Precision Cosmology with Cosmic Voids

LPSC Seminar

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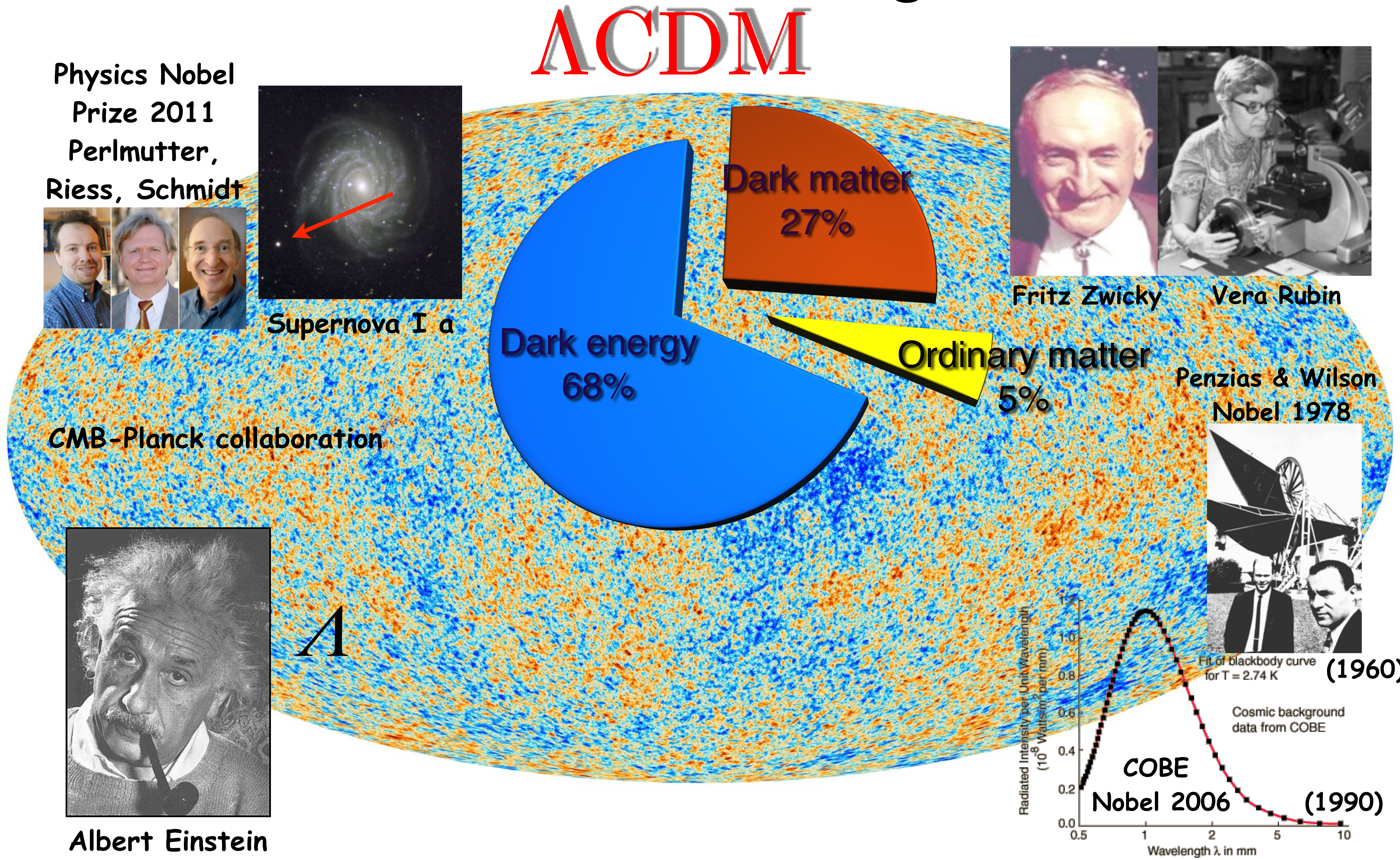
20/10/2015

Credit: Millennium simulation

Outline

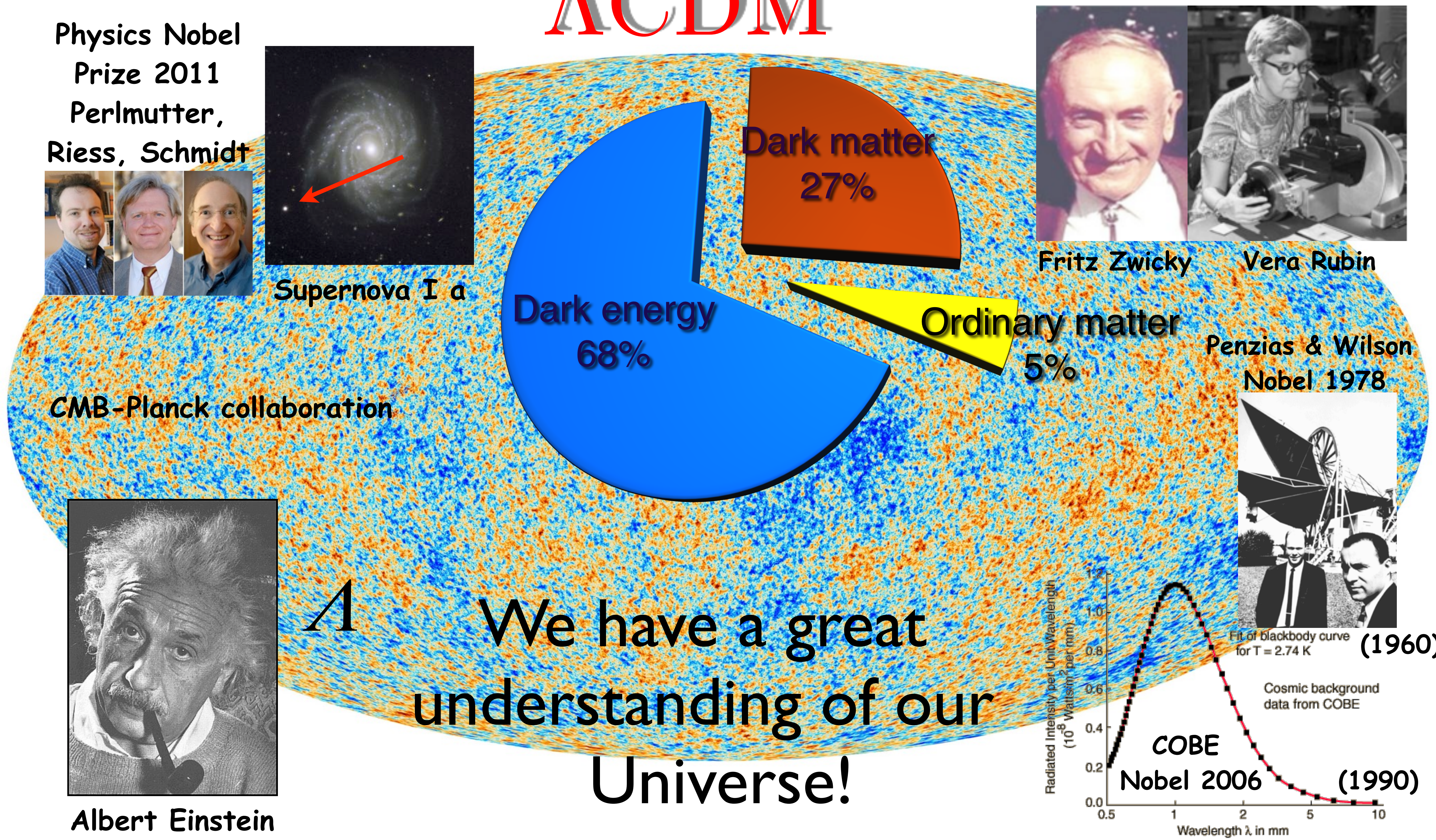
- Introduction
- Voids as tools for Cosmology
- Finding voids and measuring the expansion
- Can we access to the real space information?
- Can we master peculiar velocities on voids?
- What can we expect from the future?

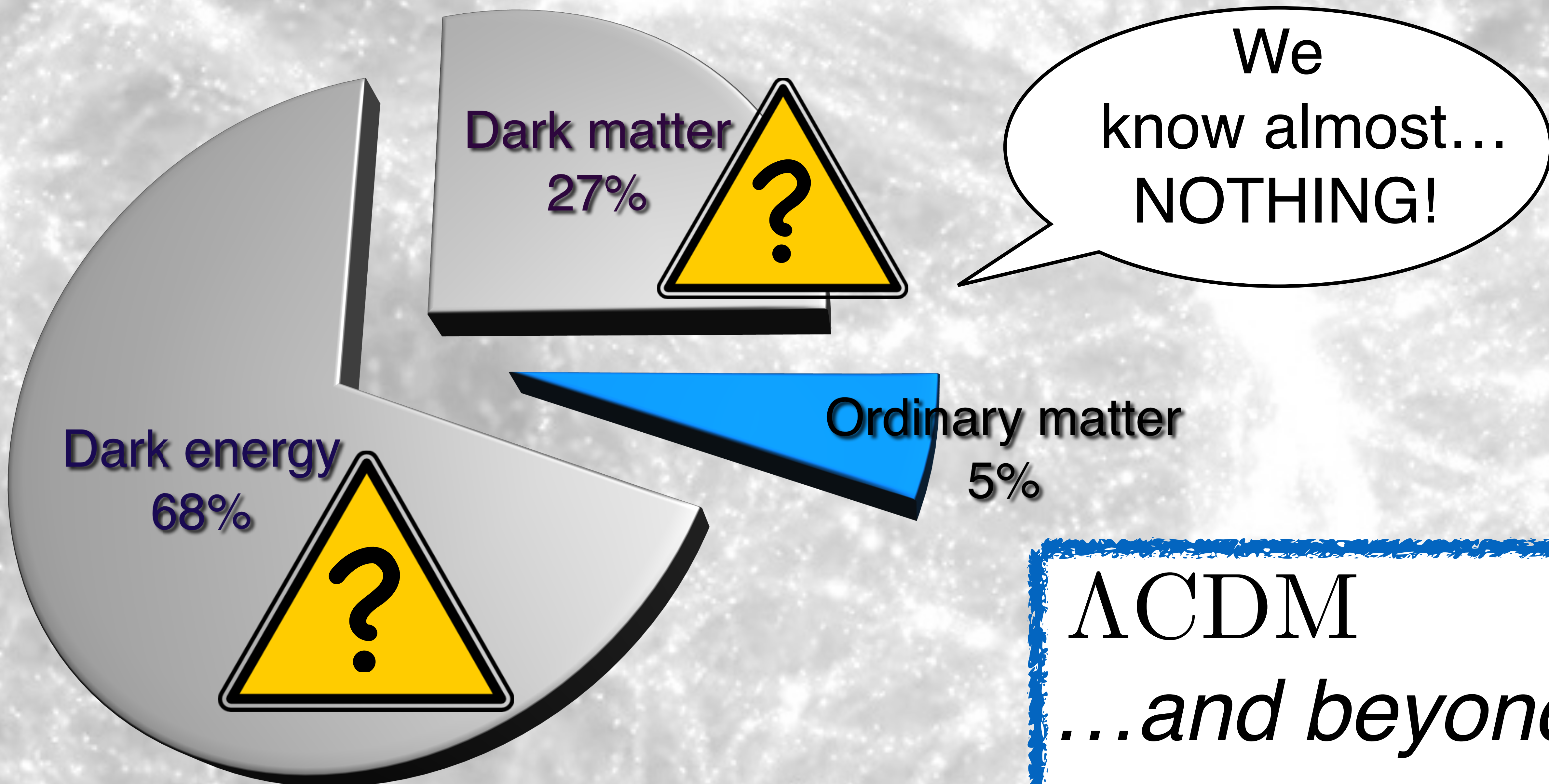
The standard cosmological model



The standard cosmological model

ΛCDM



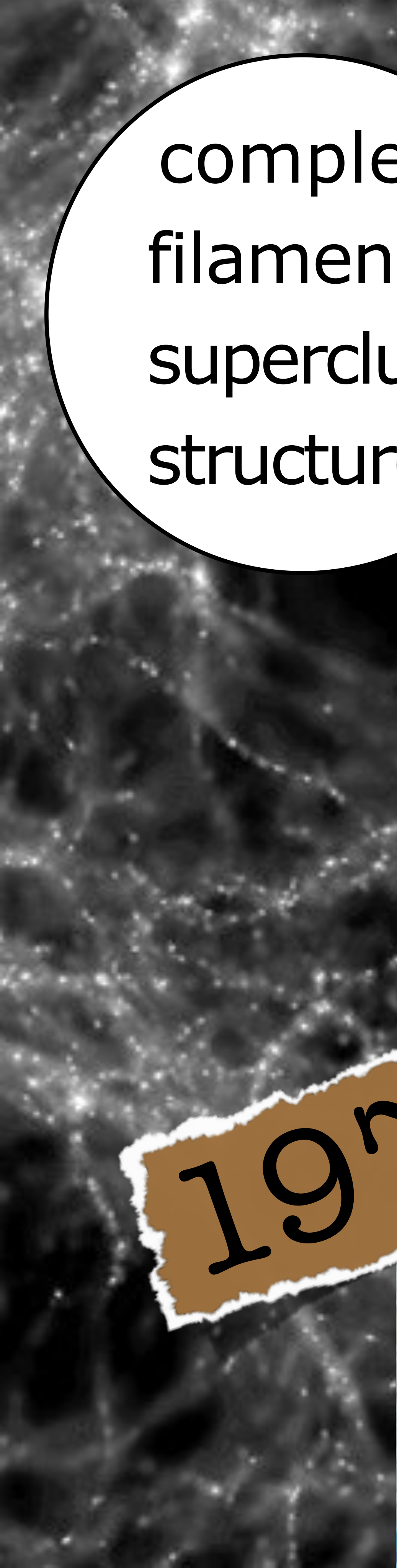


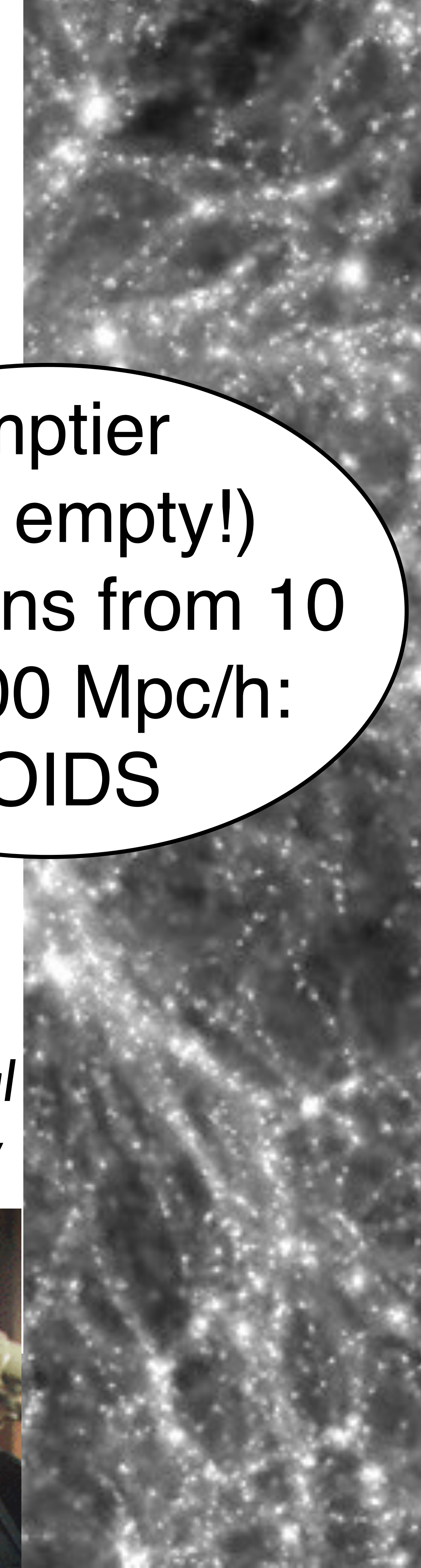
ΛCDM

…and beyond

The study of large scale structures is a powerful tool to understand the composition of the universe.

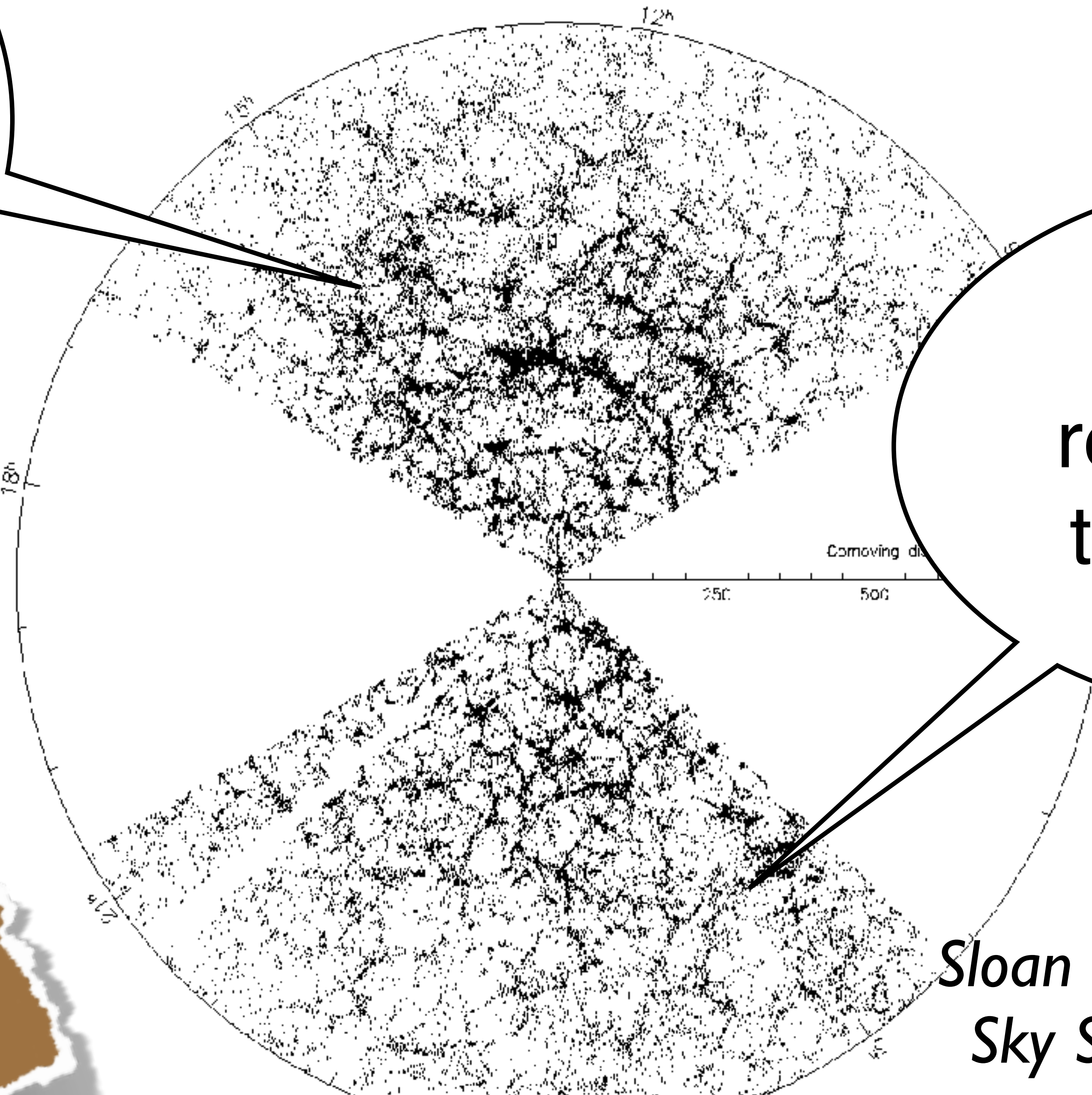
The cosmic web





complex filamentary supercluster structures

emptier (not empty!) regions from 10 to 100 Mpc/h: VOIDS



Sloan Digital Sky Survey

1977

Are voids there?

1977

Credit: Thompson and Gregory 1977

Peebles Abell Longair Einasto

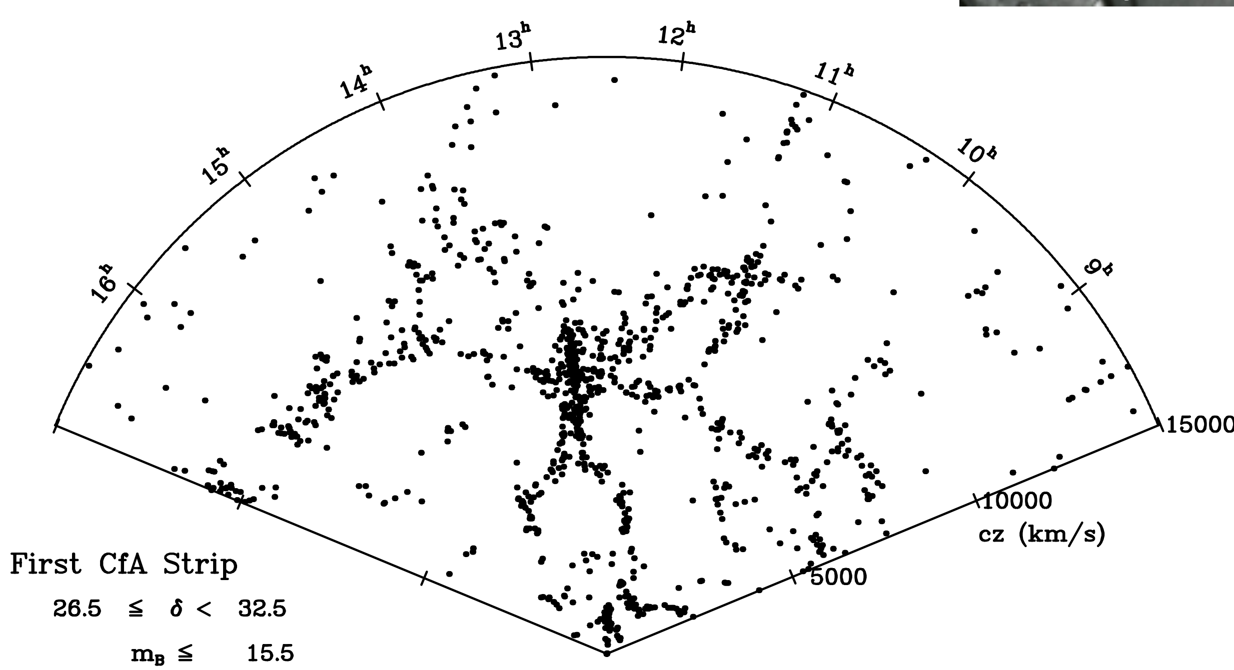
Are voids there?

1977

Credit: Thompson and Gregory 1977

Credit: Jaan Einasto private collection

Peebles Abell Longair Einasto



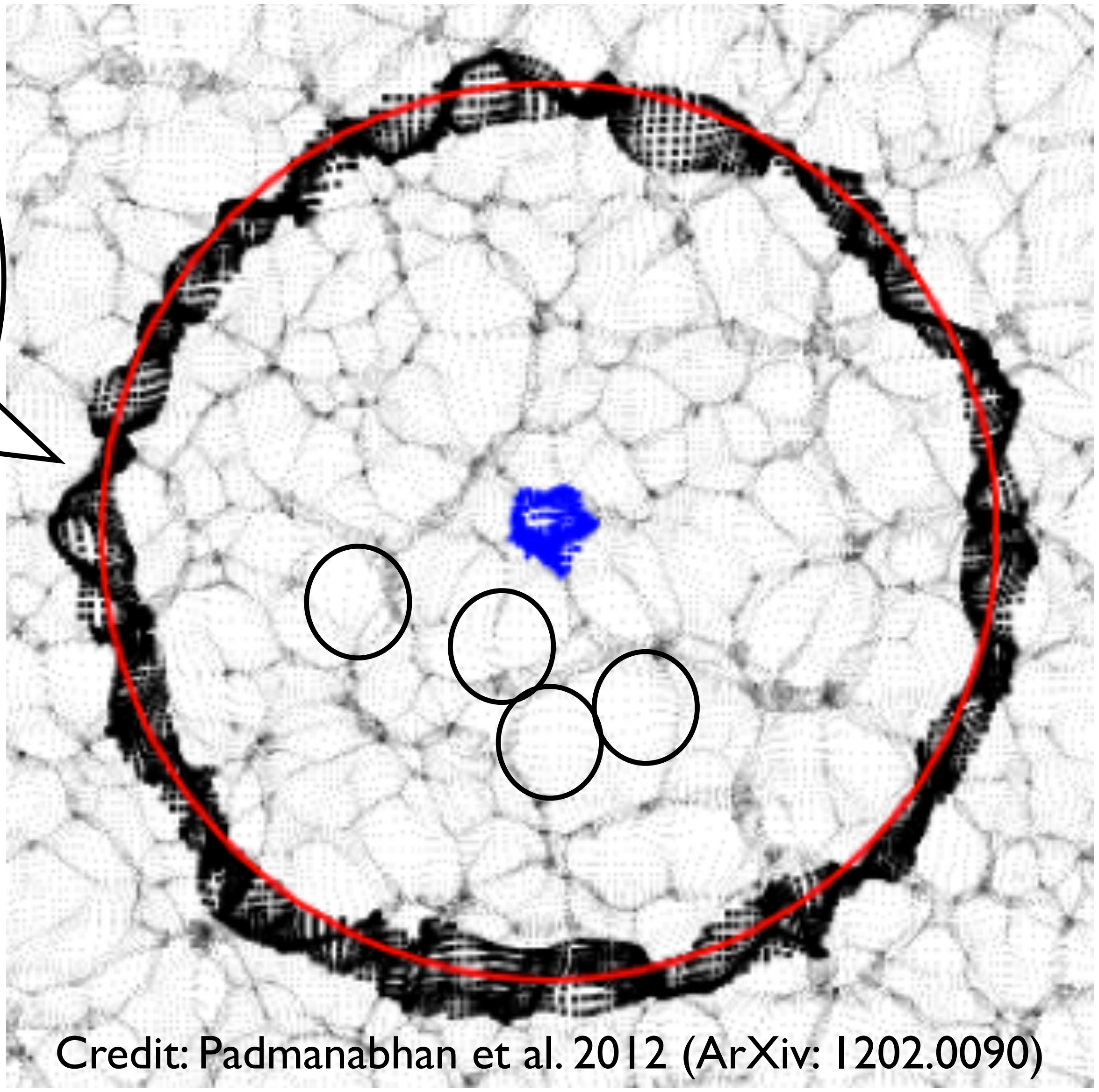
1986

Credit: de Lapparent et al. 1986

Can we use voids to get cosmological information?

In voids matter is missing=> Dark Energy

BAO compared to void



Small to intermediate scale distribution is potentially more sensitive: more scales!

Fundamental physics: voids are more likely to be sensitive to diffuse components (e.g. ν).

If Dark Energy exists, cosmic voids are a new tool to constrain it.

If not ΛCDM ? Do we need to modify gravity?

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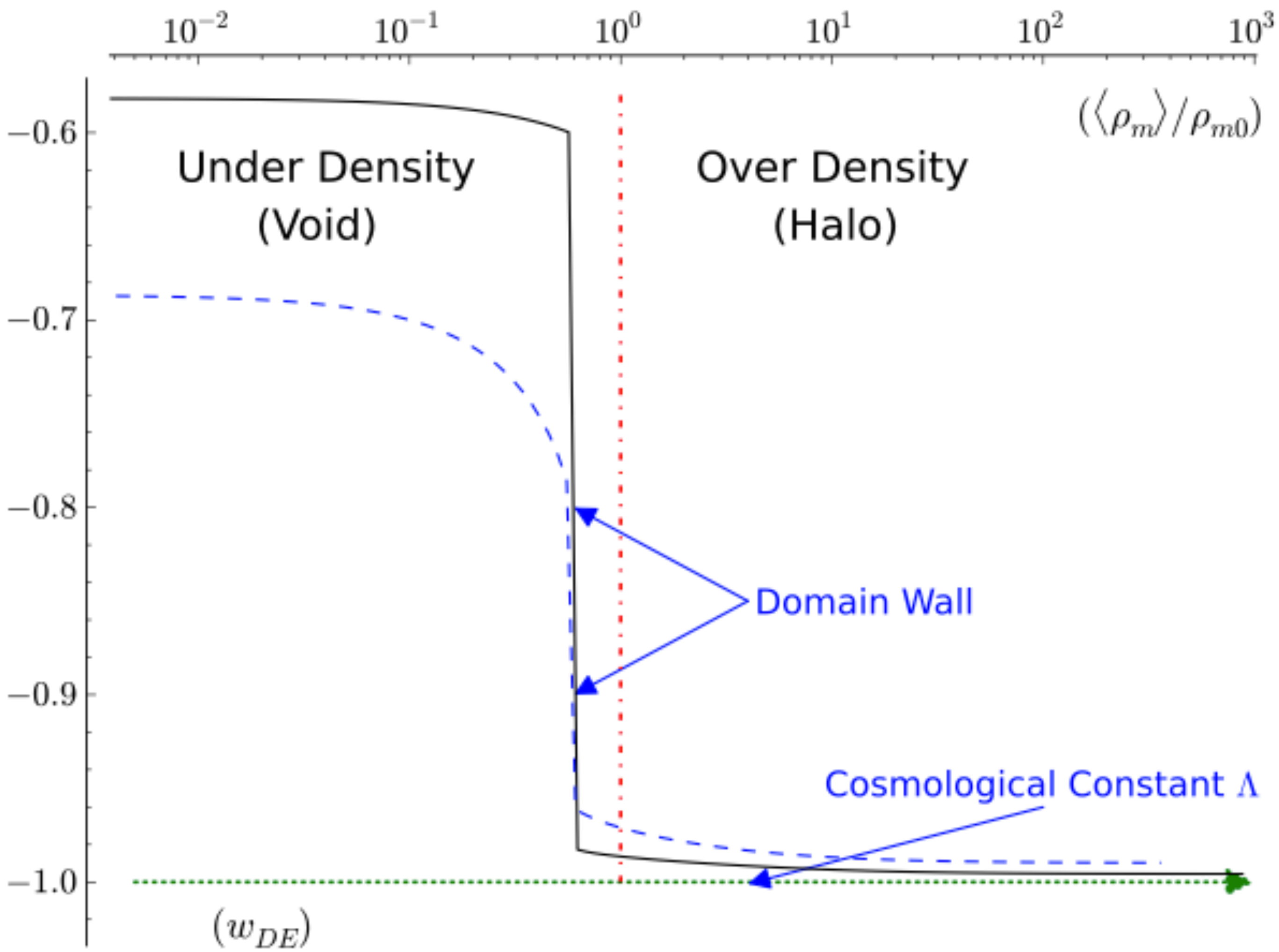


MASSIVE GRAVITY MODELS

Graviton could become massive, which would introduce a new scalar field.

