Structure and Dynamics in the Universe
Galaxy halos and Cosmic voids

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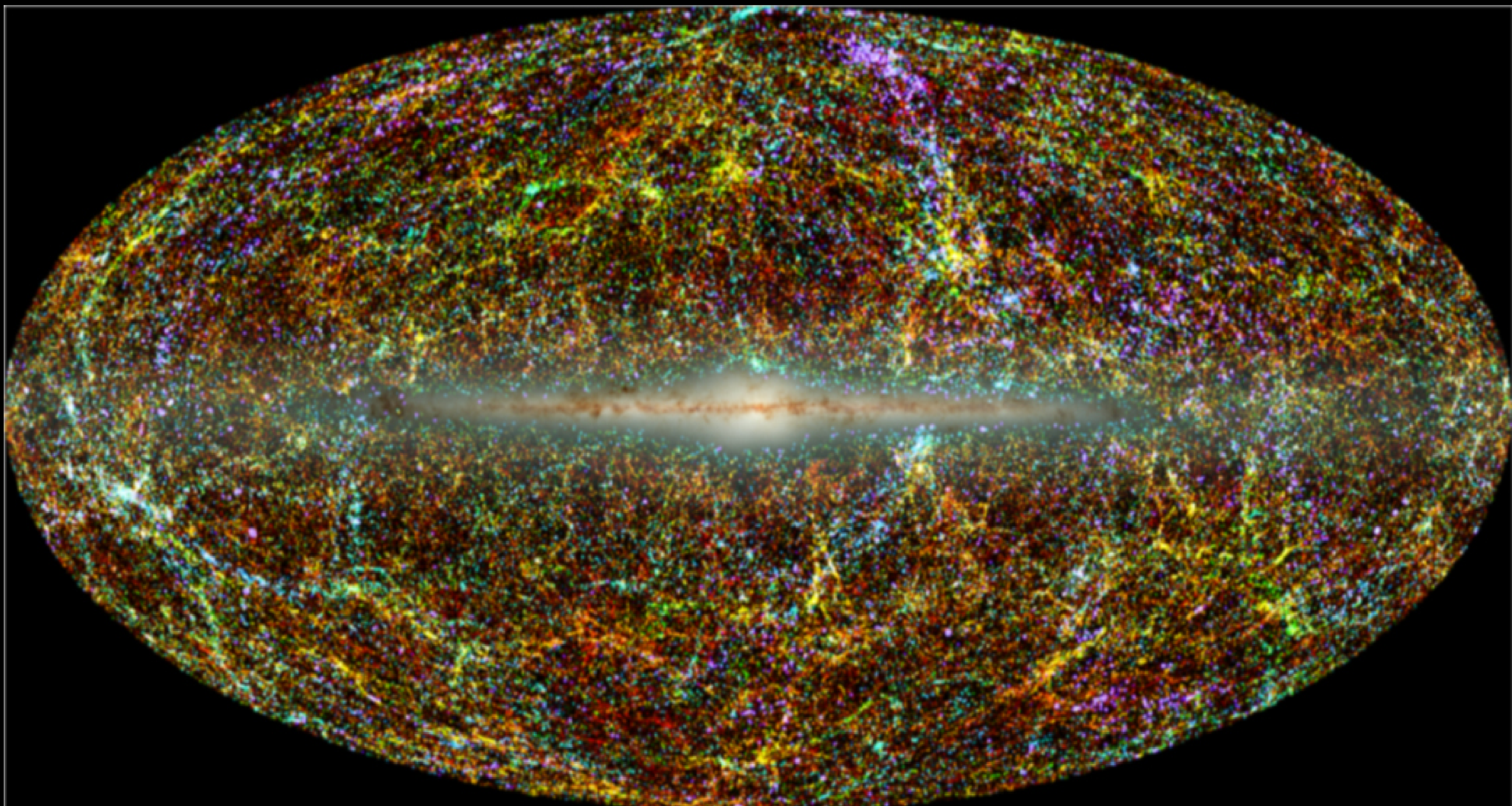
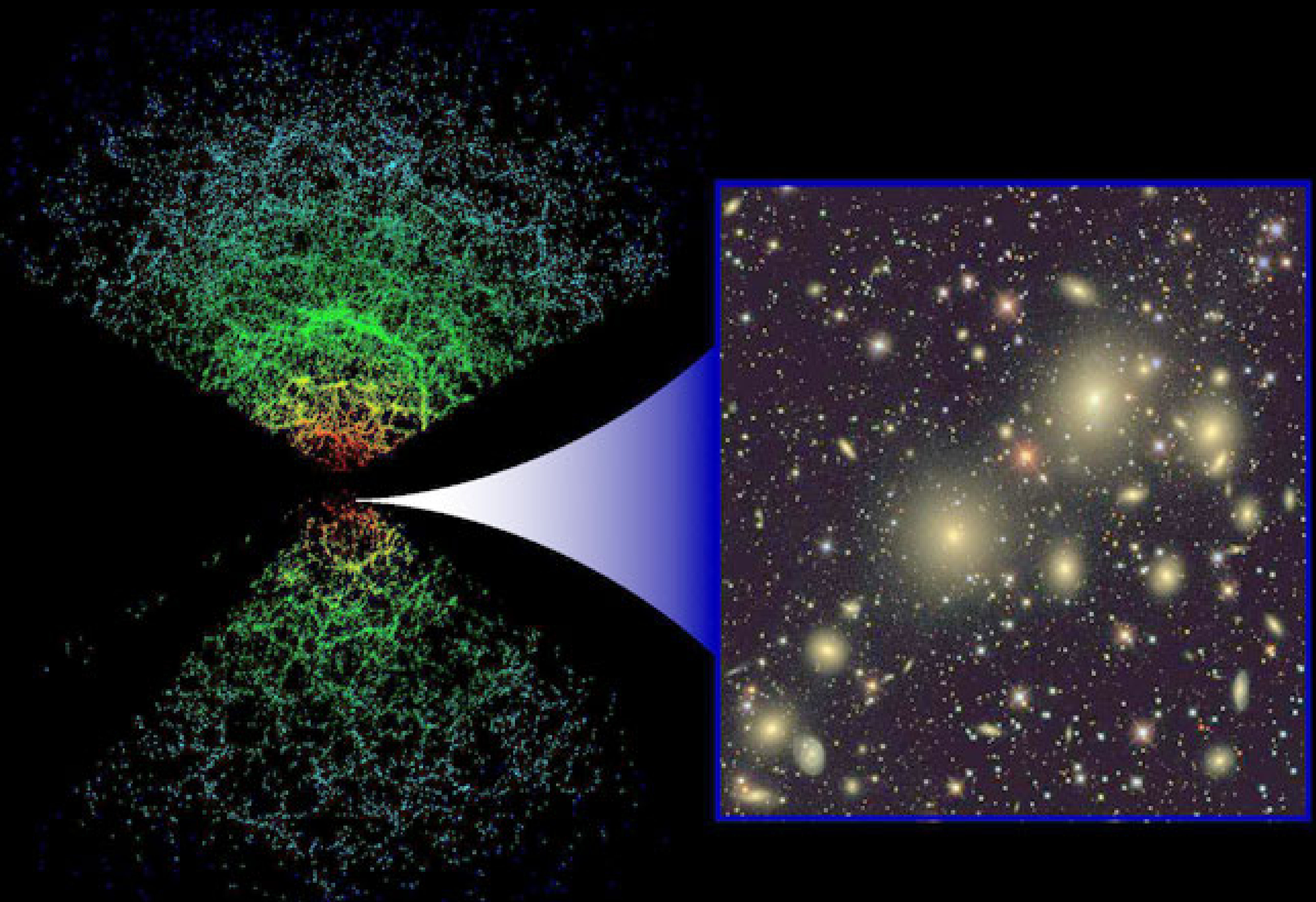
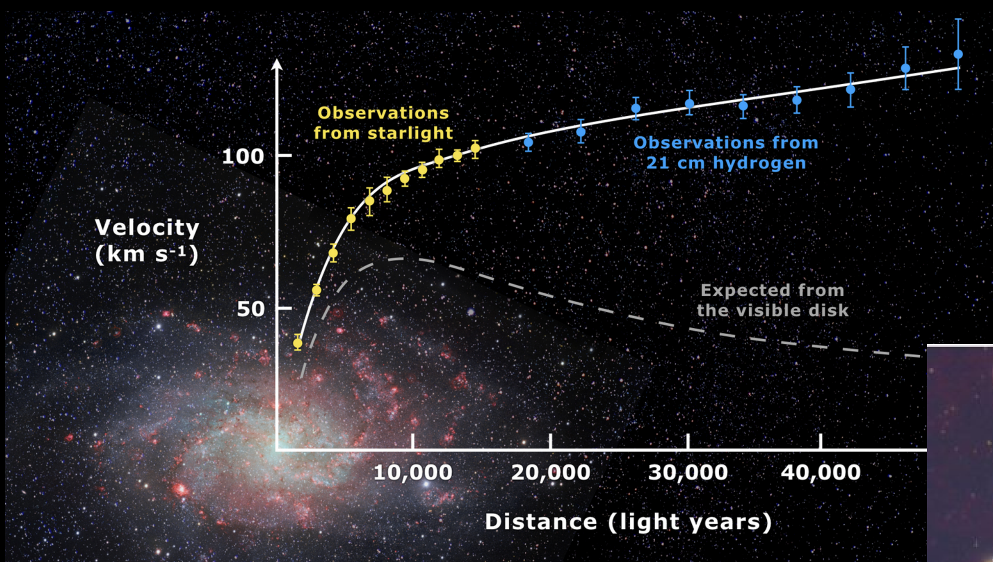
Cosmo UFES, May, 2022

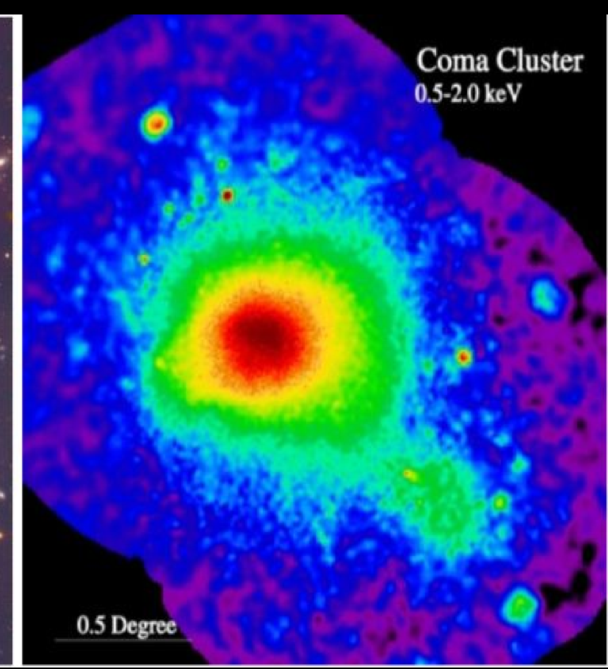


3-Dim view: Slices in depth (redshift)



Both, Galaxies and Clusters (also groups) Contain a large fraction of Dark Matter (90 % wrt galaxies +gas), needed to mantain approximately virial equilibrium.

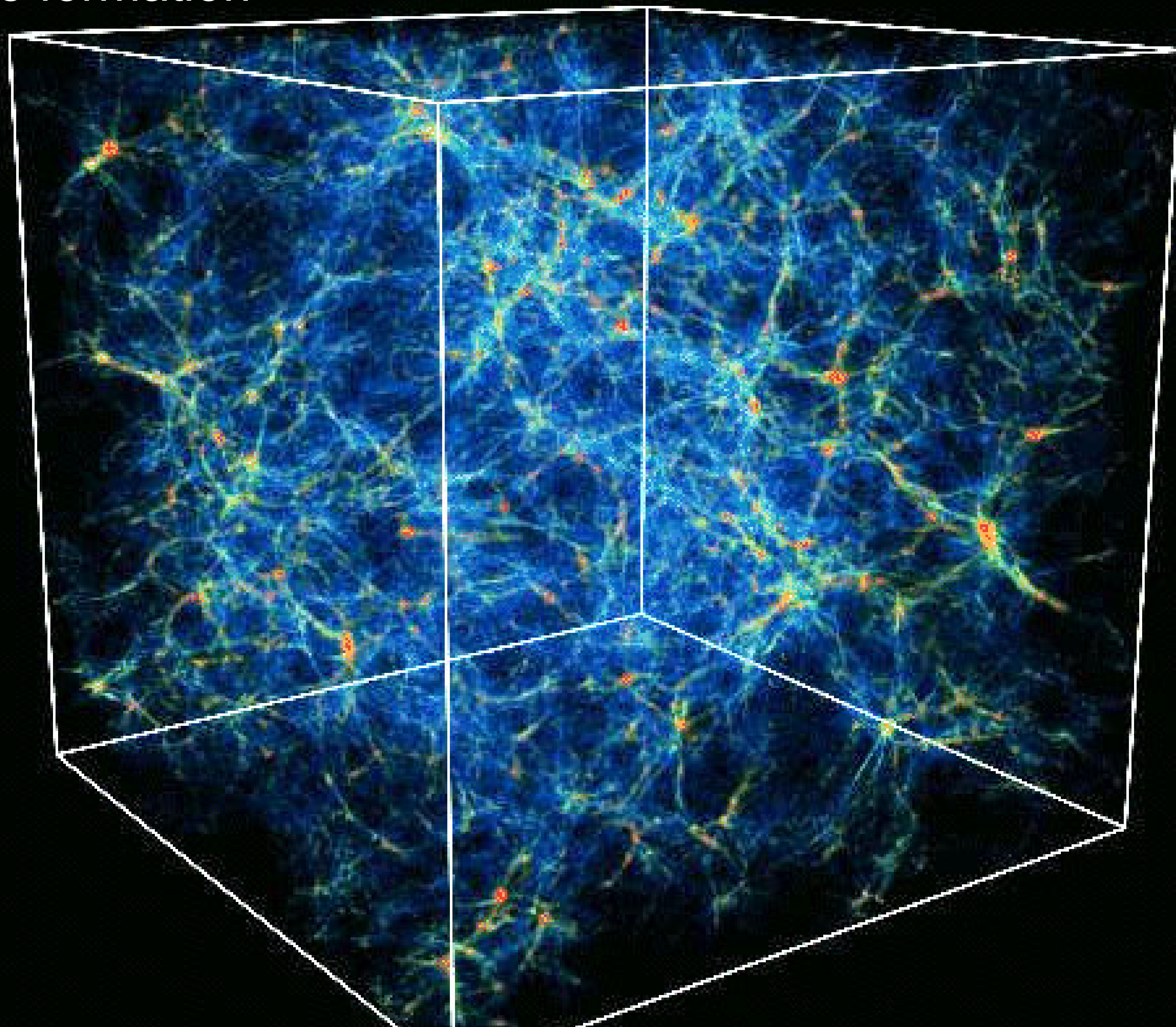




This is the clue to the HALO MODEL
Dark matter is associated to systems of galaxies and determine its origin and fate.

https://arxiv.org/abs/2104.10690

Numerical simulations (DM only) are simple and efficient models for structure formation



Structures:

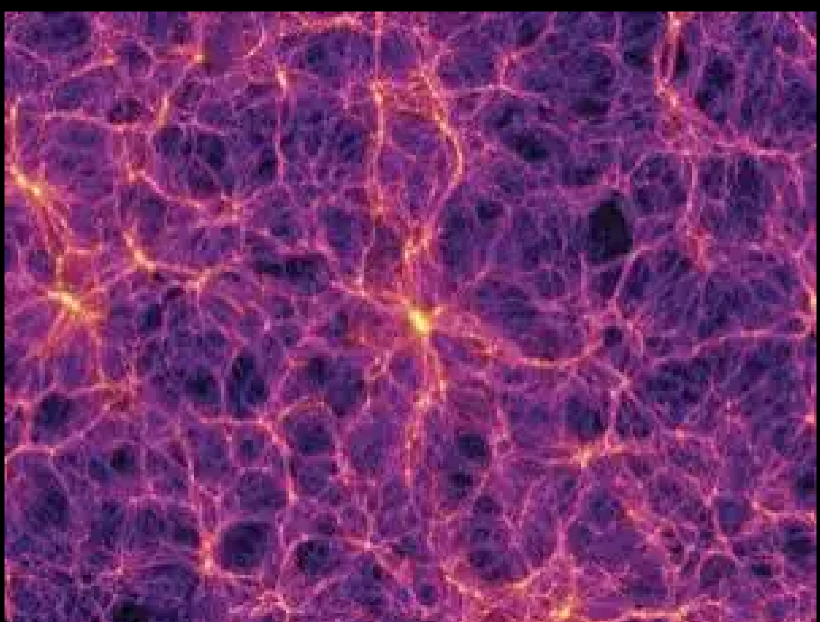
<u>Simples geometrical shapes:</u>

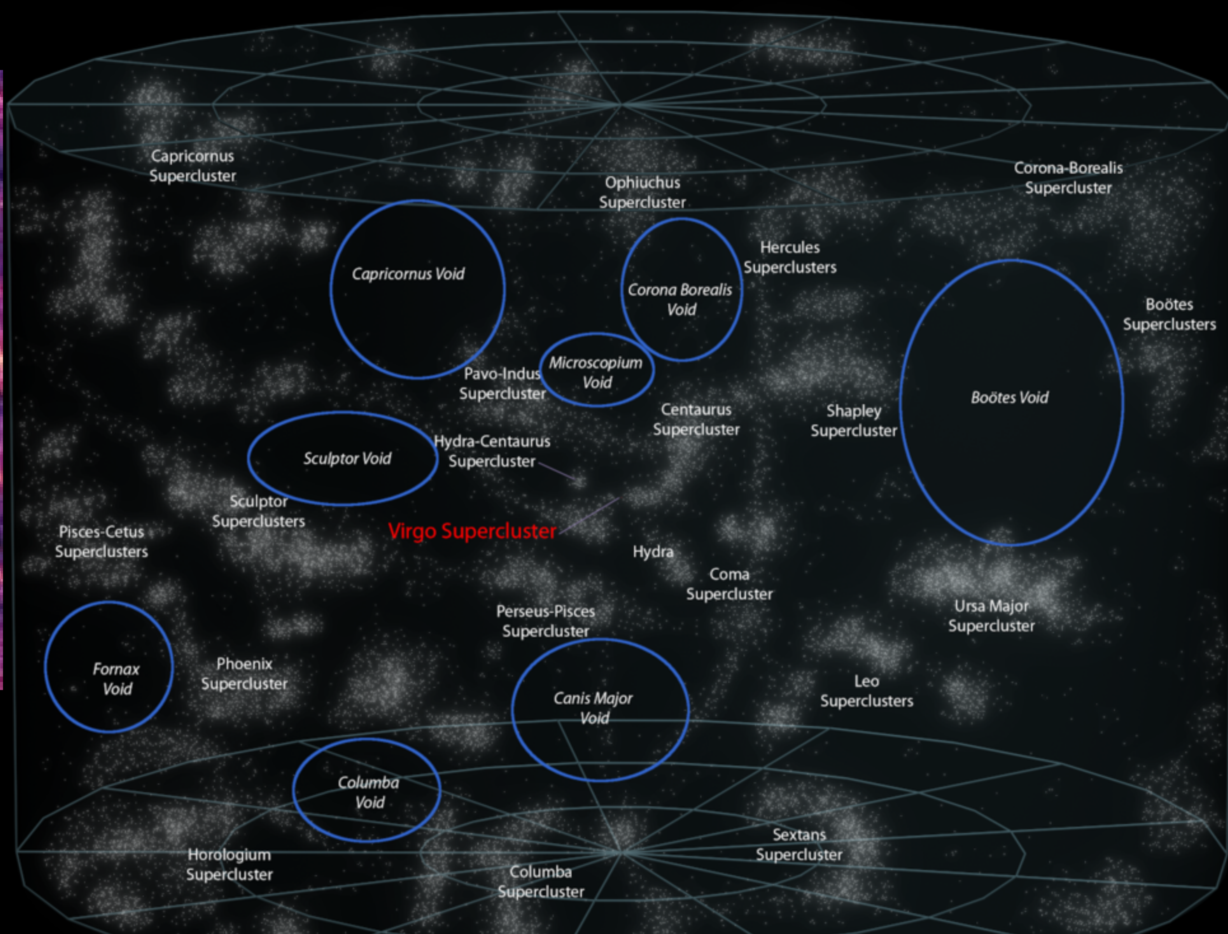
-Spherical symmetry: Clusters (very popular)

Other, such as elongated or planar structures:
Filaments and sheets

-Surveys produce suitable (complete) samples of <u>bright</u> galaxies. So, structures are traced by bright objects

There are also other systems that may be treated approximately with spherical symmetry: Cosmic Voids





Void definition

- Basically, an underdense region in the large-scale structure of the Universe lacking bright galaxies, rich and moderate rich clusters, and dense filaments.

