

Precision Cosmology with cosmic voids

Alice Pisani (CPPPM)

*Main Collaborators: N. Hamaus, Ben Wandelt, S. Escoffier,
M.-C. Cousinou, P. M. Sutter, G. Lavaux, Chris Hirata*

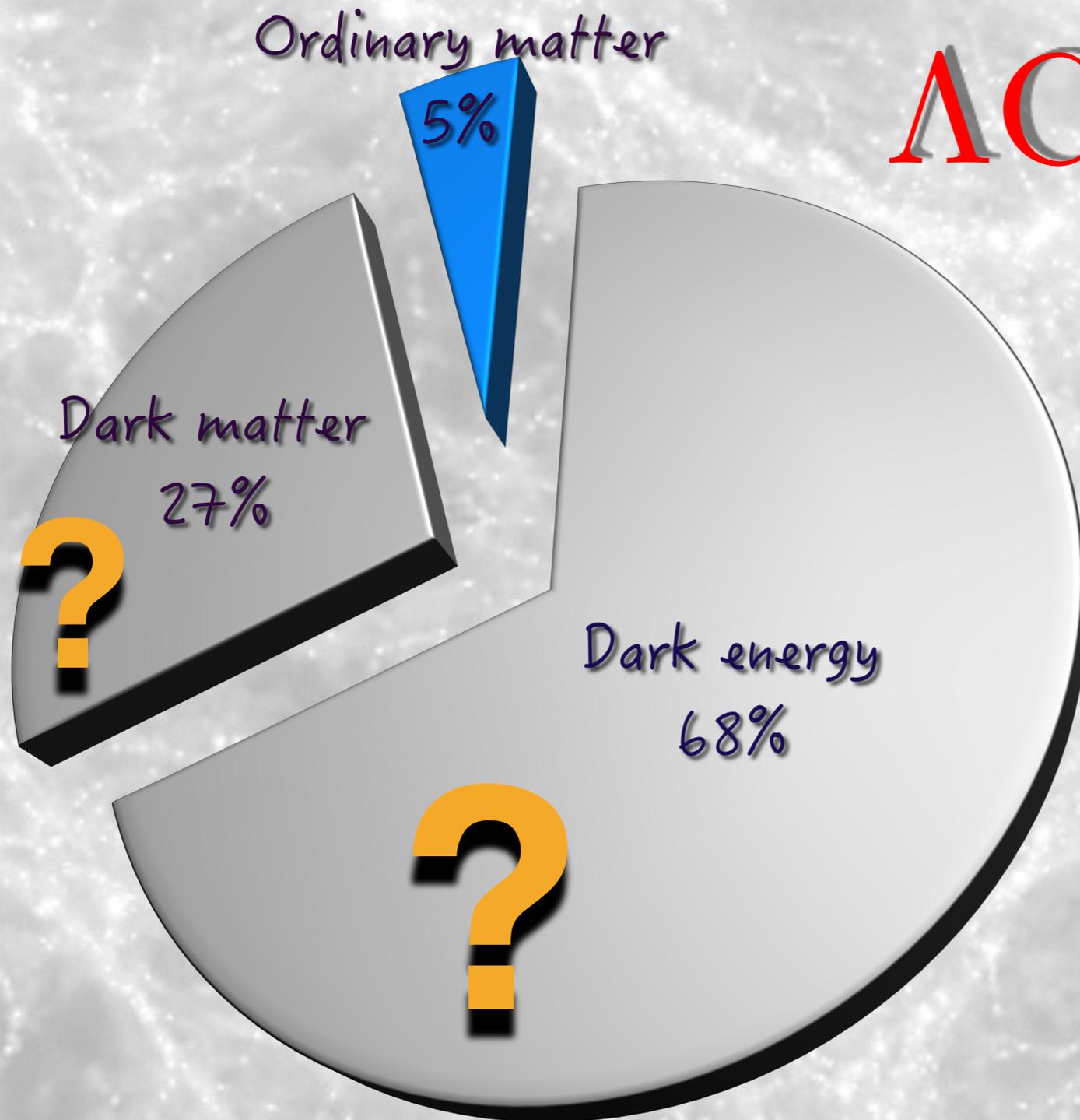
*02/03/2017
@LPC, Clermont-Ferrand
Credit: The Millennium Simulation*

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?

Standard model and precision cosmology

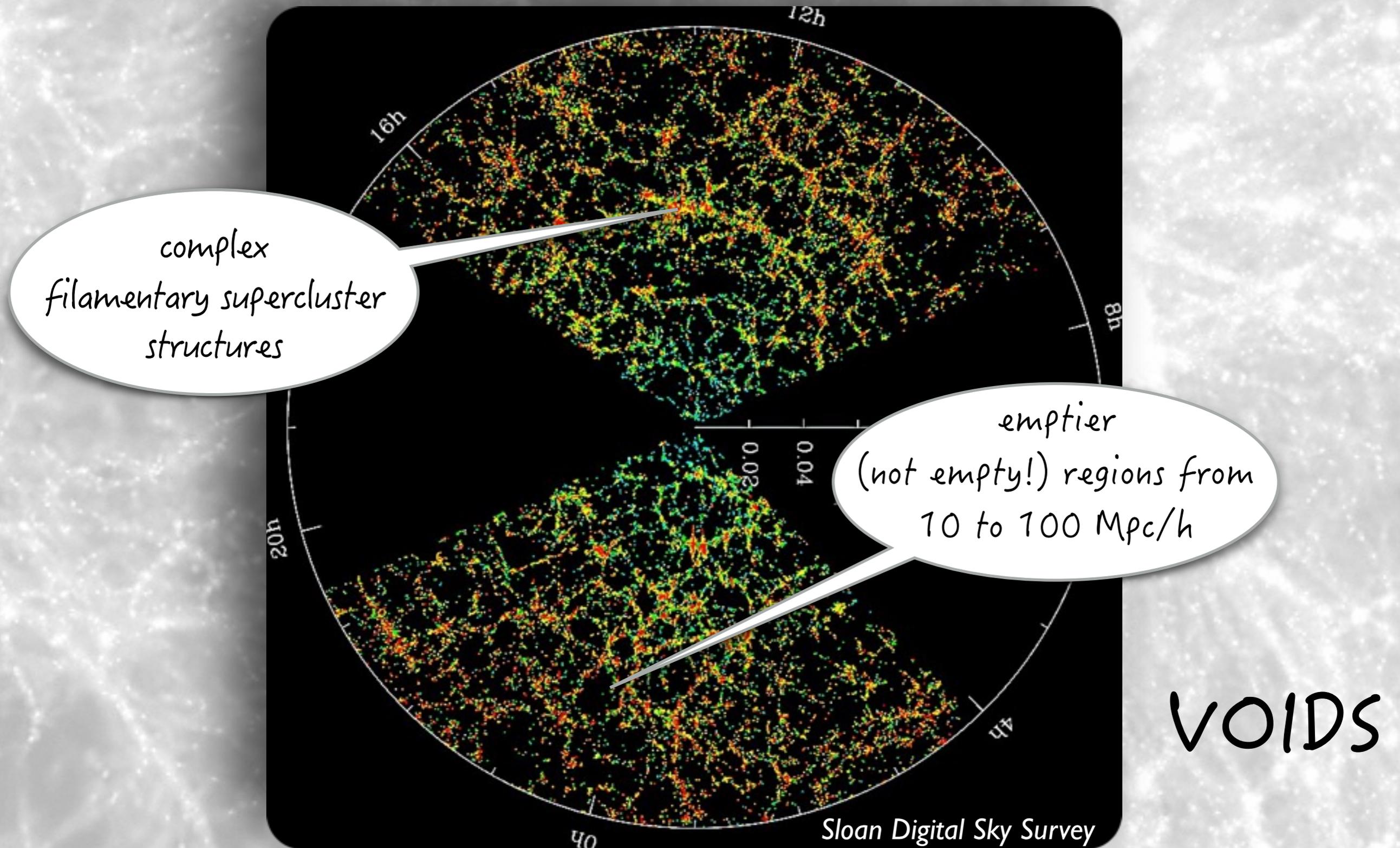
Λ CDM



Actually lots of unknown!

A powerful tool to improve understanding is the study of the Universe at large scales

The cosmic web



Are voids there?

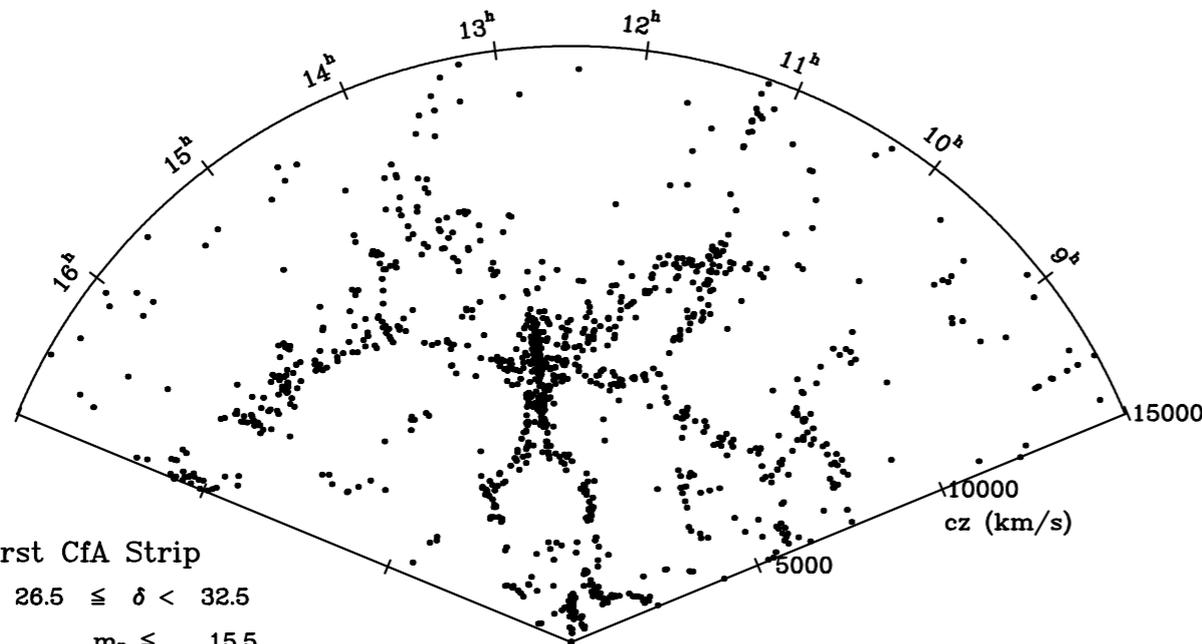
1977



Credit: Thompson and Gregory 1977



Credit: Jaan Einasto private collection



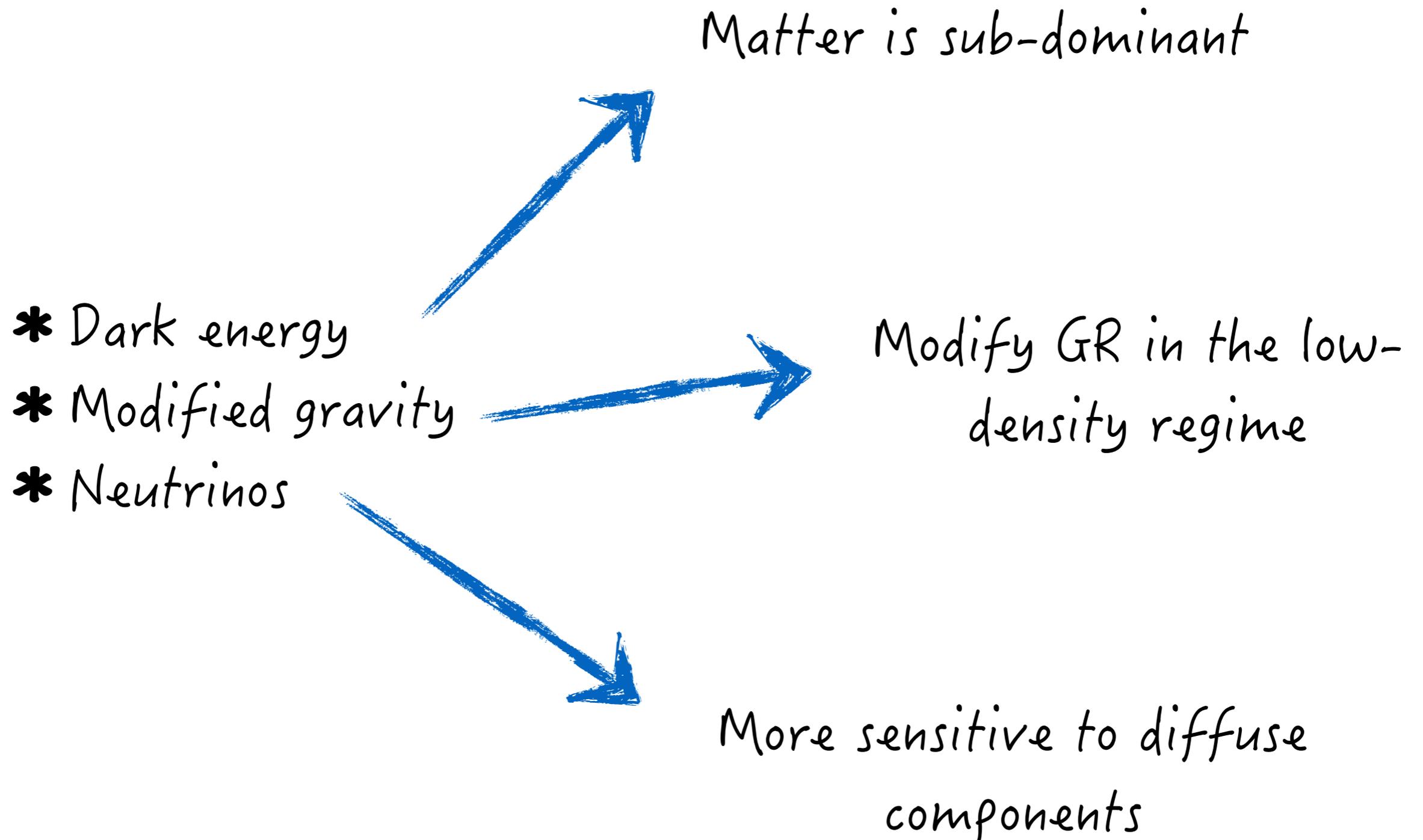
1986

Credit: de Lapparent et al. 1986

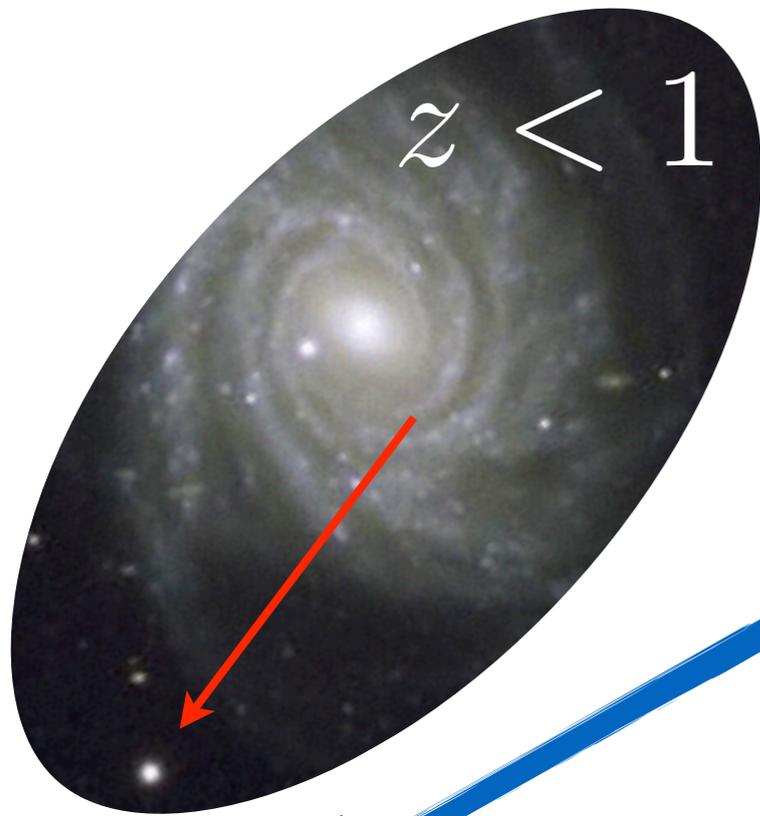
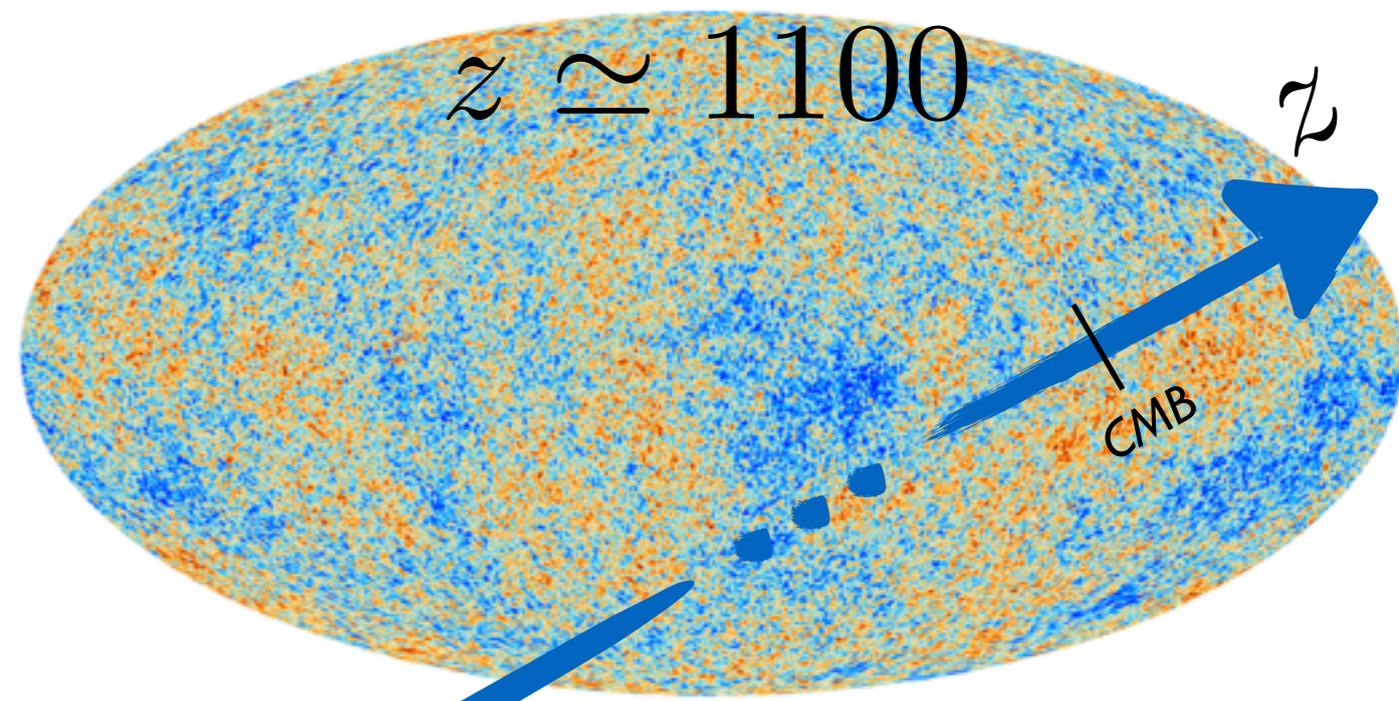
A visualization of the cosmic web, showing a complex network of dark blue filaments and nodes. The nodes are highlighted with bright orange and yellow colors, representing galaxy clusters and individual galaxies. The background is a light blue, textured surface.

