Precision Cosmology with Cosmic Voids

Séminaire CPPM

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Marseille
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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

ΛCDM

Physics Nobel Prize 2011 Perlmutter, Riess, Schmidt

Supernova I a

CMB-Planck collaboration

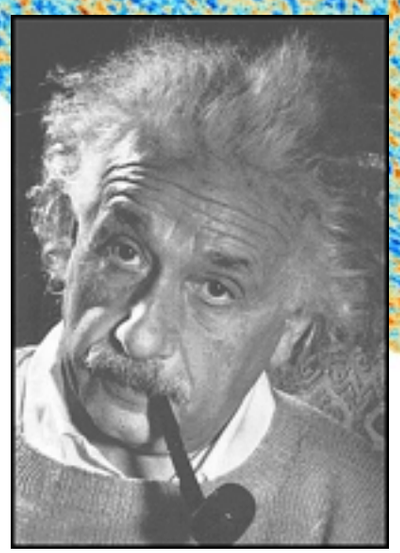
Fritz Zwicky

Vera Rubin

Penzias & Wilson Nobel 1978

(1960)

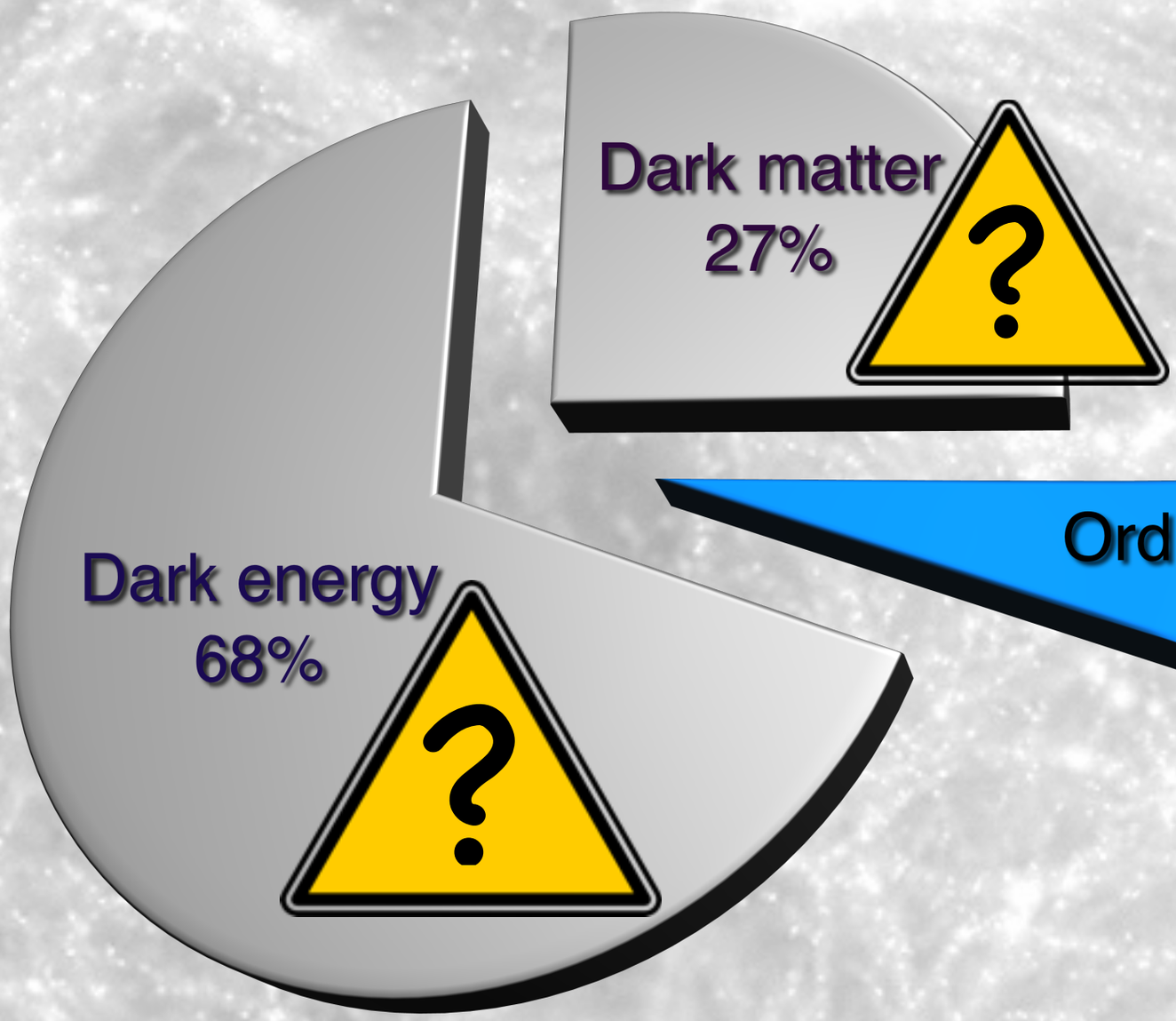
COBE Nobel 2006 (1990)



Albert Einstein

Λ

We have a great understanding of our Universe!



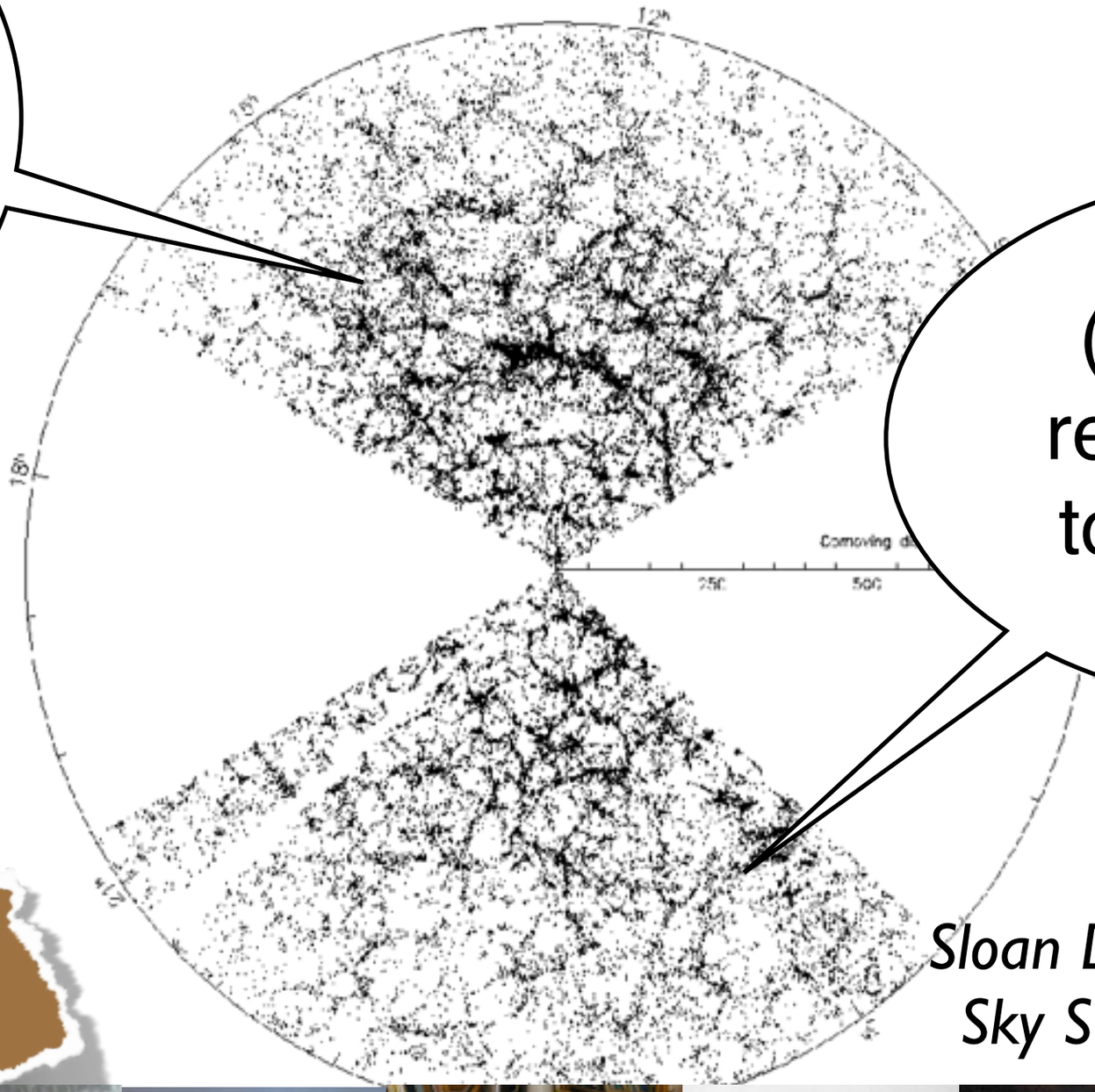
We
know almost…
NOTHING!

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


Gregory


Thompson


Joeveer


Einasto


Tago

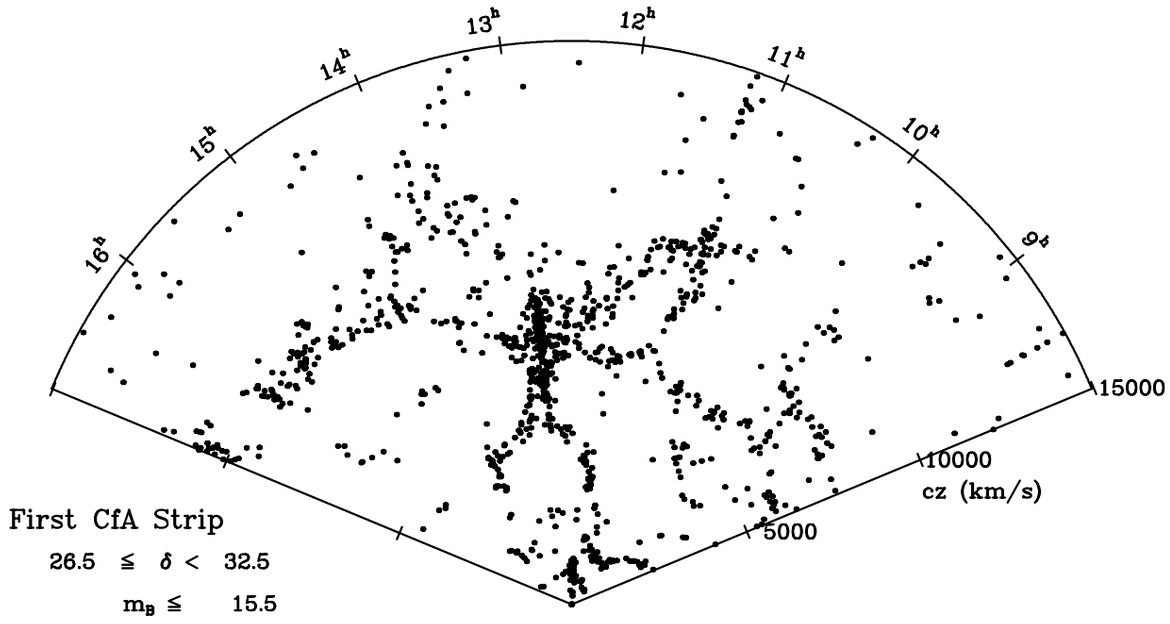
Are voids there?

1977

Credit: Thompson and Gregory 1977

Credit: Jaan Einasto private collection

Peebles Abell Longair Einasto



Credit: de Lapparent et al. 1986

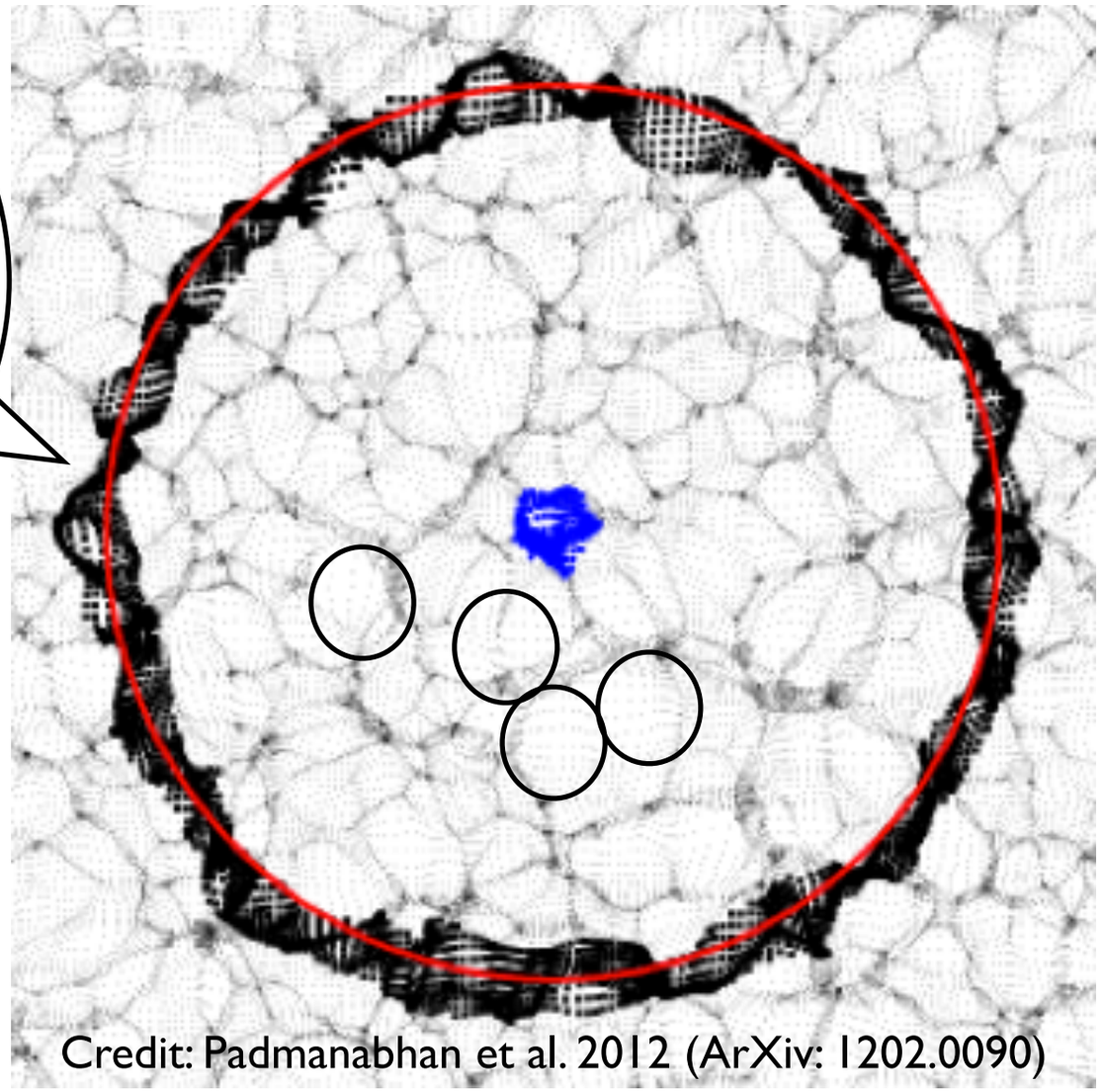
1986

Can we use voids to get cosmological information?

In voids matter is missing=> Dark Energy

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

BAO compared to void

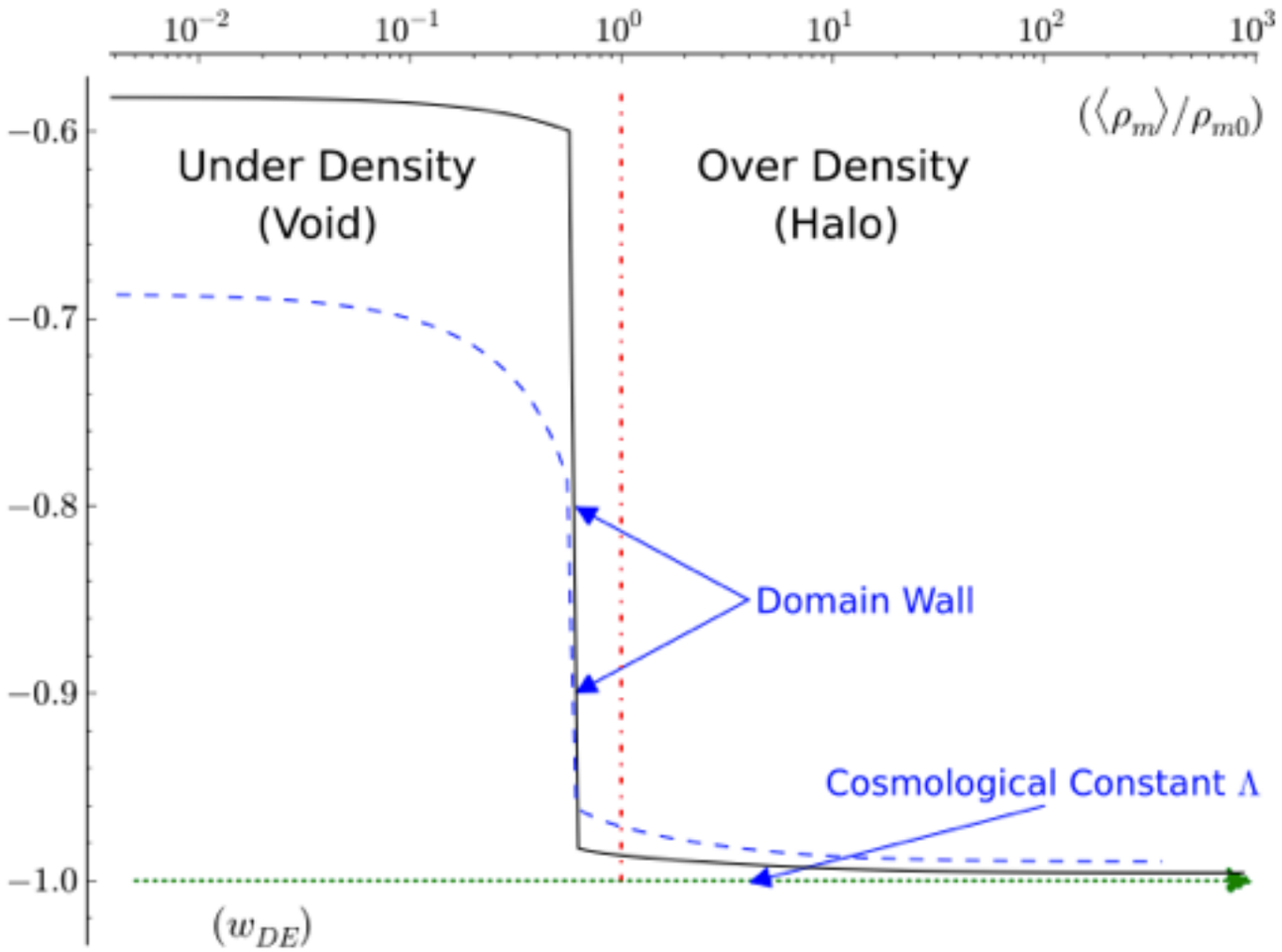


Credit: Padmanabhan et al. 2012 (ArXiv: 1202.0090)

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?



