# Unveiling the Cosmic Web from galaxy redshift surveys

Leibniz Institute for Astrophysics in Potsdam

Francisco-Shu Kitaura

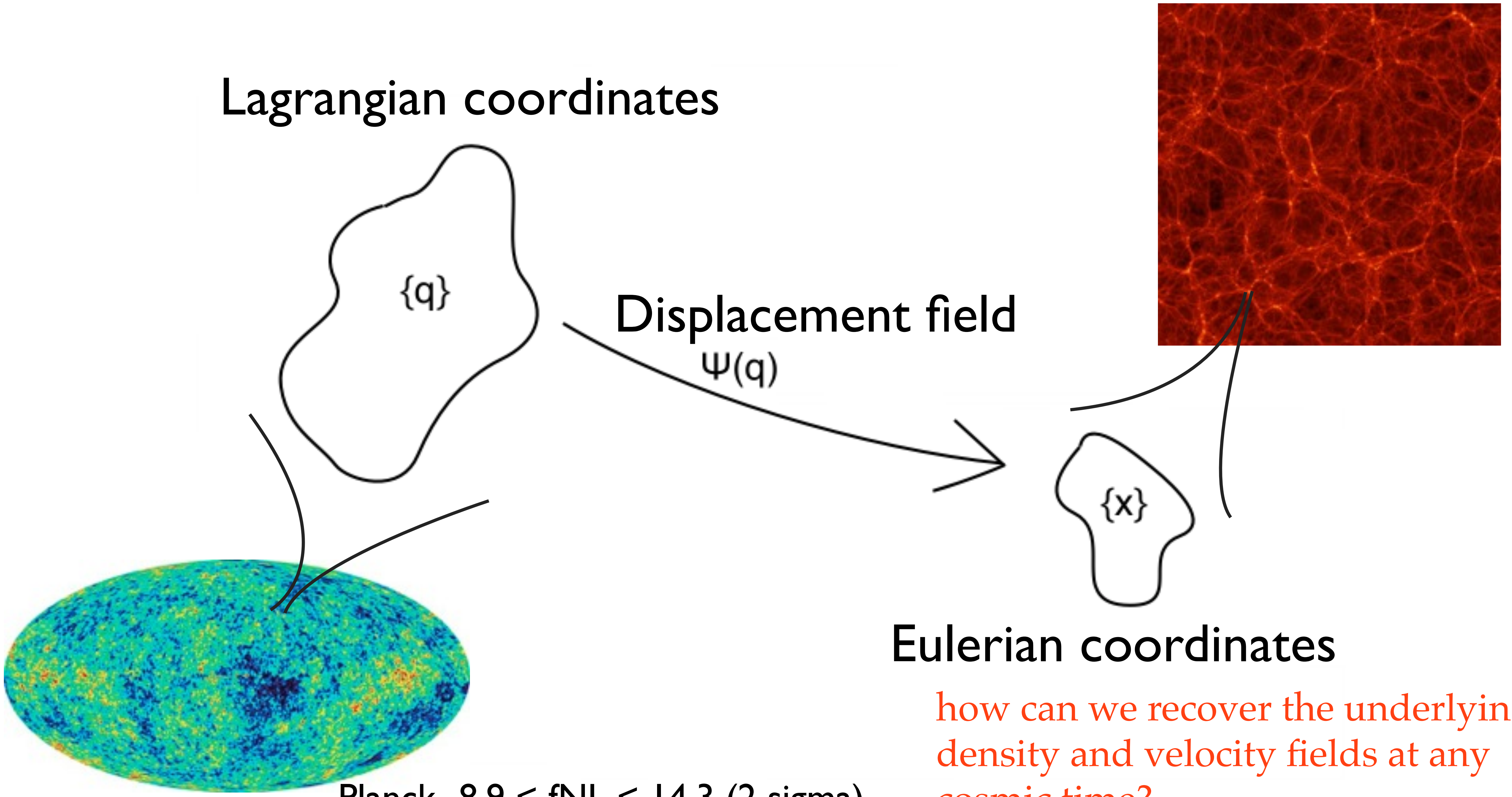
Karl-Schwarzschild fellow

Tallinn

IAU Symposium 308
The Zeldovich Universe

*June 26 2014*

# Standard cosmological paradigm



~13.7 billion years after the Big Bang

Lagrangian coordinates

Displacement field

Ψ(q)

Eulerian coordinates

how can we recover the underlying density and velocity fields at any cosmic time?

Planck -8.9 < fNL < 14.3 (2 sigma)

WMAP

*(Suyama+13)*

~300 000 years after the Big Bang

# By reconstructing the primordial fluctuations!

how can we undo gravity?

# Inverse approaches

# Time-reversal machines

- Linear Lagrangian perturbation theory: Zeldovich approximation

  *Nusser A. & Dekel A., 1992, ApJ, 391, 443*
  *Kolatt T., Dekel A., Ganon G., Willick J. A., 1996, ApJ, 458, 419*

  BAO reconstructions!

  *Eisenstein D. J., Seo H.-J., Sirko E., Spergel D. N., 2007, ApJ, 664, 675*
  *Padmanabhan N., Xu X., Eisenstein D. J. et al 2012, MNRAS*

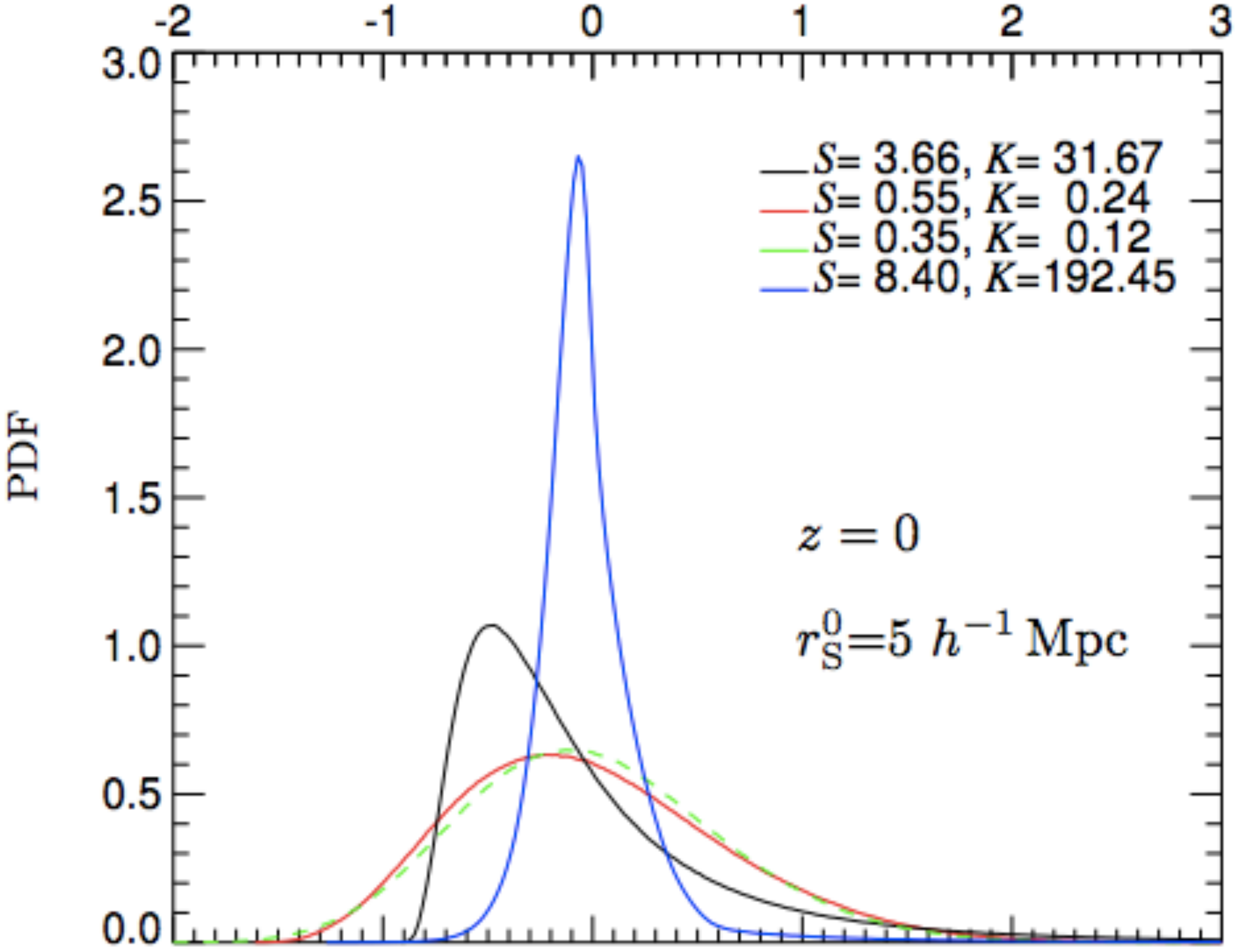
- Non-linear Lagrangian perturbation theory

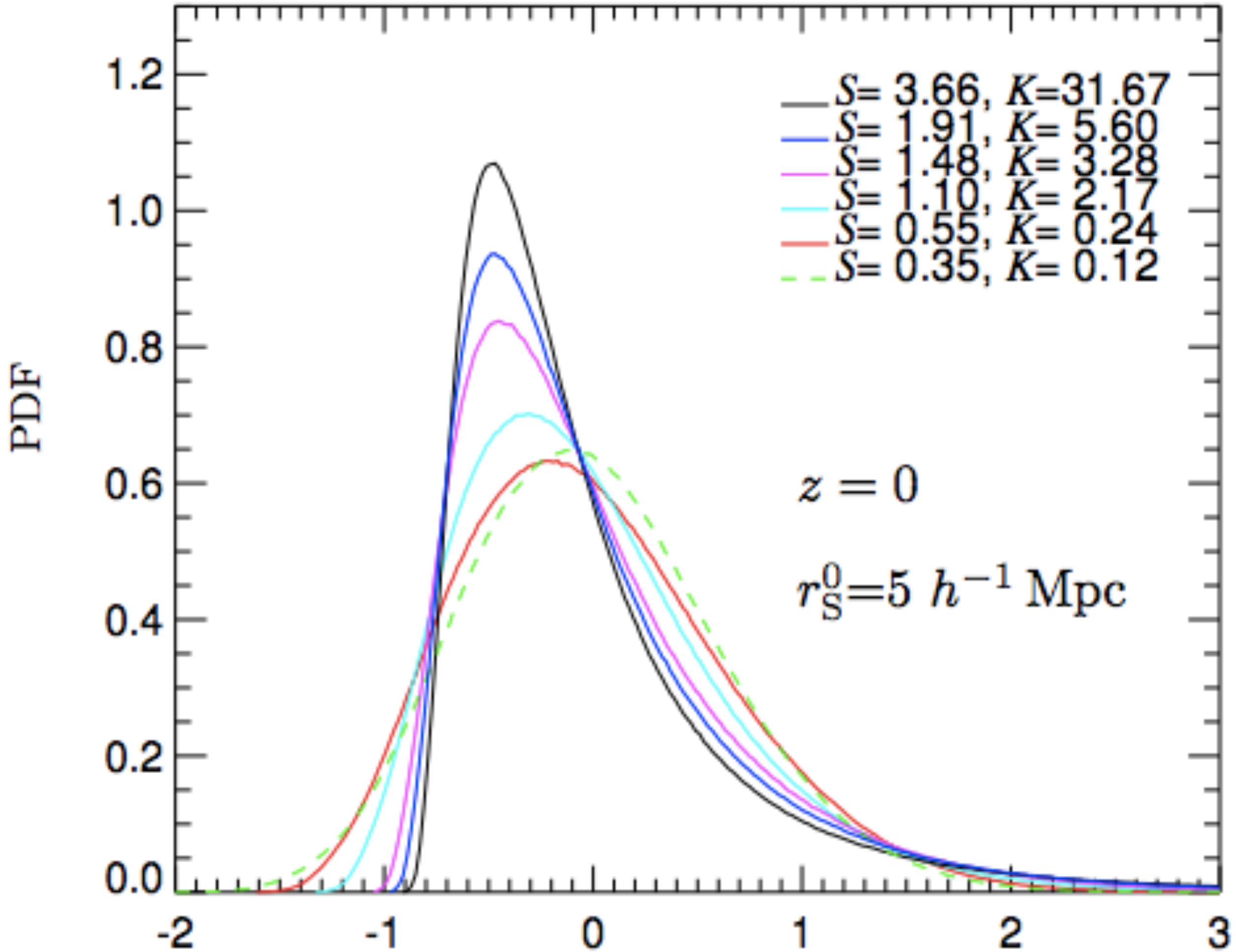
  *Moutard 1991; Buchert & Ehlers 1993; Buchert 1993; Bouchet et al 1995; Catelan 1995*
  *Gramann 1993a, 1993b; Monaco & Efstasthiou 1999; Kitaura & Angulo 2012*

- Least action principle

  *Peebles J. 1989, ApJ, 344, L53*
  *Nusser A. and Branchini E. 2000, MNRAS, 313, 587*
  *Branchini E. et al. 2002, MNRAS, 335, 53*
  *Croft & Gaztañaga 1997, MNRAS, 285, 793*
  *Frisch U., Matarrese S., Mohayaee R., Sobolevski A., 2002, Nature, 417, 260*
  *Brenier Y., Frisch U., Hénon M., Loeper G., Matarrese S., Mohayaee R., Sobolevskiĭ A., 2003, MNRAS, 346, 501*
  *Lavaux G., 2010, MNRAS, 406, 1007*

# Linearisation with cosmological perturbation theory





remember Adi Nusser's talk

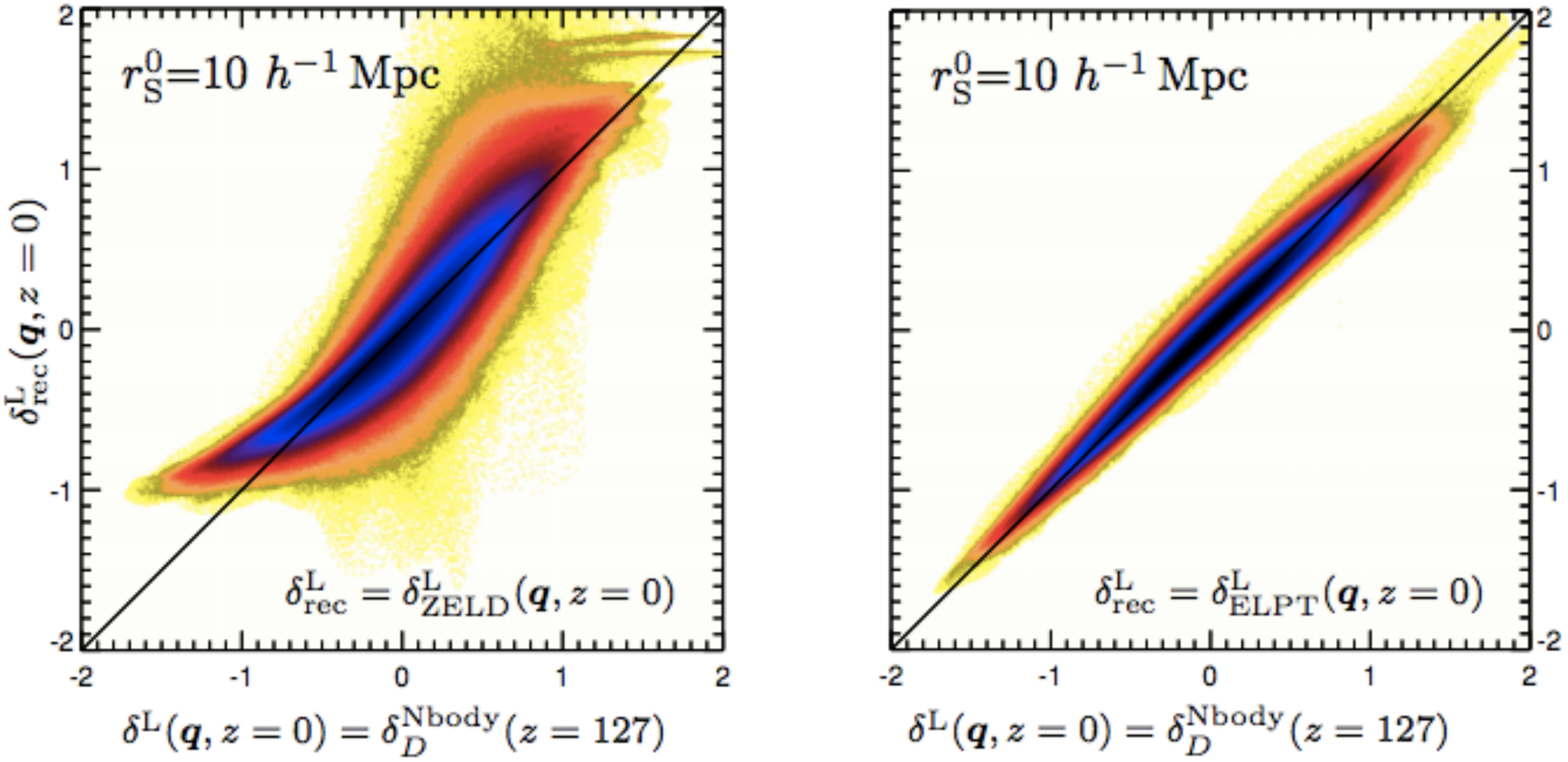
$$\begin{aligned}\delta(\boldsymbol{x},z) &= |1-\nabla_{x}\cdot\boldsymbol{\Psi}(\boldsymbol{x},z)|-1 \qquad (15)\\ &\simeq -\nabla_{x}\cdot\boldsymbol{\Psi}(\boldsymbol{x},z)+\mu^{(2)}[\Theta](\boldsymbol{x},z)+\mu^{(3)}[\Theta](\boldsymbol{x},z)\,.\end{aligned}$$

*Kitaura F. S. & Angulo R. E., 2012, MNRAS, 425, 2443, arXiv:1111.6617*

*(see Gaussianisation: Neyrinck et al 2009, 2011)*

# Time-reversal machines

Comparison between the reconstructed initial density field and true initial conditions from Millennium Run N-body simulation

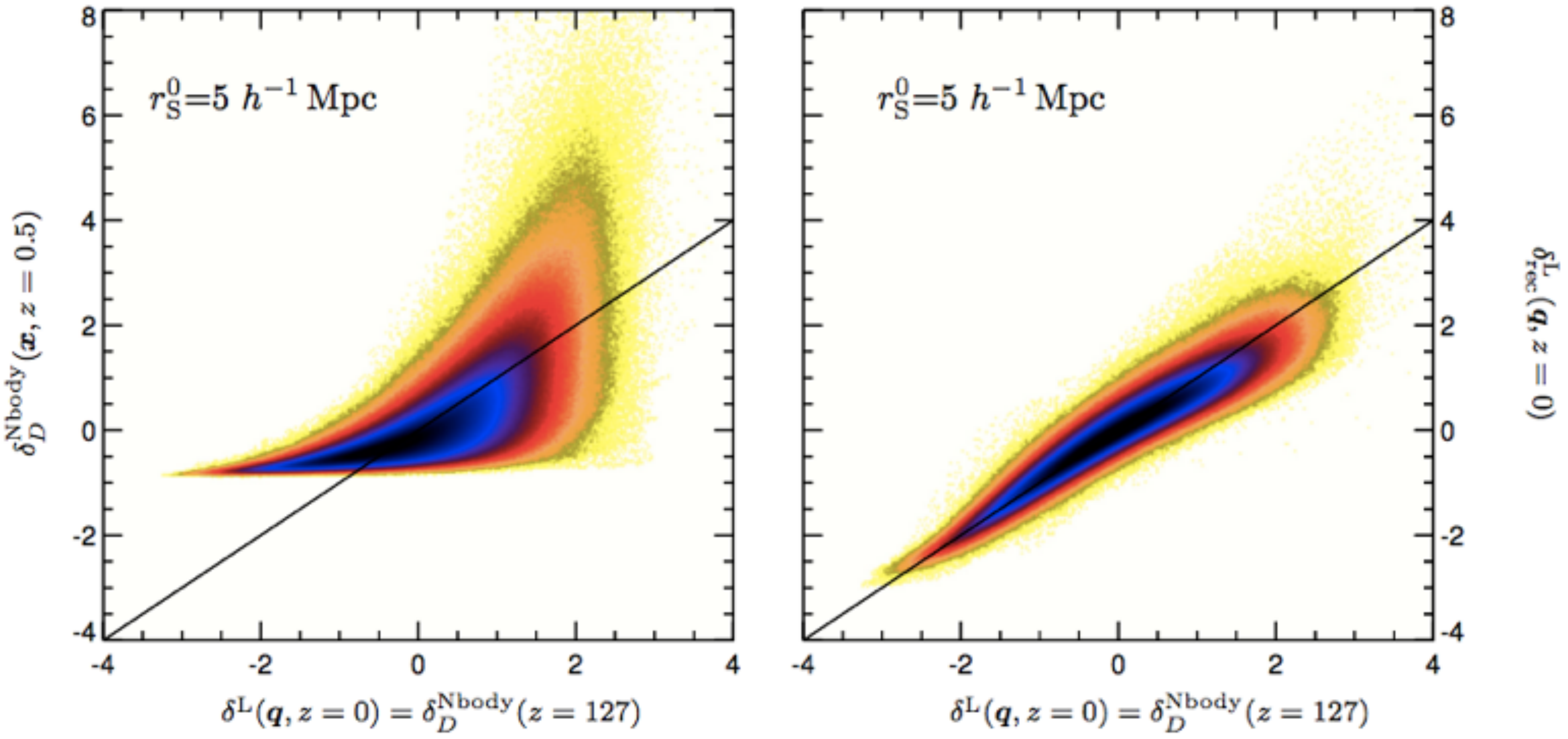


Zeldovich backwards

2LPT backwards

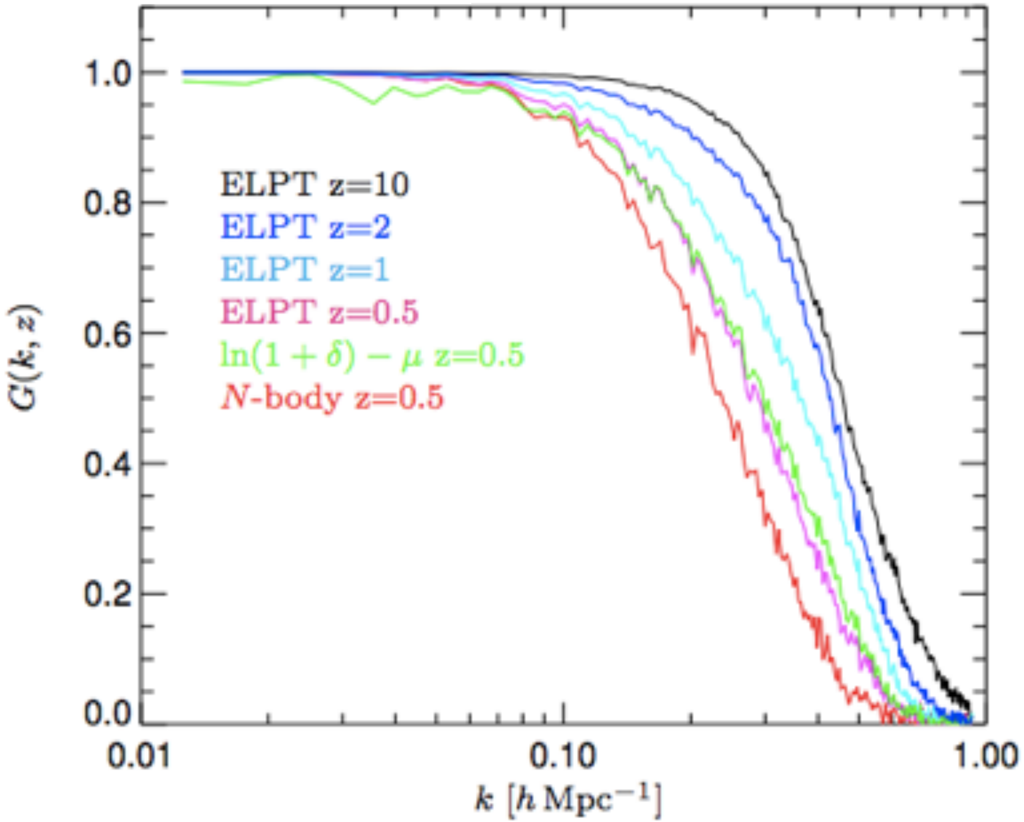
*Kitaura F. S. & Angulo R. E., 2012, MNRAS, 425, 2443, arXiv:1111.6617*

# pushing down to scales of 5 Mpc/h



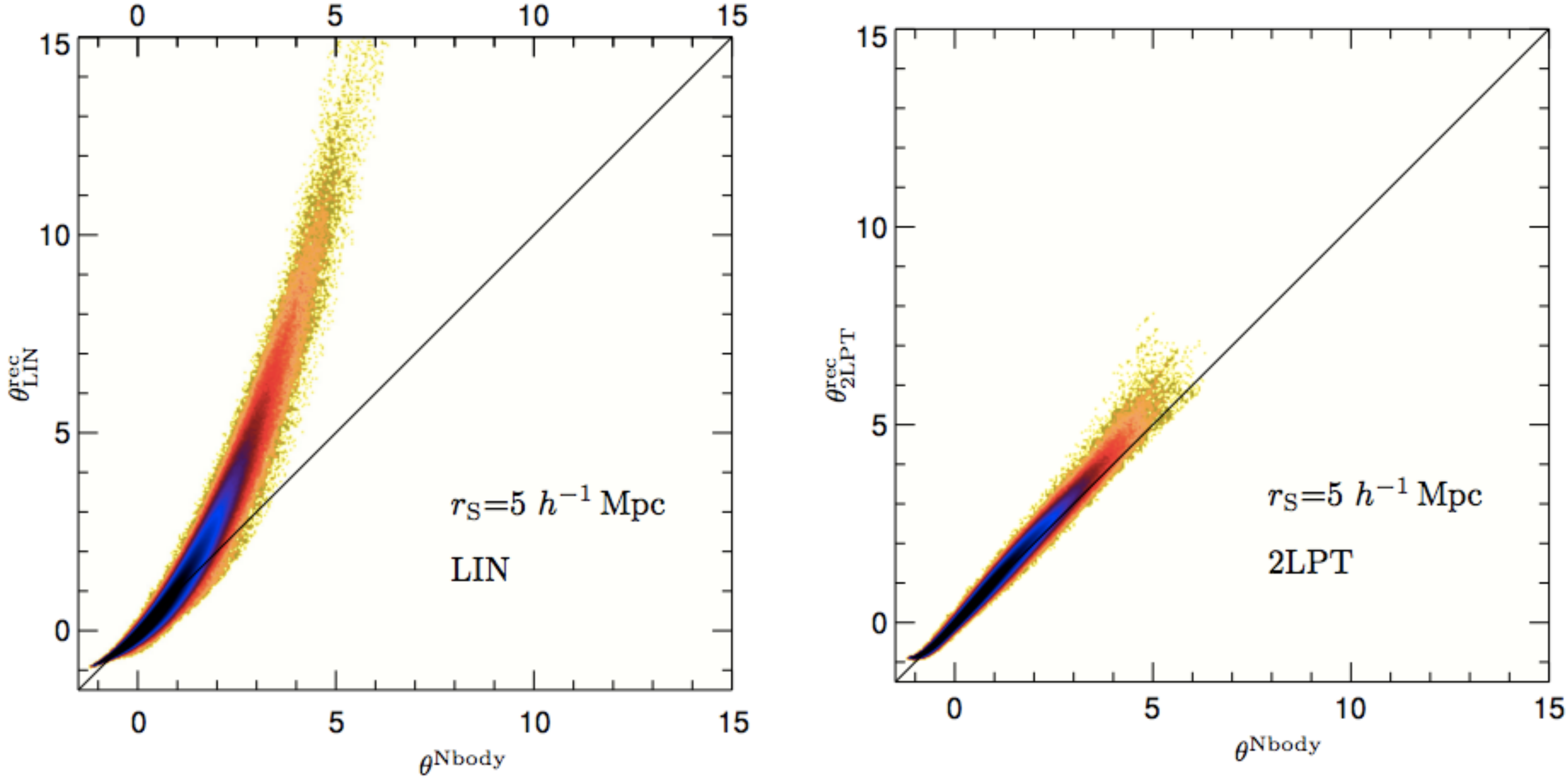
*Kitaura F. S. & Angulo R. E., 2012, MNRAS, 425, 2443, arXiv:1111.6617*

propagator:



# Velocity field reconstruction

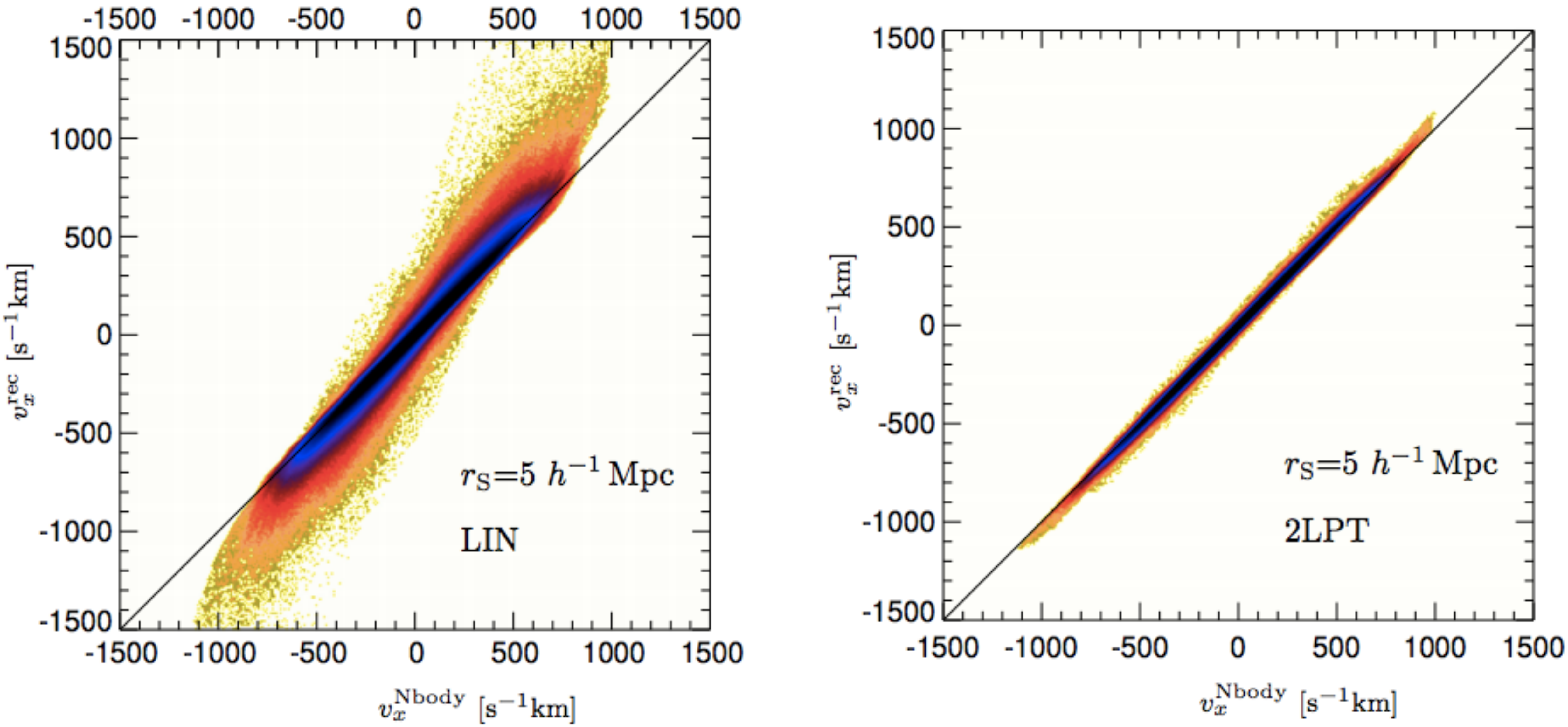
Comparison between the reconstructed normalised divergence of the velocity field and true one from Millennium Run



*Kitaura F. S., Angulo R. E., Hoffman Y. & Gottlöber S. 2012, MNRAS, 422, 2422, arXiv:1111.6629* remember Adi Nusser's talk

# Velocity field reconstruction

Comparison between the reconstructed x-component of the velocity field and true one from Millennium Run



*Kitaura F. S., Angulo R. E., Hoffman Y. & Gottlöber S. 2012, MNRAS, 422, 2422, arXiv:1111.6629*

# Time-reversal machines

- Linear or higher order Lagrangian perturbation theory

  needs to smooth the density field on a grid on scales of >~ 5 Mpc/h!
  lead to an aliased estimate of the primordial density fluctuations!