Can we use cosmic voids to get
cosmological information?

Voids for cosmology

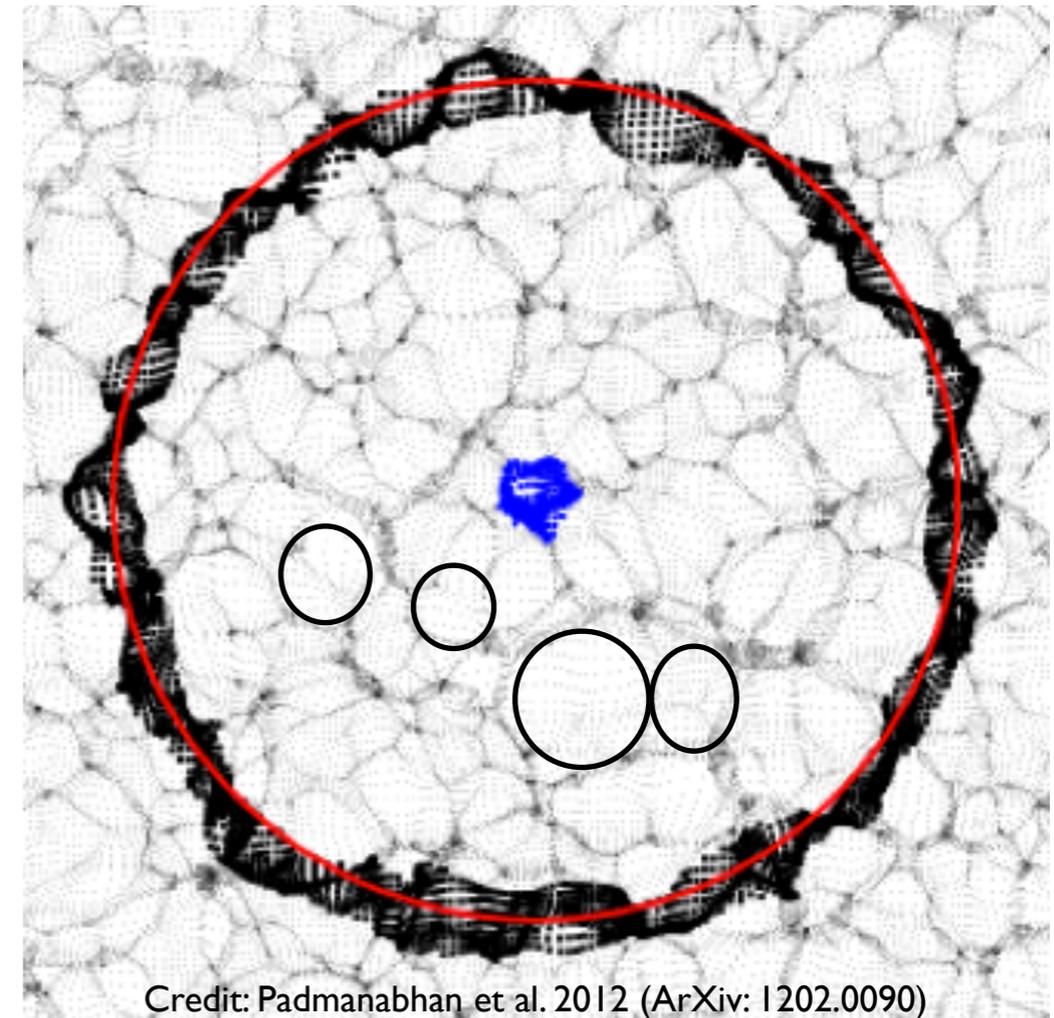


Where are we looking?



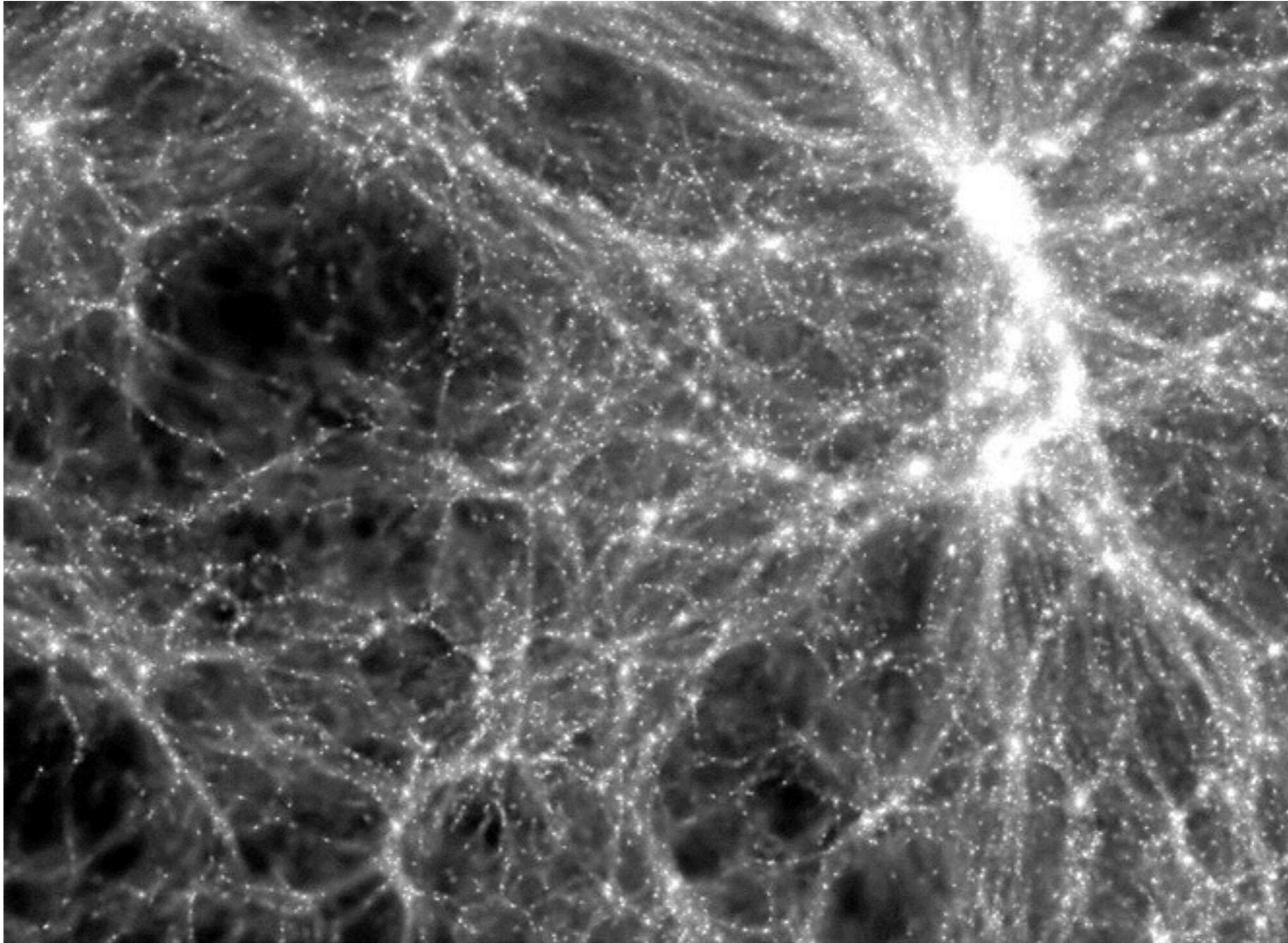
Large Scale Structure

Sensitive at more scales!



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

So, voids can be used for cosmology but first ...



we need to find them!

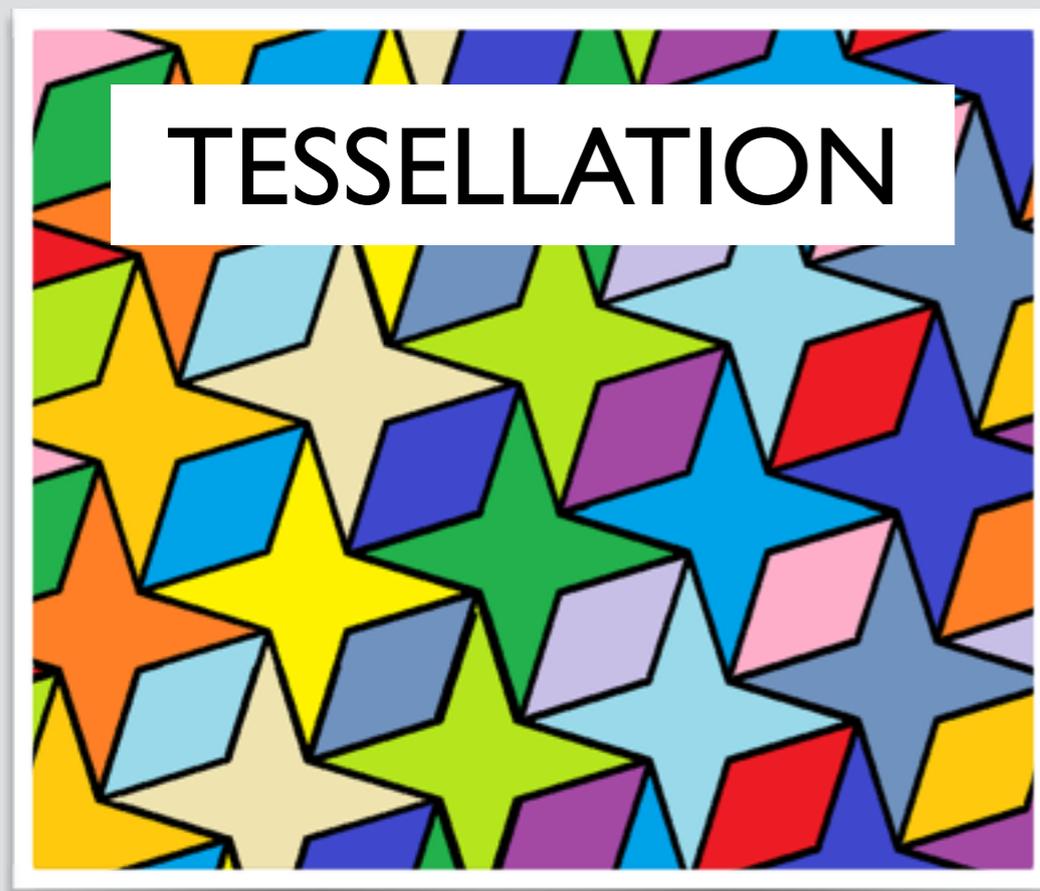
VIDE: Void IDentification and Examination

Sutter et al 2015, based on Zobov (Neyrinck 2008)



VIDE: Void IDentification and Examination

galaxy survey
or simulation → Voronoi
tessellation



A tessellation with physical meaning.

Tracer

All points
closer to
the tracer
than to any
other point

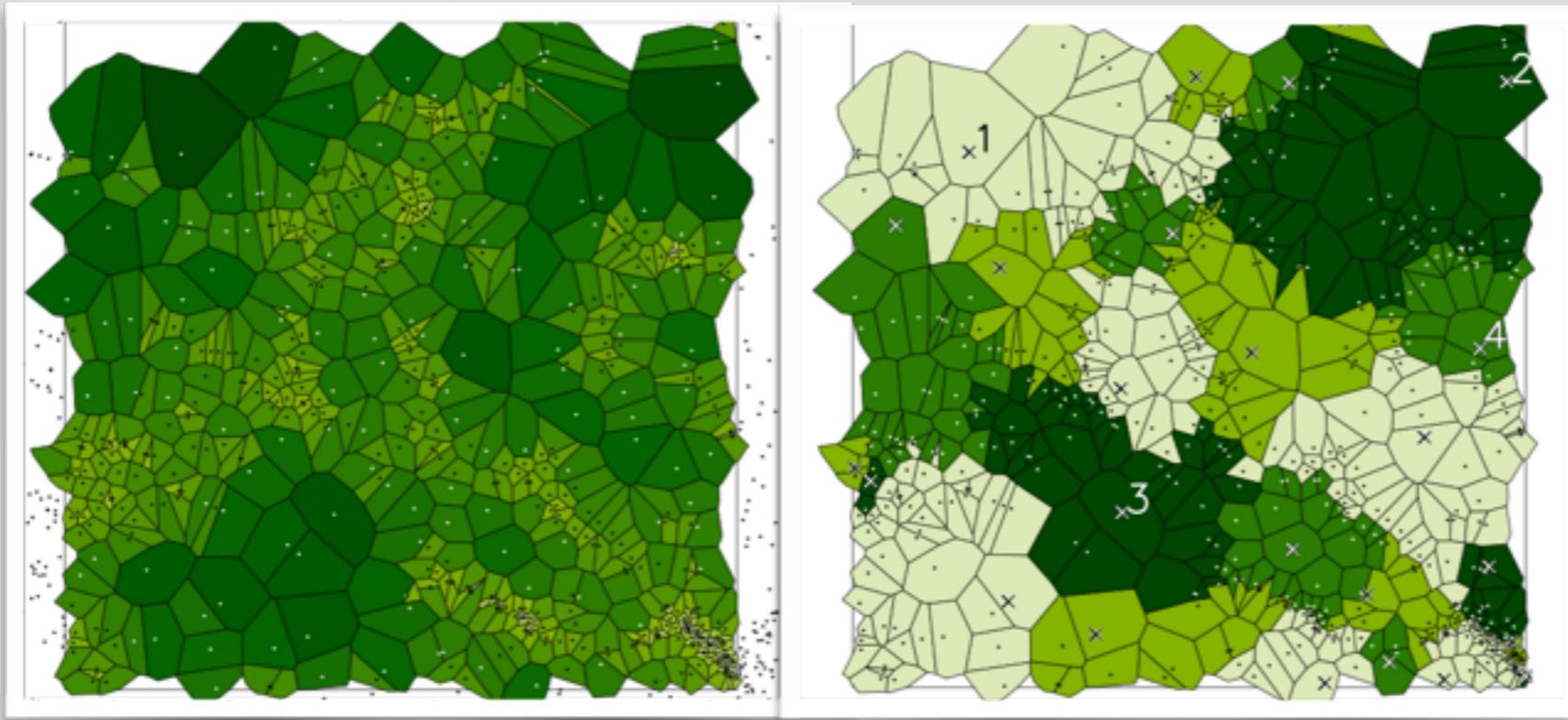
$$\rho_{local} = \frac{1}{V_{cell}}$$



We have a local estimation of the density

VIDE: Void IDentification and Examination

galaxy survey or simulation → Voronoi tessellation → Watershed transform

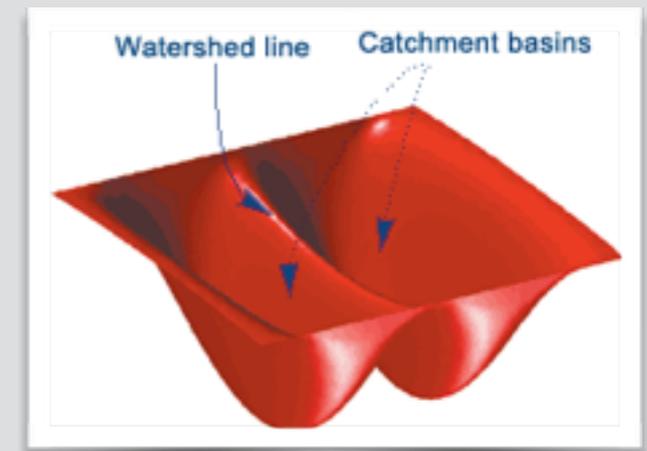
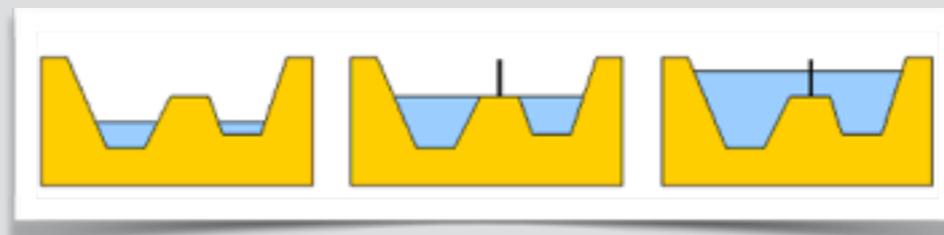


Merge cells in basins, and basins are merged if the border with lower density is common.

