Flows on $100\ h^{-1}$ Mpc Scales

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Peculiar Velocity Field

Measure the line of sight peculiar velocities:

$$v_p = cz - H_o r$$

The difference between the redshift and the distance

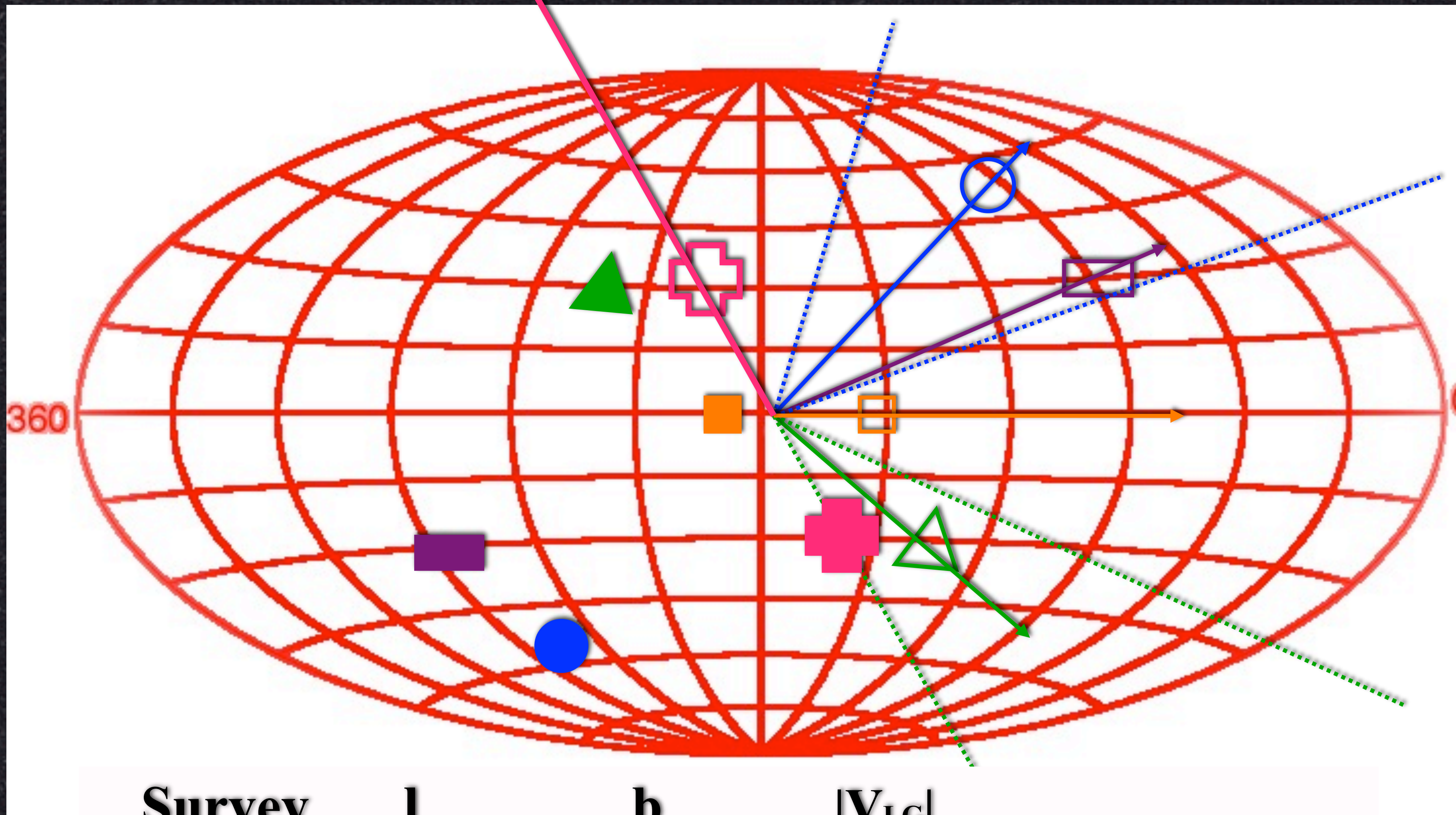
Why should we study v_p ?

- ★ The peculiar velocity field is dominated by large scales

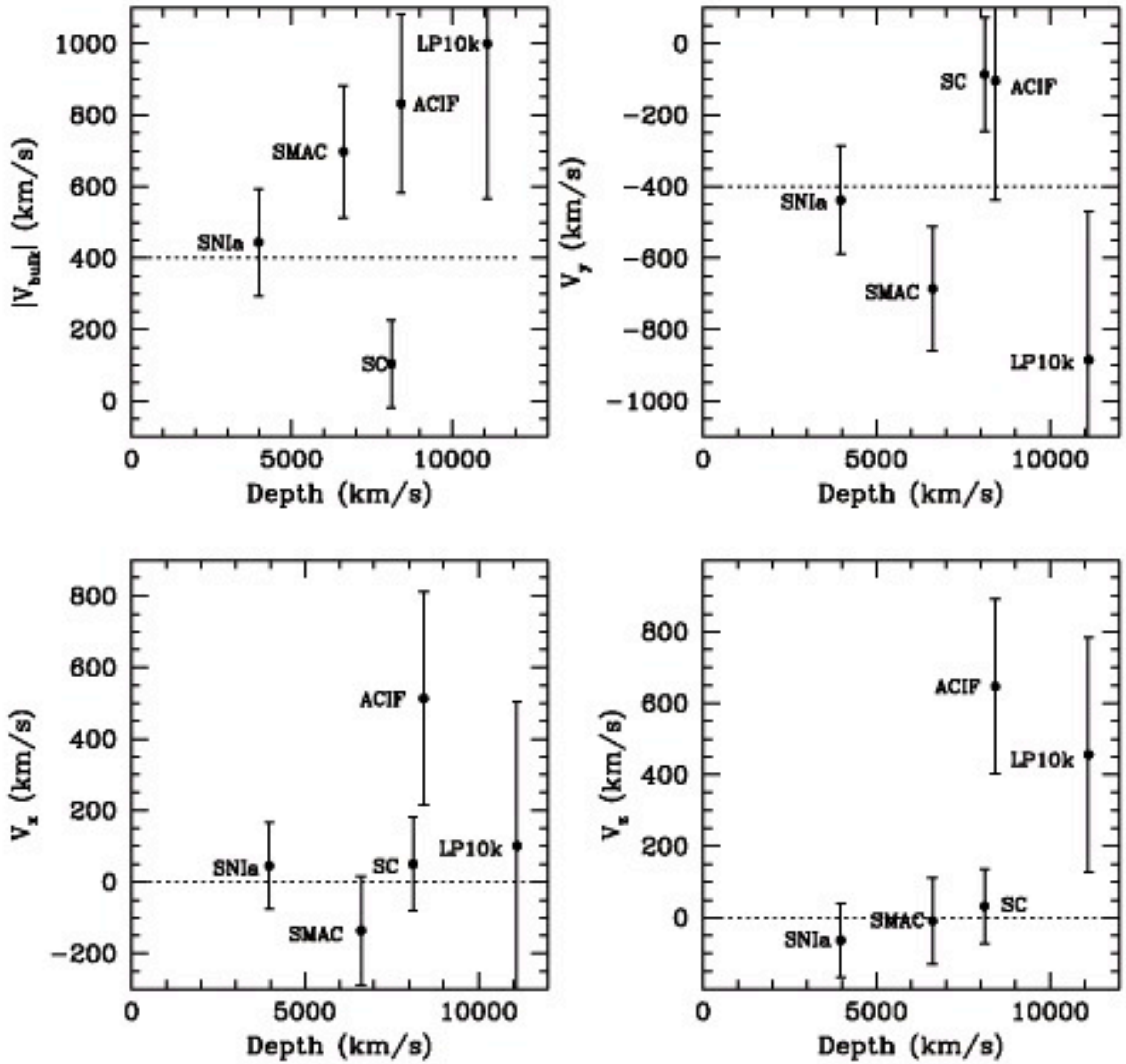
→ Linear structure

- ★ Test of gravitational instability model $\vec{\nabla} \cdot \vec{V} = \frac{\delta \rho}{\rho}$ $\vec{\nabla} \times \vec{V} = 0$
- ★ A direct probe of the mass distribution $\vec{V} = -\vec{\nabla}\phi$
- ★ Comparison of velocity fields & Luminous matter distribution → bias, Ω ...

Local Group Velocity (Cautionary History Lesson)



Survey	l	b	$\|V_{LG}\|$
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


1000
800
600
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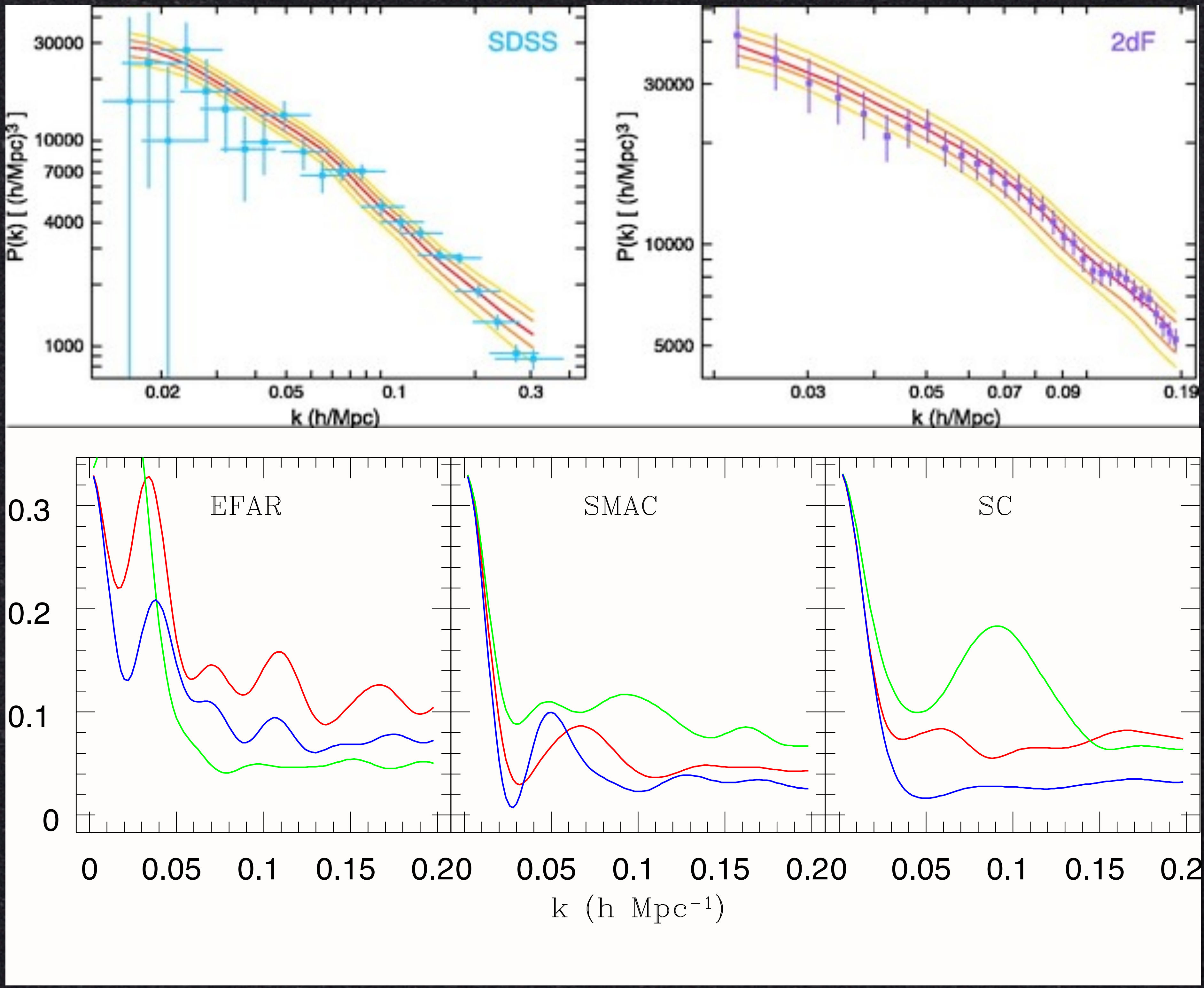
0
$|V_{bulk}|$ (km/s)
LP10k
ACIF
SMAC
SNIa
SC
0
5000
10000
Depth (km/s)
0
−200
−400
−600
−800
−1000
V_y (km/s)
SC
ACIF
SNIa
SMAC
LP10k
Depth (km/s)
800
600
400
200
0
−200
V_x (km/s)
ACIF
SNIa
SC
LP10k
SMAC
Depth (km/s)
V_z (km/s)
ACIF
LP10k
SC
SMAC
SNIa
Depth (km/s)

$$\tilde{p} = N\int \frac{d^3k}{(2\pi)^3}\, p(\vec{k})W(\vec{k})$$



Velocity Fields

The Modern Version

HAF, Watkins & Hudson, arXiv.0911.5516 *(2009)*

Watkins, HAF & Hudson, MNRAS, 392, 743-756 (2009)

HAF & Watkins, MNRAS 387, 825-829 (2008)

Watkins & HAF, MNRAS 379, 343-348 (2007)

Sarkar, HAF & Watkins, MNRAS 375 691-697 (2007)

Redshift-Distance surveys

- Construct the full three dimensional bulk-flow vectors.
- Compare bulk-flow for peculiar velocity surveys.
- Surveys differ in their
  - o geometry
  - o measurement errors
  - o galaxy types.
- The overall errors are
  - Statistical
  - Systematic
  - Aliasing

The Physics of Velocity Fields

On scales that are small compared to the Hubble radius, galaxy motions are manifest in deviations from the idealized isotropic cosmological expansion

$$cz = H_0 r + \hat{\mathbf{r}} \cdot [\mathbf{v}(\mathbf{r}) - \mathbf{v}(0)]$$

The redshift-distance samples, obtained from peculiar velocity surveys, allow us to determine the radial (line-of-sight) component of the peculiar velocity of each galaxy:

$$v(r) = \hat{\mathbf{r}} \cdot \mathbf{v}(\mathbf{r}) = cz - H_0 r$$

The Physics of Velocity Fields

Galaxies trace the large-scale linear velocity field $v(r)$ which is described by a Gaussian random field that is completely defined, in Fourier space, by its velocity power spectrum $P_v(k)$.

Fourier Transform of the line-of-sight velocity

$$\hat{\mathbf{r}} \cdot \mathbf{v}(\mathbf{r}) = \frac{1}{(2\pi)^3} \int d^3\mathbf{k}\, \hat{\mathbf{r}} \cdot \hat{\mathbf{k}}\, v(\mathbf{k})\, \mathbf{e}^{\mathbf{ik}\cdot\mathbf{r}}$$

Define the velocity power spectrum $P_v(k)$

$$\langle v(\mathbf{k}) v^*(\mathbf{k}') \rangle = (2\pi)^3 P_v(k) \delta_D(\mathbf{k} - \mathbf{k}')$$

The Physics of Velocity Fields

In linear theory, the velocity power spectrum is related to the density power spectrum

$$P_v(k) = \frac{H^2}{k^2} f^2(\Omega_{m,0}, \Omega_\Lambda) P(k)$$

The rate of growth of the perturbations at the present epoch

The Physics of Velocity Fields

In linear theory, the velocity power spectrum is related to the density power spectrum

$$P_v(k) = \frac{H^2}{k^2} f^2(\Omega_{m,0}, \Omega_\Lambda) P(k)$$

The power spectrum provides a complete statistical description of the linear peculiar velocity field.

Likelihood Methods for Peculiar Velocities

A catalog of peculiar velocities galaxies, labeled by an index n

Positions r_n

Estimates of the line-of-sight peculiar velocities S_n

Uncertainties σ_n

Assume that observational errors are Gaussian distributed.

Model the velocity field as a uniform streaming motion, or bulk flow, denoted by U, about which are random motions drawn from a Gaussian distribution with a 1-D velocity dispersion σ_*

Likelihood Methods for Peculiar Velocities

Likelihood function for the bulk flow components

$$L(U_i) = \prod_n \frac{1}{\sqrt{\sigma_n^2 + \sigma_*^2}} \exp\left(-\frac{1}{2} \frac{(S_n - \hat{r}_{n,i} U_i)^2}{\sigma_n^2 + \sigma_*^2} \right)$$

Maximum likelihood solution for bulk flow

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

where

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

Likelihood Methods for Peculiar Velocities

The measured peculiar velocity of galaxy n

$$S_n = \hat{r}_{n,i} v_i(\mathbf{r}_n) + \epsilon_n$$

A Gaussian with zero mean and variance $\sigma_n^2 + \sigma_*^2$

Theoretical covariance matrix for the bulk flow components

$$R_{ij} = \left\langle v_i v_j \right\rangle = R_{ij}^{(v)} + \delta_{ij}\left(\sigma_i^2 + \sigma_*^2\right)$$

$$R_{ij}^{(v)} = \frac{1}{(2\pi)^3} \int P_{(v)}(k) W_{ij}^2(k) d^3k$$

$$= \frac{H^2 f^2(\Omega_0)}{2\pi^2} \int P(k) W_{ij}^2(k) dk$$

Likelihood Methods for Peculiar Velocities

Question: Are surveys consistent with each other?

Even if two surveys are measuring the same underlying velocity field, they will not necessarily give the same bulk flow.

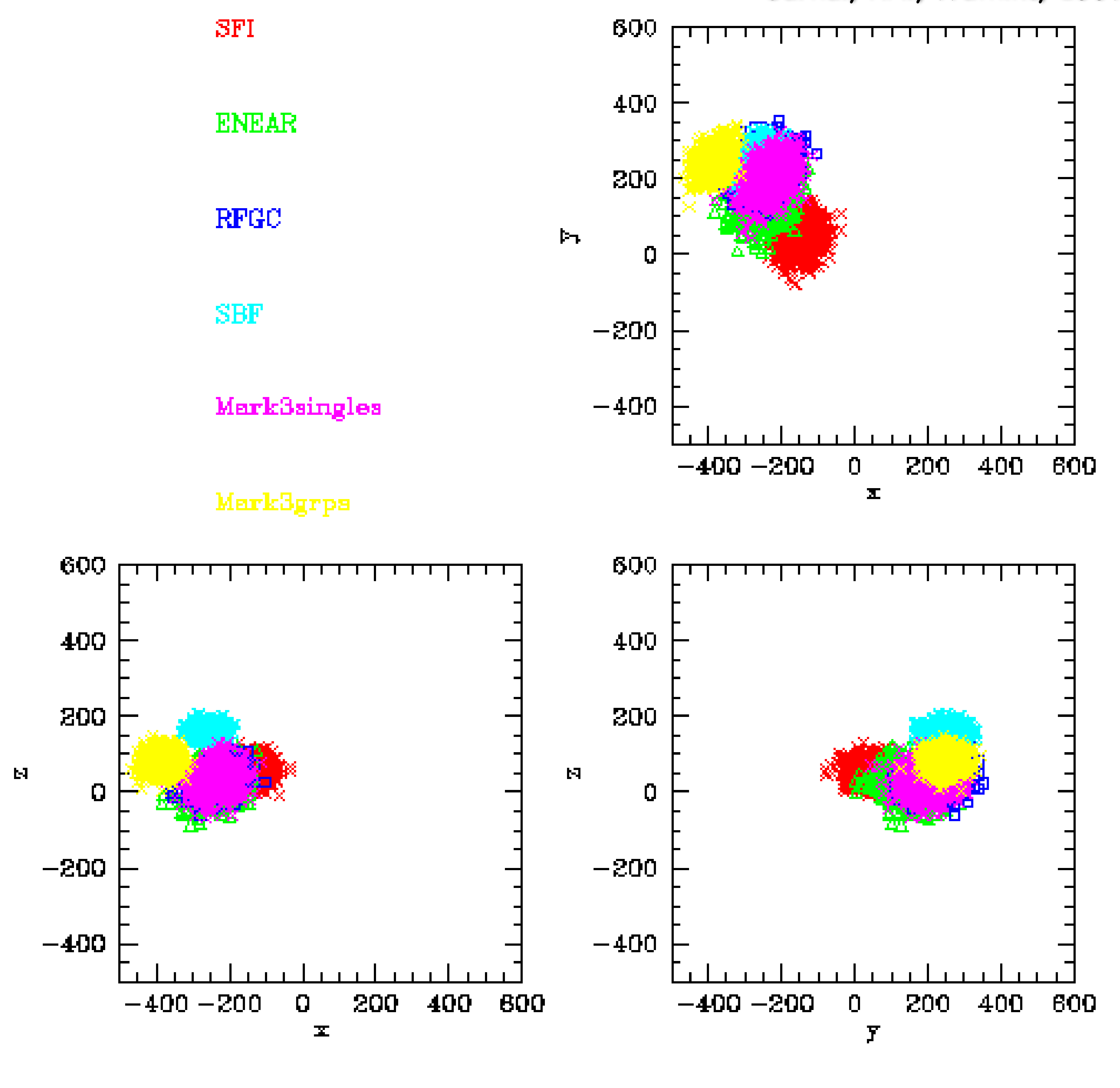
Reasons:

★ measurement errors in the peculiar velocities

★ surveys probe the velocity field in a different way

Comparing Velocity Field Surveys

Sarkar, HAF, Watkins, 2007



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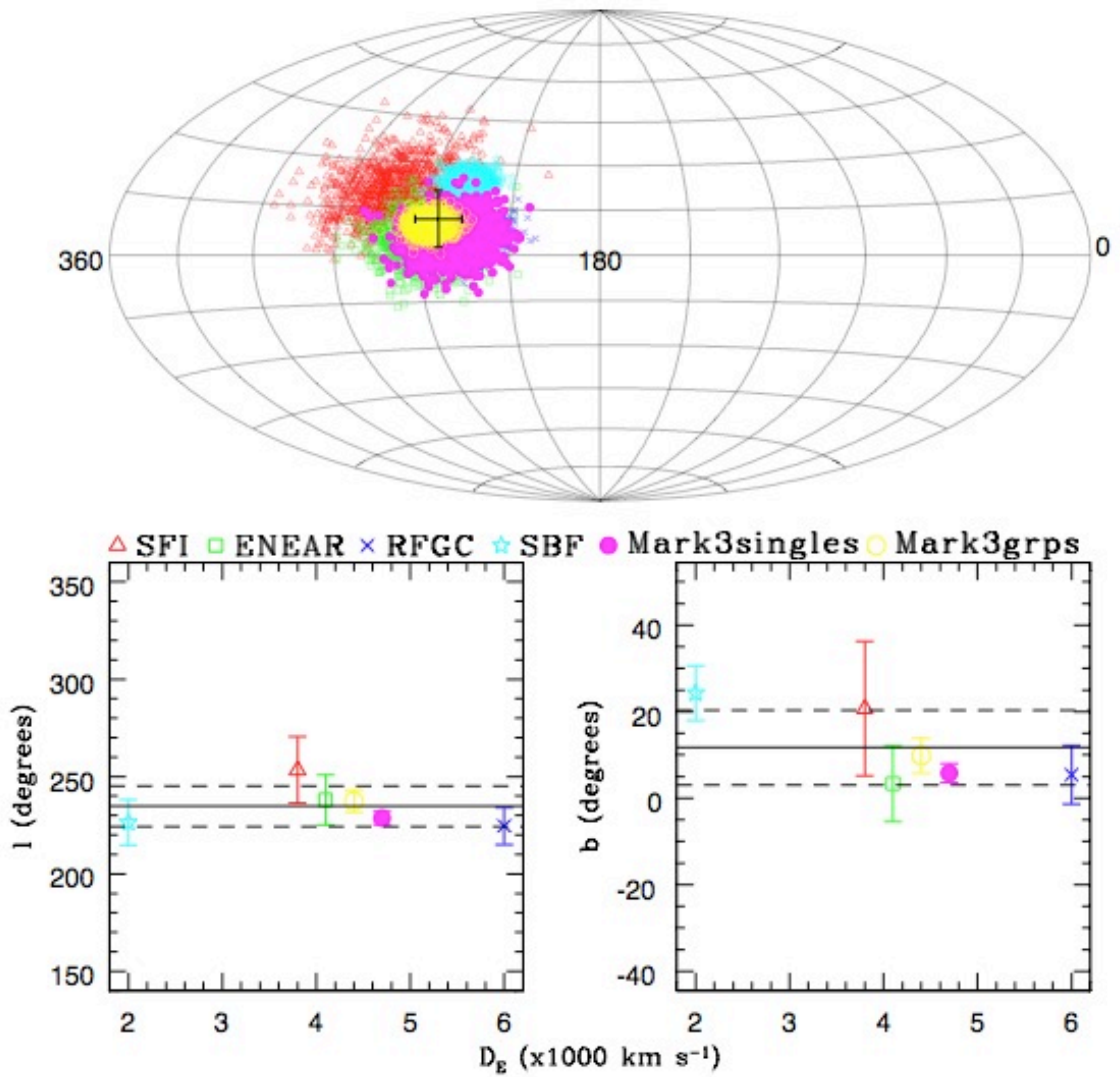
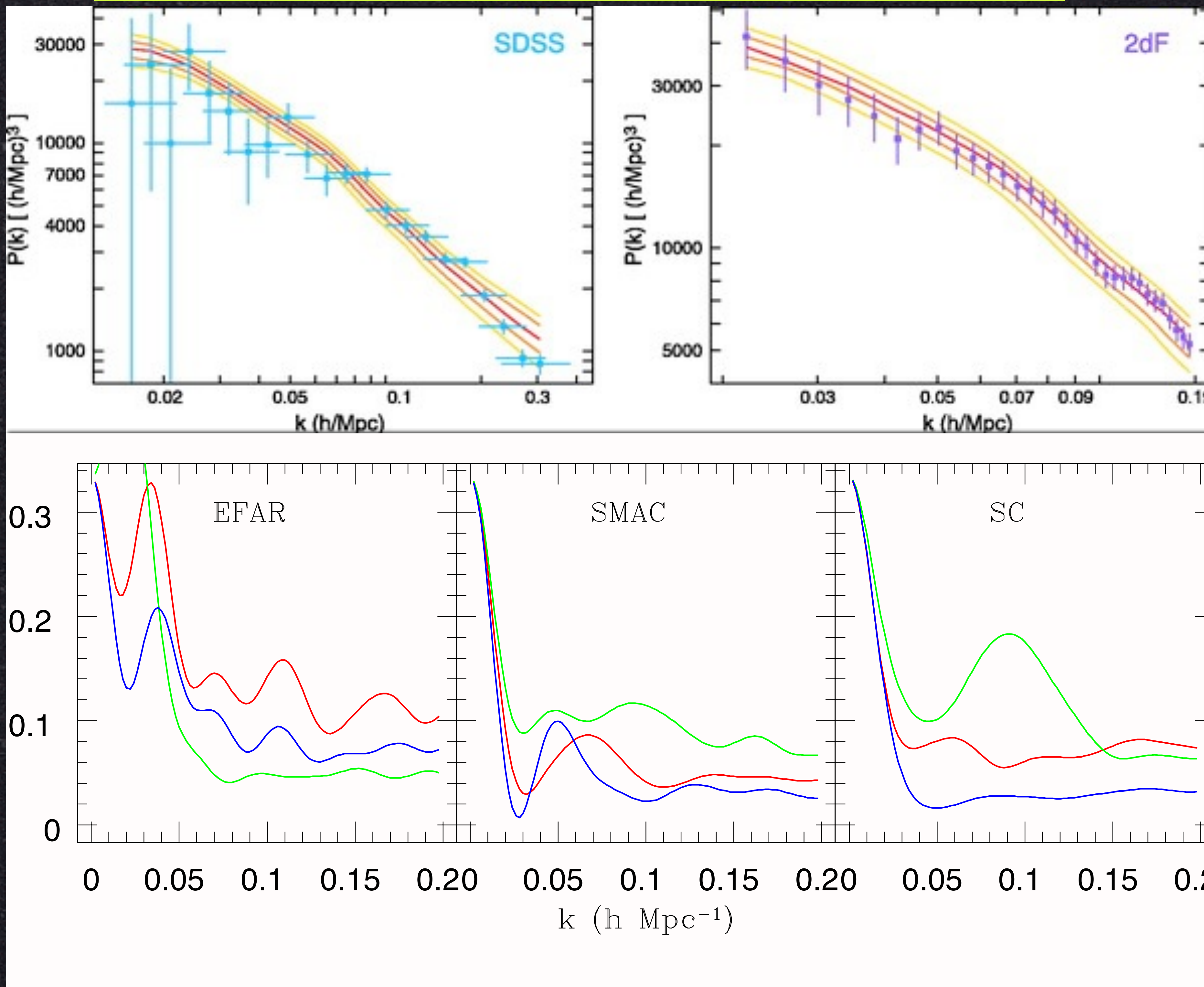


Can we do better?

Get rid of small scale aliasing?

Improve the window function design

$$\tilde{p} = N\int \frac{d^3k}{(2\pi)^3}\, p\left(\vec{k}\right) W\left(\vec{k}\right)$$



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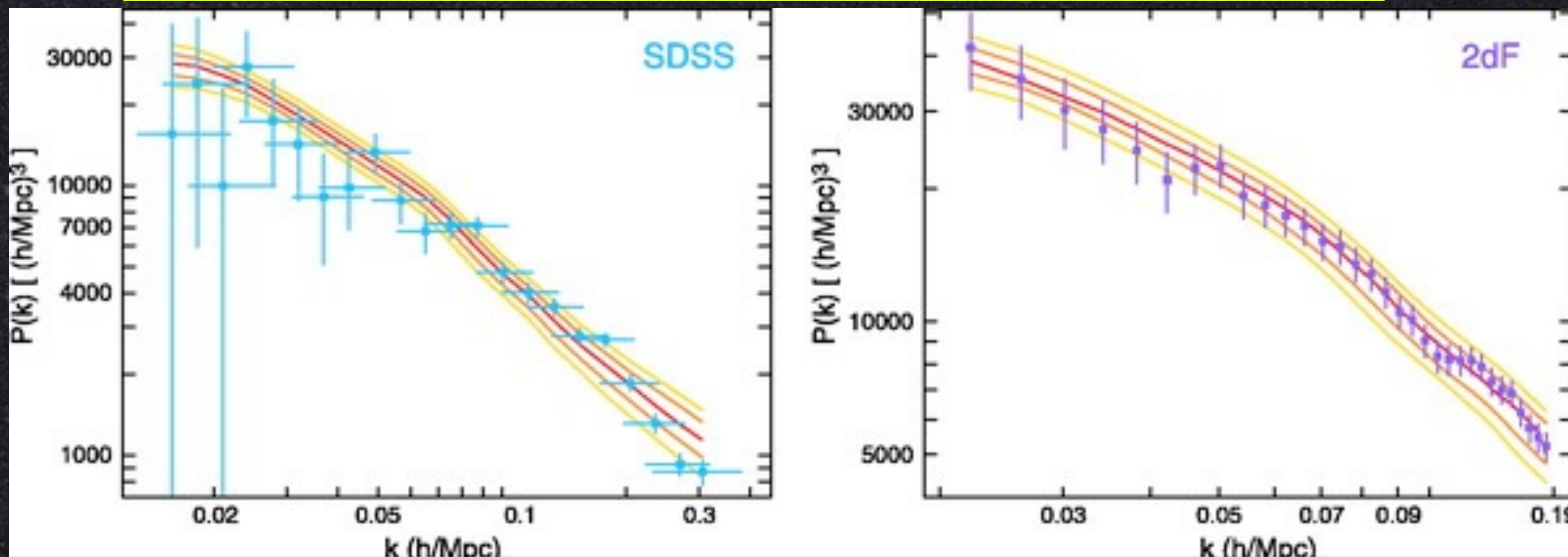
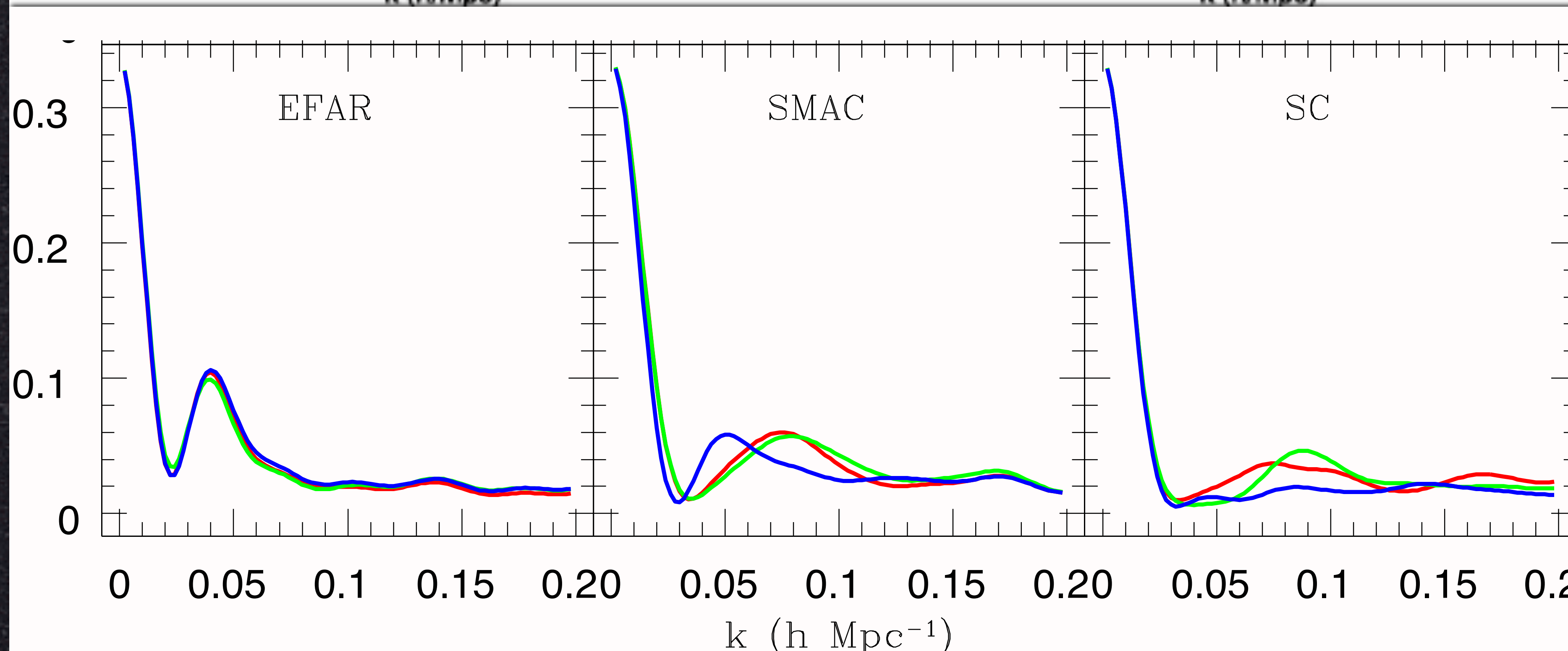




Window Function Design

Decomposition of the velocity field

Kaiser 88, Jaffe & Kaiser 95

$$v_i(\mathbf{r}) = U_i + U_{ij}r_j + U_{ijk}r_jr_k + \ldots$$

Bulk Flow Shear Octuple

If the velocity is a potential flow then both shear and octuple are symmetric (curl Free)

> 3 DoF for BF
> 6 DoF for shear
> 10 DoF for Octuple

} 19 Independent components

Window Function Design

The BF Maximum Likelihood Estimates of the weights (MLE)

$$w_{i,n} = A_{ij}^{-1} \sum_n \frac{\mathbf{x}_j \cdot \mathbf{r}_n}{\sigma_n^2 + \sigma_*^2}$$

depends on the spatial distribution and the errors.

Goal:

- Study motions on largest scales
- Require WF that
  - have narrow peaks
  - small amplitude outside peak

Window Function Design

Consider an ideal survey

- Very large number of points
- Isotropic distribution
- Gaussian falloff $n(r) \propto \exp(-r^2/2R_I^2)$

R_I Depth of the survey

Find the weights that specify the moments

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

that minimize the variance $\langle (u_i - U_i)^2 \rangle$

Window Function Design

BF and shear moments are orthogonal by design
Higher moments are not.

e.g.: A pure octupole flow in a given volume V

$$v_i = U_{ijk} r_i r_k$$

contains a net bulk flow

$$\int_V U_{ijk} r_i r_k \, d^3 r$$

Which leads to a strong correlation between the bulk flow and octupole moments

Window Function Design

Redefine the octuple moments

$$v_i(\mathbf{r}) = U_i + U_{ij} r_j + U_{ijk}\left(r_j r_k - \Lambda_{jk}\right) + \ldots$$

where

$$\Lambda_{jk} = \int_V r_j r_k \, d^3 r$$

For a spherically symmetric volume
only Λ_{ii} are non-zero

Window Function Design

Line-of-sight peculiar velocity

$$s(\mathbf{r}) = \vec{v}\cdot\hat{r}$$
$$= U_i\hat{r}_i + U_{ij}r\hat{r}_i\hat{r}_j + U_{ijk}\left(r^2\hat{r}_i\hat{r}_j\hat{r}_k - \Lambda_{jk}\hat{r}_i\right) + \ldots$$
$$= \sum_{p=1}^{19} U_p g_p(\mathbf{r})$$

Where

$$U_p = \{U_1, U_2, U_3, U_{11}, U_{22}, U_{33}, U_{12}, U_{23}, U_{13}, U_{111}, U_{222}, U_{333}, U_{112}, U_{223}, U_{331}, U_{122}, U_{233}, U_{113}, U_{123}\}$$

and

$$g_p(\mathbf{r}) = \{\hat{r}_1, \hat{r}_2, \hat{r}_3, r\hat{r}_1^2, r\hat{r}_2^2, r\hat{r}_3^2, 2r\hat{r}_1\hat{r}_2, 2r\hat{r}_2\hat{r}_3, 2r\hat{r}_1\hat{r}_3, r^2\hat{r}_1^3 - \Lambda_{11}\hat{r}_1, r^2\hat{r}_2^3 - \Lambda_{22}\hat{r}_2, r^2\hat{r}_3^3 - \Lambda_{33}\hat{r}_3, 3r^2\hat{r}_1^2\hat{r}_2 - \Lambda_{11}\hat{r}_2, 3r^2\hat{r}_2^2\hat{r}_3 - \Lambda_{22}\hat{r}_3, 3r^2\hat{r}_3^2\hat{r}_1 - \Lambda_{33}\hat{r}_1, 3r^2\hat{r}_2^2\hat{r}_1 - \Lambda_{22}\hat{r}_1, 3r^2\hat{r}_3^2\hat{r}_2 - \Lambda_{33}\hat{r}_2, 3r^2\hat{r}_1^2\hat{r}_3 - \Lambda_{11}\hat{r}_3, 6r^2\hat{r}_1\hat{r}_2\hat{r}_3\}$$

Window Function Design

Ideal velocity moments

$$U_p = \frac{1}{N_o}\sum_{n=1}^{N_o} g_p(\mathbf{r}_n)s_n = \sum_n w'_{p,n}s_n$$ where $w'_{p,n} = \frac{g_p(\mathbf{r}_n)}{N_o}$

Given U_p, find the weights $w_{p,n}$ such that

$$u_p = \sum_{n=1}^{N} w_{p,n}S_n$$

gives the best possible estimates of U_p

$\Rightarrow$ On average, the correct amplitudes $\langle u_p\rangle = U_p$ for the velocity moments

Require that $$\sum_n w_{p,n}g_q(\mathbf{r}_n) = \delta_{pq}$$

Window Function Design

Enforce this constraint using Lagrange multiplier

$$\langle (U_p - u_p)^2 \rangle + \sum_q \lambda_{pq} \left(\sum_n w_{p,n} g_q(\mathbf{r}_n) - \delta_{pq} \right)$$

or expand out the variance

$$\langle U_p^2 \rangle - \sum_n 2 w_{p,n} \langle S_n U_p \rangle + \sum_{n,m} w_{p,n} w_{p,m} \langle S_n S_m \rangle +$$

$$\sum_q \lambda_{pq} \left(\sum_n w_{p,n} g_q(\mathbf{r}_n) - \delta_{pq} \right)$$

Minimize with respect to $w_{p,n}$

Window Function Design

$$-2\langle S_n U_p \rangle + 2\sum_m w_{p,m}\langle S_n S_m \rangle + \sum_q \lambda_{pq} g_q(\mathbf{r}_n) = 0$$

$$w_{p,n} = \sum_m G^{-1}_{nm}\left(\langle S_m U_p \rangle - \frac{1}{2}\sum_q \lambda_{pq} g_q(\mathbf{r}_m)\right)$$

$$\mathbf{G}_{nm} = \langle S_n S_m \rangle$$ individual velocity covariance matrix

$$\lambda_{pq} = M^{-1}_{pl}\left(\sum_{m,n} G^{-1}_{nm}\langle S_m U_l \rangle g_q(\mathbf{r}_n) - \delta_{lq}\right)$$

$$M_{pq} = \frac{1}{2}\sum_{n,m} G^{-1}_{nm} g_p(\mathbf{r}_n) g_q(\mathbf{r}_m)$$

Window Function Design

The covariance matrix

$$G_{nm} = \langle s_n s_m \rangle + \delta_{nm}(\sigma_*^2 + \sigma_n^2)$$
$$= \langle \hat{\mathbf{r}}_n \cdot \mathbf{v}(\mathbf{r}_n) \;\; \hat{\mathbf{r}}_m \cdot \mathbf{v}(\mathbf{r}_m) \rangle + \delta_{nm}(\sigma_*^2 + \sigma_n^2).$$

The cross correlation

$$\langle S_m U_p \rangle = \sum_{n'} w'_{pn'} \langle s_m s_{n'} \rangle$$

Window Function Design

The correlation matrix

$$R_{pq} = \langle u_p u_q \rangle = \sum_{nm} w_{pn} w_{qm} \langle s_n s_m \rangle = \sum_{nm} w_{pn} w_{qm} G_{nm}$$

$$= R_{pq}^{(v)} + R_{pq}^{(\epsilon)}$$

Velocity correlation matrix

$$R_{pq}^{(v)} = \frac{\Omega_m^{1.1}}{2\pi^2} \int dk \; P(k) \mathcal{W}_{pq}^2(k)$$

Noise correlation matrix

$$R_{pq}^{(\epsilon)} = \sum_n w_{pn} w_{qn} \left(\sigma_n^2 + \sigma_*^2 \right)$$

Window Function Design

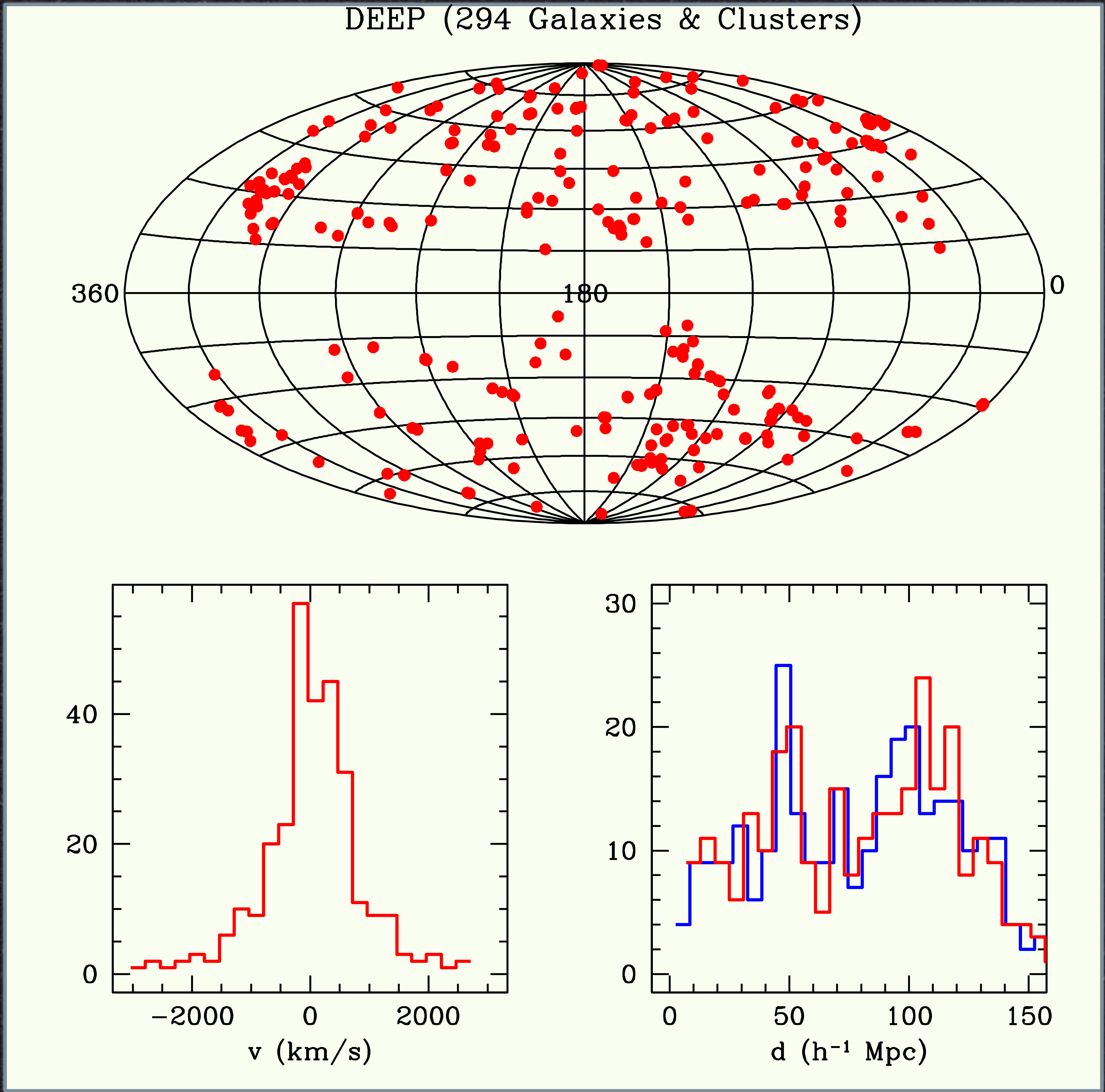
Tensor square window function

$$\mathcal{W}^2_{pq} = \sum_{n,m} w_{pn} w_{qm} f_{nm}(k)$$

where

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

Peculiar Velocity Surveys



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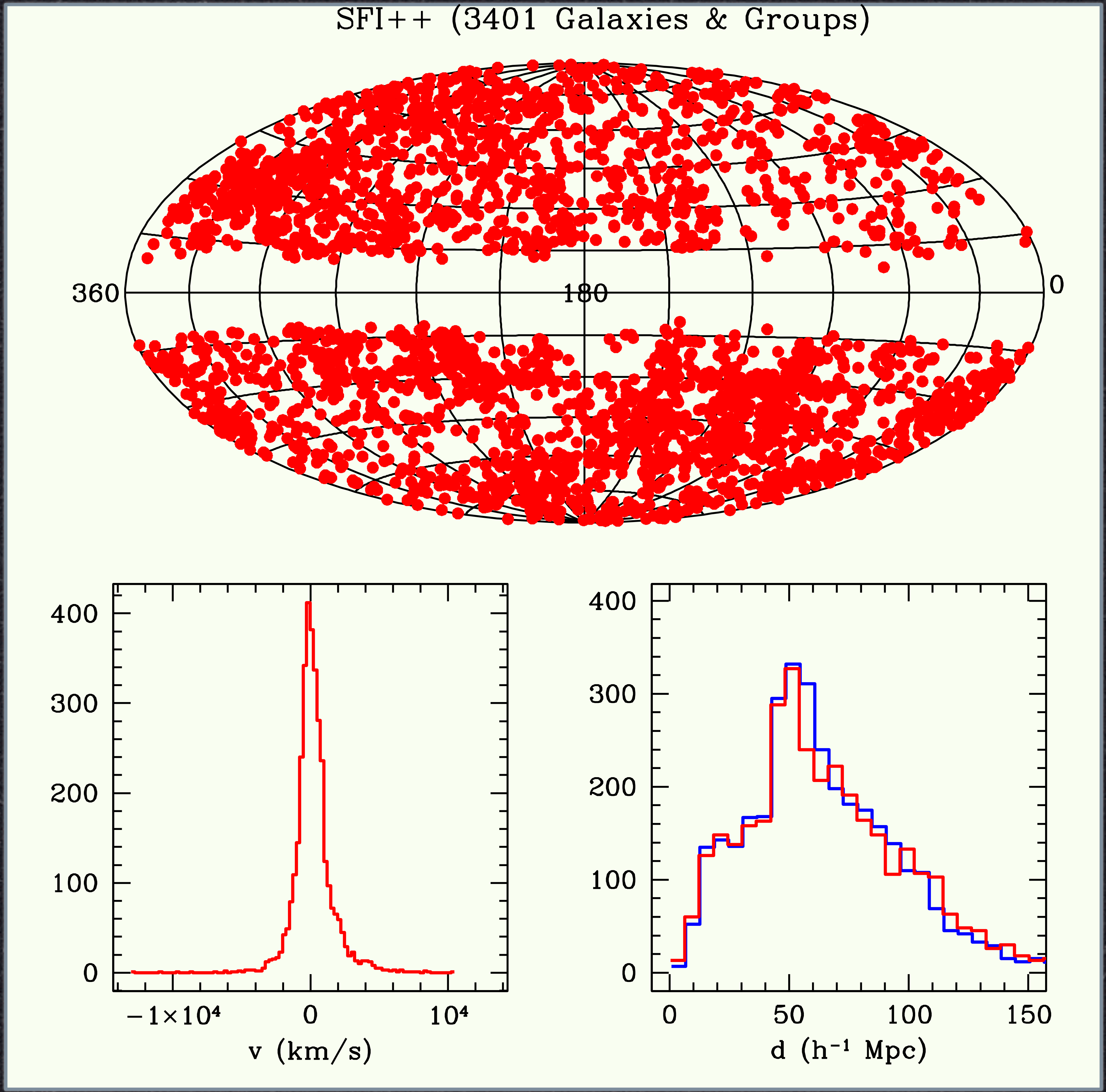

