CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

OCEVU

Cosmology with Cosmic Voids

Physics for both infinities :
L'École d'été France Excellence 2017

Alice Pisani (CPPM)

18/07/2017
Marseille

Credit: Millennium simulation

Summary

- Extremely short cosmology reminder
- Voids, a tool for cosmology
- Finding voids
- The shape of voids
- Constraining General Relativity
- Count to understand Dark Energy

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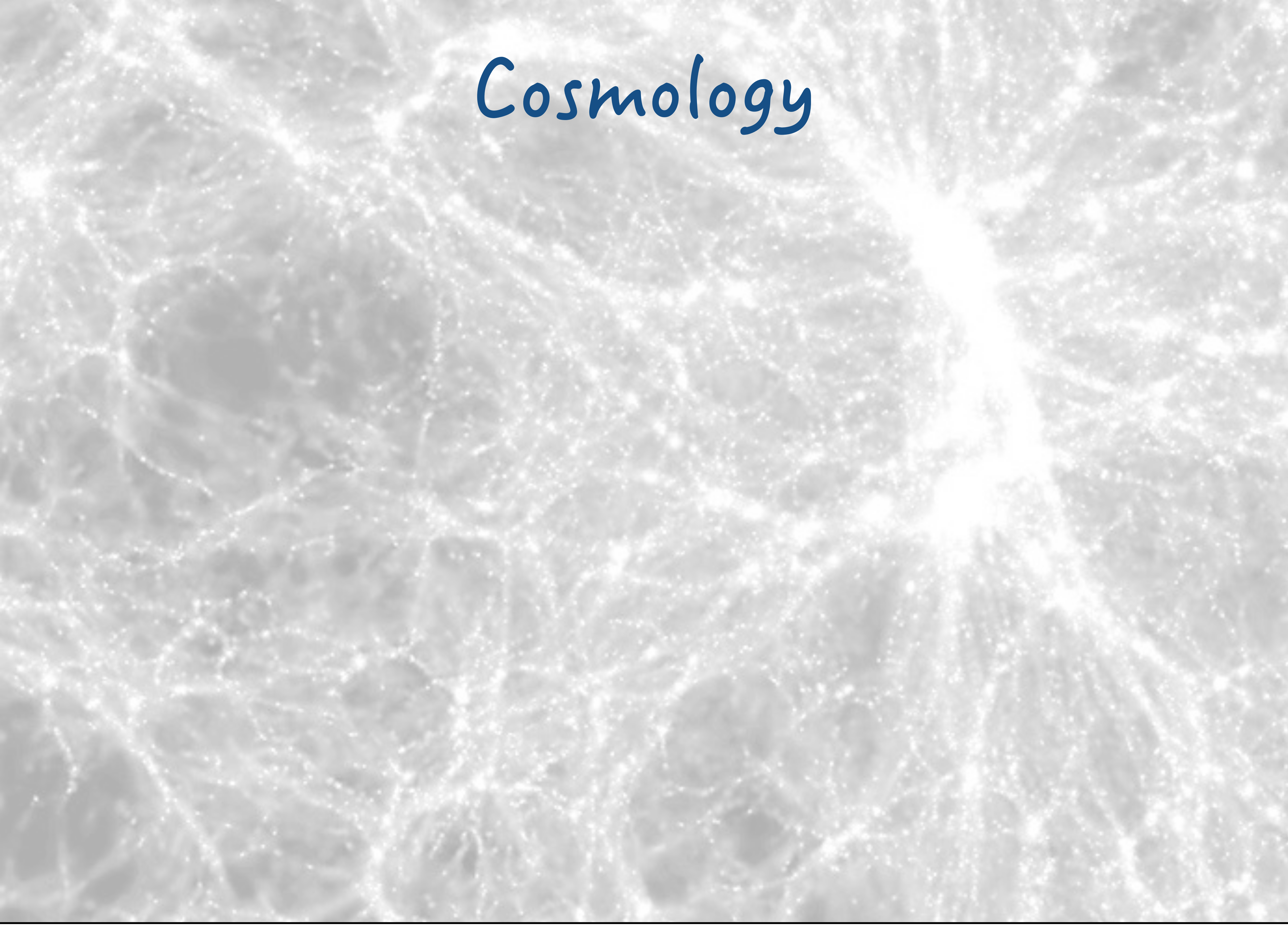
Cosmology



Cosmology

is the science that studies our Universe as a whole.

