AIP

ASTROPHYSIKALISCHES INSTITUT POTSDAM

The structure of voids

Stefan Gottlöber
sgottloeber@aip.de

Collaboration

Anatoly Klypin (NMSU, Las Cruces)
Gustavo Yepes (UAM, Madrid)
Ewa Łokas (Copernicus Center, Warsaw)
Yehuda Hoffman (Hebrew University, Jerusalem)
Arman Khalatyan (AIP, Potsdam)
Victor Turchaninov (IAM, Moscow)

Topics

- How to find voids?
- The structure of voids
- Voids in the MareNostrum Universe

What is a void?

The Void (From Wikipedia, the free encyclopedia)

In fiction:

- The Void, the infinite nothingness between dimensions in the British science fiction television series Doctor Who
- The Void (Dungeons & Dragons), part of the Dungeons and Dragons cosmology
- The Void (Middle-earth), the part of the Middle-earth fictional universe which is uninhabited
- The Void (The Three Worlds), Darwinian place that separates Aachan, Tallallame and Santhenar in Ian Irvine's The Three Worlds cycle

In science:

- Void (astronomy), the empty spaces between filaments
- Void coefficient, estimated number in nuclear engineering
- Void ratio, volume of voids in a mixture divided by the volume of solids (material sciences)

My (simple) void definition

A void is a region in a point distribution which does not contain any point.

- "Points" can be the halos in cosmological simulations selected under certain conditions (for example mass larger than a certain threshold or circular velocity larger than a given threshold)
- "Points" can be the observed galaxies in the universe selected under certain conditions, for example with luminosities higher than a given threshold.
- "Points" can be DM or gas particles (or cells) with local (SPH) densities larger than a given threshold.

An alternative definition could be given via a density threshold in a density field.

Numerical simulation of a void

ΛCDM cosmological model

- matter density $\Omega_0 = 0.3$
- cosmological constant $\Omega_\Lambda = 0.7$
- Hubble parameter $H = 70$ km/s/Mpc
- normalization $\sigma_8 = 0.9$
- age $t_0 = 13.5$Gyrs

Starting point: “low” mass resolution simulation

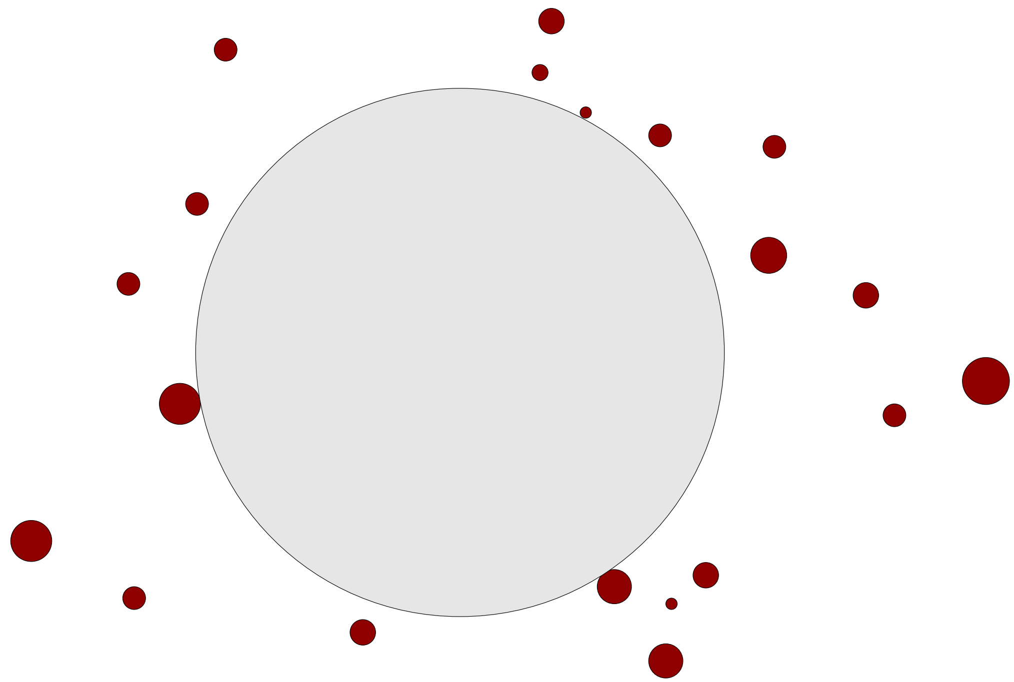
Finding halos in this simulation

- Friends-of-friends algorithm
- Bound-density-maxima algorithm

Finding voids

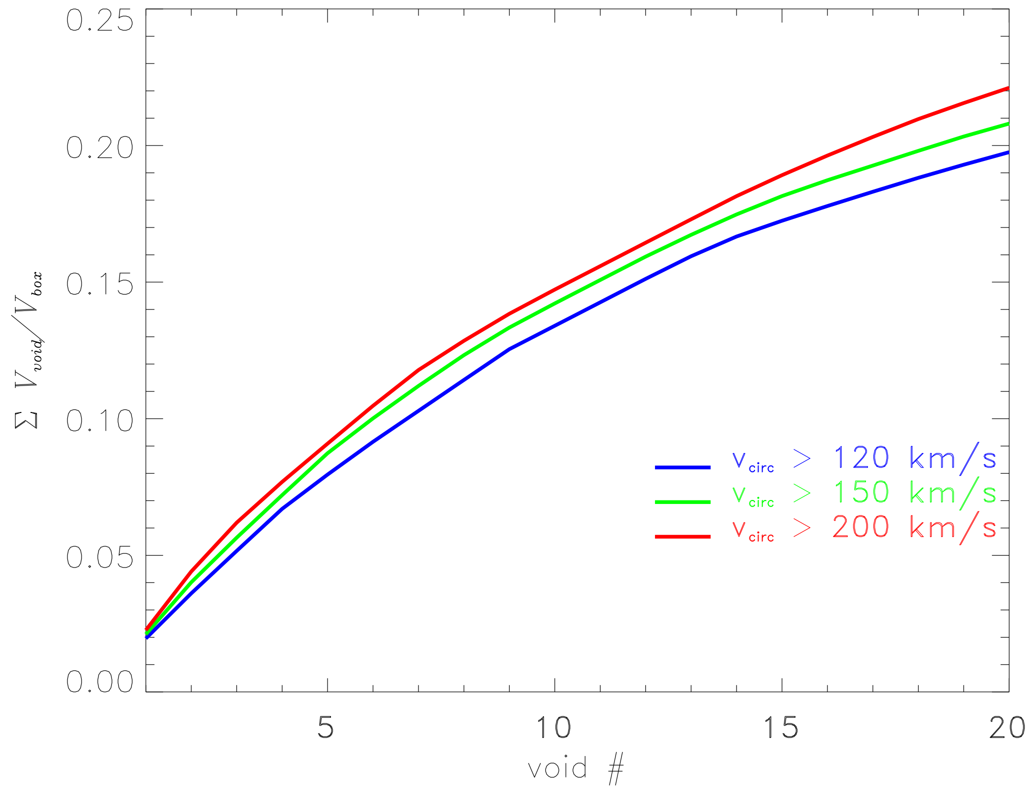
High mass resolution simulation of voids

How to find "spherical voids" in numerical simulations?



- Select a set of halos ($m_{halo} \geq 2.0 \times 10^{11} h^{-1} \mathrm{M}_{\odot}$)
- Find the "most distant point" and its distance to this set.
  - ▷ This is the center and radius of the largest void.
- Exclude this region and find the next "most distant point".

The size of voids



Voids in a distribution of galaxies with different circular velocities v_{circ}.

The size of the voids depends only slightly on the selection criterion of objects defining the void.

Re-simulation of voids

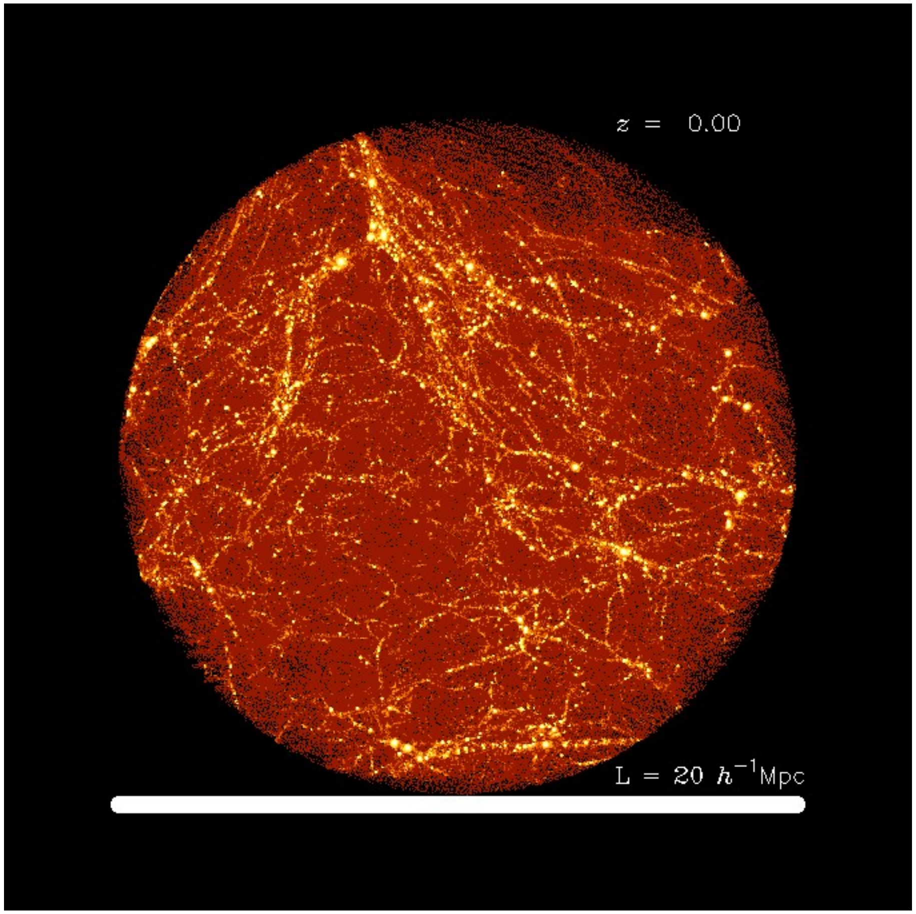
- Find a void in "low" resolution simulation (128^3 particles in a $80h^{-1}$Mpc box, 512^3 particles in a $50h^{-1}$Mpc box)

- Calculate the initial condition within that void on the basic of 1024^3 or 2048^3 particles and add around the void buffering layers of more massive particles until the background low resolution is reached.
  - ▷ $m_p = 4.0 \times 10^7 h^{-1}\mathrm{M}_\odot$ (corresponds to 1024^3 particles in a $80h^{-1}$Mpc box)
  - ▷ $m_p = 1.2 \times 10^6 h^{-1}\mathrm{M}_\odot$ (corresponds to 2048^3 particles in a $50h^{-1}$Mpc box)

- We have re-simulated several voids using ART and GADGET (see the talks of Gustavo Yepes and Matthias Hoeft).