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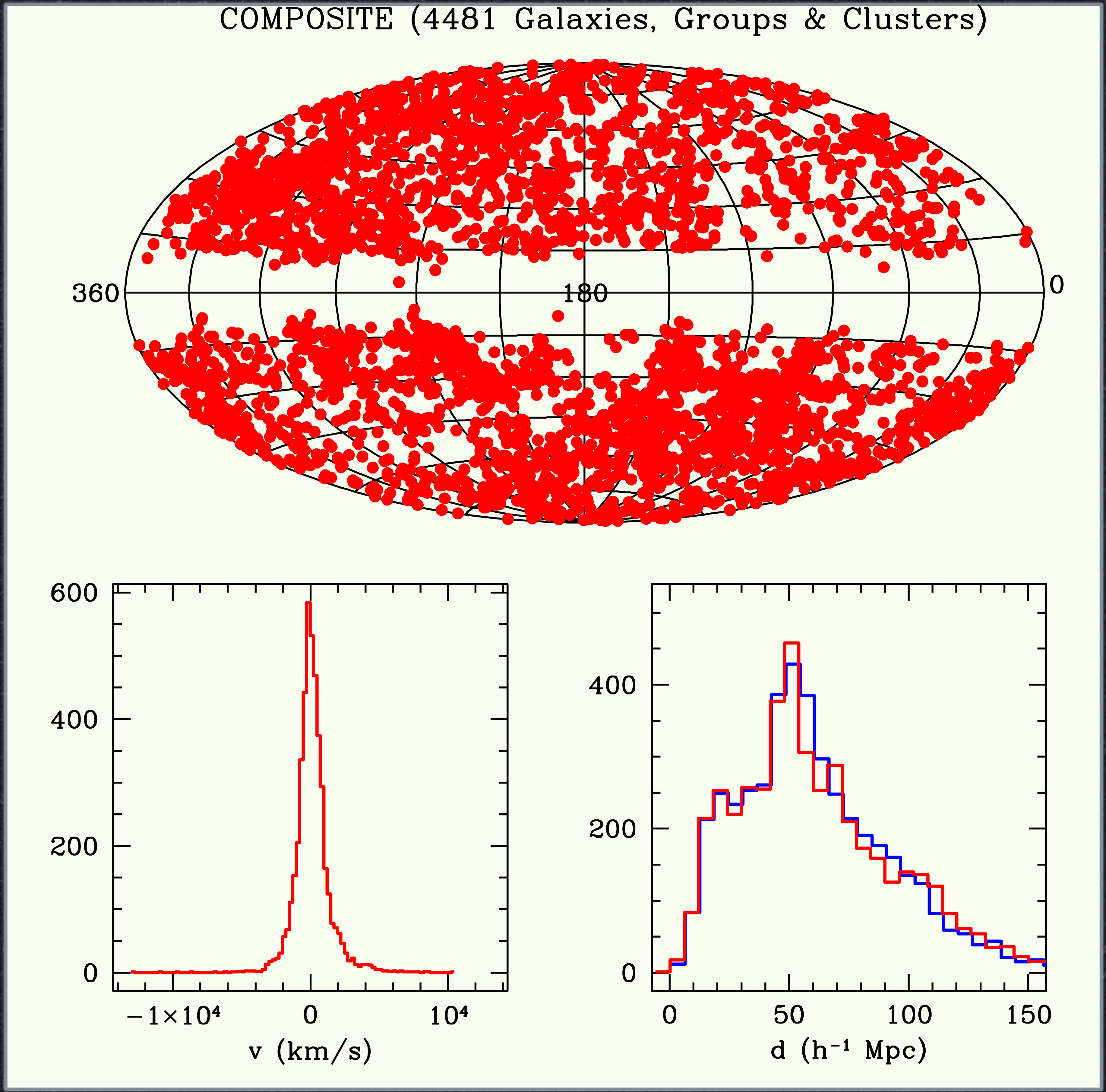

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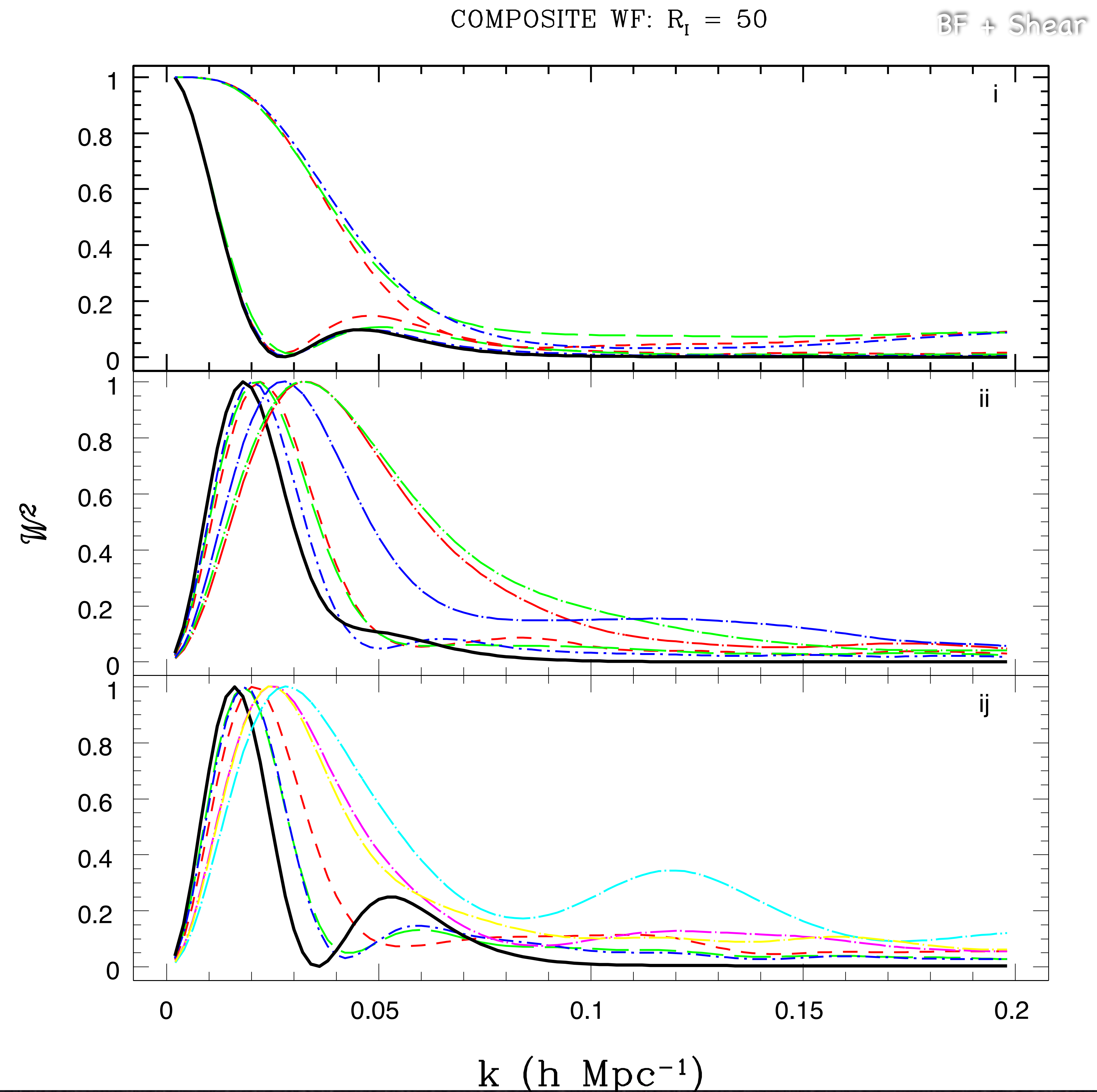

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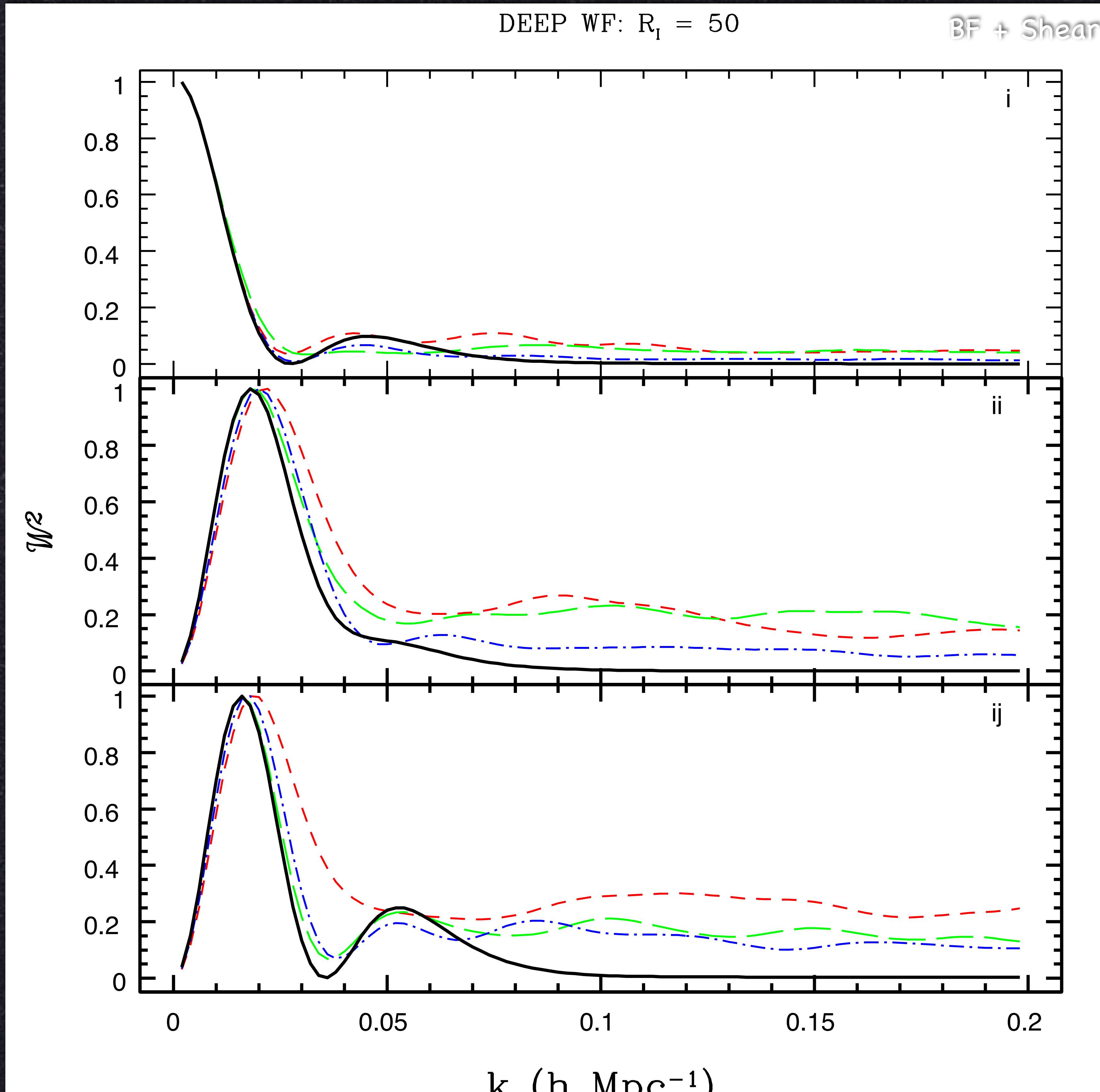

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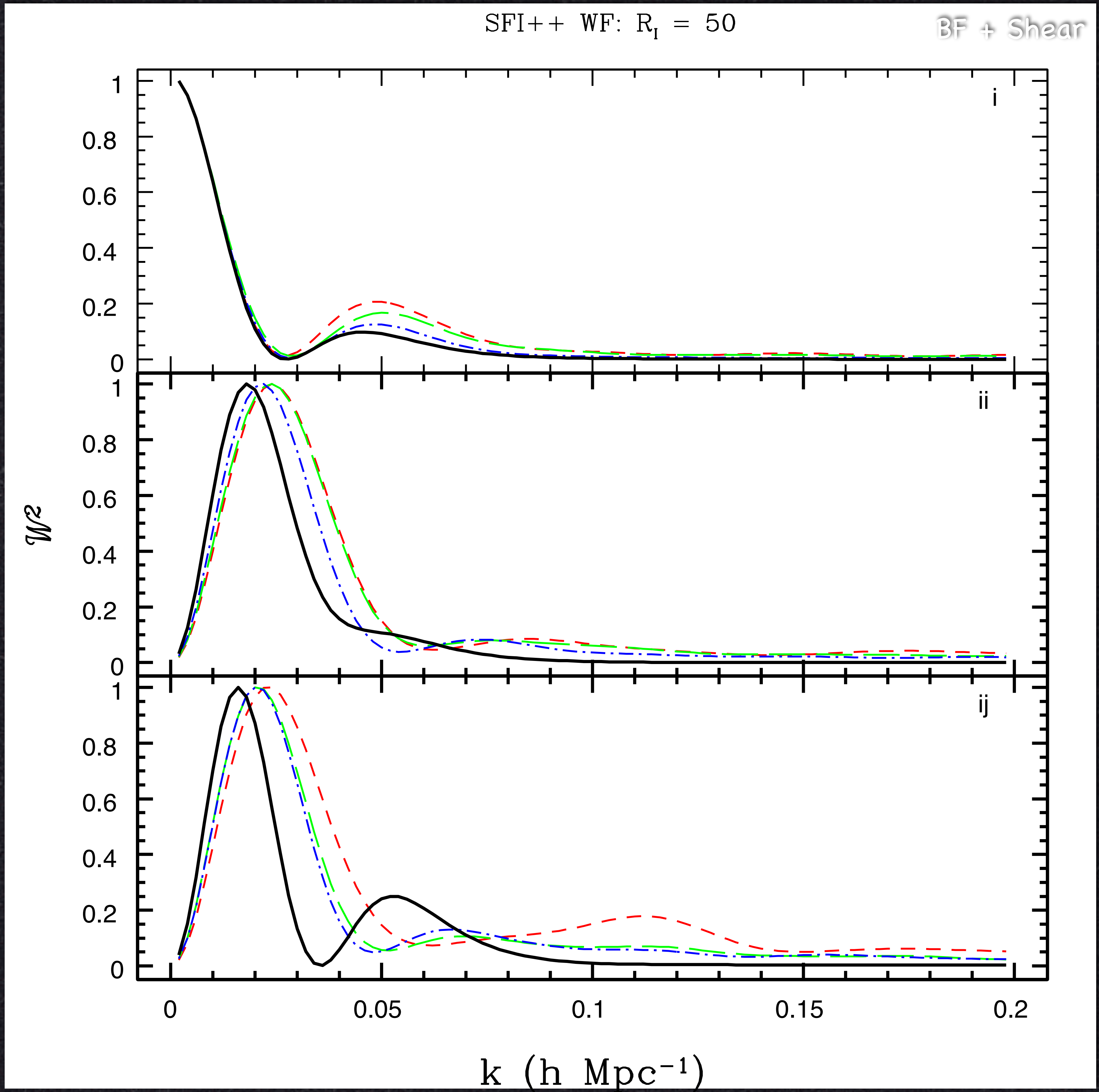

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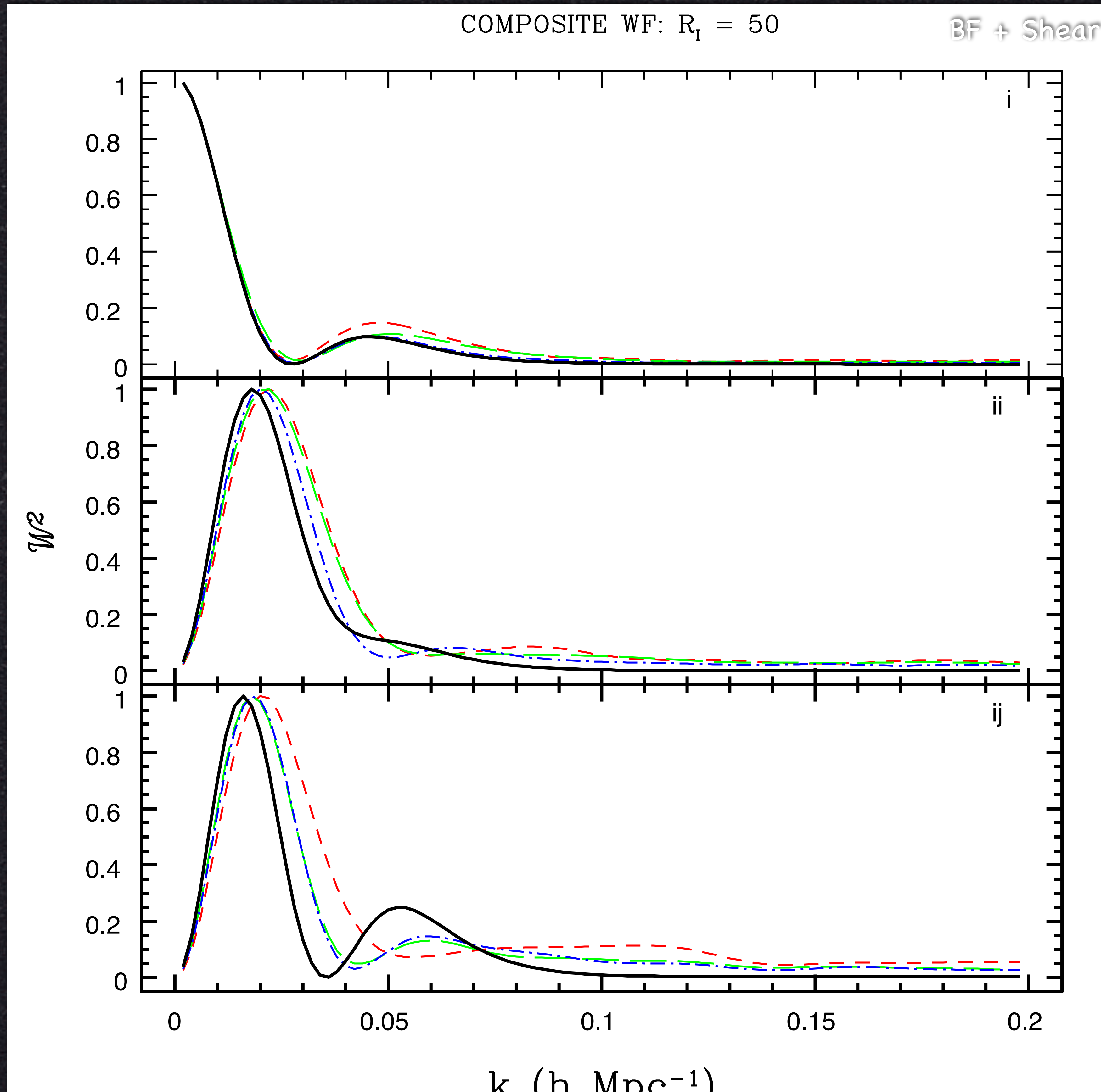

