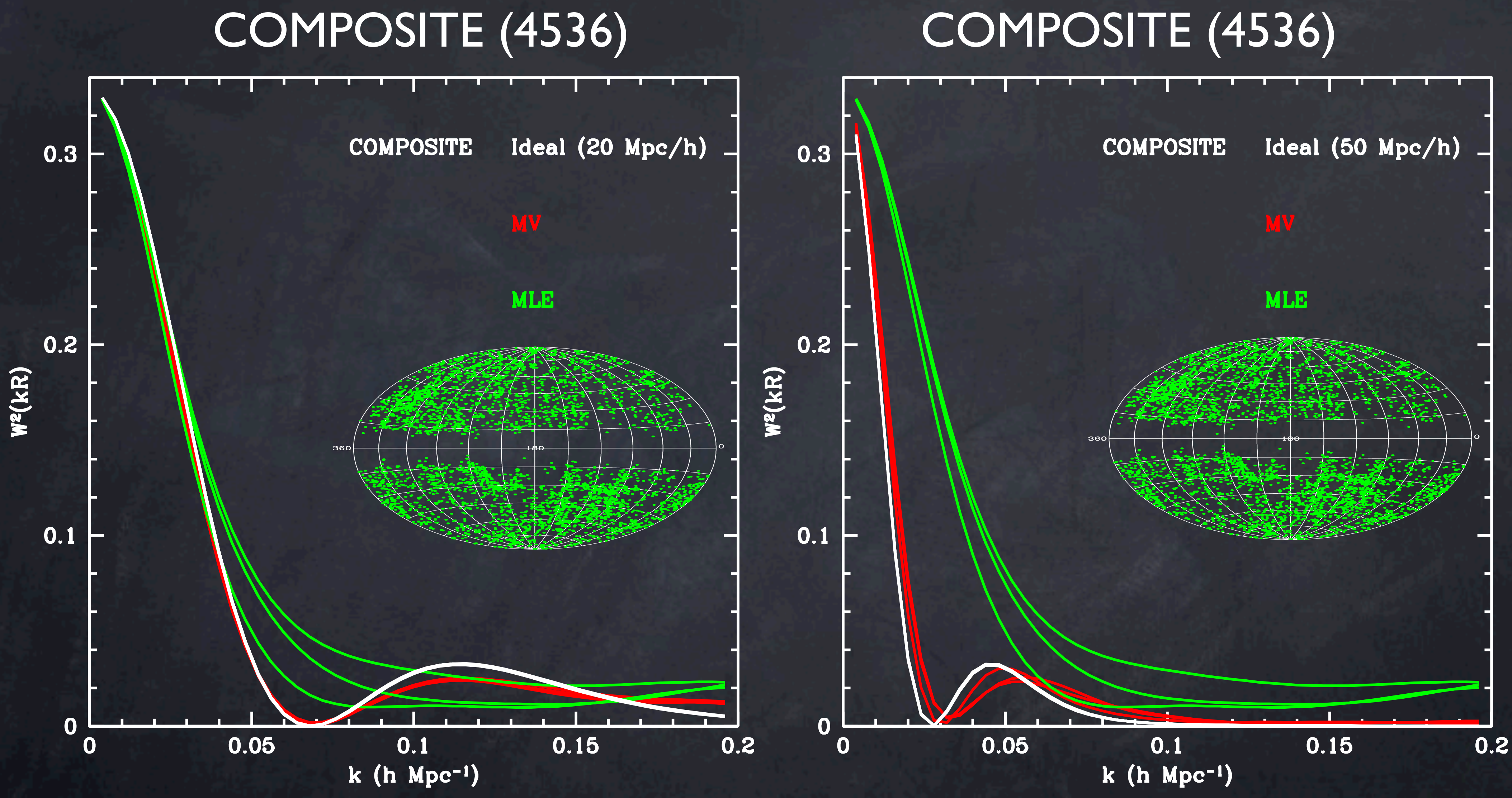


SFI (2821)



For dense + uniform surveys, MV window functions are better fits to the ideal window function.

Survey Window Functions

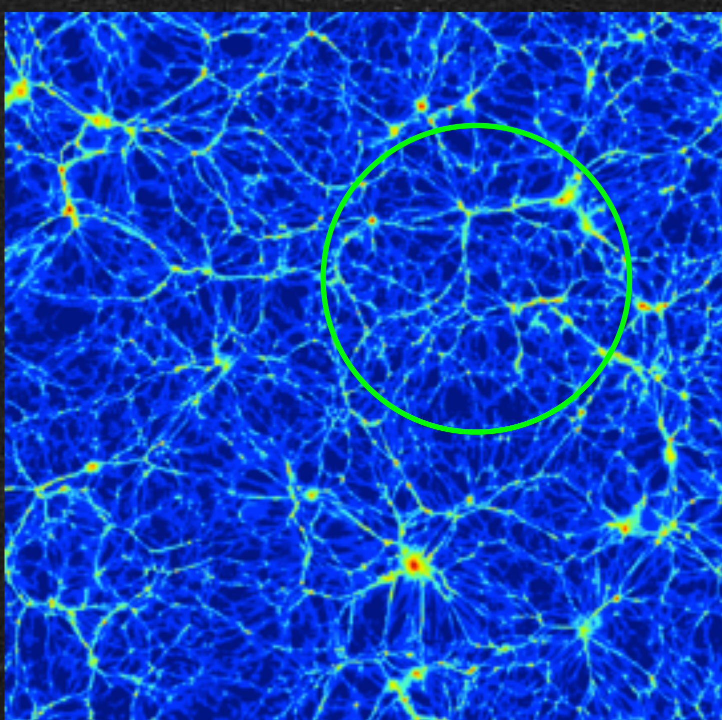


Near-ideal catalogs over a range of scales can be extracted from dense + uniform surveys.

Testing the MV Formalism

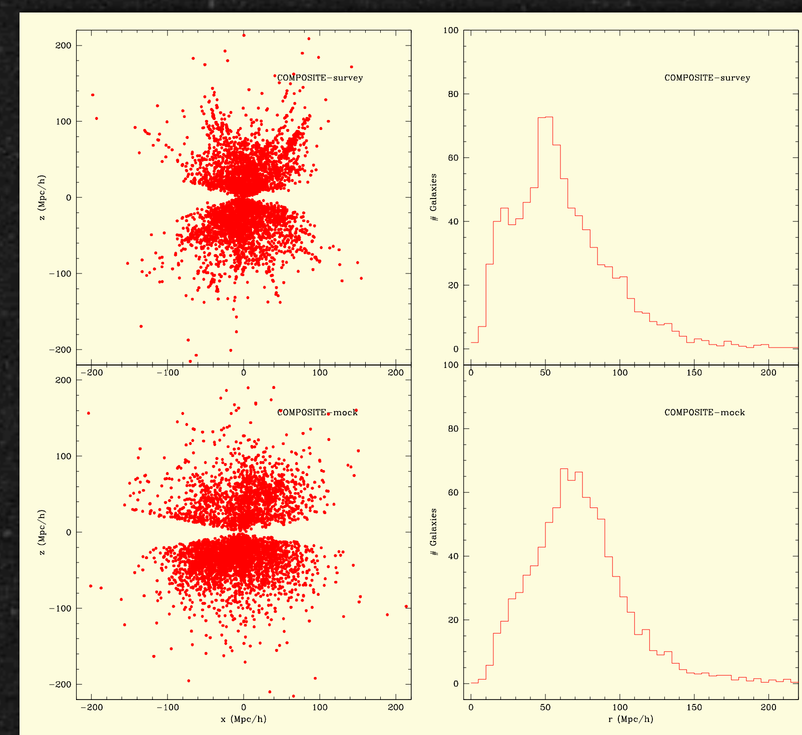
Use N-body simulations to investigate the robustness of the MV formalism

N-body V



Compare

U Mock Survey



To create the mock catalogues we used two different simulations

	LasDamas (McBride et al. 2011)	Horizon Run (Kim et al. 2009)
Ω_m	0.25	0.26
Ω_b	0.04	0.044
Ω_Λ	0.75	0.74
h	0.7	0.72
σ_8	0.8	0.974
n_s	1.0	0.96
L_{box}	1.0 h^{-1}Gpc	6.592 h^{-1}Gpc
	41 simulation boxes with ~ $1.3\cdot10^6$ particles each	1 simulation box with ~ $87\cdot10^6$ particles
Galaxy ID	Subhalos (Kim etal 2008)	FOF (Gardner etal 2007)

Making a Mock Catalogue

The **MV** weighting scheme assigns weights as a function of radial and angular distribution and errors.
Construct mock catalogues in such a way that the weight of each galaxy is the same as the **MV** weights of the real catalogues.