- Multiple definitions/identification procedures depending on the algorithm used .

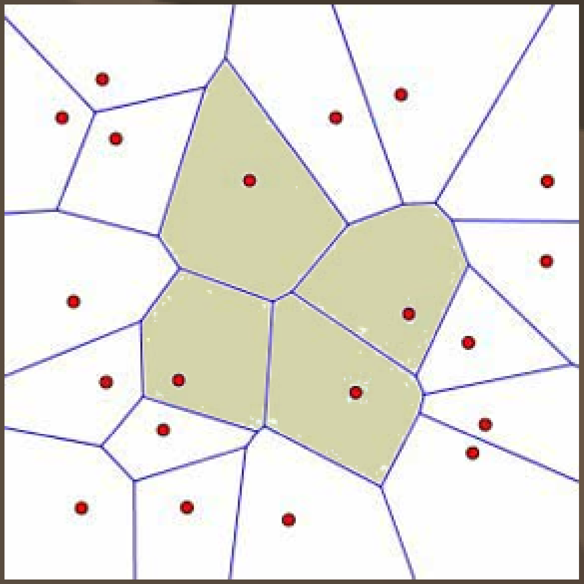
- These differences can be noticed in the Aspen-Amsterdam Void Comparison Project (Colberg+2008)

Our definition/identification procedure

- Voids: spherical regions with <10% the mean density of tracers, massive halos or luminous galaxies (Padilla+2005; Ceccarelli+2006; Ruiz+2015).

- Start with a Voronoi tessellation of the matter tracers, to identify the low density regions in the catalogue or simulation box.

- Each Voronoi cell has an associated density which is given by the inverse of the cell volume, $\rho_{cell} = 1 / V_{cell}$

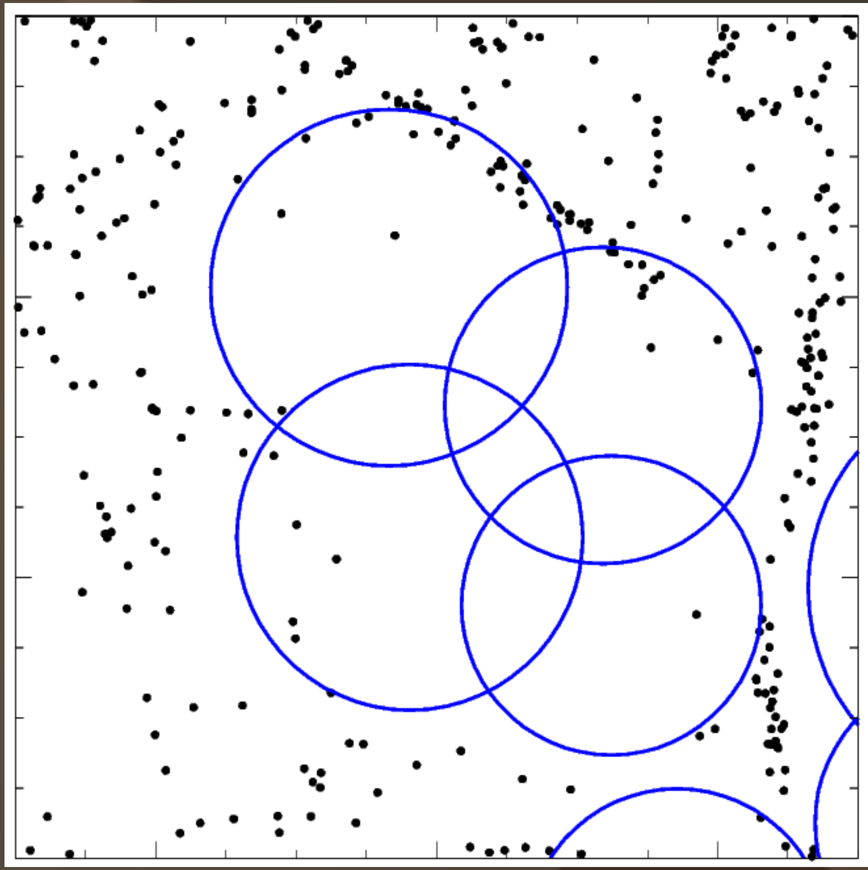


- All cells with $\delta = \rho_{cell}/\rho_{mean} - 1 < -0.8$ are selected as centers of underdense regions: a possible void among these cells.

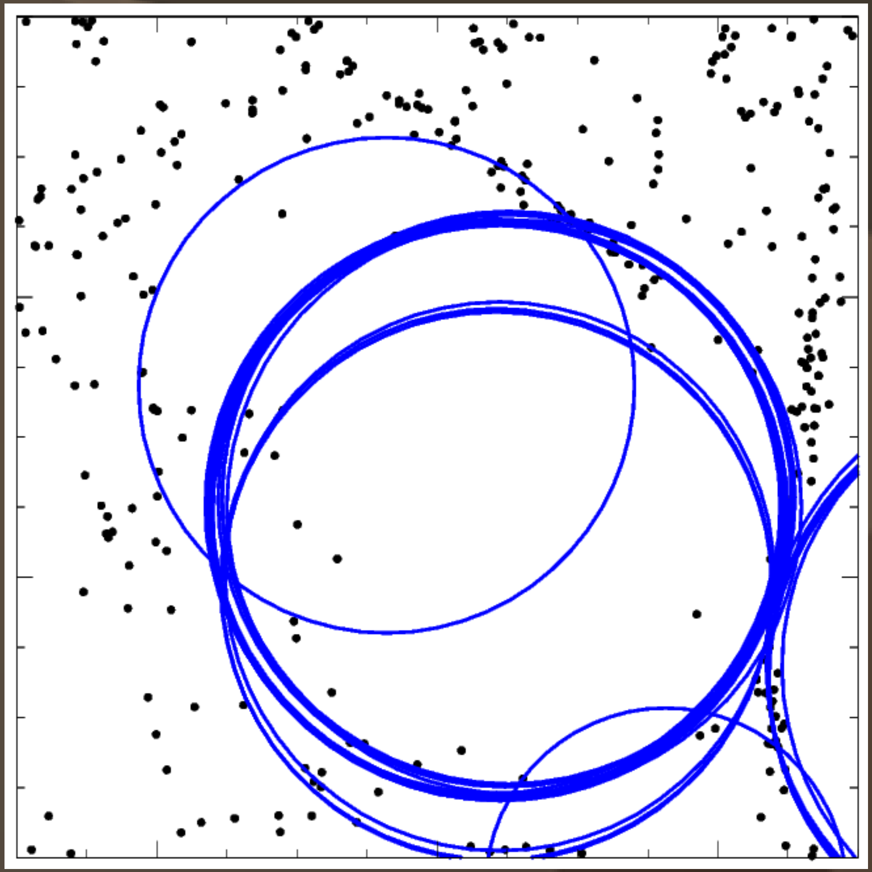
- Void candidates are all spherical volumes centered on cells with an integrated density contrast of tracers satisfying:

$$\Delta(R_{\rm void}) = \frac{3}{R_{\rm void}^3}\int_0^{R_{\rm void}} \delta(r) r^2 dr < -0.9,$$

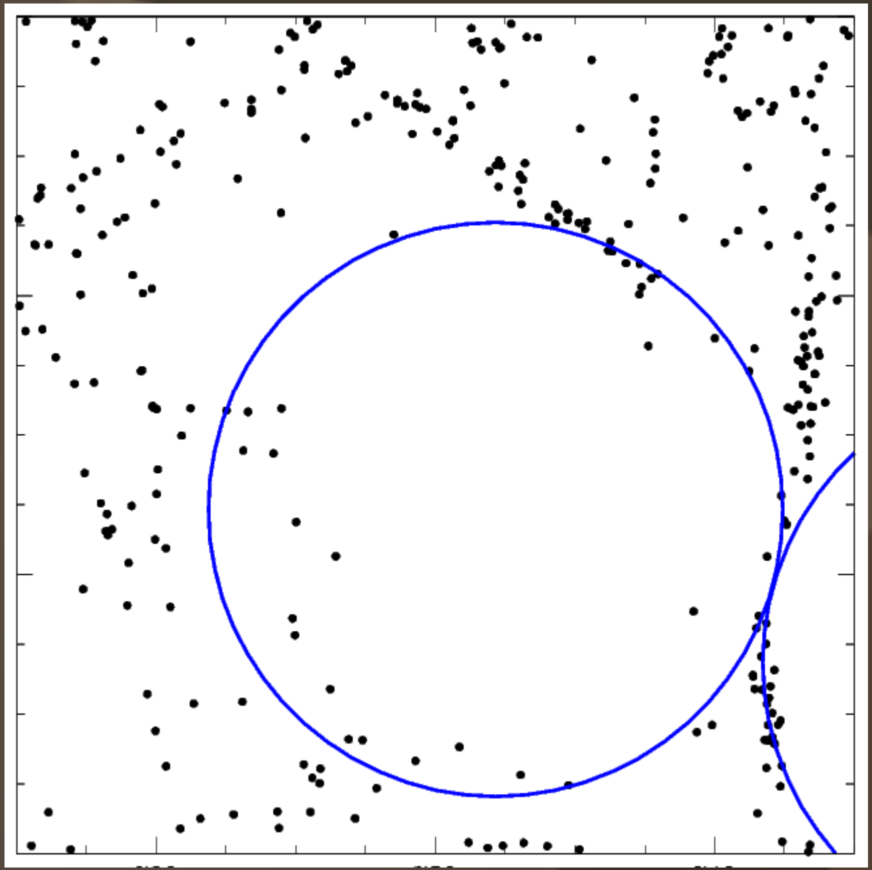
- A potential problem: several overlapped spheres not centered in the true local minimum of the density field.



- To solve this, we repeat the computation of Δ in a close perturbed center, and keep the new void candidate if its radius is larger.
-



- To solve this, we repeat the computation of Δ in a randomly perturbed center, keeping the new void candidate if his radius is larger.
- Repeat with all void candidates, mimicking a random walk which center candidates in the true minimum.

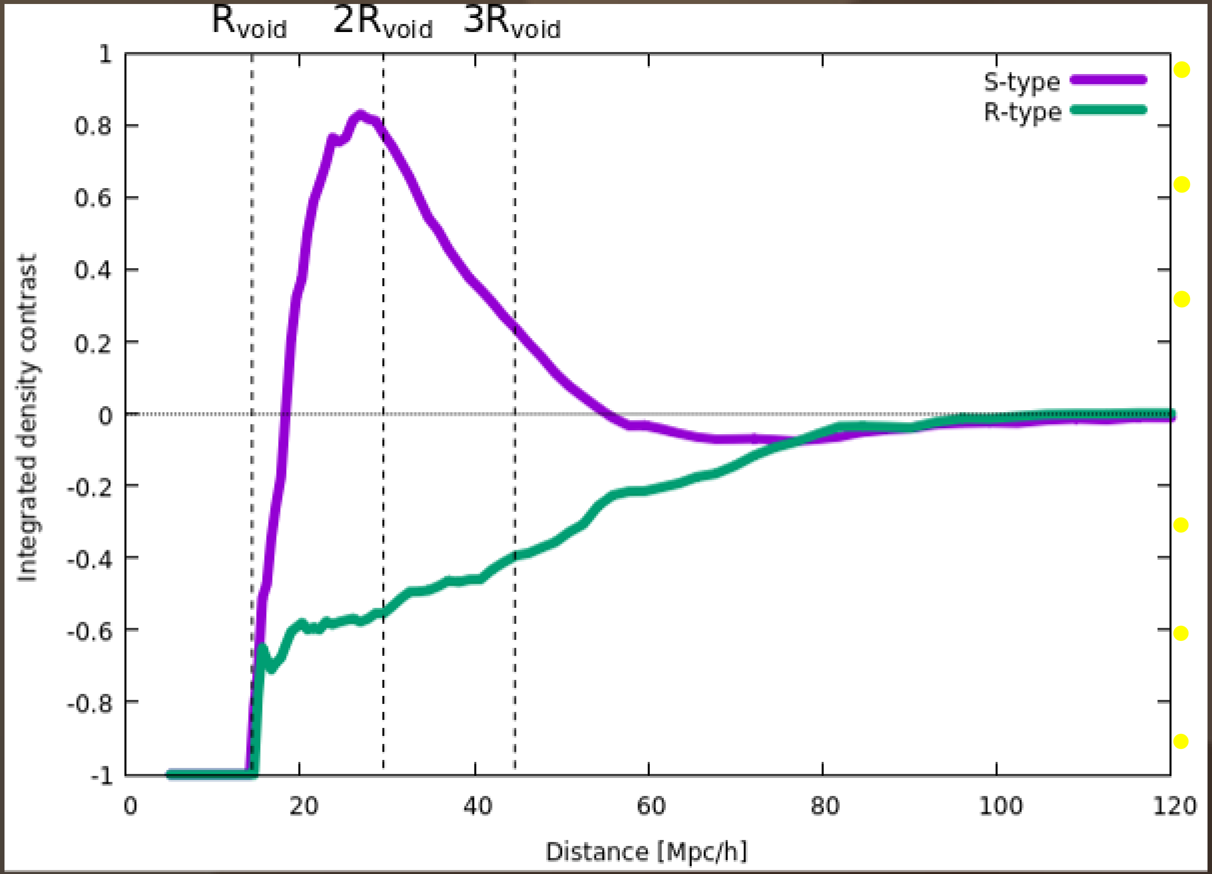


- To solve this, we repeat the computation of Δ in a randomly perturbed center, keeping the new void candidate if his radius is larger.
- We do this several times with all void candidates, mimicking a random walk which centers our candidates in the true minimum.

- The final void catalogue is then formed by the largest candidates which do not overlap.