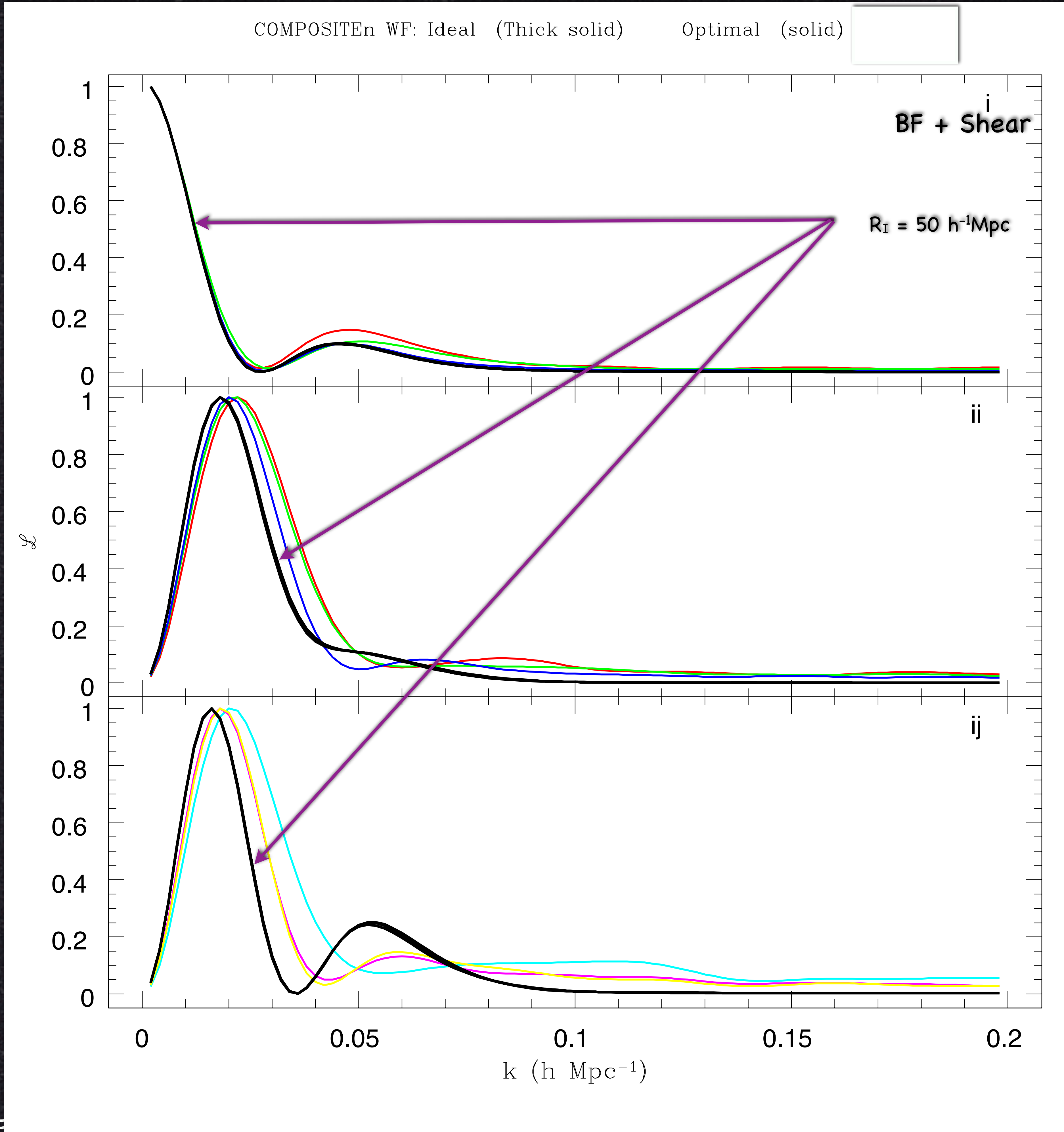
COMPOSITEn WF: Ideal (Thick solid) Optimal (solid)
BF + Shear
i
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R_I = 50 h^{-1}Mpc
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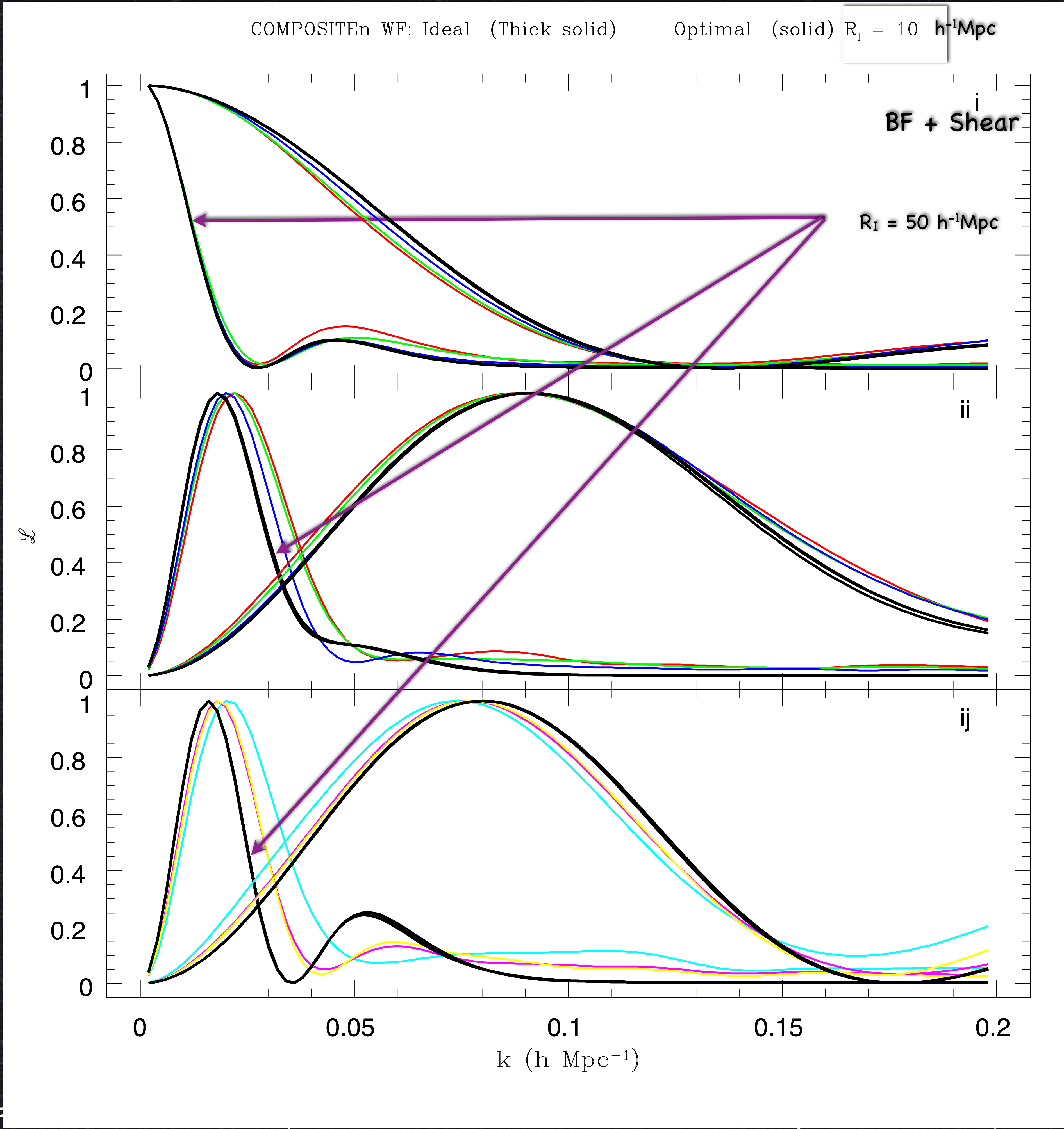
k (h Mpc⁻¹)



COMPOSITEn WF: Ideal (Thick solid) Optimal (solid) R_I = 10 h^{-1}Mpc
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BF + Shear
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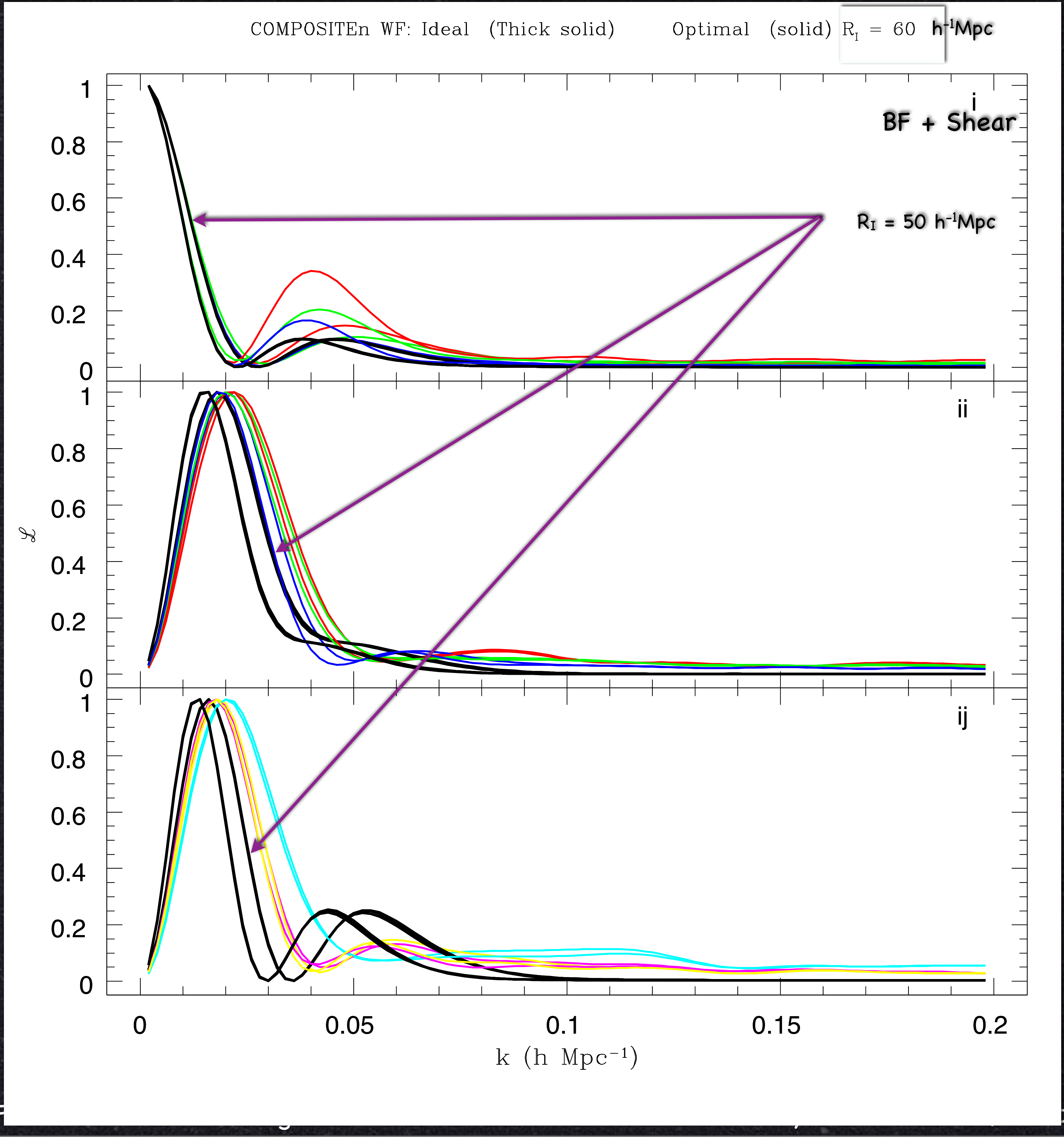
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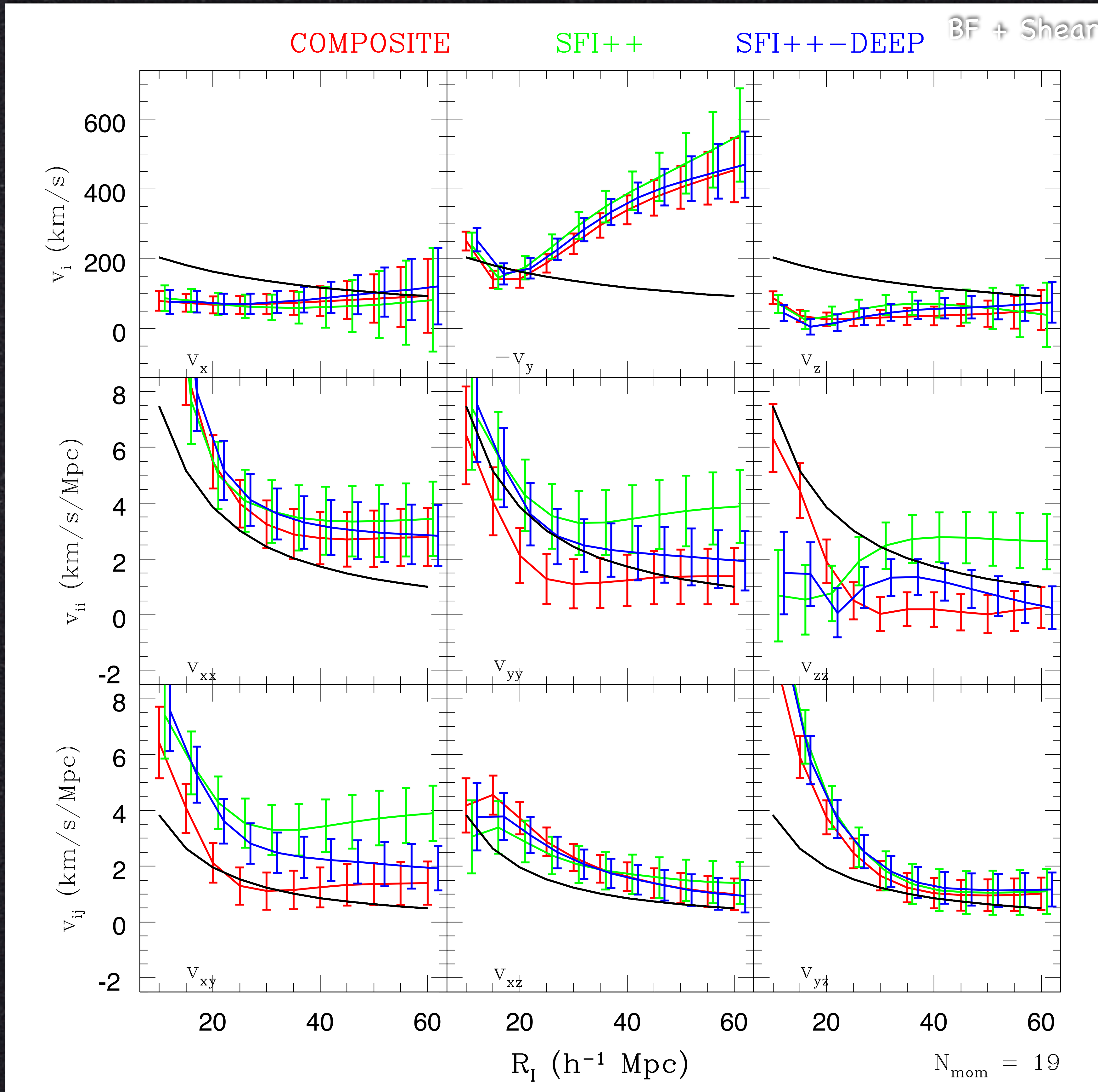
Comparing Surveys



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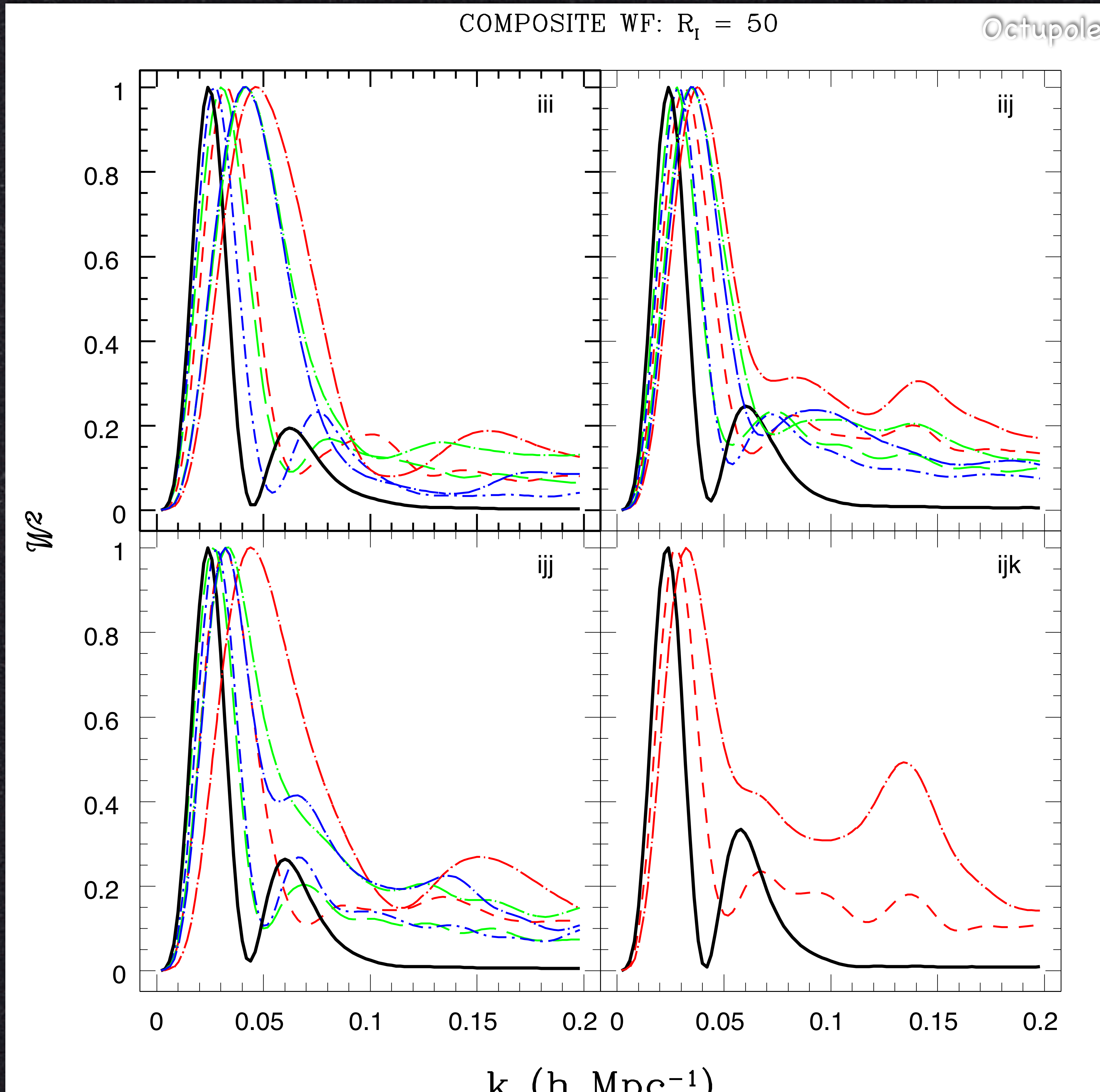

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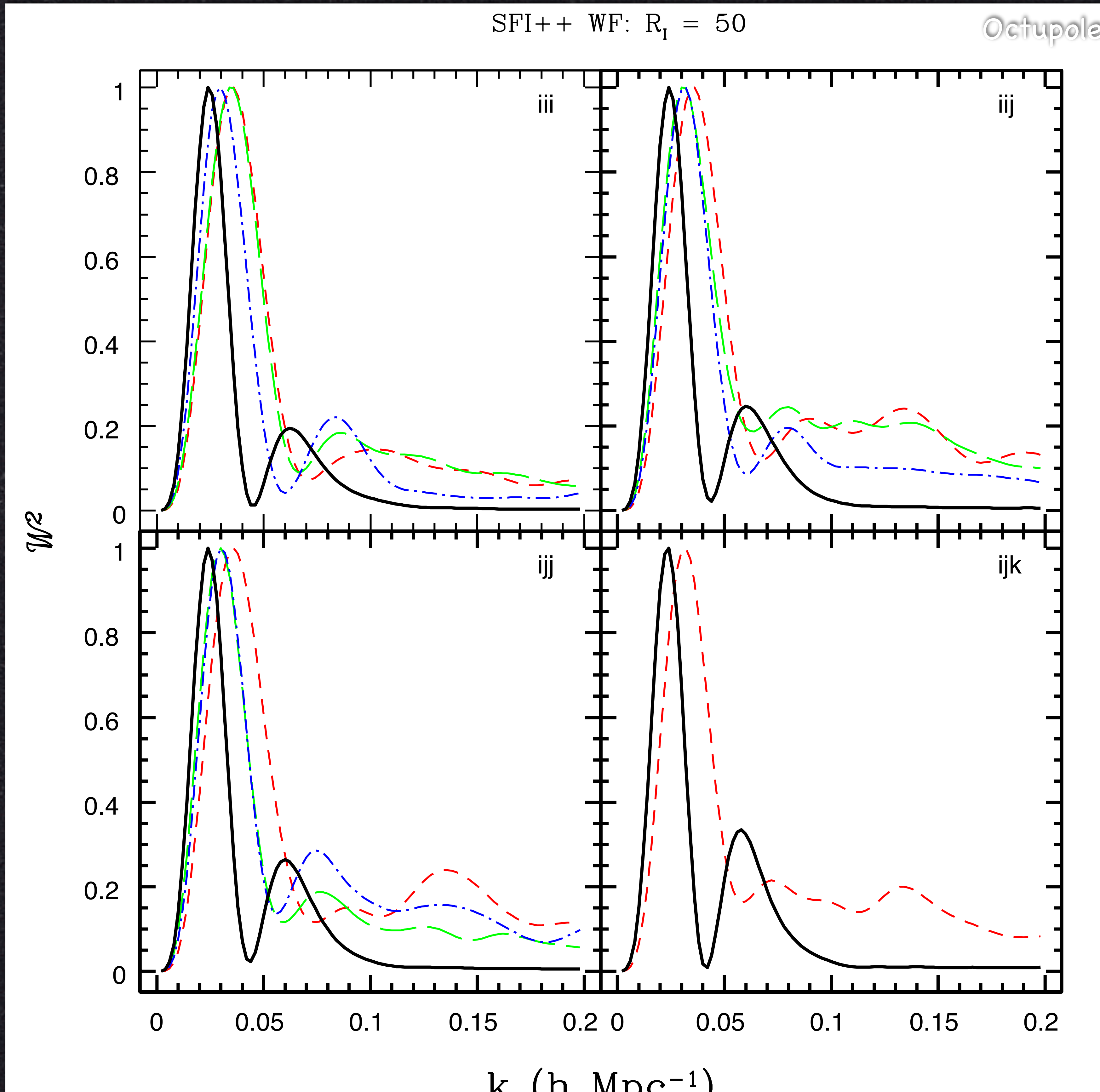

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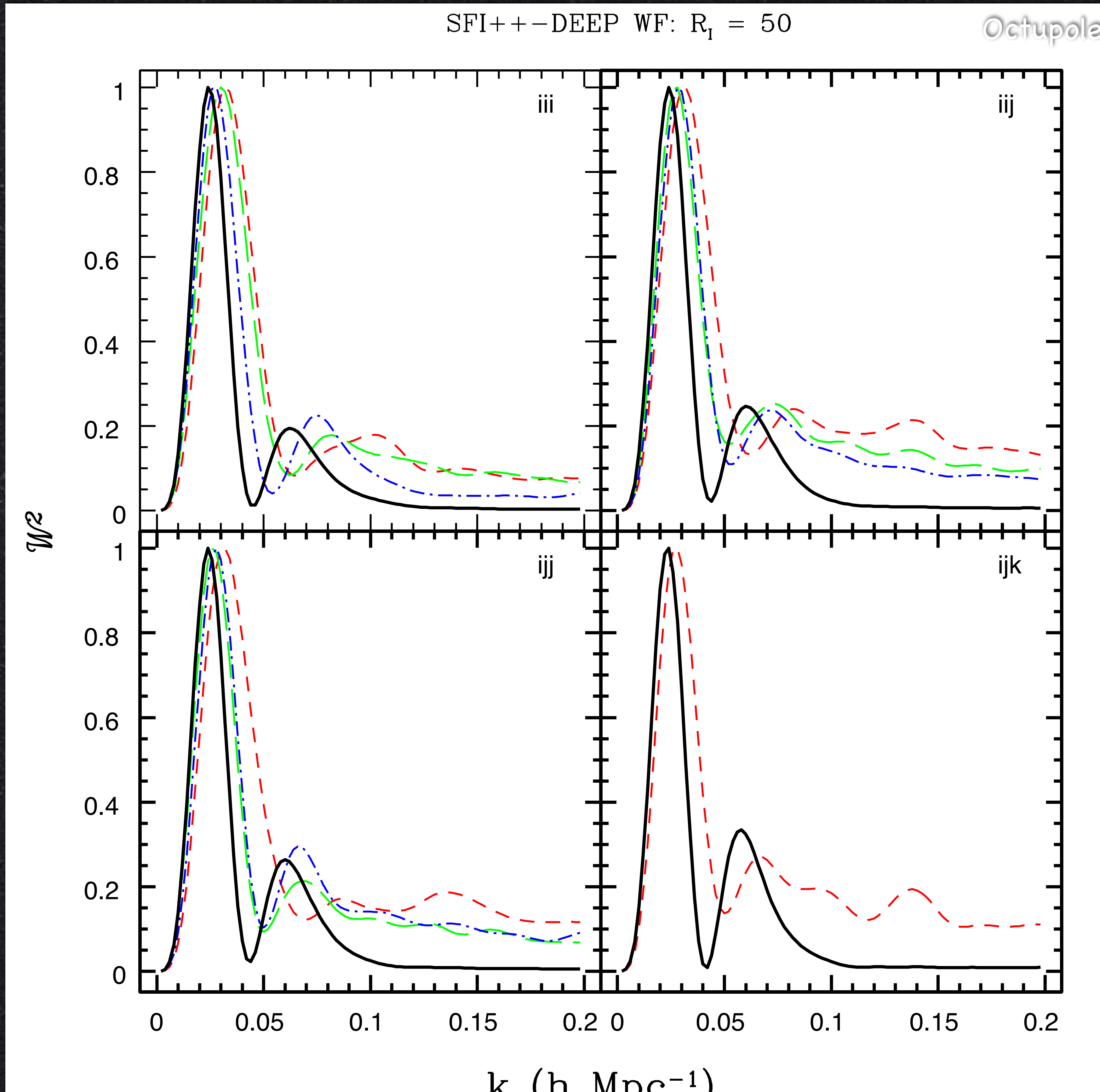