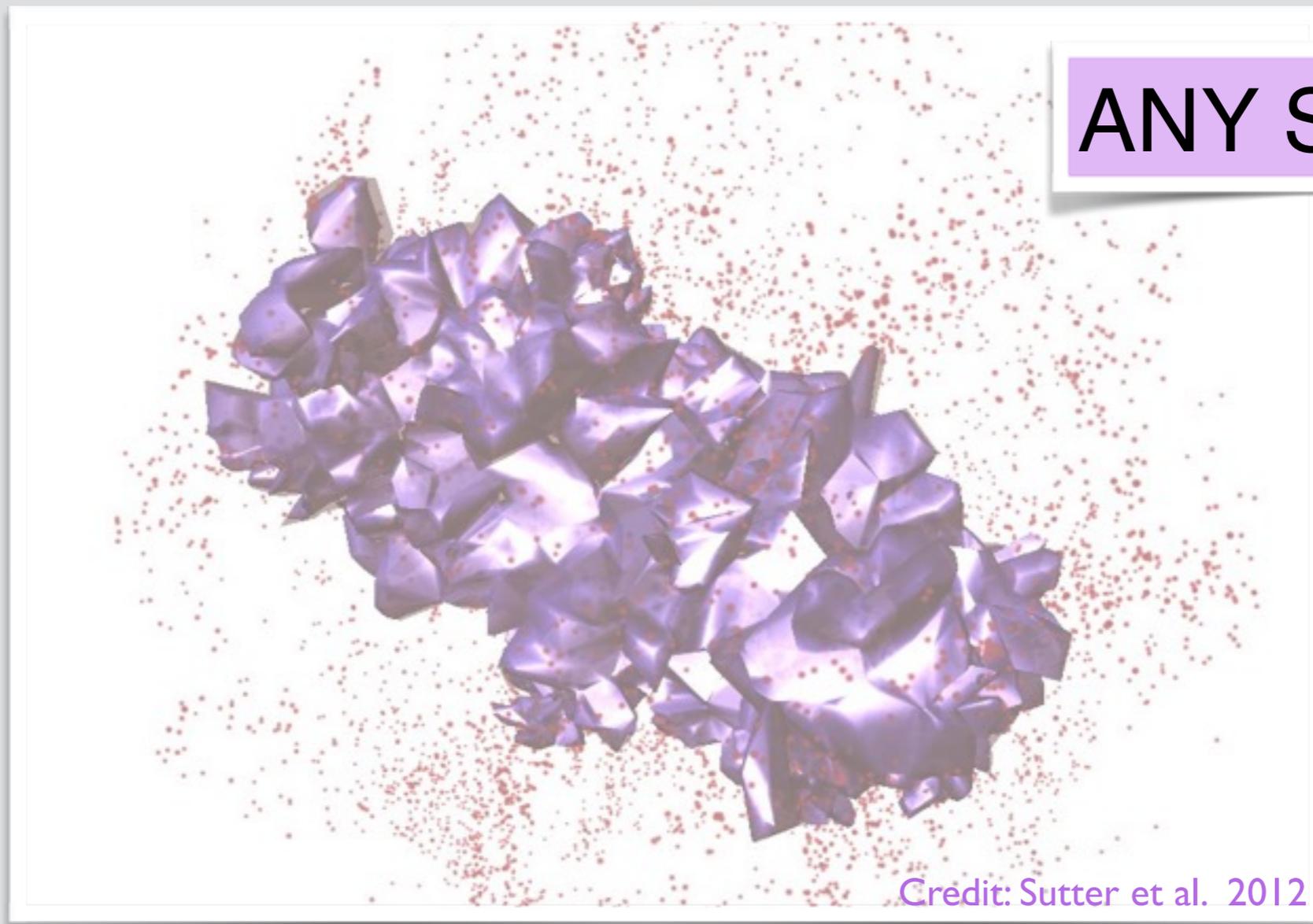
Neyrinck 2008

Density cuts:

- 1) all cells mean density < -0.8
 - 2) density in $R_{\text{eff}}/4 < -0.8$
- + exclude voids below mps



VIDE: Void IDentification and Examination

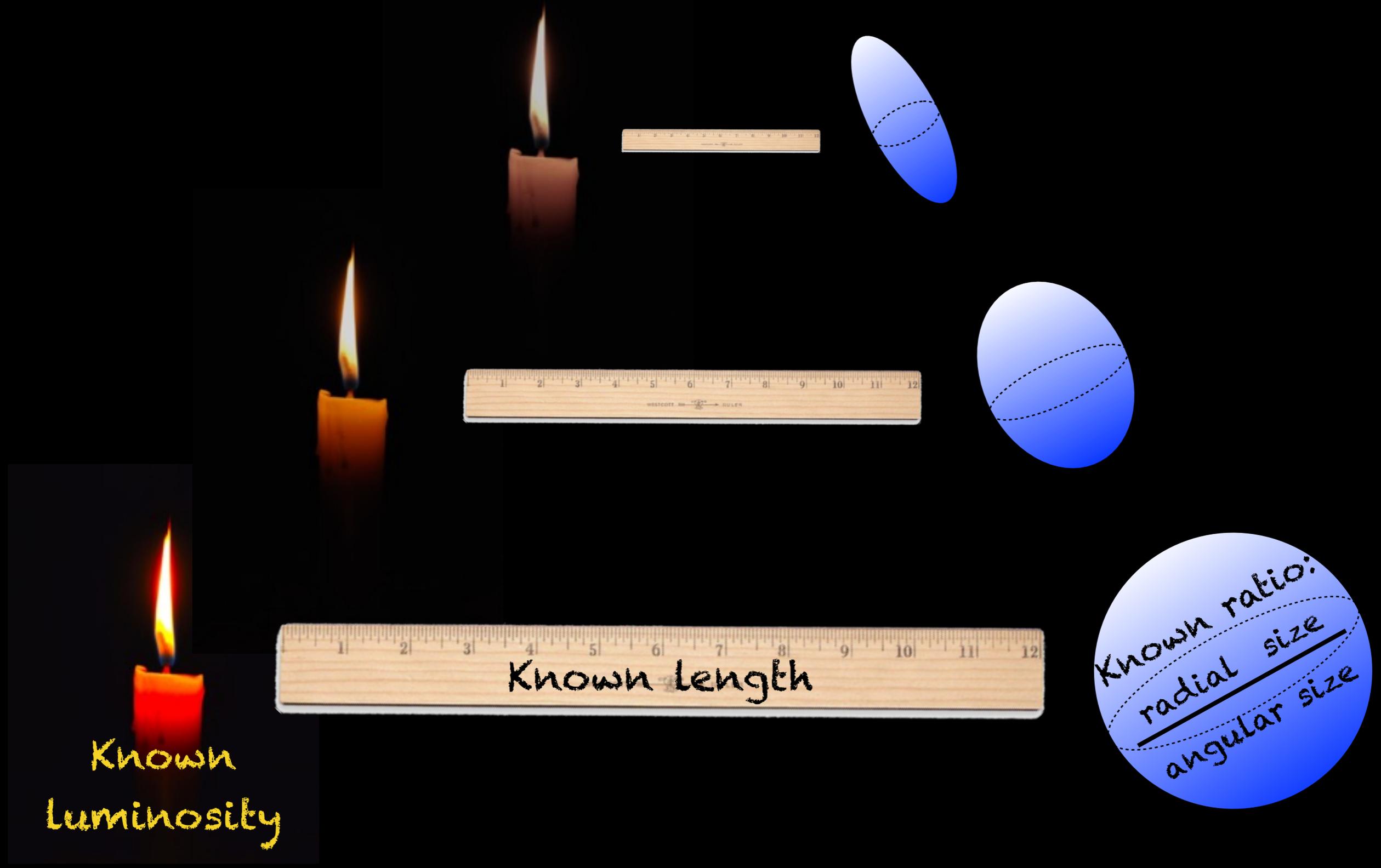


ANY SHAPE

VIDE takes into account survey boundaries and masks

We have voids, now how
do we use them to
measure the expansion of
the Universe?

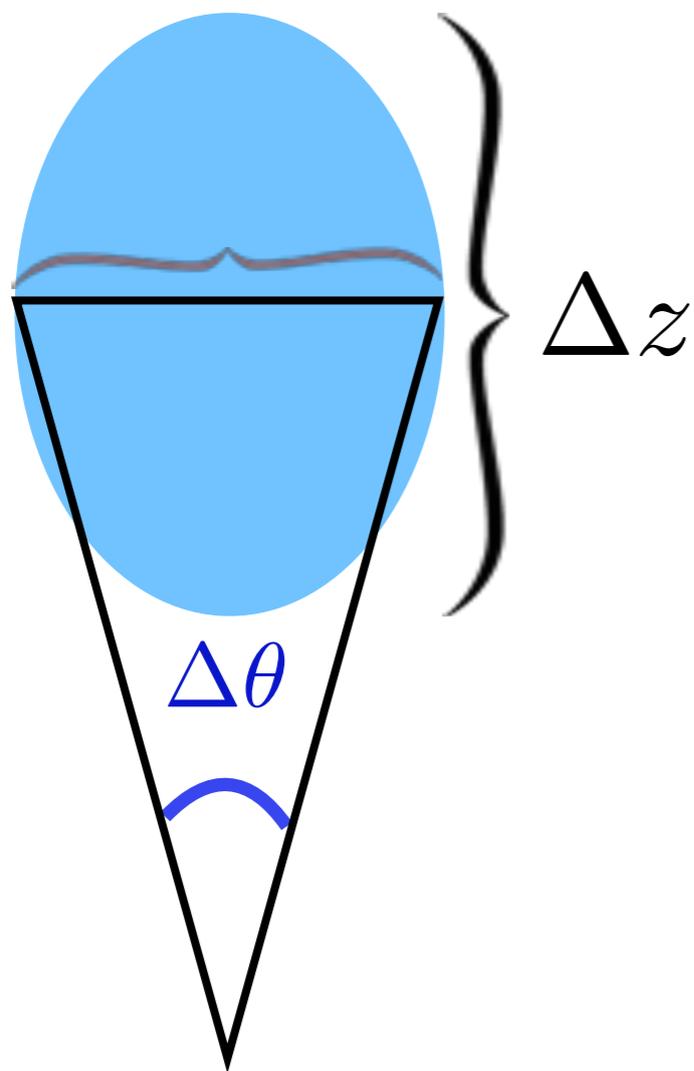
Standard objects



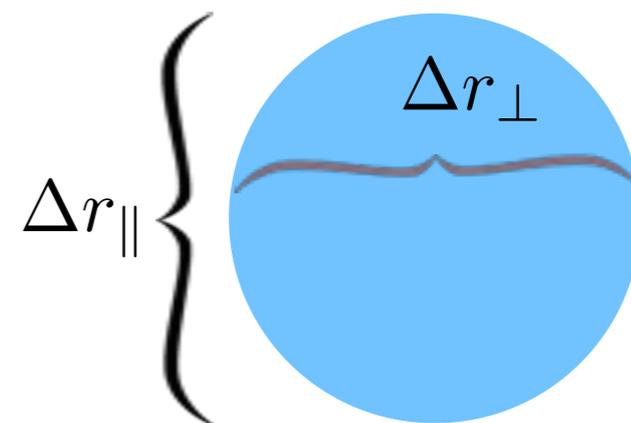
Known
Luminosity

Known ratio:
radial size
angular size

What we measure:



Real length scales:



physical sizes of the object

Δr_{\perp} *in the transverse direction*

Δr_{\parallel} *in the longitudinal direction*

Cosmology, of course!

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

*angular diameter
distance*

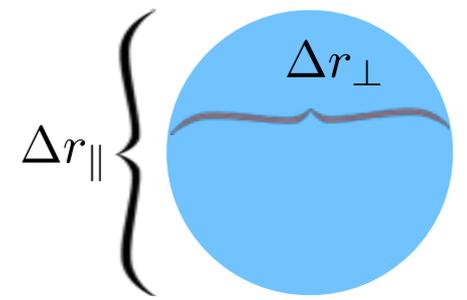
$$c\Delta z = H(z) \Delta r_{\parallel}$$

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

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

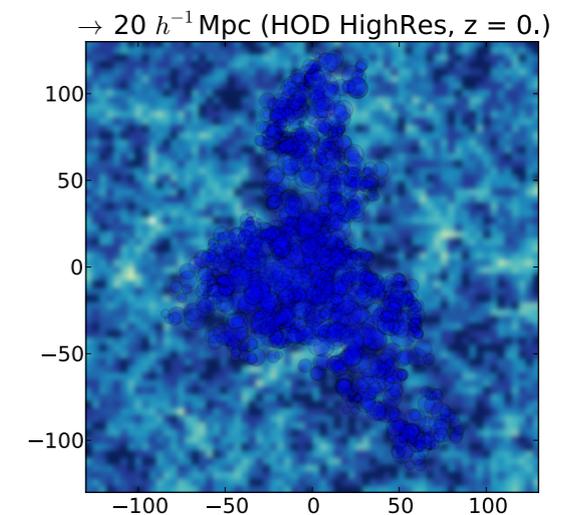
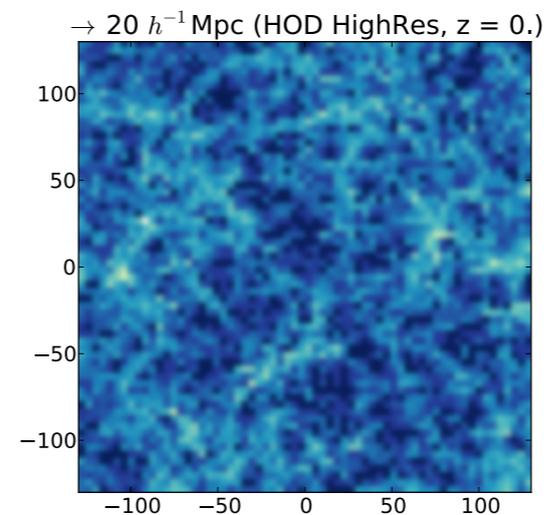
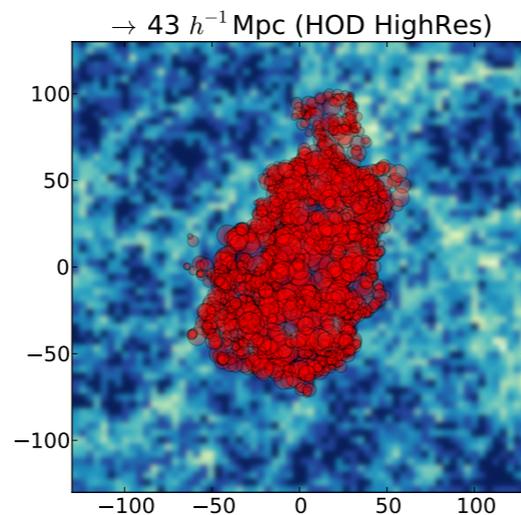
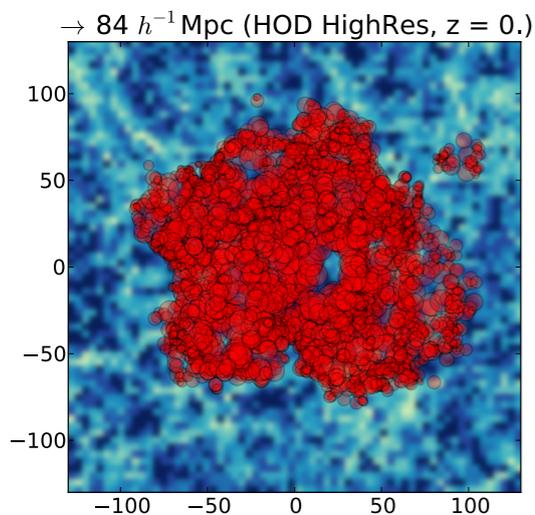
The deviations from fiducial cosmology cause geometrical distortions.