- Current project: voids in the local Universe, constrained simulation (Yehuda Hoffman's talk), $160h^{-1}$Mpc box (1024^3 particles, 4096^3 particles possible), WMAP3 normalisation

The evolution of a void

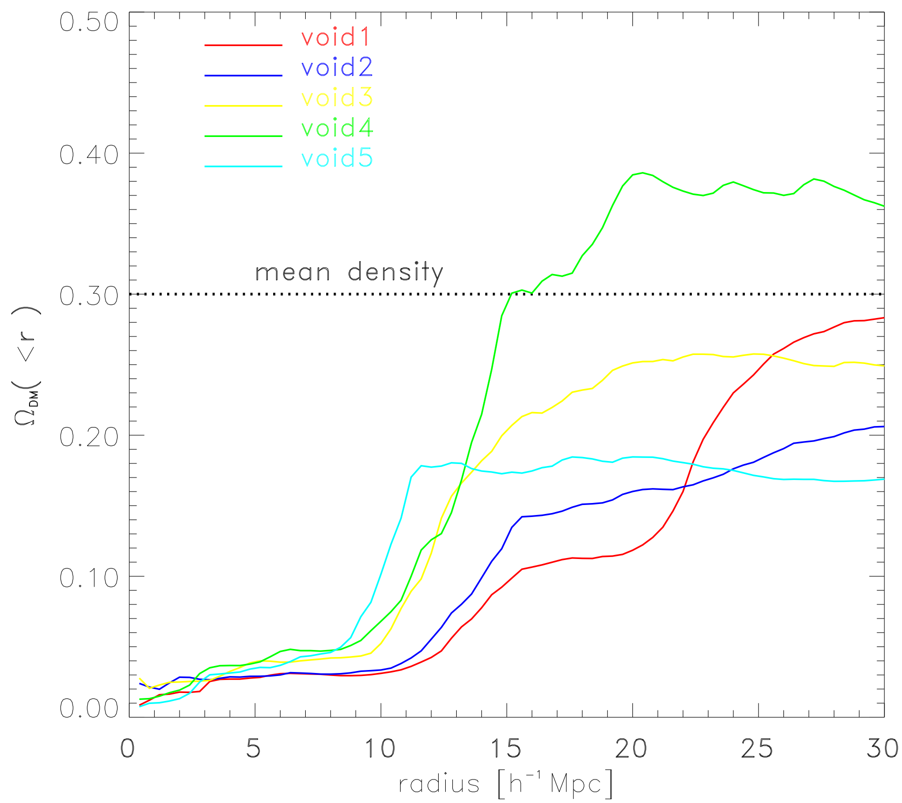


490 steps with $\Delta a = 0.002$

1377280 particles in the void ($m_p = 4.0 \times 10^7 h^{-1} \mathrm{M}_\odot$)

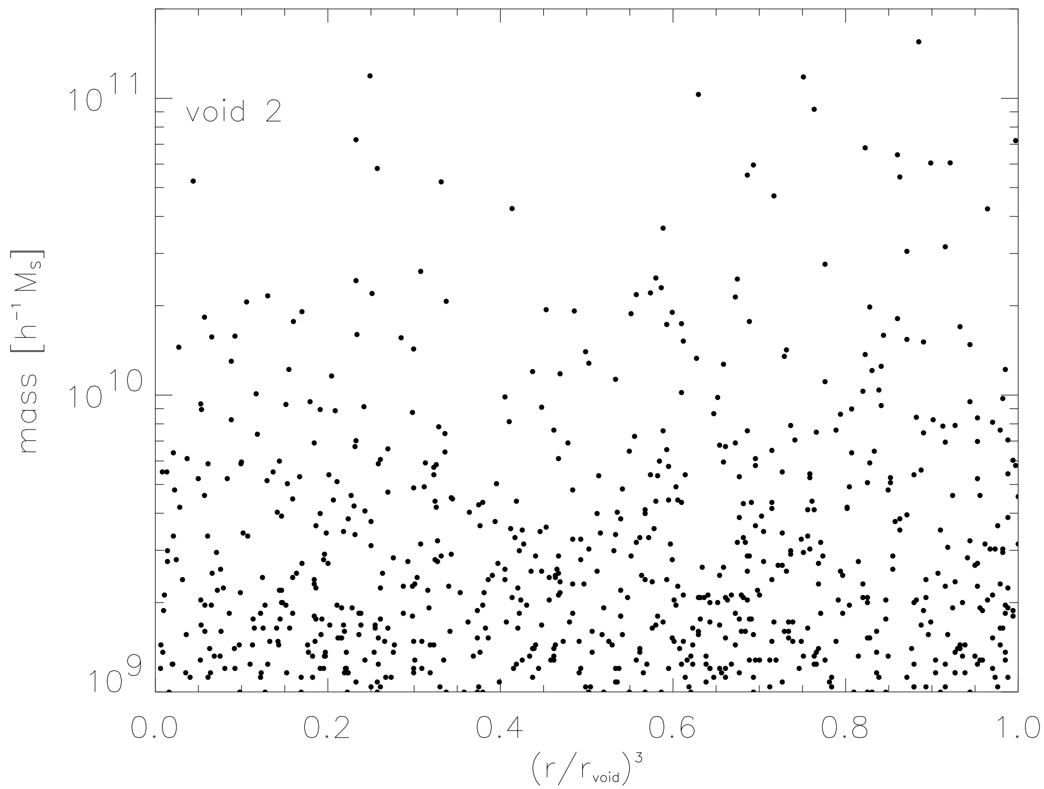
After the final size ($r = 10 h^{-1}$Mpc at $z = 0$) has been reached the camera is flying around the void to get an idea of the three-dimensional structure.

Density profile



The density is shown within spheres of radius r centered at the void center. Inside the void the density is typically by a factor of 10 smaller than the mean density.

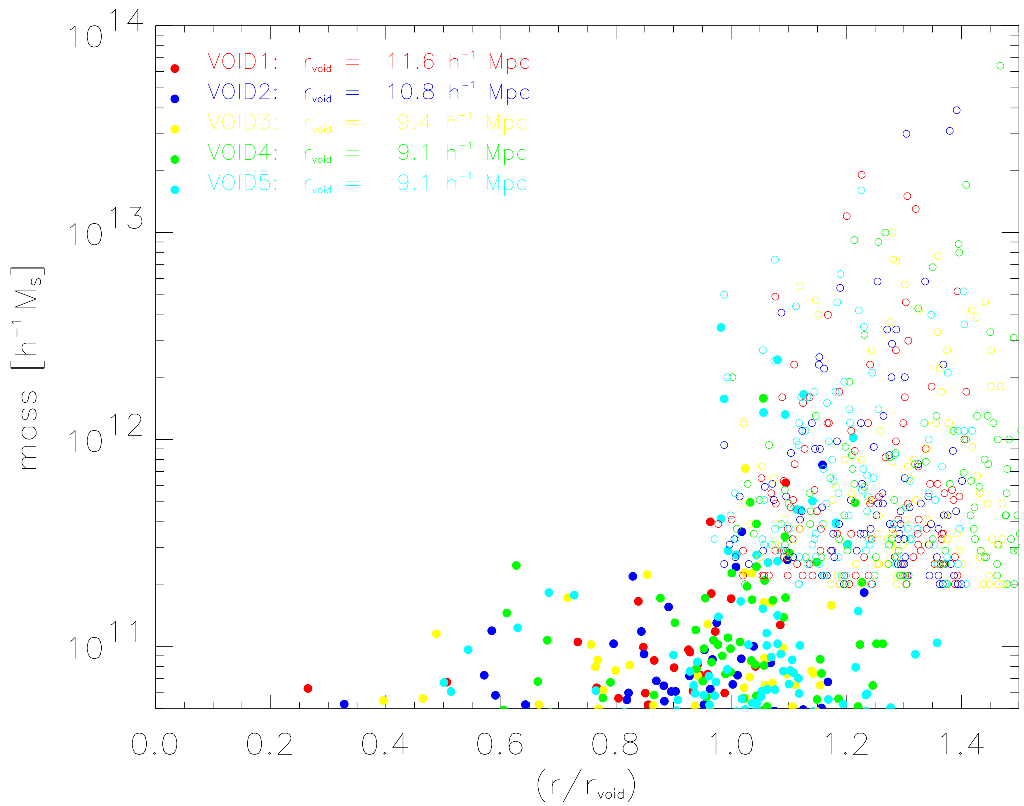
Distribution of halos in voids



Halo distribution depending on volume $(r/r_{\mathrm{void}})^3$.

Low mass halos are even distributed, more massive halos tend to be concentrated in the outer regions.