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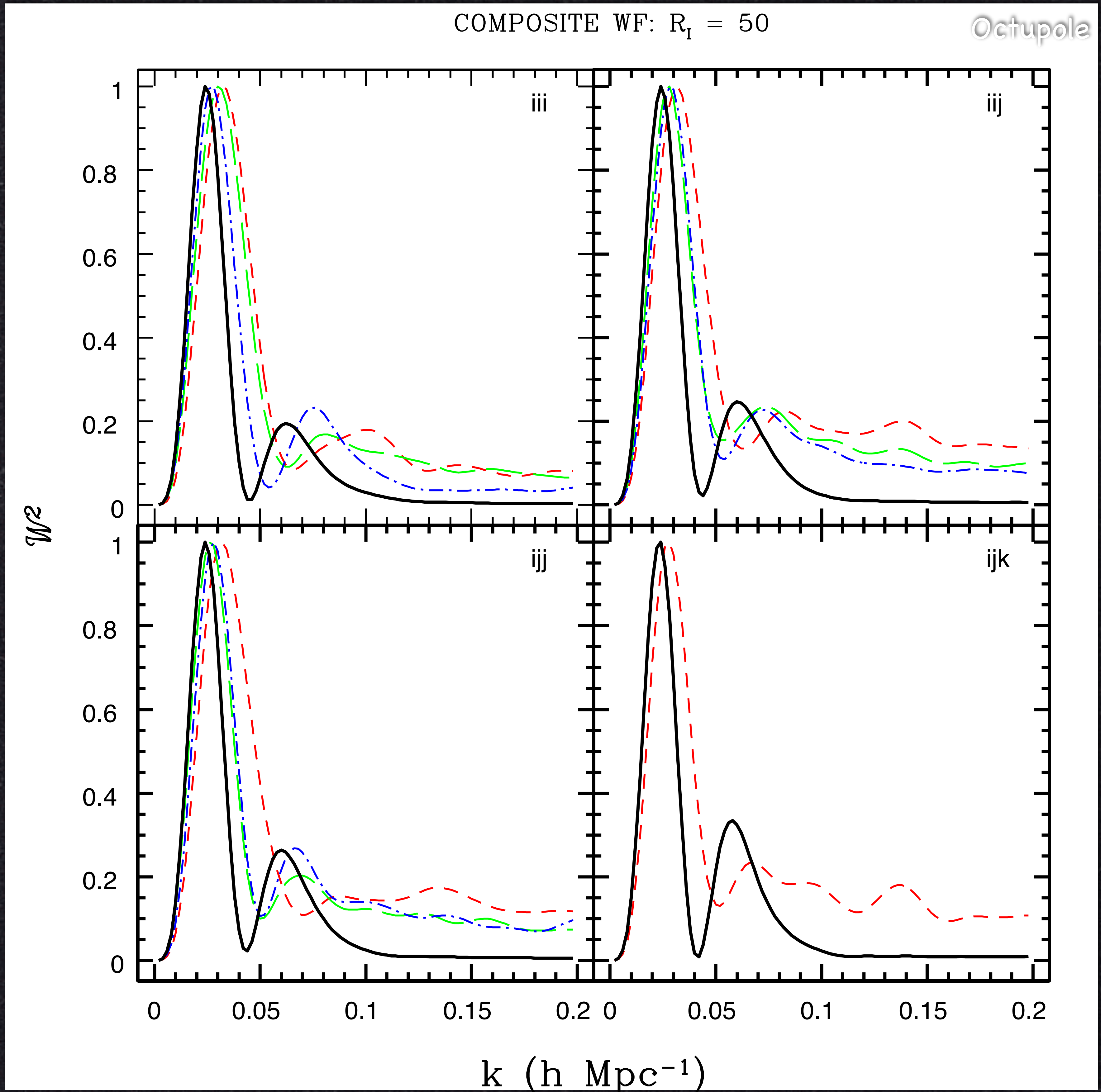

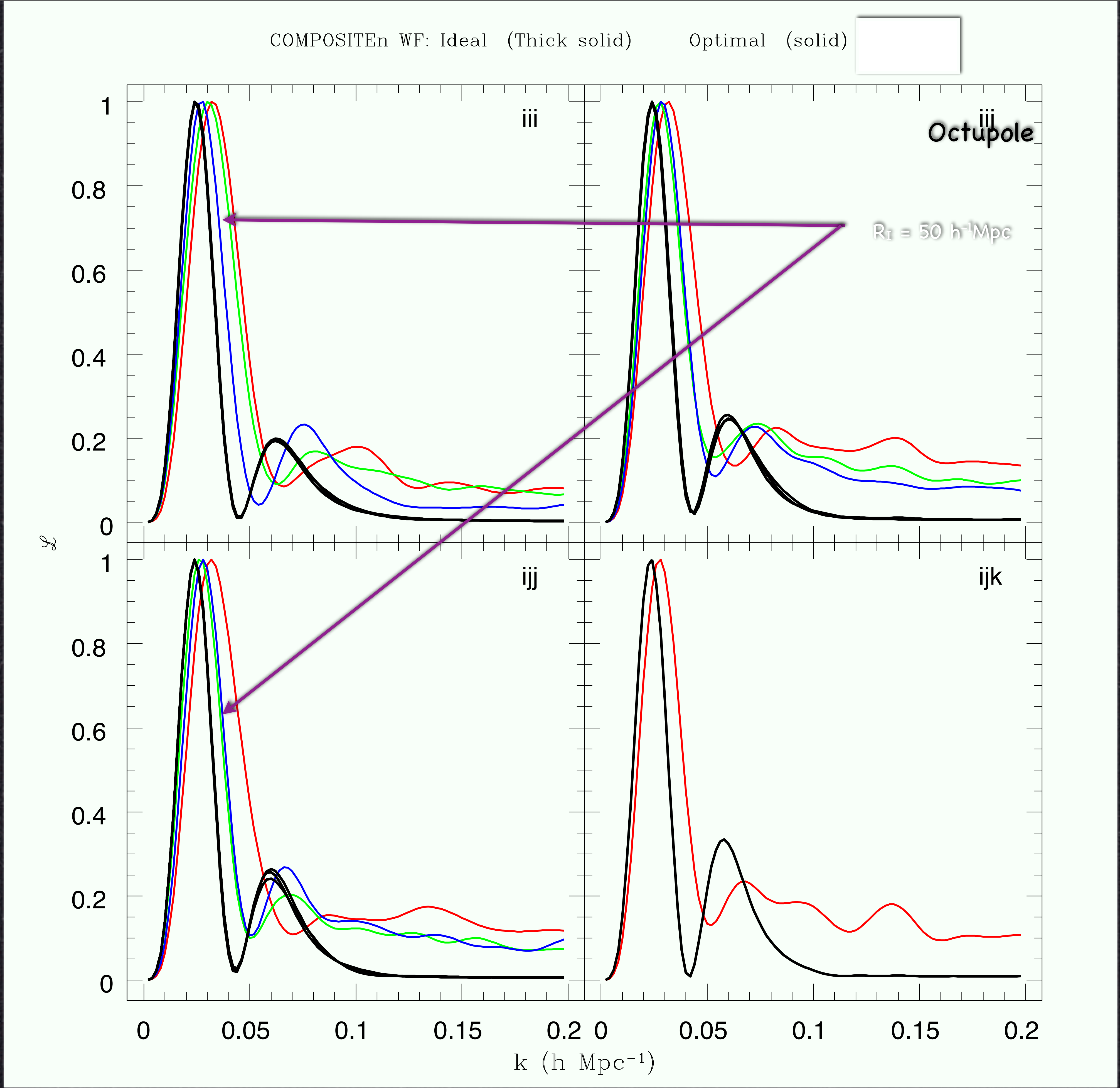
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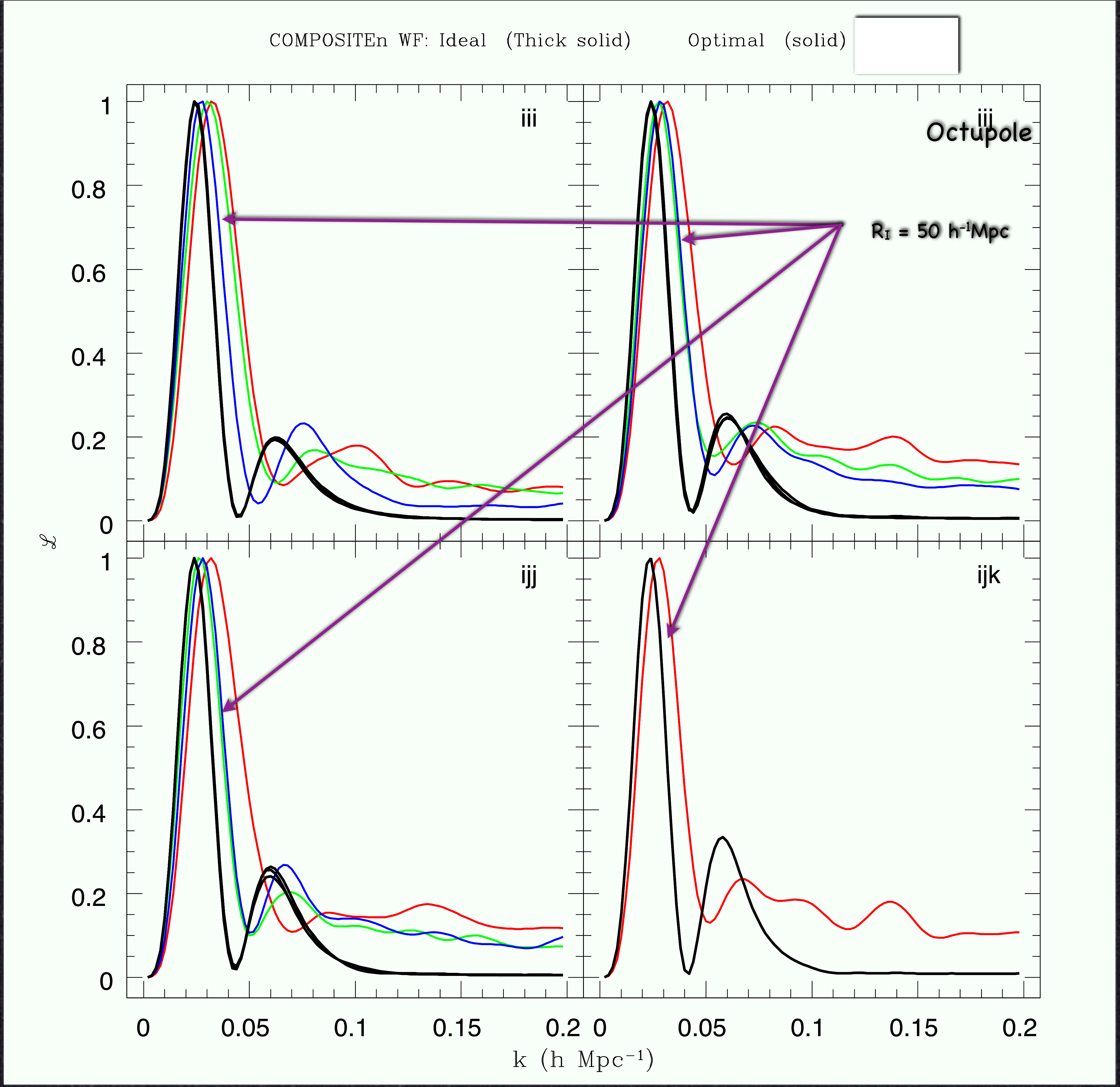
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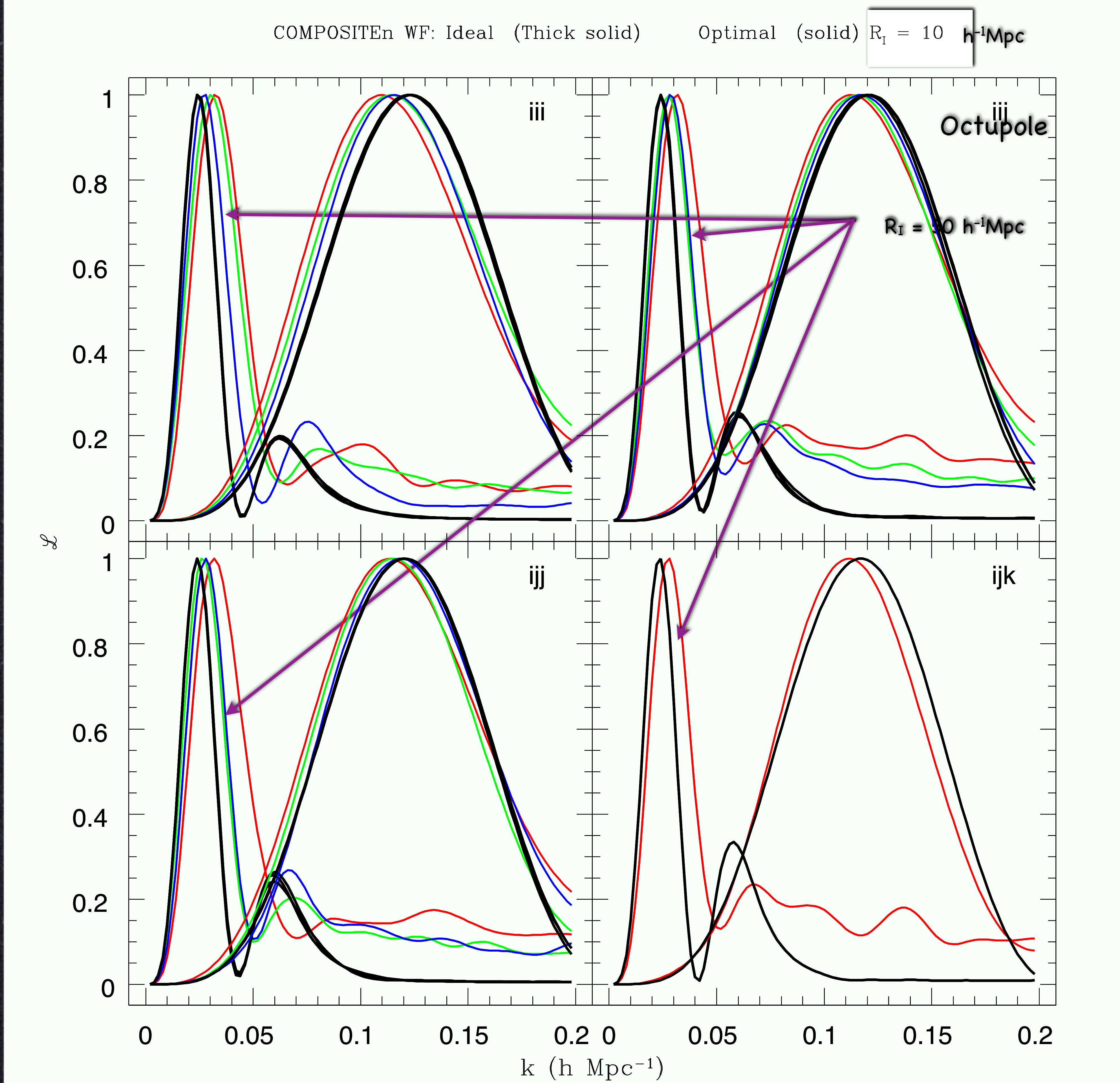
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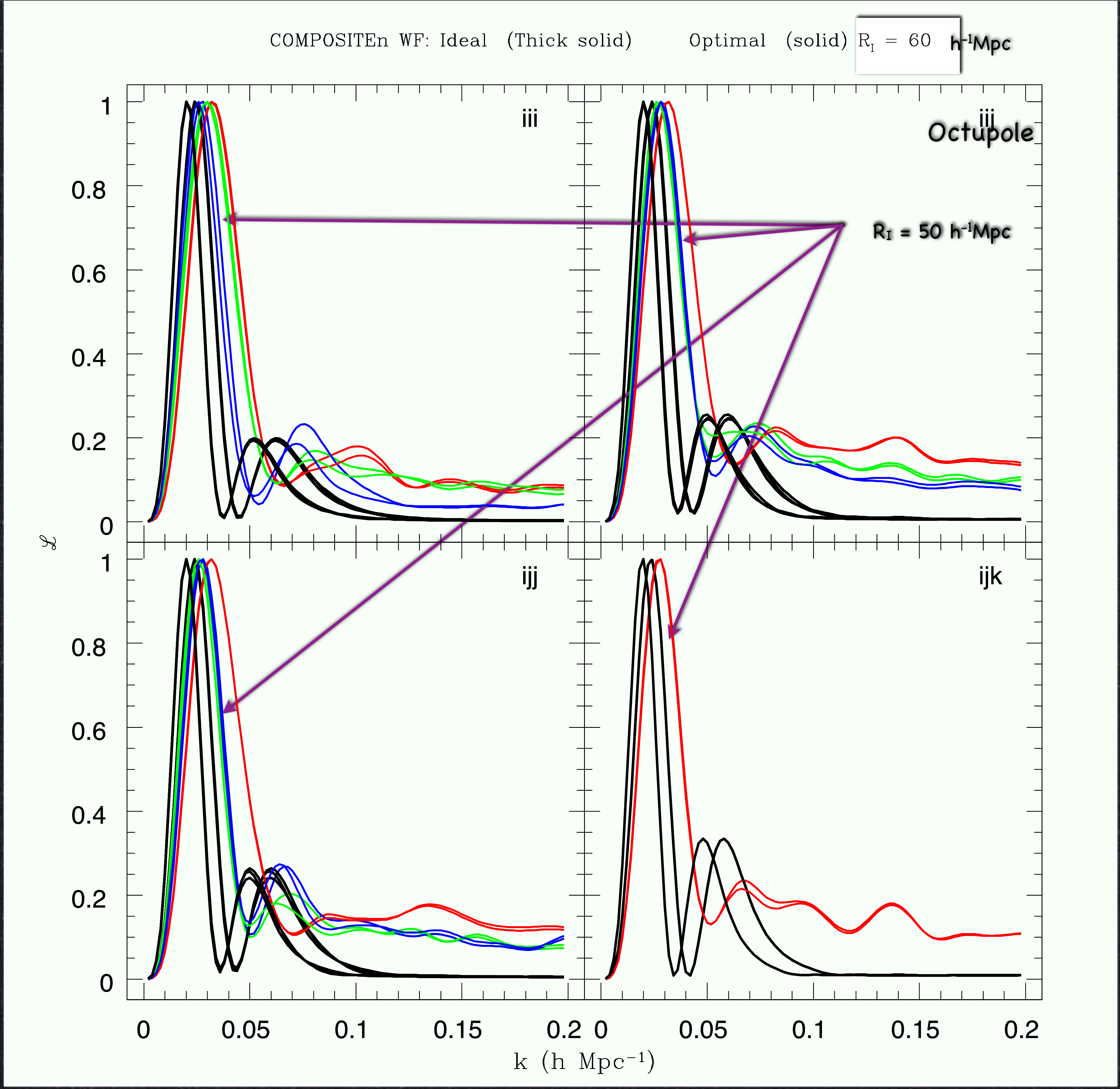
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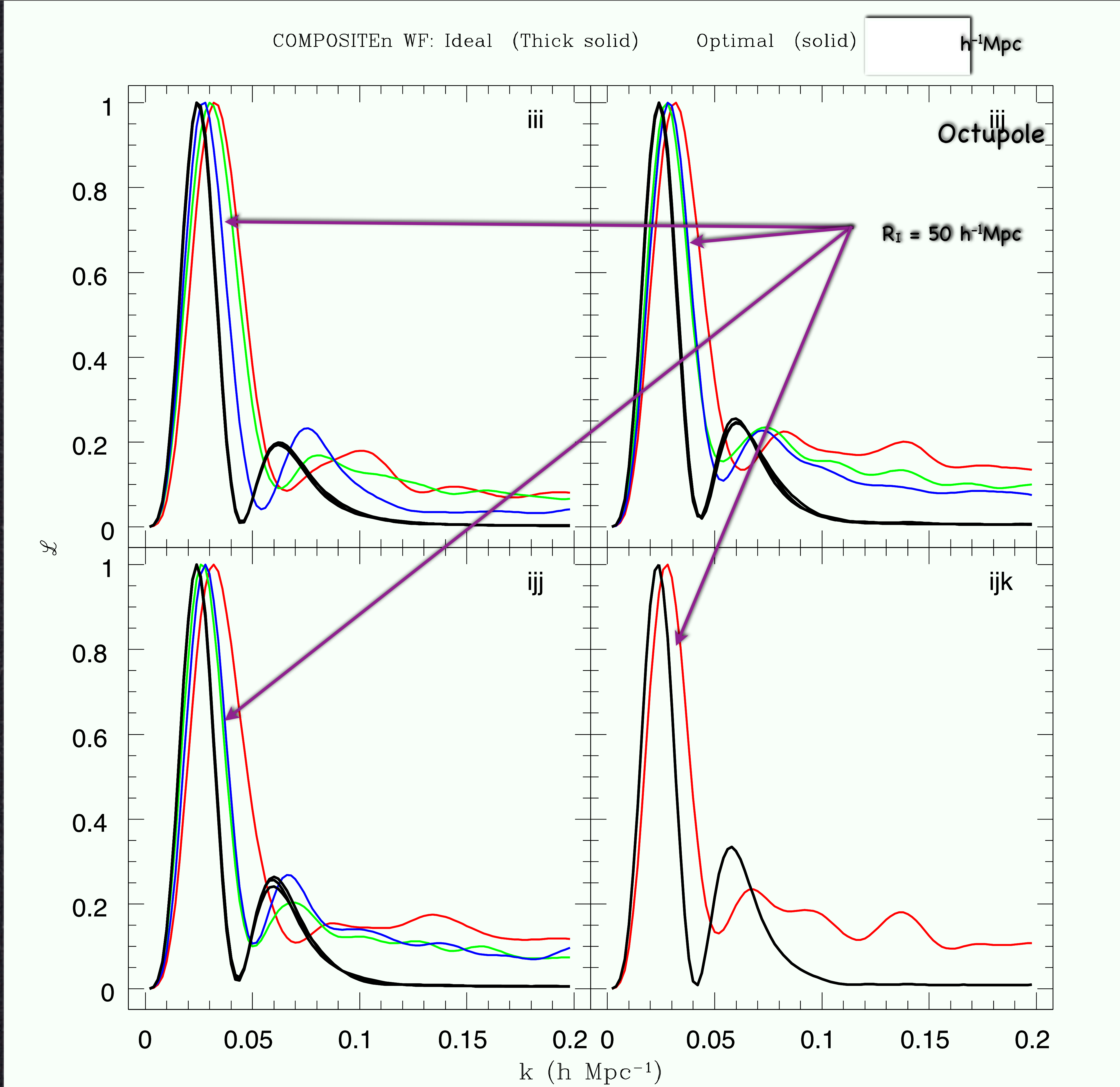
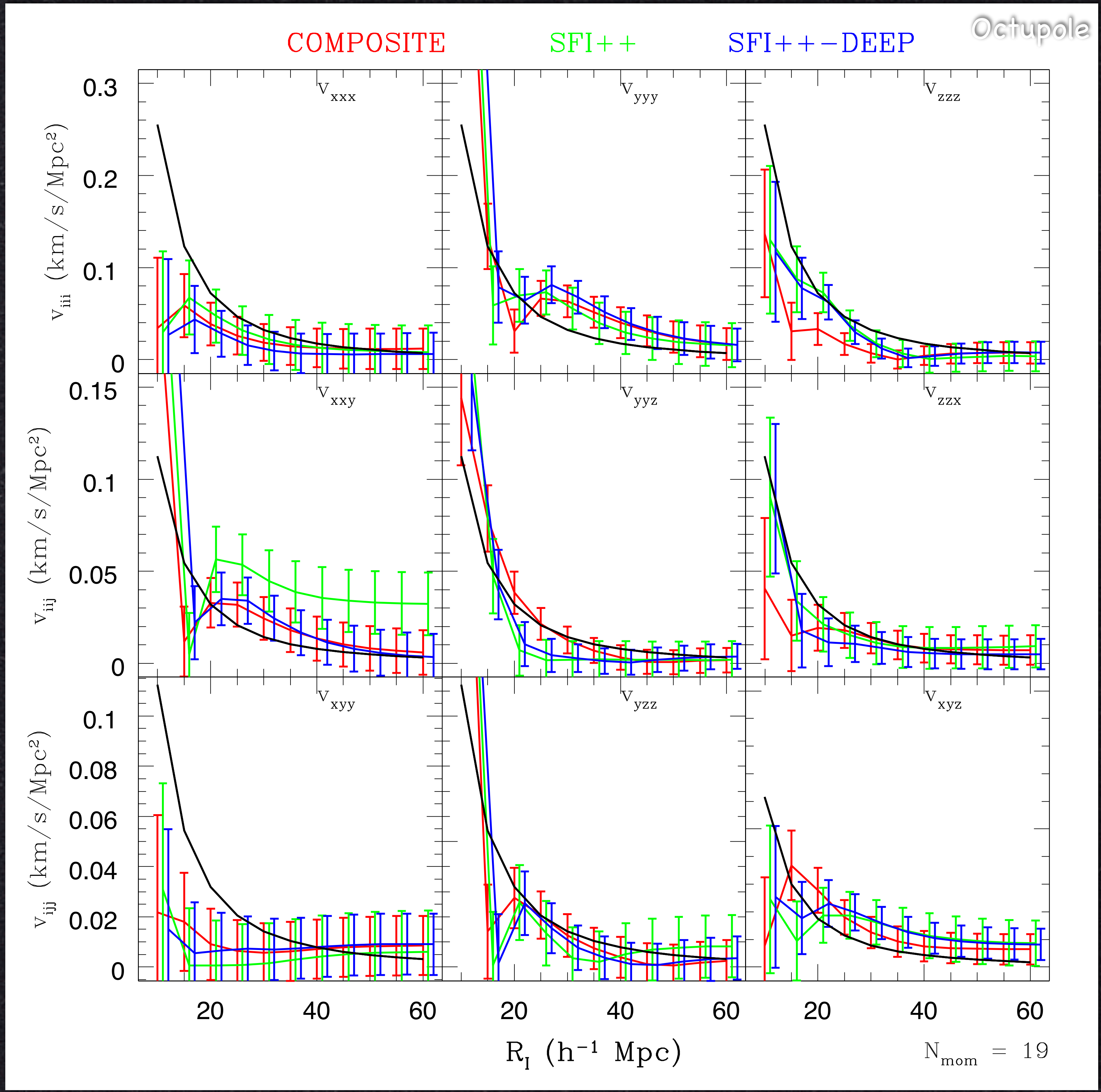
0.15
0.2


