# Popcorn Voids: towards another void definition

(work in progress)


**Dante Paz**

(IATE - OAC Córdoba, Argentina)

**Collaborators:**

Carlos Correa

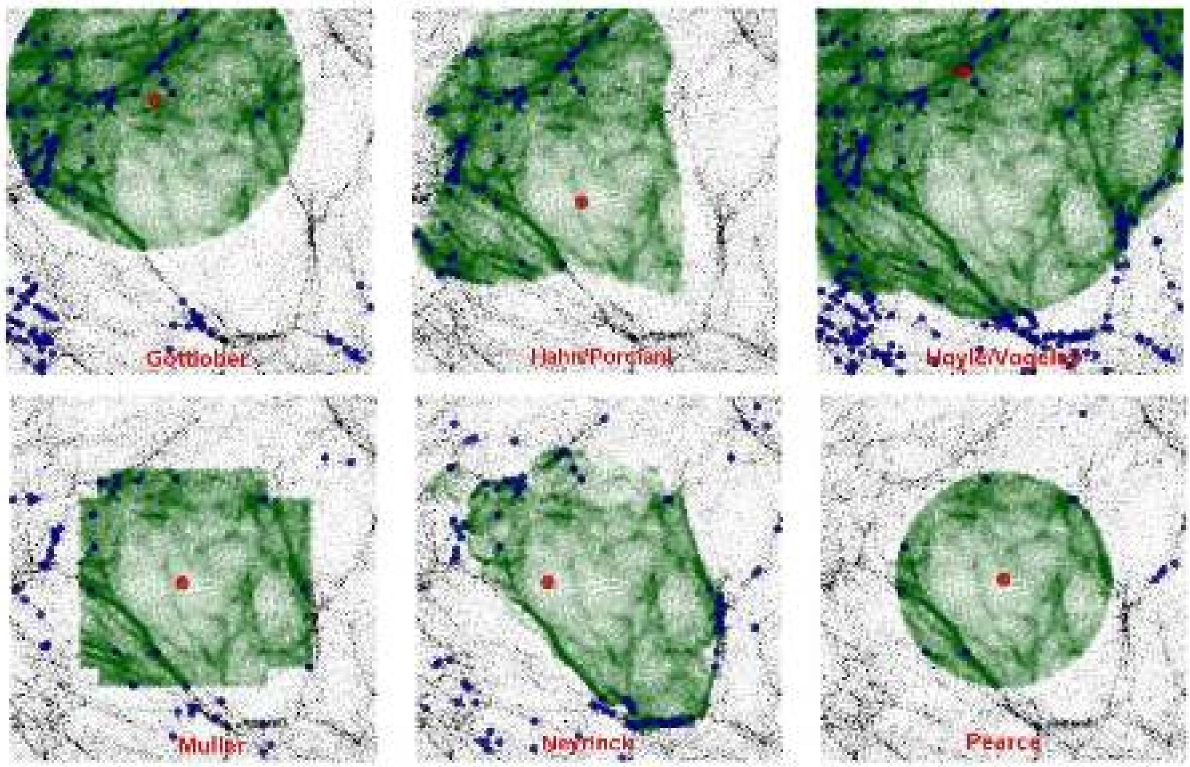
Andrés Ruiz

Marcelo Lares

(IATE-OAC)

# There is no unique way to define a cosmic void:

- Hoffman et al. 1982
- El-Ad & Piran 2000
- Padilla, Ceccarelli, Lambas 2005
- ZOBOV Neyrinck 2008 (e.g VIDE)… and many more...




Types of void finders:

- Integrated density (in mass or in halos)
- Using the diff. density field, by smoothing or tessellating the space
- Analyzing the dynamics (orbits, hessian matrix, grav. potential)

**The Aspen-Amsterdam void finder comparison project, Colberg et al. 2008**

depends on what you want to do...

# Why do we want to study voids?

- **Plenty of reasons:**
  - Curiosity: Obvious features of the LSS
  - Coherent velocity fields
  - Primordial environment to study galaxy formation
  - **They are sensitive to the cosmological model:**
    I. Matter content and growth rate (recall Carlos Correa talk)
    II. Dark energy models (e.g. Pisani et al. 2015)
    III. Modify gravity models (e.g. Cai, Padilla & Li 2014)
    IV. Neutrino mass (e.g. Massara et al. 2015)

  Mostly based on void-galaxy cross correlation and void abundance statistics

# Voids as cosmological laboratories

Void-galaxy cross correlation functions:

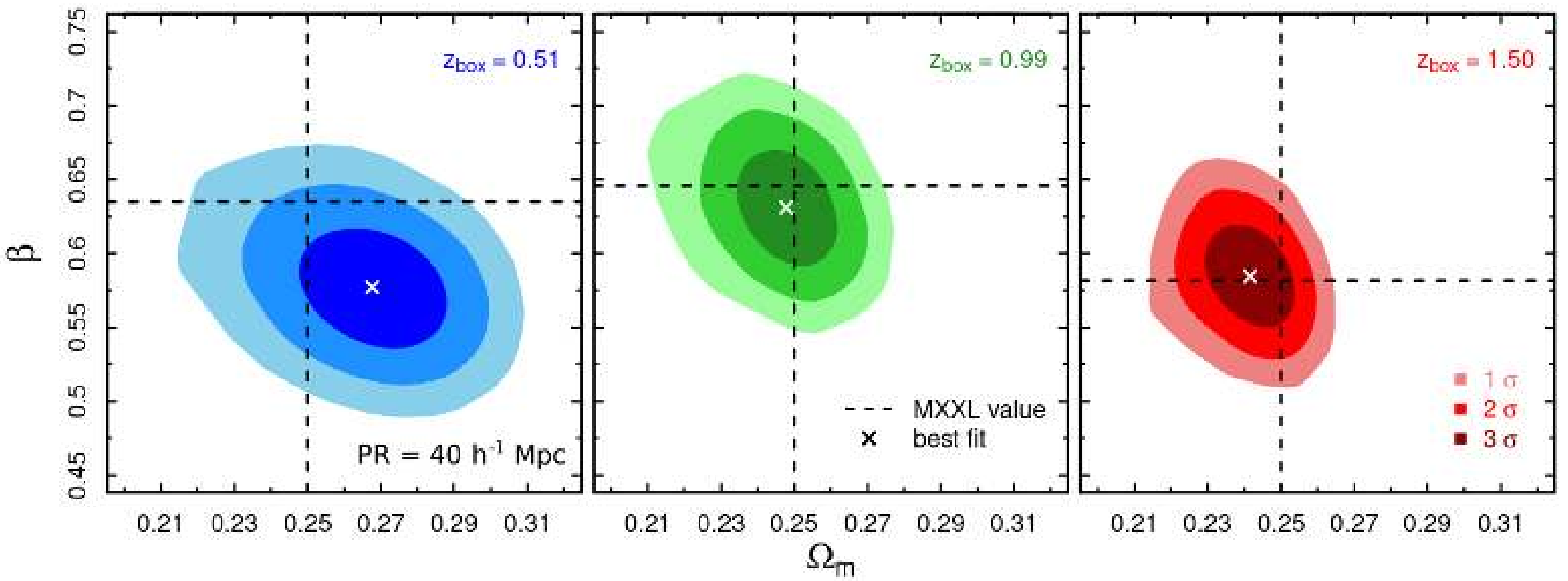



**Figure 6.** Marginalised likelihood distributions onto the $\Omega_m - \beta$ plane for the case PR = 40 $h^{-1}$Mpc for each MXXL snapshot. From the inner to the outermost, the coloured contour levels enclose $1\sigma$ (68.3%), $2\sigma$ (95.5%) and $3\sigma$ (99.7%) confidence regions. Dashed lines indicate the respective MXXL values, whereas the white crosses, the best fit values.

