Unveiling the Cosmic Web with Bayesian Perturbation Theory

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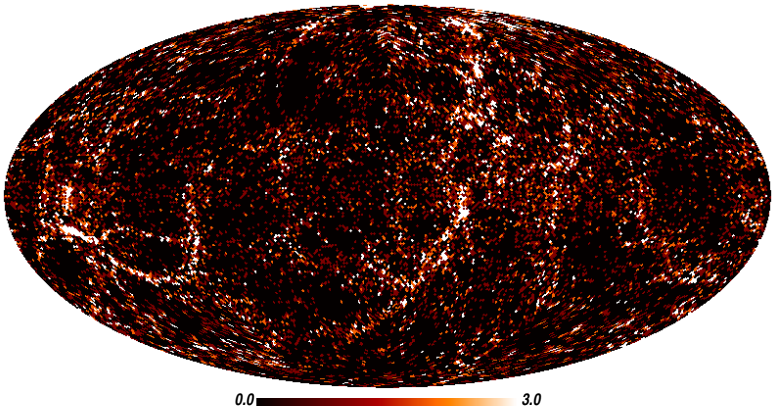
Introduction

- the cosmological large-scale structure encodes a wealth of information about the evolution and origin of the Universe
- this information has been altered by gravity
- nonlocal and nonlinear mode-coupling/mixing between the larger and the smaller scales has hidden the information
- can we undo gravity to extract this information?

Examples

- Zeldovich backwards: BAO reconstruction Eisenstein et al 2007
- Gaussianization: tighter constraints on cosmological parameters Neyrinck et al 2009, 2011; Joachimi et al 2011; Yu et al 2011; Zhang et al 2011 ...
- Constrained simulations to understand structure formation CLUES-project
- Cosmic web classification: environmental studies



$\longrightarrow$ sparse , noisy and incomplete sample

$\longrightarrow$ matter field $\delta_{\rm M}$?

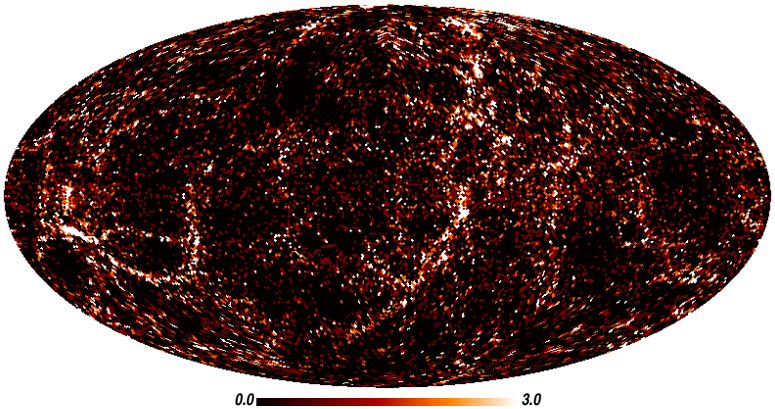
$\longrightarrow$ pec. vel. field $\mathbf{v}$?

$\longrightarrow$ grav. pot. $\Phi_{\rm Grav}$?

$\longrightarrow$ power-spectrum/BAO $P(k)$?

$\longrightarrow$ statistical analysis is necessary!

$\longrightarrow$ as precise as possible! (enviromental studies, constrained simulations)



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Bayes theorem: the posterior

$$\mathcal{P}(\mathbf{s}|\mathbf{d},\mathbf{p}) = \frac{\mathcal{P}(\mathbf{s}|\mathbf{p})\mathcal{P}(\mathbf{d}|\mathbf{s},\mathbf{p})}{\int \mathrm{d}\mathbf{s}\, \mathcal{P}(\mathbf{s}|\mathbf{p})\mathcal{P}(\mathbf{d}|\mathbf{s},\mathbf{p})}, \tag{1}$$

$\longrightarrow$ can we characterise the matter field and its biased tracers in a statistical way? (beyond the Wiener-filter)

Bayes theorem: the posterior

$$\mathcal{P}(\mathbf{s}|\mathbf{d},\mathbf{p}) = \frac{\mathcal{P}(\mathbf{s}|\mathbf{p})\mathcal{P}(\mathbf{d}|\mathbf{s},\mathbf{p})}{\int \mathrm{d}\mathbf{s}\, \mathcal{P}(\mathbf{s}|\mathbf{p})\mathcal{P}(\mathbf{d}|\mathbf{s},\mathbf{p})}, \tag{1}$$

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Bayes theorem: the posterior

Lognormal-Poisson model

$$P(\mathbf{\Phi}|\mathbf{N},\mathbf{S}) \propto G(\mathbf{\Phi}) \tag{2}$$
$$\times \prod_k \frac{\left(w_k \bar{N}\left(1+b\left(\exp\left(\Phi_k+\mu\right)-1\right)\right)\right)^{N_k} \exp\left(-w_k \bar{N}\left(1+b\left(\exp\left(\Phi_k+\mu\right)-1\right)\right)\right)}{N_k!},$$

FK & Enßlin 2008

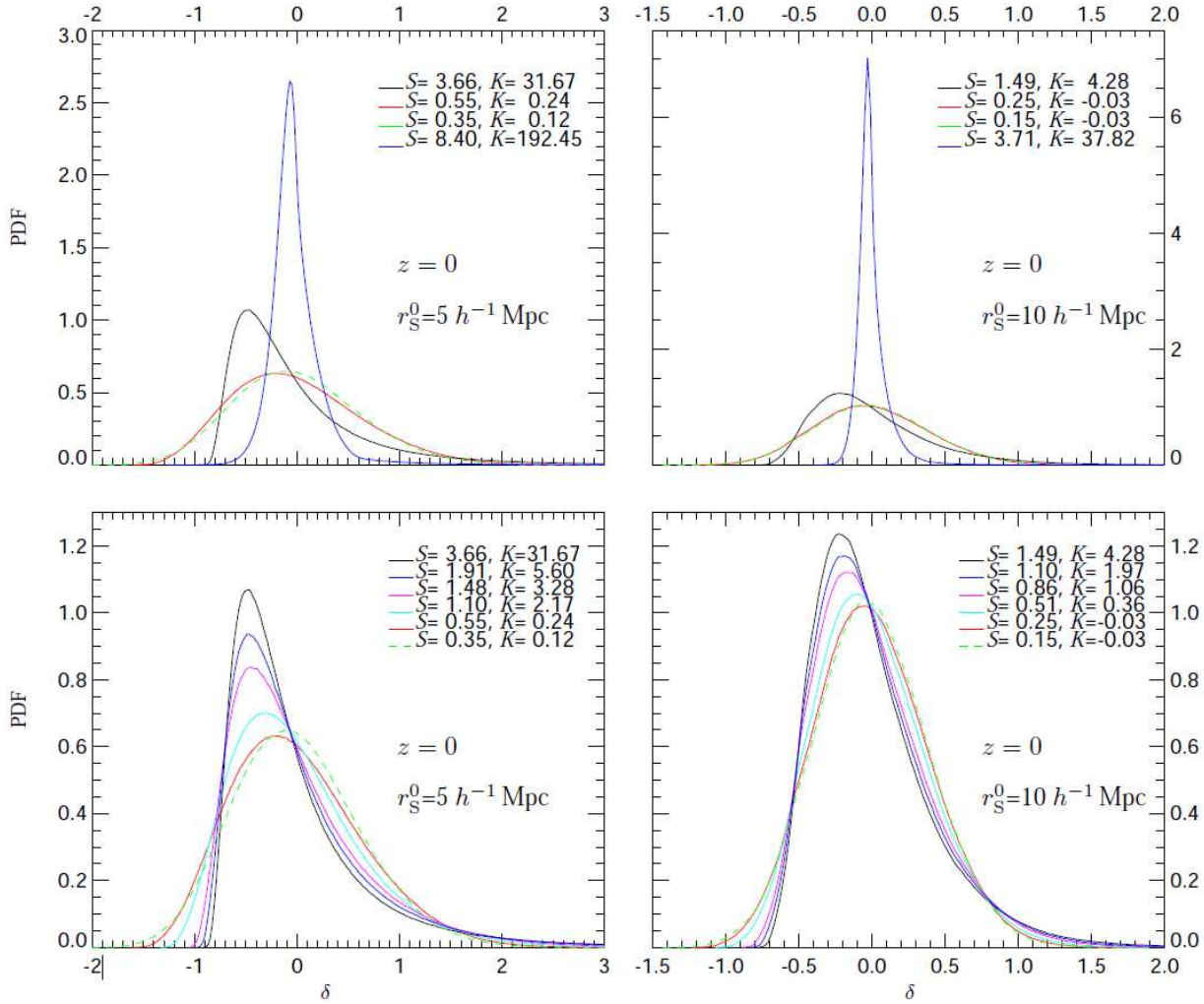
FK, Jasche & Metcalf 2010

Jasche, FK et al 2010

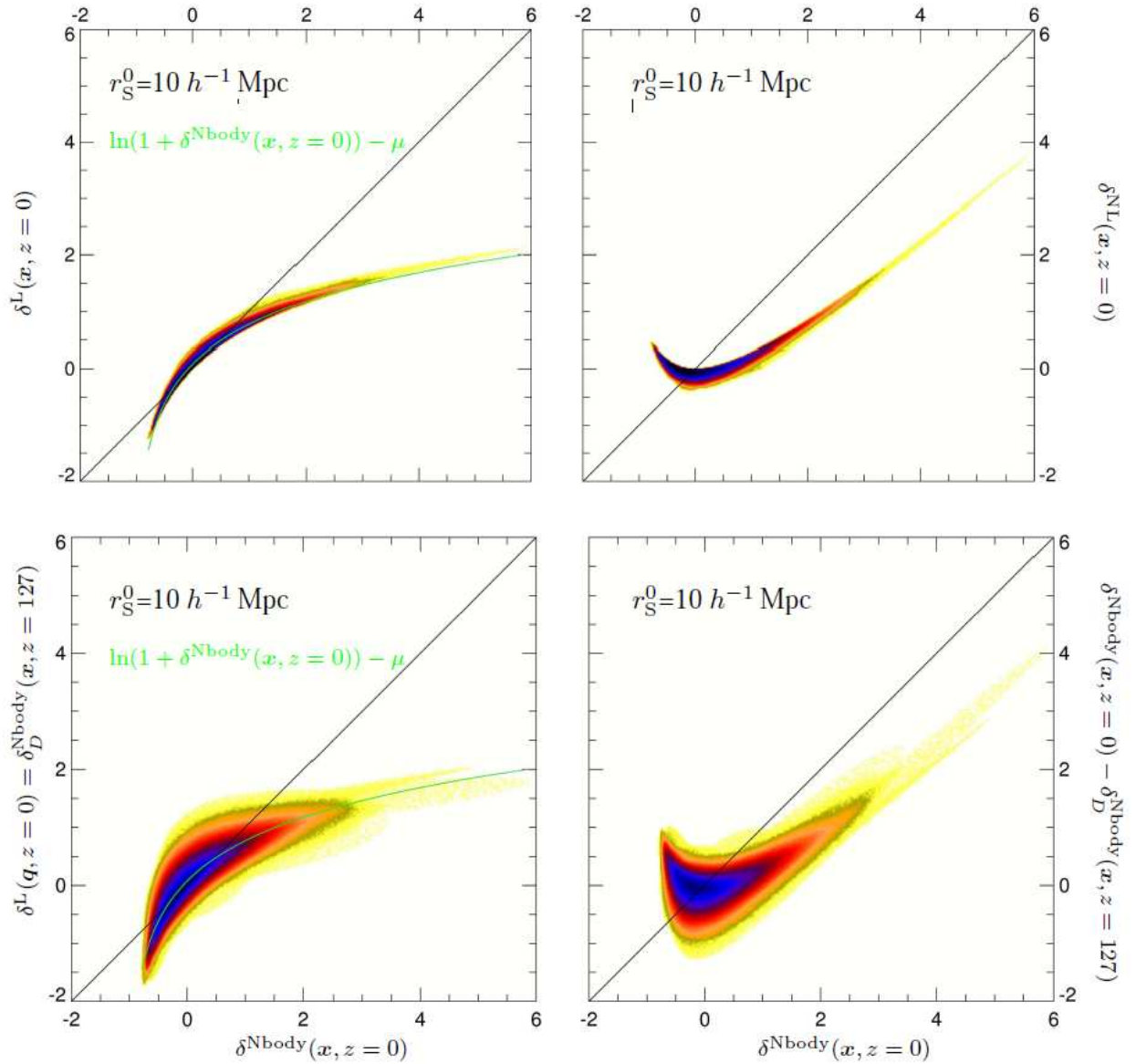
Linearization with LPT FK & Raul Angulo 2011

- Zeldovich 1970; McGill 1990; Moutarde et al 1991
- Nusser & Dekel 1992; Gramann 1993; Buchert et al 1994
- Catelan 1995; Bouchet et a 1995; Hivon et al 1995
- Monaco & Efstathiou 1999 ...

How good is the lognormal approximation?

