Virtual cosmic voids: structure and star formation activity

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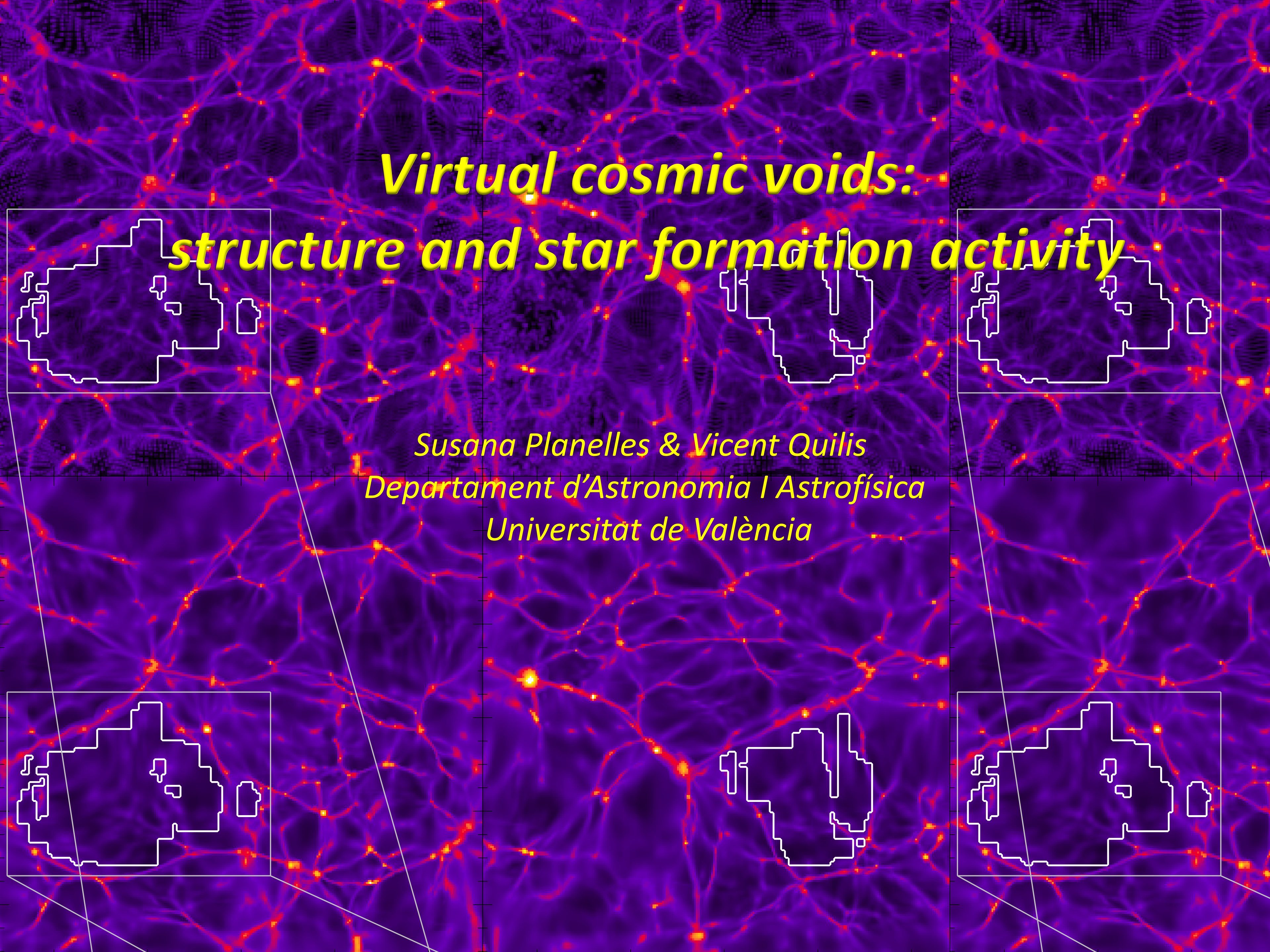
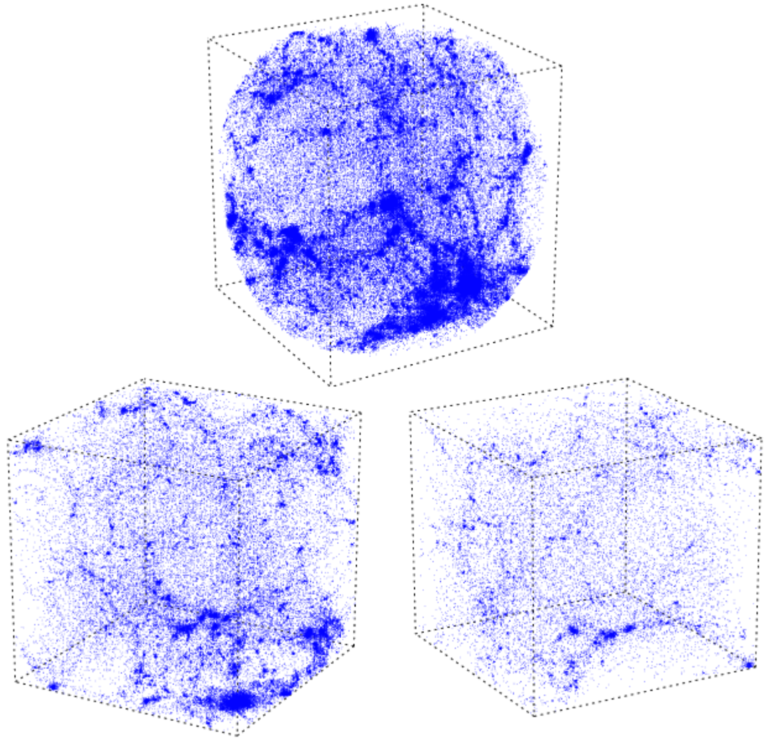


COSMIC VOIDS

- Cosmic voids are large underdense regions, forming an essential feature of the cosmic web and occupying most of the volume of the Universe
- Form from negative density fluctuations in the initial density field and then evolve from the inside out
- As they expand, the density in the interior continuously decreases and matter accumulates to the boundaries