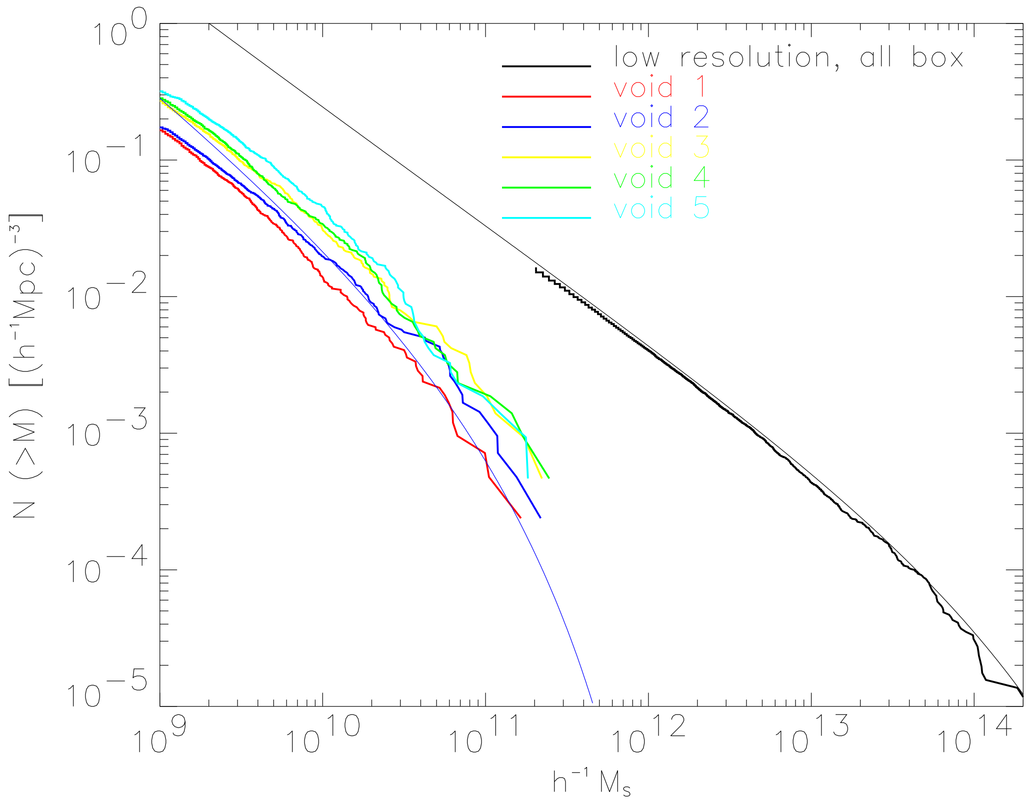
Distribution of most massive halos in voids



The distribution of massive halos depending on distance $r/r_{\rm void}$ to five void centers.

Filled symbols: High mass resolution in and around the voids. Open symbols: Low mass resolution simulation in which the voids are defined.

Mass function of halos in voids

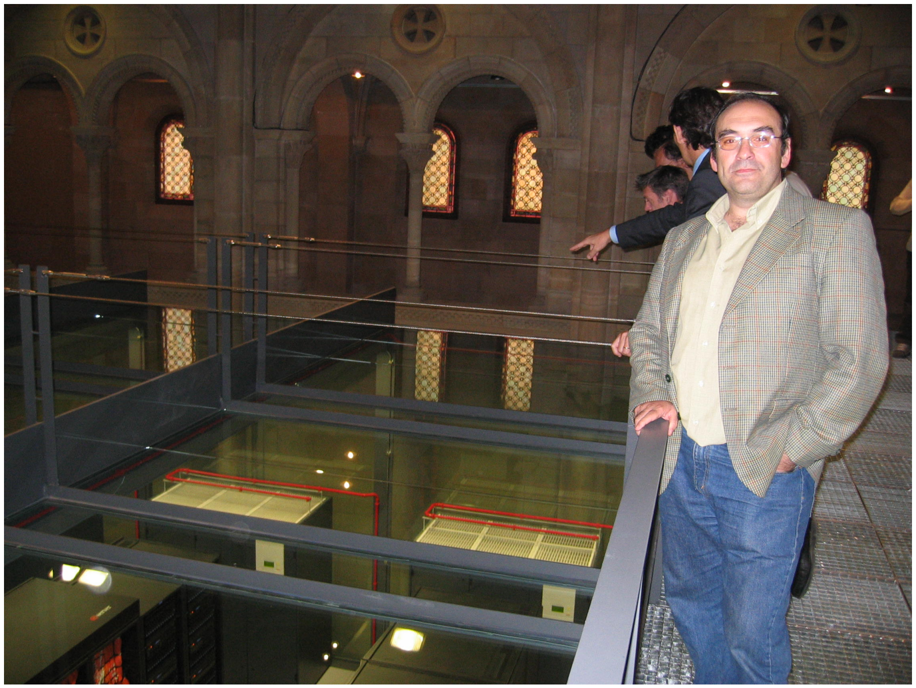


Mass function of DM halos: The black solid line shows the cumulative mass function $N(>M)$ in the whole $80h^{-1}$Mpc simulation. The colored lines show the mass functions in voids. The thin lines are the Sheth-Tormen predictions of mass functions. (MNRAS **344** (2003), 715)

What means MareNostrum?

MareNostrum at BSC Barcelona
10240 PowerPC970 FX processors
4 GB memory per node (total: 20.48 Tb main memory, 233 Tb disk)

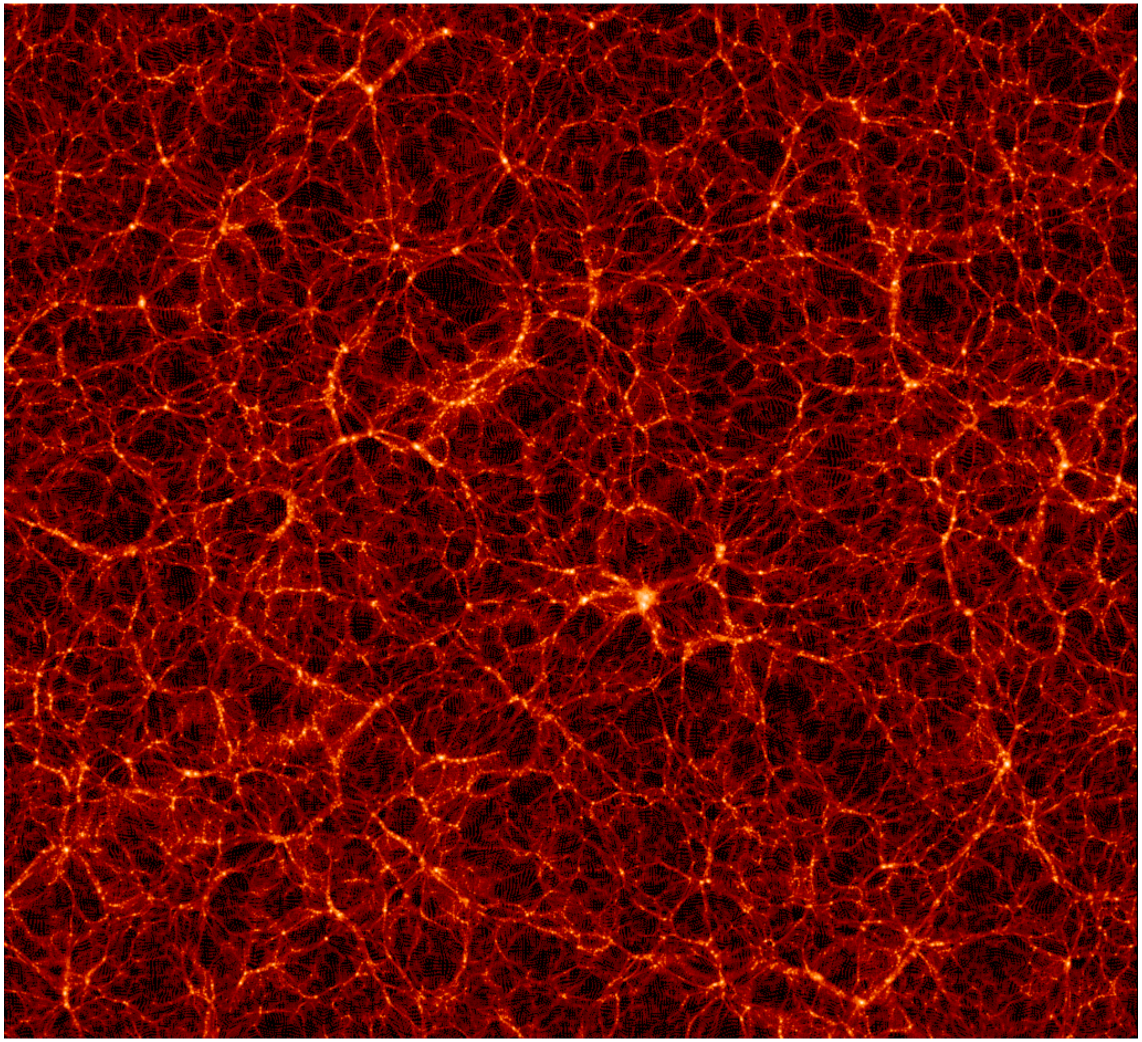
MareNostrum Universe



- initial number for random phases

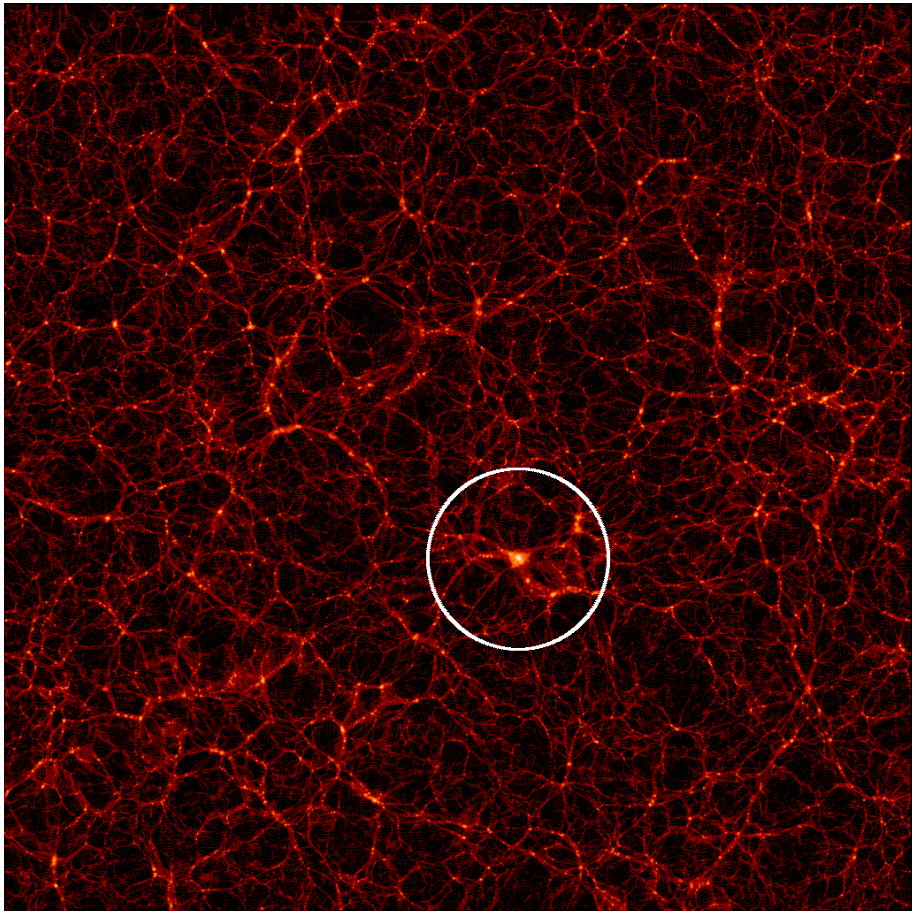
- three weeks on 512 CPUs (during testing phase)
- 29 CPU-years
- output: 8600 Gbyte (stored at NIC Jülich)