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda} \quad D_A(z) = \frac{c}{1+z} \int_0^z \frac{dz}{H(z)}$$



1995

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

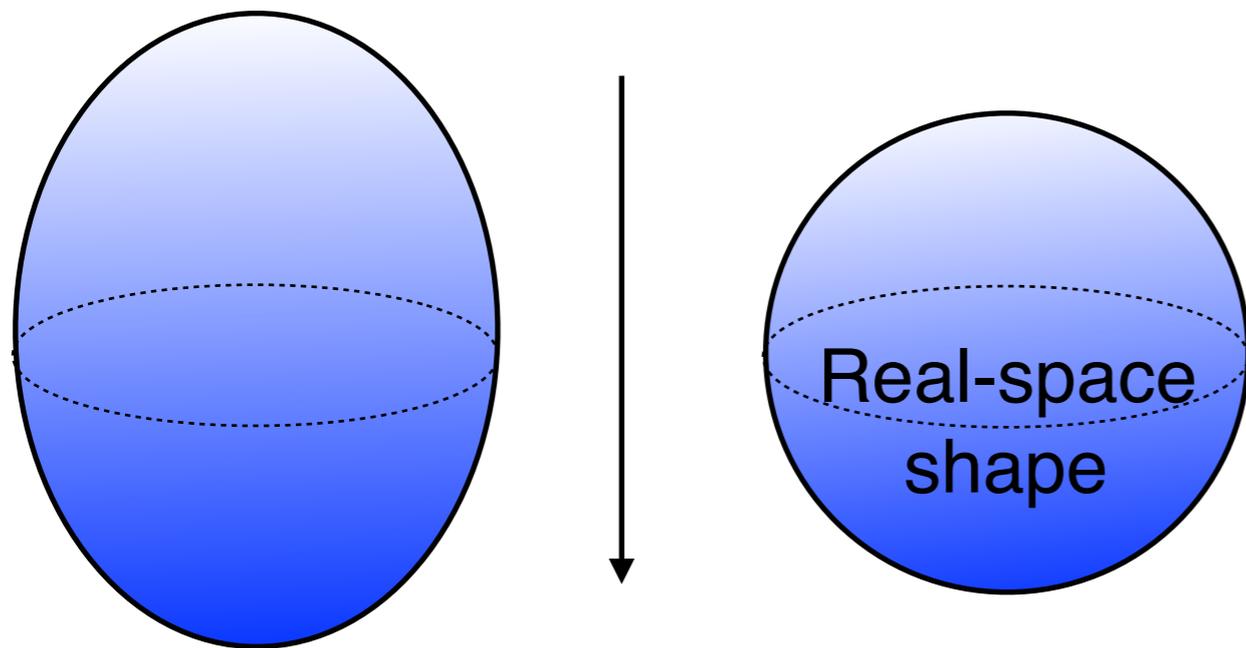
=> promising with new surveys.

Lavaux & Wandelt 2012



The void shape tells us the cosmology, but what are the systematics?

Peculiar velocities of galaxies also affect that shape.



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

z_{measured} z_{cosmo}

The equation is accompanied by two blue arrows pointing upwards towards the terms cz and $H_0 d$. The arrow under cz is labeled z_{measured} and the arrow under $H_0 d$ is labeled z_{cosmo} .

Velocities will be our main source of systematics!

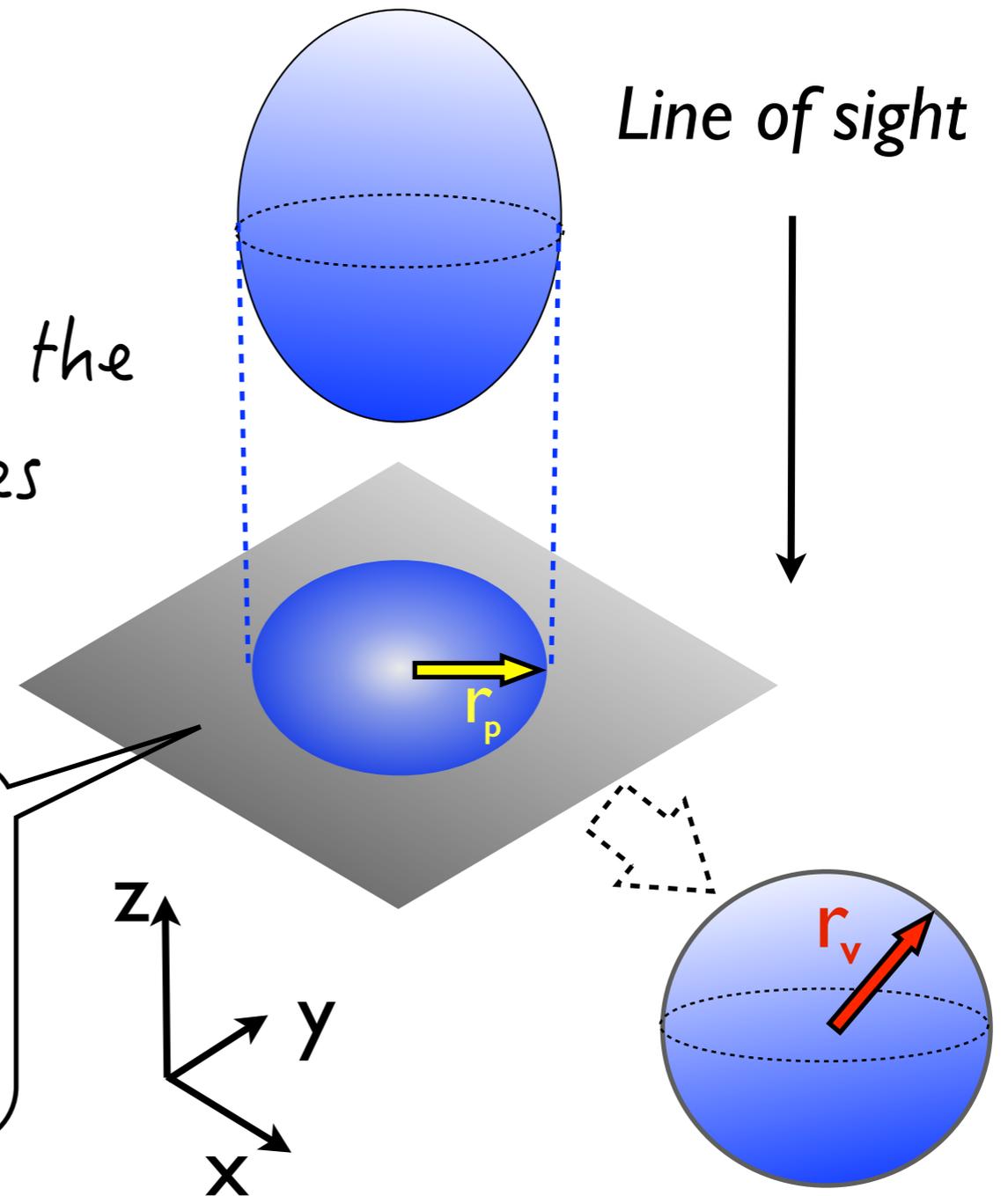
We can reduce the systematics by acting on two fronts

- ▶ better modeling the real space shape
- ▶ studying the effect of peculiar velocities

A method to obtain the real shape of voids!

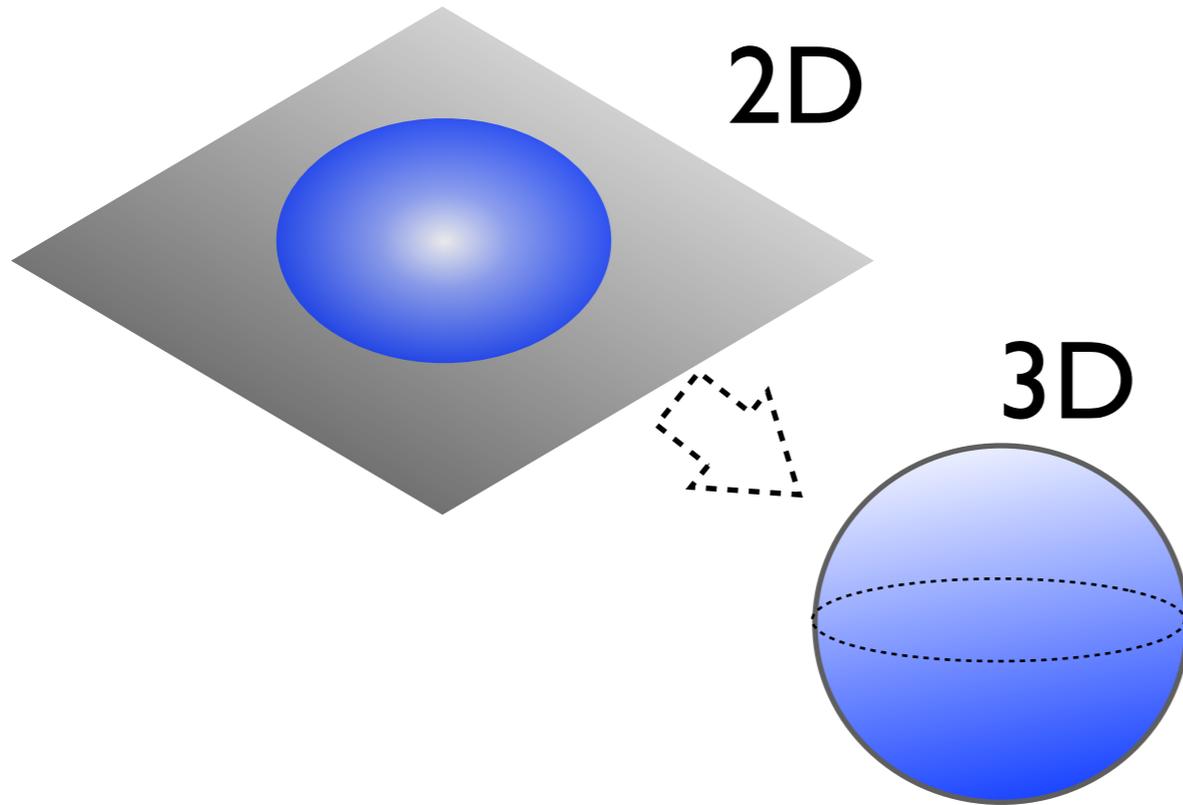
Key idea: Projecting the 3D distribution along the line of sight, the contribution of peculiar velocities disappears.

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

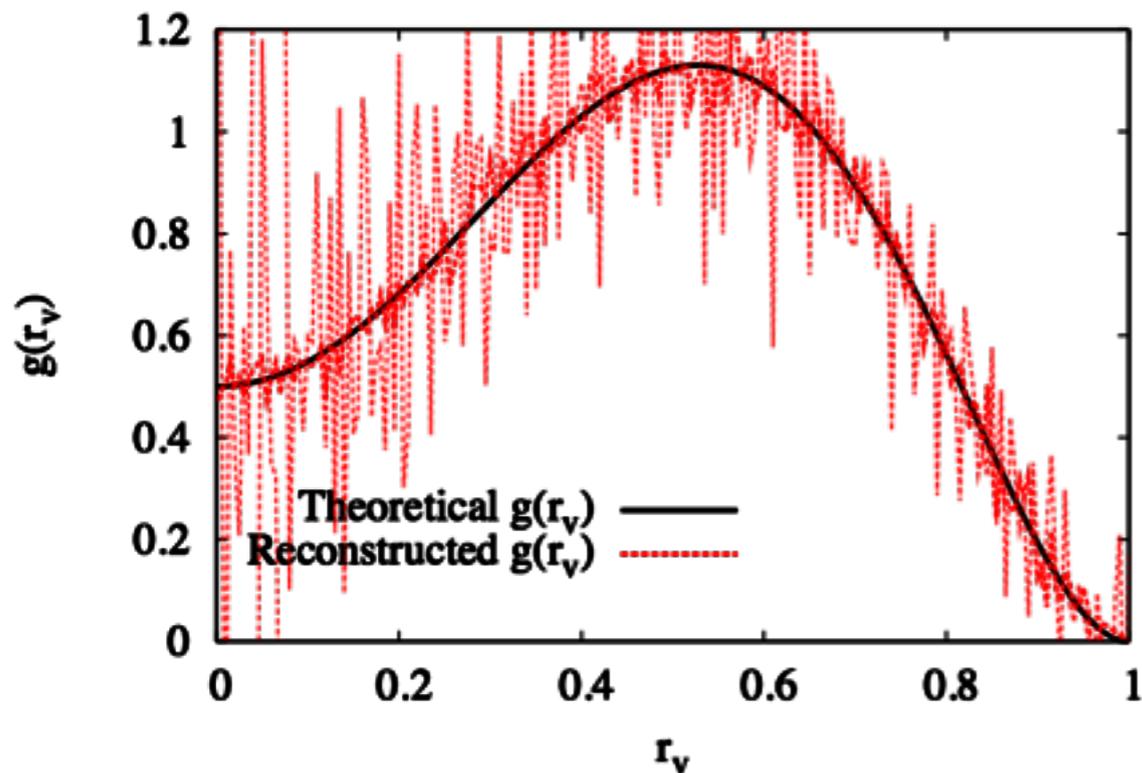
But ...

Result I

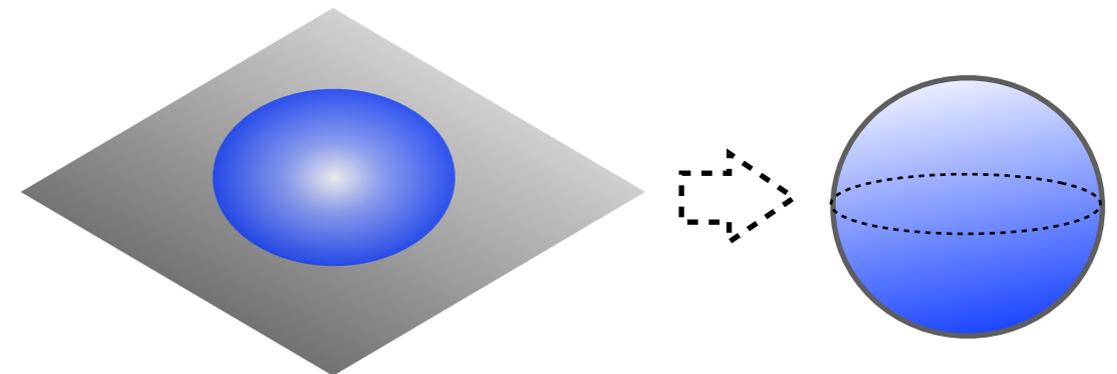
Fighting ill-conditioning

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

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



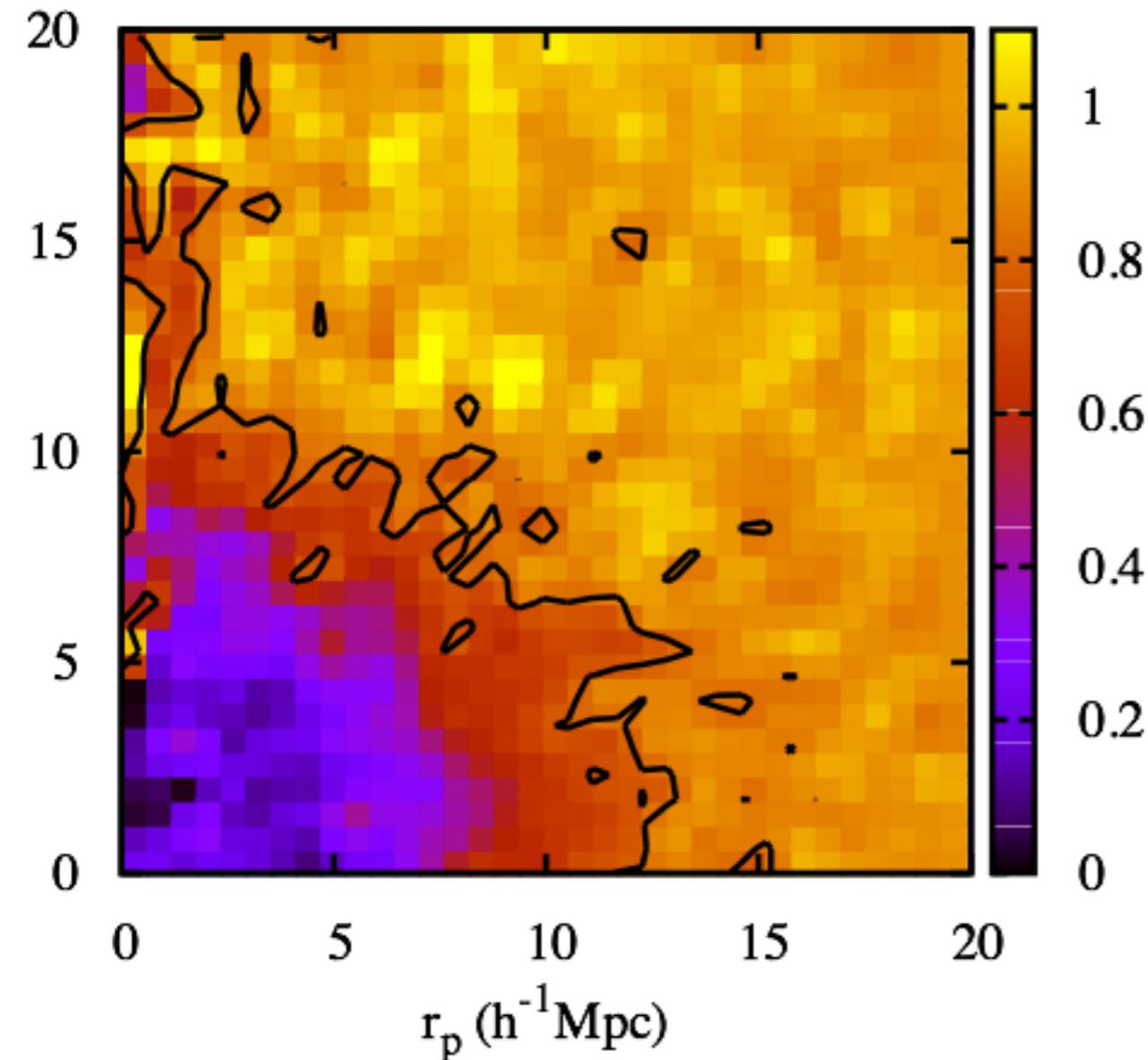
Reconstruction was with an Abel pair,
so it is a particular case



