A cosmological test using the abundance of Popcorn voids

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Cosmology from Home - 2023

Work in collaboration with:
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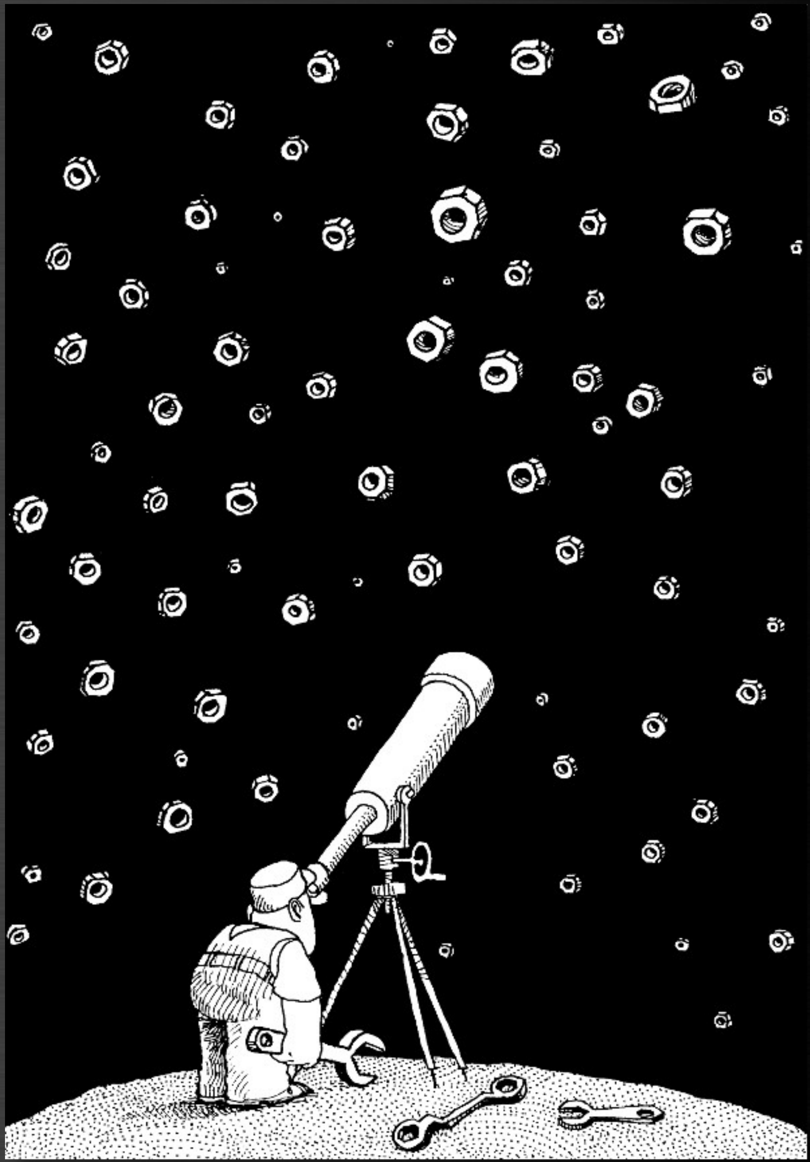
astro-ph> arXiv:2212.06849
MNRAS, 522, 2, 2553



Quino (1987) – “Dejenme inventar”

CONICET

UNC Universidad Nacional de Córdoba

I A T E

OAC Observatorio Astronómico de Córdoba

Tests for cosmological parameters in precision cosmology era

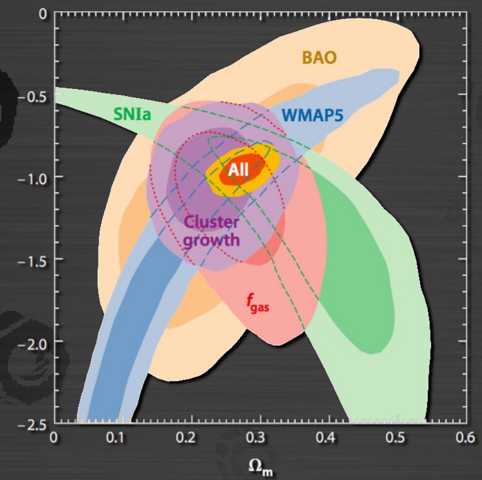
There are several probes:

- Hubble diagram, supernova,
  Light elements abundance
  Cosmic shear (lensing)
  Lyman-α Forest
  Gunn-Peterson trough
  CMB Anisotropy

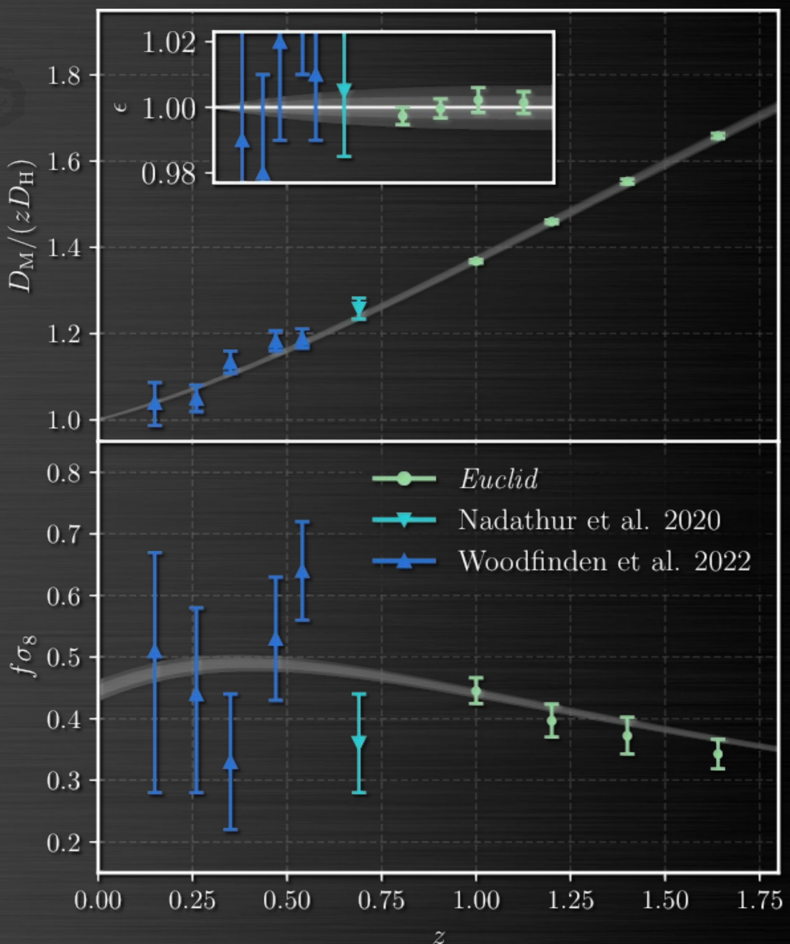
- More than a decade of precision cosmology shows the combination of different probes is the key

- Test based on Large Scale Structure (LSS, i.e. galaxy distrib. at Mpc scales)
  - Baryon Acoustic Oscillation
  - Galaxy clusters
    (abundances and mass to light ratios)
  - Cosmic Voids
    (abundances and galaxy cross-correlations).
    They seem to be more precise than BAO, but are affected by systematic errors

