The motion of emptiness

Dynamics and evolution of cosmic voids

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Large scale structure and galaxy flows

Quy Nhon, July 2016

Motivations

- Universe evolves ► galaxies flow away from voids ►the supercluster-void network emerges: large virialized clusters connected by filaments and large-scale underdense regions widely known as cosmic voids.
- The global flows of mass and galaxies associated with this clustering process are expected to be significant up to the scales of the largest structures, vanishing to a random component at larger scales.
- Galaxy flows have been reported in the local Universe at scales of a few hundred Mpc and are directly related to the large mass fluctuations associated to the inhomogeneous galaxy distribution.
- The large-scale underdensities (cosmic voids) have an active interplay with large-scale flows affecting the formation and evolution of structures in the Universe

➡ They exhibit local expansion which in some cases, depending on the large-scale environment, can be reverted to collapse at larger scales, generating global convergent or divergent flows.

However, it has not been studied into detail the bulk velocity of the void region and that of the surrounding shell of galaxies

Outline

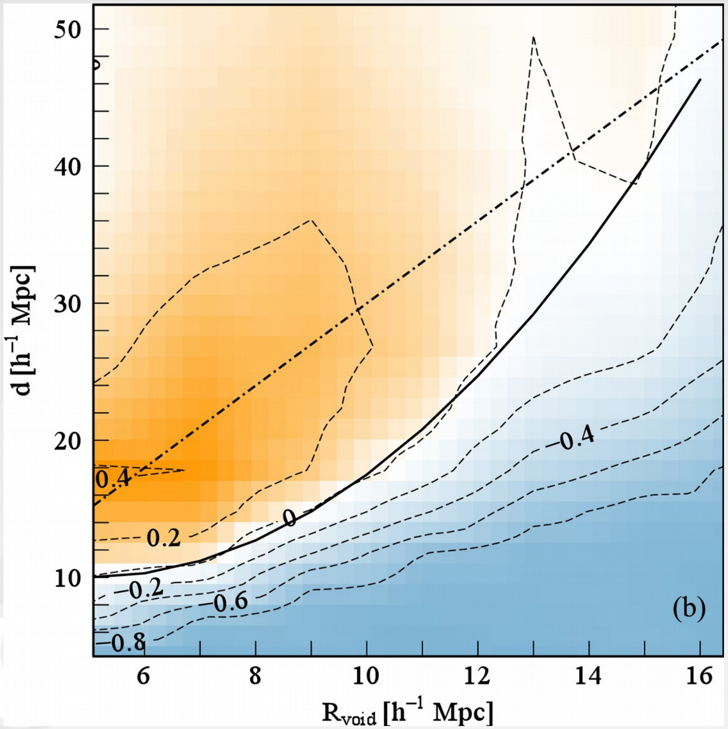
- Void evolution
- Clasification of void environments
- Void and shell bulk motions
- Linearized void velocities
  - Simulation
  - Observational data
- Void motions
  - Dependencies with void properties
  - Sources of void motion
- Pairwise void velocities

Two essential processes on void evolution determined by the surrounding global density: Expansion and collapse Seth & van de Weygaert (2004)

- **Dynamics:** two opposite modes on velocity field around voids:
  - Infall (voids embedded in overdense environments)
  - Outflowing velocities (voids embedded in underdense environments).
- **Void size evolution:**
  - Many of the smallest voids at present may show surrounding overdense shells
  - Largest voids at present are unlikely to be surrounded by overdense regions.

To deepen our understanding of the nature of voids and the evolution of their properties, it is crucial take into account the large scale structure where they are embedded.

Integrated galaxy density around voids in observational data



Contour lines of mean density contrast as a function of void radius and distance to the void centre in SDSS. Orange colours represent positive densities and cyan correspond to negative densities.

Small voids are more frequently surrounded by over-dense shells.

Larger voids are more likely embedded in underdense regions.

Clues on void evolution I. Ceccarelli, Paz, Lares, Padilla & Lambas. 2013, MNRAS, 434, 1435.

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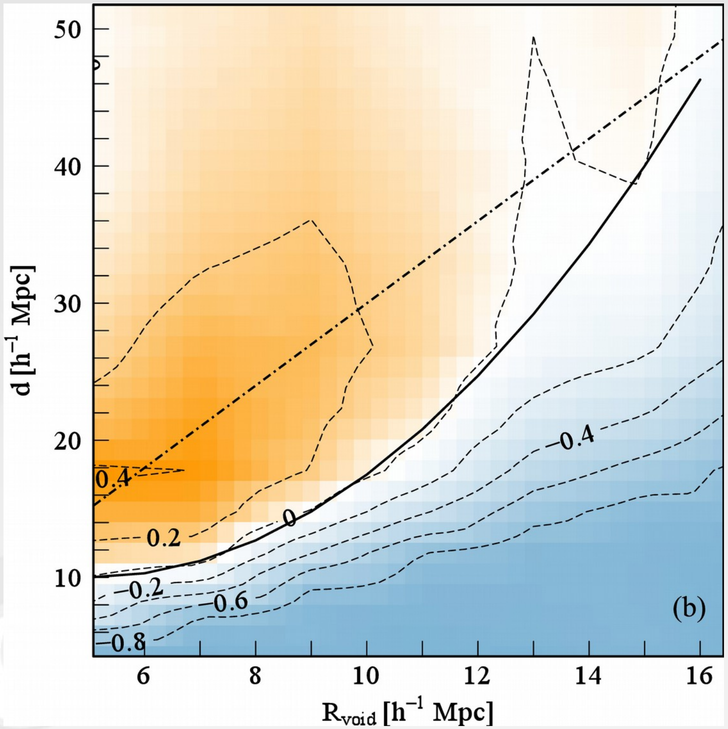

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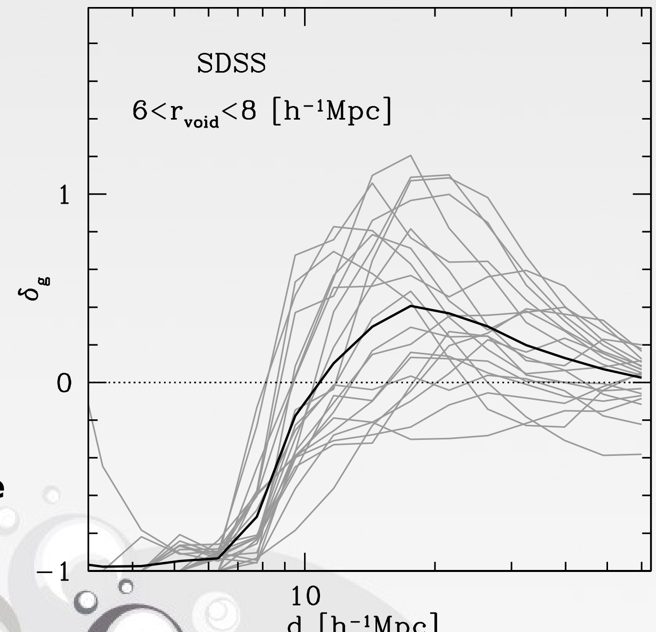
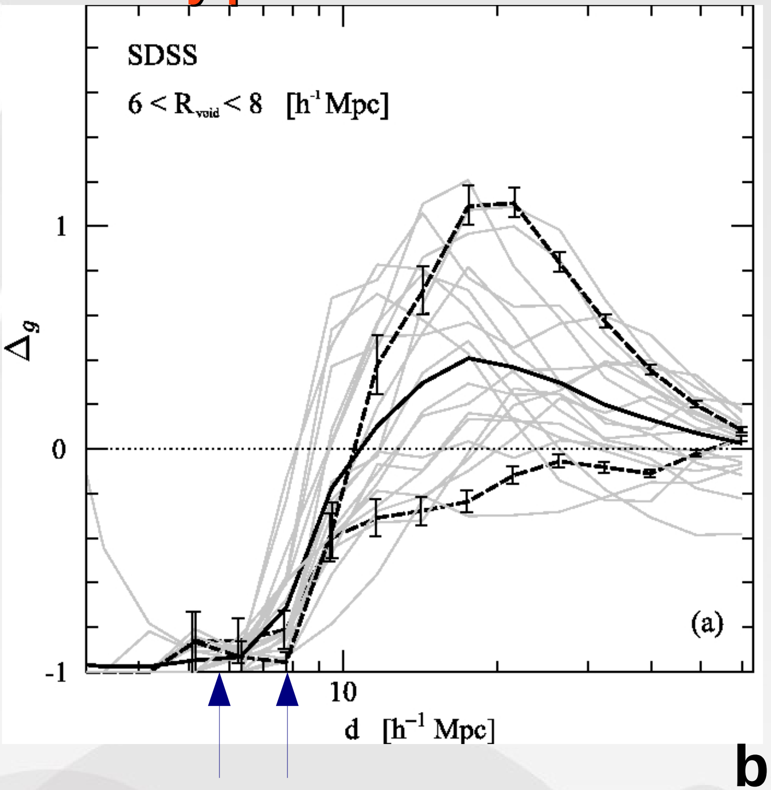


Integrated galaxy density profile for individual voids in SDSS with radii in the range 6-8 Mpc/h (gray lines). The black solid line indicates the mean density of all voids.

Clues on void evolution I. Ceccarelli, Paz, Lares, Padilla & Lambas. 2013, MNRAS, 434, 1435.