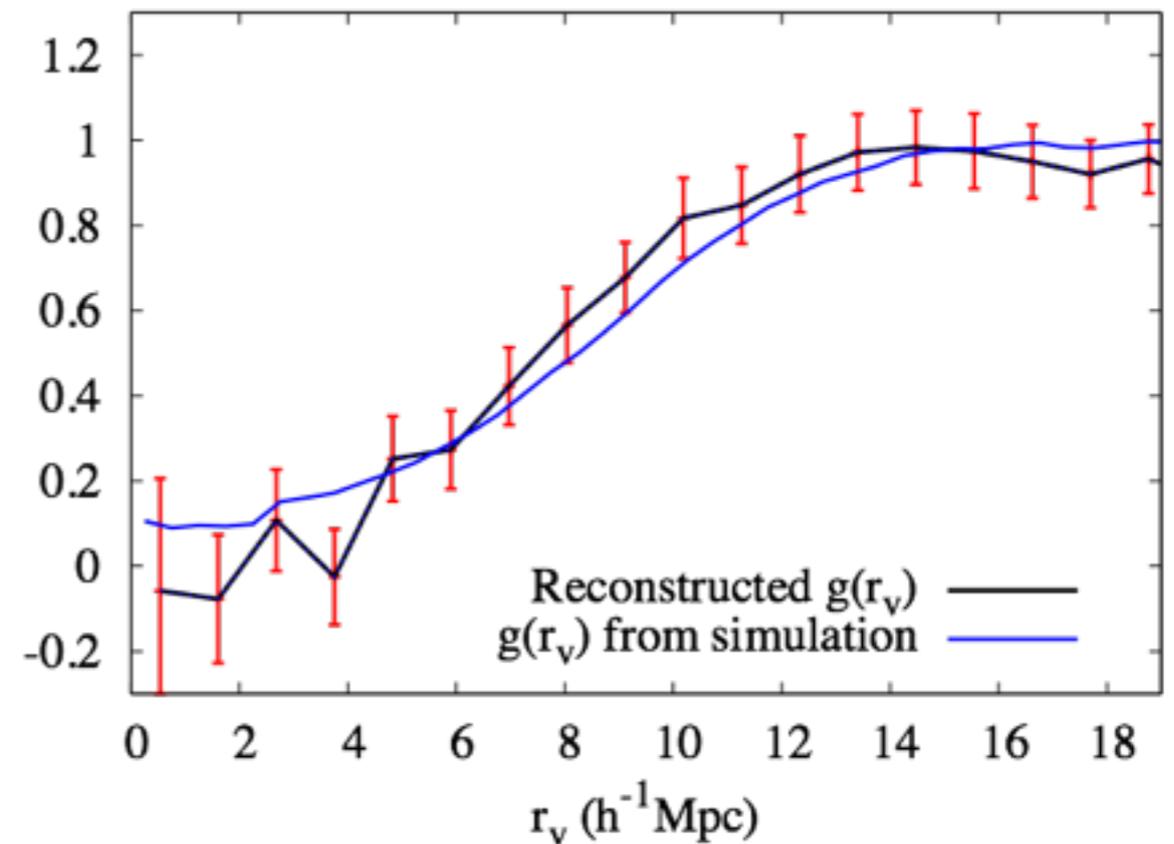
RESULT:
Very good
reconstruction!

Result II

The full simulated stacked void



Density profile reconstructed



Stack from 10 to 12 Mpc/h

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

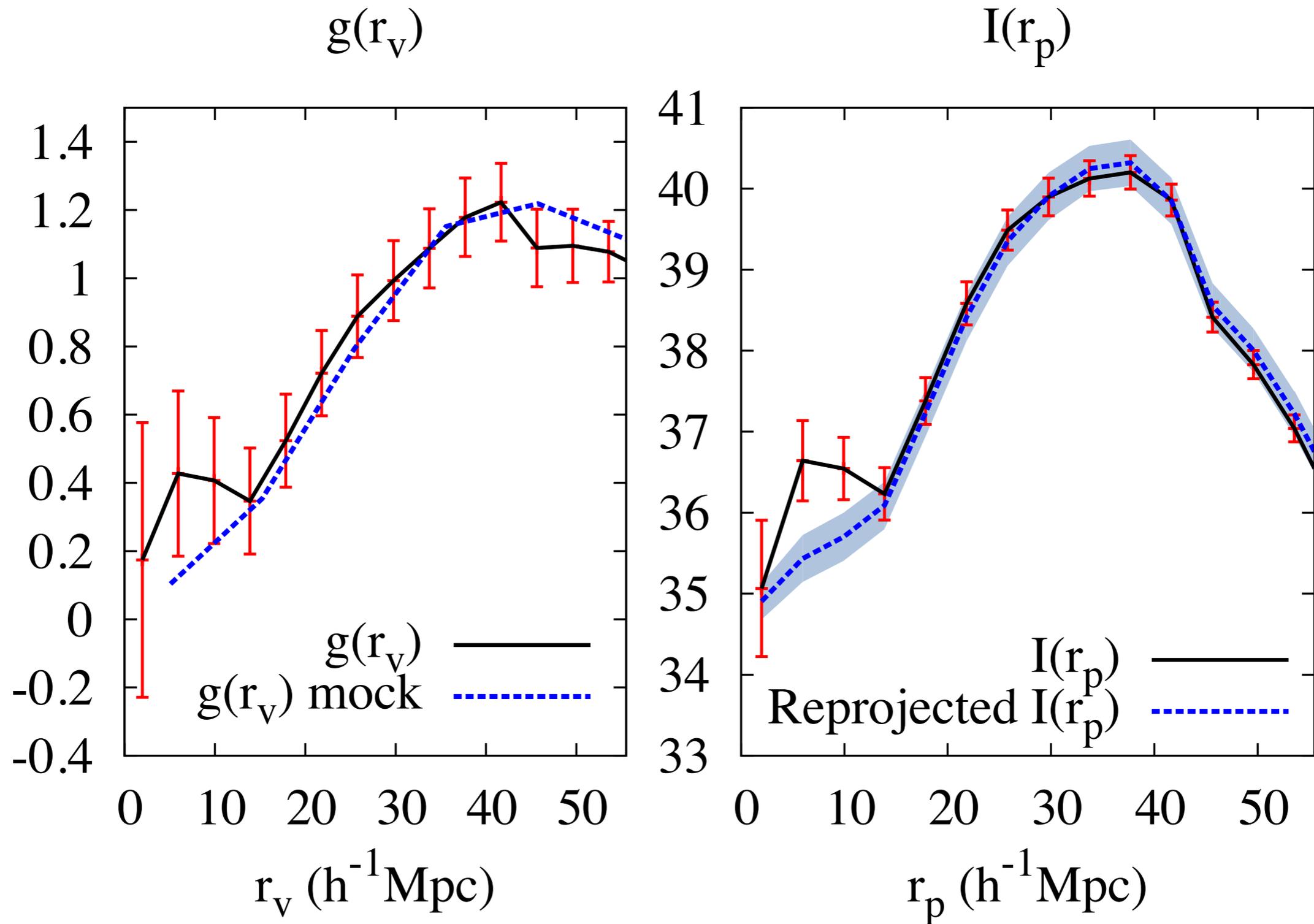
Reconstruction from stacked void with HOD model

$$\langle N_{\text{cen}}(M) \rangle = \frac{1}{2} \left[1 + \text{erf} \left(\frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right]$$
$$\langle N_{\text{sat}}(M) \rangle = \langle N_{\text{cen}}(M) \rangle \left(\frac{M - M_0}{M'_1} \right)^\alpha$$

Rockstar halo finder + HOD model assigns central and satellite galaxies
(Behroozi et al. 2013) to a dark matter halo (Zheng et al. 2007)

Matching the features of SDSS DR7

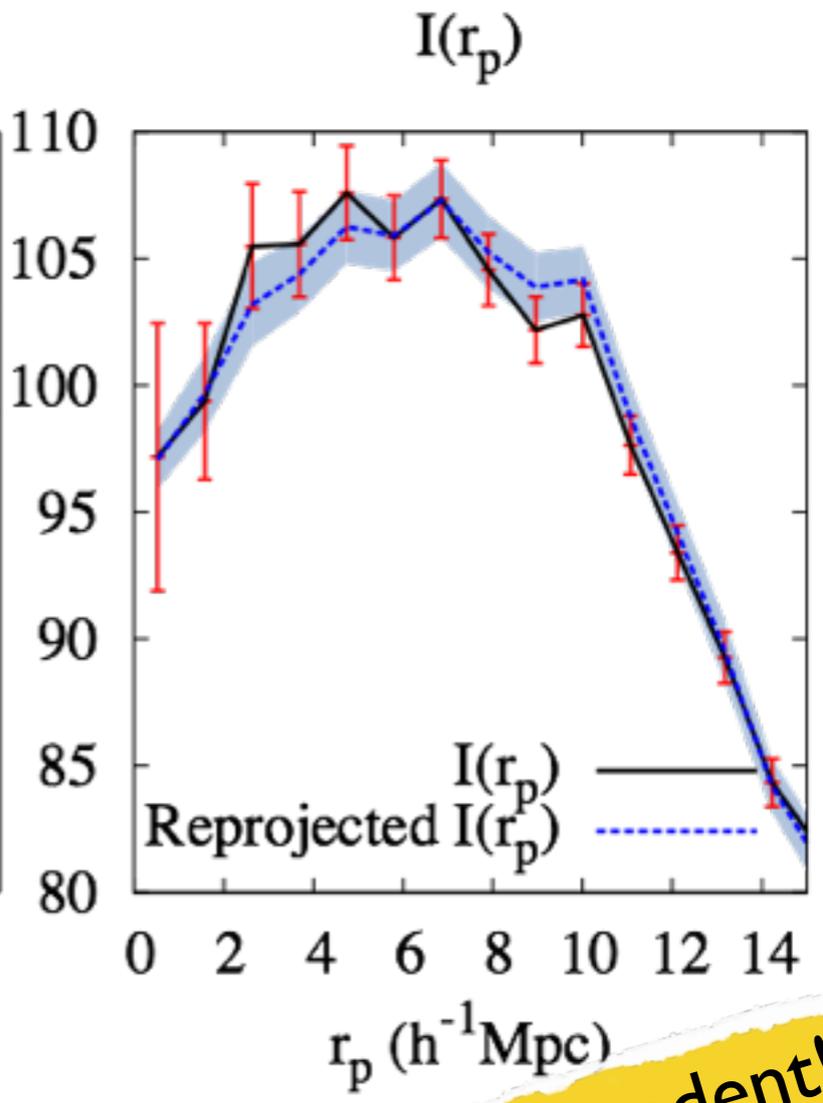
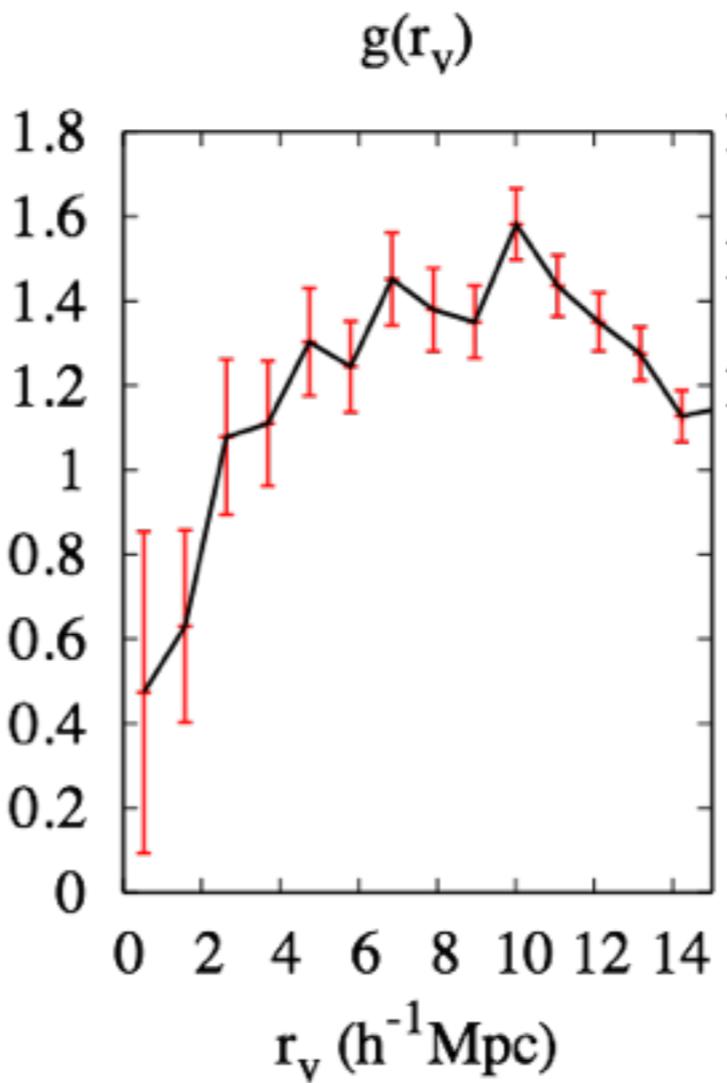
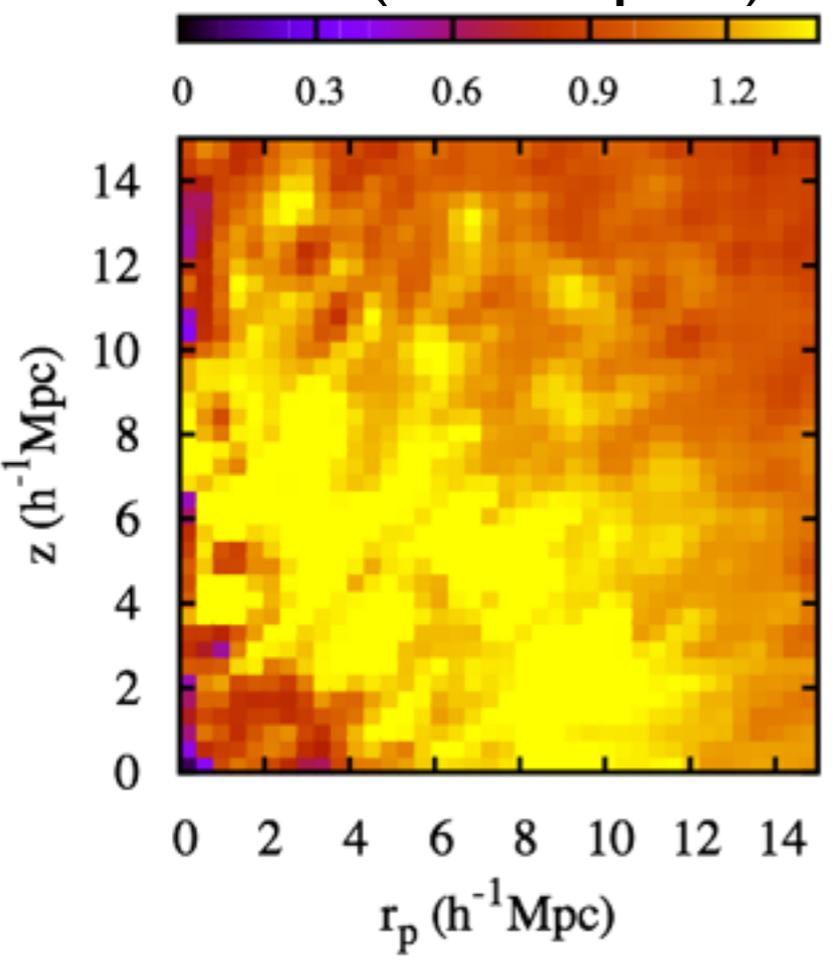
Reconstruction from stacked void of HOD model



Result III

REAL DATA from SDSS

Dim (5-15 Mpc/h)

