Structure growth & redshift-space distortions around voids

Yan-Chuan Cai

Y. Cai, A. Taylor, J. Peacock, N. Padilla, arXiv:1603.05184
V. Demchenko, Y. Cai, C. Heymans & J. Peacock, arXiv:1605.05286

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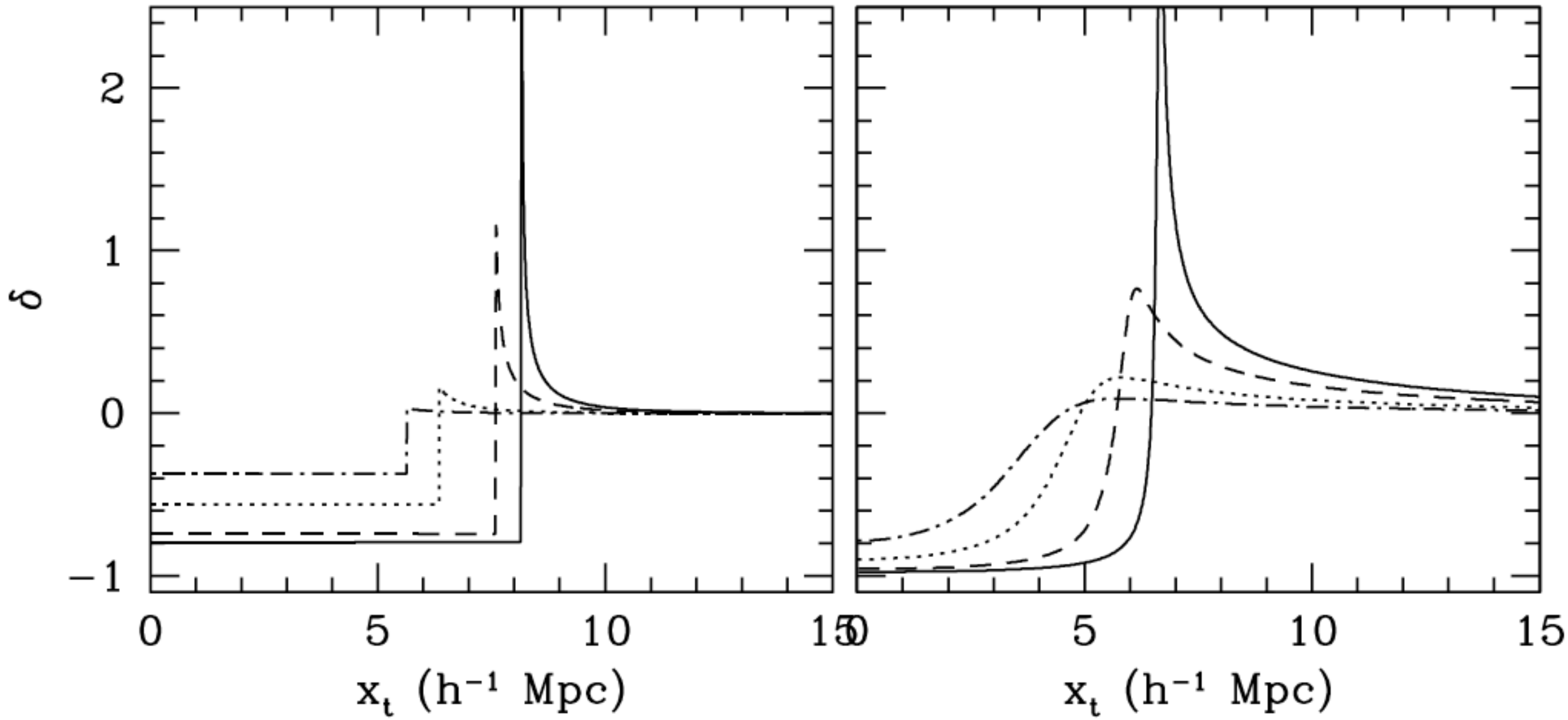
Outline

- Voids
- Why RSD around voids
- What should voids look like in z-space
- Measuring the linear growth
- Summary