Integrated galaxy density around voids in observational data

Density profiles around voids



Integrated density contrast inside voids < -0.9

It is possible to classify voids according to their large-scale density around them allowing for a subdivision of the sample into two types of voids

Void Classification
based on large scale environment

Large-scale "Shell" Profile ⇒ S-type voids
Large-scale "Rising" Profile ⇒ R-type voids

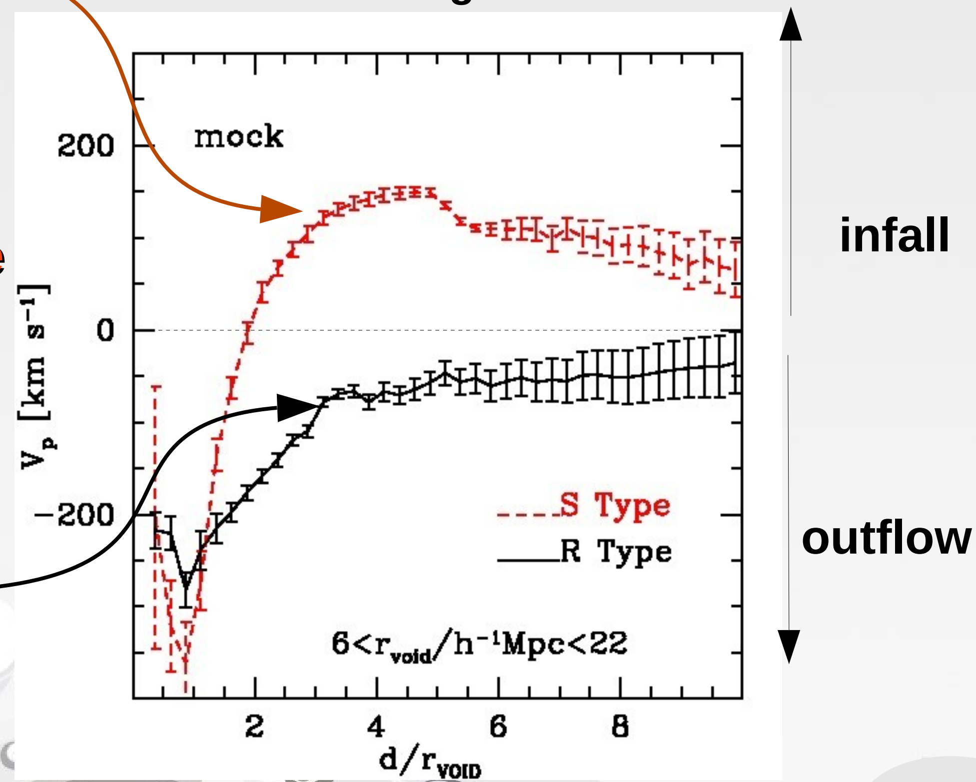
Clues on void evolution I. Ceccarelli, Paz, Lares, Padilla & Lambas. 2013, MNRAS, 434, 1435.

Dynamics around S and R type voids

Based on theoretical void evolution it is natural to expect a dependence of the peculiar velocity field around voids with the presence of a surrounding overdense shell.

Mean radial velocity as a function to distance to the void centre in mock catalogue

Voids in overdense environment



Voids in underdense environment

The velocity curves for the two types of voids suggest that there is a relation between our separation criterion and the evolution of voids.

Observational data?

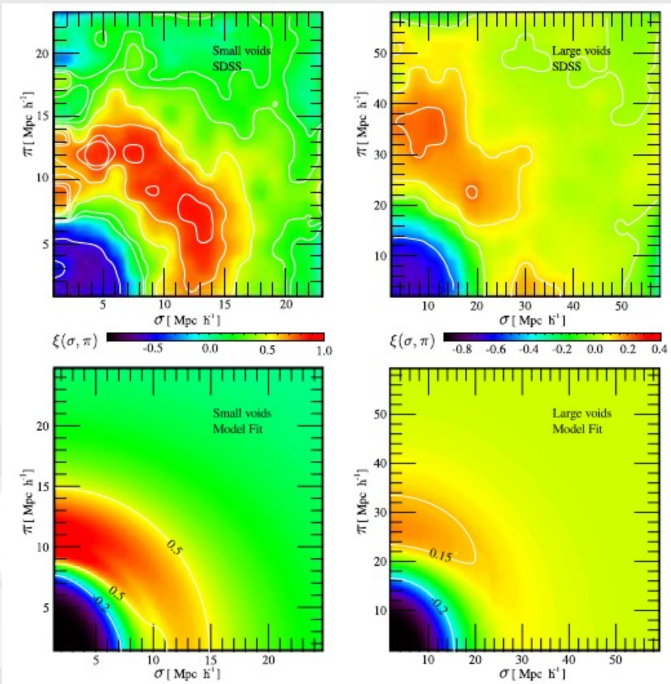
Clues I, Ceccarelli et al. 2013

Dynamics around voids vs large scale environment

Redshift space distortions in observational data ξ(σ,π) void-glx

Overdense environment — Collapsing voids

Underdense environment — Expanding voids



Voids in dense large-scale regions: inner regions are in expansion, the large–scale void walls are collapsing

Voids in under-dense large-scale regions are in expansion

Clues on void evolution II. Paz, Lares, Ceccarelli, Padilla & Lambas. 2013, MNRAS, 436, 3480.

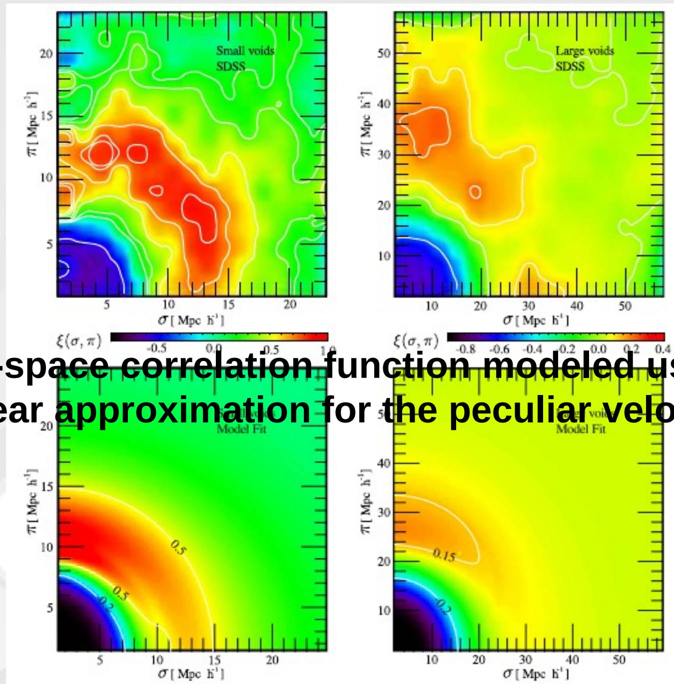
Dynamics around voids vs large scale environment

Redshift space distortions in observational data $\xi(\sigma,\pi)$ void-glx

Model results in observational data

Overdense environment
Collapsing voids

Underdense environment
Expanding voids



z-space correlation function modeled using the linear approximation for the peculiar velocity field

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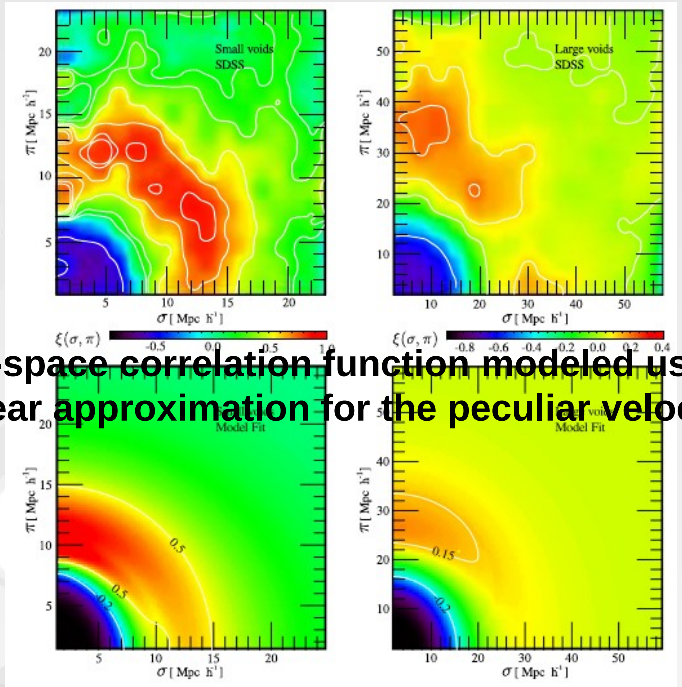
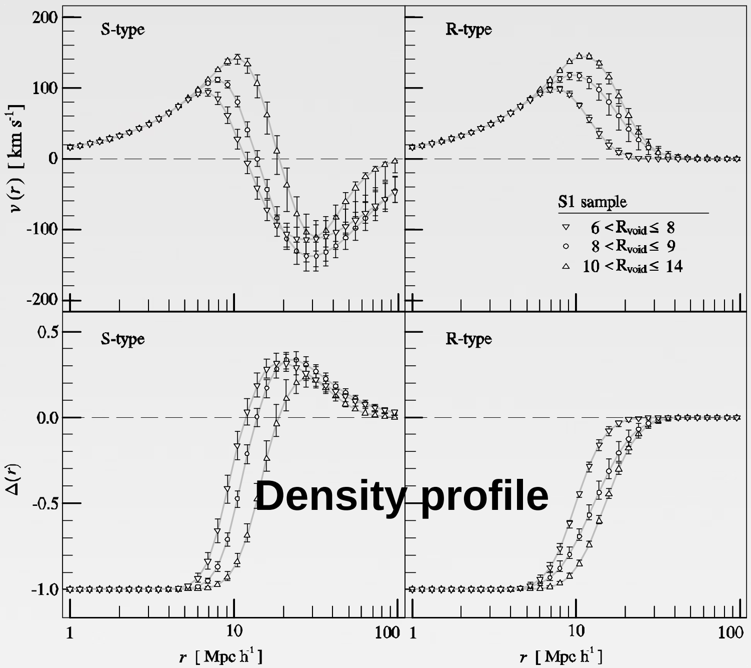


z-space correlation function modeled using the linear approximation for the peculiar velocity field

Model results in observational data

Velocity field



Density profile

Voids in dense large-scale regions: inner regions are in expansion, the large–scale void walls are collapsing

Voids in under-dense large-scale regions are in expansion

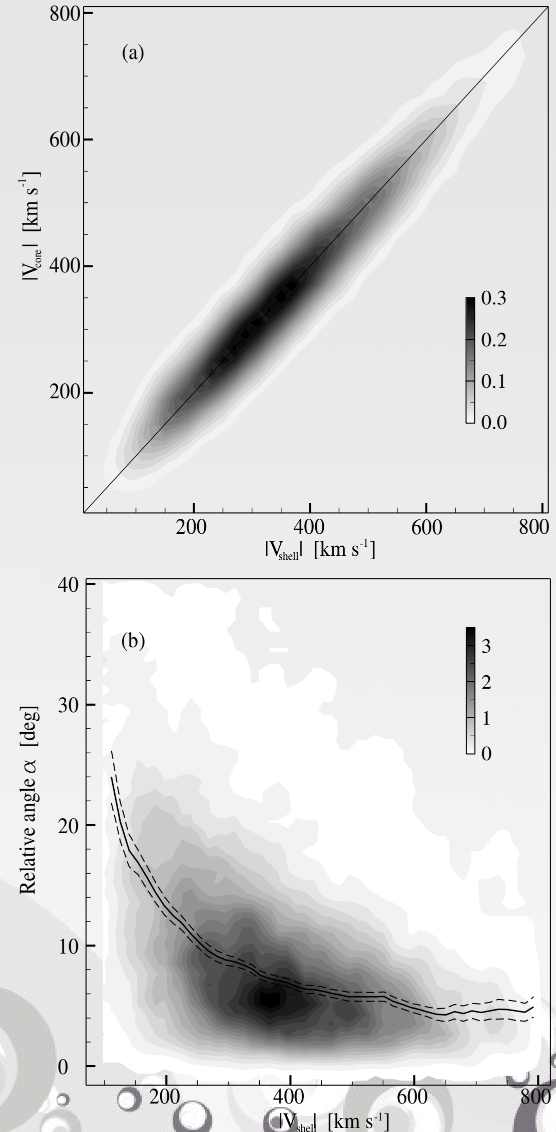
The first observational evidence of the two processes involved in void evolution

As expected from theoretical predictions!