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

The equation of state could be DENSITY and SCALE DEPENDENT

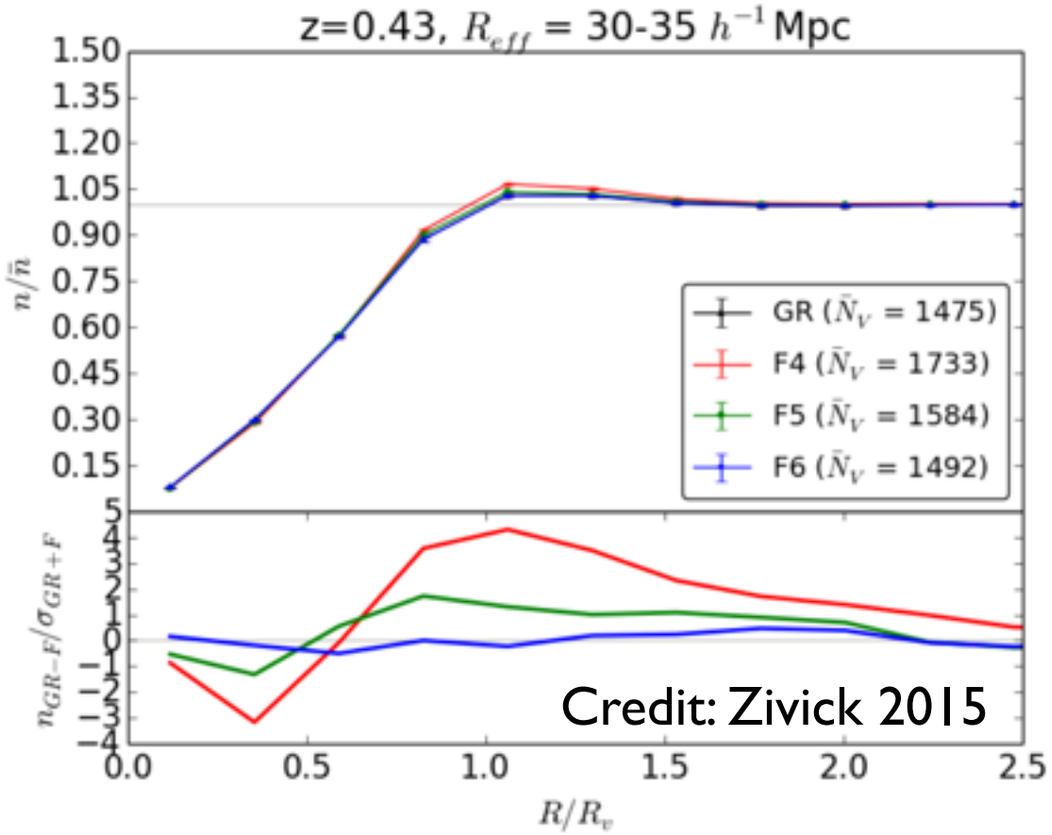
In lower density zones the effect of Modified Gravity should be different!

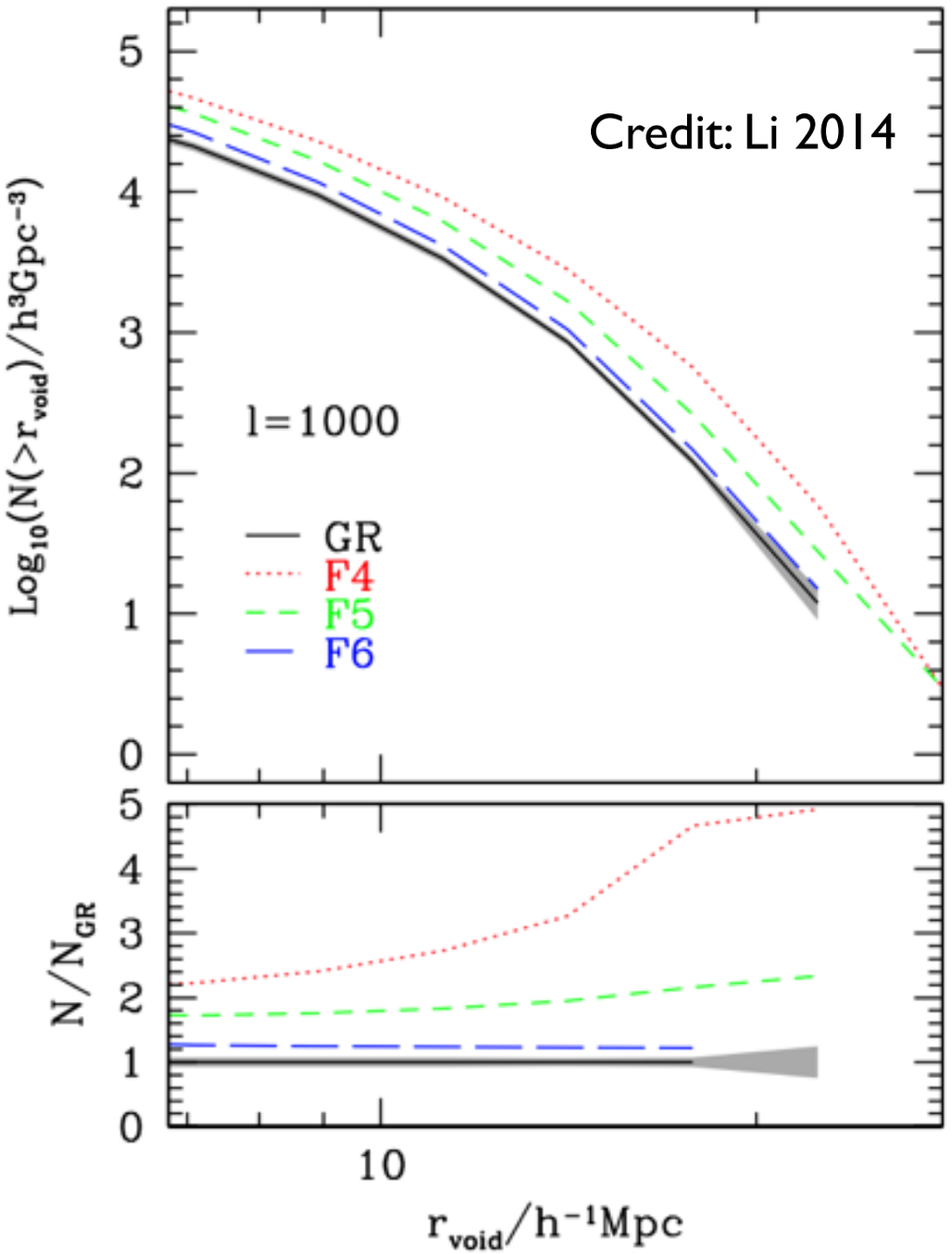
- Growth rate

Credit: Spolyar et al. (ArXiv: 1304.5239)

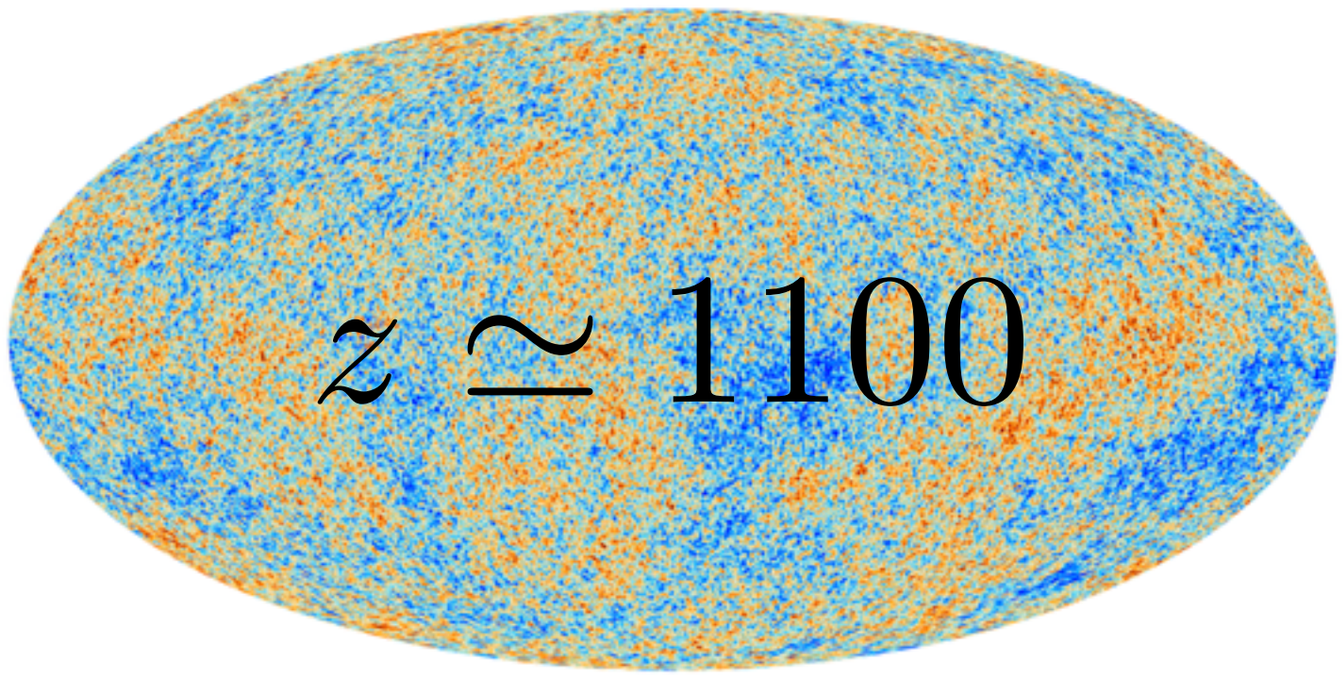
Modified gravity, the LSS might be different

- Density profiles
- Void abundances

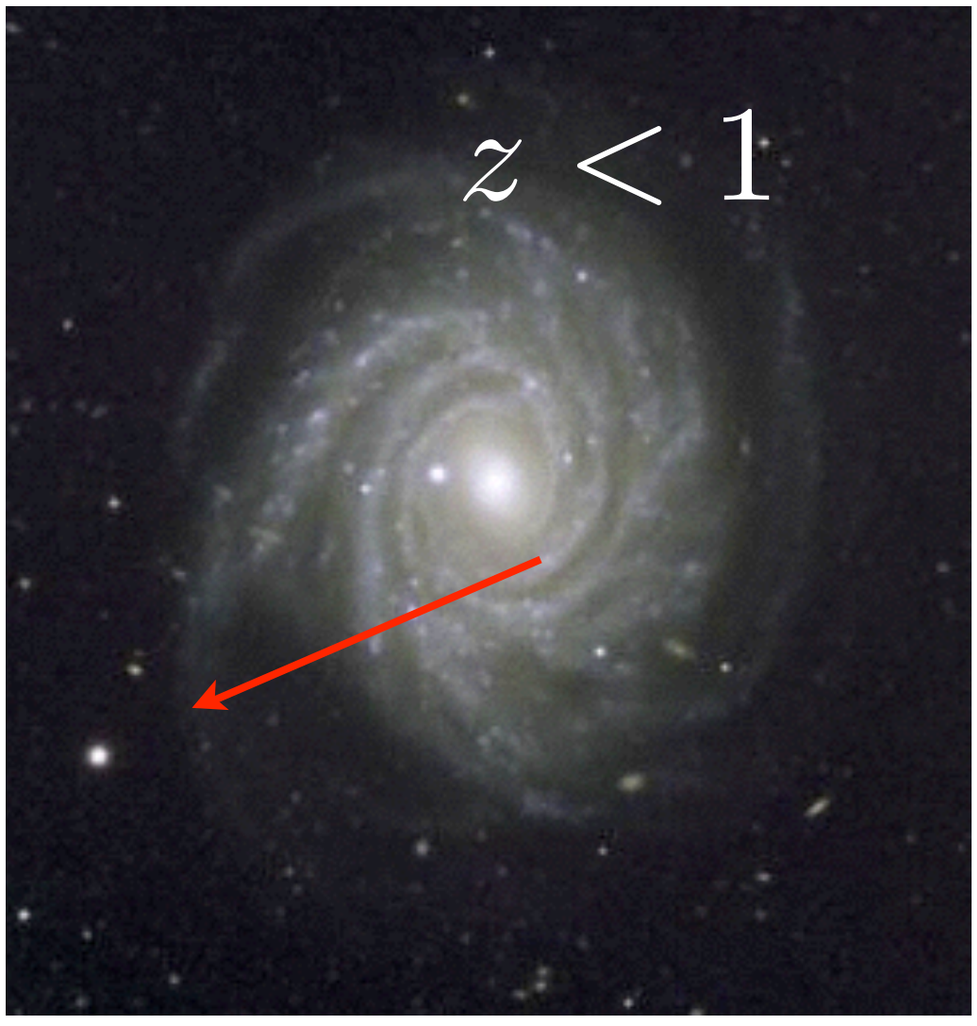




Analyze void properties to constrain cosmological models

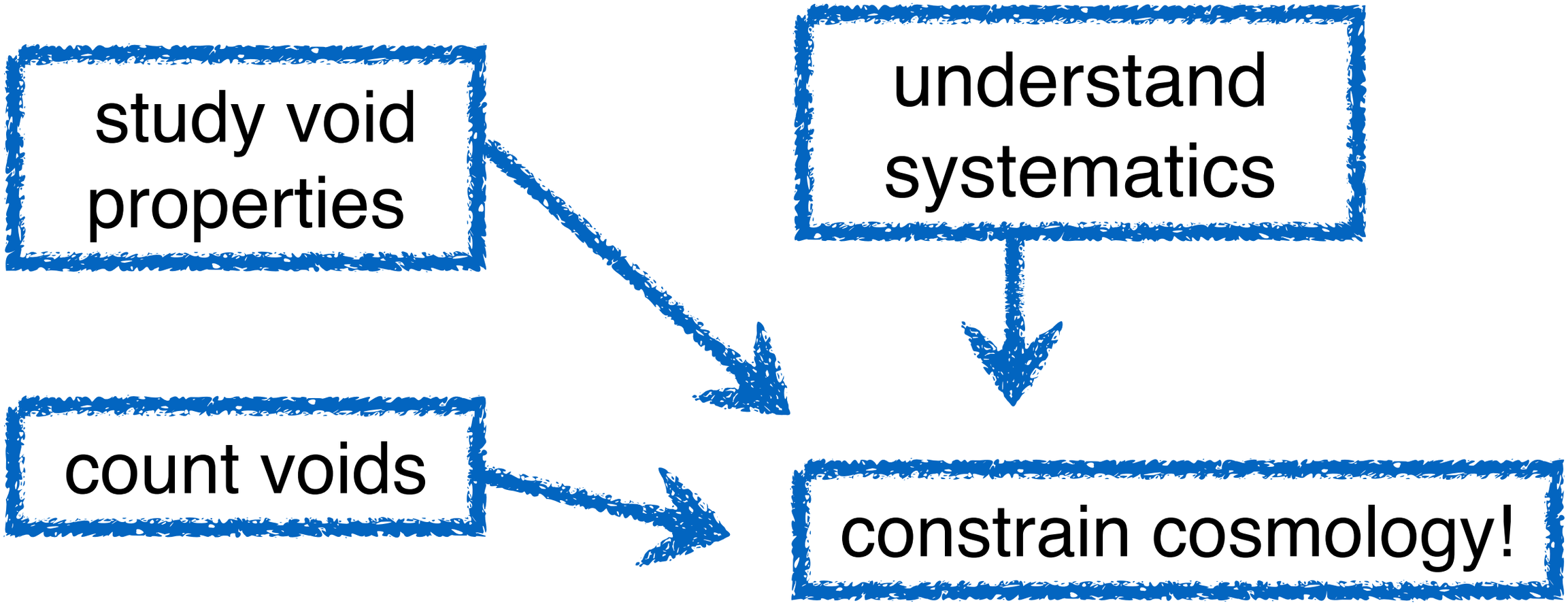


CMB anchor + late time measure of the expansion is the way to constrain dark energy



Voids (LSS) can give a measure at late time

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

Tracer

All points closer to the tracer than to any other point

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

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

Based on Zobov (Neyrinck 2008)