- Least action principle

  do not lead to an estimate of the primordial density fluctuations
  but to a distribution of matter tracers at the initial conditions!

  the inverse approach severely suffers from shell crossing!

# Statistical approaches

# Bayesian approach

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

Gaussian case: Wiener filter:

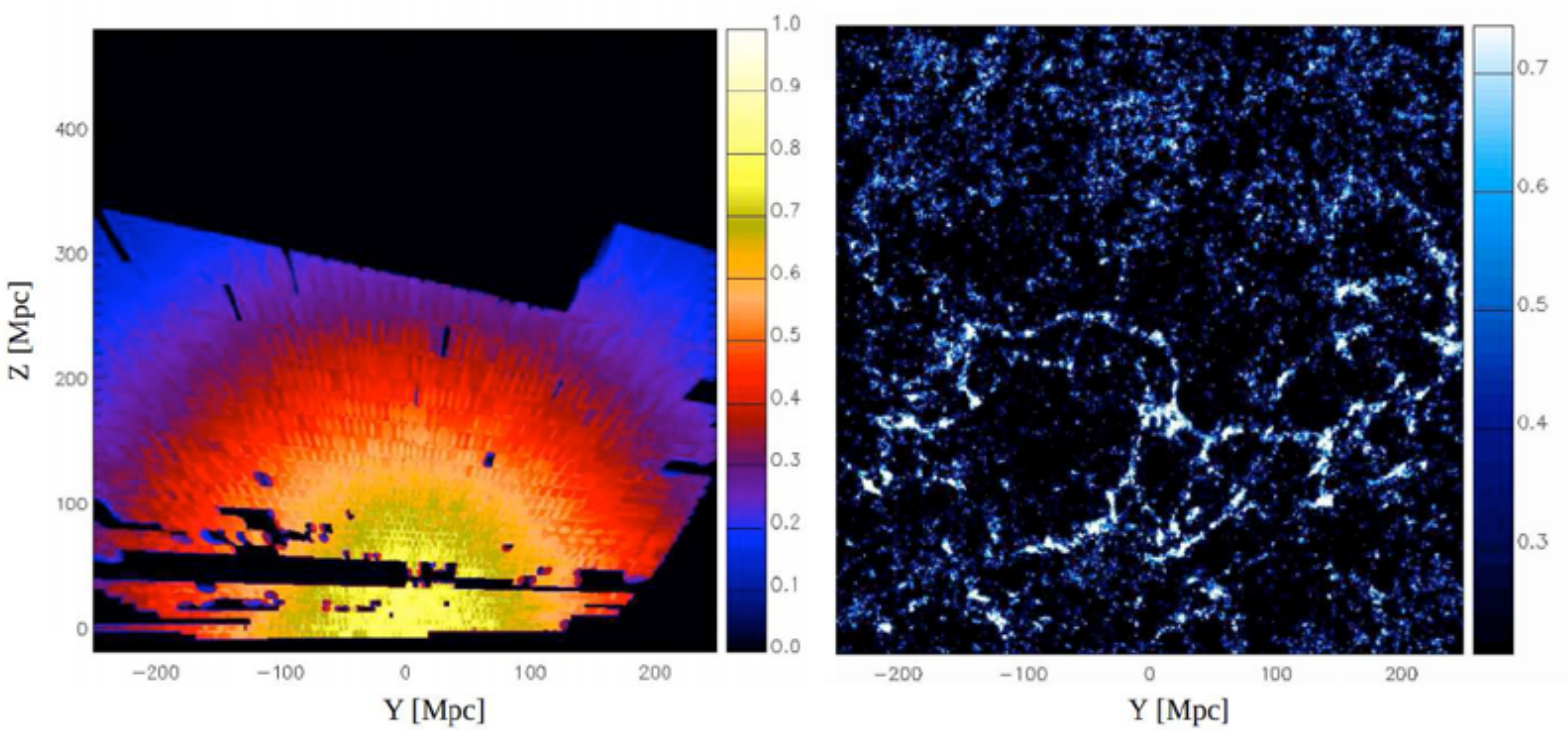
Bayesian derivation in a cosmological large-scale structure context!

*Zaroubi S., Hoffman Y., Fisher K. B., Lahav O., 1995, ApJ, 449, 446*

*Bunn E. F., Fisher K. B., Hoffman Y., Lahav O., Silk J., Zaroubi S., 1994, ApJ, 432, L75*
*Fisher K. B., Lahav O., Hoffman Y., Lynden-Bell D., Zaroubi S., 1995, MNRAS, 272, 885*
*Webster M., Lahav O., Fisher K., 1997, MNRAS, 287, 425*
*Erdogdu P., Lahav O., Zaroubi S., Efstathiou G., Moody S., Peacock J. A., Colless M., Baldry I. K., et al. 2004, MNRAS, 352, 939*
*Erdogdu P., Lahav O., Huchra J., et al. 2006, MNRAS, 373, 45*
*...*

# Gaussian prior

# improved Wiener filter from Poisson likelihood applied to Sloan



*Kitaura F. S., Jasche J., Li C., Enßlin T. A., Metcalf B., Wandelt B., Lemson G. & White S. D. M., 2009, MNRAS, 400, 183, arXiv:0906.3978*

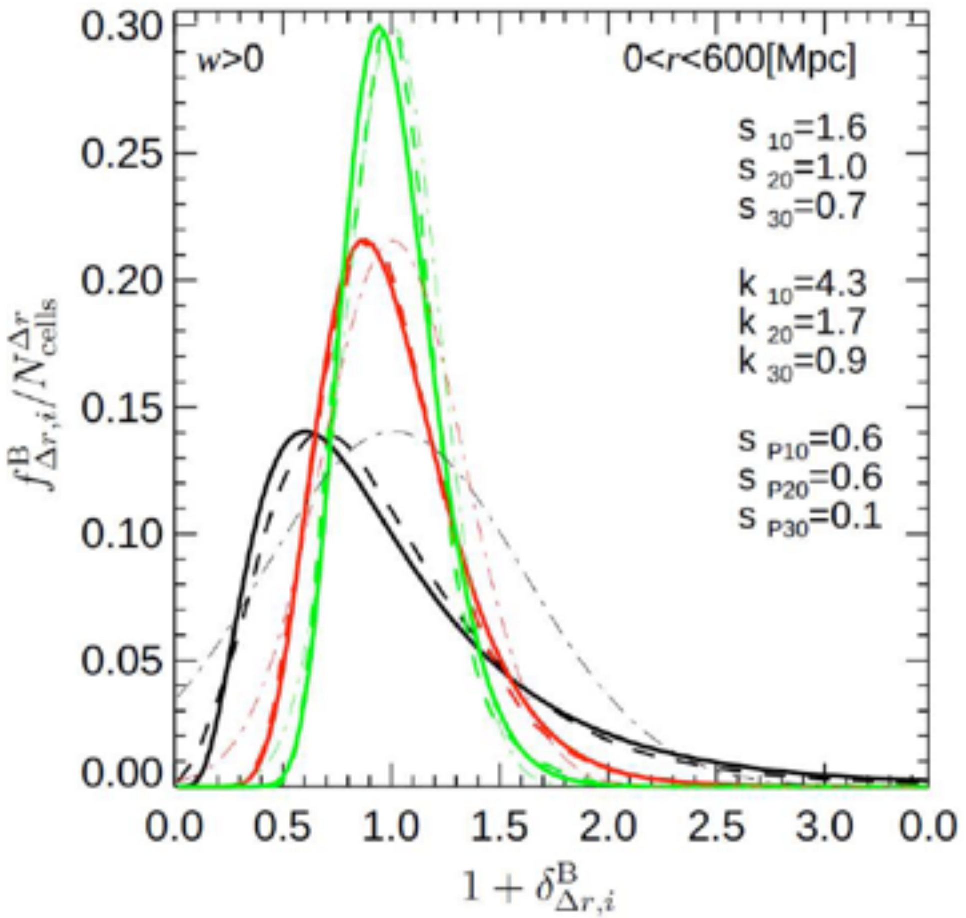
see Rien's talk!

detection of a super-void (150 Mpc cross)

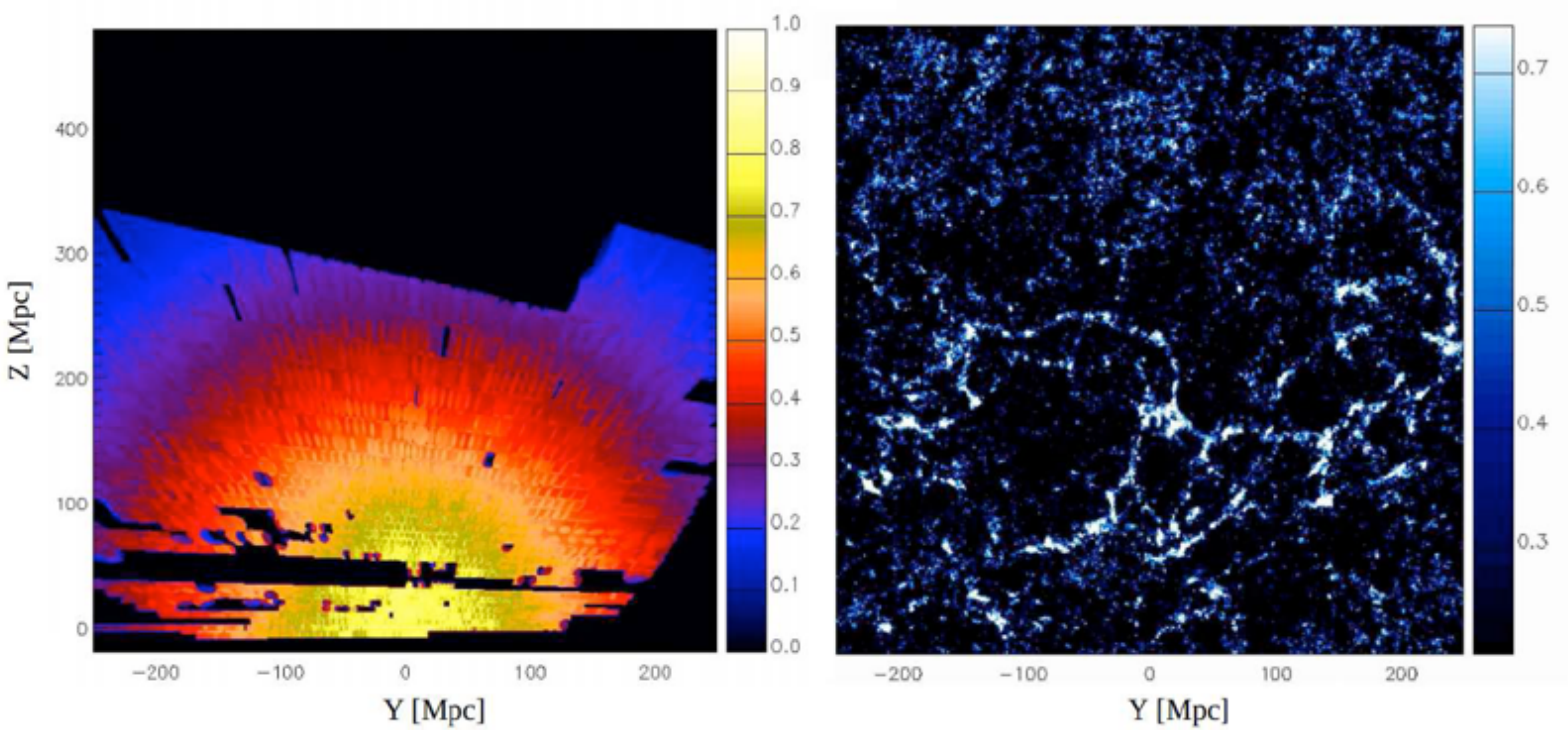
lognormal at scales >~ 10 Mpc

*Hubble E., 1934, ApJ, 79, 8*

*Coles P. & Jones B., 1991, MNRAS, 248, 1*



# improved Wiener filter from Poisson likelihood applied to Sloan



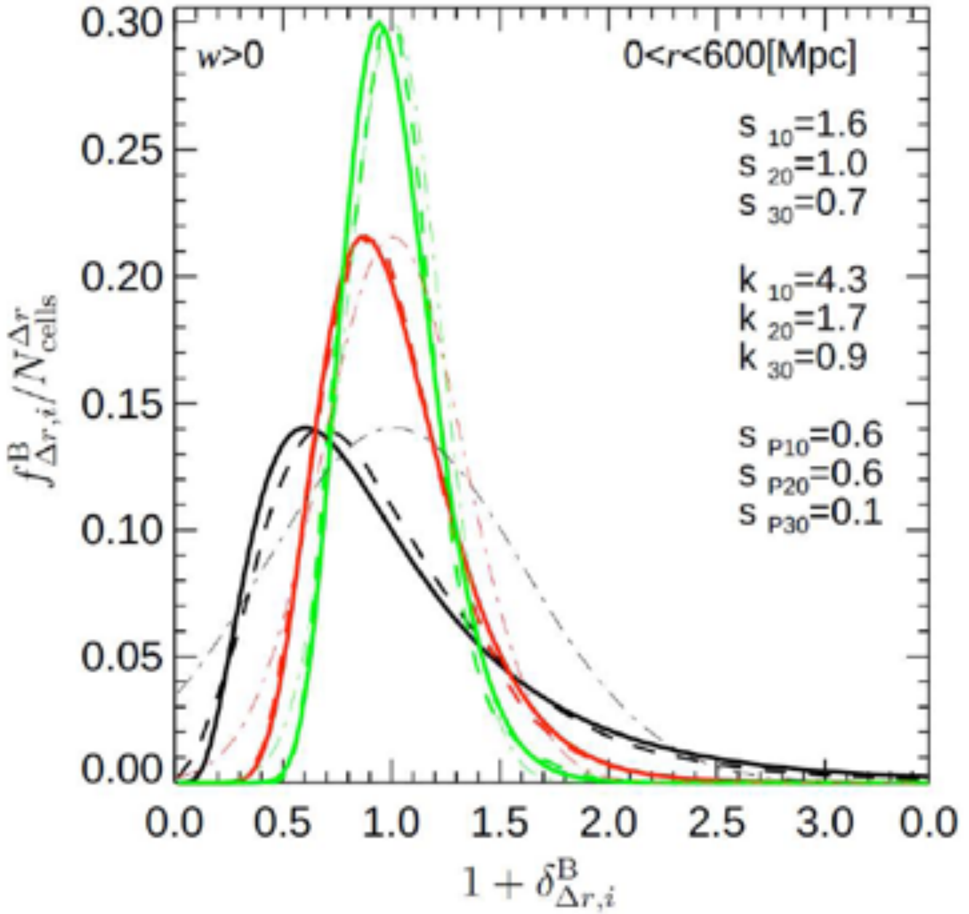
*Kitaura F. S., Jasche J., Li C., Enßlin T. A., Metcalf B., Wandelt B., Lemson G. & White S. D. M., 2009, MNRAS, 400, 183, arXiv:0906.3978*

see Rien's talk!

detection of a super-void (150 Mpc cross)

lognormal at scales >~ 10 Mpc

can we go beyond the Wiener filter?



# Lognormal prior
# + Poisson/Gaussian likelihood

# Lognormal-Poisson model

introduced by:

*Kitaura F. S. & Enßlin T. A., 2008, MNRAS, 389, 497, arXiv:0705.0429*

*Kitaura F. S., Jasche J. & Metcalf R. B., 2010, MNRAS, 403, 589, arXiv:0911.1407*

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

applications:

we introduced Hamiltonian-sampling of the LSS:

*Jasche J. & Kitaura F. S., 2010, MNRAS, 407, 29, arXiv:0911.2496*

*Jasche J., Kitaura F. S., Li C. & Enßlin T. A., 2010, MNRAS, 409, 355, arXiv:0911.2498*

*Kitaura F. S., Gallerani S. & Ferrara A., 2012, MNRAS, 420, 61, arXiv:1011.6233*

easy to handle!

other nonlinear reconstruction methods:

no additional parameters!

*Platen E., van de Weygaert R. Jones B. J. T., Vegter G., Aragon Calvo M. A. 2011*

*Schaap & van de Weygaert 2000;* the Groningen and Tartu groups!

*Einasto J.+ 2011; Saar E. + 2007; Martinez + 2005*

# Lognormal-Poisson and Lognormal-Gaussian model

Gibbs-sampling for density, peculiar velocity fields and power spectra:

first proposed by: *Kitaura F. S. & Enßlin T. A., 2008, MNRAS, 389, 497, arXiv:0705.0429*

for Gaussian case without RSDs: *Jasche J., Kitaura F. S., Wandelt B. & Enßlin T. A., 2010, MNRAS, 406, 60, arXiv:0911.2493*

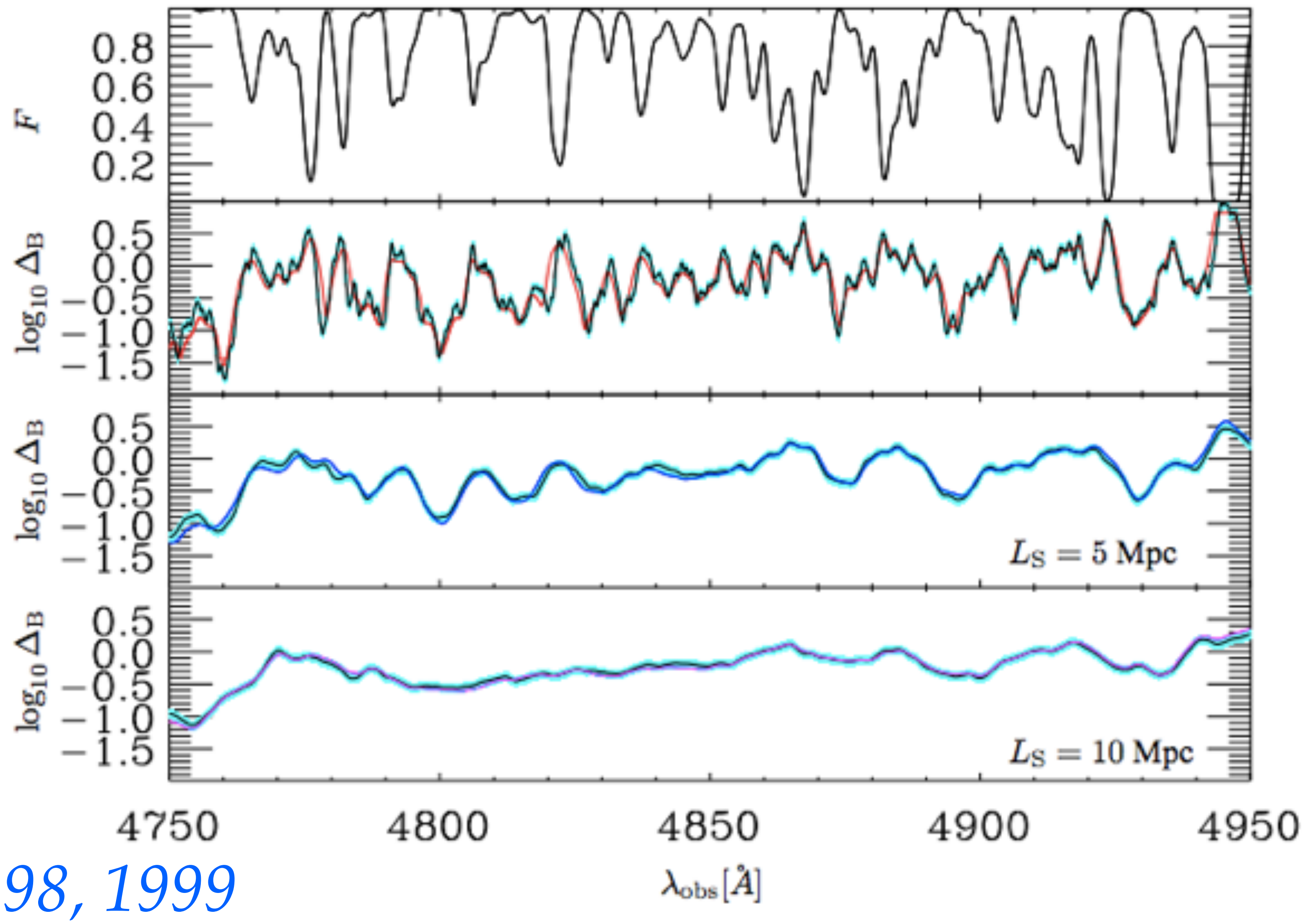
for Lognormal case including RSD:

*Kitaura F. S., Gallerani S. & Ferrara A., 2012, MNRAS, 420, 61, arXiv:1011.6233*

$$
\begin{aligned}
\boldsymbol{s}^{(j+1)} &\hookleftarrow P(\boldsymbol{s} \mid \boldsymbol{v}^{(j)}, \mathbf{S}, \boldsymbol{d}^{z}),\\
\mathbf{S}^{(j+1)} &\hookleftarrow P(\mathbf{S} \mid \boldsymbol{s}^{(j+1)}),\\
\boldsymbol{v}^{(j+1)} &\hookleftarrow P(\boldsymbol{v} \mid \boldsymbol{s}^{(j+1)}),
\end{aligned}
$$

# Lyman alpha forest reconstruction on simulations

Let us assume that we have reconstructed the density field along the line-of-sight:



*Croft et al 1998, 1999*

*Nusser & Haehnelt 1999*

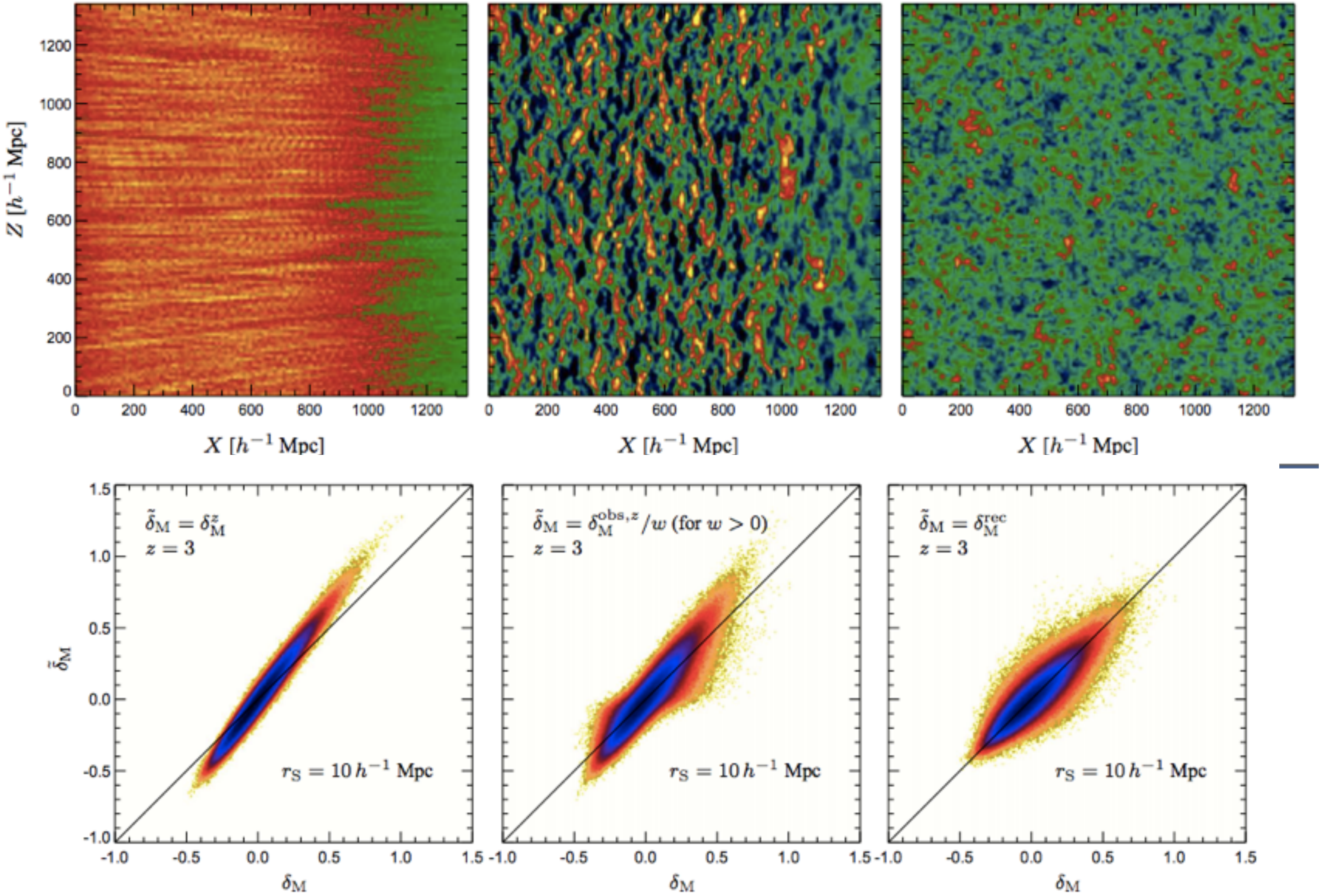
*Gallerani et al 2011*

How do we get the 3D density fields correcting for RSDs and sampling the power spectra?

see Avery Meiksin, Nicolas Tejos & Khee-Gan Lee's talk

# Lyman alpha forest reconstruction on simulations

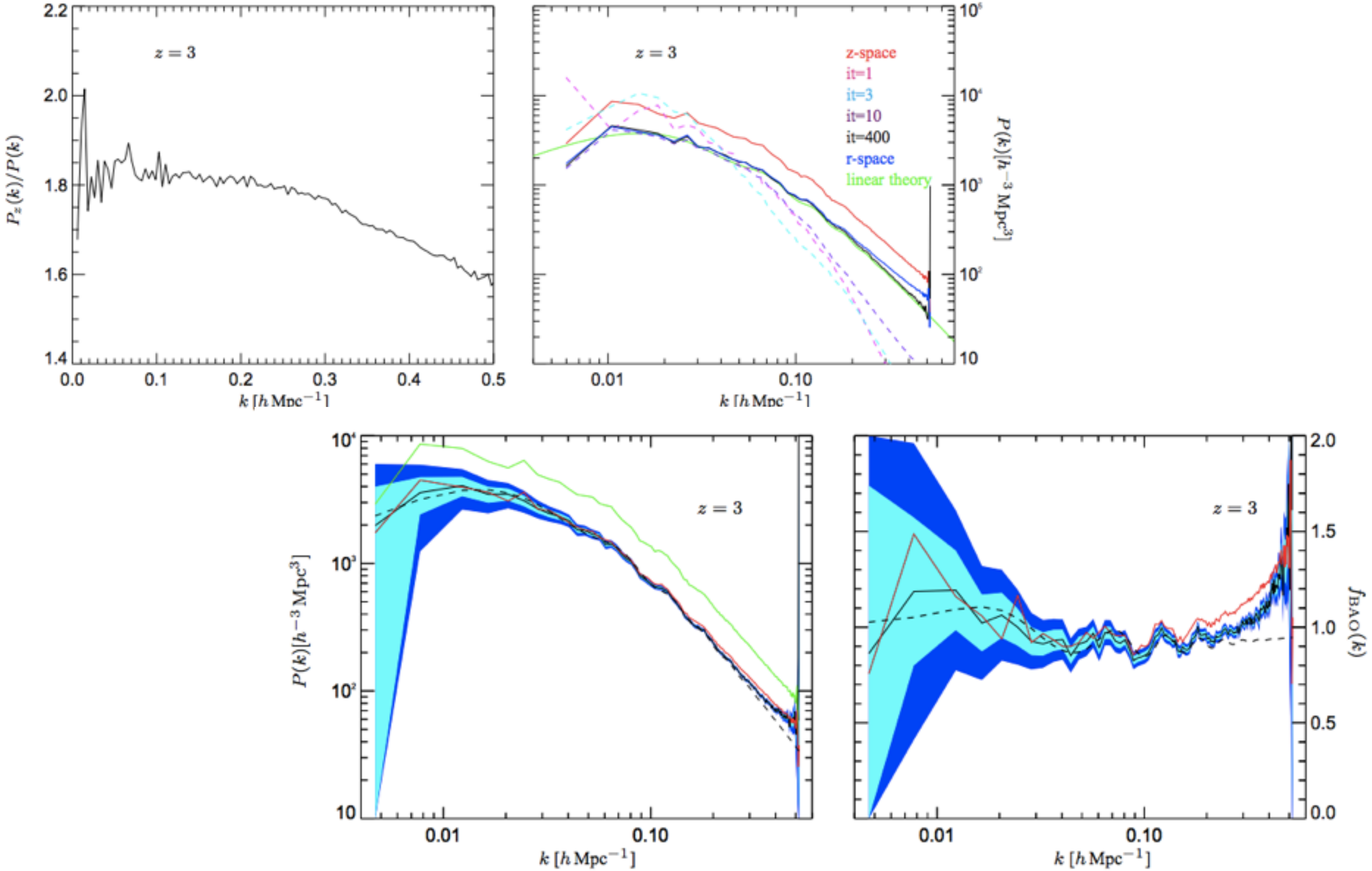
## (N-body 1340 Mpc/h side at z=3 from R. Angulo L-Basic)



*Kitaura F. S., Gallerani S. & Ferrara A., 2012, MNRAS, 420, 61, arXiv:1011.6233*

*(see also Pichon et al 2001 with nonlinear least squares approach!)*

# Linear component BAO reconstruction



*Kitaura F. S., Gallerani S. & Ferrara A., 2012, MNRAS, 420, 61, arXiv:1011.6233*

# Redshift-space distortions correction

*Kitaura F. S., Ata M., Angulo R. E., et al in prep*

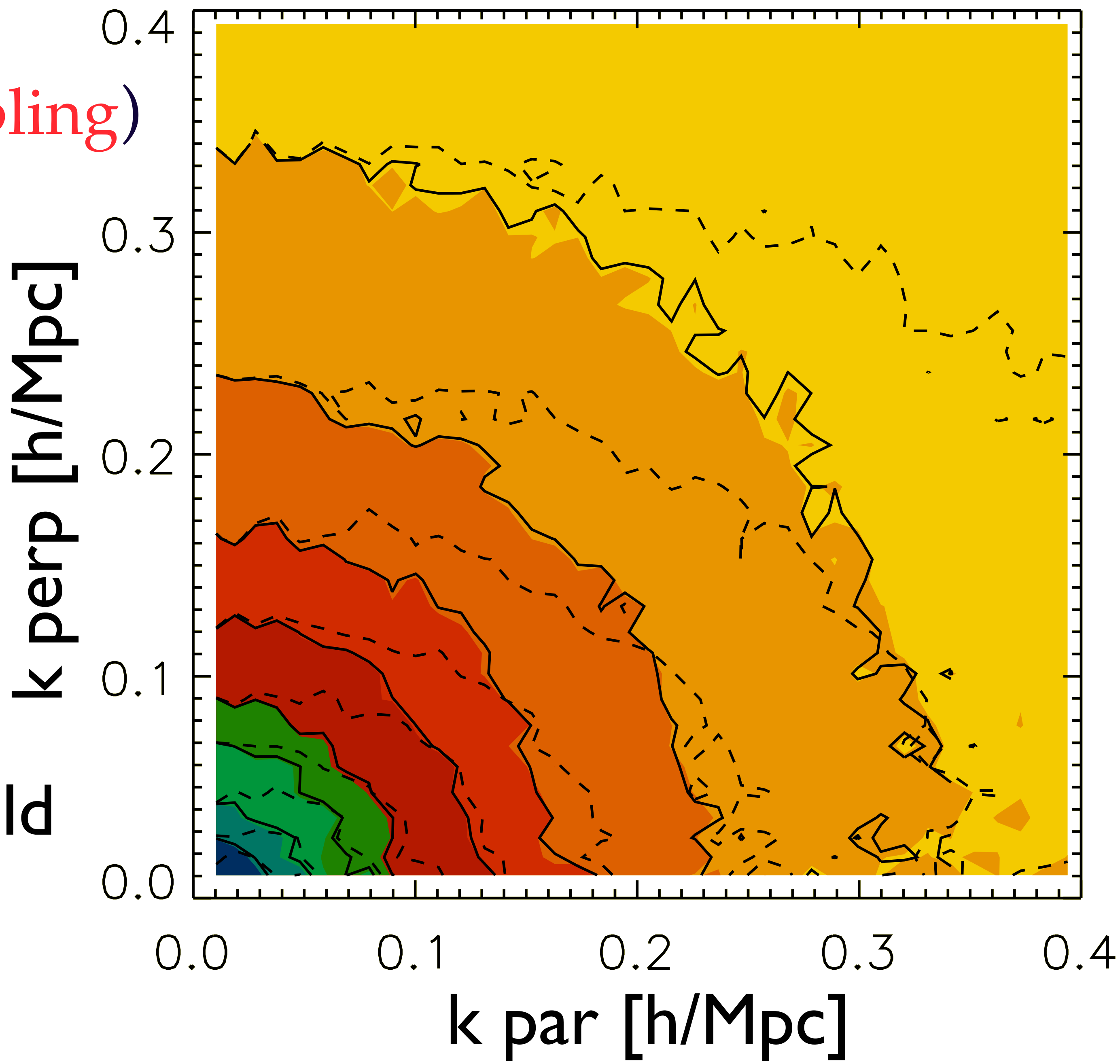
(using the ARGO-code Gibbs-sampling)

we use the L-basic simulation
with 1340 Mpc/h side
taking haloes >10^12 solar masses

Bayesian model with
Lognormal prior for the density field

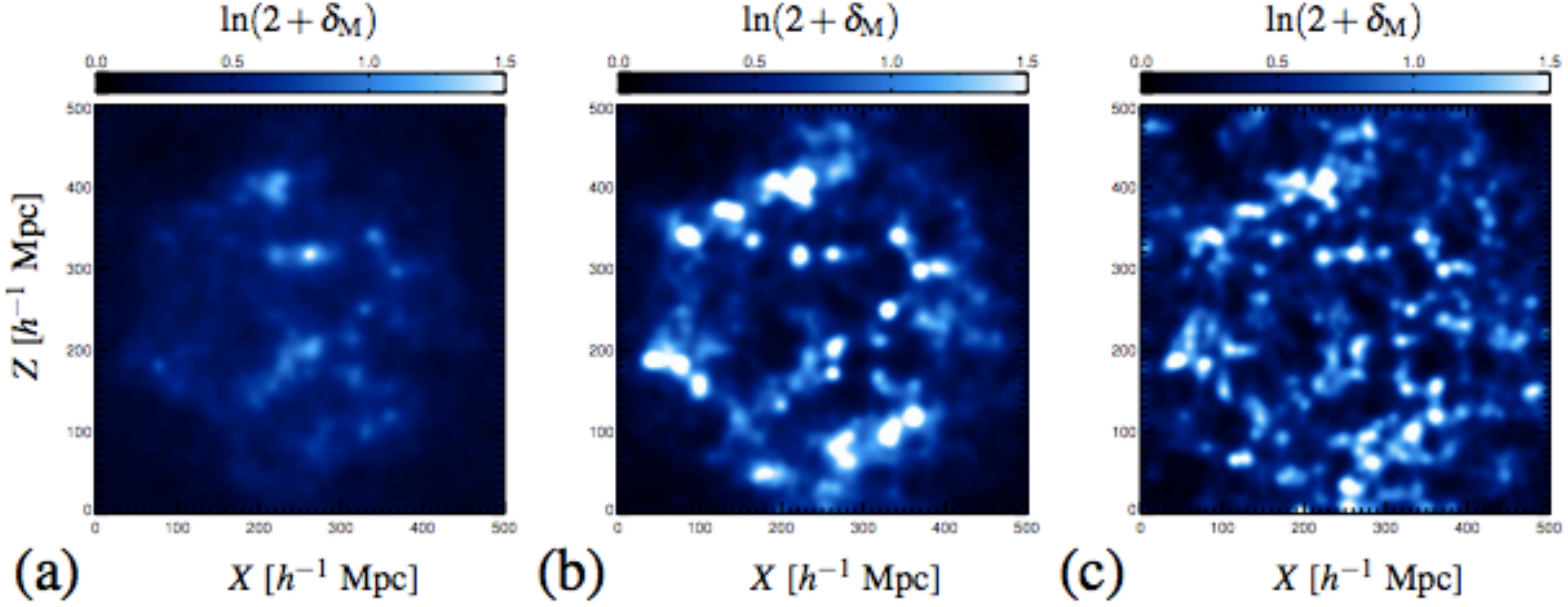
can/should we go beyond the
Lognormal approximation?