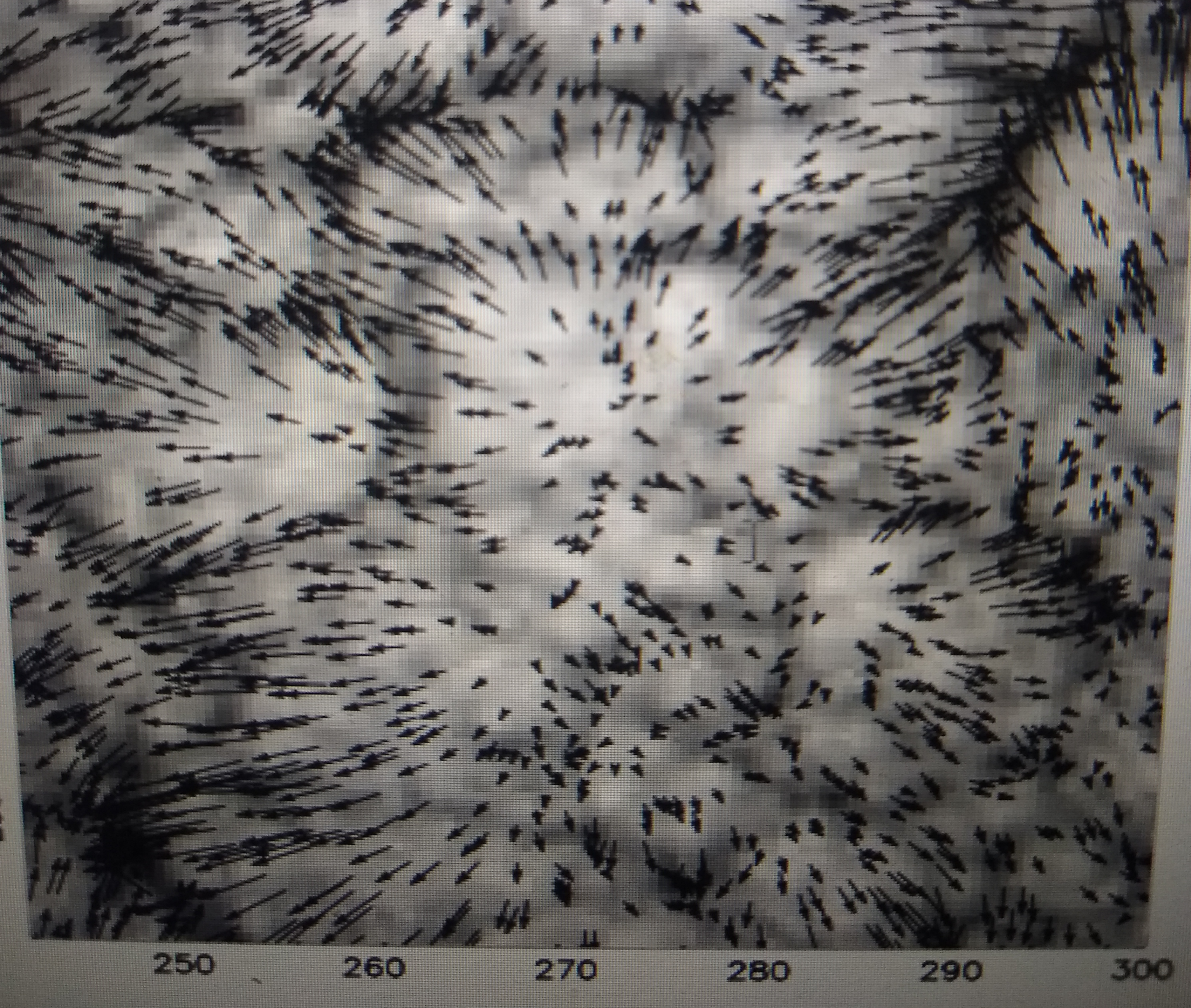
Voids and their environment

- Voids may be surrounded by large-scale structures. A useful characterization of void environment is given by the value of Δ between 2 and 3 void radii (Ceccarelli+2013; Paz+2013; Ruiz+2015)



- R-type (Rising profiles)
- S-type (Shell profiles)
- R-type → void-in-void
- S-type → void-in-cloud
- Sheth & van de Weygaert 2004

https://arxiv.org/abs/1306.5799



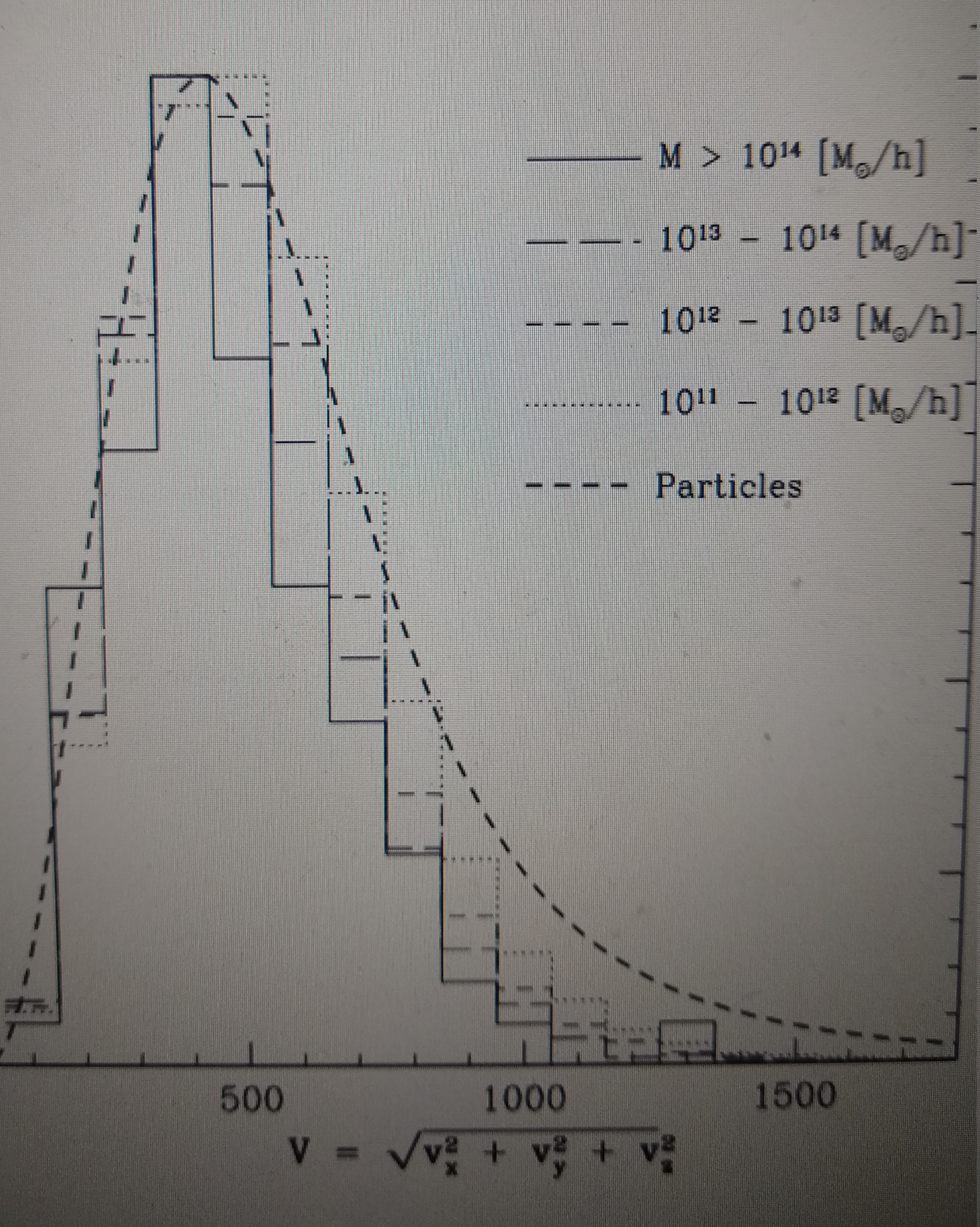
Void vs Clusters

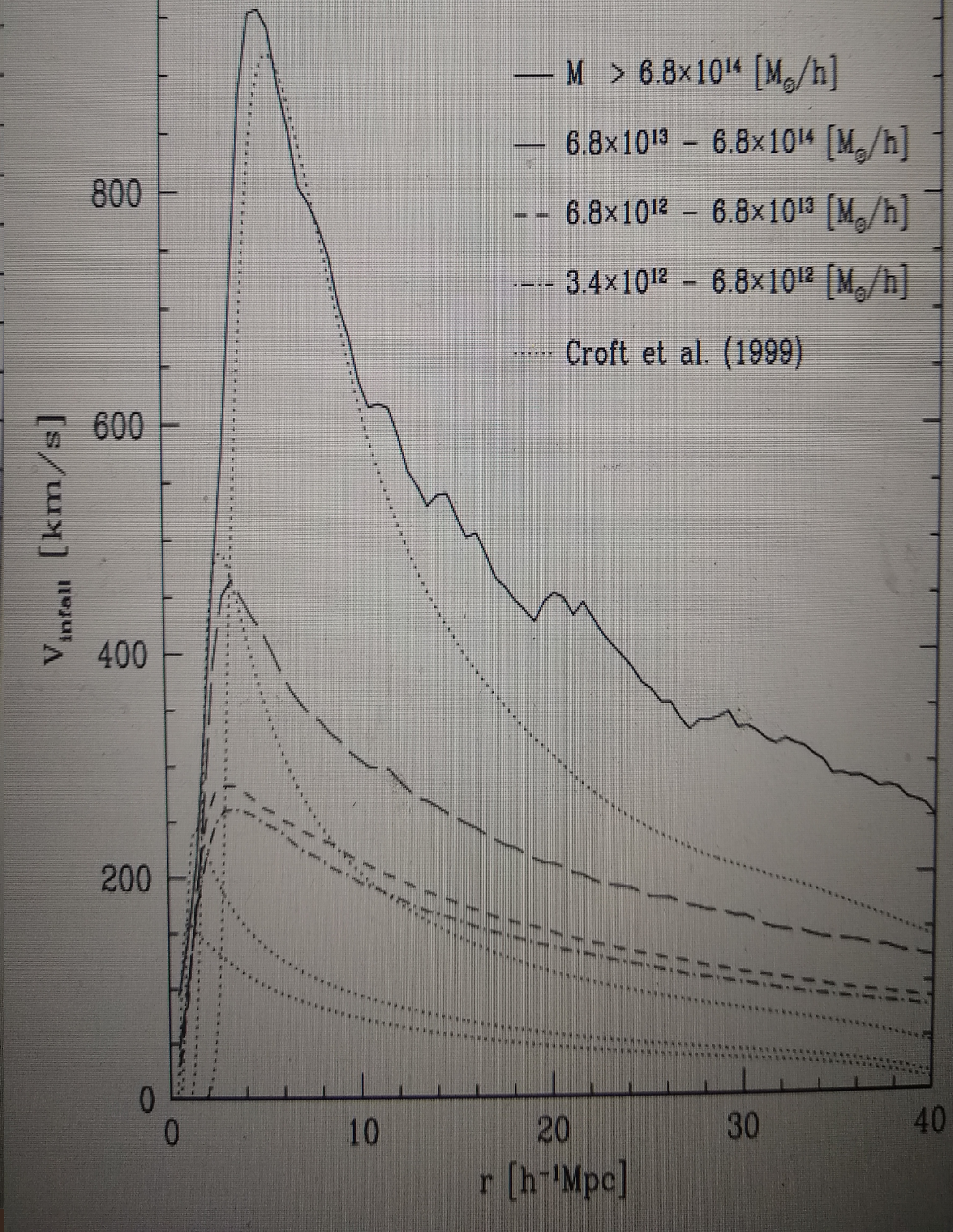
Expansion vs Contraction

Large Clusters at rest ?

- Are Cluster at relatively rest in comoving coordinates ?
- (Maybe this is a good approximation..., large clusters are at the center of local potential wells, and may average nearby peculiar motions...)

- Recall that:
- The CMB dipole implies the local group of galaxies differs from rest by approximately 600 km/s
- Statistical measures of peculiar velocities of galaxies are of this same order 500 - 600 km/s





similar peculiar velocity distributions !

* Velocity of accretion increases with cluster mass (as expected)

* However, cluster mean mean peculiar velocity is nearly independent of cluster mass...(unexpected)

- The lack of mass dependence relates to the presence of large-scale flows dominating the dynamics of structures in the Universe.
- (In linear theory, this relates to the relation between velocity and two-point correlation function, which converges at hundreds of Mpc. So, the very large structures are the motion drivers, and relative cluster masses are irrelevant in comparison.
-

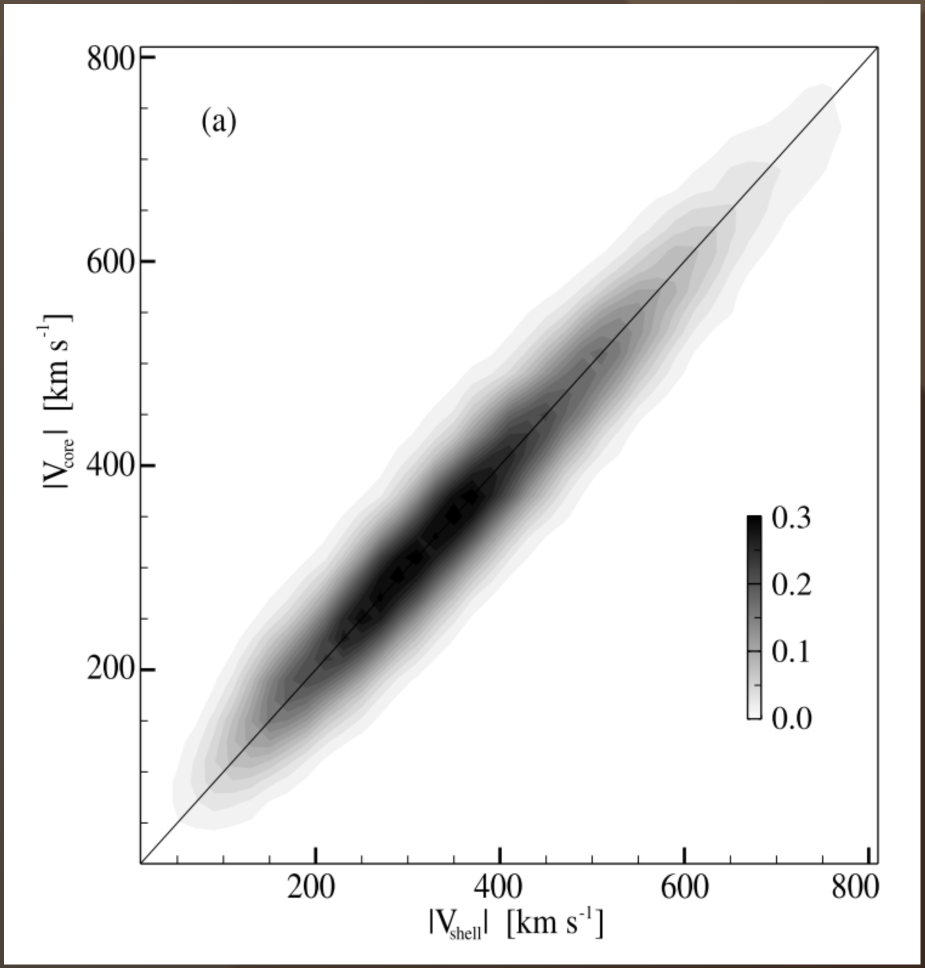
Voids at rest ?
The sparkling Universe

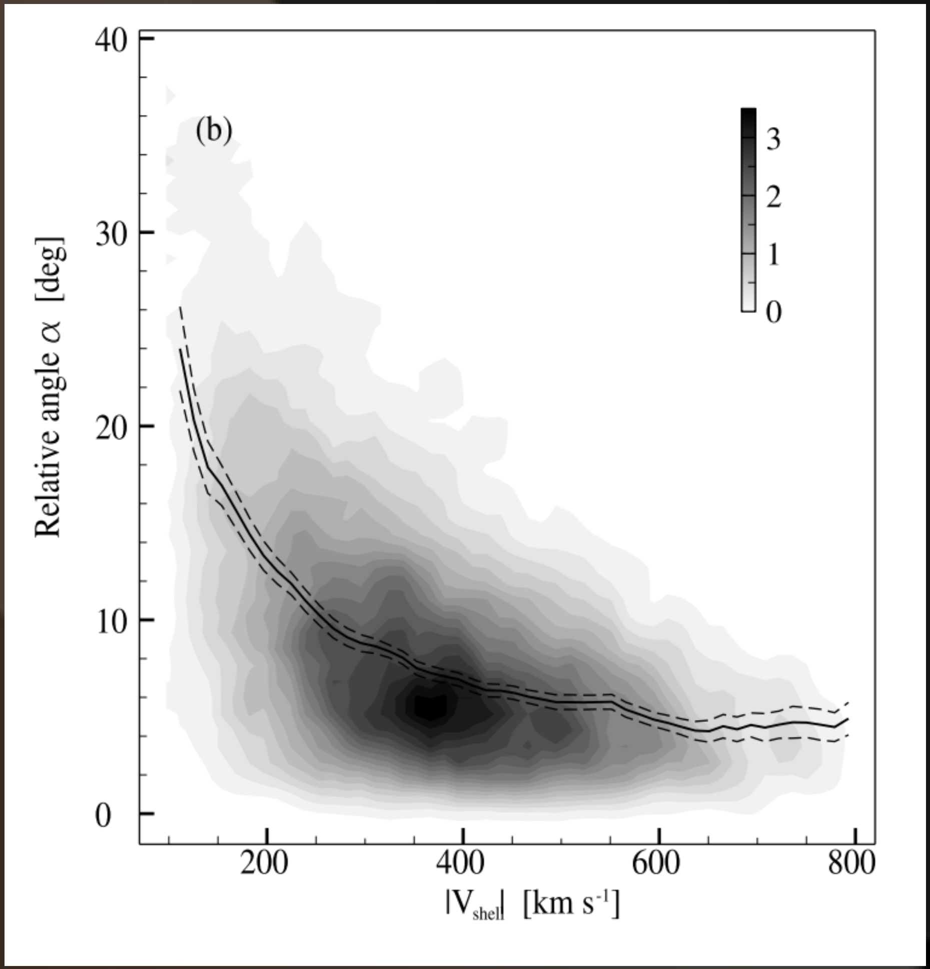
-

- Cosmic velocity flows have been reported in the local Universe at scales of hundred of Mpc
- (Watkins+2009, Lavaux+2010; Feldman+2010, Colin+2011, Watkins & Feldman 2015).
- Void bulk velocity, vs. motion of the surrounding shell ?
- We use both observations (SDSS-DR7 + linear velocity field form Wang+2009, 2012) and simulations (Millennium + Guo+2011 semi-analytic galaxies).

How to define the bulk velocity of a region (DM) which lacks suitable velocity tracers (massive haloes or luminous galaxies) ?