Correa et al. 2019 (MNRAS in press)

# Voids as cosmological laboratories

Void-galaxy cross correlation functions:

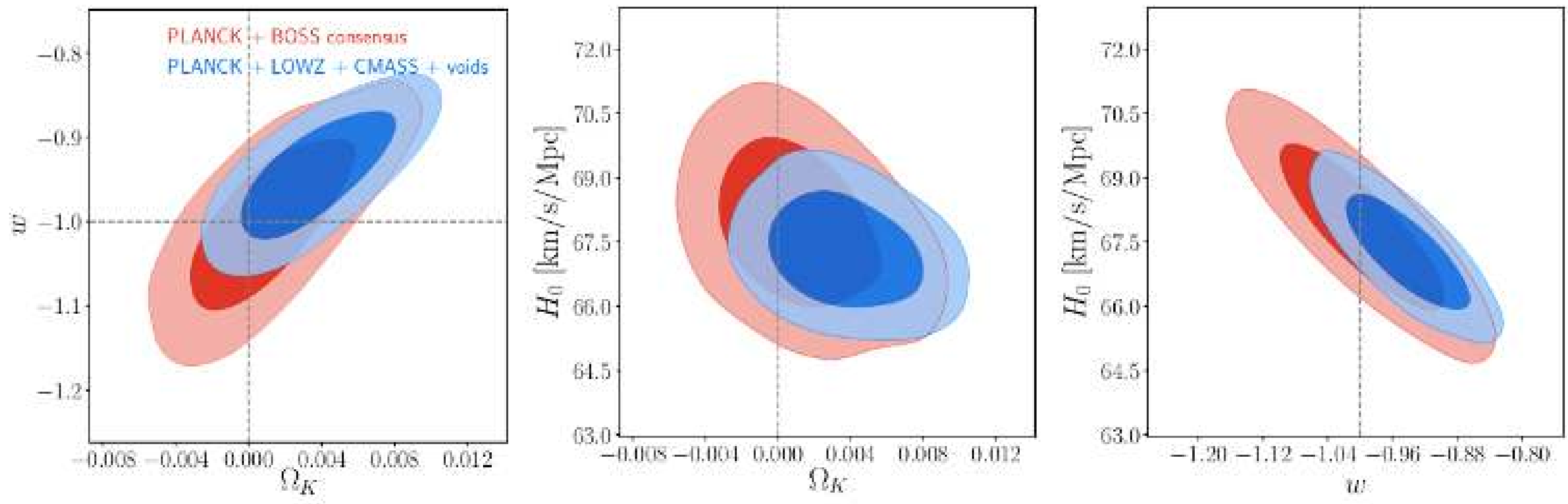



FIG. 16. Parameter constraints on the dark energy equation of state $w$, curvature $\Omega_K$ and Hubble constant $H_0$ in 2-parameter extension to the standard flat ΛCDM cosmological model referred to as $ow$CDM, comparing the results for the combination of Planck with BOSS consensus results [16] (red contours), and with the addition of the CMASS void results from this work (blue). Contours enclose 68% and 95% of the probability. The improved Alcock-Paczynski measurement provided by our void analysis significantly tightens constraints on dark energy and curvature in this class of models without the need for additional primary data.

Nadathur et al. 2019 (submitted 1 April )

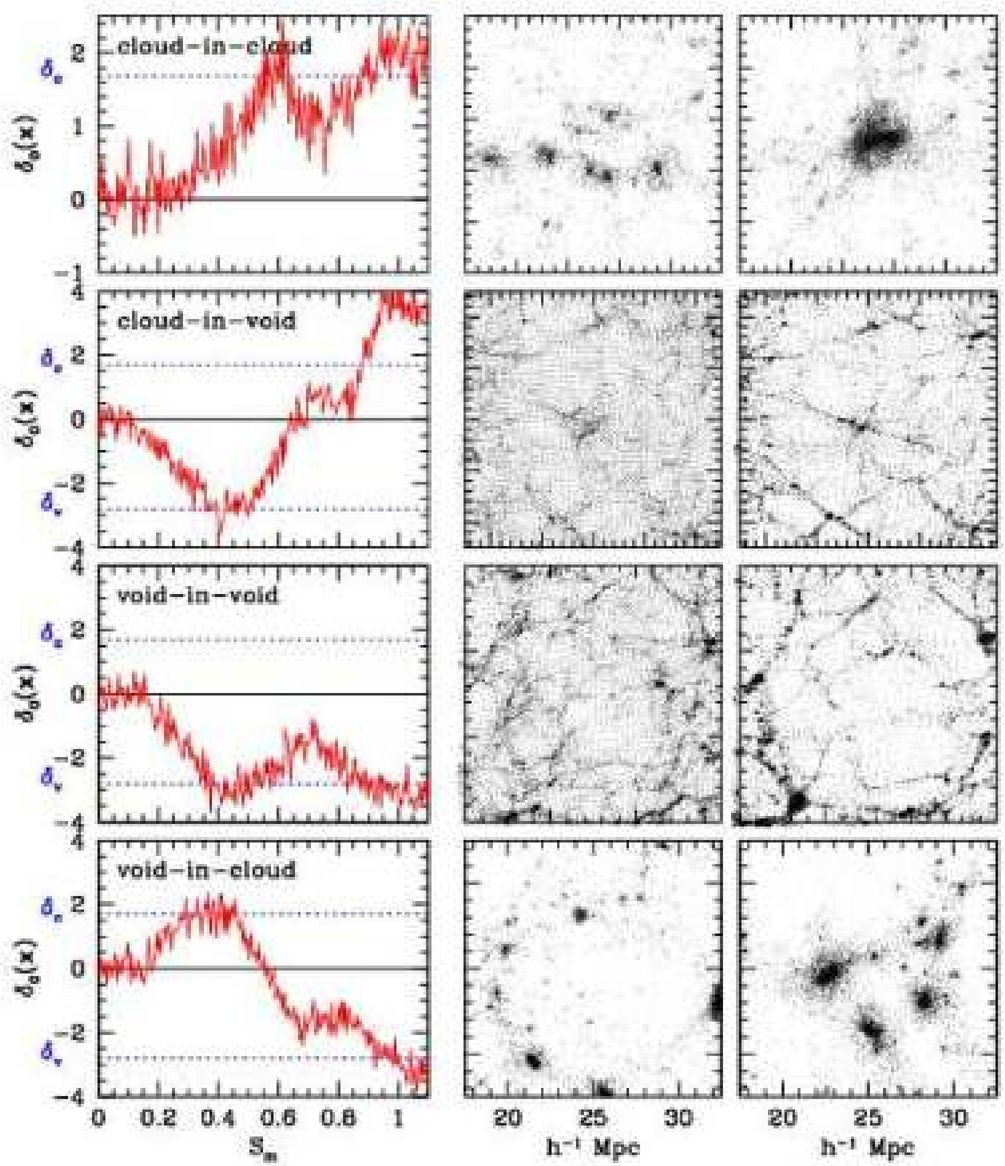
# Voids as cosmological laboratories

## Void abundance

### A hierarchy of voids: Much ado about nothing

Ravi K. Sheth[1] & Rien van de Weygaert[2]
[1] Dept. of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara St., PA 15260, U.S.
[2] Kapteyn Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Nether
Email: rks12@pitt.edu, weygaert@astro.rug.nl

SVdW model, 2003




- Excursion set theory can be used to predicts the void abundances (Markov process)
- The model depends on the cosmological parameters
- Works for voids defined over the mass
- Do not work properly for voids identified over biased tracers

$$\delta(x, R) = \int \frac{d^3k}{(2\pi)^3} \delta(k) W(k, R) e^{-ik\cdot x}$$

$$\sigma^2(R) = S(R) = \int \frac{dk}{k} \frac{k^3 P(k)}{2\pi^2} |W(k, R)|^2$$

# Voids as cosmological laboratories

## Void abundance

### The abundance of voids and the excursion set formalism

Elise Jennings[1*], Yin Li[1,2], Wayne Hu[1,3]

[1] The Kavli Institute for Cosmological Physics and Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, U. S.