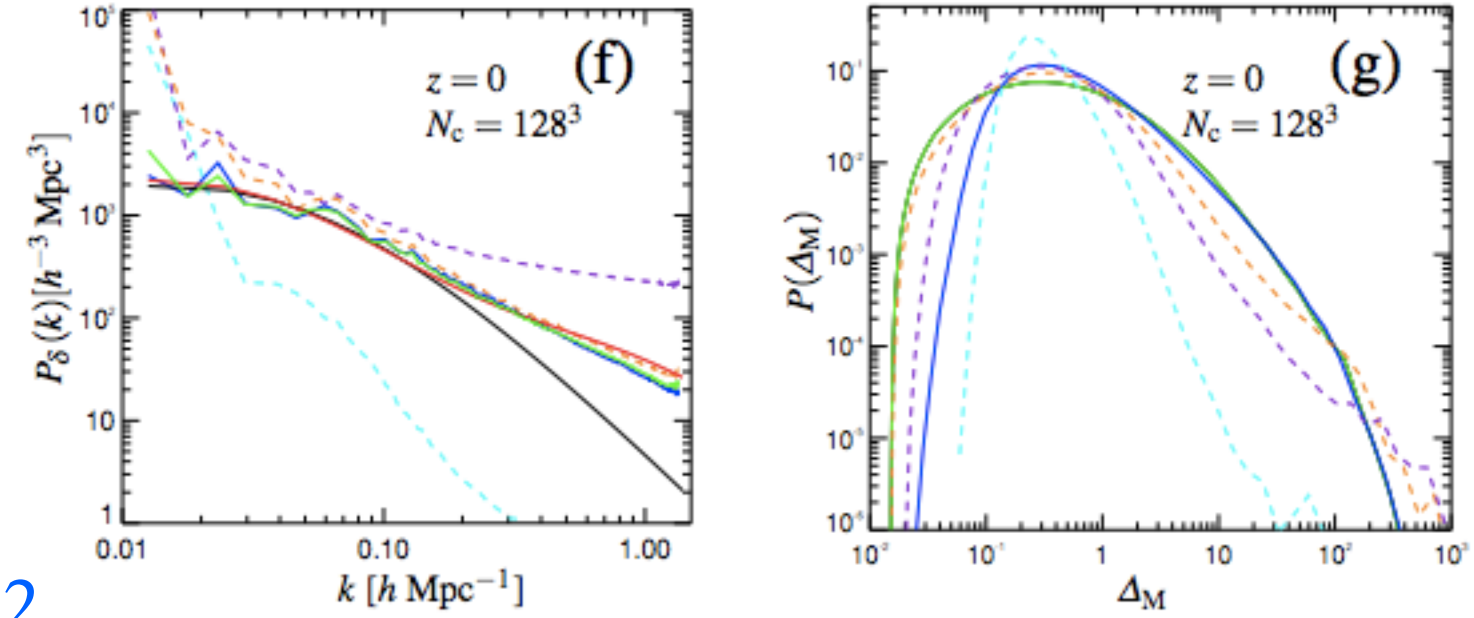
2D power-spectrum



# Limits of the Lognormal approximation

Poisson subsample of dark matter particles with radial selection function from Millennium Run N-body simulation on scales of 3.9 Mpc/h

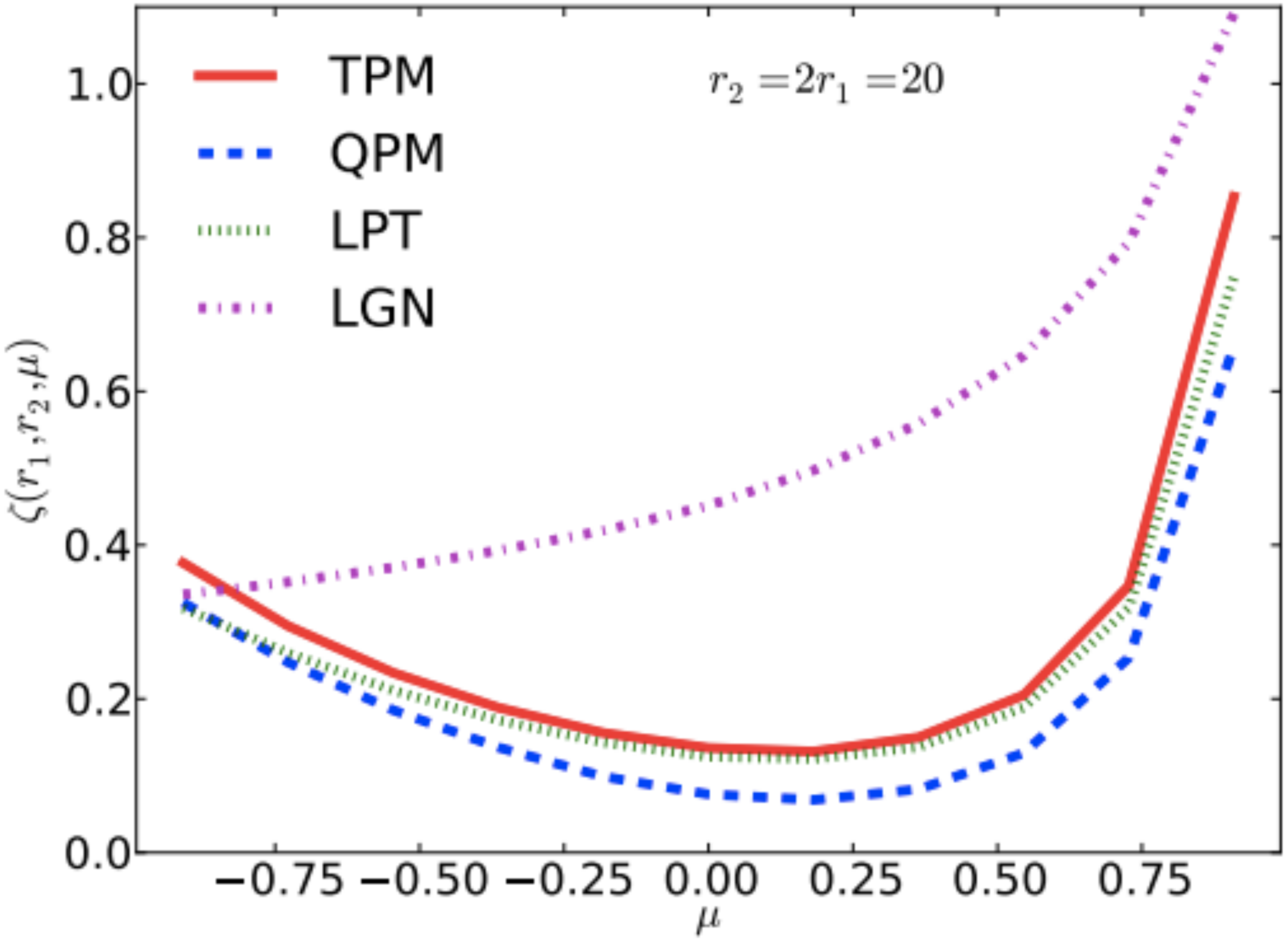




*Kitaura F. S. 2012,*
*Springer Series in Astrostatistics, 143,*
*arXiv:1112.0492*

wrong PDF at underdense regions,
but right at high-density regions!
right two-point statistics

The lognormal approximation has the wrong 3pt statistics! However, in a Bayesian approach the likelihood can weight more in the presence of good enough data!



*calculation by Martin White et al 2014*

# Can we improve the likelihood?

## Biasing

- non-linear
- scale dependent
- non-local
- stochastic

Let us imagine we would know the halo/galaxy density field, i.e. the expected number of halos/galaxies per finite volume (cell).

# Stochastic biasing

$$N_h \curvearrowleft \mathcal{P}(N_h|\rho_h)$$

caution! we still need to know the deviation from Poissonity!

over-dispersion modelled by the NB PDF:

$$P(N_i \mid \lambda_i, \beta) = \frac{\lambda_i^{N_i}}{N_i!} \frac{\Gamma(\beta + N_i)}{\Gamma(\beta)(\beta+\lambda)^{N_i}} \frac{1}{(1+\lambda/\beta)^{\beta}}$$

*Kitaura, Yepes & Prada 2014, MNRAS, arXiv:1307.3285*

*non-Poissonian PDFs:*
*Saslaw W.C., Hamilton A.J.S., 1984, ApJ, 276, 13*
*Sheth R. K., 1995, MNRAS, 274, 213*

*stochastic bias:*
*Dekel A., Lahav O., 1999, ApJ, 520, 24*
*Sheth R. K., Lemson G., 1999, MNRAS, 304, 767*

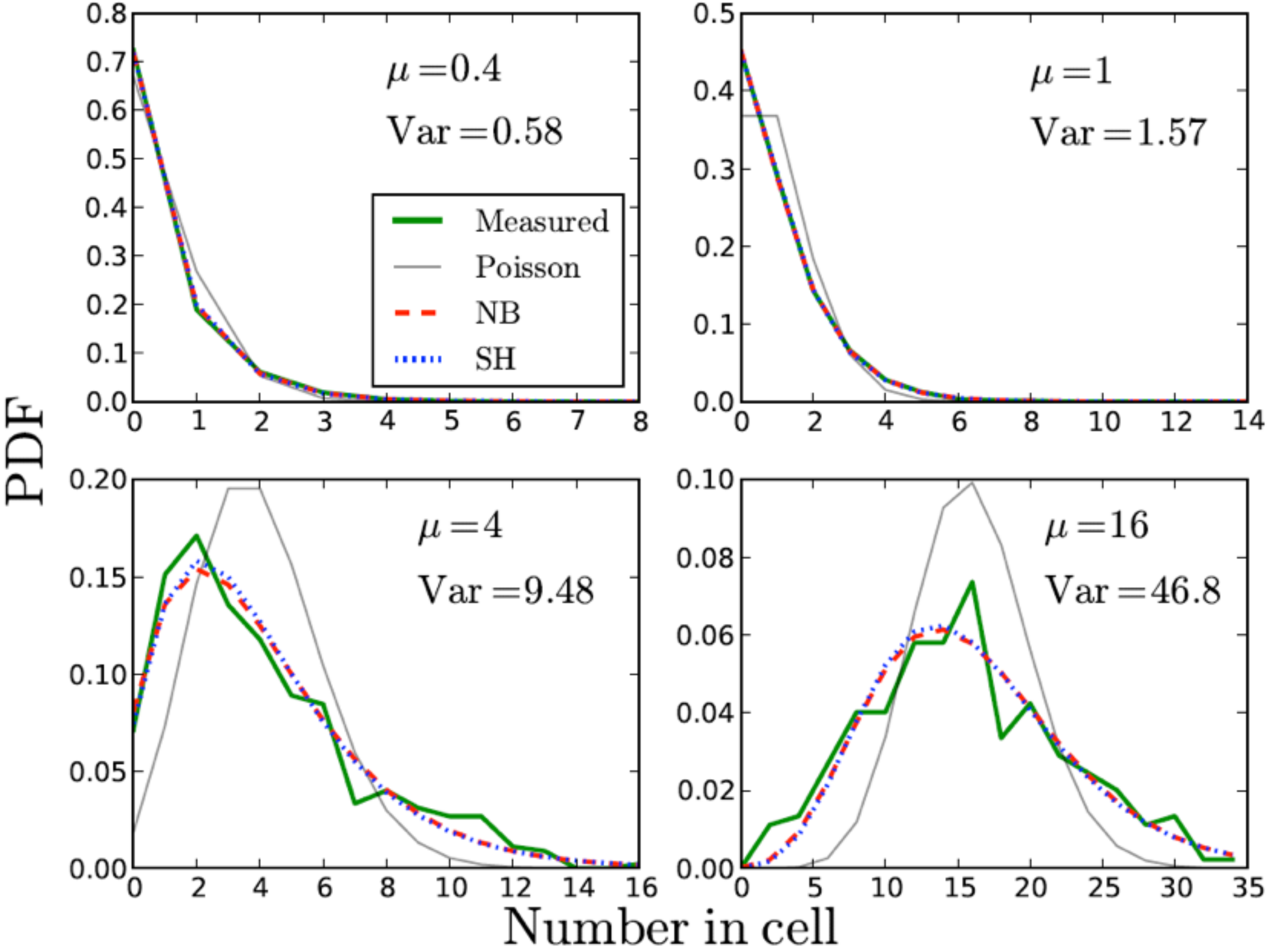
remember Tobias Baldauf's talk

*and many more see references in e.g. Kitaura et al 2013 like Baldauf+13*

*Somerville et al 2001, MNRAS, 320, 289*
*Casas-Miranda et al 2002, MNRAS, 333, 730*

remember Miguel's talk!

*Neyrinck M et al 2013; Aragon-Calvo M. 2013*



# Deterministic biasing parametrization

*Fry & Gaztañaga 1993*

$$\rho_h = f_h^a \sum_i a_i \delta_{\mathrm{M}}^i$$

see Luigi Guzzo & Sylvain de la Torre's talk

*Cen & Ostriker 1993; de la Torre & Peacock 2013*

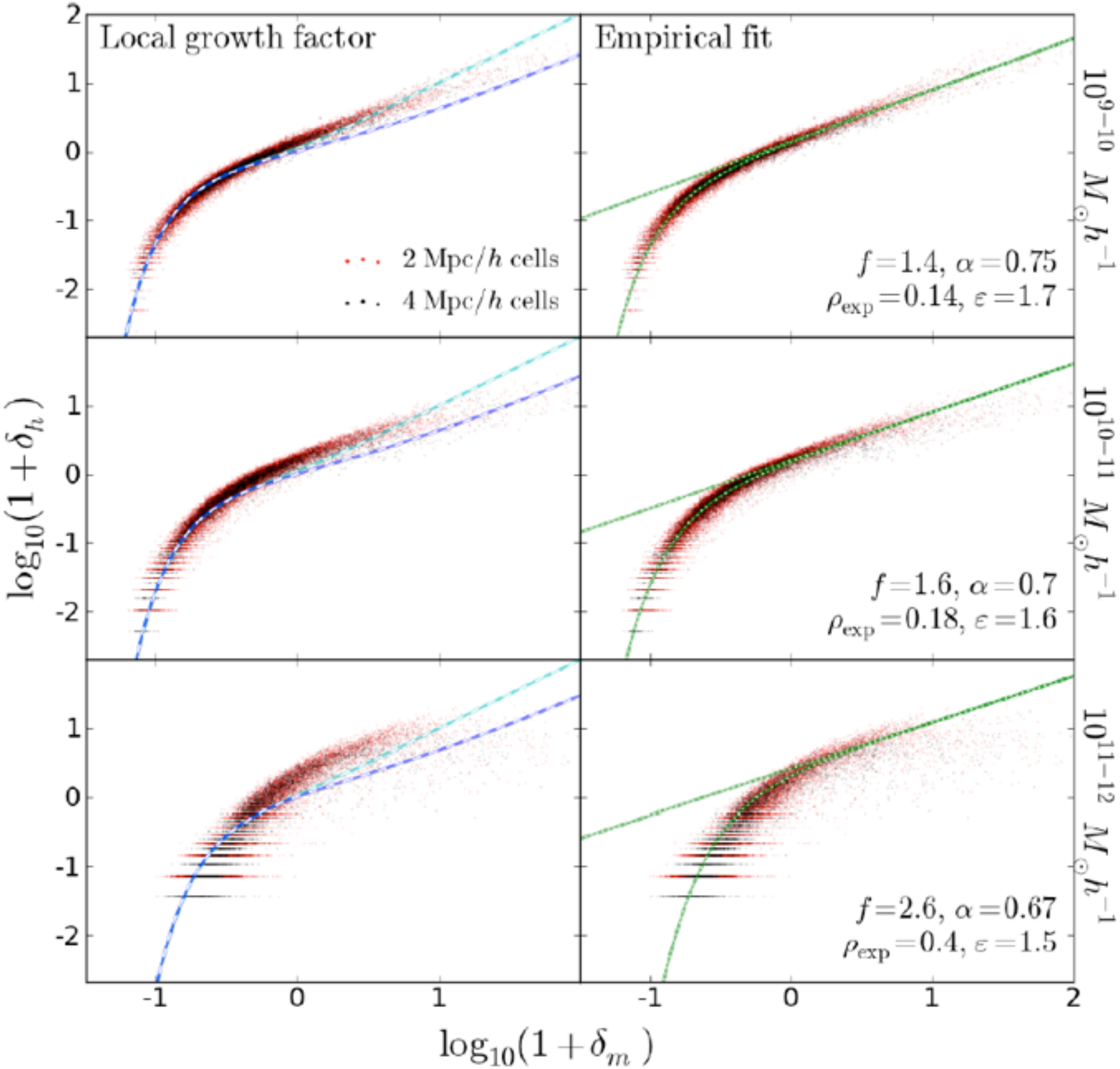
$$\rho_h = f_h^b \exp\left[\sum_i b_i \log\left(1+\delta_{\mathrm{M}}\right)^i\right]$$

*Kitaura, Yepes & Prada 2014 + Neyrinck et al 2014*

$$\rho_h = f_h\,\theta(\rho_{\mathrm{M}} - \rho_{\mathrm{th}})\,\rho_{\mathrm{M}}^{\alpha} \exp\left[-\left(\frac{\rho_{\mathrm{M}}}{\rho_\epsilon}\right)^{\epsilon}\right]$$

thresholding: *Kaiser 1984*

*Neyrinck M et al 2013; Aragon-Calvo M. 2013*



# Perturbative approaches to model BAOs

we are performing mocks for BOSS, 4MOST, JPAS, EUCLID,…

collaborators: F. Prada, G. Yepes, V. Müller, C. Scoccola, C.-H. Chuan, H. Gil-Marin, S. Rodriguez

Reference N-body simulation (Gadget): BIGMULTIDARK
Volume: (2500 Mpc/h)^3
Number of particles: 3840^3 (2M cpu hs)
halos selected with bdm (density peaks) according to vmax>~350 km/s (LRGs)
-> I consider 8 sub-volumes of (1250 Mpc/h)^3

*Hess et al in prep*
*Prada et al in prep*

Simulations with PATCHY: PerturbAtion Theory Catalog generator of Halo/galaxY distributions
Volume: (1250 Mpc/h)^3
Grid number of cells: 512^3
Resolution of the grid: (2.4 Mpc/h)^3
same cosmology (Planck-like)
same redshift: z=0.577
on my laptop (quad core i7, 4 cpus+4 virtual cpus, 8 Gb RAM)
about 15 mins

*Kitaura, Yepes & Prada 2014, MNRAS, arXiv:1307.3285*

relies on ALPT: see later slides!

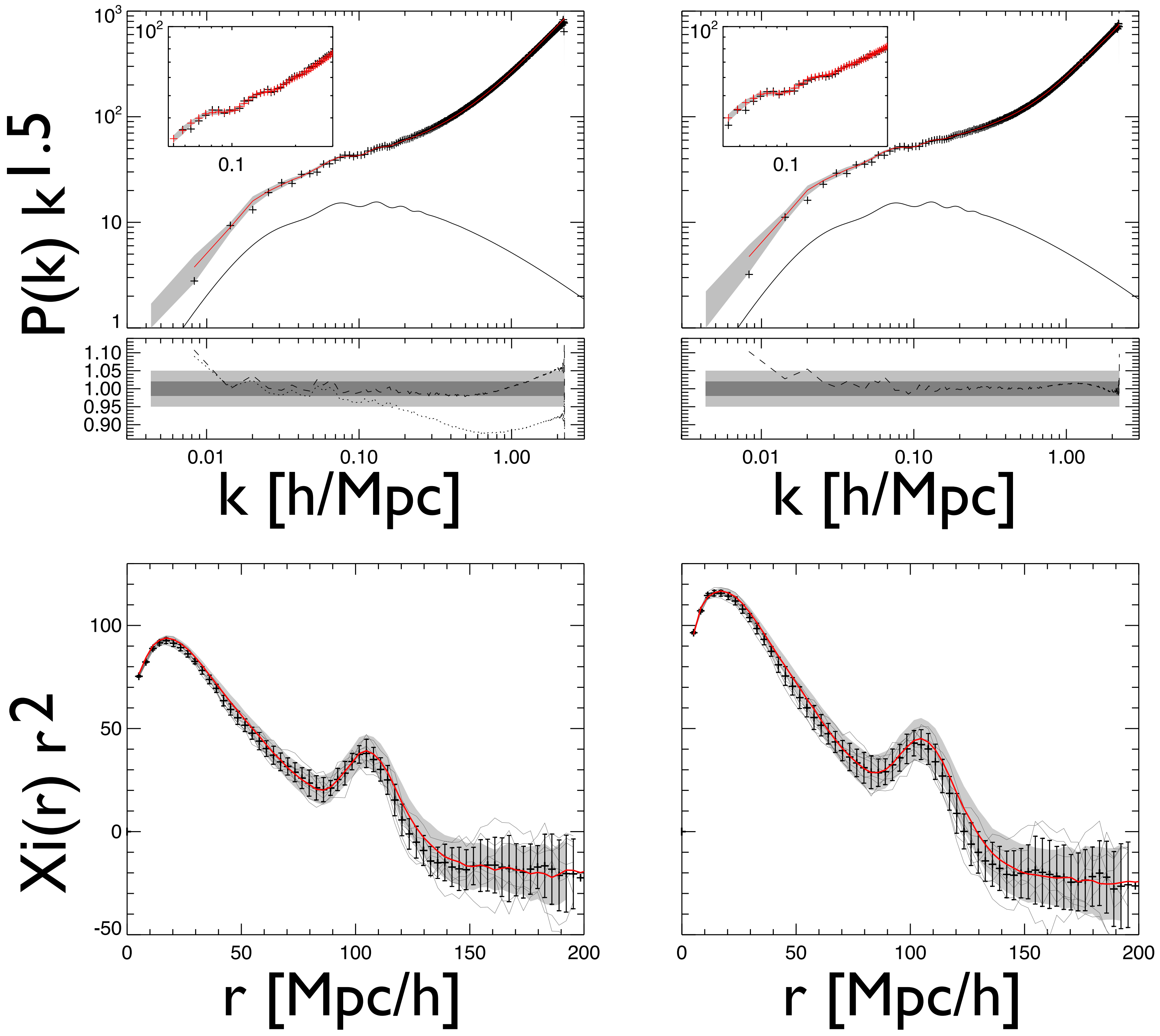
53 times lower resolution required!

# Calibration of PATCHY with N-body simulations

*Kitaura, Yepes & Prada 2014, MNRAS, arXiv:1307.3285 and Kitaura+ in prep*

real-space

redshift-space

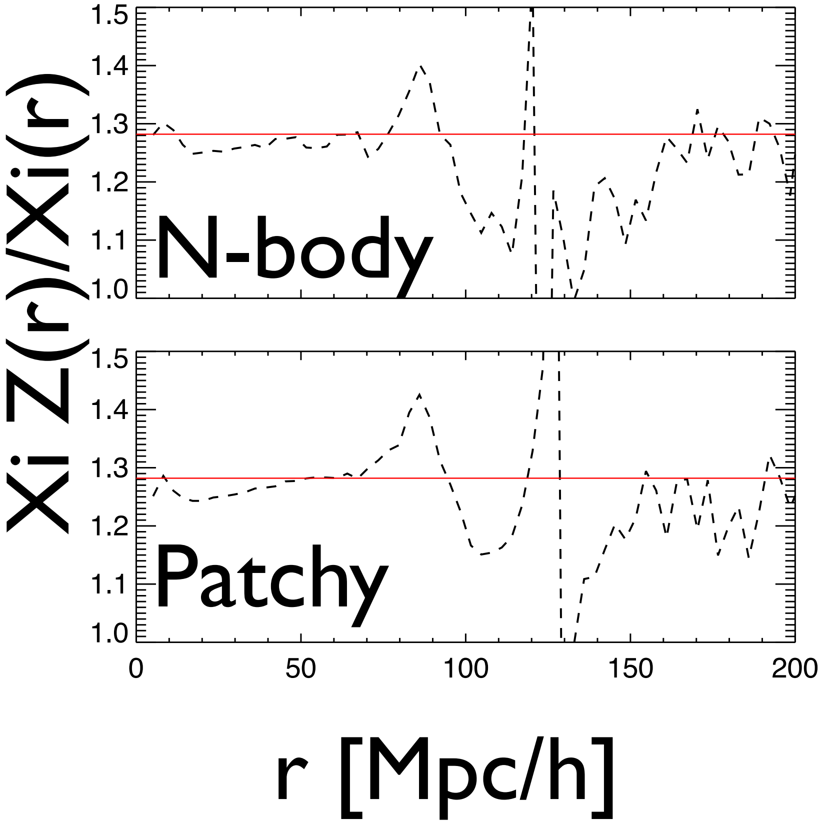


N-body in black

Patchy in red

agreement within 2%!