Clues on void evolution II. Paz, Lares, Ceccarelli, Padilla & Lambas. 2013, MNRAS, 436, 3480.

Void motions

Bulk velocities of void shells and cores



Bulk velocities of void shells and cores in the simulation.

V_{shell}: dark matter haloes mean velocity within 0.8<r/R_void<1.2. V_{core}: mean velocity of dark matter particles within 0.8 R_void.

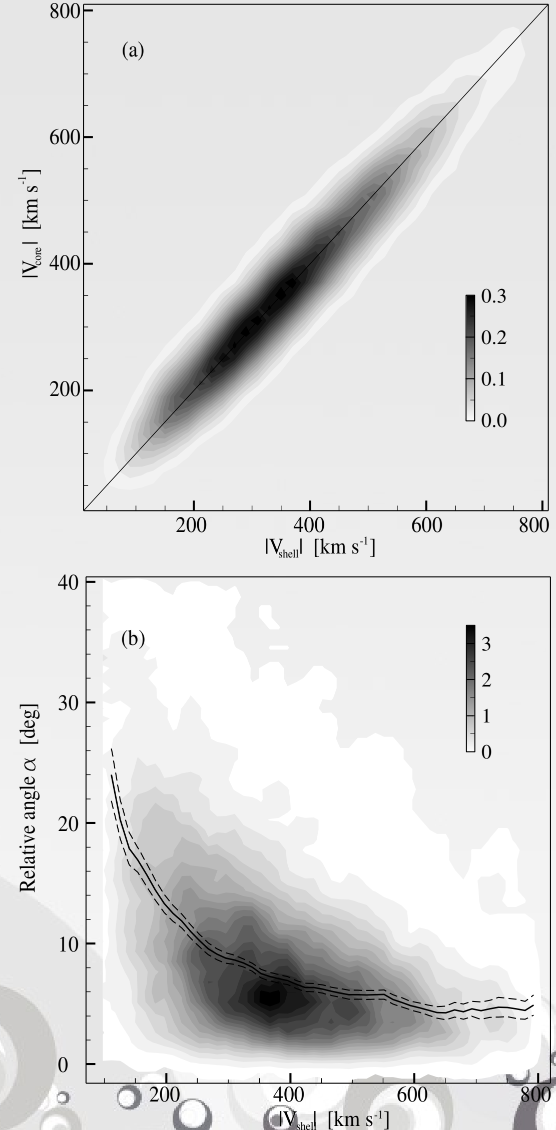
Upper: Distribution function of void counts in V_{shell}, V_{core} bins. Solid line shows the one-to-one relation. Lower: Distribution function of void counts in bins of V_{shell} and the relative angle α between shell and core velocities. Solid and dashed lines correspond to the median and its standard error.

Lambas, Lares, Ceccarelli, Ruiz, Paz, Maldonado, Luparello. 2016, MNRAS Letters, 455, 99

Void motions

Bulk velocities of void shells and cores

The dark matter in the void inner region and the haloes in the surrounding shell exhibit remarkably similar velocities (in magnitude and direction).



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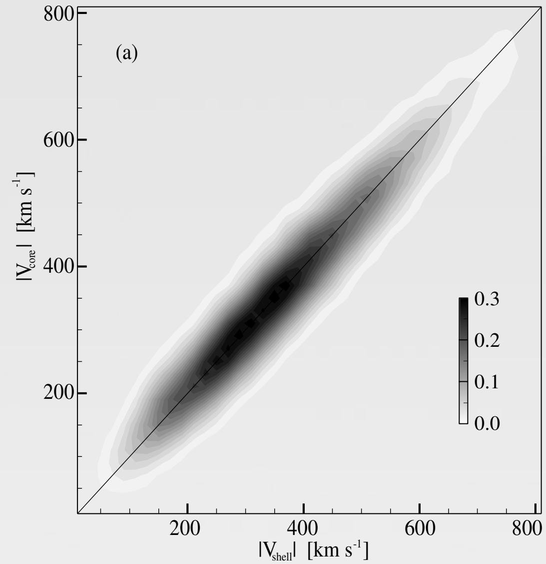

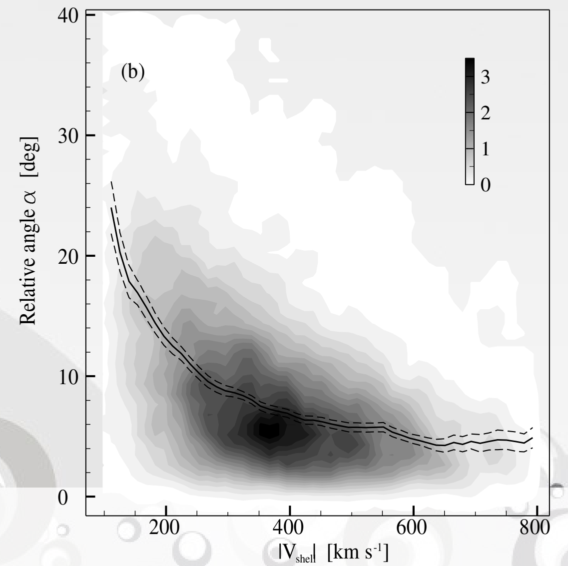

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Void inner material and the surrounding haloes have a global common motion.

Lambas, Lares, Ceccarelli, Ruiz, Paz, Maldonado, Luparello. 2016, MNRAS Letters, 455, 99

Void motions

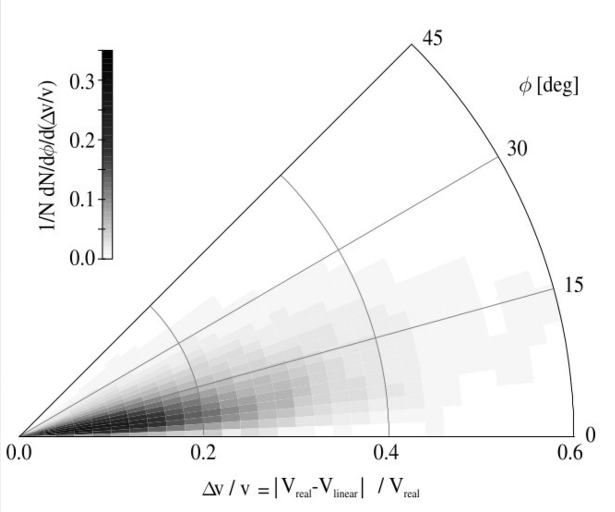
Bulk velocities of void shells and cores

Velocities in observational data

We have adopted the peculiar velocity field derived from linear theory by Wang et al. 2012. They use groups of galaxies as tracers of dark matter halos and its cross correlation function with mass, in order to estimate the matter density field over the survey domain. The linear relation between mass overdensity and peculiar velocity is used to reconstruct the 3D velocity field.

$$v(r) \approx -\mathrm{H} r \Delta(r) \frac{\Omega_m^{0.6}}{3}$$

Comparison between real and linearized velocities of voids in the simulation.



Polar diagram of the probability density as a function of the angle and the relative difference between the full and linearized velocities of voids.

Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

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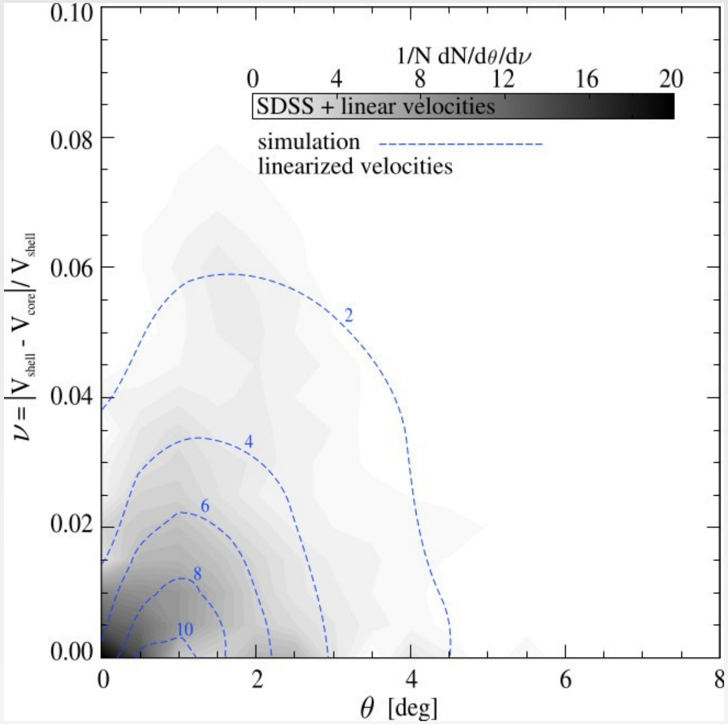
Bulk velocities of void shells and cores in SDSS



Probability density as a function of the angle between the core and shell velocities and the relative difference between both velocities obtained from the SDSS+linearized velocity field. The dashed lines correspond to the same quantities computed through the linearized velocities of the simulation.

Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

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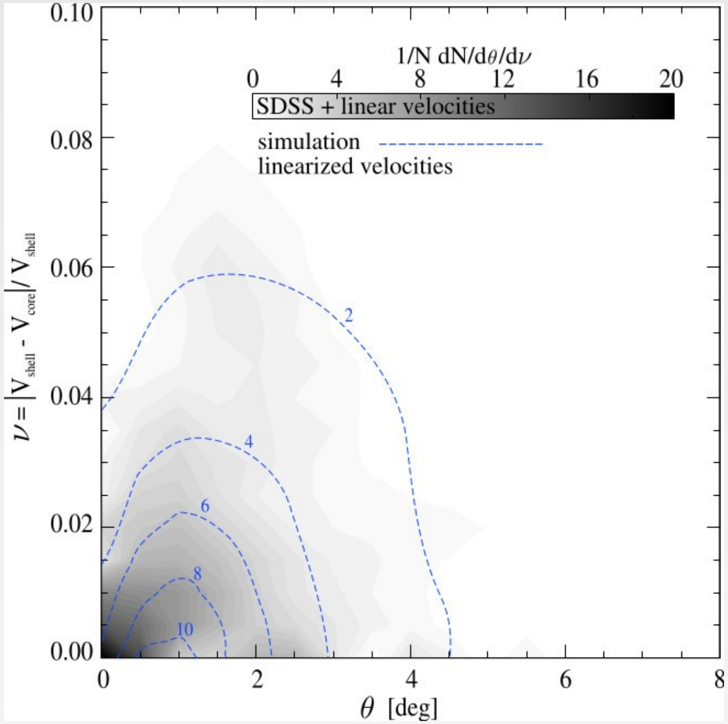


Probability density as a function of the angle between the core and shell velocities and the relative difference between both velocities obtained from the SDSS+linearized velocity field. The dashed lines correspond to the same quantities computed through the linearized velocities of the simulation.