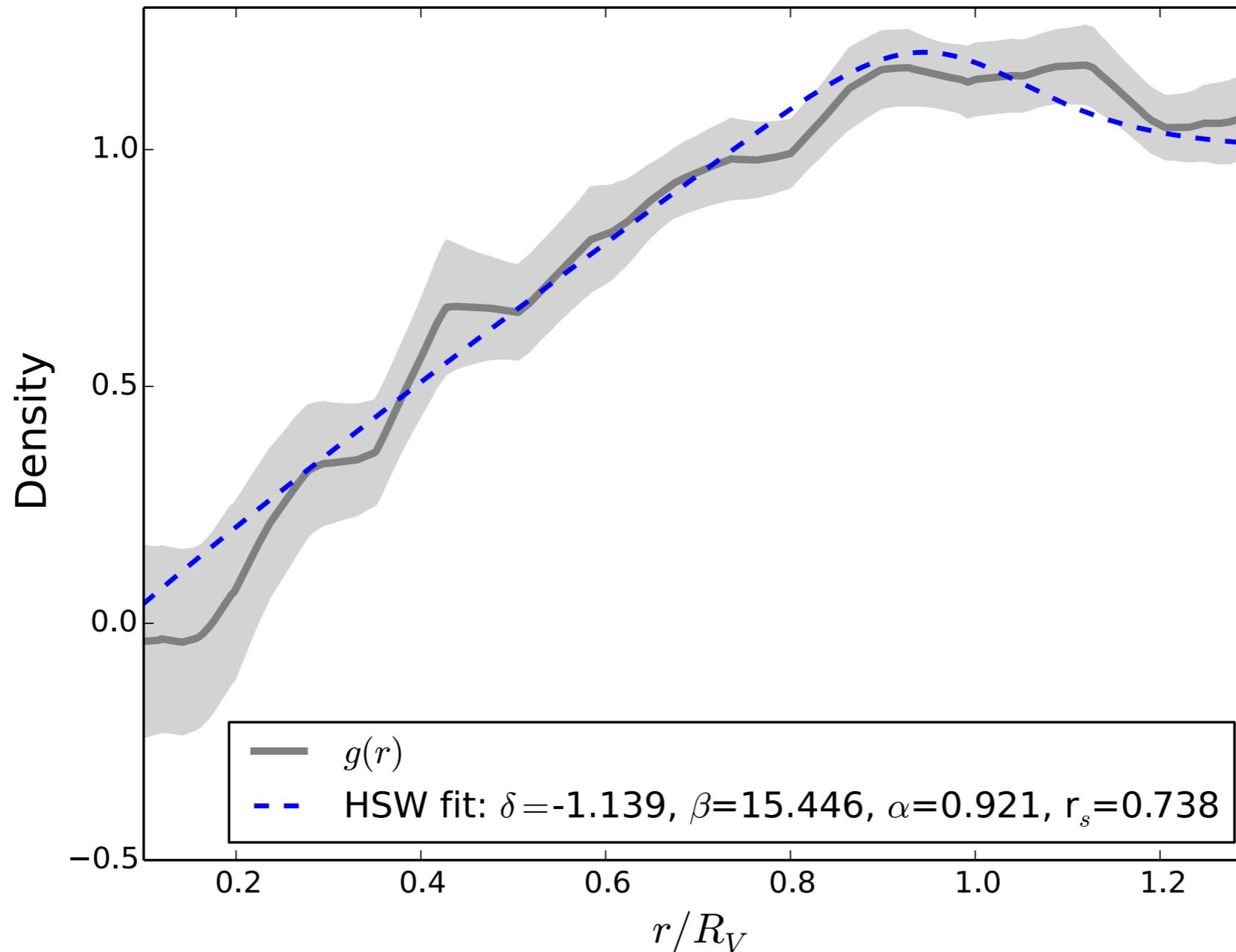


Stack radius	Redshift	Dataset	Galaxies	Voids
5-15	0.05-0.10	dim2	173929	173
10-15	0.05-0.10	dim2	43527	41
20-25	0.10-0.15	bright1	21241	17
25-45	0.15-0.20	bright2	51913	37

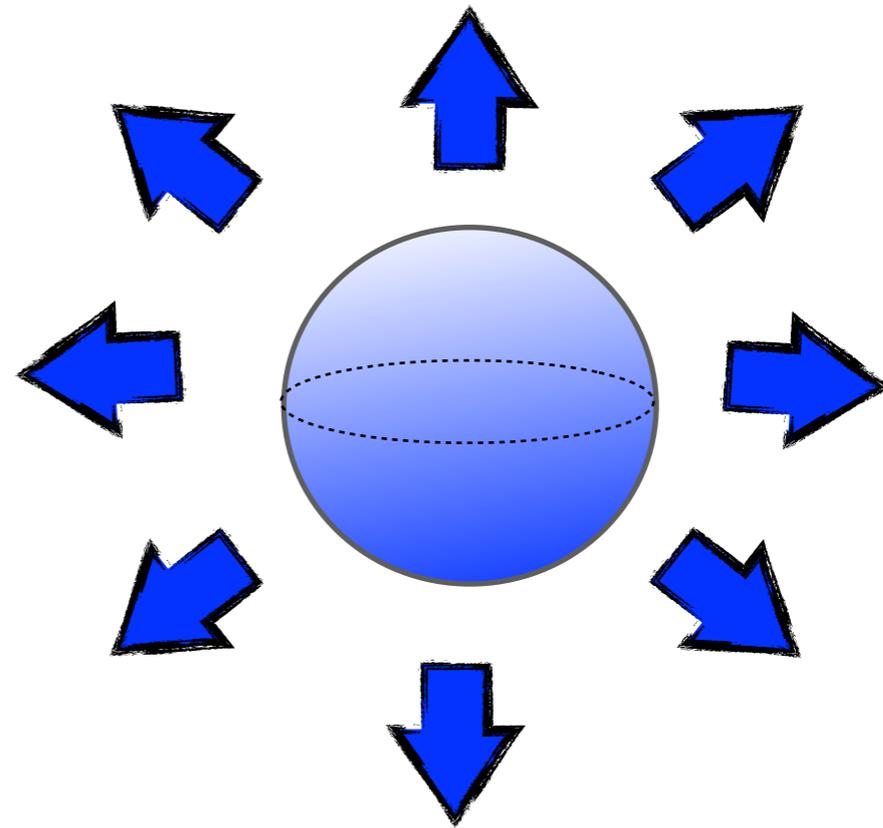
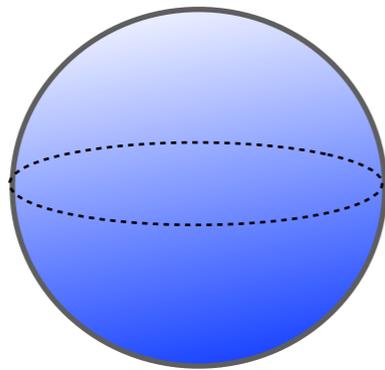
Model independent!
No assumption about RD

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?
Modeling the void ...



STATIC!!!!

DYNAMICS ?????

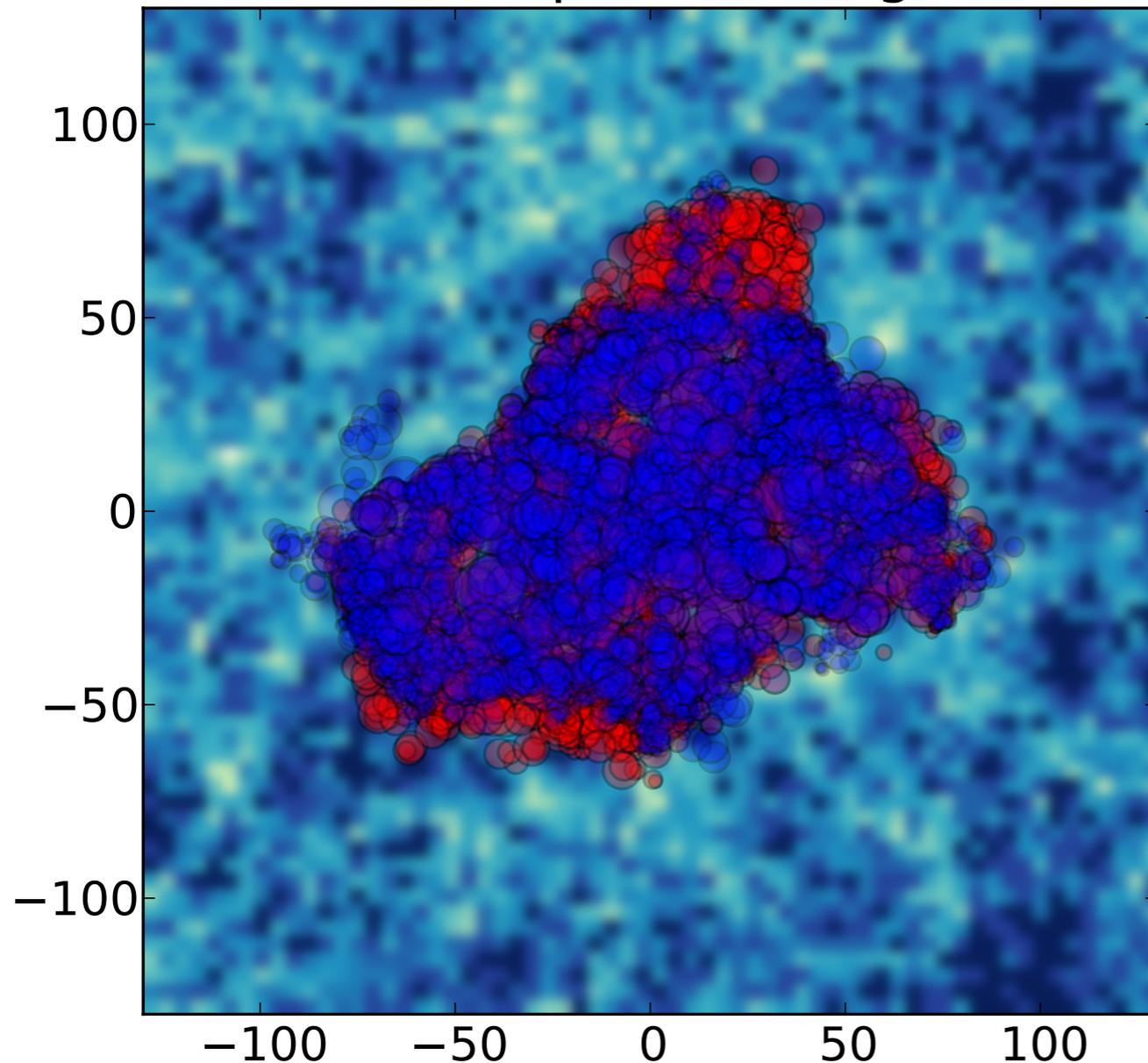
How do velocities impact the way the void
finder selects voids?



Let's give a look at voids...

HOD nopv
versus
HOD + pv

→ $54 h^{-1}$ Mpc (HOD HighRes)

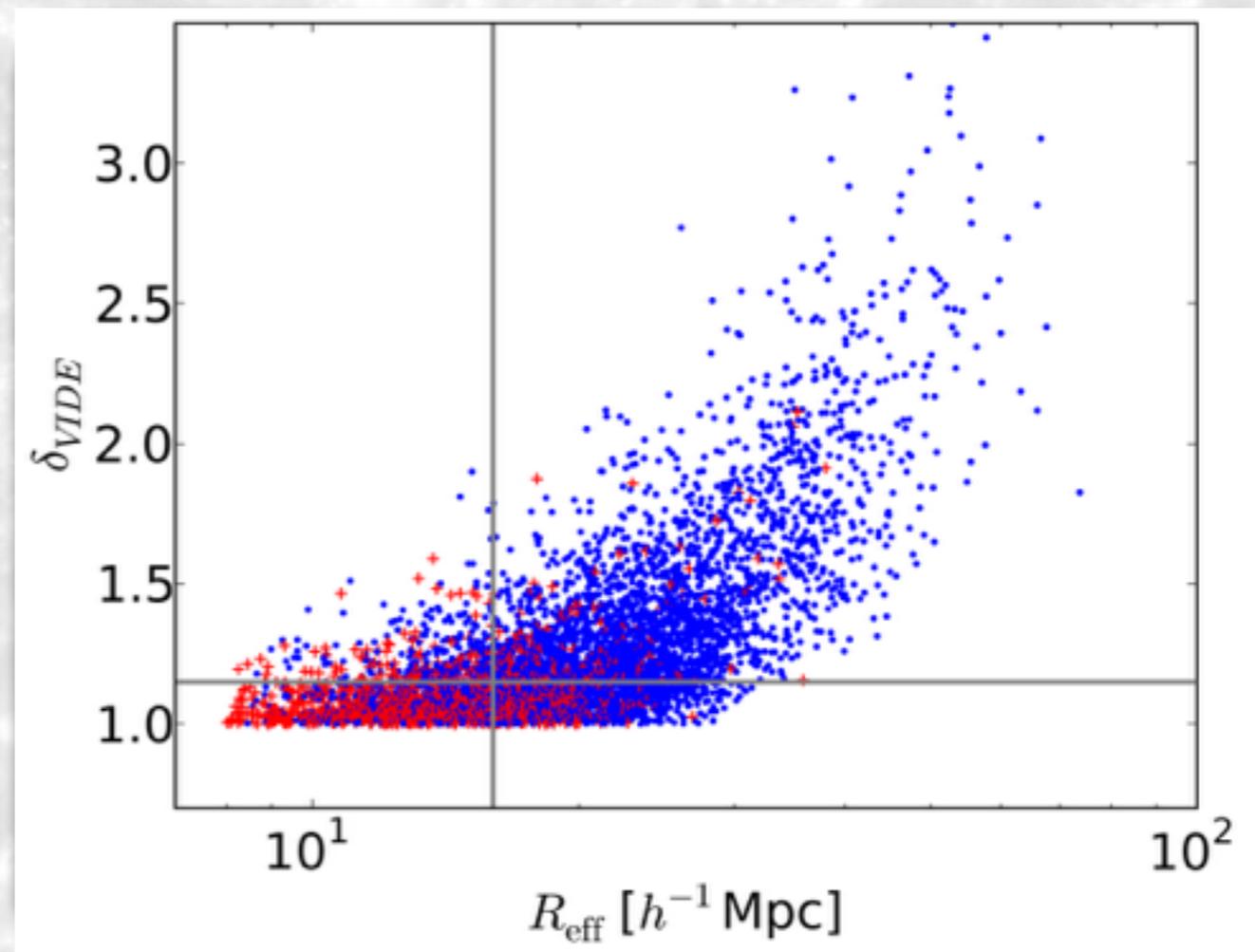
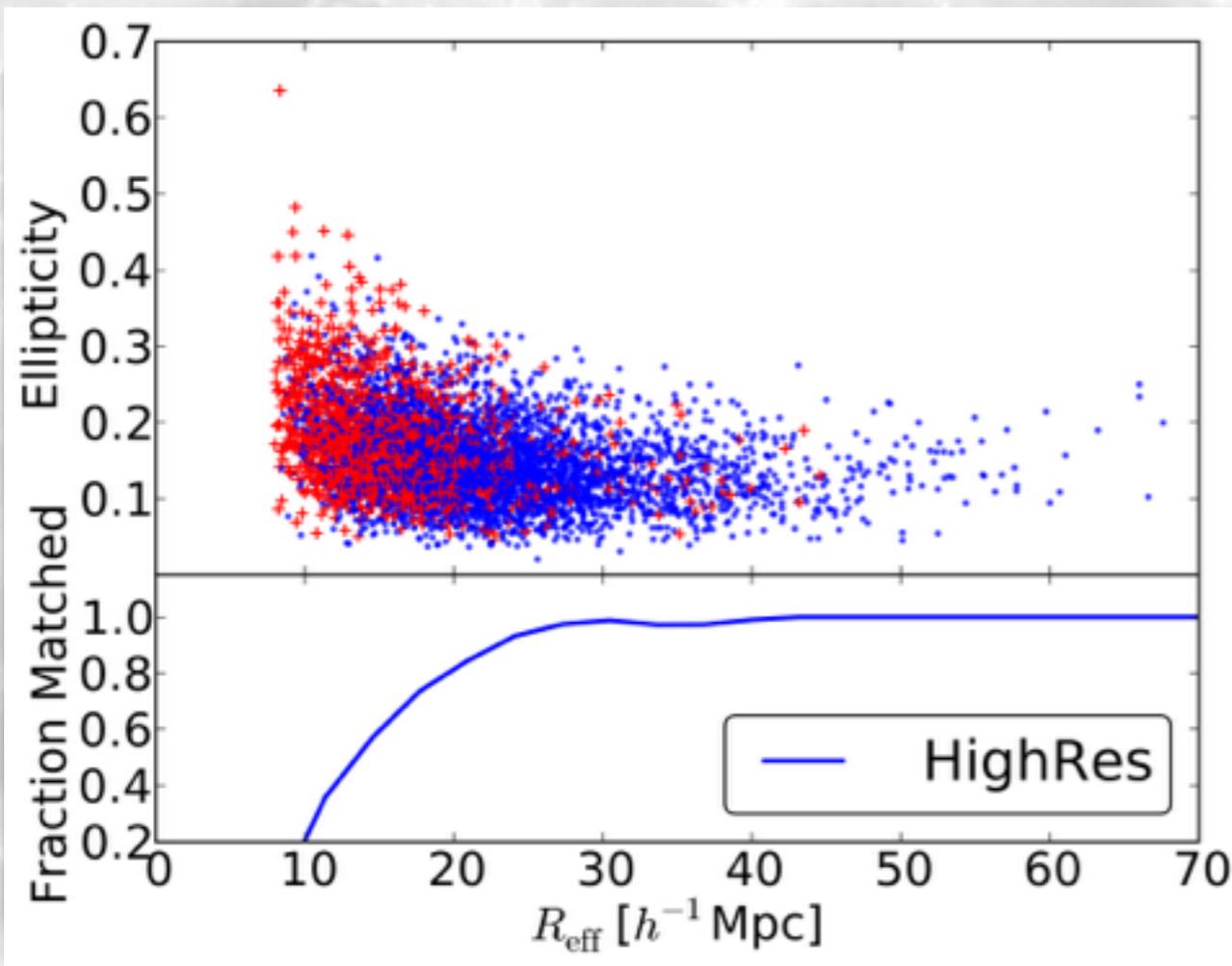


Is the cosmological signal washed out by velocities in a certain kind of voids?