*Kaiser (87) factor due to RSD!*



1st time perturbation theory matches the two-point statistics in the nonlinear regime

# Three-point function

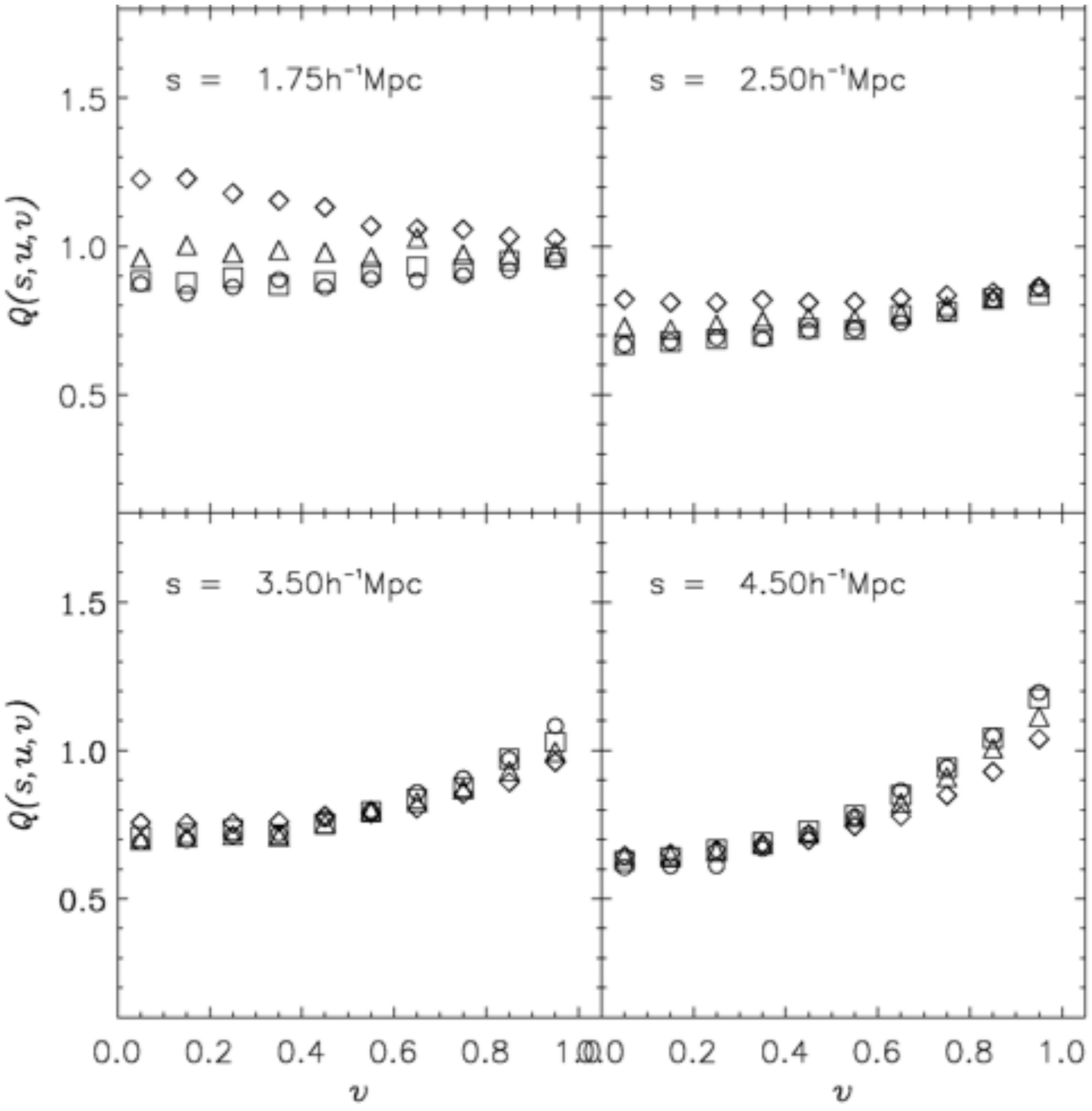
*calculations by Volker Müller*

◇ u=1.5
△ u=2.5
□ u=3.5
○ u=4.5

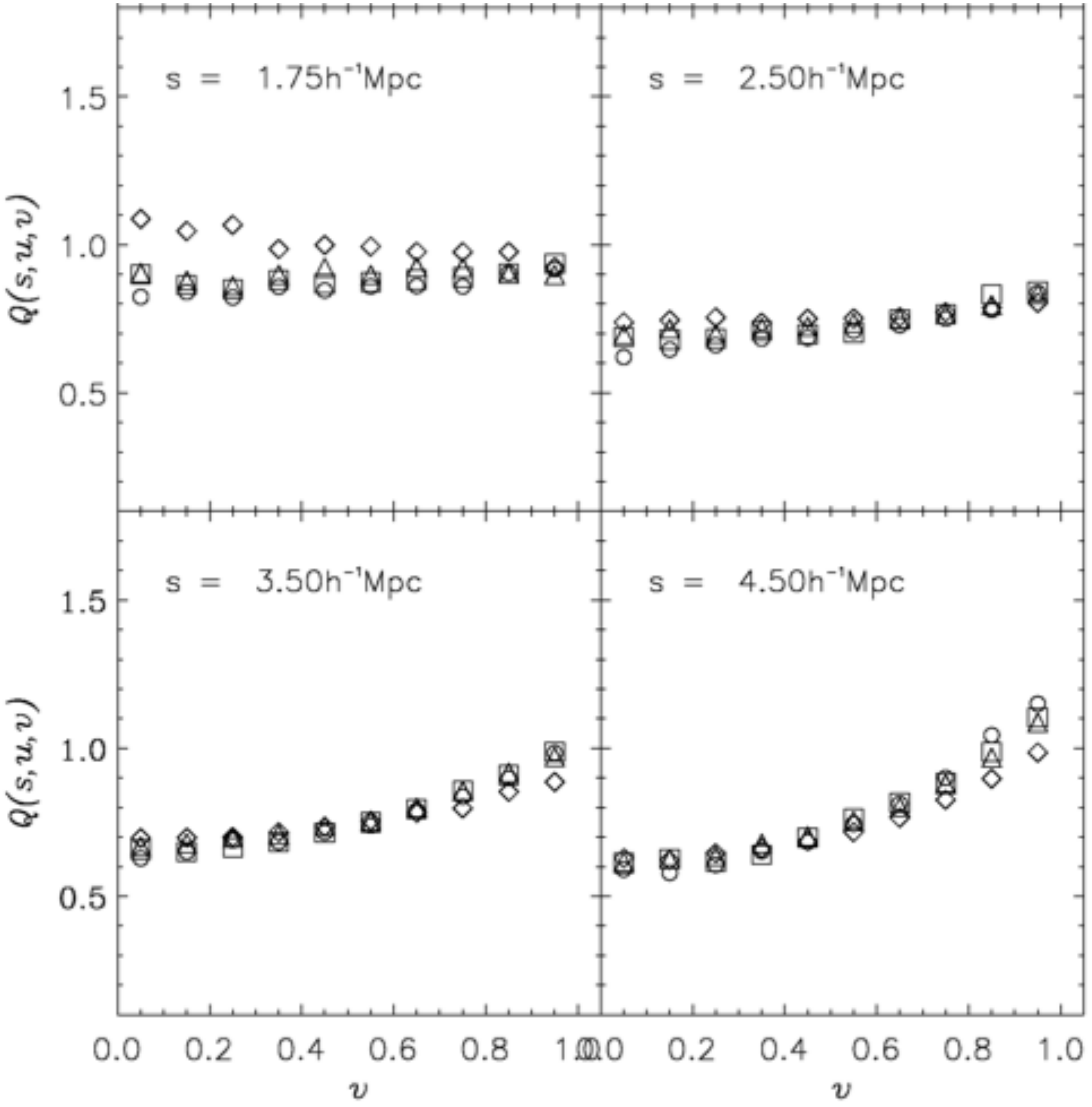
Triangle sides: s, su, and s(u+v)

The 3-point function is described by the hierarchical ansatz
Q(s,u,v) = (s,u,v)/( (r12) (r23)+c.c.),
i.e. the increase from v=0 to 1 means transition to linear structures.

N-body

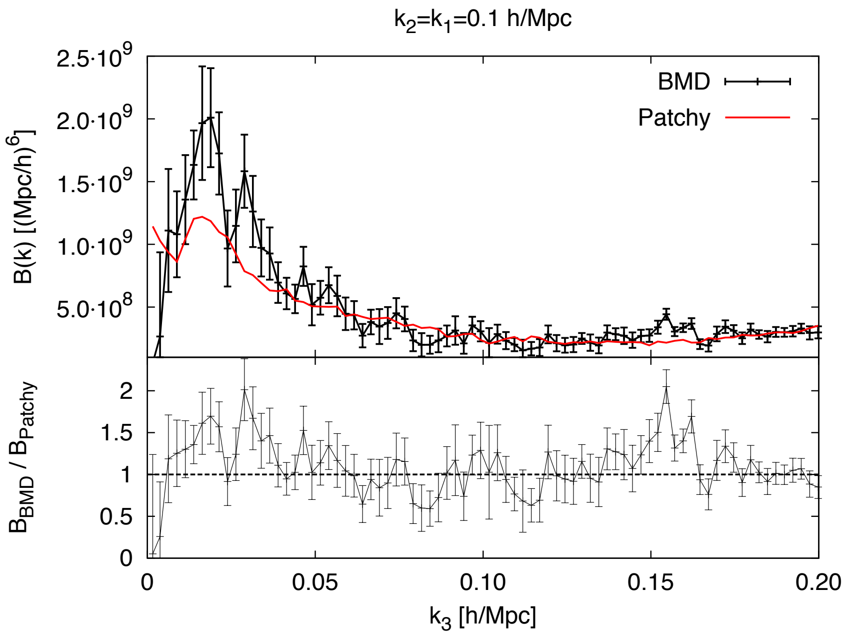


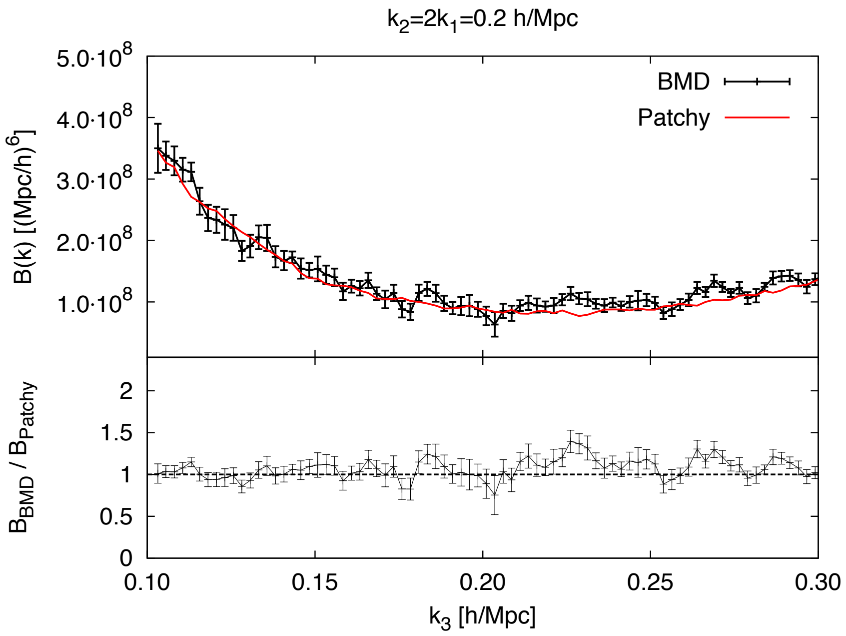
ALPT in PATCHY

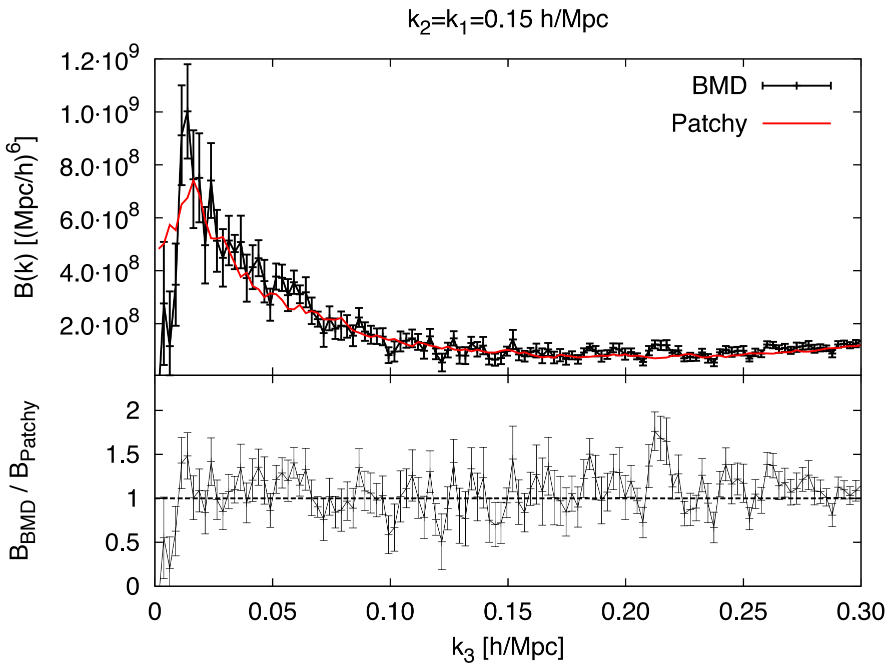


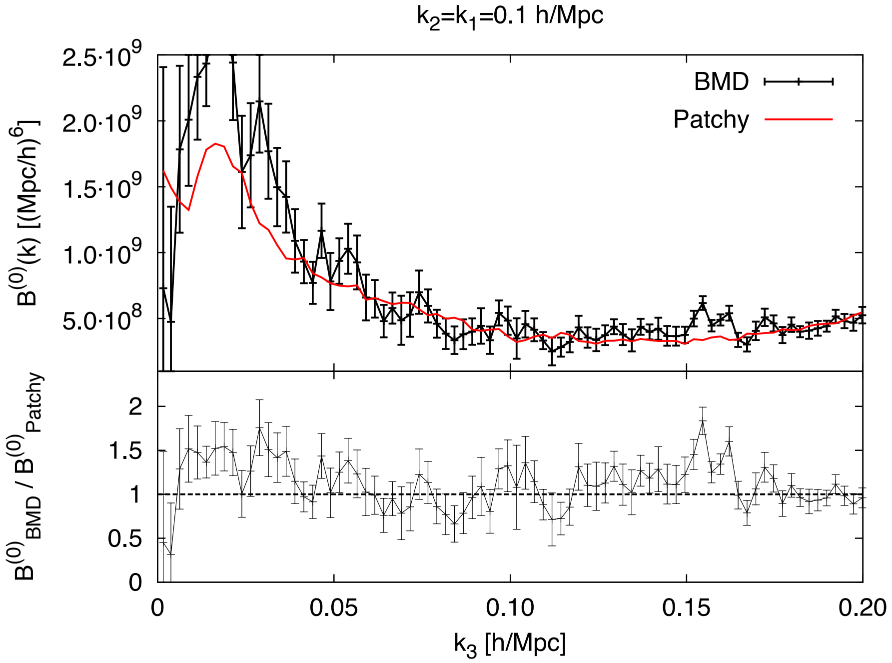
*calculations by Hector Gil-Marin*

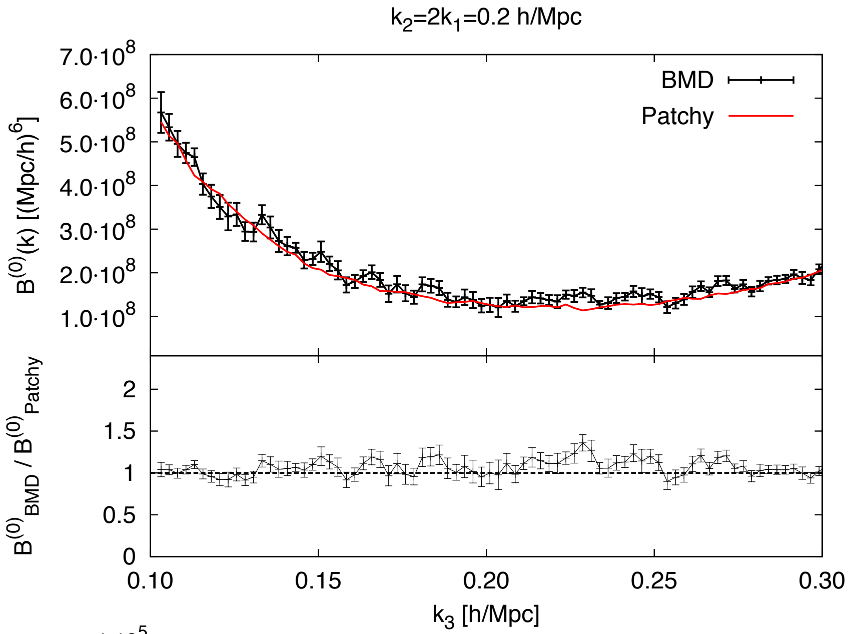
# Bispectrum

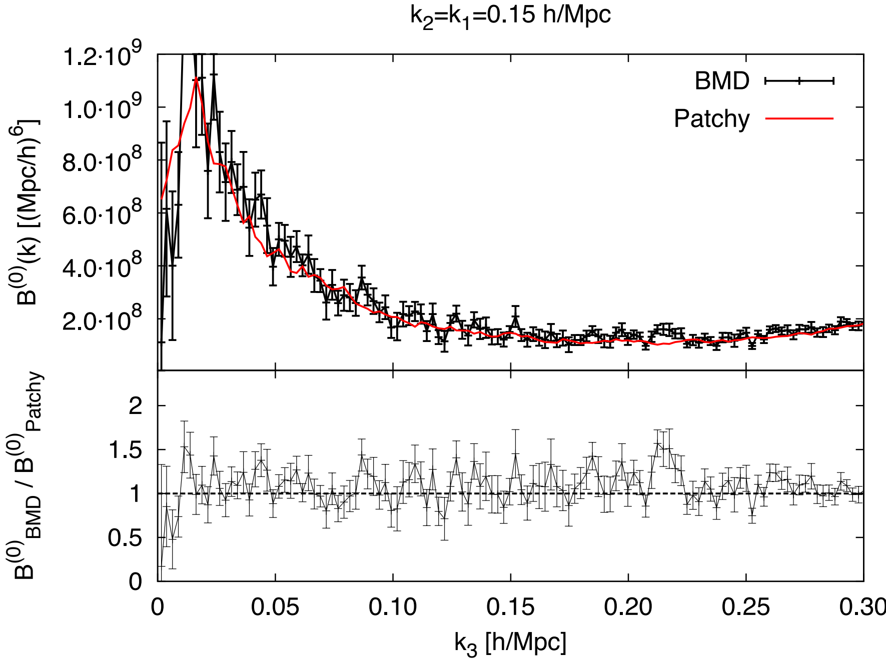


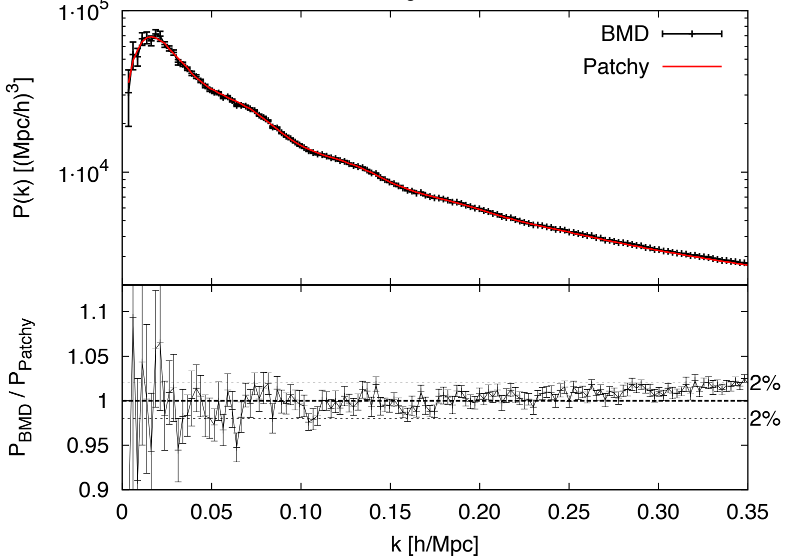












# Can we use this biasing description within Bayesian inference?

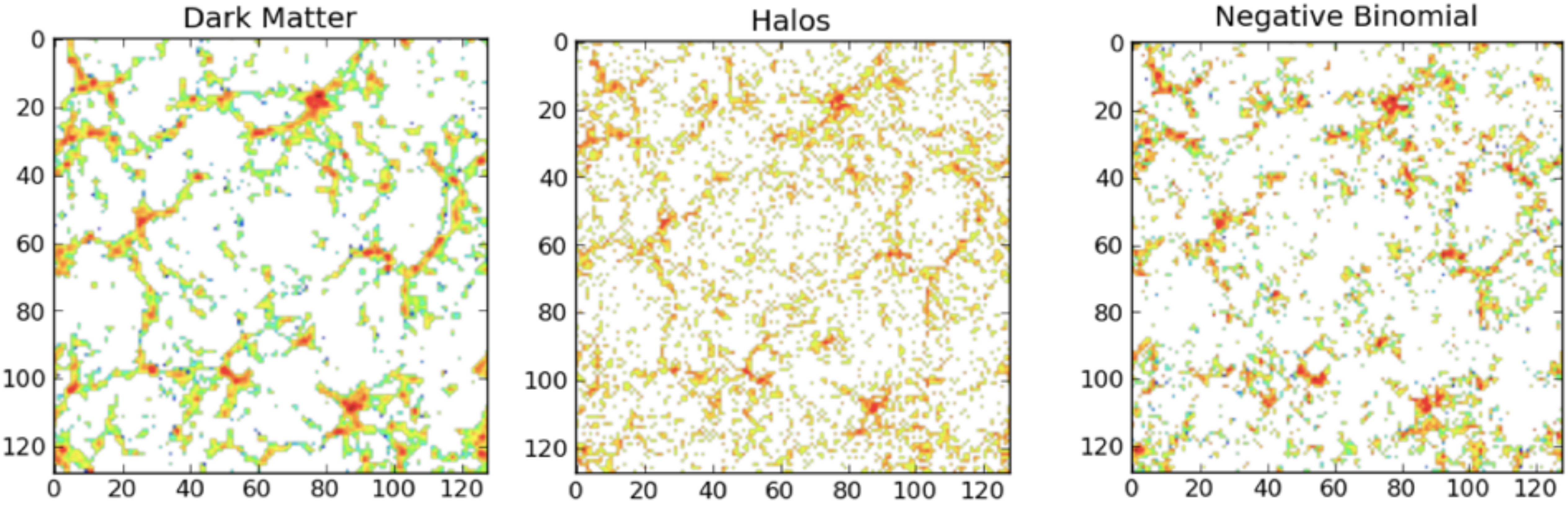
# Bayesian density reconstruction from biased galaxy data (e.g. eLGs)

$$\rho_h = f_h\,\theta(\rho_{\rm M}-\rho_{\rm th})\,\rho_{\rm M}^{\alpha}\,\exp\left[-\left(\frac{\rho_{\rm M}}{\rho_\epsilon}\right)^{\epsilon}\right]$$

*Ata, Kitaura & Müller to be submitted*

See Metin Ata's poster!

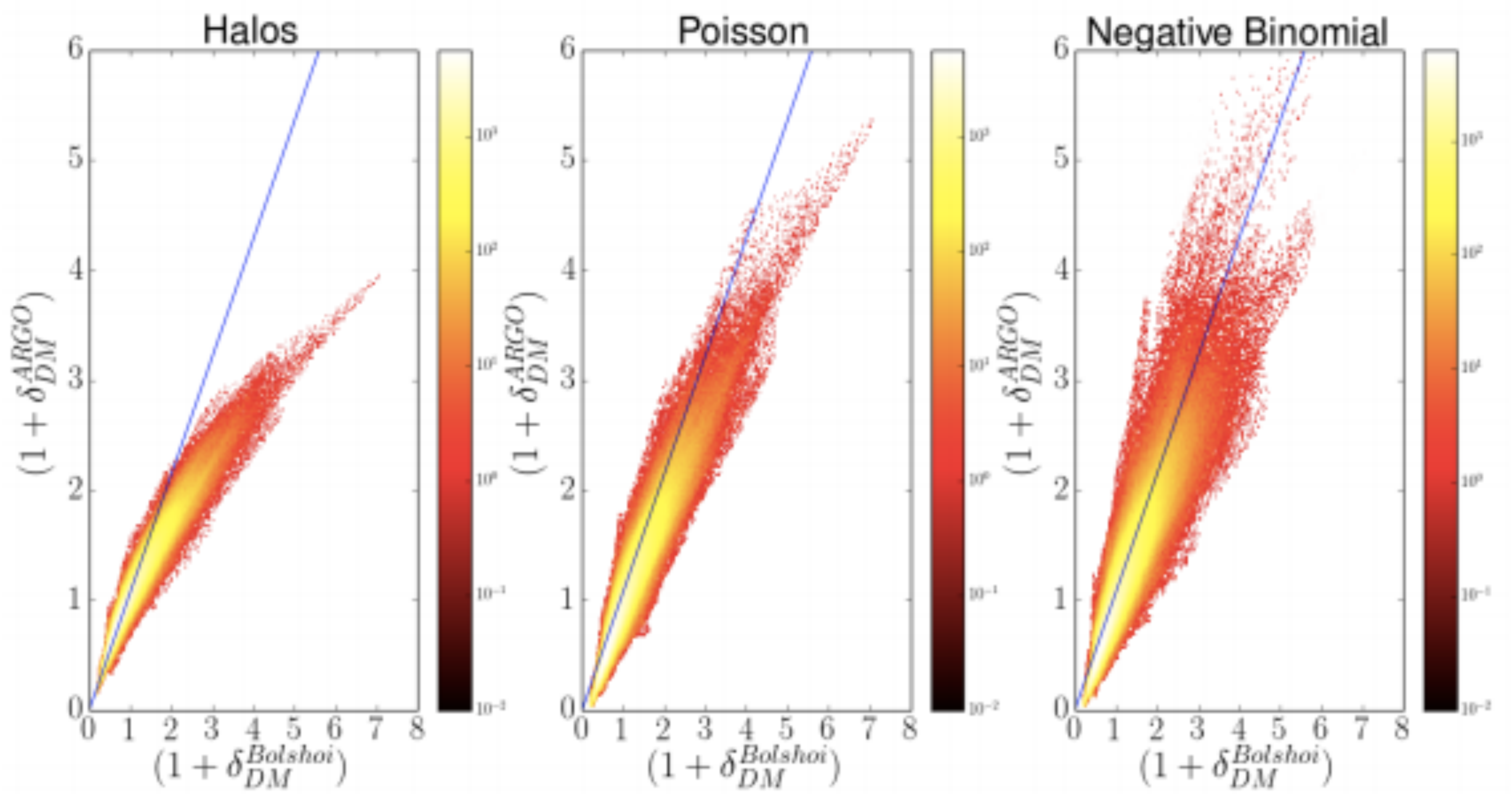
$$P(N_i \mid \lambda_i, \beta) = \frac{\lambda_i^{N_i}}{N_i!}\,\frac{\Gamma(\beta+N_i)}{\Gamma(\beta)(\beta+\lambda)^{N_i}}\,\frac{1}{(1+\lambda/\beta)^{\beta}}$$



Bayesian approach with the ARGO-code

*Kitaura & Enßlin 2008; Kitaura et al 2010; Kitaura et al 2012*

# Bayesian density reconstruction from biased galaxy data (e.g. eLGs)

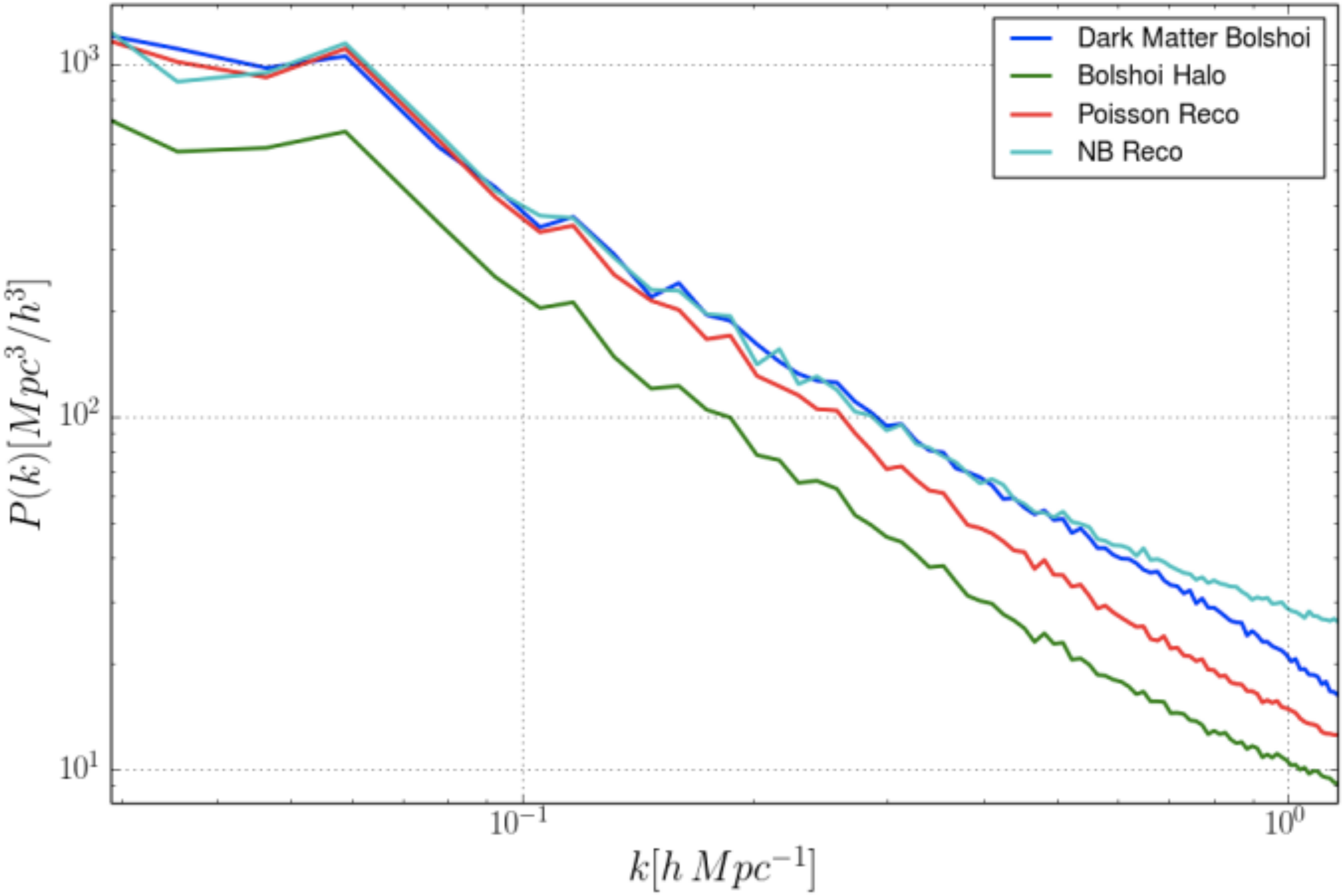


*Ata, Kitaura & Müller to be submitted*

1st time a nonlinear scale-dependent stochastic bias is explicitly implemented in a Bayesian framework

# Bayesian density reconstruction from biased galaxy data (e.g. eLGs)

unbiased DM field reconstructions in terms of cell-to-cell correlation and two-point statistics!



*Ata, Kitaura & Müller to be submitted*

# Can we improve the prior?

# Expansion of the Lognormal prior

see also talk by Dmitri Pogosyan and Sandrine Codis!