Spherical expansion

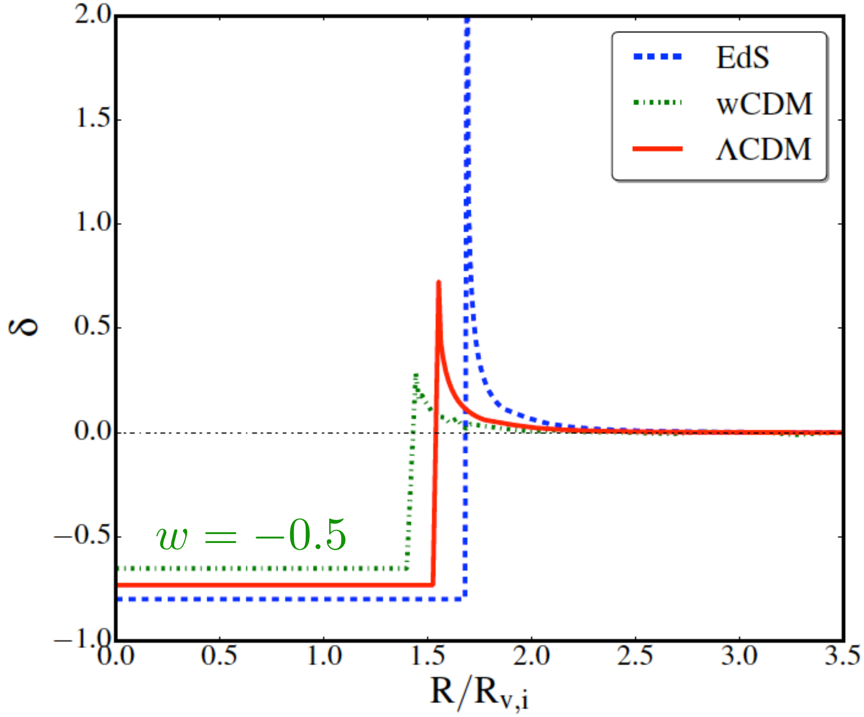
Sheth & van de Weygaert, 2004

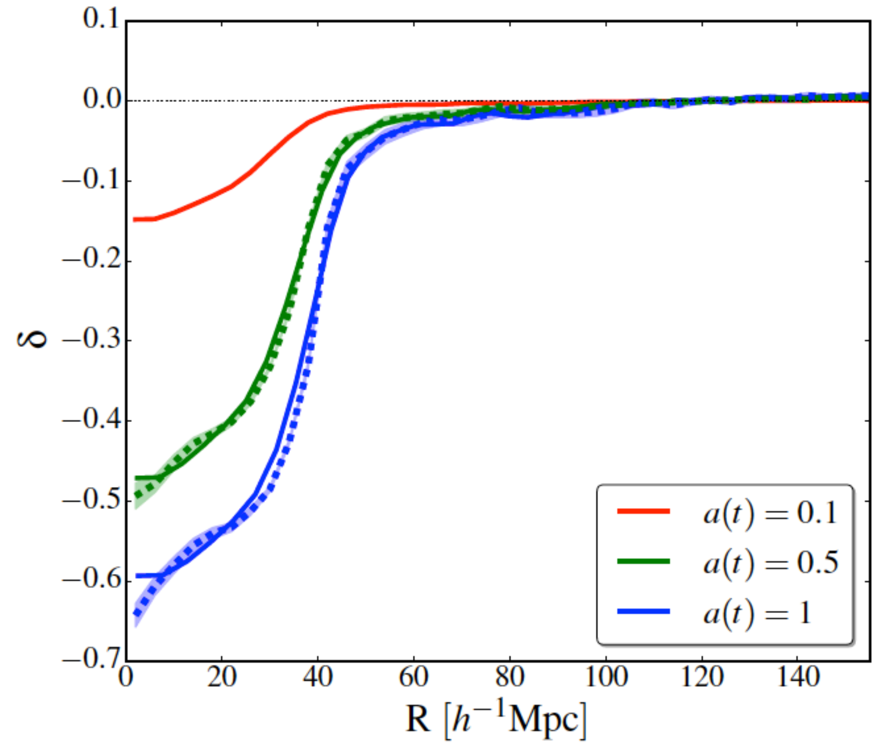


In LCDM, shell-crossing occurs at $\delta = -0.8.$

$$R_f/R_{int} \sim 1.7$$

Spherical evolution model

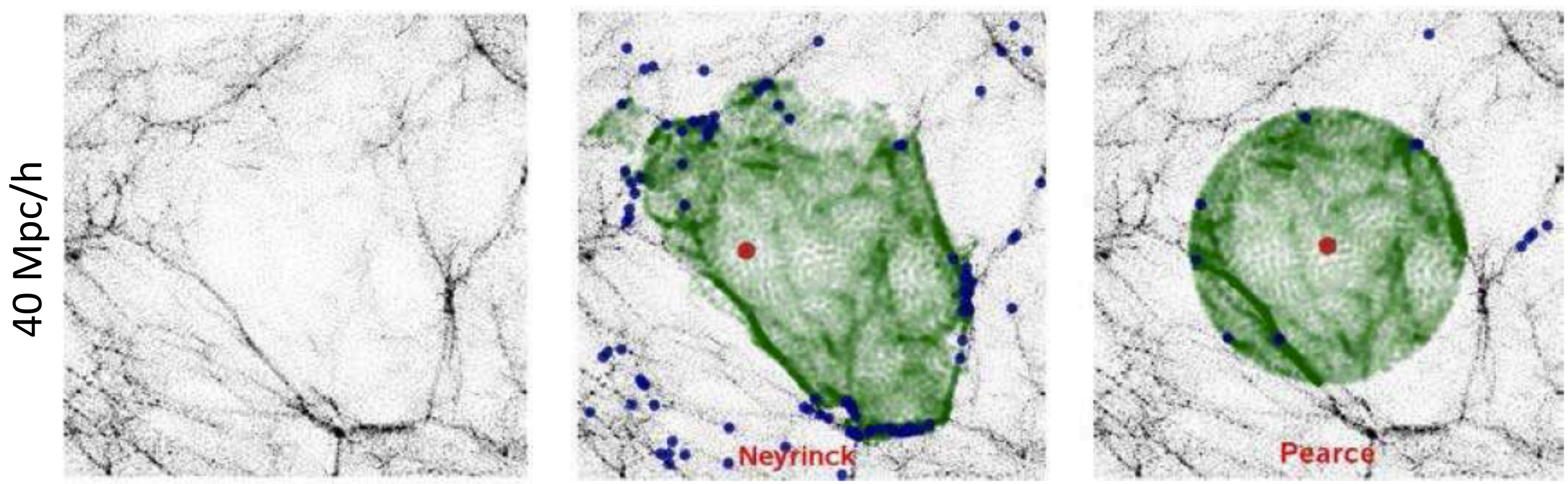




Demchenko, Cai, Heymans & Peacock, 2016

Voids in Simulations

The Aspen–Amsterdam void finder comparison project



Millennium Simulation — ZOBOV — Spherical overdensity

Colberg et al. 2008

Voids in observations

- SDSS voids from

Pan et al. 2012

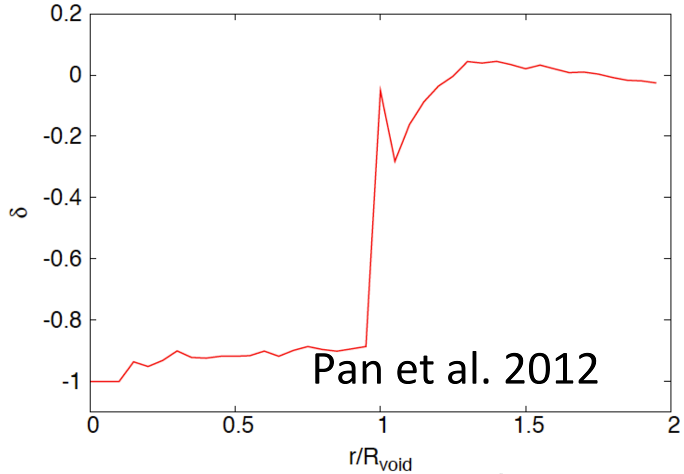
Sutter et al. 2012

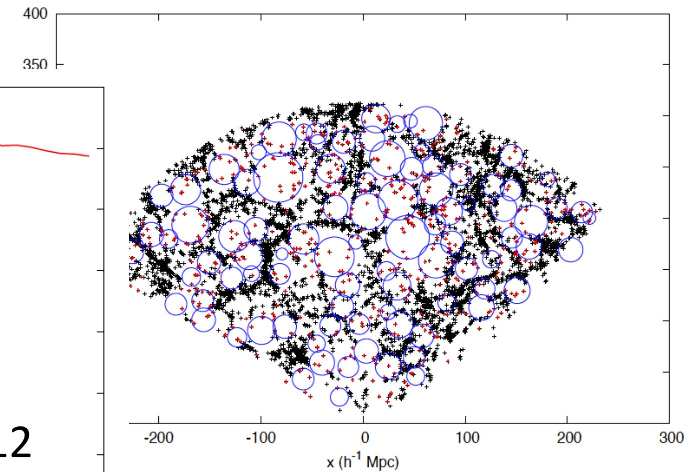
Cai et al. 2014

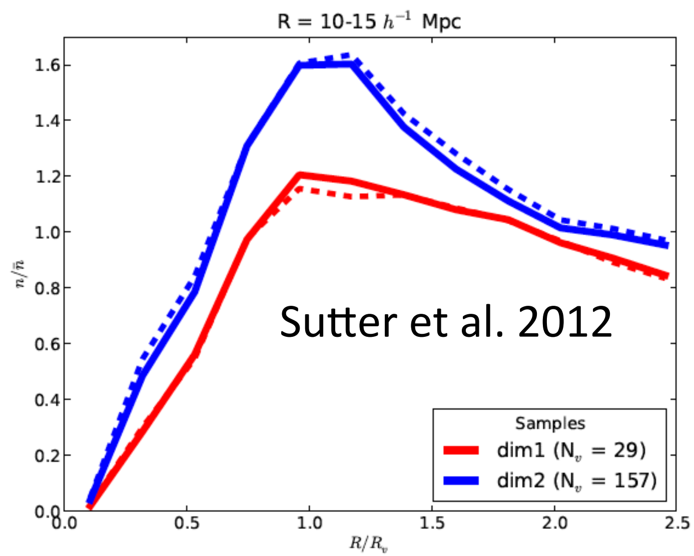
Nadathur et al. 2014

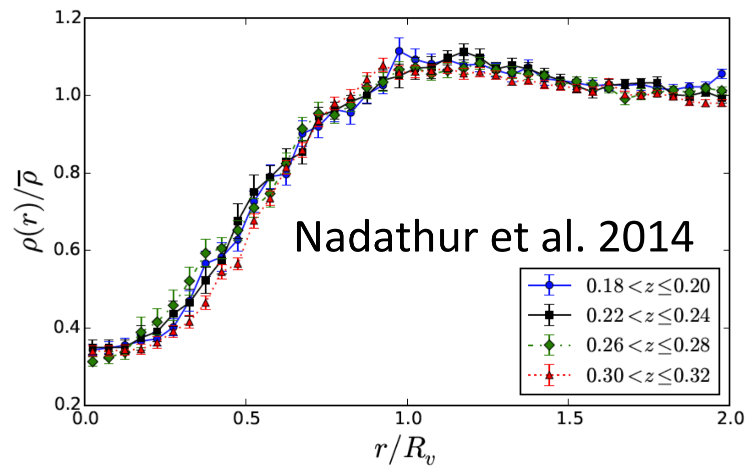
Mao et al. 2016

…

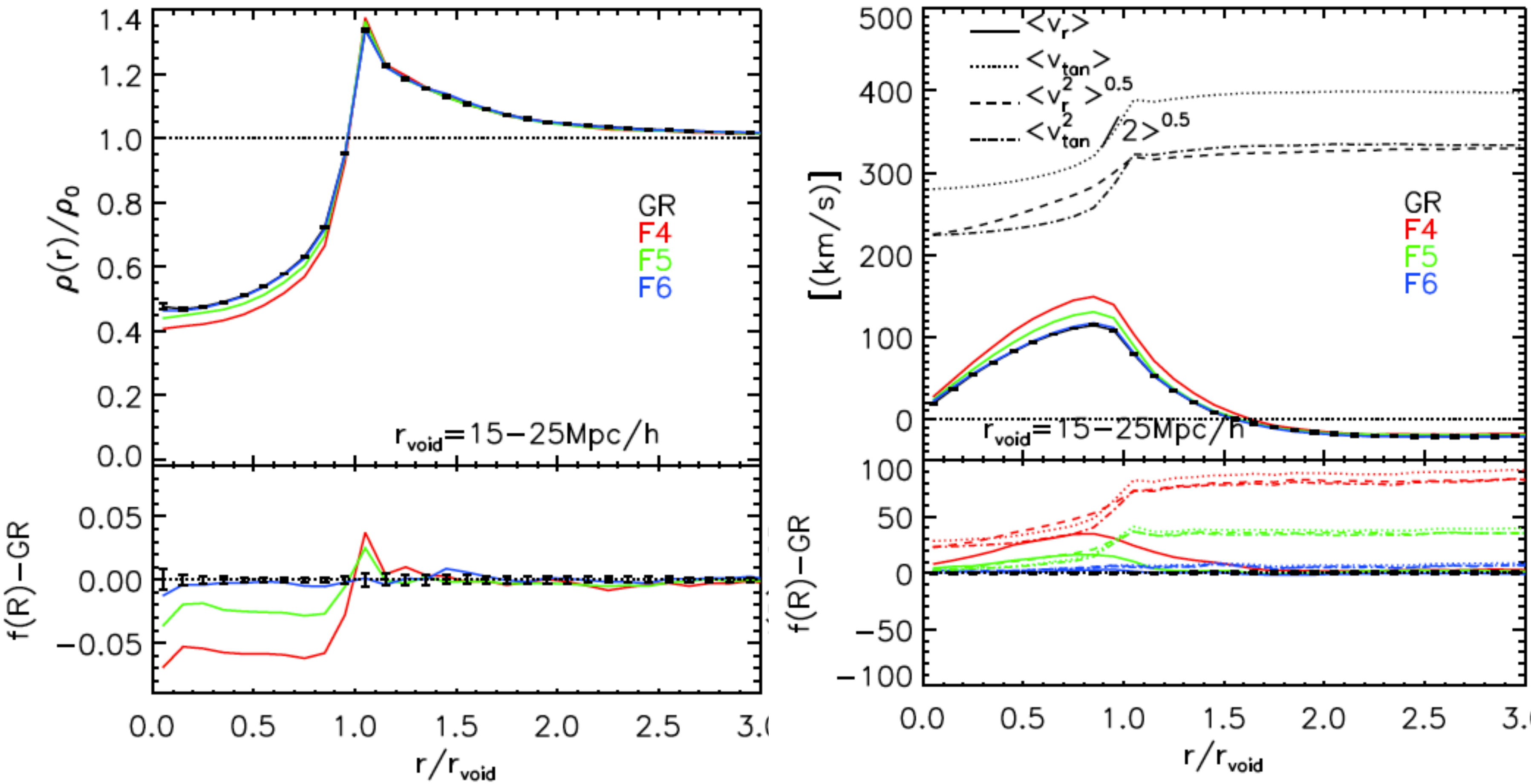








Testing gravity with voids



f(R) voids are emptier than GR voids
f(R) voids expand faster

Cai, Li & Padilla 2015

Alcock-Pasczynski test with voids

IF voids are spherical

LOS distance $\Delta l = \frac{c}{H(z)} \Delta z$

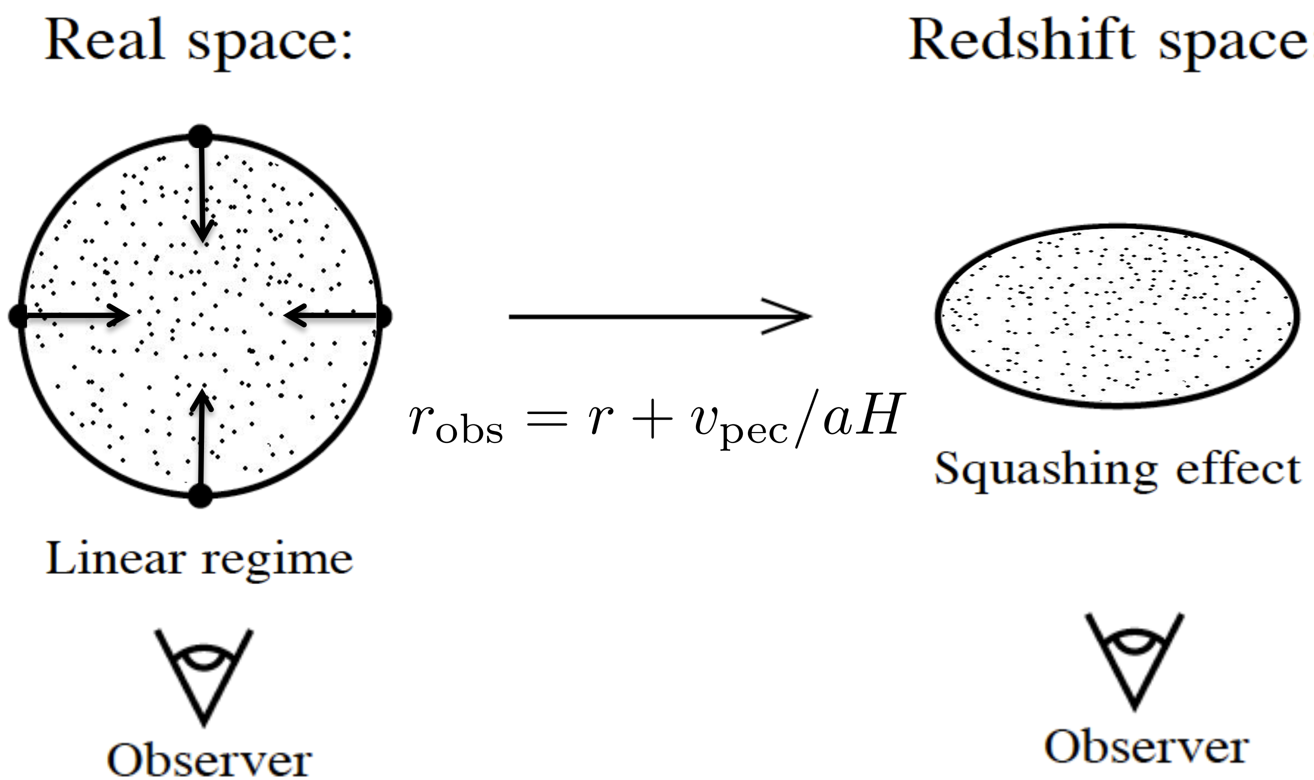
transverse distance $\Delta r = (1+z) D_A(z) \Delta\theta$

$$e(z) = \frac{\Delta l'}{\Delta r'} = \frac{D_A(z)H(z)}{D'_A(z)H'(z)}$$

Voids are distorted in redshift space

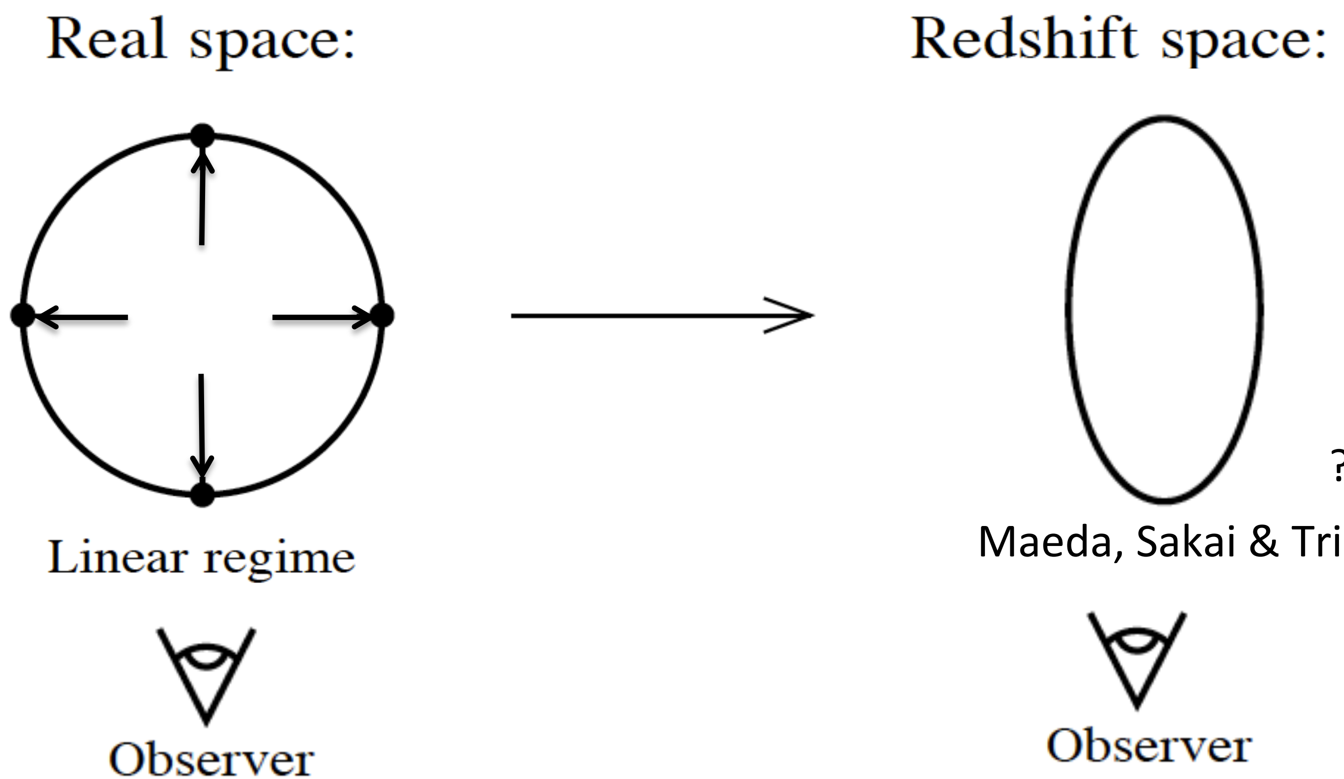
14% flattening in redshift space, Lavaux & Wandelt (2012)