COMPOSITEn WF: Ideal (Thick solid) Optimal (solid) h⁻¹Mpc
Octupole
R_I = 50 h⁻¹Mpc
iii
ijj
ijk
1
0.8
0.6
0.4
0.2
0
0
0.05
0.1
0.15
0.2
k (h Mpc⁻¹)

Comparing Surveys



Moments and correlation coefficients

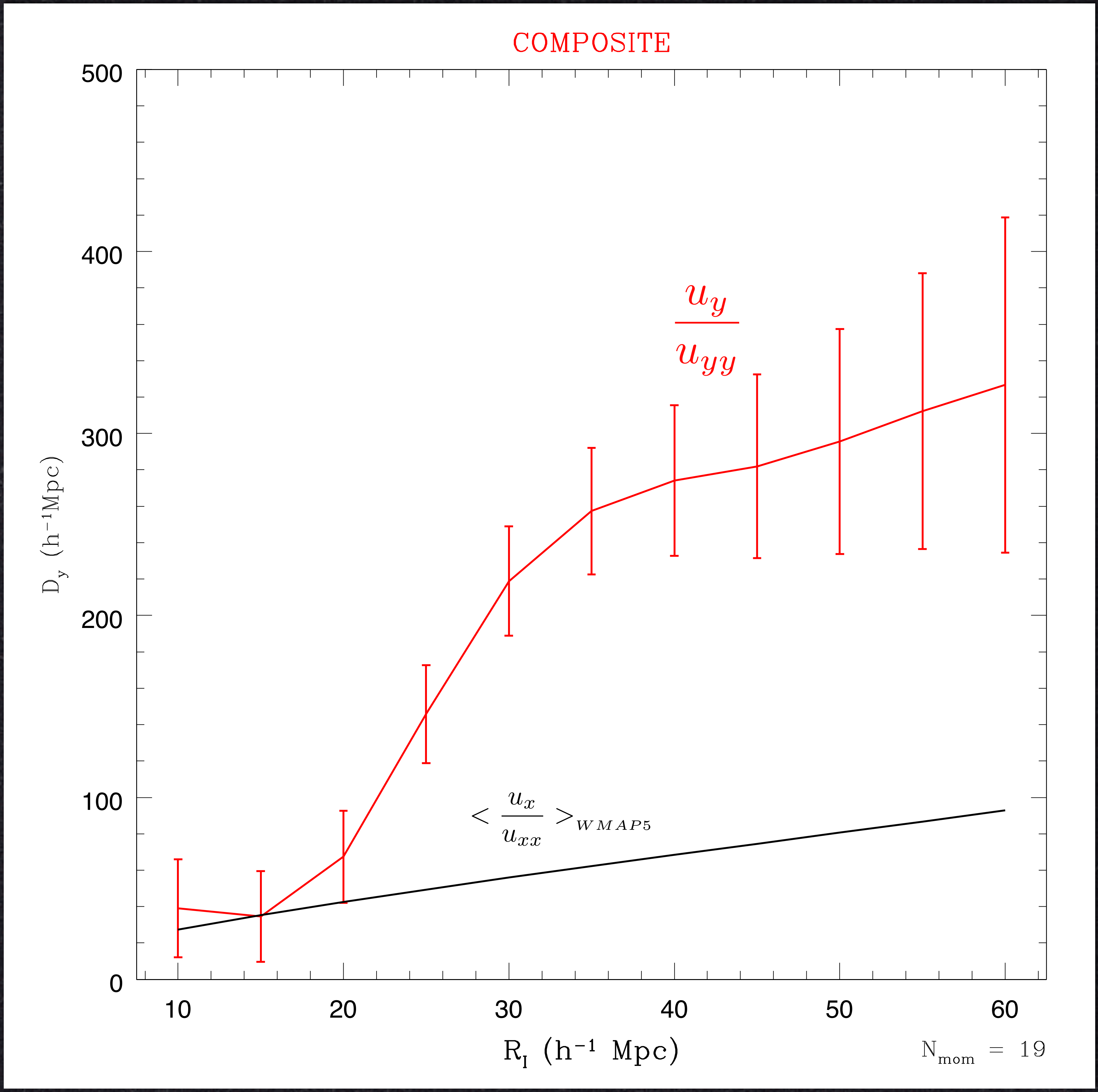
	COMPOSITE		SFI++–DEEP		SFI++		DEEP	
x	86.5 ± 68.8	0.74	104.7 ± 71.0	0.72	69.0 ± 95.7	0.64	192.7 ± 115.6	0.51
y	-404.9 ± 61.8	0.77	-430.3 ± 63.8	0.75	-473.6 ± 87.2	0.67	-320.7 ± 106.0	0.51
z	42.8 ± 37.7	0.89	64.9 ± 38.7	0.88	57.7 ± 59.3	0.80	62.0 ± 55.8	0.76
xx	2.73 ± 1.01	0.69	2.94 ± 1.05	0.68	3.36 ± 1.29	0.62	2.19 ± 1.76	0.47
yy	1.37 ± 0.98	0.69	2.07 ± 1.02	0.68	3.72 ± 1.27	0.63	-0.19 ± 1.79	0.42
zz	-0.03 ± 0.68	0.80	0.68 ± 0.72	0.79	2.72 ± 0.96	0.71	-0.72 ± 1.04	0.67
xy	0.13 ± 0.76	0.51	-0.01 ± 0.79	0.50	-0.71 ± 0.98	0.42	0.27 ± 1.29	0.31
yz	-0.95 ± 0.57	0.63	-1.14 ± 0.59	0.62	-1.05 ± 0.78	0.52	-0.71 ± 0.94	0.40
zx	1.22 ± 0.54	0.66	1.14 ± 0.56	0.65	1.50 ± 0.74	0.56	0.98 ± 0.84	0.47
xxx	-1.2e-2 ± 2.2e-2	0.38	-5.8e-3 ± 2.3e-2	0.37	-9.3e-3 ± 2.9e-2	0.31	1.0e-2 ± 3.6e-2	0.25
yyy	-2.4e-2 ± 1.7e-2	0.41	-2.3e-2 ± 1.8e-2	0.40	-1.9e-2 ± 2.4e-2	0.34	-2.2e-2 ± 2.7e-2	0.24
zzz	-7.2e-3 ± 1.1e-2	0.61	-7.7e-3 ± 1.1e-2	0.60	-3.3e-3 ± 1.6e-2	0.48	-2.5e-3 ± 1.6e-2	0.47
xyy	-8.2e-3 ± 1.2e-2	0.30	-5.7e-3 ± 1.3e-2	0.30	-3.3e-2 ± 1.7e-2	0.23	2.0e-2 ± 1.9e-2	0.20
yzz	5.8e-4 ± 6.6e-3	0.44	2.8e-3 ± 6.7e-3	0.44	-1.8e-3 ± 1.0e-2	0.33	8.9e-3 ± 9.6e-3	0.30
zxx	7.3e-3 ± 7.8e-3	0.45	4.9e-3 ± 8.1e-3	0.45	8.7e-3 ± 1.1e-2	0.34	-2.1e-3 ± 1.2e-2	0.34
xxy	8.3e-3 ± 1.2e-2	0.29	9.0e-3 ± 1.2e-2	0.28	5.7e-3 ± 1.6e-2	0.24	2.2e-2 ± 1.9e-2	0.16
yyz	6.3e-4 ± 8.3e-3	0.40	2.2e-3 ± 8.5e-3	0.40	7.7e-3 ± 1.2e-2	0.28	-2.5e-3 ± 1.2e-2	0.30
zzx	1.2e-2 ± 7.6e-3	0.46	9.9e-3 ± 7.8e-3	0.46	-2.5e-3 ± 1.1e-2	0.35	1.6e-2 ± 1.1e-2	0.34
xyz	6.6e-3 ± 5.5e-3	0.34	8.7e-3 ± 5.6e-3	0.34	9.3e-3 ± 8.2e-3	0.25	4.9e-3 ± 8.2e-3	0.22

The total observed $P(>\chi^2)$ in percent for N_{MOM} = 3, 9 and 19 for R_I =50 h^{-1} Mpc, and the WMAP5 central parameters Ω_m = 0.258 and σ_8 = 0.796.

	$N_{MOM}=3$	$N_{MOM}=9$			$N_{MOM}=19$			
	BF	Total	BF	shear	Total	BF	shear	octupole
COMPOSITE	1.89	6.01	1.81	41.76	17.00	0.50	52.60	78.33
SFI++-DEEP	0.92	2.80	0.85	33.21	13.67	0.20	39.47	86.37
SFI++	3.11	1.73	3.22	7.70	16.19	0.22	11.22	89.38
DEEP	6.02	30.41	6.29	82.62	55.54	3.18	91.22	81.61

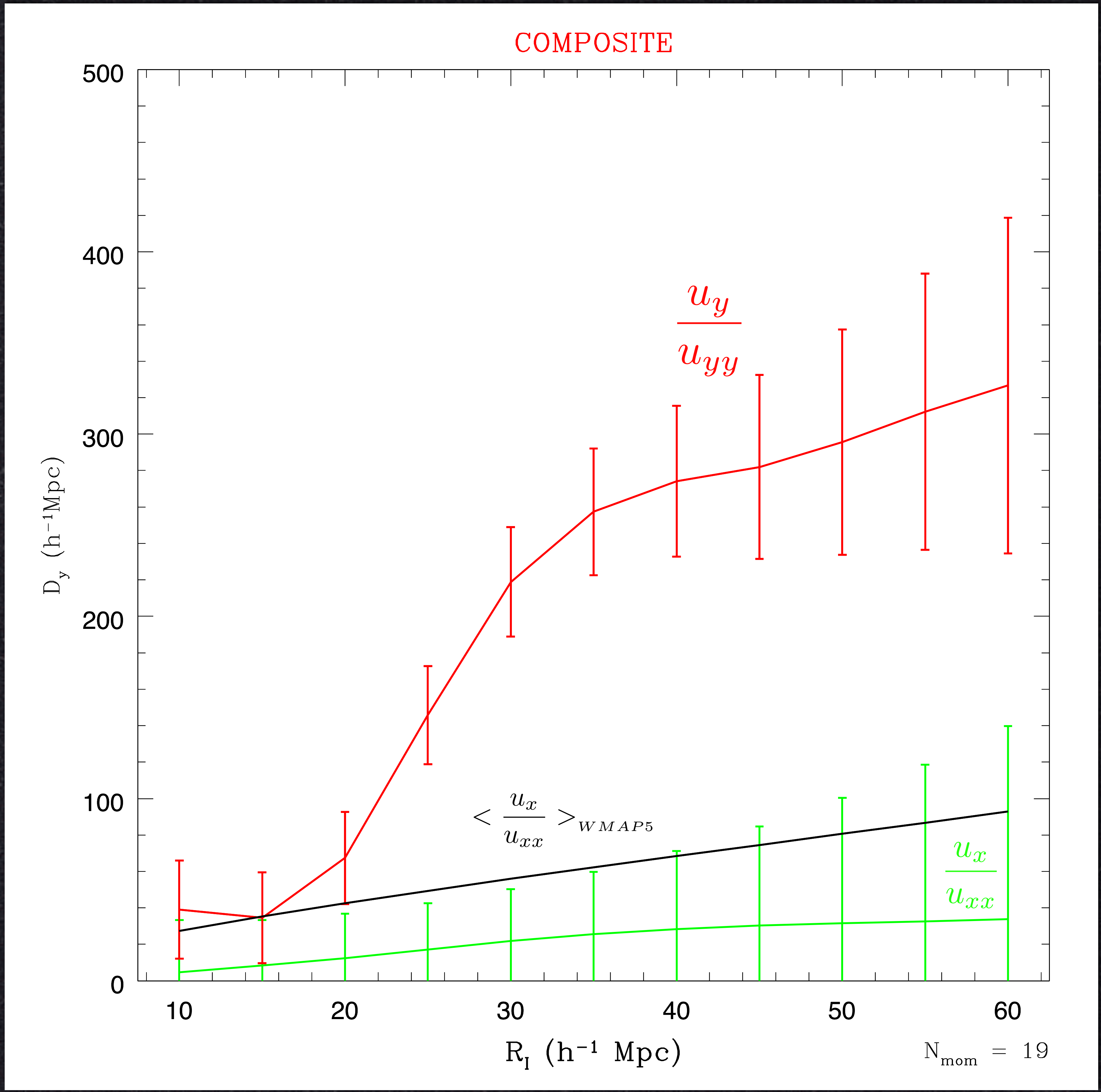
Sources of the Flow

Work in progress

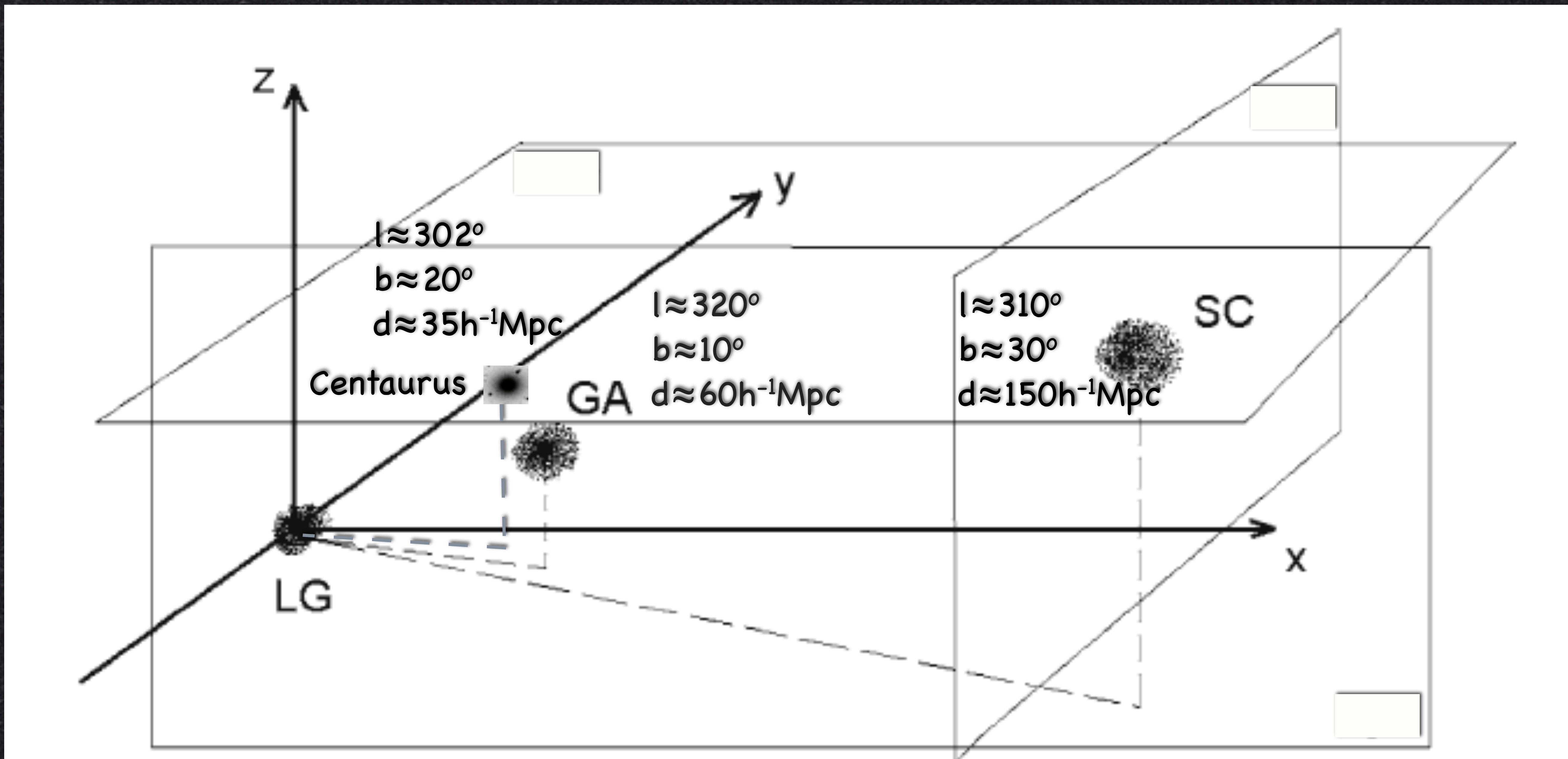


Sources of the Flow

Work in progress

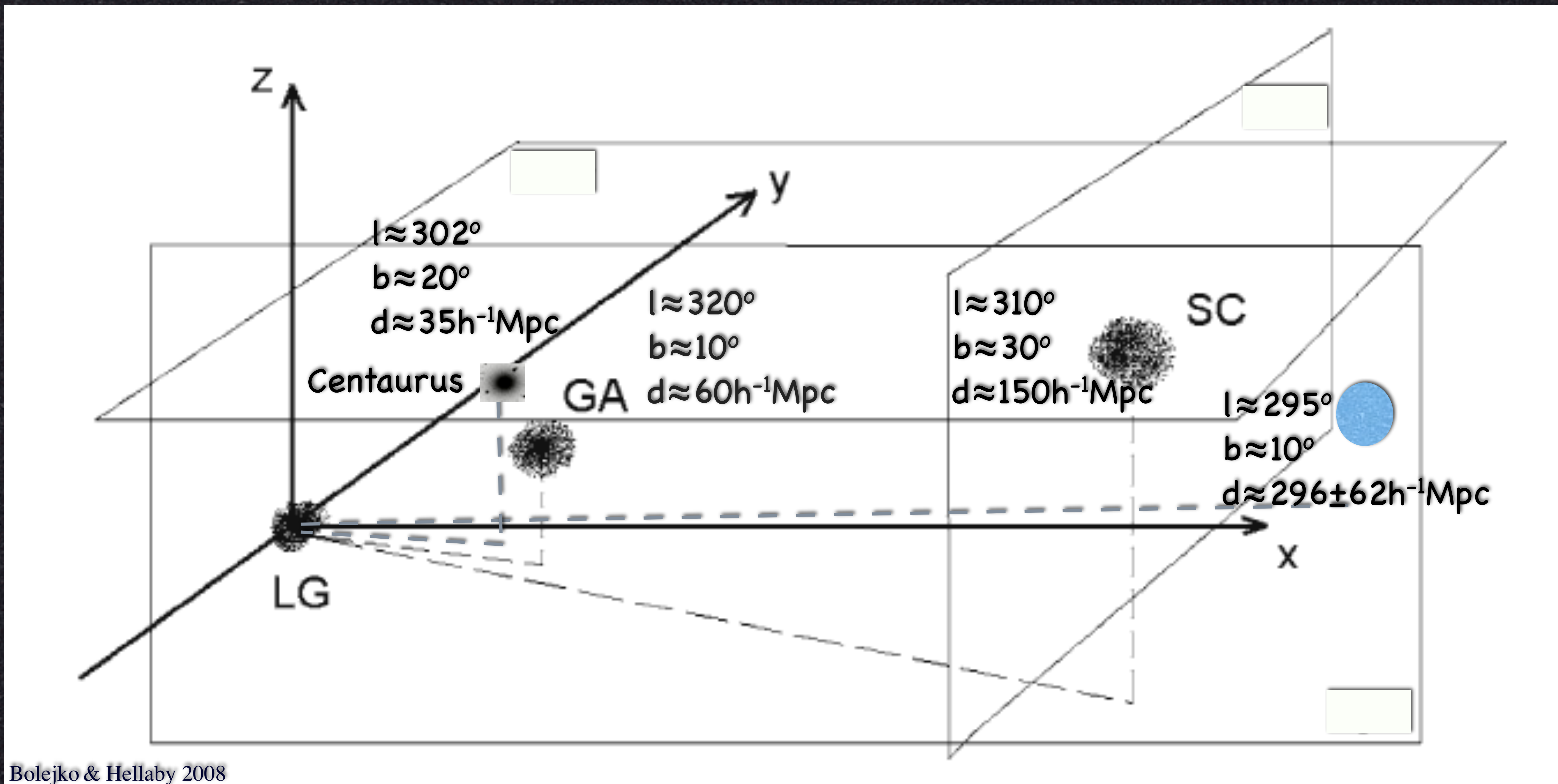


Is there an attractor?