Filaments and voids

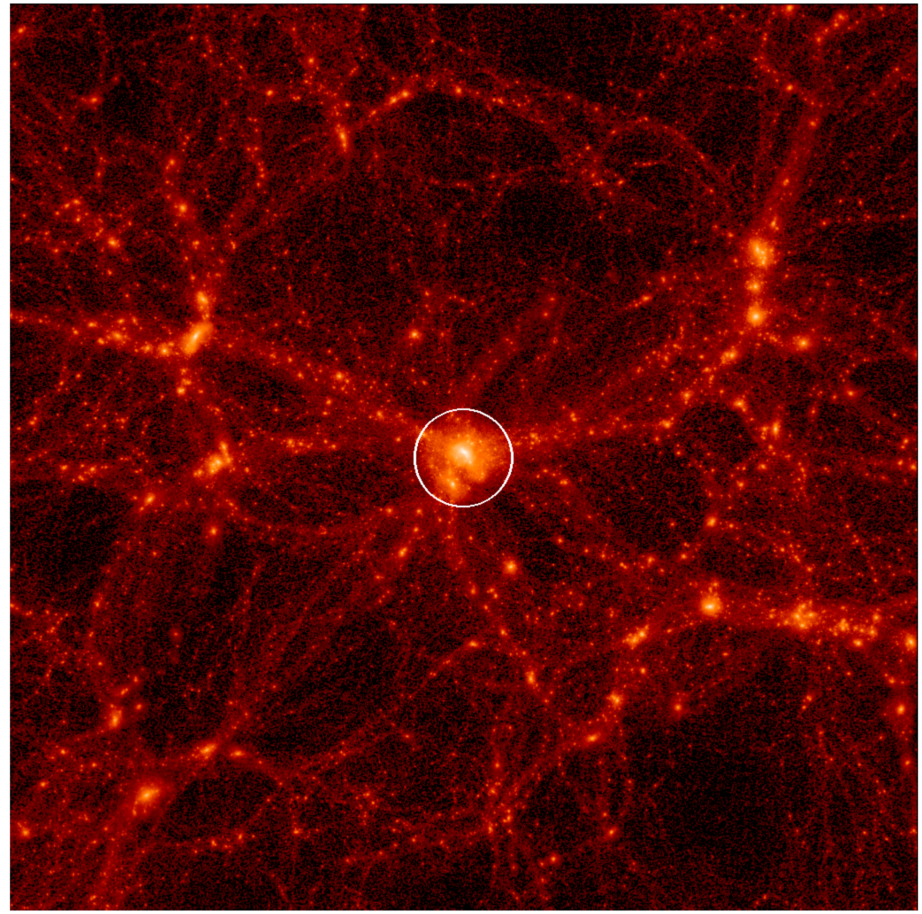


- 500 h^{-1}Mpc box
- 1024^3 DM particles, 1024^3 gas particles,
- GADGET II (Volker Springel)
- non-radiative simulation
- force resolution: 15 kpc