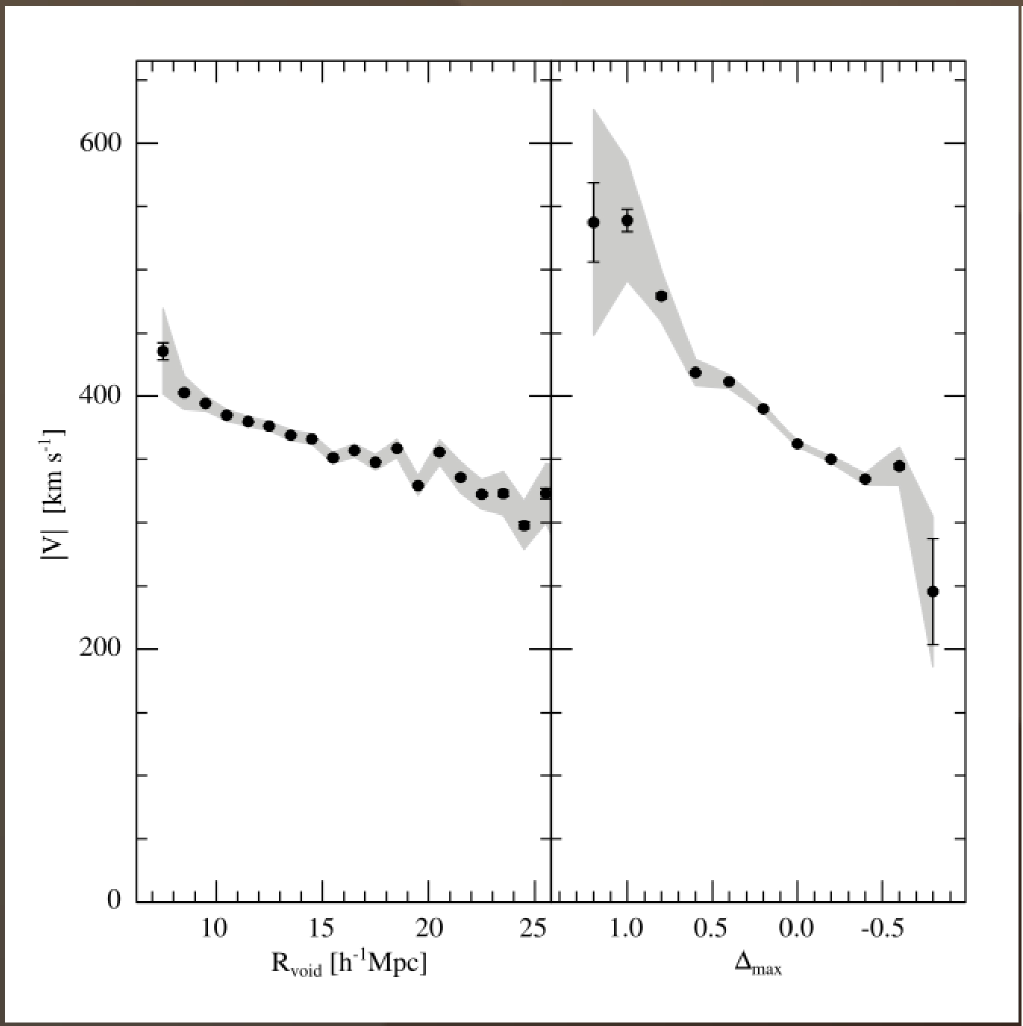
- Void motion can be well measured using tracers located in a shell between 0.8 and 1.2 void radius!

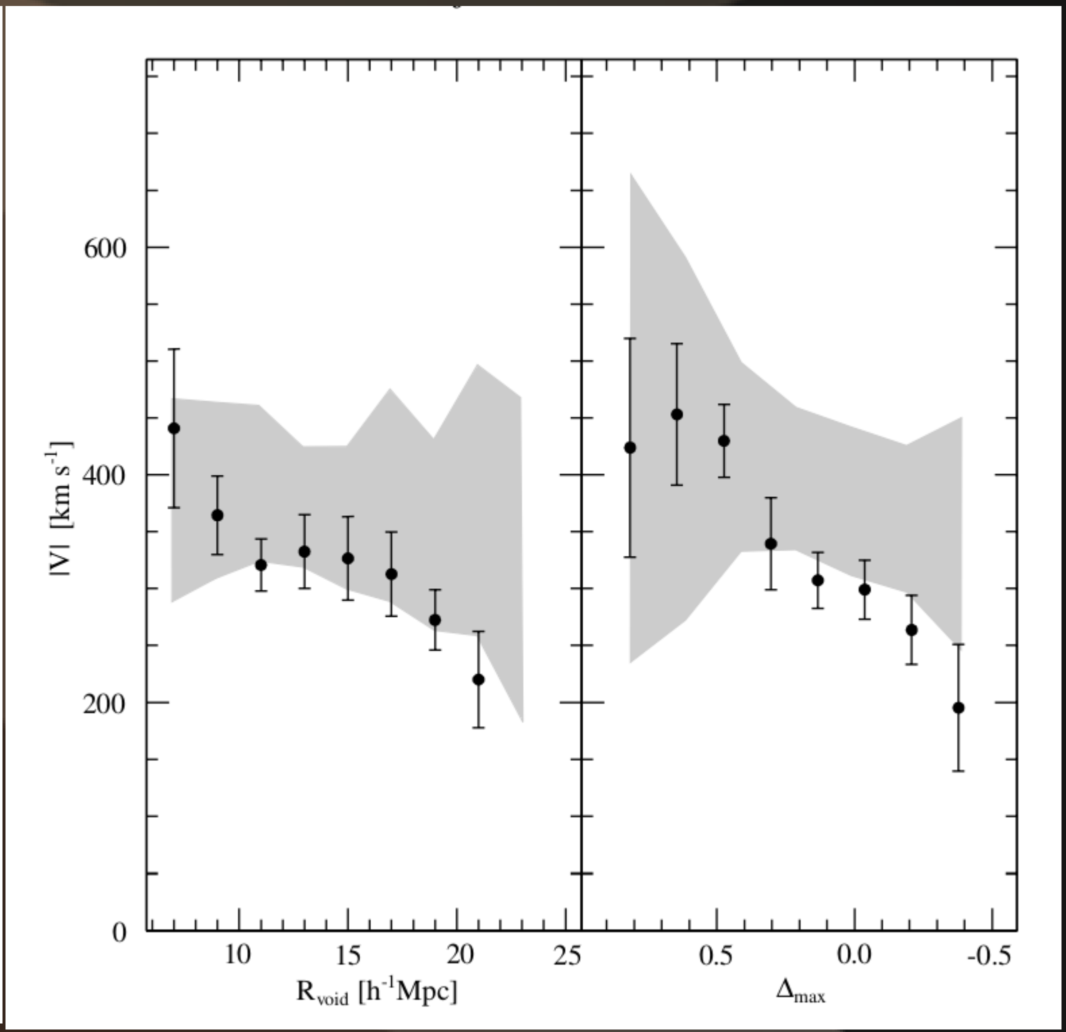




- Non negligible void bulk motions (Ceccarelli+2016)

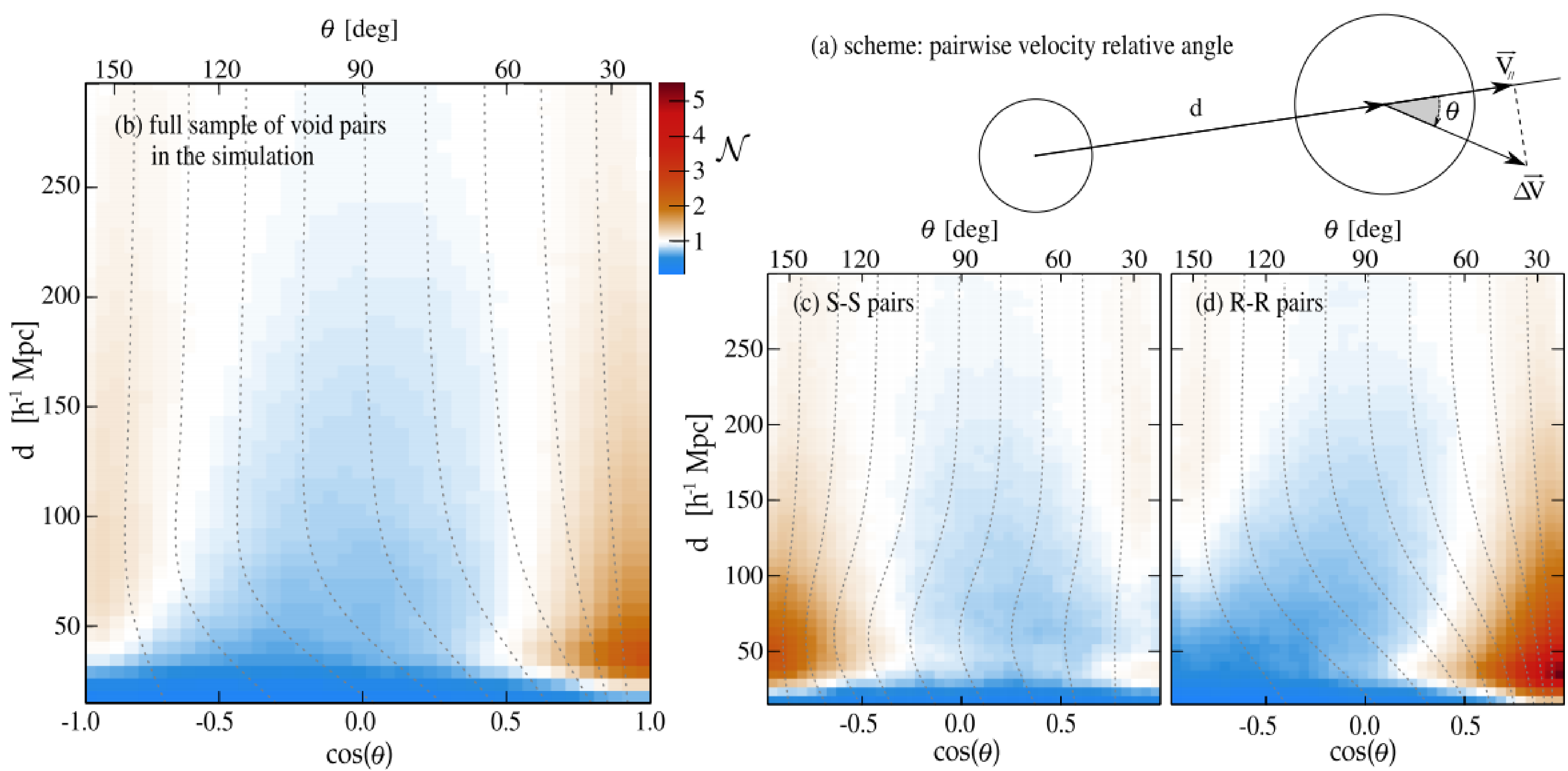
https://arxiv.org/pdf/1511.06741.pdf





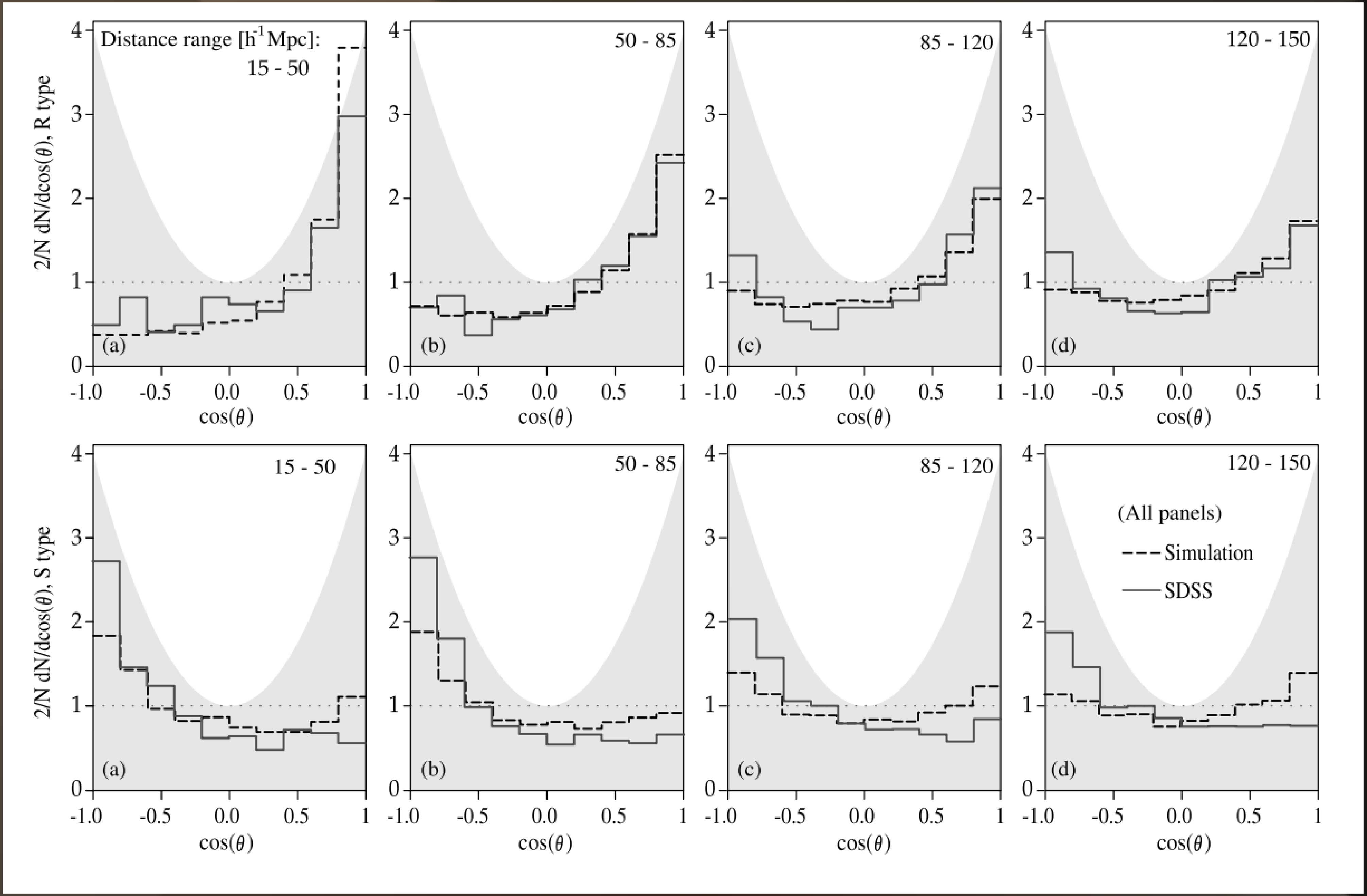
- Simulation
- Observations

- Void velocities are coherent (Lambas+2016).
- Pairwise velocities shown as concentrations in the cosθ-d plane

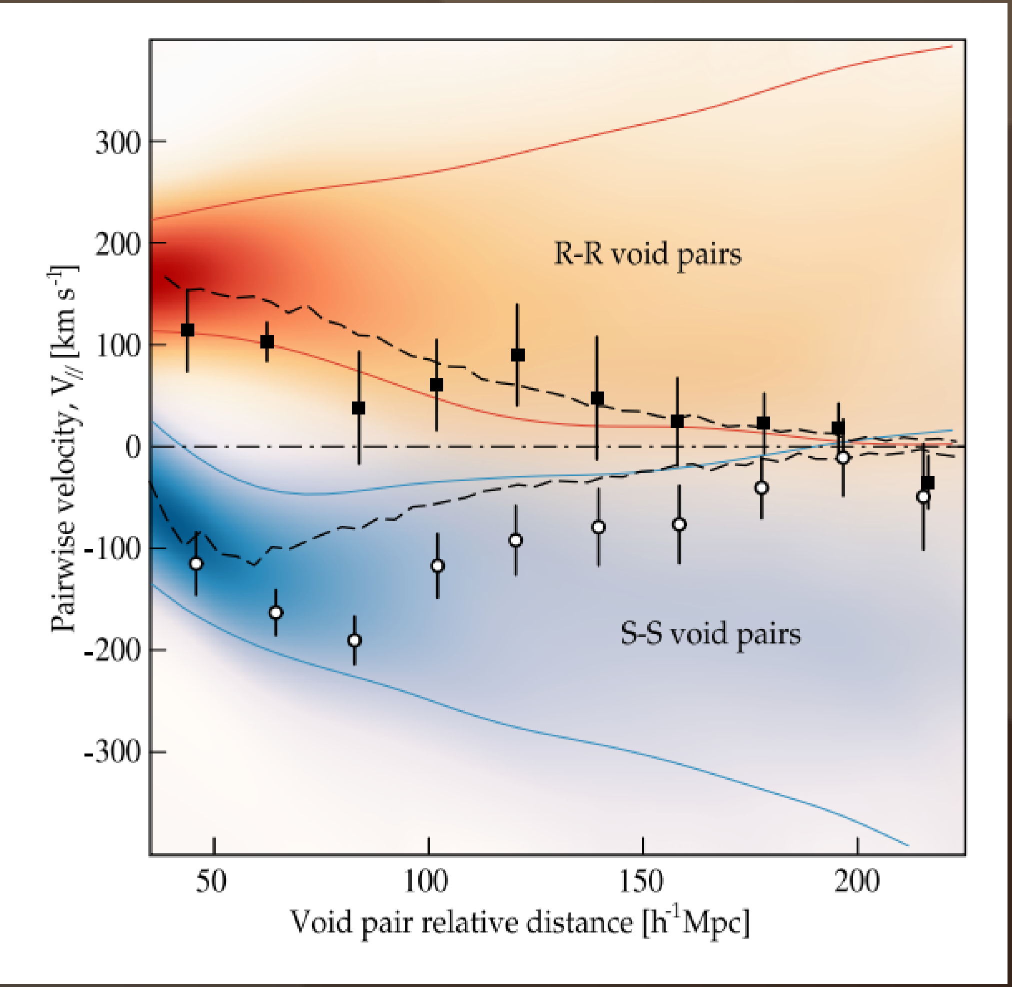


- R-type voids are mutually receding, cosθ > 0
- S-type voids are mutually approaching, cosθ < 0

- The same behavior found in SDSS voids (linear velocity field derived by Wang+2009, 2012)