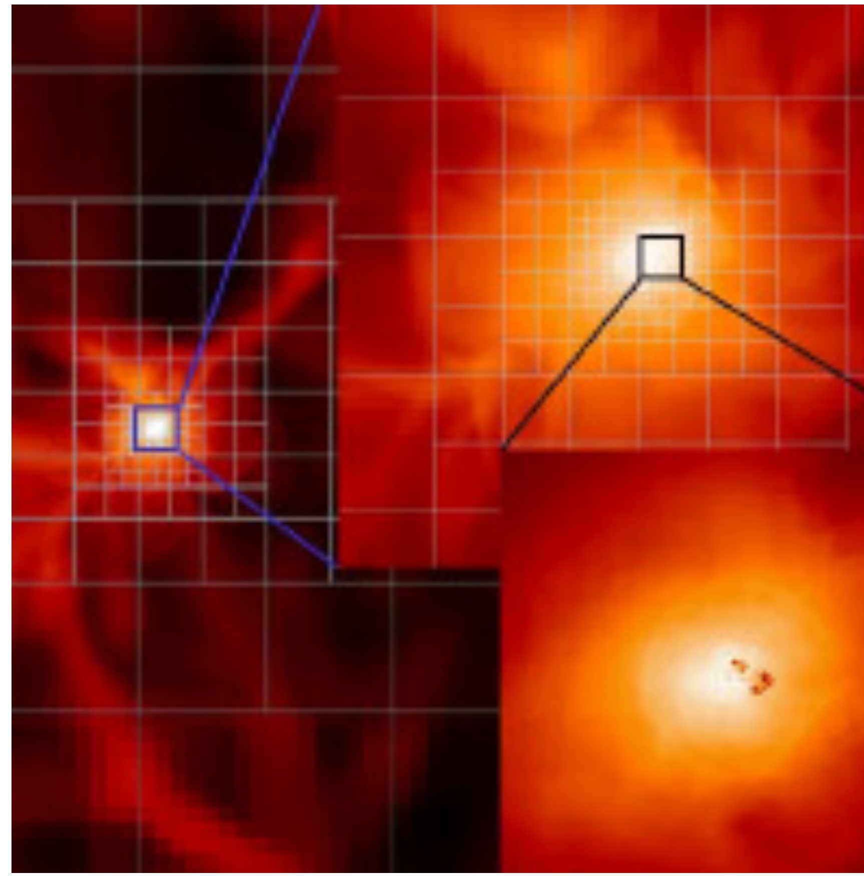
We want to study voids with a AMR simulation refining the regions with the minimum density

Cosmological code

Mesh Adaptive Scheme for CosmologicaL structurE evoluTion
cosmological N-body and Eulerian hydrodynamic code (Quilis 2004)
Based on Adaptive Mesh Refinement (AMR):

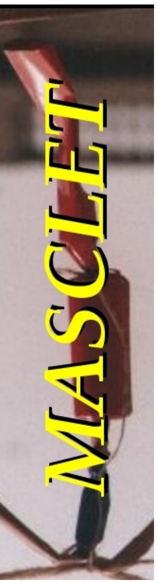
Standard AMR scheme:

Computational grid is refined in the cells satisfying some predefined conditions (usually the high density of the cells)
→ hierarchy of nested grids (or levels of refinement)



Simulations

- New AMR scheme designed to study the formation and evolution of low density regions: (Ricciardelli, Quilis, Planelles 2013)



First level of refinement: (l=1): computational grid refined in low density regions

$$\rho/\rho_b < 10$$

Higher levels (l>1): Refined in the densest regions to follow the formation of structures within voids

Simulation details

- ✓ Side length of the box: 512 Mpc/h
- ✓ Levels of refinement: 1
- ✓ Best resolution (l=1): 1024^3 (0.5 Mpc/h)
- ✓ Best particle mass: $m=6\times10^{10}\ M_\odot$
- ✓ Cosmology: $\Omega_m=0.27$; $\Omega_\Lambda=0.73$, h=0.71
- ✓ Grids used for voids search: 512^3 (0.8 Mpc/h)

- ✓ Side length of the box: 100 Mpc/h
- ✓ Levels of refinement: 7
- ✓ Base level resolution (l=0): 256^3 (0.4 Mpc/h)
- ✓ Best spatial res. (l=7): 3 kpc/h
- ✓ Best particle mass: $m=5\times10^{8}\ M_\odot$
- ✓ Cosmology: $\Omega_m=0.25$; $\Omega_\Lambda=0.75$, h=0.73
- ✓ Grids used for voids search: 128^3 (0.8 Mpc/h)
- ✓ Grids used for subvoids: 256^3, 512^3