[2] Department of Physics, University of Chicago, 5720 South Ellis Avenue, Chicago, IL 60637, U. S.

[3] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, U. S.

- The VdN model fits better voids on simulations than SVdW
- However the parameters for both models (VdN and SVdW) are largely affected by halo bias
- Assumes the conservation of the volume fraction at a given numerical density (not isolated voids)
- Fits ZOBOV once the sample is cleaned….

$$\mathcal{F}_{\rm L}(R_{\rm L}) = \int_{R_{\rm L}}^{\infty} \frac{{\rm d}r_{\rm L}}{r_{\rm L}} V(r_{\rm L}) \frac{{\rm d}n_{\rm L}}{{\rm d}\ln r_{\rm L}}, \qquad (15)$$

then this fraction is conserved if we define the non-linear abundance as

$$V(r)\,{\rm d}n = V(r_{\rm L}){\rm d}n_{\rm L}\Big|_{r_{\rm L}(r)}. \qquad (16)$$

VdN model, 2013

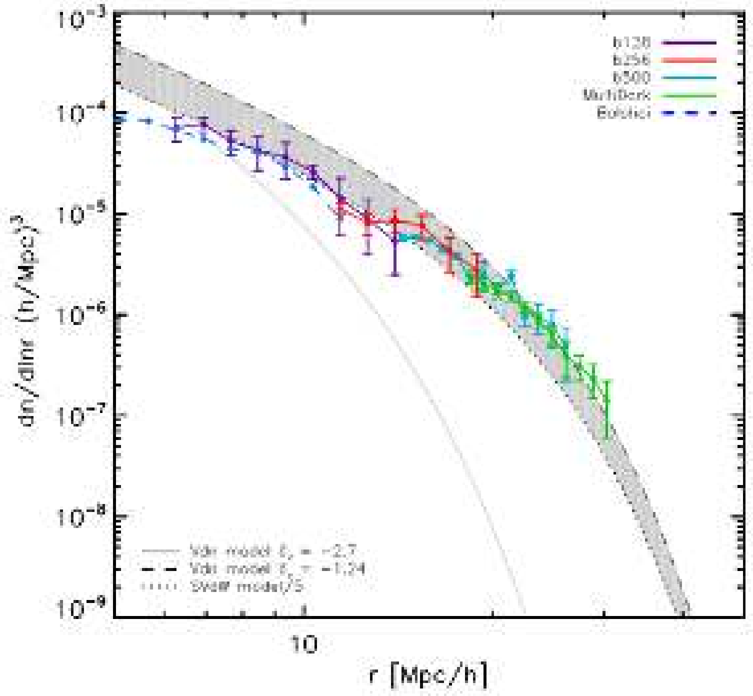



**Figure 10.** The number density of voids with $n_v = 0.2 n_h$ in the halo distribution from the 128 (purple), 256 (red), 500 (cyan) $h^{-1}$Mpc simulation boxes. The results from the MultiDark (Bolshoi) simulation are shown in dark green (blue). The error bars represent the error on the mean from eight simulations. The errors on the MultiDark simulation represent the Jackknife error on the mean. The grey shaded region bounded by the black dashed and dotted line represents the volume conserving model with $\delta_v = -1.24$ and varying amplitude as in Fig. 7. The grey solid line represents the Vdn model with $\delta_v = -2.7$.

# Zobov or Watershed vs. Spherical underdensity Voids

Padilla and friends...

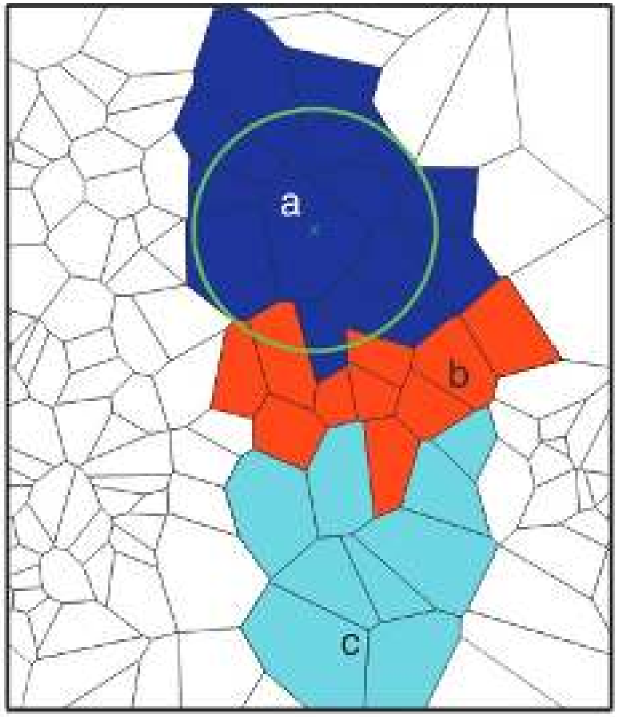



**Figure 5.** An illustration of a spherical void identified using the zones output from ZOBOV after Voronoi tessellation of the region. The Void # 1 output from ZOBOV given in Table 1 is shown as three shaded zones, *a* (blue), *b* (red) and *c* (cyan). The core particle of zone *a* is shown as a green cross while the void we identify in this region of a given density is shown as a green circle.

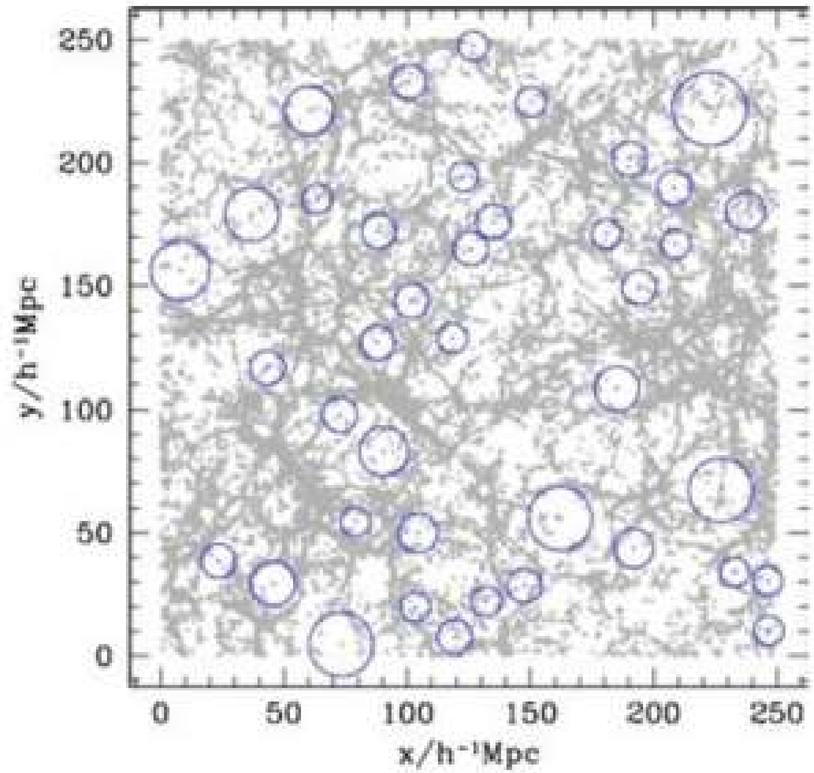



**Figure 1.** Slice of the numerical simulation box, corresponding to $100 < z < 110\,h^{-1}$ Mpc, showing the positions of semi-analytic galaxies (black dots) and voids found from the galaxy positions (grey dots). The circles indicate the spatial extent of the voids.