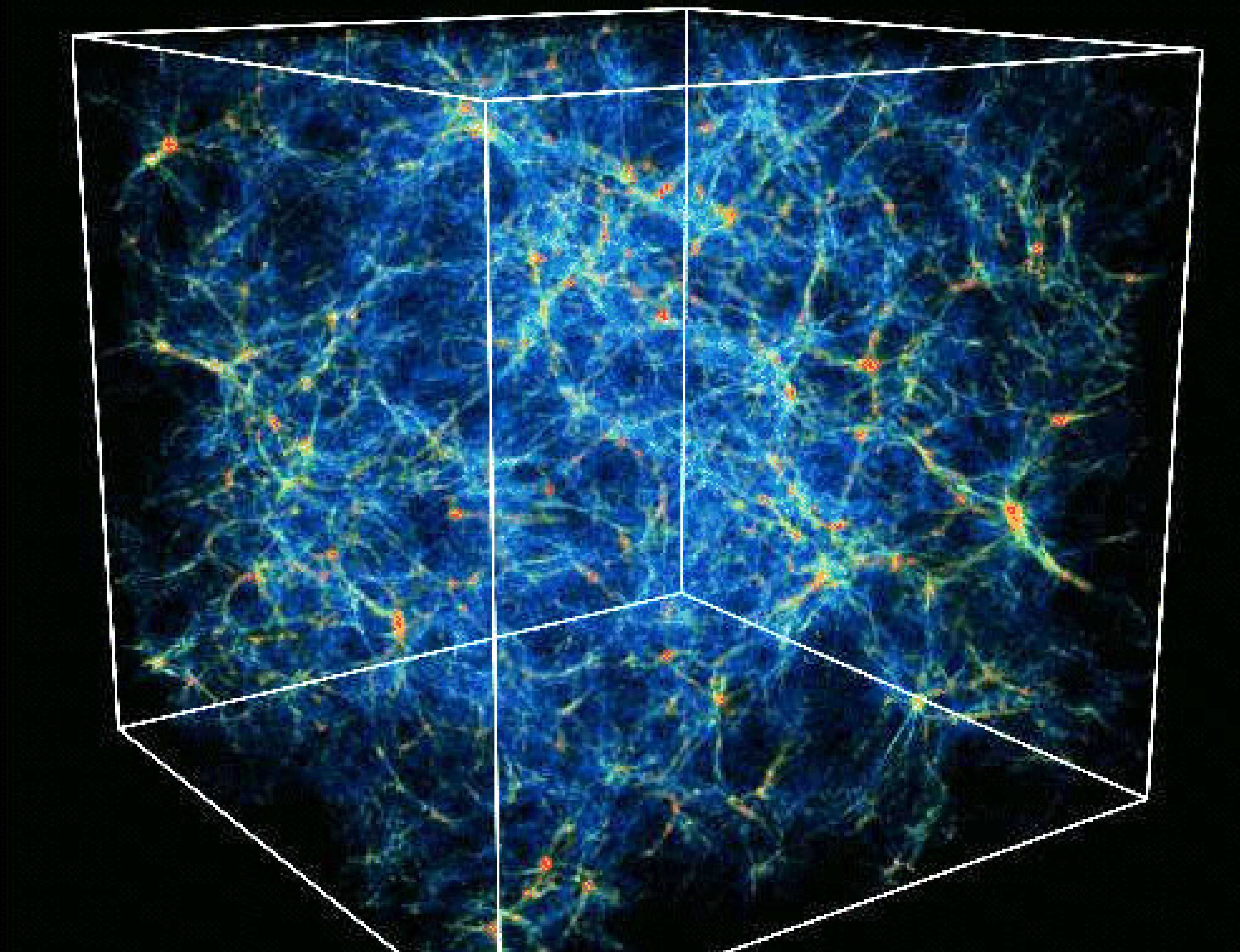
https://arxiv.org/abs/1510.00712

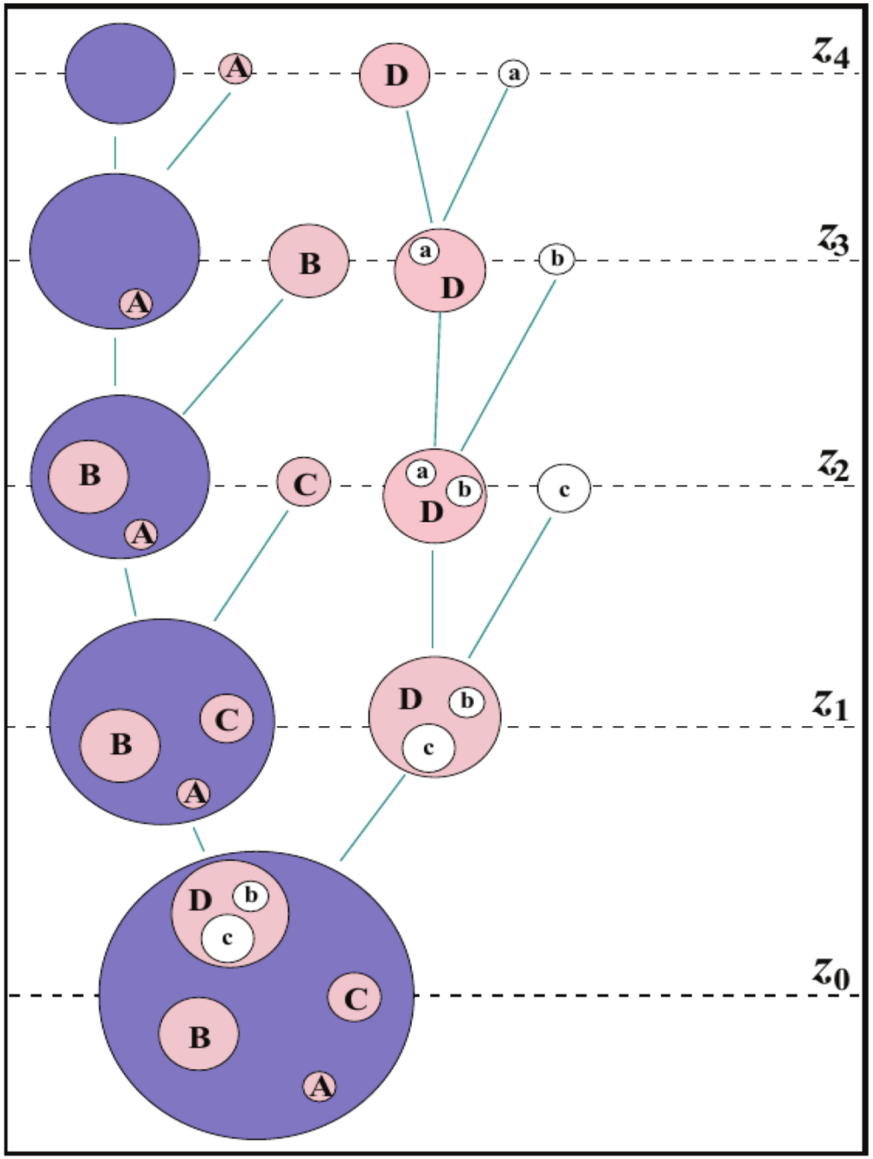


- The correlated mutual void velocities induce partially the motion of clusters and galaxies at intermediate densities, in filaments or walls.

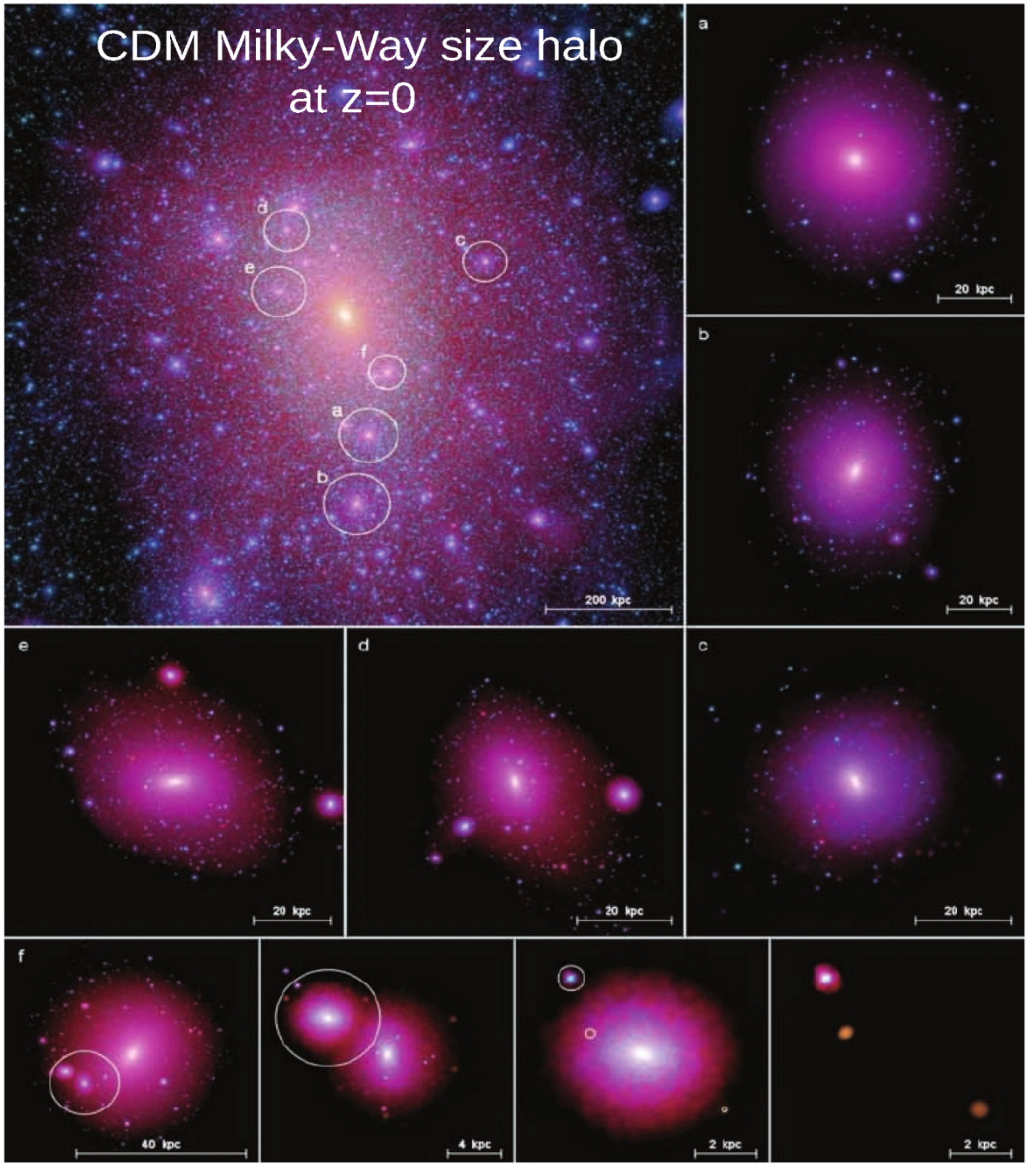
Returning to the halo model...

https://arxiv.org/abs/2003.06255





z_4
z_3
z_2
z_1
z_0
A
B
C
D
a
b
c



CDM Milky-Way size halo
at z=0
200 kpc
a
b
c
d
e
f
20 kpc
40 kpc
4 kpc
2 kpc

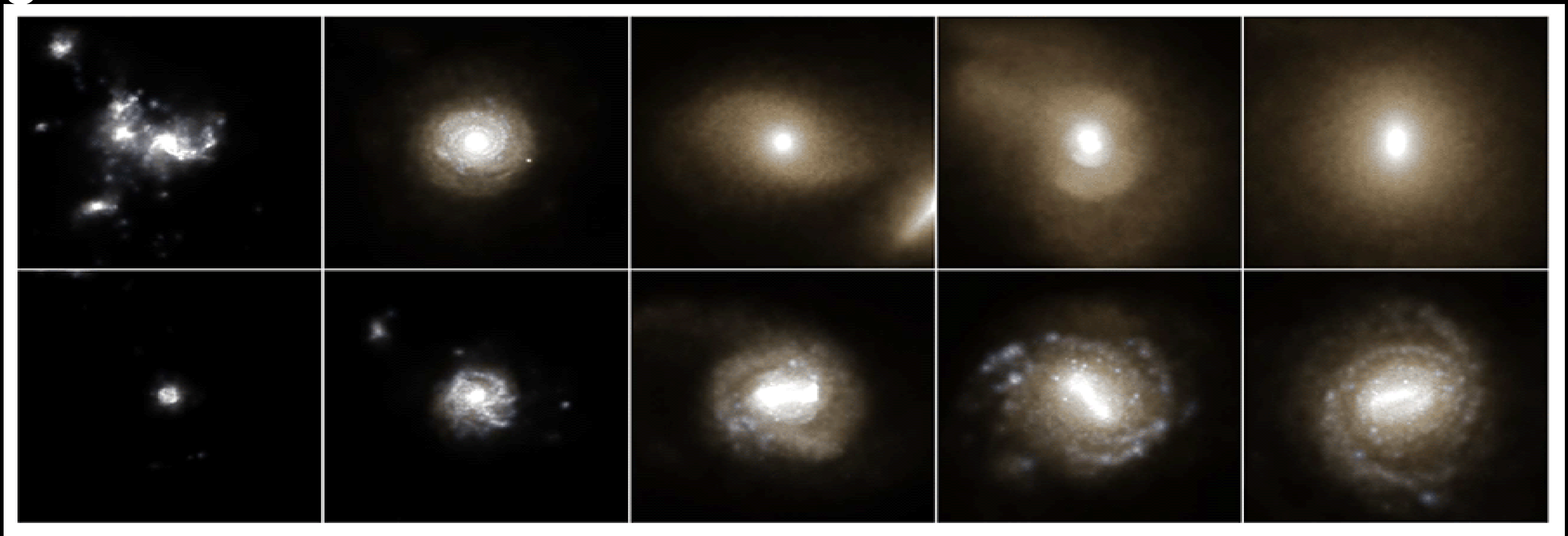
Full numerical hydrodynamical simulations are limited by:

-Star formation (recipies)

-stellar feedback (models)

-Central massive BH feedback (uncertain)

There is still significant modelling and parametrization in these simulations.
eg. Illustris

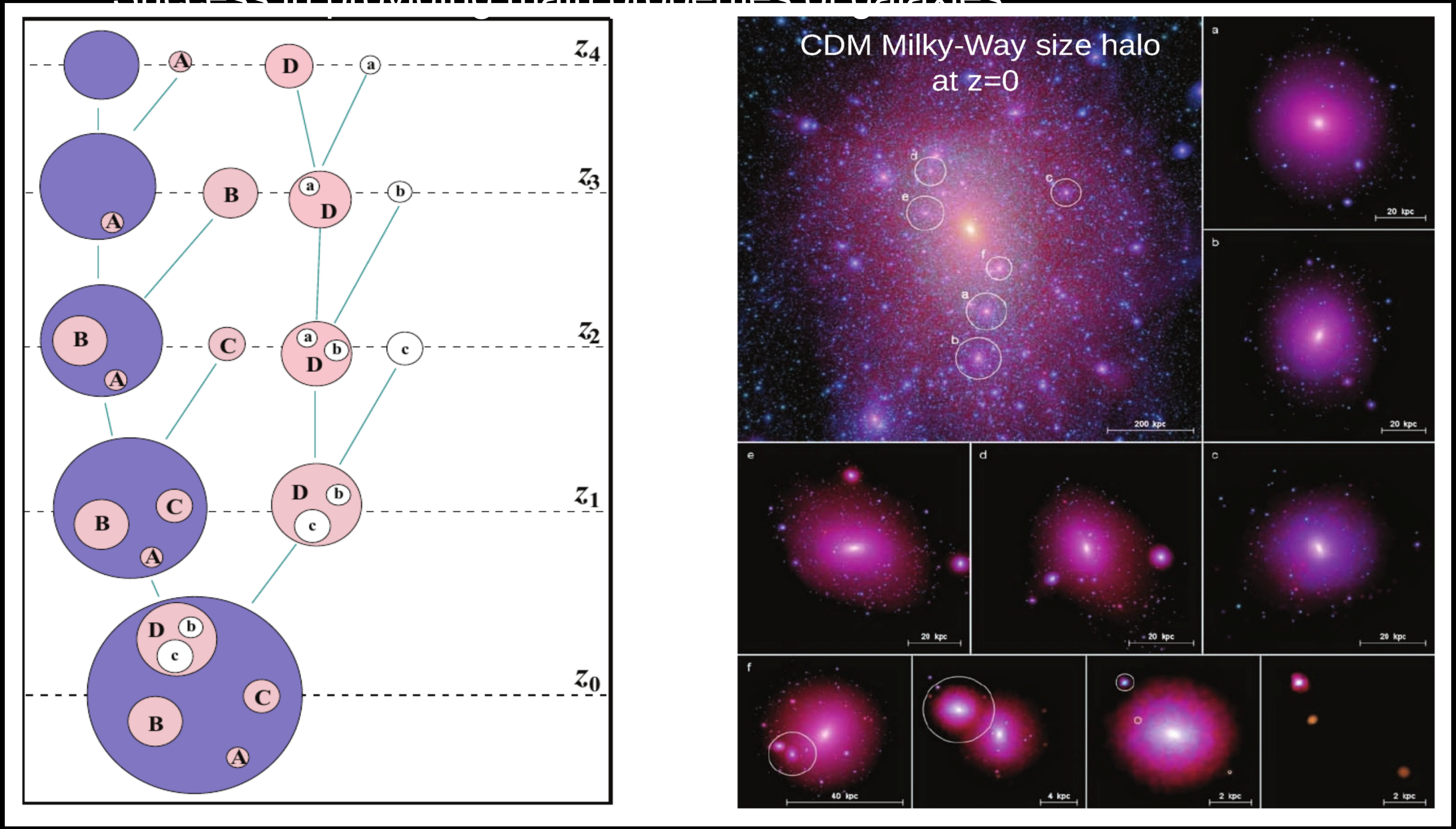


MULTIDARK (& other) Semianalytic Models:

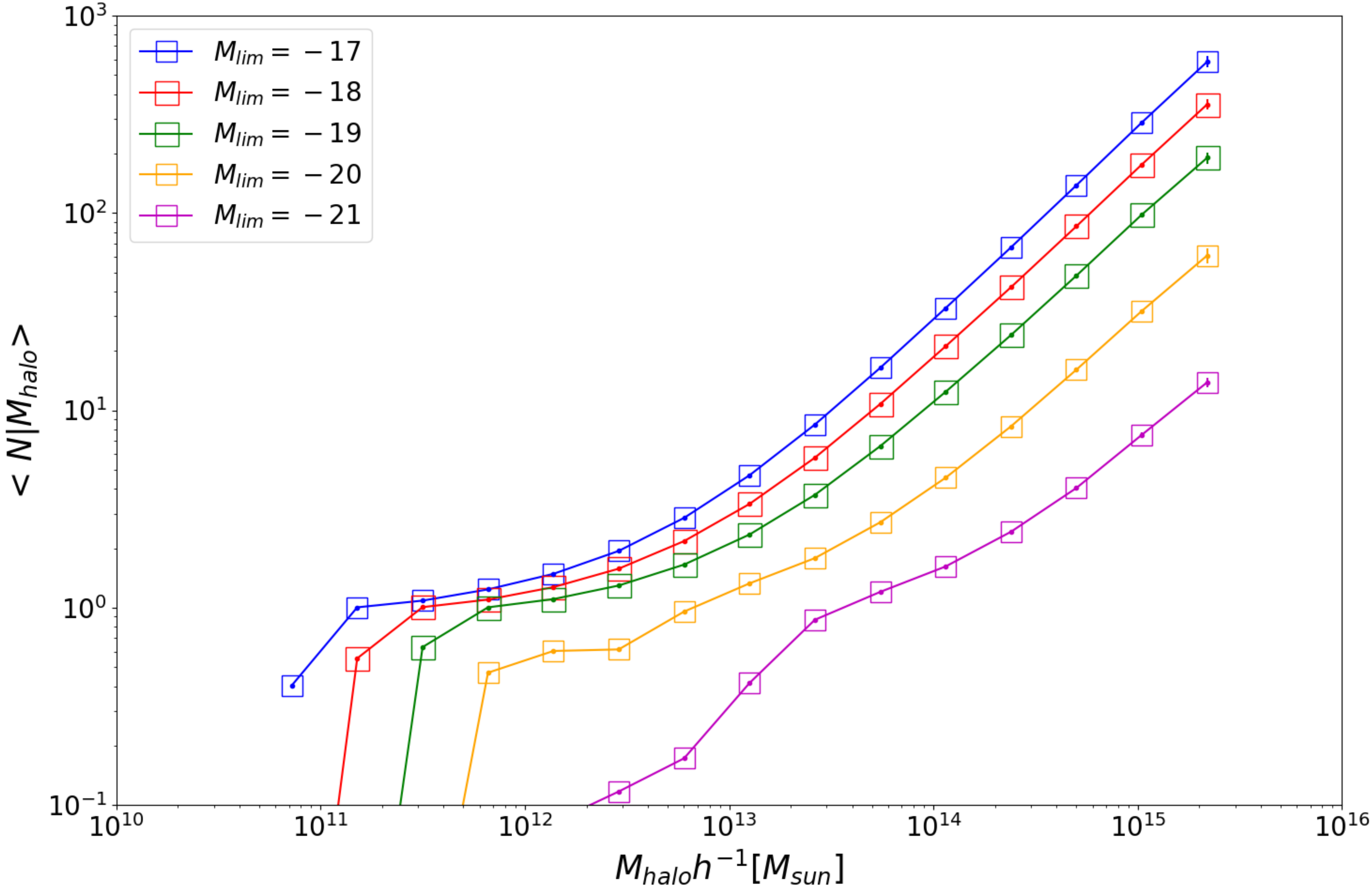
Recipies for baryons producing stars

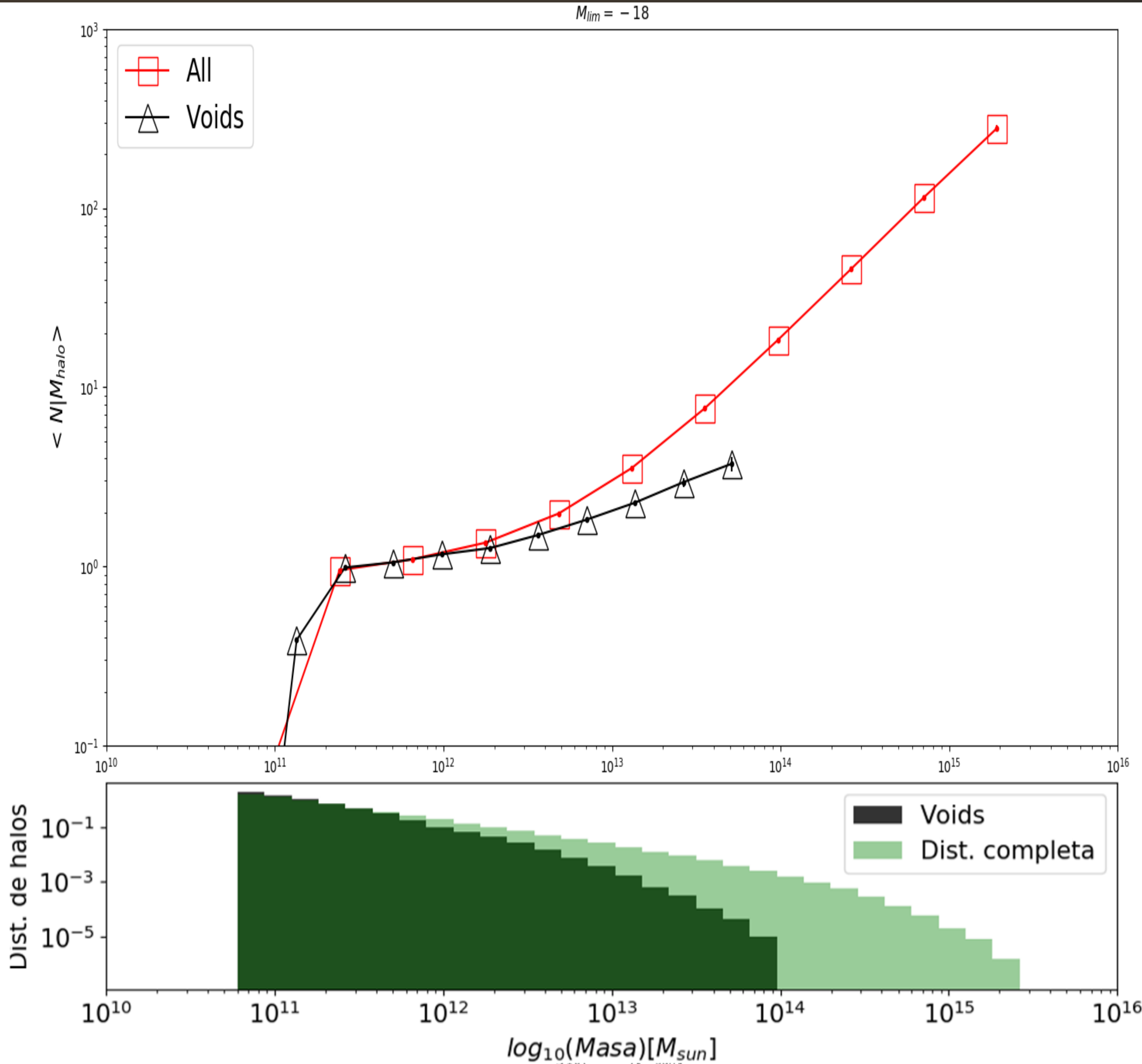
Effects of tidal stripping + ram pressure + harassment etc.

* Success in providing main properties of galaxies

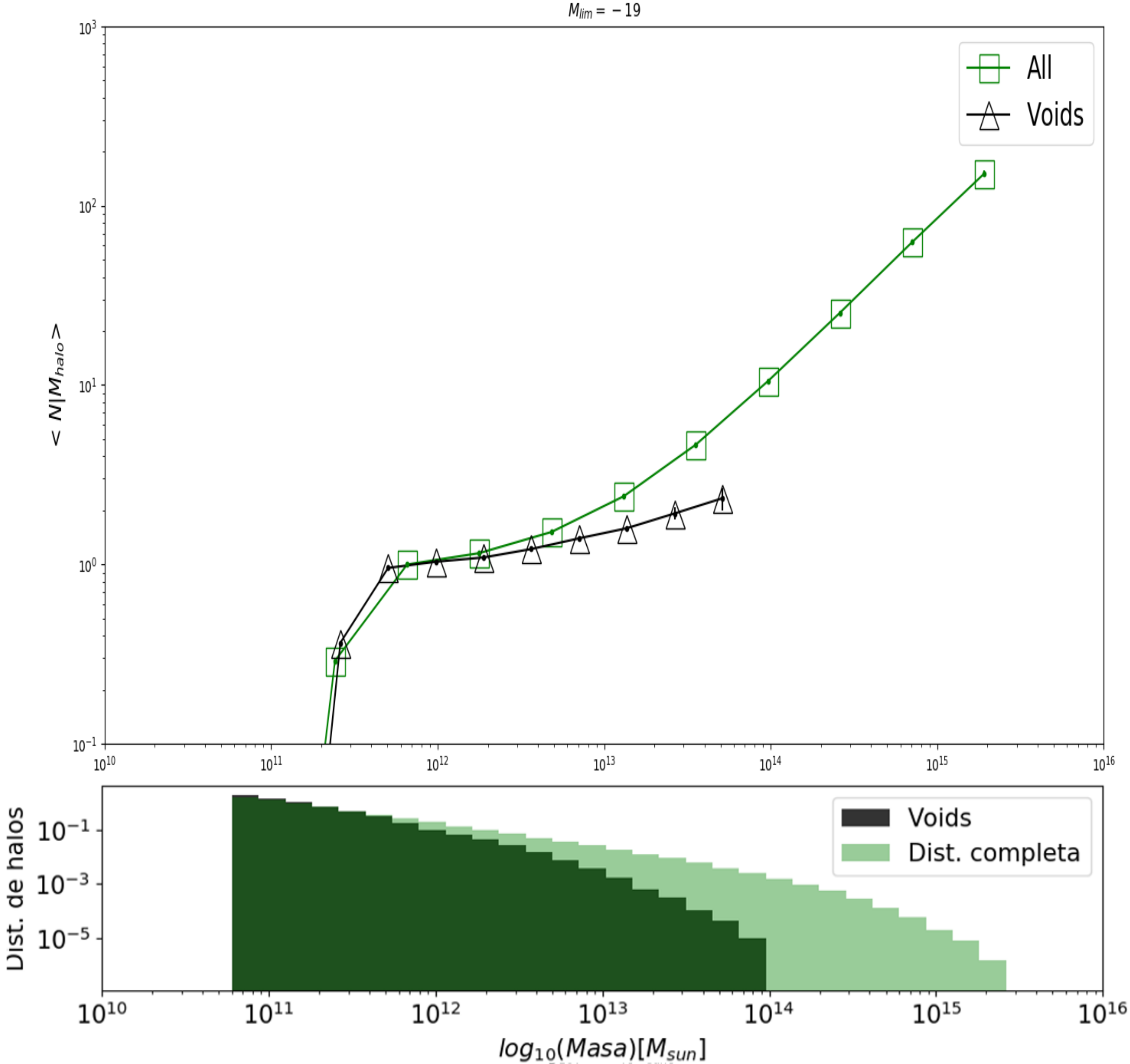


HOD in MD simulations

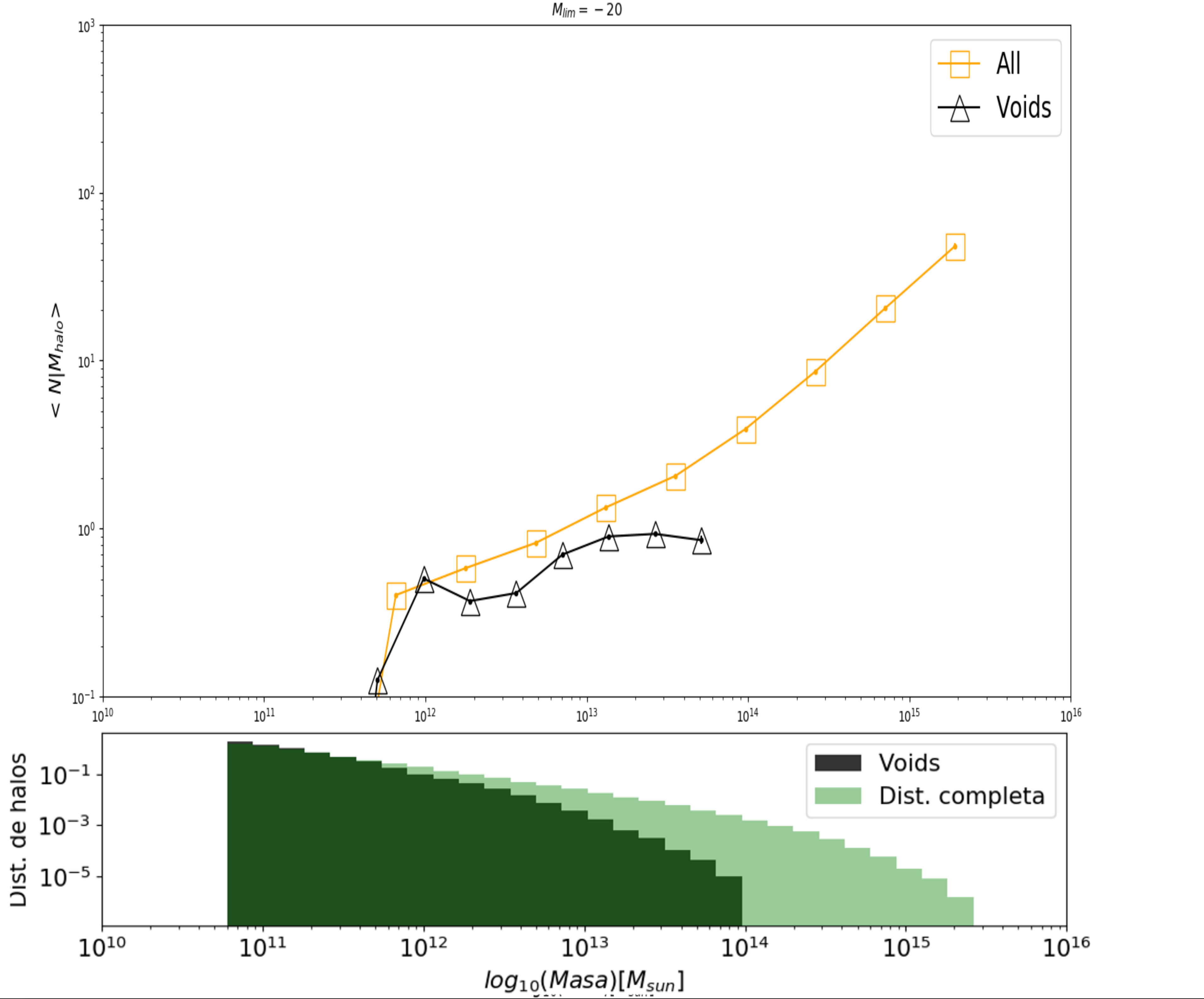




$M_{lim} = -18$
All
Voids
$< N|M_{halo} >$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
Dist. de halos
10^{-1}
10^{-3}
10^{-5}
Voids
Dist. completa
$log_{10}(Masa)[M_{sun}]$



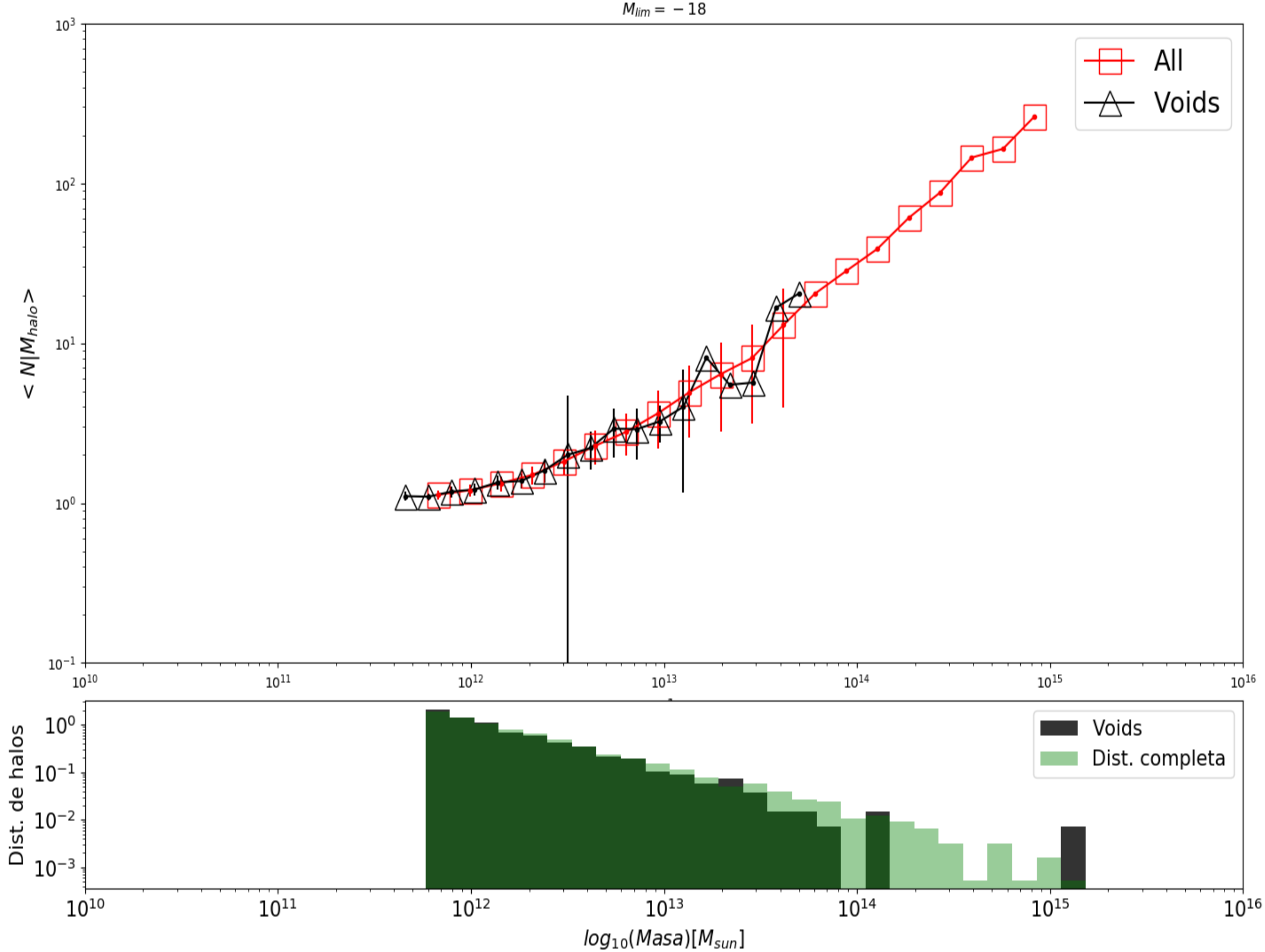
$M_{lim} = -19$
All
Voids
$< N|M_{halo} >$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
Voids
Dist. completa
Dist. de halos
10^{-1}
10^{-3}
10^{-5}
$log_{10}(Masa)[M_{sun}]$


$M_{lim} = -20$
All
Voids
$< N|M_{halo} >$
Voids
Dist. completa
Dist. de halos
$log_{10}(Masa)[M_{sun}]$