COSMIC VOIDS

Void finder

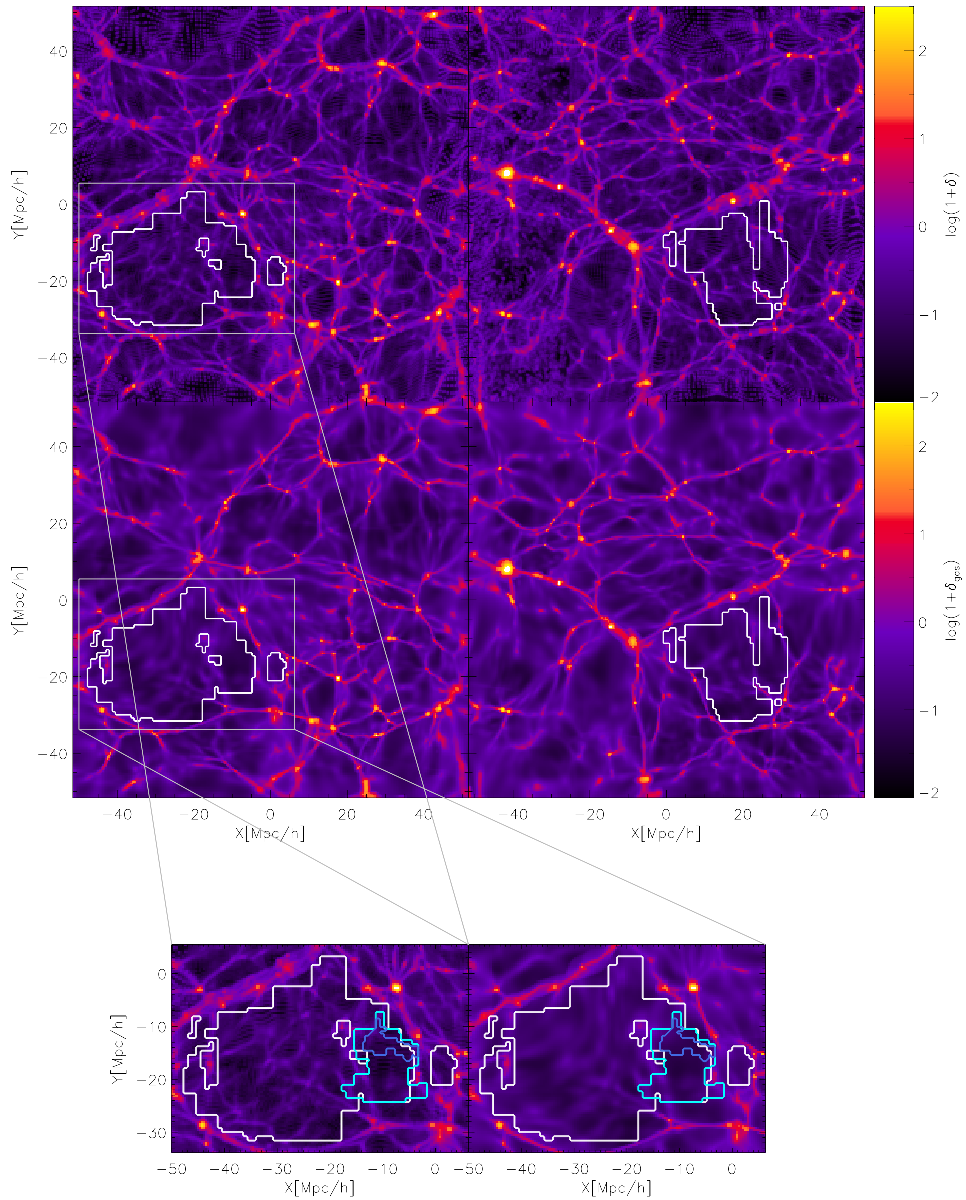
Basic assumptions:

(i) Voids have positive velocity divergence in the interior, with the inner shells expanding faster than the outer regions → centers in the cells with highest $\nabla \cdot v$

(ii) The density at the edges has a sharp increase, hence a steep gradient. Void edges found at jumps in the density gradient

Overlapping voids are allowed
→ we can build voids with arbitrary shape and study their morphology

Algorithm and free parameters tested with mock voids having realistic density profiles(from Colberg et al. 2005)



(Ricciardelli et al. 2013)

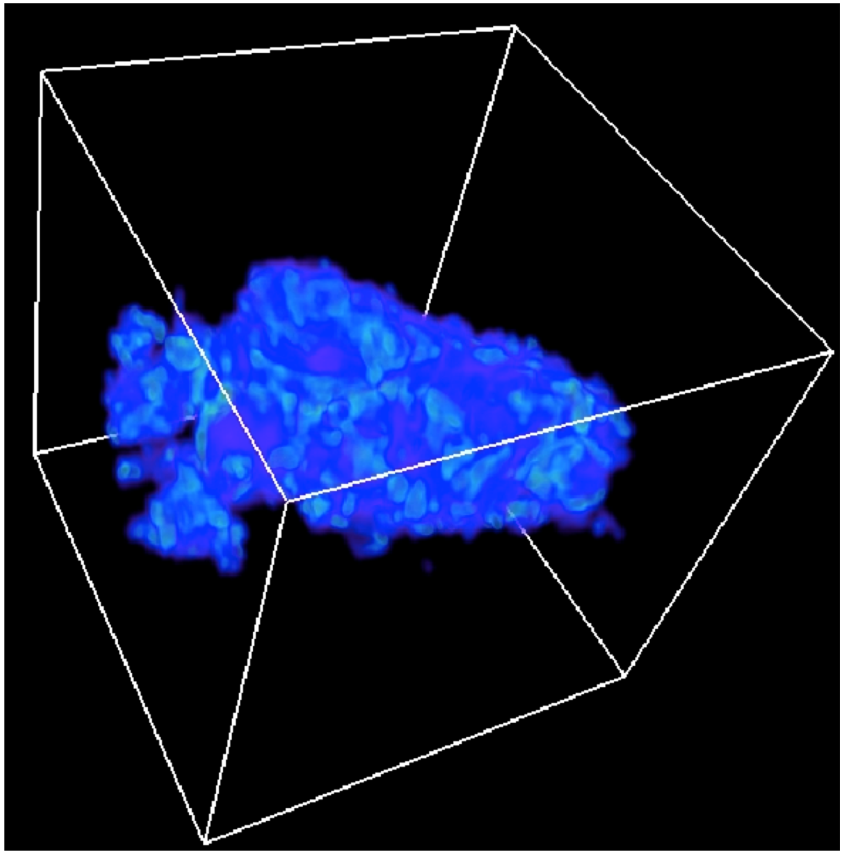
Void morphology

- Voids fitted with an ellipsoid having the same inertia tensor of the void:

$$I_{xy} = \frac{1}{N_{cell}} \sum_{i=1}^{Ncell} (\delta_{xy} r_i - r_{xi} r_{yi})$$

Ncell= #cells in the void
r_i= cell dist to void cent
r_{xi}=components
δ_{xy}= Kroneker delta

- Eigenvalues of the inertia tensor (I_1, I_2, I_3) are used to determine the semi-axes of the fitting ellipsoid: a,b,c