The equation of state could be DENSITY and SCALE DEPENDENT

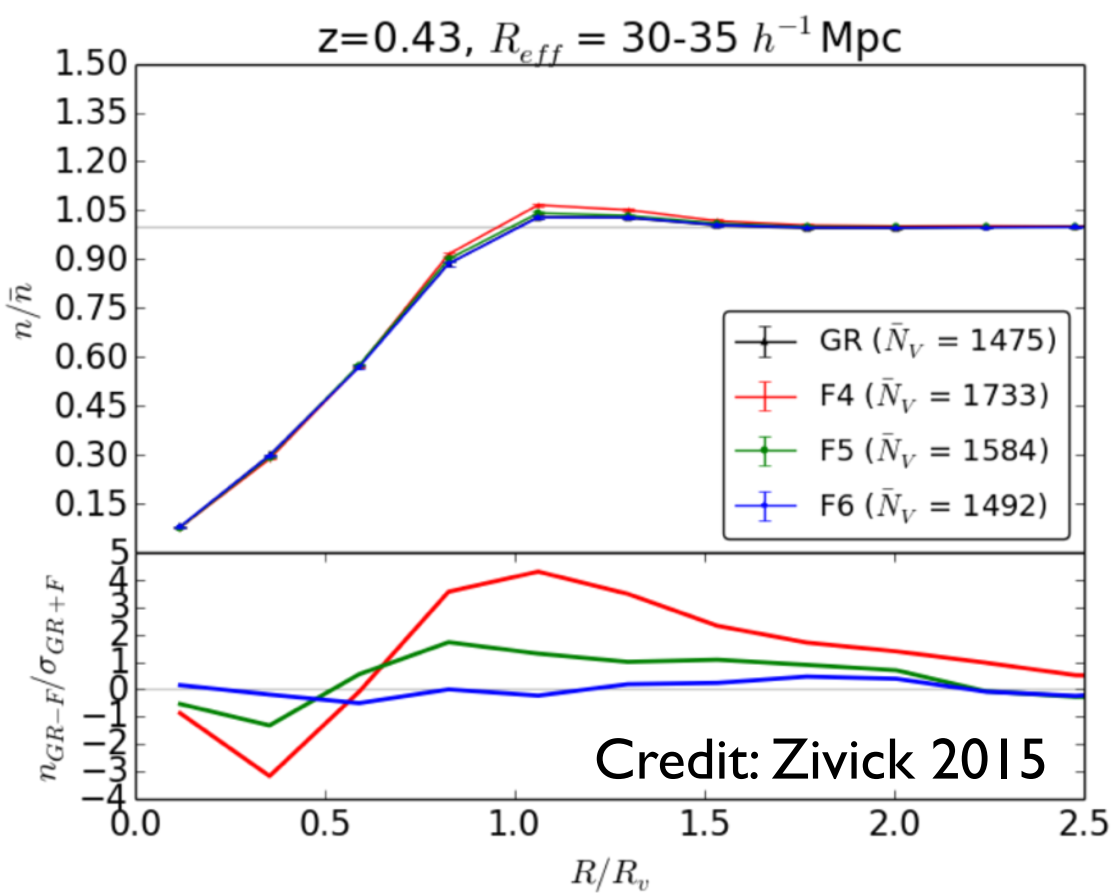
In lower density zones the effect of Modified Gravity should be different!

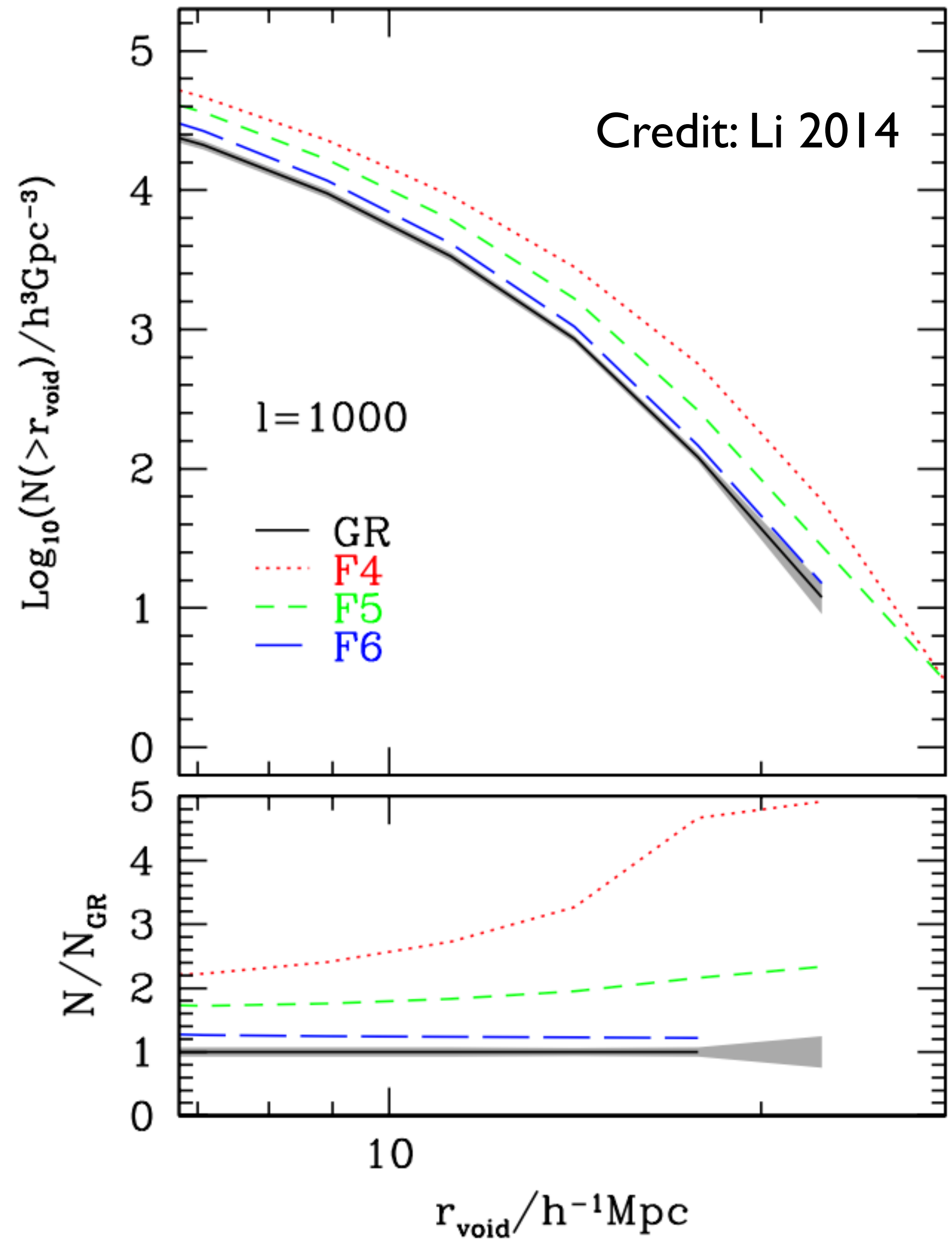
▶ Growth rate

Credit: Spolyar et al. (ArXiv: 1304.5239)

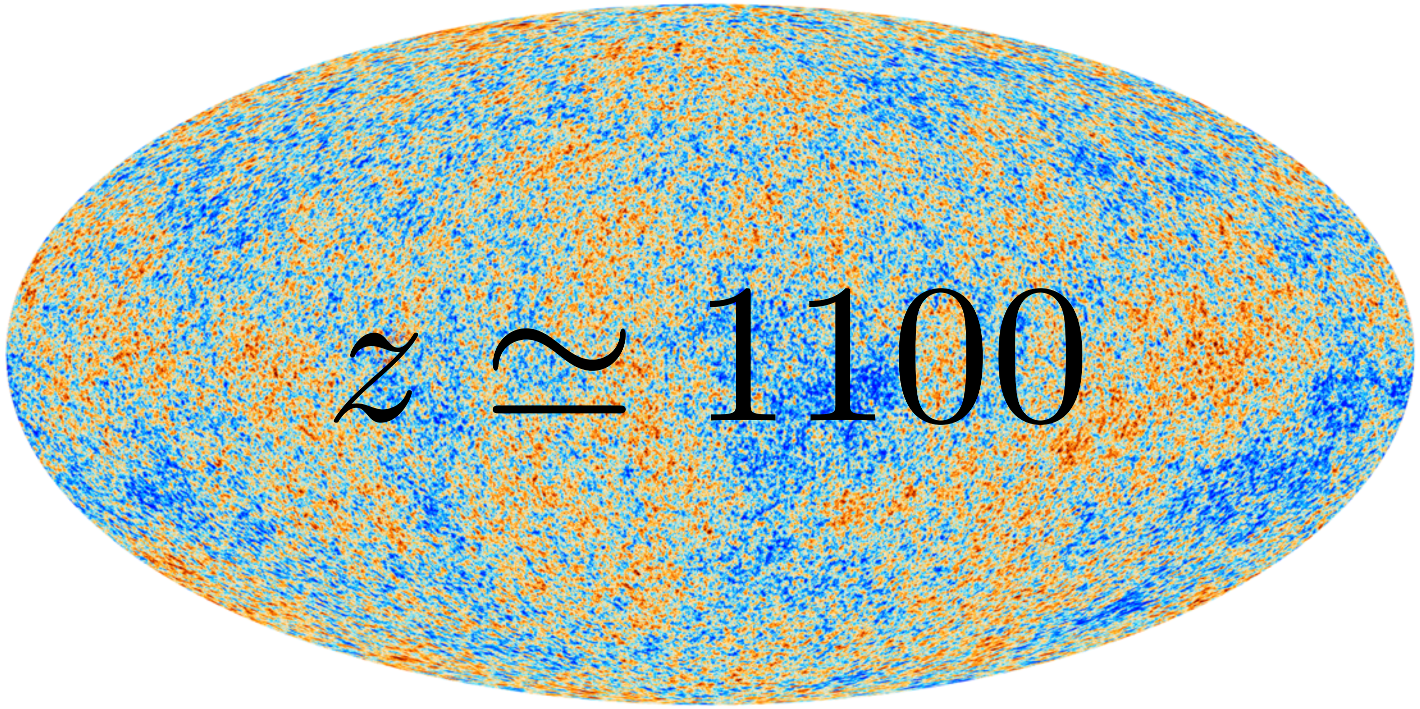
Modified gravity, the LSS might be different

- Density profiles
- Void abundances

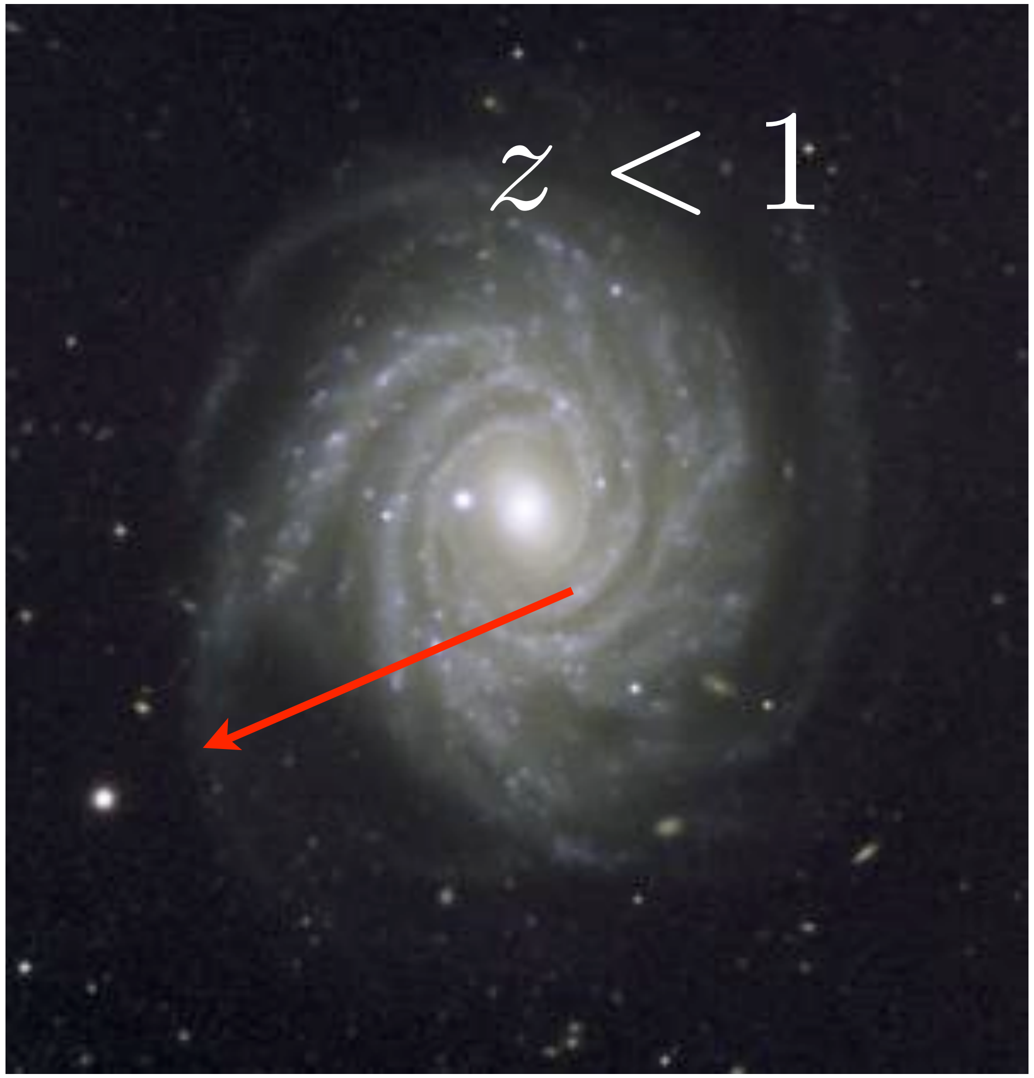


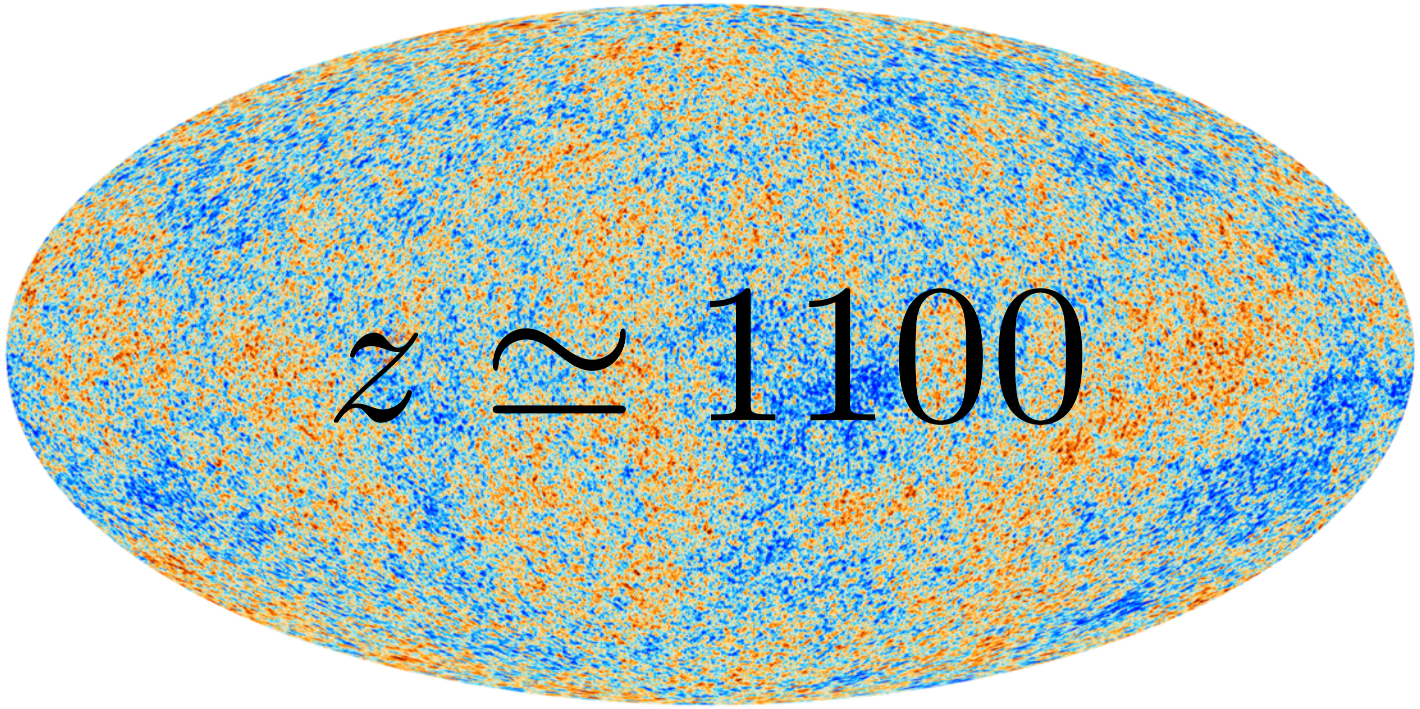


Analyze void properties to constrain cosmological models



CMB anchor + late time measure of the expansion is the way to constrain dark energy





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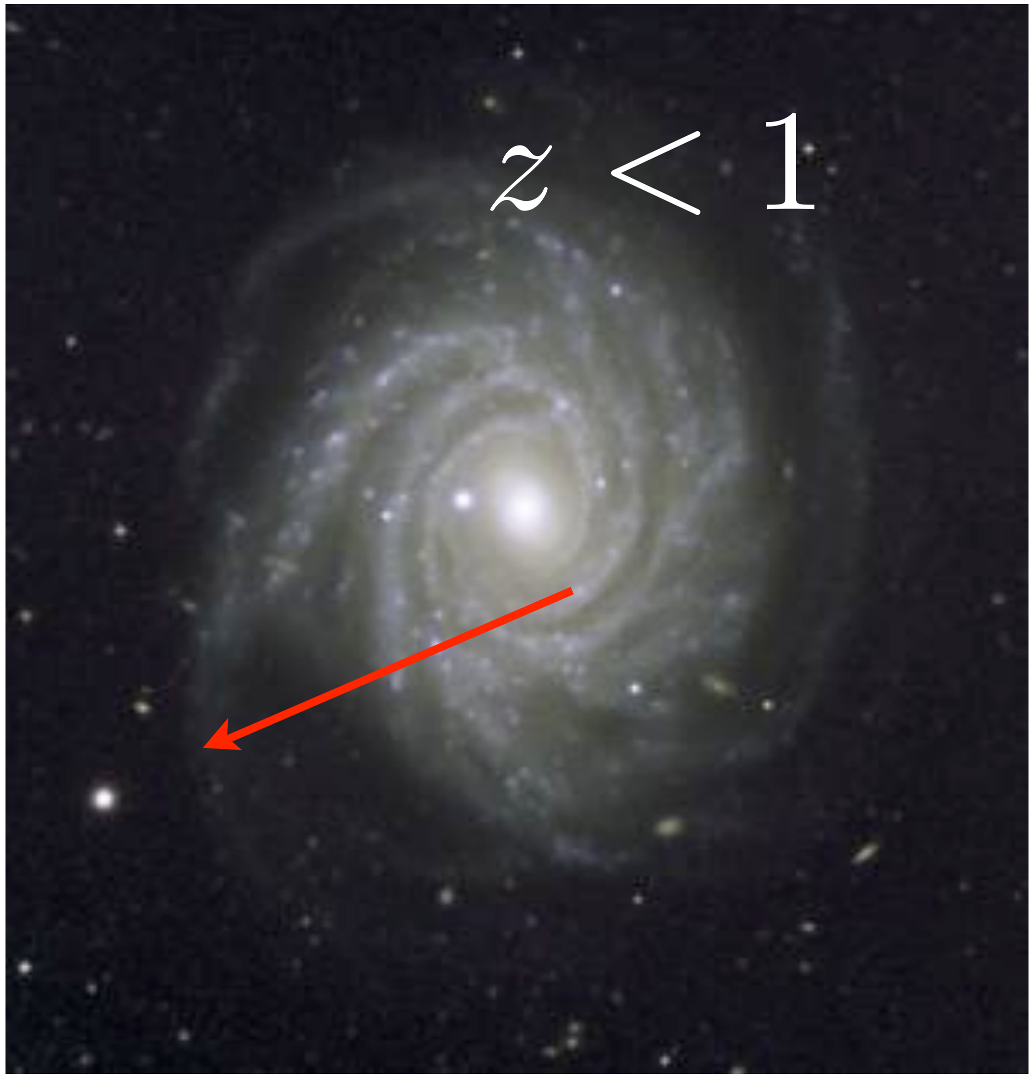


Voids (LSS) can give a measure at late time

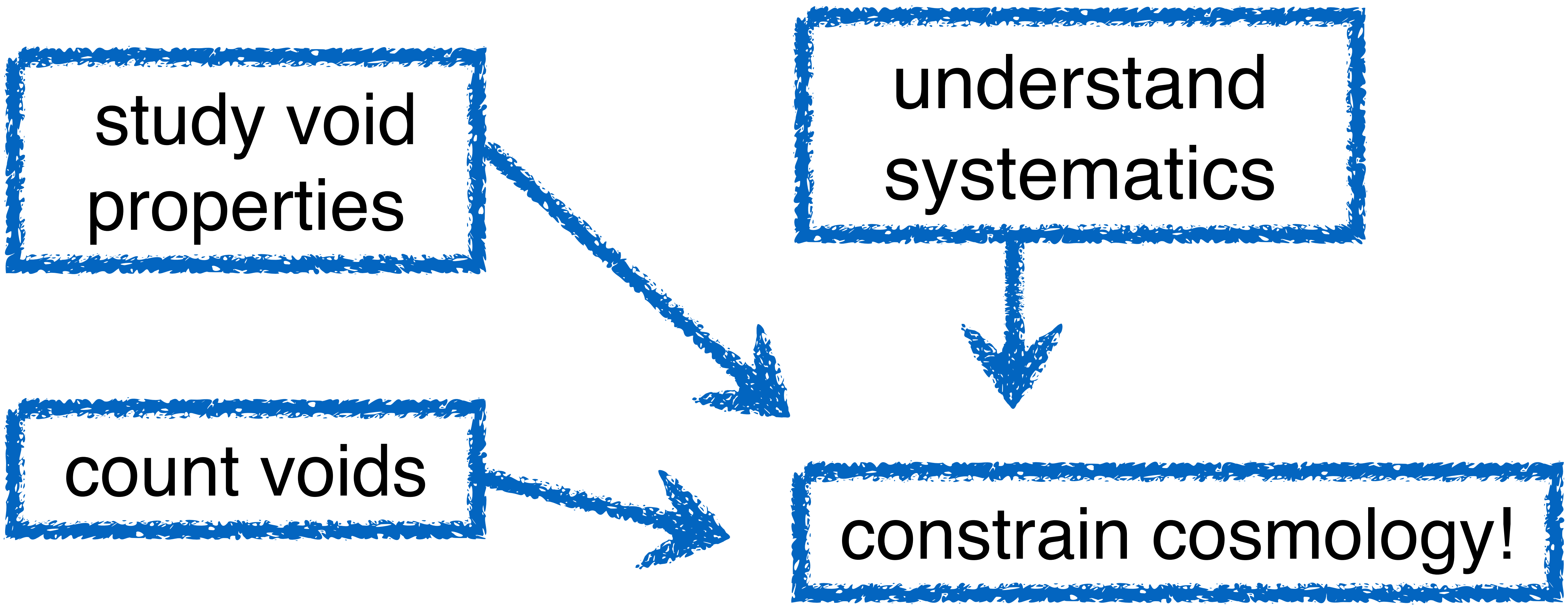
Studying voids gives a window on dark energy

study void properties

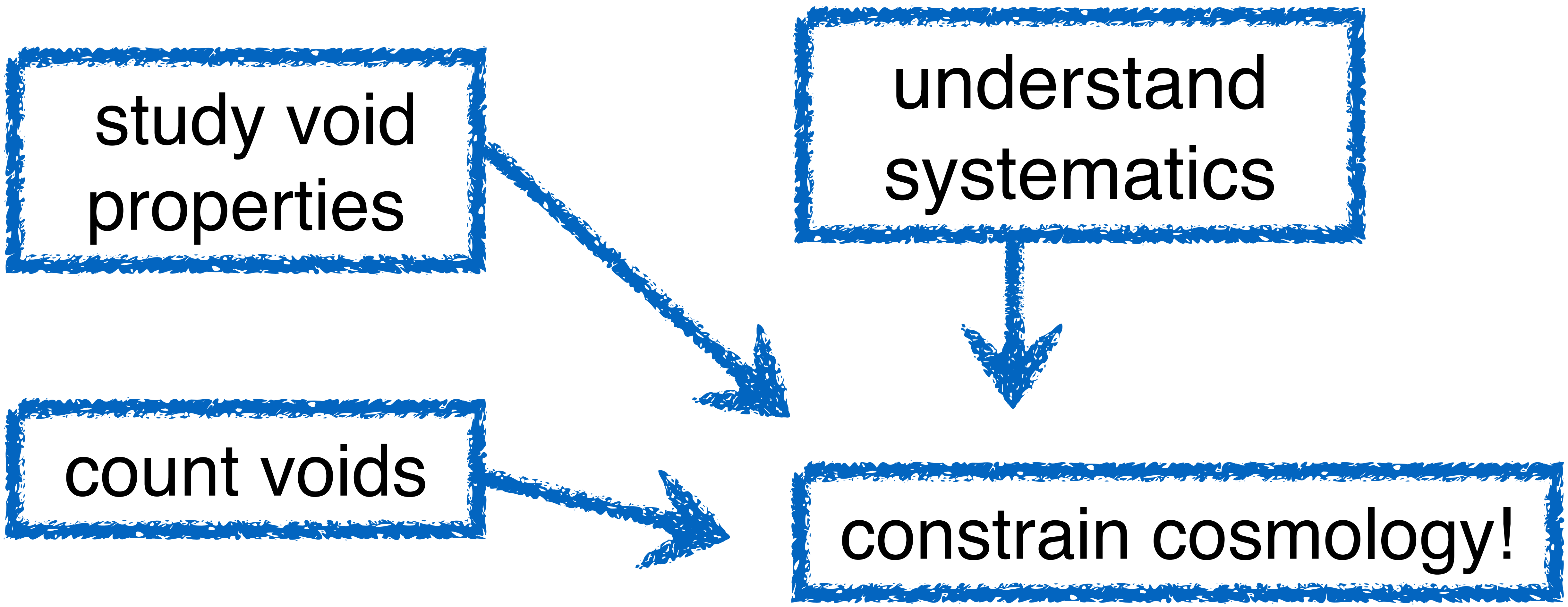
understand systematics

count voids

Studying voids gives a window on dark energy



Studying voids gives a window on dark energy



But first we need to ***find voids***

Void IDentification and Examination

Based on Zobov (Neyrinck 2008)

galaxy survey or simulation → Voronoi tessellation → Watershed transform → Voids

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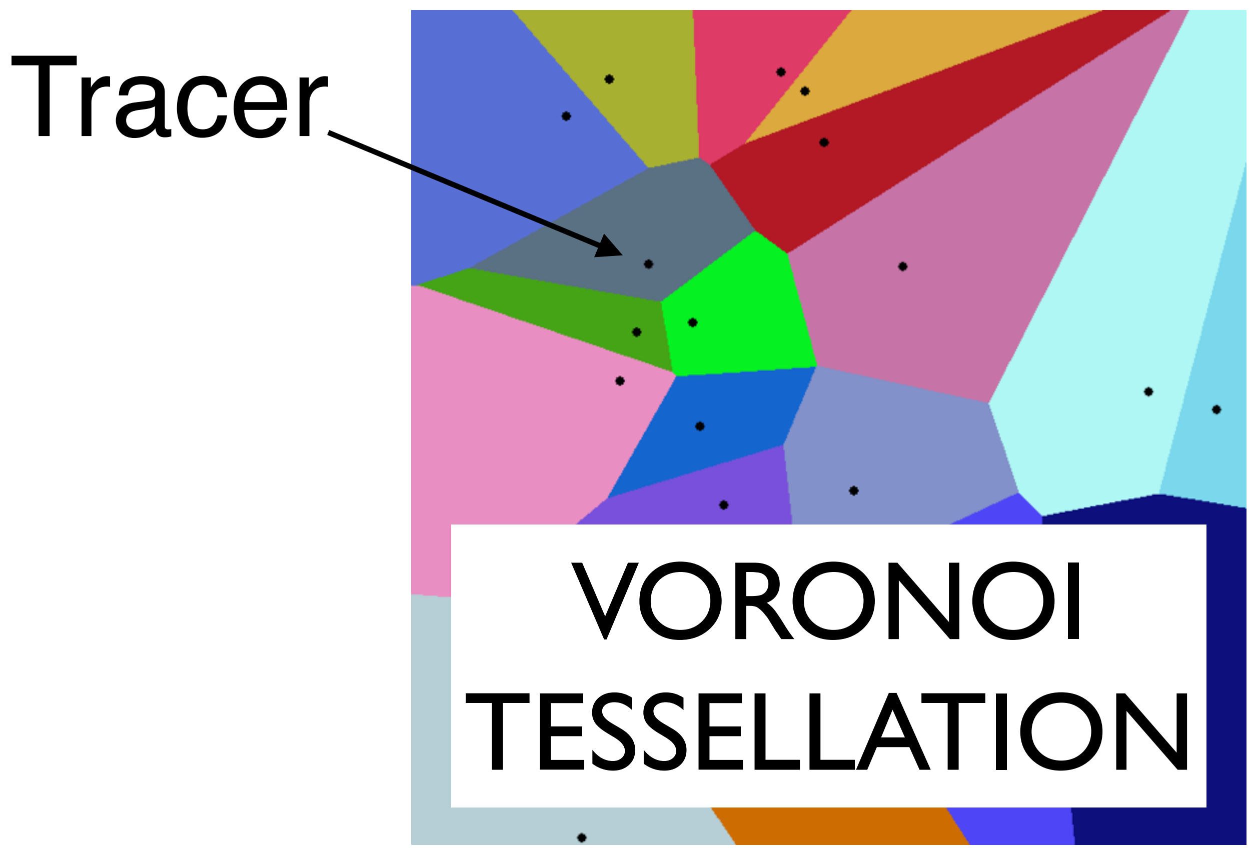

Void IDentification and Examination

Based on Zobov (Neyrinck 2008)

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Tracer

All points closer to the tracer than to any other point

$$\rho_{local} = \frac{1}{V_{cell}}$$

Icke & Van de Weygaert (1987)

Void IDentification and Examination

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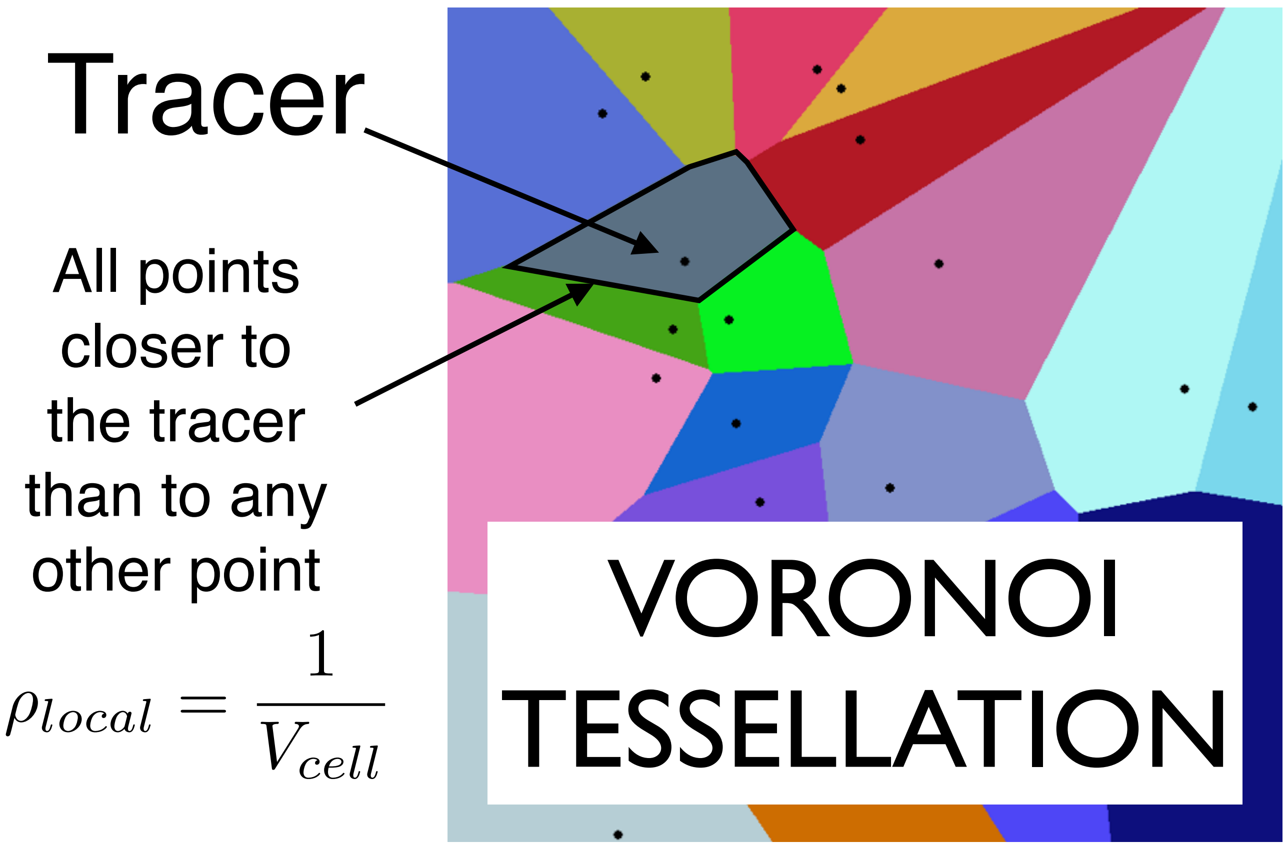

$$\rho_{local} = \frac{1}{V_{cell}}$$

Cells merged into basins, which center is the cell only surrounded by higher density cells (local minima).