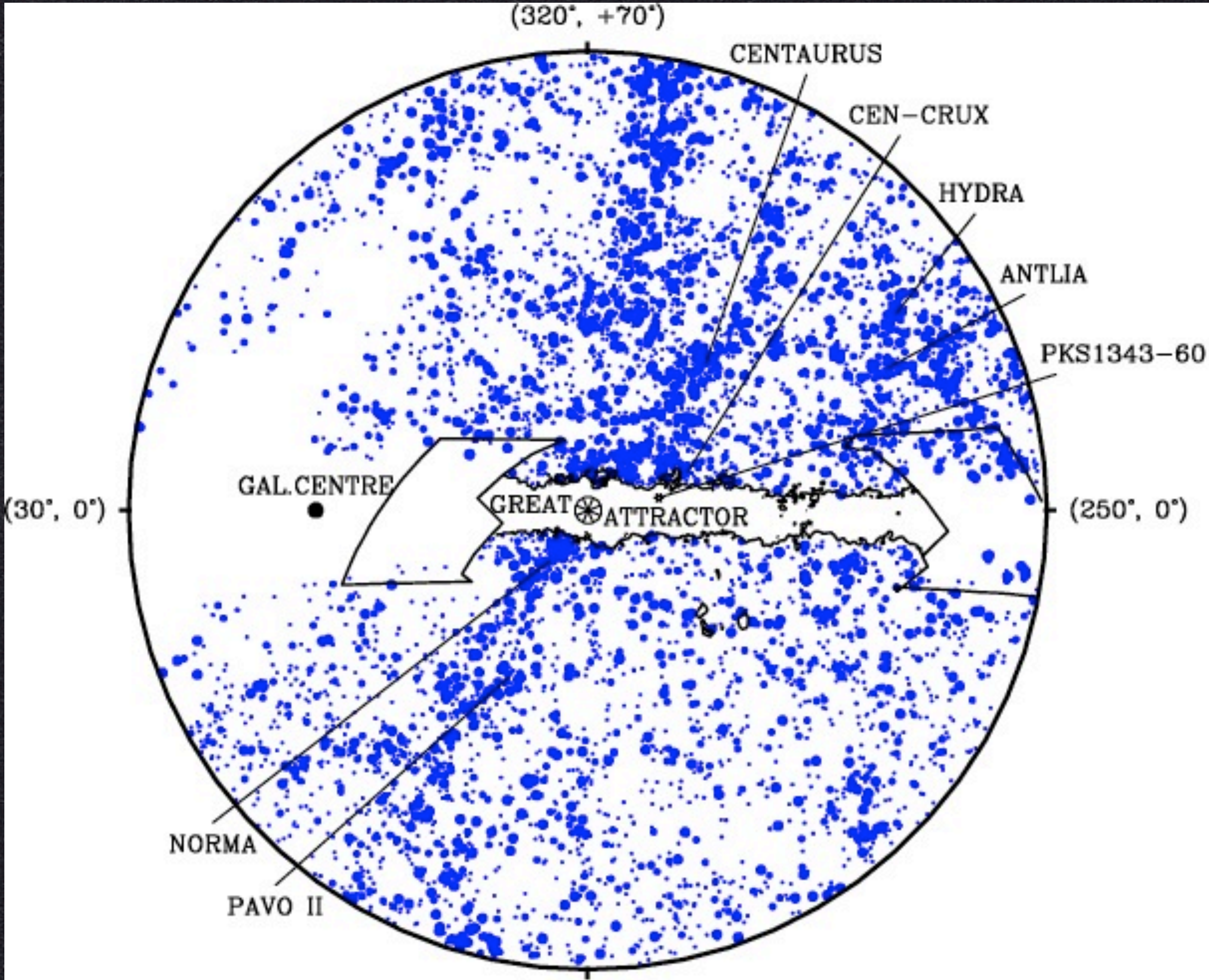


Bolejko & Hellaby 2008

Is there an attractor?

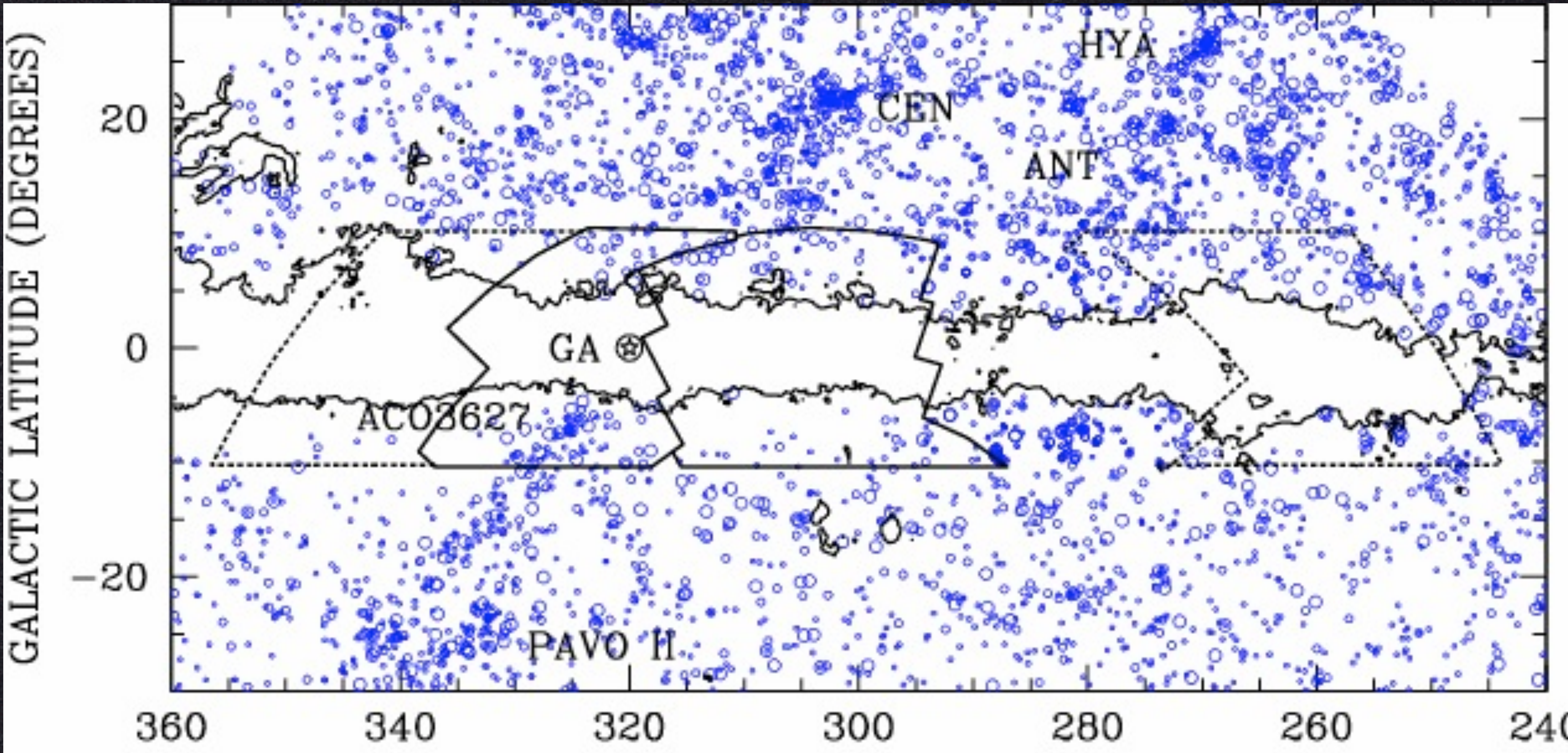


Is there an attractor?



Wouldt & Kraan-Korteweg, 2001

Is there an attractor?



Wouldt & Kraan-Korteweg, 2001

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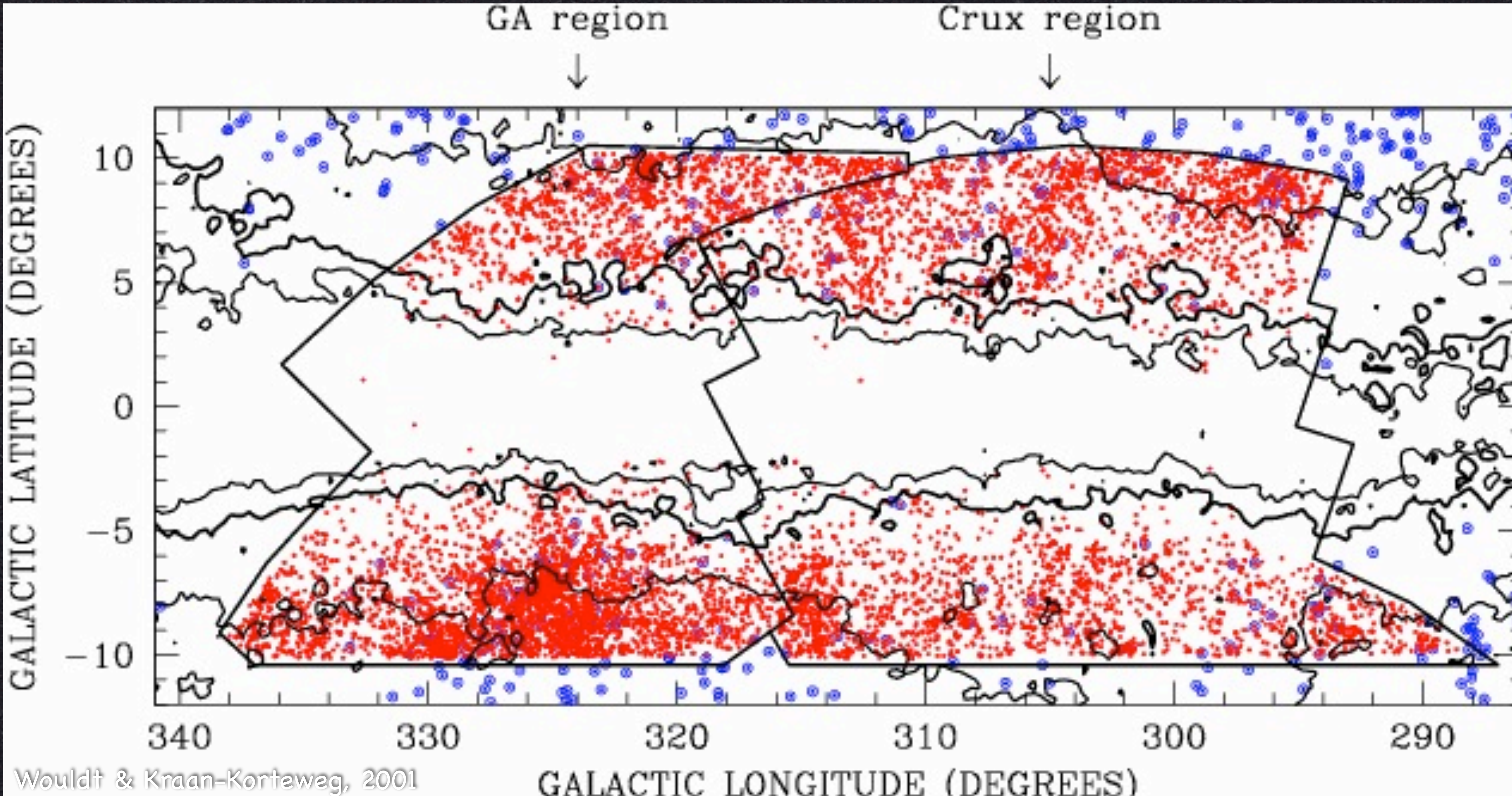
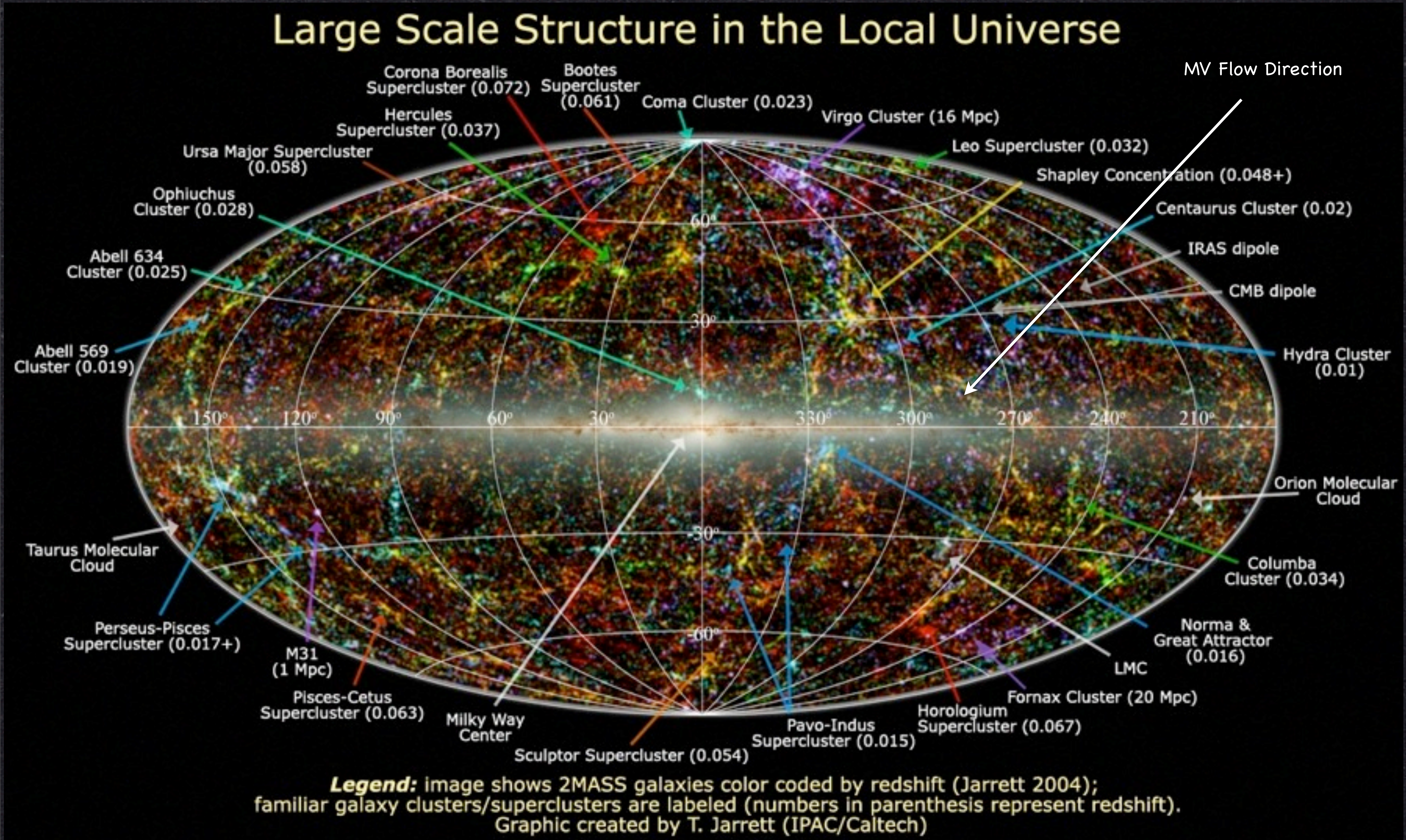
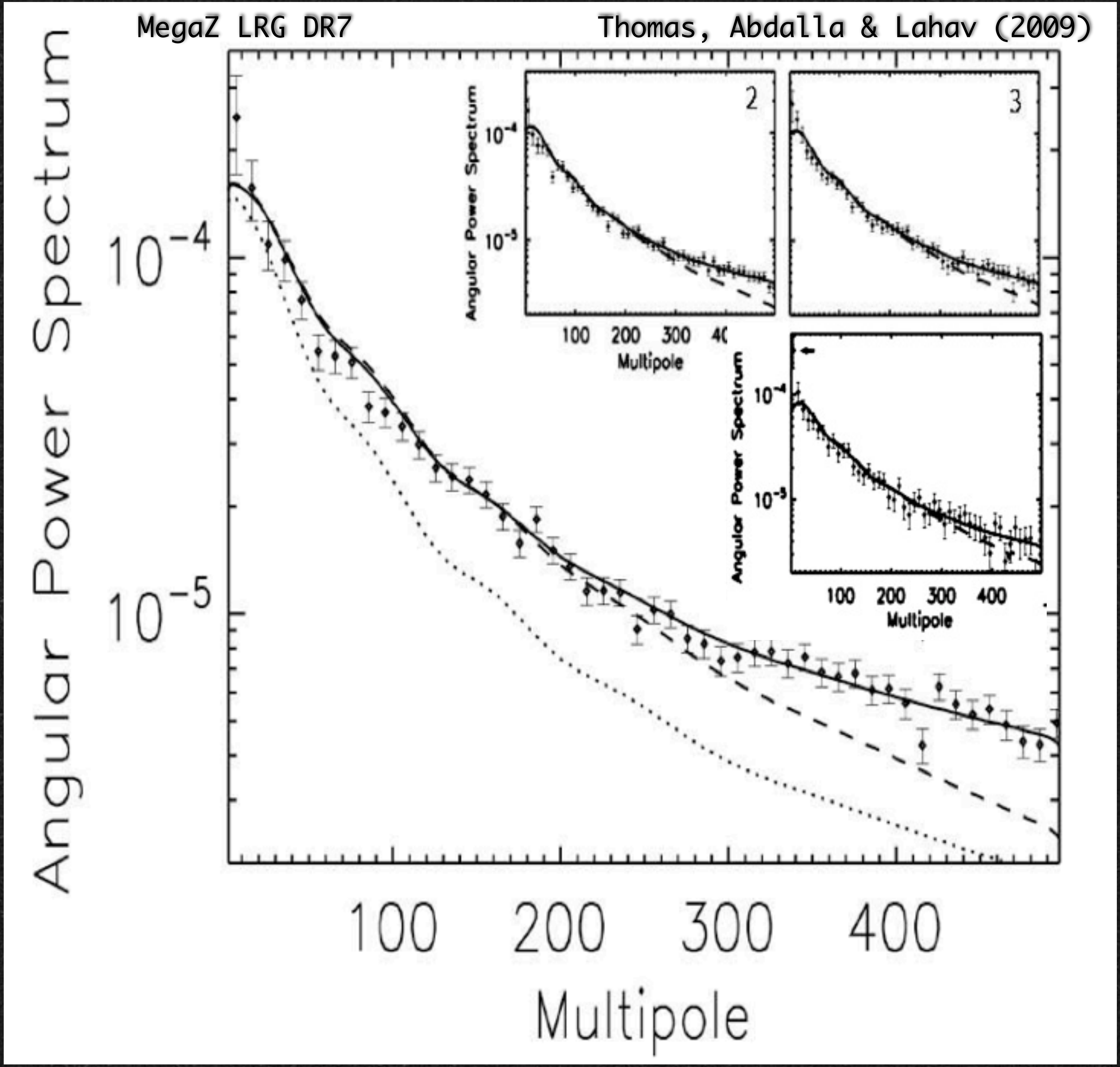
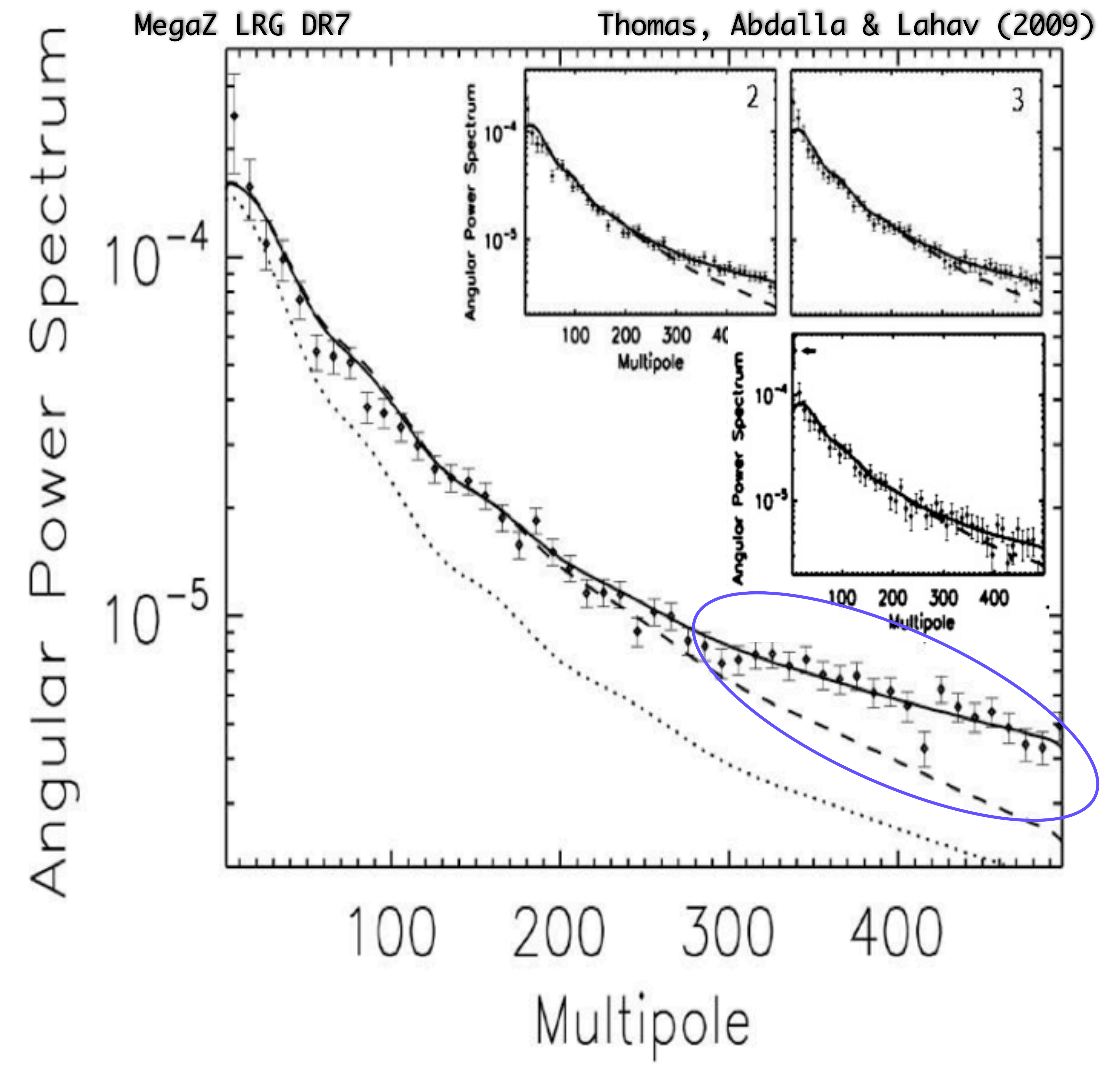


Is there an attractor?