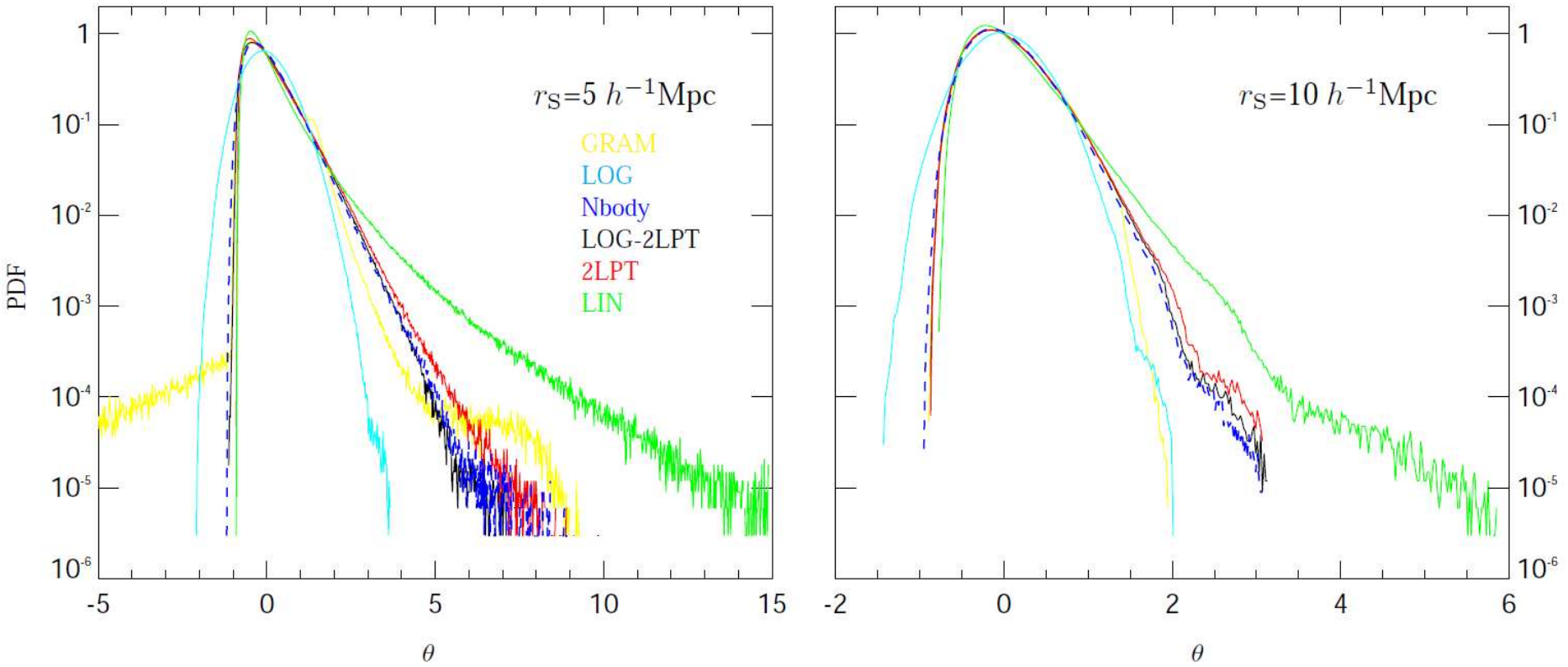


FK & Angulo 2011

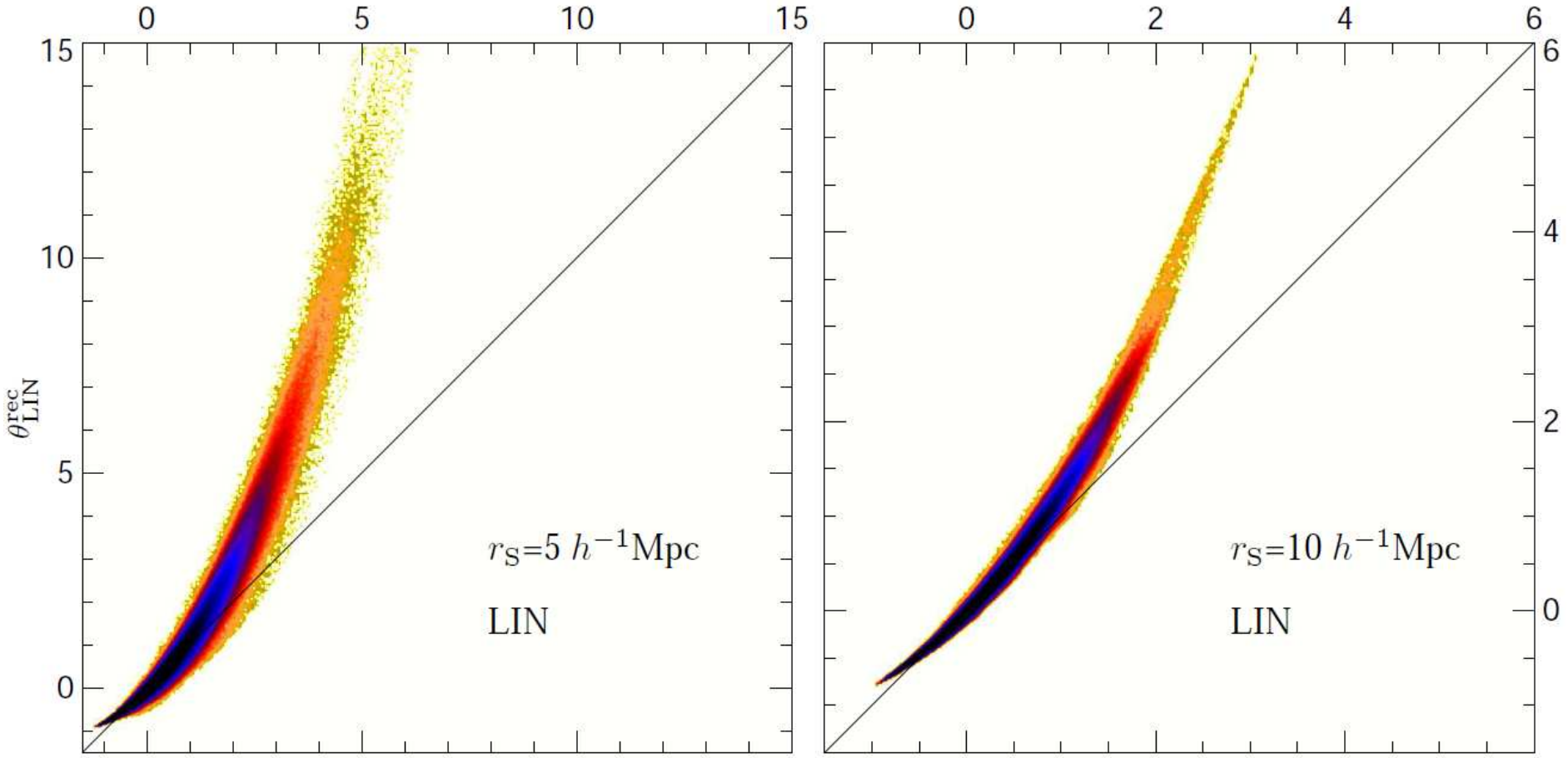

r_S^0=10 h^{-1} Mpc
$\ln(1+\delta^{\rm Nbody}(x,z=0))-\mu$
$\delta^{\rm L}(x,z=0)$
$\delta^{\rm NL}(x,z=0)$
$\delta^{\rm L}(q,z=0)=\delta_D^{\rm Nbody}(x,z=127)$
$\delta^{\rm Nbody}(x,z=0)$
$\delta_D^{\rm Nbody}(x,z=0)-\delta_D^{\rm Nbody}(x,z=127)$