1. Identify a random point in the simulation box.
2. Extract a set of galaxies with the same radial selection function about this point as the real catalogue.
3. Impose a 10^o latitude zone-of-avoidance cut.
4. From the simulations for each galaxy we find
   a) the angular position *l* and *b*,
   b) the true line-of-sight peculiar velocity v_s and the true distance d_s,
   c) the redshift $cz = d_s + v_s$ for each mock galaxy
   d) perturb the true radial distance d_s of the mock galaxy with a velocity error drawn from a Gaussian distribution of width equal to the corresponding real galaxy's velocity error, σ_n
   e) The mock galaxy's line-of-sight peculiar velocity v_p is $v_p = cz - d_p$

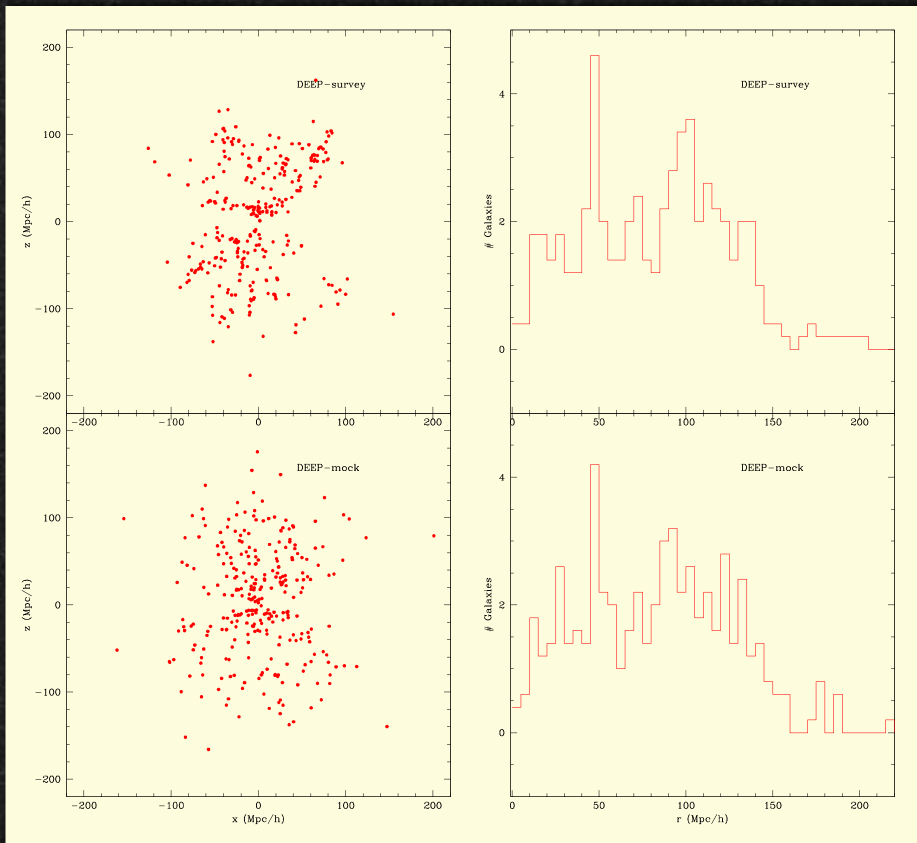
Alternatively

d) perturb the true line-of-sight velocity v_s of the mock galaxy with a velocity error drawn from a Gaussian distribution of width equal to the corresponding real galaxy's velocity error, σ_n
e) The mock galaxy's distance d_p is $d_p = cz - v_p$

Making a Mock Catalogue

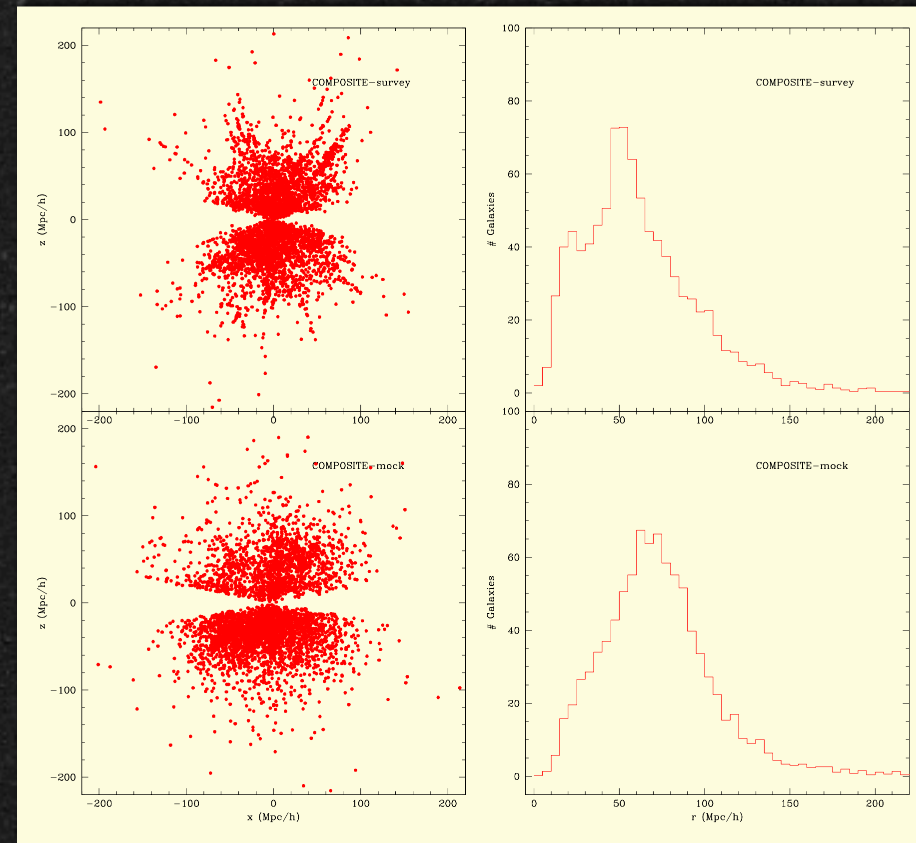
DEEP

COMPOSITE



Surveys

Mocks



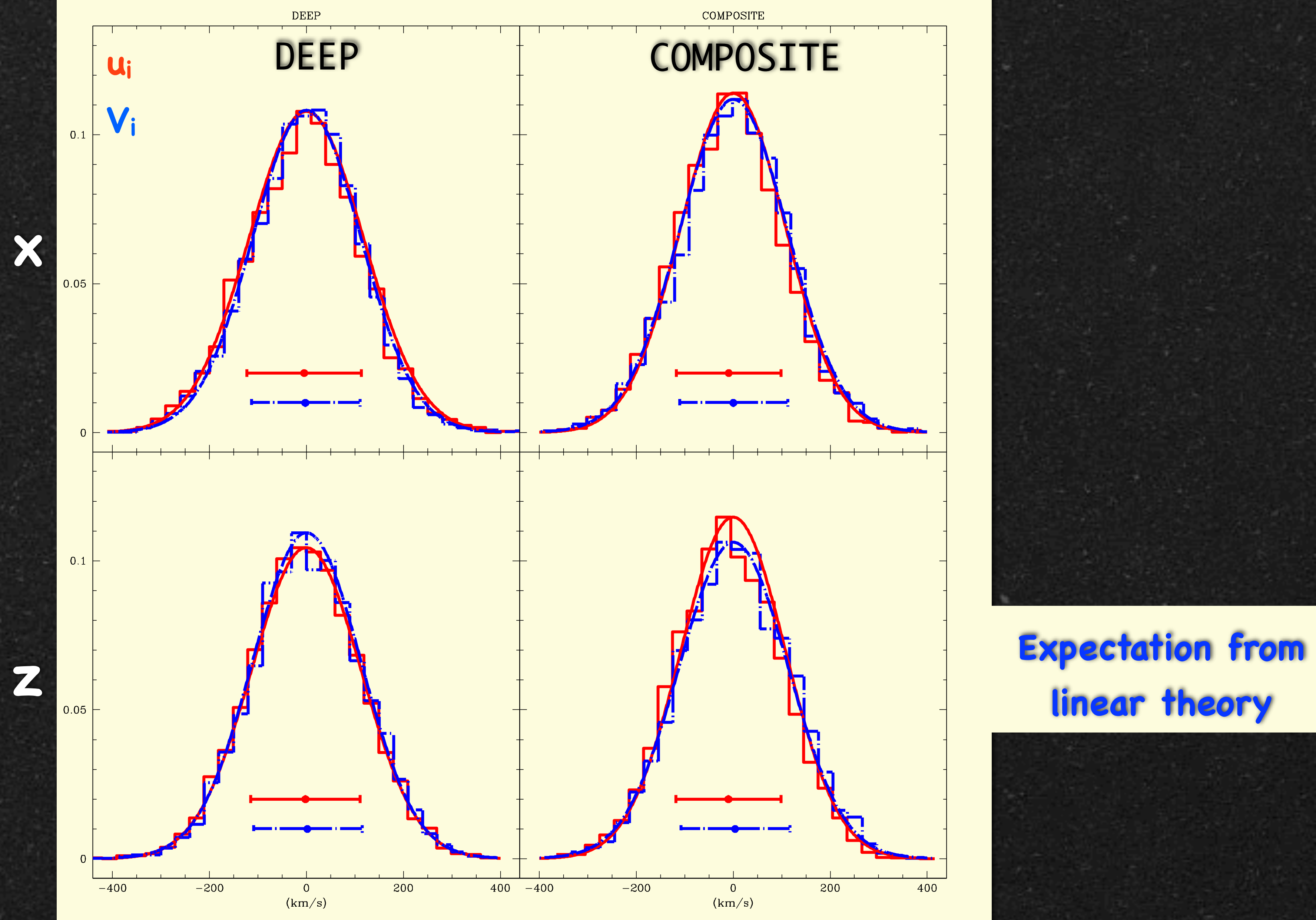
The weights depend on the radial distribution, errors and the angular distribution

The weights we assign to the mock galaxies are similar to the weights for the real galaxies