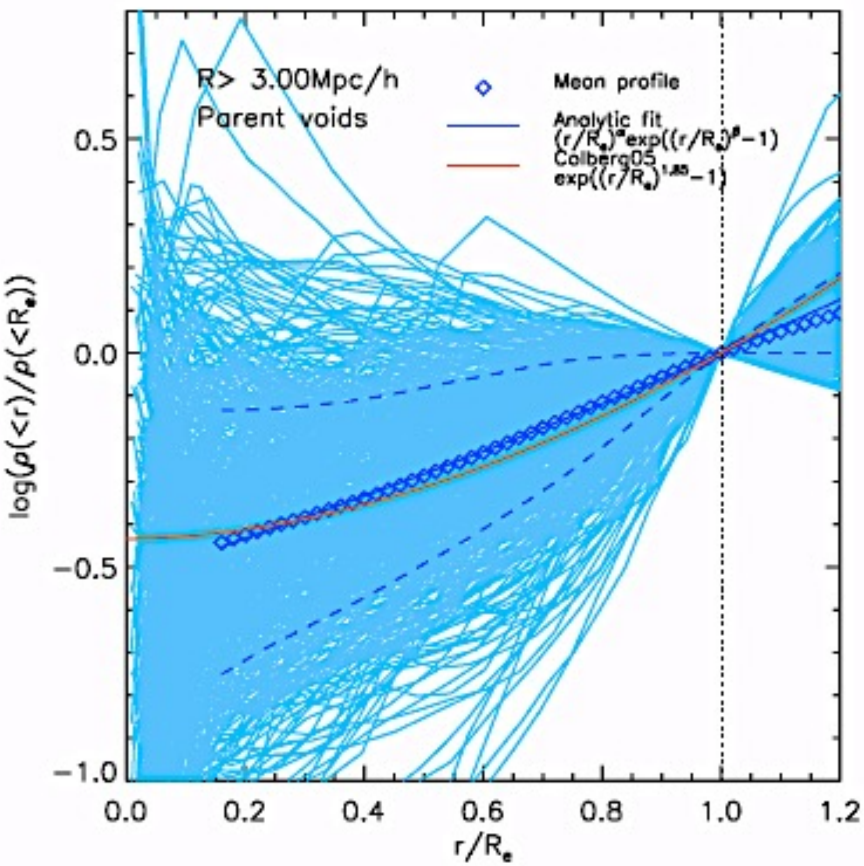


Ellipticity $\epsilon=1-c/a$

Inverse Porosity $IP=V_E/V$

c=semi-minor axis
a=semi-major axis
V_E=volume of the ell.
V=void volume $V = \sum_{i=1}^{N_{cell}} V_{cell}$

Density profile



Robust mean (cumulative) profile of ~600 voids at z=0 with R_e>3 Mpc/h

R_e: equivalent spherical radius of the void

Extreme underdense centre (δ<-0.9) and monotonic increase in the density towards the void edges

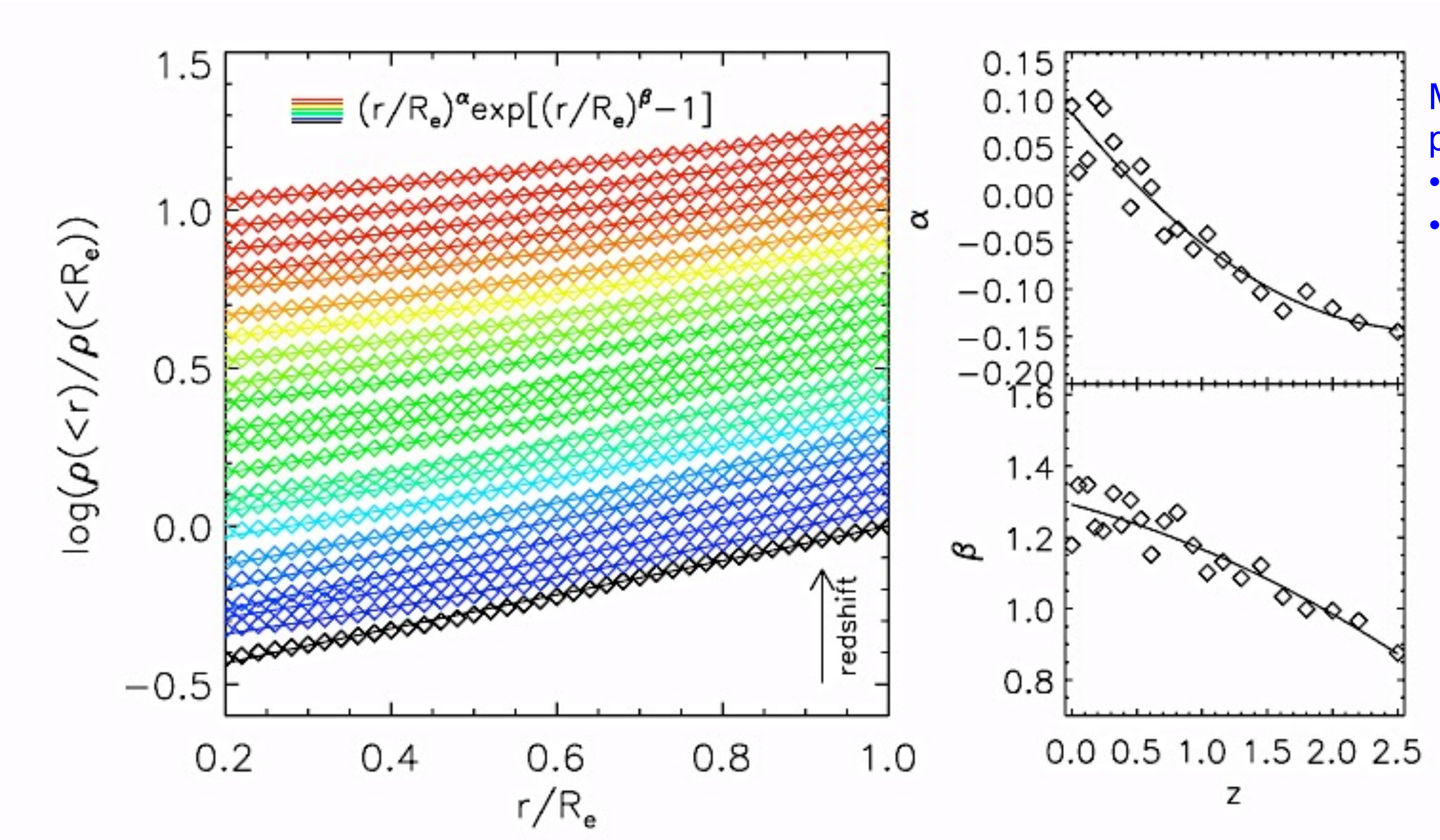
Good agreement with Colberg05, although small deviations exist.