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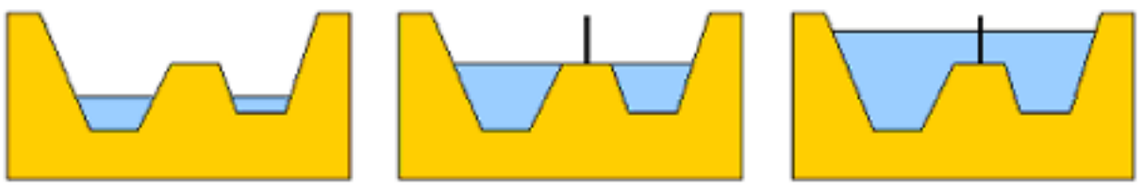
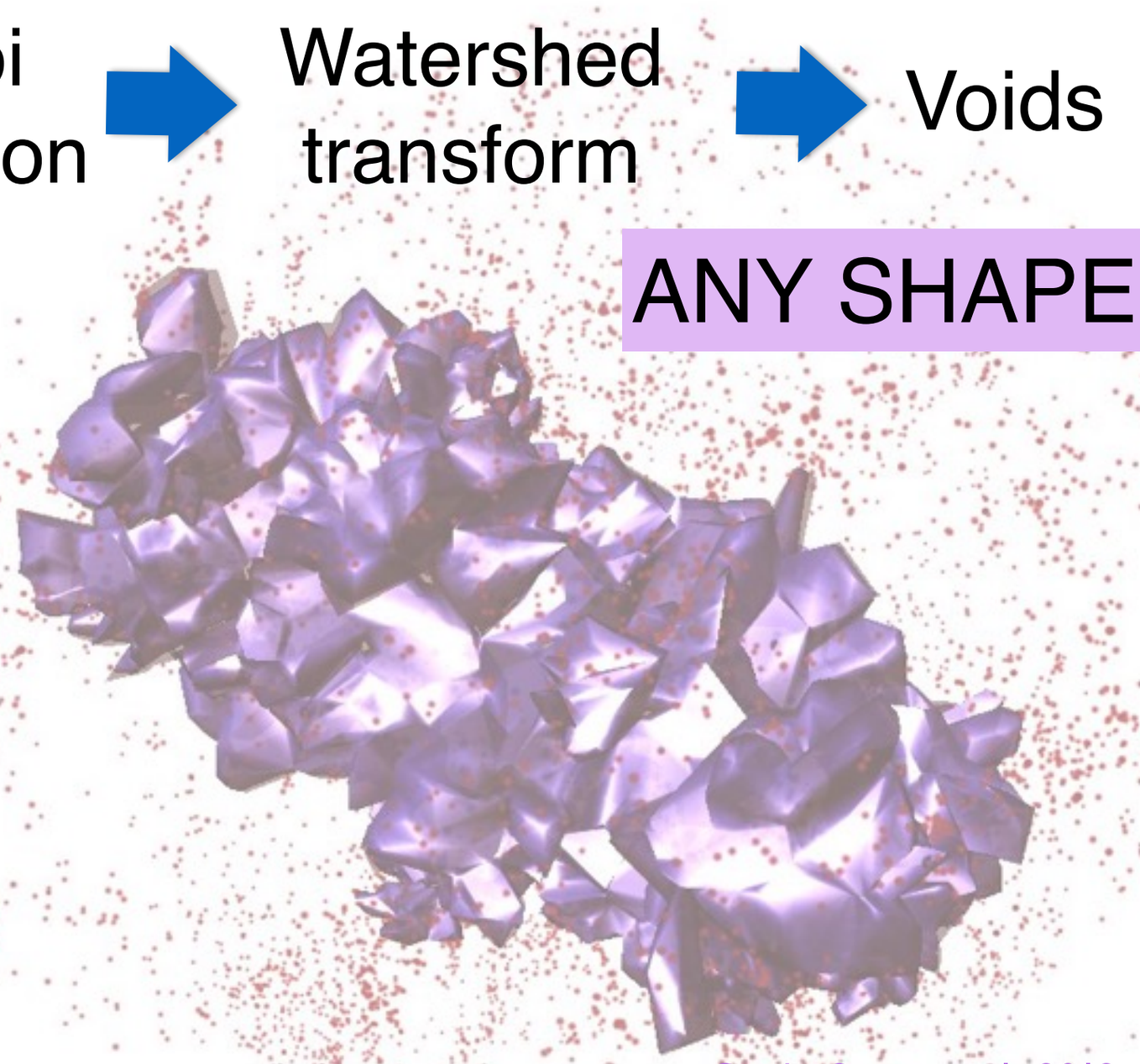
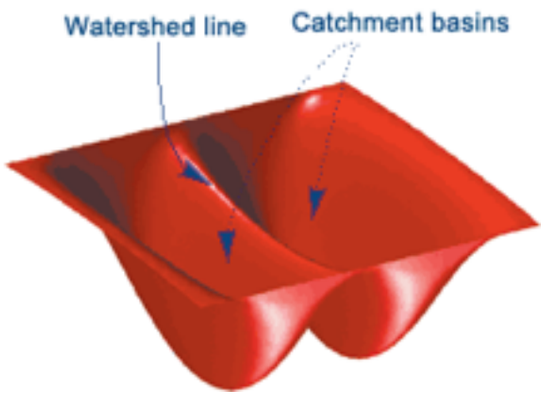


ANY SHAPE



Credit: Sutter et al. 2012

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

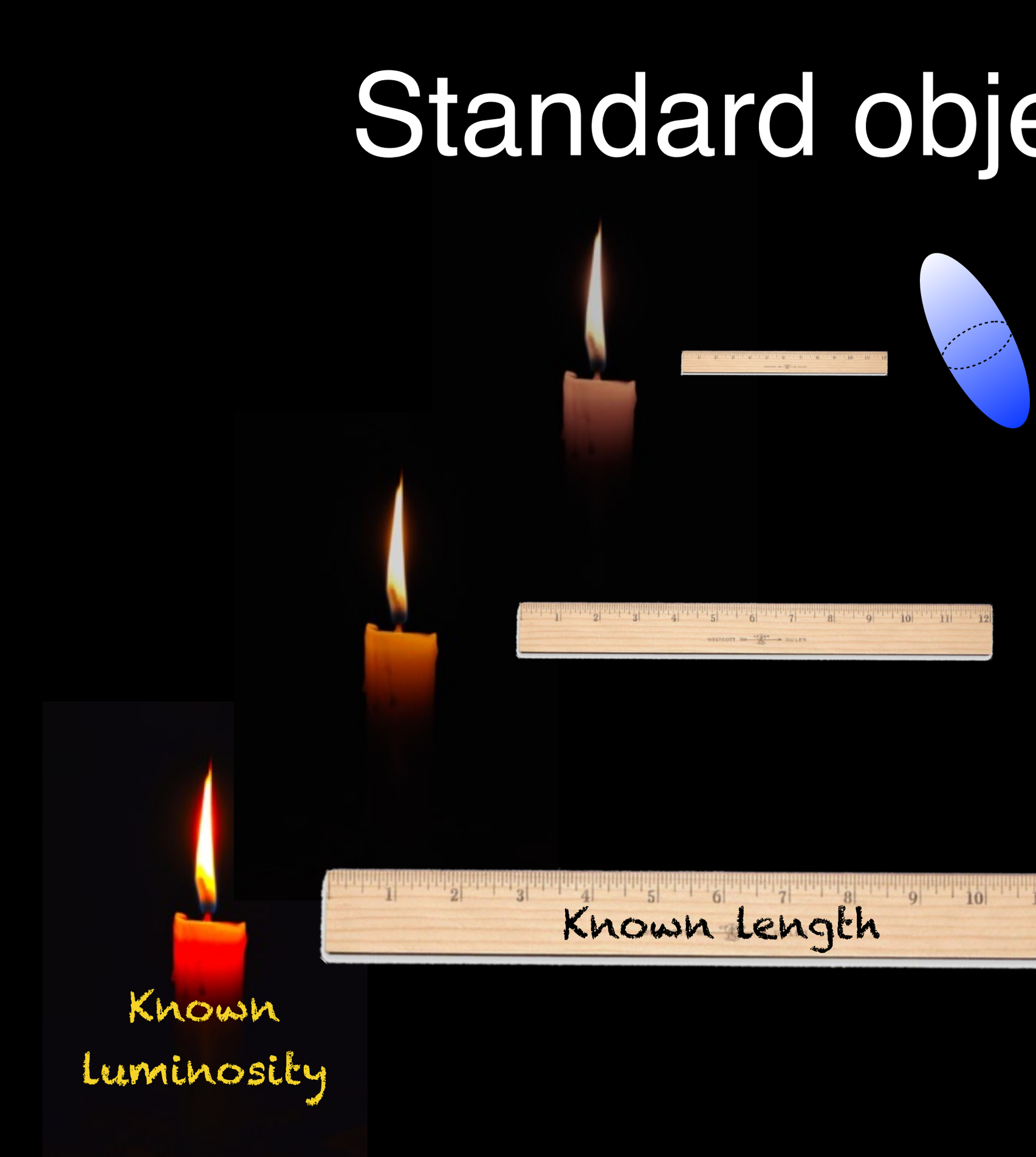


Density cuts:
1)all cells mean density <-0.8
2)density in Reff/4<-0.8
+ exclude voids below mps

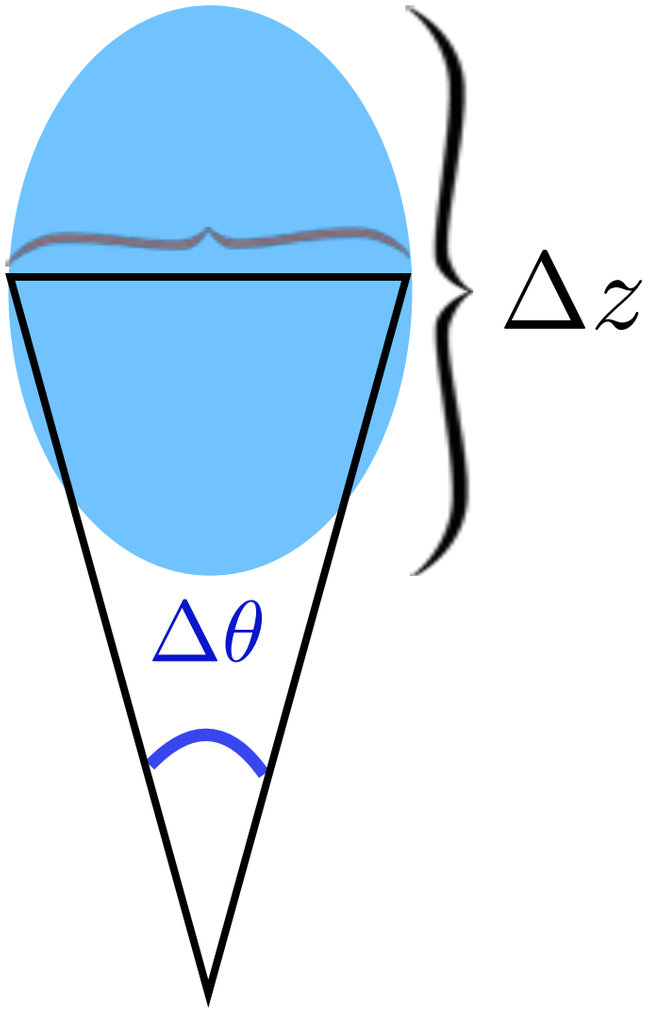
+ it takes into account survey boundaries and masks

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

Standard objects

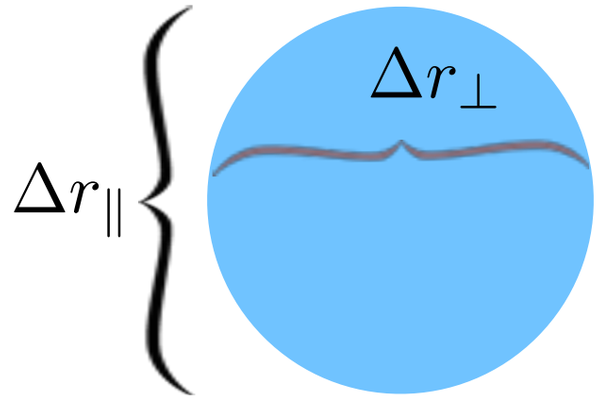


What we measure:



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…

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

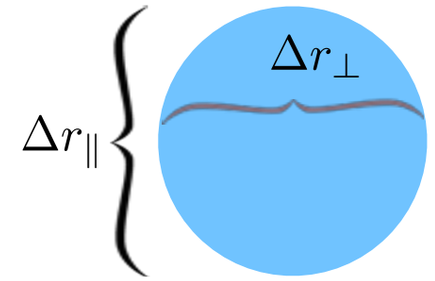
angular diameter distance

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

Hubble parameter

Alcock-Paczyński test (1979)

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



what we know

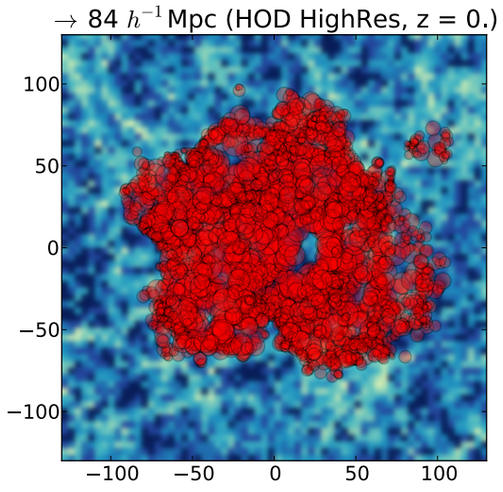
$$\frac{c\Delta z}{\Delta\theta} = D_A(z)H(z)$$

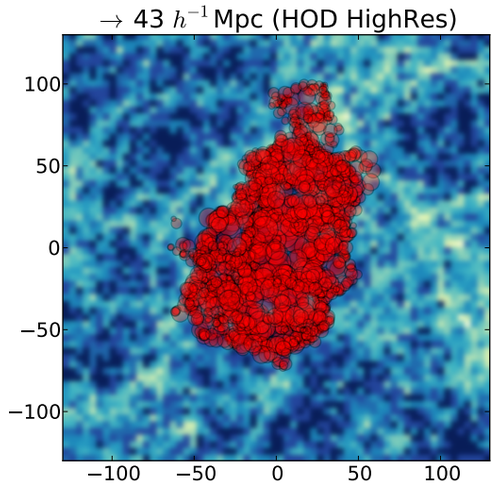
what we don't know

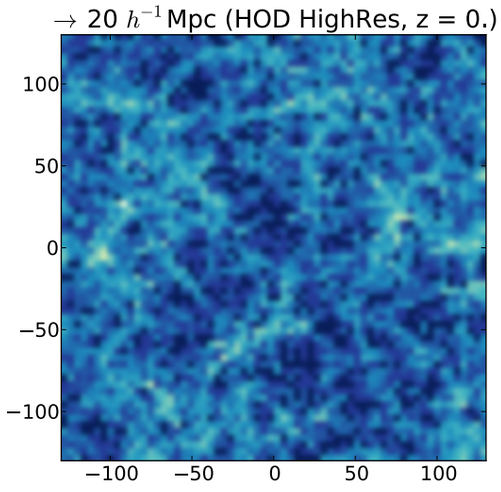
To perform the test we measure stretch $e_V(z)$

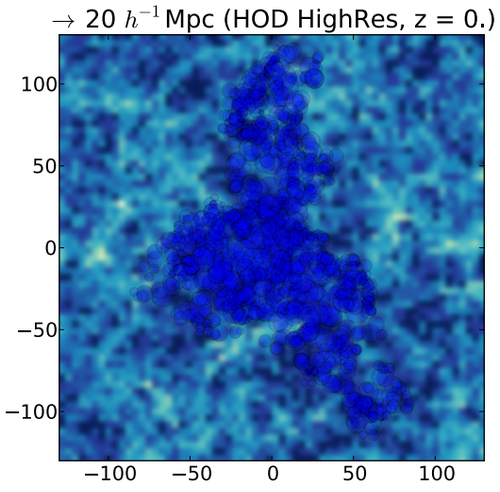
The deviations from fiducial cosmology cause geometrical distortions.

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









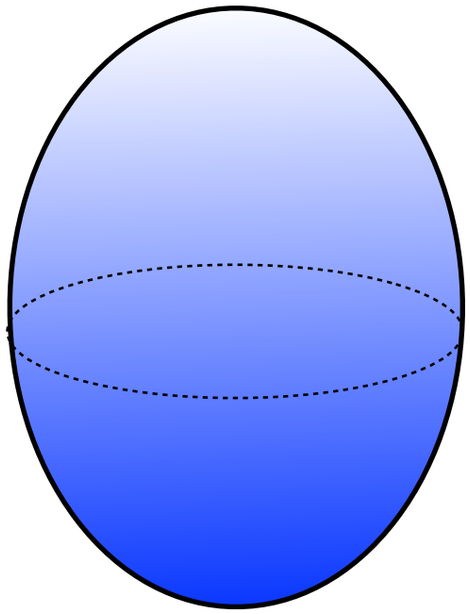
Voids have different shapes but **spherical** average shape in an isotropic and homogeneous universe!

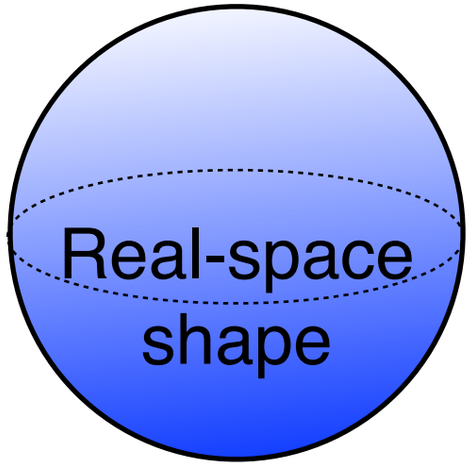
We can use **stacked voids** for the test

=> promising with new surveys.