Making a Mock Catalogue

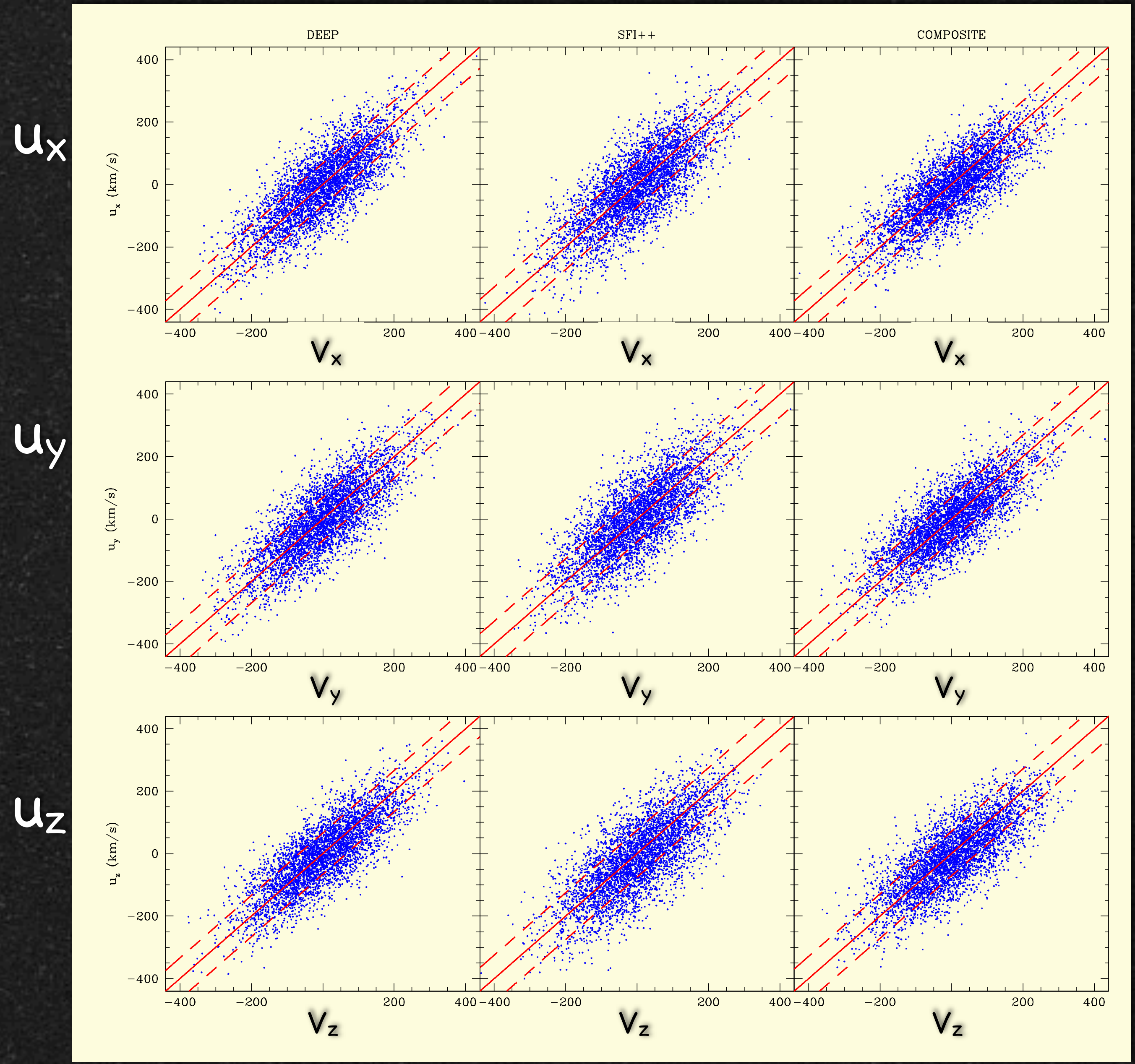
- For each of the 4100 LasDamas (5000 Horizon Run) mocks, estimate the bulk flow moments $\{u_x, u_y, u_z\}$ using the MV weighting scheme.
- Compare the results to the Gaussian-weighted bulk moments $\{V_x, V_y, V_z\}$.
- The Gaussian moments are calculated by going to the same central points for each of the 4100 LasDamas (5000 Horizon Run) mock catalogues and averaging the velocities of all the galaxies in the simulation box, each galaxy being weighted by a Gaussian weight of width R_G