Allen et al. 2008



Euclid Voids Forecast: Radinović et al. 2023



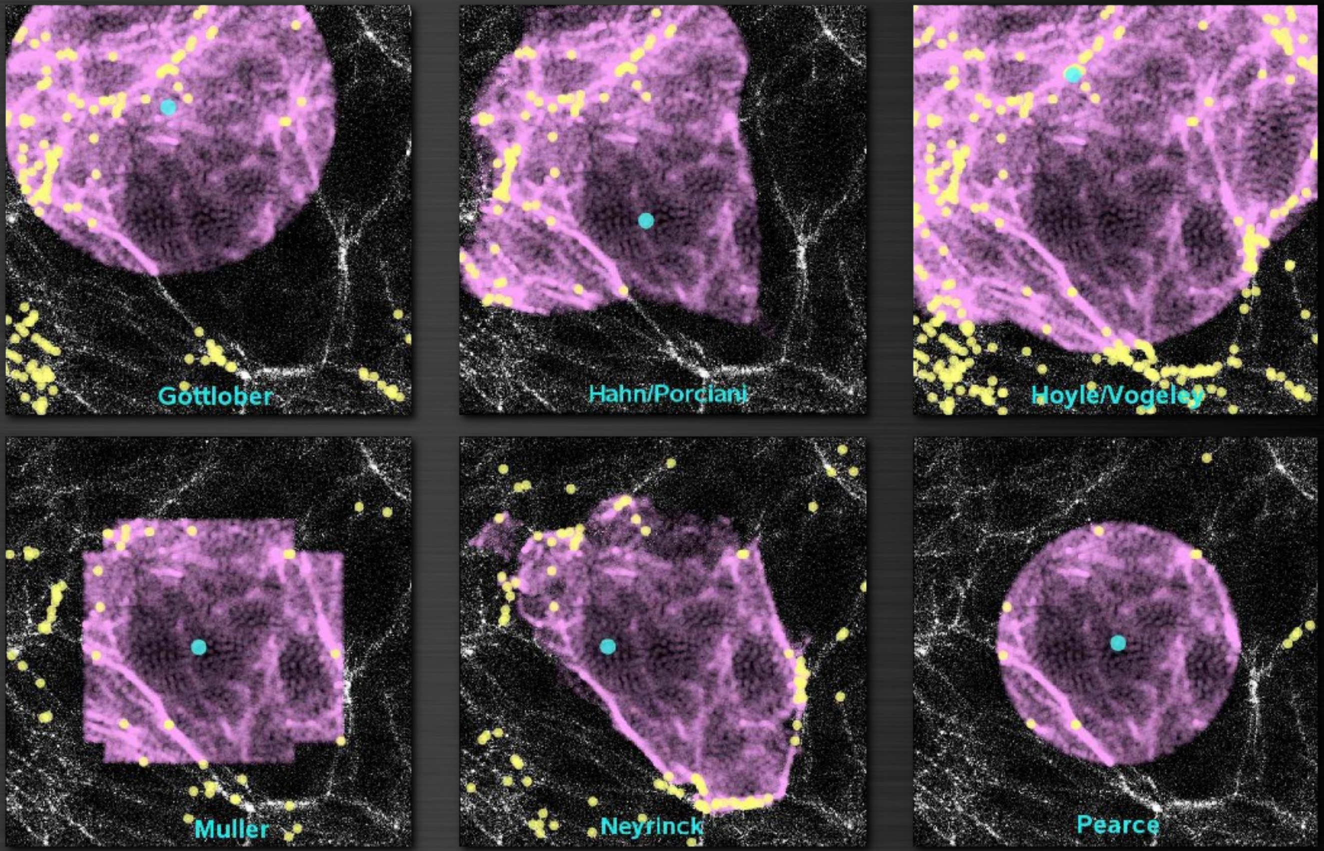
What is a Cosmic Void?

- Voids are underdense regions in the LSS. There is no unique way to define them.

Types of definitions:

- Estimating $\rho(\vec{x})$ by smoothing or tessellating the space (filament detection, watershed transform, etc.)
- Analyzing the dynamics (orbits, hessian matrix, grav. Potential)
- Integrated density $\Delta < \Delta_v$ (by assuming a shape)

$$\Delta = \frac{1}{\bar{\rho}} \int_V \rho dv - 1$$



Colberg et al. 2008

The choose of a void definition depends on the specific analysis for which the voids are intended.

Once you define voids an identification method or void finder is set

Voids as cosmological laboratories

There are 3 types of probes proposed in the community using Voids:

- Cross-correlation with galaxy tracers (VGCF):
  - Linear theory + Gaussian streaming can be used to fit VGCF (Paz et al. 2013, Correa, Paz, et al. 2019) and depends on params
  - VGCF is a function of the comoving scale, can be used in an Alcock Paczynski test (AP)
- Void intrinsic ellipticities (Park & Lee 2007): Intrinsic shapes of voids depend on the cosmological model
- Statistics of its abundance, or void size function (VSF):

$$A_{\rm v}(R_{\rm v}) = \frac{d\mathrm{n}_{\rm v}}{d\ln R_{\rm v}}$$

- Can be derived from cosmological model using excursion set theory then its shape depends on cosmo-params (Sheth & van de Weygaert 2003, SvdW, Jennings et al. 2013, Vdn).
- VSF is a function of comoving scale, it can be used in tomographic bins to measure the geometry of universe (test AP: Correa, Paz, et al. 2021)

Voids as cosmo labs

The main problem: Systematic errors!

- Redshift space distortions
  - VGCF is greatly affected by RSD (Paz et al 2013, Correa, Paz, et al. 2021, 2022)
- Galaxy bias
  - The VGCF and VSF modelling has become challenging due to the bias of the galaxy distribution respect to the matter field behaves differently than in other LSS environments (Polina et al. 2017, 2019).
- Void definition/identification (this work, Paz et al 2023)
  Are common void finders optimal for use in cosmology?
  In the case of VGCF and VSF we have some problems:
  - Fragmentation (multiple objects in a single region)
  - Integrated density estimation
    (abundance theory and RSD requires a well defined total matter density of the region)

The spherical void finder

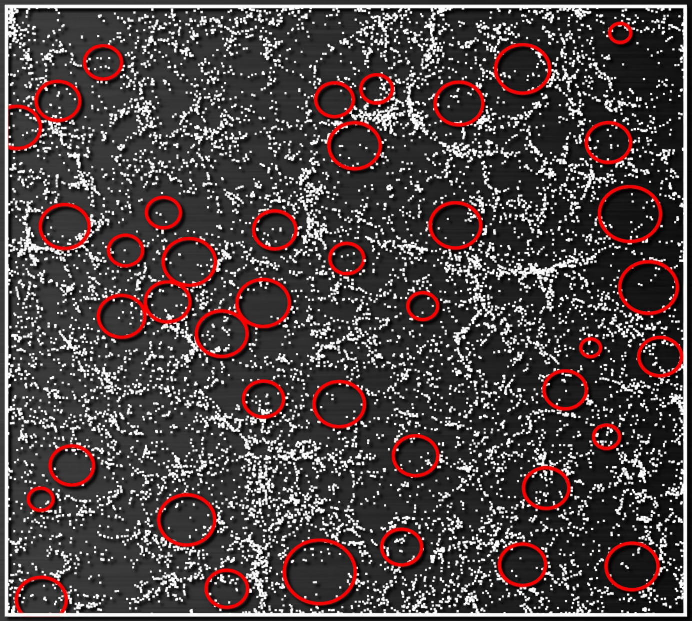
- Voids are defined as spherical underdense regions (SV)