Voids on all scales

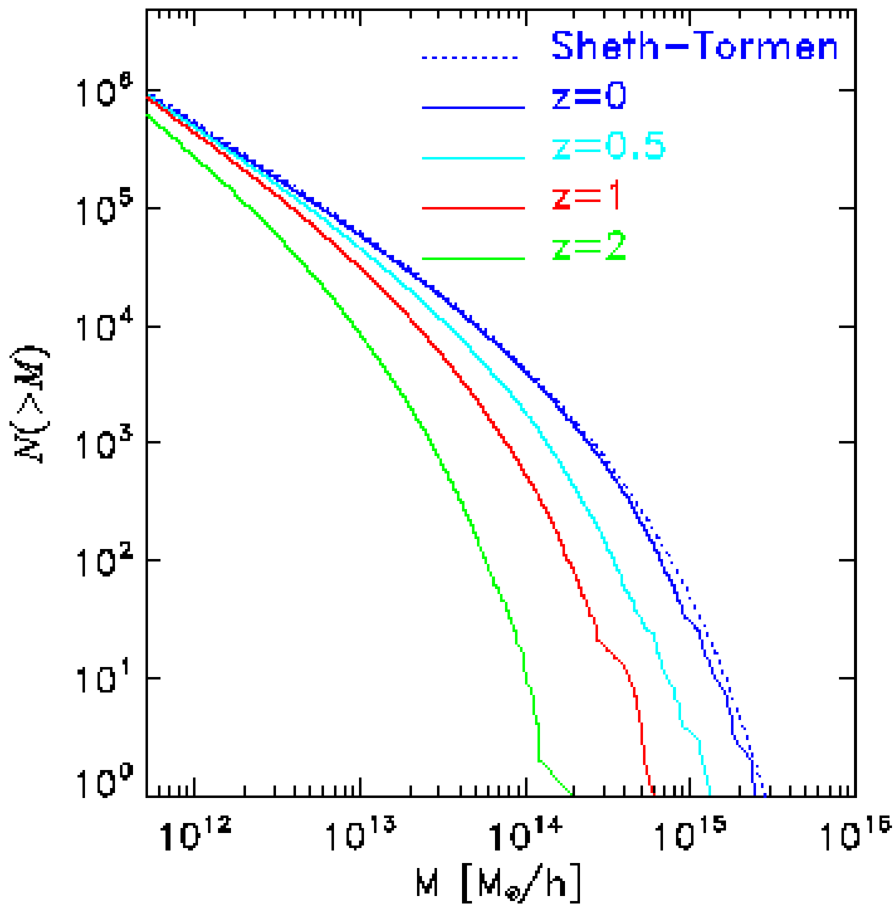


circle $100h^{-1}$Mpc

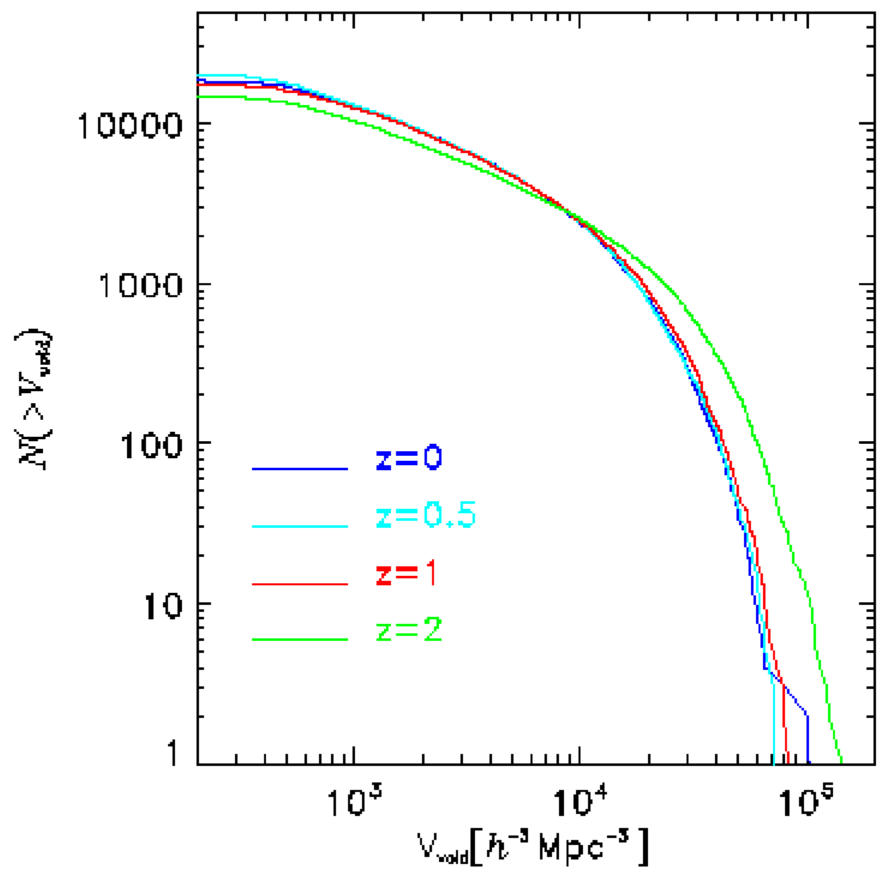


circle $20h^{-1}$Mpc

Halo mass function — void function

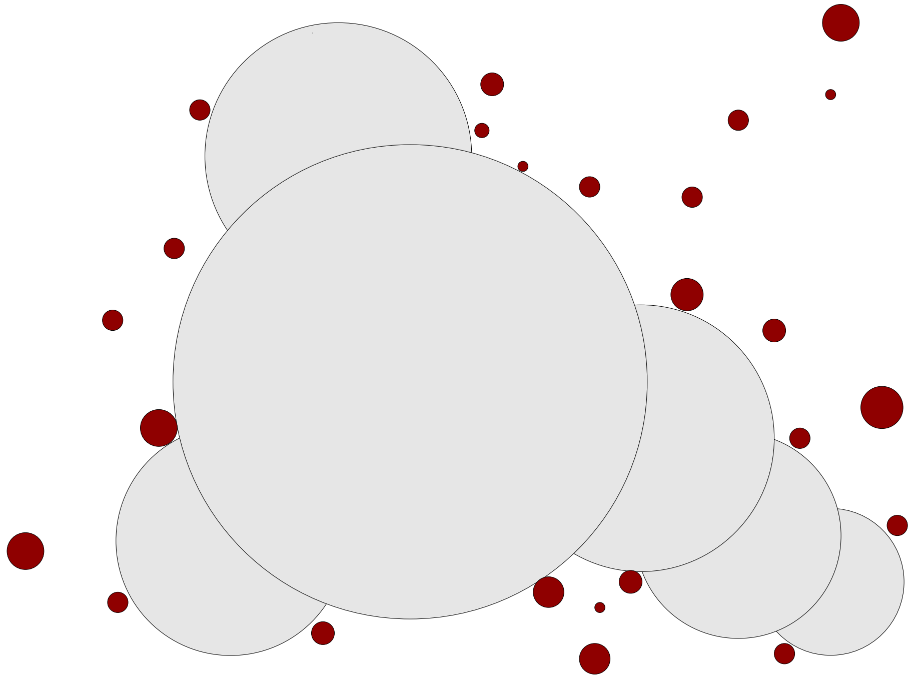


halo mass function



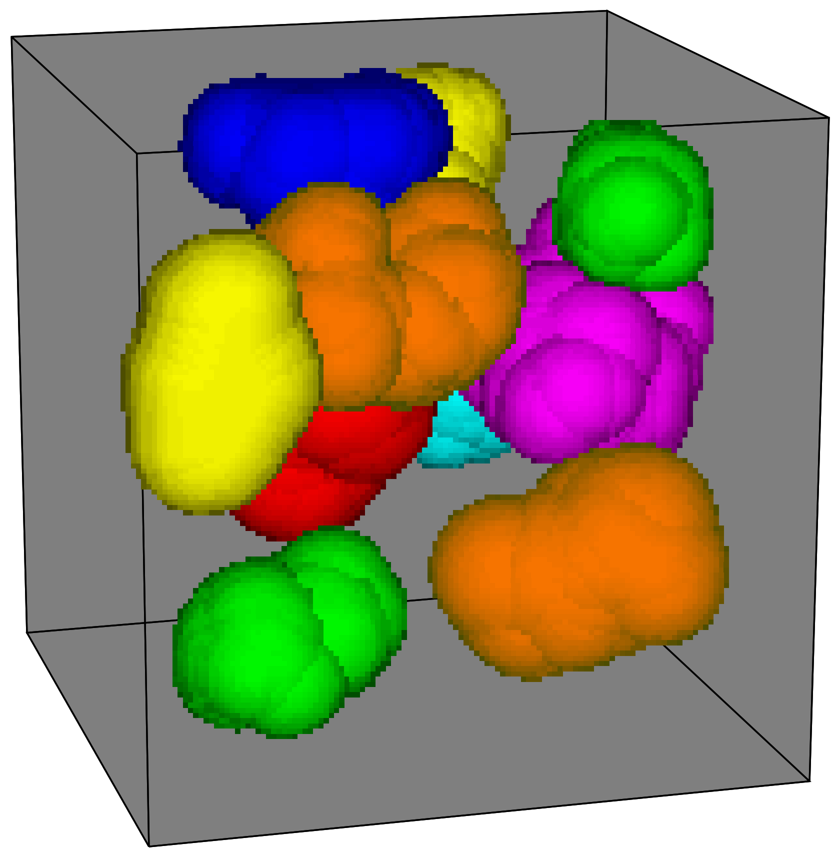
voids in the distribution of halos with $M > 10^{12}h^{-1}\mathrm{M}_\odot$

How to find "non-spherical voids" in numerical simulations?



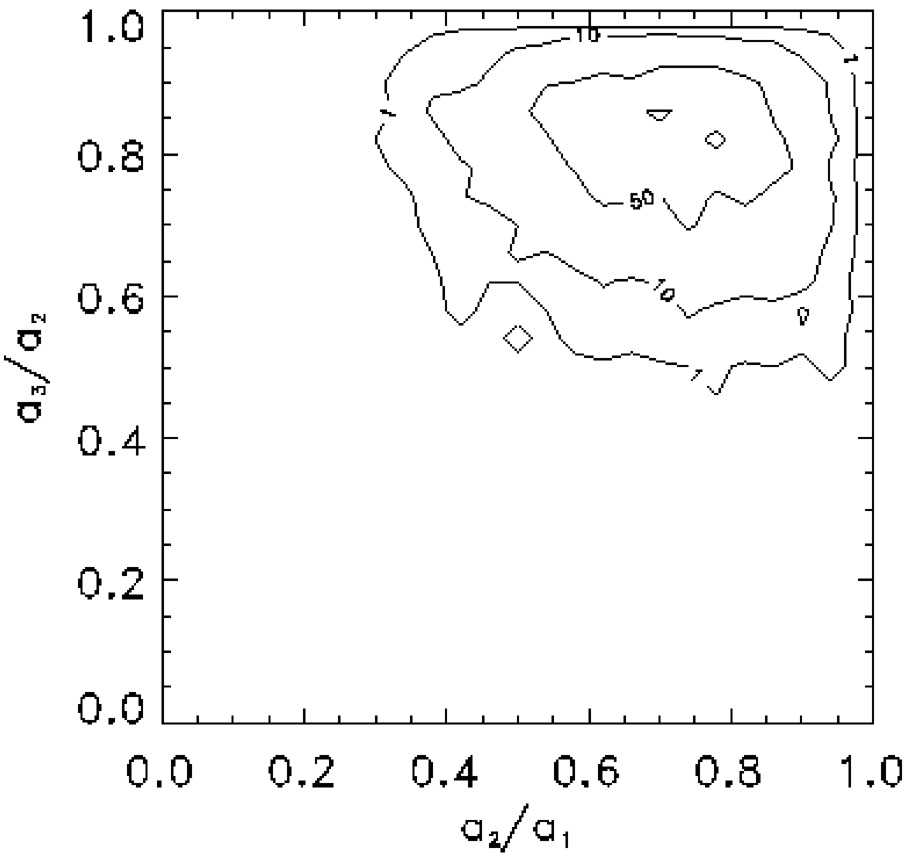
- Find first a spherical void.
- Extend this void in all directions using smaller spheres.
- Stop after two or three iterations to avoid fingers and/or tunneling.

“Non-spherical voids” — an example



10

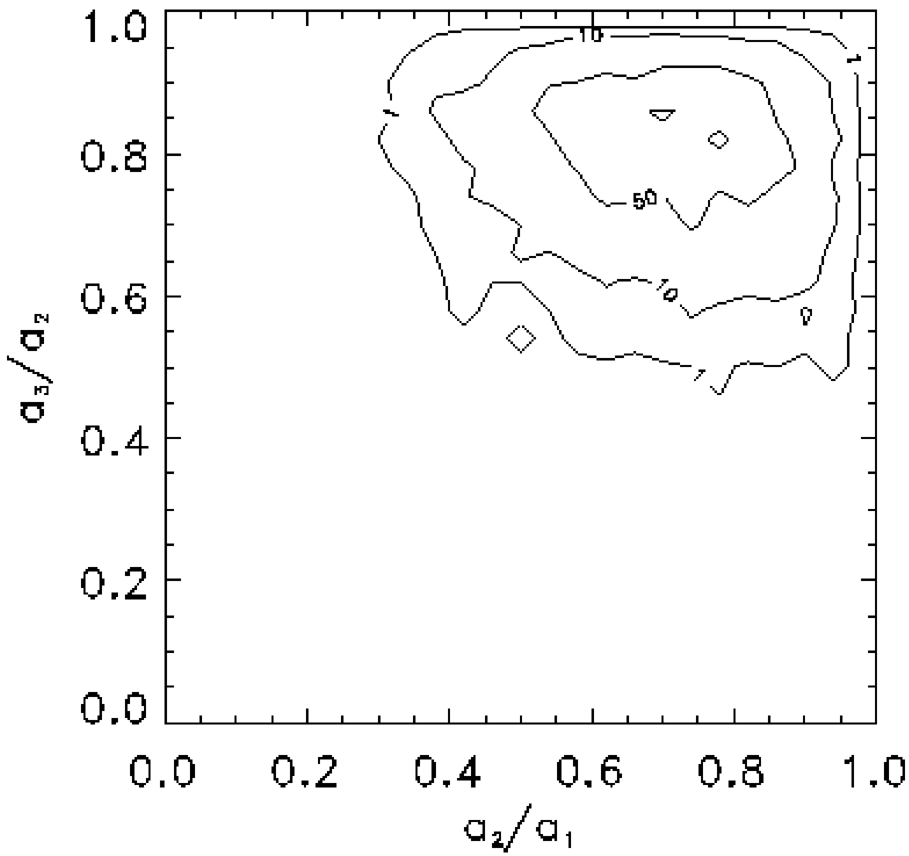
Shape of the voids



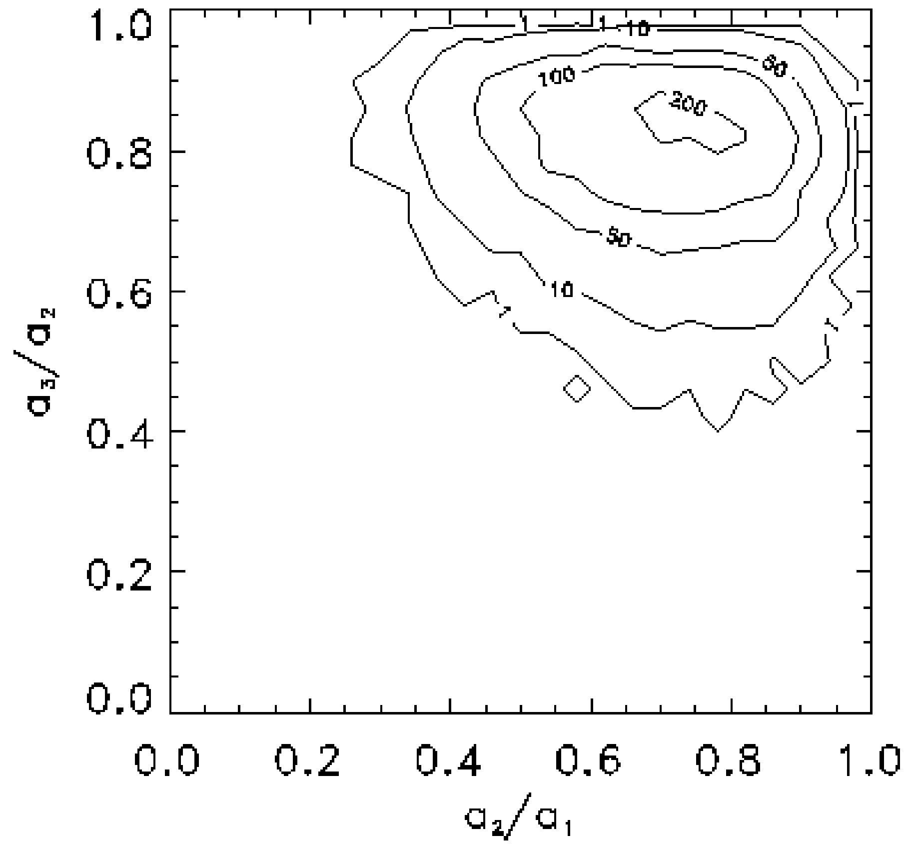
shape of the voids defined by objects with $M > 10^{12}h^{-1}\mathrm{M}_\odot$

- main axii $a_1 > a_2 > a_3$
- shown is the number of voids per bin (25 in each direction)
- shape of voids concentrated around $a_2/a_1 \approx 0.7$, $a_3/a_2 \approx 0.85$,

Does shape depend on selection criterion?