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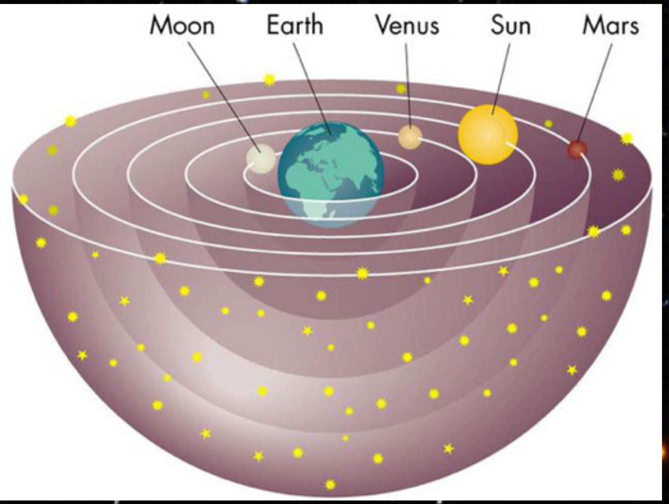
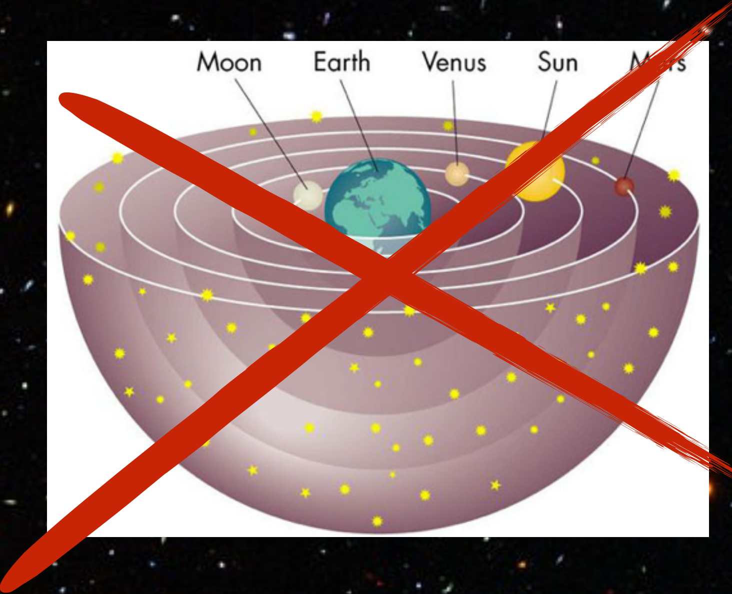
So, what do we know about the Universe?