We propose a two parameters analytical fit:

$$\frac{\rho(<r)}{\rho(<\mathrm{Re})} = \left(\frac{r}{\mathrm{Re}}\right)^{\alpha} \exp\left[\left(\frac{r}{\mathrm{Re}}\right)^{\beta} - 1\right]$$

α=0.07; β=1.32

Time dependence



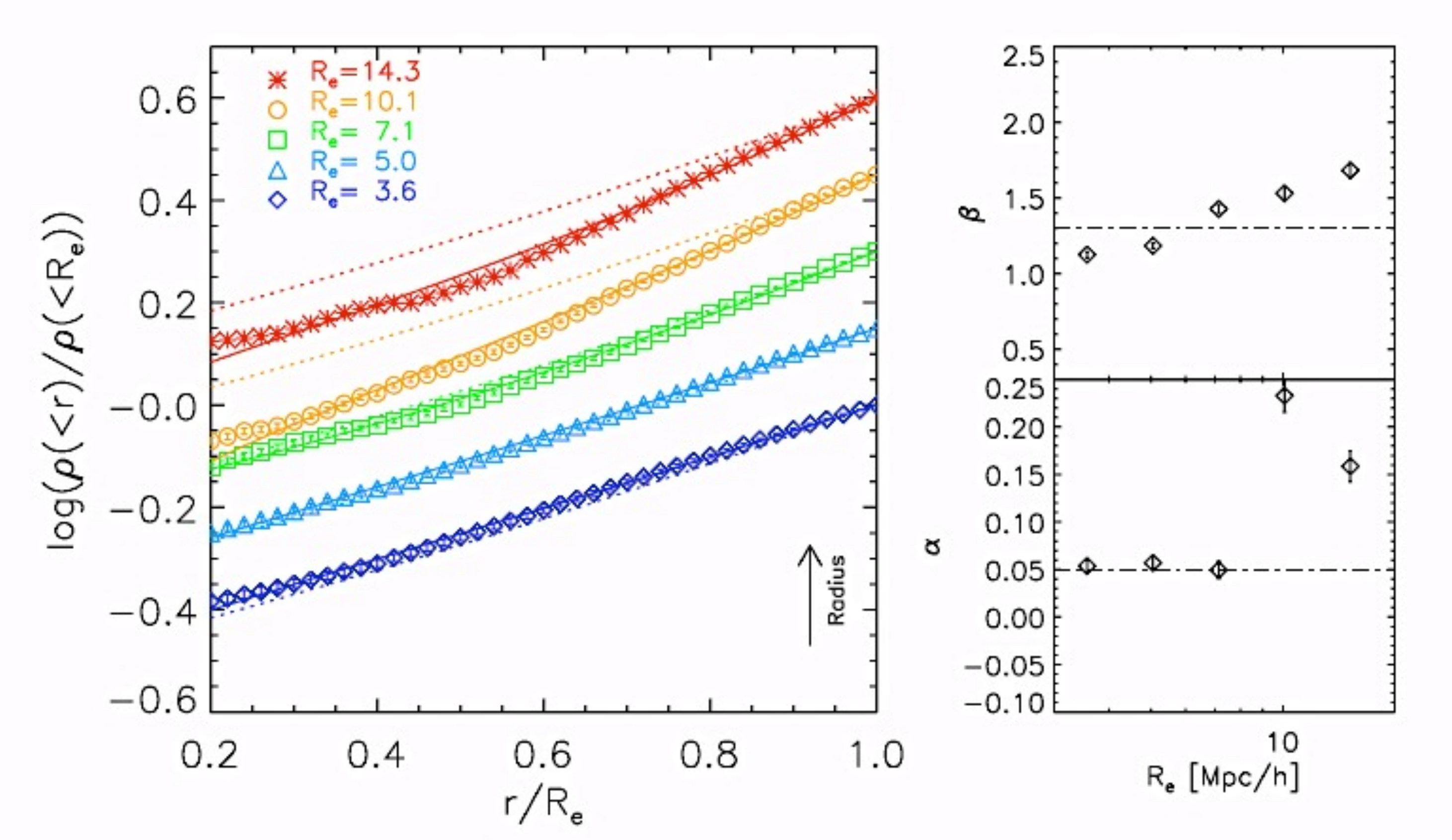
Mean density profiles:

- $z=2.5 \rightarrow 0$
- $R_e > 3$ Mpc/h

Voids become **progressively steeper** as time proceeds (low-z), suggesting that the interior of voids is emptying

In agreement with theoretical expectations of void evolution towards a “reverse top-hat shape” (Sheth & van de Weygaert 2004)

Size dependence



Mean density profile of voids z=0-0.25

The same best-fit profile applies for voids up to R=8 Mpc/h

Steeper profiles for larger voids?

SDSS void catalogue

(Varela et al. 2012)

- **The Data**: sample selected from NYU-VACGS catalogue (Blanton et al. 2007), based on SDSS/DR7
- **Void definition**: spherical volume devoid of galaxies brighter than the mag limit (-20.17)
- **Void catalogue**: ~1500 voids larger than 7 Mpc/h