Linear Redshift Space Distortion (RSD)



Kaiser 1987, Hamilton 1997

RSD for void



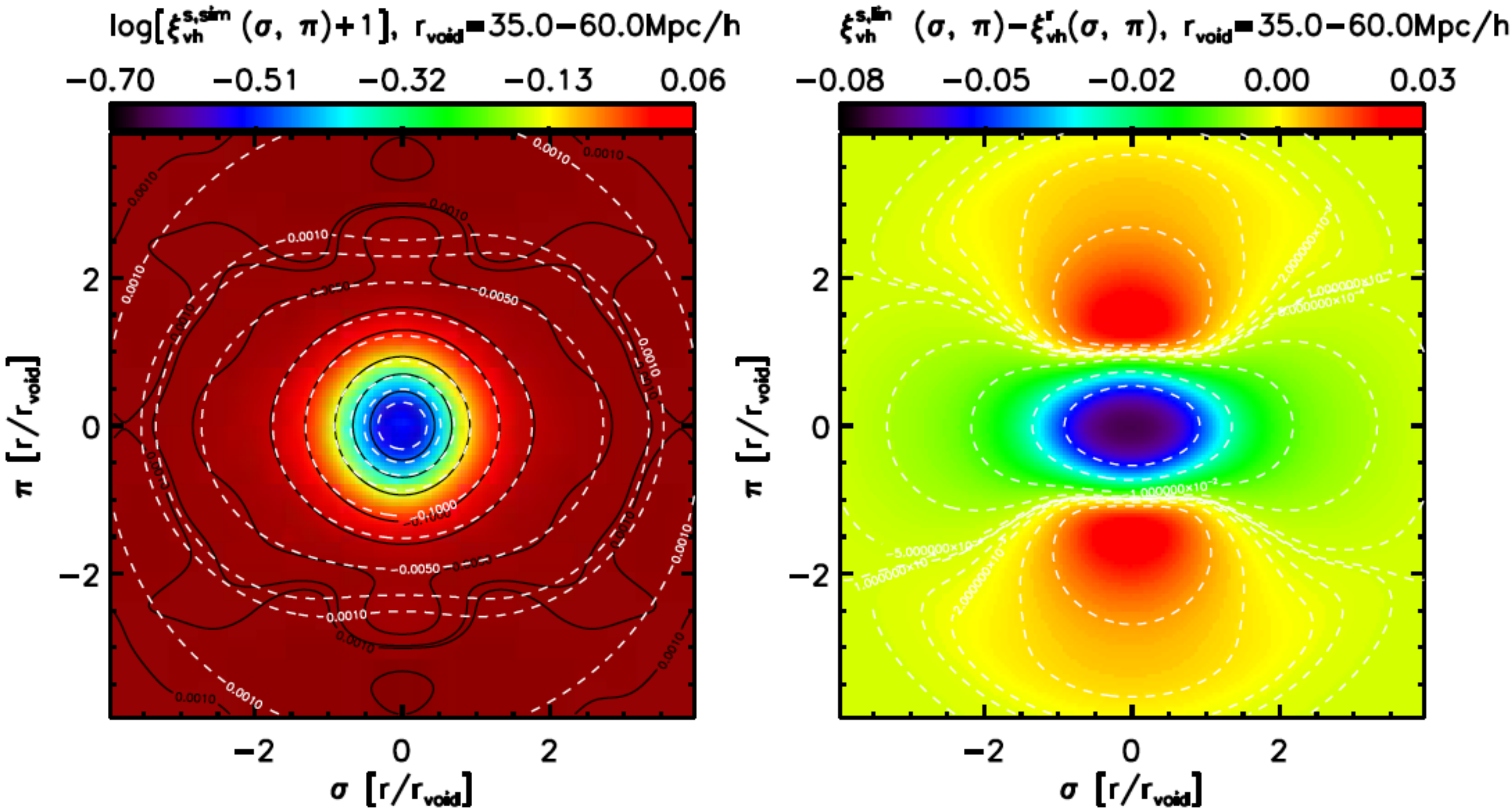
Maeda, Sakai & Triay, 2011

$$\delta^s(\mathbf{r}) = \delta(r) - (1-\mu^2)\frac{1}{aH}\frac{v(r)}{r} + \mu^2\frac{1}{aH}\frac{\partial v(r)}{\partial r}$$

$$= \delta(r) + \frac{1}{3}f\bar{\delta}(r) + f\mu^2[\delta(r) - \bar{\delta}(r)]$$

$$\mu = \cos\theta$$

Void-halo correlation function



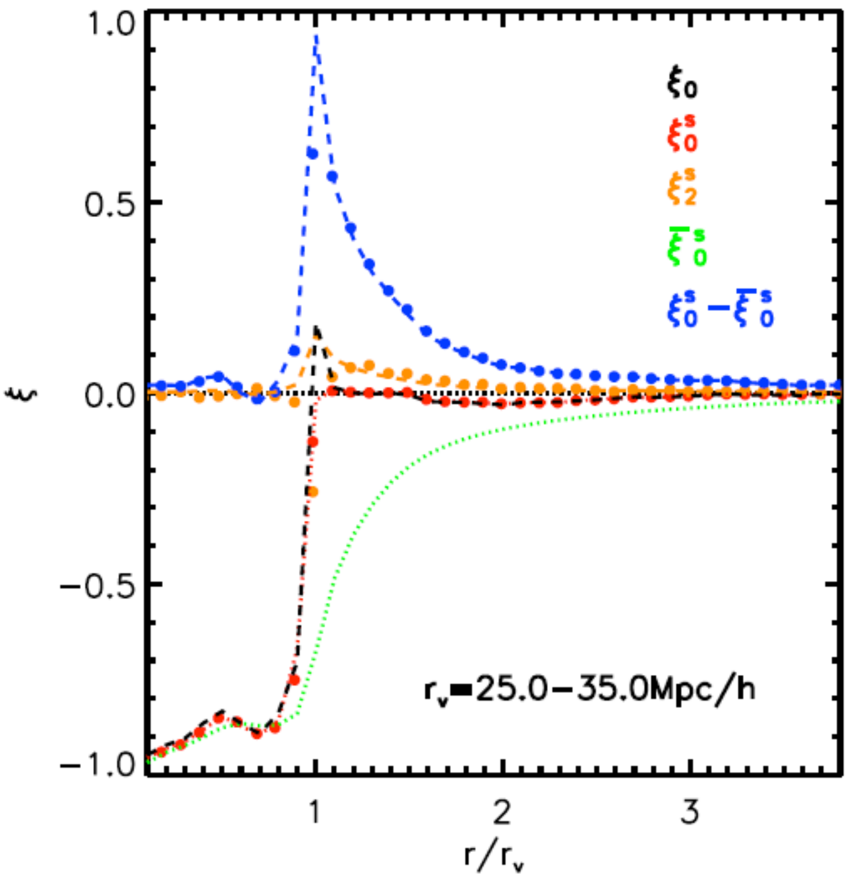
$$\xi^s(r,\mu) = \xi(r) + \frac{1}{3}\beta\bar{\xi}(r) + \beta\mu^2[\xi(r) - \bar{\xi}(r)]$$

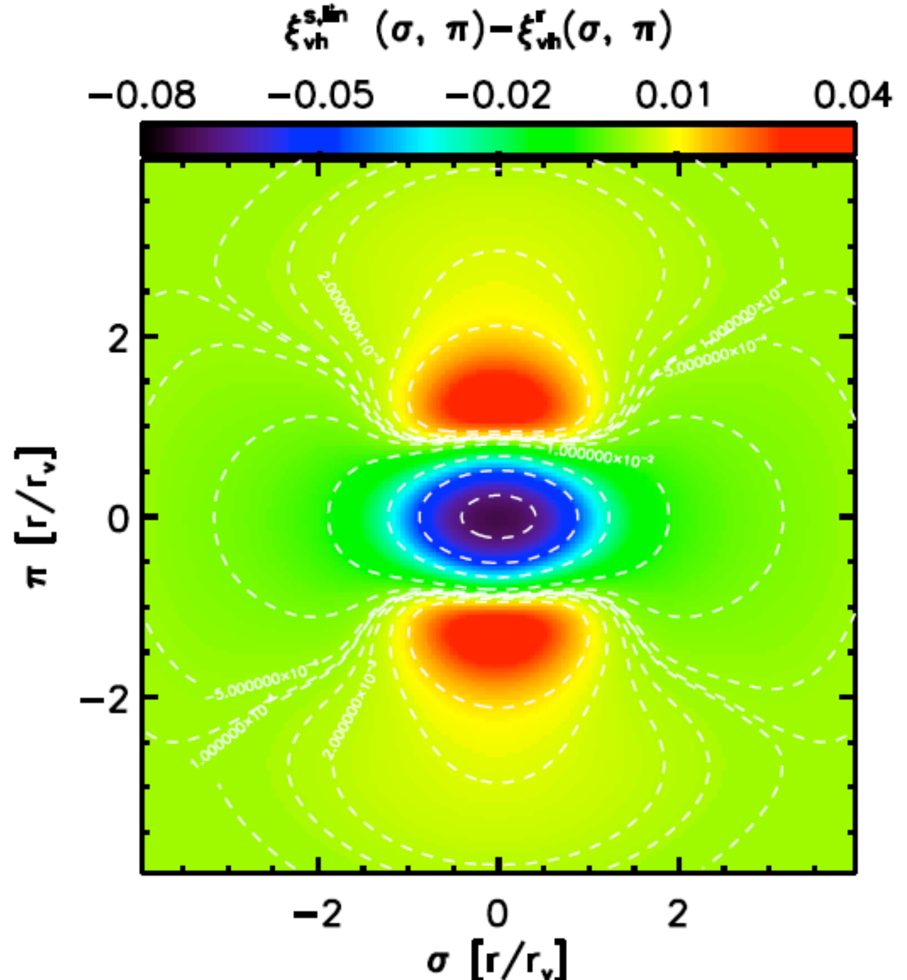
$$\beta = f/b$$

$$\xi^s(r,1) = (1+\beta)\xi(r) - \frac{2}{3}\bar{\xi}(r)$$ (line of sight)