$R_G = 50\ h^{-1}$Mpc

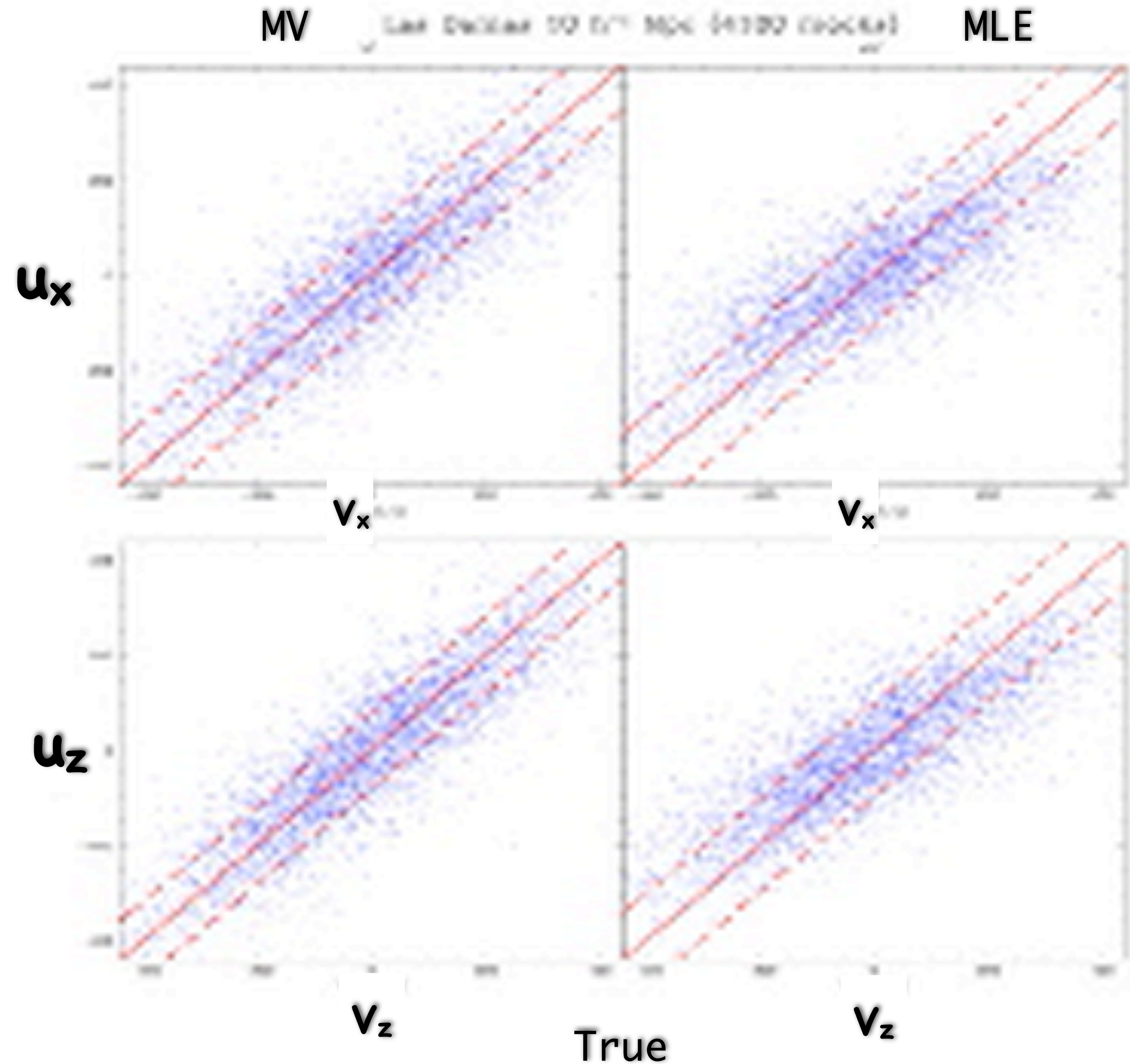


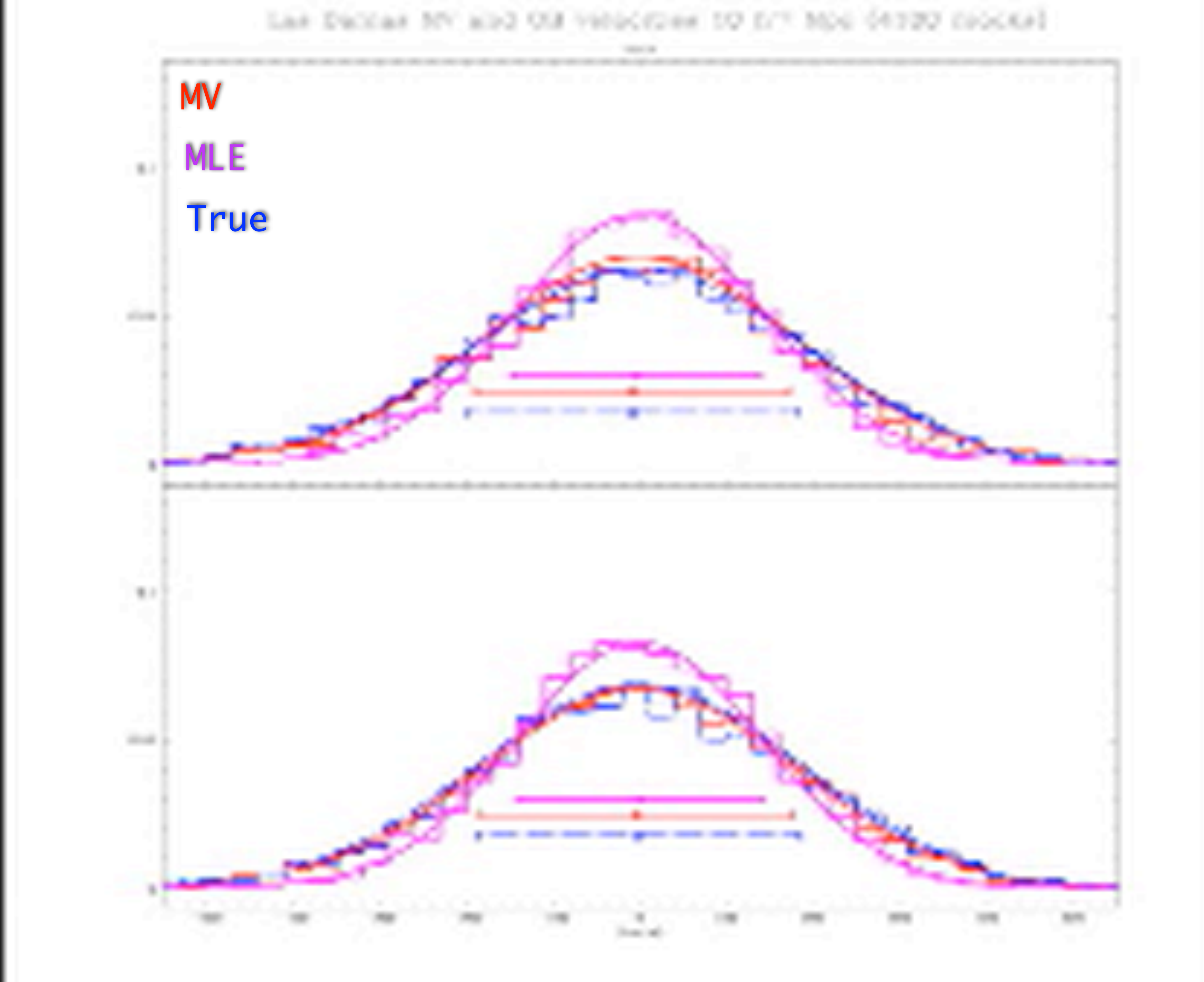
Normalized probability distribution for the MV (u_i) and the Gaussian-weighted bulk flow moments (V_i)

R_G = 50 h^{-1}Mpc



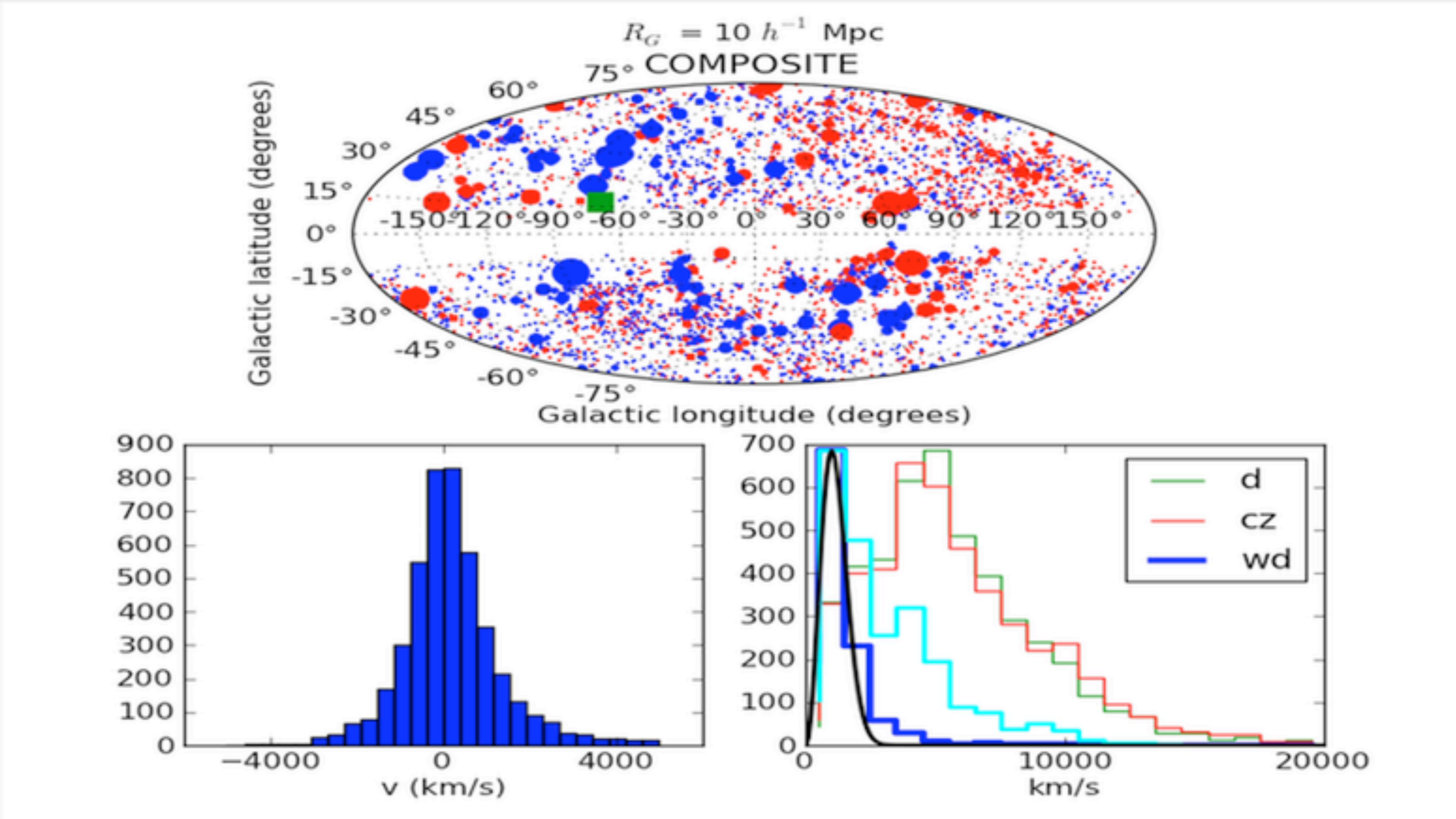
The MV bulk flow moments u_i vs. the Gaussian-weighted “true” moments V_i


MV
MLE
u_x
v_x
v_x
u_z
v_z
v_z
True


MV
MLE
True

The MV moments are unbiased estimators of the bulk flow of a volume of a given scale, independent of the geometry of a particular survey.