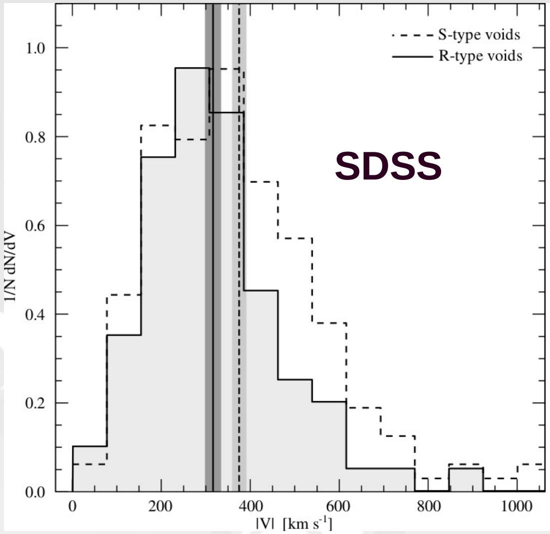
shell bulk velocities trace well the void core motions

void velocities: mean bulk velocity of haloes/glxs located at void-centric distances between 0.8 and 1.2 void radius (denser shell surrounding voids).

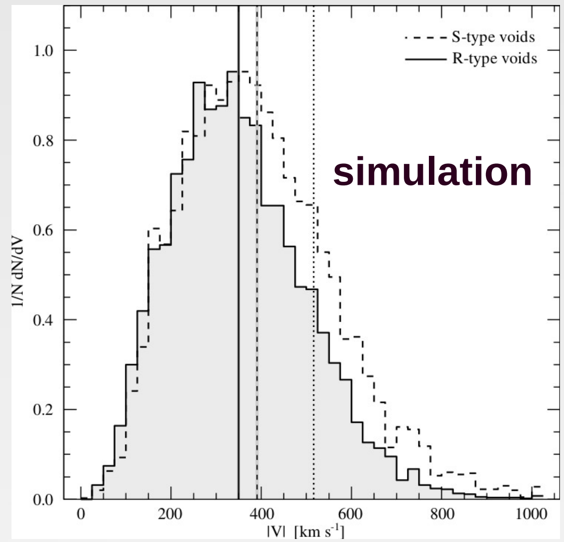
Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

Void Bulk Motions

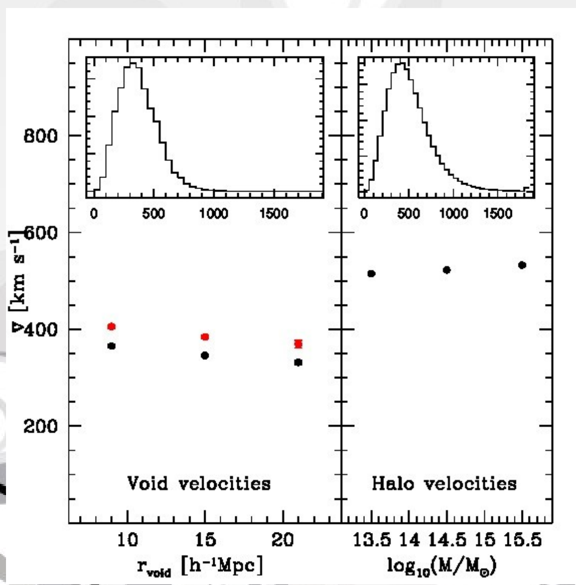
Void velocity normalized distributions in SDSS and simulations.



Solid (dashed) line represents voids in under (over) dense regions. Vertical lines and bands show the corresponding mean velocities and standard errors (~300-400 km/s).



Dotted line → mean velocity of haloes having $M > 10^{12}$ M_{sun}/h (~515 km/s).



It is remarkable that mean void and halo velocities are of the same order despite their very different nature, haloes being the most compact, extremely dense objects, and voids the largest empty regions in the Universe

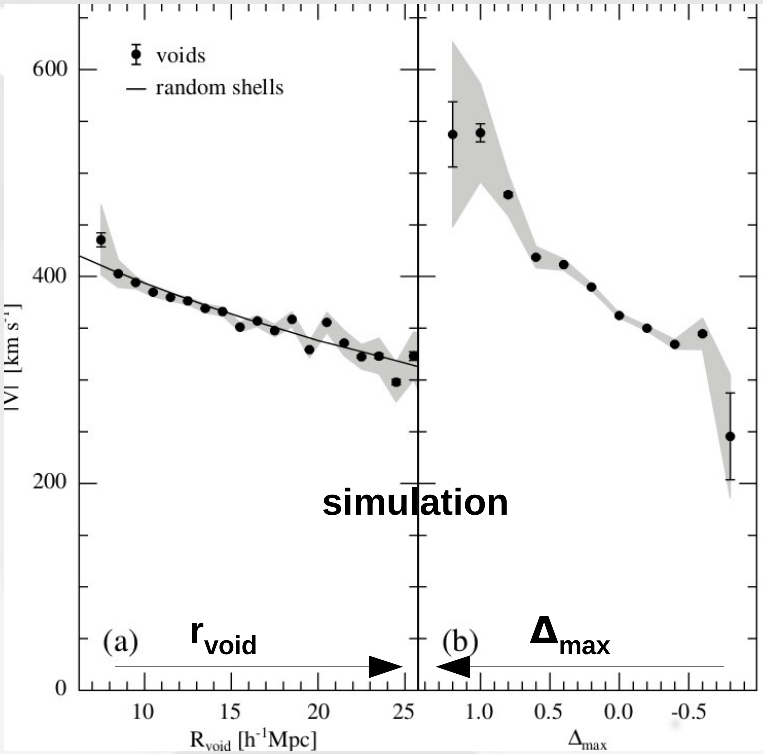
Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

Void Motion

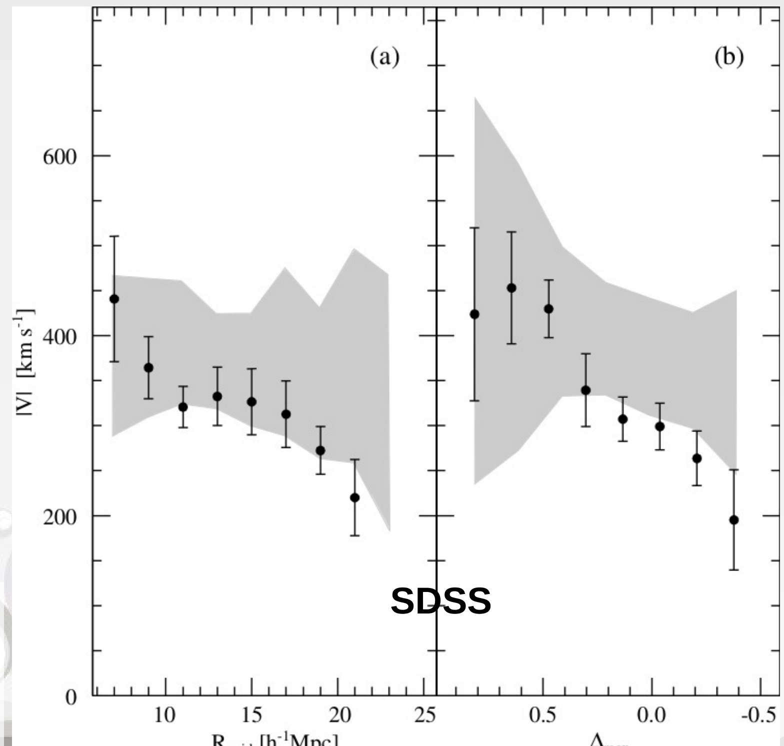
Dependence of mean velocity with size and surrounding density

Void velocities tend to be smaller as void size increases.

Smaller voids (r_{void}<8 Mpc/h) exhibit mean velocity as larger as 400 km/s and this velocity decreases to 300 km/s for the largest voids (r_{void}>17 Mpc/h).



Mean velocity for voids as a function of void radii (left) and Δ_{max} (right)



There is a clear trend of void velocities to be larger as surrounding density increases.

Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

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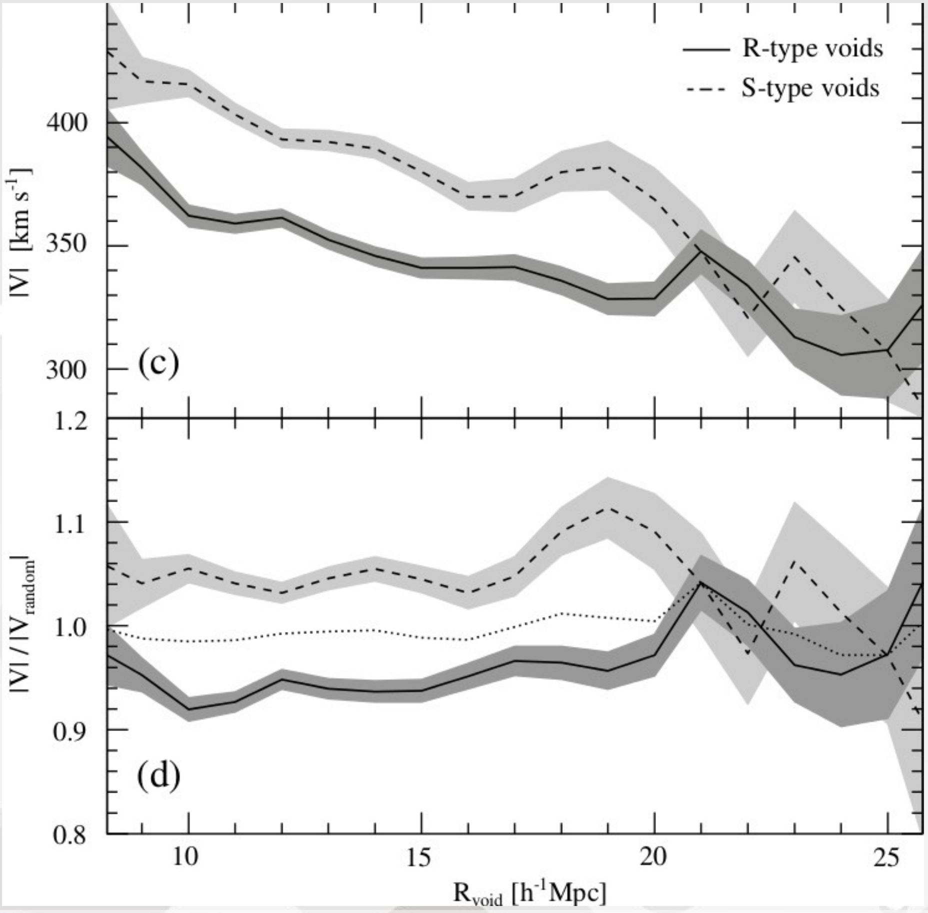
Dependence of mean velocity with size and surrounding density



Results in simulation

Upper: Mean velocity as a function of the void radius for voids en over (dashed line) and under (solid line) dense regions in the simulation. Lower: Ratio between the velocities of void and random spheres.