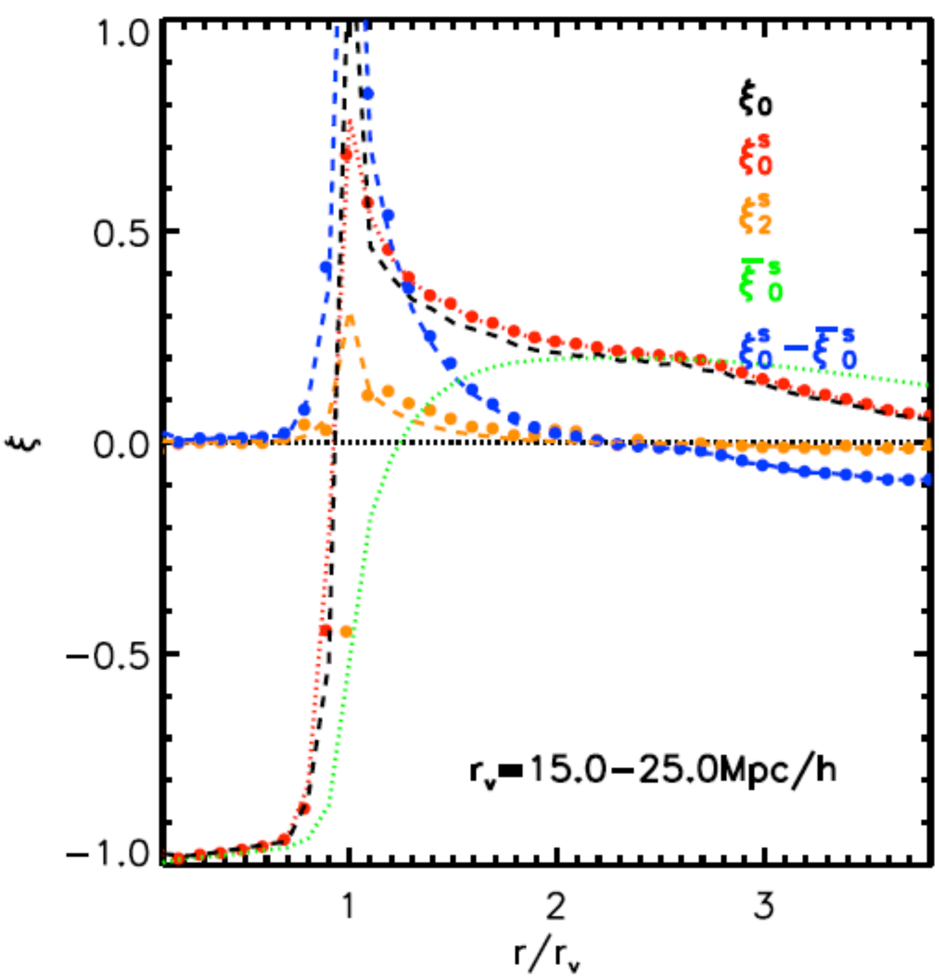
$$\bar{\xi}(r) = \frac{3}{r^3}\int_0^r \xi(r')r'^2 dr'$$

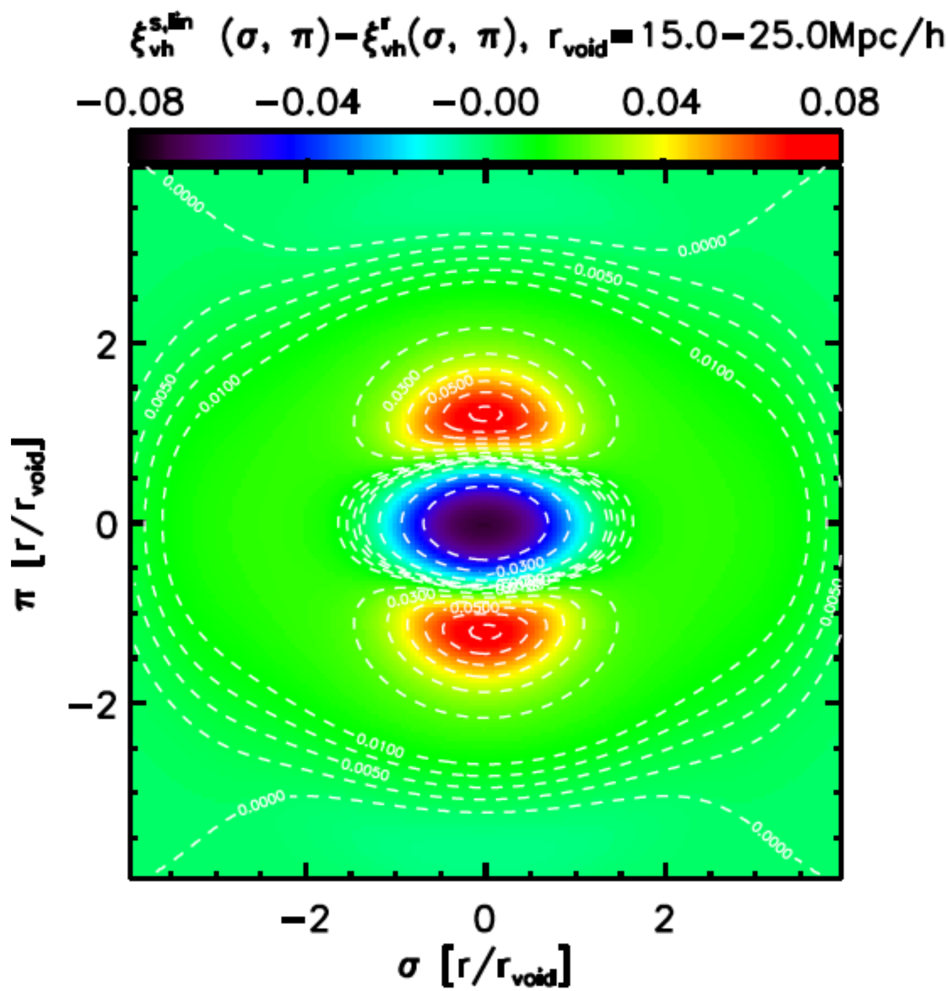
$$\xi^s(r,0) = \xi(r) + \frac{1}{3}\beta\bar{\xi}(r)$$ (transverse LOS)