Lessons from the past: our position is not privileged



Lessons from the past: our position is <u>not</u> privileged



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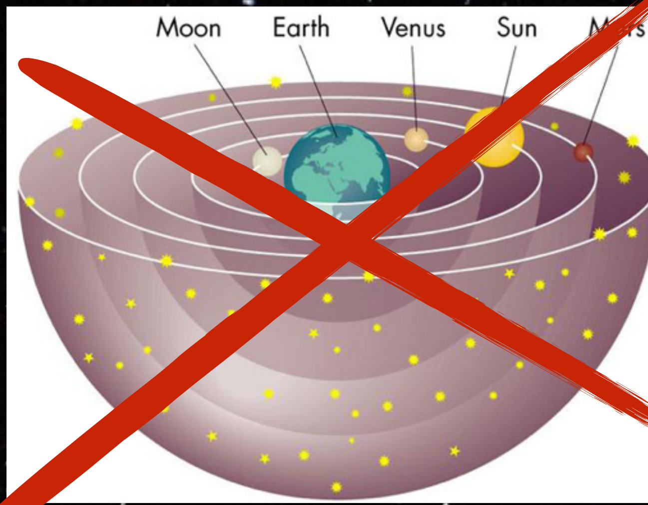
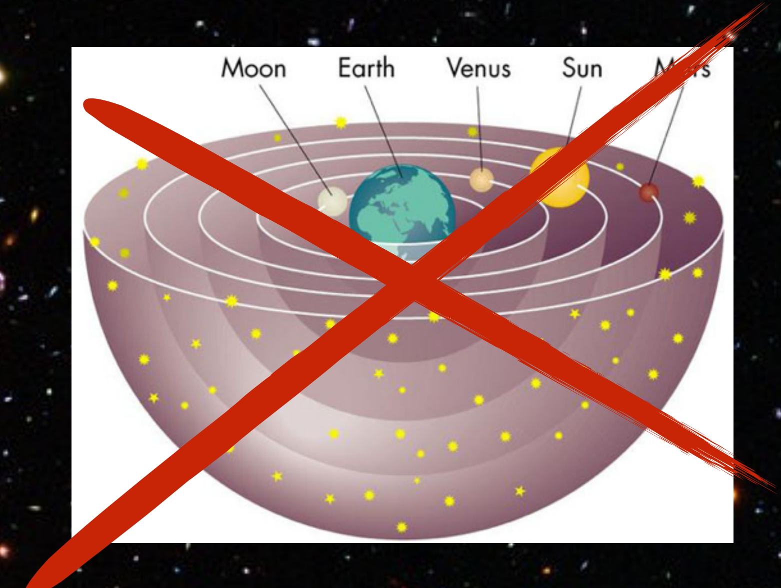