Lavaux & Wandelt 2012

The void shape tells us the cosmology





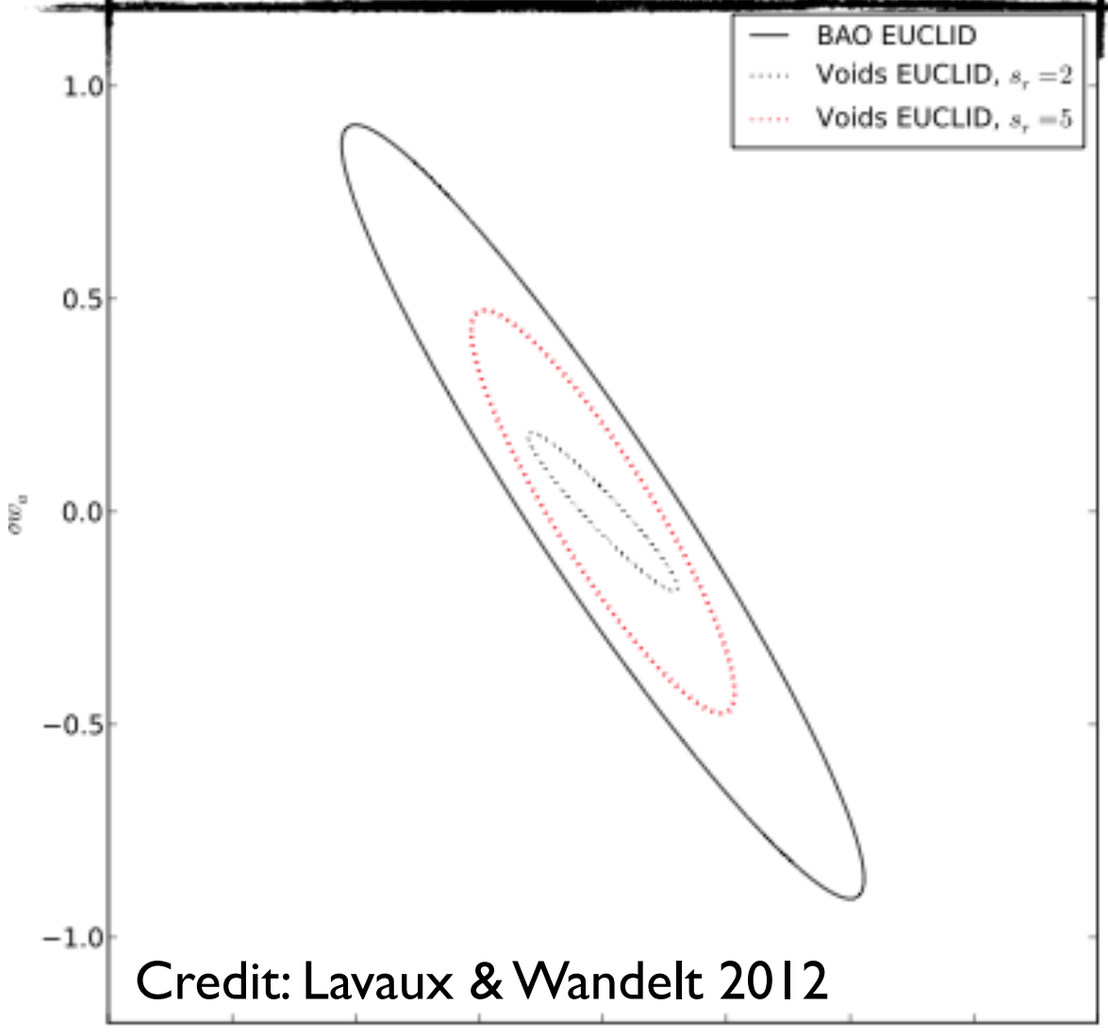
$$cz = H_0 d + v cos\theta$$

$z_{measured}$ z_{cosmo}

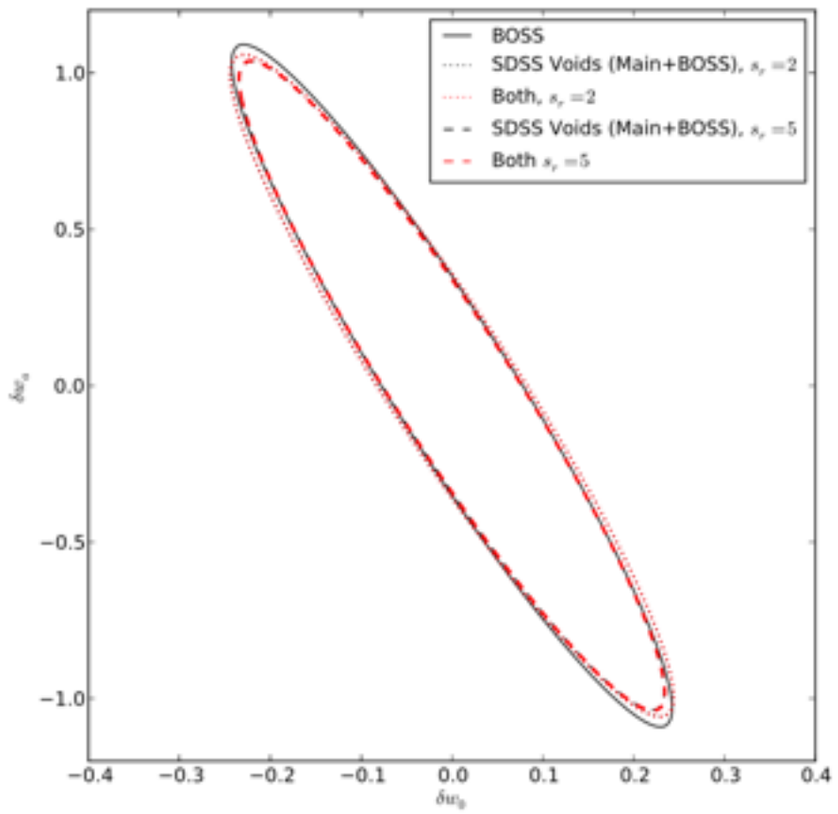
But… the velocities of galaxies also affect that shape.

Velocities will be our main source of systematics!

AP test with void stacks has the potential to beat BAO in constraining DE

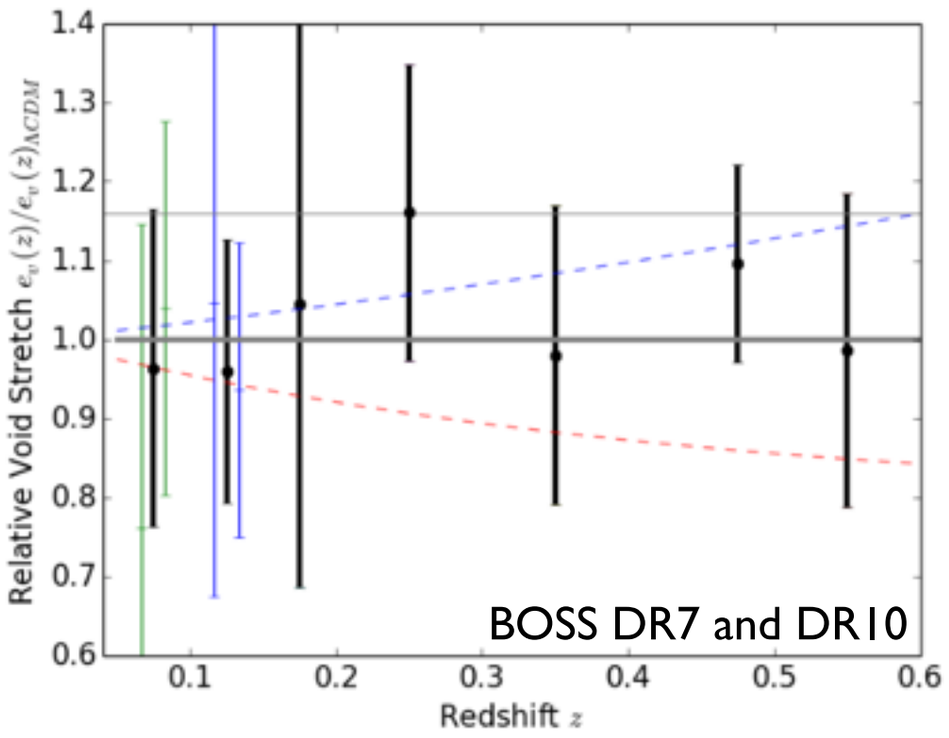


Credit: Lavaux & Wandelt 2012



How to turn this into a precise constrain?

We have a measurement!



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

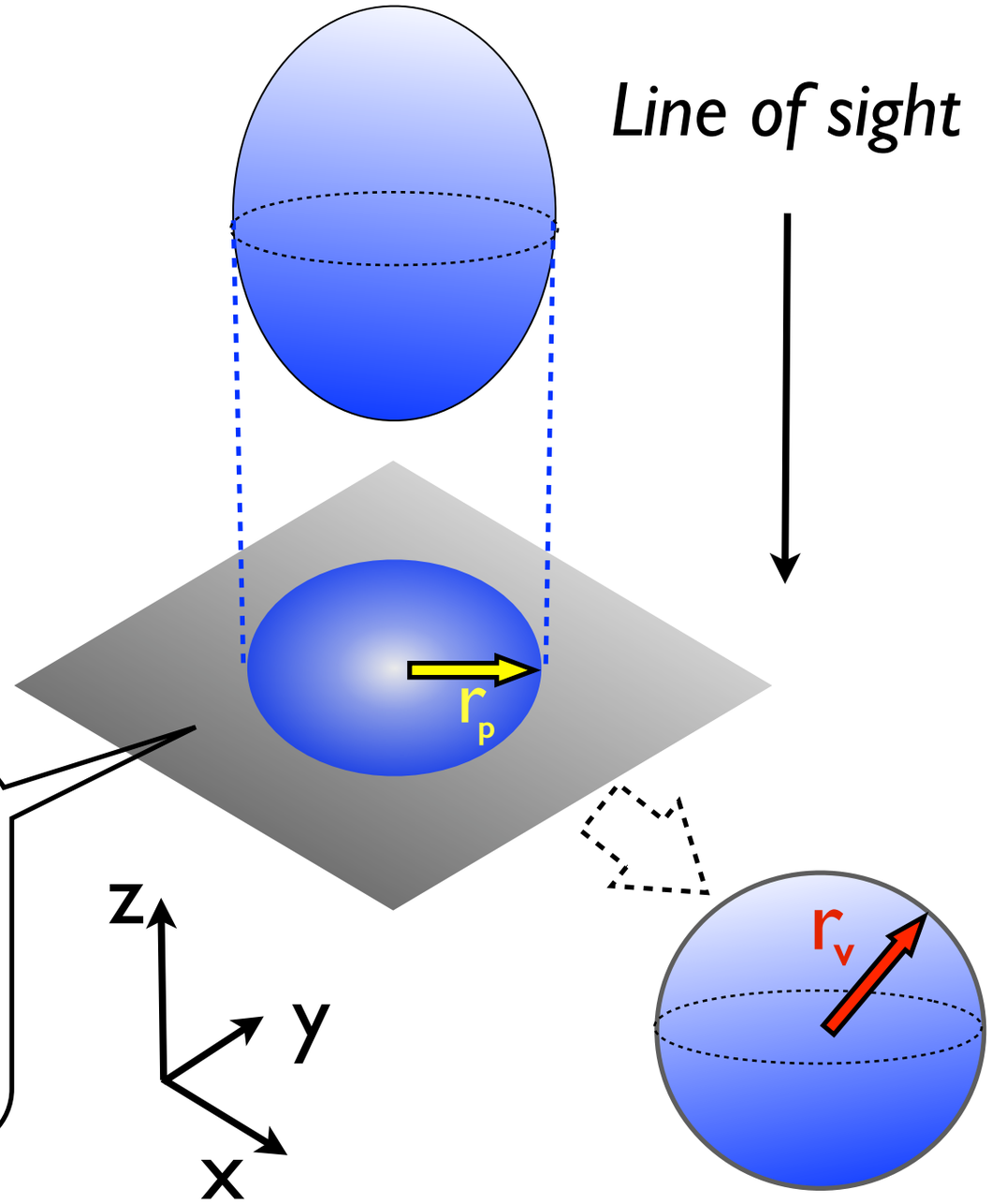
We can reduce systematics by:

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.

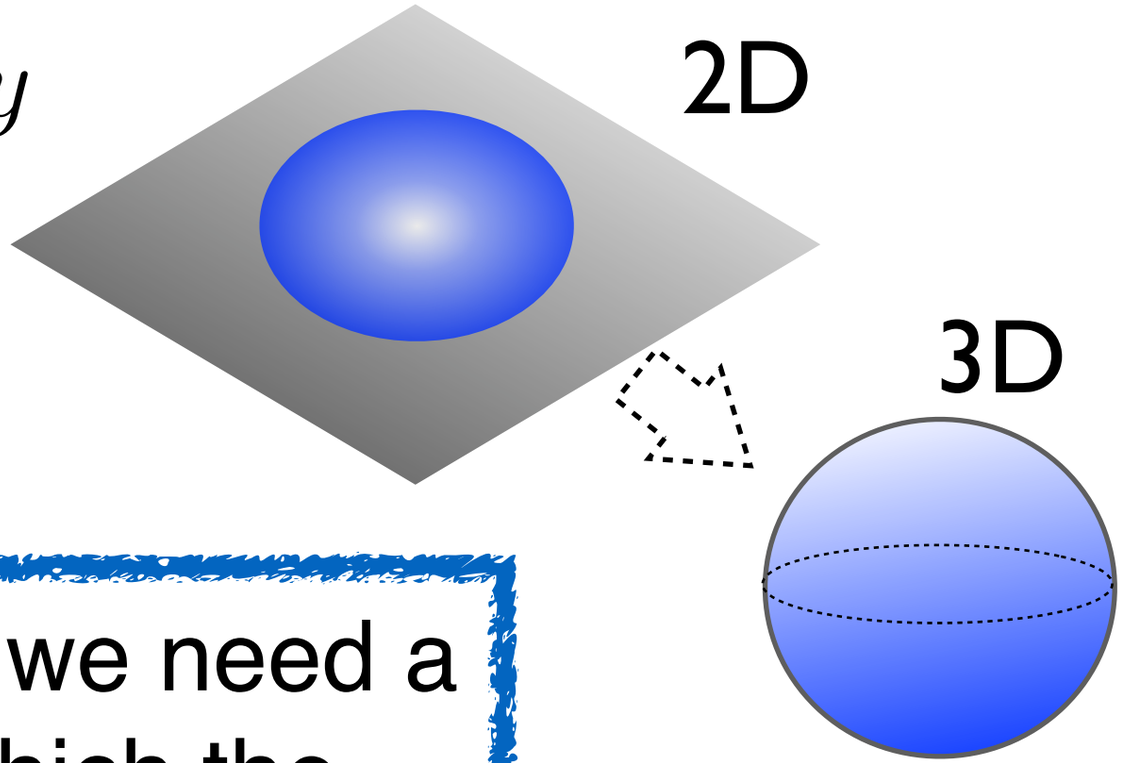


From this projection we reconstruct a 3D profile without the contribution of peculiar velocities.