# Cosmological exploitation of cosmic void statistics

## New numerical tools in the CosmoBolognaLib to extract cosmological constraints from the void size function

Tommaso Ronconi[1,2] and Federico Marulli[2,3,4]

[1] SISSA - International School for Advanced Studies, via Bonomea 265, I-34136 Trieste, I
[2] Dipartimento di Fisica e Astronomia - Università di Bologna, viale Berti Pichat 6/2, I-40
[3] INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
[4] INFN - Sezione di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy

- CosmoBolognaLib is a friendly and useful library on C++ for a wide variety of cosmological and LSS analyzes.
- It has a cleaning module to filter void catalogs allowing comparison with models
- The cleaning on ZOBOV/VIDE is large
- When running over integrated density voids the cleaning algorithm keeps everything

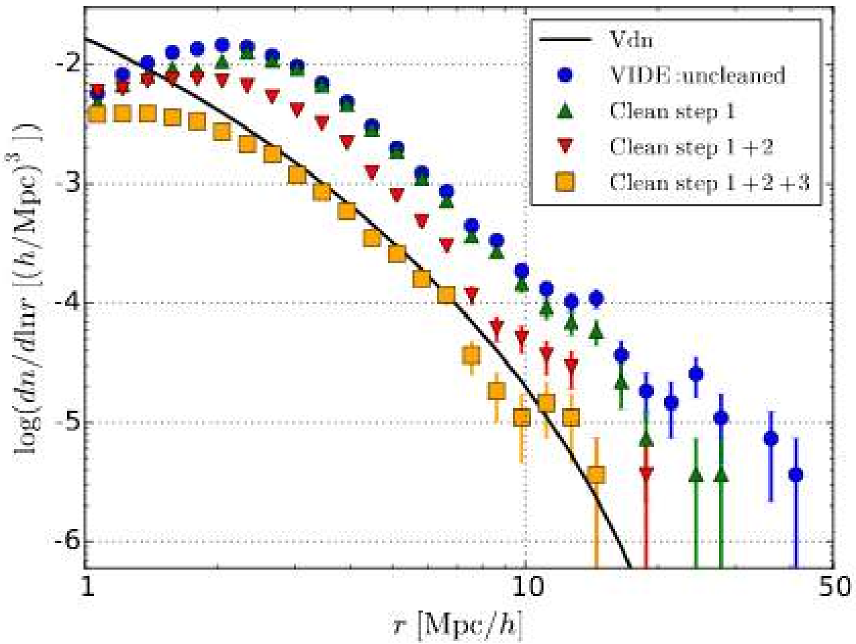



**Fig. 2.** The void size function at the different steps of the cleaning procedure. The blue dots show the distribution of voids detected by VIDE from a ΛCDM N-body simulation. The green triangles are obtained by applying both the $r_{min}$-$r_{max}$ criterion and the central density criterion (first step). The red upside-down triangles show the void distribution after having rescaled the voids (second step), while the orange squares are the final output of the cleaning algorithm in case the larger-favoured overlapping criterion chosen (third step) is the decreasing central density (for the density contrast criterion see Fig. D.1 in the Appendices). The black line shows the Vdn model prediction.

# Popcorn Voids: An improved non spherical (VdN friendly?) and integrated underdense regions (abundance theory friendly)

The Recipe:

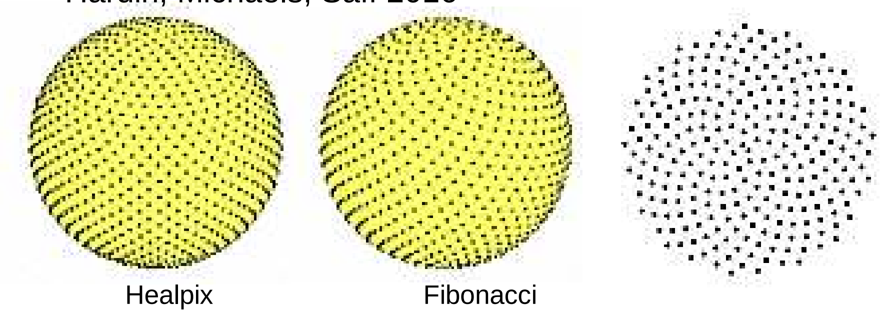
Ruiz et al. 2013: Spherical Voids (as Nelson's good friend)

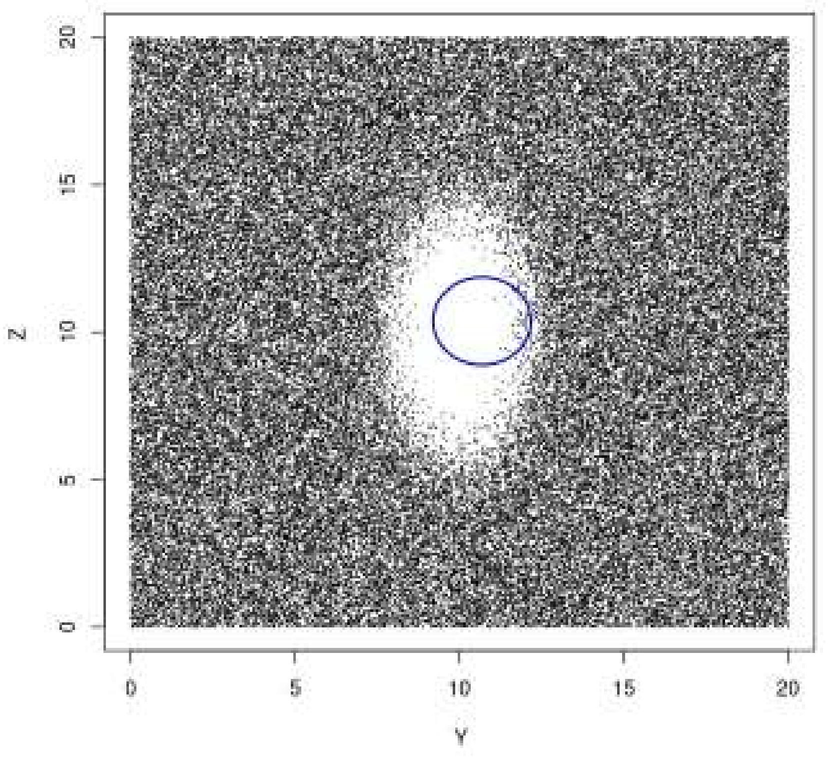
1) Maximal Sphere (maximum size, not overlapped)
   a) Seeded on low density Voronoi cells ($\delta < \delta_{seed}$).
   b) Radius increases up to a density threshold ($\Delta < \Delta_{lim}$).
   c) Random walking around center until converges
   d) Overlapping cleaning