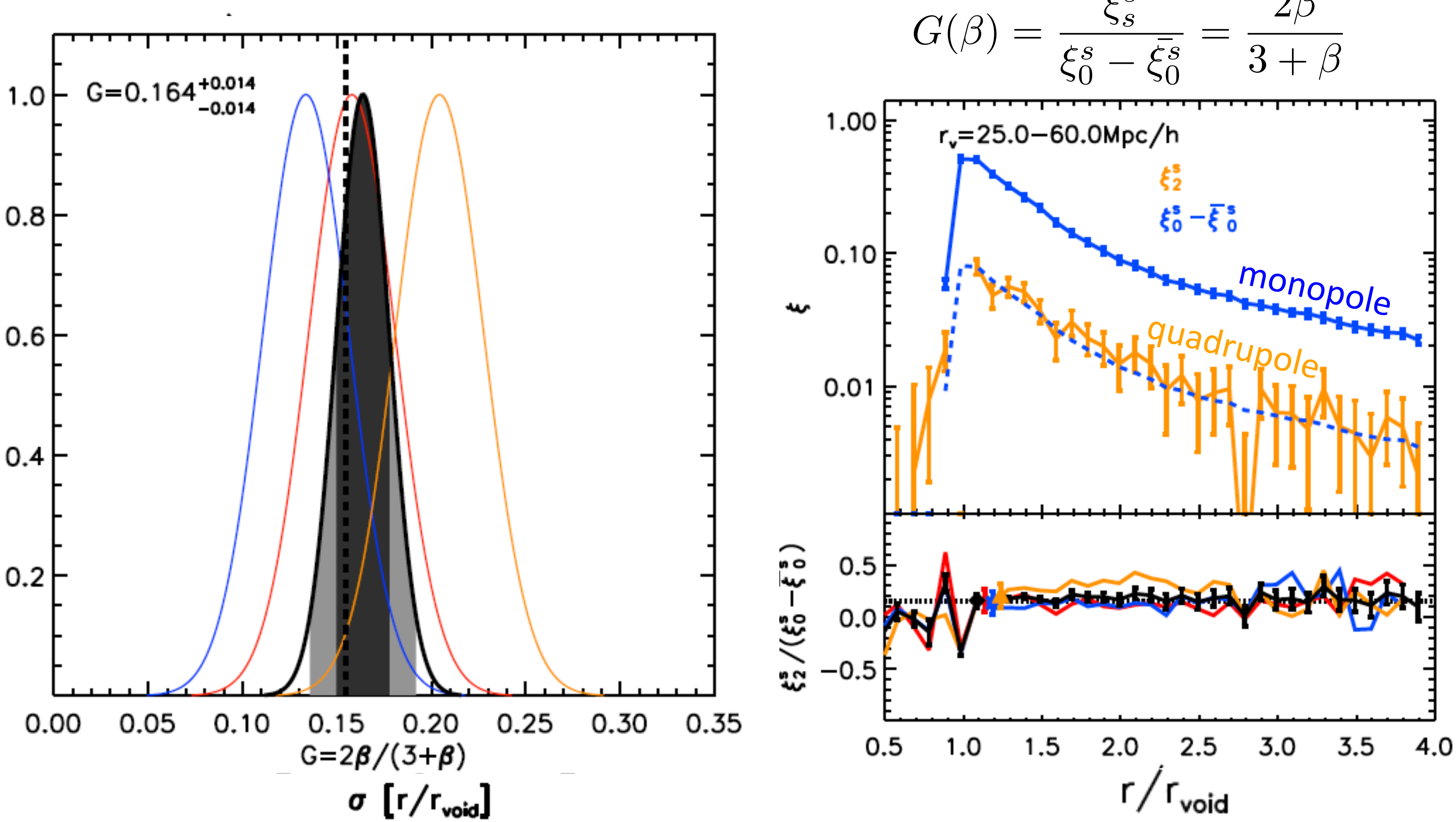
Void-halo correlation function

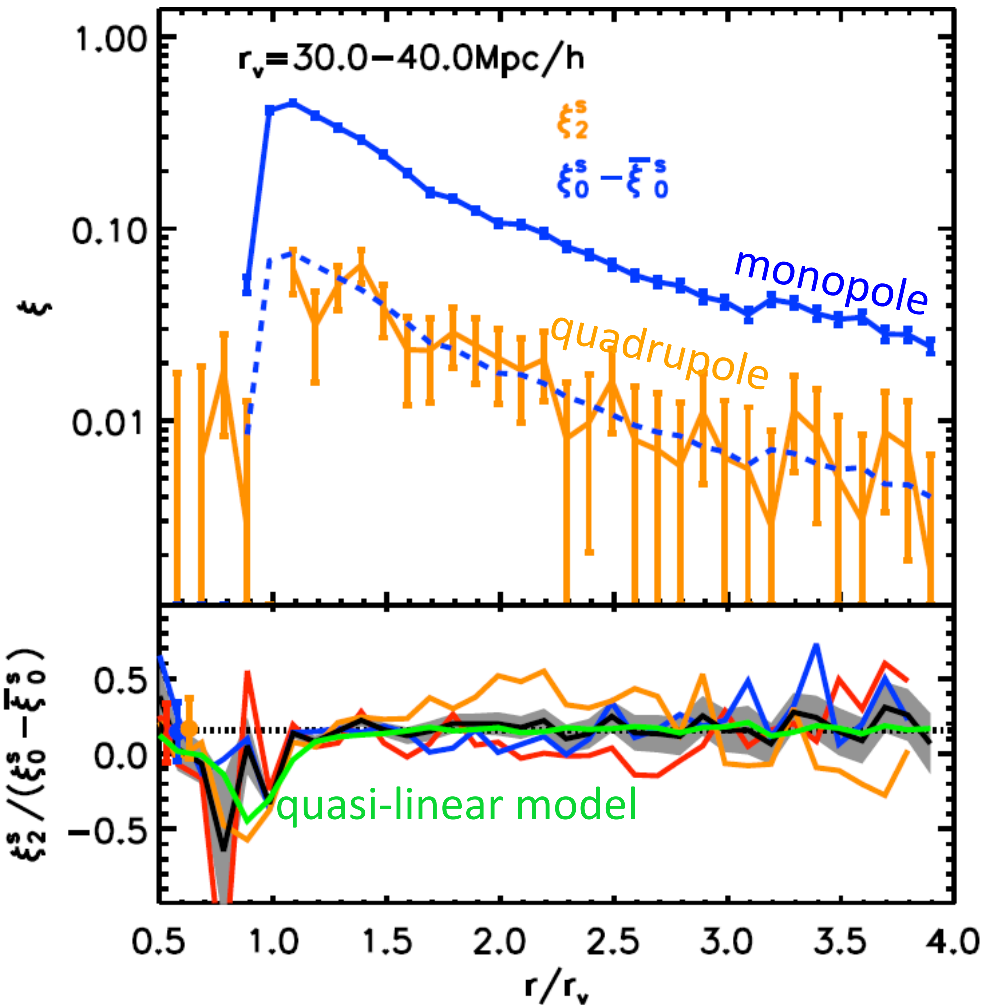




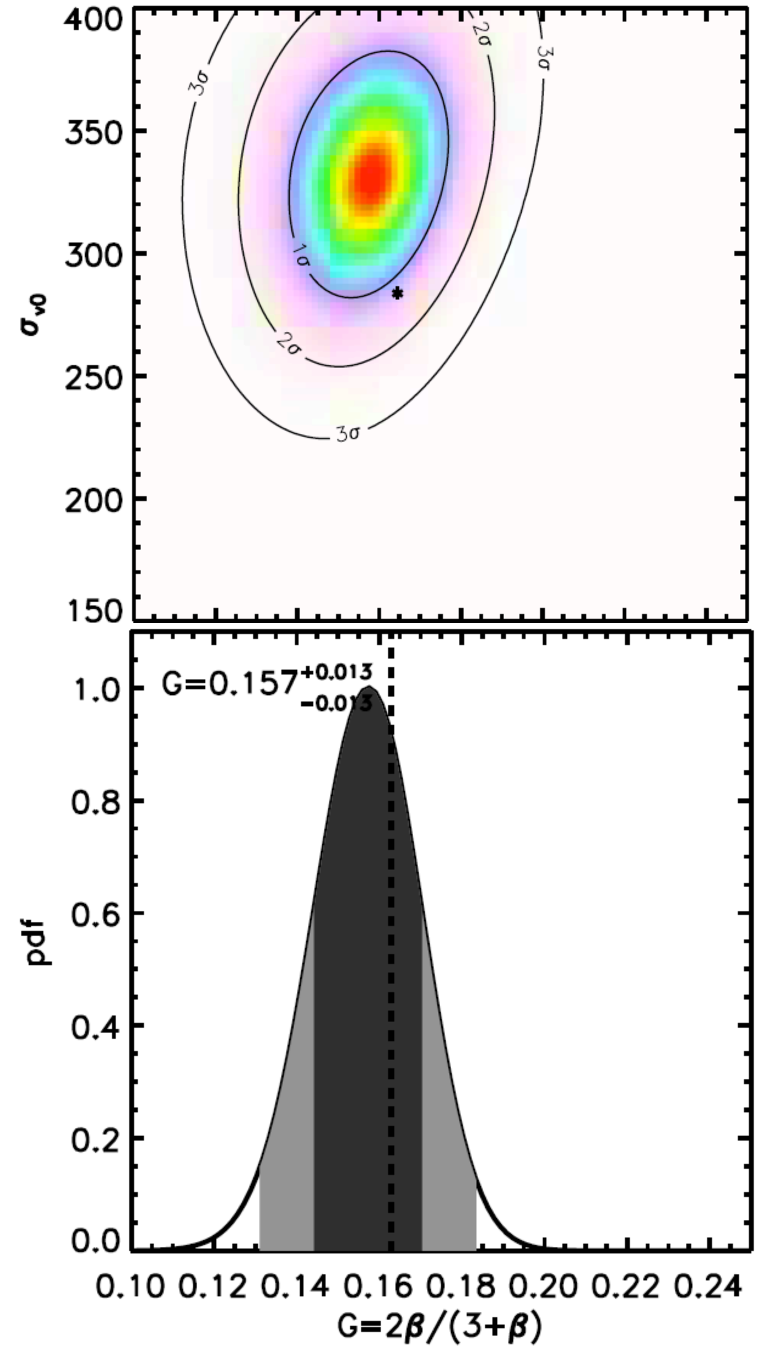
Extracting the linear growth

$$G(\beta) = \frac{\xi_s^s}{\xi_0^s - \bar{\xi}_0^s} = \frac{2\beta}{3+\beta}$$





$$1+\xi^{s}_{\rm vm}(r_\sigma,r_\pi)=\int_{-\infty}^{\infty}\left[1+\delta\left(r_\sigma,r_\pi-\frac{v_\pi}{aH}\right)\right]\times$$
$$\frac{1}{\sqrt{2\pi}\sigma_{\rm v}}\exp\left(-\frac{[(v_\pi-v(r)\mu]^2}{2\sigma_{\rm v}^2(r)}\right)dv_\pi$$



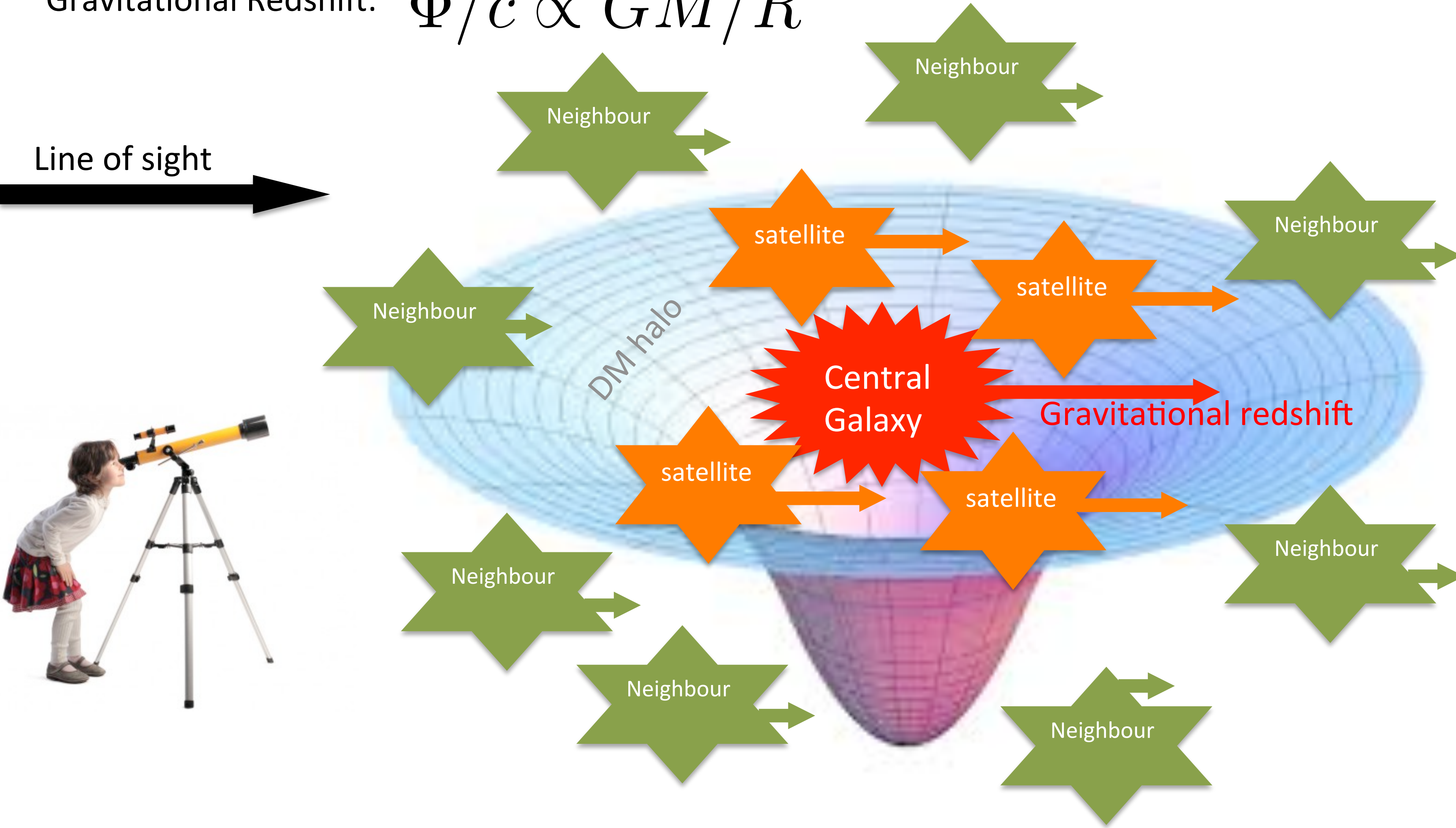
Summary

* Diverse shapes of voids in z-space
* Complicates Alcock-Paczynski test
* Unbiased linear growth at 12 Mpc/h
* 5% constraint for β with 3 Gpc/h^3

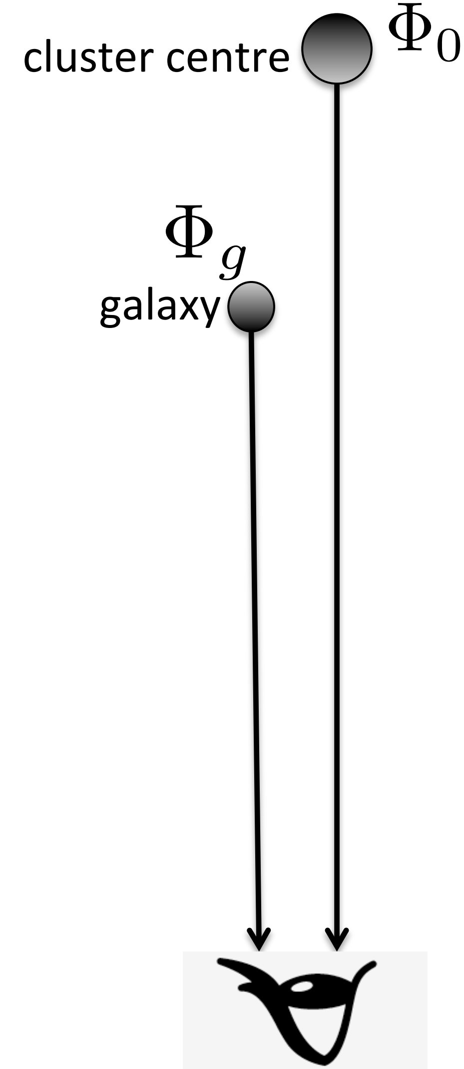
Gravitational Redshift from Stacked Clusters