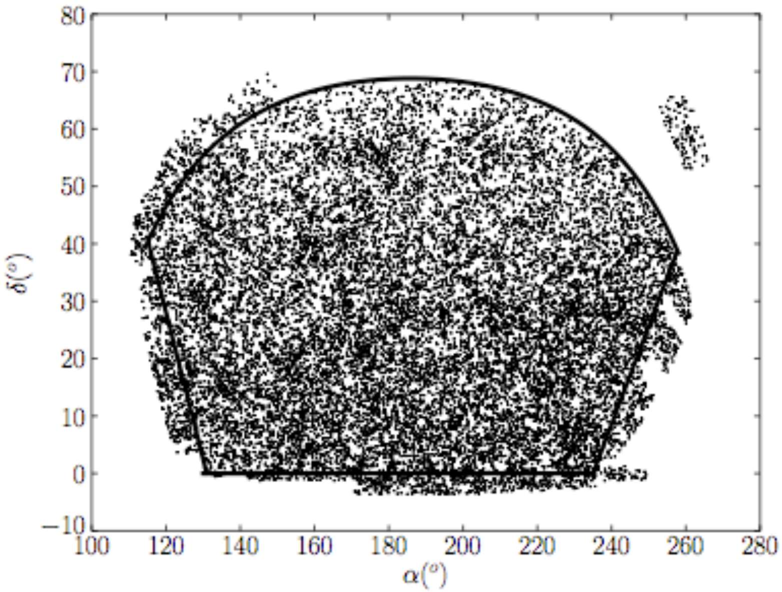


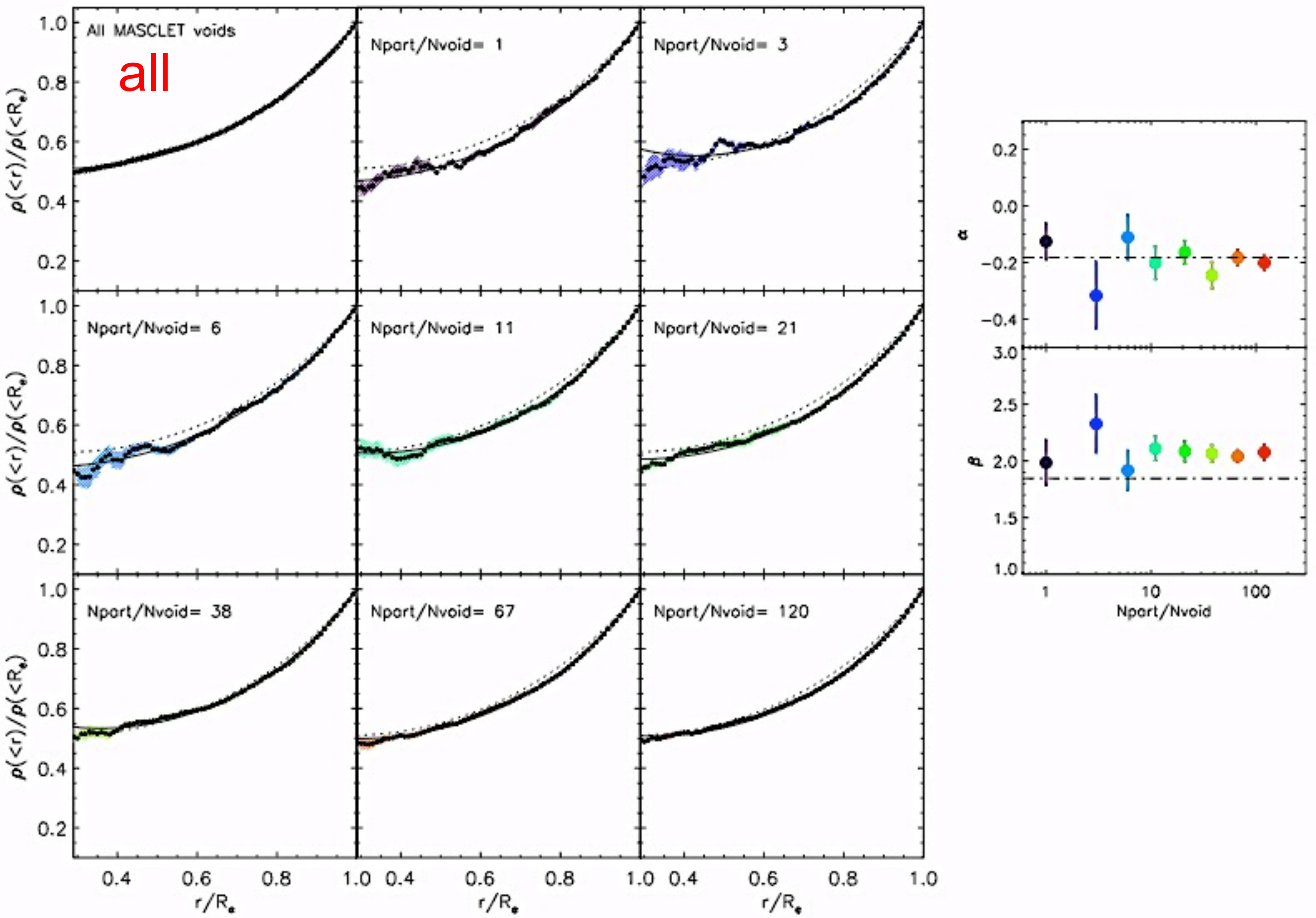
Table 1
Summary of Properties of the Reference Catalog

Reference catalog	NYU-VAGC (Galaxies)
Spectroscopic completeness limit	$r \leqslant 17.8$
Redshift limits	$0.005 < z < 0.12$
Absolute magnitude limit	$M_r - 5\log h \leqslant -20.17$
Number of galaxies	142127
Total projected area	1.941484 sr
	$0.1545 \times 4\pi$
Total volume	$0.0276556\ (h^{-1}\ \mathrm{Gpc})^3$
Average density of galaxies	$0.00514\ (h^{-1}\ \mathrm{Mpc})^{-3}$

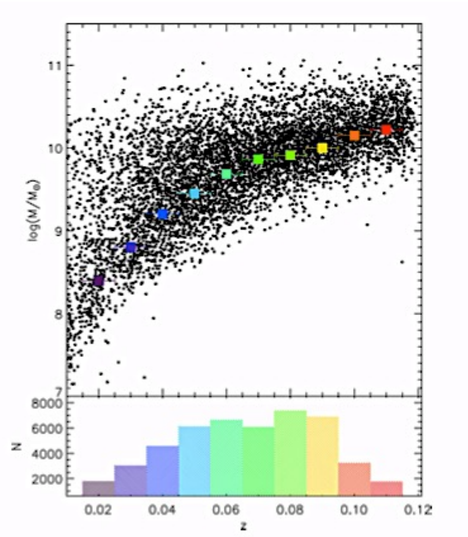
Impact of sparsity (simulation)

Subsamples of voids populated with a increasing number of tracers (N_{part}/N_{void}=[1:120])