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

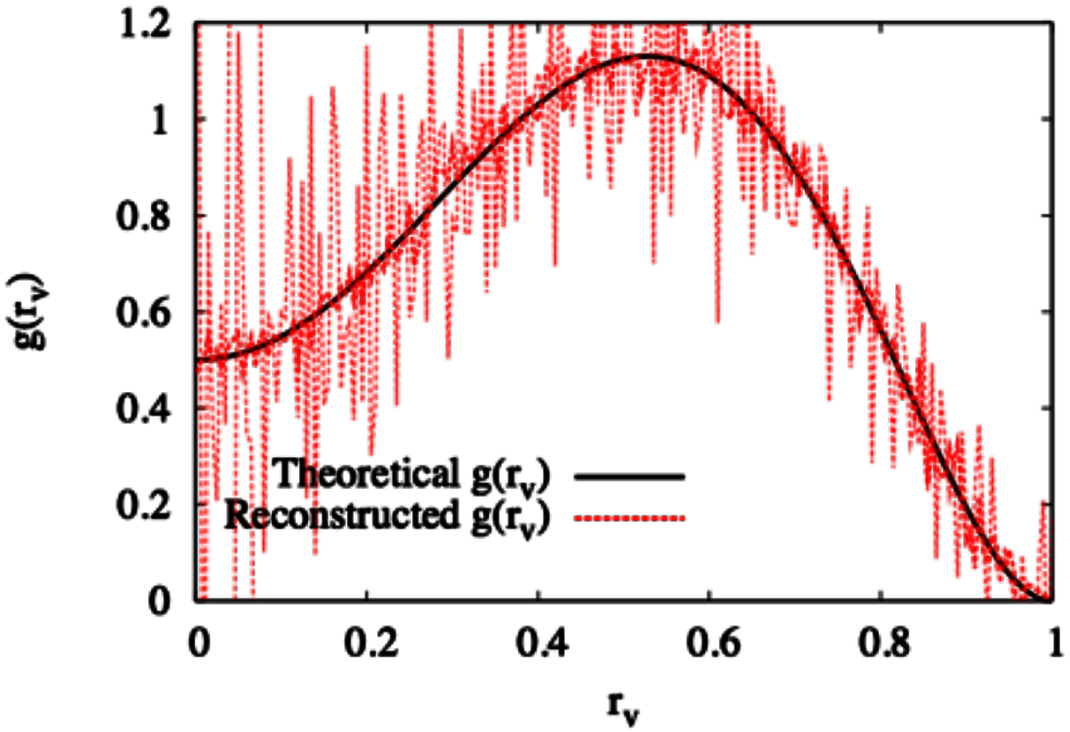
But…

Result I

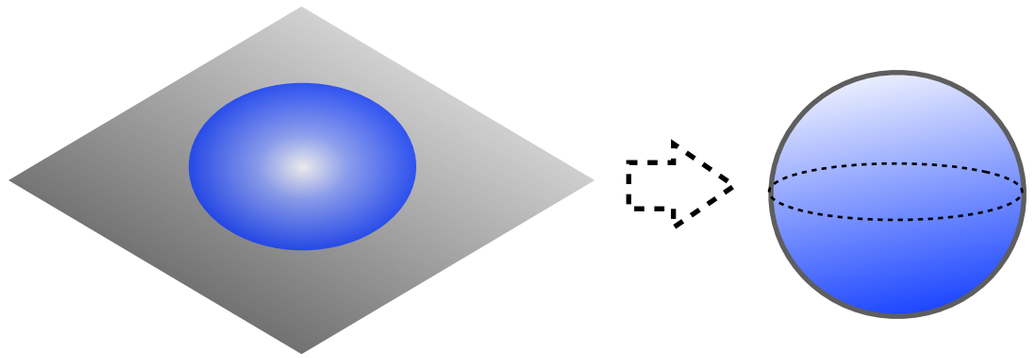
Fighting ill-conditioning

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

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



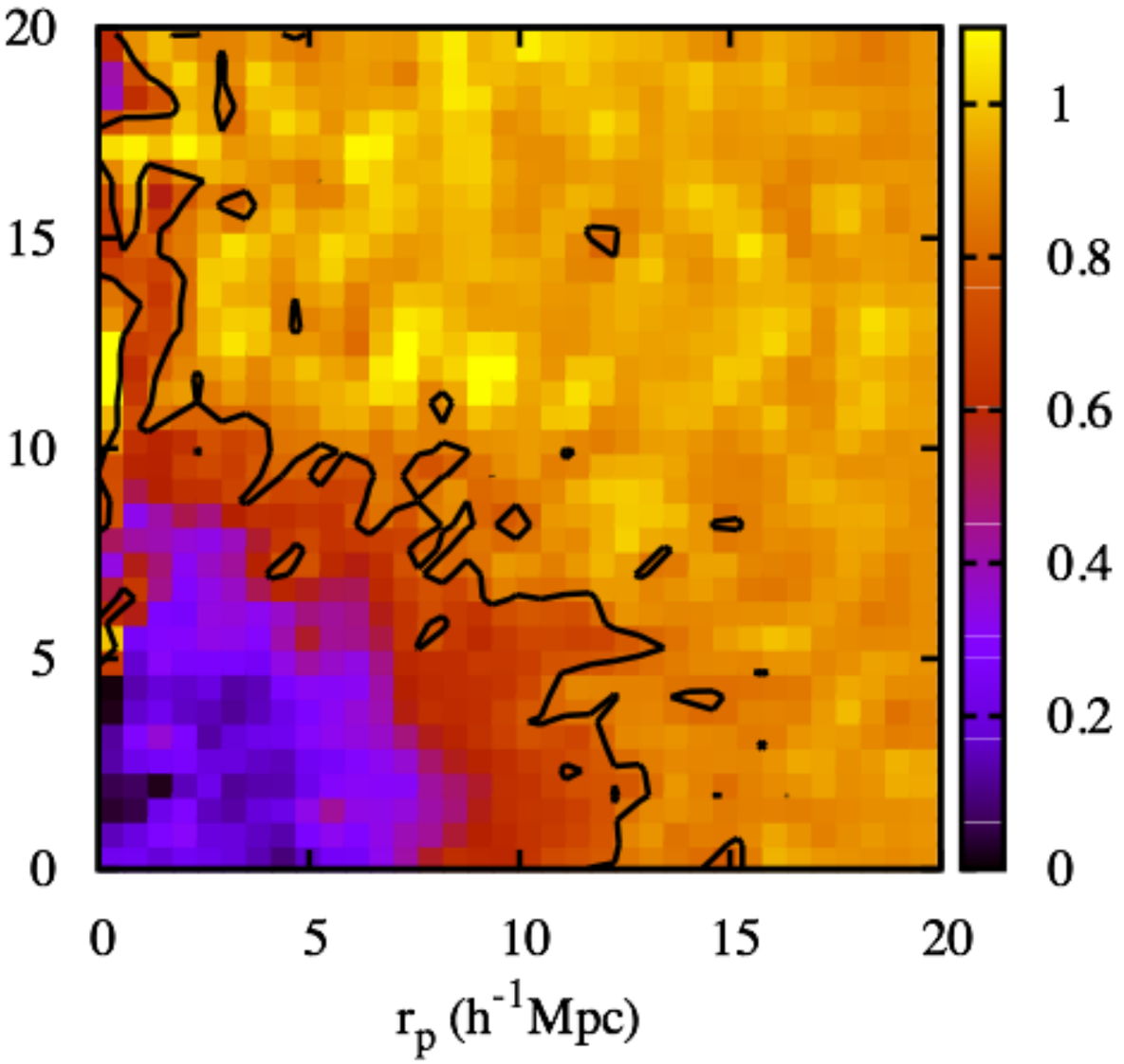
Reconstruction was with an Abel pair,
so it is a particular case

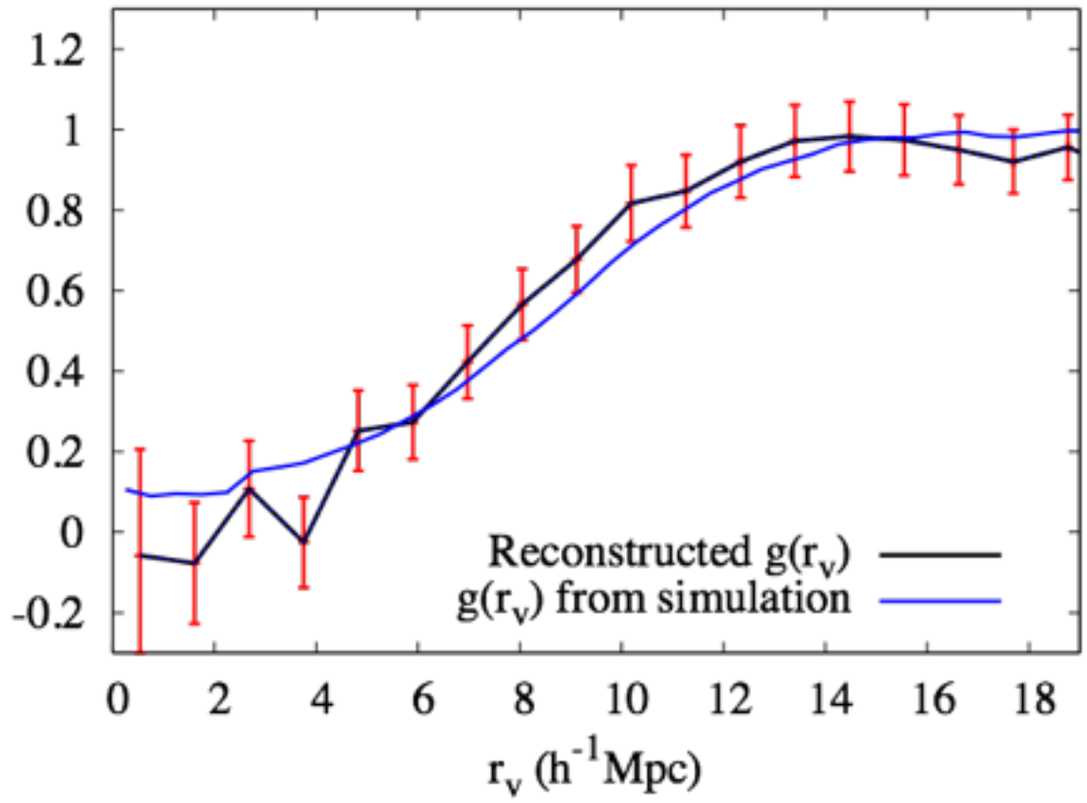


RESULT:
Very good
reconstruction!

Result II

The full simulated stacked void

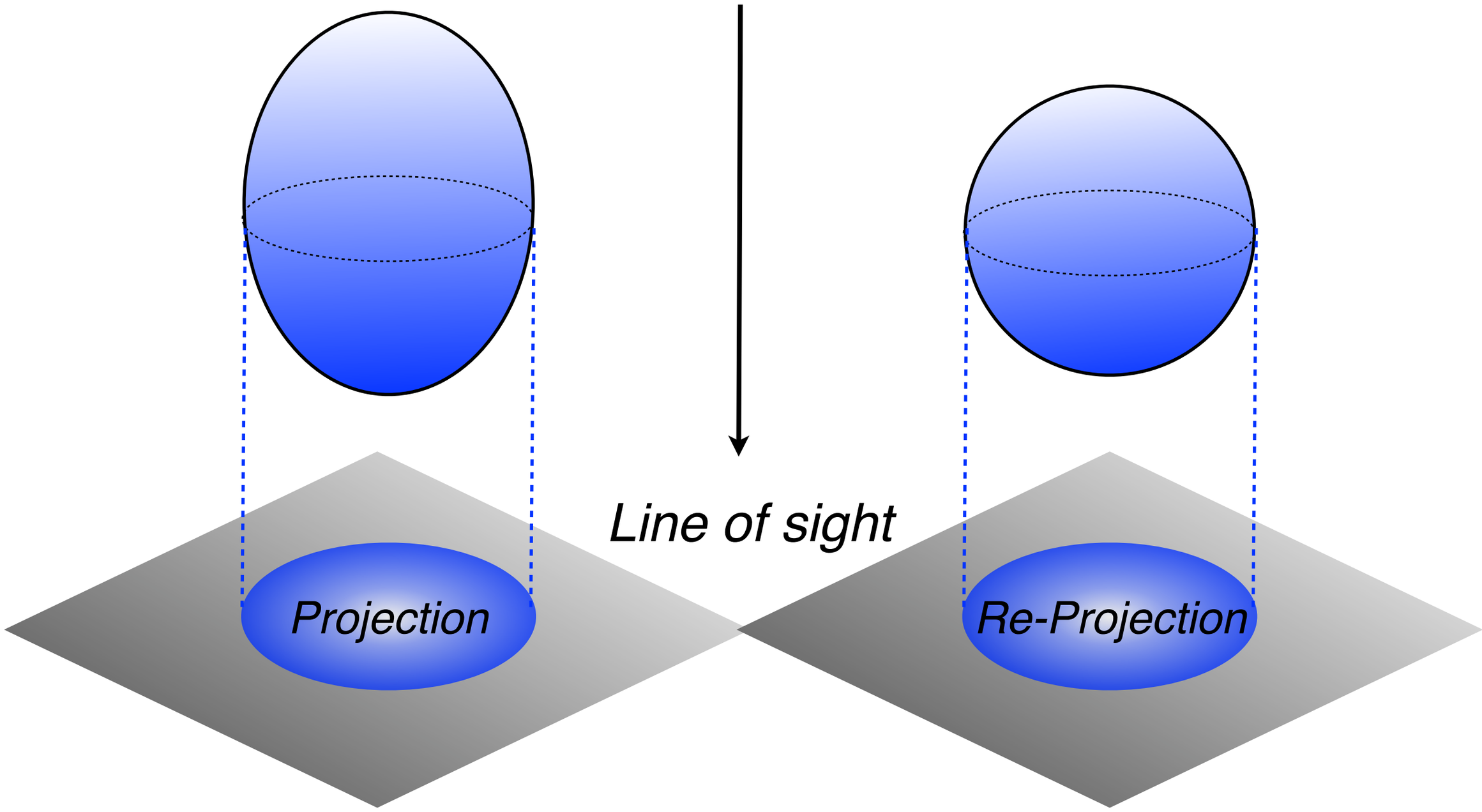




Stacking from 10 to 12 Mpc/h

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

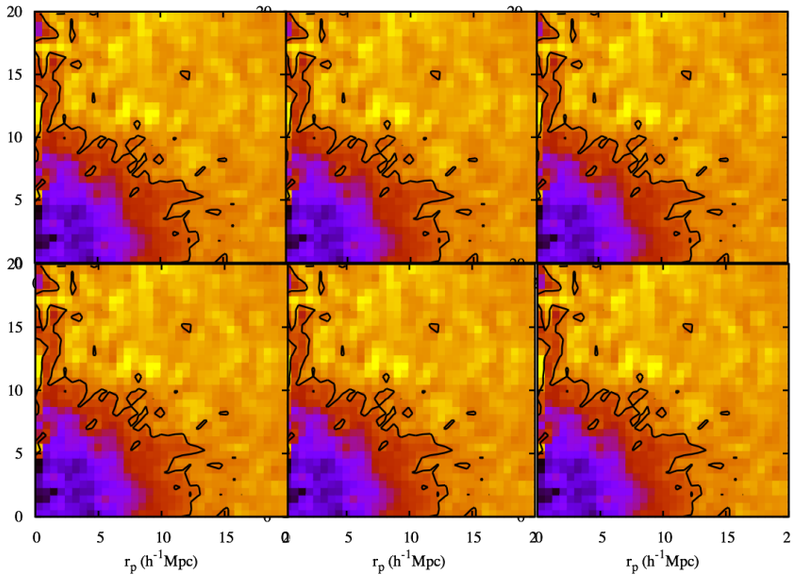
The sanity check for the reconstruction



Check the reconstruction

A robust error estimation

Bootstrap samples



$\cdots$

takes into account
noise in a realistic way

Akaike criteria

$$AICc = 2k - 2\ ln(L) + \frac{2k(k+1)}{n-k-1}$$

penalises overfitting

But algorithm only applied to a DM sim.

Reconstruction from stacked void with HOD model

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

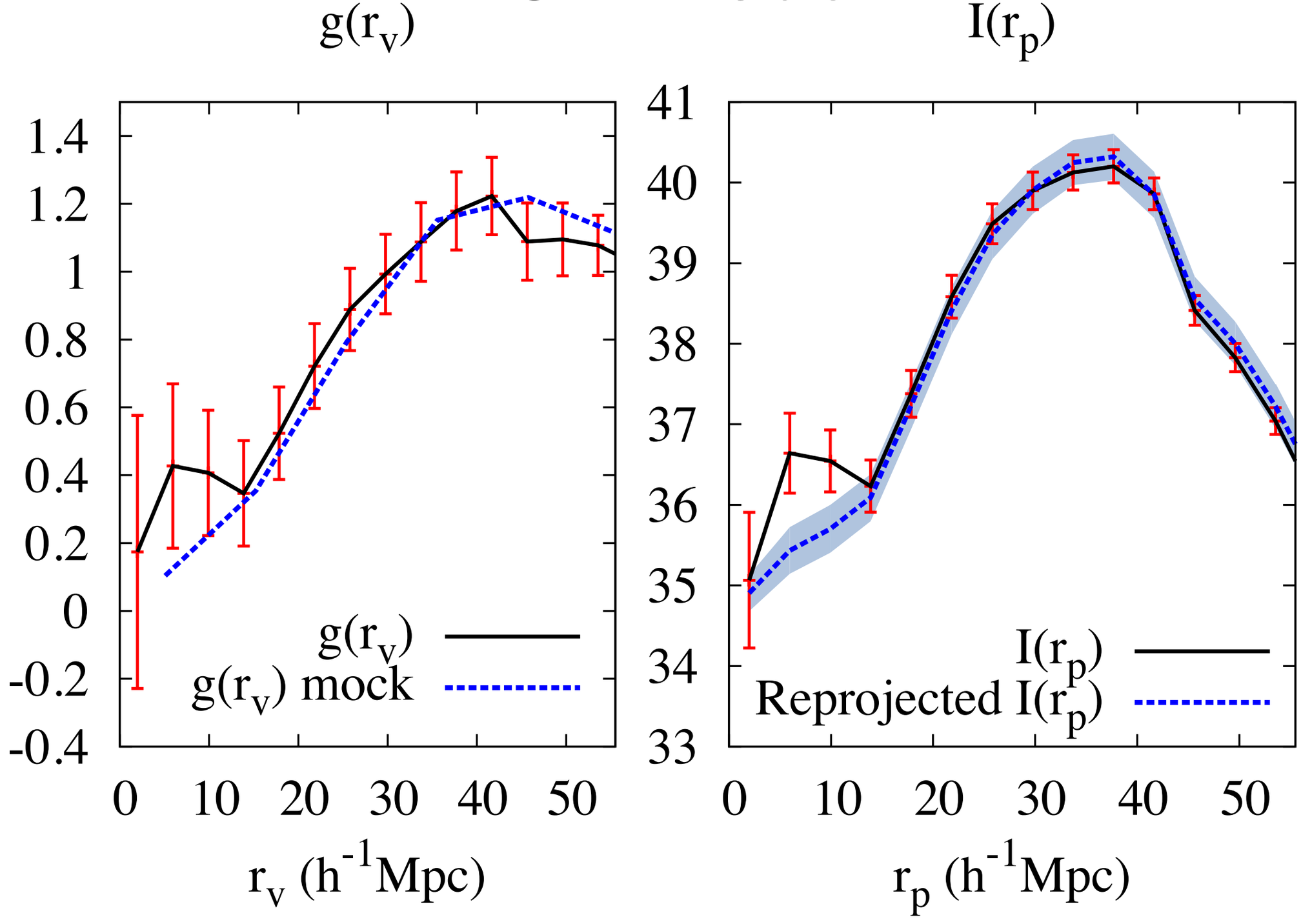
$$\langle N_{\rm sat}(M)\rangle = \langle N_{\rm cen}(M)\rangle\left(\frac{M-M_0}{M_1'}\right)^{\alpha}$$

Rockstar halo finder (Behroozi et al. 2013)