Besides the dependence of void size with the density of the region surrounding the void the magnitude of mean void velocity is related with both, void size and environment.

Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

Void Bulk Motions

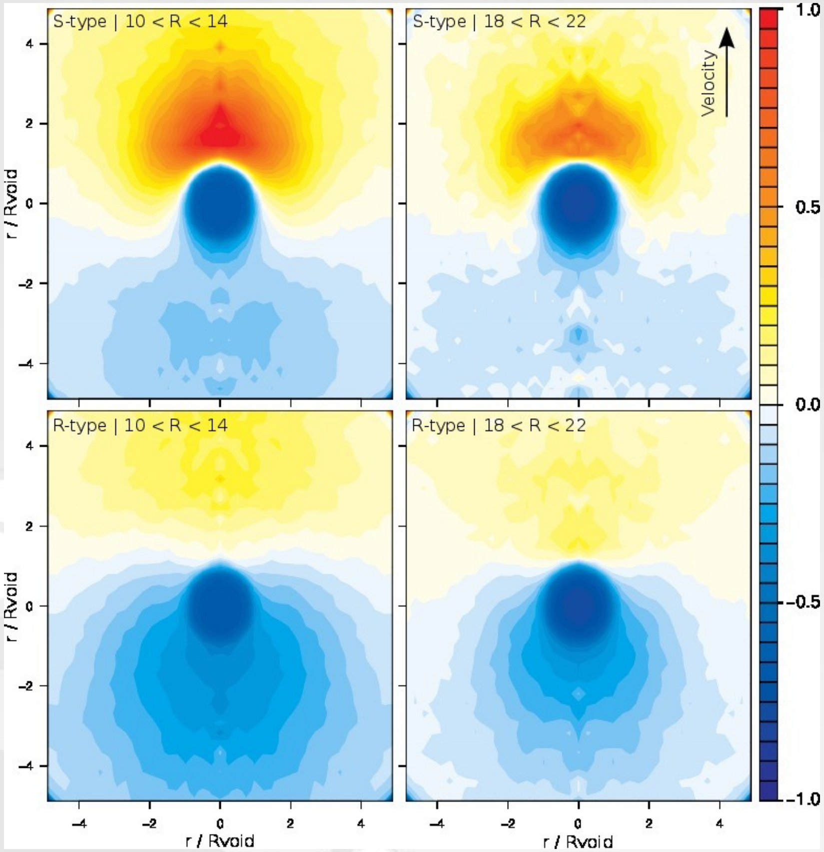
Pull & push mechanism

Voids in overdense environments

S-type voids

Voids in underdense environments

R-type voids



Density maps of stacked voids, the y-axis direction correspond to the void velocity vector. Overdensity increases from blue to red and white colour correspond to the mean density.

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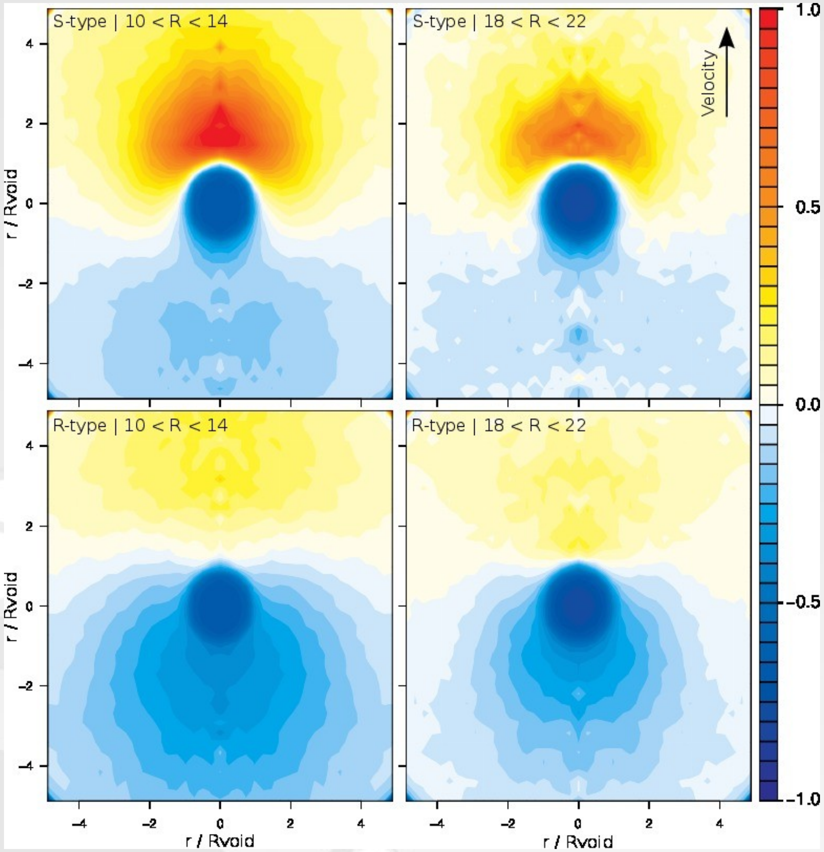

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There is a remarkable overdensity in the direction of velocity whereas in the opposite it is observed an underdensity

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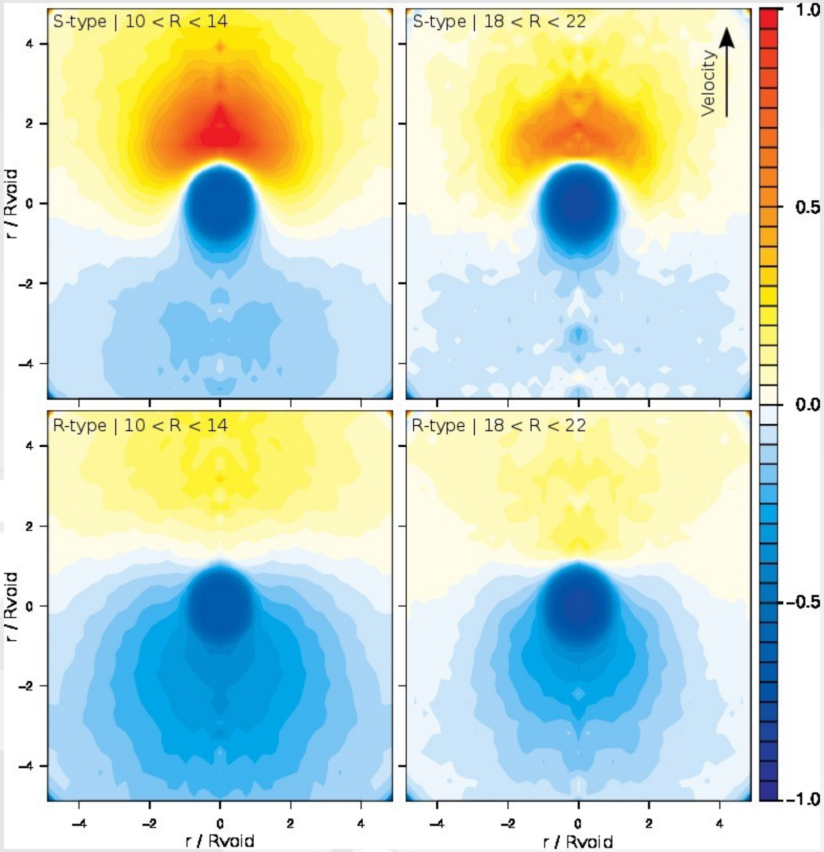

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Voids seem to be abandoning low dense regions and moving to overdensities

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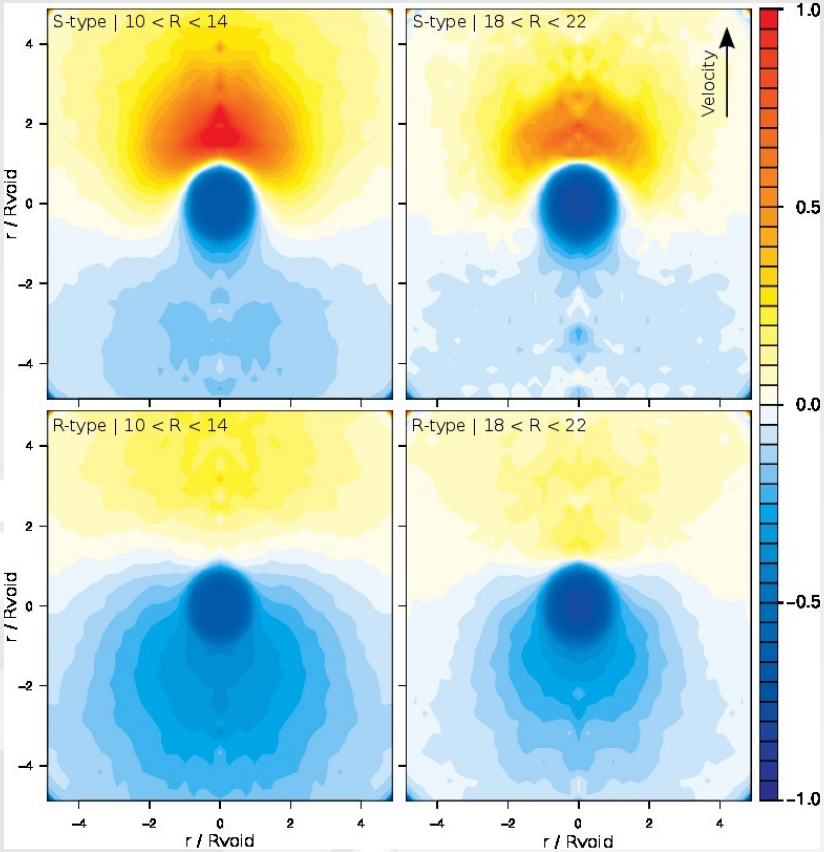