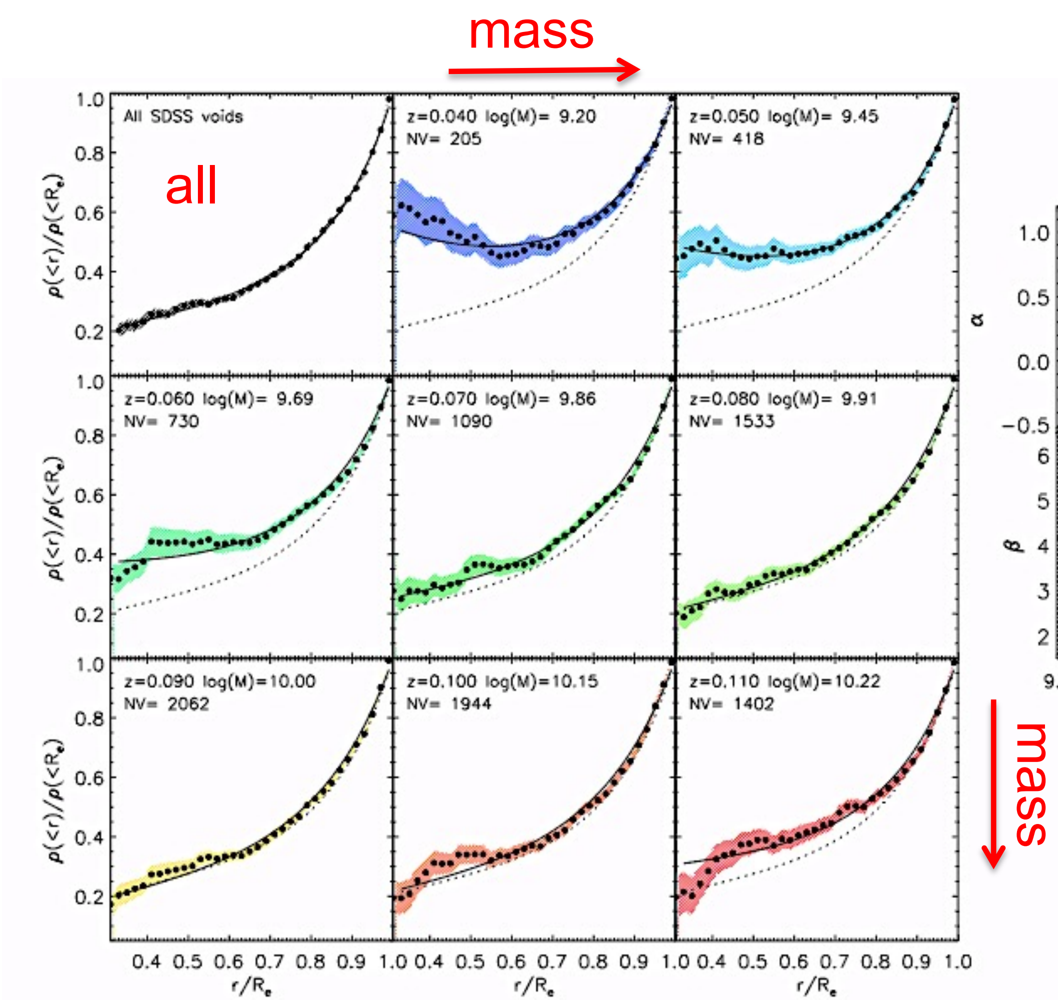
No systematic effect is observed for underpopulated samples

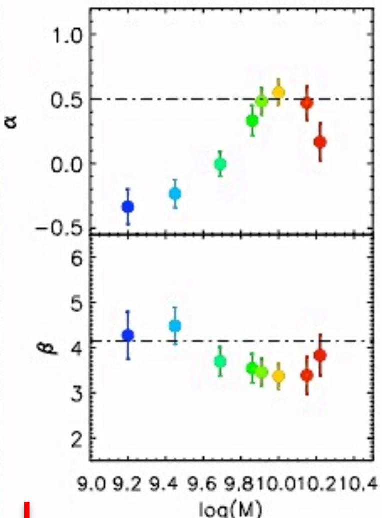


Impact of the mass tracers (observations)



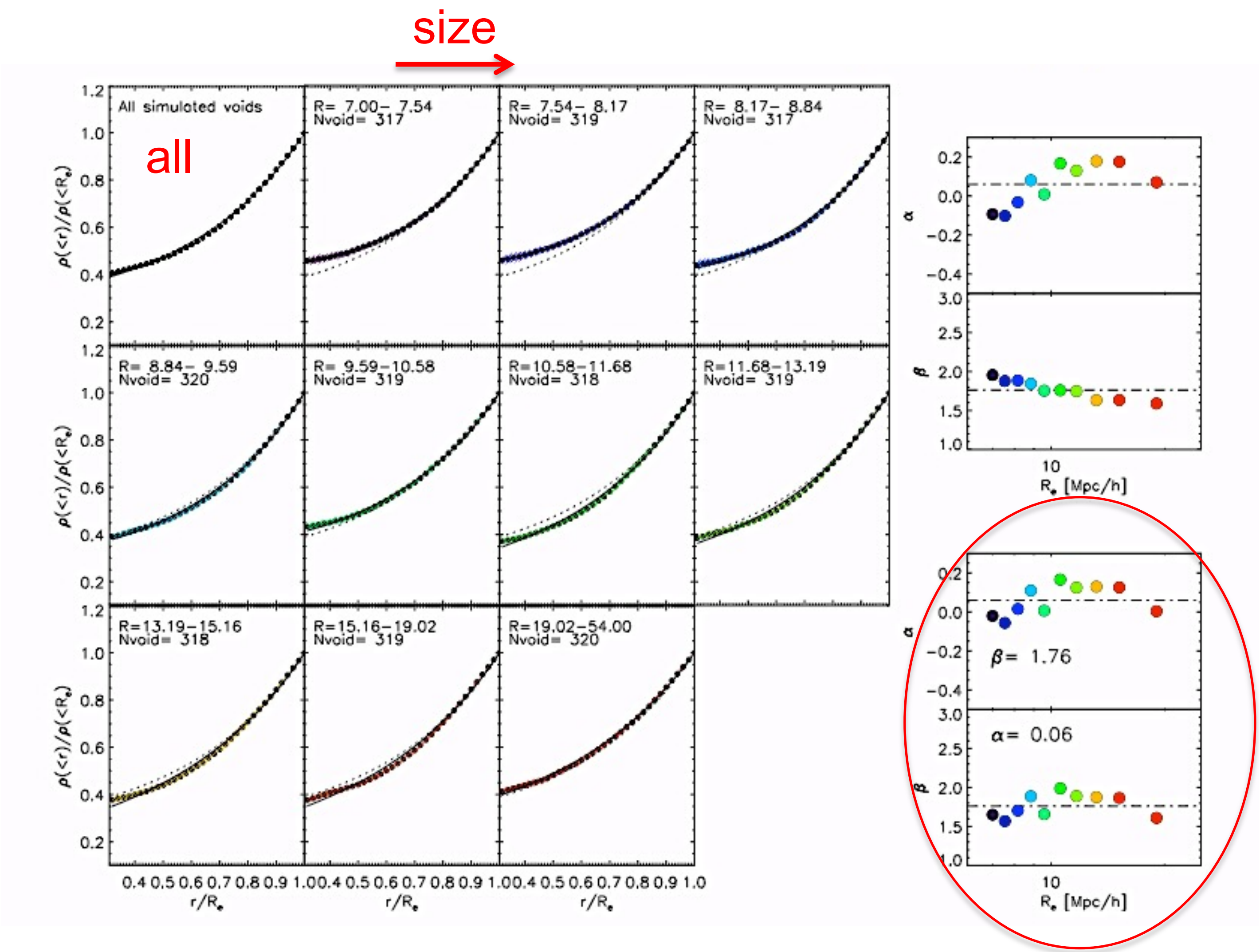
Volume limited samples of galaxies having mass down to the completeness limit