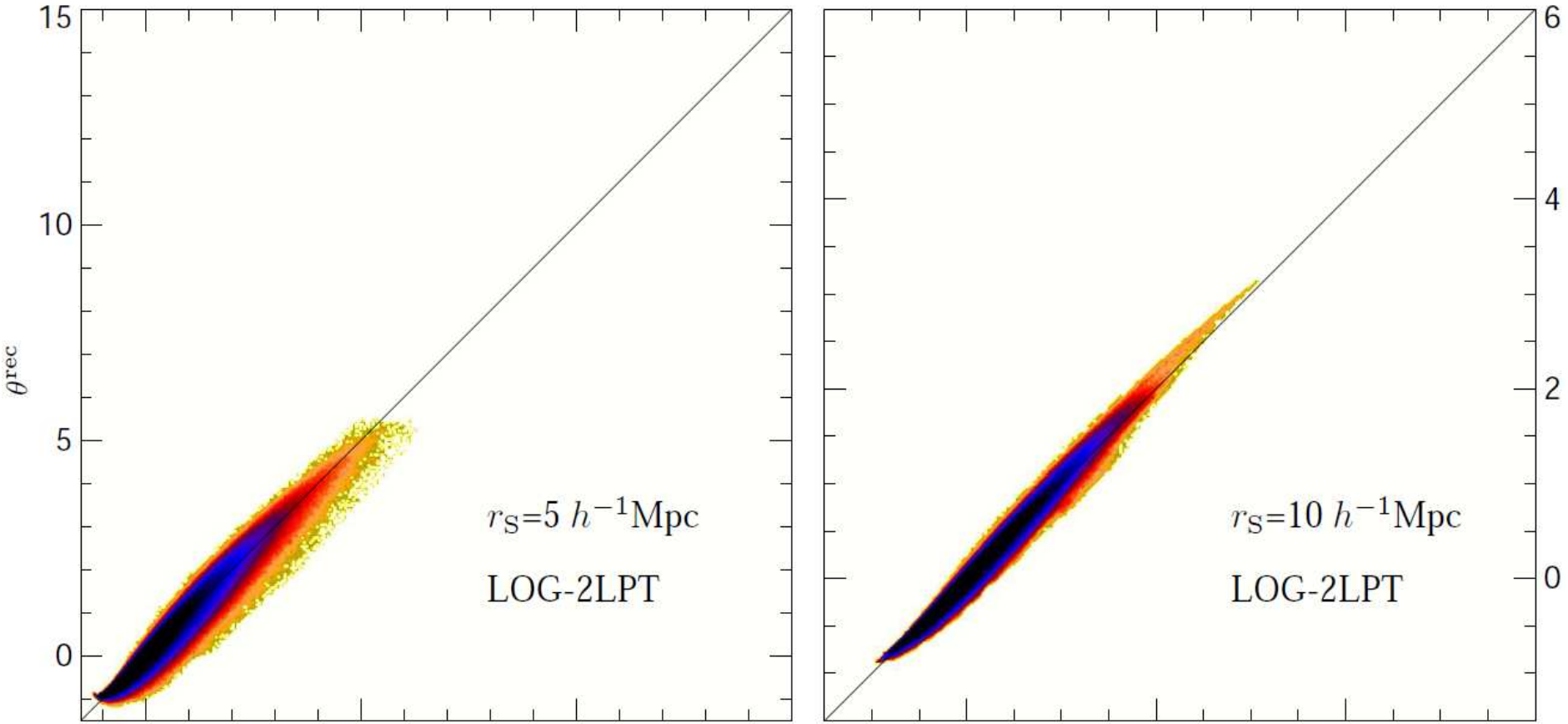
Velocity reconstruction with LPT

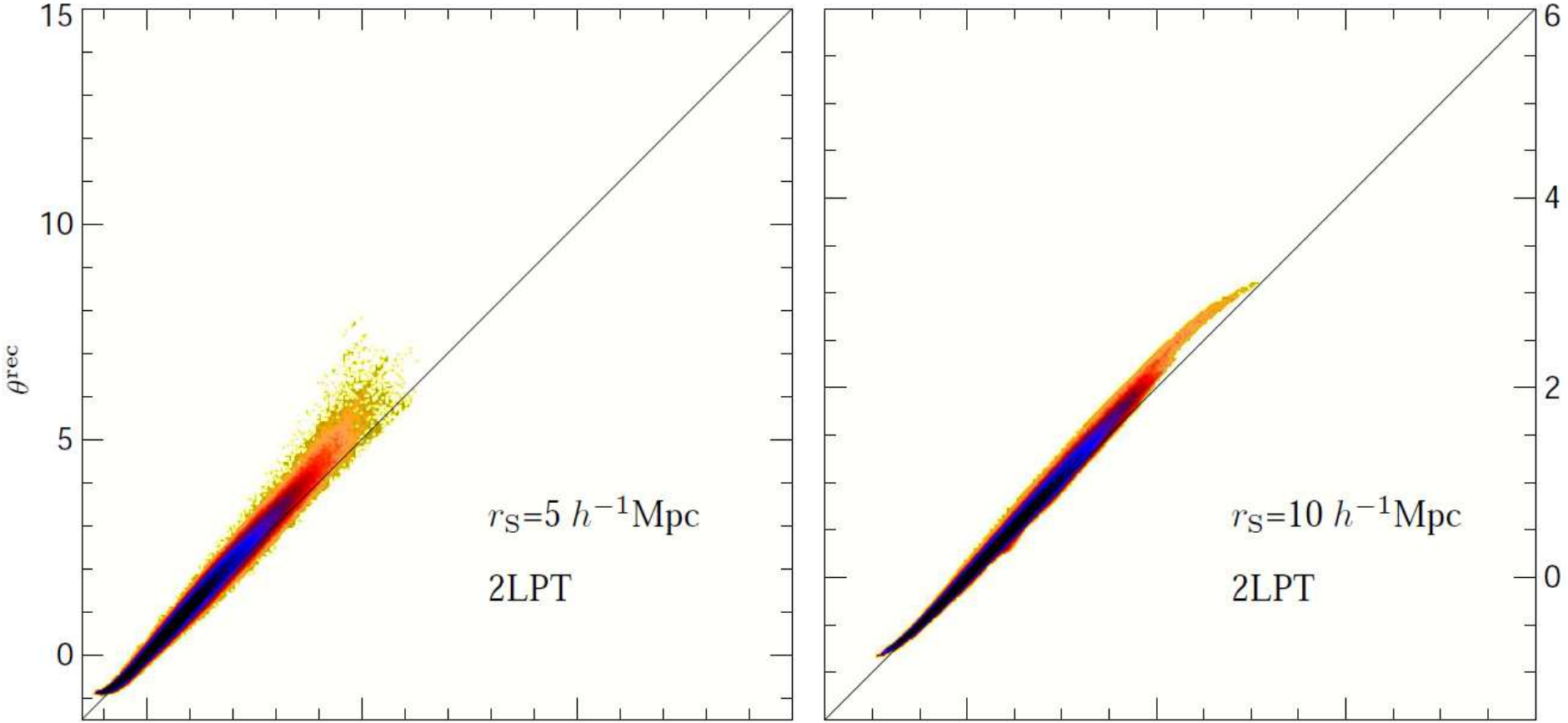
FK, Angulo, Hoffman & Gottlöber 2011

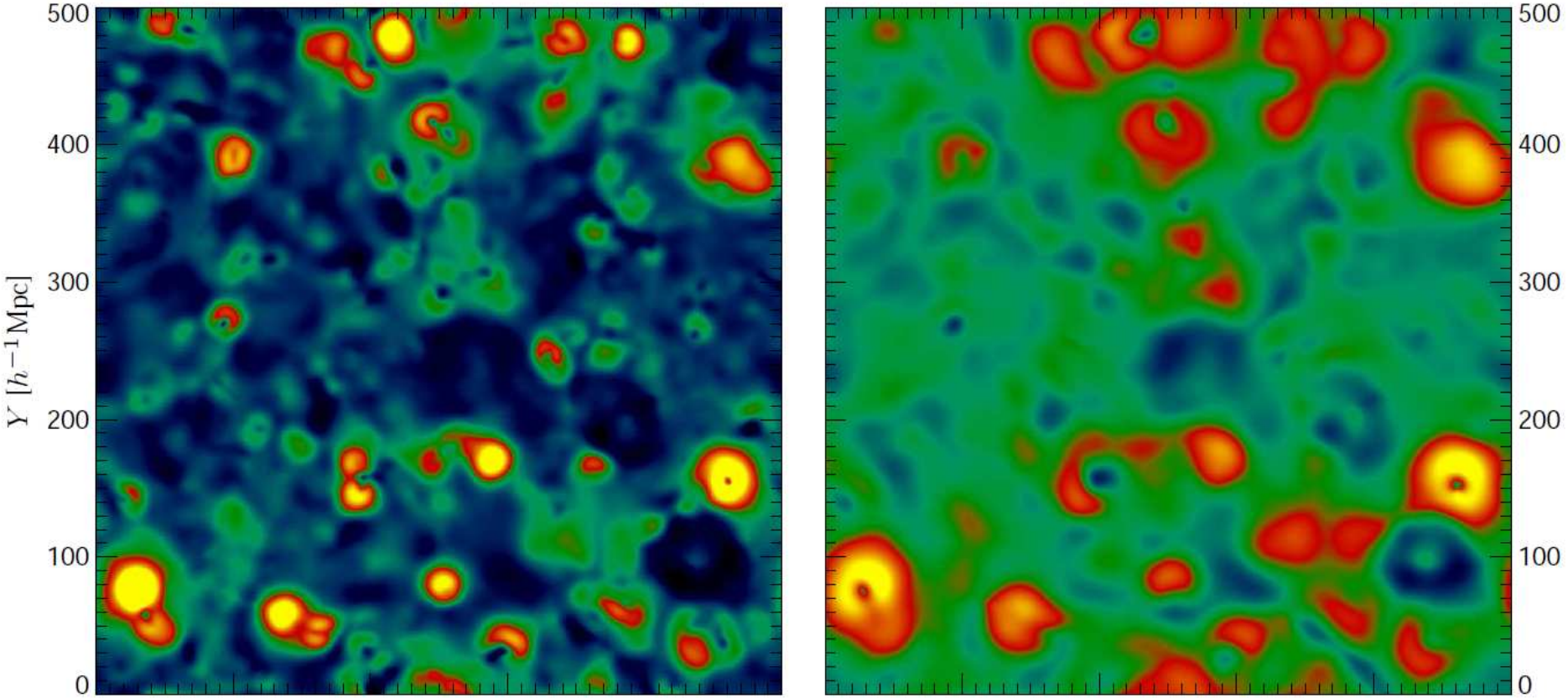


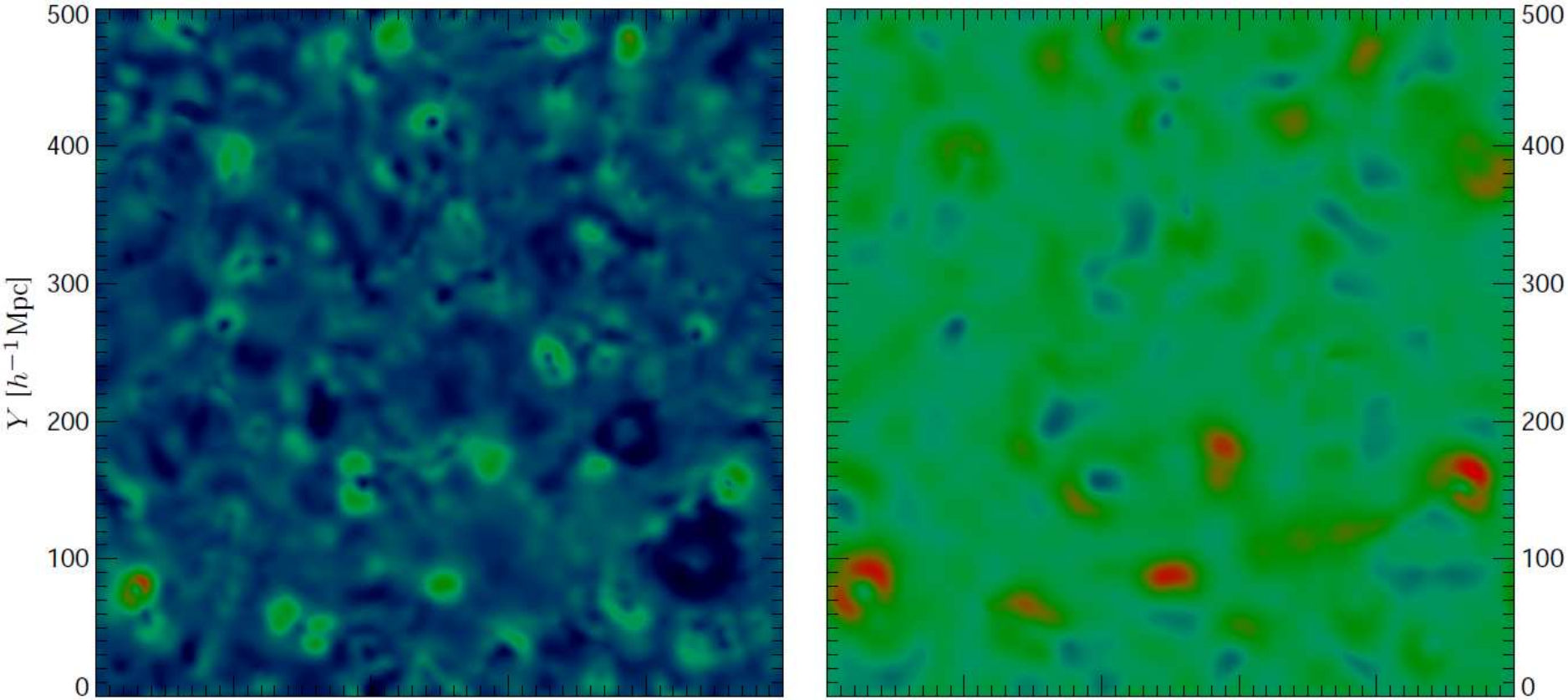
see also MAK: Mohayee et al 2005; Lavaux et al 2008

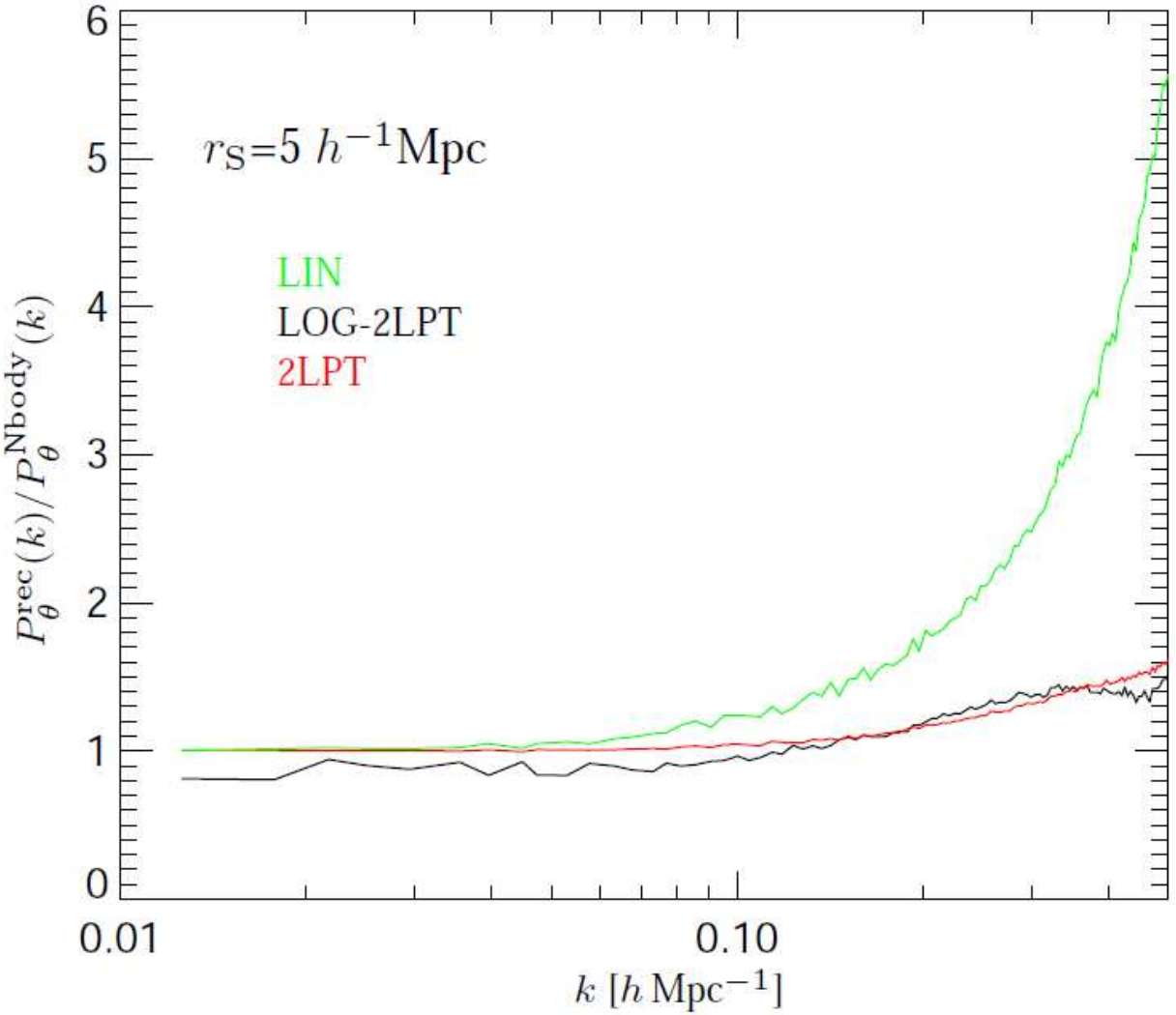

0
5
10
15
0
2
4
6
15
10
5
0
6
4
2
0
$\theta^{\rm rec}_{\rm LIN}$
$r_{\rm S}$=5 h^{-1}Mpc
LIN
$r_{\rm S}$=10 h^{-1}Mpc
LIN

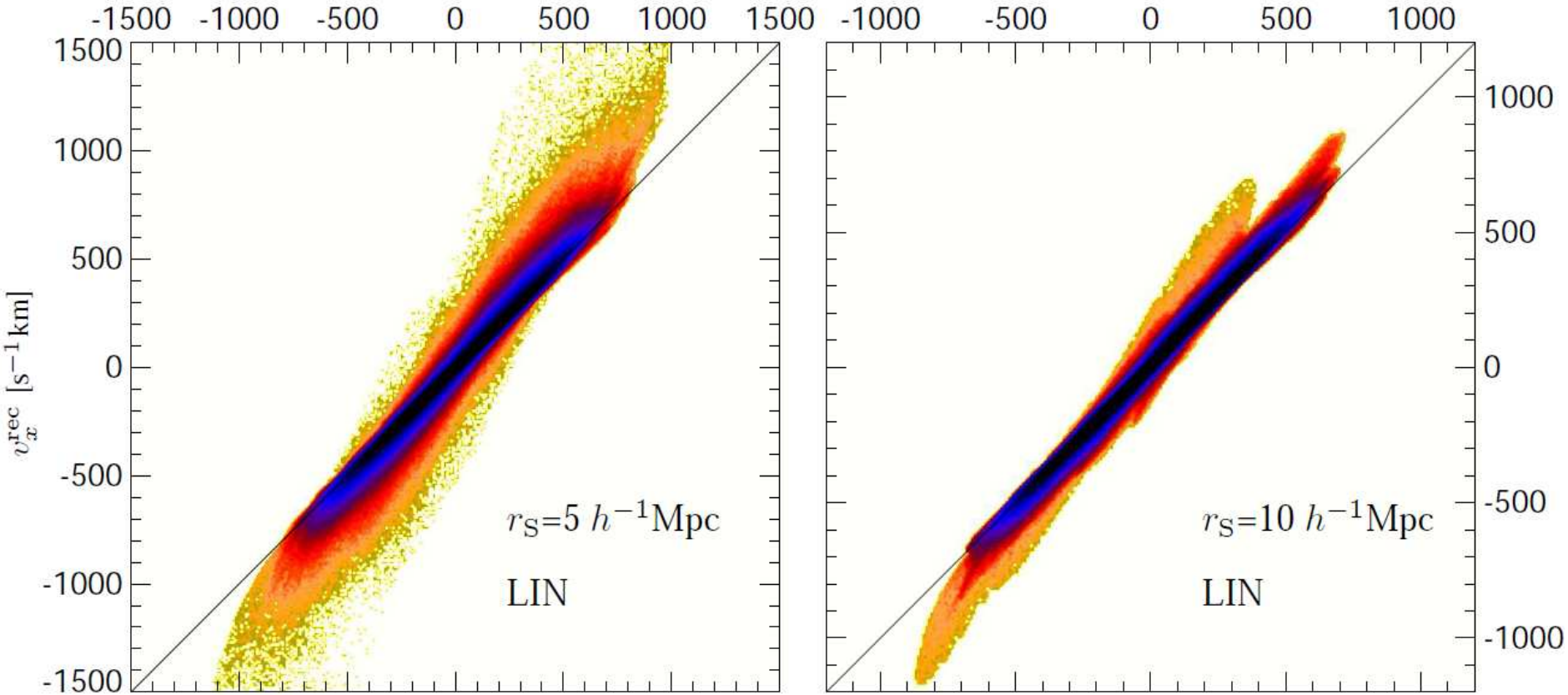

15
10
5
0
$\theta^{\rm rec}$
$r_{\rm S}$=5 h^{-1}Mpc
LOG-2LPT
6
4
2
0
$r_{\rm S}$=10 h^{-1}Mpc
LOG-2LPT

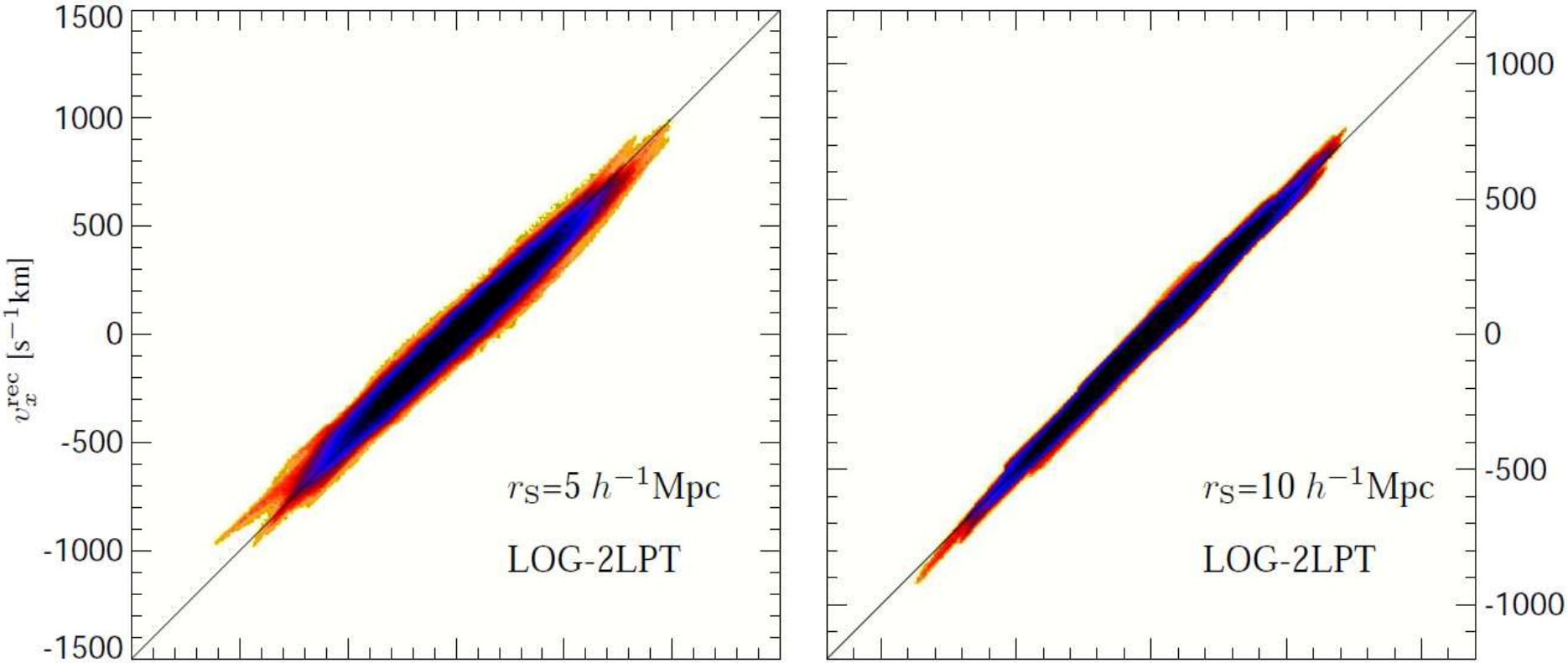

15
10
5
0
$\theta^{\rm rec}$
$r_{\rm S}$=5 h^{-1}Mpc
2LPT
6
4
2
0
$r_{\rm S}$=10 h^{-1}Mpc
2LPT