Can we identify them and boost the cosmological signal?

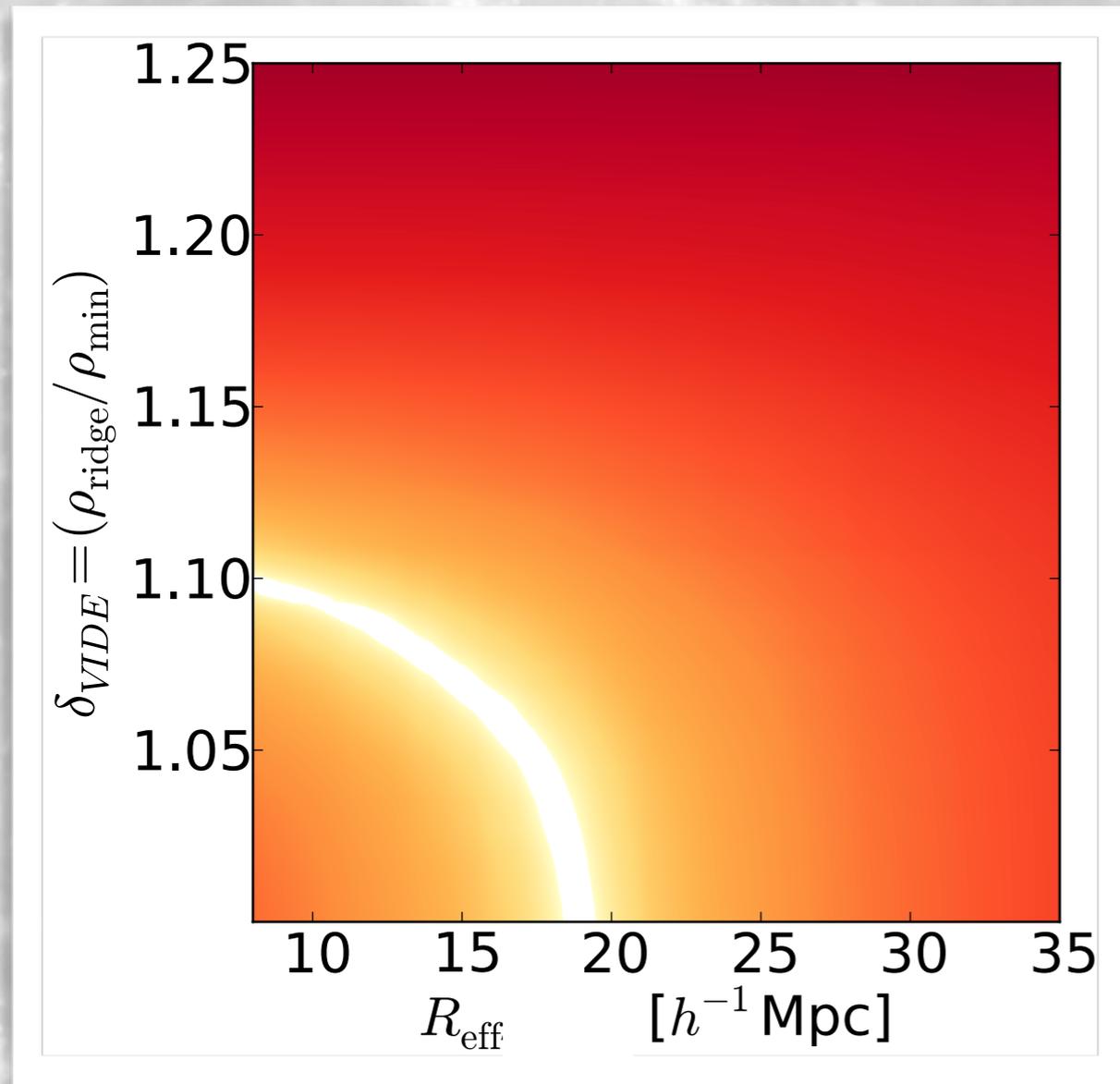
A. **Pisani**, P.M. Sutter, B. Wandelt, 2015b arXiv:1506.07982

Peculiar velocities: which voids are affected most?



Small and shallow voids are the most affected.
=> Apply cuts to boost the signal to noise for
cosmological information.

An EMPIRICAL RECIPE: optimal cuts for real surveys!



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

$$\eta = \frac{N_{\text{unmatch removed}}}{N_{\text{match kept}}}$$

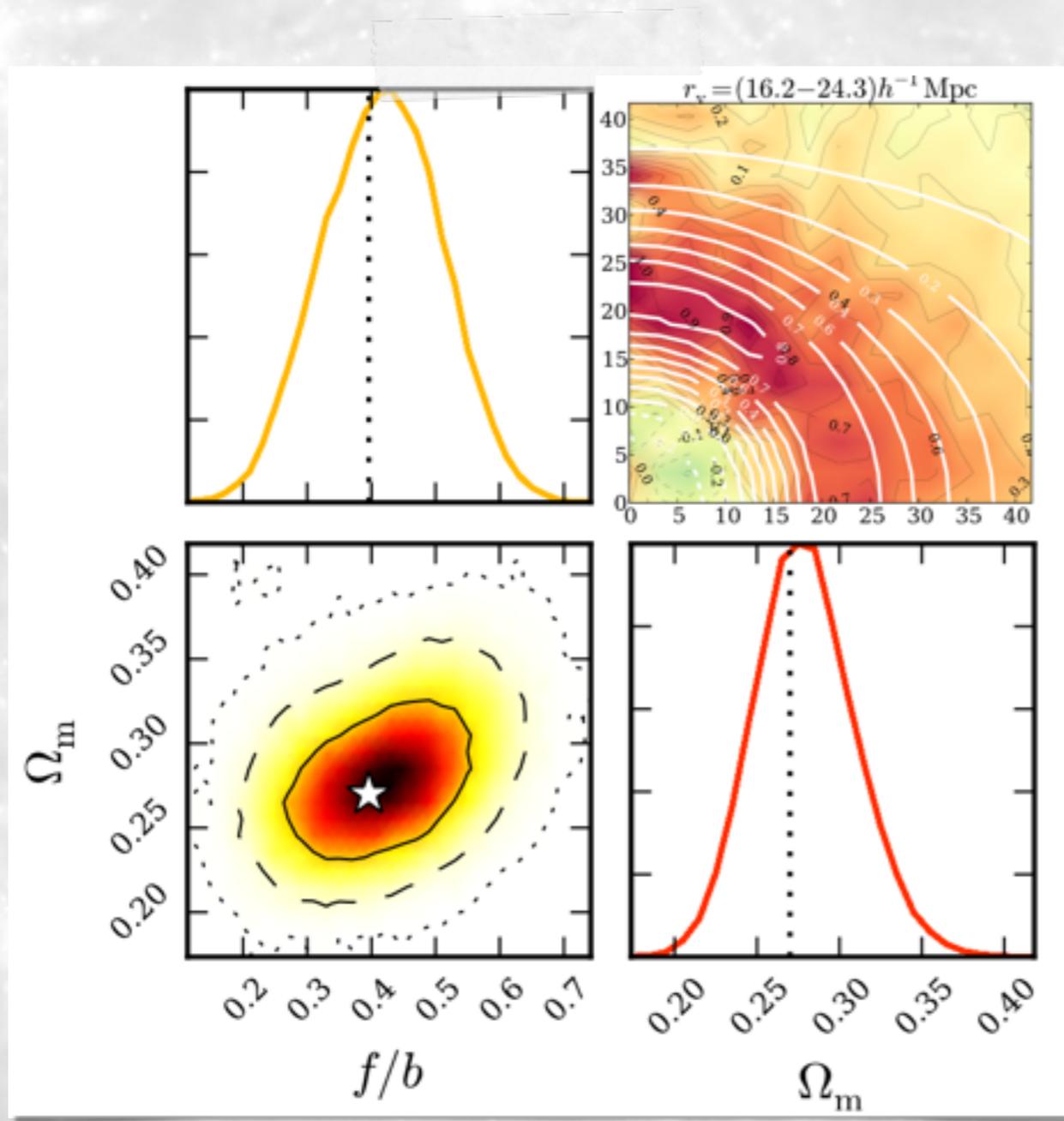
We only keep voids very mildly affected by velocities!
This correction does not need any prior knowledge!

So to deal with velocities we have an empirical recipe that looks promising.

A complementary method is to model the effect of velocities by constructing a model for the redshift space distortions.

The velocity pattern also brings information!

Linearly modeling the RSD and the void profile



=> constraints on gravity
(linear growth rate of
structures)

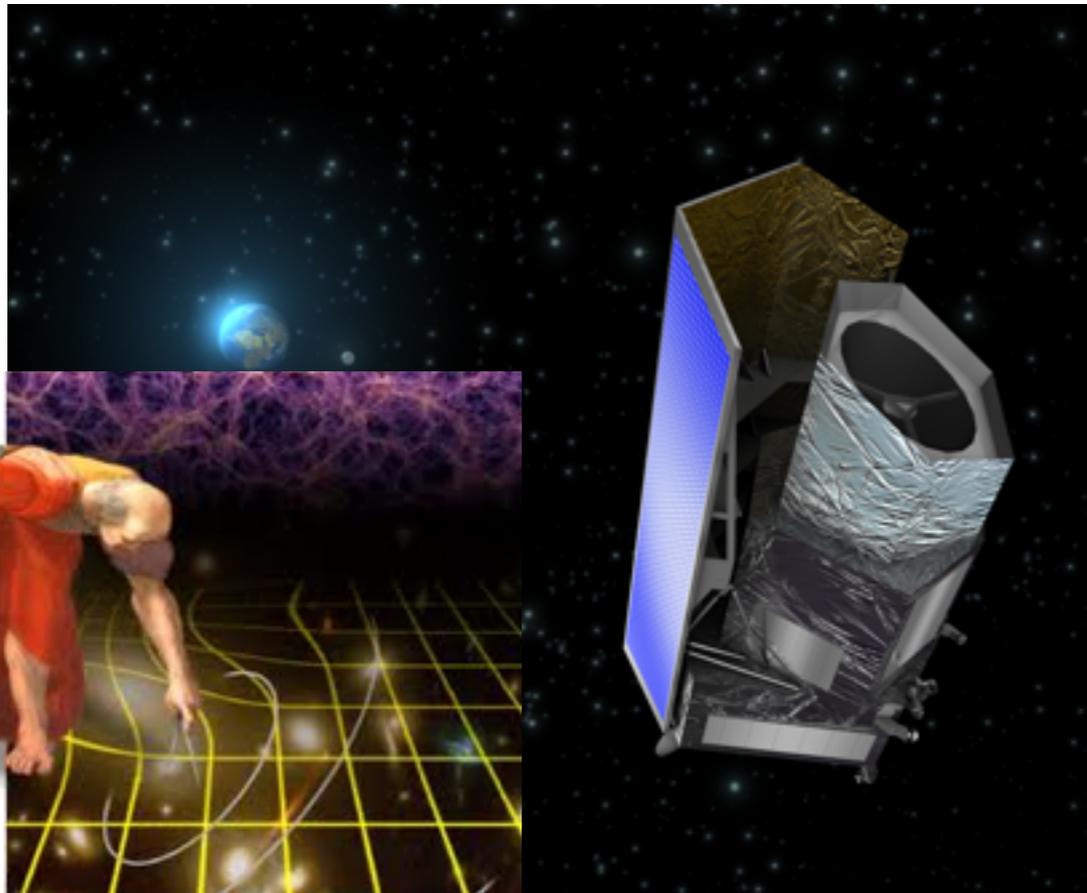
=> constraints on matter
content

We have a set of tools to beat systematics, constraints will already be improved with current data (such as eBOSS data) but ... what about increasing statistics ?

Back to the future: betting on LSS with upcoming surveys

SDSS DR7

$6.7 \cdot 10^5$ galaxies



EUCLID

$5.0 \cdot 10^7$

WFIRST

$2.0 \cdot 10^7$



Density profiles of
increased precision + a
huge statistic for AP test

How many voids?

Theory

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

Simulation

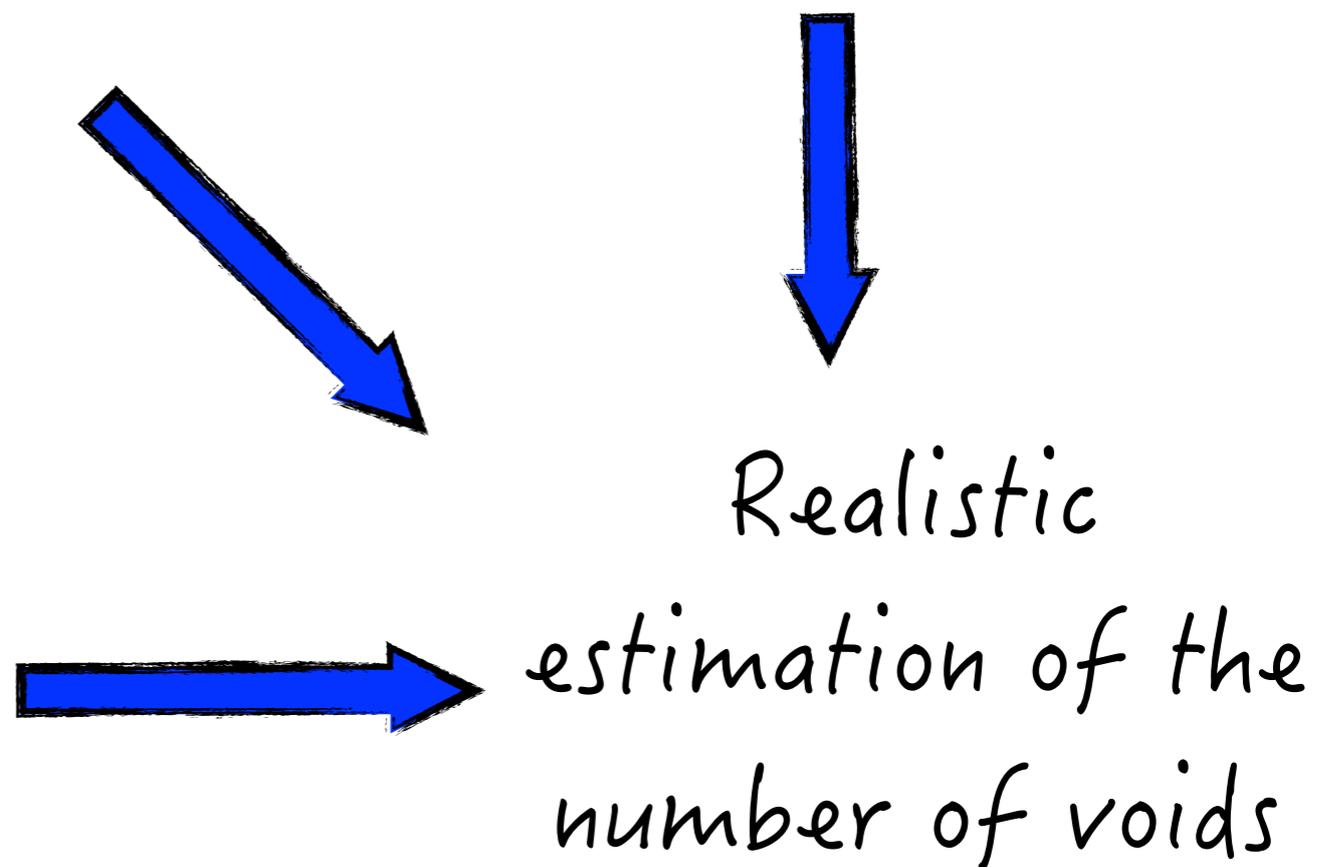
Tuned on the survey to obtain
the parameter of the model
and marginalise on parameter