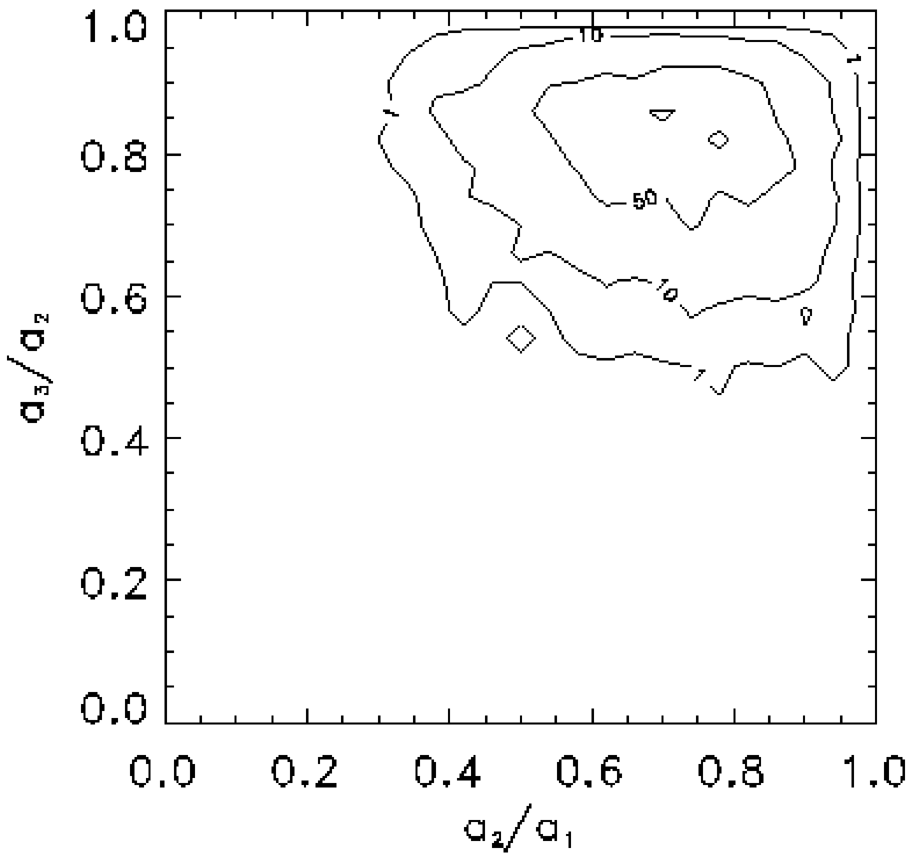


shape of the voids defined by objects with $M > 10^{12} h^{-1} \mathrm{M}_{\odot}$

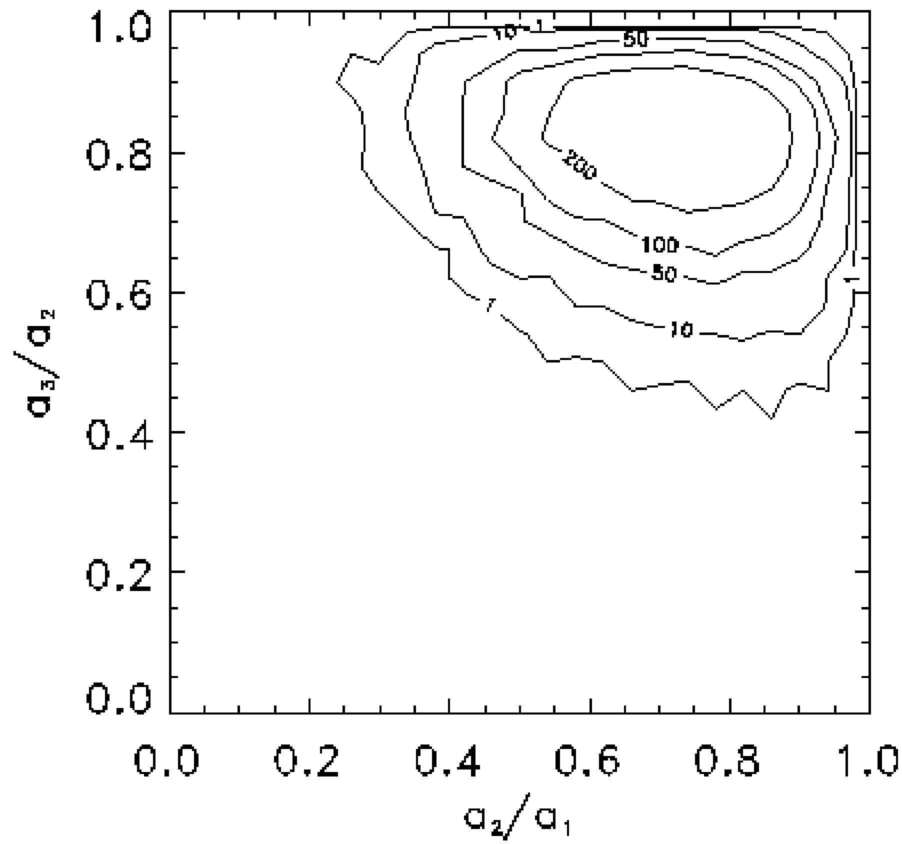


shape of the voids defined by objects with $M > 2 \times 10^{12} h^{-1} \mathrm{M}_{\odot}$

Does shape depend on selection criterion?