MegaZ LRG DR7
Thomas, Abdalla & Lahav (2009)
Angular Power Spectrum
10^{-4}
10^{-5}
100
200
300
400
Multipole
2
3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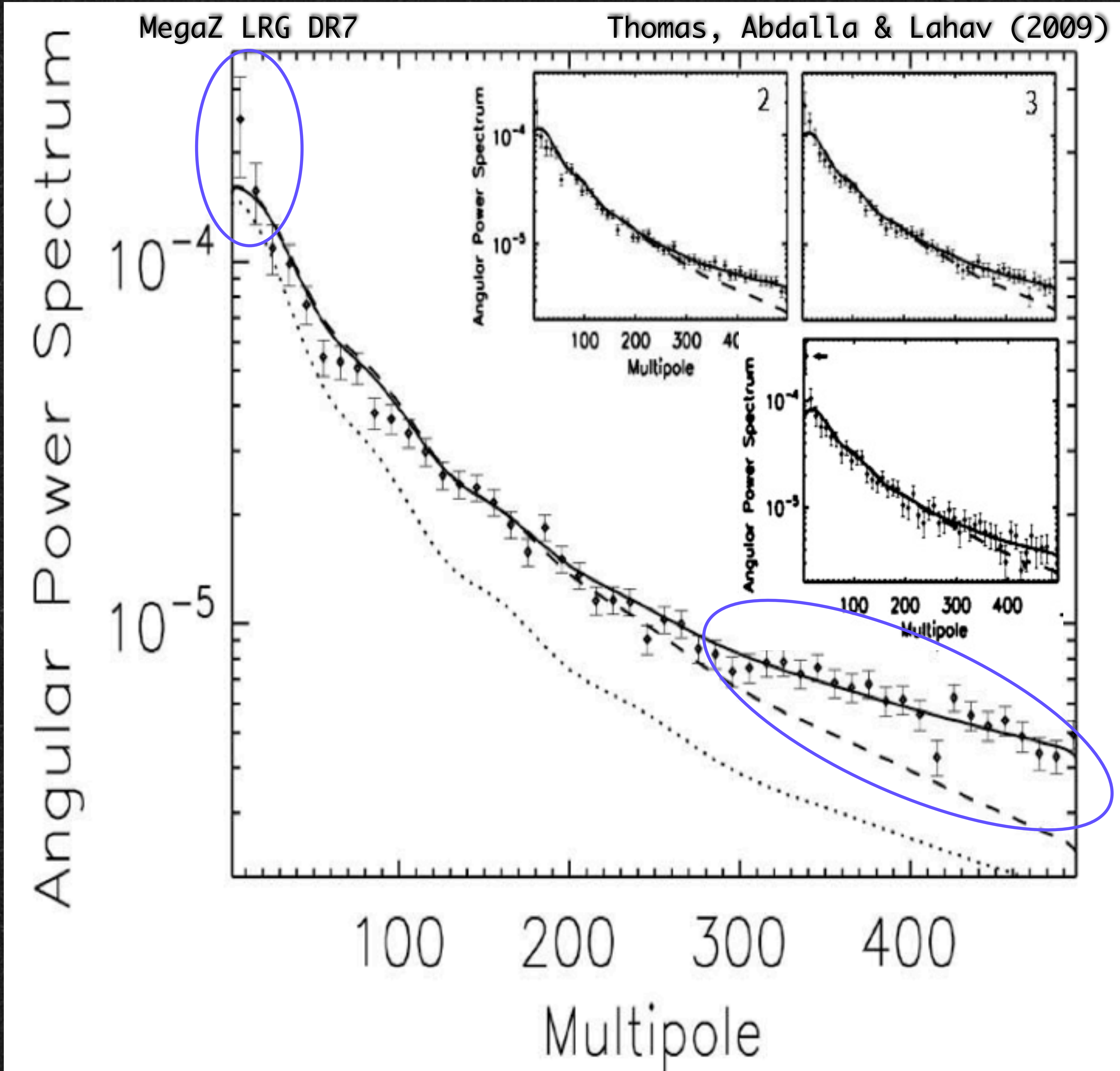
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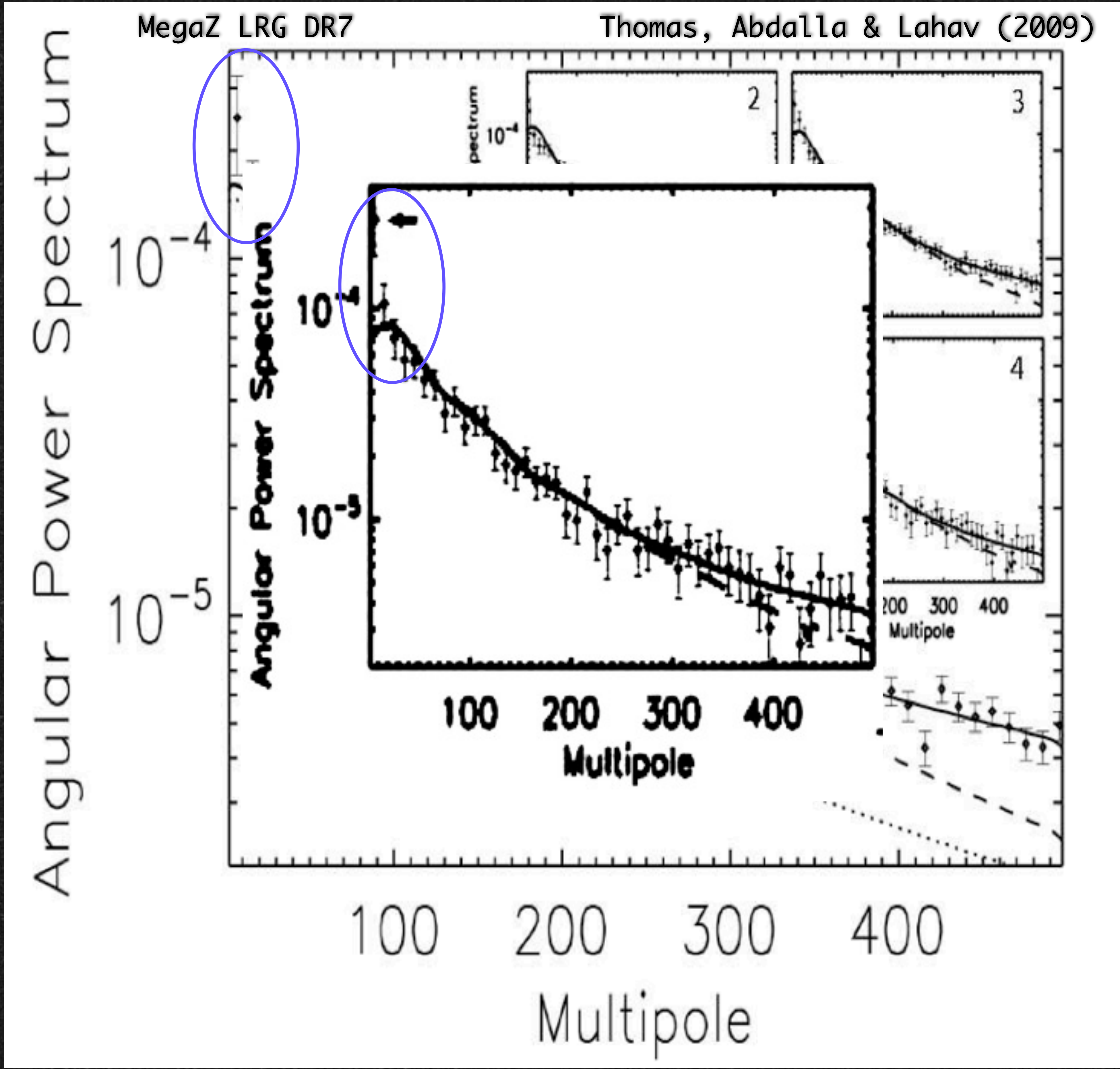
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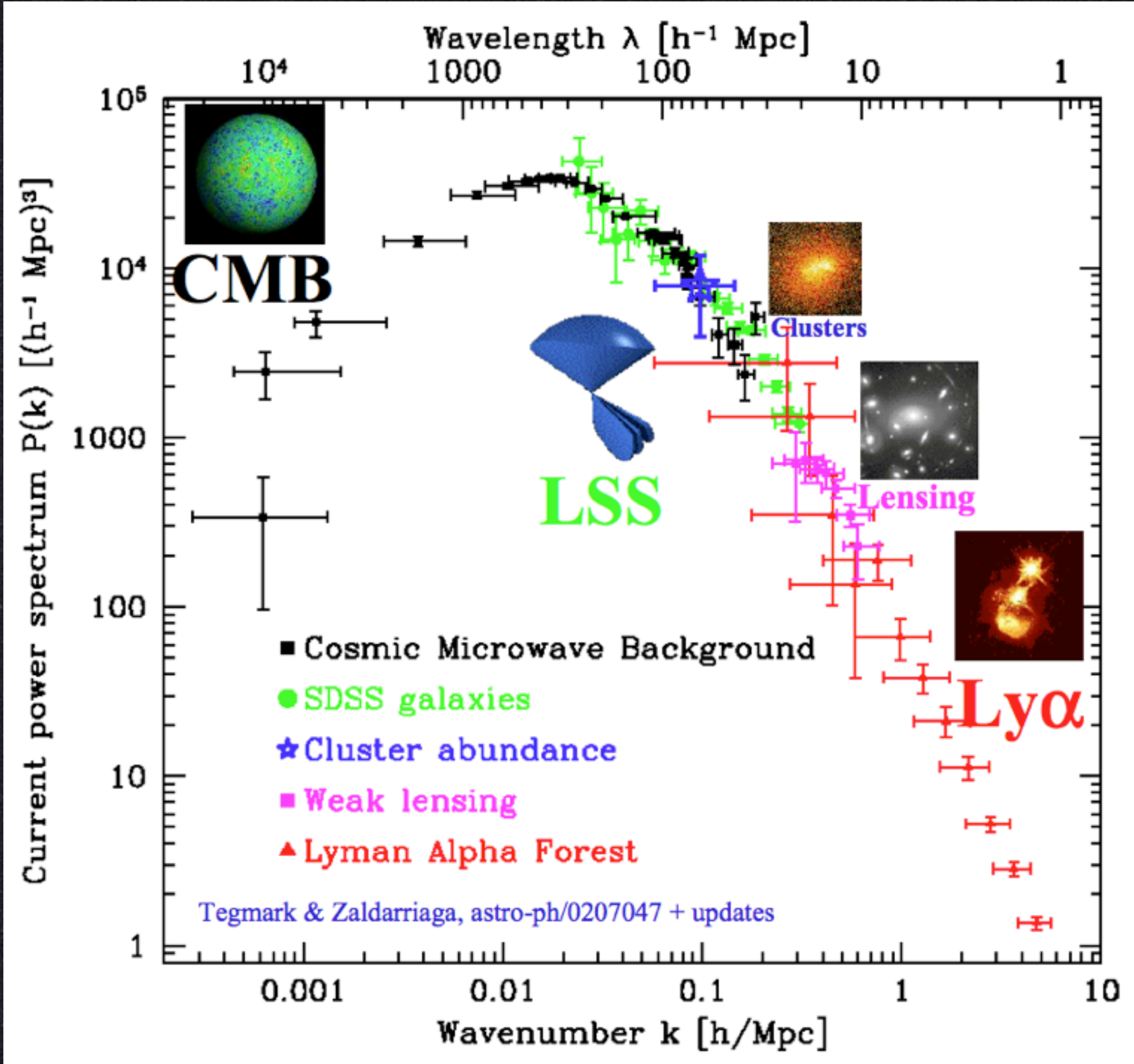
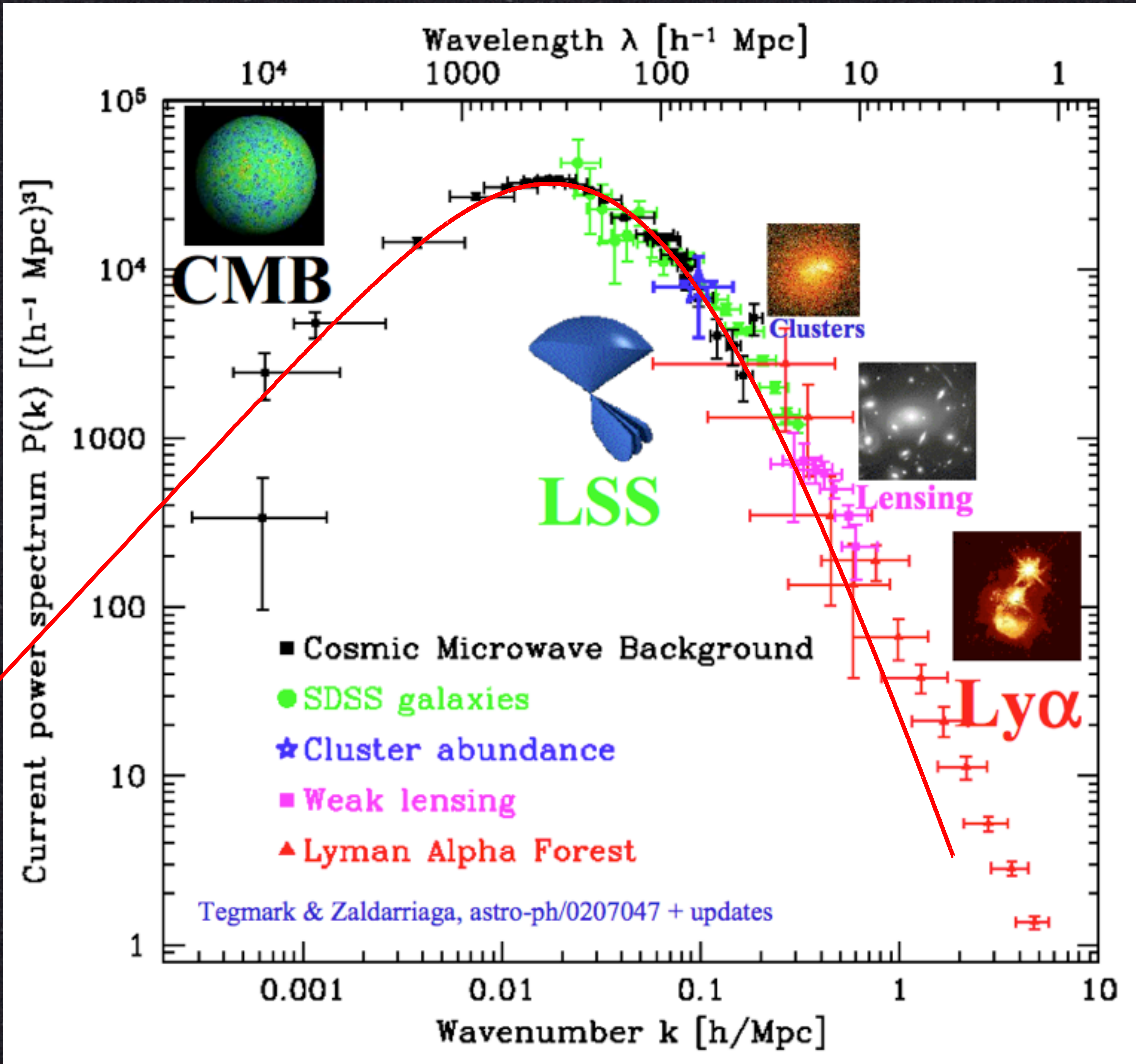
Angular Power Spectrum
10^{-4}
10^{-5}
100
200
300
400
Multipole
2
3
4


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
CMB
LSS
Clusters
Lensing
Lyα
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]


Wavelength λ [h⁻¹ Mpc]
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100
10
1
10⁵
10⁴
1000
100
10
1
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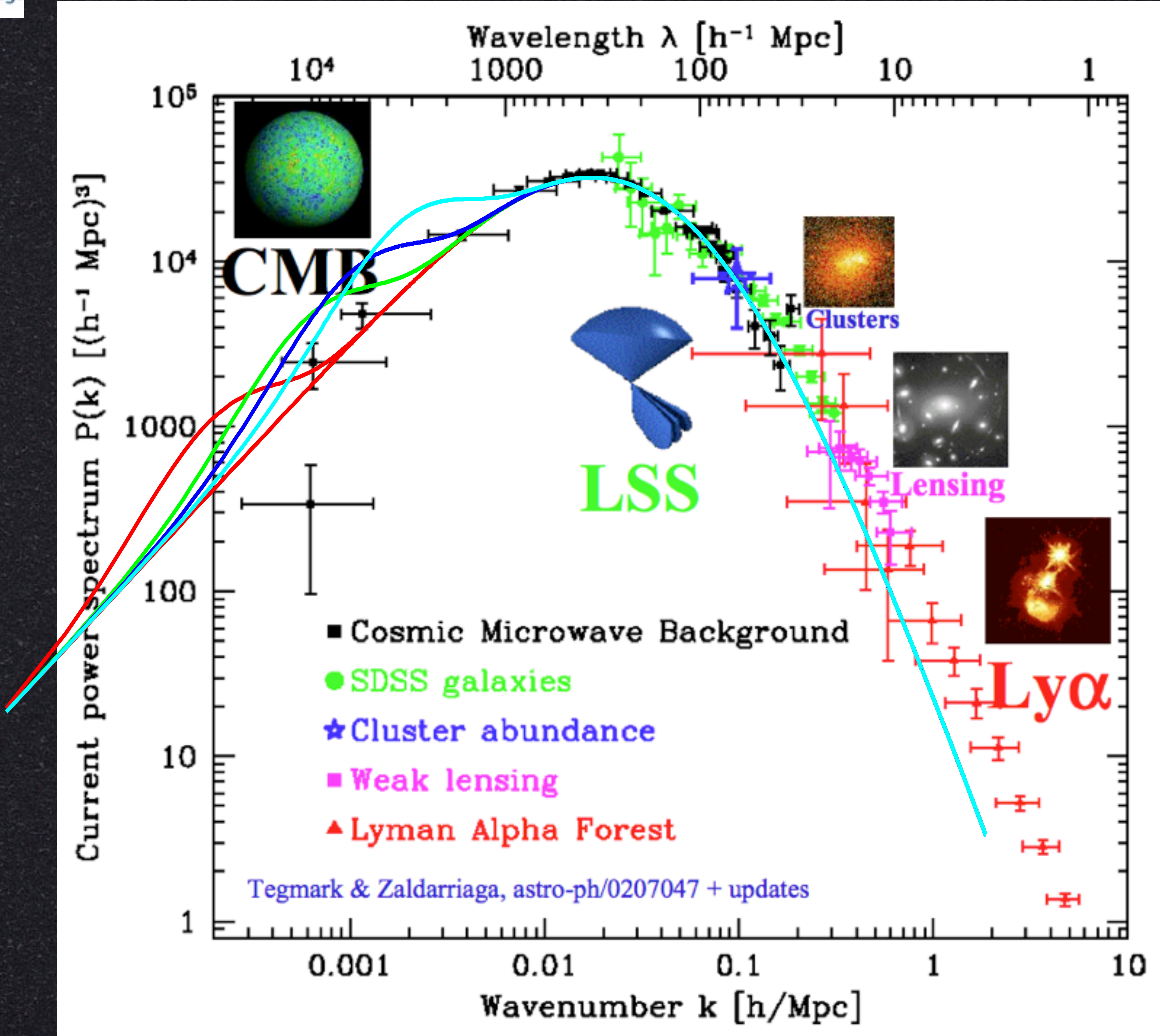
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1000
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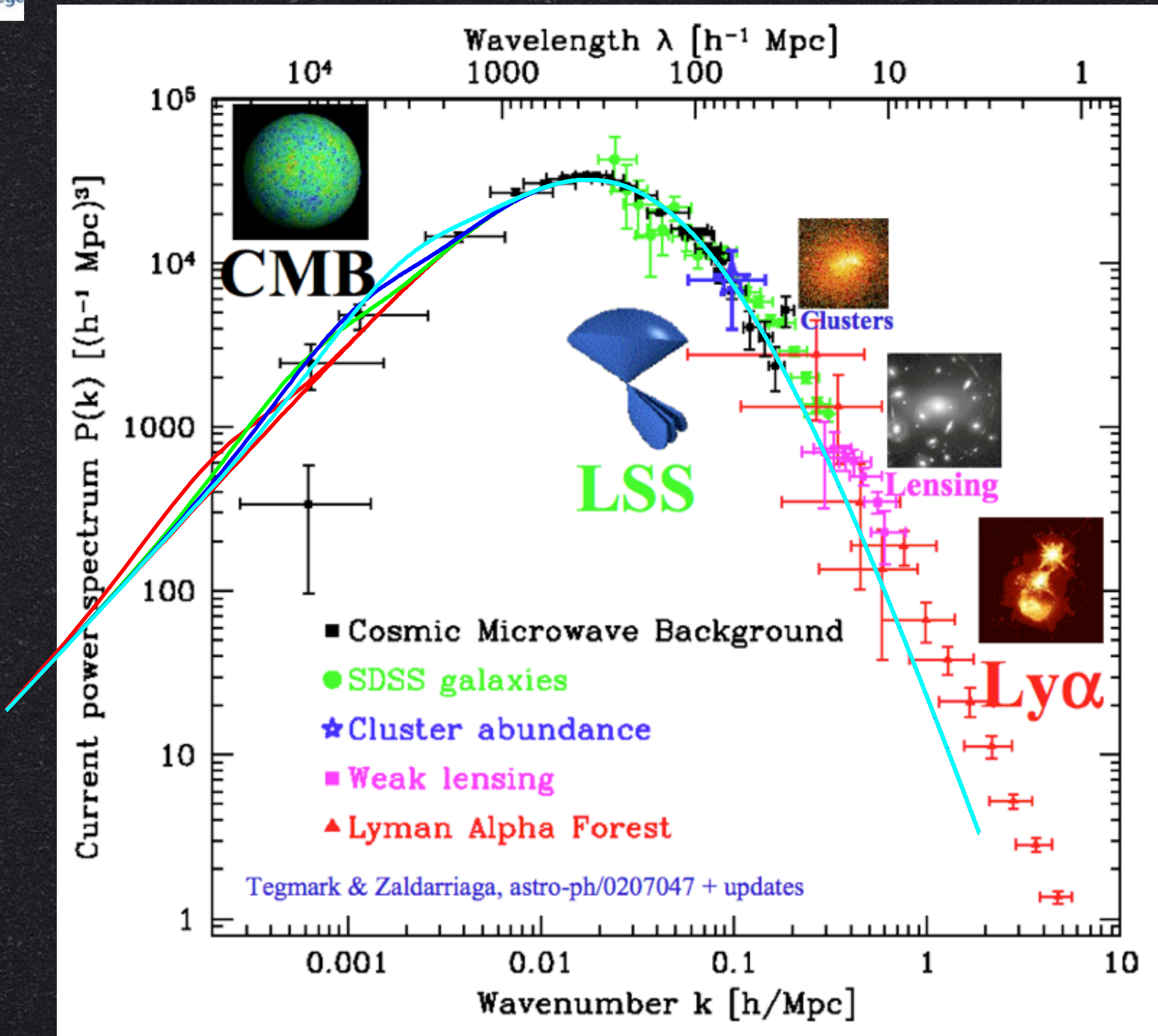
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1
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100
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0.01
0.1
1
10
Wavenumber k [h/Mpc]

Conclusions

- ☑ Given appropriate window functions, velocity field surveys are consistent with each other.
- ☑ Maximum Likelihood parameter estimation are robust and mostly agree with other methods.
- ☑ There is a minimal sensitivity to small-scale aliasing which biases the results, hiding large-scale flows
- ☑ Optimization of window functions removes the bias and shows the flow
- ☑ Bulk flow disagrees with the Standard ΛCDM parameters (WMAP5) to $\sim 3\sigma$
- ☑ More power on k $\lesssim$ 0.01 will make these results likely

Thank you