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

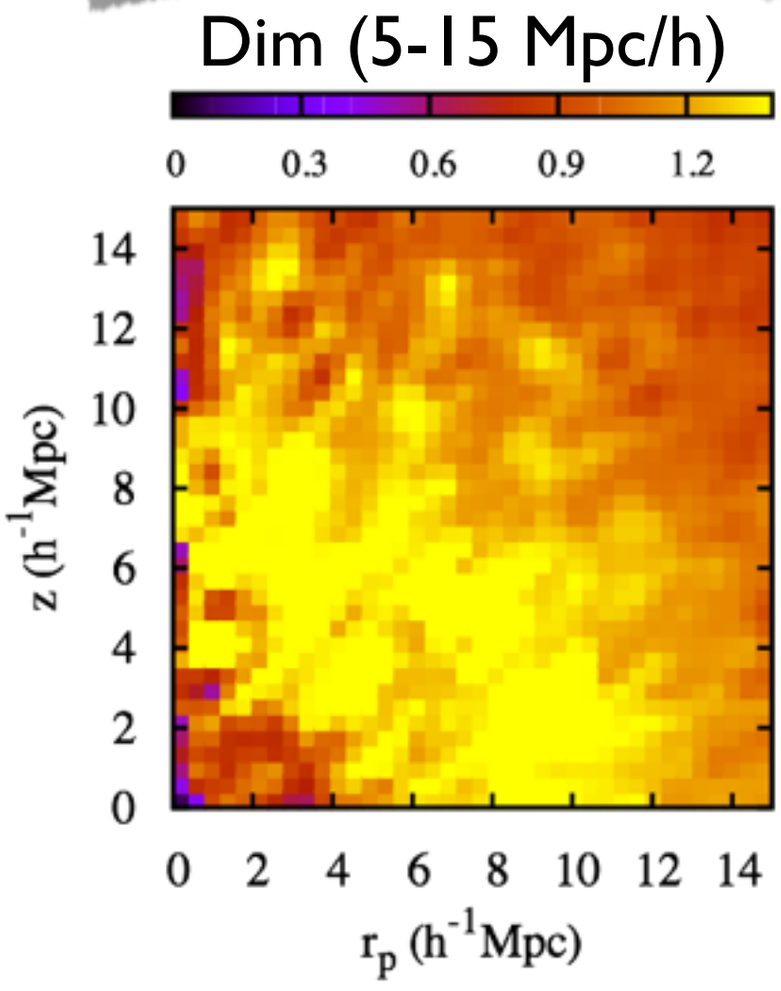
Matching the features of SDSS DR7

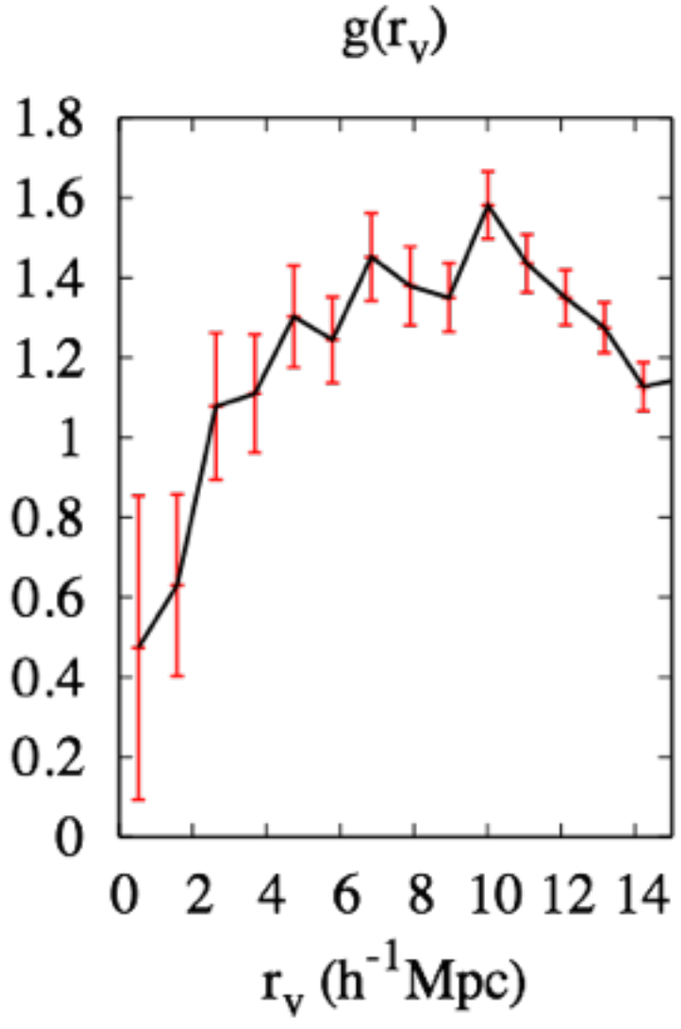
Reconstruction from stacked void of HOD model

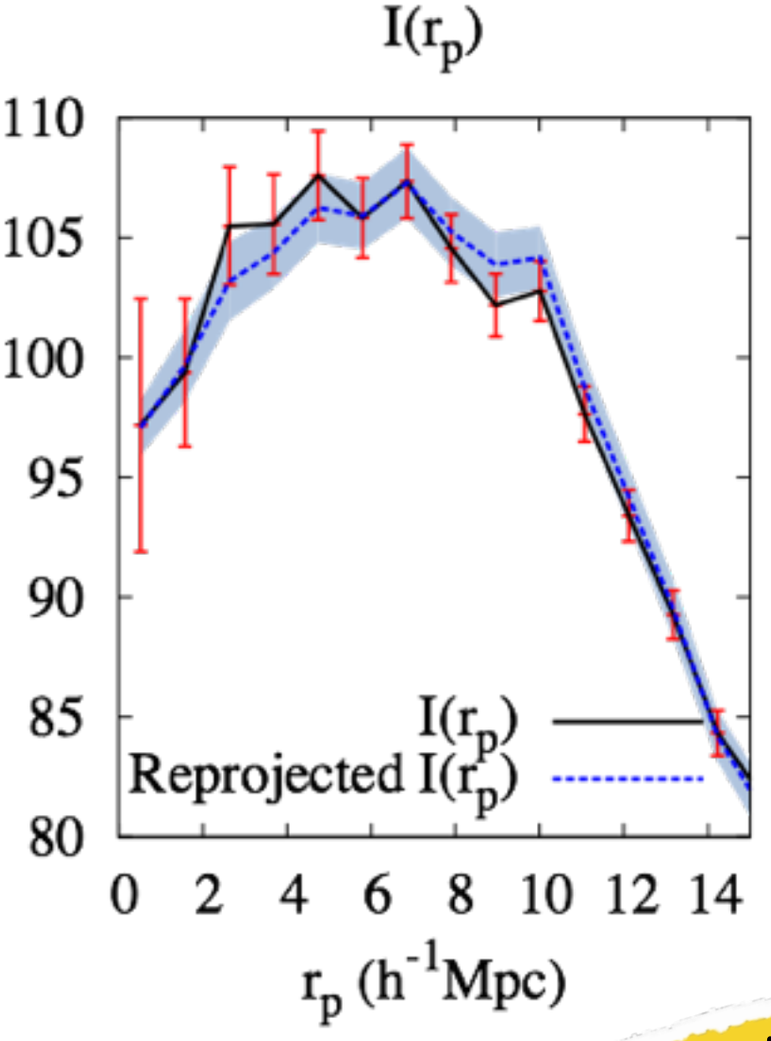


Result III

REAL DATA from SDSS!!!





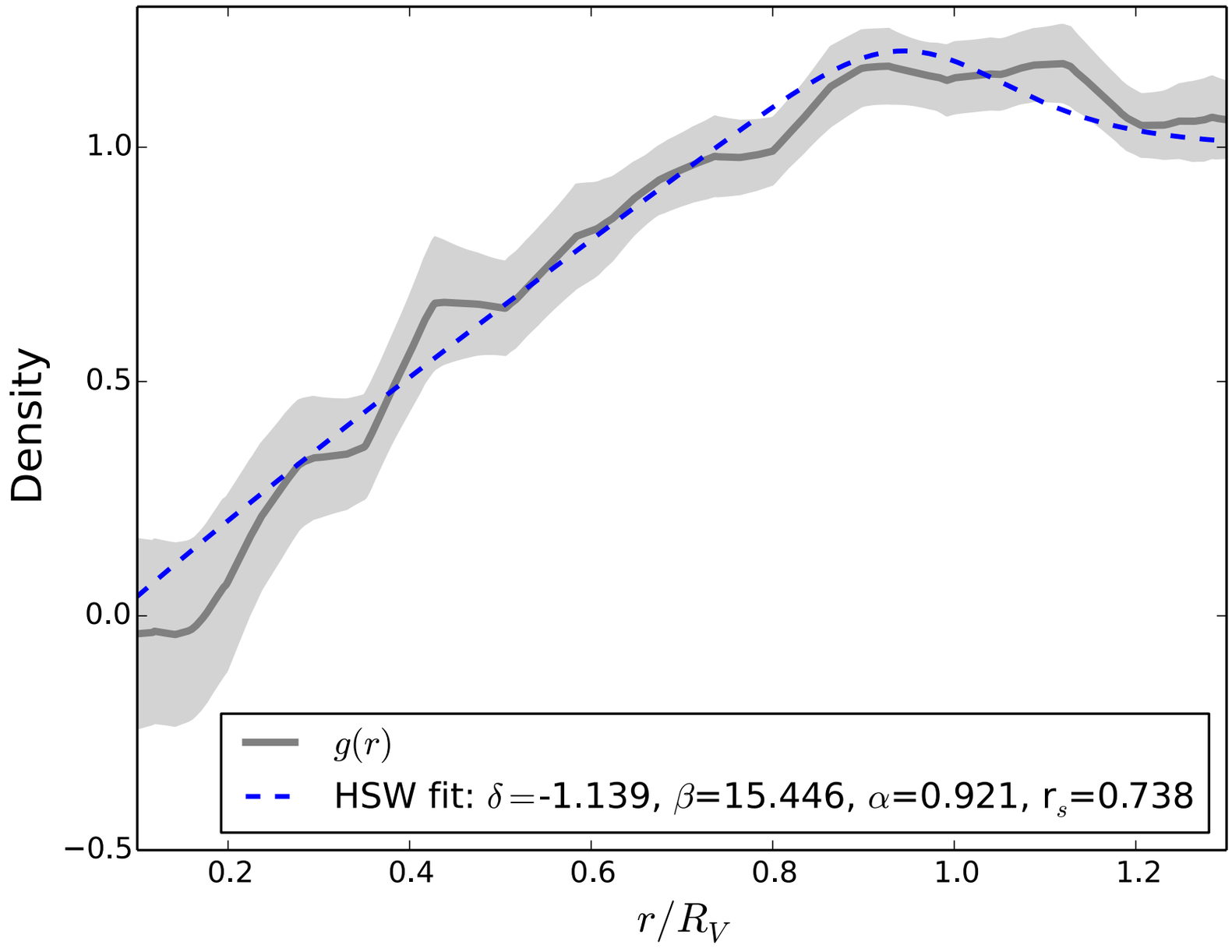


Stack radius	Redshift	Dataset	Galaxies	Voids
5-15	0.05-0.10	dim2	173929	173
10-15	0.05-0.10	dim2	43527	41
20-25	0.10-0.15	bright1	21241	17
25-45	0.15-0.20	bright2	51913	37

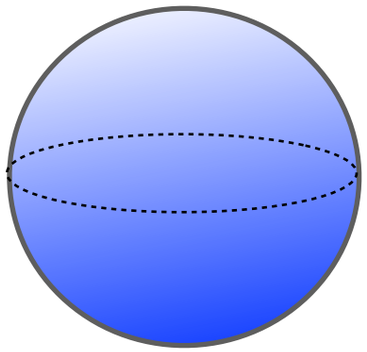
Model independent!
No assumption about RD

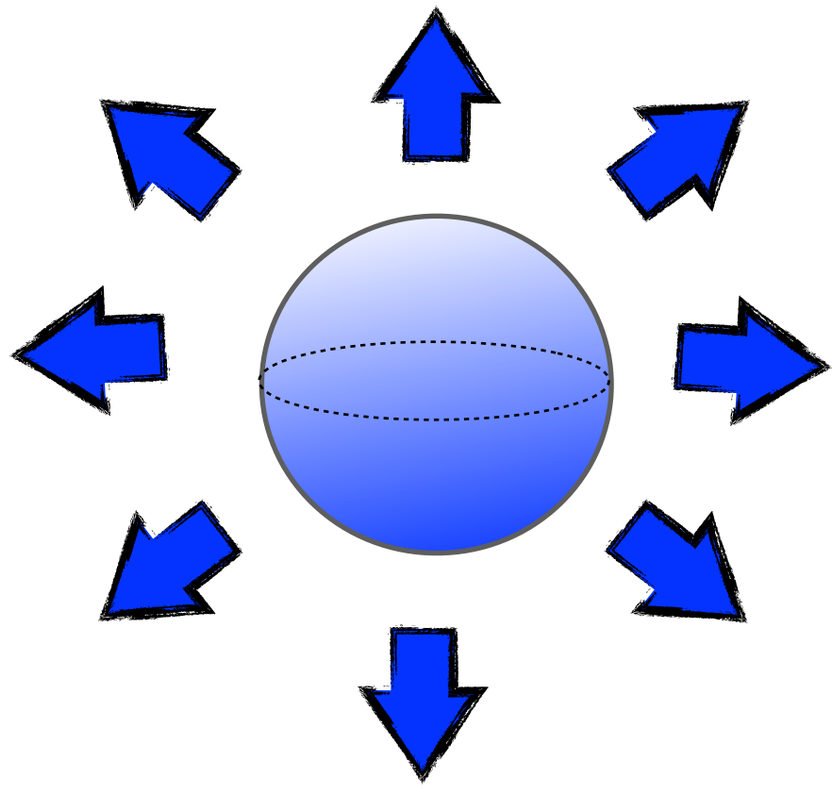
arXiv:1306.3052 (A. Pisani, G.Lavaux, P. M. Sutter, B. D.Wandelt 2013)

Average real space void from SDSS DR7 matches simulations



What do we know about voids?





STATIC!!!!

DYNAMICS ????

“Really” looking at voids…

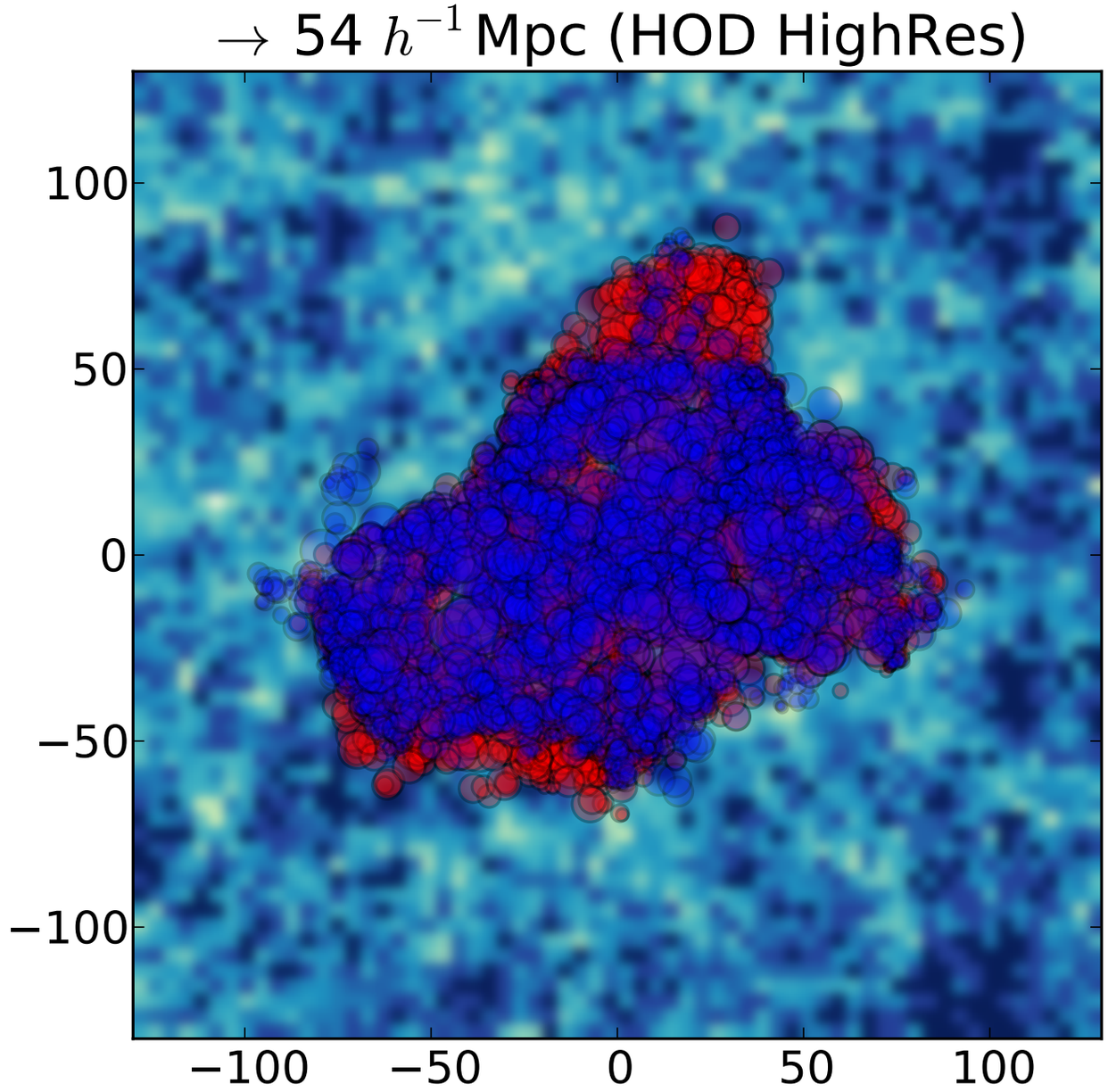
Nevertheless velocities might impact the way the void finder selects voids!