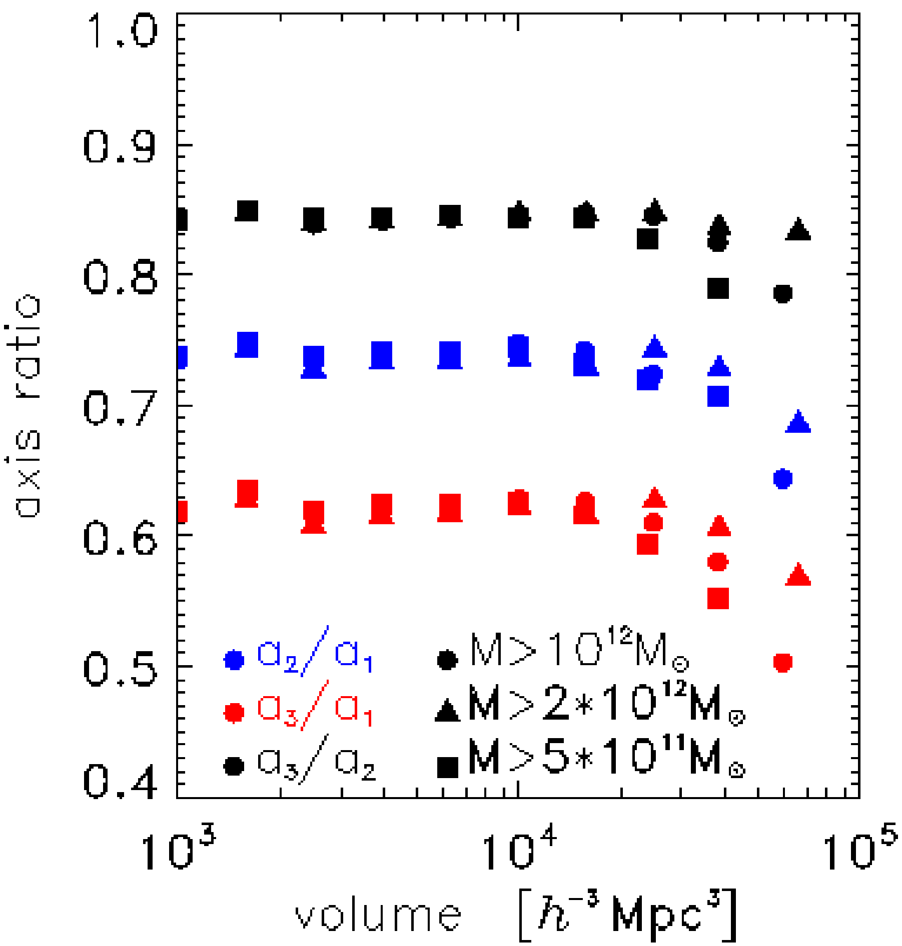


shape of the voids defined by objects with $M > 10^{12} h^{-1} \mathrm{M}_\odot$



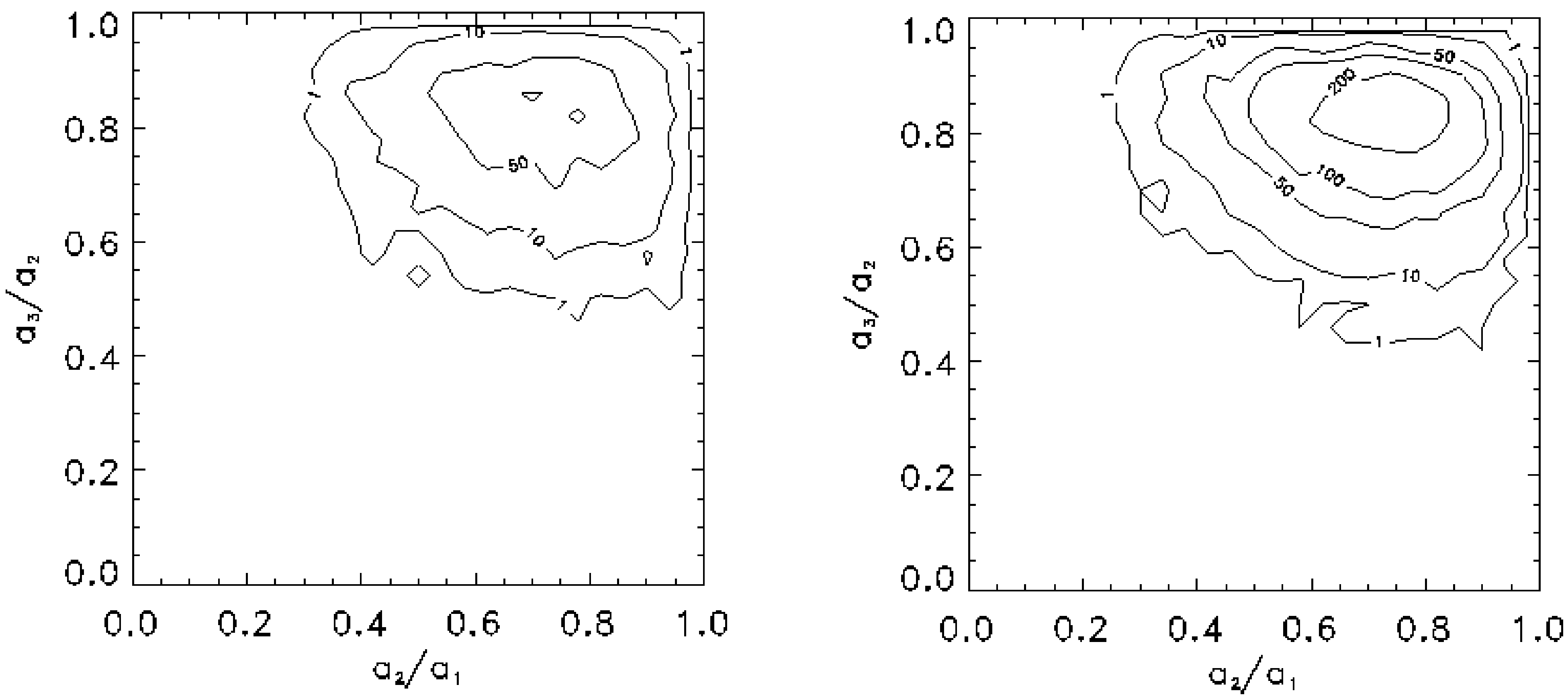
shape of the voids defined by objects with $M > 2 \times 10^{11} h^{-1} \mathrm{M}_\odot$

Does shape depend on size?



- main axii $a_1 > a_2 > a_3$
- shape of voids as a function of void volume
- circles, square and triangles denote different selection criteria

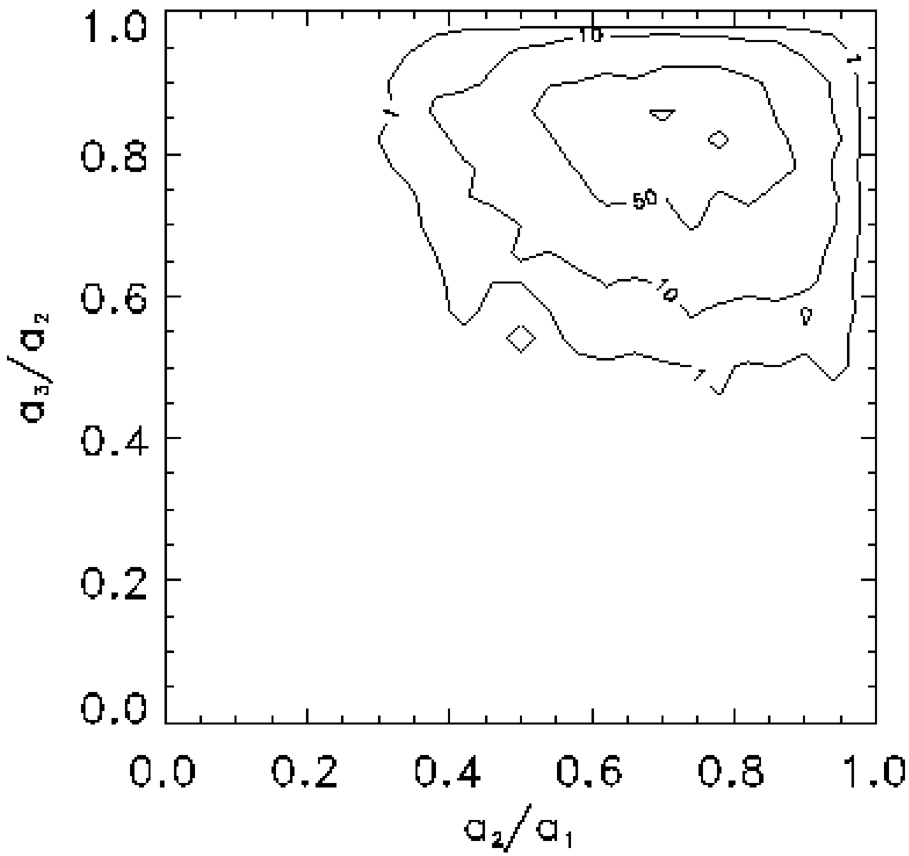
Does shape depend on time?

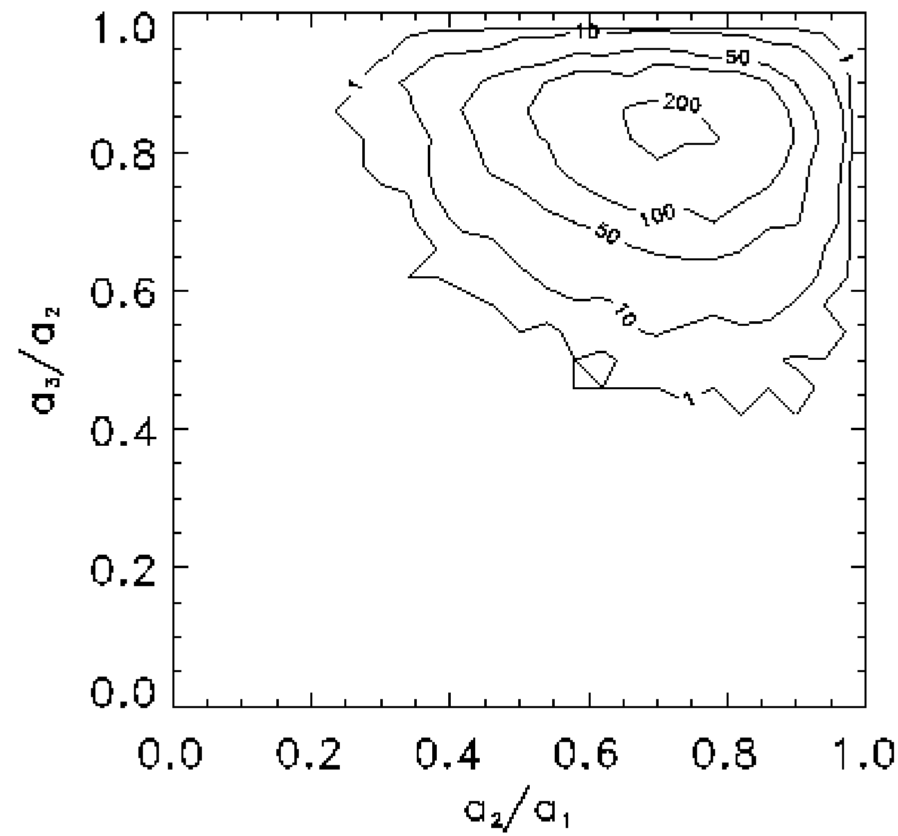


shape of the voids defined by objects with $M > 10^{12}h^{-1}\mathrm{M}_\odot$, $z = 0$

redshift $z = 1$

Does shape depend on time?