Icke & Van de Weygaert (1987)

Void IDentification and Examination

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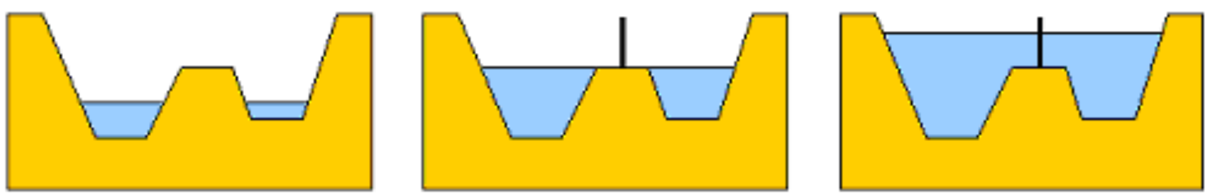
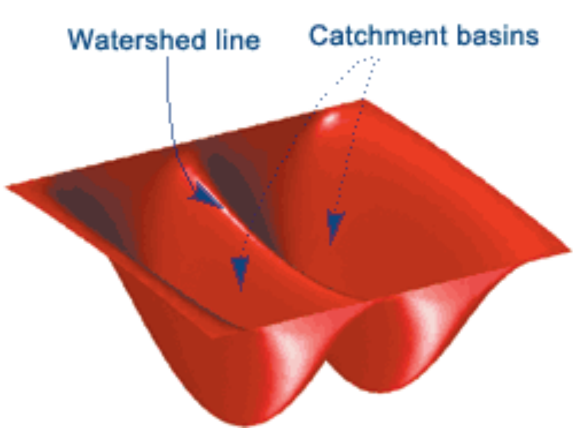


Each basin is a sub-void. Basins are merged in one void if, the border with lower density is common.



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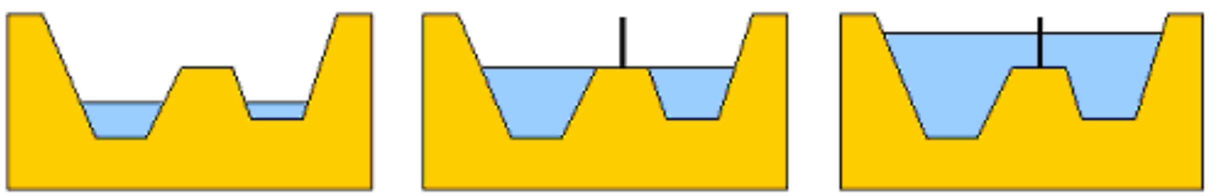
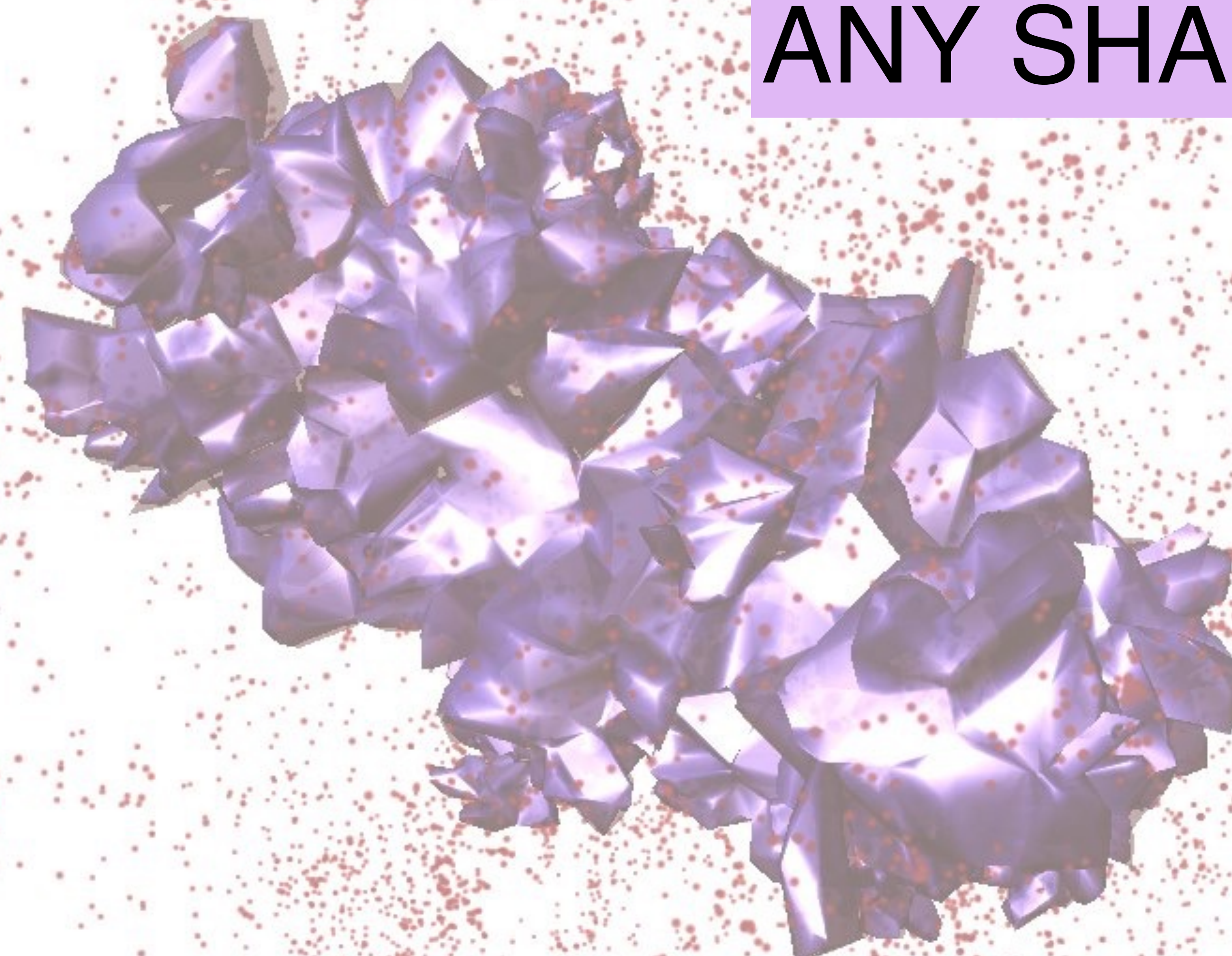


ANY SHAPE



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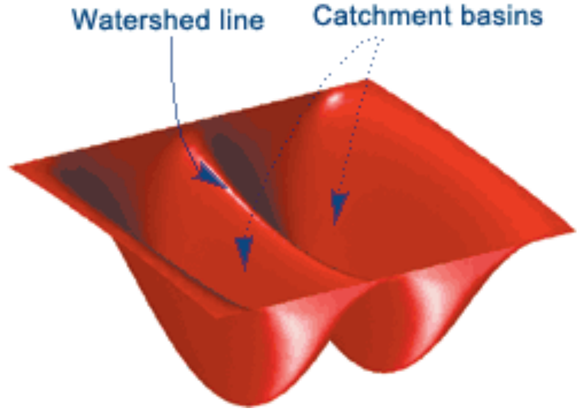
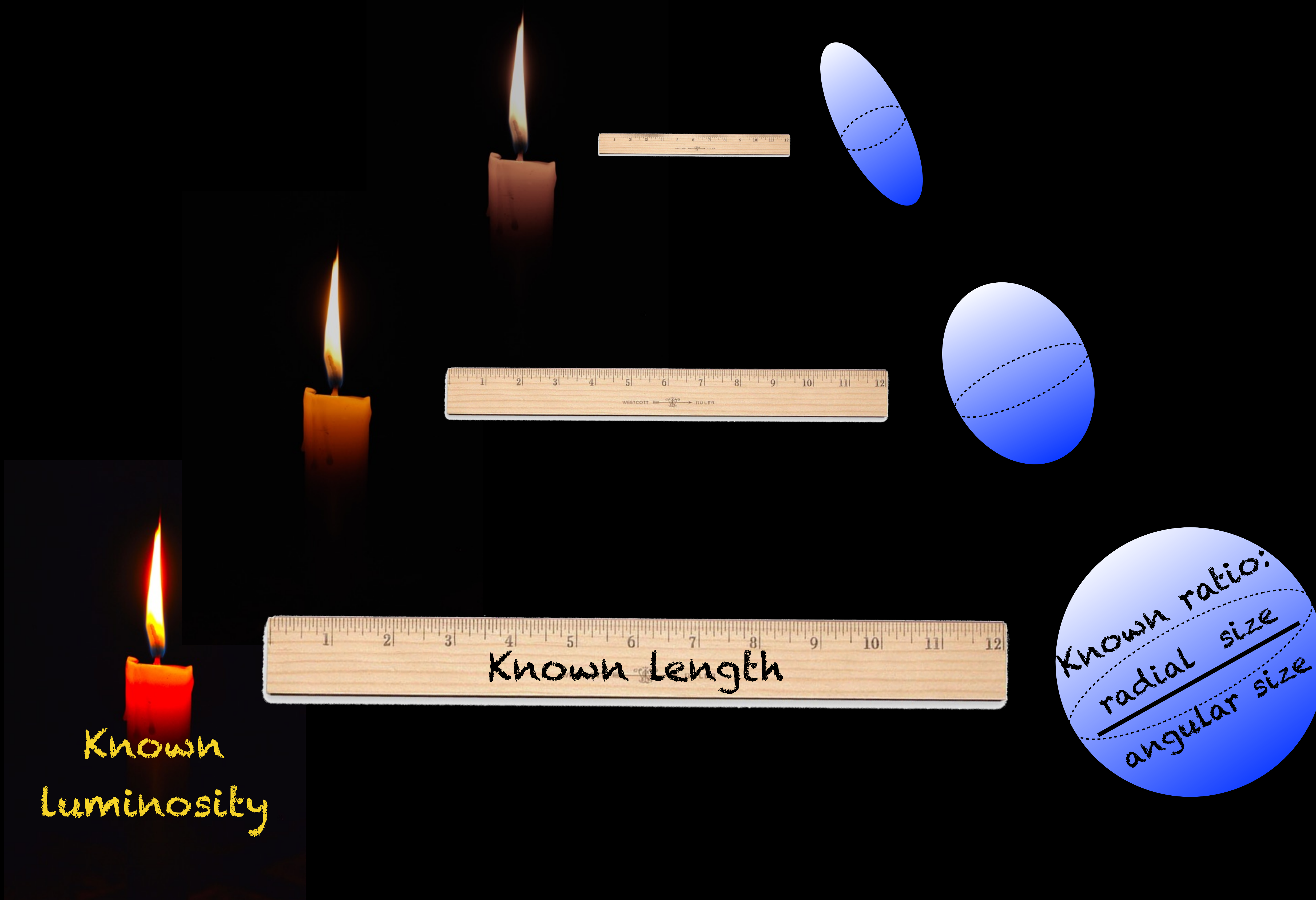


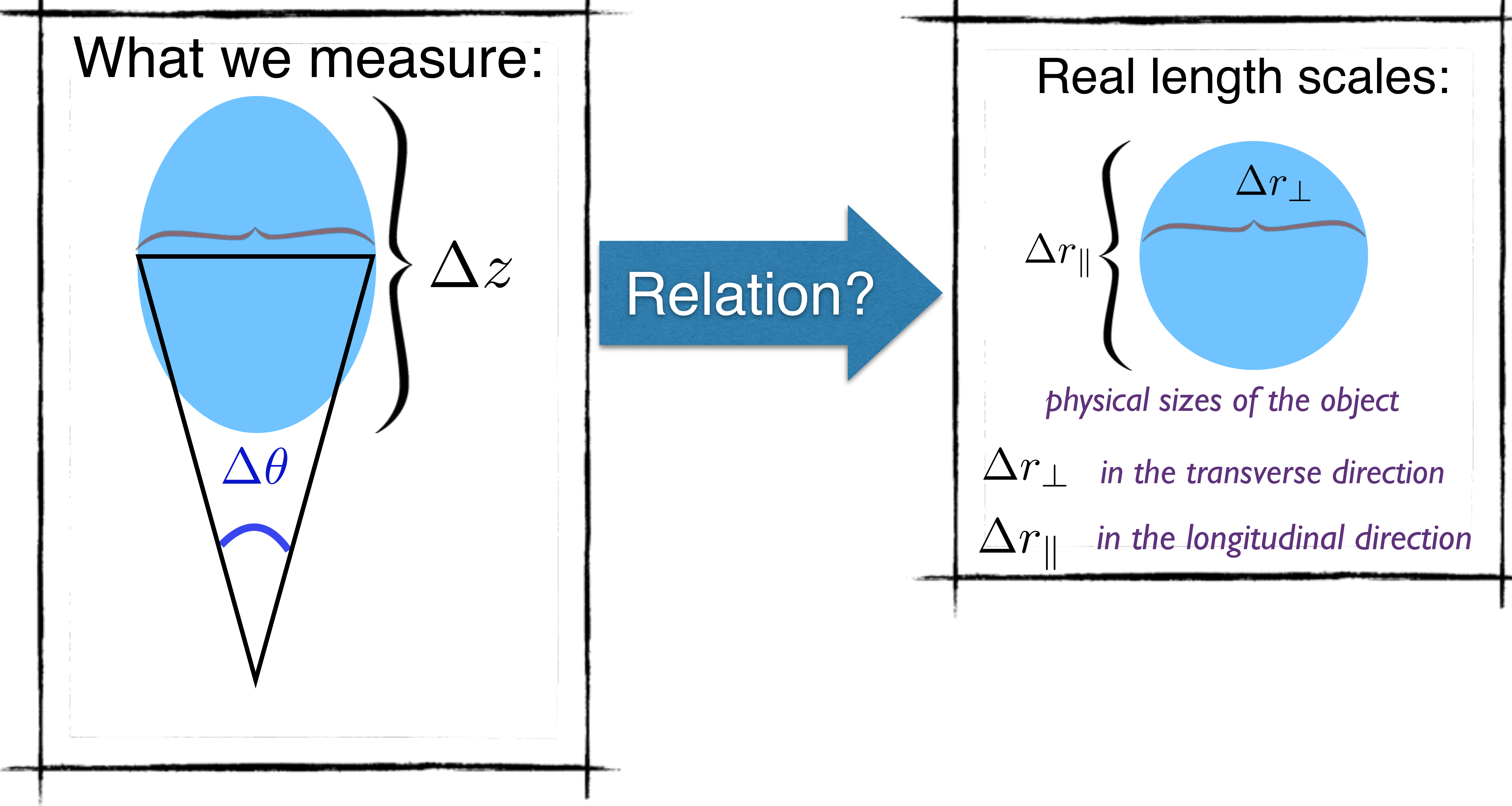
Density cuts:
1)merge if
rholink<0.2
rhomean
2)density in
Reff/4<-0.8
+ exclude voids below mps

+ it takes into account survey boundaries and masks

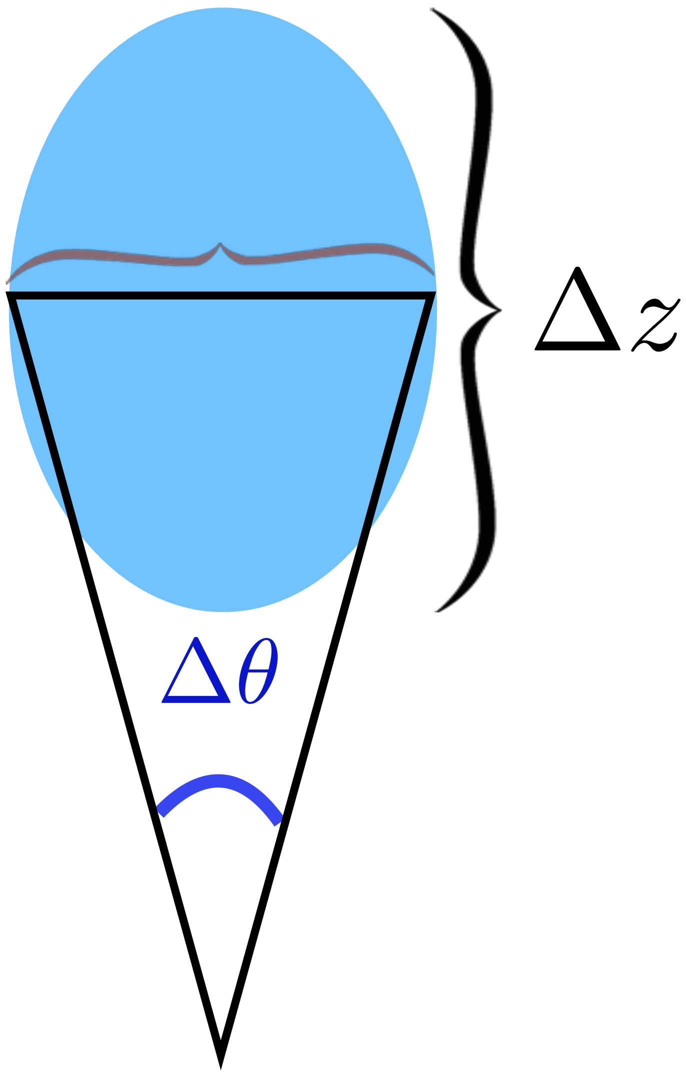
We have voids,
how can we measure
expansion with them?

Standard objects



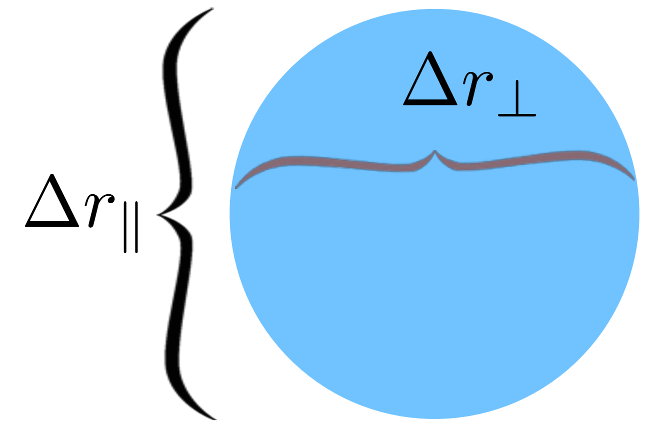

What we measure:
Δz
$\Delta\theta$
Relation?
Real length scales:
$\Delta r_\perp$
$\Delta r_\parallel$
physical sizes of the object
$\Delta r_\perp$ in the transverse direction
$\Delta r_\parallel$ in the longitudinal direction

What we measure:



Relation?

Real length scales:



physical sizes of the object

$\Delta r_{\perp}$ *in the transverse direction*

$\Delta r_{\parallel}$ *in the longitudinal direction*

Cosmology, of course…

$$\Delta r_{\perp} = D_A(z)\Delta\theta$$

angular diameter distance

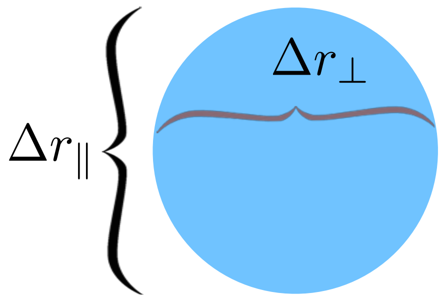
$$c\Delta z = H(z)\Delta r_{\parallel}$$

Hubble parameter

Alcock-Paczyński test (1979)

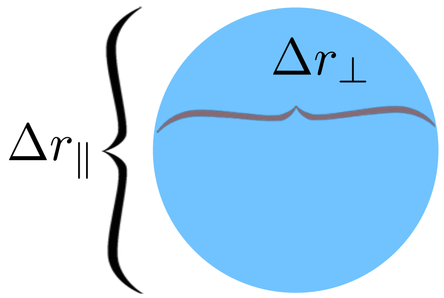
Alcock-Paczyński test (1979)

$$\Delta r_{\perp} = \Delta r_{\parallel}$$



Alcock-Paczyński test (1979)

$$\Delta r_\perp = \Delta r_\parallel$$



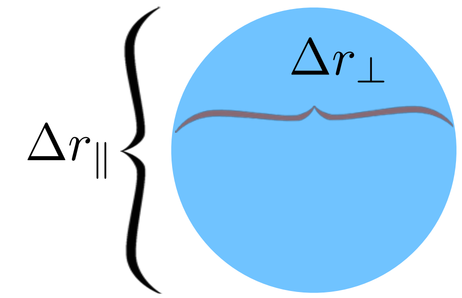
what we know

$$\frac{c\Delta z}{\Delta\theta} = D_A(z)H(z)$$

what we don't know

Alcock-Paczyński test (1979)

$$\Delta r_{\perp} = \Delta r_{\parallel}$$



what we know

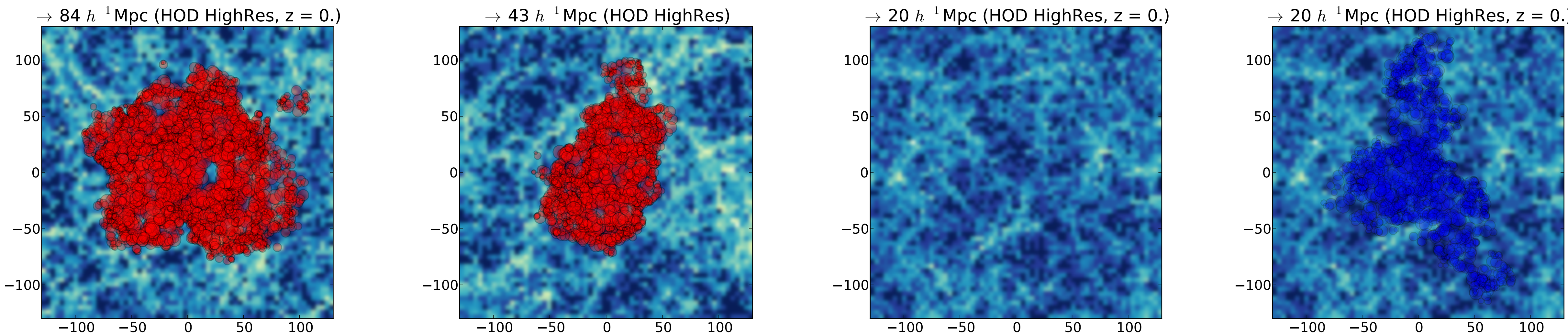
$$\frac{c\Delta z}{\Delta\theta} = D_A(z)H(z)$$

what we don't know

To perform the test we measure stretch $e_V(z)$

The deviations from fiducial cosmology cause geometrical distortions.

Barbara Ryden intuition: apply the Alcock-Paczyński test on voids



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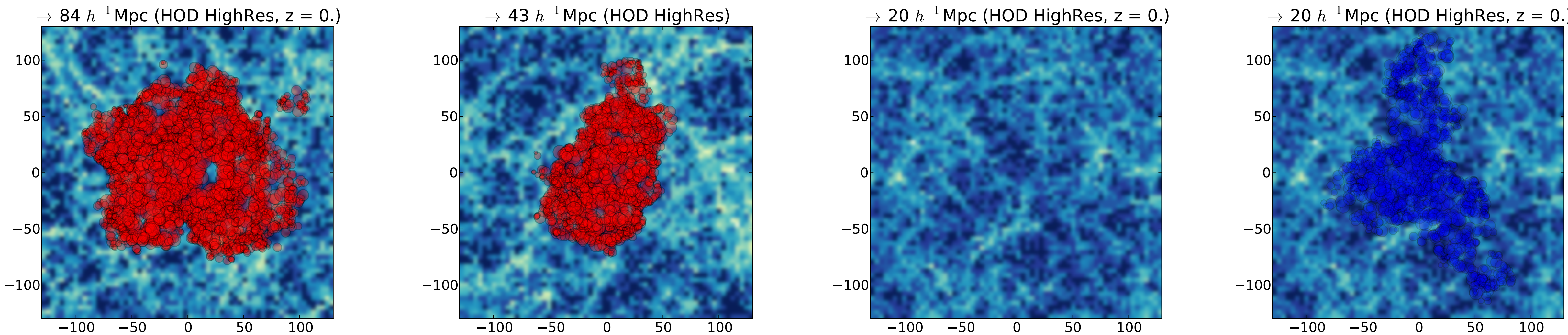


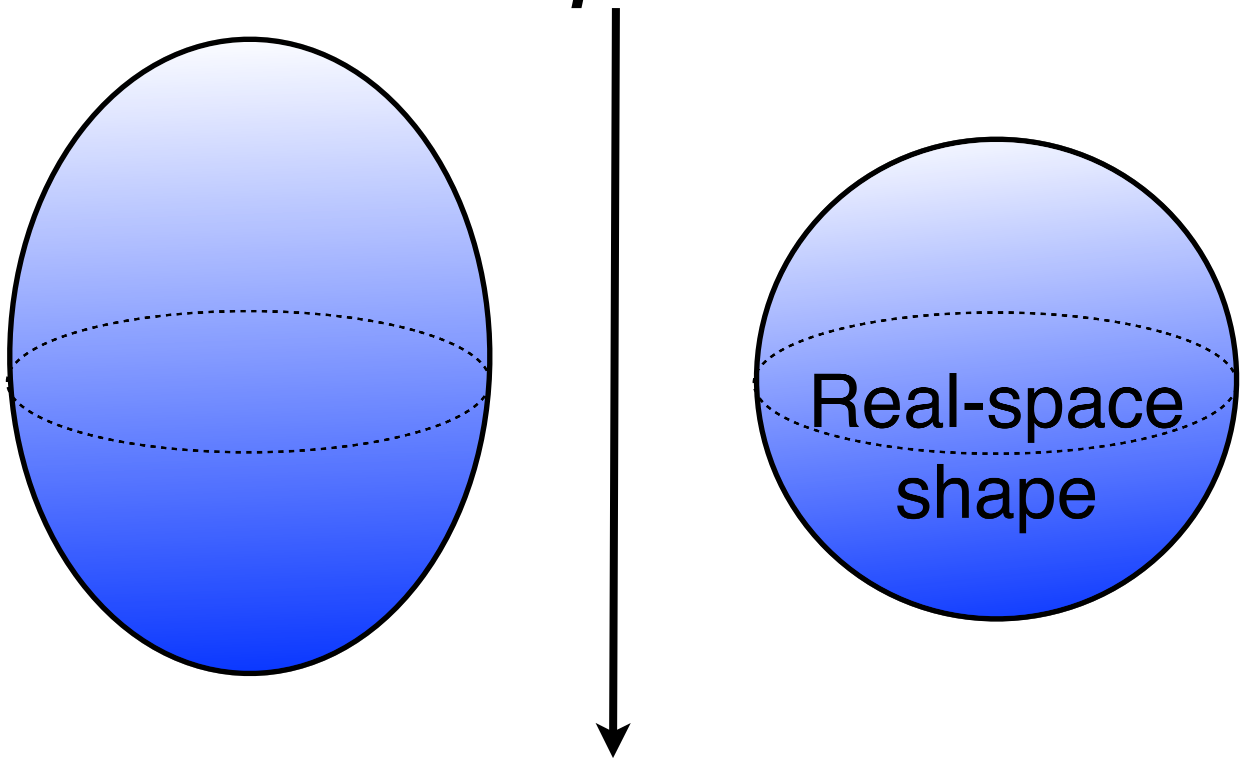
Voids have different shapes but spherical average shape in an isotropic and homogeneous universe!

We can use stacked voids for the test

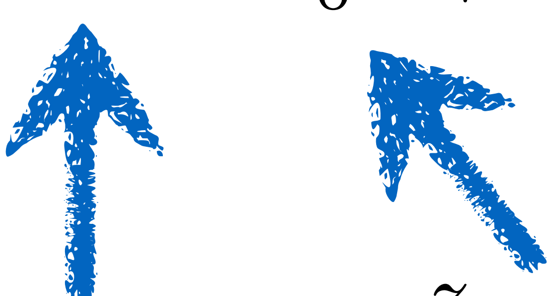
=> promising with new surveys.

Lavaux & Wandelt 2012

The void shape tells us the cosmology

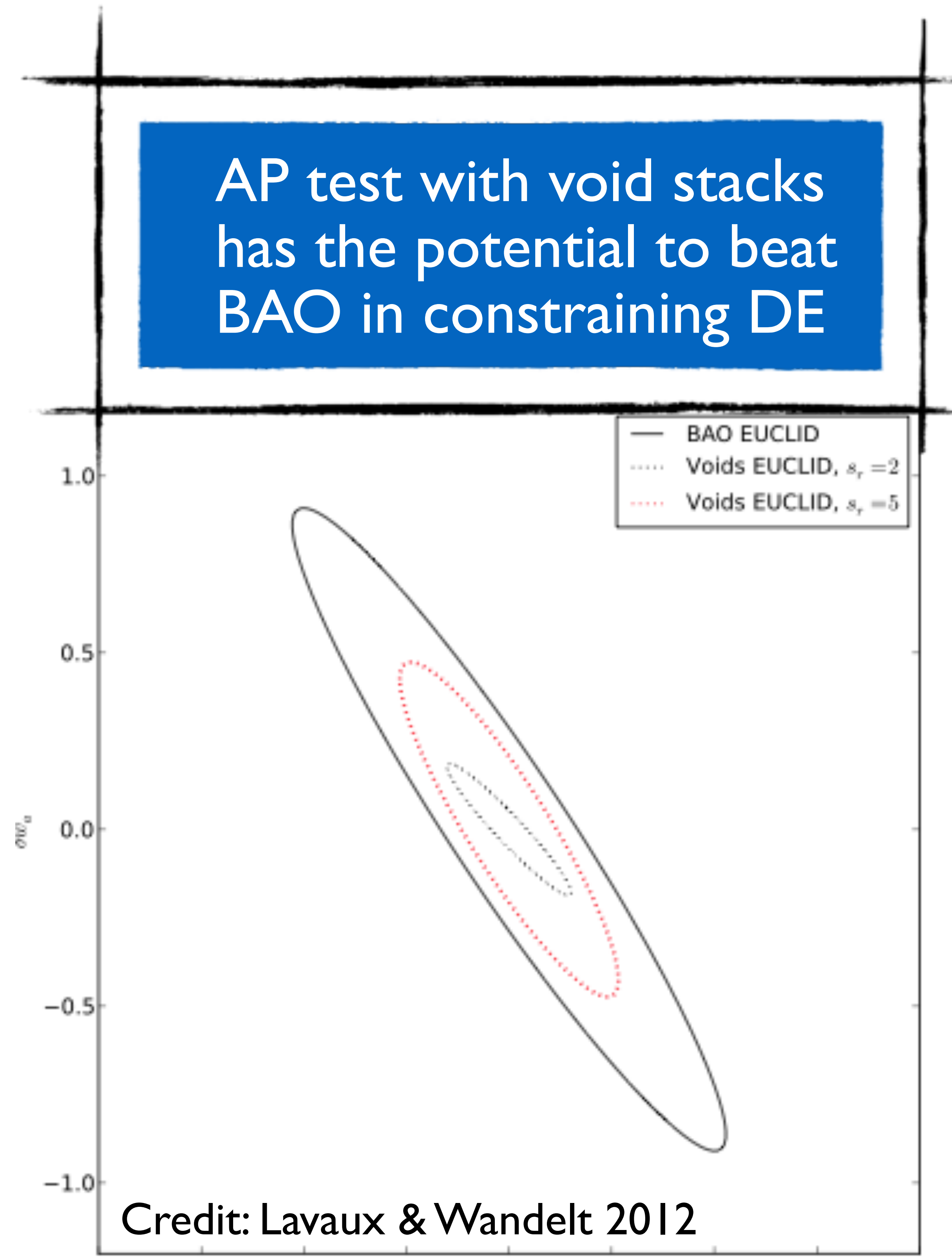


$$cz = H_0 d + v cos\theta$$



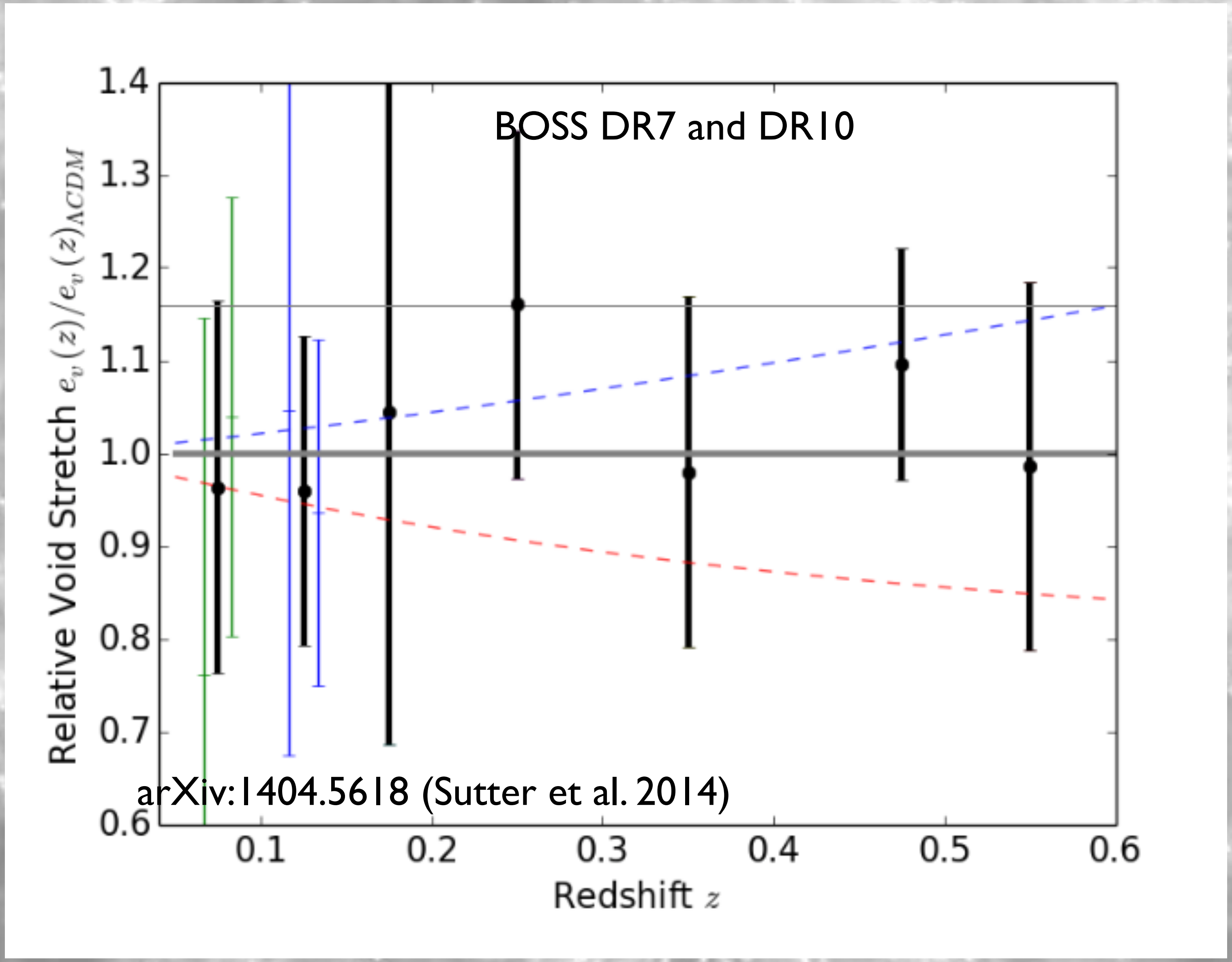
But… the velocities of galaxies also affect that shape.