Let's give a look at voids…

HOD nopv

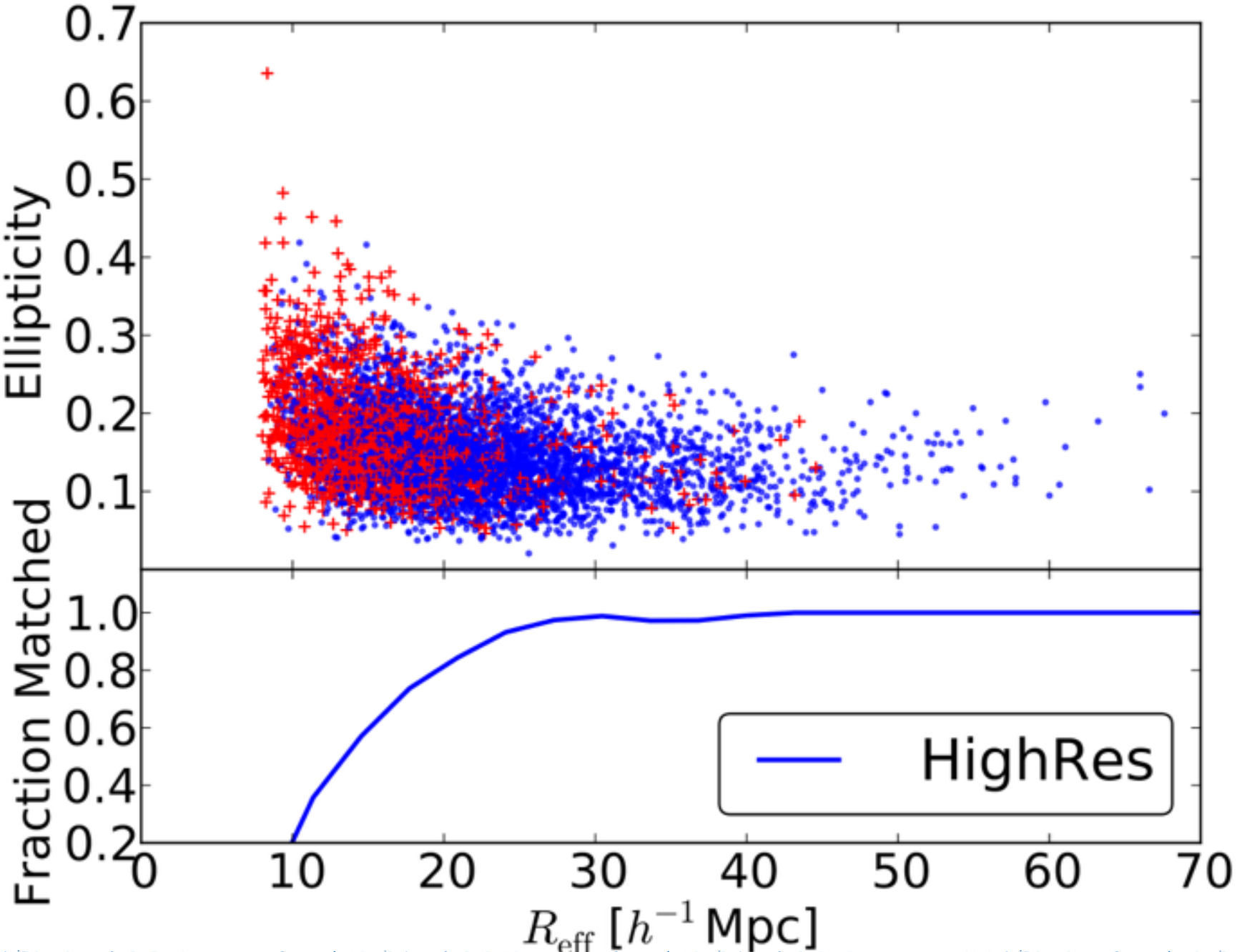
versus

HOD + pv



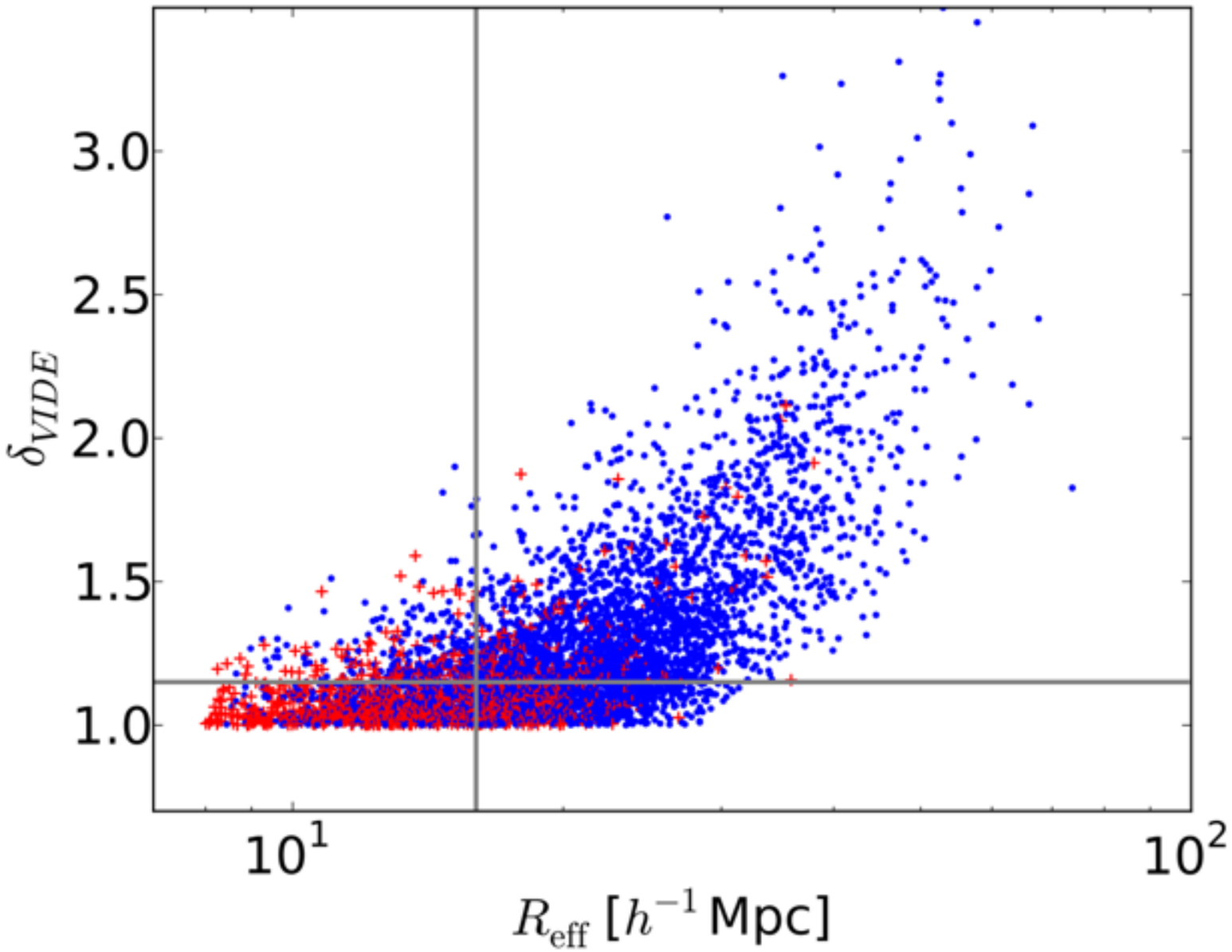
Is the cosmological signal washed out by velocities in a certain kind of voids? Can we identify them and boost the cosmological signal?

Which voids are affected most?



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

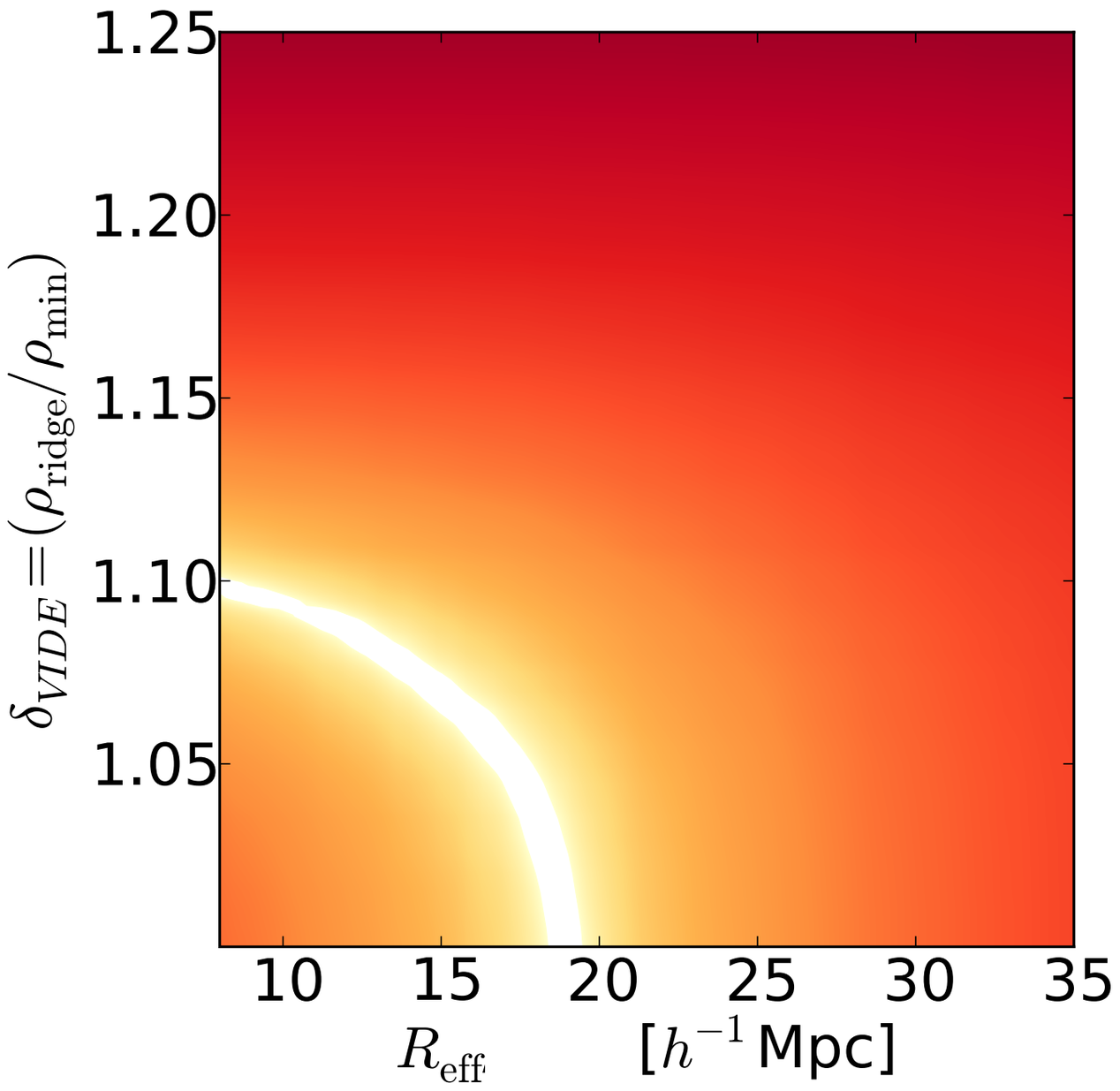
Identify them by properties



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

NB: depends on goal

Optimal cuts for real surveys!



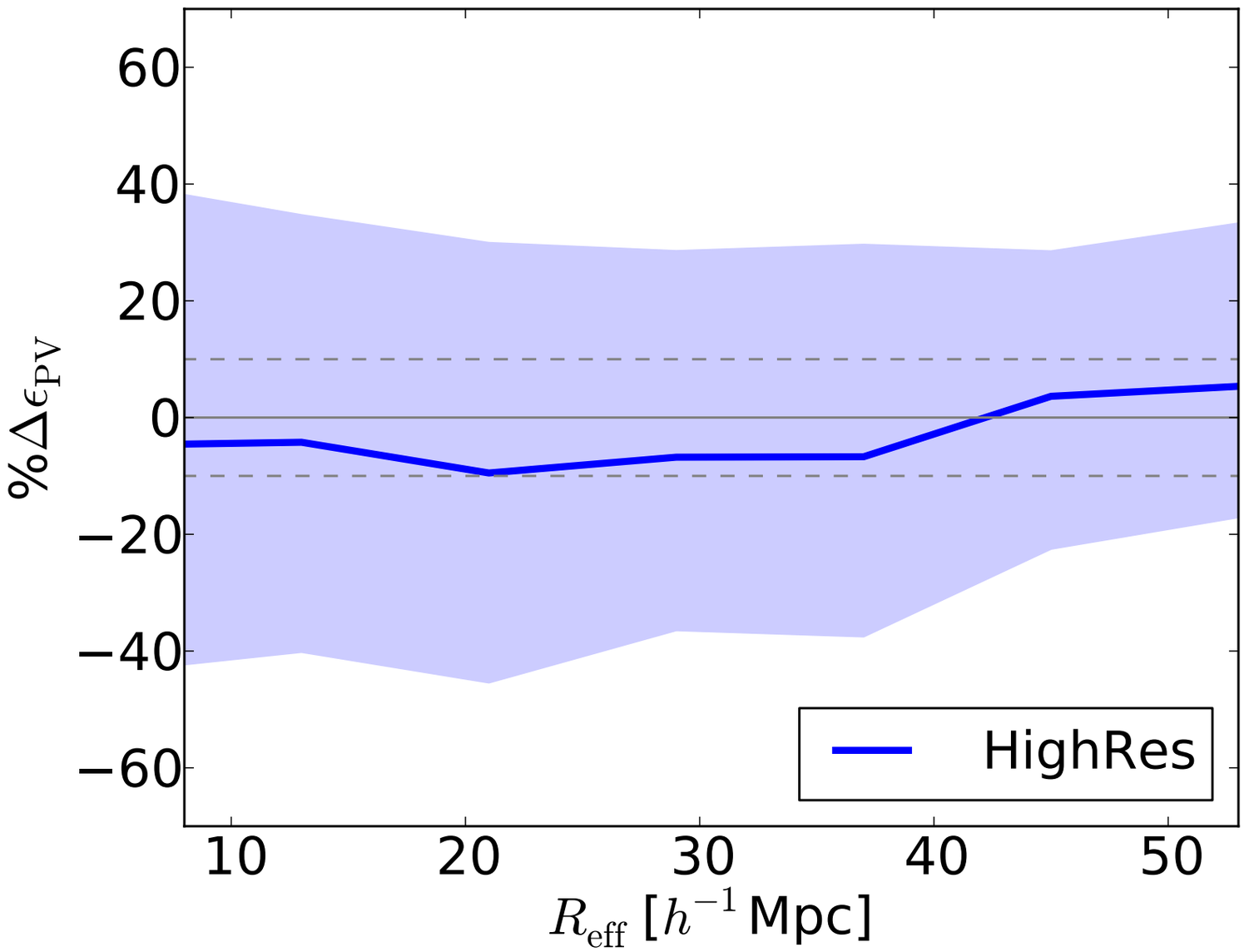
Maximize the number of unmatched removed and the number of matched kept

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

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

- Applying **cuts** on **radius** and **density contrast** that match our physical sense

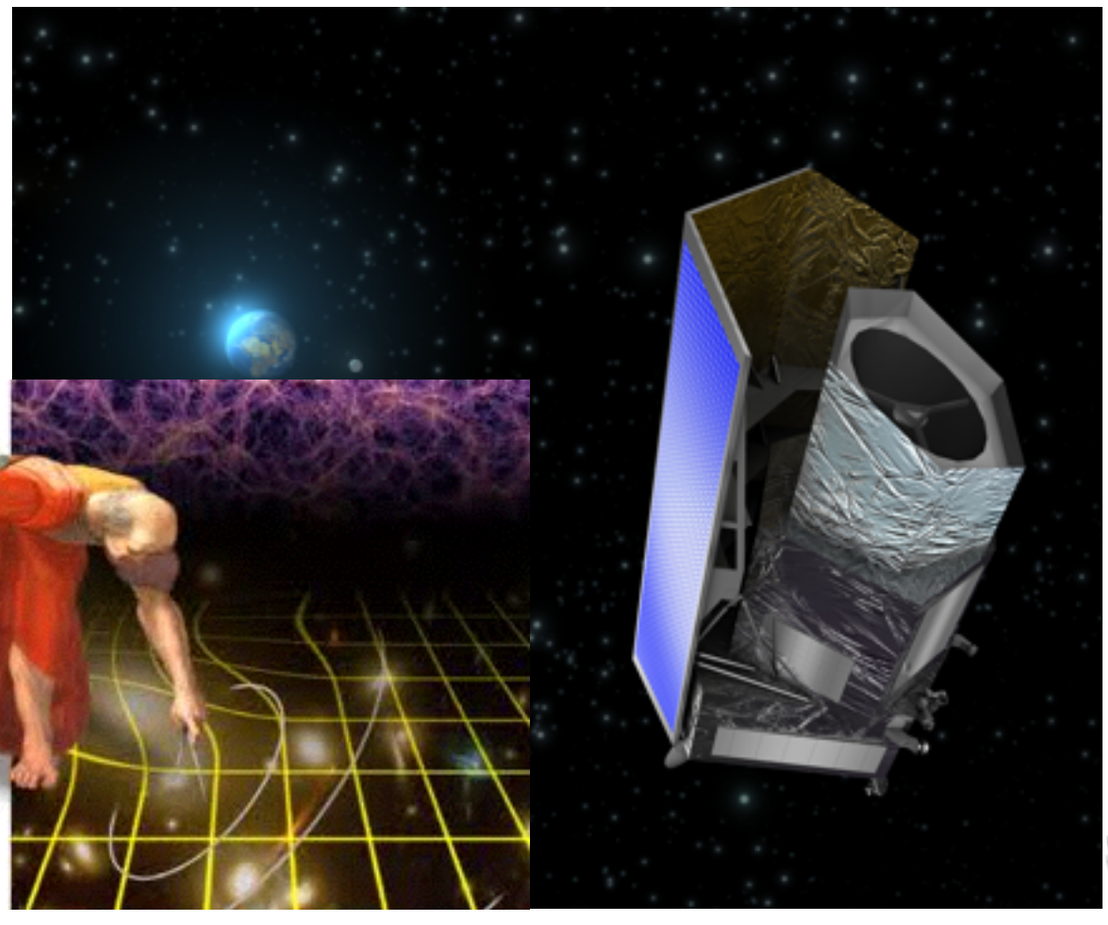
- Correct for the effect of velocities on **ellipticities**

- Set of tools to **beat systematics** even on current dataset

- What about an increase in **statistics**?