If we know the higher order correlations for the logarithm of the density field, we can perform multidimensional Edgeworth expansions:

*Kitaura F. S., 2012, MNRAS, 420, 2737, arXiv:1012.3168*

$$
\begin{aligned}
P(\boldsymbol{\Phi}) &= (\det(\mathbf{S}))^{-1/2} G(\boldsymbol{\nu}) \qquad (43)\\
&\times \Bigg[ 1 + \frac{1}{3!} \sum_{i'j'k'} \langle \Phi_{i'} \Phi_{j'} \Phi_{k'} \rangle_{\rm c} \sum_{ijk} S_{ii'}^{-1/2} S_{jj'}^{-1/2} S_{kk'}^{-1/2} h_{ijk}(\boldsymbol{\nu})\\
&+ \frac{1}{4!} \sum_{i'j'k'l'} \langle \Phi_{i'} \Phi_{j'} \Phi_{k'} \Phi_{l'} \rangle_{\rm c} \sum_{ijkl} S_{ii'}^{-1/2} S_{jj'}^{-1/2} S_{kk'}^{-1/2} S_{ll'}^{-1/2} h_{ijkl}(\boldsymbol{\nu})\\
&+ \frac{1}{6!} \sum_{i'j'k'l'm'n'}\\
&\times \left[ \frac{1}{3!3!2} \sum_{j_1 \ldots j_6 \in [1,\ldots,6]} \tilde{\epsilon}_{j_1 \ldots j_6} \langle \Phi_{i'_{j_1}} \Phi_{i'_{j_2}} \Phi_{i'_{j_3}} \rangle_{\rm c} \langle \Phi_{i'_{j_4}} \Phi_{i'_{j_5}} \Phi_{i'_{j_6}} \rangle_{\rm c} \right]_{10}\\
&\times \sum_{ijklmn} S_{ii'}^{-1/2} S_{jj'}^{-1/2} S_{kk'}^{-1/2} S_{ll'}^{-1/2} S_{mm'}^{-1/2} S_{nn'}^{-1/2} h_{ijklmn}(\boldsymbol{\nu}) + \ldots \Bigg],
\end{aligned}
$$

Univariate lognormal expansion introduced by *Colombi 1994*

Univariate Gaussian expansion *Juszkiewicz et al 1995*

If we know the higher order correlations for the logarithm of the density field, we can perform multidimensional Edgeworth expansions:

*Kitaura F. S., 2012, MNRAS, 420, 2737, arXiv:1012.3168*

$$P(\boldsymbol{\nu}) = G(\boldsymbol{\nu})\left[1+\mathcal{S}(\boldsymbol{\nu})+\mathcal{K}(\boldsymbol{\nu})+\ldots\right]$$

$$\boldsymbol{\Phi} \equiv \ln\boldsymbol{\rho} - \langle \ln\boldsymbol{\rho}\rangle \qquad\qquad \nu_i \equiv \sum_j S_{ij}^{-1/2}\Phi_j$$

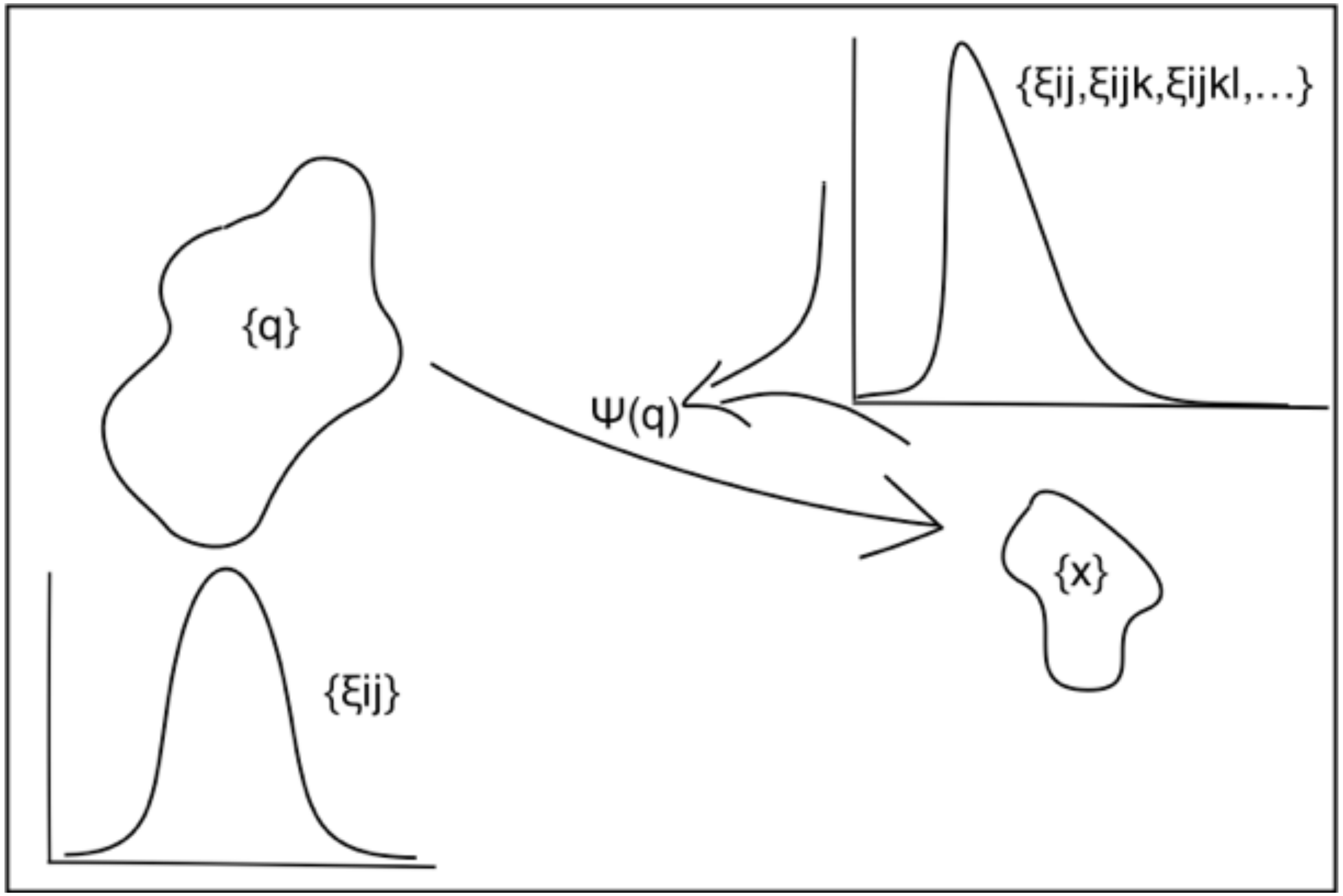
$$\begin{aligned}\mathcal{S}(\boldsymbol{\nu}) &\equiv \frac{1}{3!}\sum_{ijk}\kappa_{ijk}h_{ijk}(\boldsymbol{\nu}) = \frac{1}{3!}\sum_{i'j'k'}\xi_{i'j'k'}\tilde{h}_{i'j'k'}(\boldsymbol{\nu}) \qquad (60)\\ &= \frac{Q_3}{3!}\sum_{i'j'k'}\left[S_{i'j'}S_{i'k'}+S_{i'j'}S_{j'k'}+S_{i'k'}S_{j'k'}\right]\tilde{h}_{i'j'k'}(\boldsymbol{\nu})\\ &= Q_3\left[\frac{1}{2}\sum_i\Phi_i^2\eta_i-\frac{1}{2}\sum_i S_{ii}\eta_i-\sum_i\Phi_i\right],\end{aligned}$$

complicated + expensive!

$$\eta_i \equiv \sum_j S_{ij}^{-1}\Phi_j$$

# Can we improve the prior with a physical model?

# The reconstruction problem: Lagrangian to Eulerian problem



primordial density fluctuations can be fully characterized by the 2-point correlation function (neglecting non-Gaussianities)
the action of gravity can be summarised by the displacement field

## Towards forward approaches

*see Kitaura 2013, Kitaura et al 2012*
*Jasche & Wandelt 2013, Wang et al 2013, Hess et al 2013*

# The posterior distribution function of the primordial fluctuations

$$\delta(\boldsymbol{q}) \curvearrowleft P(\delta(\boldsymbol{q})|\{\boldsymbol{s}\}, \mathcal{M}_\Psi, \mathcal{M}_v, \mathcal{B}_{\mathrm{EUL}}, \{p_{\mathrm{c}}\})$$

$$\boldsymbol{s} = \boldsymbol{q} + \boldsymbol{\Psi} + (\boldsymbol{v} \cdot \hat{\boldsymbol{r}})\hat{\boldsymbol{r}}/(Ha))$$

# The posterior distribution function of the primordial fluctuations

If we ignore the nonlinear stochastic Bias and RSDs and use a 2LPT-Poisson model

$$\delta(\boldsymbol{q}) \curvearrowleft P(\delta(\boldsymbol{q})|\{\boldsymbol{s}\}, \mathcal{M}_{\Psi}, \{p_{\rm c}\})$$

very complex solution, but beautiful, because it is a one-step posterior expression!

solution by *Jasche & Wandelt 2013*

see Florent Leclerque's talk

It can be improved with data preparation:
halo model reconstruction and linear RSDs correction

solution within Zeldovich approximation by

*Wang et al 2013*

self-consistent RSDs correction is missing see Patrick Bos' talk radical simplification of the problem ready for arbitrary structure formation model through Gibbs-sampling splitting approach:

# Bayesian Networks Machine Learning (artificial intelligence)

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

adaptive, particle based likelihood comparison

$$\delta(\boldsymbol{q}) \curvearrowleft P(\delta(\boldsymbol{q})|\{\boldsymbol{q}\},\mathcal{B}_{\rm LAG})$$

$$\{\boldsymbol{q}\} \curvearrowleft P(\{\boldsymbol{q}\}|\{\boldsymbol{s}\},\delta(\boldsymbol{q}),\mathcal{M}_{\Psi},\mathcal{M}_{v},\{p_{\rm c}\})$$

1) constrained realisation

*Bertschinger 87; Hoffman & Ribak 91;*
*van de Weygaert & Bertschinger 96; Jasche & FK 10, FK+12*

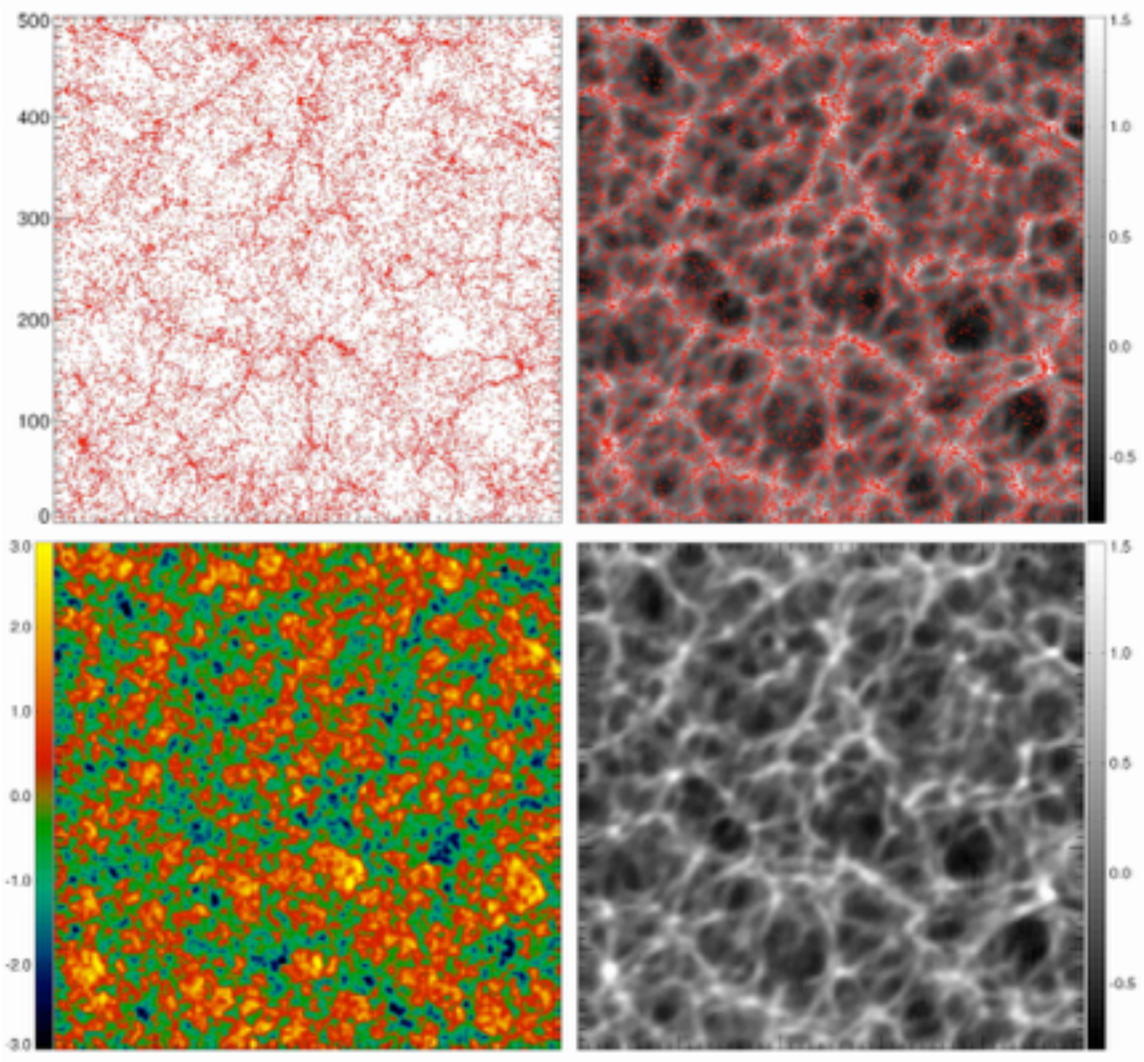
2) constrained simulation

# **KIGEN-code:** 1st self-consistent phase-space reconstruction code

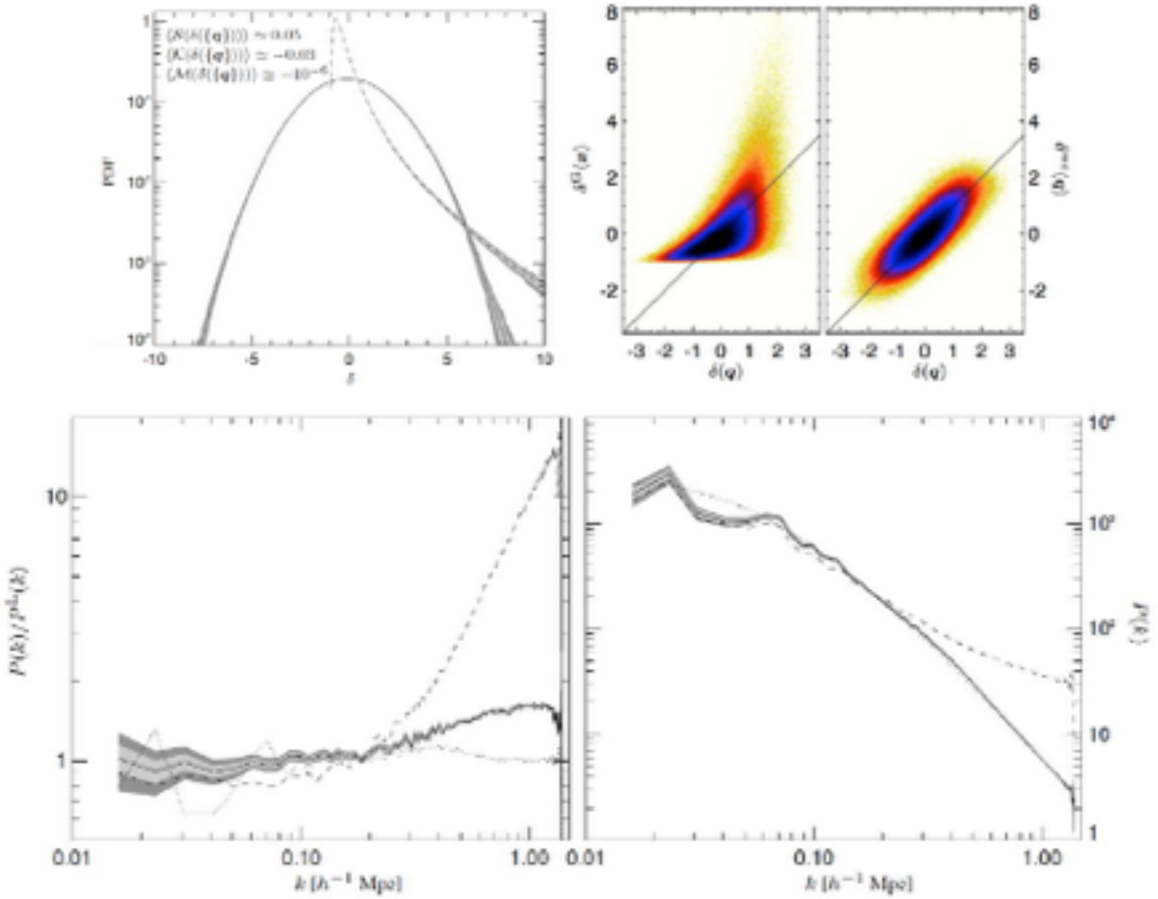
## Hamiltonian sampling combined with Gibbs-sampling

*Kitaura F. S., 2013, MNRAS, 429, L84, arXiv:1203.4184*

*Kitaura F. S., Erdogdu P., Nuza S. E., Khalatjan A., Angulo R. E., Hoffman Y. & Gottlöber S., 2012, MNRAS, arXiv:1205.5560*



Top Left: de Lucia mock catalog at z=0
Bottom Left: reconstructed ICs
Right: Cosmic Web at z=0



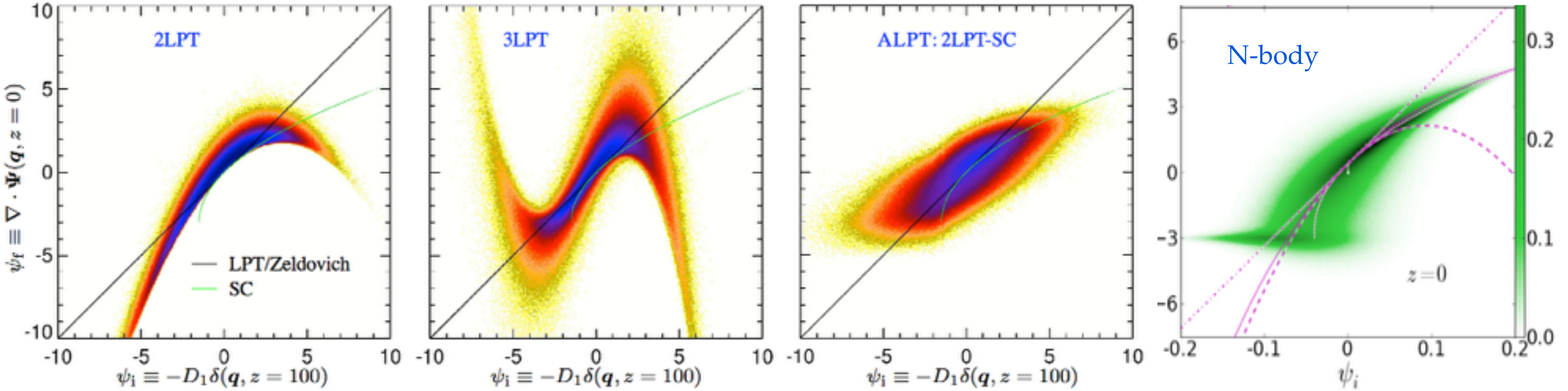
Top Left: matter PDF z=0 and z=127
Top Right: cell-to-cell between mock galaxy vs N-body ICs fields
Millennium Run and Reconstructed ICs vs N-body ICs
Bottom: Power-spectra ratio and power-spectra

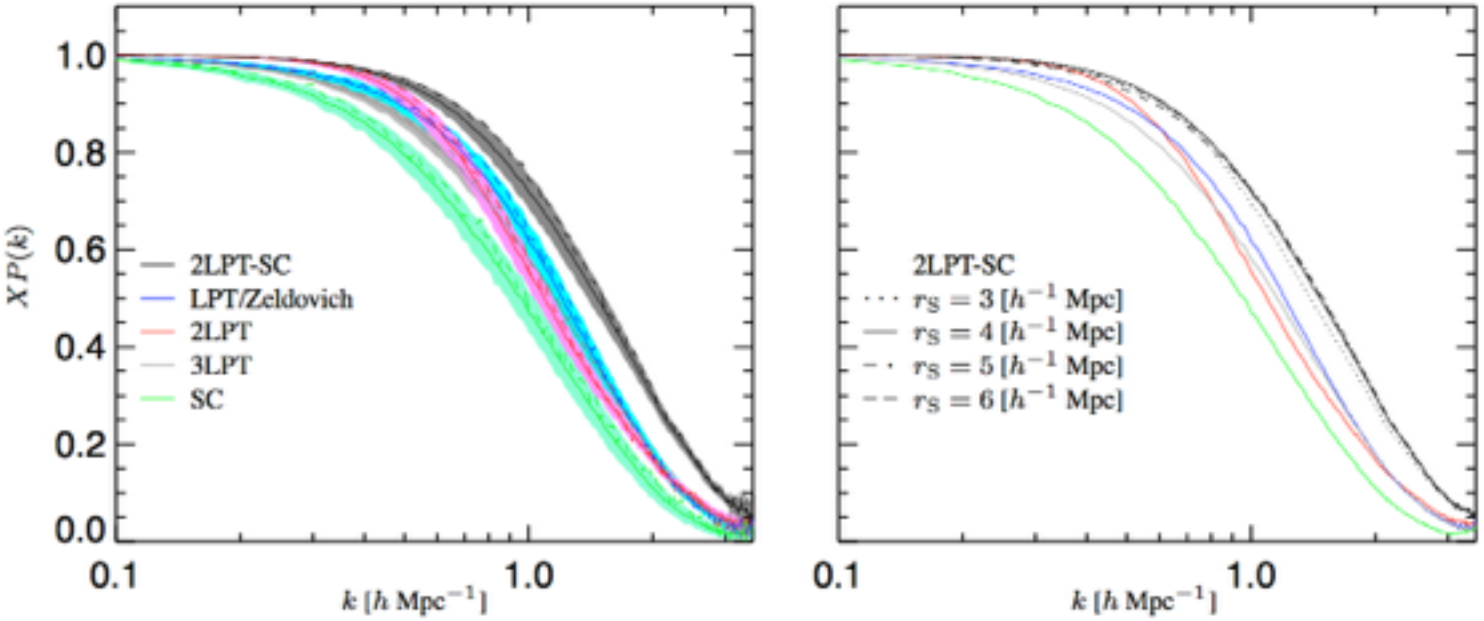
We need accurate and efficient structure formation models!

# ALPT: Augmented Lagrangian Perturbation Theory

*Kitaura F. S. & Heß S. 2013, MNRAS, 435, L78, arXiv:1212.3514*

*the instability of higher order LPT Sahni V. & Shandarin S. 1996*



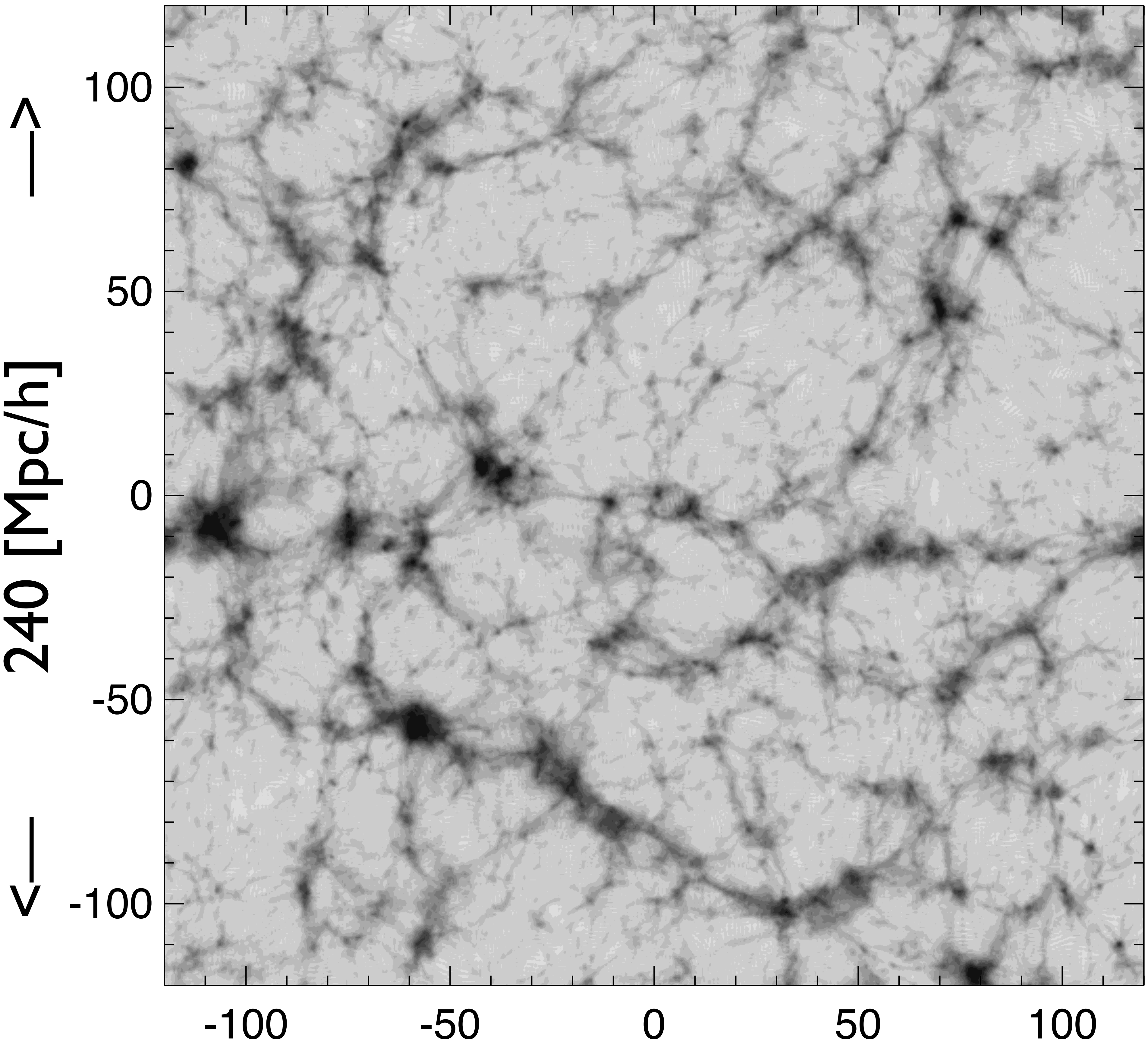


Top: relation between displacement field divergence vs ICs density field
Left: normalised cross-power spectra (propagator) at z=0 for different approximations vs N-body

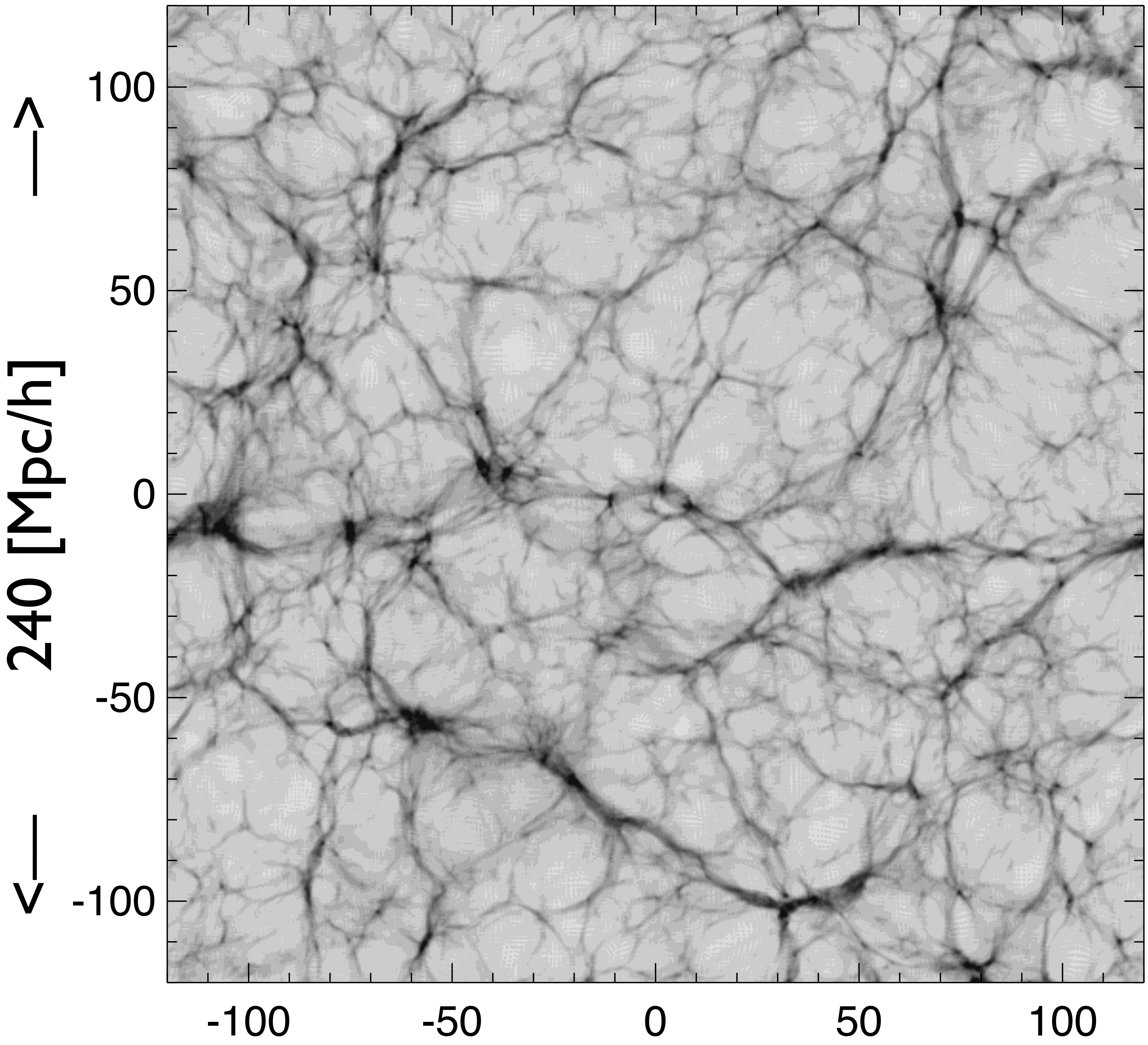
*for N-body relation see Neyrinck M. C., 2013, MNRAS, 428, 141*
*for the spherical collapse relation see also Bernardeau F. 1994; Mohayee R. 2006*

*see also Tassev S. & Zaldarriaga M., 2012, JCAP, 4, 13 for other LPT improvements with transfer functions (less correlated with the N-body solution than ALPT)*

# 2LPT z=0



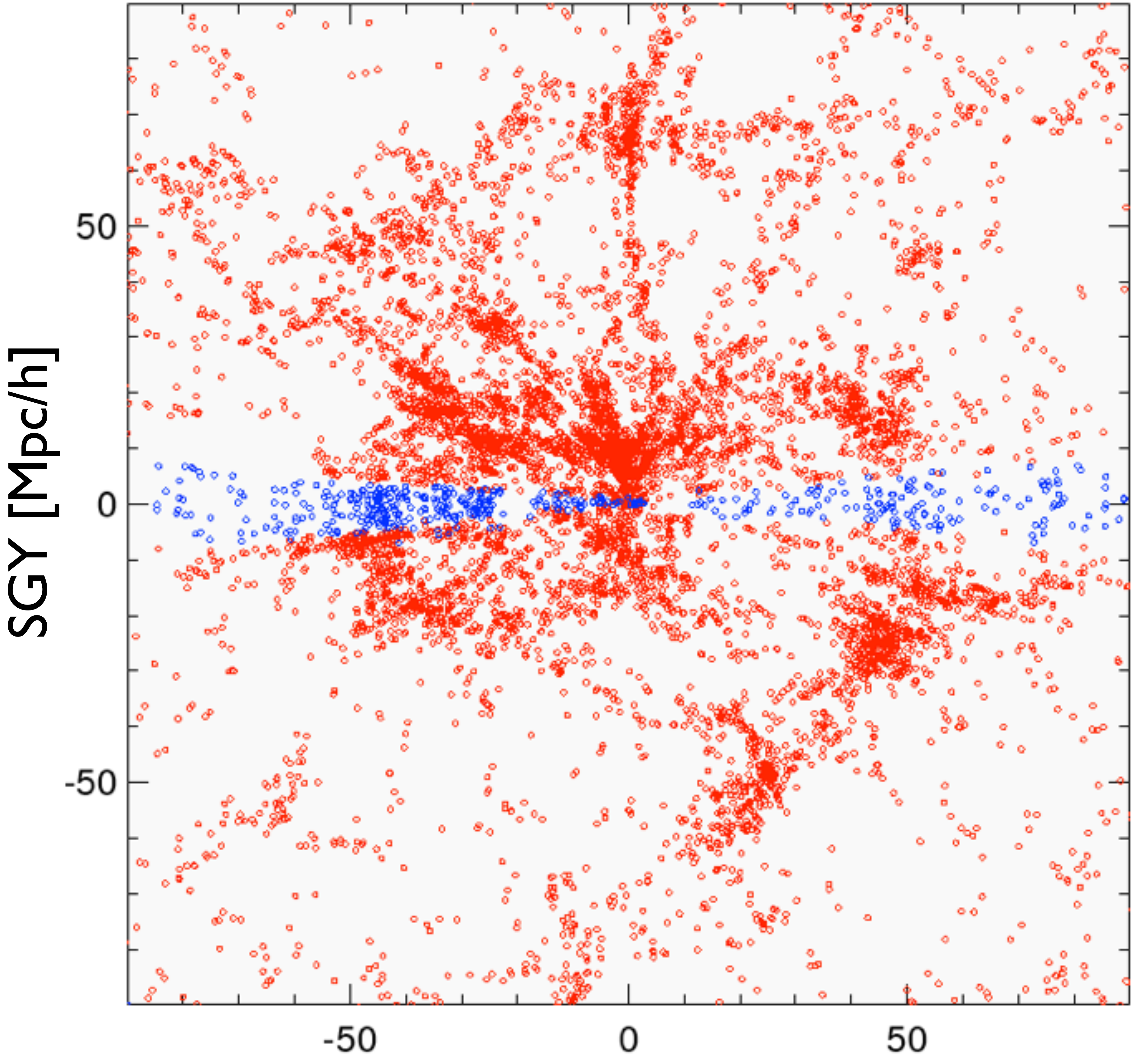
ALPT z=0



Now we have a complete method!