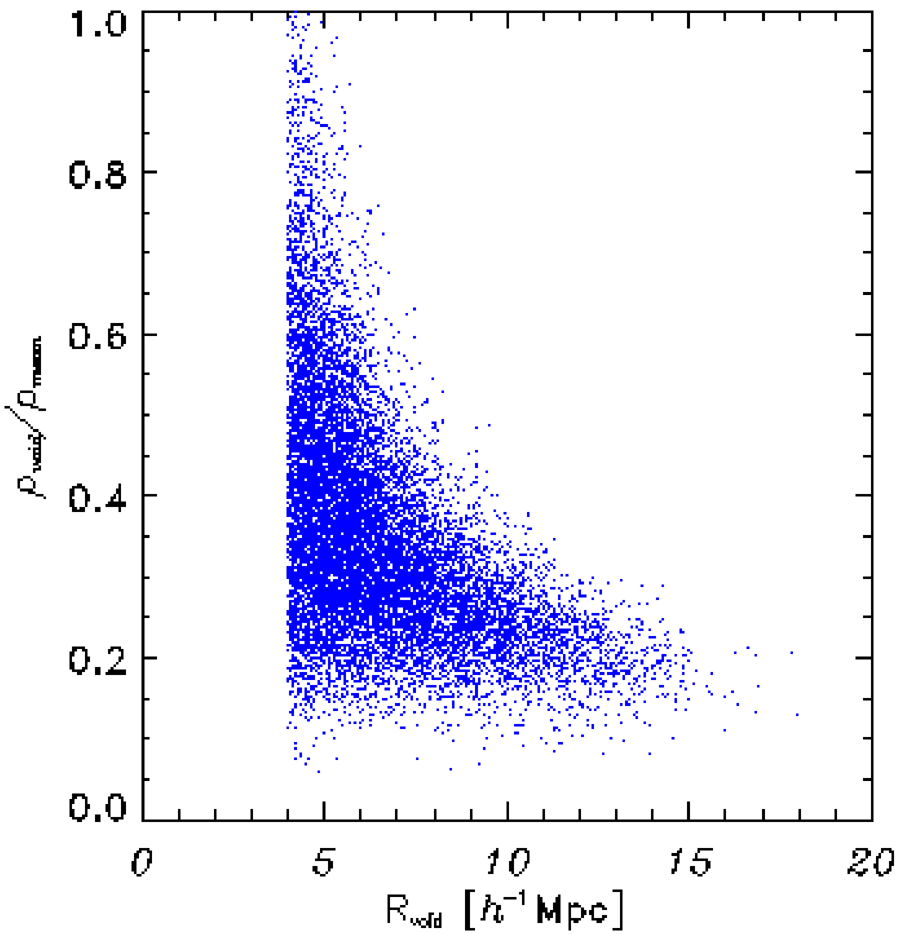




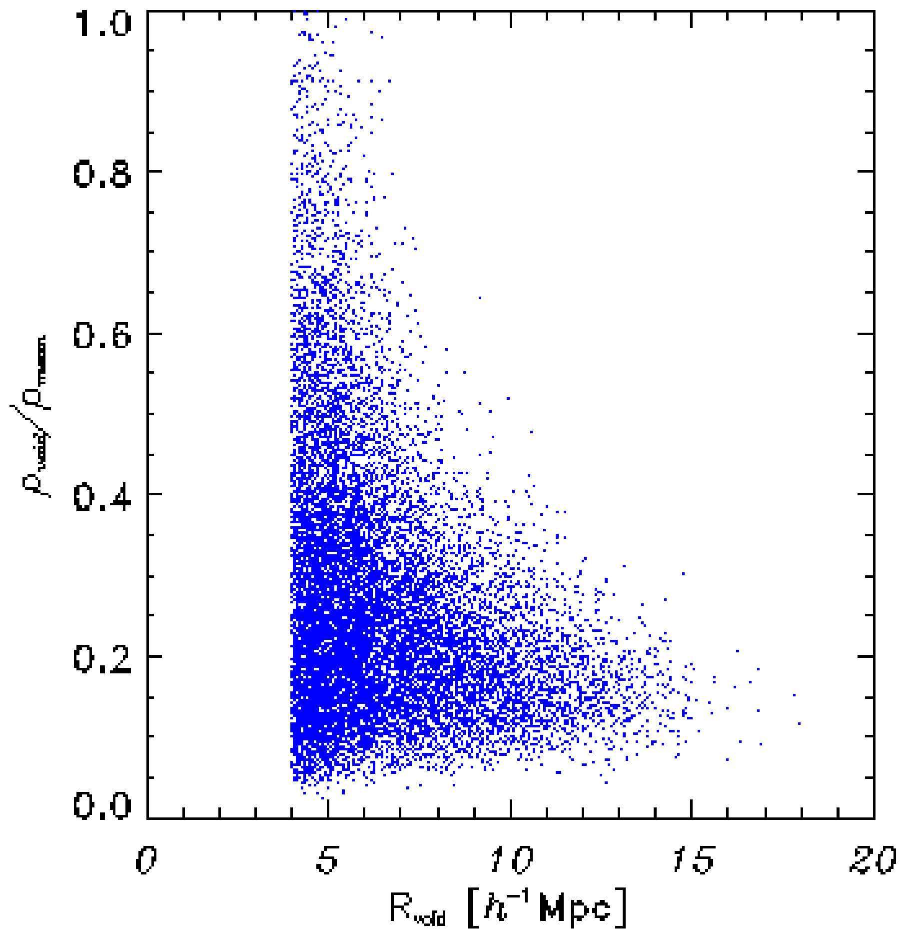
shape of the voids defined by objects with $M > 10^{12}h^{-1}\mathrm{M}_{\odot}$, $z = 0$

redshift $z = 2$

Density in voids



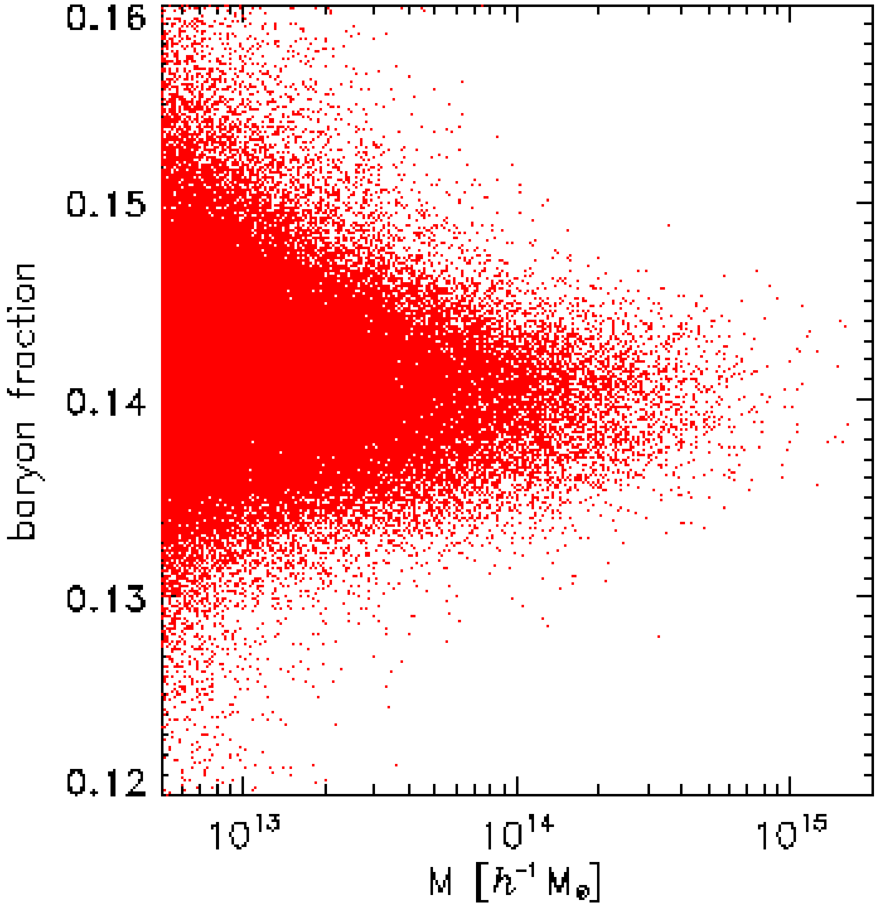
Mean density in the void.

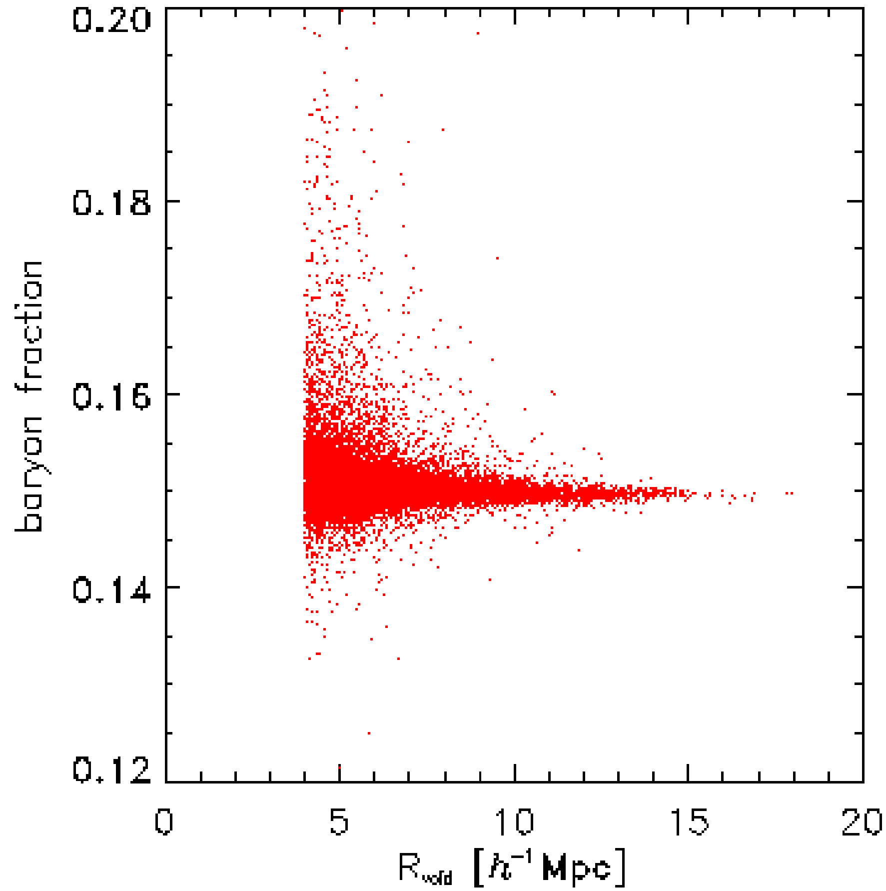


Mean density in the central 20 % of the volume ($0.58 R_{void}$).

Mean density in voids as a function of void radius.

Baryon fraction





Baryon fraction around halos within spheres of radius $2R_{vir}$

Baryon fraction in voids of radius R_{void}

The cosmic mean baryon fraction is 0.15.

Summary

The density in voids is by a factor of 10 smaller than the mean density, the density increases slightly with radius. The more massive objects are concentrated towards the outer regions of the void.

There are almost 100 objects with masses larger than 10^{10} $h^{-1}\mathrm{M}_{\odot}$ in a typical void of 20 h^{-1}Mpc diameter (and several hundreds with masses between 10^9 $h^{-1}\mathrm{M}_{\odot}$ and 10^{10} $h^{-1}\mathrm{M}_{\odot}$.

The mass function of halos in voids is steeper than the mean mass fuction in the universe.

Summary

Using a billion of gas particles and another billion of DM particles we have performed on MareNostrum (Barcelona) one of largest simulations of the evolution of large scale structure in the universe.

We discussed the identification of non-spherical voids, the void function, the shapes of the voids, and the baryon fraction in voids.

The shape of the voids is independent of the selection criterion.

The shape of the voids is almost independent of size.

The baryon fraction in voids scatters around the mean one (0.15).