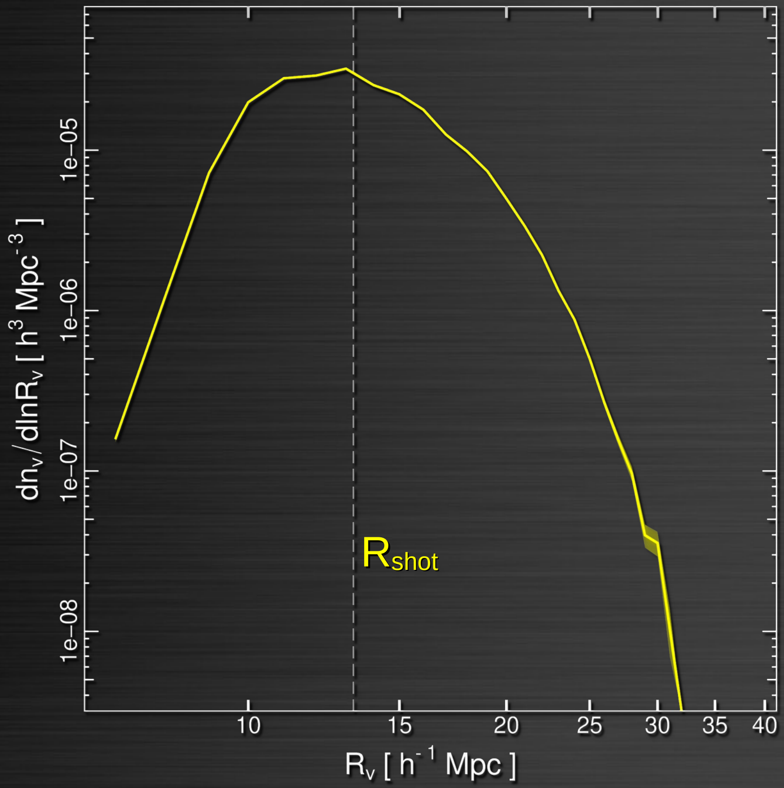
  (Padilla et al. 2005, Ruiz et al. 2015)

  - The algorithm selects centers in low-density regions and grows spheres until the density crosses a barrier $\Delta < \Delta v$

$$\Delta = \frac{1}{\bar{\rho}} \int_{S_R} \rho dv - 1$$

  - After this, the algorithm rejects all overlapping spheres favoring the largest candidates, starting with the largest sphere and eliminating the smallest ones.





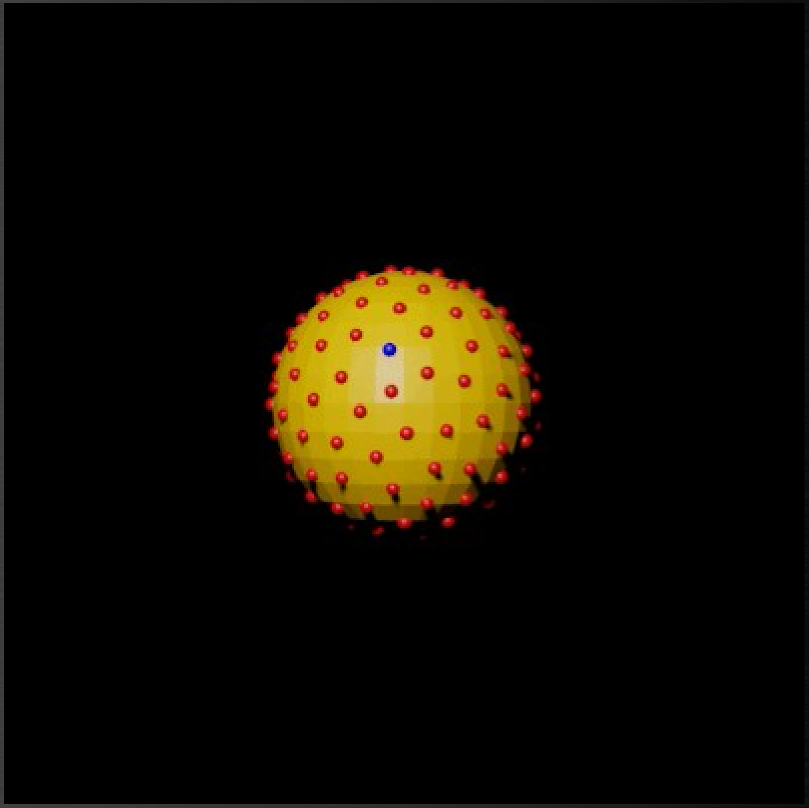
- In ΛCDM, it is expected that the void abundance follows a similar behaviour to that of a Schechter function.
- At smaller scales, the lower abundances are dominated by shot noise.
- The radius of the most frequent SV is a transition scale from the shot noise dominance to the real distribution, which we will define as R_{shot}

The popcorn void finder, the recipe:

1) Run the spherical void (SV) finder and measure R_{shot}
2) Recursively add correction spheres to SVs
   I. Cover regularly the surface of the popcorn candidate with seeds.
   II. Expand each seed to the largest radius that the condition $\Delta < \Delta_v$ allows in the joint volume.
   III. If the radius is smaller than R_{shot} the sphere is discarded.
   IV. The most larger seed is accepted and covered by seeds, now the popcorn have a new sphere member.

   The process is repeated since step I until no new member can be added

   V. Remove all overlapping Popcorn voids keeping those expanded from the larger SV



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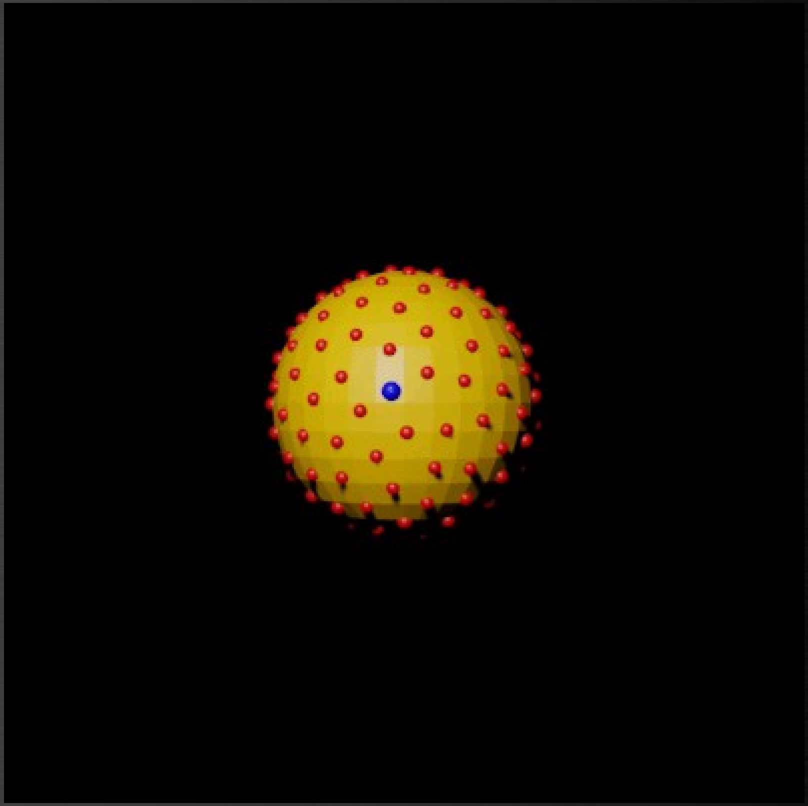