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

SDSS DR7 $6.7 \cdot 10^5$ galaxies



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)

+

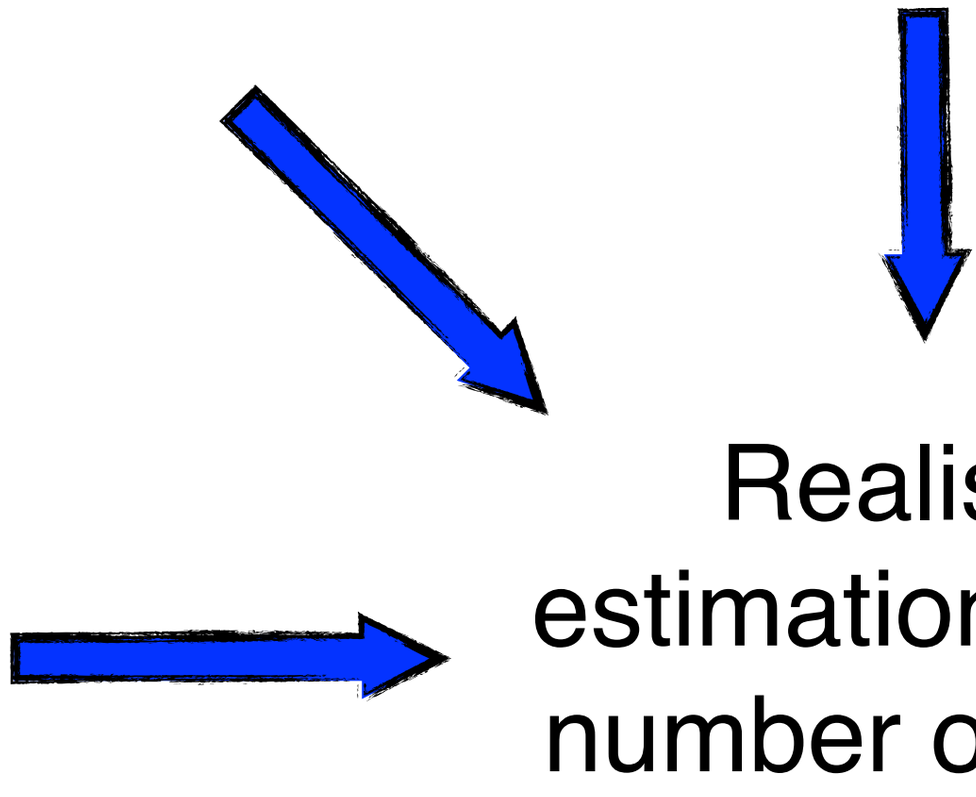
Simulation

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

+

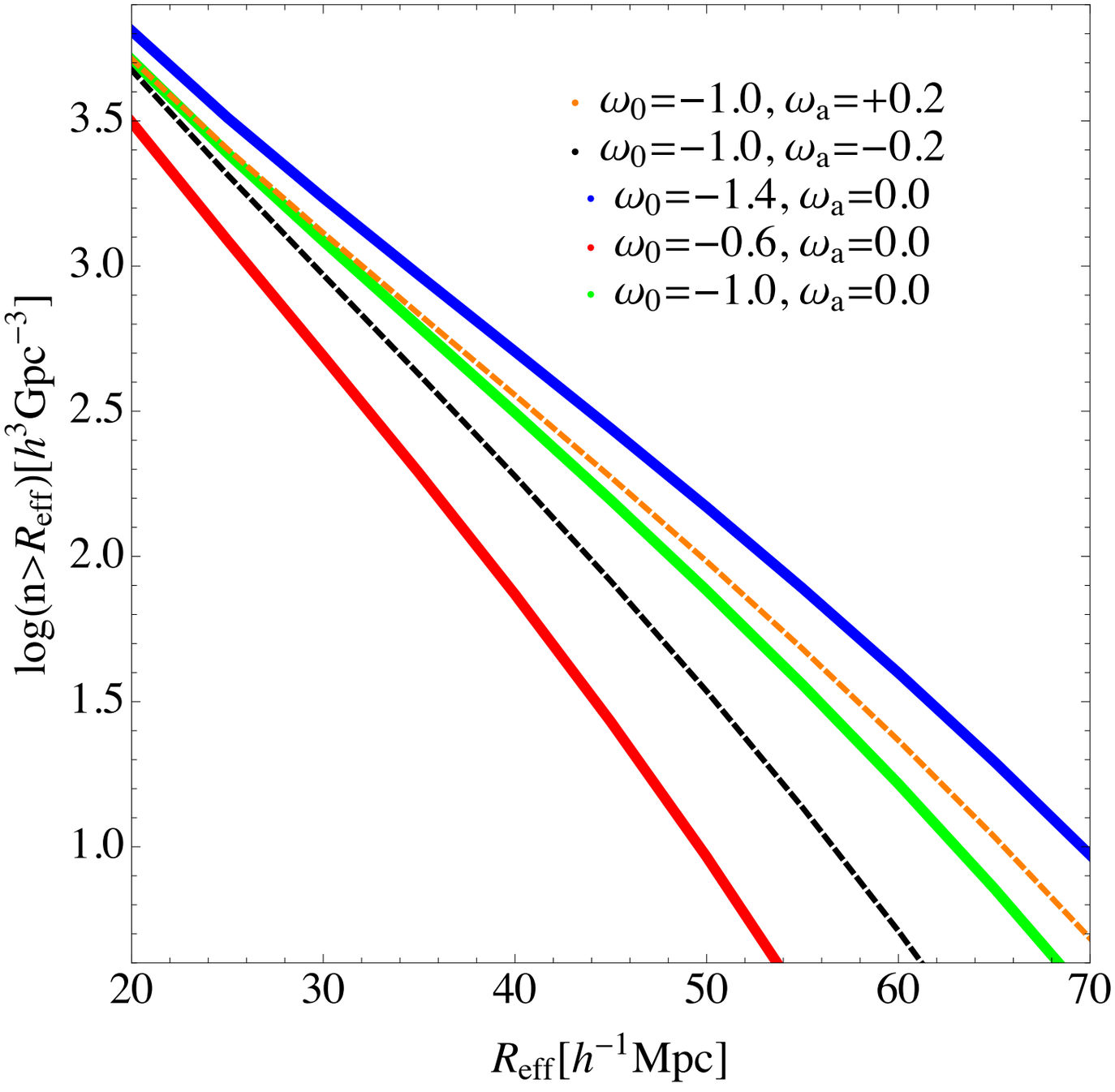
Survey

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



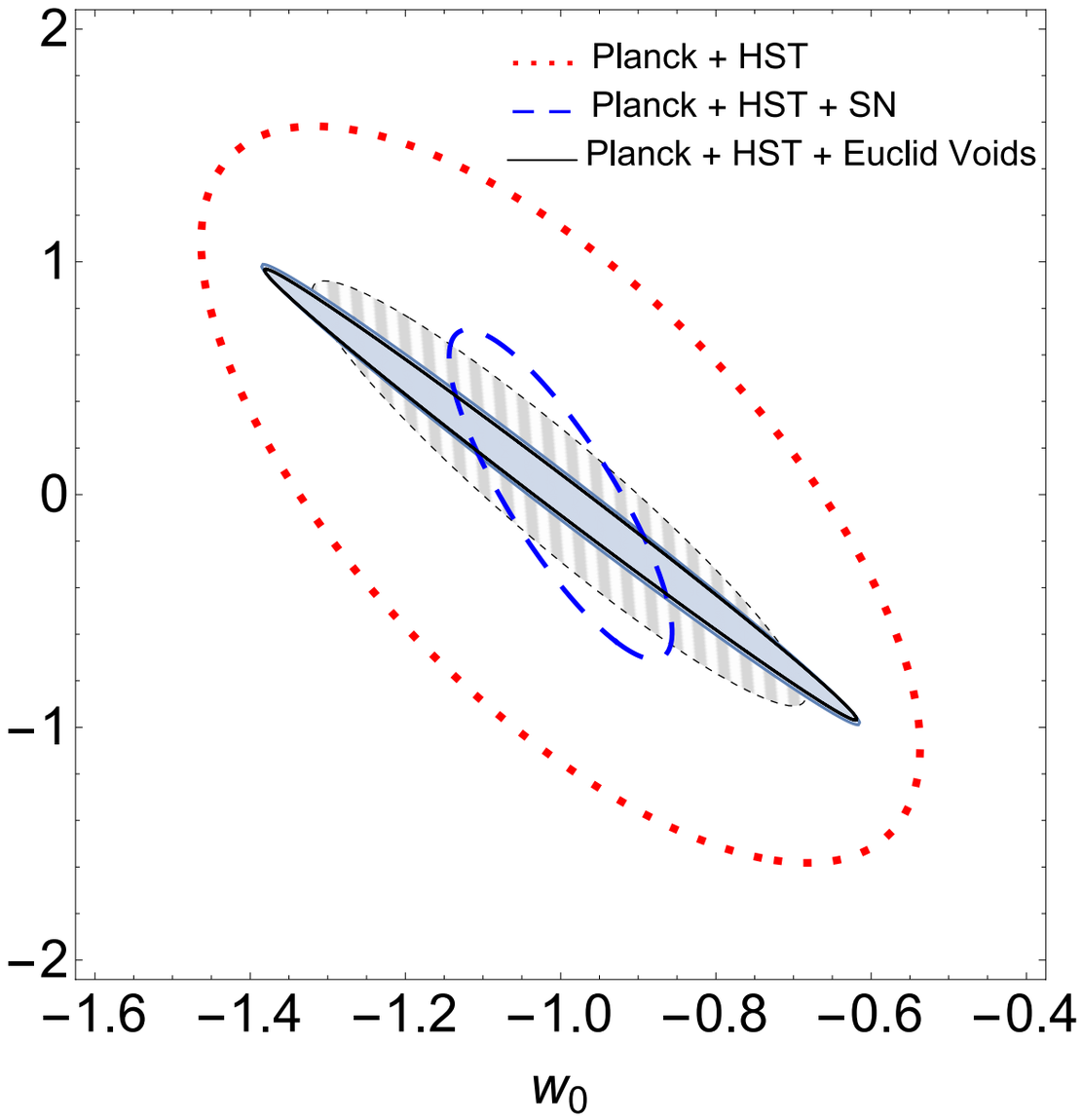
Realistic estimation of the number of voids

Abundances to constrain Cosmology



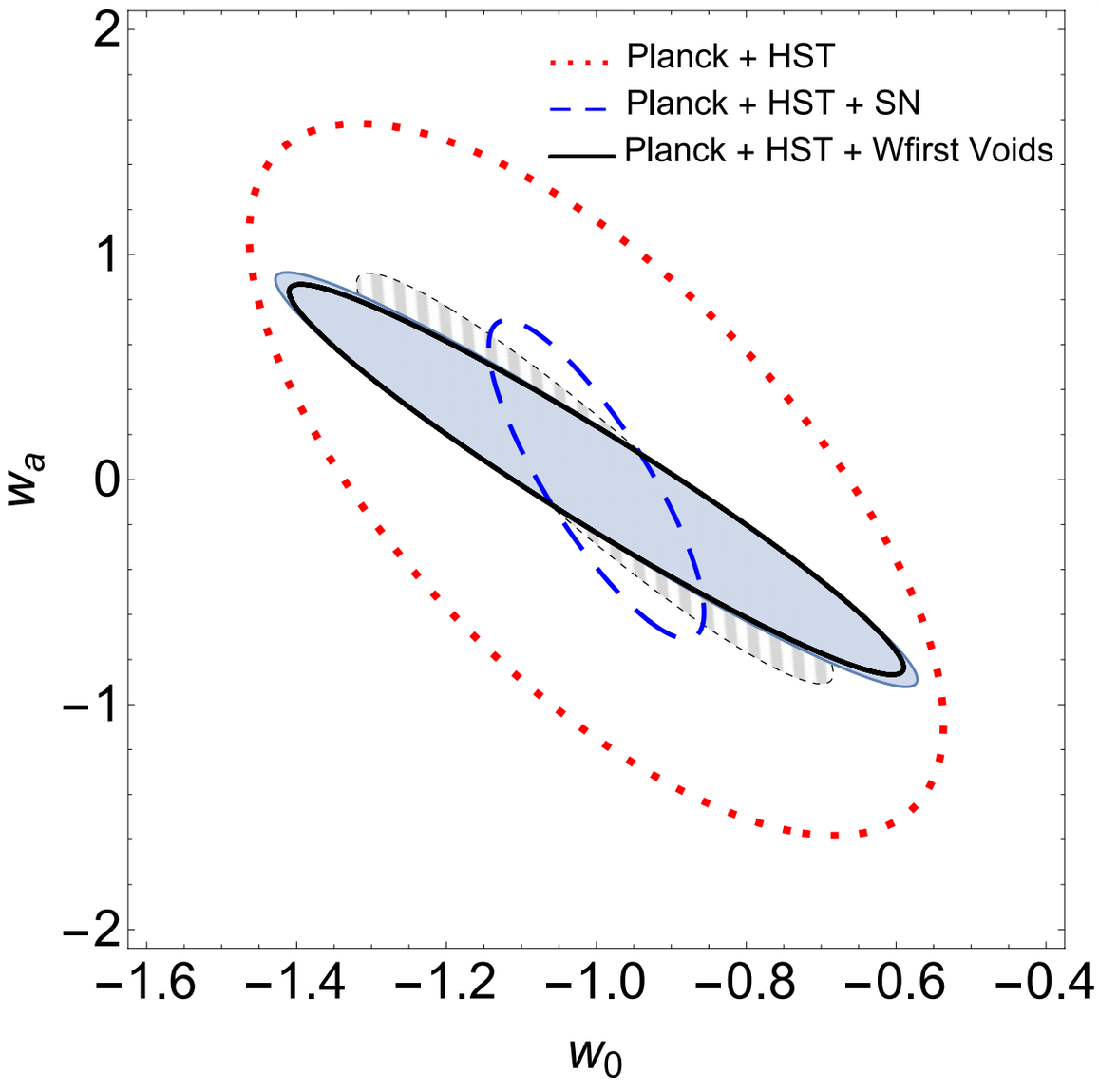
Comparing future surveys

EUCLID



7.8×10^5

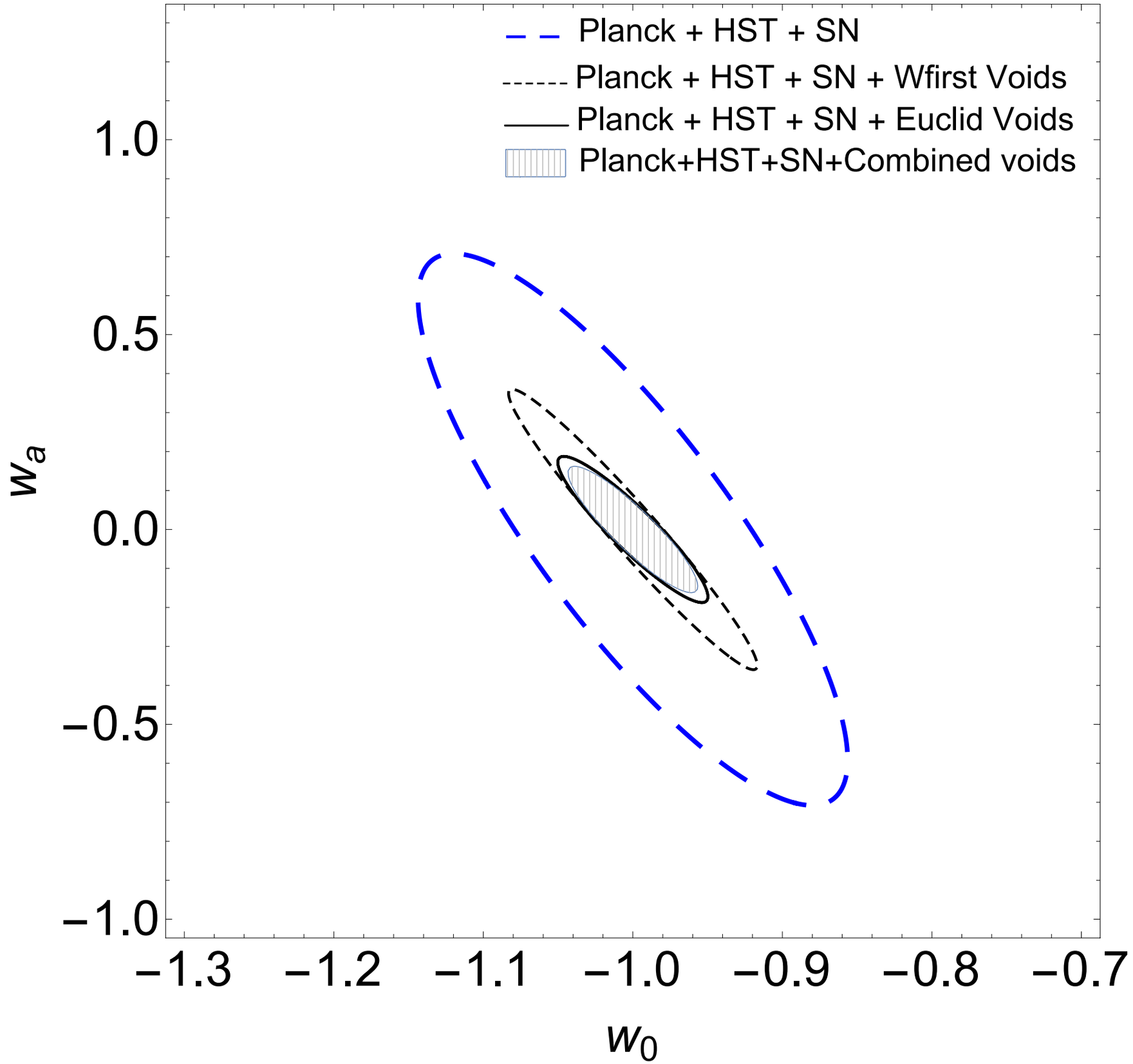
WFIRST



2.5×10^5

arXiv:1503.07690 (Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata 2015)

Combining future surveys



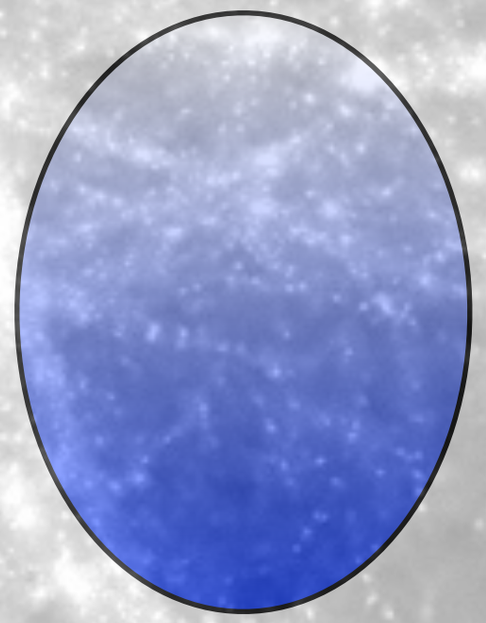
Conclusion

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



Thank you!

BOSS and eBOSS (high z) apply these innovative techniques