Homogeneity and Isotropy

The same everywhere

The same in every direction

Lessons from the past:
our position is not privileged



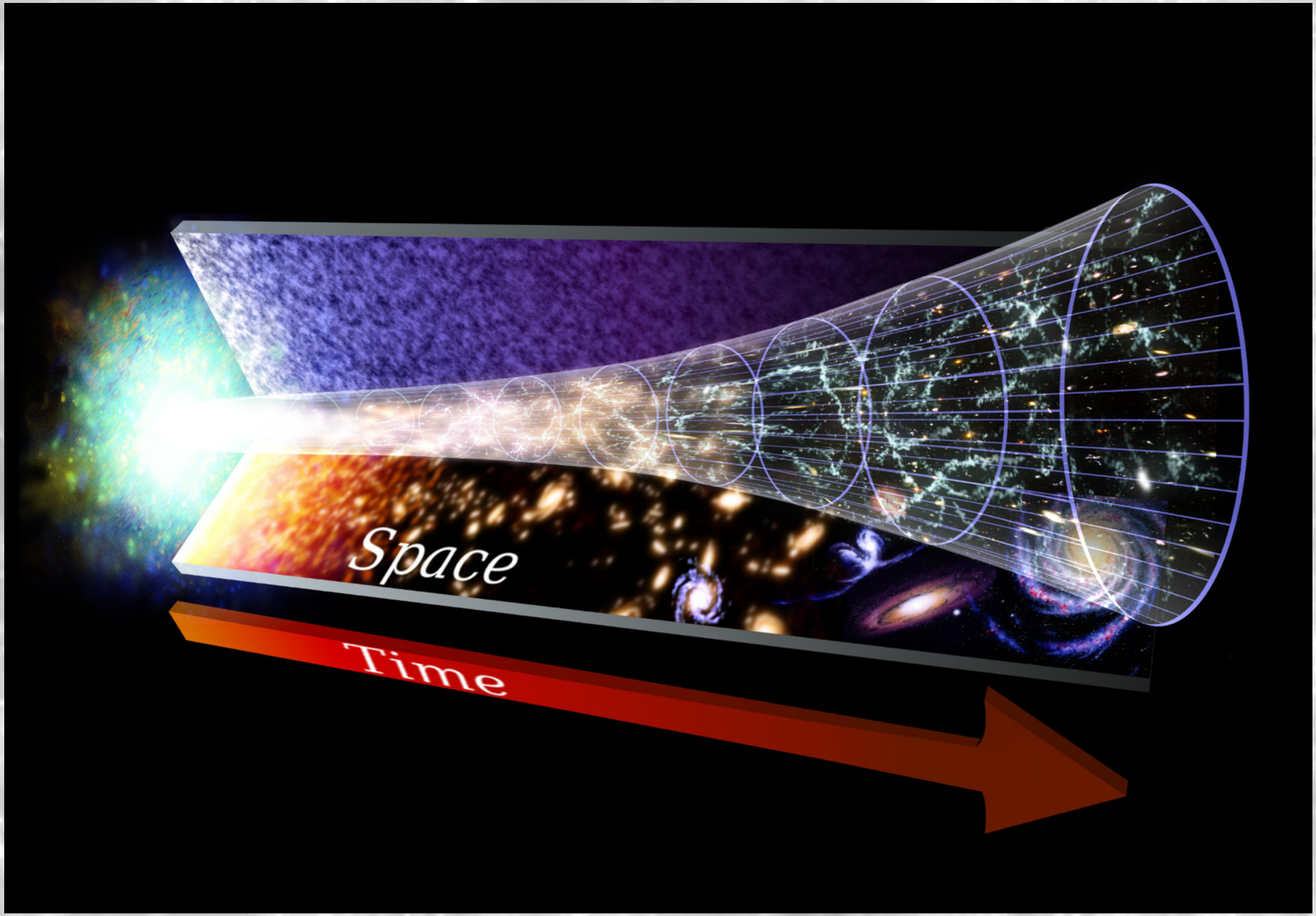
Homogeneity and Isotropy

The same everywhere

The same in every direction

The cosmological principle

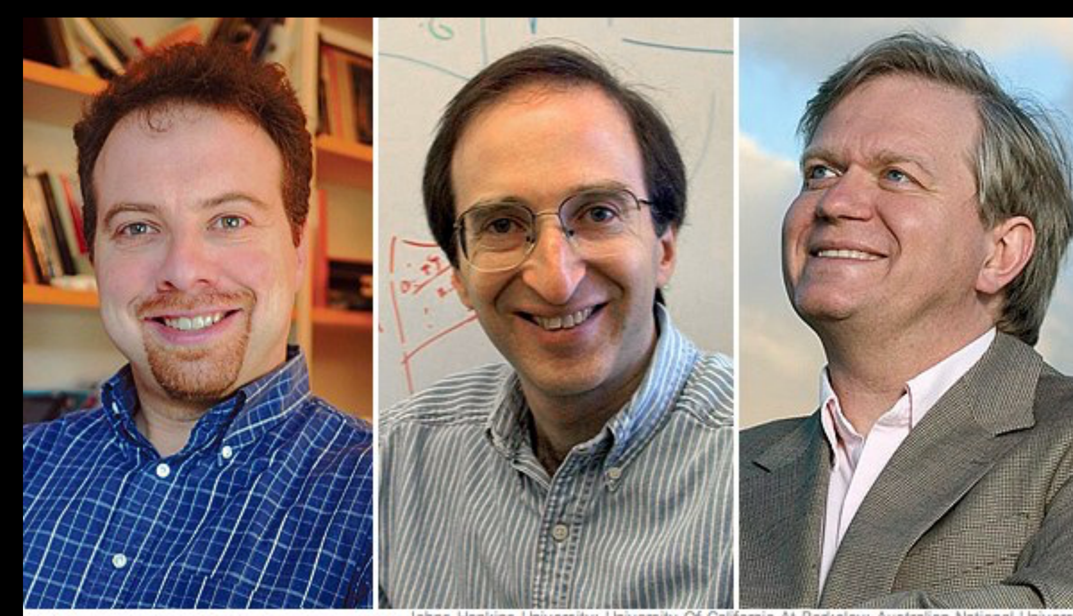
The Universe is expanding



Lemaître, Slipher, Hubble

…at an accelerated rate!

Standard candels
Type Ia Supernovae



From left, Adam Riess, Saul Perlmutter and Brian Schmidt shared the Nobel Prize in physics awarded Tuesday.