Yan-Chuan Cai, Nick Kaiser & Shaun Cole, *in prep.*

Gravitational Redshift: $\Phi/c \propto GM/R$



The observed redshift



To the lowest order of the potential and peculiar velocity

$$cz = Hx + v_x$$

In the weak field limit in GR

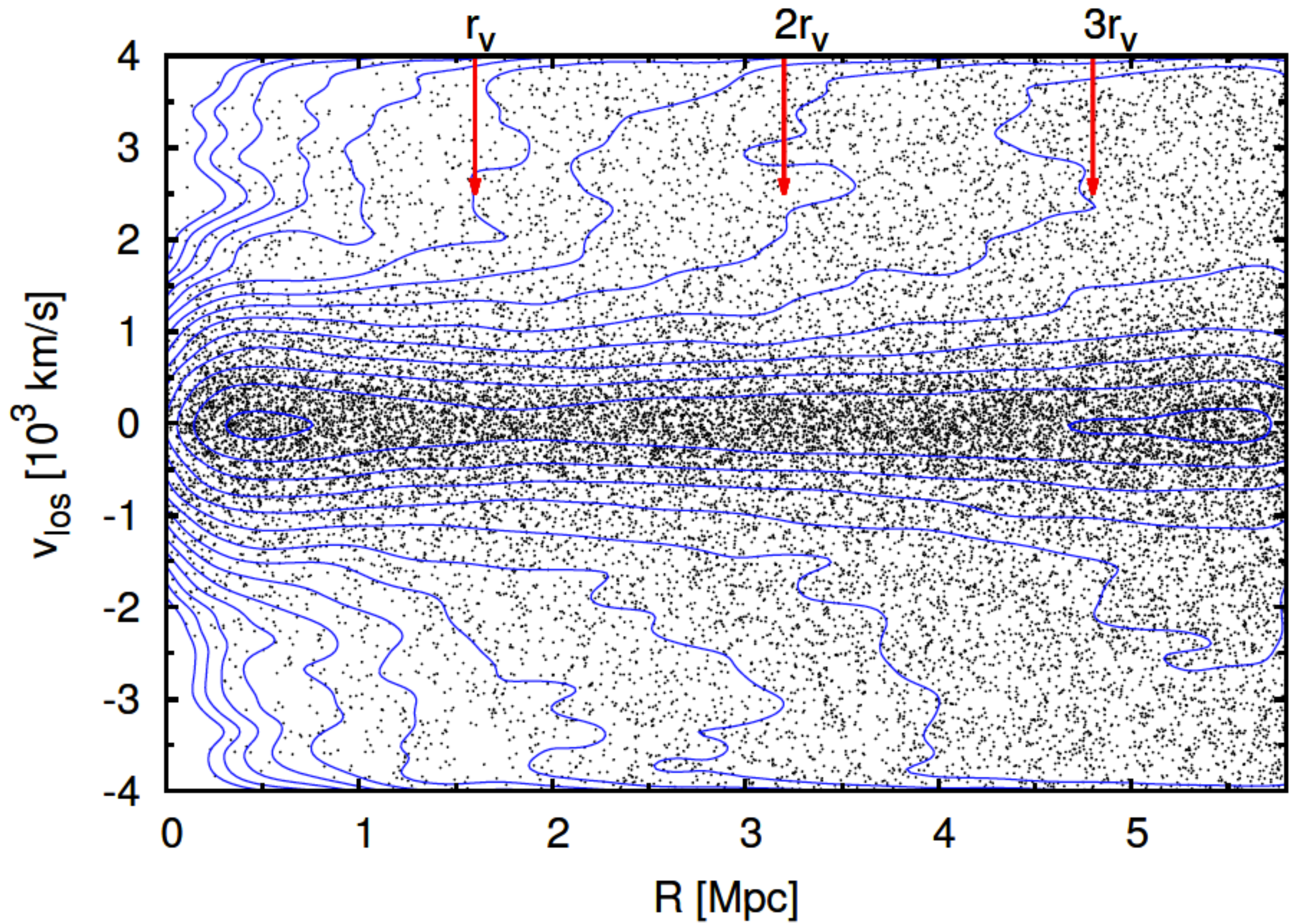
$$cz = Hx + v_x - \Phi/c$$

Stacking to beat velocity dispersion

$$< cdz > = < cz_g - cz_0 > = < \Phi_0 - \Phi_g > /c$$

Wojtak, Hansen & Hjorth, 2011

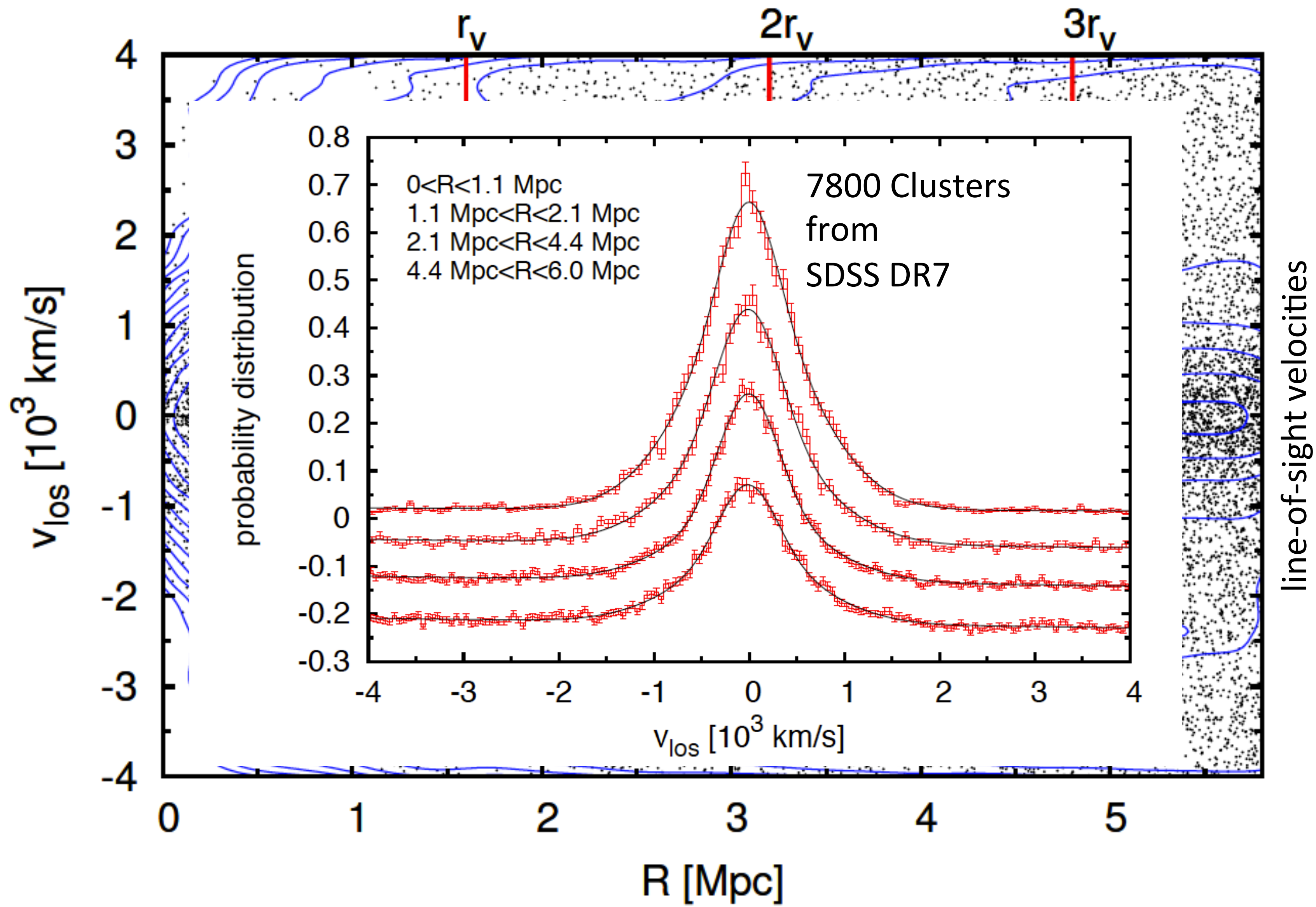
7800 Clusters from SDSS DR7



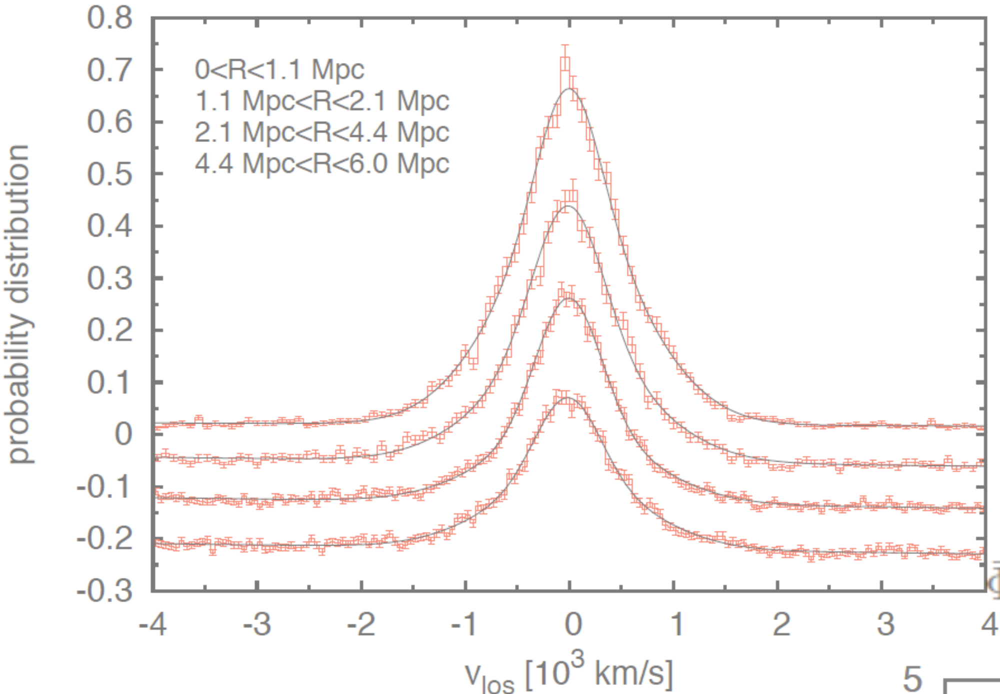
line-of-sight velocities

Projected Radius from the Composite Cluster

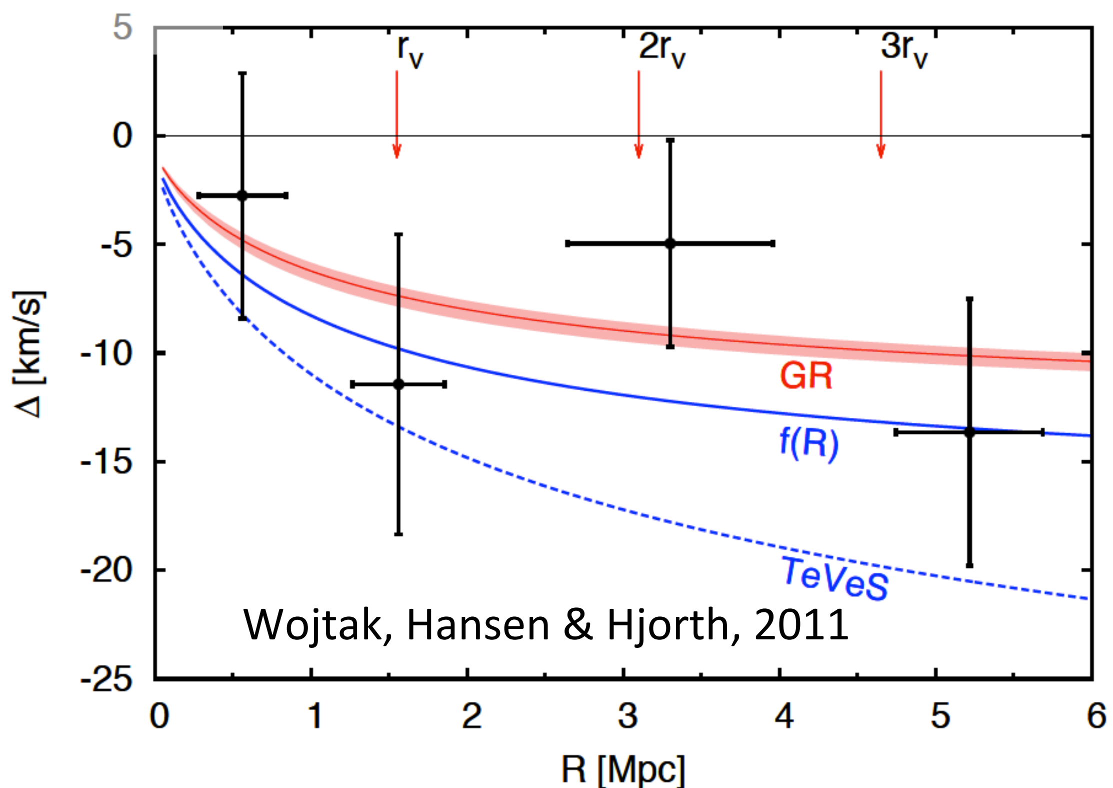
Wojtak, Hansen & Hjorth, 2011, Nature 477:567-569



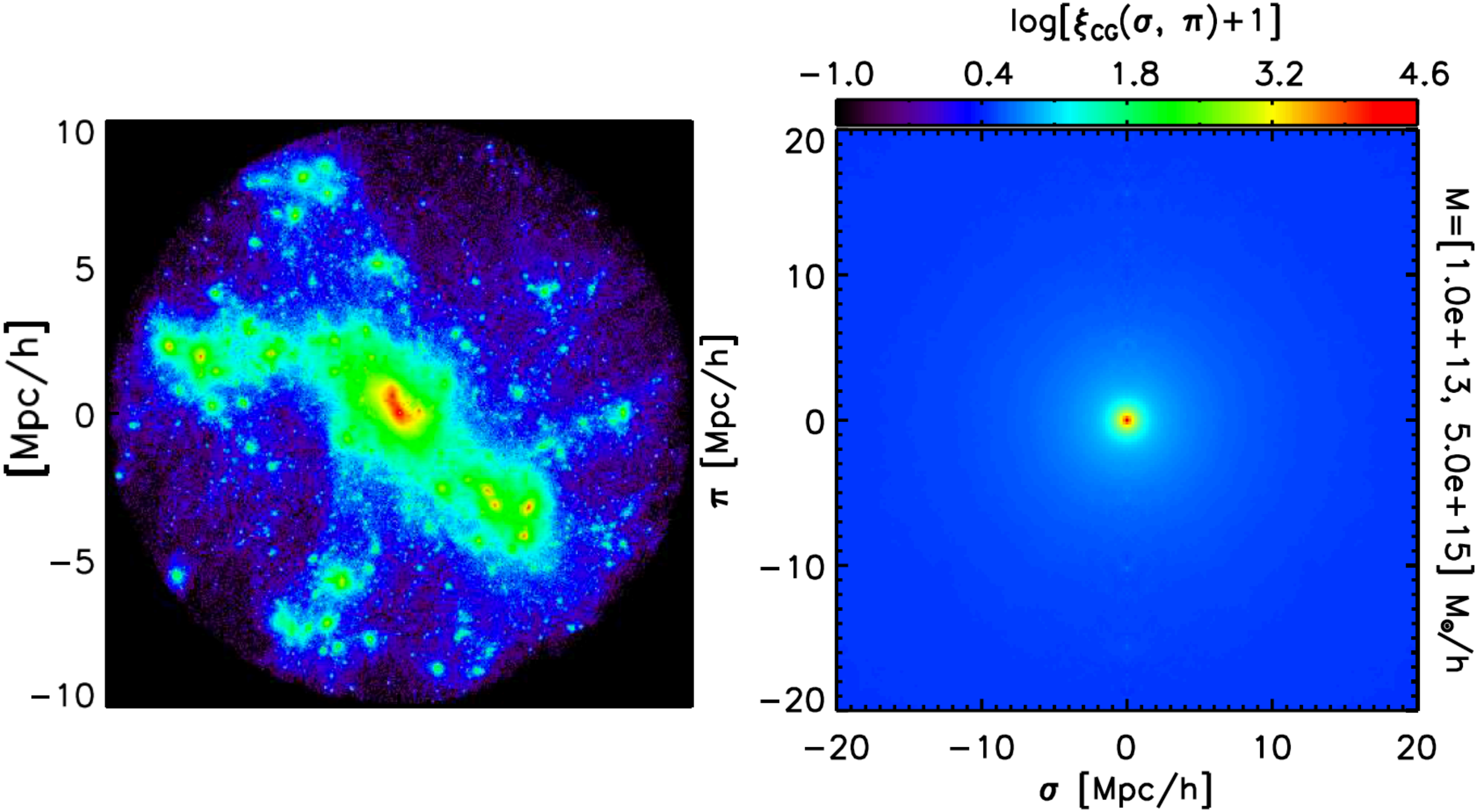
Projected Radius from the Composite Cluster