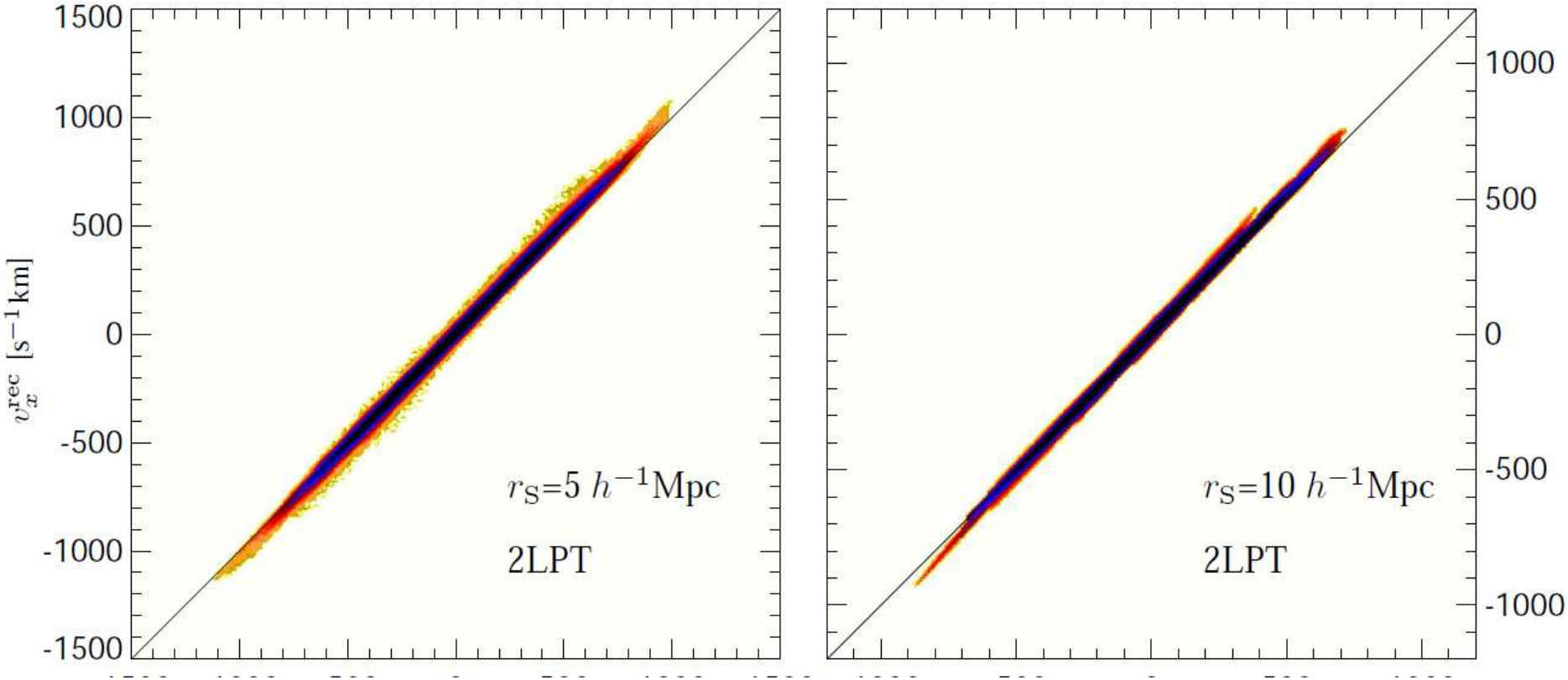

500
400
300
200
100
0
$Y\ [h^{-1}\mathrm{Mpc}]$
500
400
300
200
100
0

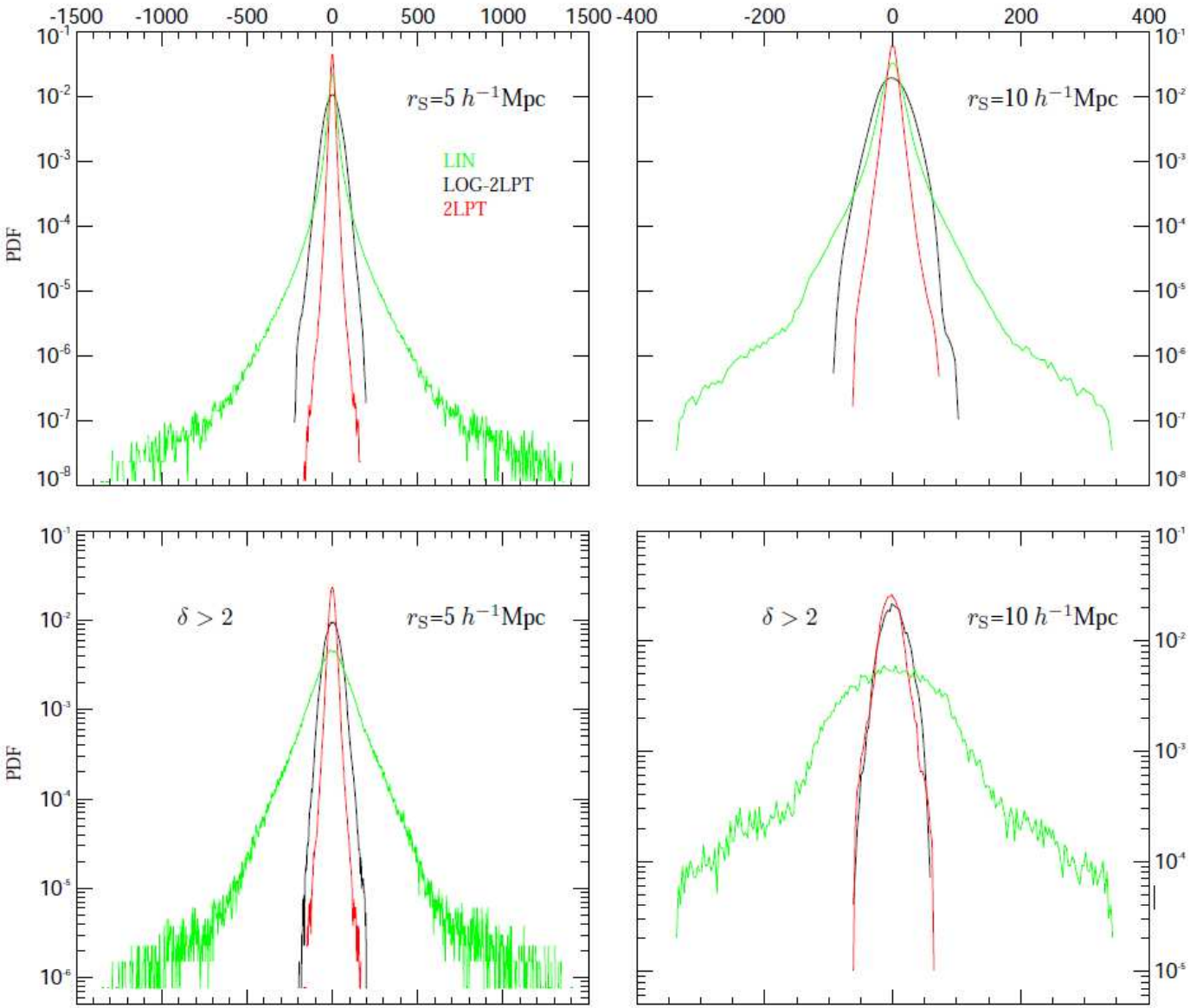

500
400
300
200
100
0
$Y\ [h^{-1}\mathrm{Mpc}]$
500
400
300
200
100
0


r_S=5 h^{-1}Mpc
LIN
LOG-2LPT
2LPT
$P_\theta^{\rm rec}(k)/P_\theta^{\rm Nbody}(k)$
k [h Mpc^{-1}]
0
1
2
3
4
5
6
0.01
0.10


-1500
-1000
-500
0
500
1000
1500
$v_x^{\rm rec}$ [s^{-1}km]
$r_{\rm S}$=5 h^{-1}Mpc
LIN
$r_{\rm S}$=10 h^{-1}Mpc
LIN


1500
1000
500
0
-500
-1000
-1500
$v_x^{\rm rec}$ [s^{-1}km]
$r_{\rm S}$=5 h^{-1}Mpc
LOG-2LPT
1000
500
0
-500
-1000
$r_{\rm S}$=10 h^{-1}Mpc
LOG-2LPT

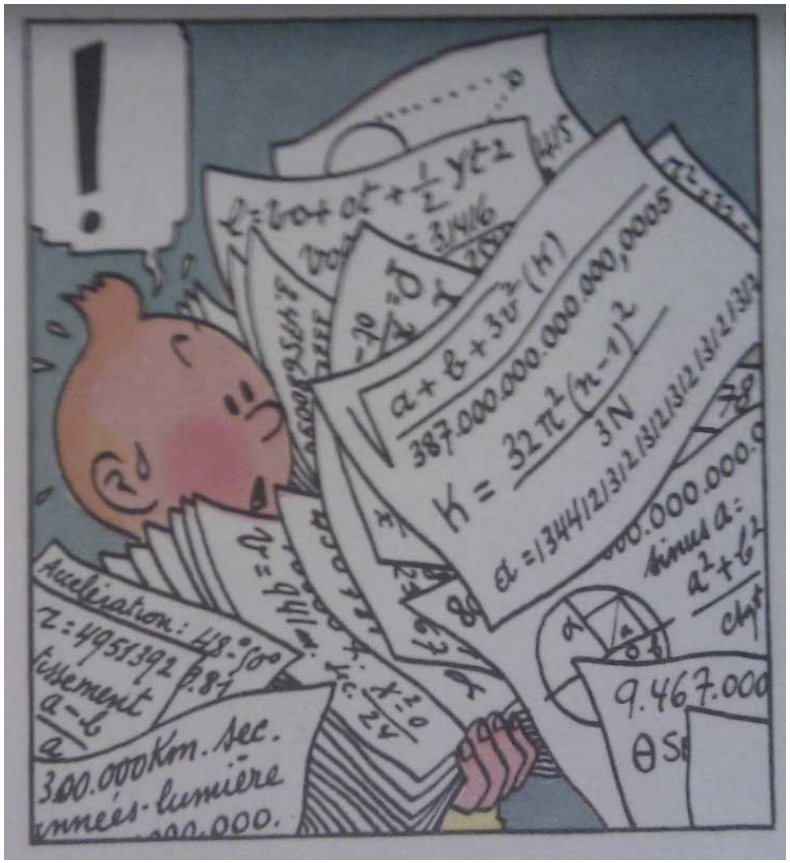

1500
1000
500
0
-500
-1000
-1500
$v_x^{\rm rec}$ [s^{-1}km]
$r_{\rm S}$=5 h^{-1}Mpc
2LPT
1000
500
0
-500
-1000
$r_{\rm S}$=10 h^{-1}Mpc
2LPT


r_S=5 h^{-1}Mpc
LIN
LOG-2LPT
2LPT
r_S=10 h^{-1}Mpc
$\delta > 2$
r_S=5 h^{-1}Mpc
$\delta > 2$
r_S=10 h^{-1}Mpc
PDF
PDF

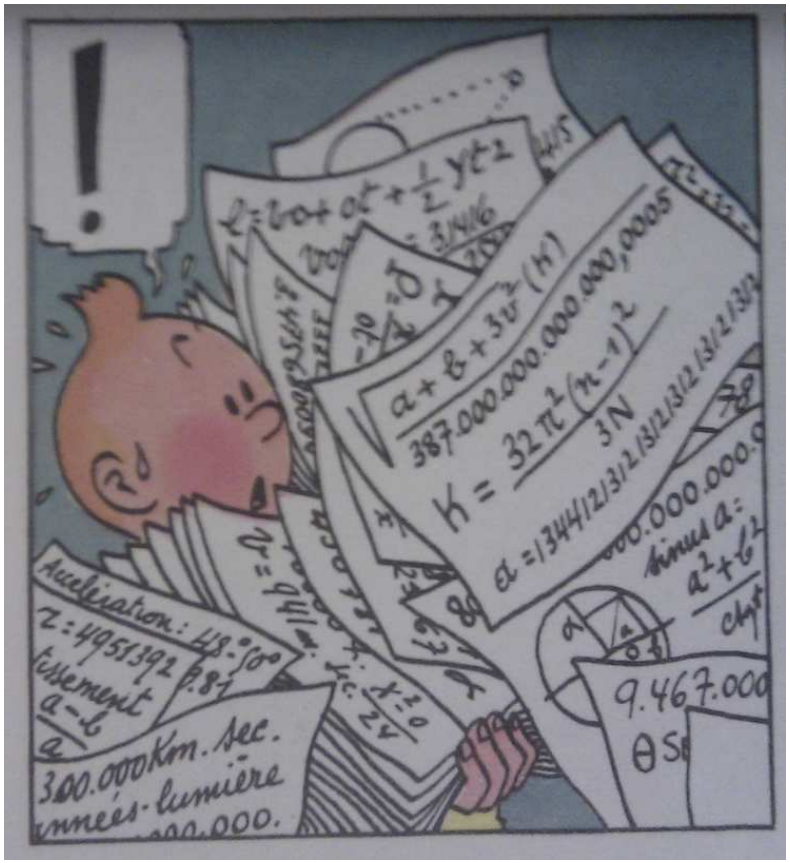
Beyond the Lognormal Poisson model?

$$
\begin{aligned}
&P(\delta_{\rm M}|\mathbf{N},\mathbf{S},...) \\
&\quad\propto \left\{\prod_l \frac{1}{1+\delta_{{\rm M}l}}\exp\left(-\frac{1}{2}\sum_{ij}\left(\ln\left(1+\delta_{{\rm M}i}\right)-\mu_i\right)S_{ij}^{-1}\left(\ln\left(1+\delta_{{\rm M}j}\right)-\mu_j\right)\right)\right\} \\
&\quad\times\left\{\left[1+\frac{1}{3!}\sum_{i'j'k'}\left\langle\Phi_{i'}\Phi_{j'}\Phi_{k'}\right\rangle_{\rm c}\sum_{ijk}S_{ii'}^{-1/2}S_{jj'}^{-1/2}S_{kk'}^{-1/2}h_{ijk}(\mathbf{S}^{-1/2}\mathbf{\Phi})\right.\right. \\
&\quad\left.\left.+\frac{1}{4!}\sum_{i'j'k'l'}\left\langle\Phi_{i'}\Phi_{j'}\Phi_{k'}\Phi_{l'}\right\rangle_{\rm c}\sum_{ijkl}S_{ii'}^{-1/2}S_{jj'}^{-1/2}S_{kk'}^{-1/2}S_{ll'}^{-1/2}h_{ijkl}(\mathbf{S}^{-1/2}\mathbf{\Phi})+\ldots\right]\right\} \\
&\quad\times\left\{\prod_k\frac{\sum_j(\delta^{\rm K}_{k,j}-Q_{k,j})w_j\bar{N}(1+B(\delta_{\rm M})_j)}{N^{\rm g}_k!}\right. \\
&\quad\times\left(\sum_l(\delta^{\rm K}_{k,l}-Q_{k,l})w_l\bar{N}(1+B(\delta_{\rm M})_l)+\sum_m Q_{k,m}N^{\rm g}_m\right)^{N^{\rm g}_k-1} \\
&\quad\left.\times\exp\left(-\sum_n(\delta^{\rm K}_{k,n}-Q_{k,n})w_n\bar{N}(1+B(\delta_{\rm M})_n)-\sum_o Q_{k,o}N^{\rm g}_o\right)\right\}, \qquad (3)
\end{aligned}
$$

Juskiewick et al 1995; Colombi et al 1995; Saslaw 1984; FK 2010,11



Let us go back to the original problem.