The profiles steepen as galaxies at higher stellar masses are used

Dependence on void size (simulation)

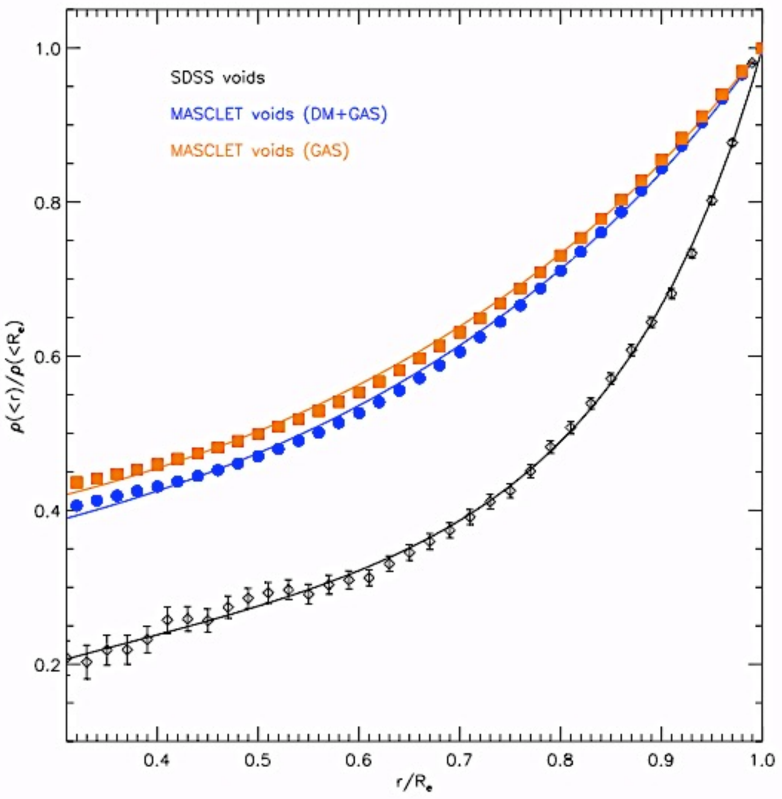


MASCLET voids
R_{void}=[7:50]Mpc/h

No evidence of a dependence of the profiles on radius
→ universality of void density profiles

Simulations vs Observations

Ricciardelli, Quilis, Varela 2014



$$\frac{\rho(<r)}{\rho(<\mathrm{Re})} = \left(\frac{r}{\mathrm{Re}}\right)^{\alpha} \exp\left[\left(\frac{r}{\mathrm{Re}}\right)^{\beta} - 1\right]$$

$\alpha=-0.18$ $\beta=1.85$ $\alpha=0.5$ $\beta=4.15$

MASCLET stack

SDSS stack

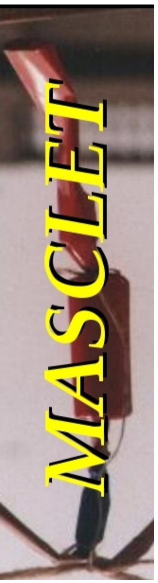
- The same functional form can describe both the observed and simulated profile
- Good agreement between gas and total matter profile
- The observed profile is much steeper than the simulated one

Galaxies in voids

- Star formation activity of void galaxies
  - Void galaxies form stars more efficiently that shell galaxies and control sample
- Dependence on the environment?
  - Star formation is independent on the environment (excluding clusters)
- Galaxy properties vs void-centric distance
- Galaxy properties vs void size

Next generation simulations

- New AMR scheme designed to study the formation and evolution of low density regions:



First level of refinement: (l=1): computational grid refined in low density regions

$$\rho/\rho_b < 10$$

Higher levels (l>1): Refined in the densest regions to follow the formation of structures within voids

Simulation details

- ✓ Side length of the box: 100 Mpc/h
- ✓ Levels of refinement: 10
- ✓ Base level resolution (l=0): 128^3 (0.78 Mpc/h)
- ✓ Best spatial res. (l=10): **0.76 Kpc/h**
- ✓ Best particle mass: m=$\mathbf{9.5\times10^8\ M_\odot}$
- ✓ Cosmology: Ω_m=0.31; Ω_Λ=0.69, h=0.678

Finished !!!