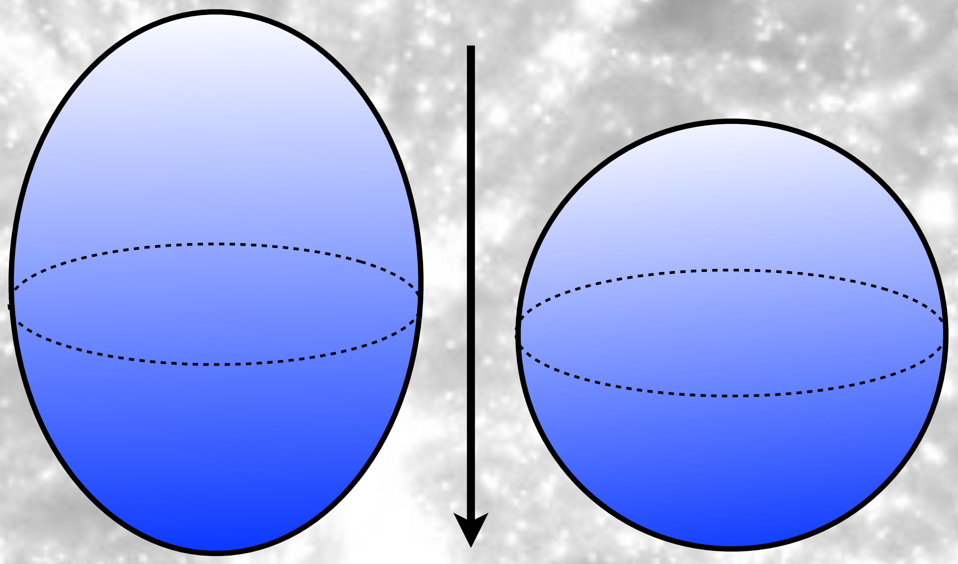
Velocities will be our main source of systematics!



Current situation?

We have a measurement!





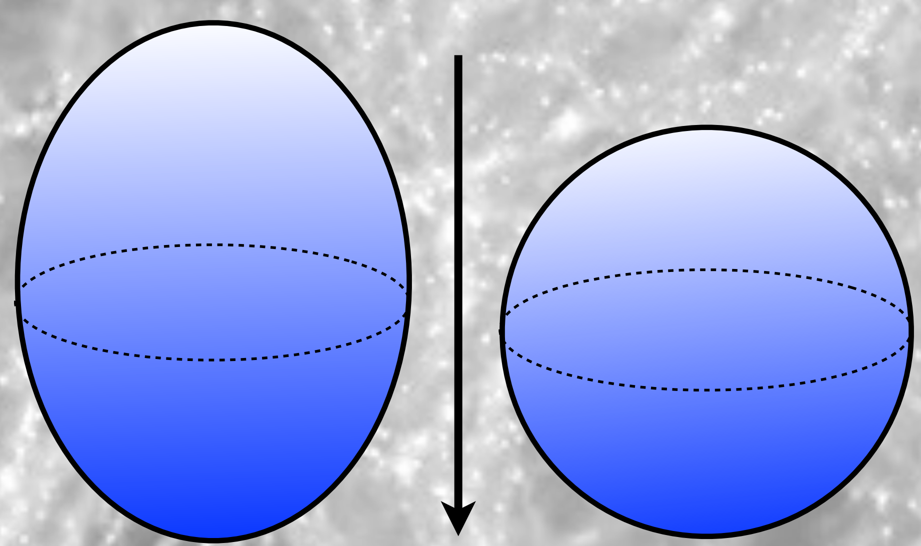
How to turn this into a precise constrain?

arXiv:1404.5618 (Sutter, Pisani, Wandelt, Weinberg 2014)

We can reduce systematics by:

1) better modeling of the real space shape

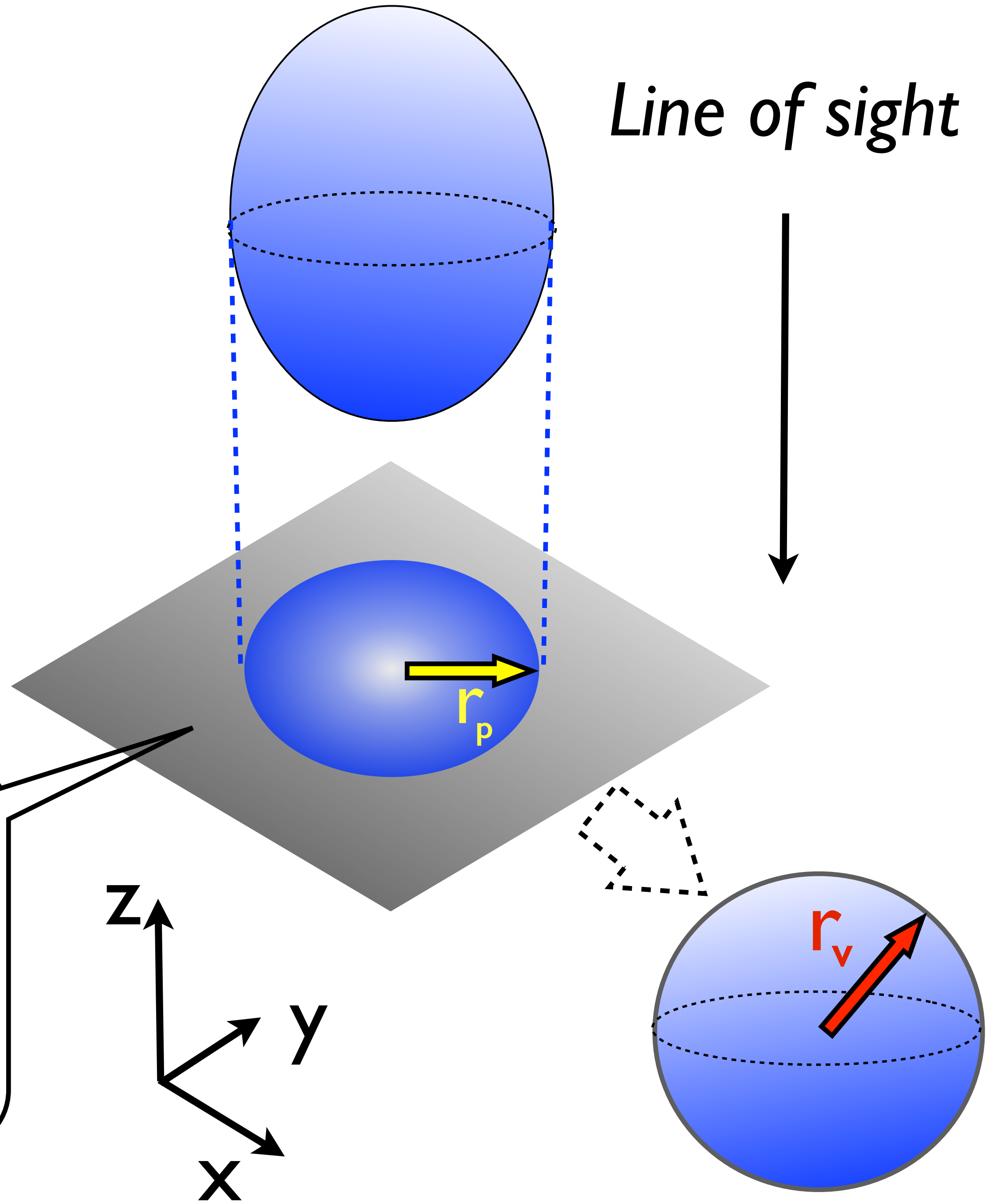
2) studying the effect of peculiar velocities



The method to get the spherical profile

Key idea

Projecting the 3D distribution along the line of sight, the contribution of peculiar velocities disappears.

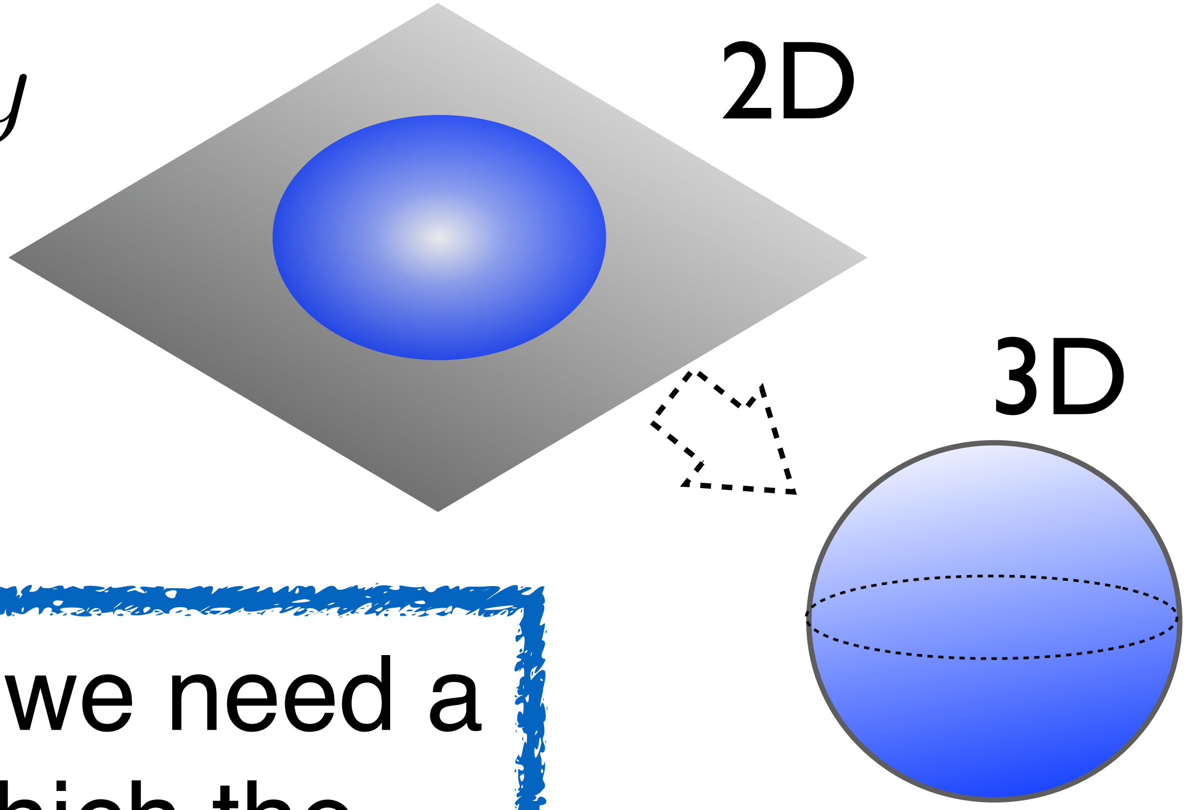


From this projection we reconstruct a 3D profile without the contribution of peculiar velocities.

→ We can obtain the SPHERICAL density profile of stacked voids in real space.

The Abel inverse transform

$$g(r) = -\frac{1}{\pi}\int_r^1 \frac{I'(y)}{\sqrt{y^2 - r^2}}dy$$



To test the reconstruction we need a class of functions for which the inverse is known: Abel Pairs

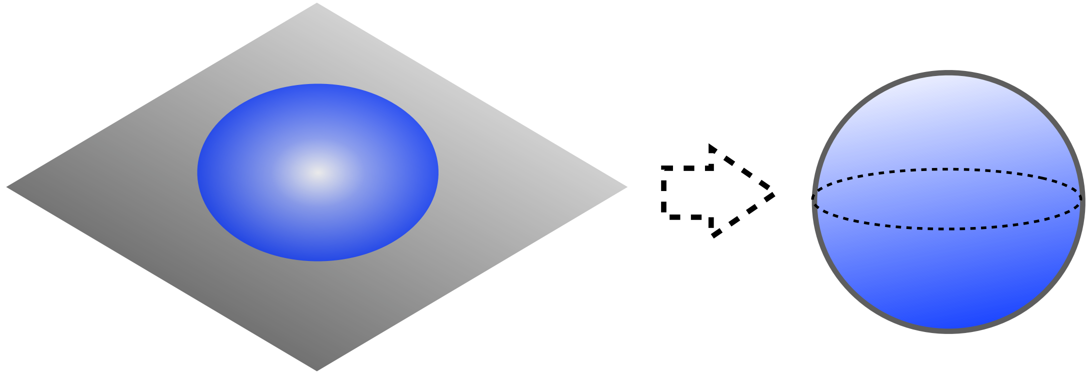
But…

Result I

Fighting ill-conditioning

$$g(r) = -\frac{1}{\pi}\int_r^1 \frac{I'(y)}{\sqrt{y^2 - r^2}}dy$$

Abel inverse transform: mathematically well-defined but ill-conditioned!



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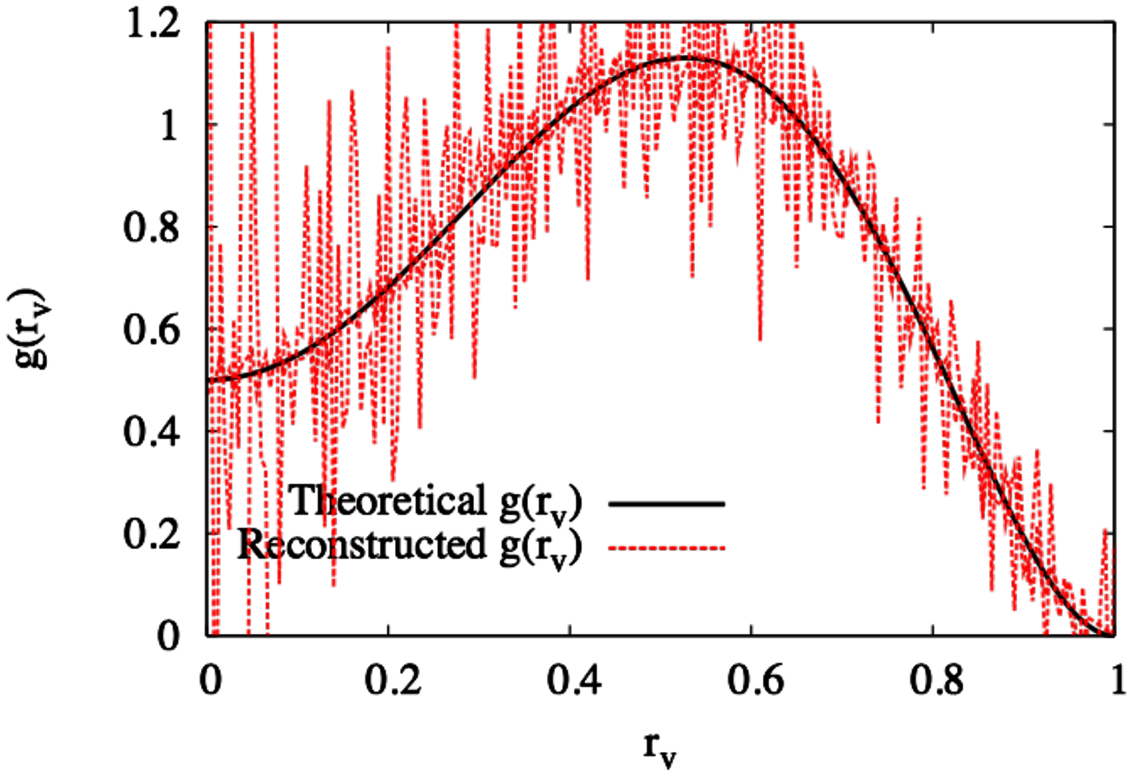

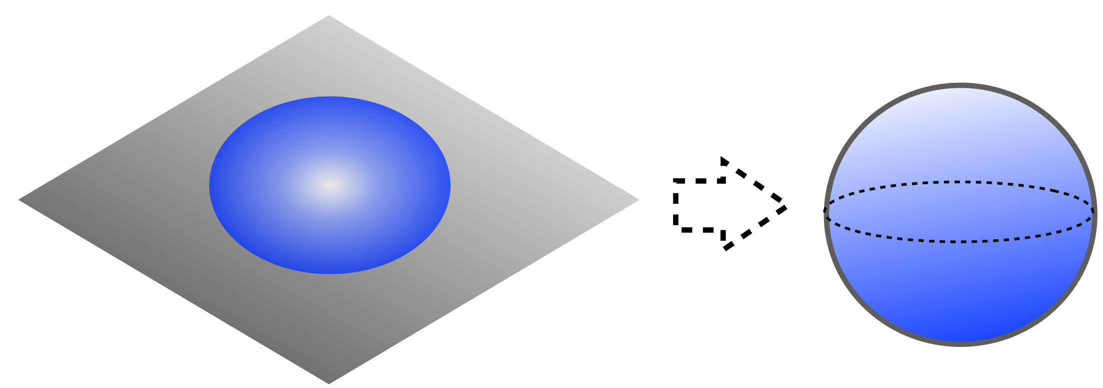

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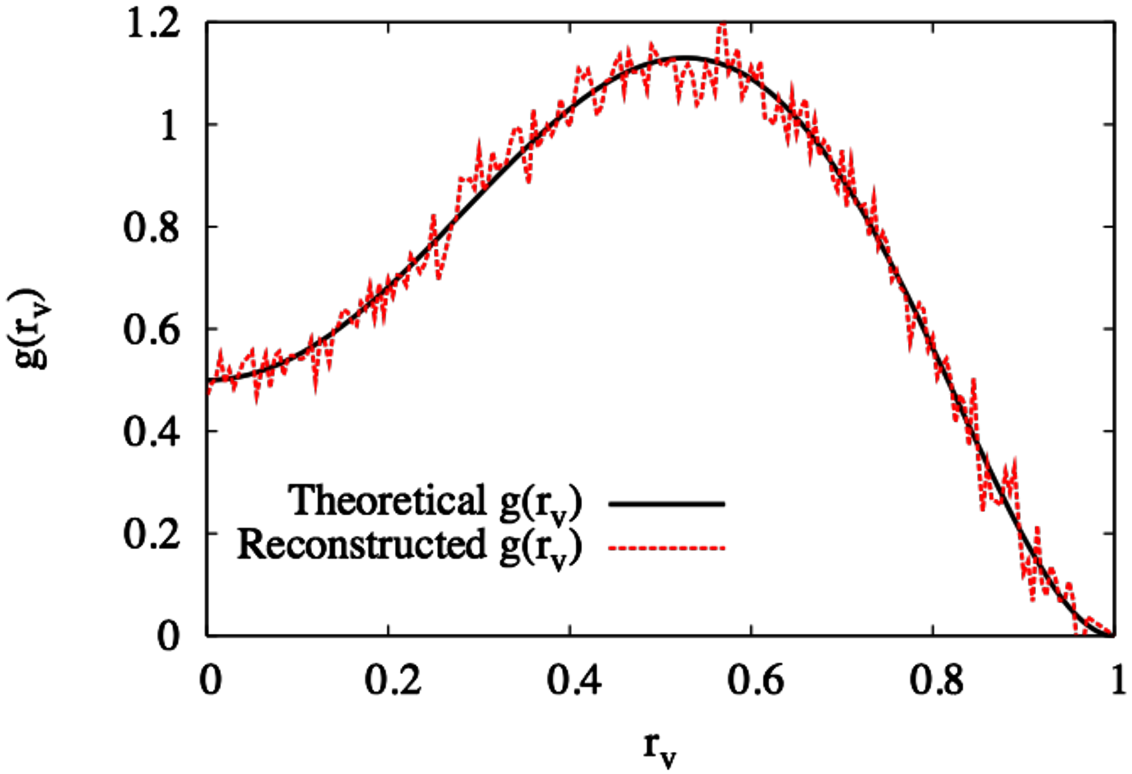
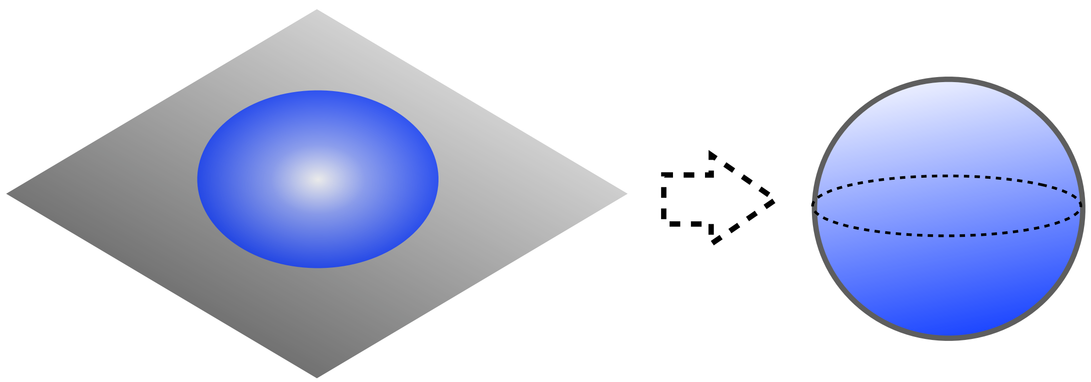


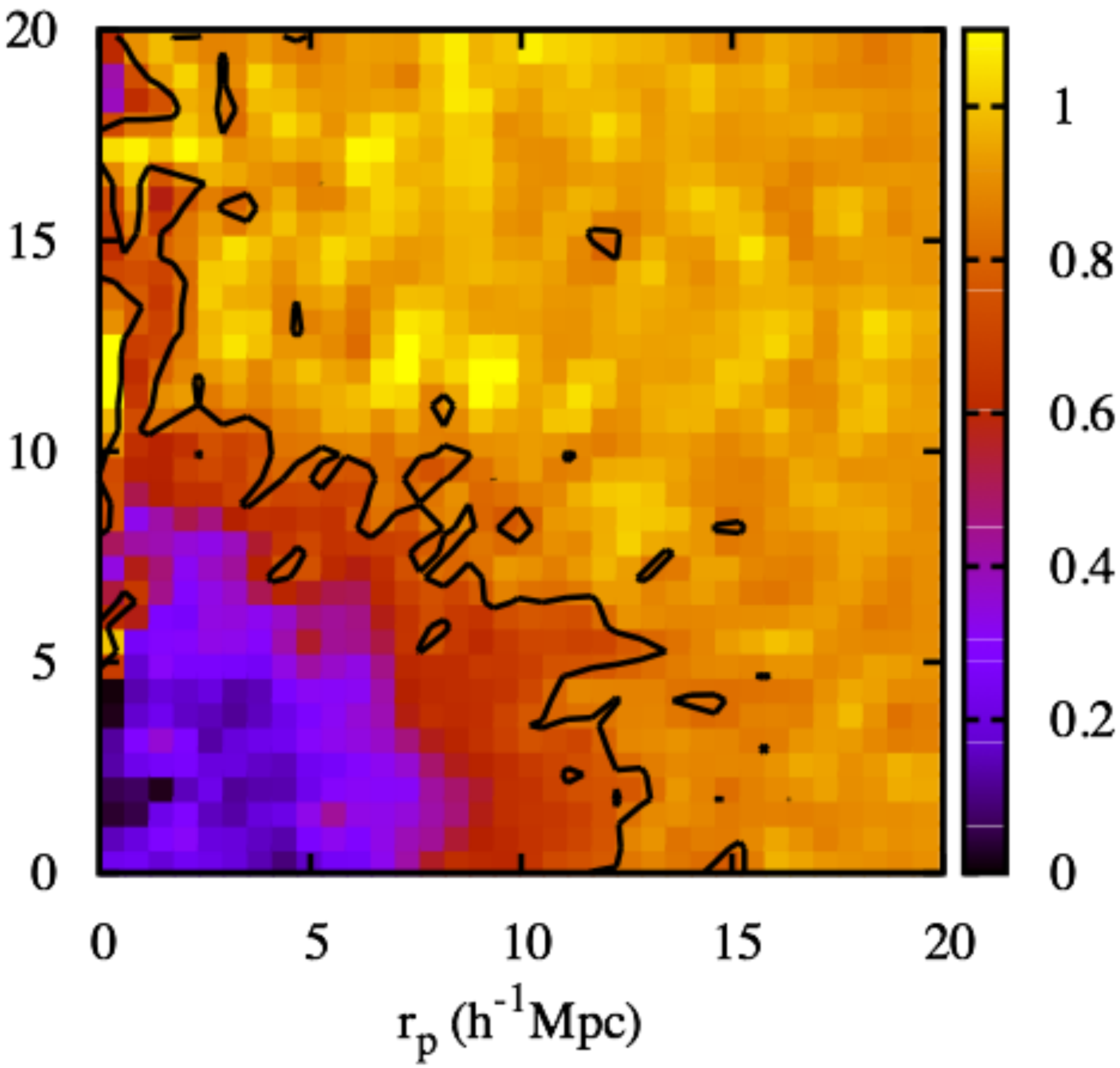


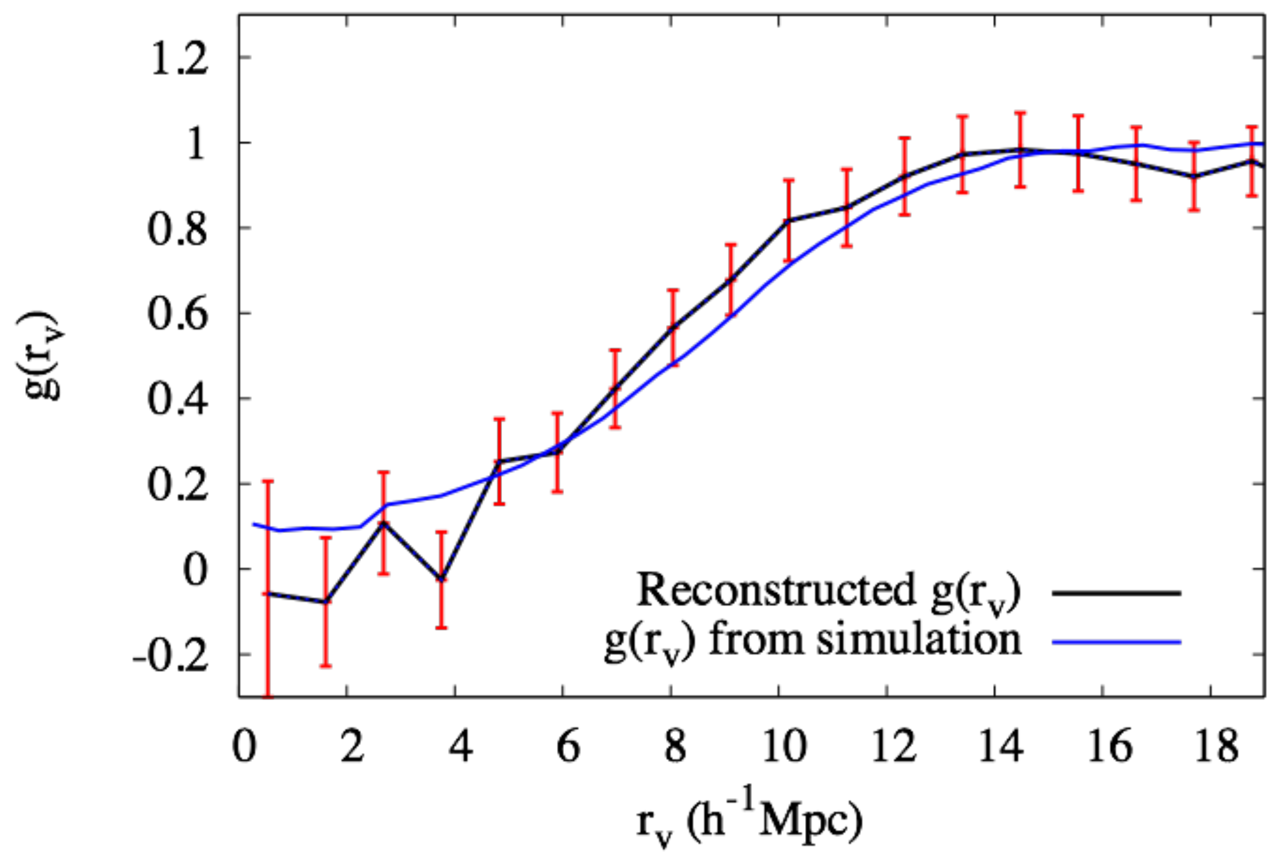
Reconstruction was with an Abel pair, so it is a particular case

RESULT: Very good reconstruction!