HOD in Voids in MD Simulations differ significantly from those elsewhere,

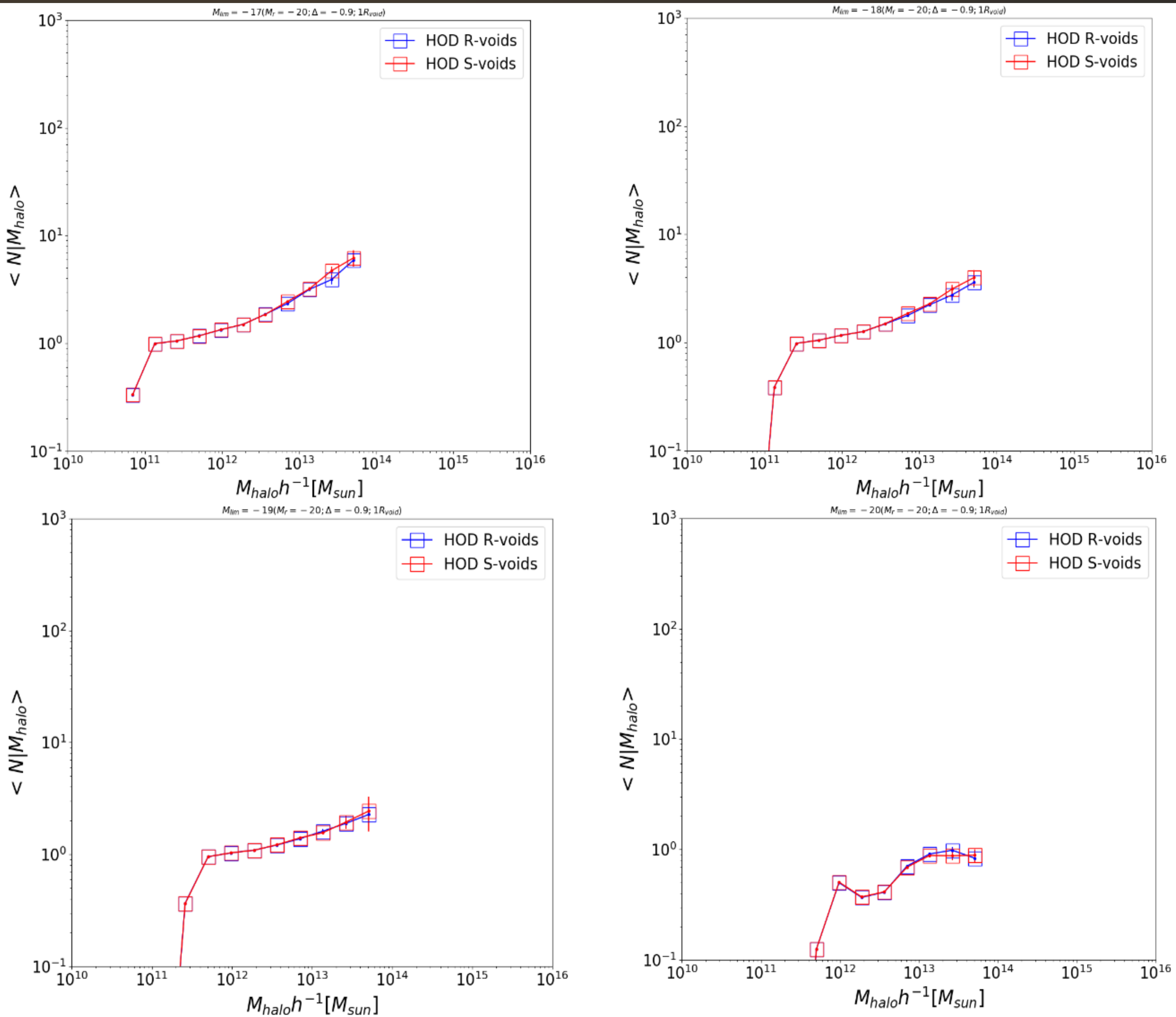
Yang et al. HOD for SDSS are similar

SDSS, Yang et al.



Void internal structure & void environment

- Internal structure in voids is independent of void environment (as measured by HOD)



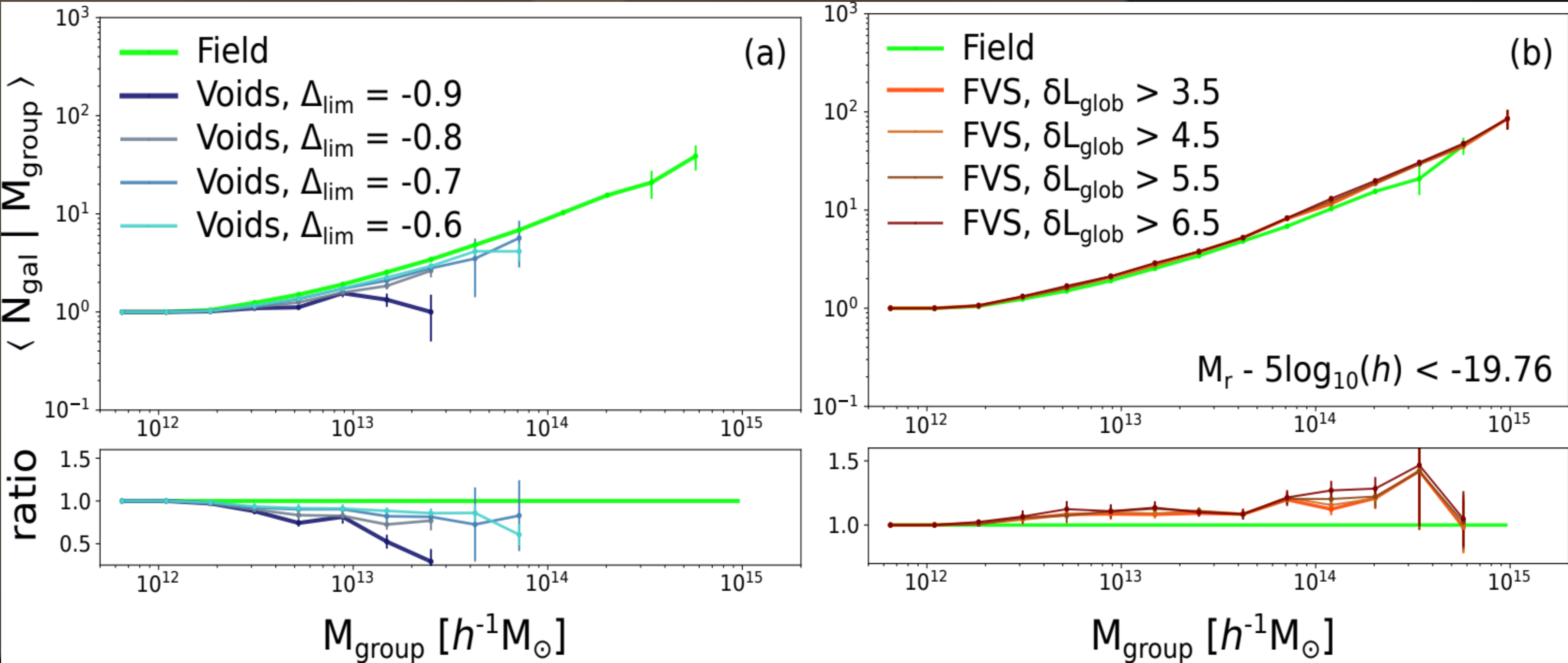
$M_{lim} = -17 (M_r = -20; \Delta = -0.9; 1R_{void})$
$M_{lim} = -18 (M_r = -20; \Delta = -0.9; 1R_{void})$
$M_{lim} = -19 (M_r = -20; \Delta = -0.9; 1R_{void})$
$M_{lim} = -20 (M_r = -20; \Delta = -0.9; 1R_{void})$
HOD R-voids
HOD S-voids
$< N|M_{halo} >$
$M_{halo} h^{-1} [M_{sun}]$

Void internal structure & void environment

- SDSS data show that galaxies in halos differ most in voids (regardless void radius) compared to high density environments.

Void internal structure & void environment

- The observations show that galaxies in halos differ most in voids compared to high density environments.



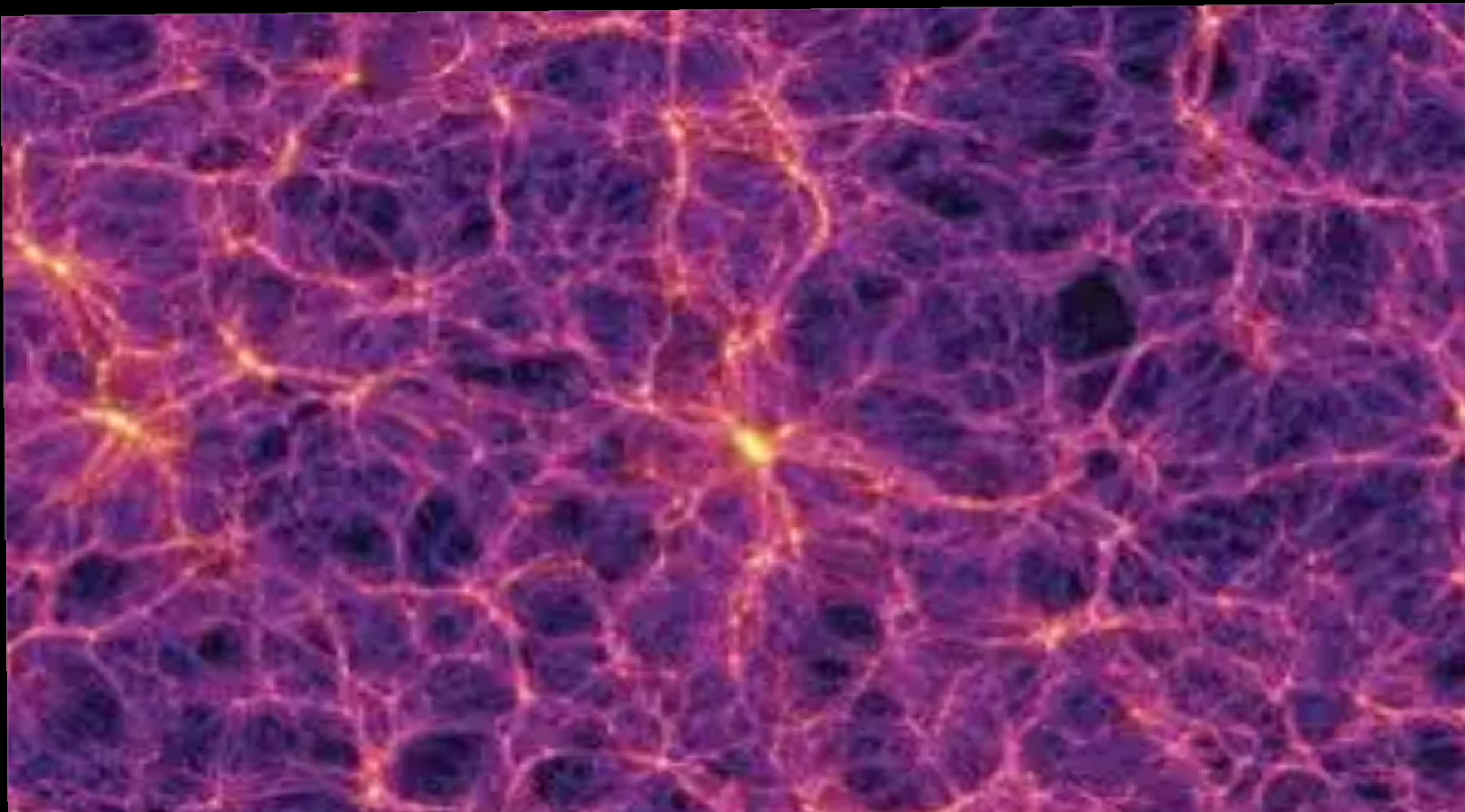
Summarizing galaxy properties inside voids...

- Void galaxies tend to be bluer and of late-type, with younger stellar populations and higher star formation rates (Rojas+2005, Patiri+2006, Ceccarelli+2008; Hoyle+2012).

- The void expansion and its low density environment conspire against structure growth, so we expect a different dynamical behavior of galaxies residing in voids.

Structure and dynamics in Cosmic Voids:

https://arxiv.org/abs/1812.05532

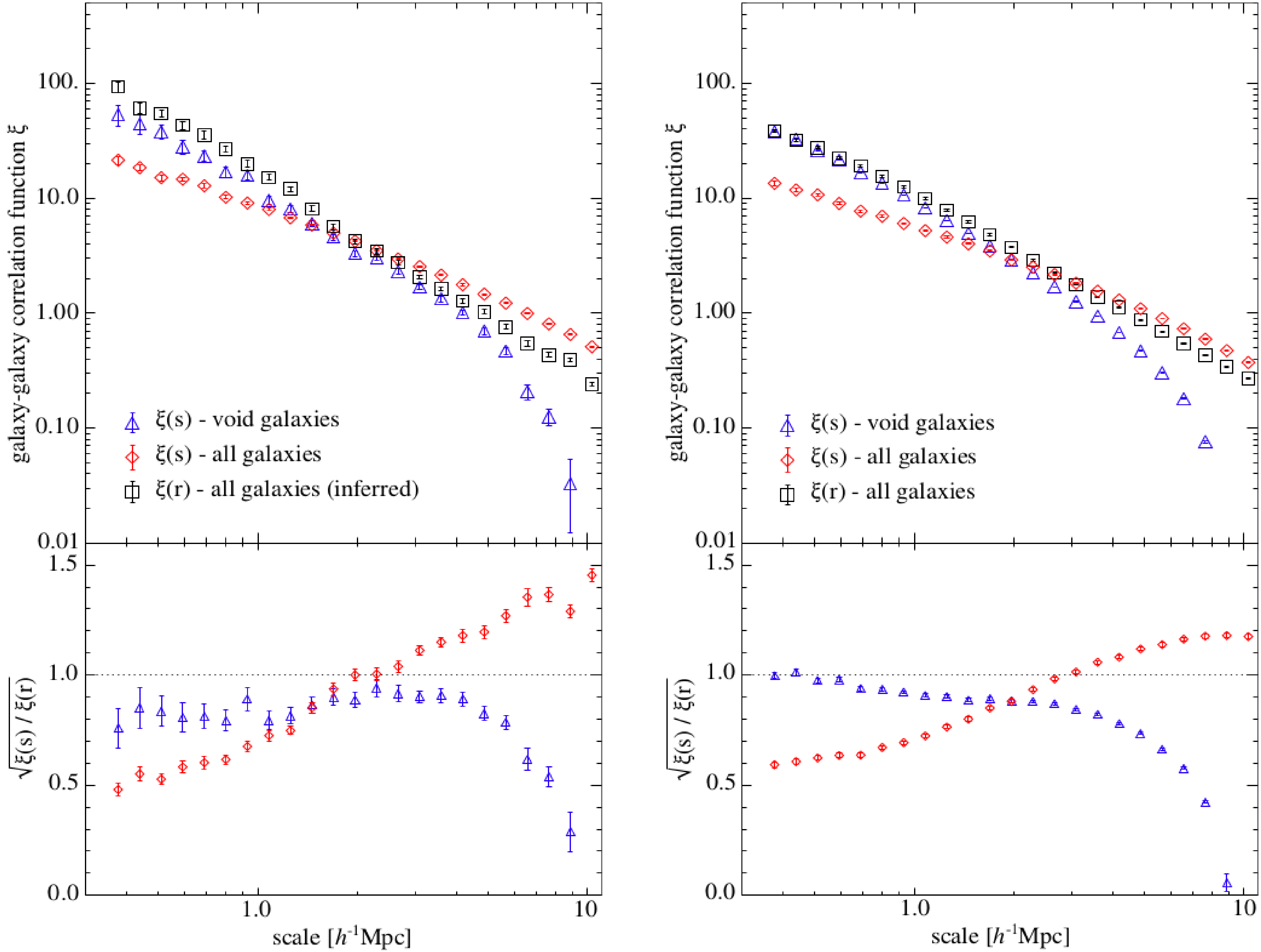


We use SDSS-DR7 galaxies in a limited volume sample at z=0.085 and the SAG (Cora+2018) semi-analytic catalogue from the MultiDark Database (Knebe+2018).

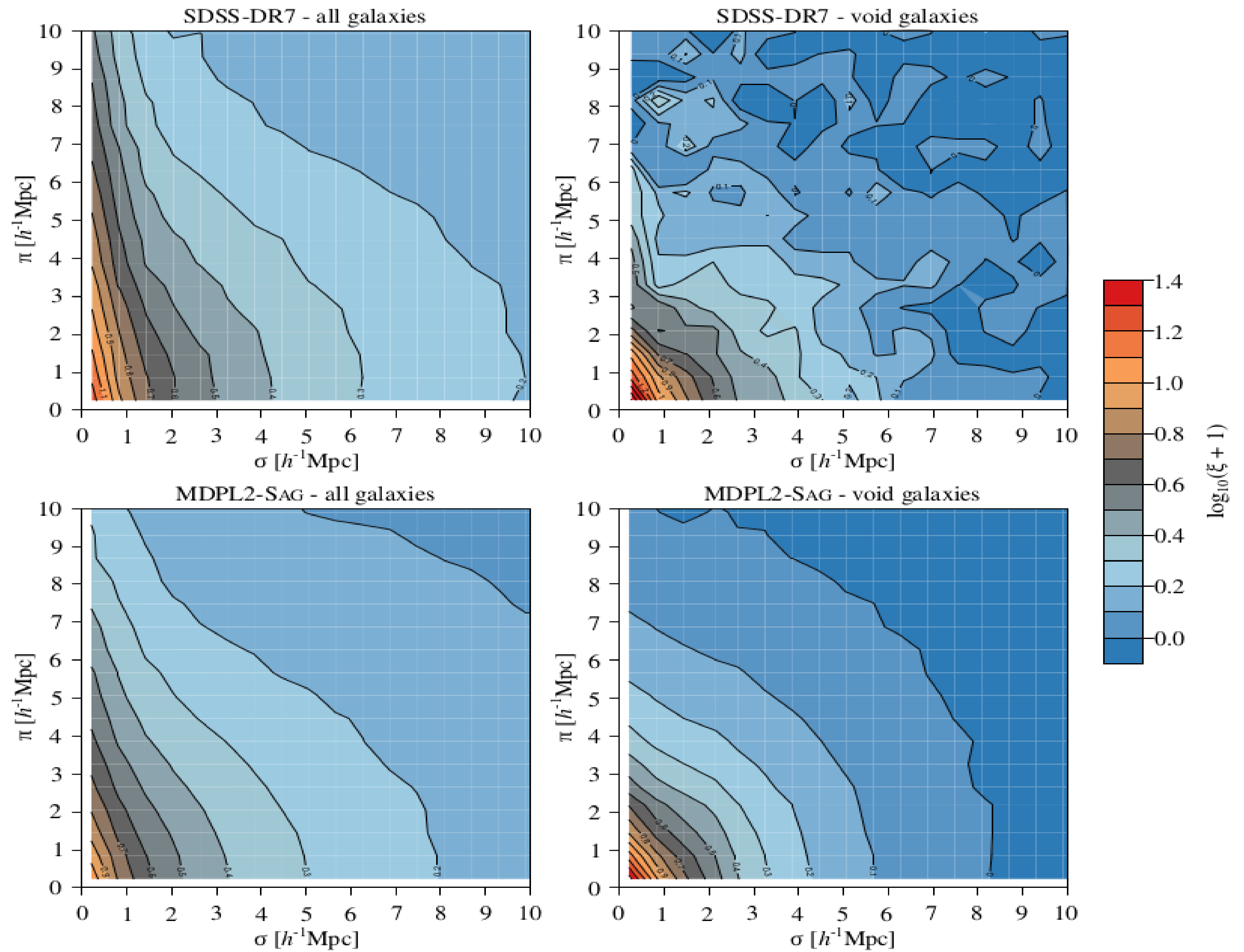
-

- Voids identified using bright galaxies ($M_r < -20$), and are populated with faint galaxies ($-18 > M_r > -20$).