The BF estimators are negligibly affected by non-linear flows

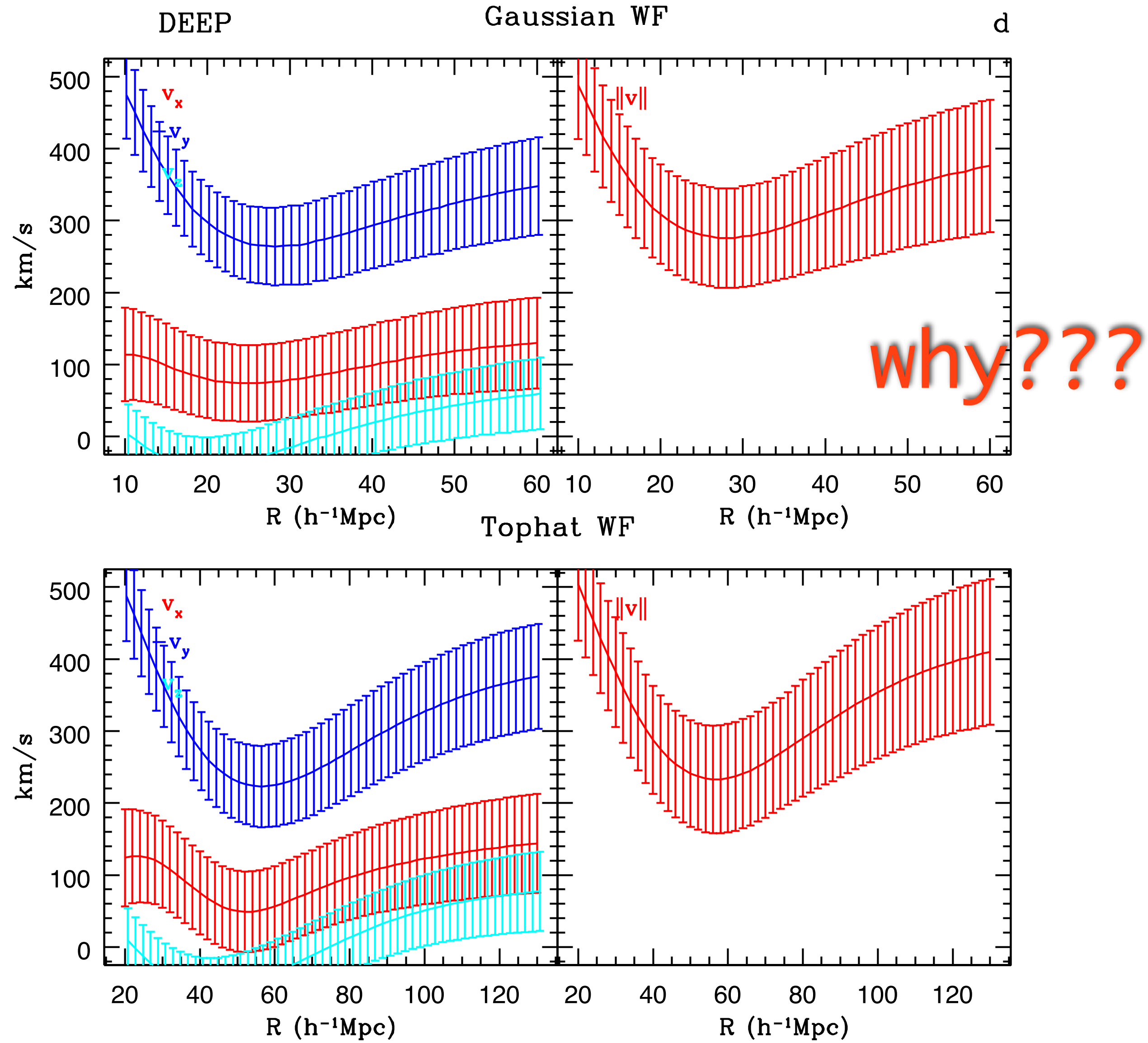


Direction of flow

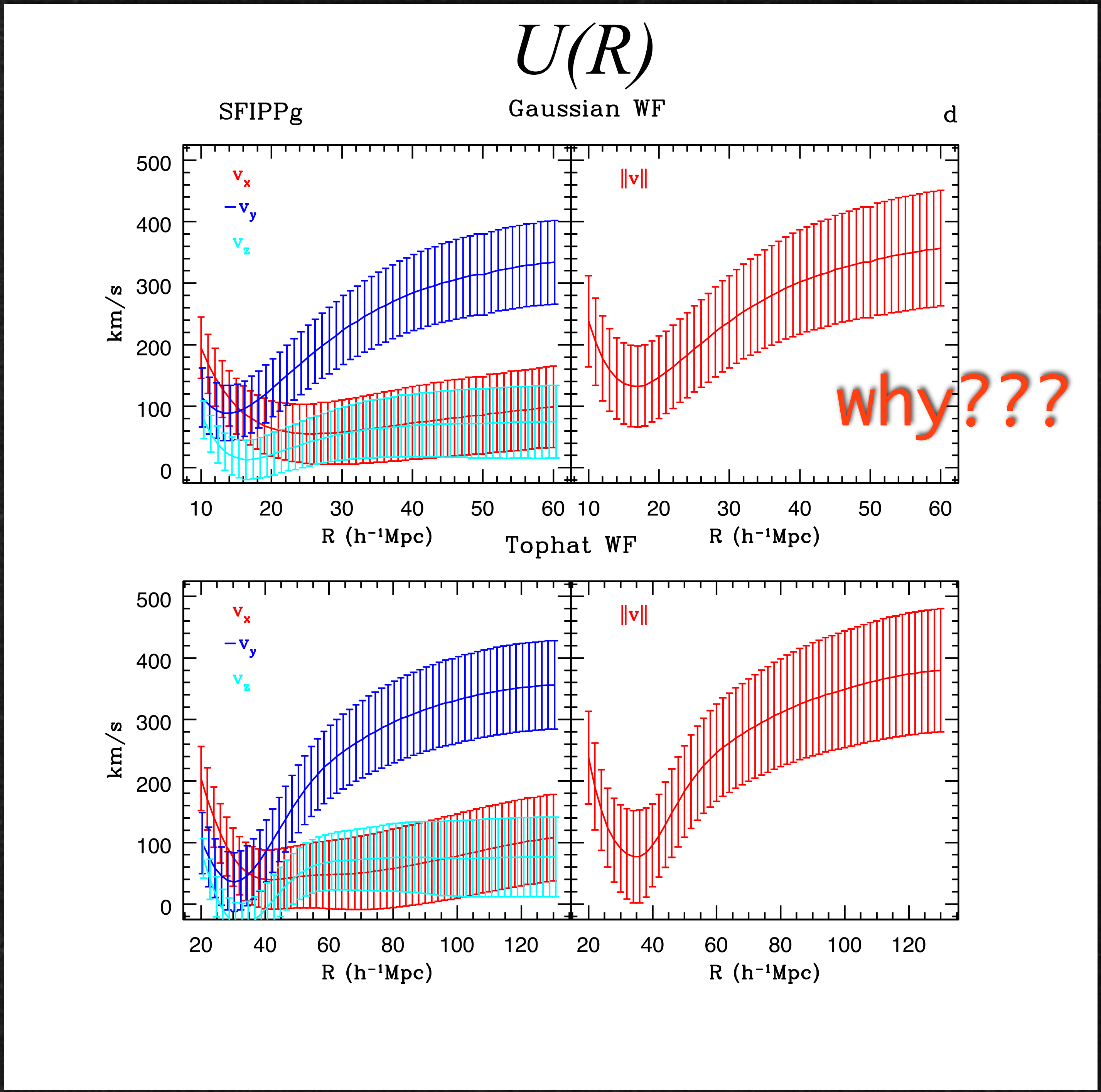
Velocities Outgoing Incoming

Symbol area weight

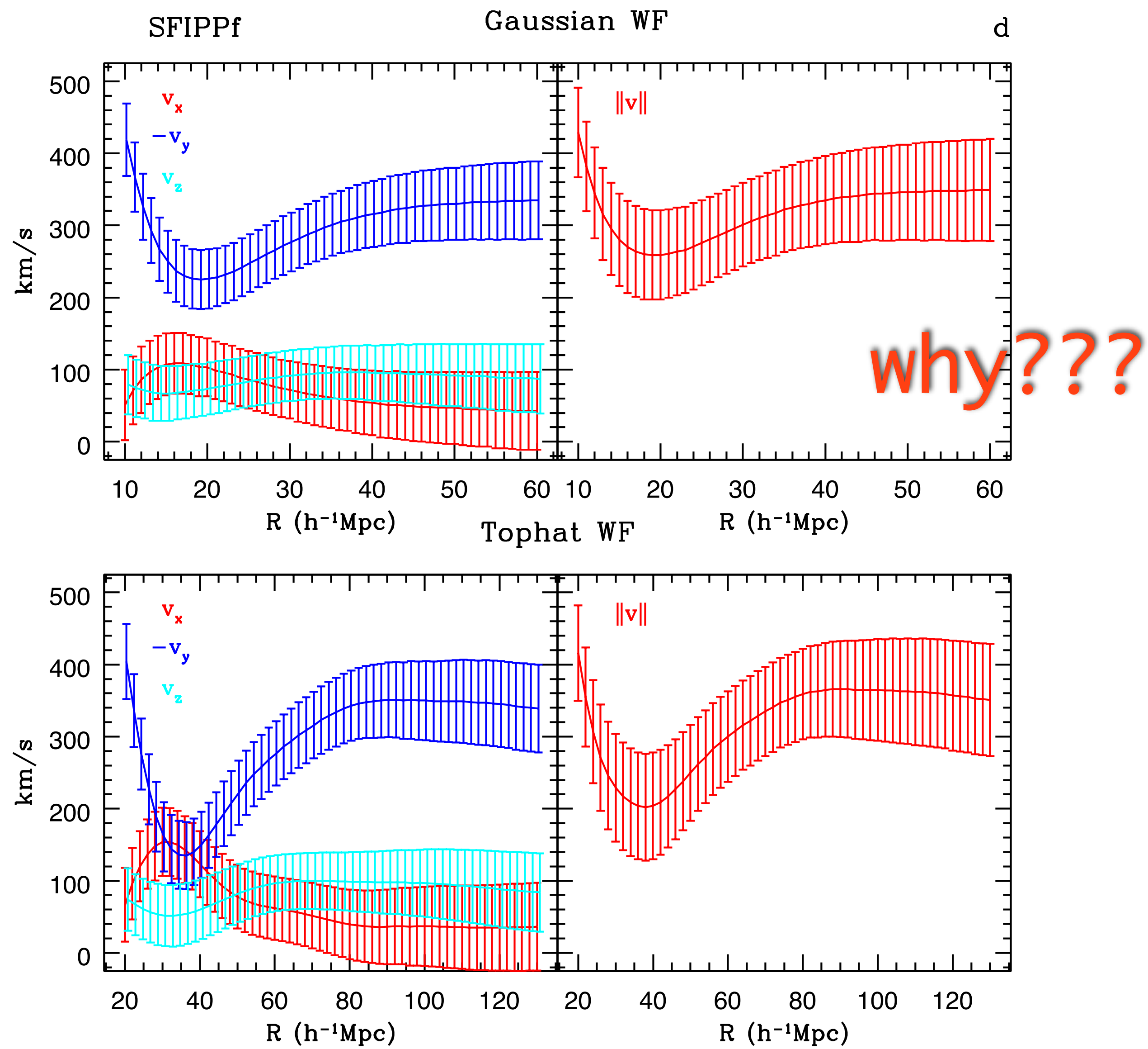
U(R)