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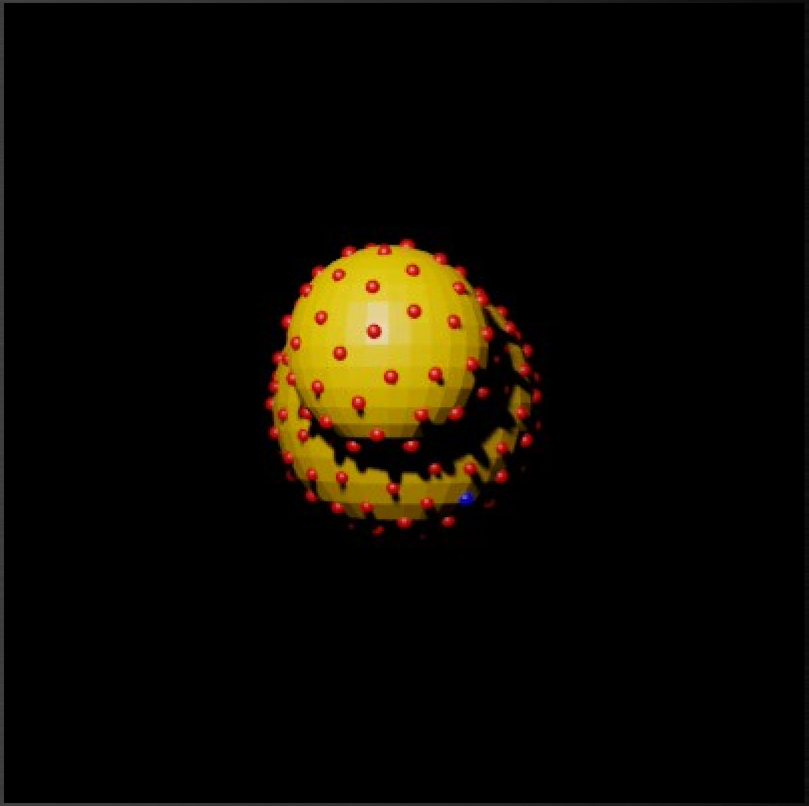

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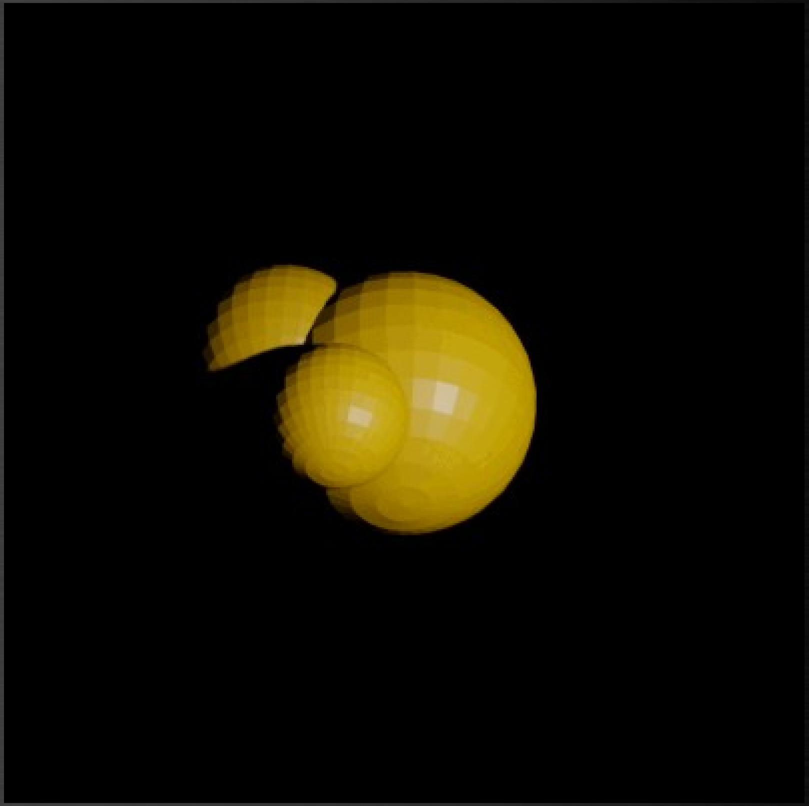
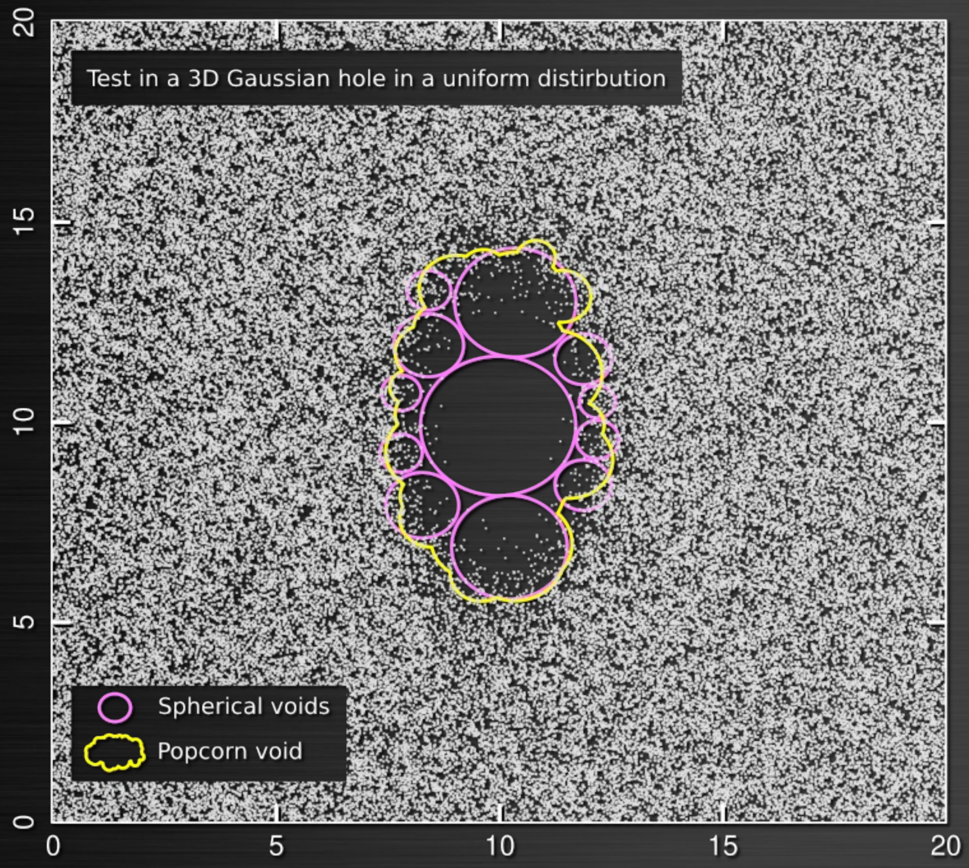
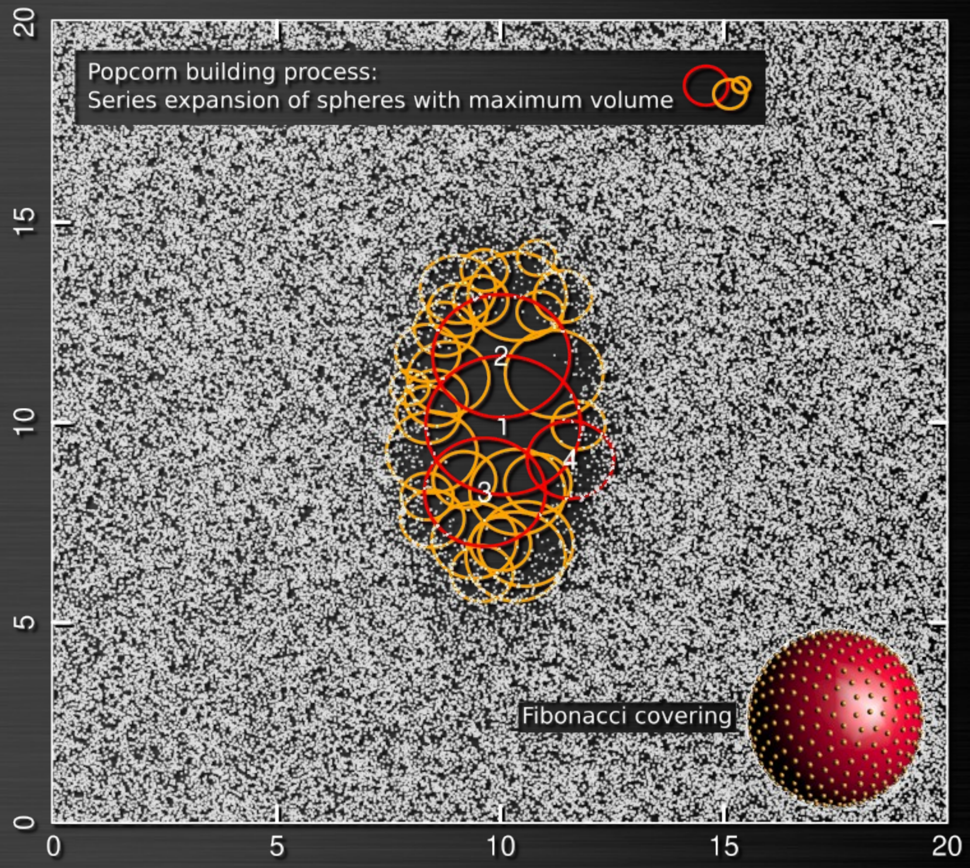