# Applications to the Local Volume

# 44,599 2MRS galaxies with Ks <= 11.75 mag and |b| >= 5  97.6% complete covers 91% of the sky

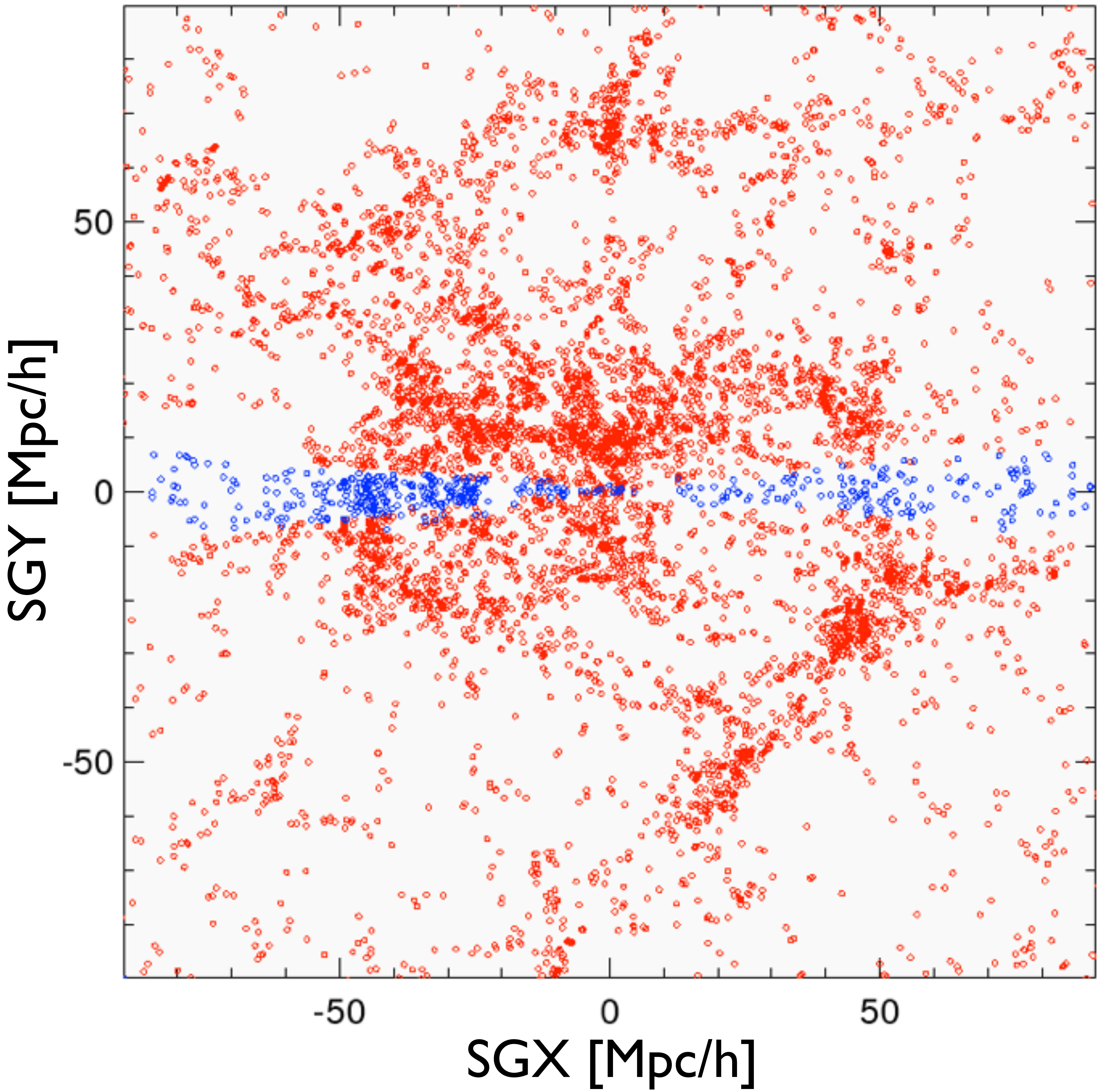


*Huchra J. P., Macri L. M., Masters K. L., Jarrett T. H. et al 2012, Rev.Astrn.Astrophys., 199, 26*

remember Maciej Bilicki's talk

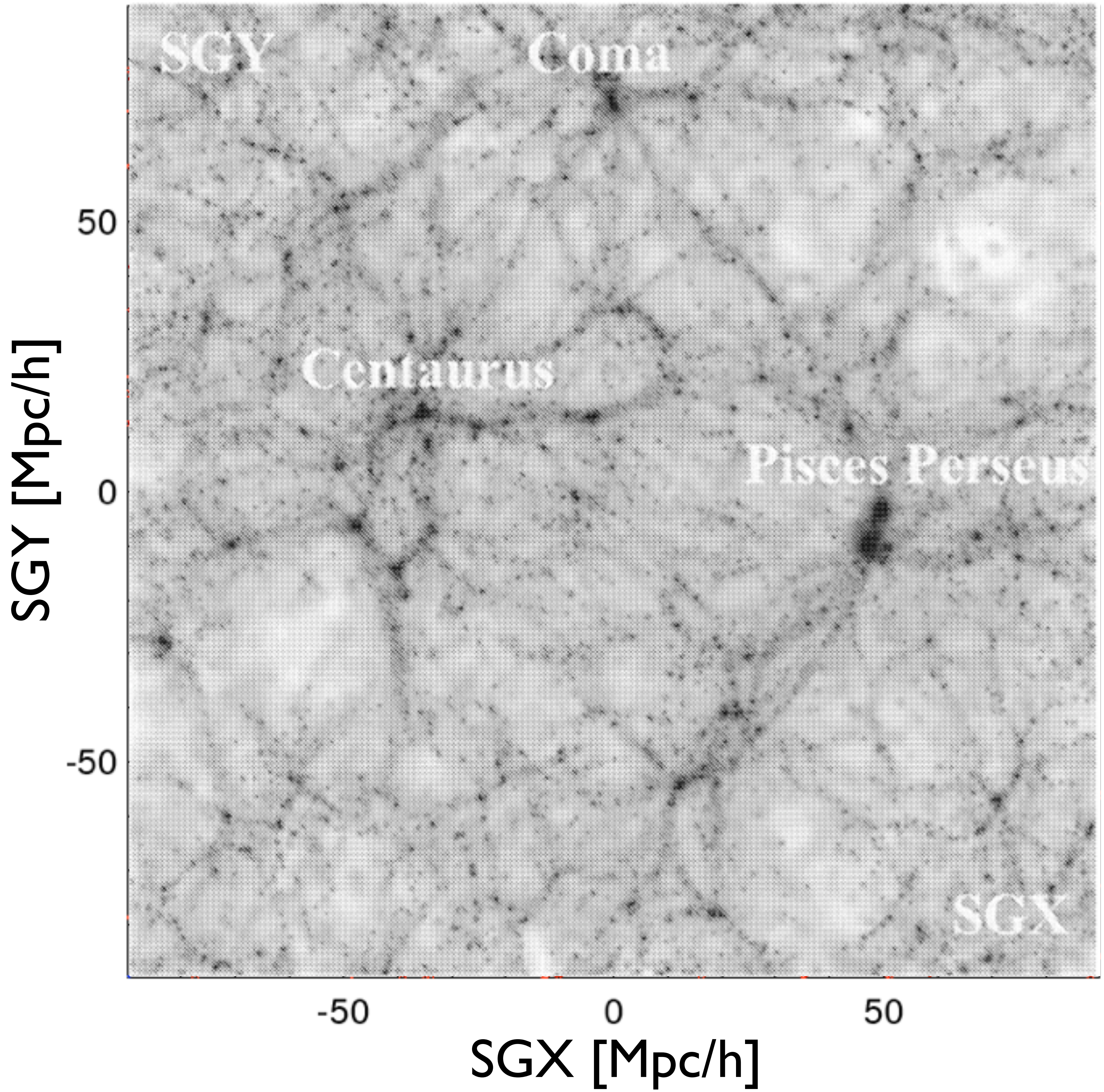
see Elmo Tempel's talk

fogs compression



*Kitaura F. S. & Khalatjan A.*
*using Tegmark M. et al., ApJ, 606, 702*

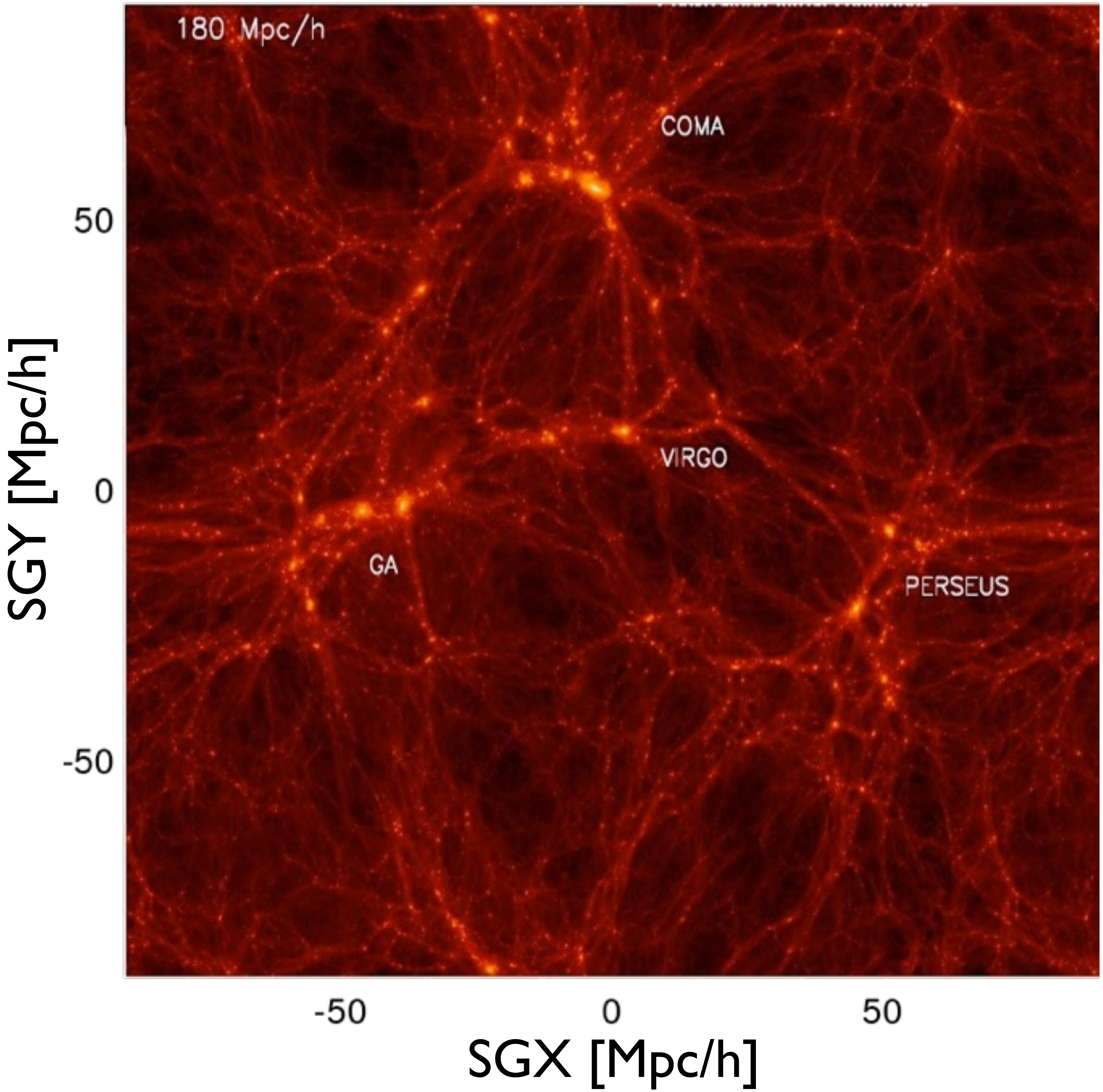
# 2002 from the IRAS survey with reverse Zeldovich



*Mathis H., Lemson G., Springel V., Kauffmann G., White S. D. M., Eldar, A. & Dekel A., 2002, MNRAS, 333, 739*

2003 from velocity fields
see new generation Source et al 2014 with reverse Zeldovich

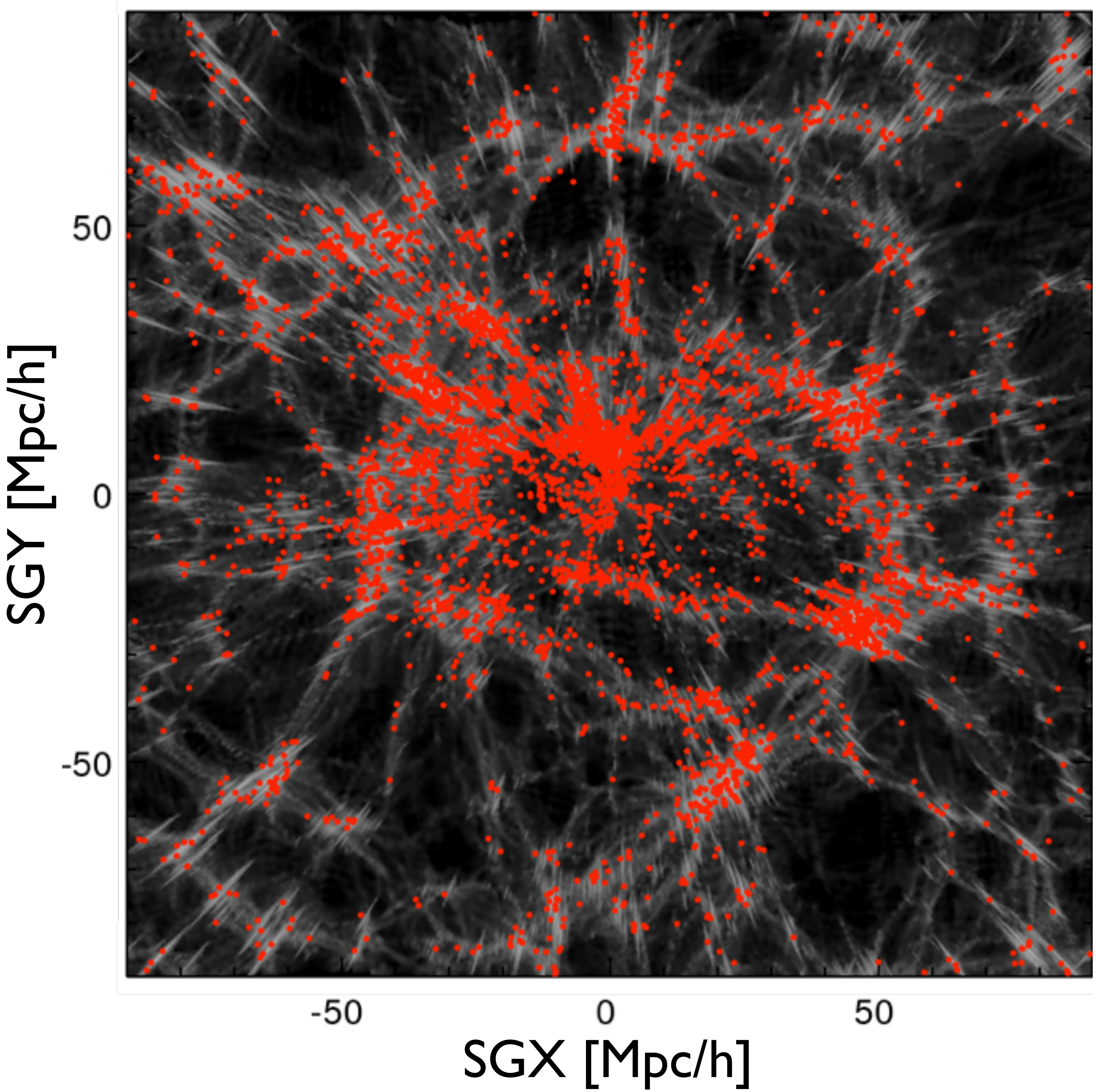
see Stefan Gottlöber's talk



*Klypin A., Hoffman Y., Kravtsov A. V., Gottlöber S., 2003, ApJ, 596, 19*

# 2013: 1st constrained simulation based on a self-consistent phase-space reconstruction code

*Hess Steffen, Kitaura F. S. & Gottlöber S., 2013, MNRAS, 435, 2065, arXiv:1304.6565*



Red dots represent galaxies from the 2MRS survey (2% are randomly augmented in the galactic plane)

Underlying countour represents the DM constrained simulation

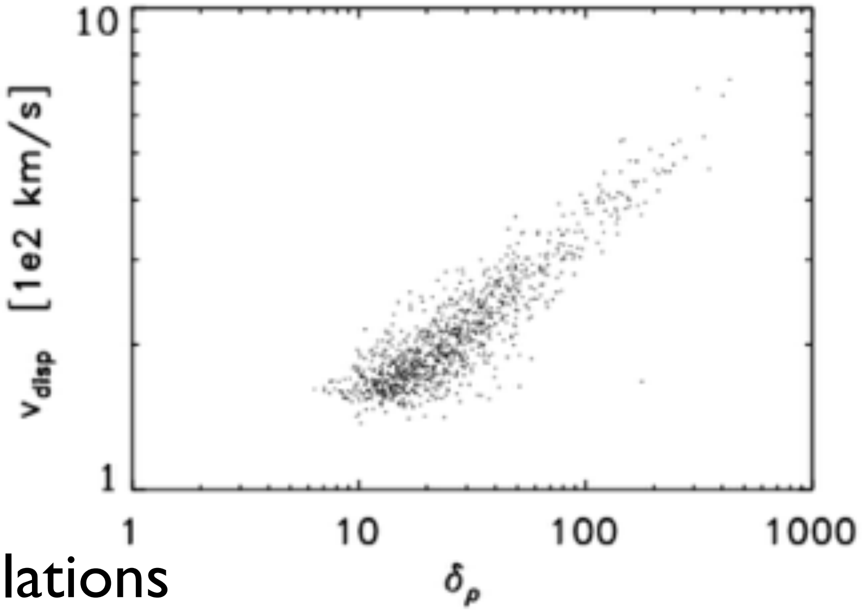
# Modelling redshift space distortions

*Kitaura F. S. PhD 2007 from MR sim (Hess & Kitaura in prep)*

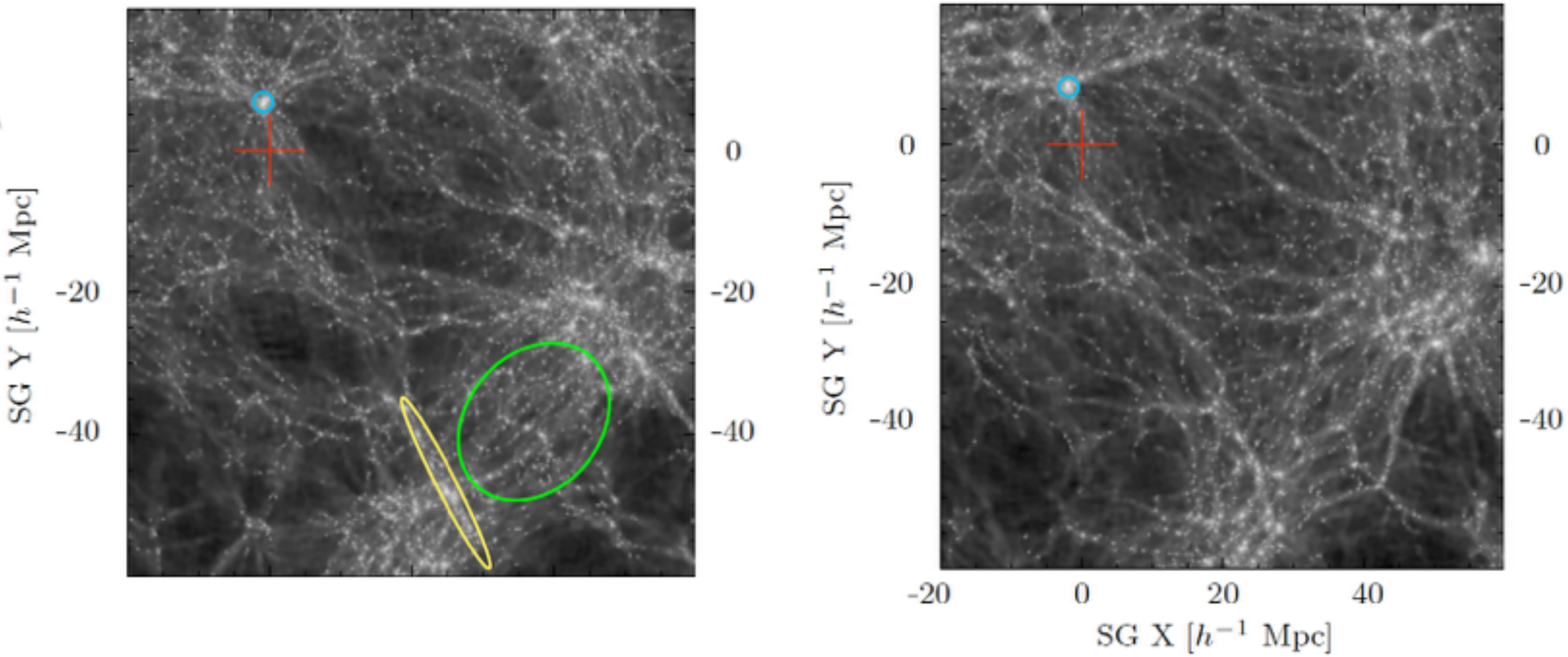
*Kitaura, Yepes & Prada 2014, MNRAS*

$$\boldsymbol{v} = \boldsymbol{v}^{\rm coh} + \boldsymbol{v}^{\sigma}$$

$$\boldsymbol{v}^\sigma_r \equiv (\boldsymbol{v}^\sigma\cdot\hat{\boldsymbol{r}})\hat{\boldsymbol{r}}/(Ha) = \mathcal{G}\left(g\times\left(1+b^{\rm ALPT}\delta^{\rm ALPT}(\boldsymbol{x})\right)^{\gamma}\right)\hat{\boldsymbol{r}}$$



Application of KIGEN to 2MRS: constrained simulations



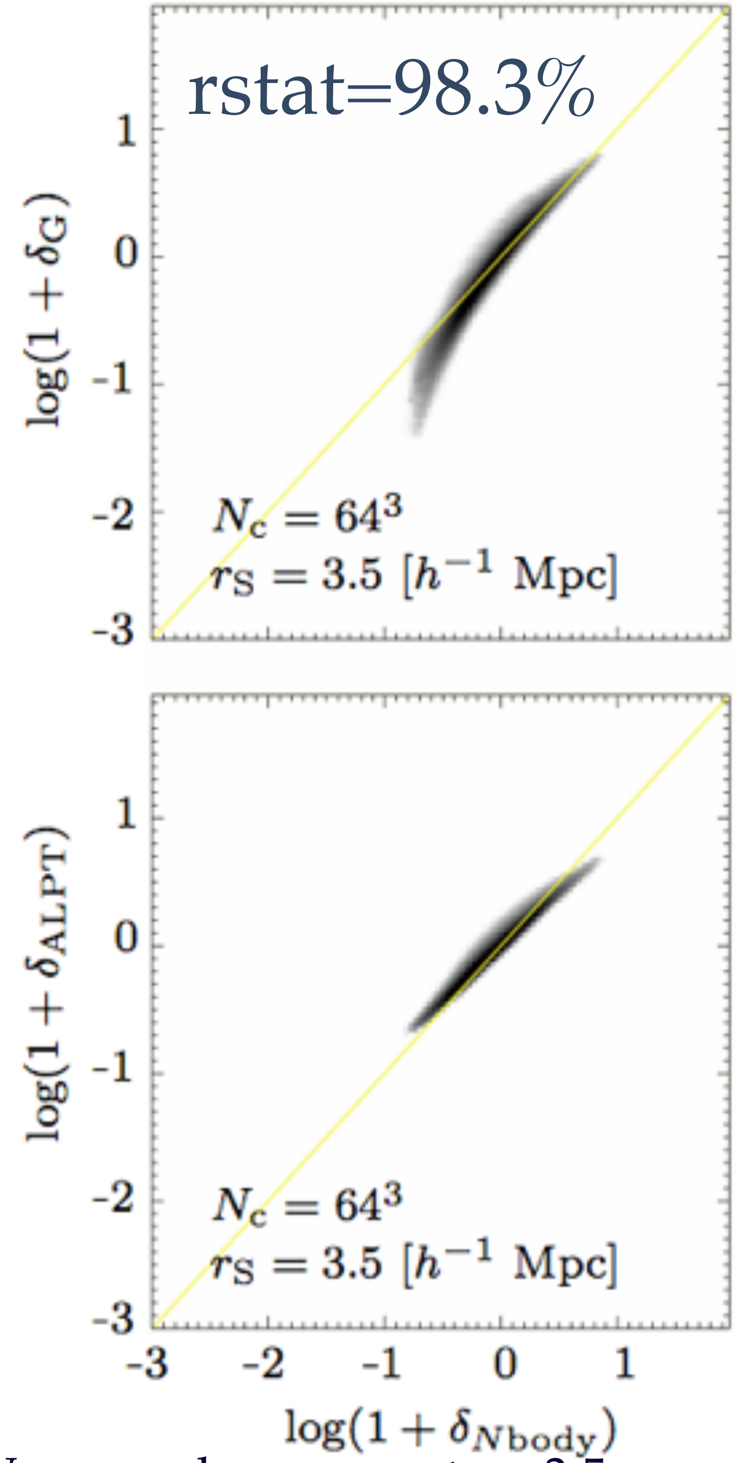
Left: constrained simulation based on 2LPT and compressed fogs

Right: constrained simulation based on ALPT modelling fogs

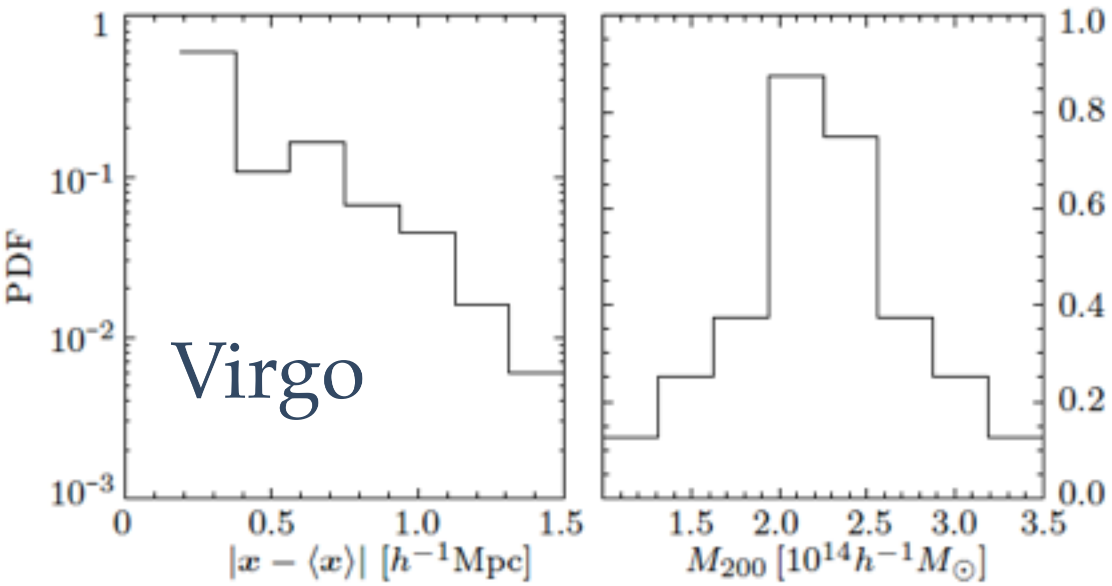
*Hess Steffen, Kitaura F. S. & Gottlöber S., 2013, MNRAS, 435, 2065*

*Hess Steffen, Kitaura F. S. & Gottlöber S., 2013, MNRAS, 435, 2065*

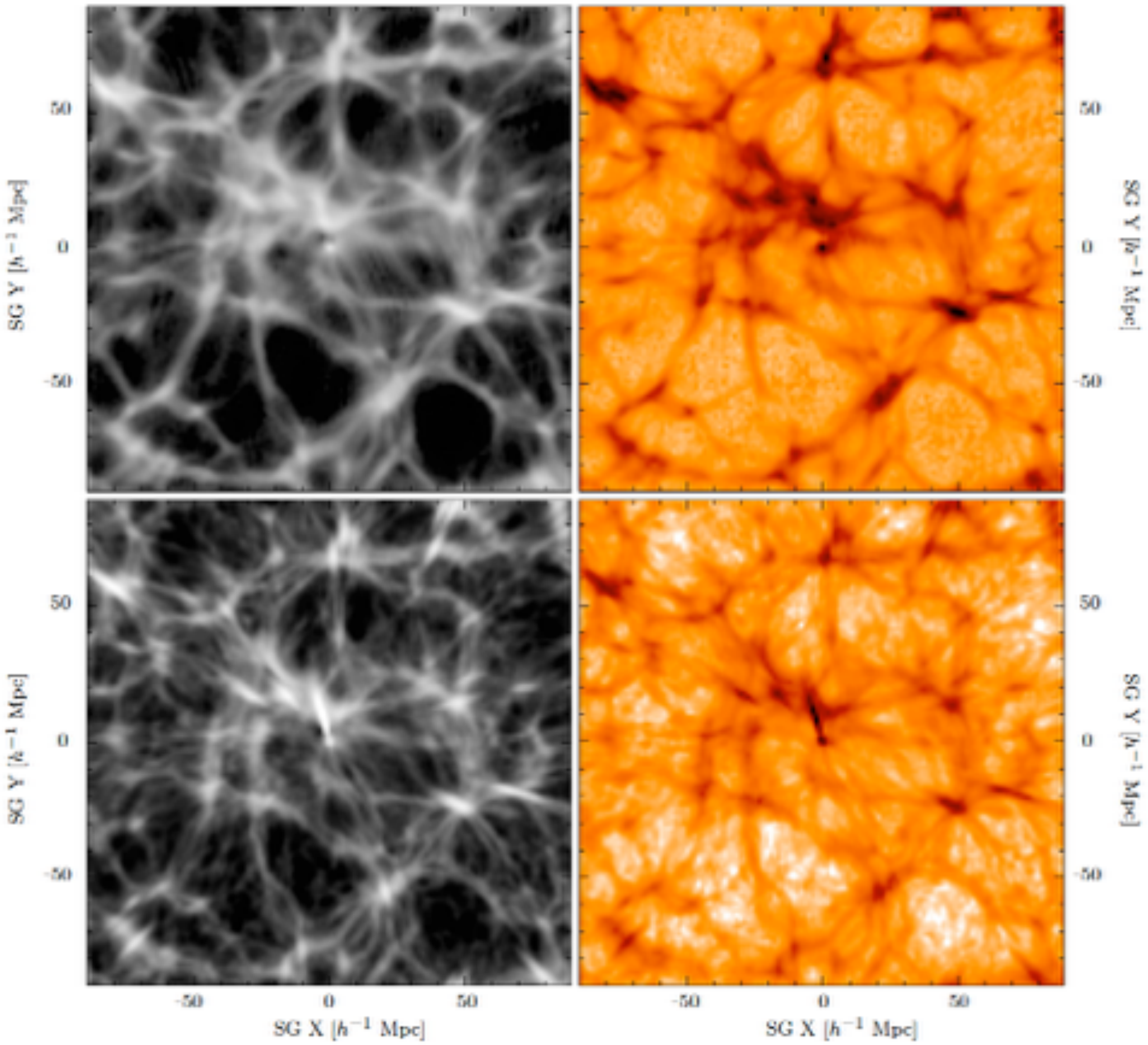
correlation shows bias between 2MRS galaxies and reconstructed DM field:



Very good agreement on 3.5 Mpc/h scales between ALPT and N-body



Small scatter for Virgo candidate indicates a precision of 1-2 Mpc/h

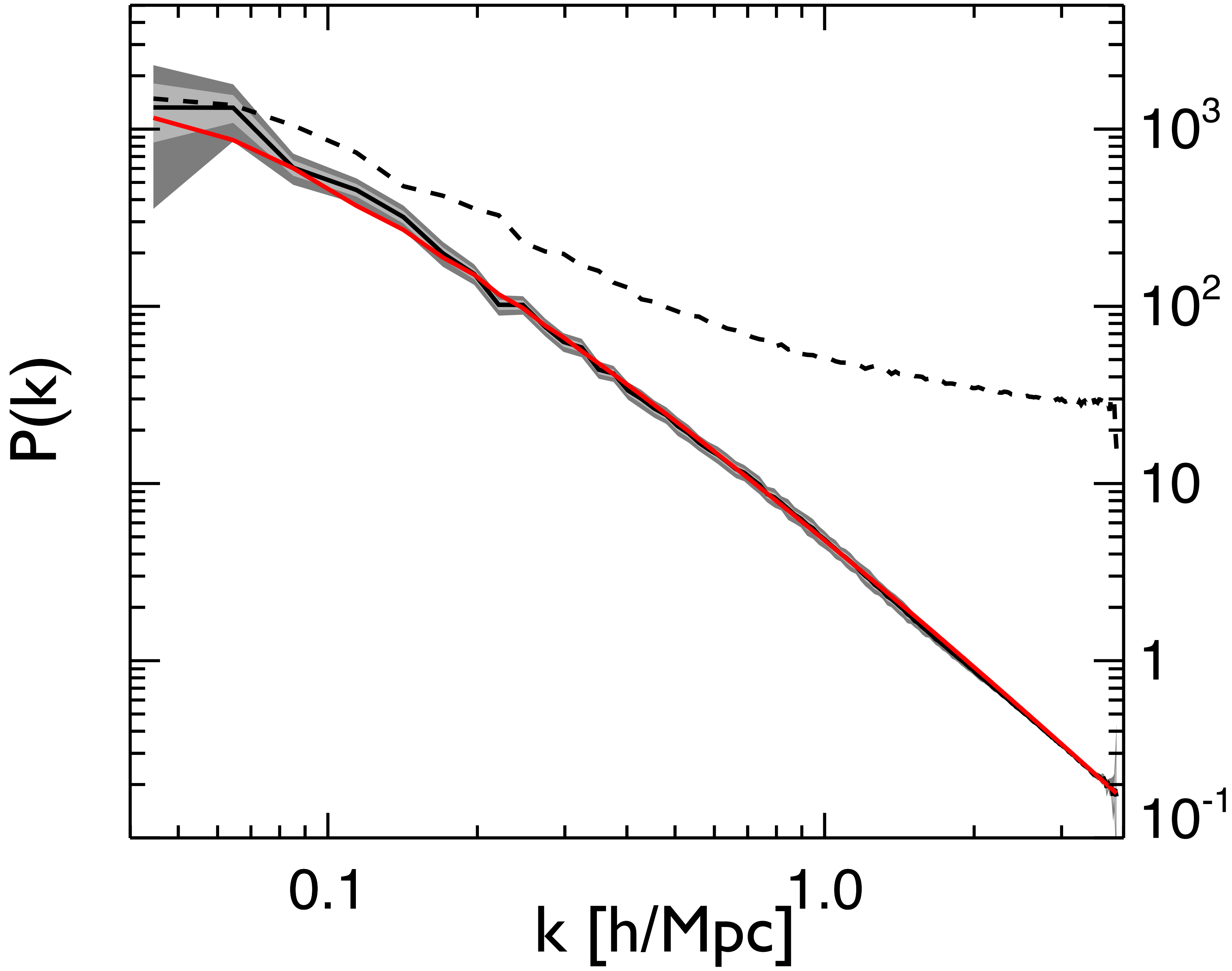


Top: mean and signal-to-noise ratio from 25 reconstructions with ALPT

Bottom: same from N-body simulations

please ask me how we can solve for the nonlinear, stochastic bias!