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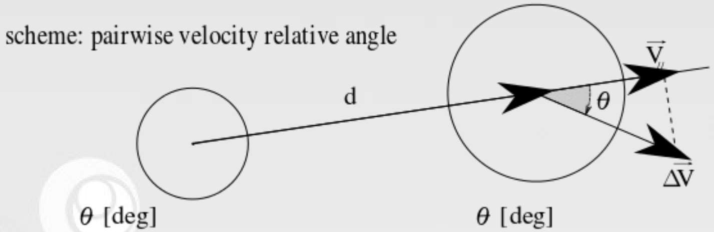
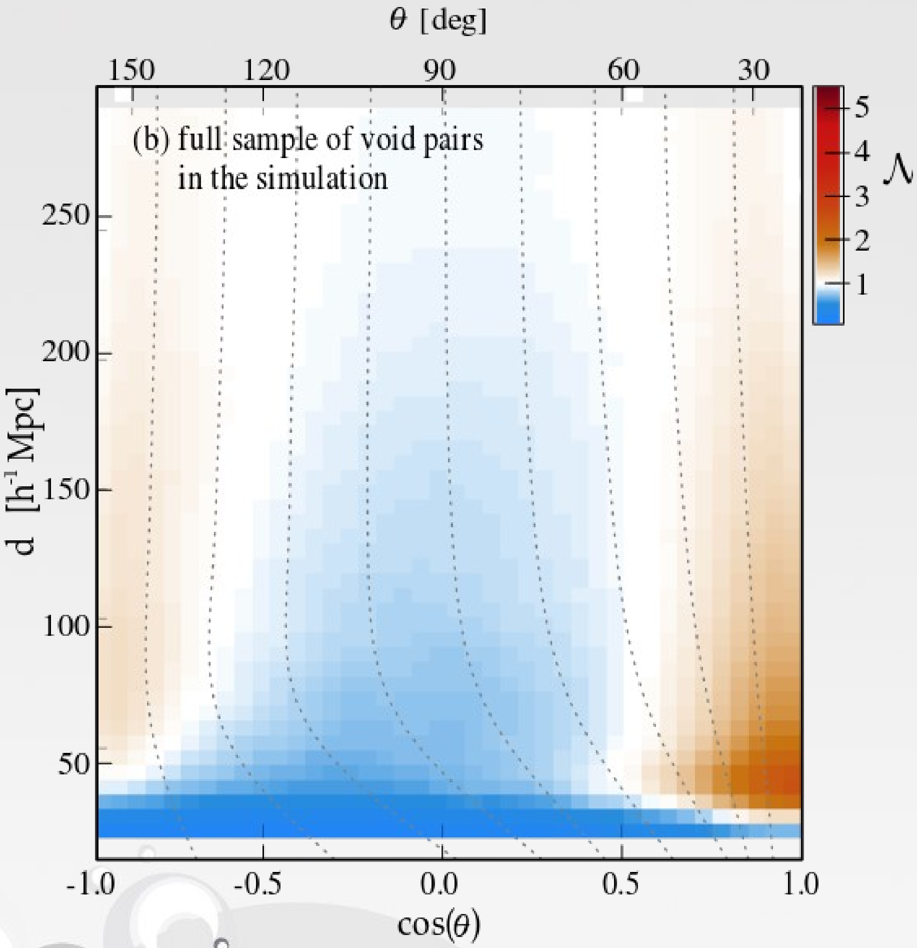
Large-scale flows can be understood as the result of the process of gravitational instability with overdense (underdense) regions attracting (repelling) material.

Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

The coherent motions of cosmic voids

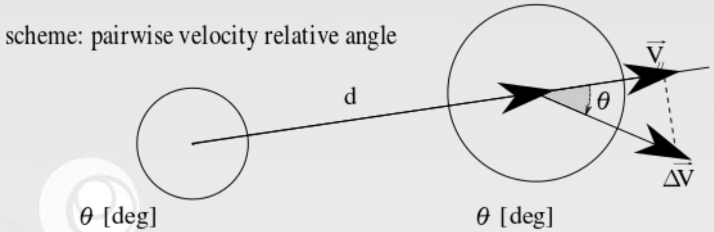


θ : angle between the void relative velocity and the void relative separation vectors



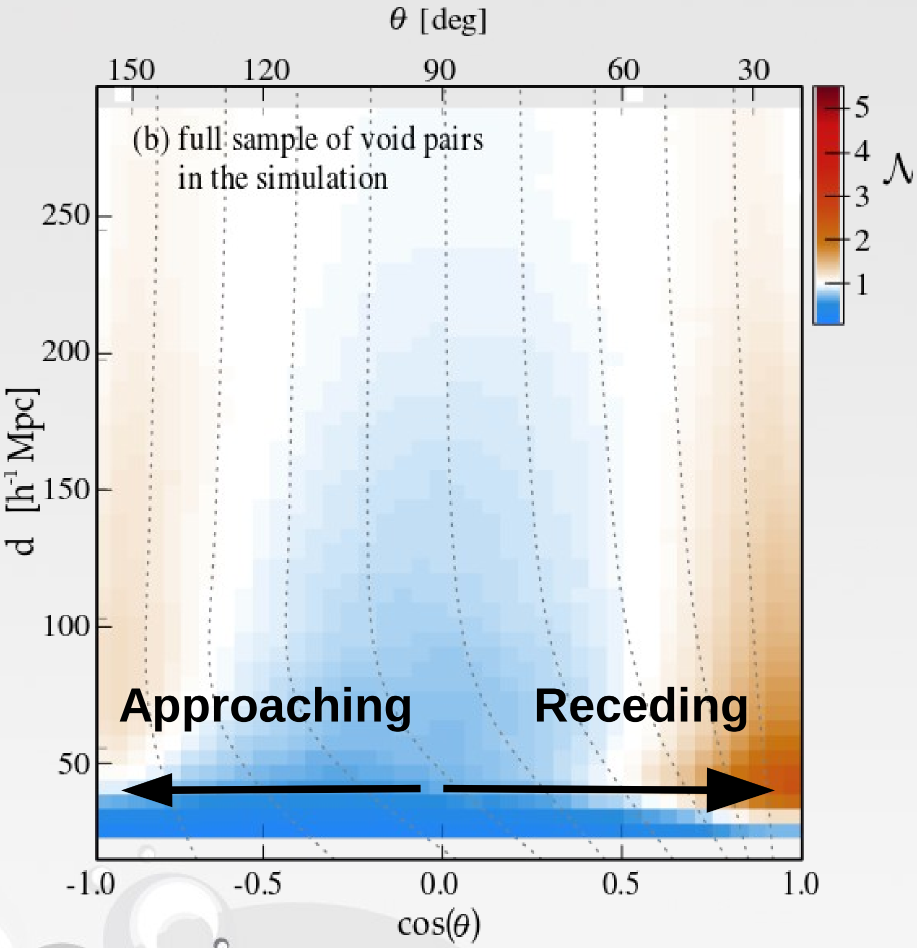
Lambas, Lares, Ceccarelli, Ruiz, Paz, Maldonado, Luparello. 2016, MNRAS Letters, 455, 99

The coherent motions of cosmic voids



the angle between the void relative velocity and the void relative separation vectors exhibits two peaks,

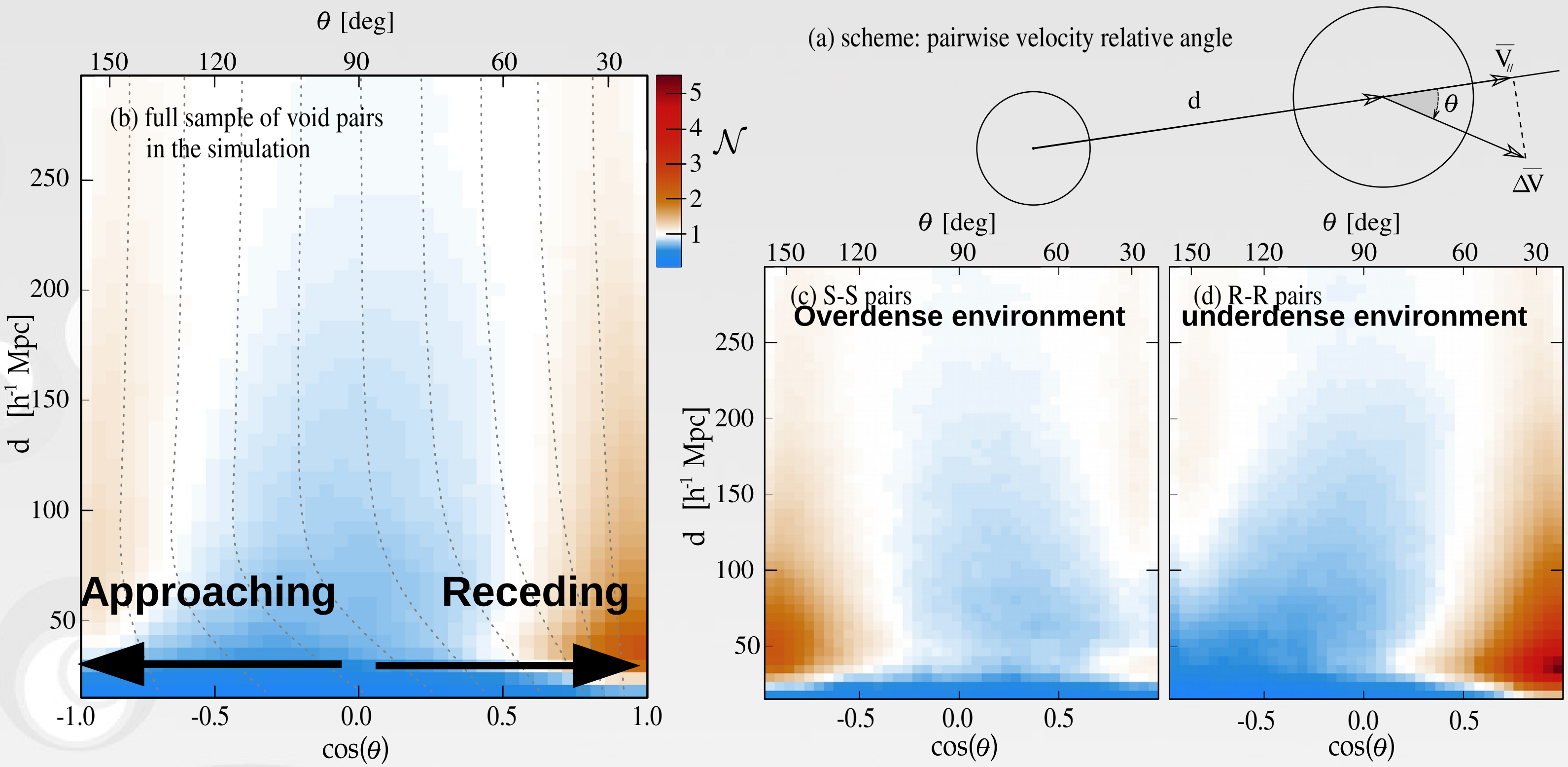
showing the presence of two populations with voids mutually receding and approaching



Given the strong dichotomy of void dynamics, link to local environment?