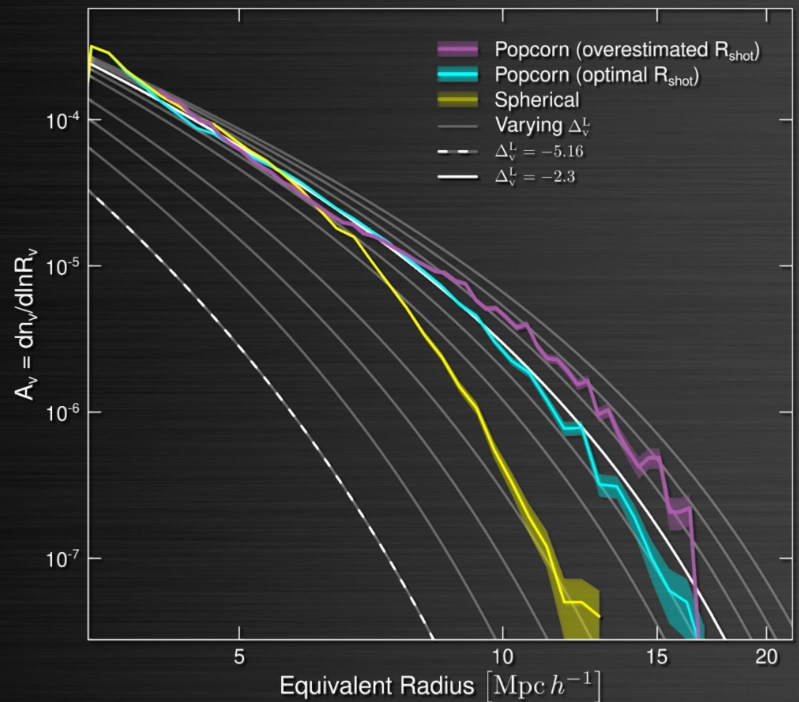
The popcorn void finder in a sandbox

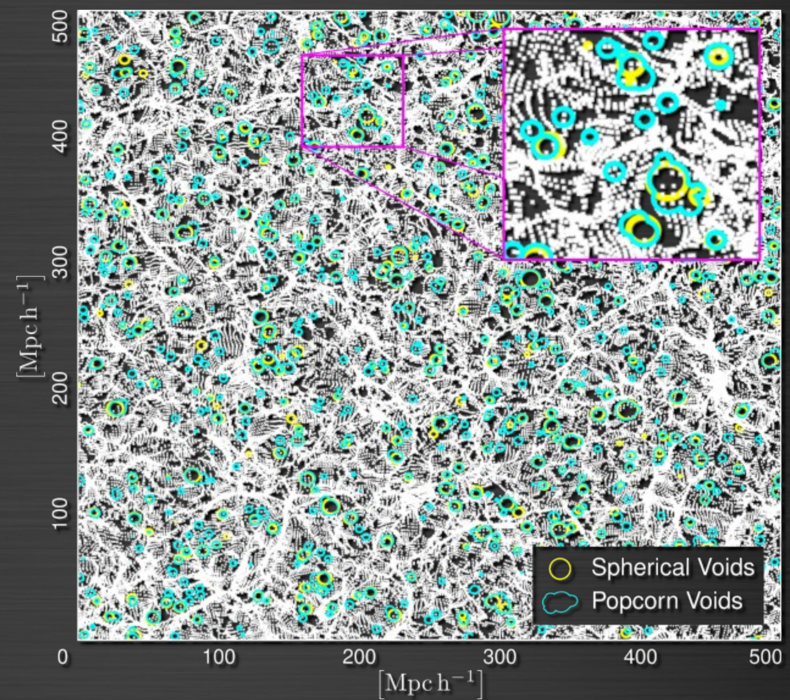




- As can be seen there is a fragmentation of the regions by the SV finder.
- After cleaning overlappings the Popcorn void of a region is the limit of a series of sphere sets with the largest joint volume of 1,2,..N spheres.
- The volume of the void uniformly converges to the expected volume of the gaussian hole.

Abundances of voids in the matter field





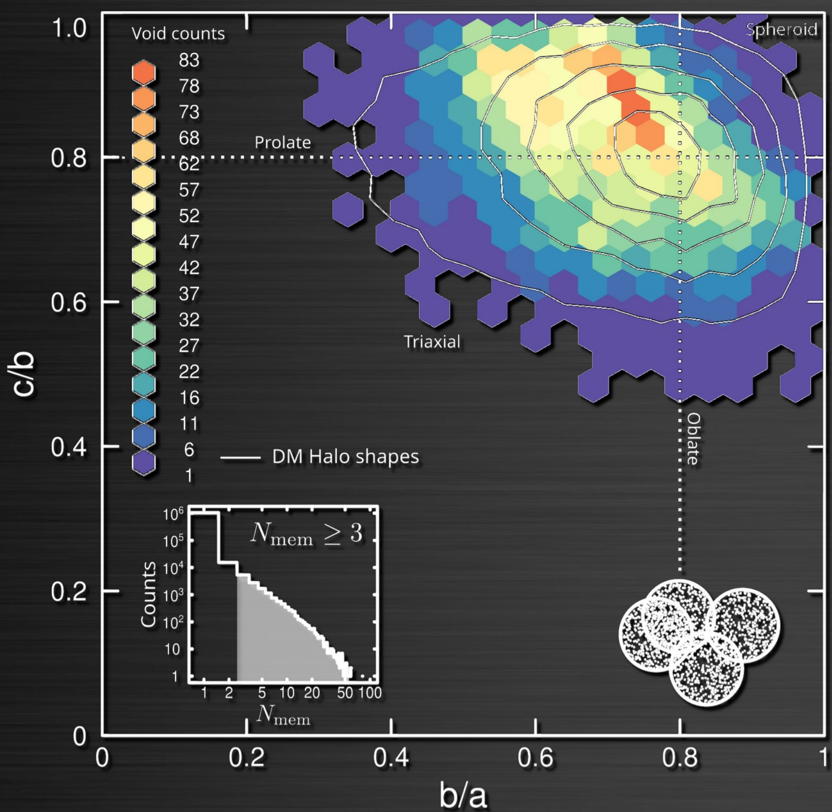
Equivalent Radius:

$$R_{\rm eq} = \sqrt[3]{\frac{3}{4\pi}\mathrm{Vol}}$$

DM only sim 1024^3 particles in 1000^3 Mpc

- The abundance of Popcorn voids in the matter field can be well-fitted by choosing an adequate linear barrier Δ^L_v=-2.3 in the Vdn model.
- Usually, this barrier is fixed using the spherical expansion model (Δ^L_v=-5.1), but for Popcorn, large values are required. This could be an effect of their triaxial shapes.
- SV cannot be fitted using excursion set theory with any value of Δ^L_v. In the matter field, the Vdn model is more appropriate than SvdW.
- Popcorn voids are less frequent at small scales than SV and have larger sizes, due to the fixing of the fragmentation problem of SV.
- An overestimation of R_{shot} produces a wavy behaviour for A_v, while an underestimation produces complex (multiconnected regions) and artificially large voids.