Result II

The full simulated stacked void

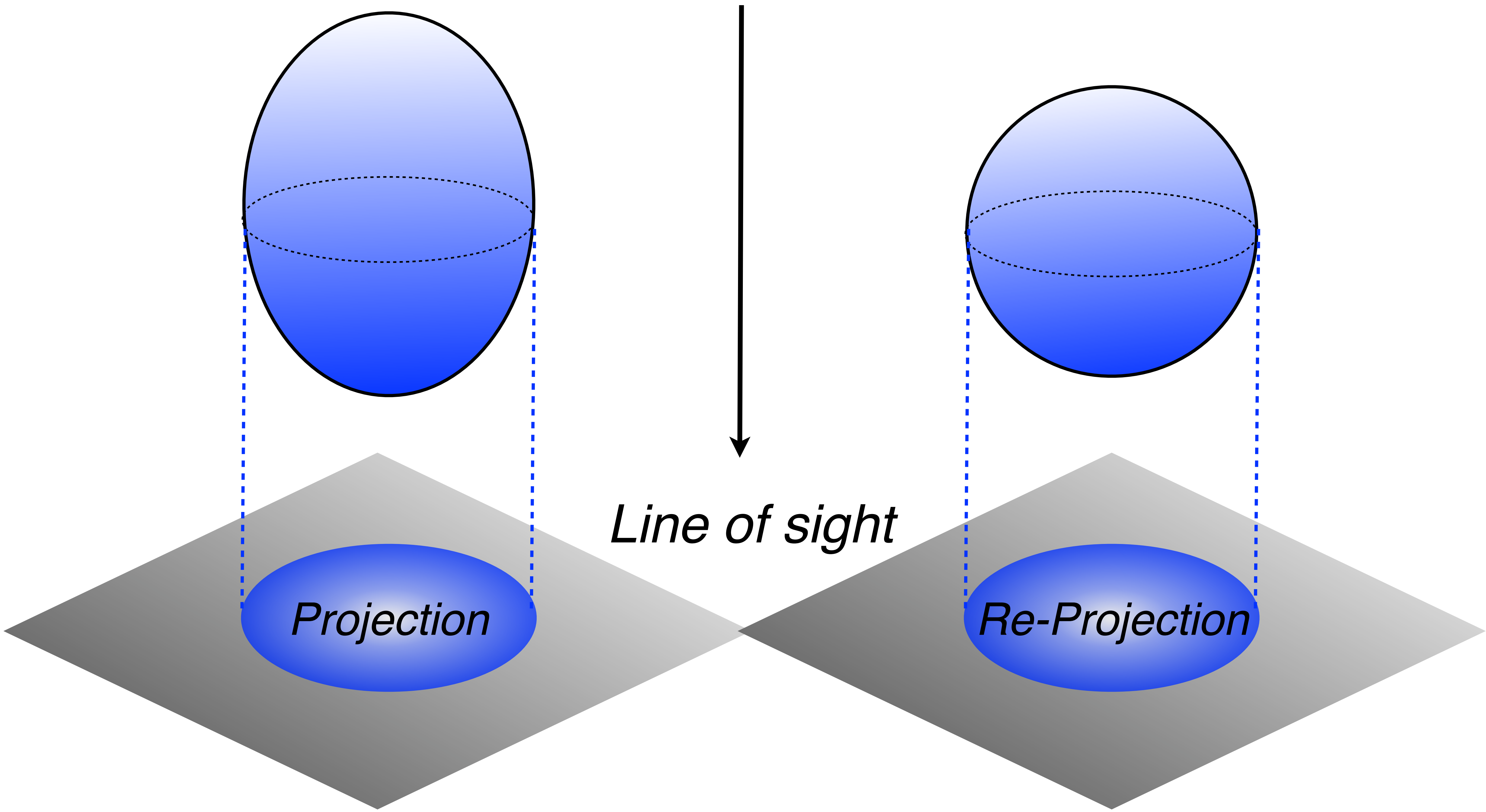




Stacking from 10 to 12 Mpc/h

arXiv:1306.3052 (A. Pisani, G.Lavaux, P. M. Sutter, B. D.Wandelt 2013)

The sanity check for the reconstruction



Check the reconstruction

Reconstruction from stacked void with HOD model

$$\langle N_{\rm cen}(M)\rangle = \frac{1}{2}\left[1+{\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

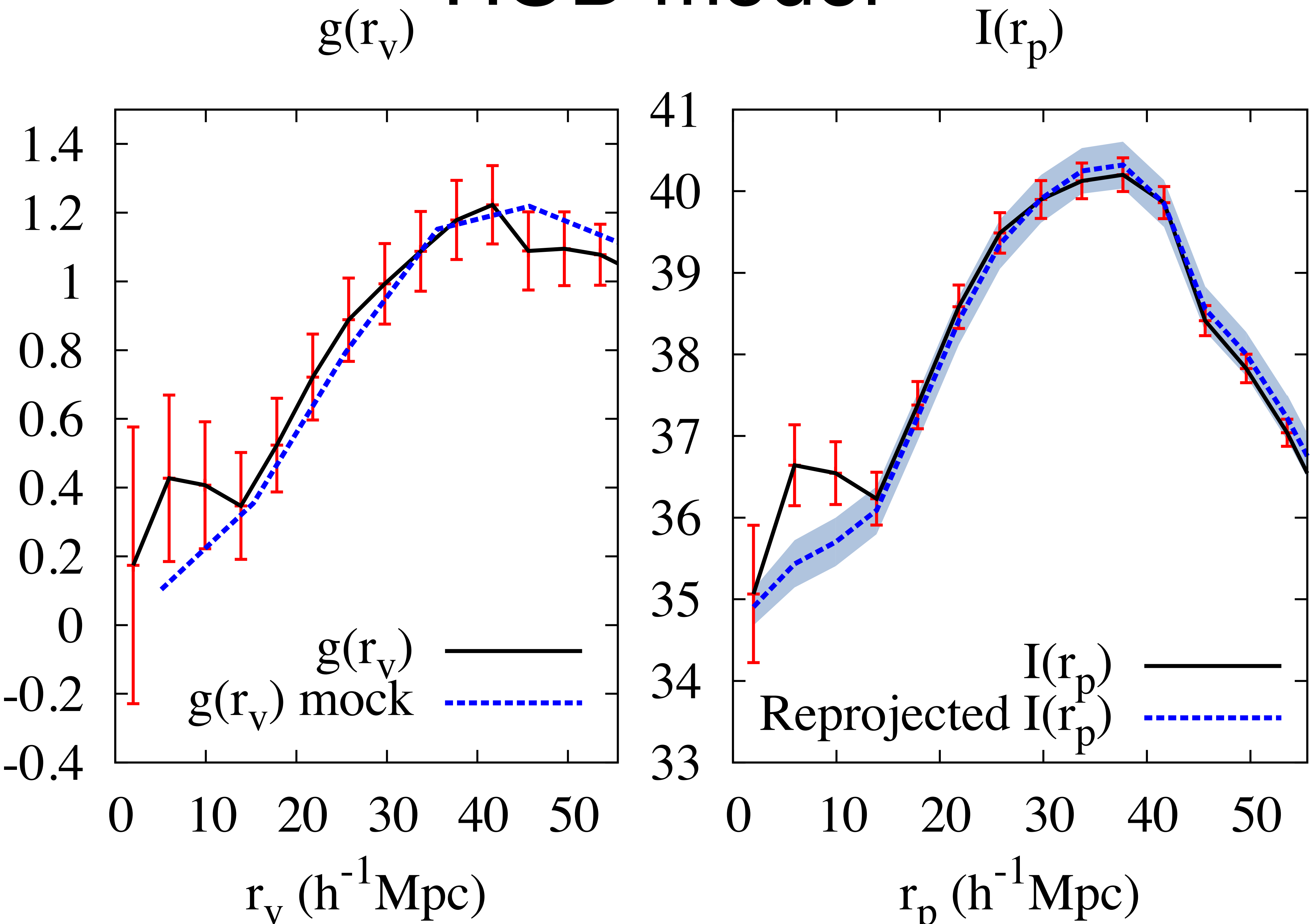
$$\langle N_{\rm sat}(M)\rangle = \langle N_{\rm cen}(M)\rangle \left(\frac{M - M_0}{M_1'}\right)^{\alpha}$$

Rockstar halo finder (Behroozi et al. 2013)

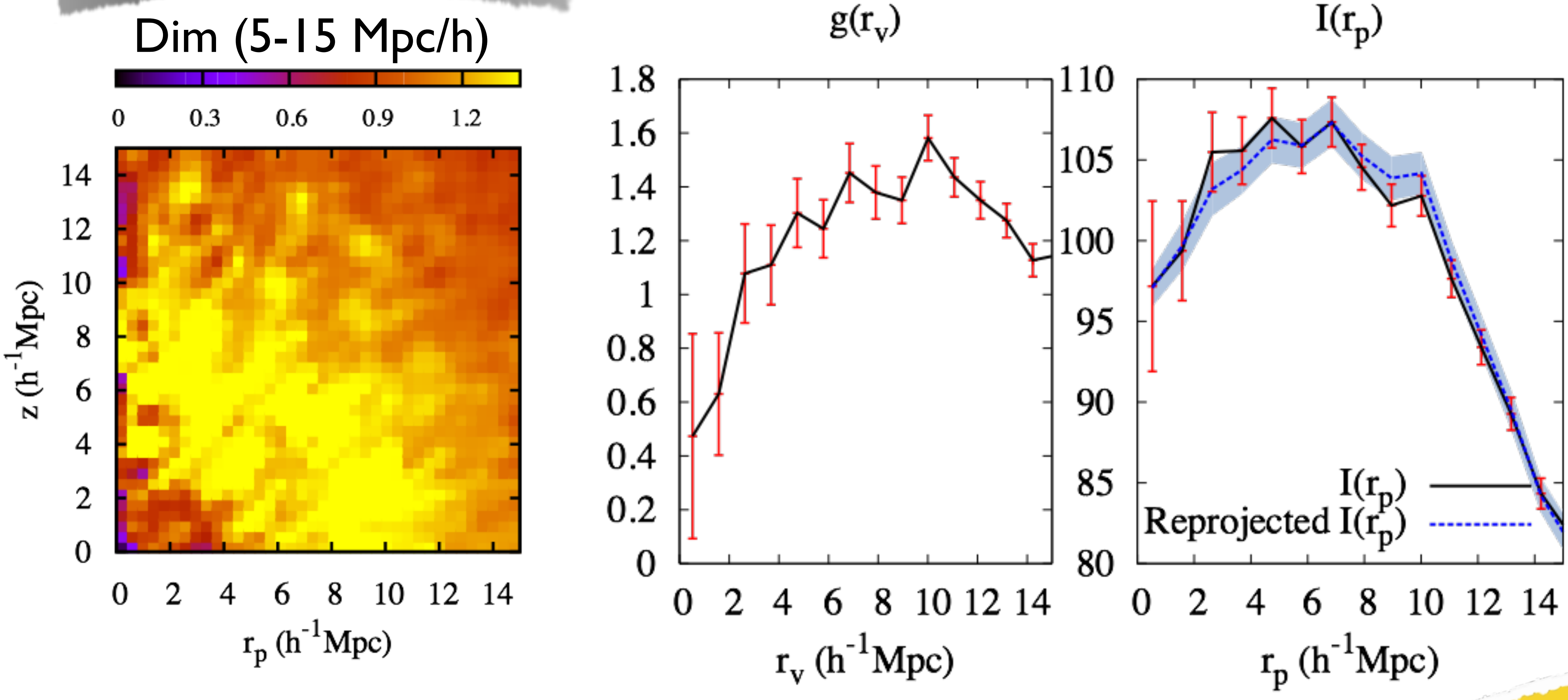
+ HOD model assigns central and satellite galaxies to a dark matter halo (Zheng et al.2007)

Matching the features of SDSS DR7

Reconstruction from stacked void of HOD model



Result III REAL DATA from SDSS!!!

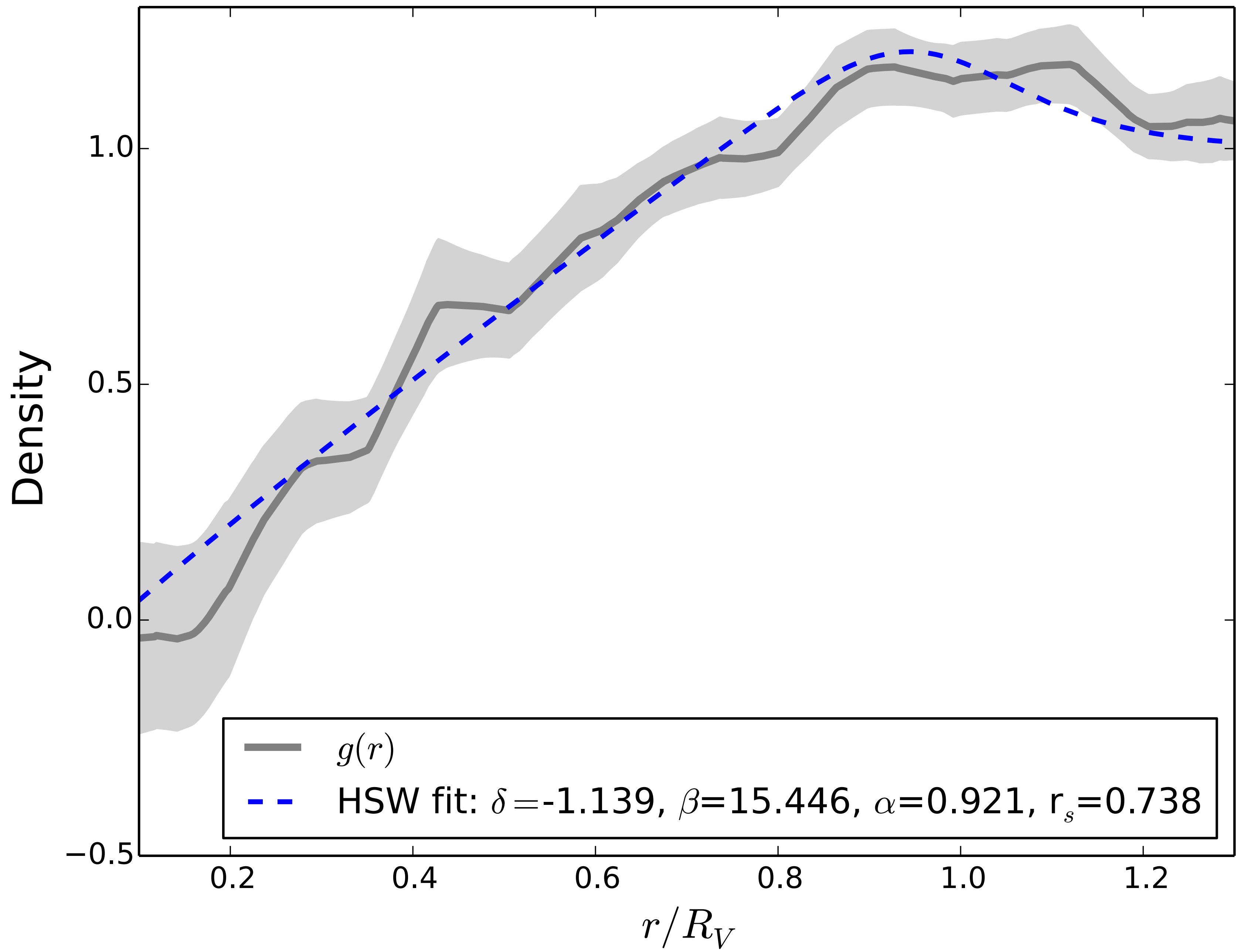


Stack radius	Redshift	Dataset	Galaxies	Voids
5-15	0.05-0.10	dim2	173929	173
10-15	0.05-0.10	dim2	43527	41
20-25	0.10-0.15	bright1	21241	17
25-45	0.15-0.20	bright2	51913	37

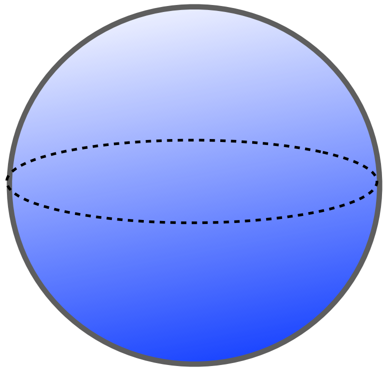
Model independent!
No assumption about RD

arXiv:1306.3052 (A. Pisani, G.Lavaux, P. M. Sutter, B. D.Wandelt 2013)

Average real space void from SDSS DR7 matches simulations

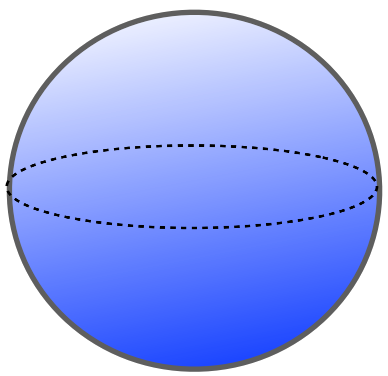


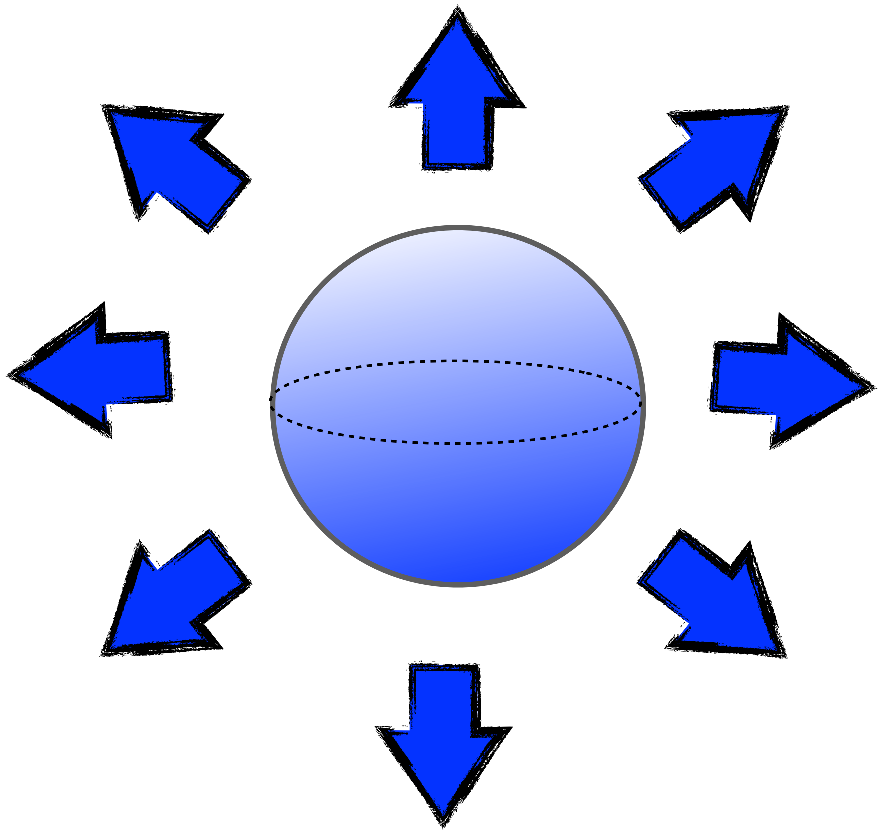
What do we know about voids?



STATIC!!!!

What do we know about voids?





STATIC!!!!

DYNAMICS ????

“Really” looking at voids…

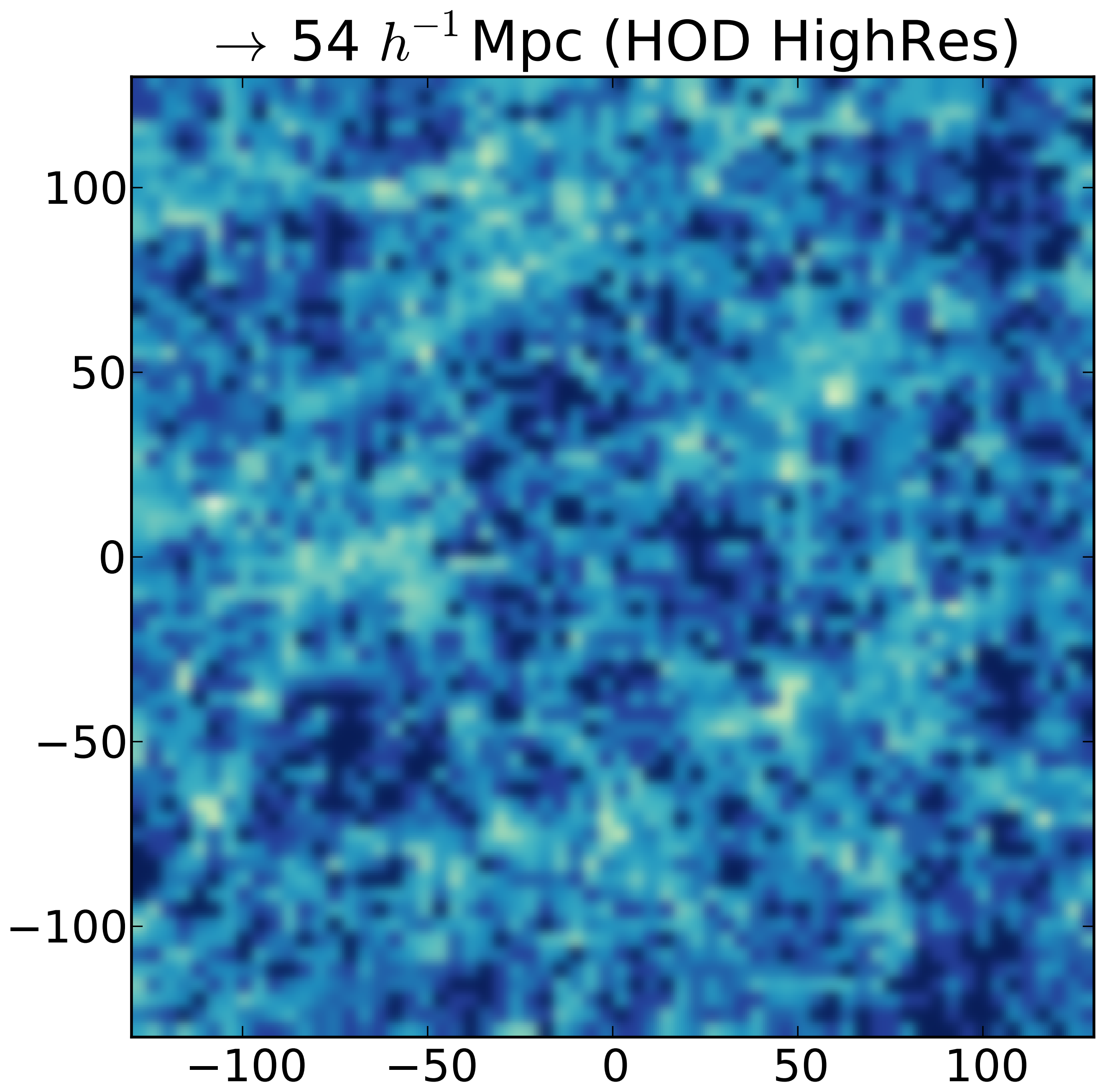
How do velocities impact the way the void finder selects voids?

Let's give a look at voids…

HOD nopv

versus

HOD + pv



Is the cosmological signal washed out by velocities in a certain kind of voids? Can we identify them and boost the cosmological signal?

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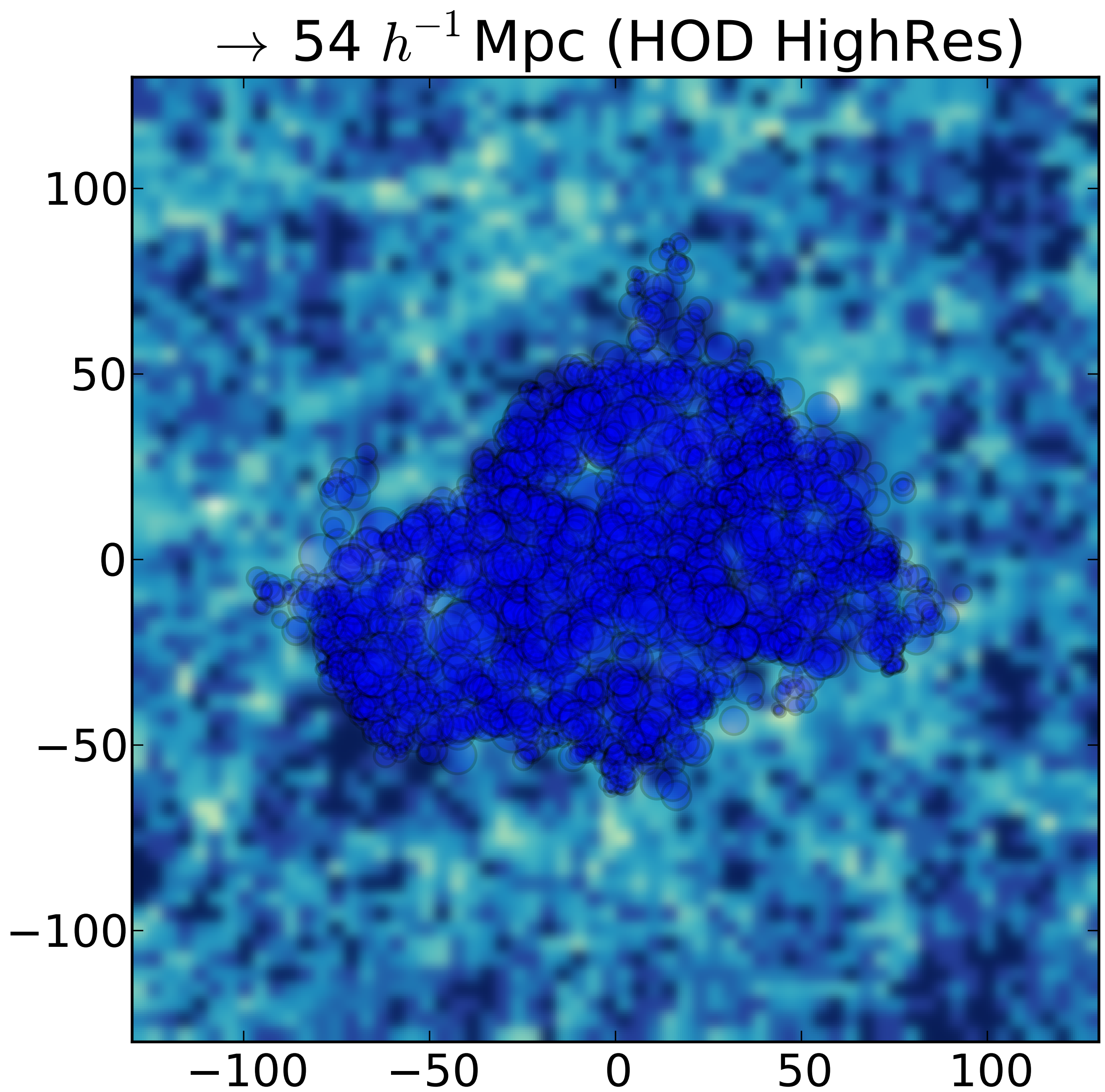

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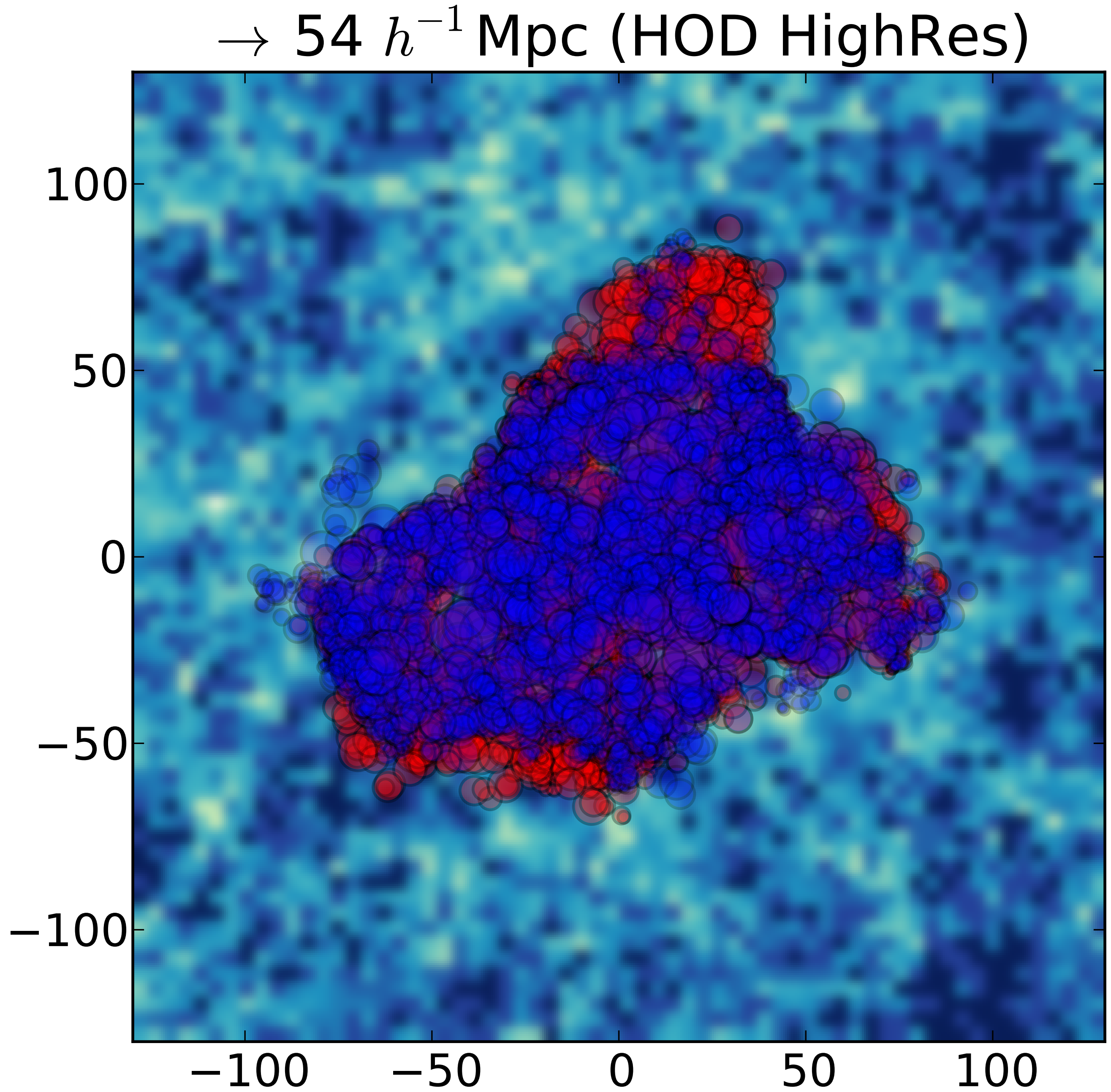
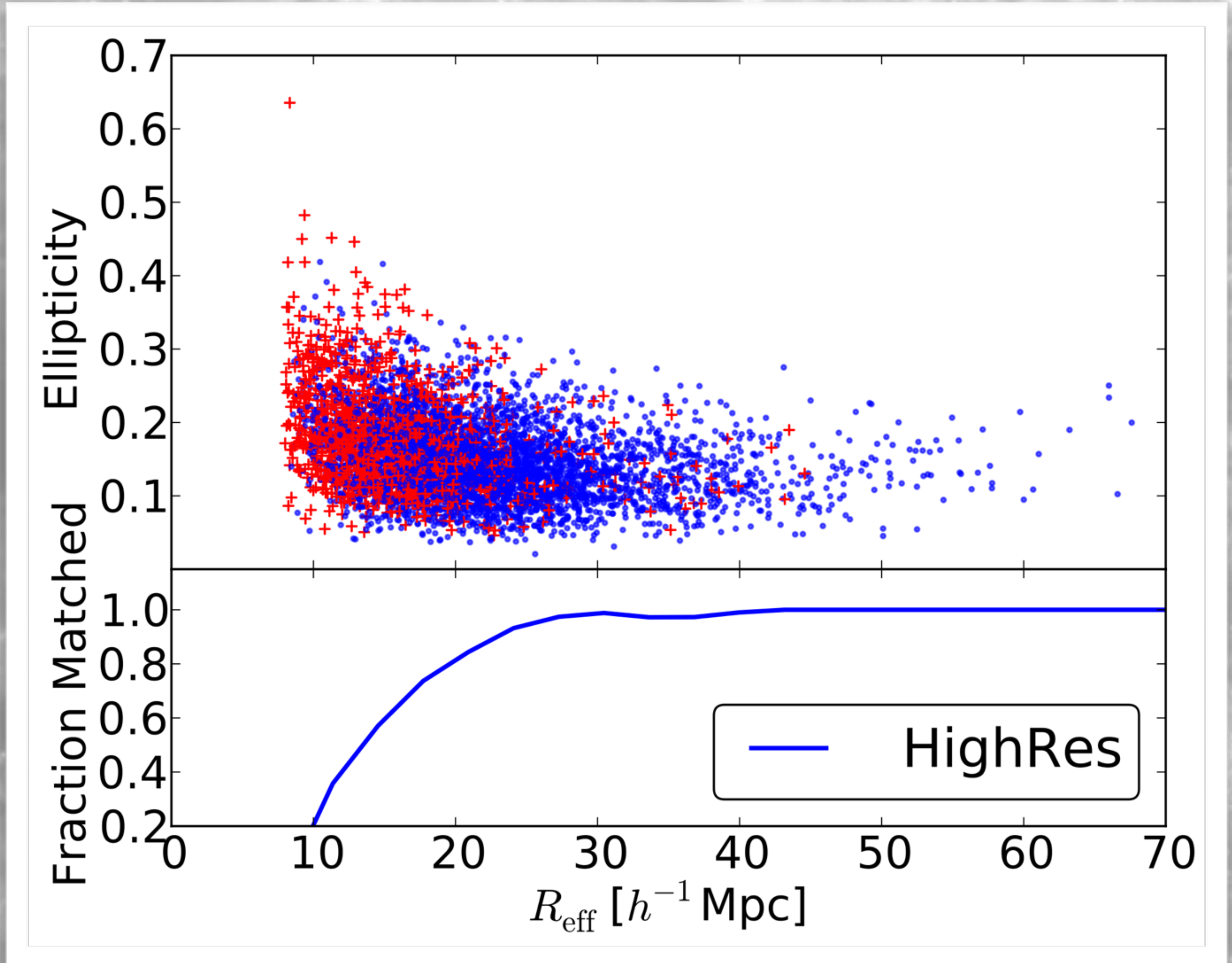


Is the cosmological signal washed out by velocities in a certain kind of voids? Can we identify them and boost the cosmological signal?