Let us go back to the original problem.

Where does the matter come from which formed the structures we observe today?

$$\delta(\{\mathbf{q}\}) \curvearrowleft P(\delta(\{\mathbf{q}\})|\{\mathbf{x}_{\rm G}\})\,, \tag{4}$$

Let us model the linear Gaussian initial field in the prior and encode the nonlinear evolution in the likelihood
(FK, Gallerani & Ferrara 2011; FK 2011)

KIGEN-code (KInetic GENeration of the initial conditions, jap. origin)

FK submitted

$$\delta(\{\mathbf{q}\}) \quad \curvearrowleft \quad P(\delta(\{\mathbf{q}\})|\{\mathbf{q}\}) \tag{5}$$

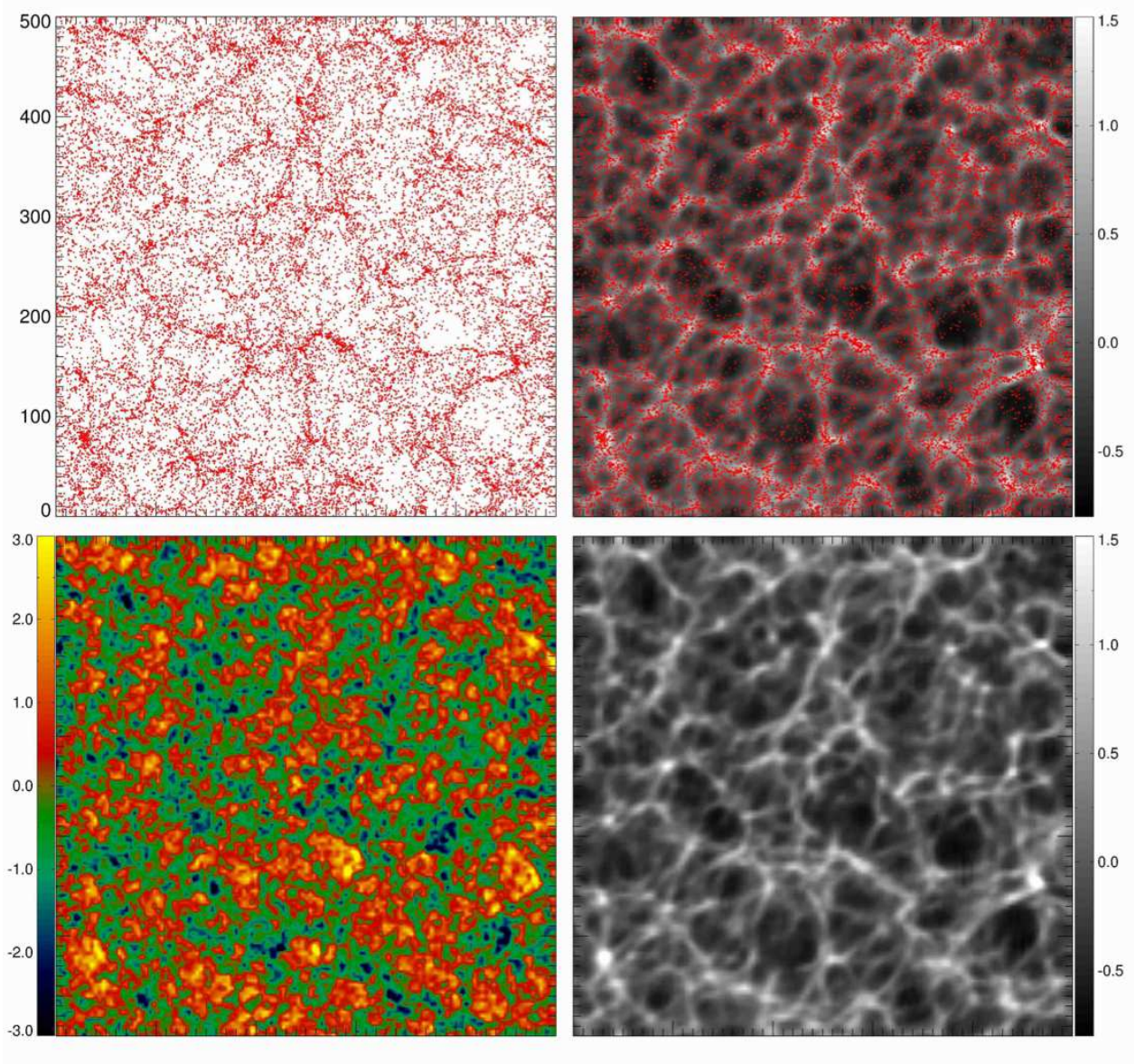
$$\{\mathbf{q}\} \quad \curvearrowleft \quad P(\{\mathbf{q}\}|\{\mathbf{x}_{\mathrm{G}}\}, \delta(\{\mathbf{q}\}))\,. \tag{6}$$

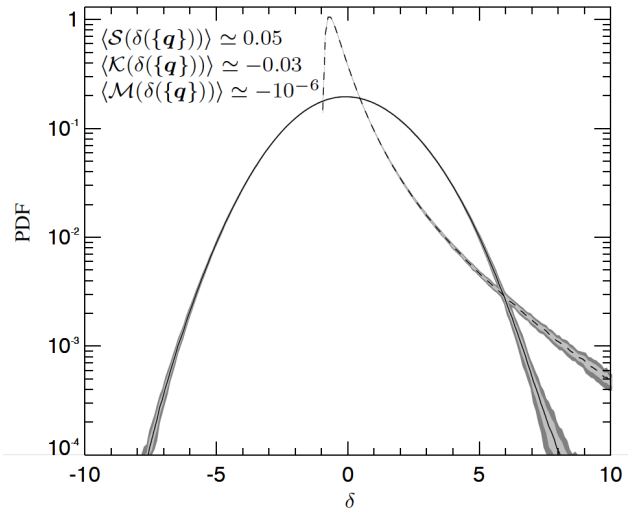
1) constrained realisation

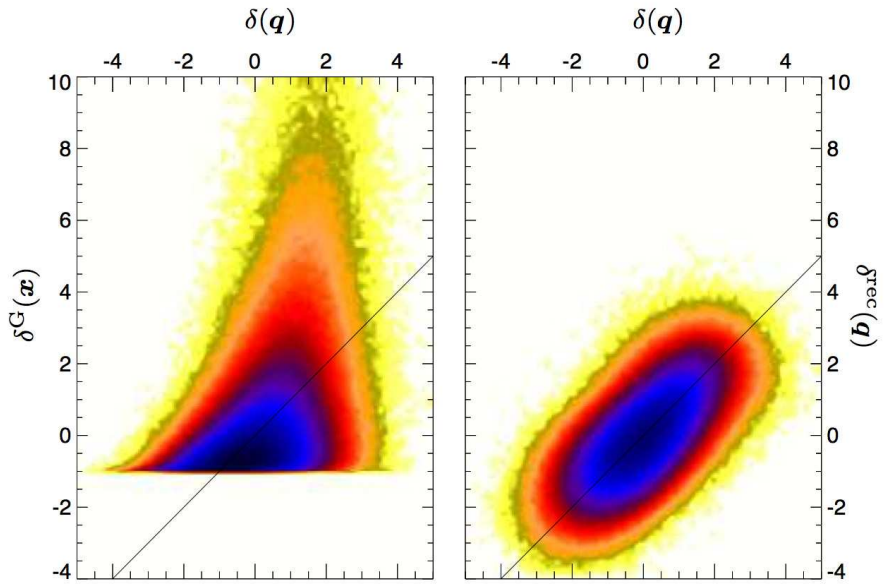
Bertschinger 1987; Hoffman & Ribak 1991; van de Weygaert & Bertschinger 1996; Jasche & FK 2010

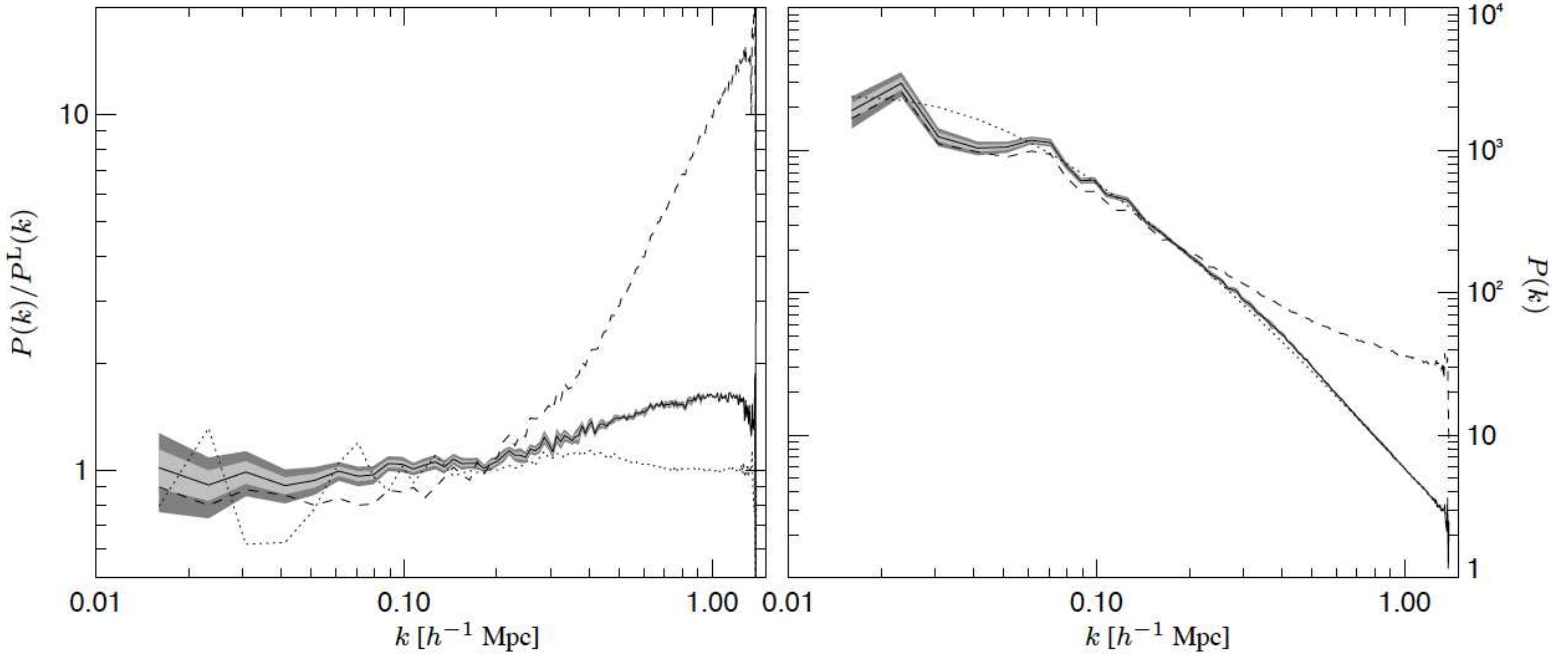
2) constrained simulation

(see also Jasche & Wandelt submitted)


500
400
300
200
100
0
1.5
1.0
0.5
0.0
-0.5
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1.5
1.0
0.5
0.0
-0.5


$\langle \mathcal{S}(\delta(\{\boldsymbol{q}\}))\rangle \simeq 0.05$
$\langle \mathcal{K}(\delta(\{\boldsymbol{q}\}))\rangle \simeq -0.03$
$\langle \mathcal{M}(\delta(\{\boldsymbol{q}\}))\rangle \simeq -10^{-6}$
PDF
δ

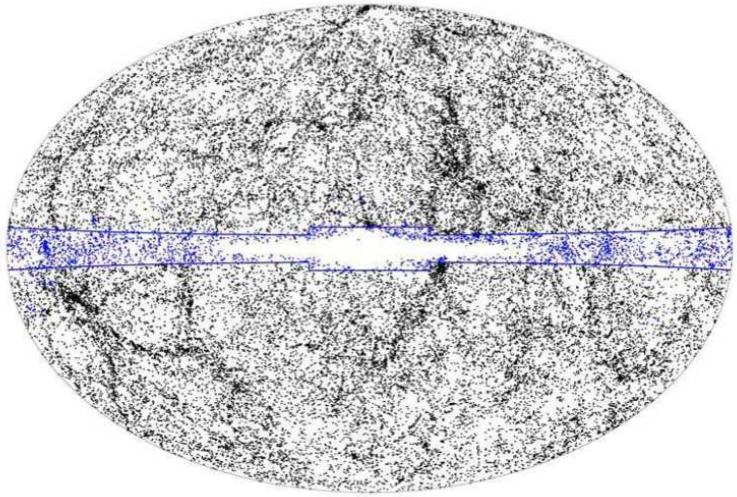

$\delta(\boldsymbol{q})$
$\delta(\boldsymbol{q})$
$\delta^{\rm G}(\boldsymbol{x})$
$\delta_{\rm rec}(\boldsymbol{q})$


$P(k)/P^{\rm L}(k)$
$k\ [h^{-1}\ {\rm Mpc}]$
$P(k)$
$k\ [h^{-1}\ {\rm Mpc}]$


OH!
?