Popcorn void shapes



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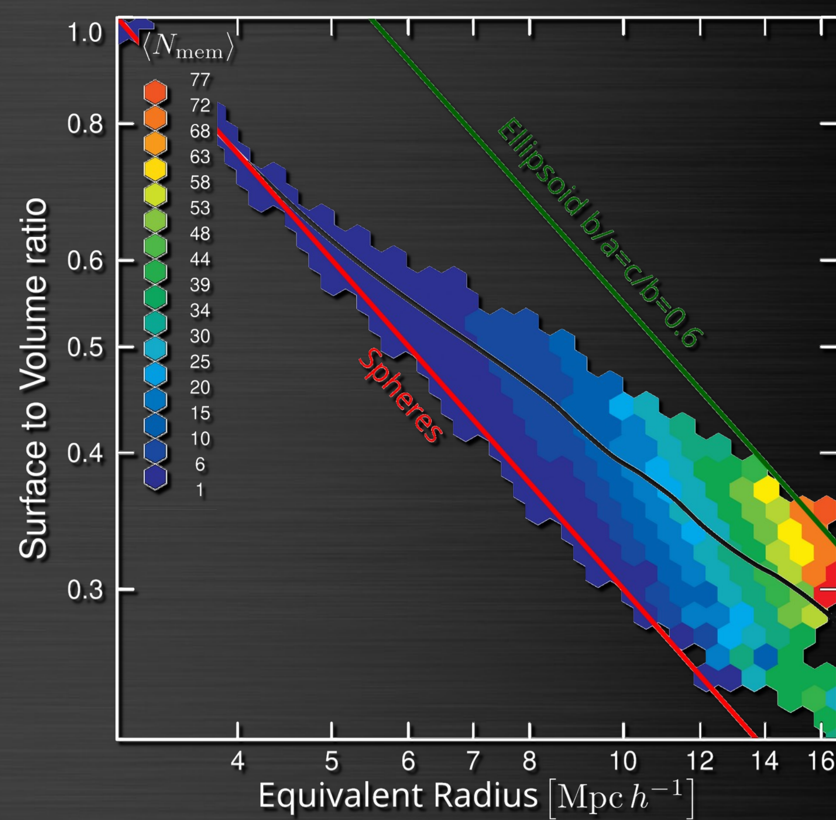


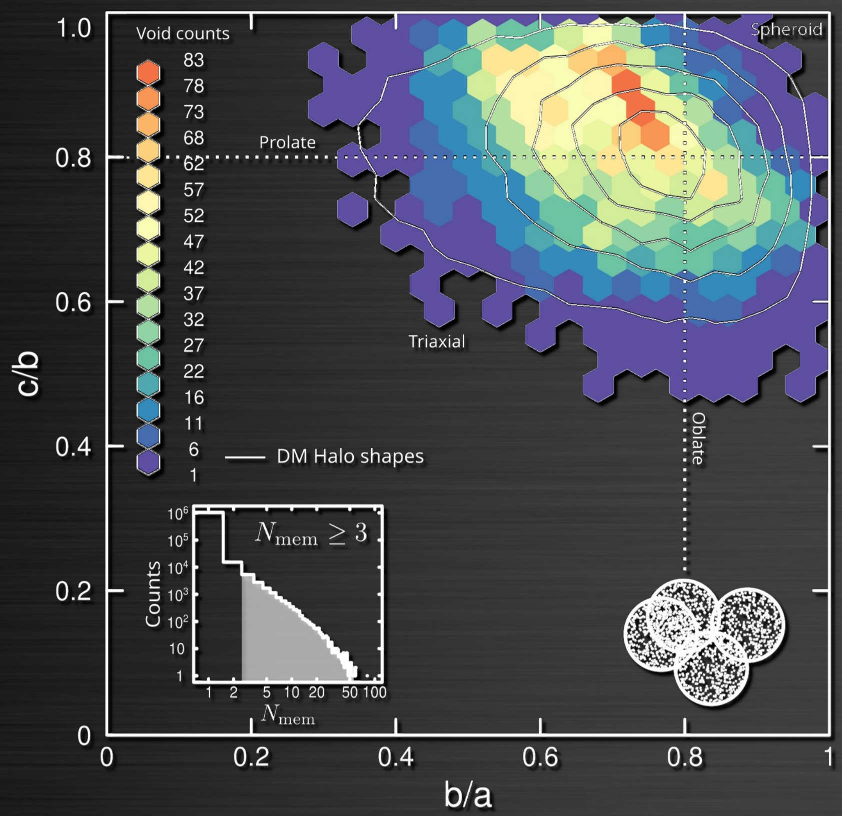
- The shapes are determined using the eigenvalues of a Monte Carlo estimate of the shape tensor. For each member sphere a set of uniform random points is drawn:

$$m_{\mathrm{k}} = \frac{1}{N_{\mathrm{sph}}} \qquad \bar{x}_{\mathrm{i}} := \frac{1}{N_t} \sum_{\mathrm{k}=0}^{N_t} m_{\mathrm{k}} x_{\mathrm{i}}^{\mathrm{k}} \qquad I_{\mathrm{ij}} := \frac{1}{N_t} \sum_{\mathrm{k}=0}^{N_t} m_{\mathrm{k}} \left(x_{\mathrm{i}}^{\mathrm{k}} - \bar{x}_{\mathrm{i}}\right)\left(x_{\mathrm{j}}^{\mathrm{k}} - \bar{x}_{\mathrm{j}}\right)$$