As a measure of structure and dynamics of galaxies in voids, we compute galaxy-galaxy correlation functions in real and redshift-space



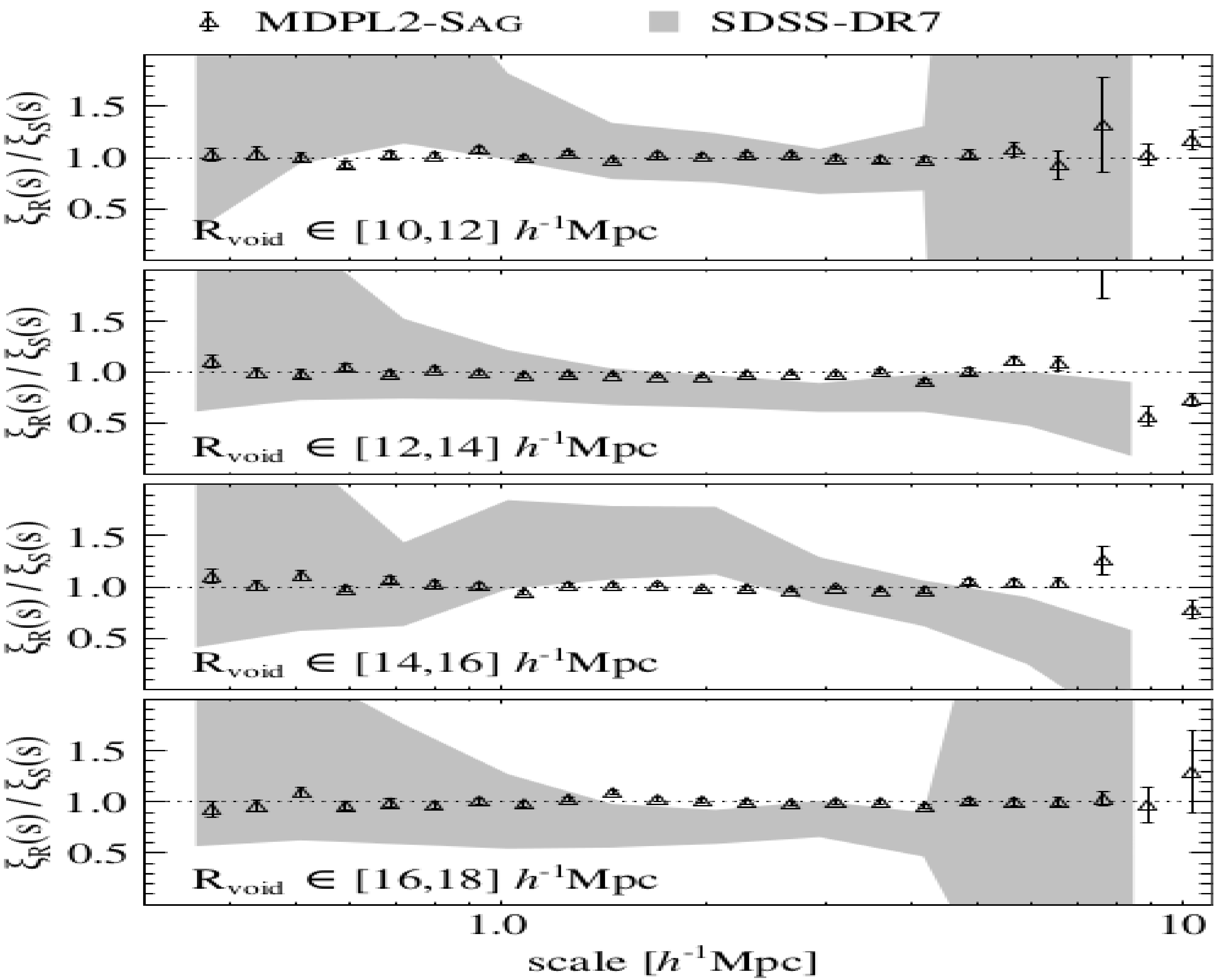
galaxy-galaxy correlation function ξ
ξ(s) - void galaxies
ξ(s) - all galaxies
ξ(r) - all galaxies (inferred)
$\sqrt{\xi(s)}\,/\,\xi(r)$
scale [h^{-1}Mpc]
galaxy-galaxy correlation function ξ
ξ(s) - void galaxies
ξ(s) - all galaxies
ξ(r) - all galaxies
$\sqrt{\xi(s)}\,/\,\xi(r)$
scale [h^{-1}Mpc]



SDSS-DR7 - all galaxies
SDSS-DR7 - void galaxies
MDPL2-SAG - all galaxies
MDPL2-SAG - void galaxies
π [h^-1 Mpc]
σ [h^-1 Mpc]
log10(ξ + 1)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

Void internal structure & void environment Correlation functions

R vs S -type Voids


MDPL2-SAG
SDSS-DR7
1.5
1.0
0.5
$\xi_R(s)/\xi_S(s)$
$R_{void} \in [10,12]\ h^{-1}$Mpc
$R_{void} \in [12,14]\ h^{-1}$Mpc
$R_{void} \in [14,16]\ h^{-1}$Mpc
$R_{void} \in [16,18]\ h^{-1}$Mpc
1.0
10
scale [h^{-1}Mpc]

Deriving pairwise velocity distributions from redshift-space correlations:

Measure of clumped Dark Matter content In Voids

- $\xi(\sigma,\pi)$ modeled with a convolution (Peebles 1980; Kaiser 1987),
- fitting w and β.

$$\xi(\sigma,\pi) = \int_{-\infty}^{+\infty} \xi_{\rm K}(\sigma, \pi - v/H_0) f(v) dv.$$

$$\xi_{\rm K}(\sigma,\pi) = \sum_{i=0,2,4} \xi_i(s) P_i(\cos\theta)$$

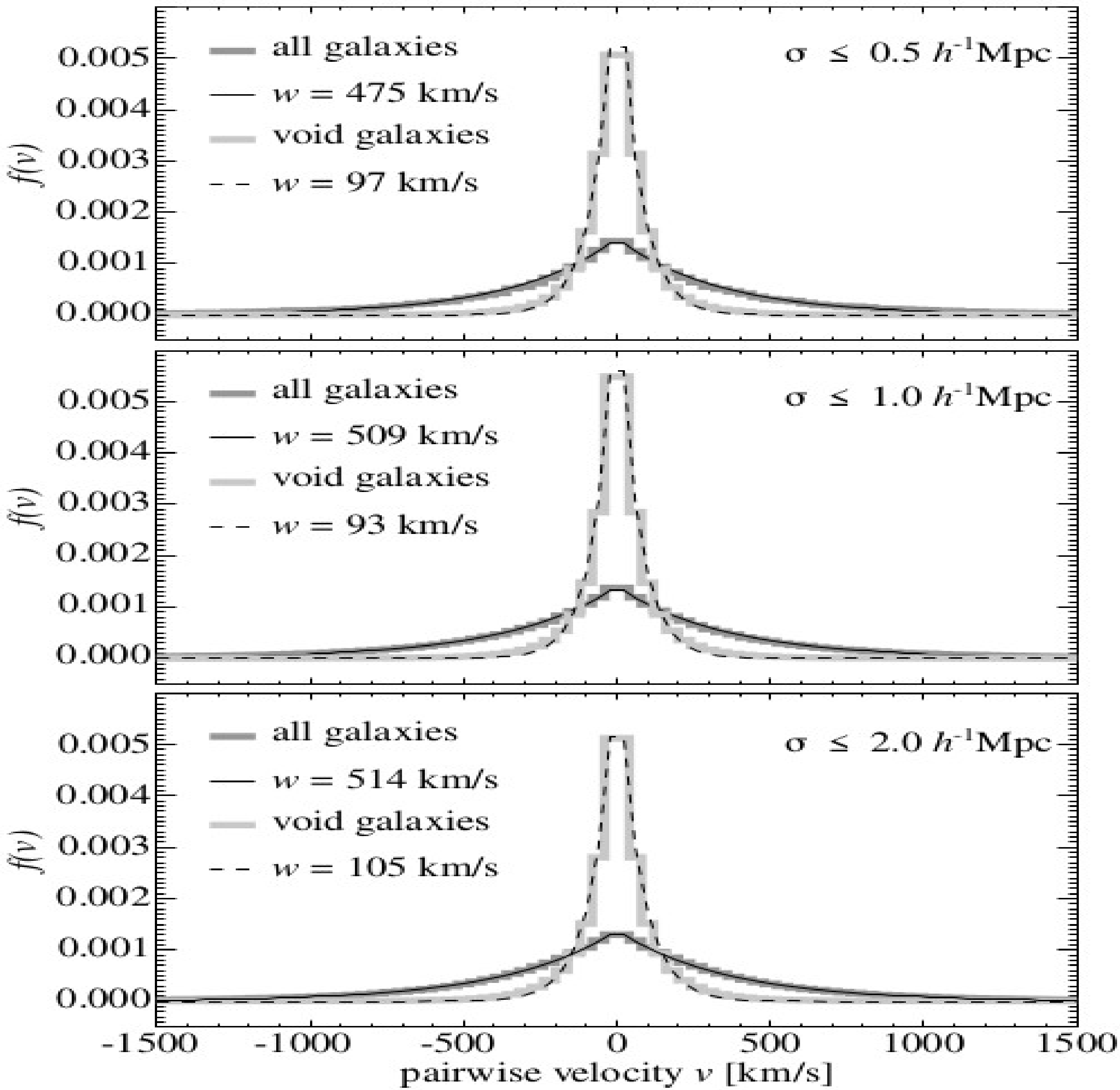
$$f(v) = \frac{1}{\sqrt{2}\,w} \exp\left(-\frac{\sqrt{2}\,|v|}{w}\right),$$

$$\begin{aligned}
\xi_0(s) &= \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right) \xi(r) \\
\xi_2(s) &= \left(\frac{4\beta}{3} + \frac{4\beta^2}{7}\right)\left(\frac{\gamma}{\gamma-3}\right) \xi(r) \\
\xi_4(s) &= \frac{8\beta^2}{35}\left(\frac{\gamma(2+\gamma)}{(3-\gamma)(5-\gamma)}\right) \xi(r)
\end{aligned}$$

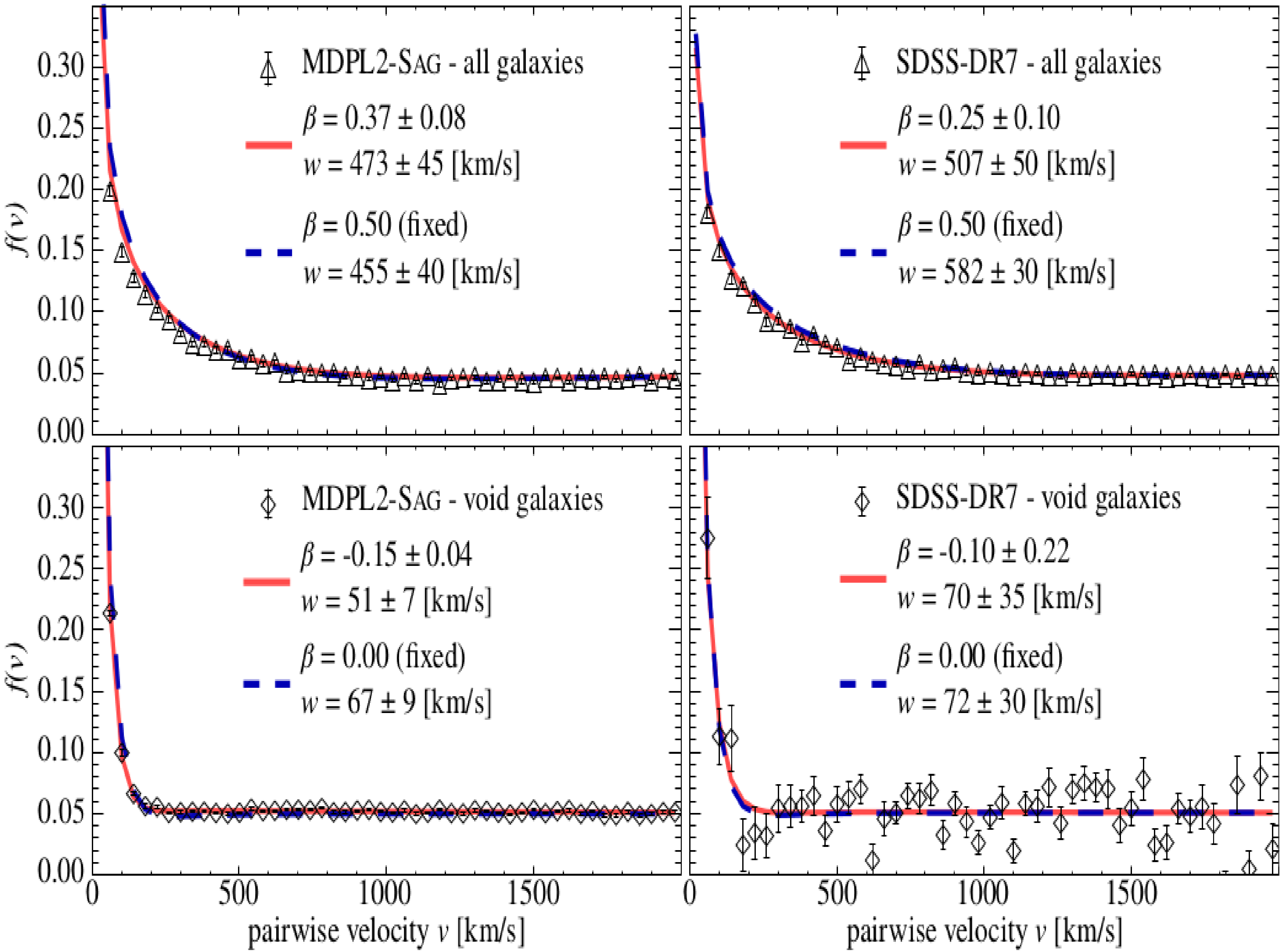
- From $\xi(\sigma,\pi)$ we can directly estimate the pairwise velocity distribution

$$\begin{aligned}
\Xi_\sigma &= \Xi(\sigma) = 2\int_0^{\pi_{\rm lim}} \xi(\sigma,\pi) d\pi \\
\Xi_\pi &= \Xi(\pi) = 2\int_0^{\sigma_{\rm lim}} \xi(\sigma,\pi) d\sigma
\end{aligned}$$

$$f(v) = \mathcal{F}^{-1}\left[\frac{\mathcal{F}[\Xi_\pi]}{\mathcal{F}[\Xi_\sigma]}\right]$$



all galaxies
w = 475 km/s
void galaxies
w = 97 km/s
σ ≤ 0.5 h-1Mpc
all galaxies
w = 509 km/s
void galaxies
w = 93 km/s
σ ≤ 1.0 h-1Mpc
all galaxies
w = 514 km/s
void galaxies
w = 105 km/s
σ ≤ 2.0 h-1Mpc
f(v)
0.005
0.004
0.003
0.002
0.001
0.000
-1500
-1000
-500
0
500
1000
1500
pairwise velocity v [km/s]



MDPL2-SAG - all galaxies
β = 0.37 ± 0.08
w = 473 ± 45 [km/s]
β = 0.50 (fixed)
w = 455 ± 40 [km/s]
SDSS-DR7 - all galaxies
β = 0.25 ± 0.10
w = 507 ± 50 [km/s]
β = 0.50 (fixed)
w = 582 ± 30 [km/s]
MDPL2-SAG - void galaxies
β = -0.15 ± 0.04
w = 51 ± 7 [km/s]
β = 0.00 (fixed)
w = 67 ± 9 [km/s]
SDSS-DR7 - void galaxies
β = -0.10 ± 0.22
w = 70 ± 35 [km/s]
β = 0.00 (fixed)
w = 72 ± 30 [km/s]
f(v)
pairwise velocity v [km/s]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
500
1000
1500

Pairwise velocities inside Cosmic Voids are a factor 7 – 8 lower than average

- Simulation results in suitable agreement with the observations of SDSS data
- Good fit with exponential function with w$\sim$ 70 km/s $\rightarrow$
- LCDM scenario is suitable in voids
- More work in progress...

Some conclusions

Cosmic Voids have global large velocities (Possible effect in some cosmological tests such as AP)

Cosmic Voids contribute significantly to large-scale flows

Galaxies in Cosmic Voids are star-forming and reside in dark matter halos with different HOD than elswhere

Some conclusions

Galaxies in voids have smooth expansion void-centric velocities
The otherswise large pairwise velocity dispersion in the field, are negligible within Void boundaries

The external regions surrounding Cosmic Voids have no effect in any aspect of galaxy formation nor dynamics

Some conclusions

The observed negligible galaxy pairwise velocity dispersion in voids is consistent with LCDM predictions and other theories where DM cluster similarly.

Further joint studies of structure and dyanmics may shed light on several aspects of DM properties.