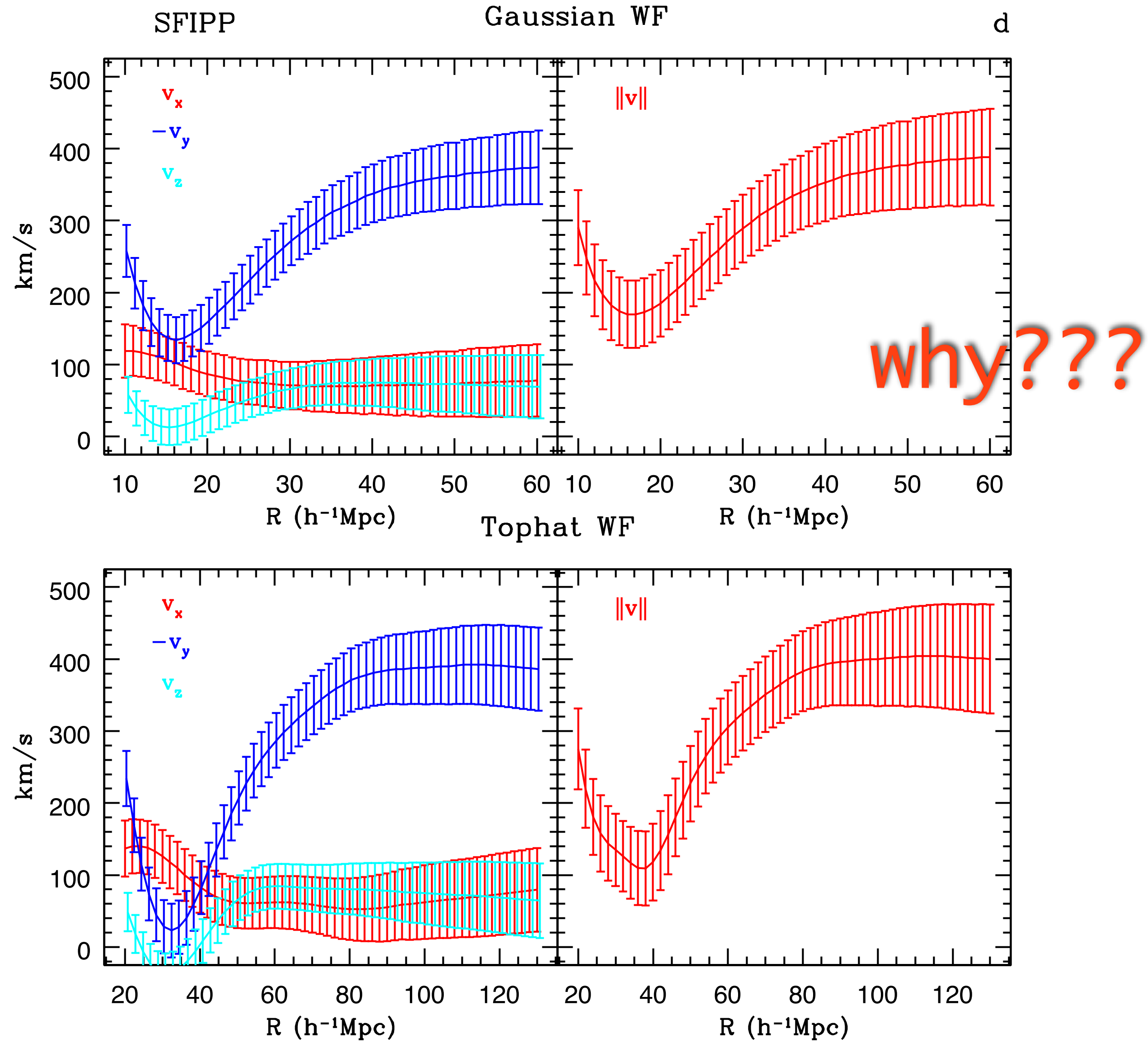
DEEP
Gaussian WF
d
500
400
300
200
100
0
km/s
v_x
v_y
v_z
||v||
10
20
30
40
50
60
R (h⁻¹Mpc)
Tophat WF
20
40
60
80
100
120
why???


U(R)
SFIPPg
Gaussian WF
d
km/s
v_x
v_y
v_z
||v||
R (h⁻¹Mpc)
Tophat WF
why???

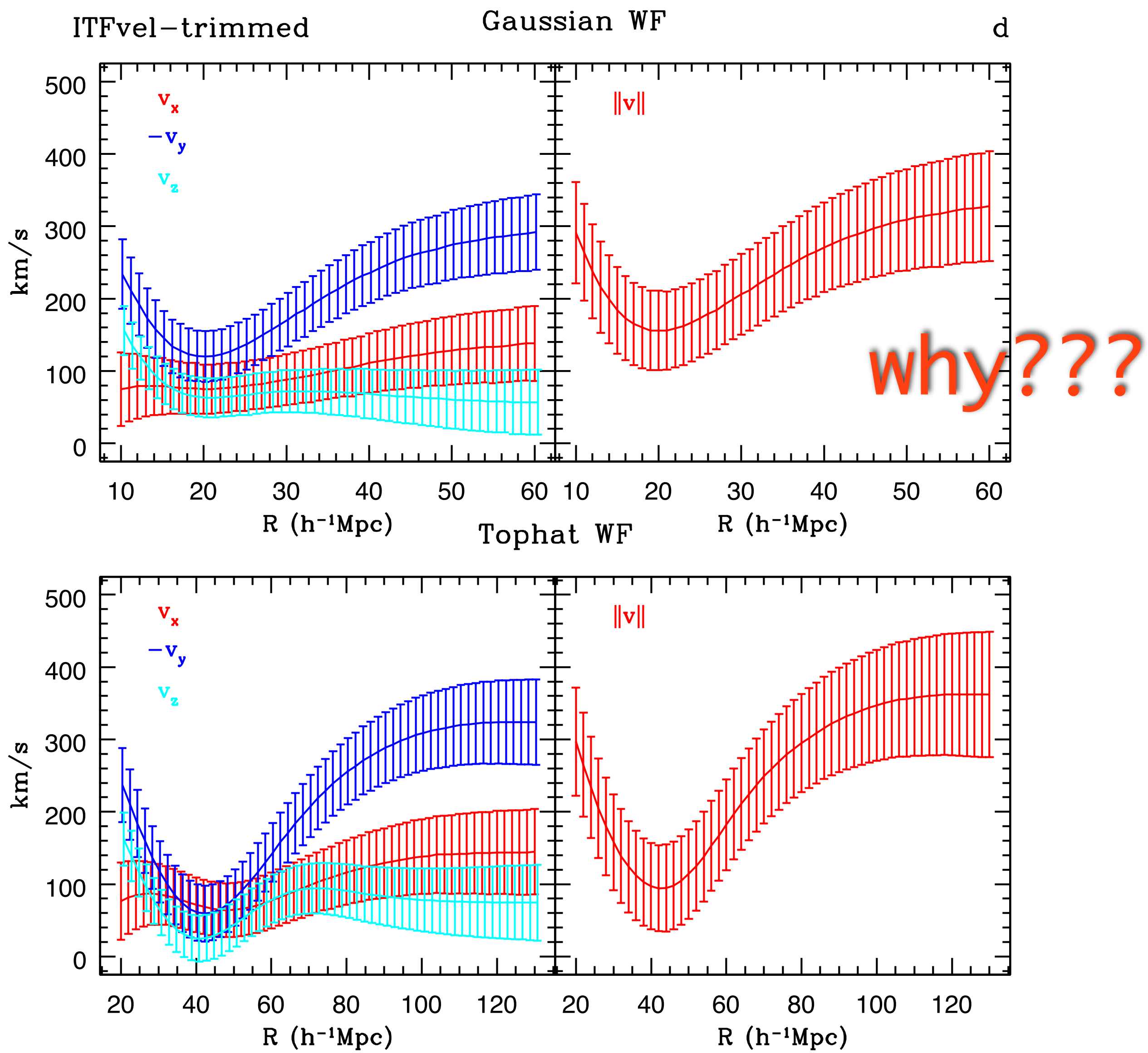
U(R)