Random point weight — Geometric center — Shape tensor

- The eigenvalues are arranged in descending order as a, b, and c

Popcorn void shapes



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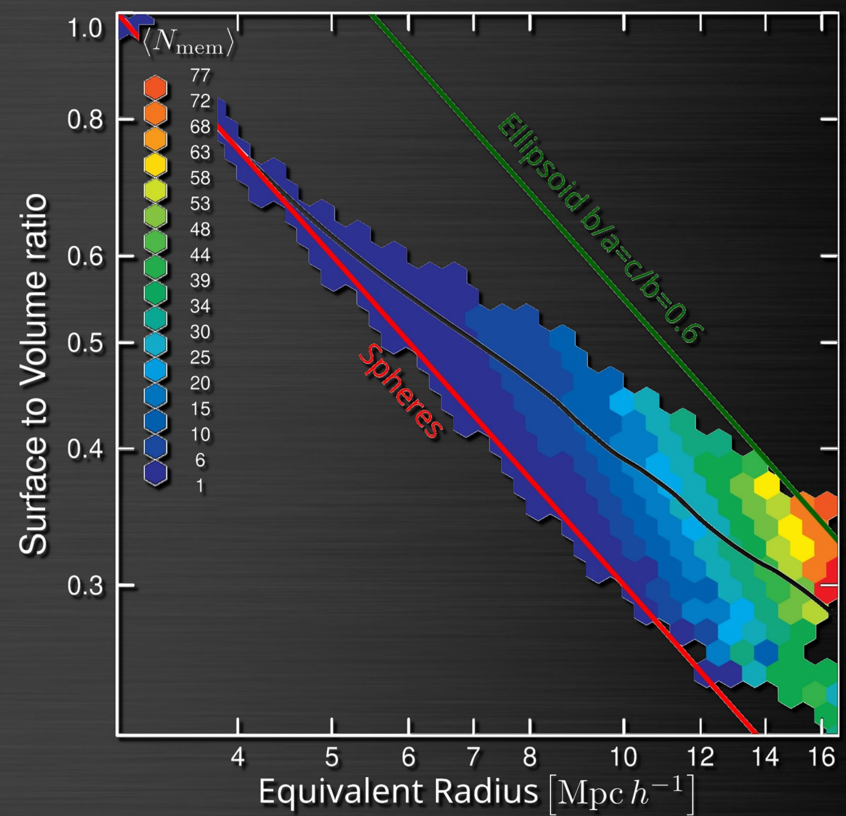
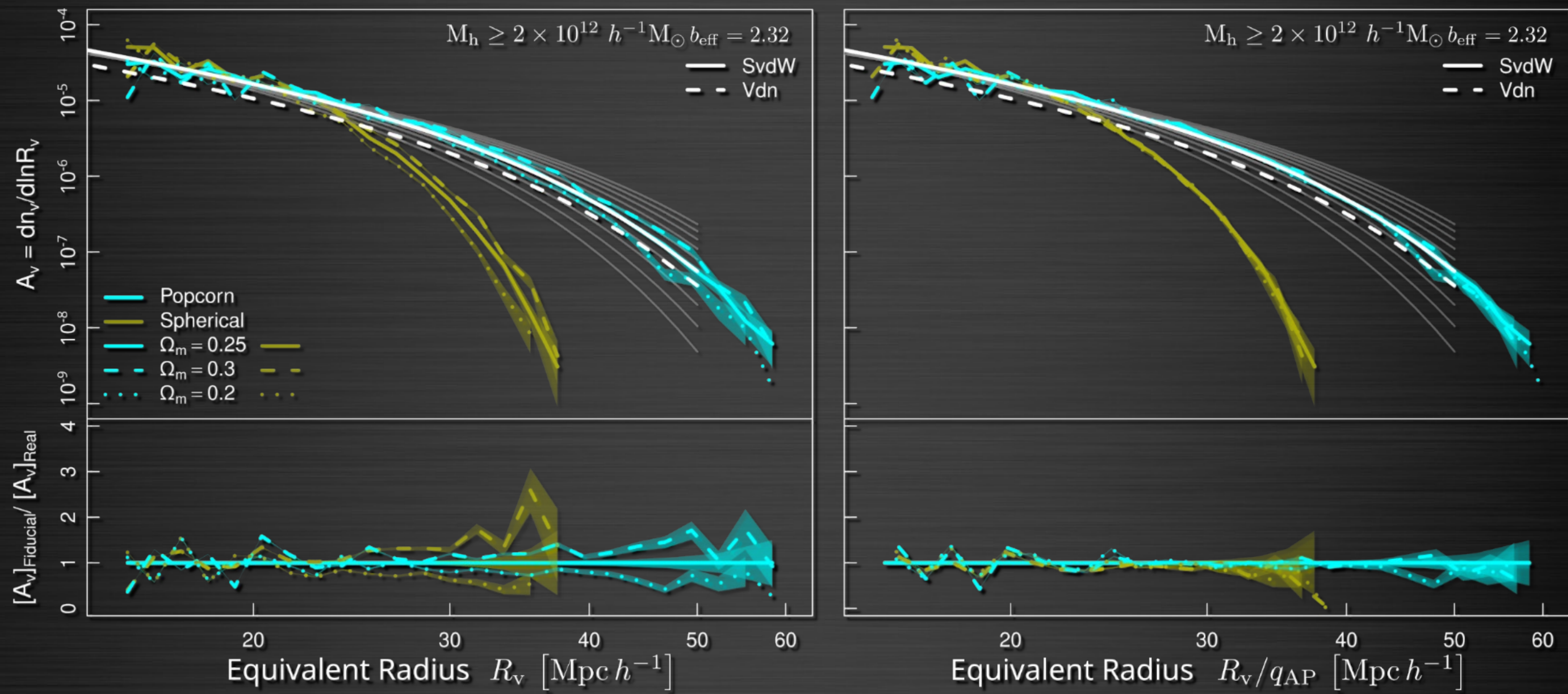


- The number of spheres follows a power law distribution.
- The shape tensor of popcorn voids with more than 3 sphere members have triaxial shapes, with a preference for prolate shapes.
- The surface to volume ratio indicates they have shapes between spheres and triaxial ellipsoids.
- Their shapes resemble what is expected in the statistics of rare peaks in a Gaussian field similar to Dark matter haloes (Bond & Myers 1996, Paz et al. 2006)

Abundances of voids traced by haloes

Results from MXXL simulation:



Left: SV and Popcorn VSF for different fiducial cosmology.
Right: Idem but correcting the void size by AP (Correa, Paz et al. 2021):

$$q_{\rm AP} = \sqrt[3]{\frac{H^{\rm true}(z)}{H^{\rm fid}(z)}\left[\frac{D_{\rm M}^{\rm fid}(z)}{D_{\rm M}^{\rm true}(z)}\right]^2} \qquad R_v^{\rm true} = R_v^{\rm fid}/q_{\rm AP}$$

The SvdW model fits well void abundances by assuming an effective bias of 2.32

By measuring real space VSF at different z, using qAP and SvdW, it is possible to perform a tomographic cosmological test, however, it is necessary to take into account RSD