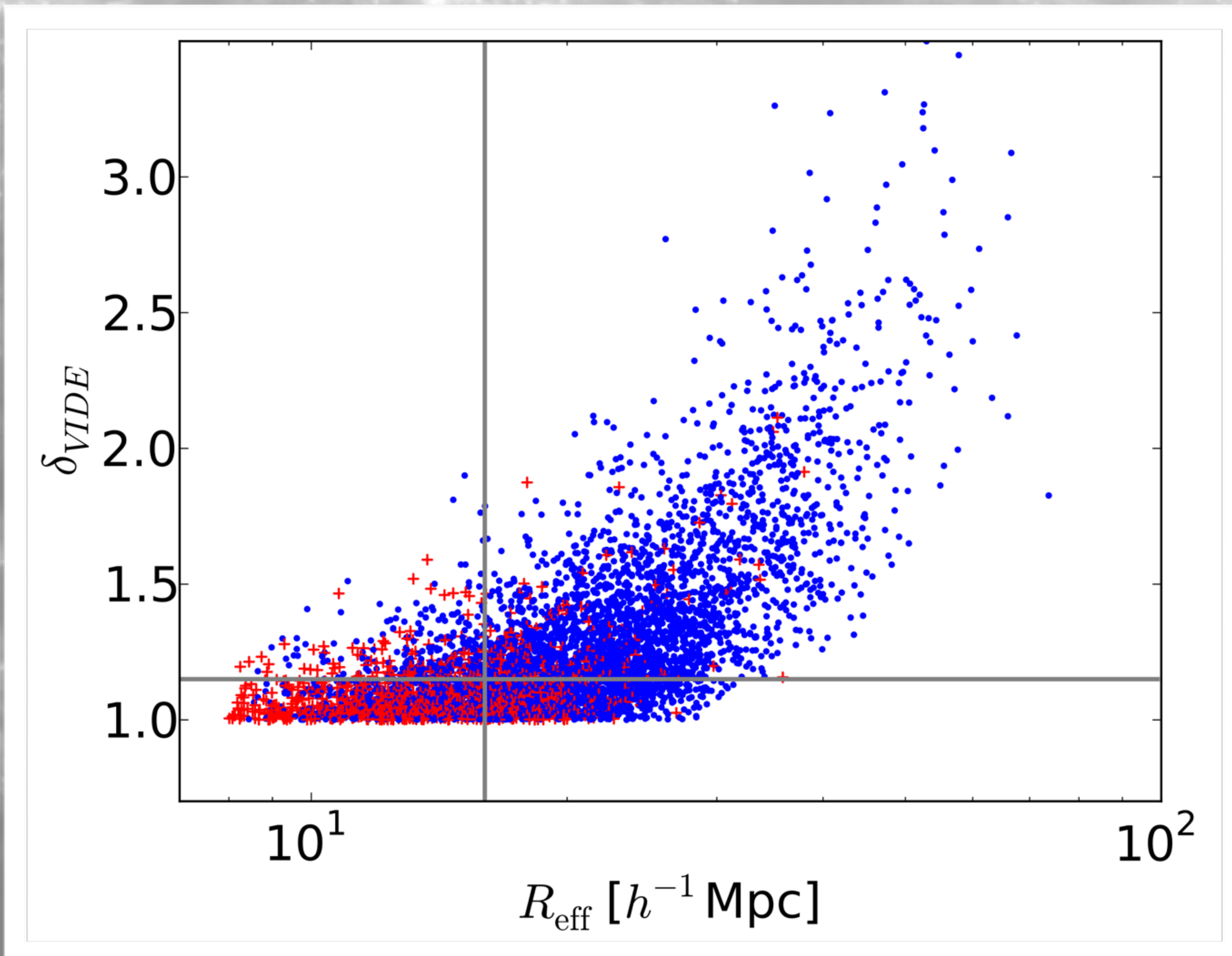
Which voids are affected most?



The number of voids without match is high for small voids.

arXiv:1506.07982 (Pisani, Sutter, Wandelt, 2015b)

Identify them by properties

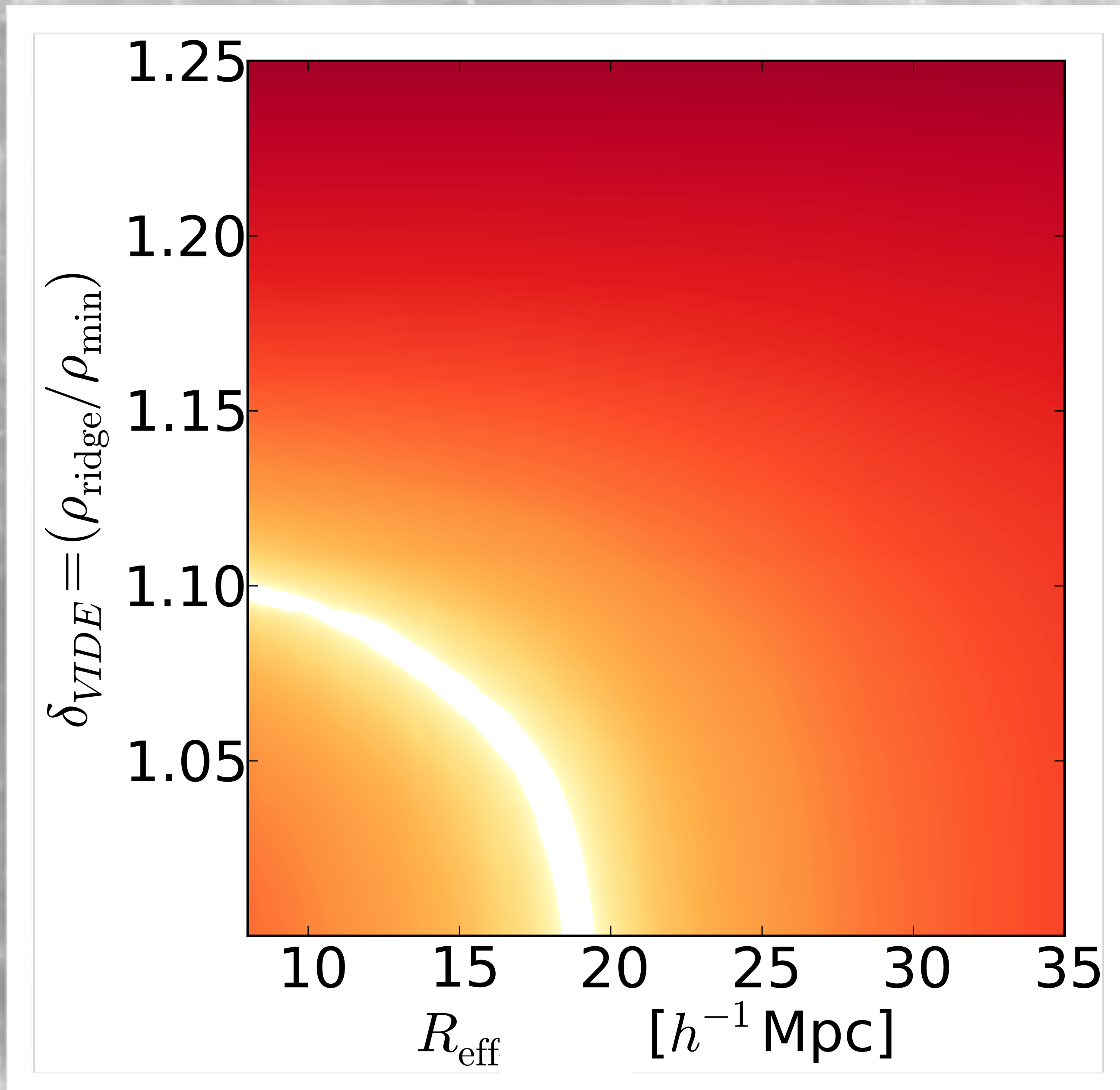


Applying cuts on these quantities we can boost the signal to noise for cosmological signal.

NB: depends on goal

arXiv:1506.07982 (Pisani, Sutter, Wandelt, 2015b)

Optimal cuts for real surveys!



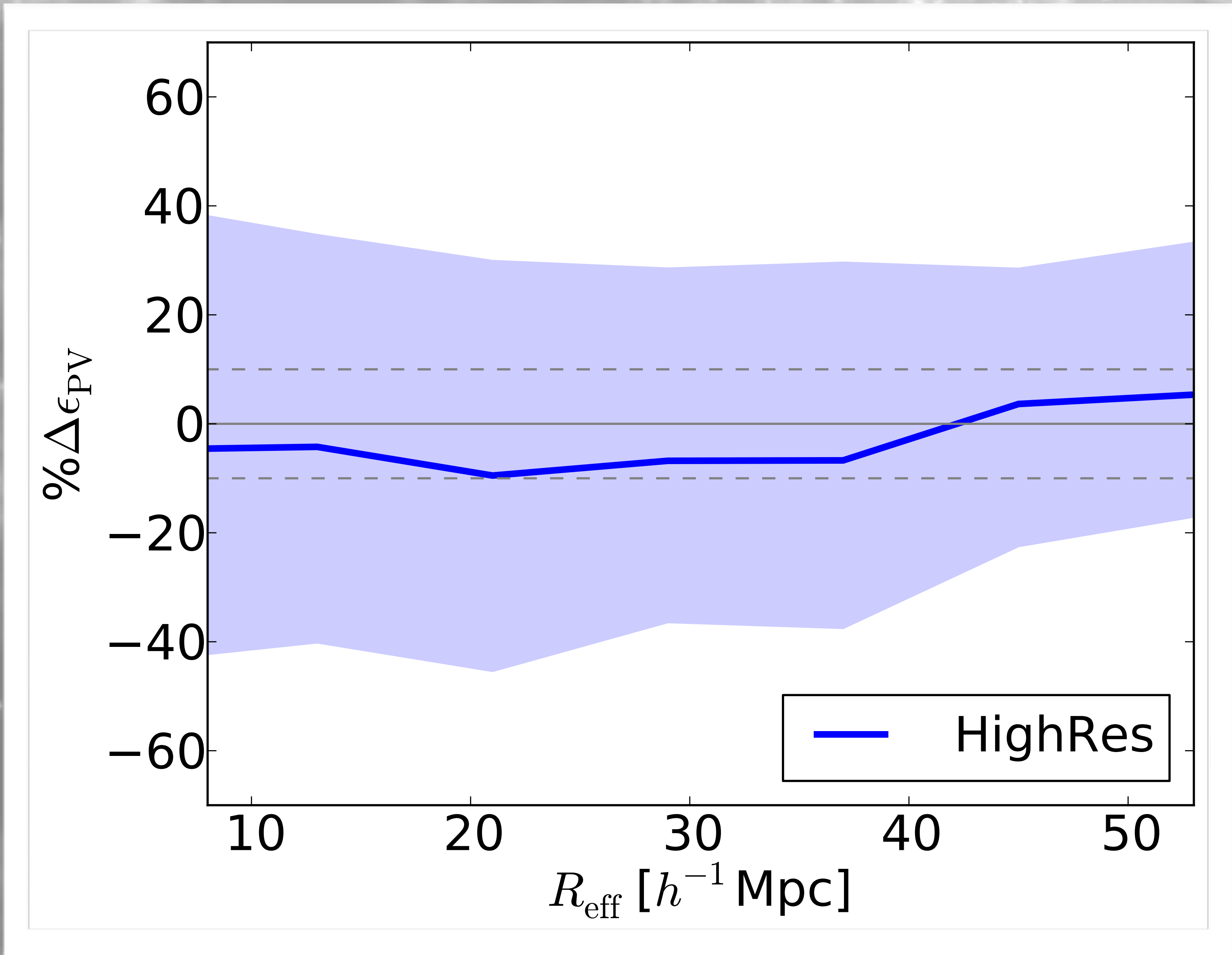
Maximize the number of unmatched removed and the number of matched kept

$$\eta = \frac{N^{unmatch}_{removed}}{N^{match}_{kept}}$$

We only keep voids very mildly affected by velocities! This correction does not need any prior knowledge!

Mastering the effects of peculiar velocities

Exclude the affected voids, but what about the others? Can we correct the properties of other voids for the effects of velocities?



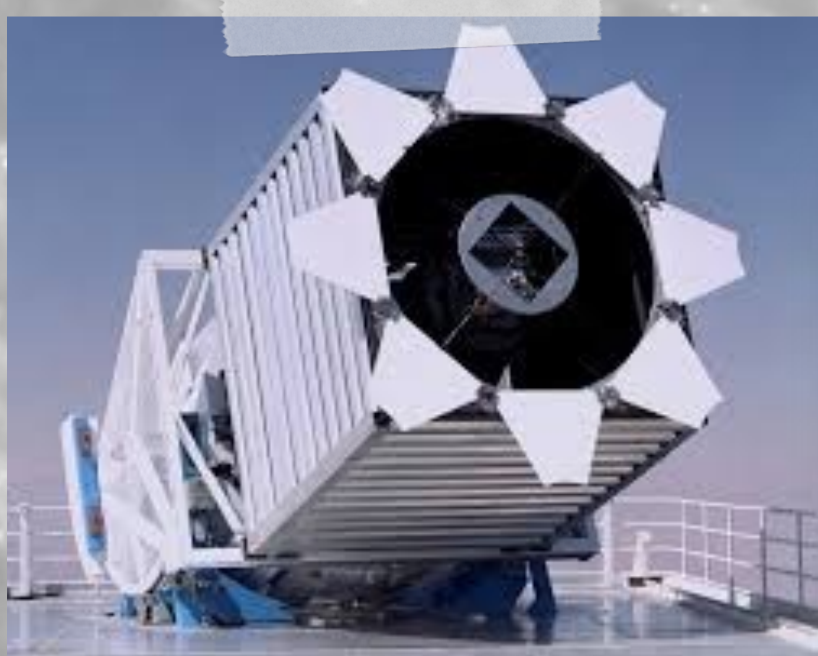
Direct ellipticity correction for the AP test application

Guidelines to boost the cosmological information

Apply **cuts** on **radius** and δ_{VIDE} that match our physical sense => boost the signal to noise for cosmological information.

Direct ellipticity correction for the AP test application

Cuts optimized for current surveys!



eBOSS: extended Baryon Oscillation Spectroscopic Survey

French Participation Group (~20)

IN2P3: APC, CPPM, LPNHE
INSU: IAP, LAM
CEA: IRFU/SPP

eBOSS

BOSS provided us with an amazing number of galaxies, to be increased by eBOSS

Set of tools to **beat systematics** and … what about increasing statistics?

For example let's go…. Back to the future to bet on LSS with upcoming surveys

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SDSS DR7 $6.7 \cdot 10^5$ galaxies

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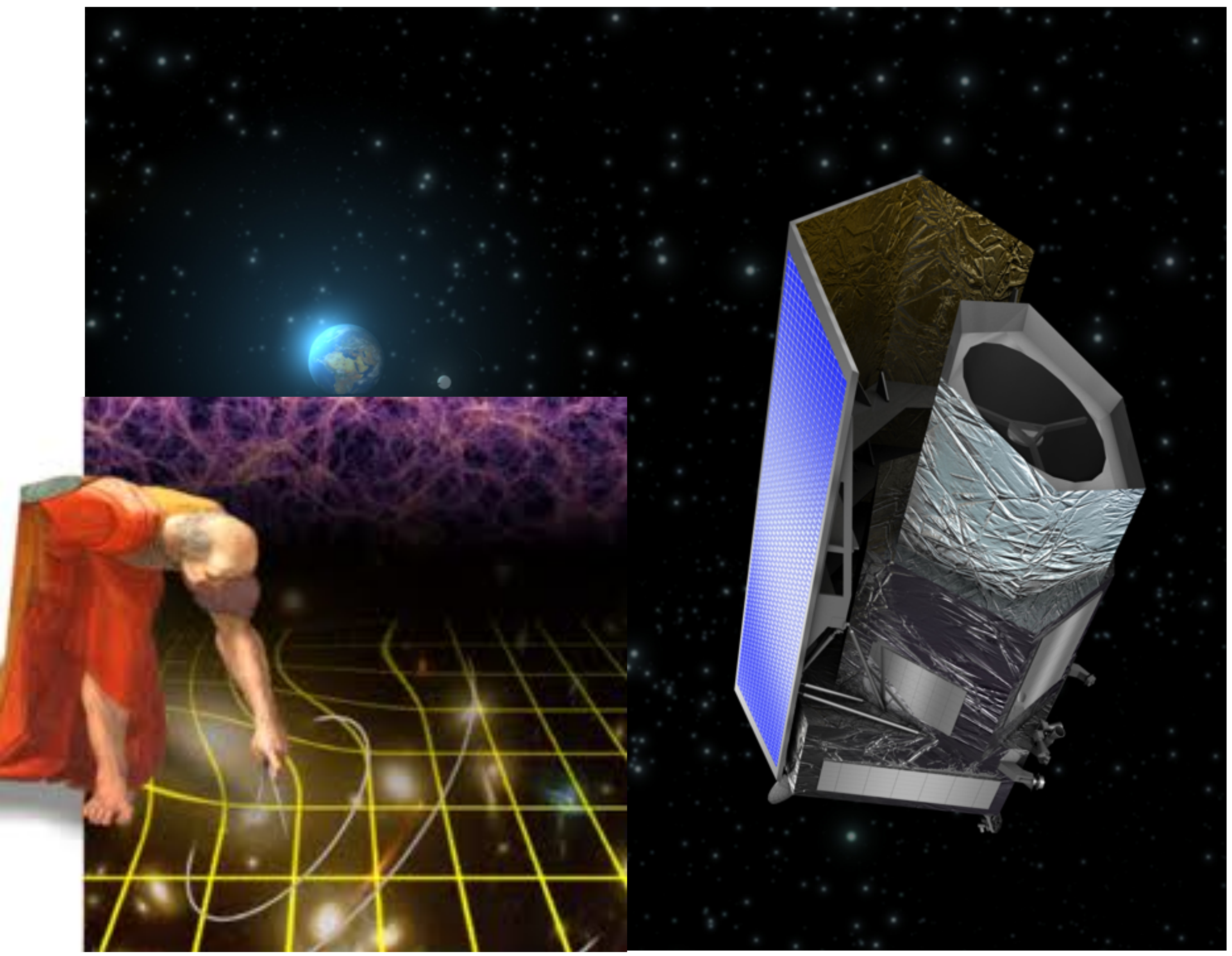
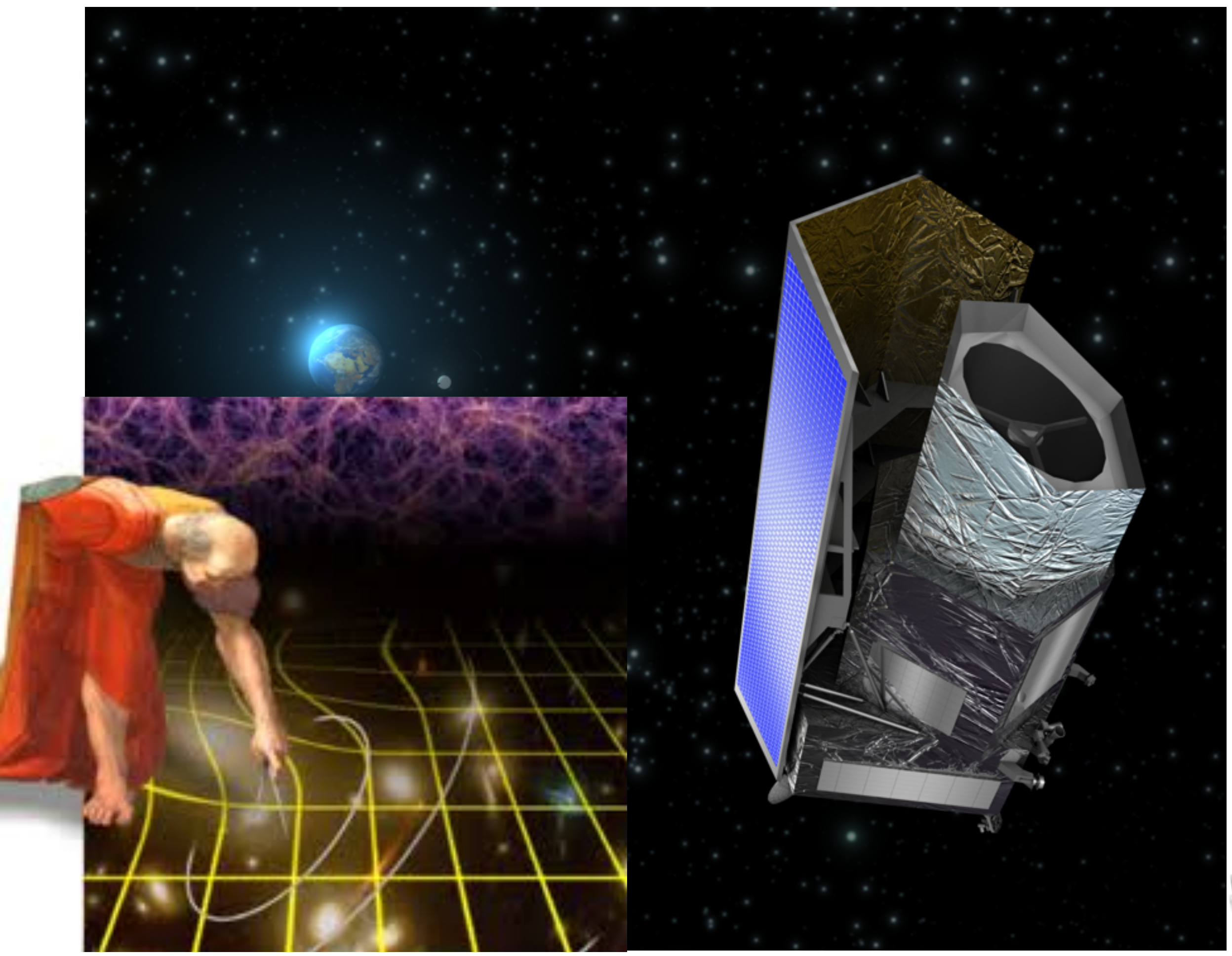


EUCLID $5.0 \cdot 10^7$

For example let's go…. Back to the future to bet on LSS with upcoming surveys

SDSS DR7 $6.7 \cdot 10^5$ galaxies



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WFIRST $2.0 \cdot 10^7$

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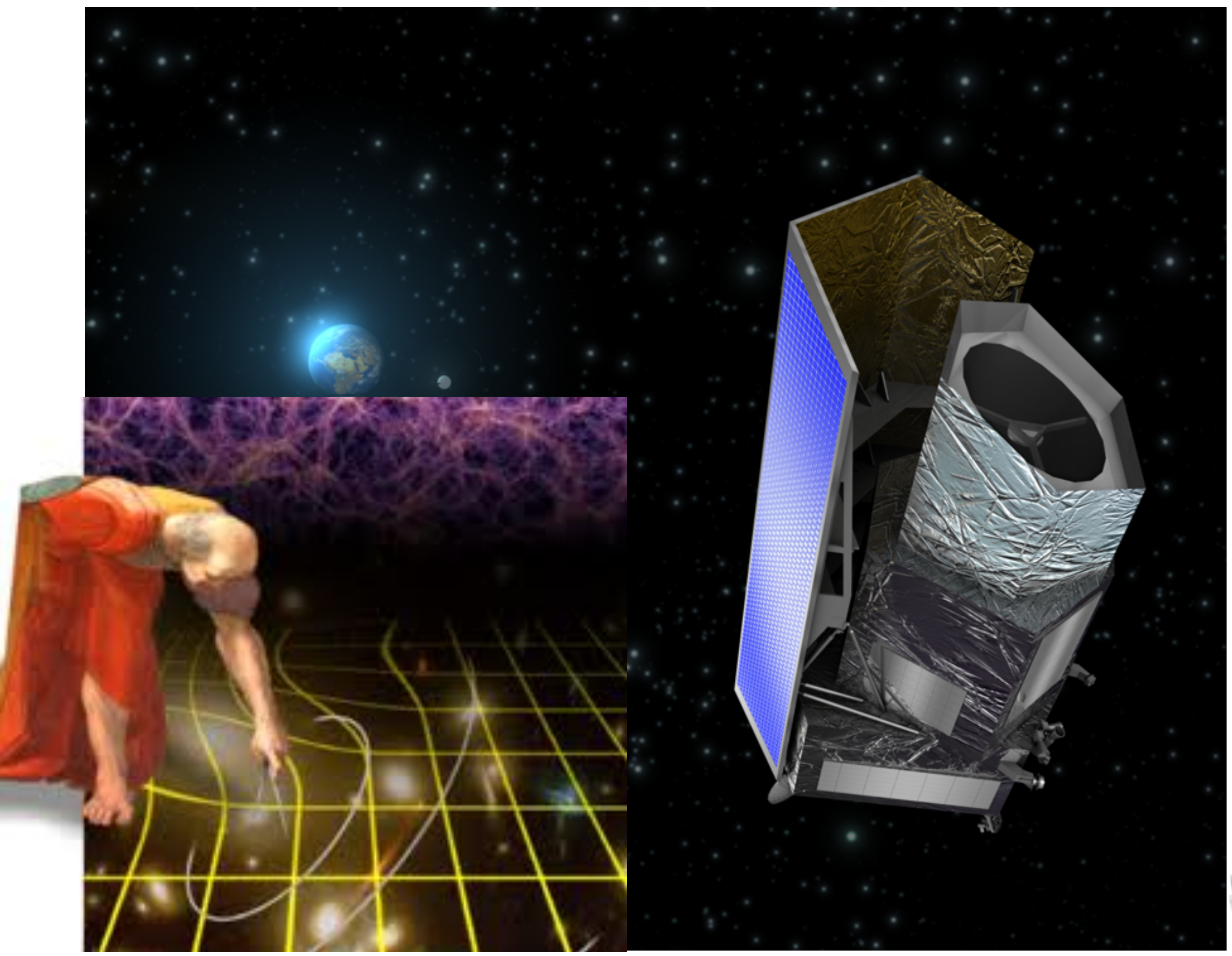

EUCLID $5.0 \cdot 10^7$

WFIRST $2.0 \cdot 10^7$

Real-space density profiles of increased precision
+ a huge statistic for AP test and abundances

Theory

Sheth Van de Weygaert excursion set model for void abundance (2004)

+

Simulation

Tuned on Euclid to obtain the parameter of the model and marginalise on parameter

+

Survey

Take into account features such as galaxy number density, survey area, redshift covering

arXiv:1503.07690(Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata 2015 - Phys.Rev. D)

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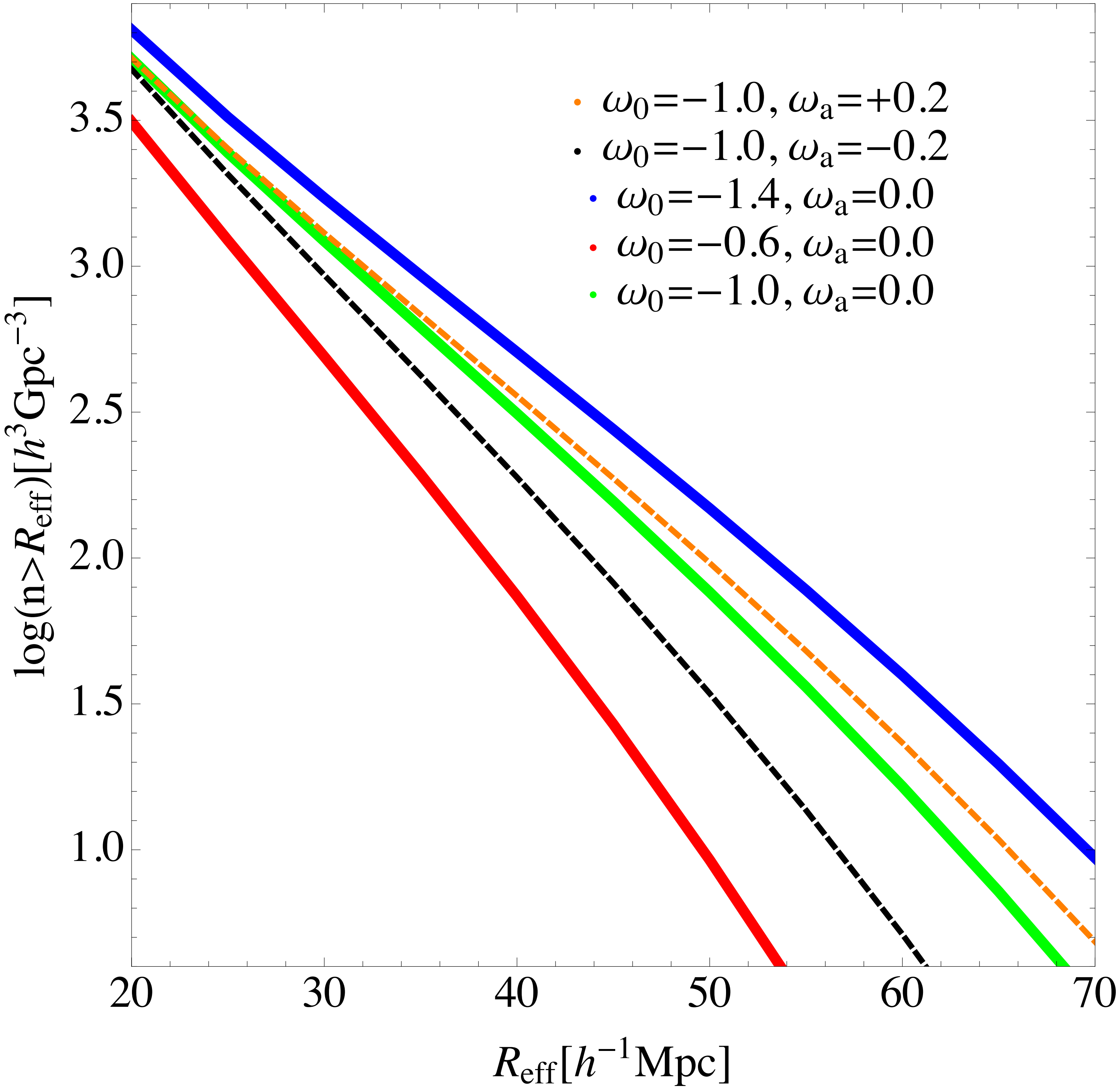
Realistic estimation of the number of voids