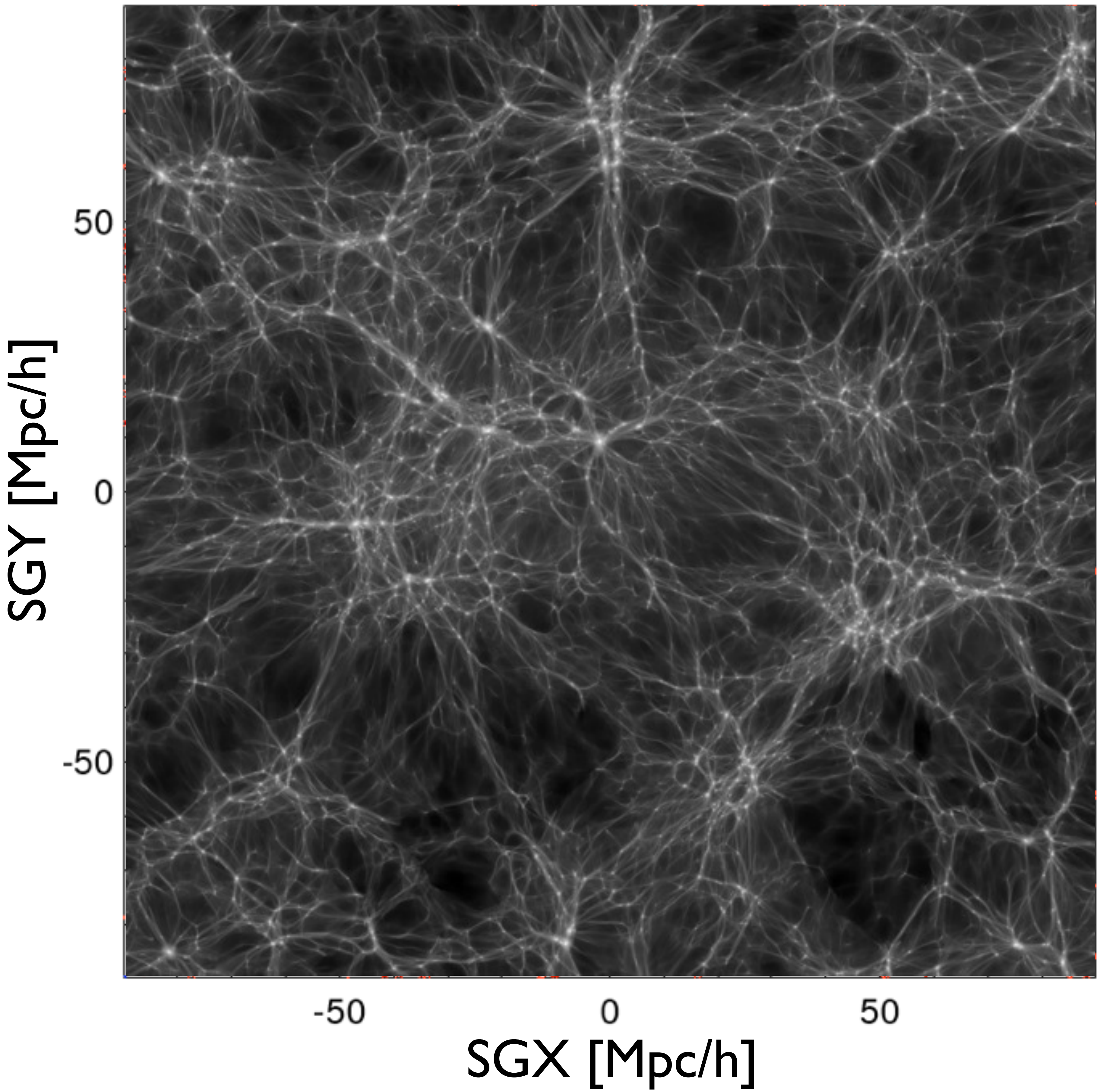
we obtain unbiased reconstructions in real-space!



If we have the initial conditions then we have the full phase-space information including the peculiar motions!

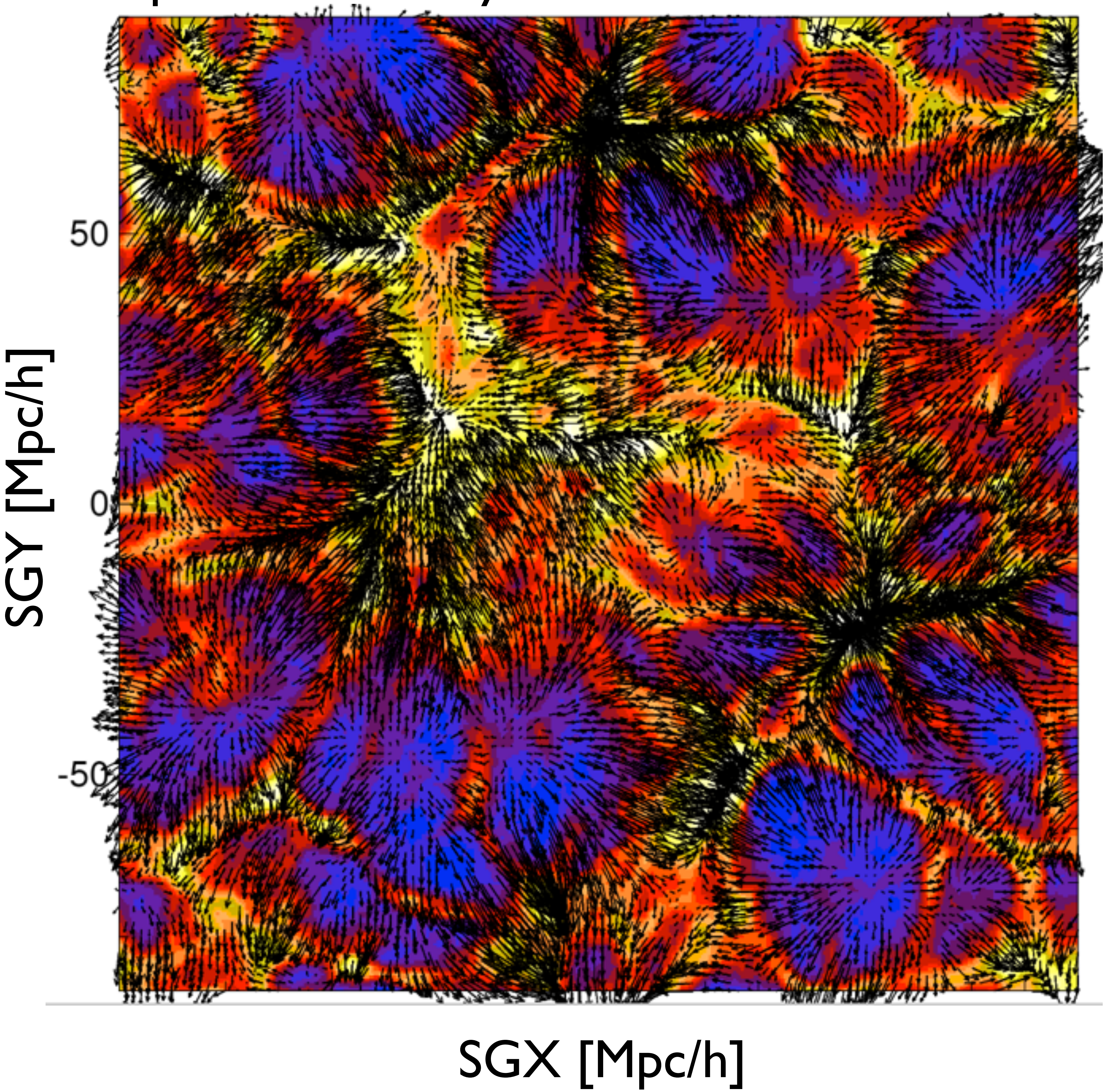
see Oliver Hahn, Sergei Shandarin, Mikhail Medvedev, Johan Hidding & Marc Neyrinck's talk

*plot by Steffen Hess in collaboration with Ralf Kaehler & Tom Abel from KIGEN reconstructions!*



see Marc Davis, Adi Nusser, Mike Hudson, Martin Feix, Jon Loveday, Christina Magoulas's talk

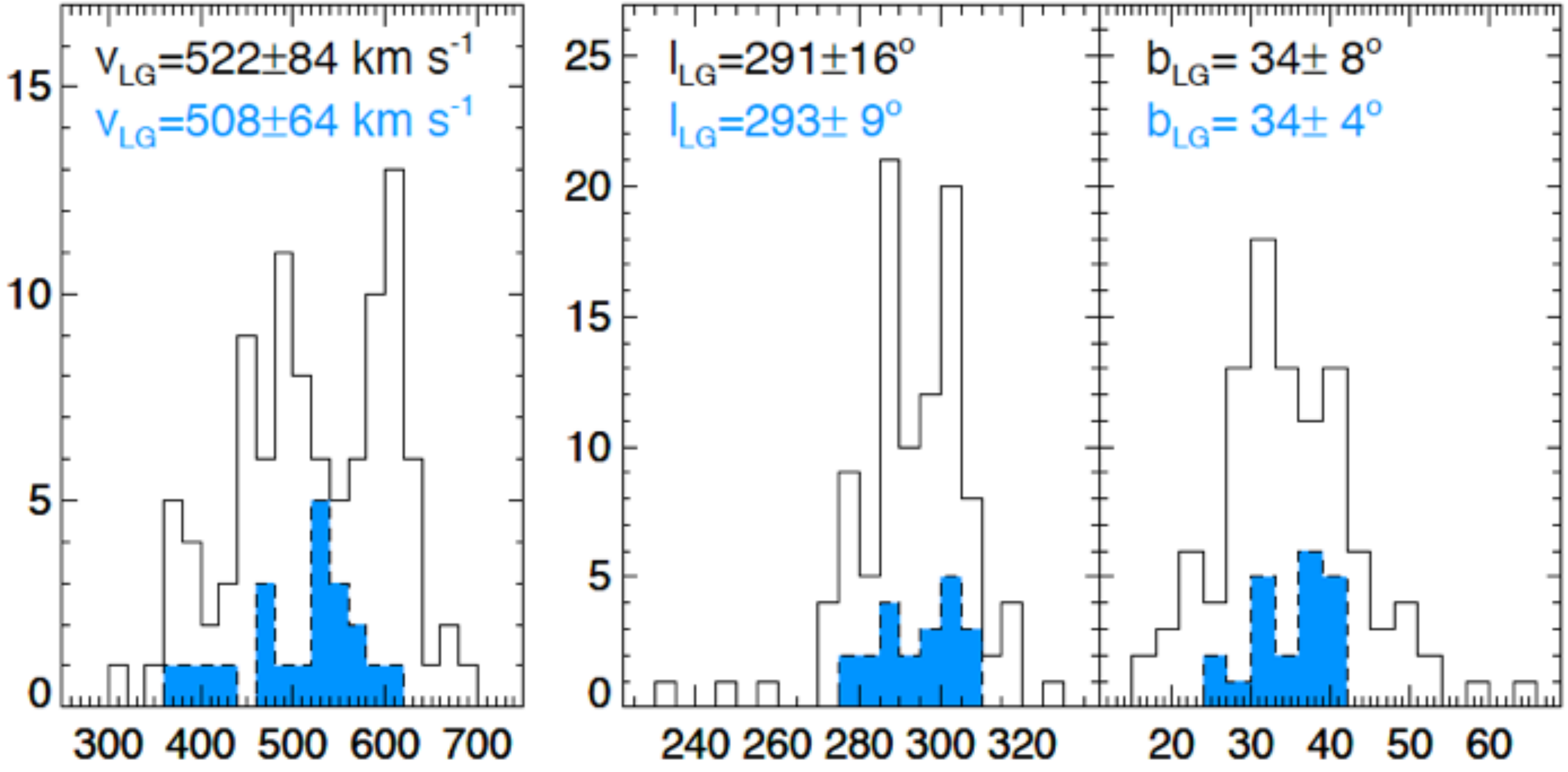
# reconstructed peculiar velocity field from ALPT!



see Brent Tully's, Adi Nusser's & Maciej Bilicki's talk

# Local Group motion

*Kitaura F. S., Erdogdu P., Nuza S. E., Khalatjan A., Angulo R. E., Hoffman Y. & Gottlöber S., 2012, MNRAS, arXiv:1205.5560*



CMB: v=627+-22 [km/s], l=276, b=30

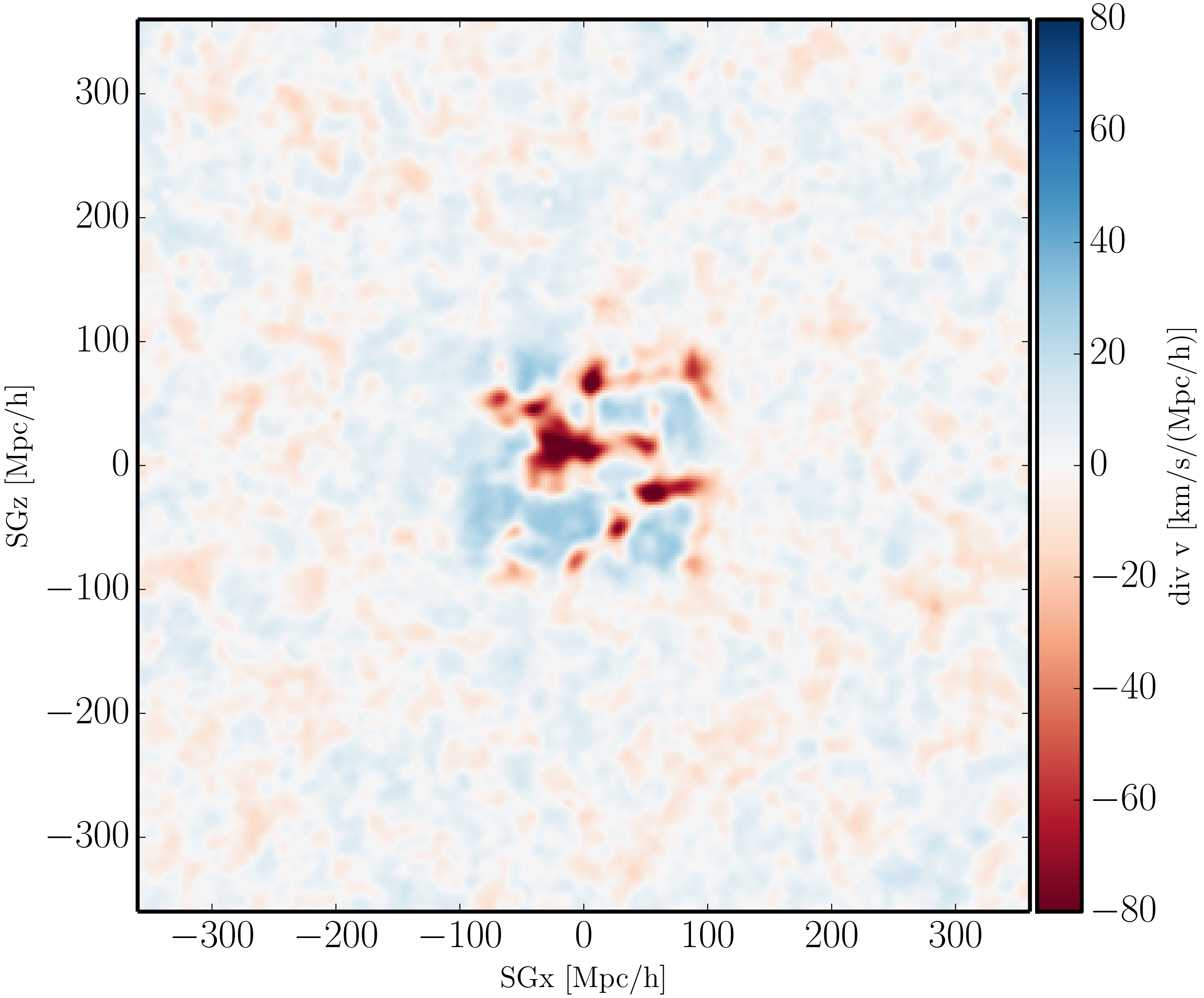
we obtain 83% of the CMB measurement in agreement with LCDM considering the matter within a box of 160 Mpc/h side

LCDM predicts 80% of the magnitude at distances of 80 Mpc/h

# Hubble flow

Boundary effects?
Missing large-scale modes?

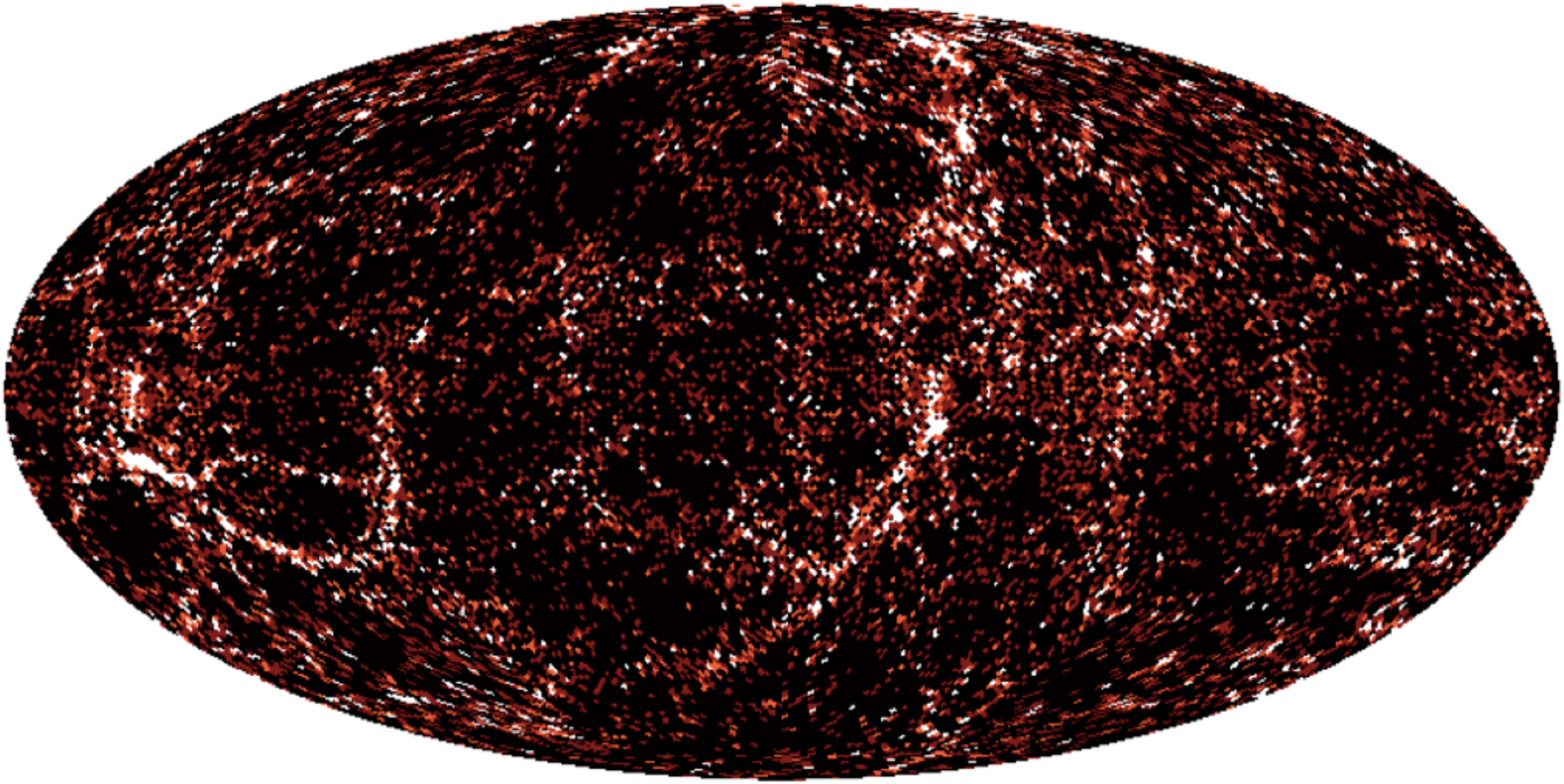
we use constrained augmented ALPT simulations to correct for these effects!



we correct the Hubble flow from estimates based on local SN and find better agreement with CMB results!

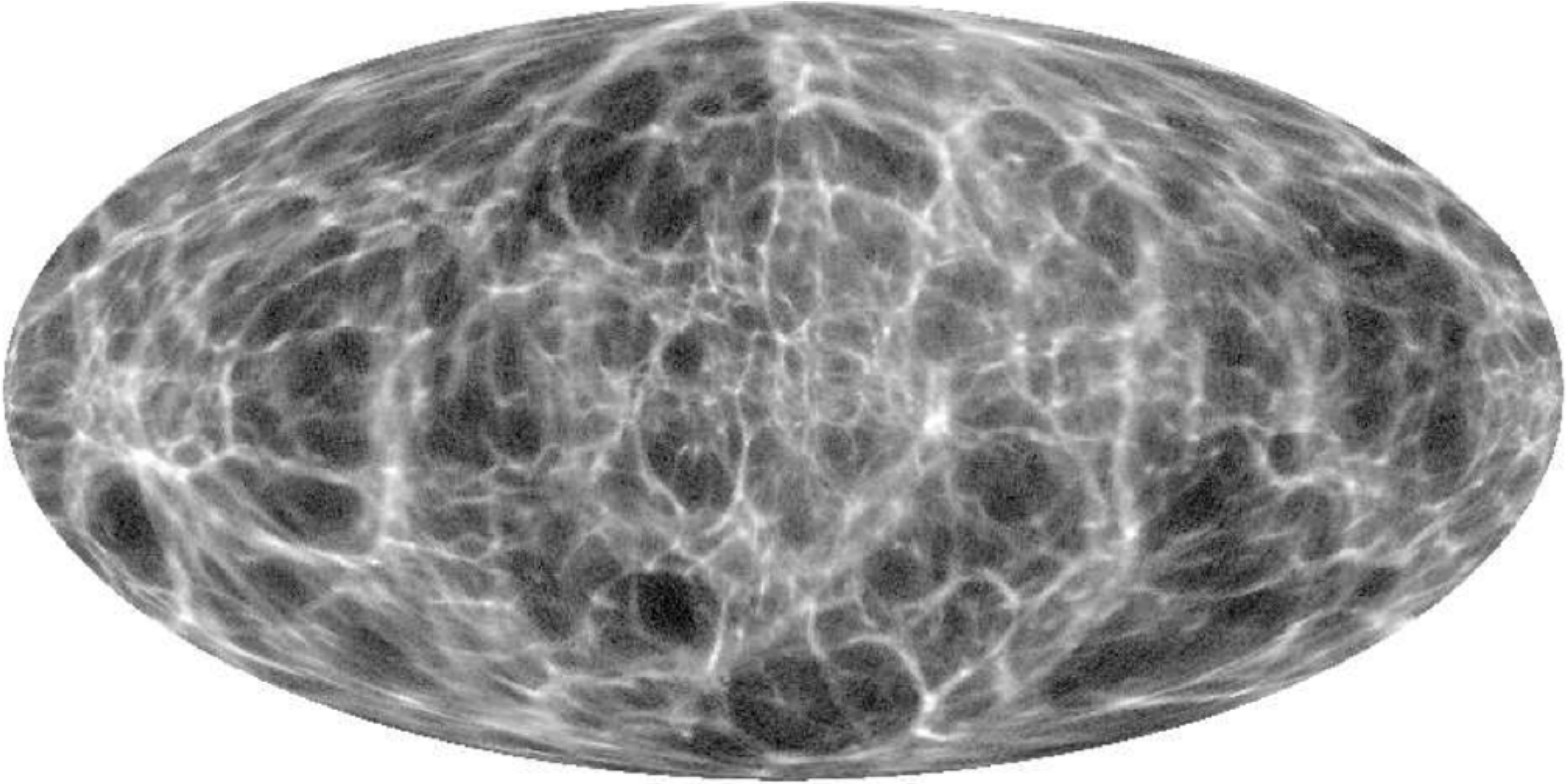
*Hess S., Kitaura F. S. & Seljak U. to be submitted*

2012: 1st application of a self-consistent forward approach to real data!



galactic plot of the 2MRS survey (shell between 0 to 80 Mpc/h)

*Kitaura F. S., Erdogdu P., Nuza S. E., Khalatjan A.,*
*Angulo R. E., Hoffman Y. & Gottlöber S., 2012, MNRAS, arXiv:1205.5560*



reconstructed cosmic web (shell between 0 to 80 Mpc/h)

now that we have the filaments …

remember Elmo Tempel's talk on filaments!