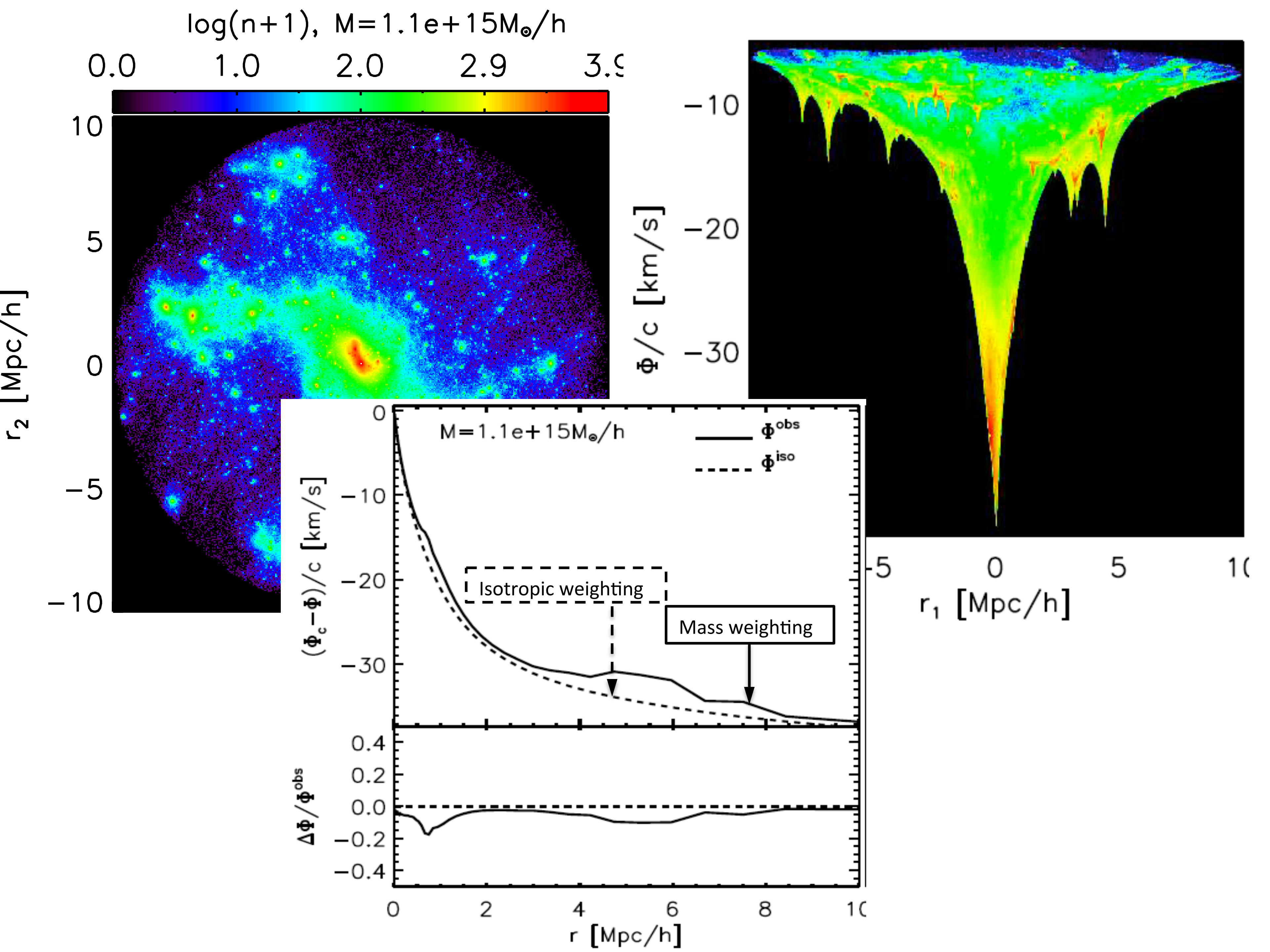
$$\bar{\Phi}^{\rm iso}(r) = \frac{\int (dN_c/dM) n_{c,g}(r)[\Phi_{\rm core} - \Phi(r)] dM}{\int (dN_c/dM) n_{c,g}(r) dM}$$



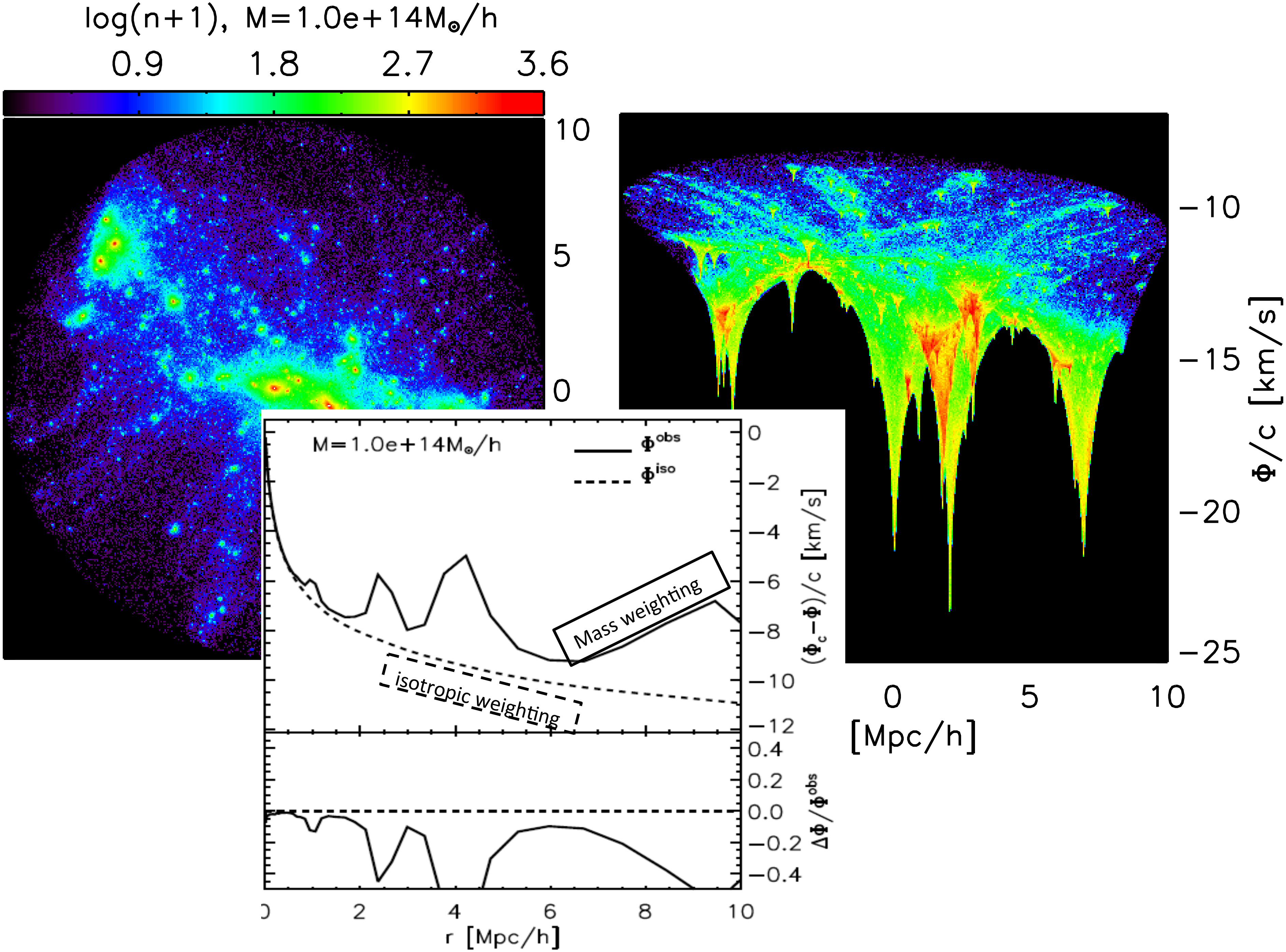
Wojtak, Hansen & Hjorth, 2011



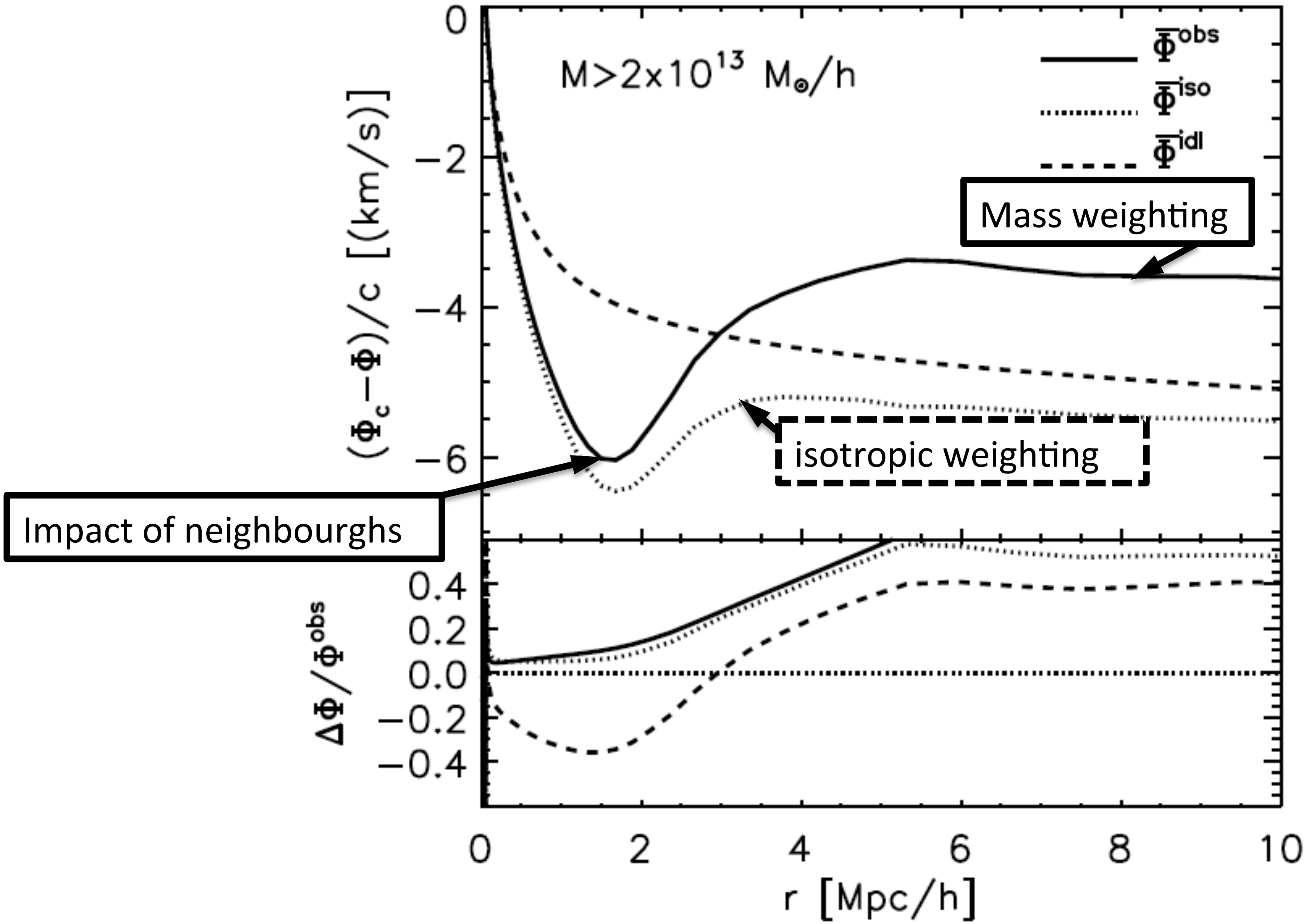
- isotropic weighting vs. galaxy weighting



log(n+1), M=1.1e+15M⊙/h
0.0
1.0
2.0
2.9
3.9
r2 [Mpc/h]
10
5
0
−5
−10
Φ/c [km/s]
−10
−20
−30
−5
0
5
10
r1 [Mpc/h]
M=1.1e+15M⊙/h
Φobs
Φiso
(Φc−Φ)/c [km/s]
0
−10
−20
−30
Isotropic weighting
Mass weighting
ΔΦ/Φobs
0.4
0.2
0.0
−0.2
−0.4
0
2
4
6
8
10
r [Mpc/h]