Lambas, Lares, Ceccarelli, Ruiz, Paz, Maldonado, Luparello. 2016, MNRAS Letters, 455, 99

The coherent motions of cosmic voids



angle between the void relative velocity and the void relative separation for voids in under/over dense environments

populations of mutually receding/approaching voids

S-type void pairs are systematically approaching each other while R-type voids are mutually receding

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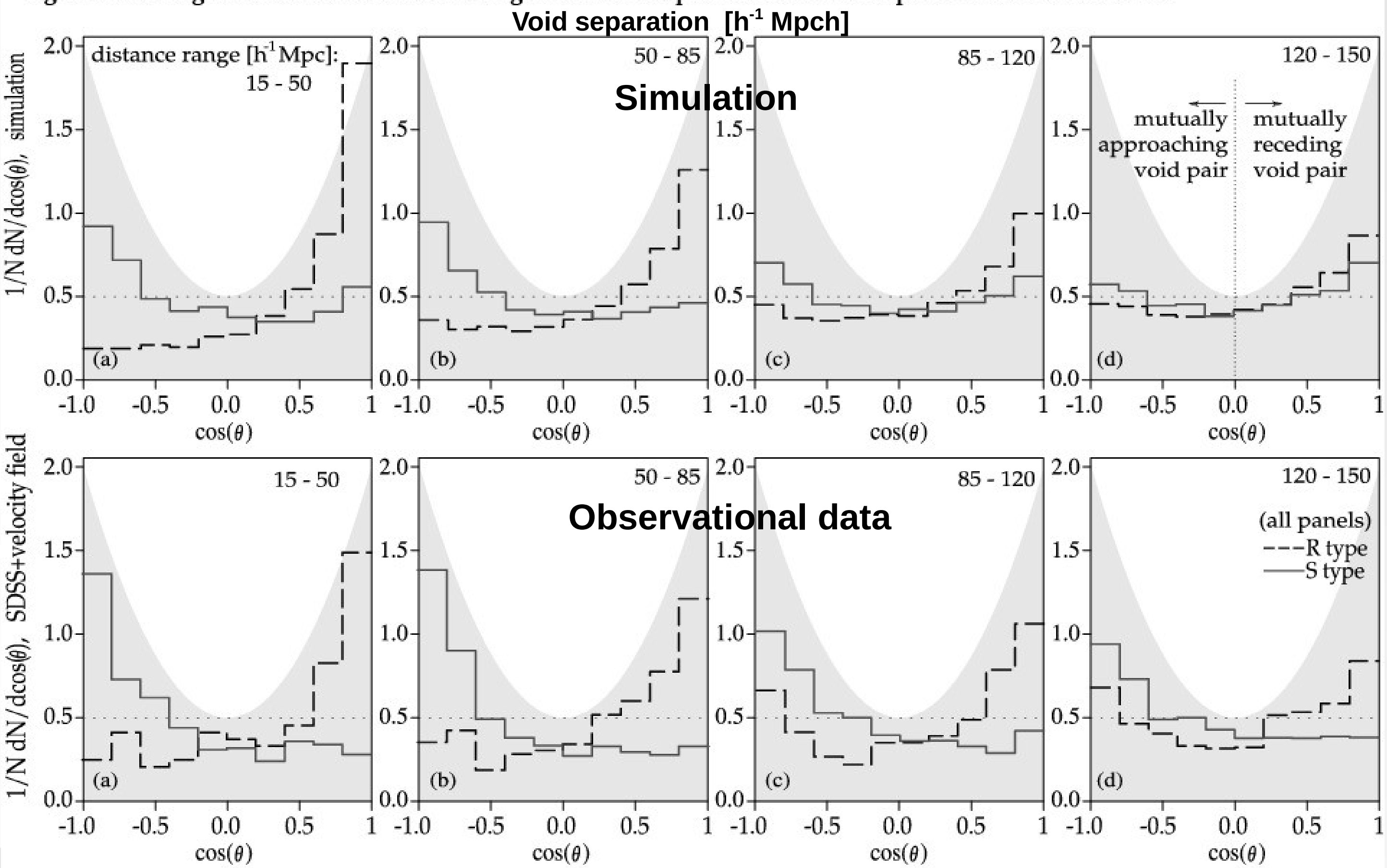
The coherent motions of cosmic voids

Bimodality of relative motions in observational data.

Histograms of cos(θ) for different void pair separations ranges in underdense (dashed) and overdense (solid) environments (R and S-types, respectively). We show for reference a quadrupolar distribution with arbitrary normalization. Histograms are normalized to show the excess of void pairs with respect to the expectation from a random distribution.

Figure 3 | Histograms of cosines of relative angles between separation vectors and pairwise relative velocities



The bimodality in observational data is consistent with the prediction of the ΛCDM model.

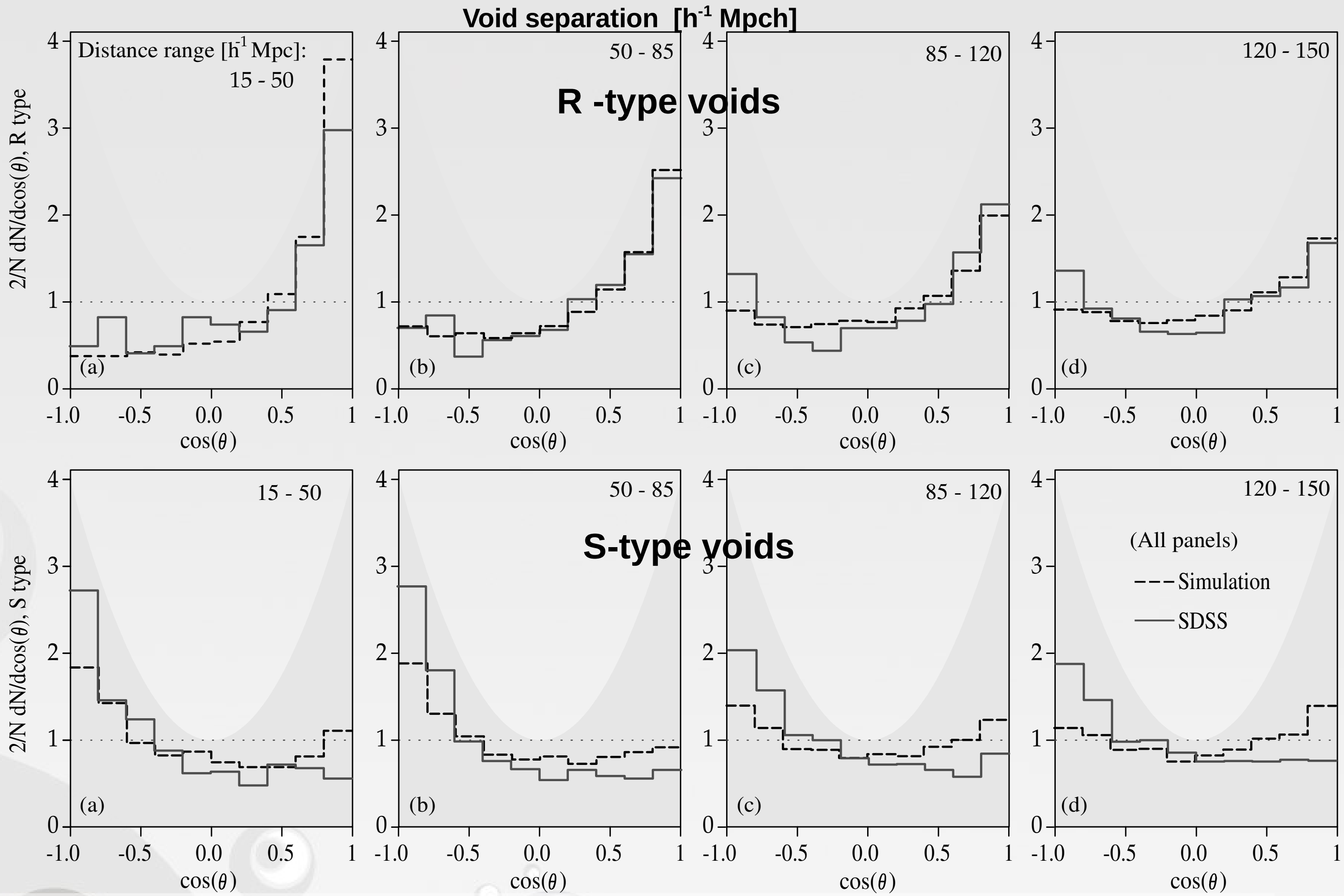
Two populations with voids mutually receding and approaching in observational data

Lambas et al. 2016

The coherent motions of cosmic voids

Bimodality of relative motions in observational data.

Histograms of cos(θ) for different void pair separations ranges in simulation box (dashed) and observational data (solid). Histograms are normalized to show the excess of void pairs with respect to the expectation from a random distribution.



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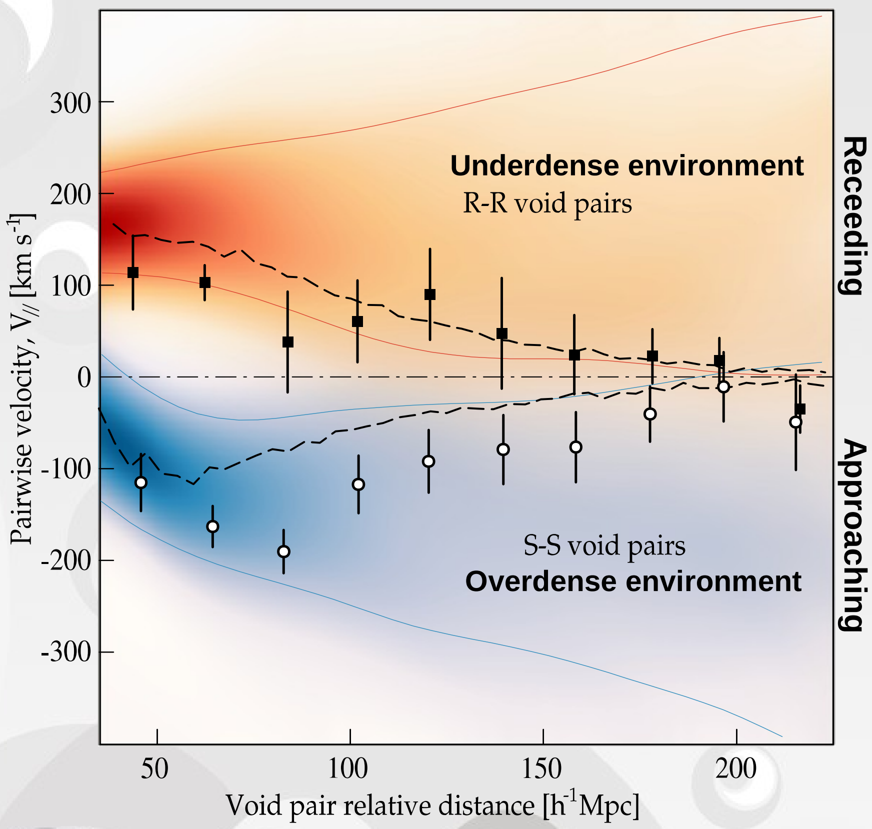
Lambas et al. 2016

The coherent motions of cosmic voids



Mean pairwise velocity values of the observational and simulated voids as a function of void relative separation.