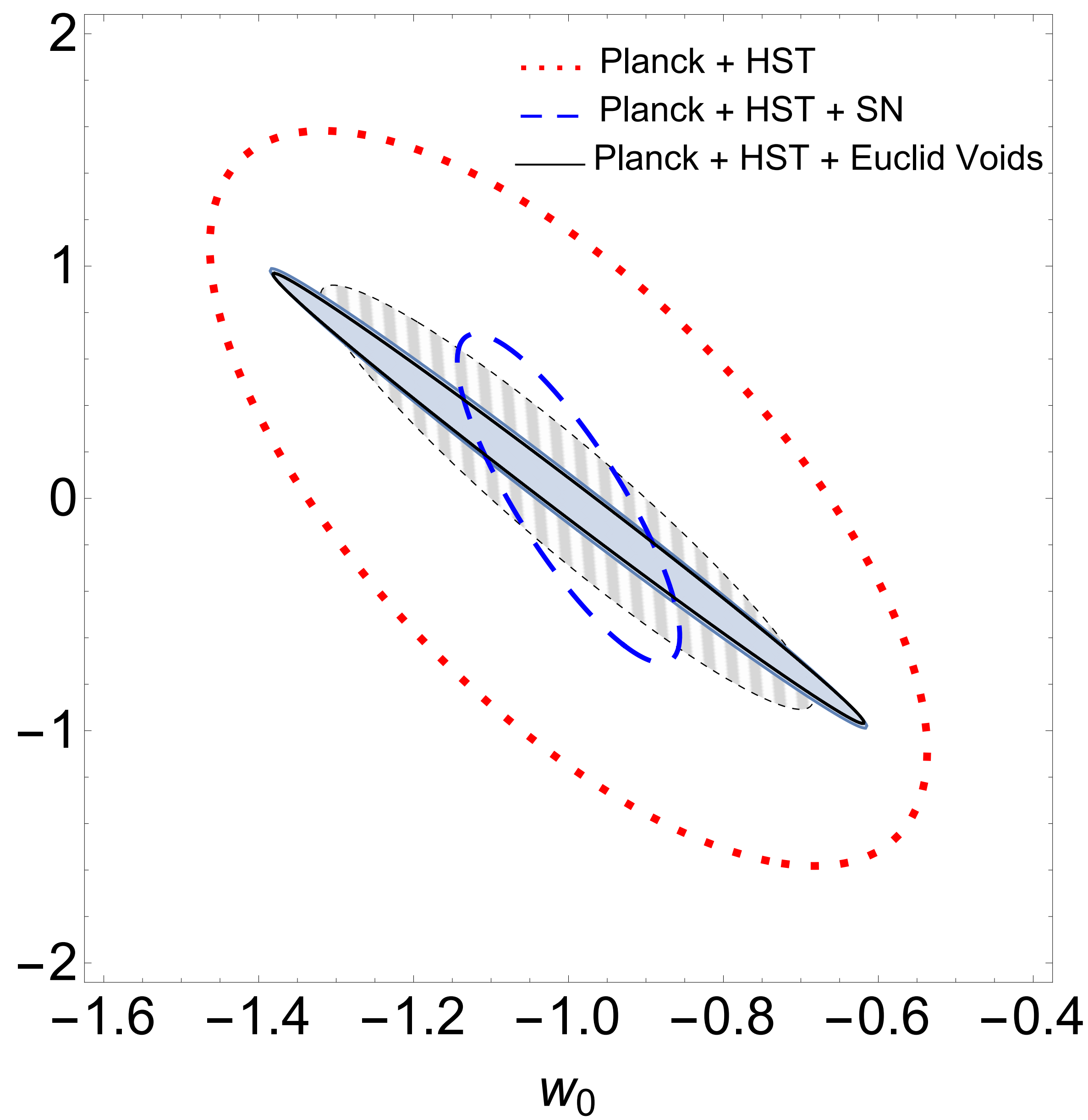
arXiv:1503.07690(Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata 2015 - Phys.Rev. D)

Abundances to constrain Cosmology



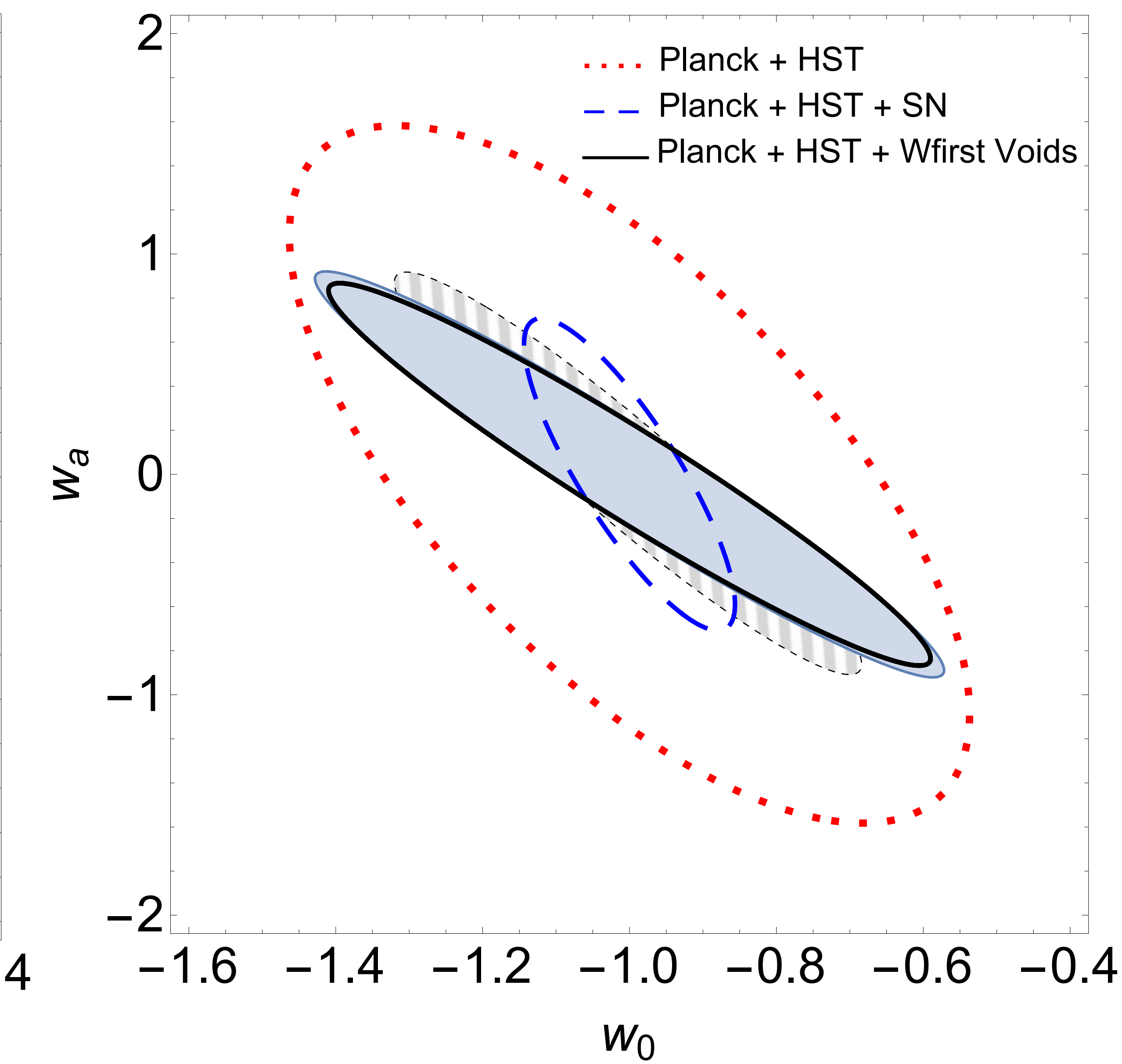
Comparing future surveys

EUCLID



$$7.8 \times 10^5$$

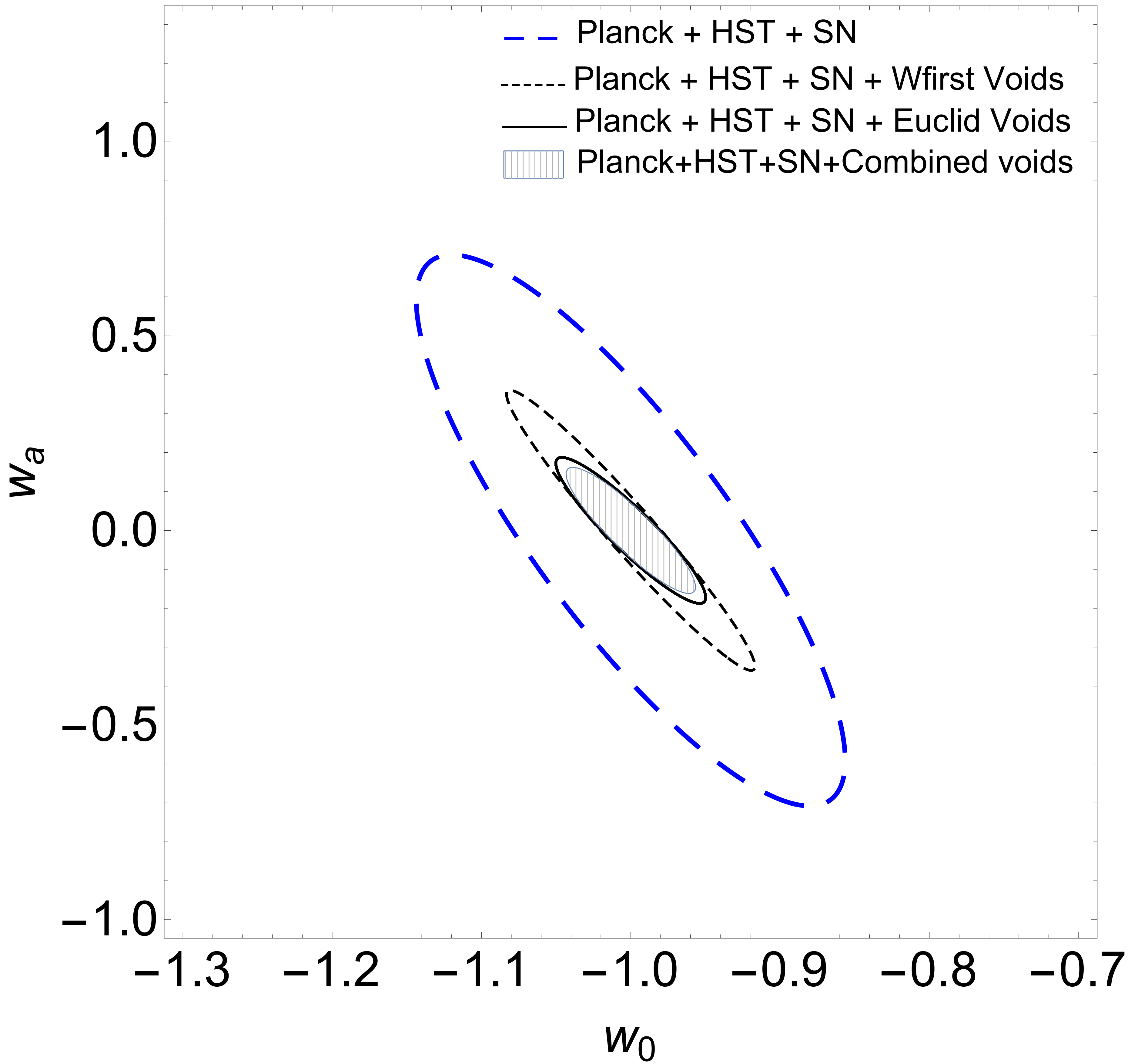
WFIRST



$$2.5 \times 10^5$$

arXiv:1503.07690(Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata 2015 - Phys.Rev. D)

Combining future surveys



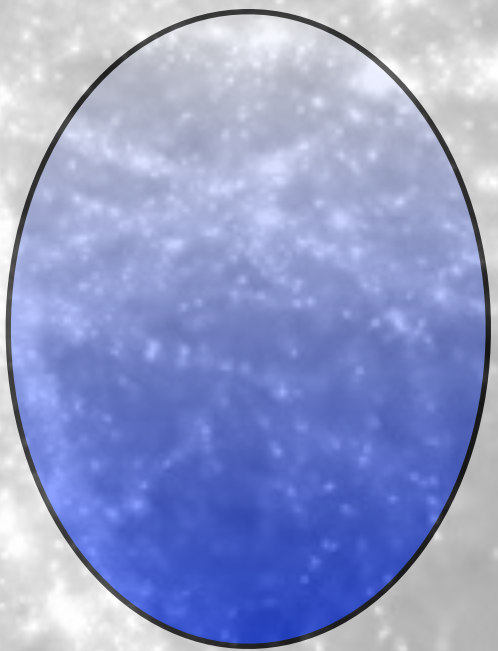
Conclusion

Voids as a **new tool** to constrain cosmology in the era of large surveys.

AP test

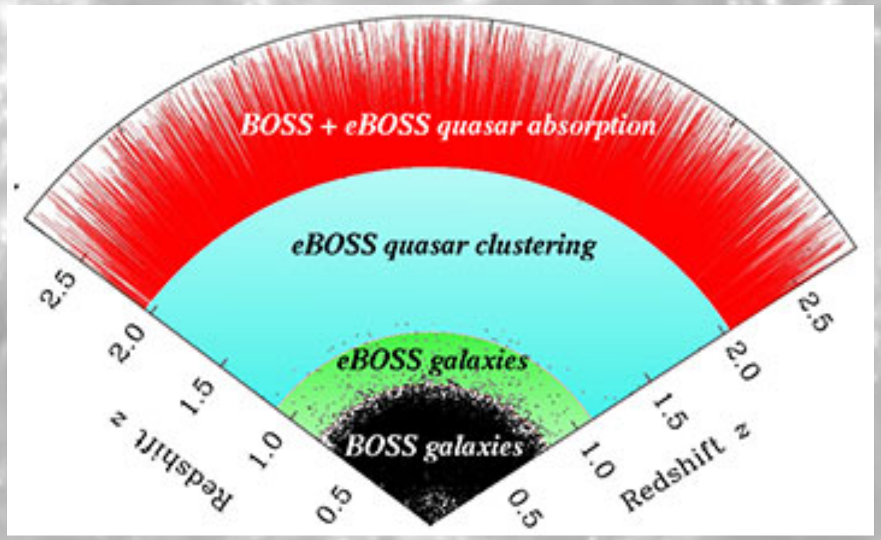
First ever **real space density profile** of voids from real data and guidelines for treatment of systematics (velocity)

Forecast for void **abundance** with Euclid



BOSS and eBOSS (high z) apply these innovative techniques

Combine!! LSST



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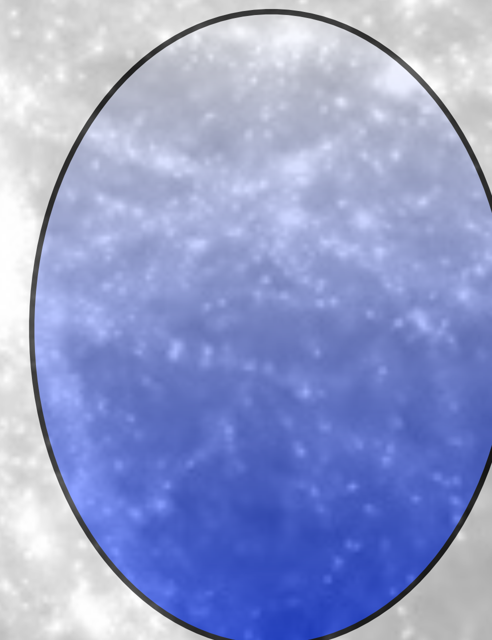
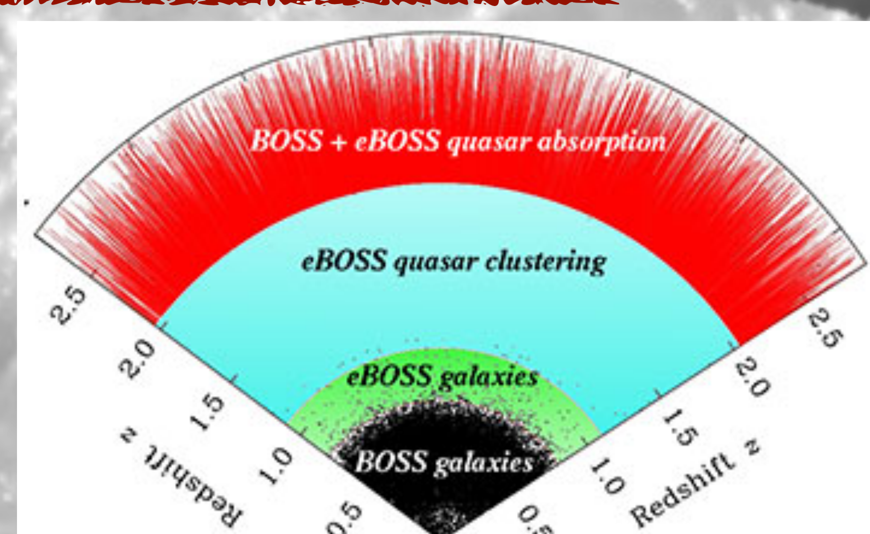


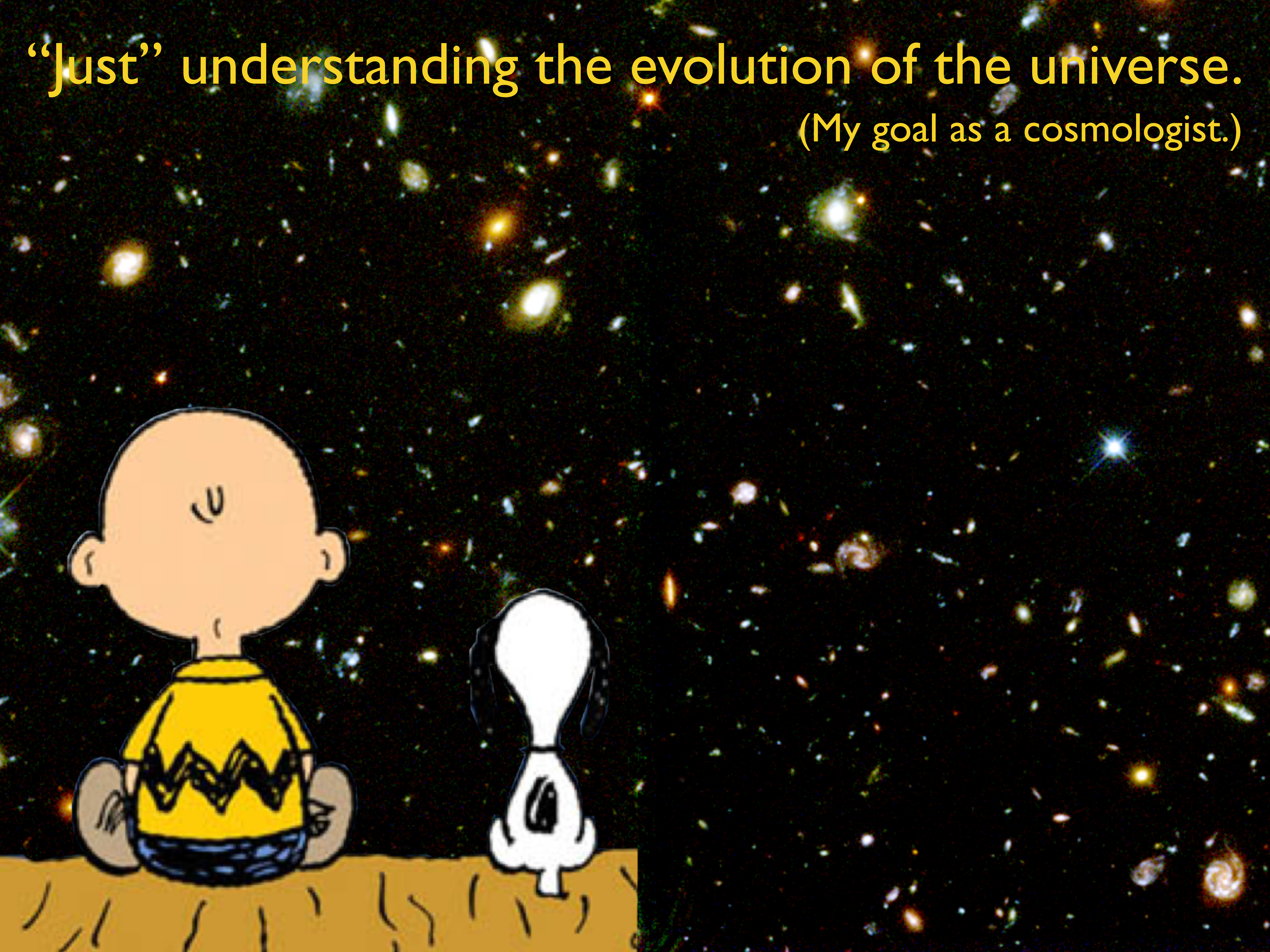
Thank you!

BOSS and eBOSS (high z) apply these innovative techniques

Combine!! LSST



Supplementary slides


"Just" understanding the evolution of the universe.
(My goal as a cosmologist.)

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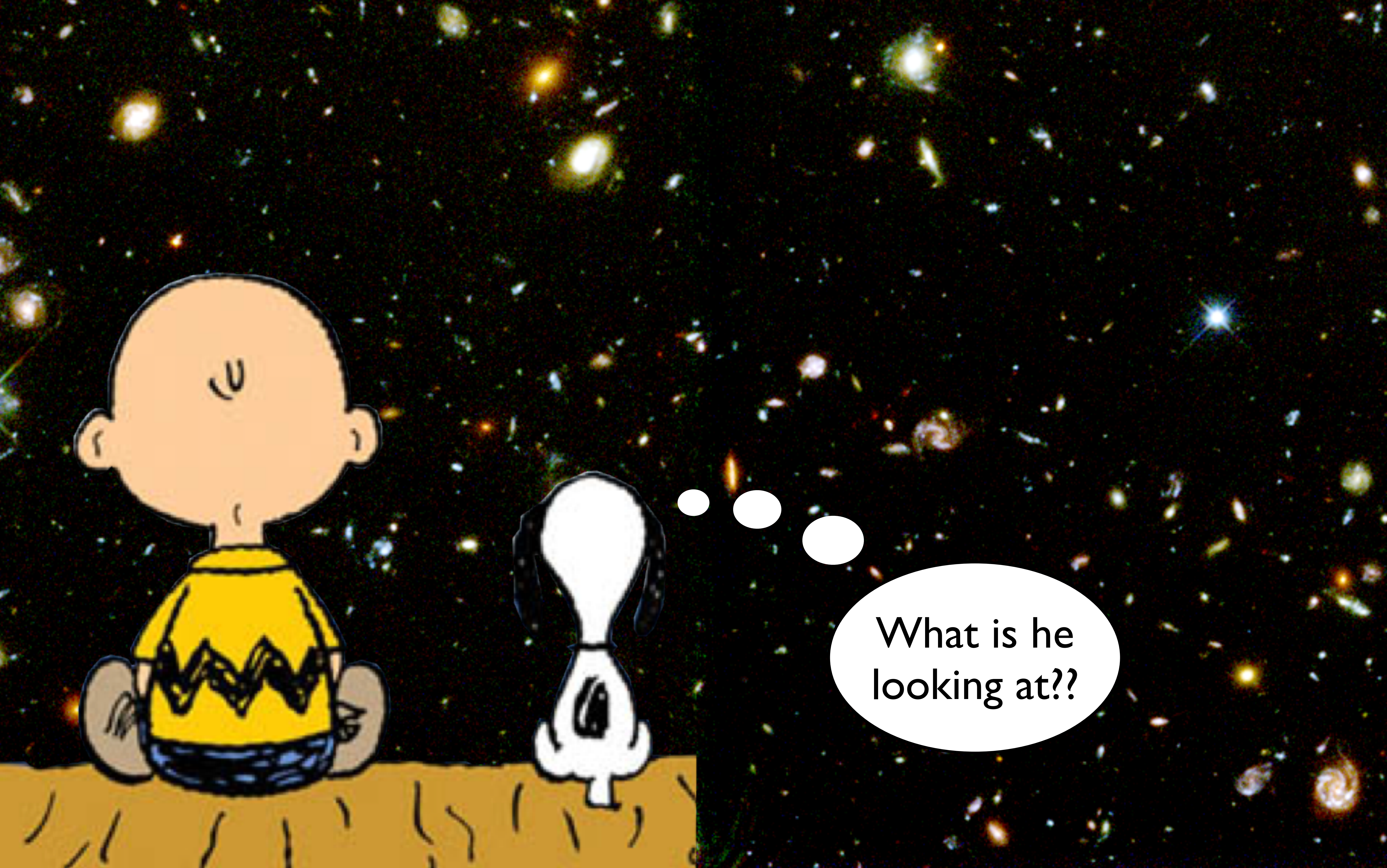

How do we calculate abundances?

Number density of voids within a given mass range

dynamics of void formation (void in void)

$$\frac{M^2\, n(M,z)}{\rho_{\rm back}(0)}\frac{\rm dM}{M} = \nu f(\nu)\frac{{\rm d}\nu}{\nu}, \qquad \nu = \frac{\delta_v^2}{\sigma^2(M)}$$

$$\sigma^2(M,a) = \int_0^\infty \frac{k^3 P_\delta(k,a)}{2\pi^2}\left|\tilde{W}(kR_{\rm Lag}(M))\right|^2 \frac{{\rm d}k}{k}.$$

$$R_L = 1.7 R_E \qquad R_L = (1+\delta_{void})^{1/3} R_E$$

$$R_{min}^{Eul} = Max[2R_{\rm mps}; R_{{\rm Eul},\sigma\simeq 1}] \qquad \sigma(R_{\rm Lag}, z) \simeq 1$$

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$$\frac{M^2\, n(M,z)}{\rho_{\rm back}(0)} \frac{\mathrm{dM}}{M} = \nu f(\nu) \frac{\mathrm{d}\nu}{\nu},$$

Linearly extrapolated underdensity

dynamics of void formation (void in void)

$$\nu = \frac{\delta_v^2}{\sigma^2(M)}$$

$$\sigma^2(M,a) = \int_0^\infty \frac{k^3 P_\delta(k,a)}{2\pi^2} \left|\tilde{W}(kR_{\rm Lag}(M))\right|^2 \frac{\mathrm{d}k}{k}.$$

Density variance inside a sphere with given mass

$$R_L = 1.7 R_E \qquad R_L = (1+\delta_{void})^{1/3} R_E$$

$$R_{min}^{Eul} = Max[2R_{\rm mps}; R_{\rm Eul,\sigma\simeq 1}] \qquad \sigma(R_{\rm Lag}, z) \simeq 1$$

Press-Schechter formalism & excursion set

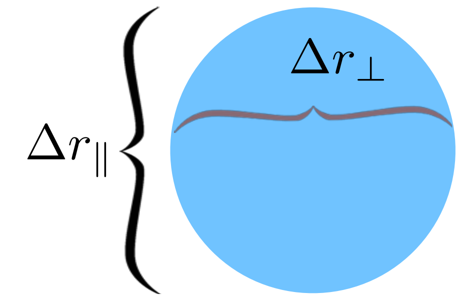
It gives the number density of objects for which the linearly extrapolated density exceed a threshold

It considers a mass element; this element will belong to a halo of given mass (>M) if the density fluctuation centred in the element and filtered over a sphere of radius prop to M^(1/3) has ð>ðc

It gives the fraction of collapsed objects with mass >M corresponding to volume samples where the initial density fluctuation >ðc

Alcock-Paczyński test

$$\Delta r_\perp = \Delta r_\parallel$$



$$\Leftrightarrow \qquad D_A(z)\Delta\theta = \frac{c\Delta z}{H(z)}$$

what we know

what we don't know

$$\frac{c\Delta z}{\Delta\theta} = D_A(z)H(z)$$

The cosmological model is telling us what we don't know:

Assuming a flat universe, $D_A(z)$ and $H(z)$ are then related to the dark energy density through

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$

$$= \sqrt{\frac{\Omega_m H_0^2}{1-\Omega_X}}\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}, \quad (3)$$

$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)}, \quad (4)$$

To perform the Alcock-Paczyński test we measure the stretch

$$e_V(z) = \frac{c}{H_0}\frac{\Delta z}{\Delta d}$$

$$e_V(z) = \frac{\Delta z}{z\Delta\theta} \qquad \Delta d = \frac{cz\Delta\theta}{H_0}$$

The deviations from fiducial cosmology cause geometrical distortions.

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Alcock-Paczyński test we measure the stretch

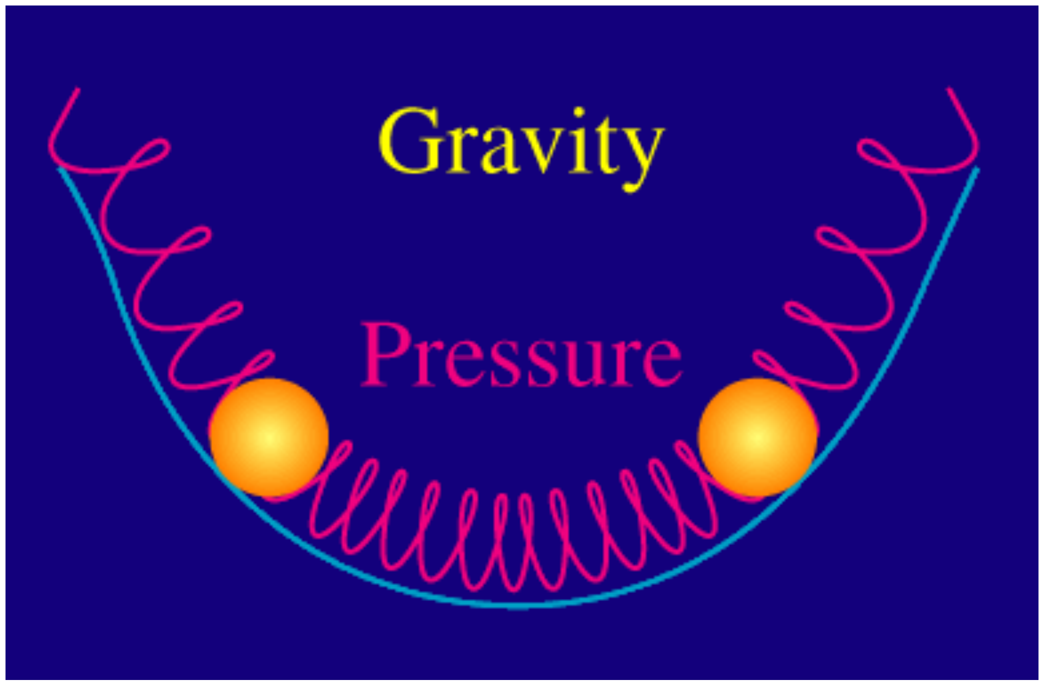
$$E(z) = \frac{H(z)}{H_0}$$

$$\frac{\delta z}{\delta d} = \frac{H_0}{c} \frac{H_0}{c} \frac{D_A(z)E(z)}{z} = \frac{H_0}{c} e_v(z)$$

$$e_v(z) = \frac{c}{H_0} \frac{\delta z}{\delta d}$$

Baryonic Acoustic Oscillations

Primordial plasma



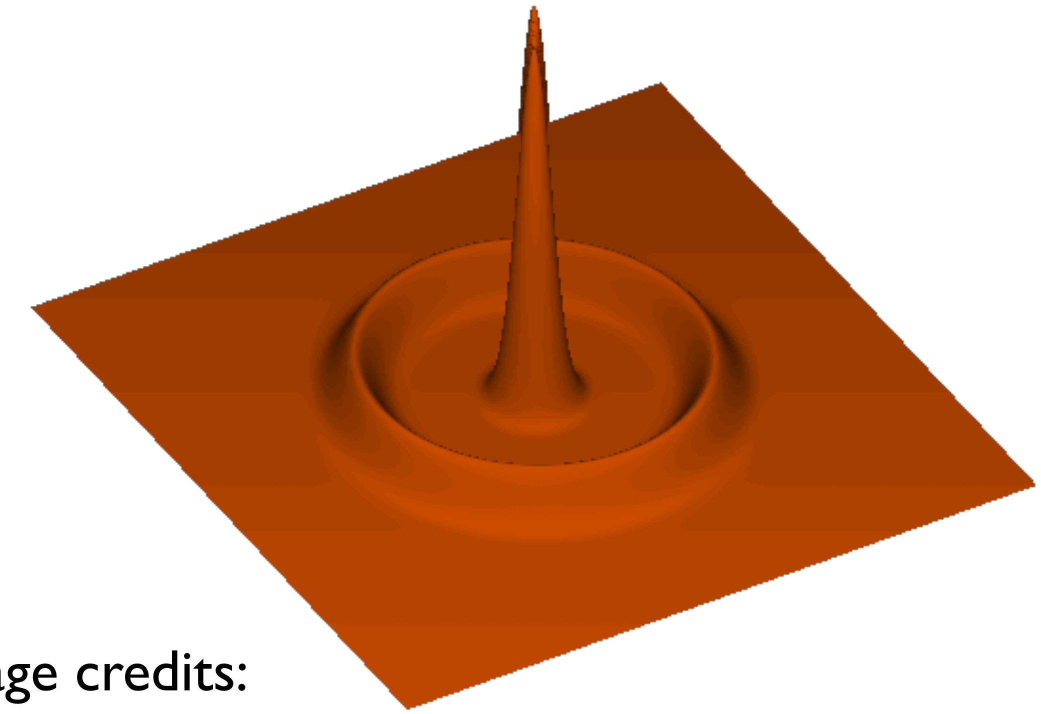


Image credits:
Hu, Eisenstein

Overdense region

Dark matter, baryons, photons

↓

Oscillations of baryons and photons

↓

Decoupling: Photons diffuse away, pressure ends

↓

Shell of baryonic matter at fixed radius

BAO can be considered an absolute AP test (i.e. with standard ruler)

A standard ruler

$$\begin{cases} \Delta r_\perp = 150 Mpc & \textit{(theory)} \\ \Delta r_\perp = D_A(z)\Delta\theta \end{cases}$$

$$D_A(z)H(z)$$

(our friend AP test)

$$\Rightarrow H(z)$$

Chevallier-Polarski-Linder parametrisation

$$w(z) = w_0 + w_a \frac{z}{z+1}$$

Methods for the AP test: Method for AP test fits real space shape to redshift shape.