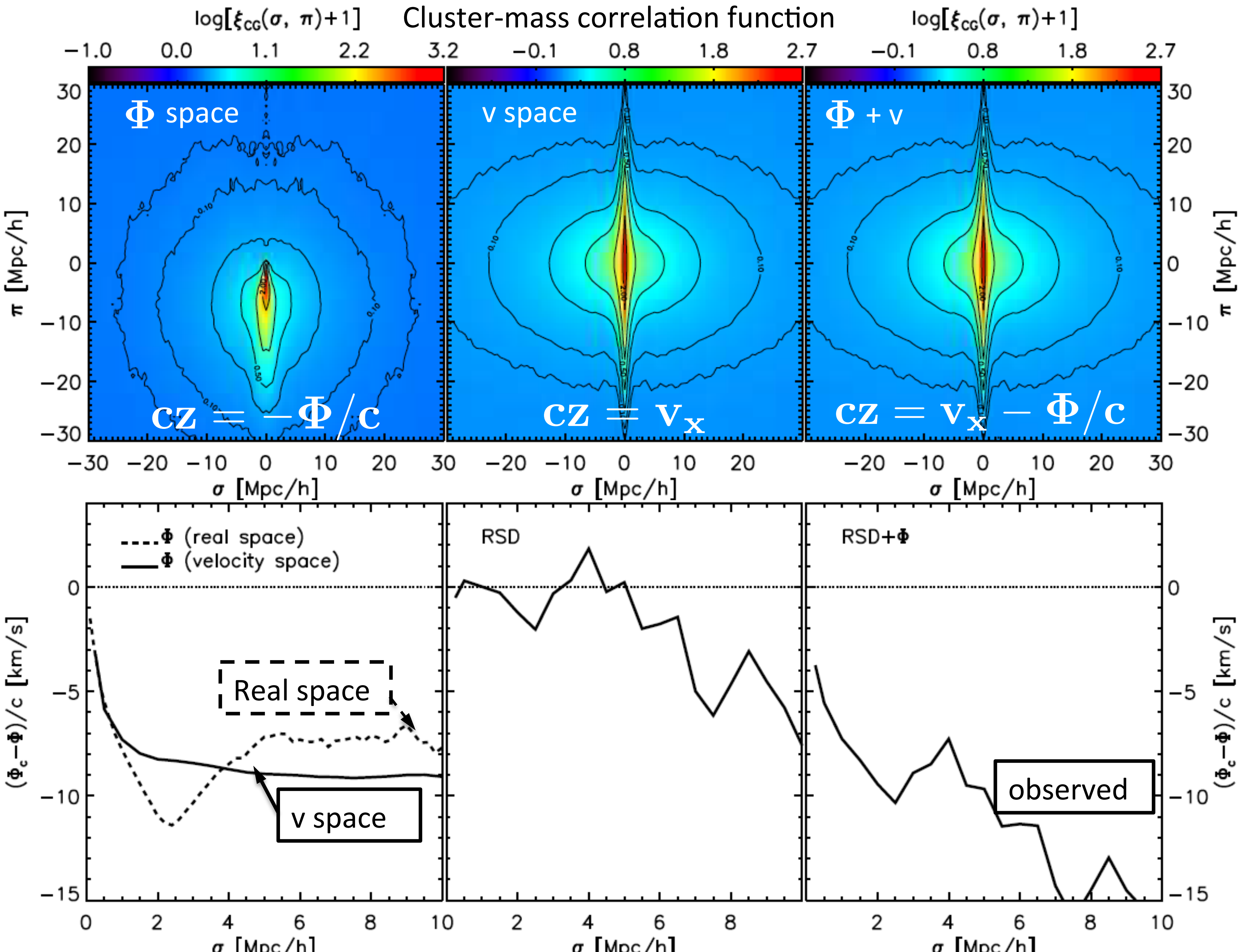


log(n+1), M=1.0e+14M⊙/h
0.9
1.8
2.7
3.6
10
5
0
M=1.0e+14M⊙/h
Φobs
Φiso
Mass weighting
isotropic weighting
(Φc−Φ)/c [km/s]
ΔΦ/Φobs
r [Mpc/h]
Φ/c [km/s]
[Mpc/h]



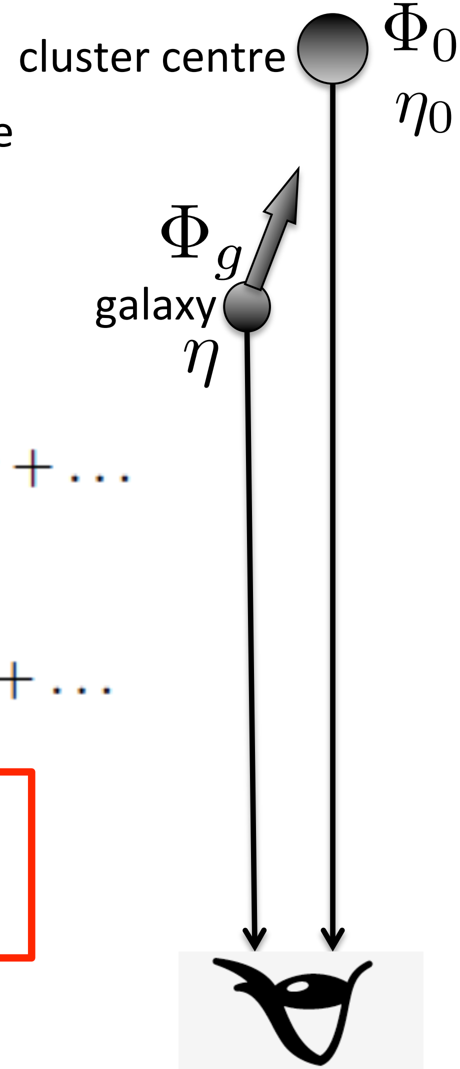
M>2x10^13 M⊙/h
Φ̄^obs
Φ̄^iso
Φ̄^idl
Mass weighting
isotropic weighting
Impact of neighbourghs
(Φc−Φ)/c [(km/s)]
ΔΦ/Φ^obs
r [Mpc/h]

real space vs. v-space



Cluster-mass correlation function
log[ξ_CG(σ, π)+1]
−1.0 0.0 1.1 2.2 3.2
−0.1 0.8 1.8 2.7
−0.1 0.8 1.8 2.7
Φ space
v space
Φ + v
cz = −Φ/c
cz = v_x
cz = v_x − Φ/c
π [Mpc/h]
σ [Mpc/h]
Φ (real space)
Φ (velocity space)
Real space
v space
RSD
RSD+Φ
observed
(Φ_c−Φ)/c [km/s]

Redshift in the past light cone



Photons emitted at time η_0 and at η are received at the same time

$$\eta = \eta_0 - \hat{\mathbf{x}} \cdot \mathbf{r}(\eta) + \dots$$

Galaxy moves: the trajectory of a galaxy

$$\mathbf{r}(\eta) = \mathbf{r} + (\eta - \eta_0)\dot{\mathbf{r}} + \dots$$

Conformal time interval $\Delta\eta = -\hat{\mathbf{x}} \cdot \mathbf{r}/(1 + \hat{\mathbf{x}} \cdot \dot{\mathbf{r}}) = -x + x\dot{x} + \dots$

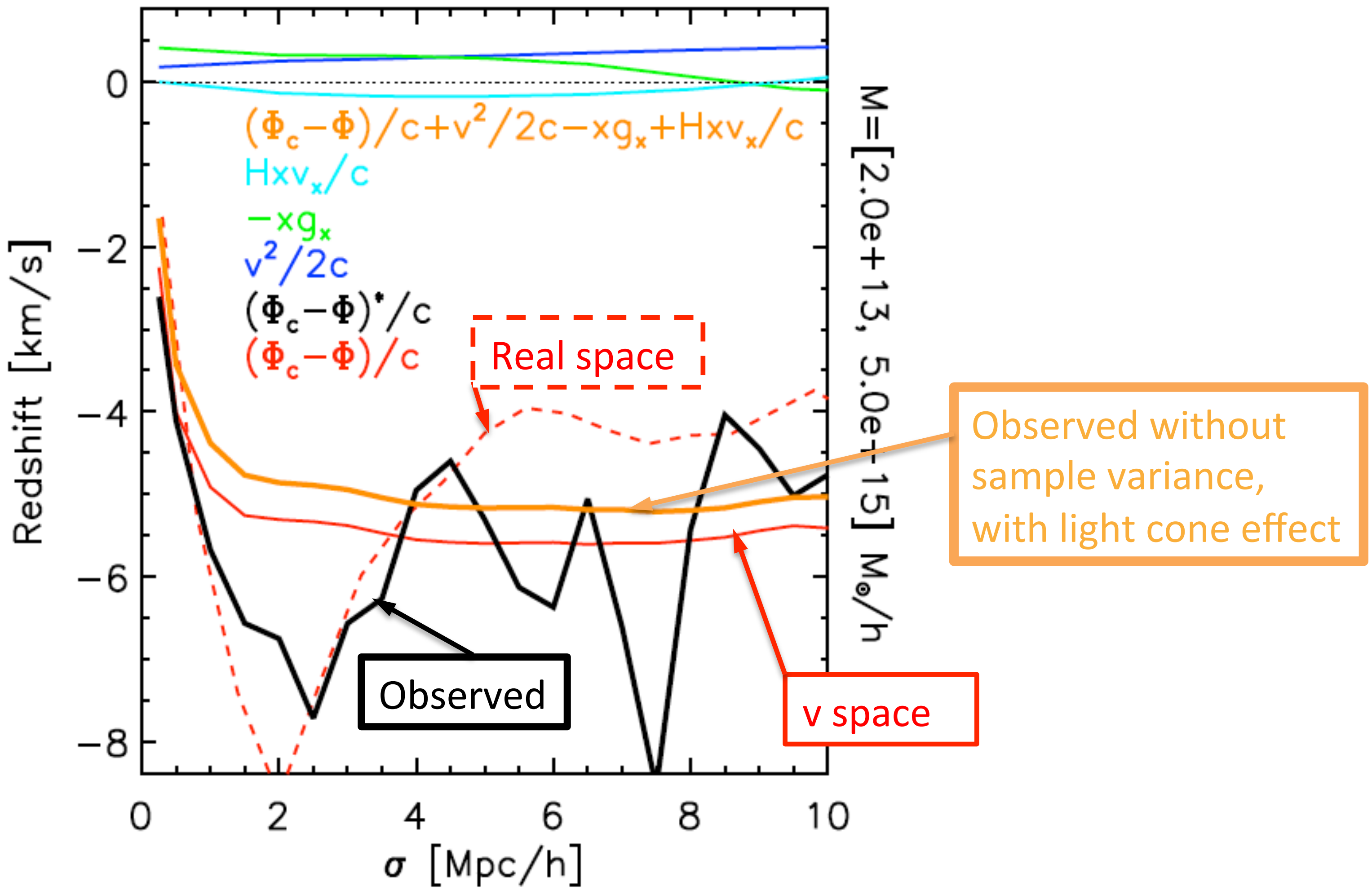
The Universe expand: expand off the redshift around η_0

$$(1+z)^{-1} = \frac{a(\eta)}{a(\eta_0)} = 1 + \frac{\dot{a}}{a}\Delta\eta + \frac{1}{2}\frac{\ddot{a}}{a}(\Delta\eta)^2 + \dots$$

$$\boxed{\begin{aligned} cz =& Hx + v_x + v^2/2c - \Phi/c \\ & - xg_x + Hxv_x/c + \left[H^2 - \ddot{a}/(2a^2)\right] x^2/c, \end{aligned}}$$

stationary observer relative to the cluster centre in conformal coordinates

The observed potential profile



Summary

- biases for modelling gravitational redshift:

  (1) substructures, neighbours

  (2) peculiar velocity

  (3) light cone effects