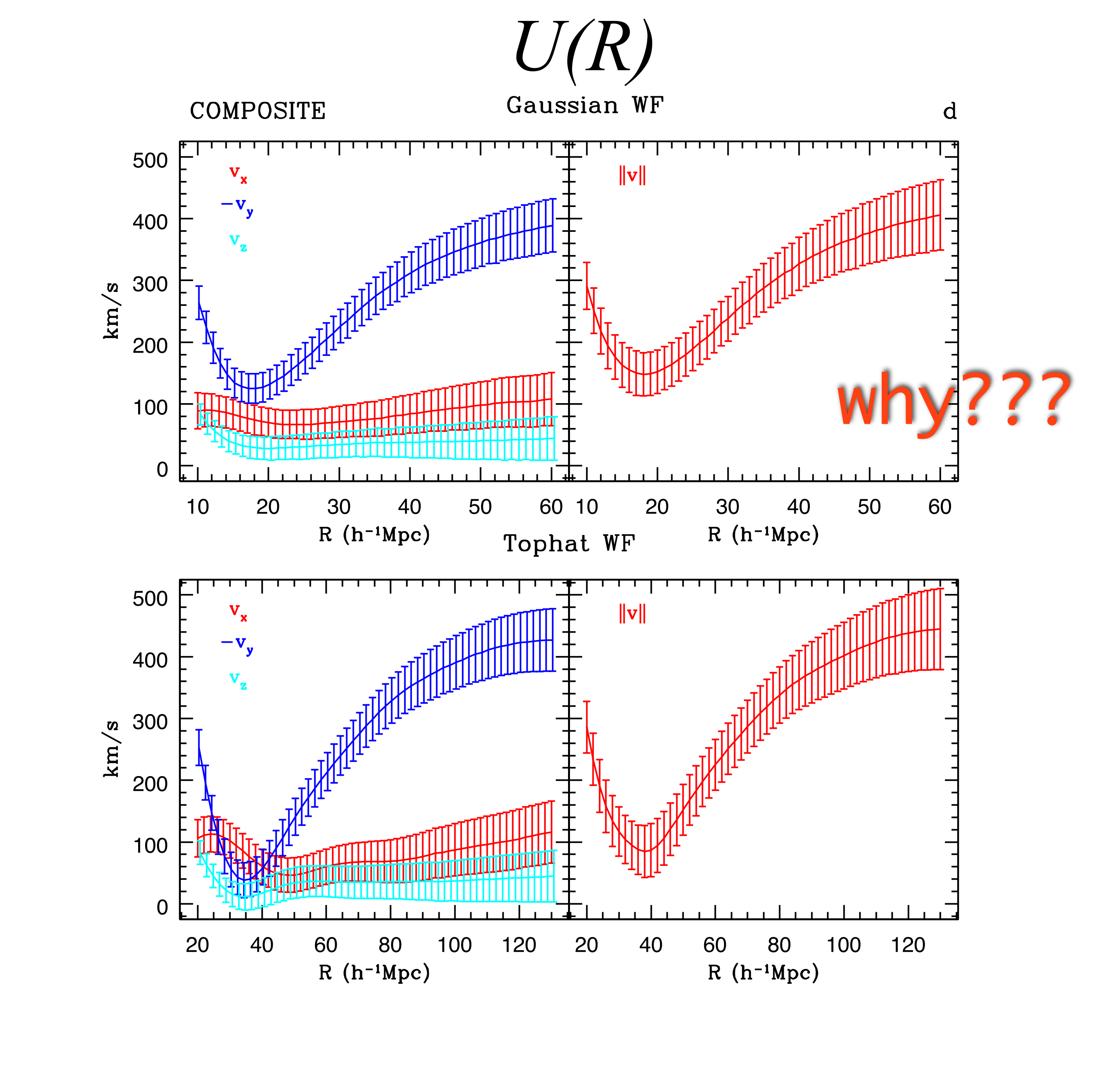

SFIPPf
Gaussian WF
d
500
400
300
200
100
0
km/s
v_x
$-v_y$
v_z
||v||
10
20
30
40
50
60
R (h⁻¹Mpc)
Tophat WF
20
40
60
80
100
120
R (h⁻¹Mpc)
why???

$U(R)$


SFIPP
Gaussian WF
d
km/s
v_x
$-v_y$
v_z
$\|v\|$
R (h^{-1}Mpc)
Tophat WF
0
100
200
300
400
500
10
20
30
40
50
60
80
100
120
why???

U(R)


ITFvel−trimmed
Gaussian WF
d
Tophat WF
km/s
R (h⁻¹Mpc)
v_x
$-v_y$
v_z
$\|v\|$
why???

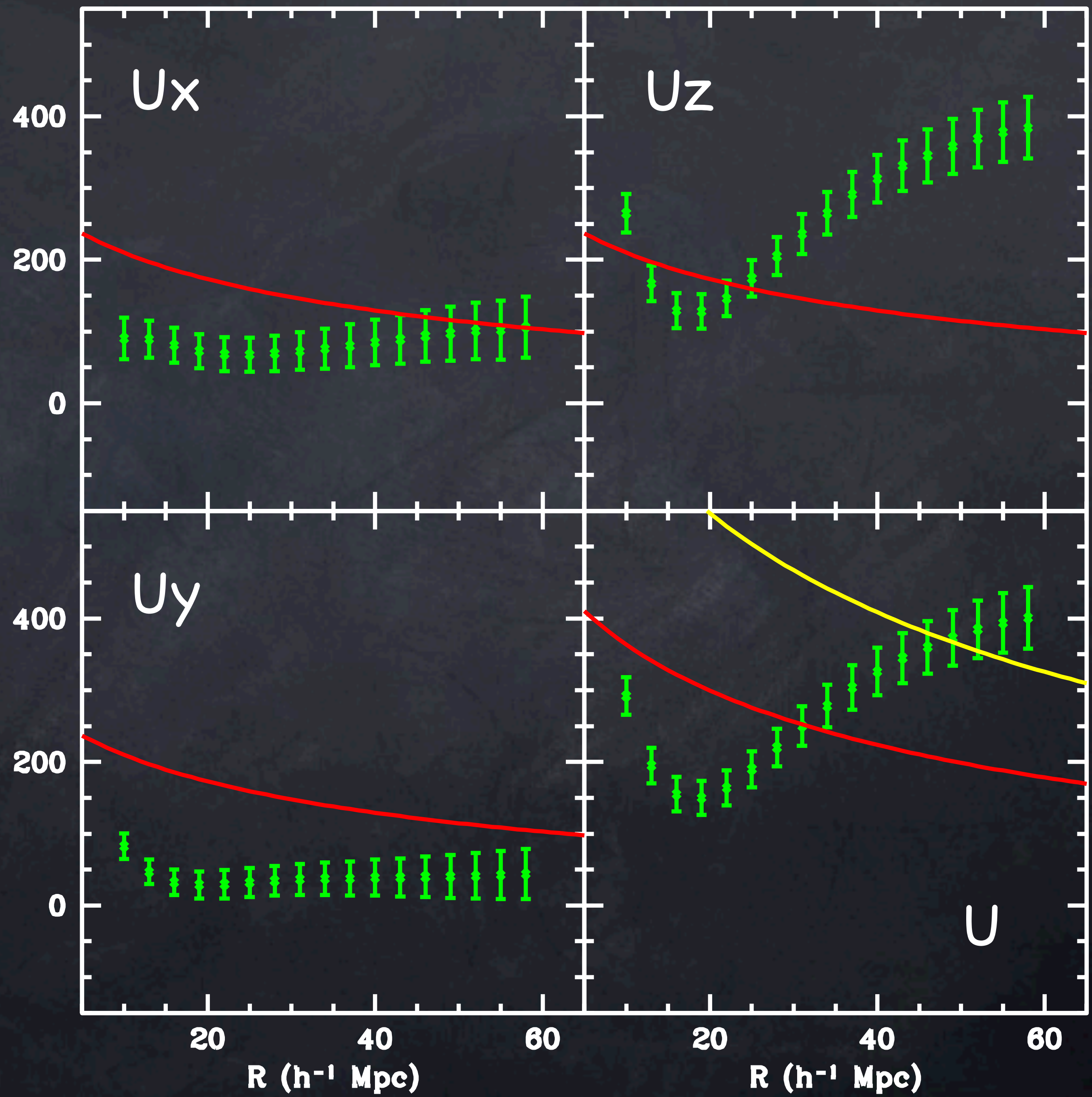

U(R)
COMPOSITE
Gaussian WF
d
Tophat WF
km/s
R (h⁻¹Mpc)
v_x
v_y
v_z
||v||
why???

$$\sigma_v^2(R) = \frac{(H_o \Omega_m^{0.6})^2}{2\pi^2} \int \mathrm{d}k \; P(k) W^2(kR)$$