Abundances in redshift space haloes

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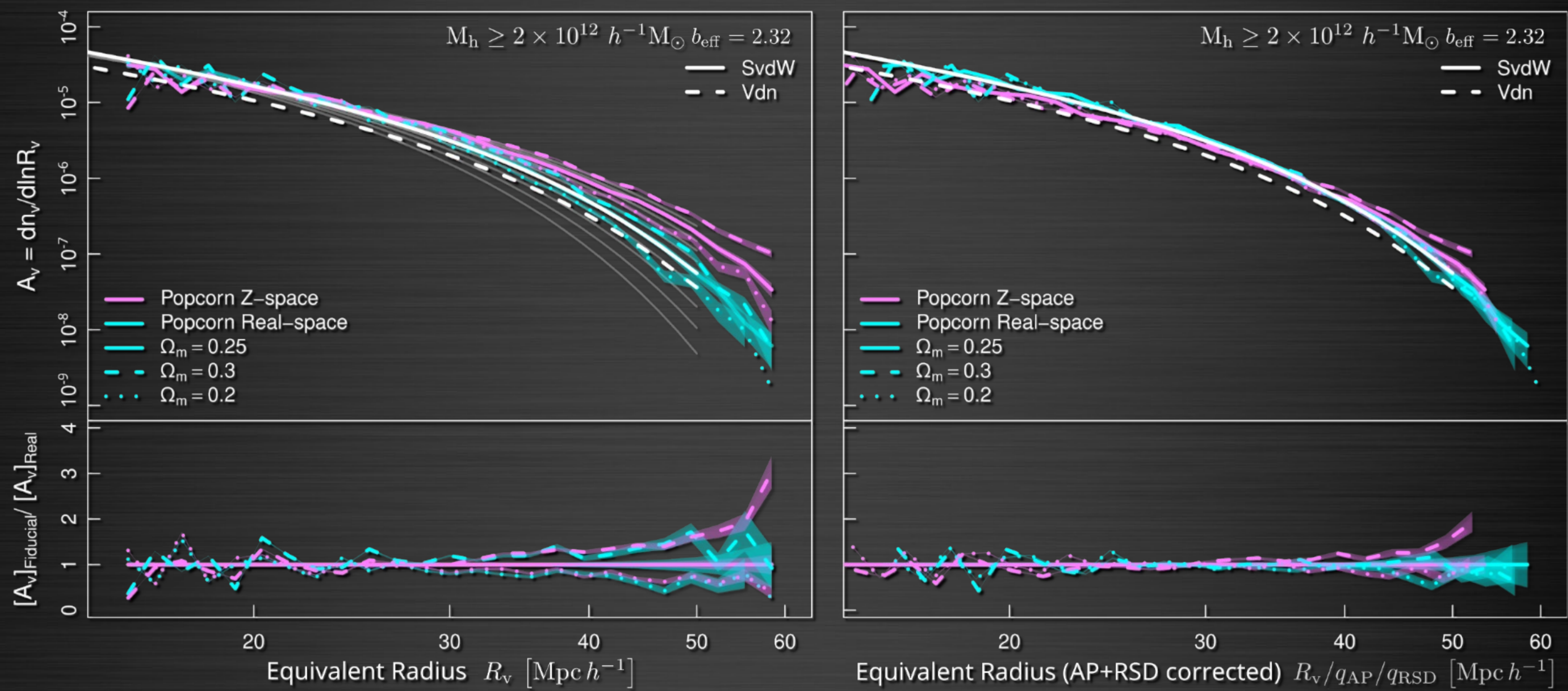

Left: Real space and Z-space Popcorn VSF for different assumptions of fiducial cosmology.
Right: Idem but correcting the void size by AP and RSD (Correa, Paz et al. 2021):

$$q_{\rm RSD} = 1 - \frac{1}{6}\beta(z)\Delta_v \qquad R^{\rm true} = R^{\rm fid,z}/q_{\rm AP}/q_{\rm RSD}$$

The $q_{\rm RSD}$ model adds a dependency on the LSS growth rate ($\beta(z)$), and therefore on the gravitational model

By measuring VSF at different z, using $q_{\rm AP}$, $q_{\rm RSD}$ and SvdW, it is possible to perform a tomographic cosmological test

Abundances in redshift space haloes

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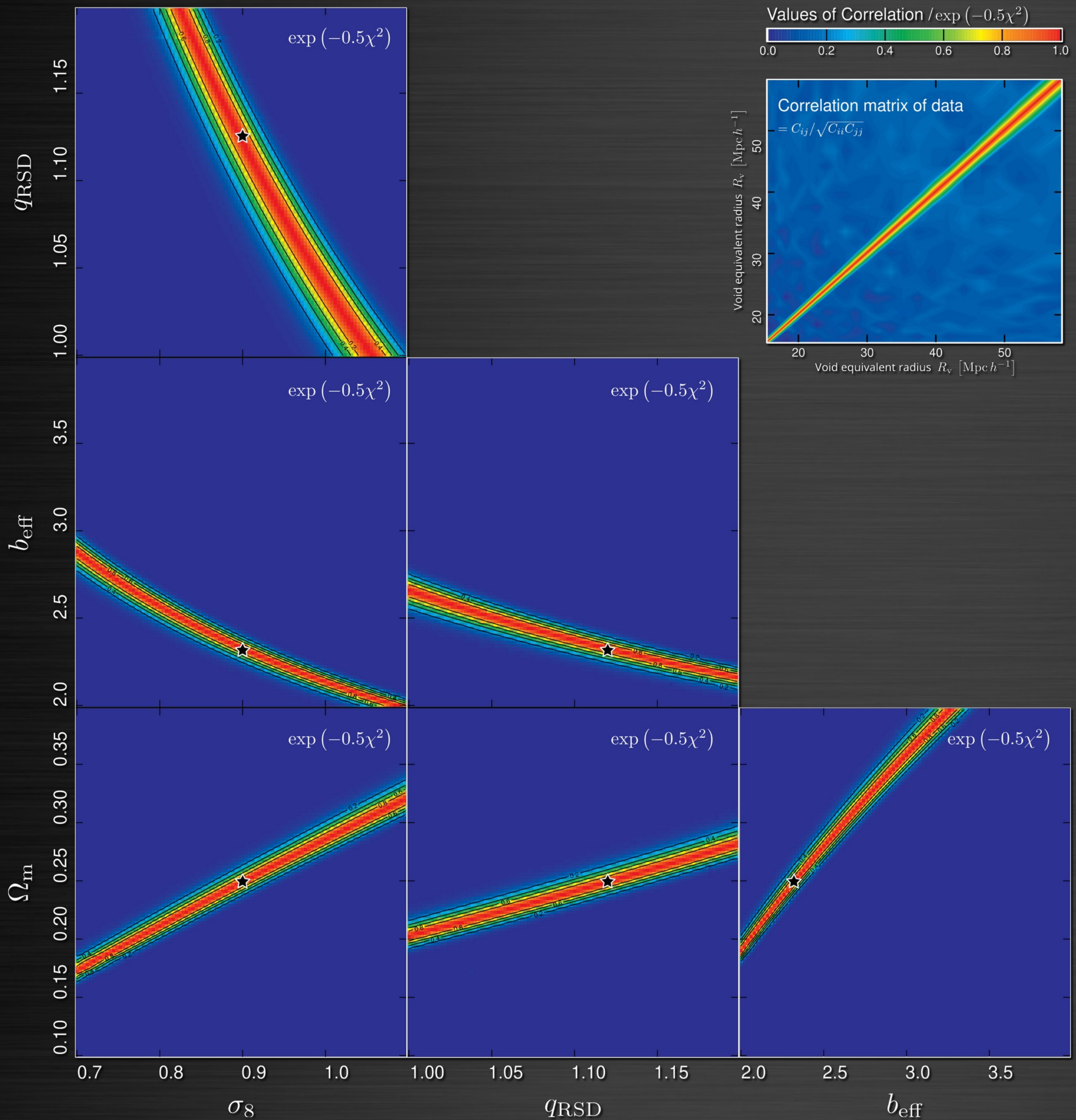

- Test in a mock catalogue using the distant observer approx.
- The VSF is in a cut centered at z=0.51, in z-space, using a biased haloe sample.
- The black star indicates the expected values, directly measured in real space or from the underlying cosmology.
- It successfully recovers the expected values.
- Large degeneracies are present, making it impossible to estimate the likelihood using MCMC methods without a prior definition.
- However, the method is remarkably precise and has great potential when combined with other probes.

Conclusions

- We have presented a new void finder, based on a definition of voids that is more friendly to VSF cosmological tests.
  - Solves the fragmentation problem.
  - Its free form adapts to any subdense region.
  - Its integrated density is assured by definition
- The code is open source, and is available under a MIT licence in https://gitlab.com/dante.paz/popcorn_void_finder
- The VSF on the matter field can be well described using the Vdn model
- The VSF on biased tracer samples are well fitted using the SvdW model, assuming an efective bias different than the clustering bias
- The formalism derived in Correa, Paz et al 2021 allows to use RSD and AP geometric distortions to fit cosmological parameters. In combination with the SvdW model it is possible to obtain unbiased estimates of cosmological parameters from a tomographic analysis in redshift space catalogues.