The Popcorn correction: add more spheres to fill the void:

2) Over each Maximal Sphere we seed new spheres following a Fibonacci covering
3) Each seed is expanded again keeping only the largest one for which the join space of accepted sphere satisfy $\Delta < \Delta_{lim}$
4) The whole surface is covered again removing seeds inside the region.
5) The queue of seeds is visited depending on the sphere size of the root sphere
6) The process is repeated from 3) until no sphere could be expanded without satisfying $\Delta < \Delta_{lim}$ or its volume contribution is below certain threshold (5% to 10%)

Hardin, Michaels, Saff 2016




The popcorn is then a tree of spheres satisfying the criteria $\Delta < \Delta_{lim}$

# Grandma secret recipe: Computing the volume

- How to compute the volume of an arbitrarily system of spheres is not trivial (analytic formula only available for the case of 2 spheres).
- Montecarlo integration is expensive and imprecise.
- Luckily this was solved on the context of Chemistry:

ARVO: A Fortran package for computing the solvent accessible surface area and the excluded volume of overlapping spheres via analytic equations ☆

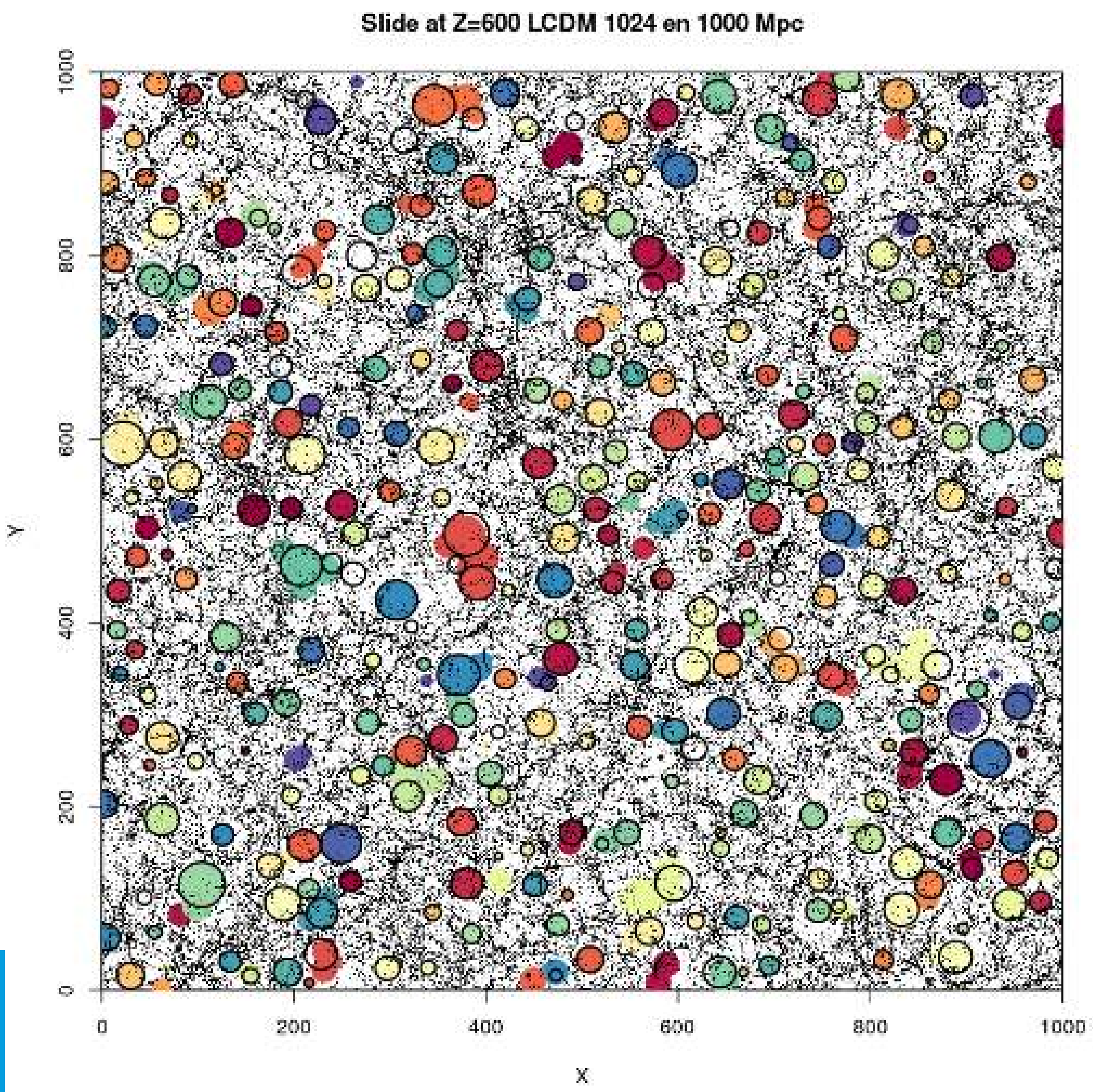
Ján Buša [a,b,c], Jozef Džurina [b,c], Edik Hayryan [a,c], Shura Hayryan [a], Chin-Kun Hu [a,*], Ján Plavka [b,c], Imrich Pokorný [b,c], Jaroslav Skřivánek [b,c], Ming-Chya Wu [a]

[a] *Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan*
[b] *Department of Applied Mathematics, Technical University in Košice, 040 01 Košice, Slovak Republic*
[c] *Laboratory of Computing Technology and Automation, Joint Institute for Nuclear Research, Dubna, Russia*

Received 25 September 2003; accepted 4 August 2004

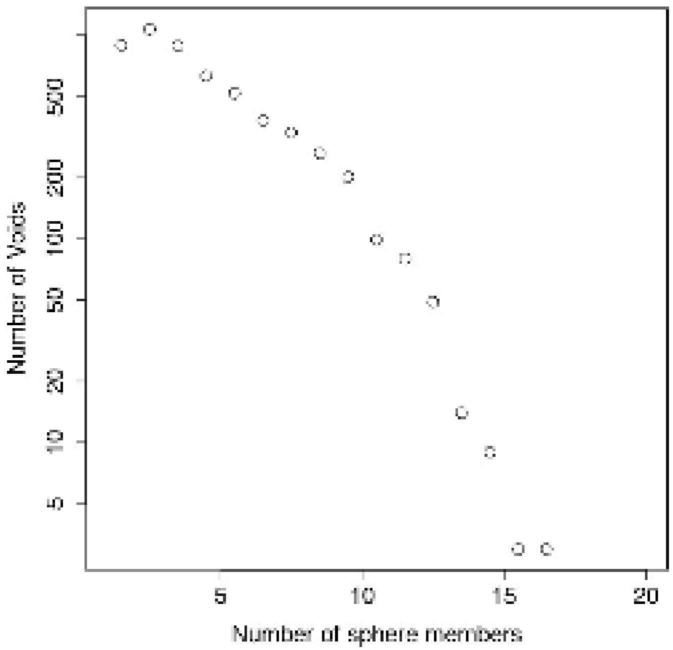
- These results were verified using montecarlo integration being 100x more faster and just limited by floating point precision.