# Detection of missing baryons from public PLANCK data!

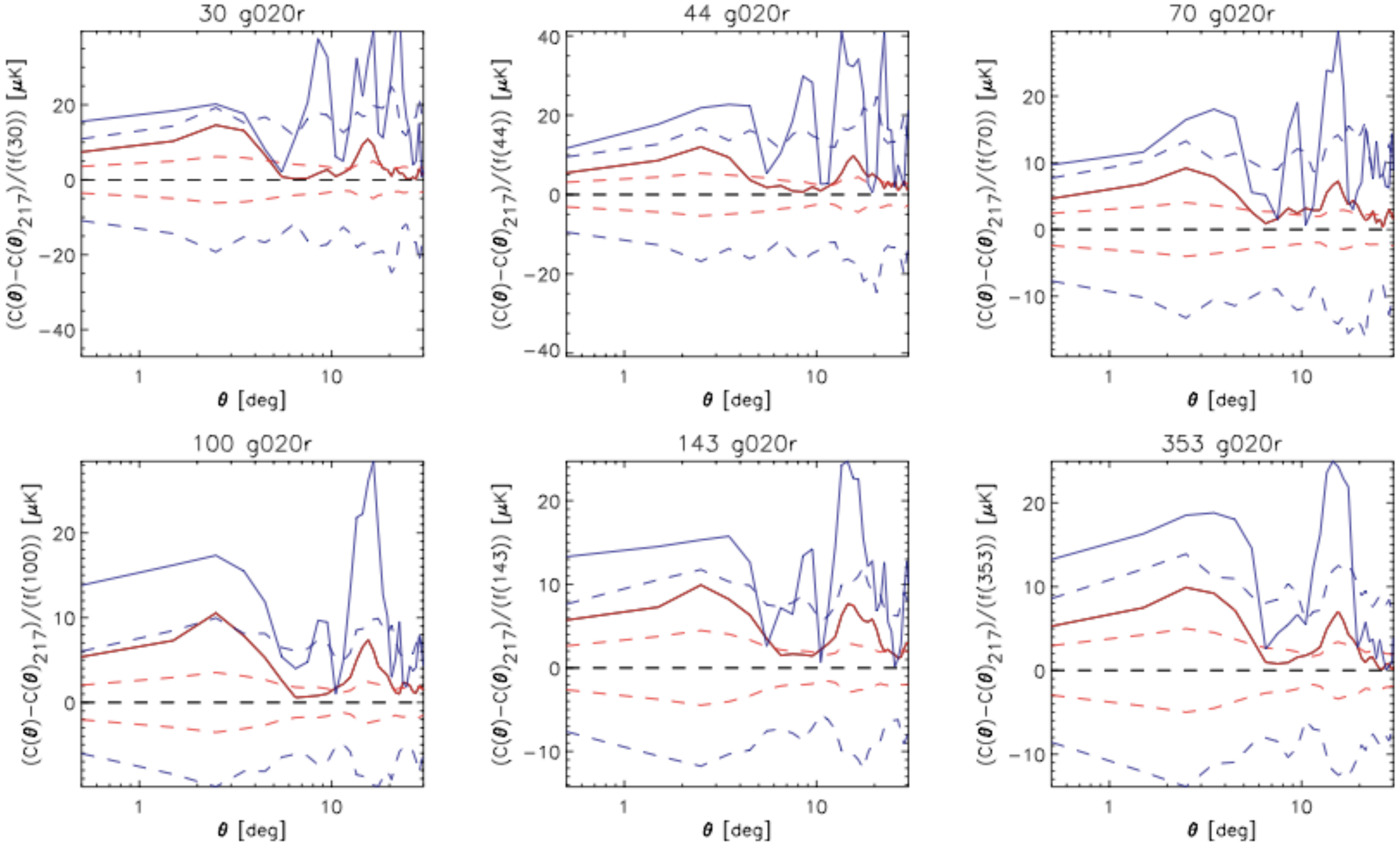
*Suarez-Velásquez I., Kitaura F.-S., Atrio-Barandela F., Mücket J. P. 2013, ApJ, 769, 7, arXiv:1303.5623*

*results from PLANCK*

see Jukka Nevalainen 's talk

*in collaboration with Genova-Santos R. T., Atrio-Barandela F., Mücket J. P. in prep*

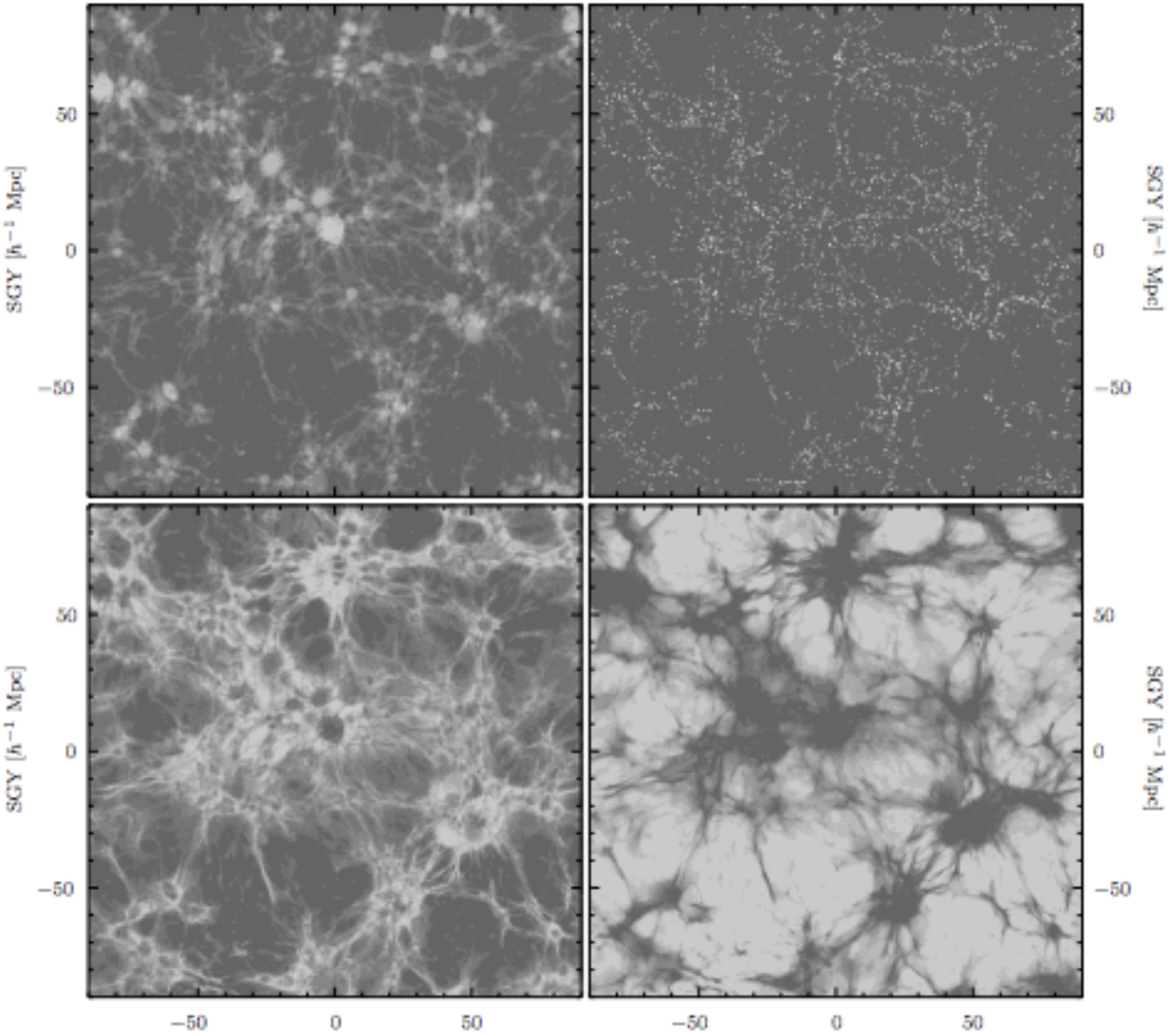
correlations up to 20 deg in all channels after subtraction of CMB (217GHz), if it were from clusters correlation should fade away at less than 1 deg!



but we have the full cosmic web…

# Reconstructions of the cosmic web

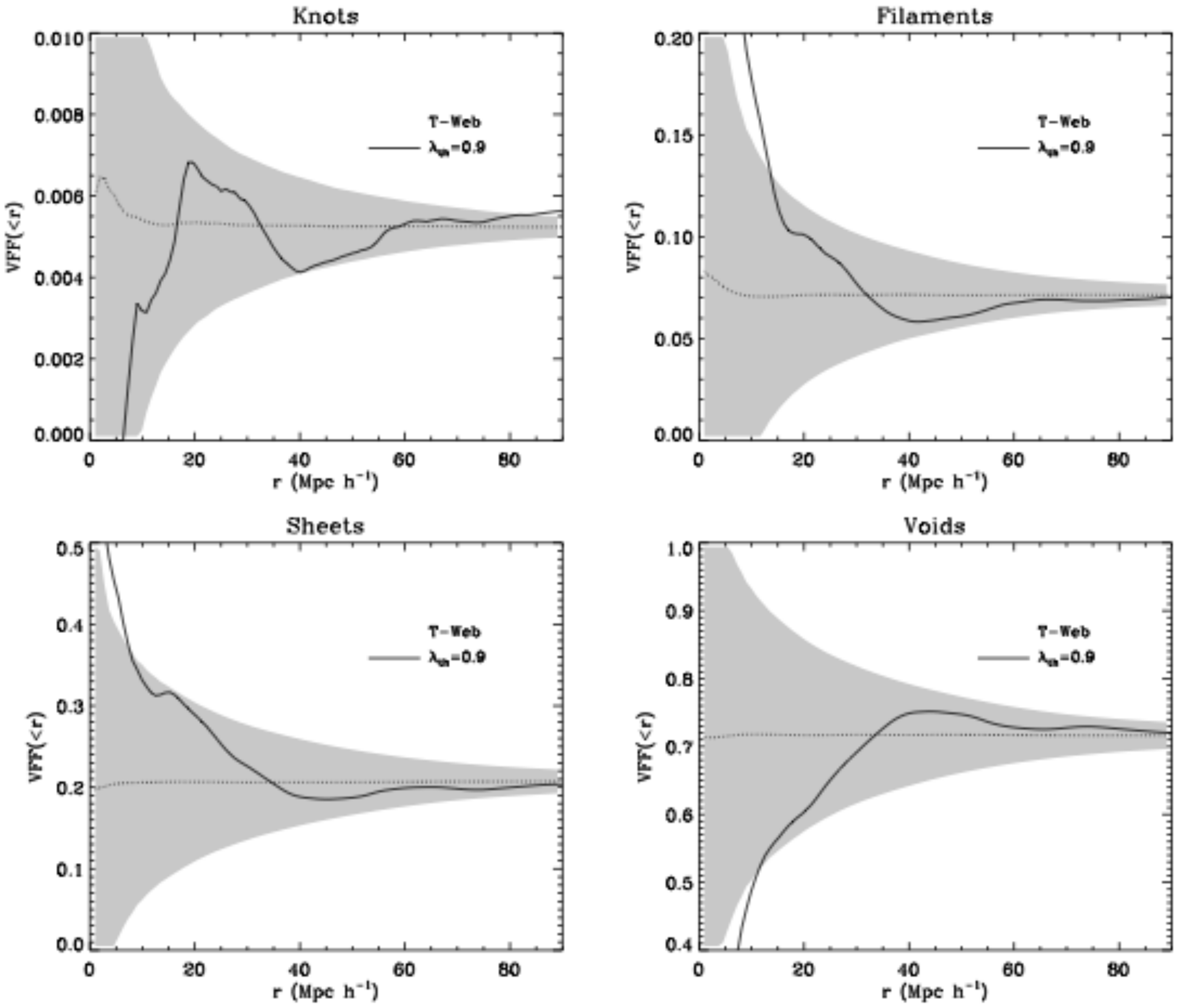
*Nuza Sebastian, Kitaura F. S., Heß S., Libeskind N. & Müller V., arXiv:1406.1004*



see Marius Cautun, Bernard Jones, Oliver Hahn & Jaime Forero-Romero's talk
and talks on voids: R. v.d. Weygaert, P. Sutter, N. Padilla, A. Hawken, Y.C. Cai, N. Hamaus, E. Ricciardelli, A. Pisani

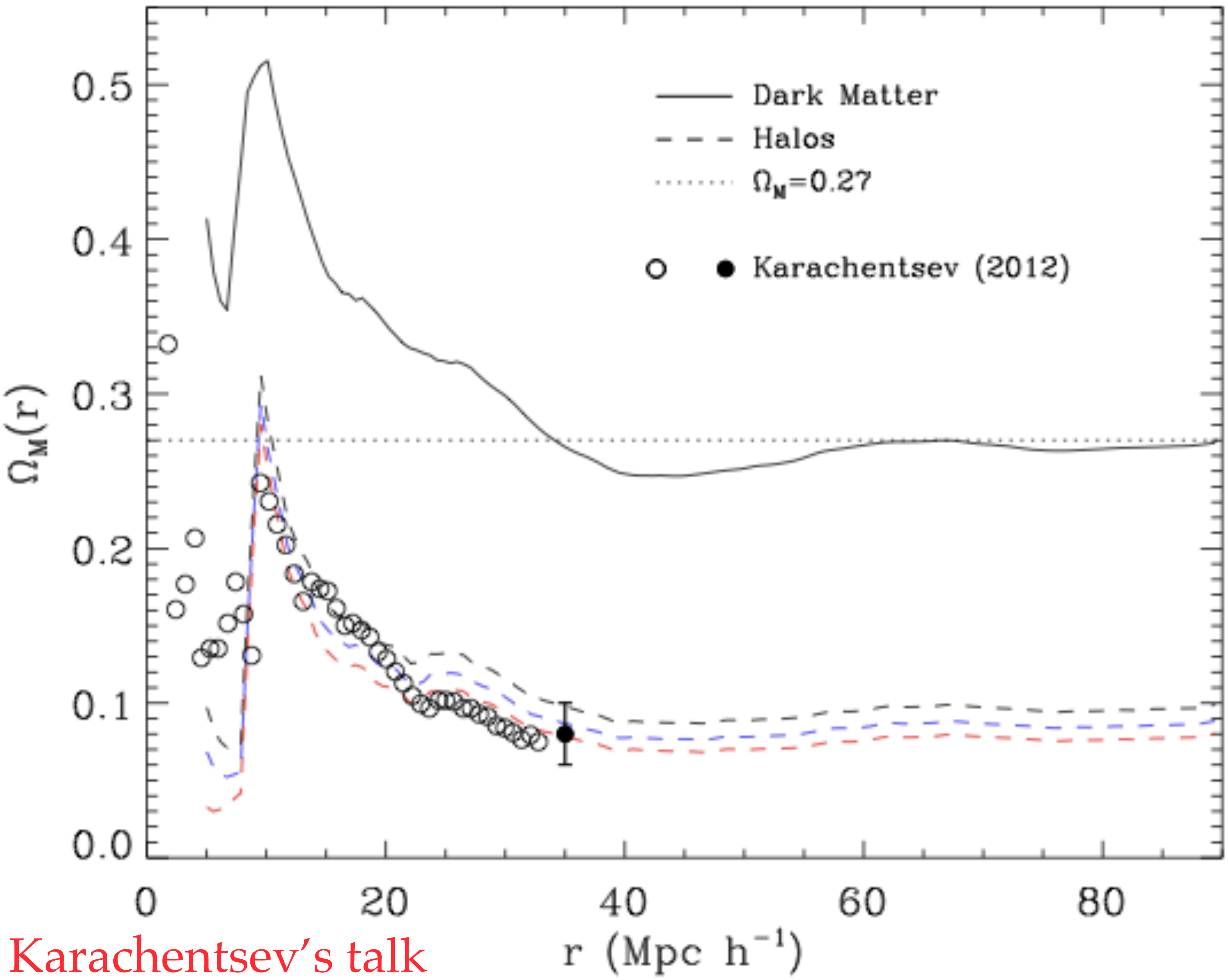
# Is our place in the Universe special?

*Nuza Sebastian, Kitaura F. S., Heß S., Libeskind N. & Müller V., arXiv:1406.1004*



# Missing mass in the Local Universe?

*Nuza Sebastian, Kitaura F. S., Heß S., Libeskind N. & Müller V., arXiv:1406.1004*



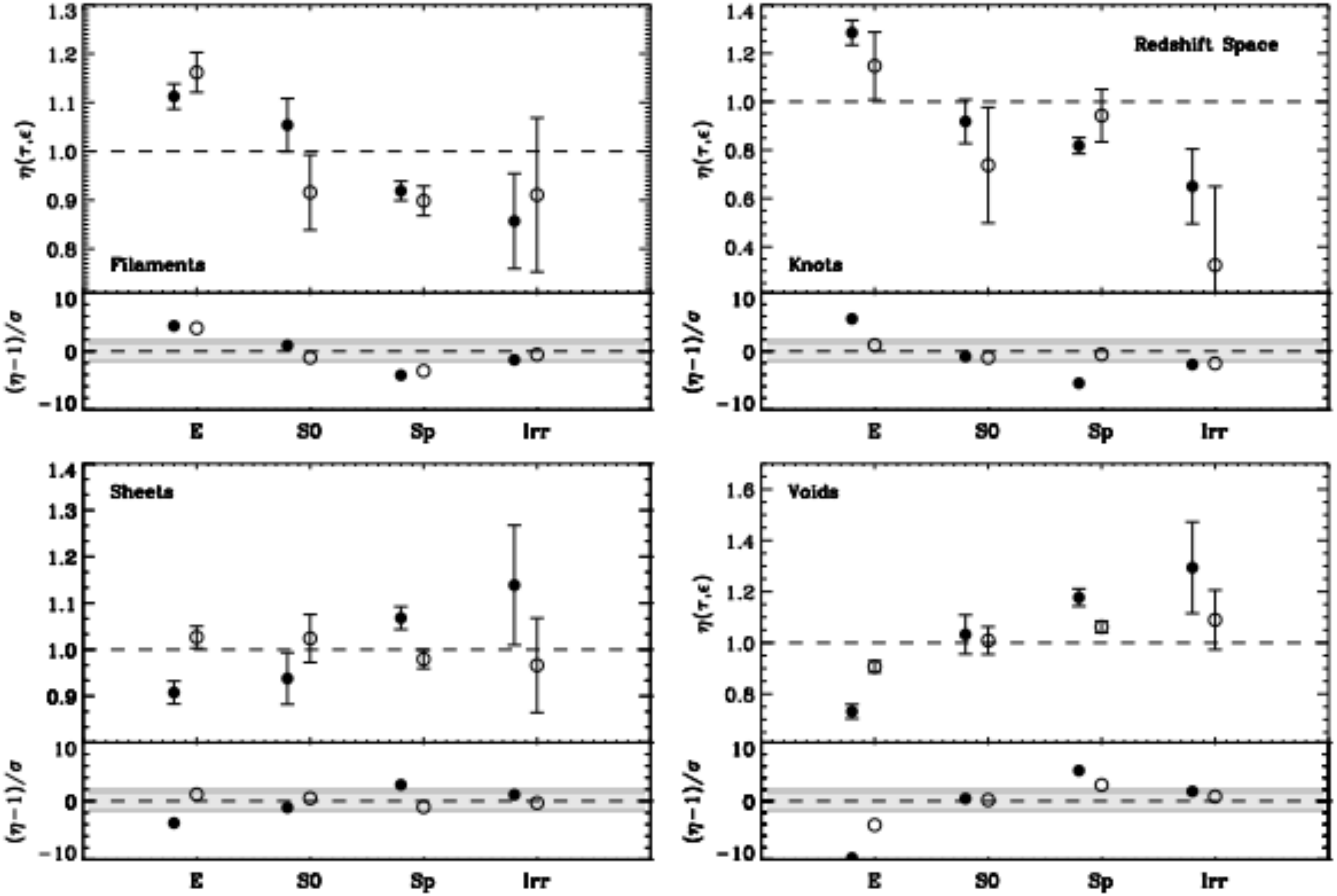
see Igor Karachentsev's talk

# Galaxy morphology-environmental study

*Nuza Sebastian, Kitaura F. S., Heß S., Libeskind N. & Müller V., arXiv:1406.1004*

see Jounghun Lee & Katarina Kovac's talk

in redshift space

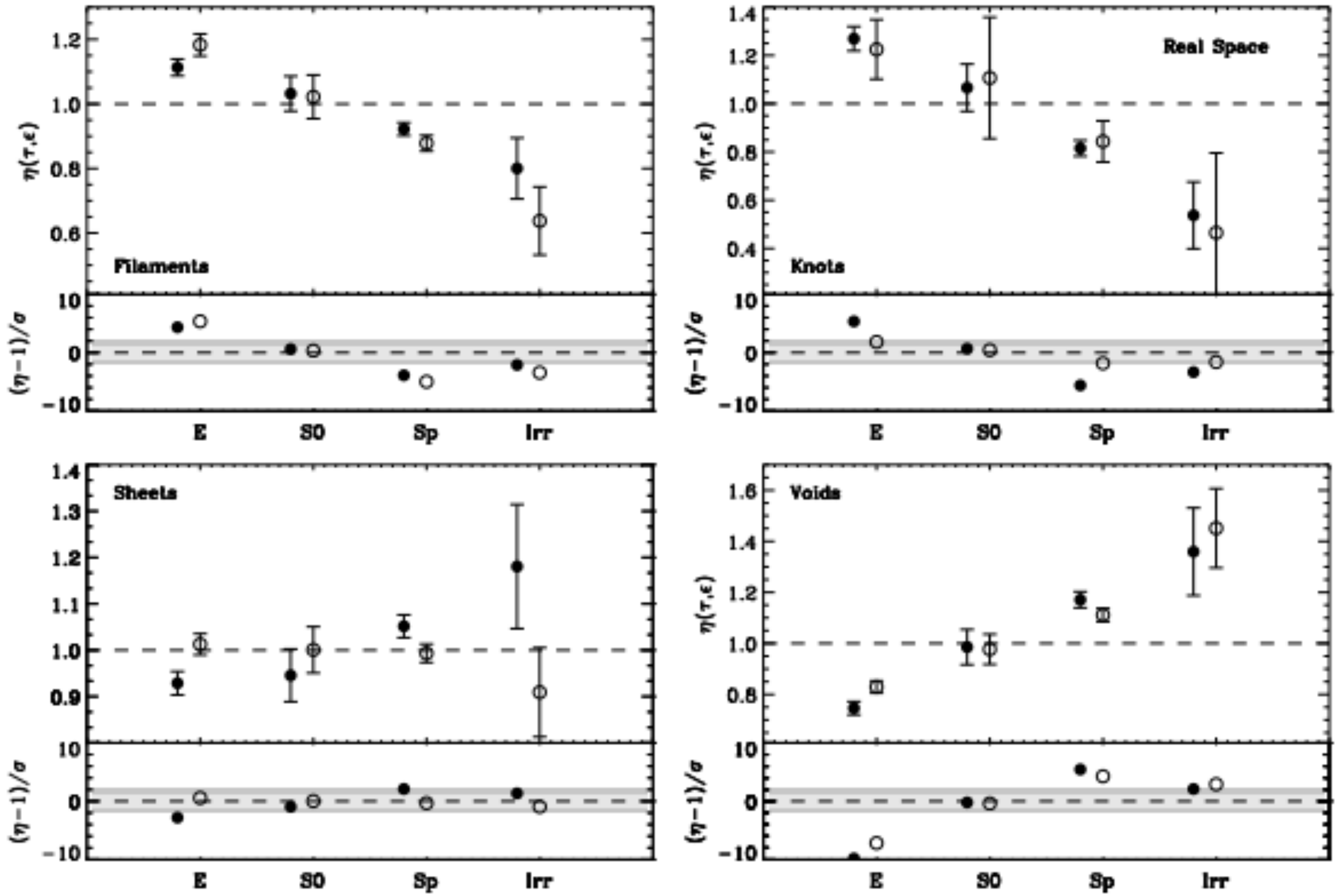


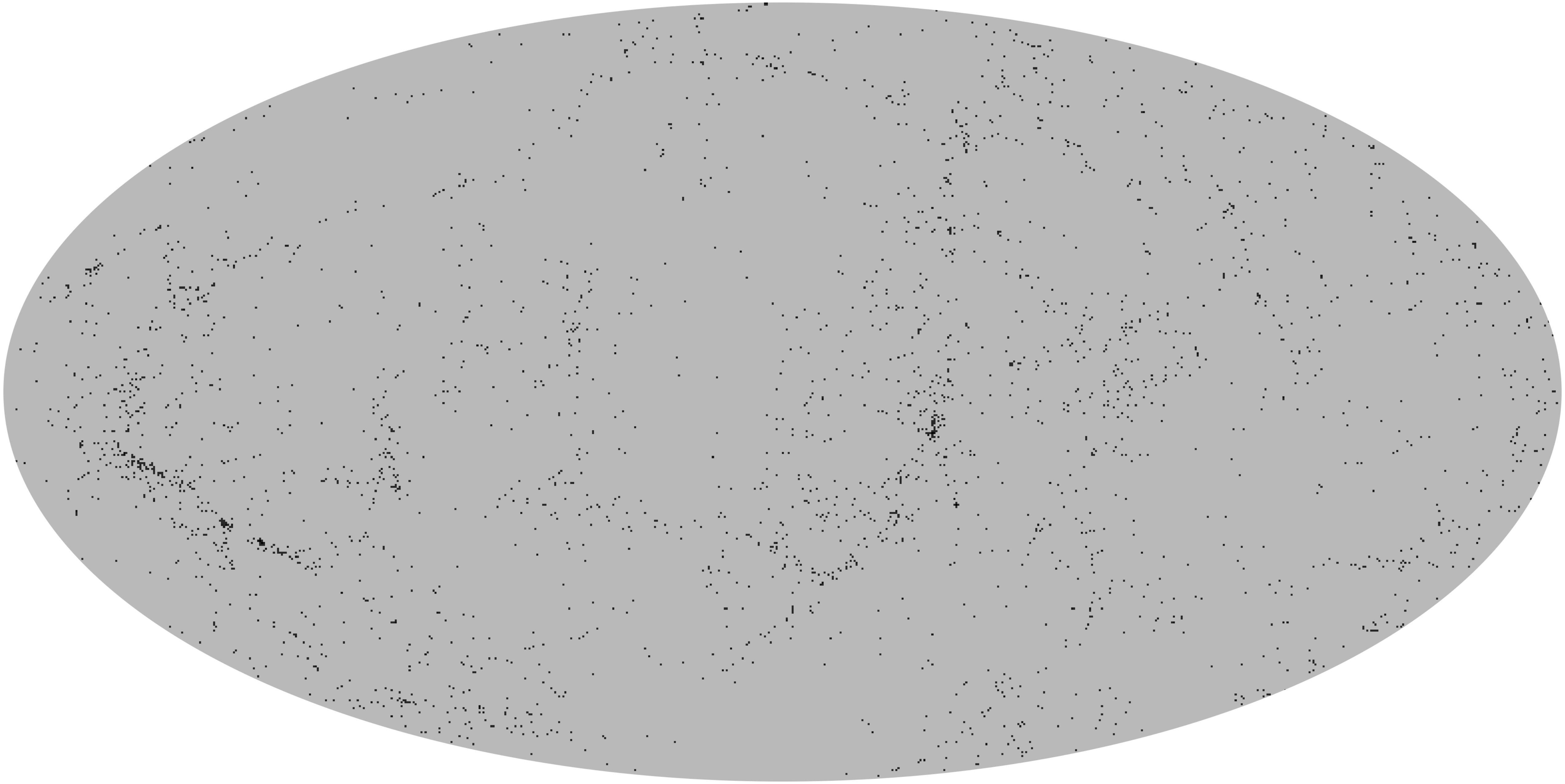
*for a similar study from the Wiener reconstruction see Lee & Lee 2008*

# Galaxy morphology-environmental study

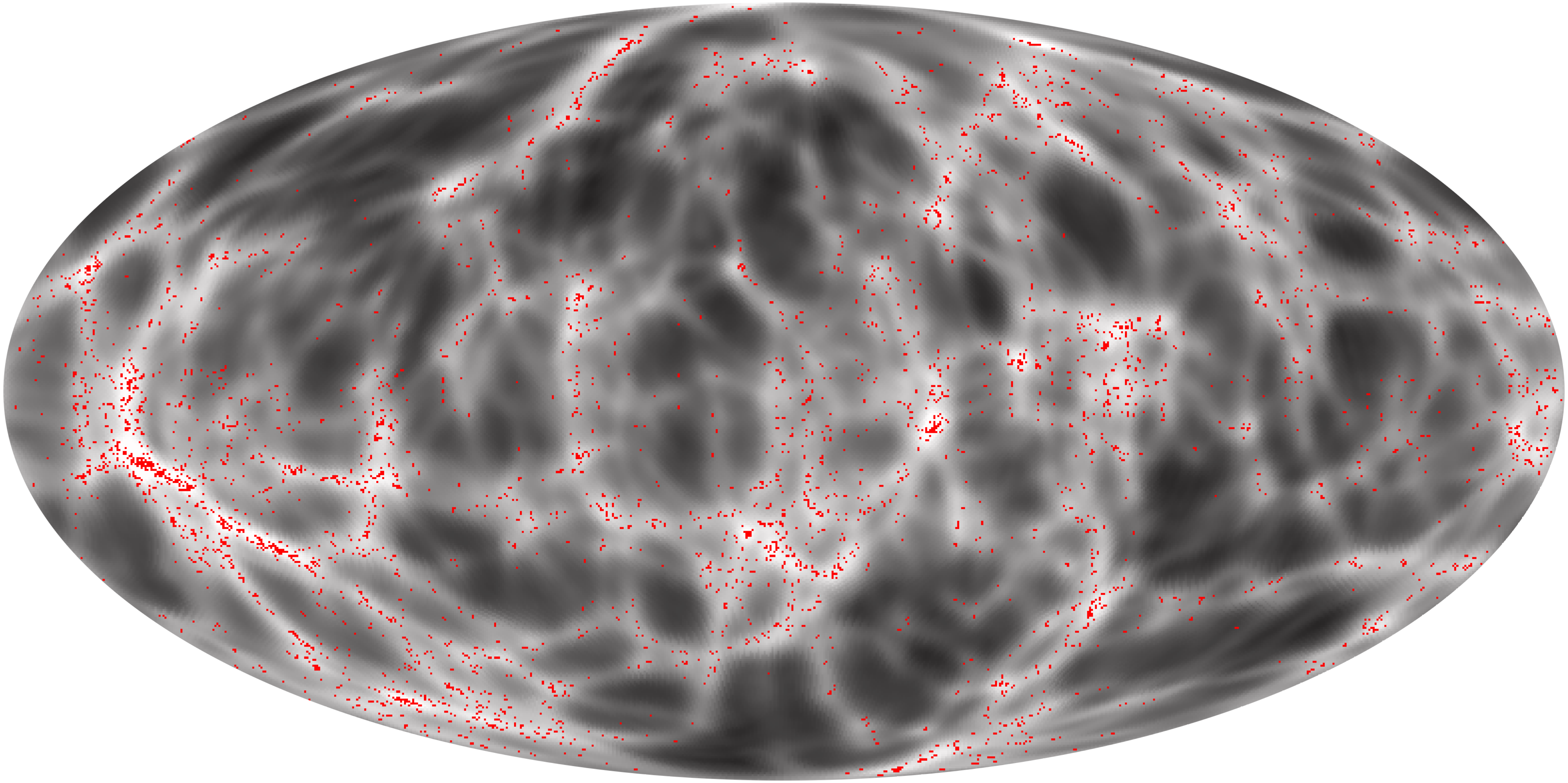
*Nuza Sebastian, Kitaura F. S., Heß S., Libeskind N. & Müller V., arXiv:1406.1004*

in real space

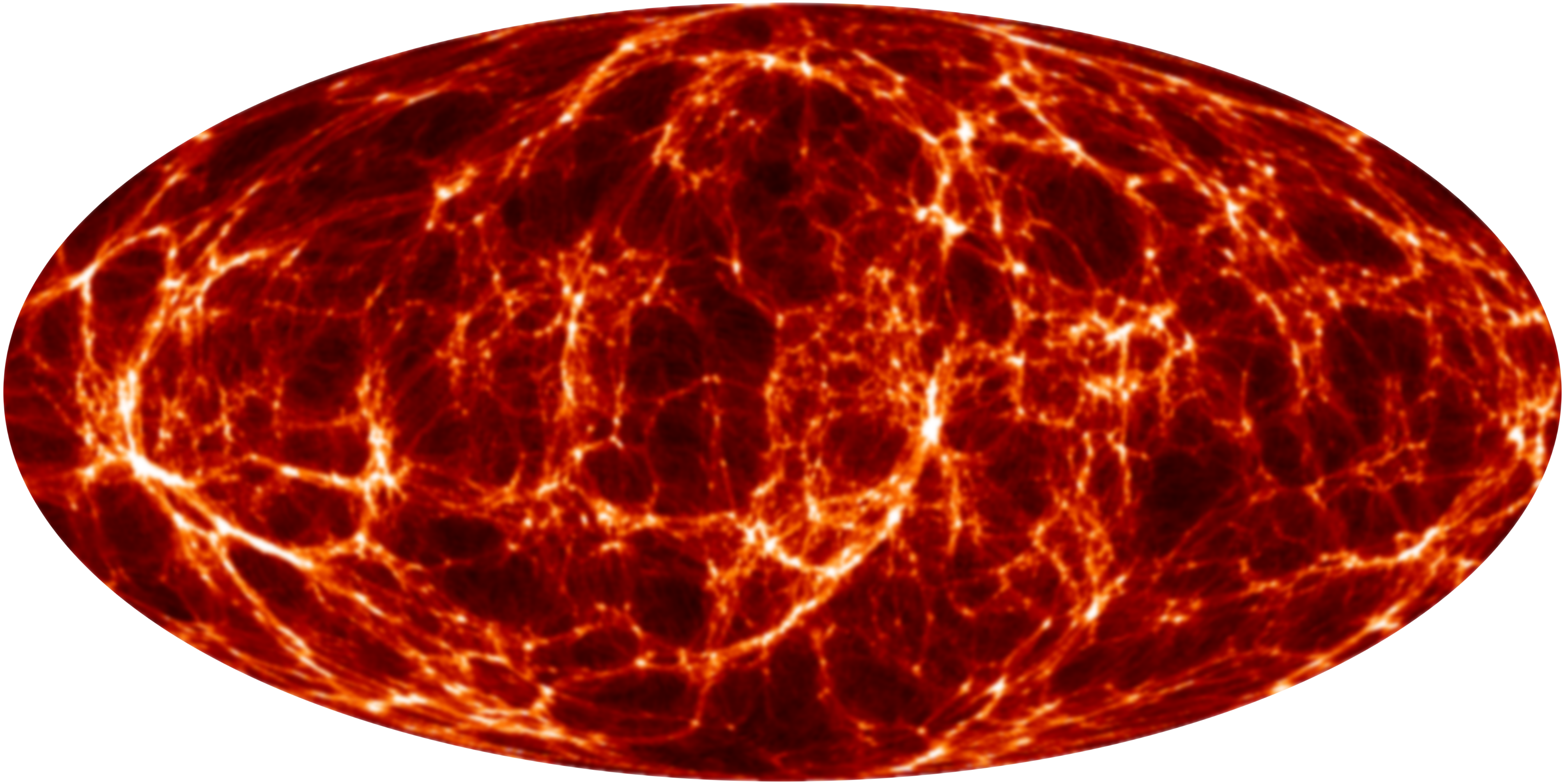




real observations!



mean over an ensemble of ALPT reconstruction!



high resolution constrained N-body simulation!

# Conclusions

- The galaxy distribution in redshift-space encodes information of the full phase-space information given some assumptions: the primordial fluctuations are closely Gaussian distributed with a given power-spectrum and the Universe isotropic. Then we can test the structure formation models with RSDs which match the data in a forward statistical approach.
- The idea of combining LPT on large-scales with small-scale structure formation corrections is very effective: augmented LPT (ALPT)
- The exponential bias with an exponential cut-off models very well the scale dependent nonlinear deterministic bias
- Deviations from Poissonity are important for precision studies of the LSS.
- RSD can be accurately modelled with ALPT + a stochastic dispersion term
- We are able to incorporate these models in a Bayesian inference framework.
- These ingredients are crucial for precision reconstructions of primordial fluctuations.
- The range of applications is very wide: CMB-dipole, Bulk flows, Hubble constant, WHIM, kSZ, BAO reconstruction, voids, filaments, clusters, walls identification, environmental studies