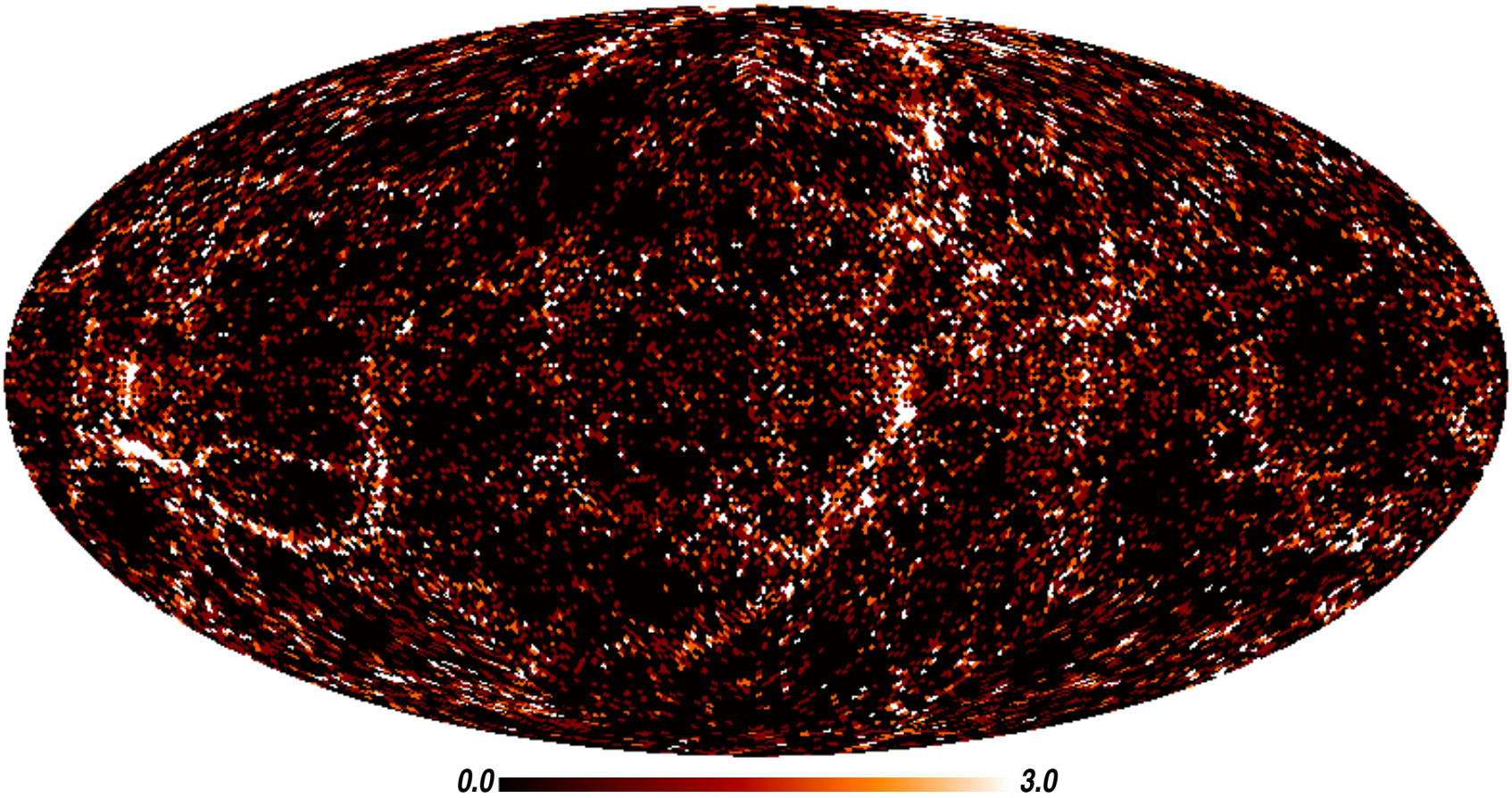
Application to the 2MRS Huchra et al 2011

FK, P. Erdogdu, S. E. Nuza, A. Khalatyan, R. E. Angulo, Y. Hoffman & S. Gottlöber submitted

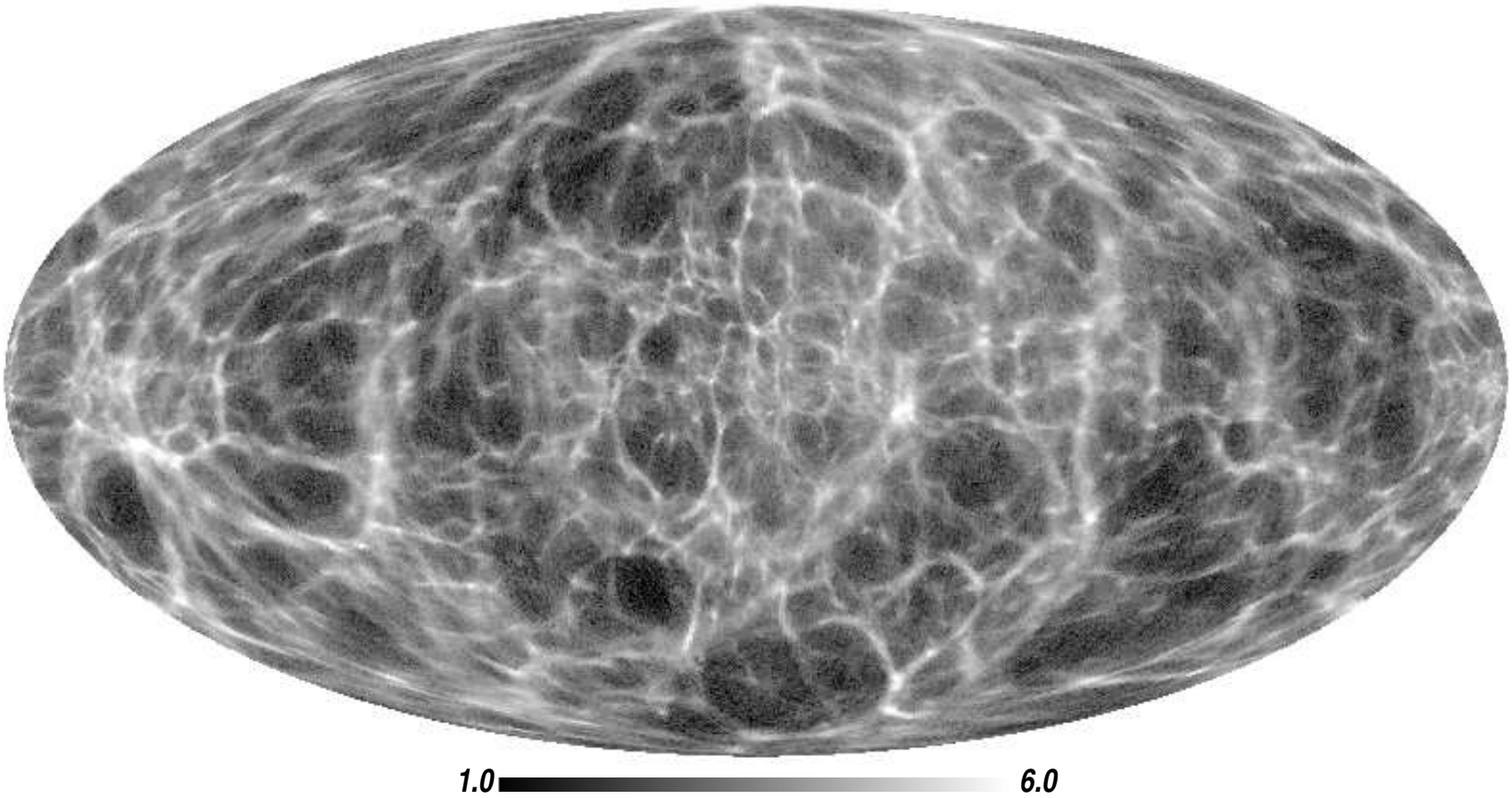


44,599 2MASS galaxies with $K_s <= 11.75$ mag and $|b| >= 5^o$ ($>= 8^o$ towards the Galactic bulge)
redshift catalog that is 97.6% complete to well-defined limits and covers 91% of the sky
Pirin Erdogdu augmented catalog following Lahav et al 1992
fog fof compression following Tegmark et al 2004
coherent RSD 2LPT $z = q + \Psi + v_r$