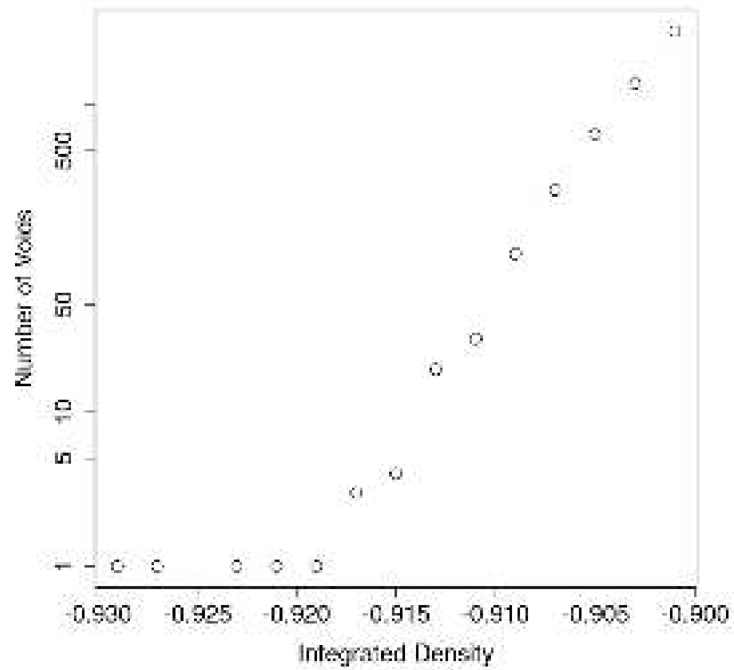
# Popcorn Voids vs. Spherical Voids

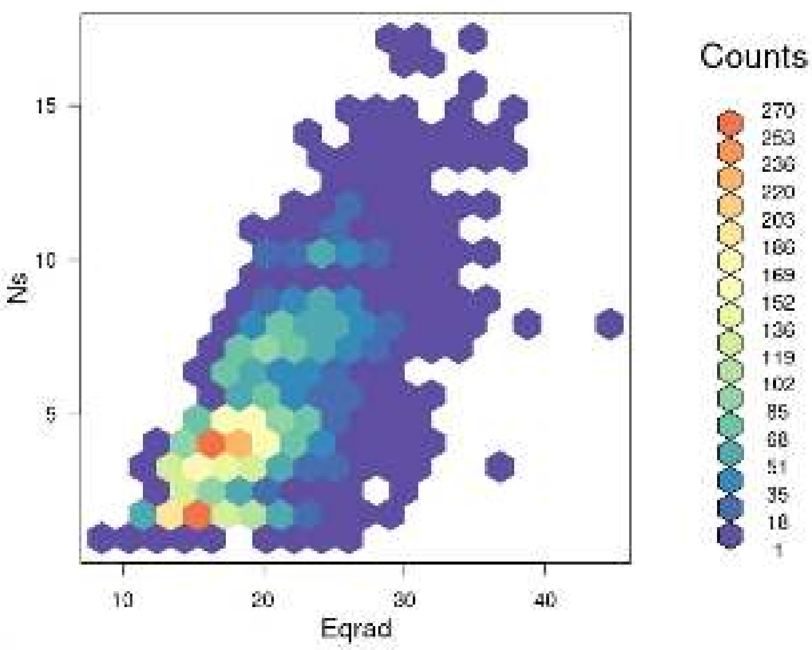


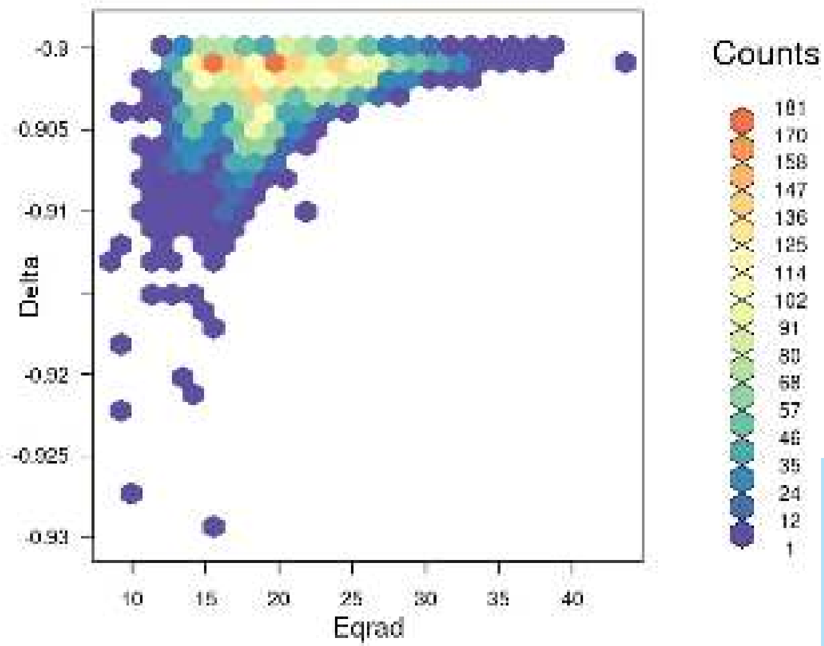

ID Parameters:
$\Delta < 0.9$
DM Halo mass > $10^{10}$
# Fibonacci seeds = 100
5% correction on volume

# Some characteristics of Popcorns:



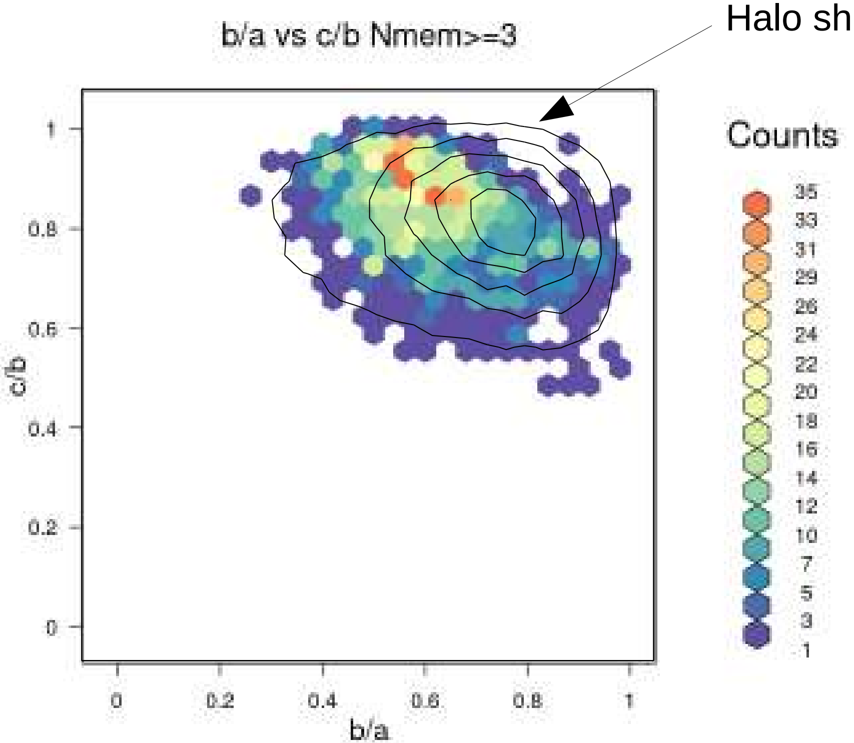



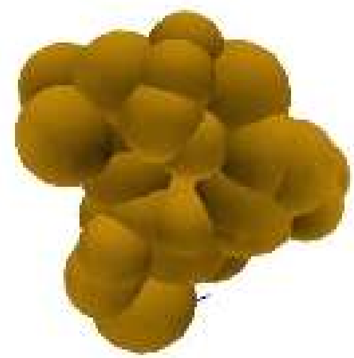



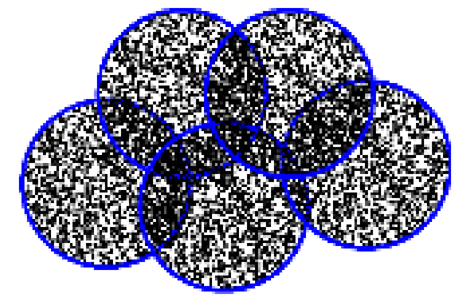
# The intrinsic shape of Voids (not AP or RSD):