+

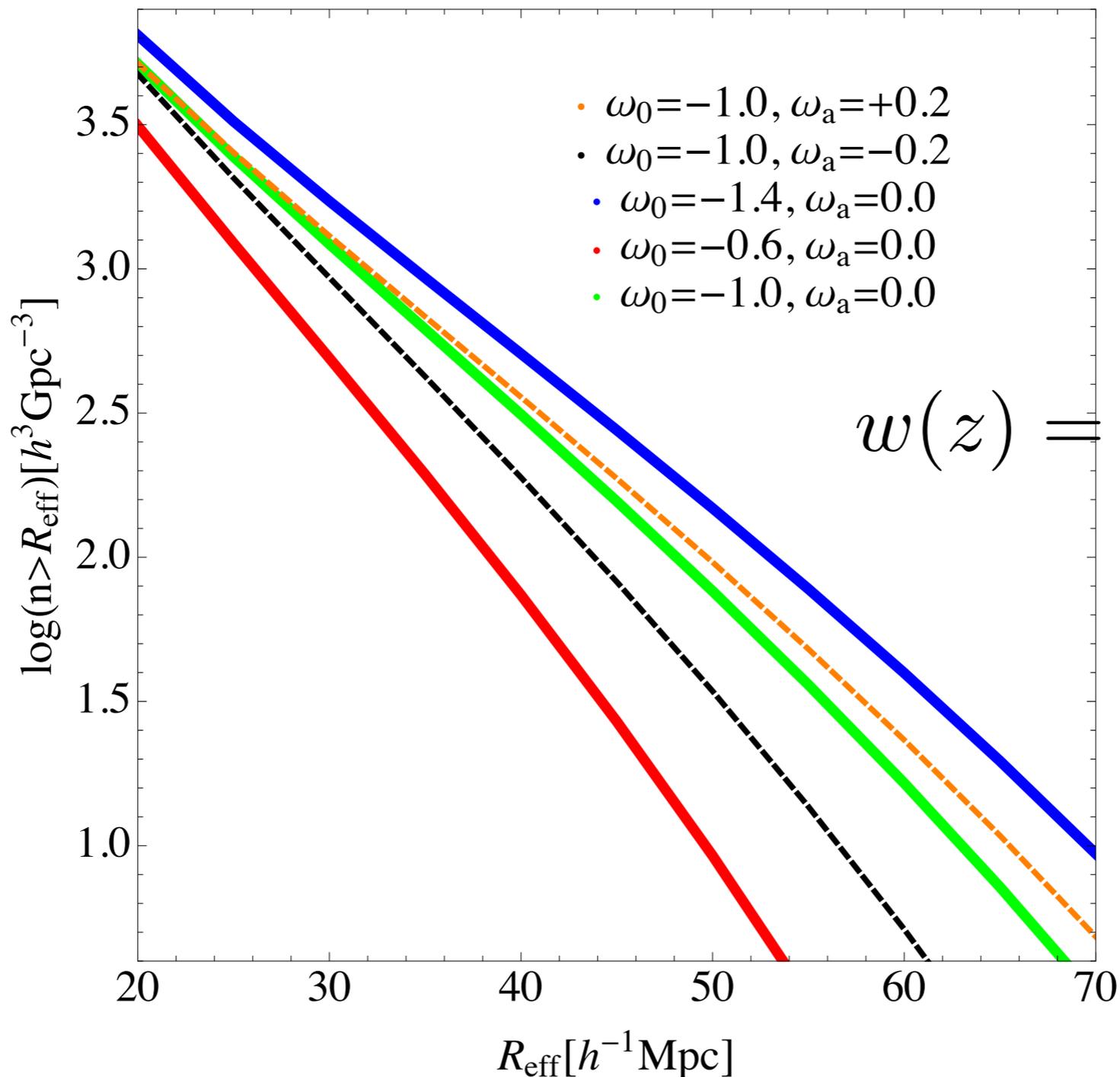
+

Survey

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



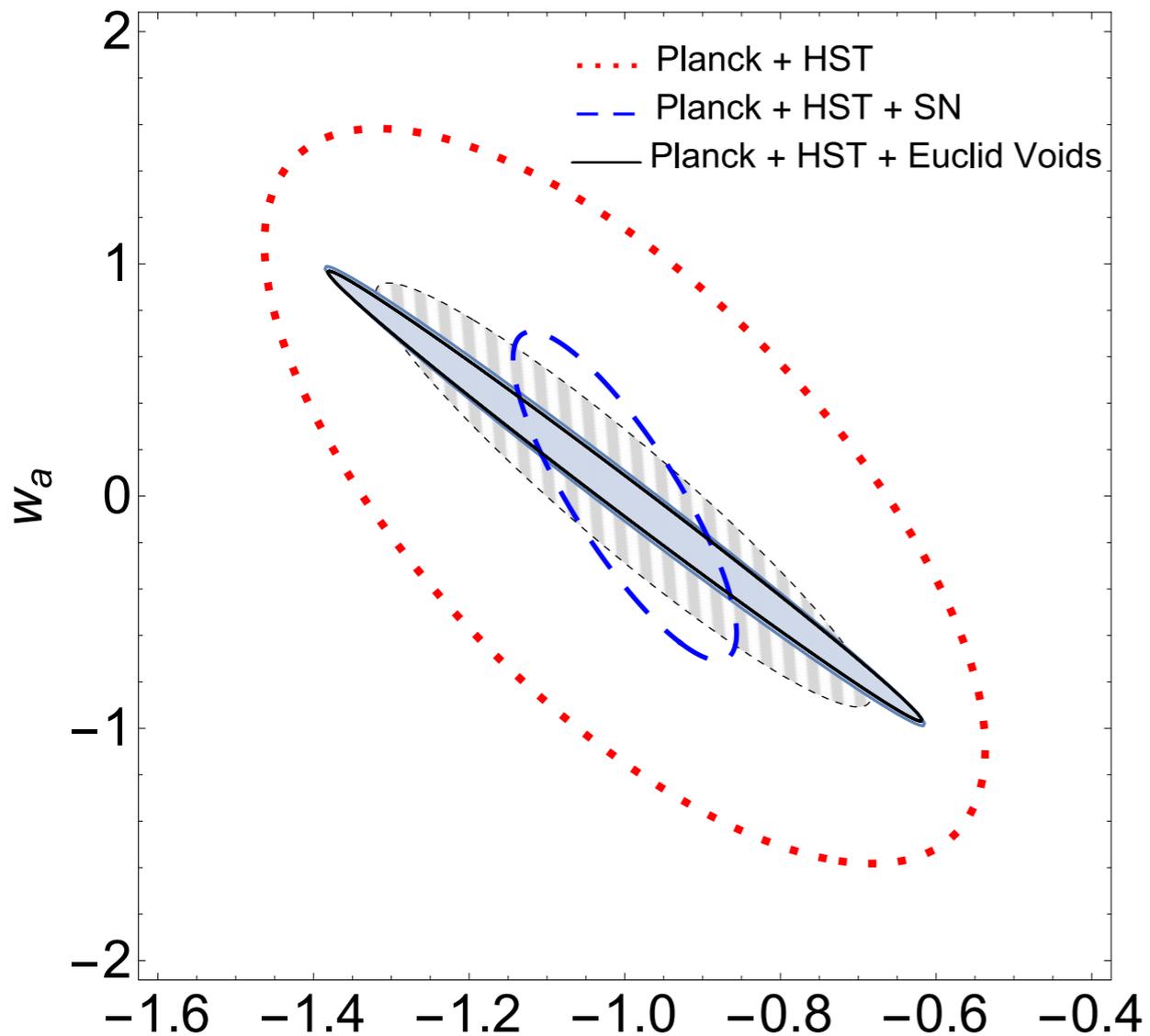
Void abundance to constrain DE



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

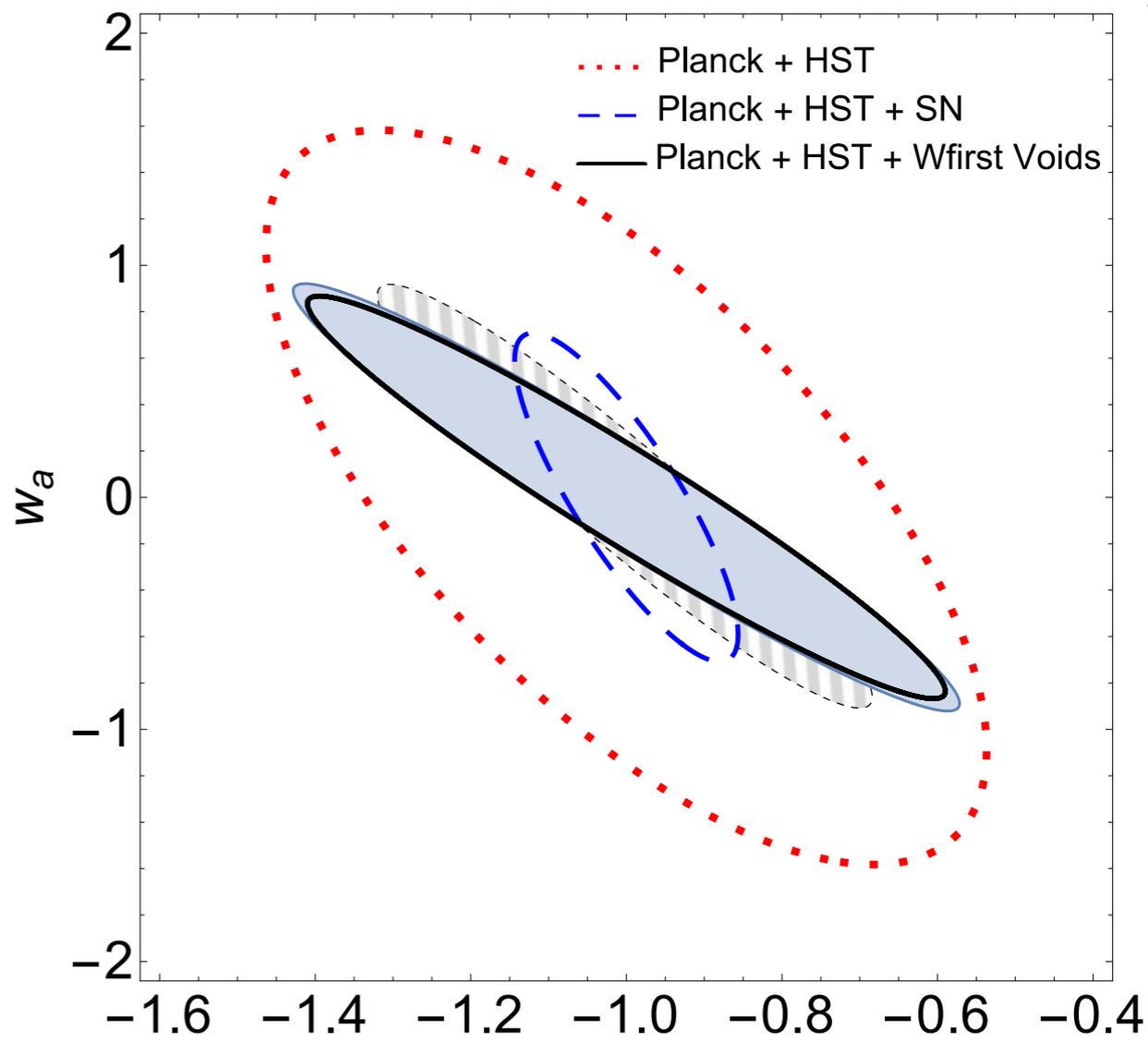
Comparing future surveys:

D - I - L - C - U - E



7.8×10^5

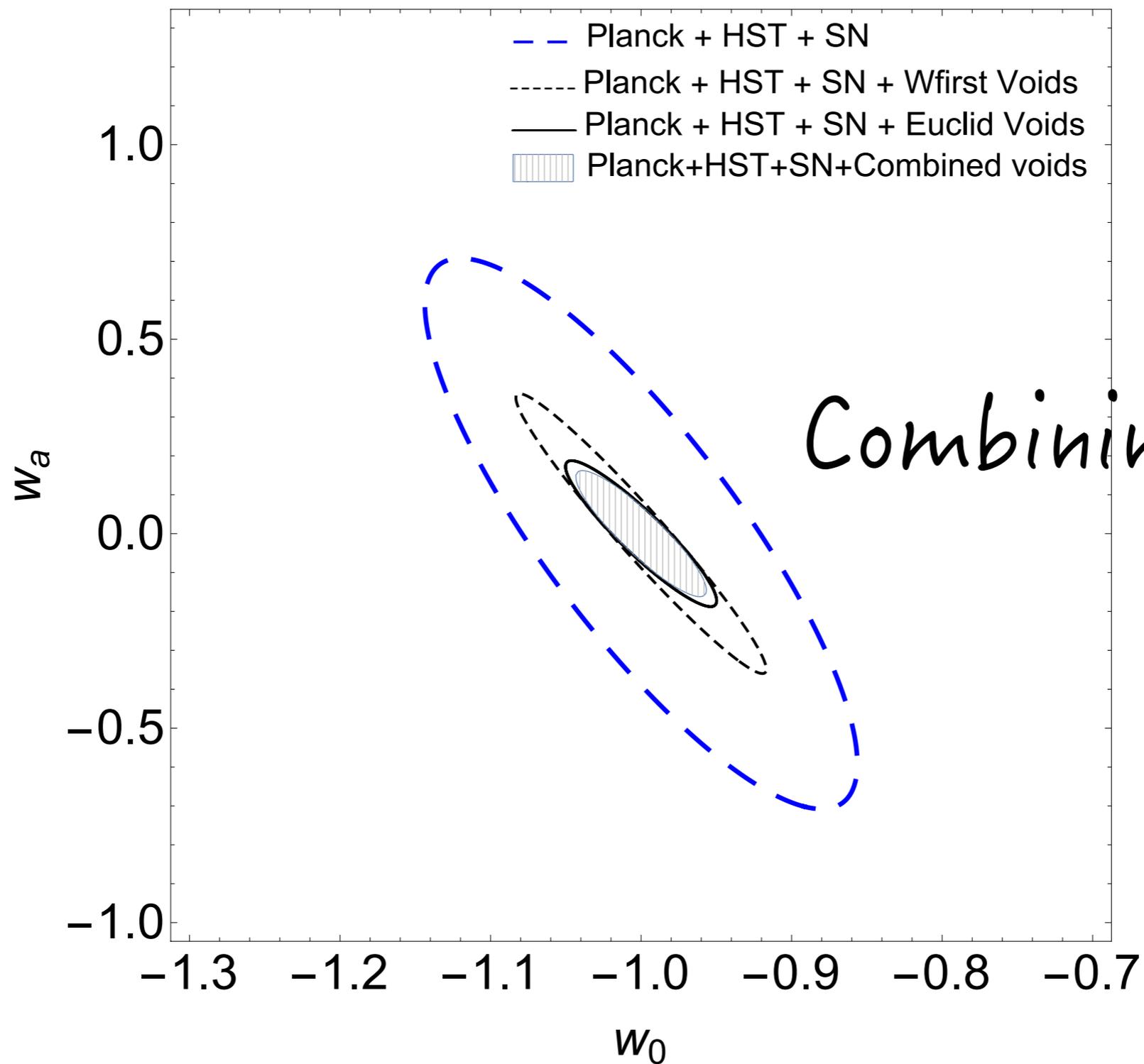
W - F - I - R - S - T



2.5×10^5

Abundance, density profiles of increased precision & a huge statistic for AP test

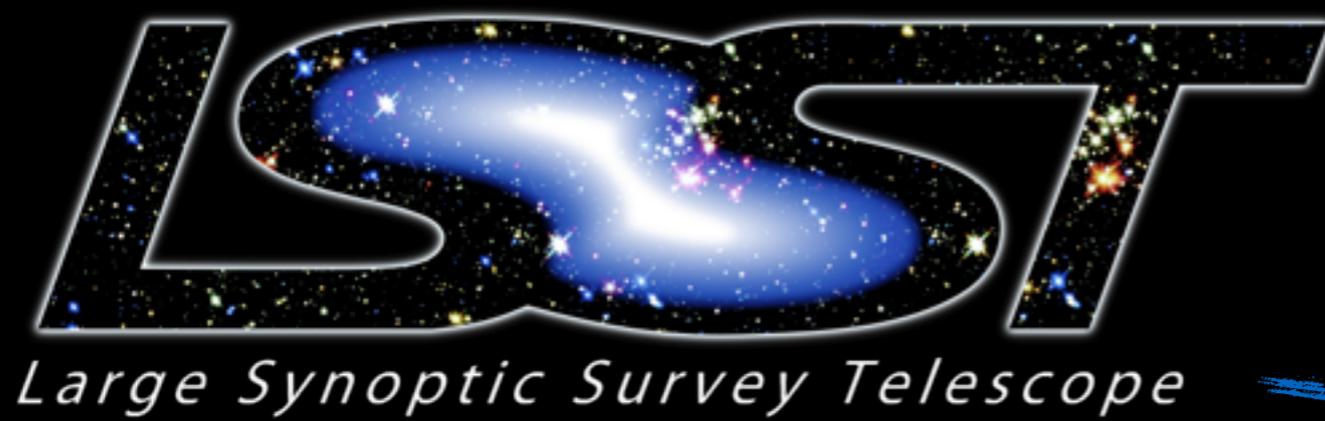
Combining future surveys:



Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata — **Phys. Rev. D 2015**, arXiv:1503.07690

So far we focused on spectroscopic surveys, but voids can be found also in photometric samples (see e.g. 1605.03982, DES collaboration)

Until now, using void finding algorithms with spherical assumption. Can we use algorithms with precise shape detection?



Voids from LSST, a tempting challenge!

void lensing
optimal to
constrain modified
gravity models

void counts
particularly sensitive
to dark energy
(+combine with
clusters)

void shape? using
simulations to assess power

voids have amazing
combining power with SN

scan the hierarchical
structure of voids at
a different level

Voids from photometric surveys promise to unlock enhanced constraints

Precision

Cosmology with Cosmic Voids

- ▶ find voids on data and use them for cosmology (AP test, void abundance)
- ▶ void science already provides tight constraints !
- ▶ voids in photometric surveys such as LSST are promising !
(abundance, lensing, combine with LSST leader topics such as SN, clusters)

Thank you!