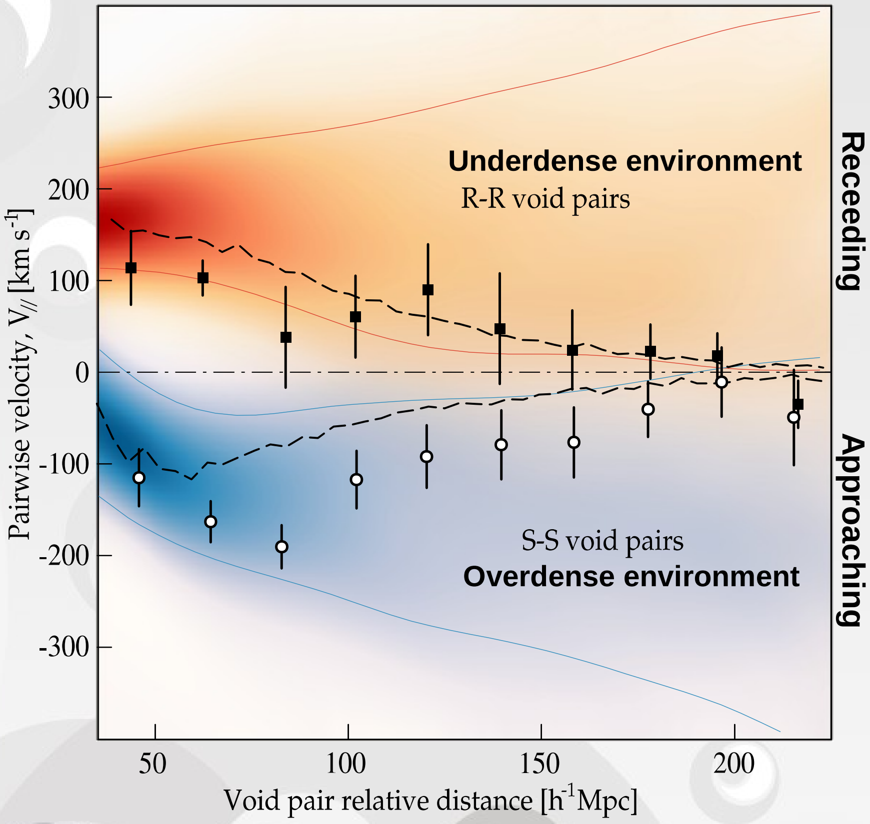
The colour density maps correspond to the results of R-R (red) and S-S (blue) void pairs in sub-boxes taken at simulation constrained to account cosmic variance in SDSS.

The thin blue and red lines correspond to the 0.16 and 0.84 quantiles of the distribution of V // , for S-S and R-R void pairs, respectively.

The thick dashed lines correspond to the full simulation box results for R-R and S-S pairs. Points represent SDSS results.

Lambas et al. 2016

The coherent motions of cosmic voids



Mean pairwise velocity values of the observational and simulated voids as a function of void relative separation.

The colour density maps correspond to the results of R-R (red) and S-S (blue) void pairs in sub-boxes taken at simulation constrained to account cosmic variance in SDSS.
The thin blue and red lines correspond to the 0.16 and 0.84 quantiles of the distribution of V // , for S-S and R-R void pairs, respectively.
The thick dashed lines correspond to the full simulation box results for R-R and S-S pairs. Points represent SDSS results.

The observational results are entirely consistent with the prediction of the ΛCDM model.

Voids behave either receding or approaching each other according to their R/S-type classification with velocities of the order of 100–150 km/s up to 200 Mpc/h separation.

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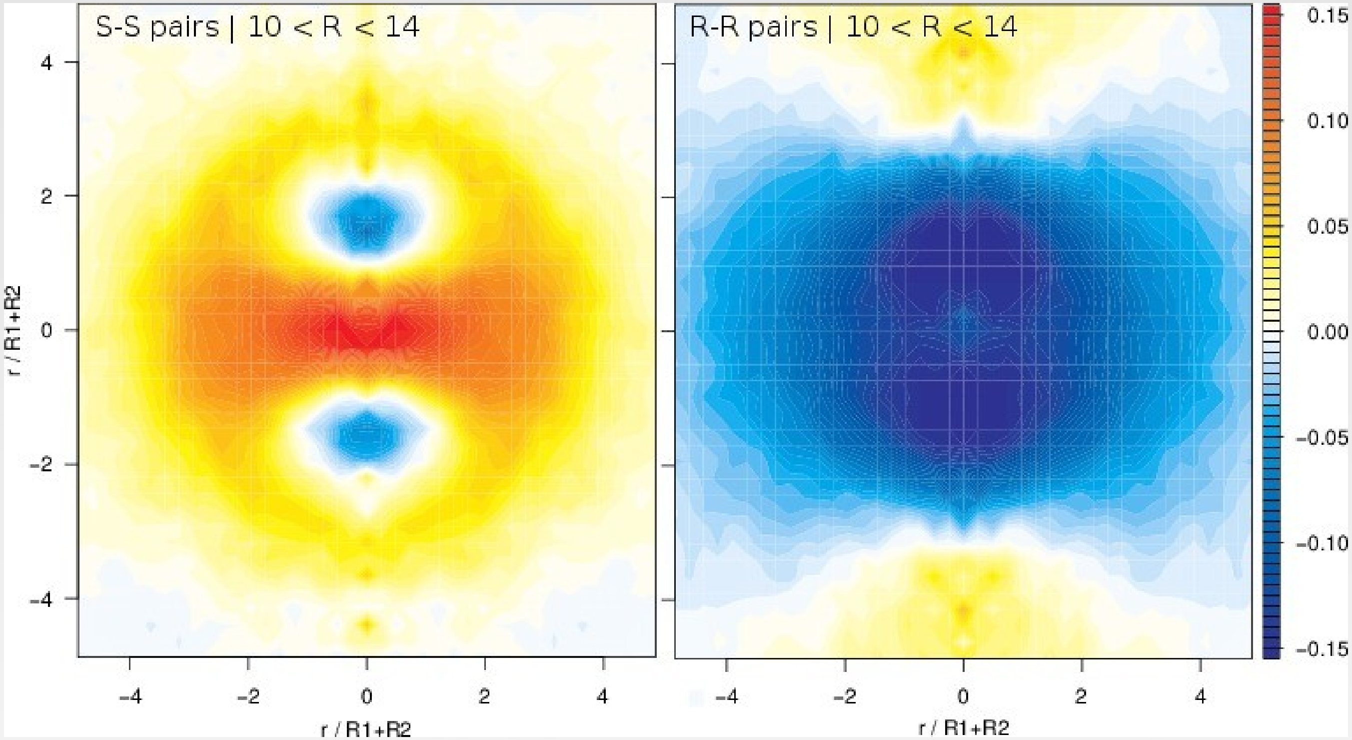


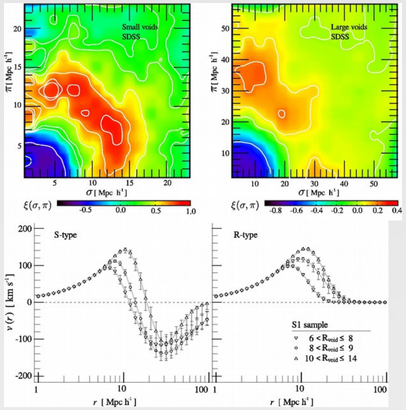
Stacked mass density for S-S and R-R void pairs. The y-axis is oriented to the velocity difference direction.

As this direction is aligned with the relative separation direction, the coherent pattern emerges

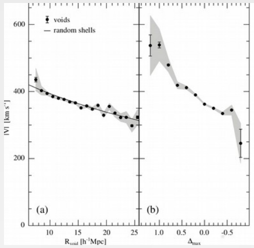
Ceccarelli, Ruiz, Lares, Paz, Maldonado, Luparello, Lambas. 2016, to be published in MNRAS.

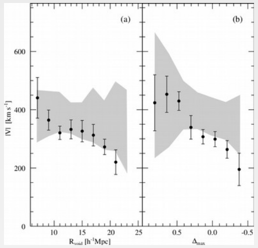
Summary: results on void dynamics

➔We obtained observational evidence of a twofold population of voids according to their dynamical properties as predicted by theoretical considerations (Ceccarelli et al. 2013, Paz et al. 2013, Ruiz et al. 2015).

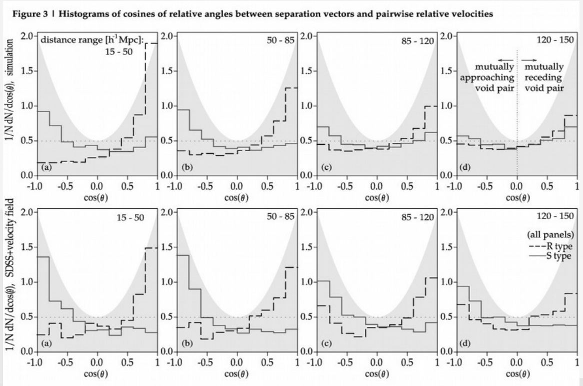


➔**We reported significant motions of cosmic voids as a whole and studied the coherence pattern associated to the void velocity field up to large cosmological scales, both in simulations and observations** (Lambas et al. 2016, Ceccarelli et al. 2016, MNRAS accepted).





➔We reported the bimodality on void pairwise velocities in simulations and observations, with approaching and receding voids according to their local environment (Lambas et al. 2016).



Summary: Final remarks

Voids have an active interplay with large--scale flows affecting the formation and evolution of structures in the Universe.

These large-scale underdensities exhibit local expansion which, depending on the large-scale environment, can be reverted to collapse at larger scales, generating global convergent or divergent flows.

Void coherent bulk velocities, with a bimodal dynamical population of mutually attracting or receding systems, contribute to imprint large scale cosmic flows, shaping the formation of future structures in the Universe.

The non-negligible void velocities suggest a scenario of galaxies flowing away from voids with the additional contribution of void bulk motion to the total galaxy velocity