Halo shapes isocontours



The shape is computed using a montecarlo approach:



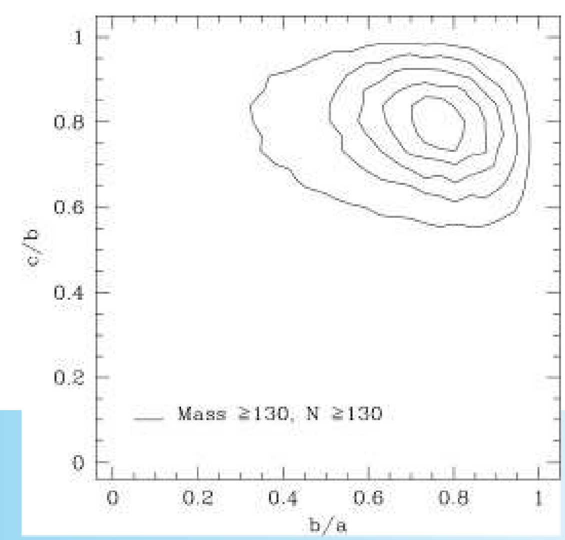
$$I_{ij} = \frac{1}{N_{\rm ran}} \sum_{r=1}^{N_{\rm ran}} X_i X_j m_r \qquad m_r = \frac{1}{N_{\rm sph}(X)}$$

They are more prolate than halos...

Bond & Myers 1996, The Peak-Patch Picture of Cosmic Catalogs:

The extremes (maximal or minimal) in a Gaussian field are prolate (Could this be used as another probe?)

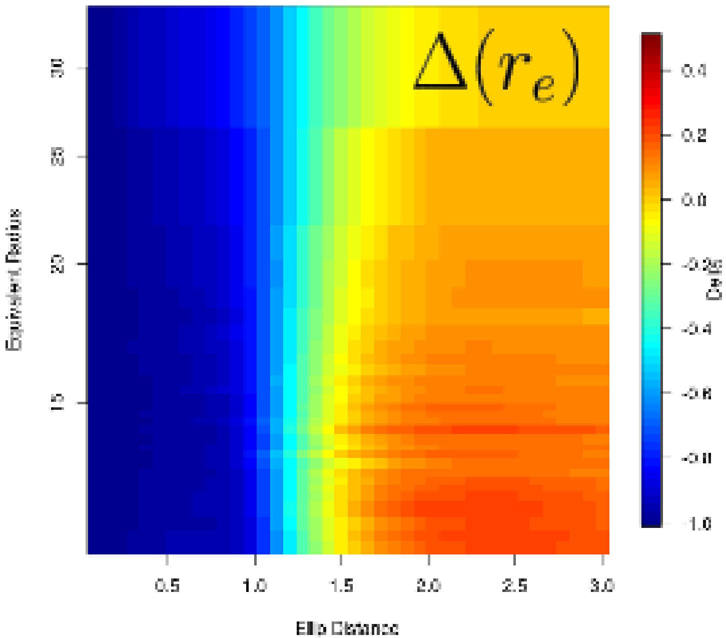
Halo shapes:

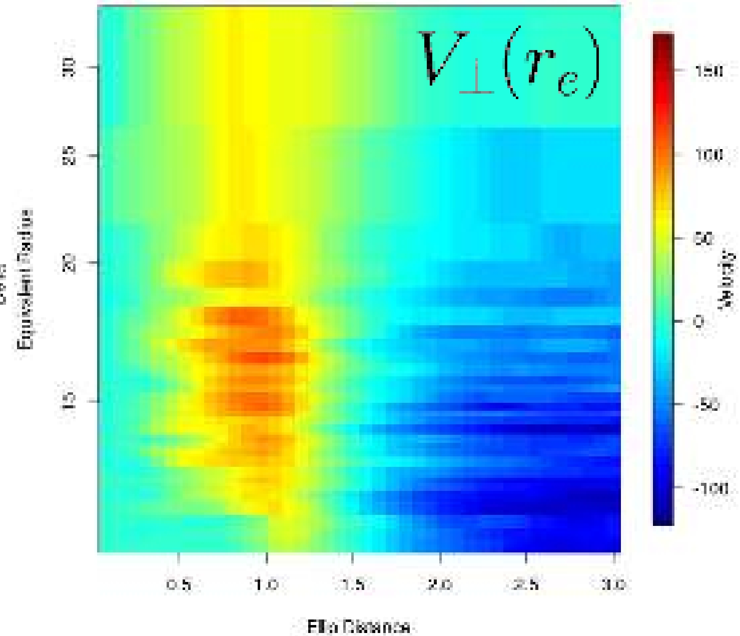



Paz et al. 2006

# Ellipsoidal profiles – Integrated density Δ and normal velocity $V_\perp$

Void in Cloud (S-type, Ceccarelli et al. 2013) →



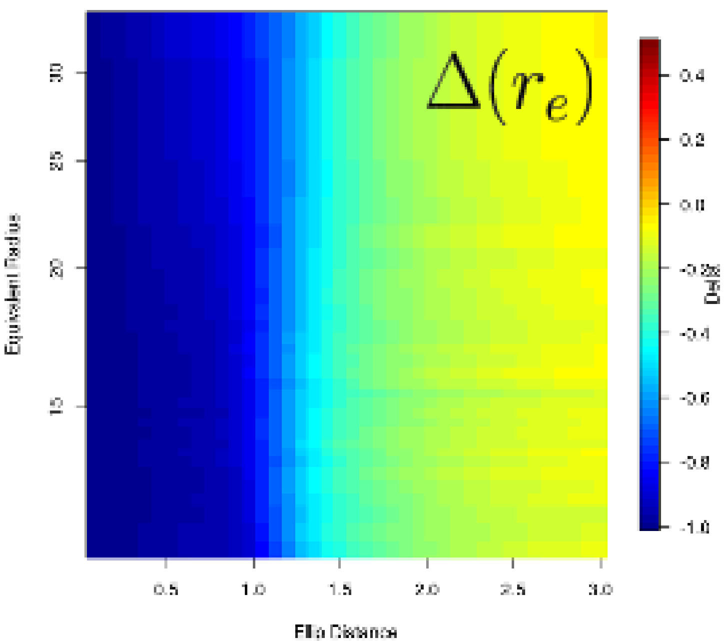



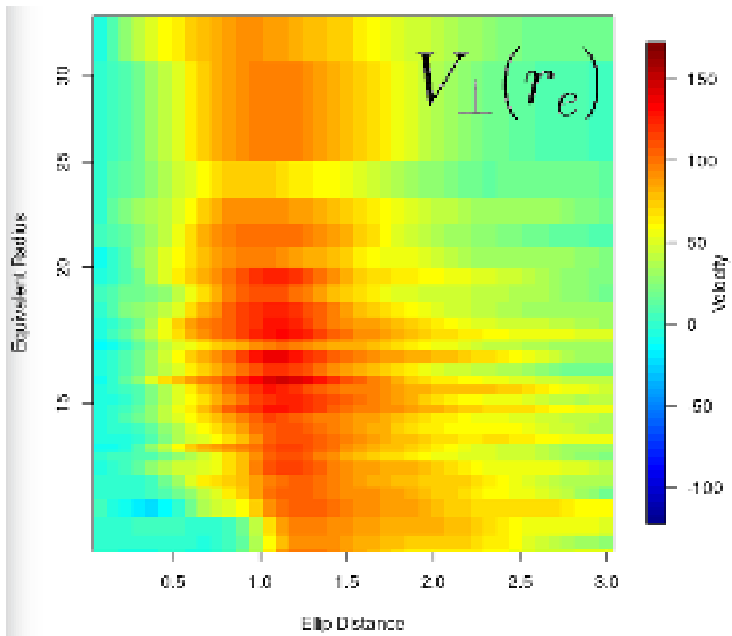

Ellip. Distance:

$$r_e^2 = \left(\frac{\hat{a}\cdot\vec{r}}{a}\right)^2 + \left(\frac{\hat{b}\cdot\vec{r}}{b}\right)^2 + \left(\frac{\hat{c}\cdot\vec{r}}{c}\right)^2$$

Equivalent Radius:

$$R_{eq} = \left[3\,\frac{V_{pop}}{4\pi}\right]^{\frac{1}{3}}$$

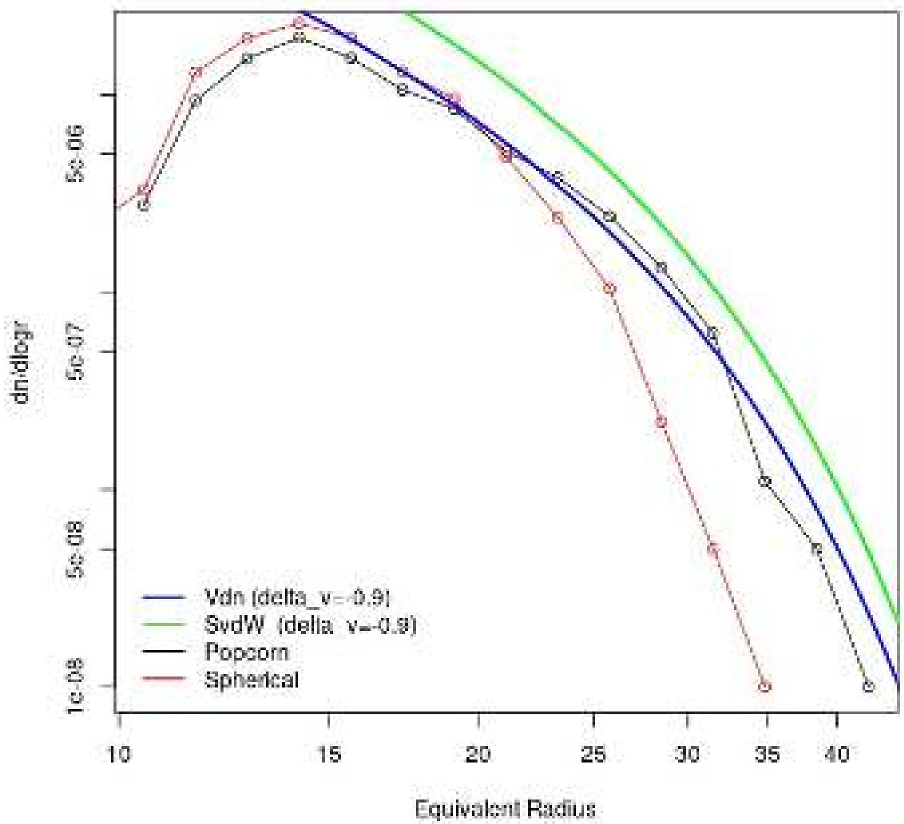


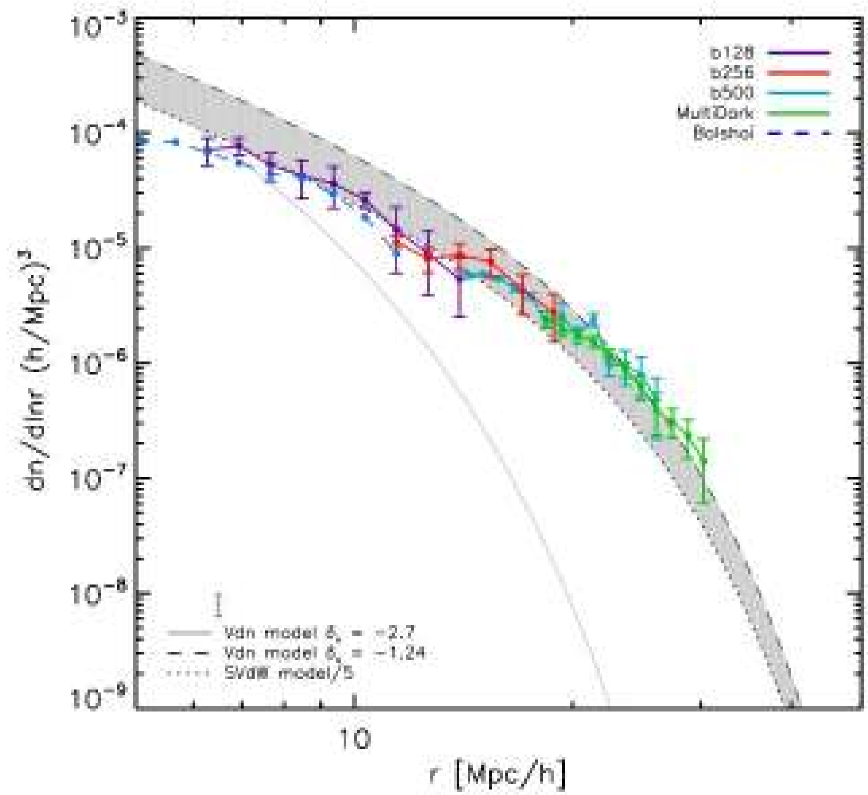

← Void in Void (R-type)

# Popcorn and spherical void abundances on biased tracer samples

This work ($\Delta < 0.9$) Halo mass > $10^{10}$



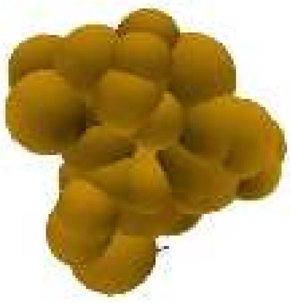

Jennings 2013 ($\Delta < 0.8$) Halo mass > $10^{12}$




Preliminary results seems promising (at least for me)….
a proper modeling of halo-void bias is needed

# Conclusions:

- The use of voids as cosmological probes is not only potential is a reality
- Void galaxy cross correlation probes have some systematic errors (recall Carlos talk) however they are now been used on real data
- In contrast, studies of the abundance face serious problems due to the bias effect on theoretical modeling
- Geometrical and dynamical distortions on abundance measurements are correctly assessed (Correa et al. in preparation)
- Integrated density void finders seems to relate more naturally with the models
- However assuming spherical shape produces some deviations from models like VdN
- Our new void definition have the potential to describe more accurately abundances while recovers other sources of information like the void shape.



- However our work is in progress (tons of to-dos)