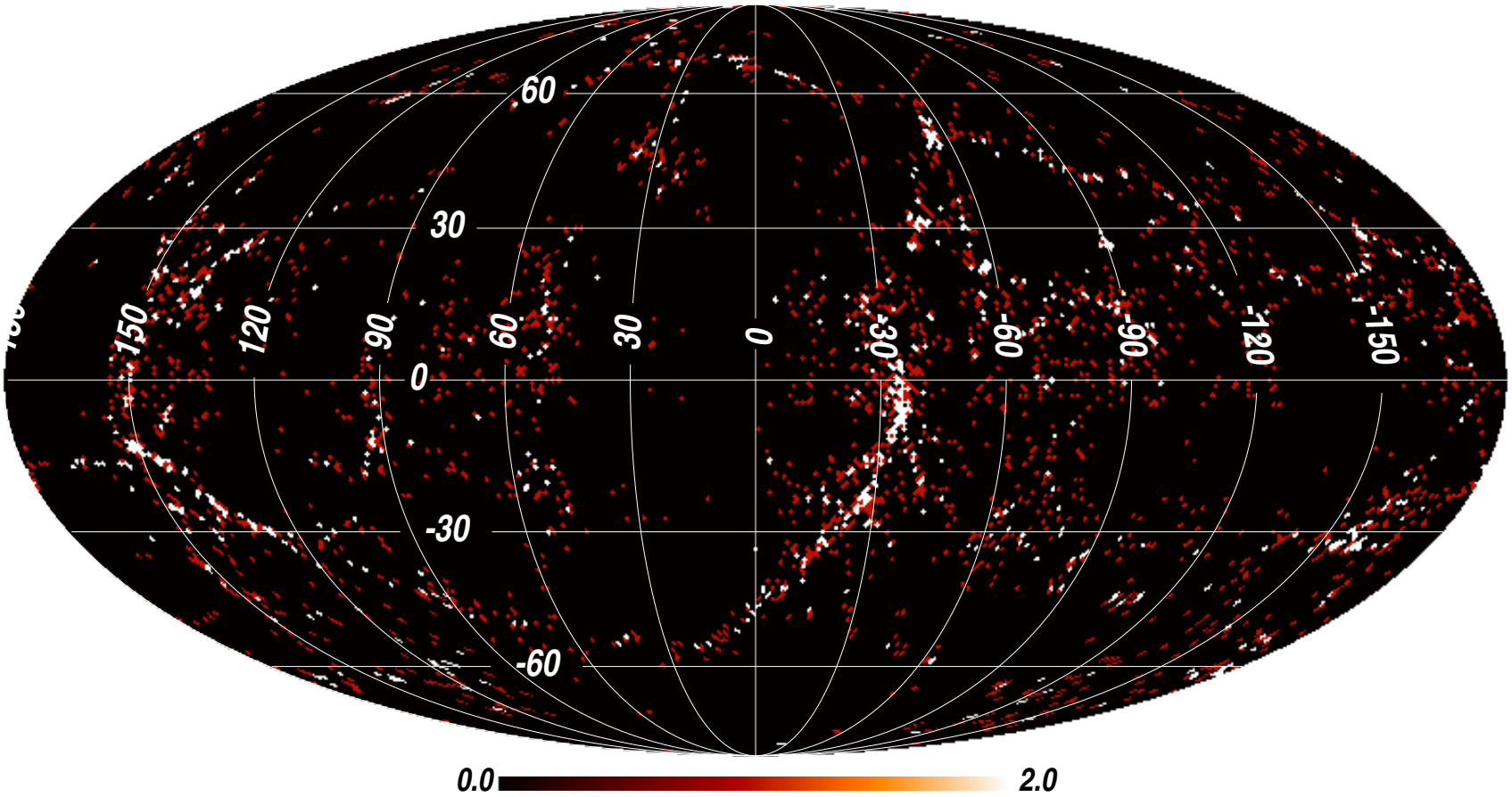
0-80 h^{-1} Mpc



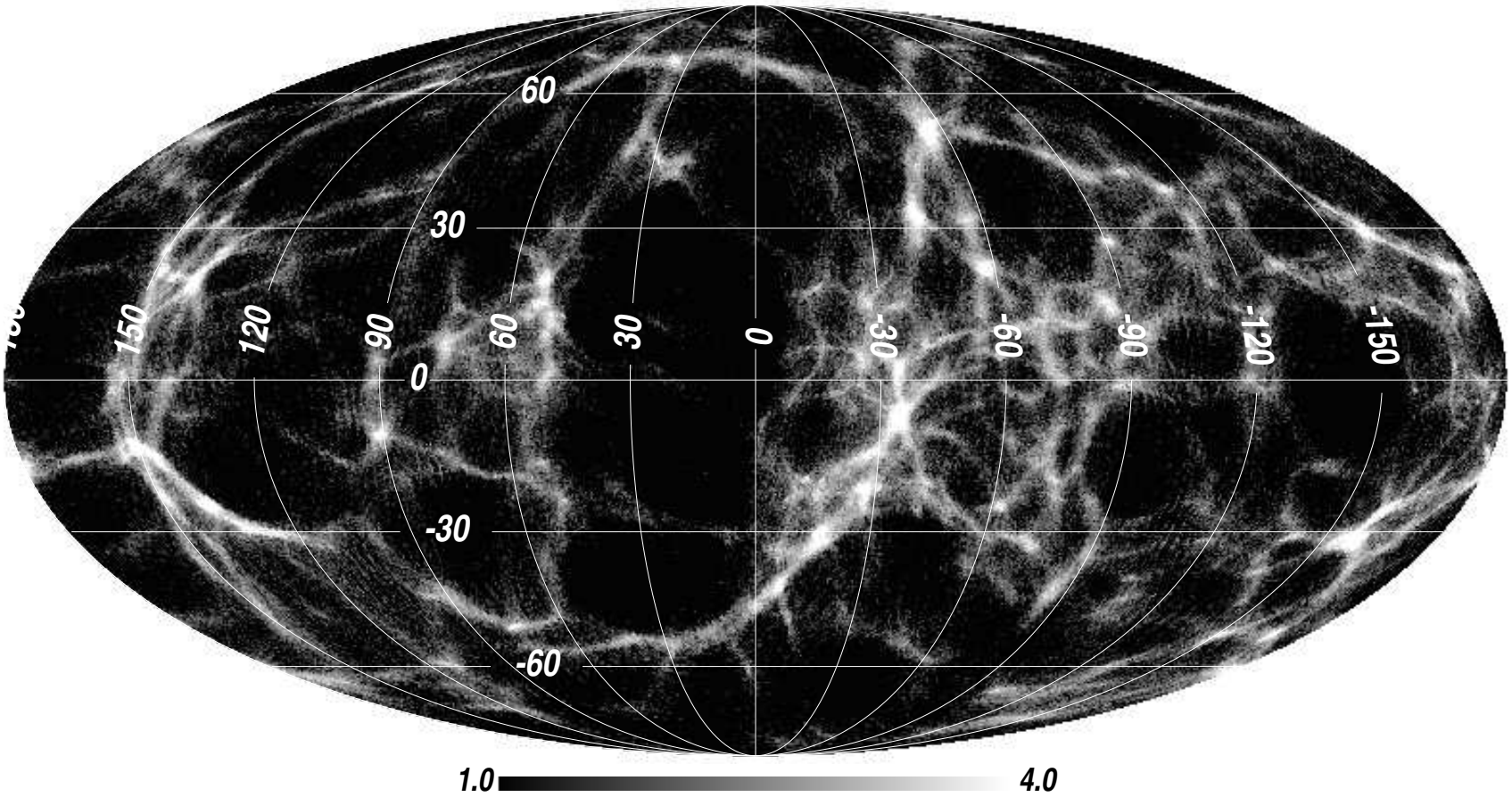
0-80 h^{-1} Mpc



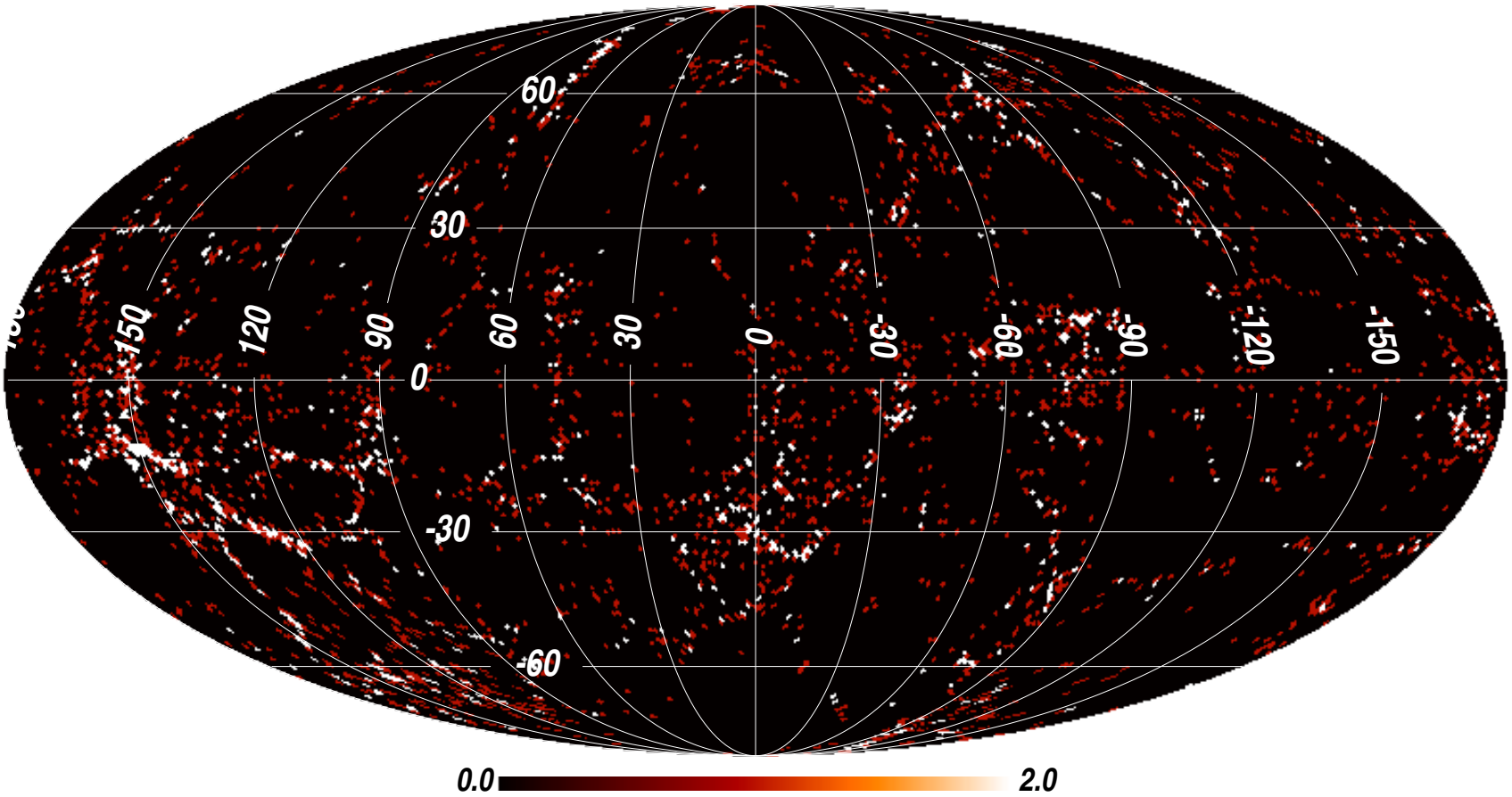
40-50 h^{-1} Mpc



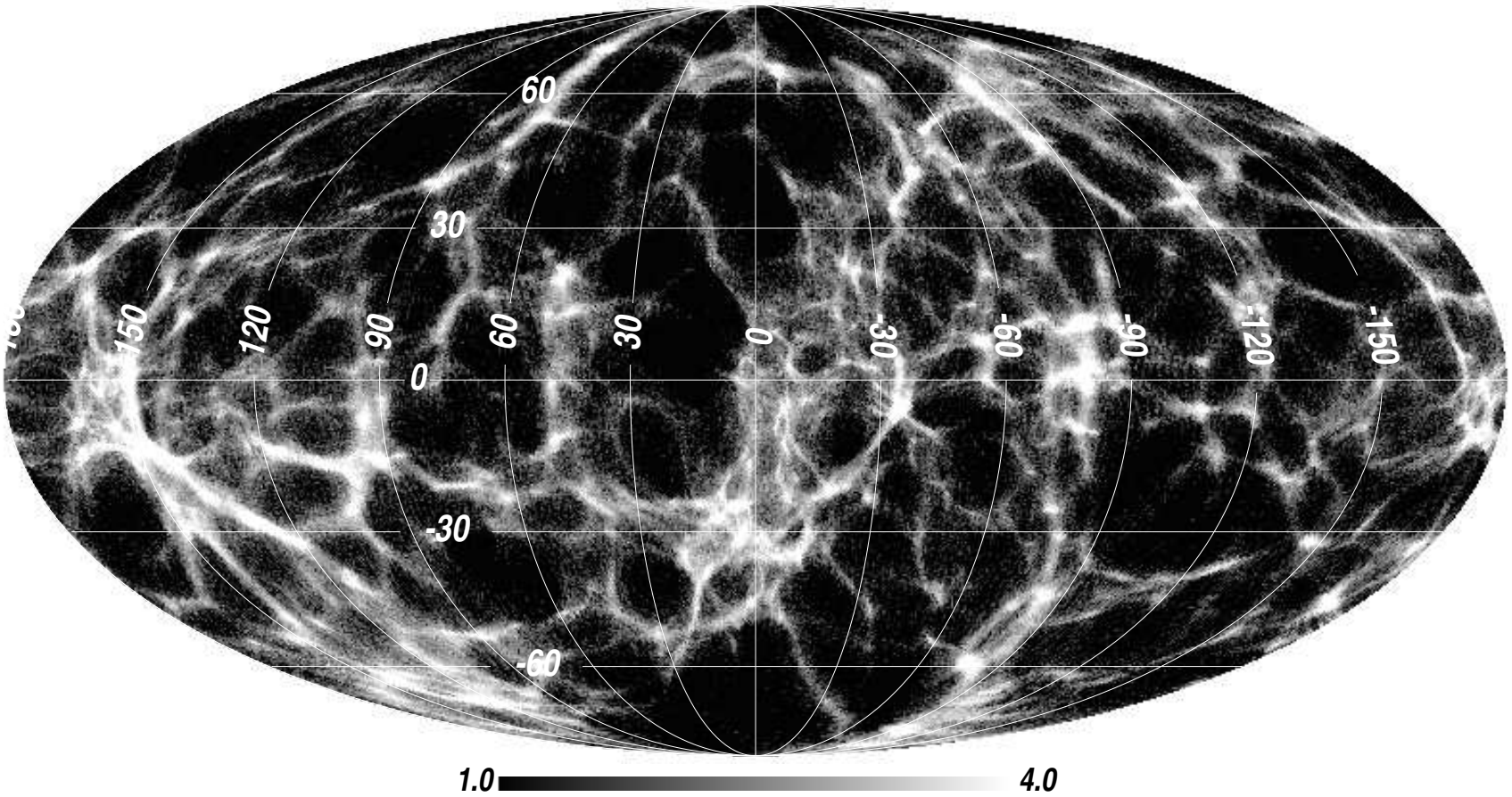
40-50 h^{-1} Mpc



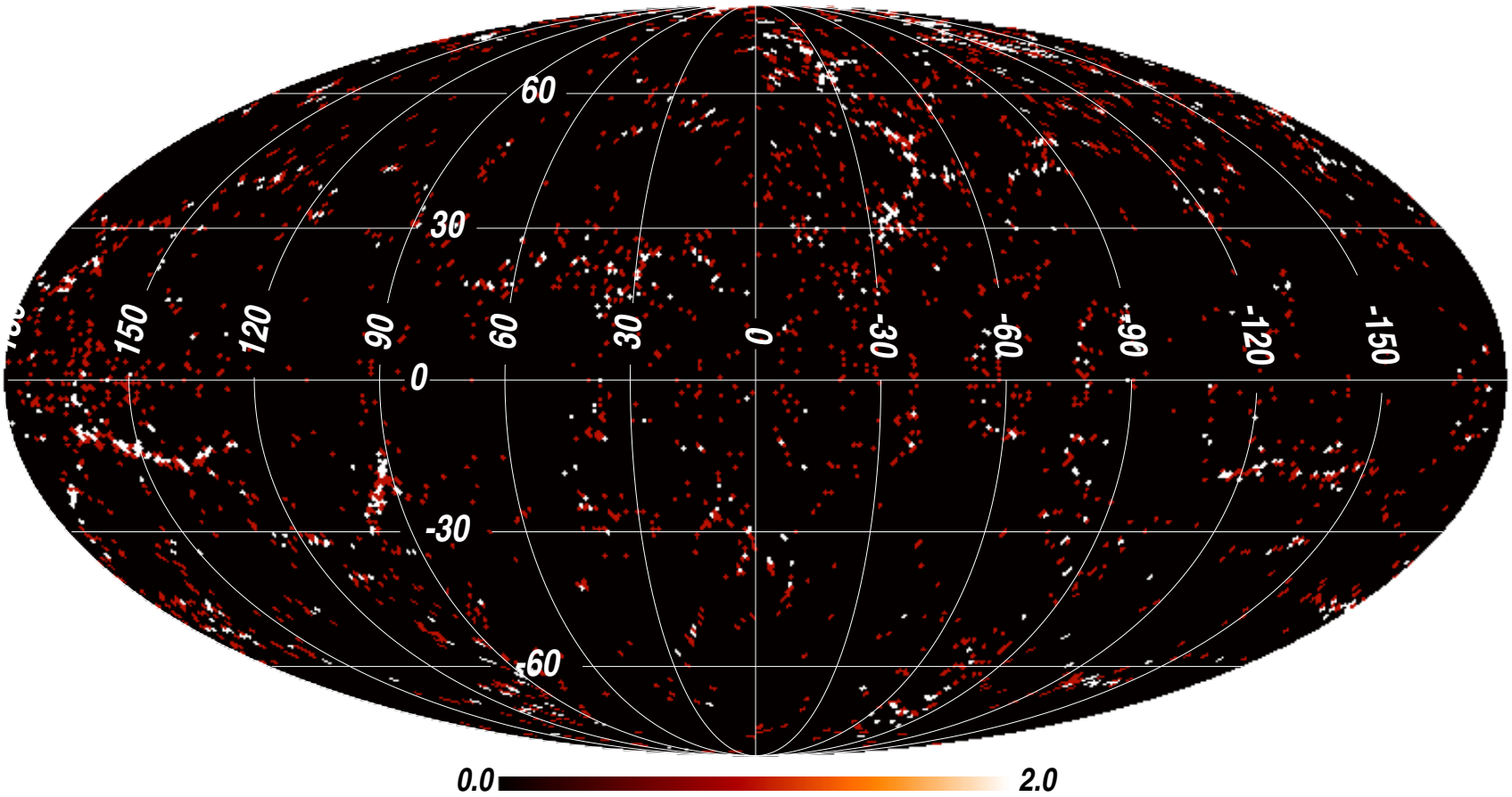
50-60 h^{-1} Mpc



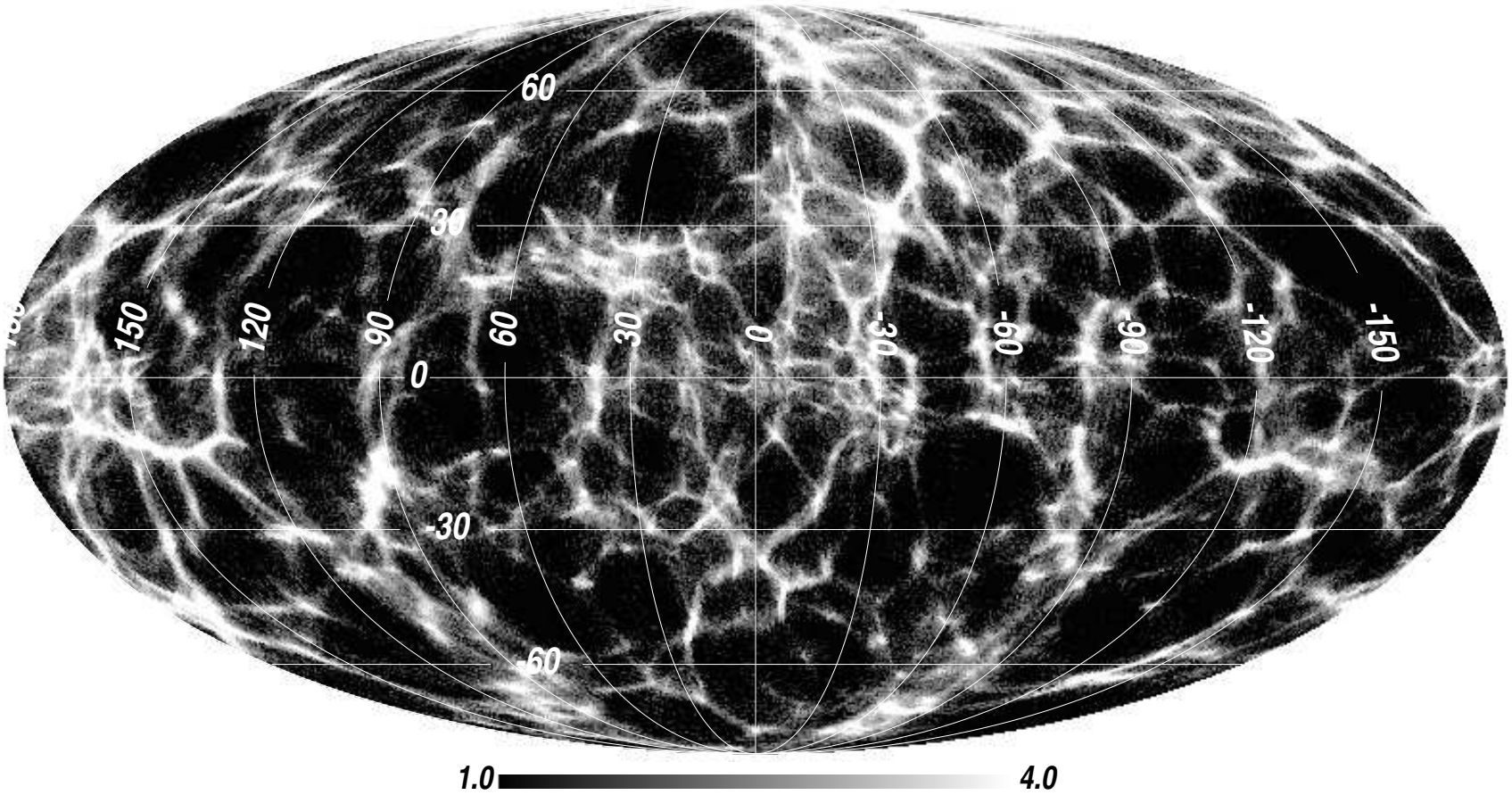
50-60 h^{-1} Mpc

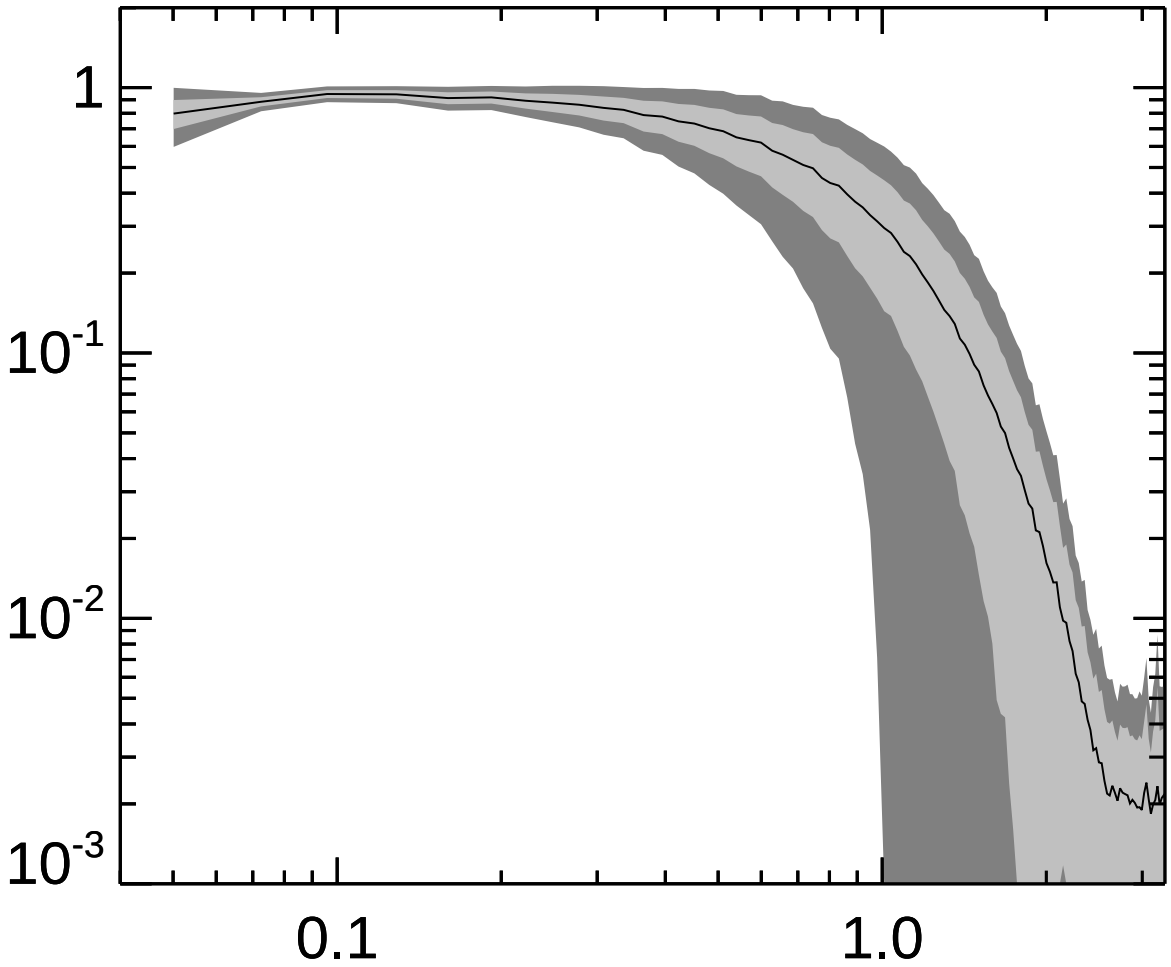


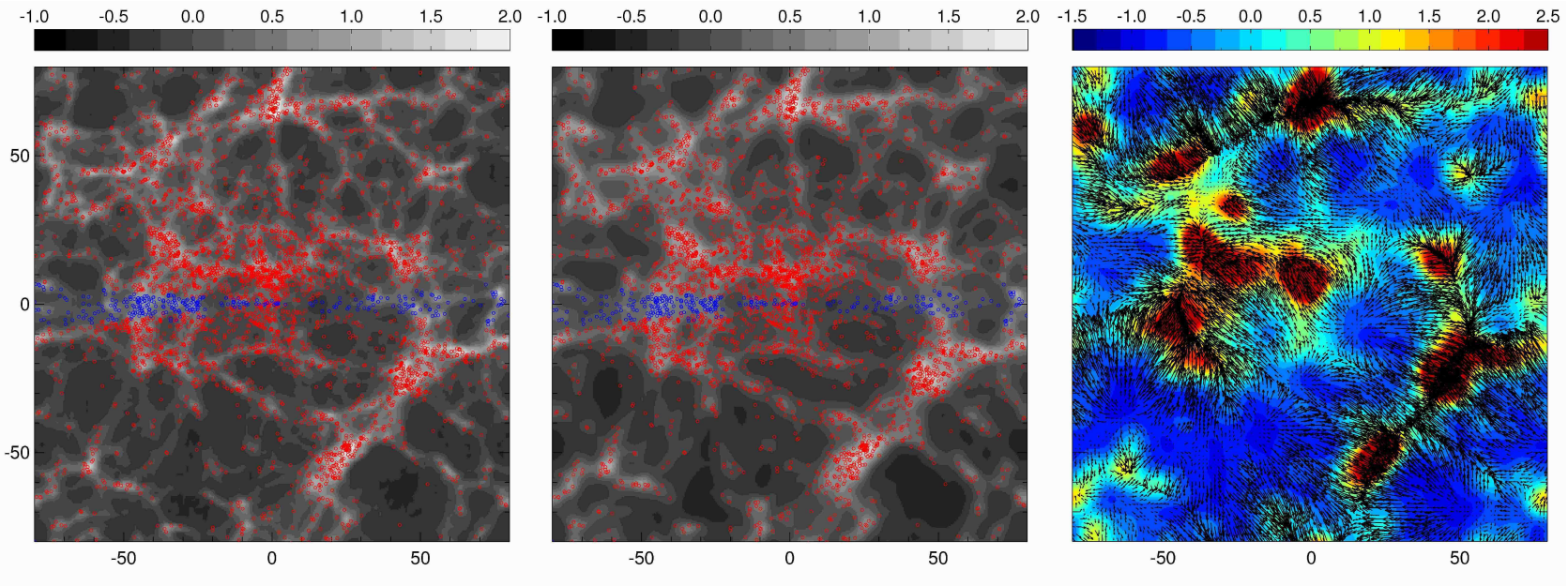
60-70 h^{-1} Mpc

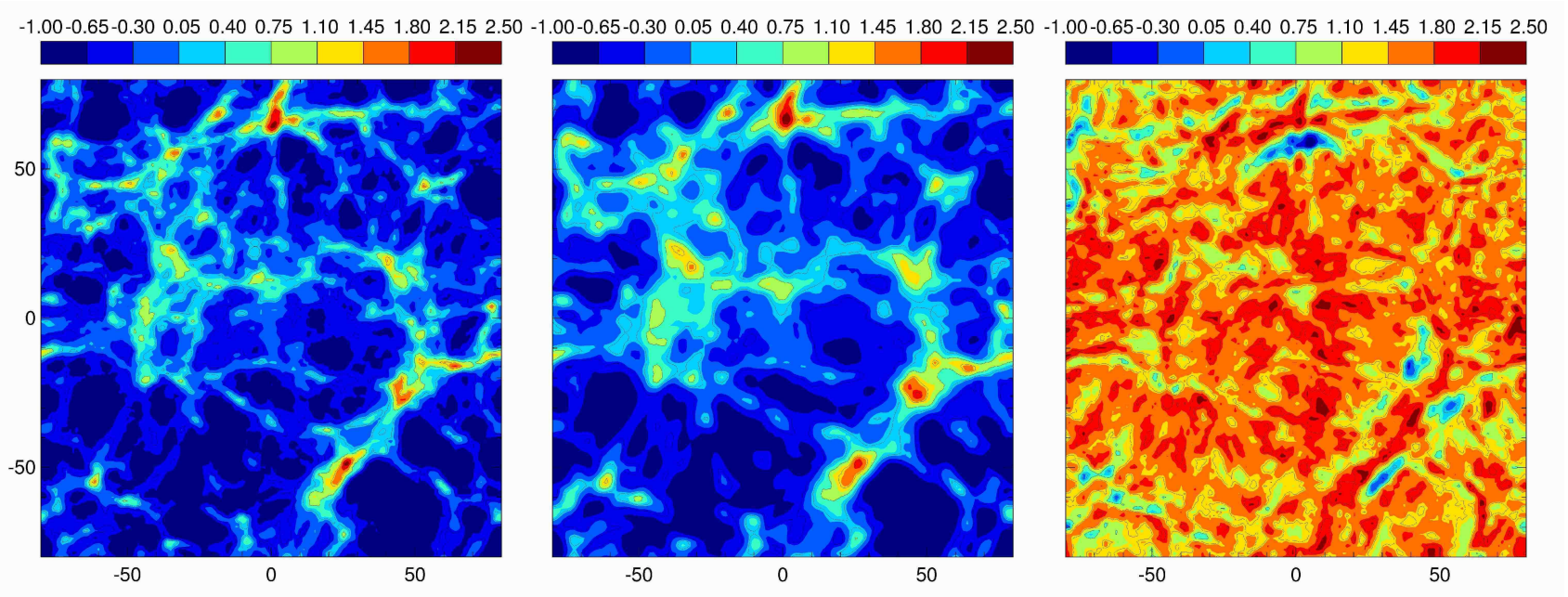


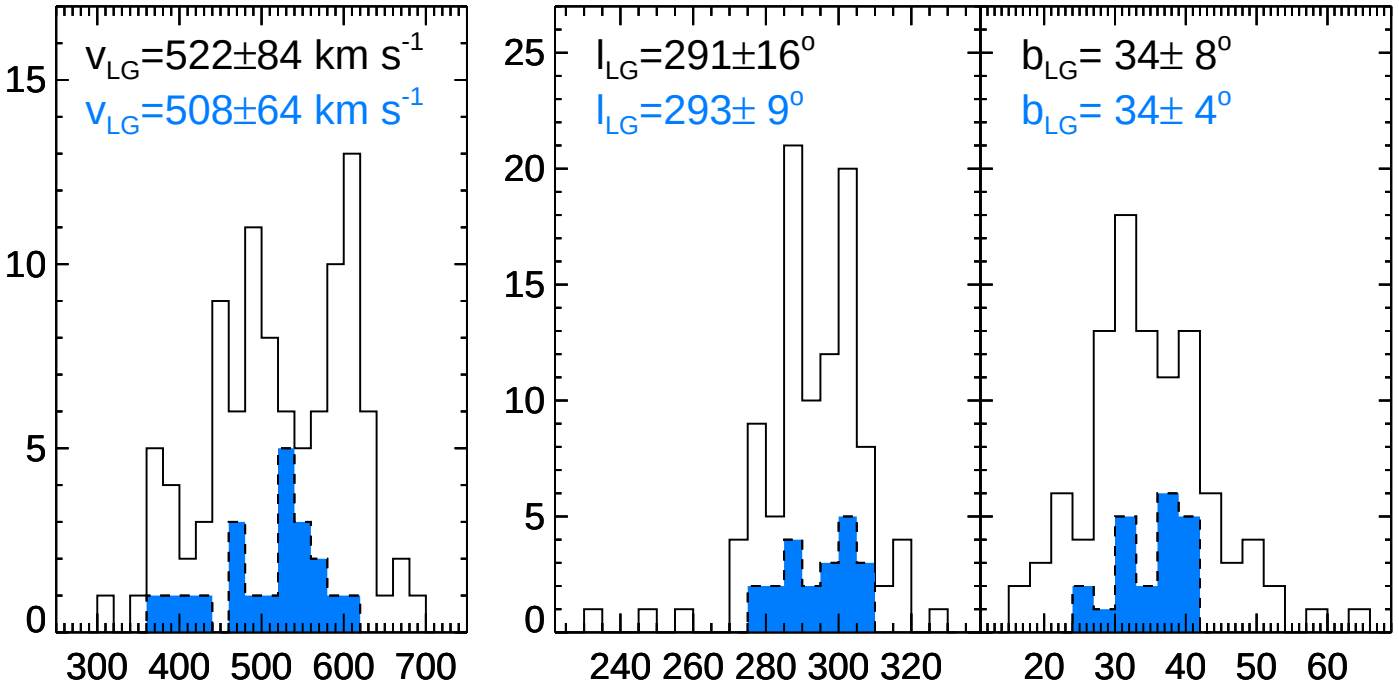
60-70 h^{-1} Mpc




1
10^{-1}
10^{-2}
10^{-3}
0.1
1.0


-1.0 -0.5 0.0 0.5 1.0 1.5 2.0
-1.0 -0.5 0.0 0.5 1.0 1.5 2.0
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
50
0
-50
-50 0 50
-50 0 50
-50 0 50


-1.00 -0.65 -0.30 0.05 0.40 0.75 1.10 1.45 1.80 2.15 2.50
-1.00 -0.65 -0.30 0.05 0.40 0.75 1.10 1.45 1.80 2.15 2.50
-1.00 -0.65 -0.30 0.05 0.40 0.75 1.10 1.45 1.80 2.15 2.50
50
0
-50
-50
0
50
-50
0
50
-50
0
50


v_{LG}=522±84 km s^{-1}
v_{LG}=508±64 km s^{-1}
l_{LG}=291±16^o
l_{LG}=293± 9^o
b_{LG}= 34± 8^o
b_{LG}= 34± 4^o
0
5
10
15
20
25
300 400 500 600 700
240 260 280 300 320
20 30 40 50 60

Constrained N-body simulation (S. Hess)

see Steffen Hess's talk!

Conclusions

- Reconstructions are necessary and usefull!
- Statistical analysis required.
- We have shown how to undo (mitigate) the effects of gravitation beyond the Zeldovich approximation.
- We have developed a new high order time-reversal machine
- We have tested higher order LPT to estimate peculiar motions from density fields
- Now we are going for the data sets to measure BAOs cosmological parameters, make constrained simulations, measure bias from velocty data ...