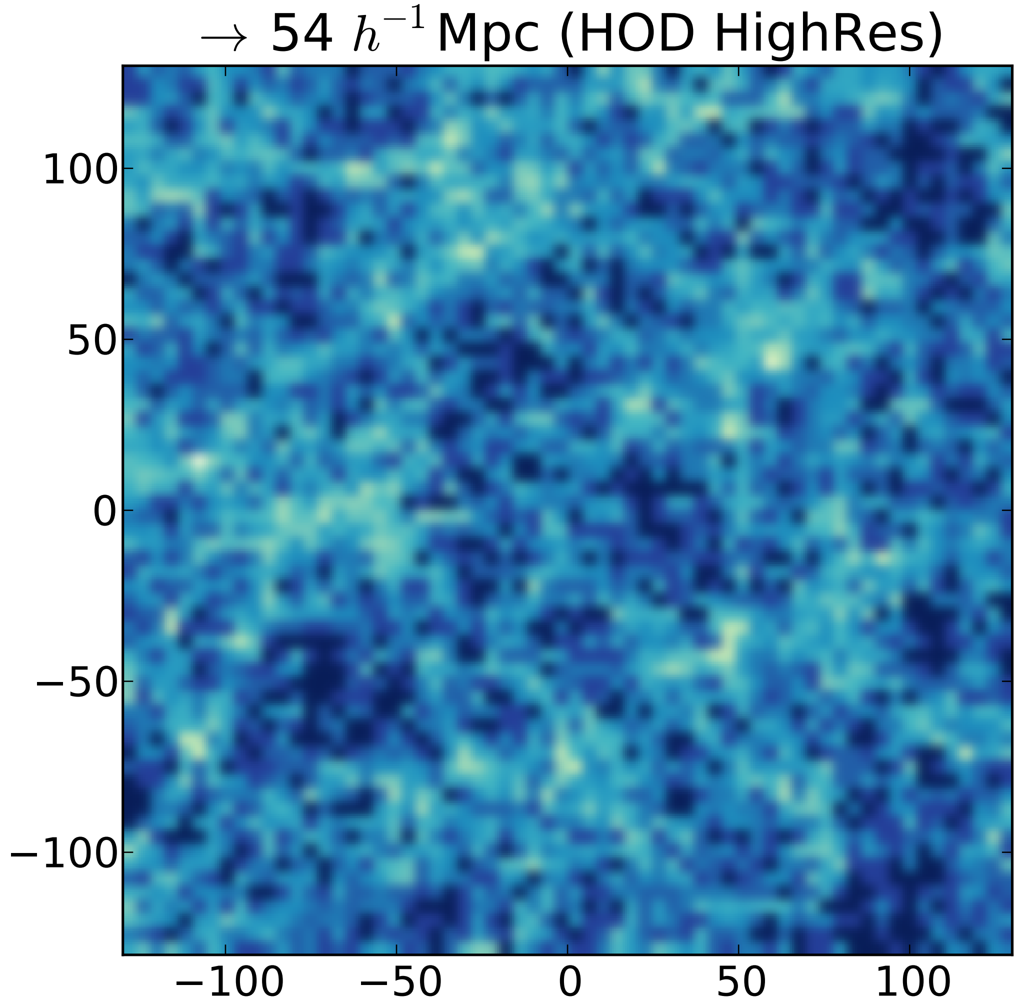
Method 1: better but needs more voids

It starts from a radial profile, fits it to an ellipse. In this ellipse equation there are δz and δd , so we get stretch (by comparing with the void) $e_v(z)$; its real space shape to redshift shape.

Method 2: worse but works with less voids

We transform the line of sight coordinate by a factor proportional to $e_v(z)$, until it matches the void, so we get stretch…

➡ From stretch we constrain $D_A(z)H(z)$



BOX: 1 h^-1Gpc side

1024^3 particles

Mass resolution:
7.36 × 10^11 h^–1 M⊙

Rockstar halo finder
(Behroozi et al. 2013)

Dense: halos above 1.47 × 10^12 h^−1 M⊙

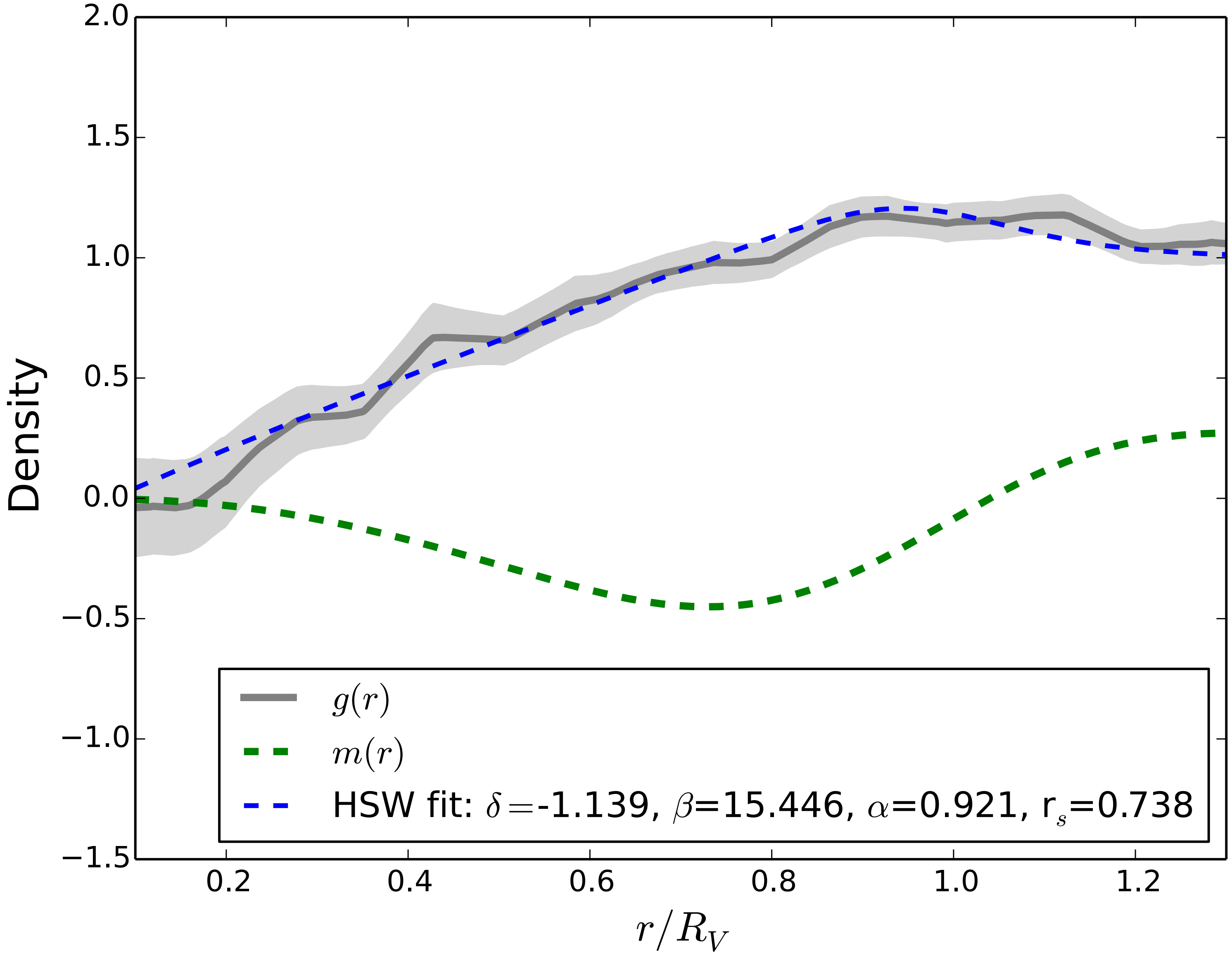
Sparse: 1.2 × 10^13 h^−1 M⊙

HOD modeling=>mock catalog

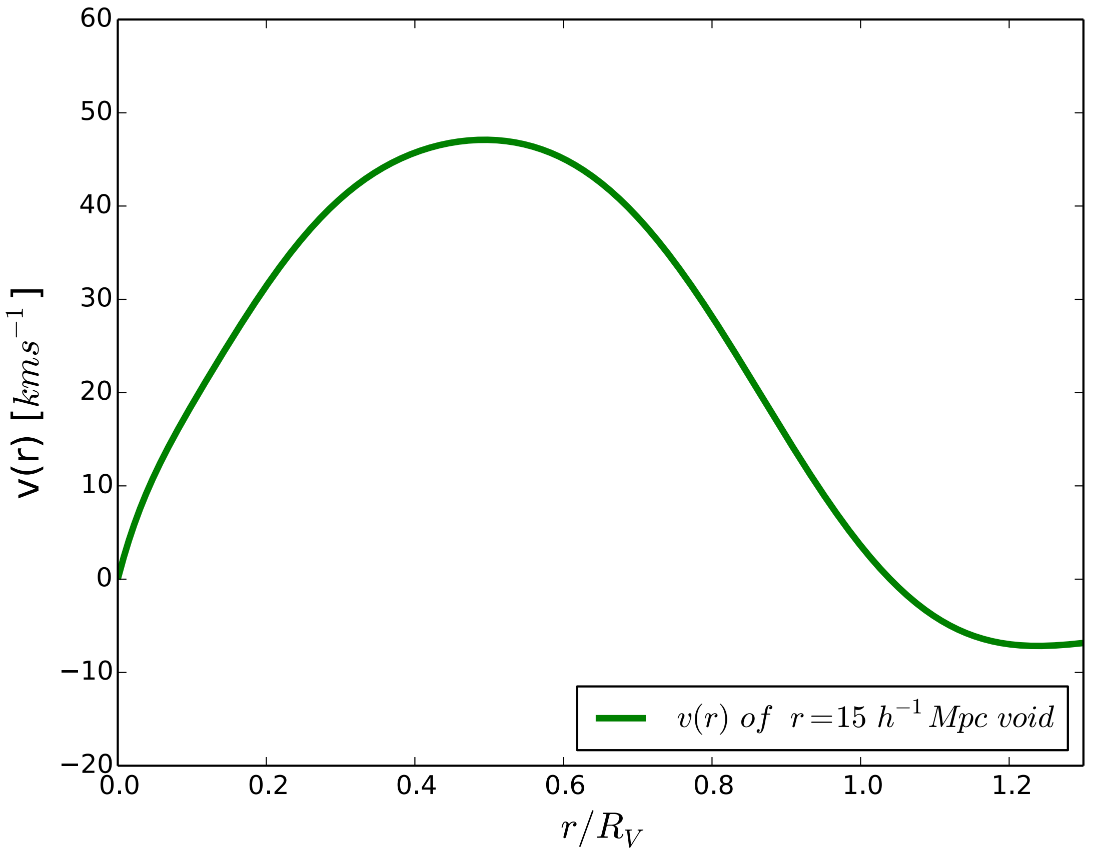
WMAP 7-year cosmological parameters

Simulation: 2HOT code, adaptive treecode
N-body method,standard symplectic integrator (Quinn et al. 1997)

A prediction for mass and velocity



mass



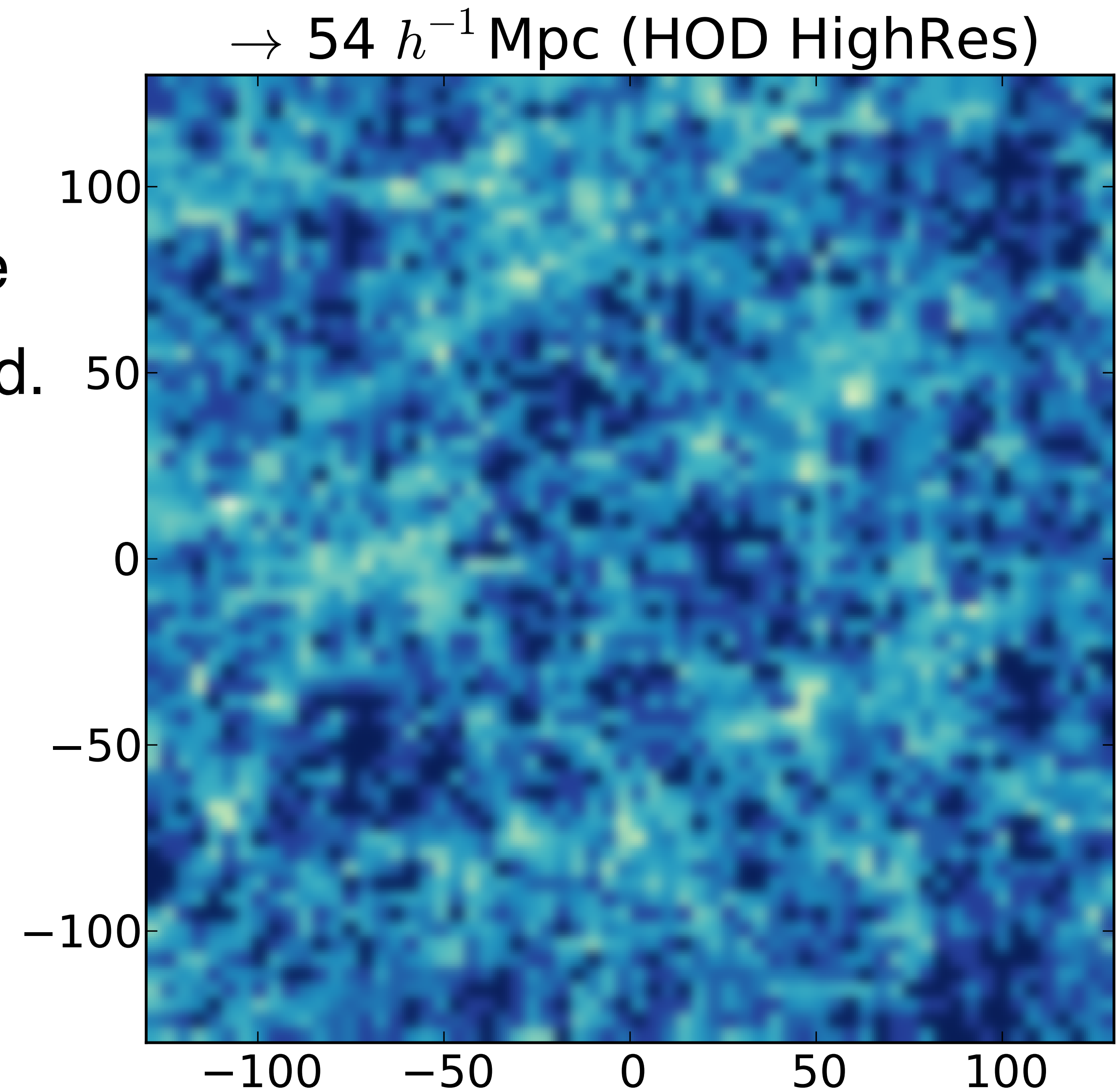
velocity

van de Weygaert and van Kampen (1993) Hamaus et al. (2014)

Matching algorithm

A "potential match" is any void whose macrocenter lies within the Voronoi volume of the original void.

The best match is the one with major cells overlap



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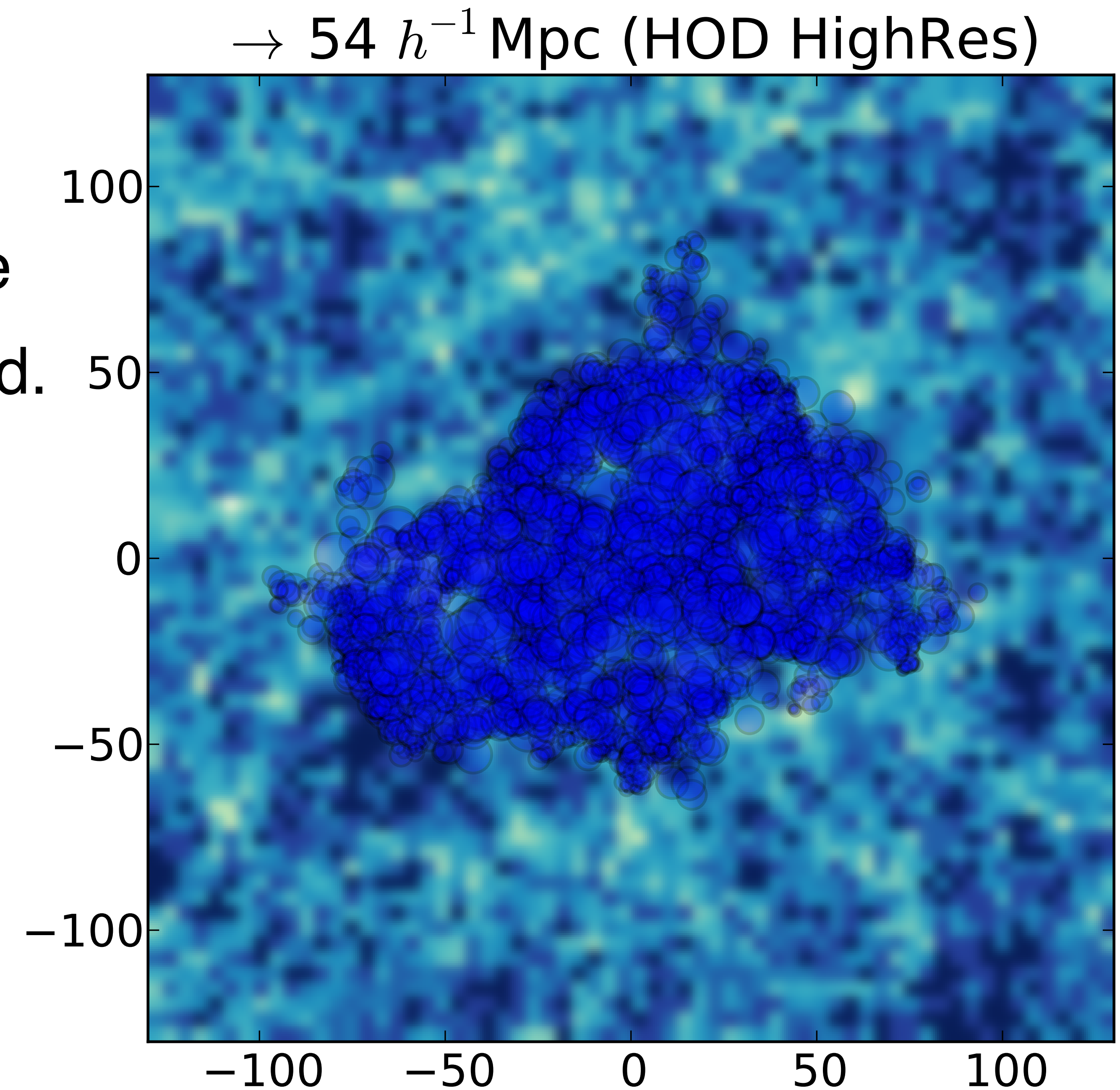

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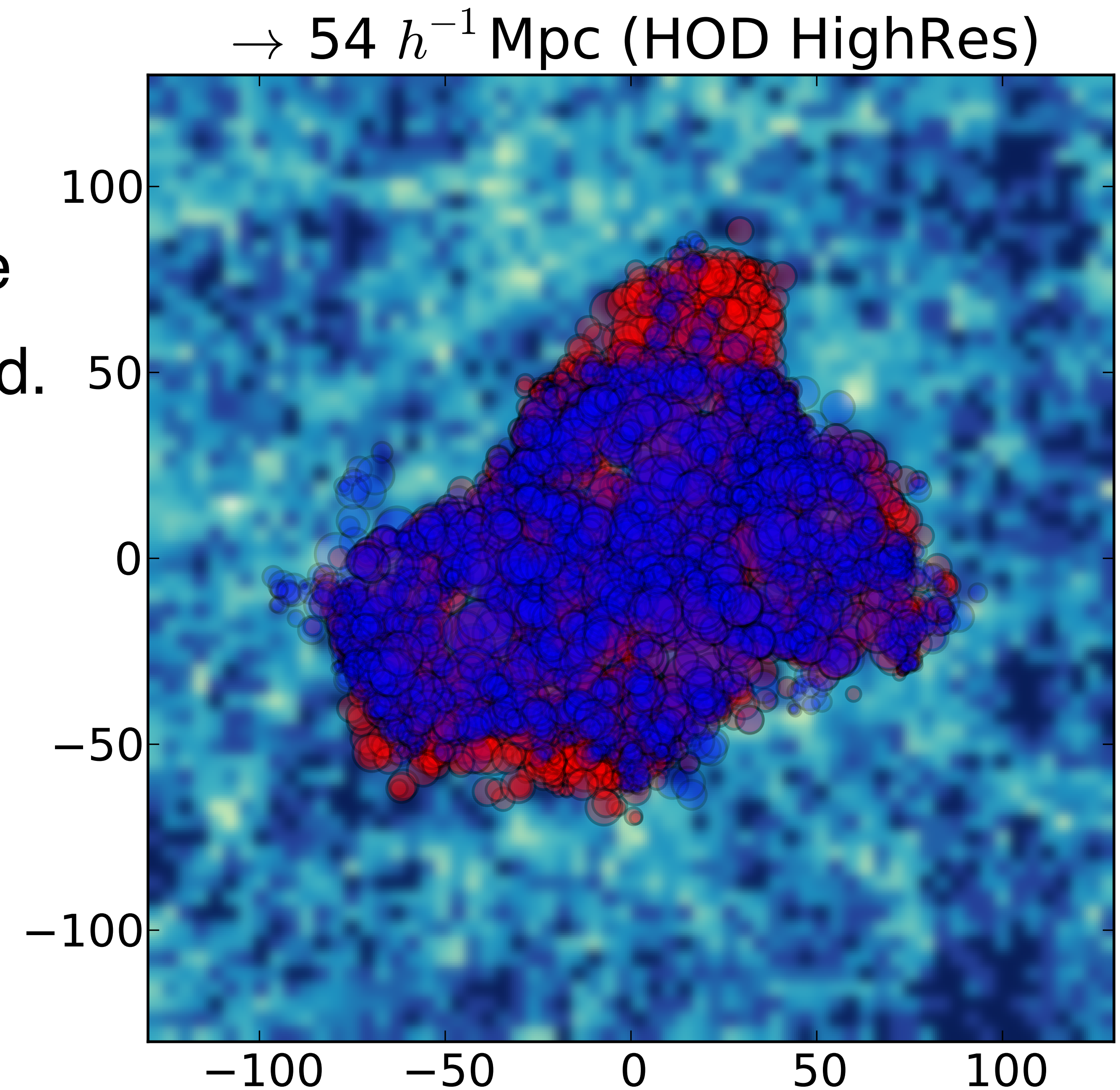
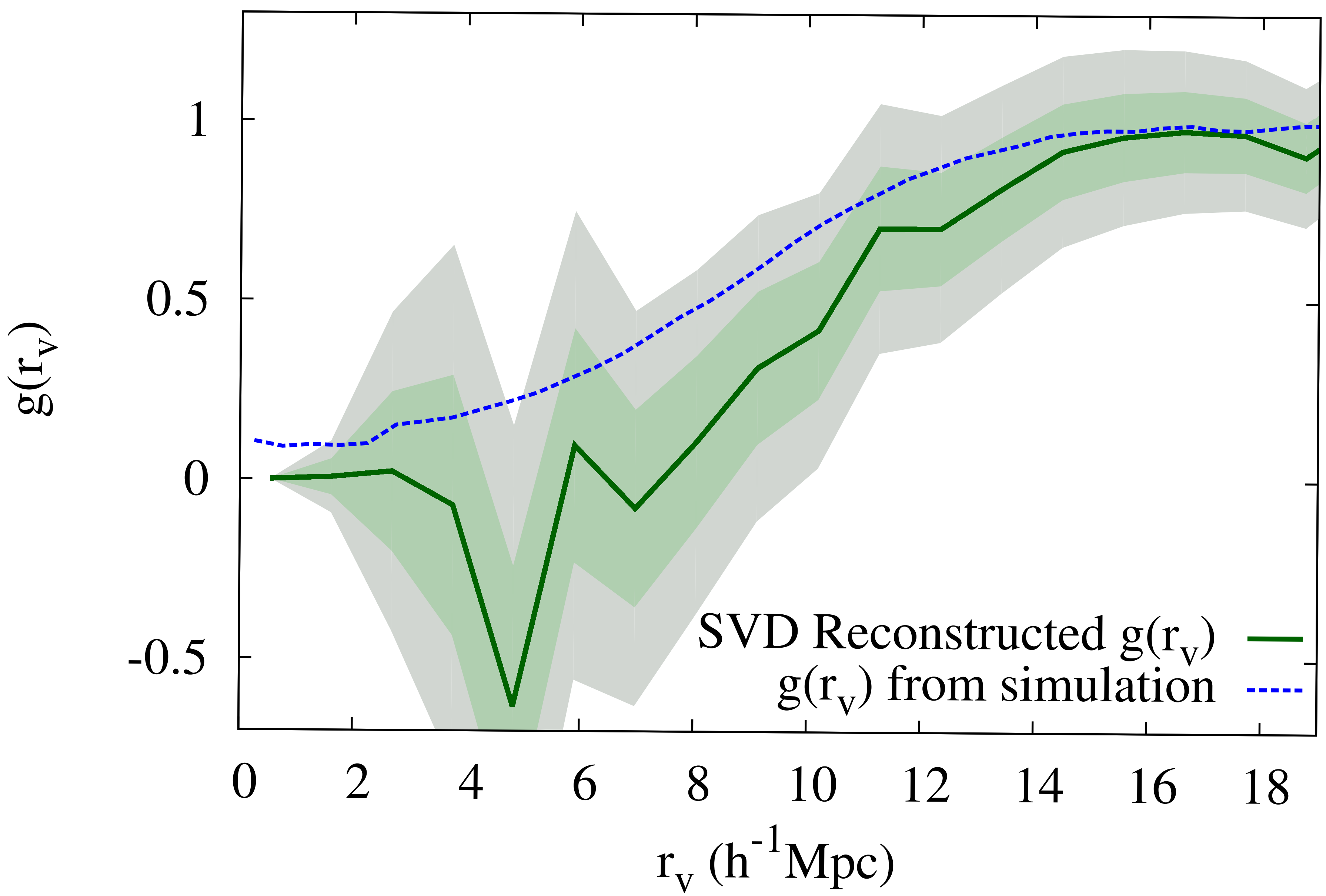


SVD reconstruction



$$M = \frac{4\pi}{3} R_{\mathrm{Lag}}^3 \rho_{\mathrm{back}}(0) = (1 + \Delta_V)\, \frac{4\pi}{3} R_{\mathrm{Eul}}^3 \rho_{\mathrm{back}}(0)$$

We use the extension of Press-Schechter for voids, proposed by Sheth and Van de Weygaert.

There is a turn over at small radii, because small voids collapse. We put ourselves above that turn over in radius (otherwise we should have assumed the two barrier excursion set model also with d_c)+ we consider 2Mps as limit.

Sheth & Van de Weygaert 2004

Another natural choice is $\delta_{ta} = 1.06$; this ignores all voids that are within regions which are beginning to turnaround, even though they may still have non-neglibigle sizes, and so underestimates the abundance of large voids. Accounting more carefully for the effect of the void-in-cloud problem is the subject of ongoing work.

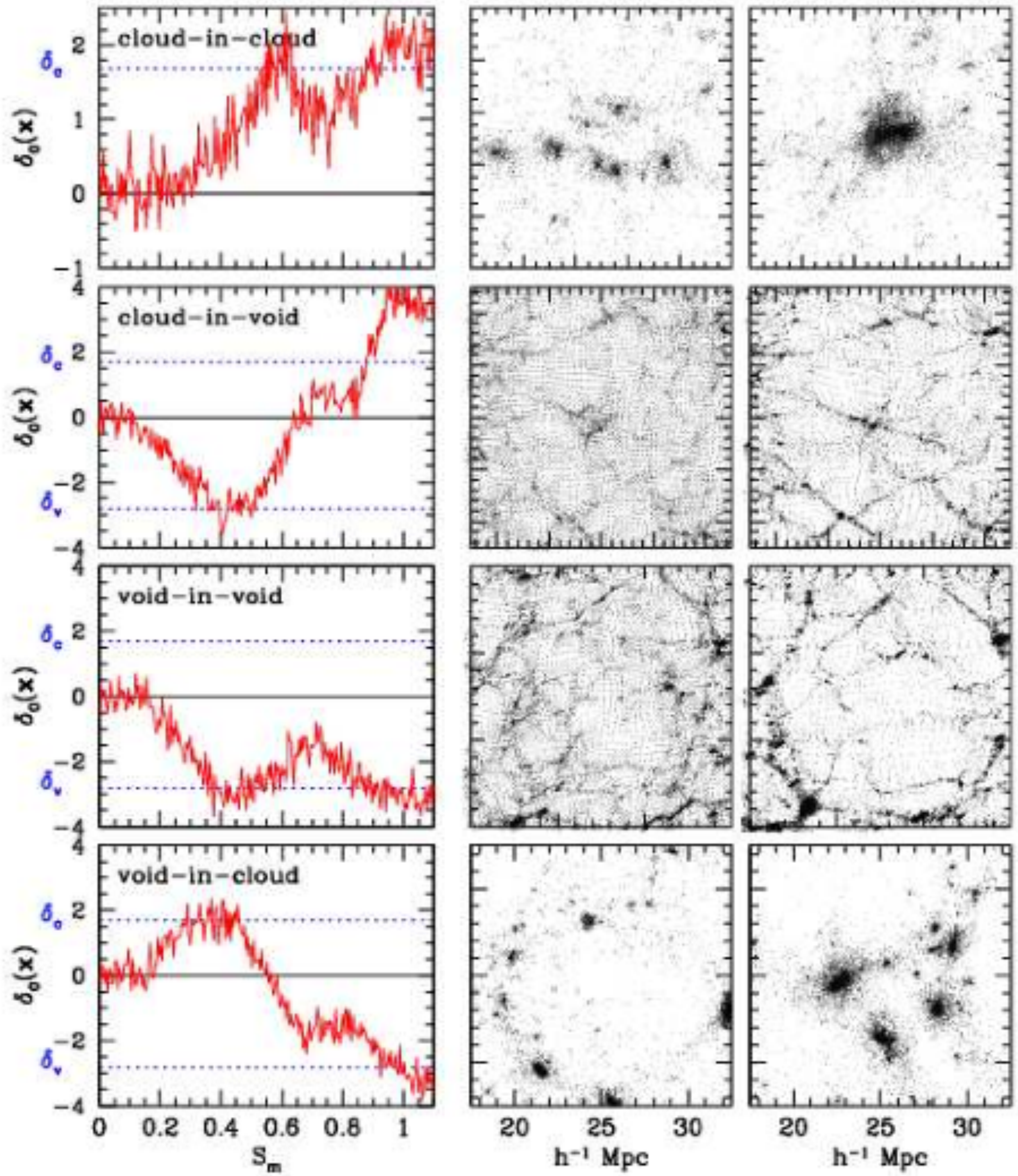


Figure 6. Four mode (extended) excursion set formalism. Each row illustrates one of the four basic modes of hierarchical clustering: the *cloud-in-cloud* process, *cloud-in-void* process, *void-in-void* process and *void-in-cloud* process (from top to bottom). Each mode is illustrated using three frames. Leftmost panels show 'random walks': the local density perturbation $\delta_0(\mathbf{x})$ as a function of (mass) resolution scale S_m (cf. Fig. 5) at an early time in an N-body simulation of cosmic structure formation. In each graph, the dashed horizontal lines indicate the *collapse barrier* δ_c and the shell-crossing *void barrier* δ_v. The two frames on the right show how the associated particle distribution evolves. Whereas halos within voids may be observable (second row depicts a halo within a larger void), voids within collapsed halos are not (last row depicts a small void which will be squeezed to small size as the surrounding halo collapses). It is this fact which makes the calculation of void sizes qualitatively different from that usually used to estimate the mass function of collapsed halos.

Sheth & Van de Weygaert

apply this on voids, considering that a void is formed when δ_v, the linearly extrapolated UNDERDENSITY is reached (when a shell forms around a sphere)