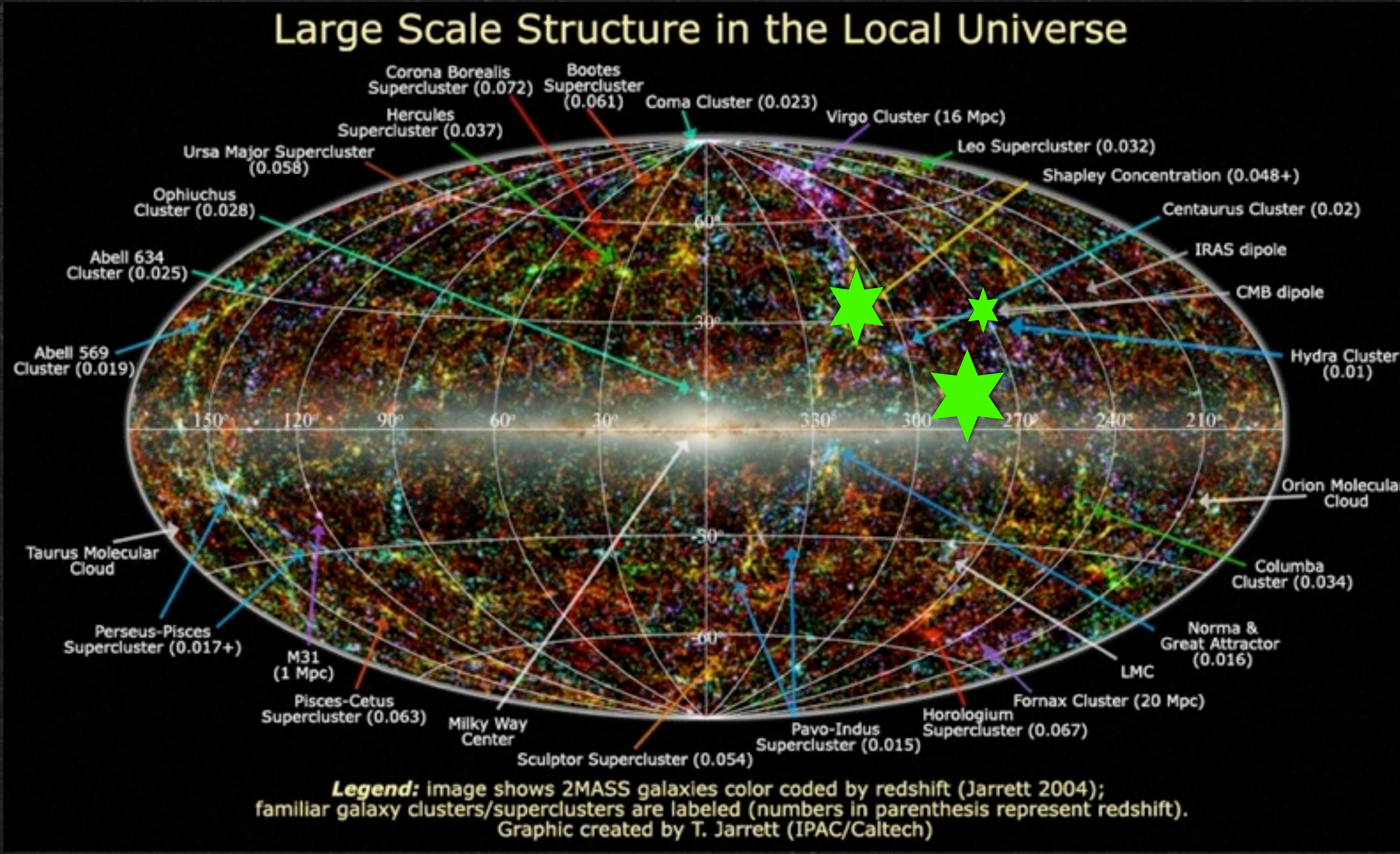
Linear Theory

98% cosmic scatter

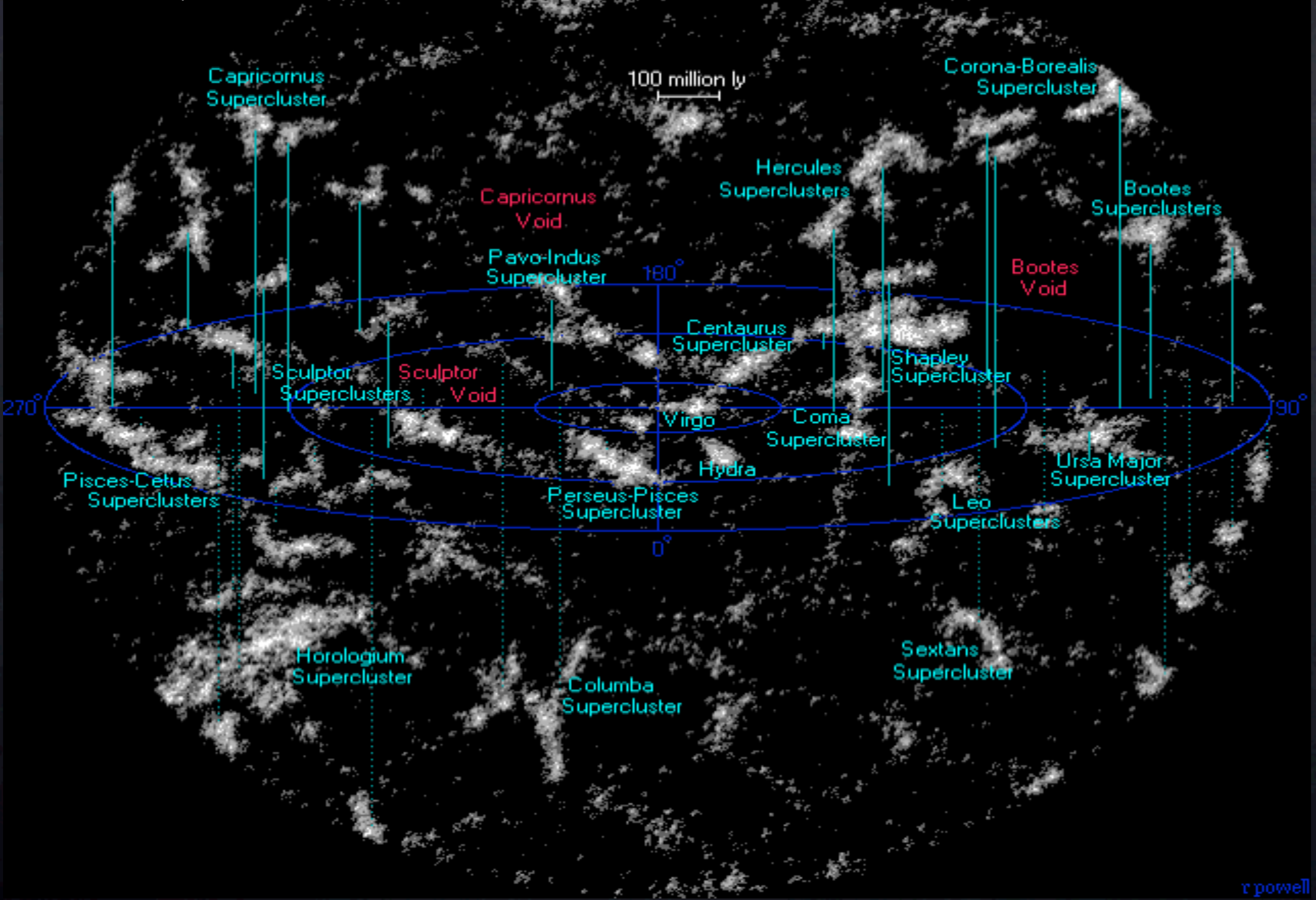
Surveys



Is there an attractor?



300 Mpc/h


100 million ly
Capricornus Supercluster
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r powell

Conclusions

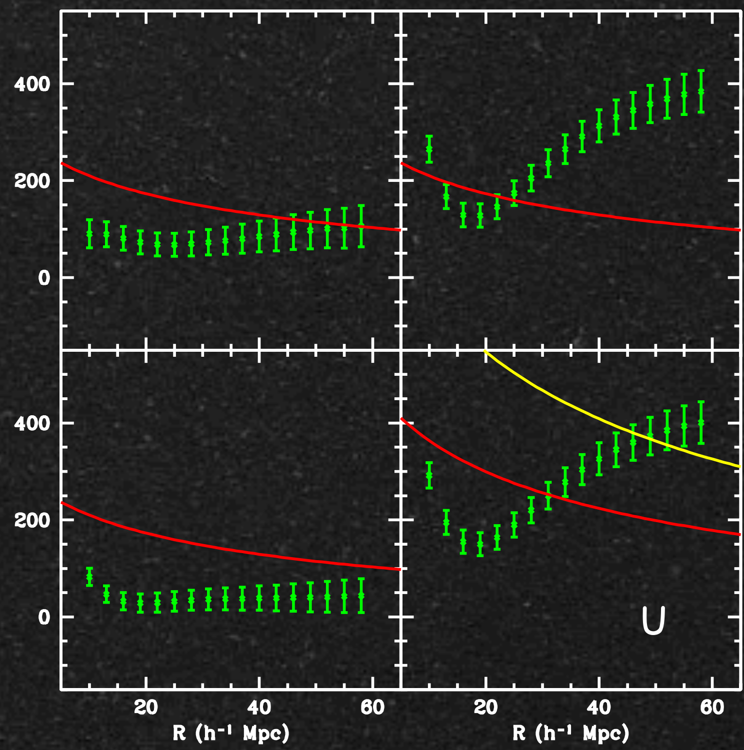
Survey → Re-design Window Function → Bulk Flow

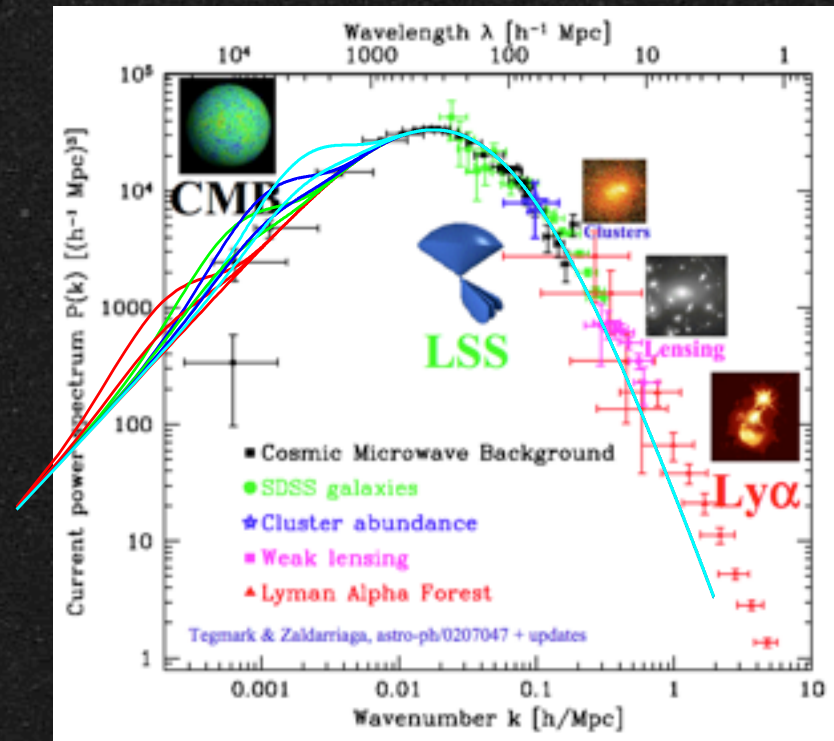
- ☑ MV method re-designs the survey window function in a way that minimizes the aliasing of small-scale power onto large scales
- ☑ The MV formalism correctly predicts the bulk flow of the volume of a particular scale
- ☑ The direct control over WF provides for comparison of bulk flow results across independent surveys with varying characteristics.
- ☑ Allows for the determination of the Bulk Flow as function of scale

Conclusions

- Bulk flow on 100 Mpc scales disagrees with the Standard ΛCDM parameters (WMAP-9) to $>2\sigma$

Need more power on large scales: more large mass concentrations - voids on scales $\gtrsim 250\ h^{-1}$ Mpc





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