The standard cosmological model

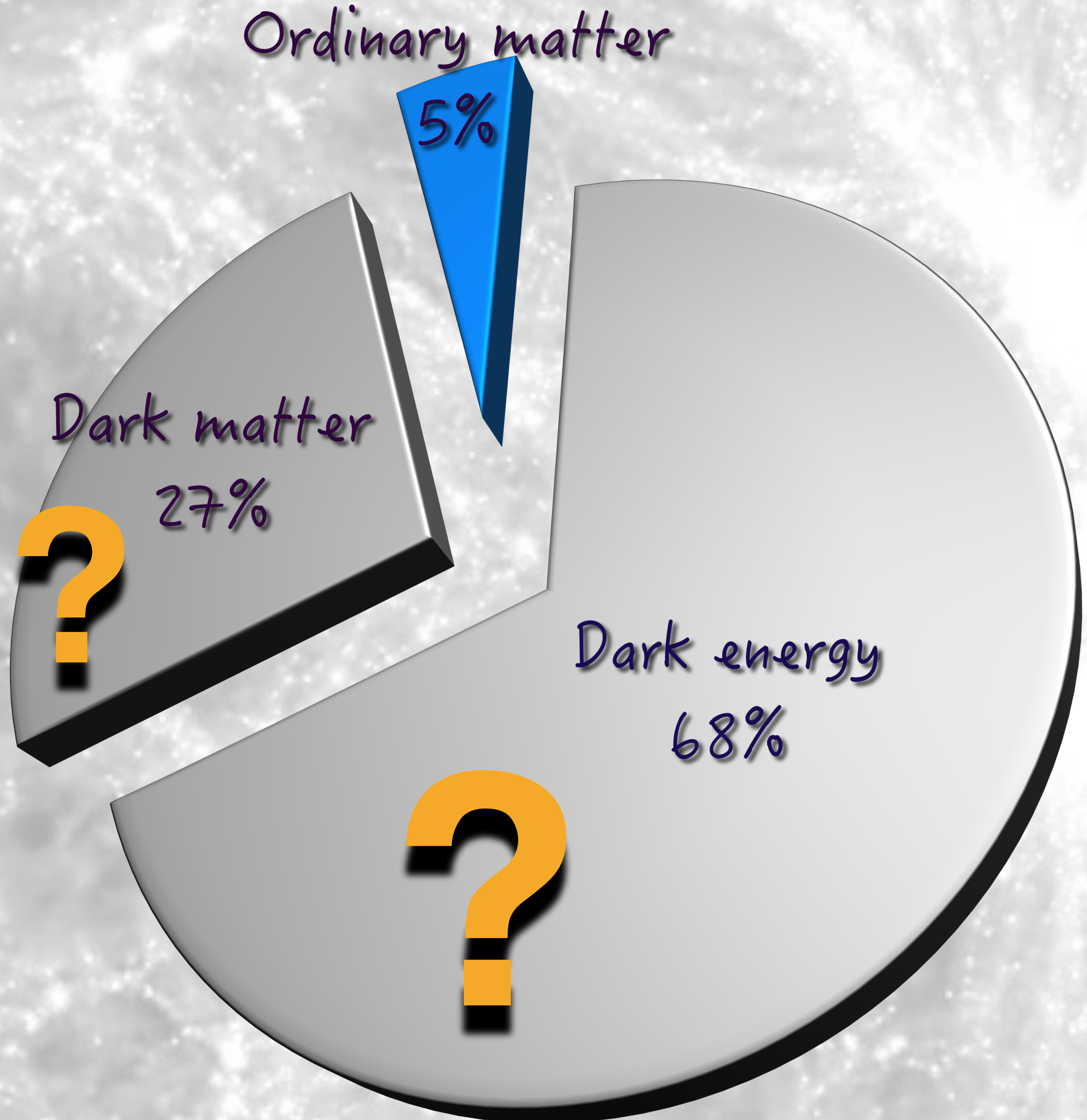
1) Cosmological principle

2) General relativity is the correct theory of gravity on cosmological scales

3) The universe is expanding at an accelerated rate

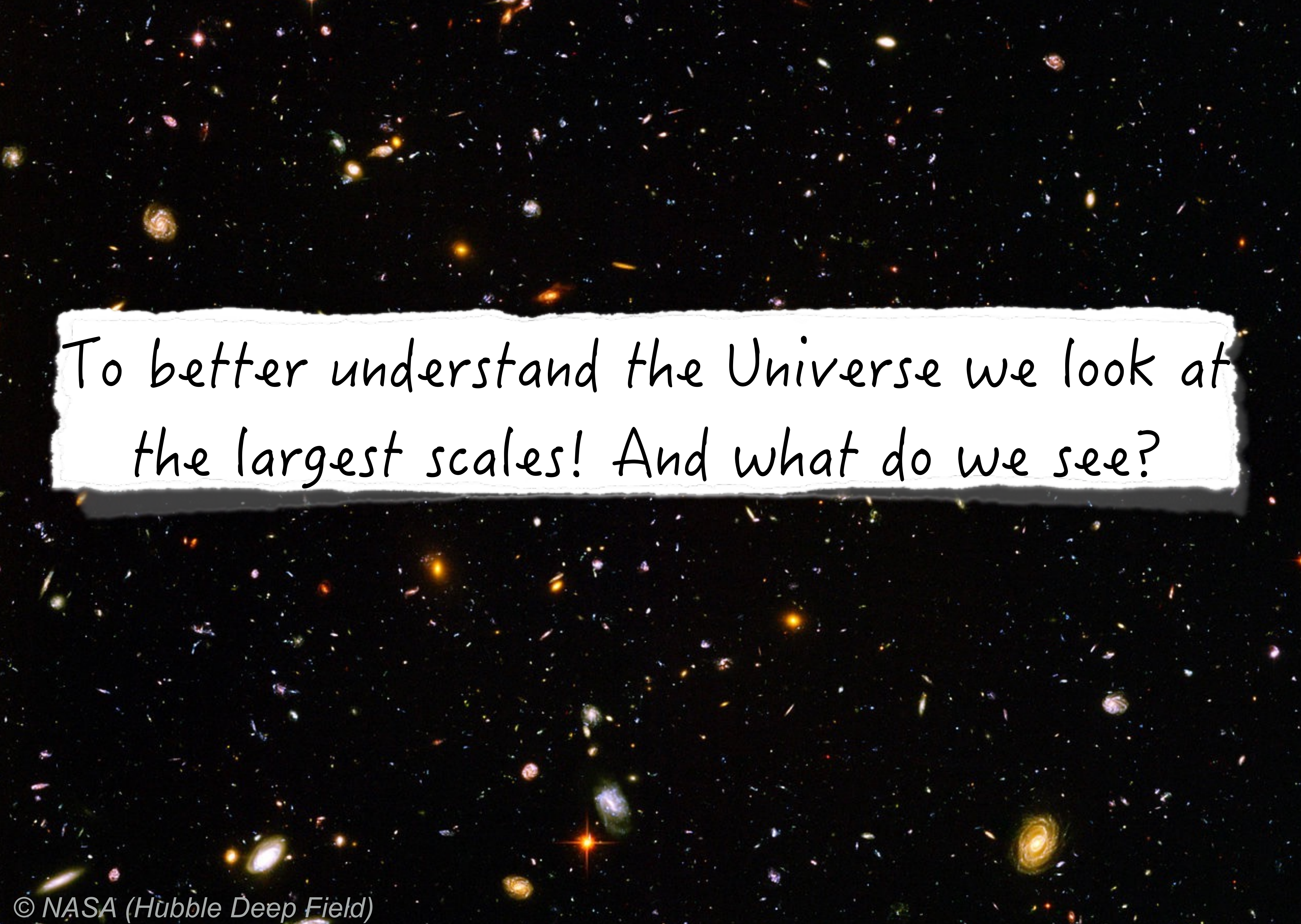
ΛCDM

Great, we know have our standard model for cosmology !! But to explain the acceleration of the expansion we need · · ·



Most of the Universe is unknown !

To better understand the Universe we look at the largest scales! And what do we see?



© NASA (Hubble Deep Field)

The Universe at Large Scale

Mapping the large scales is a recent possibility

1977

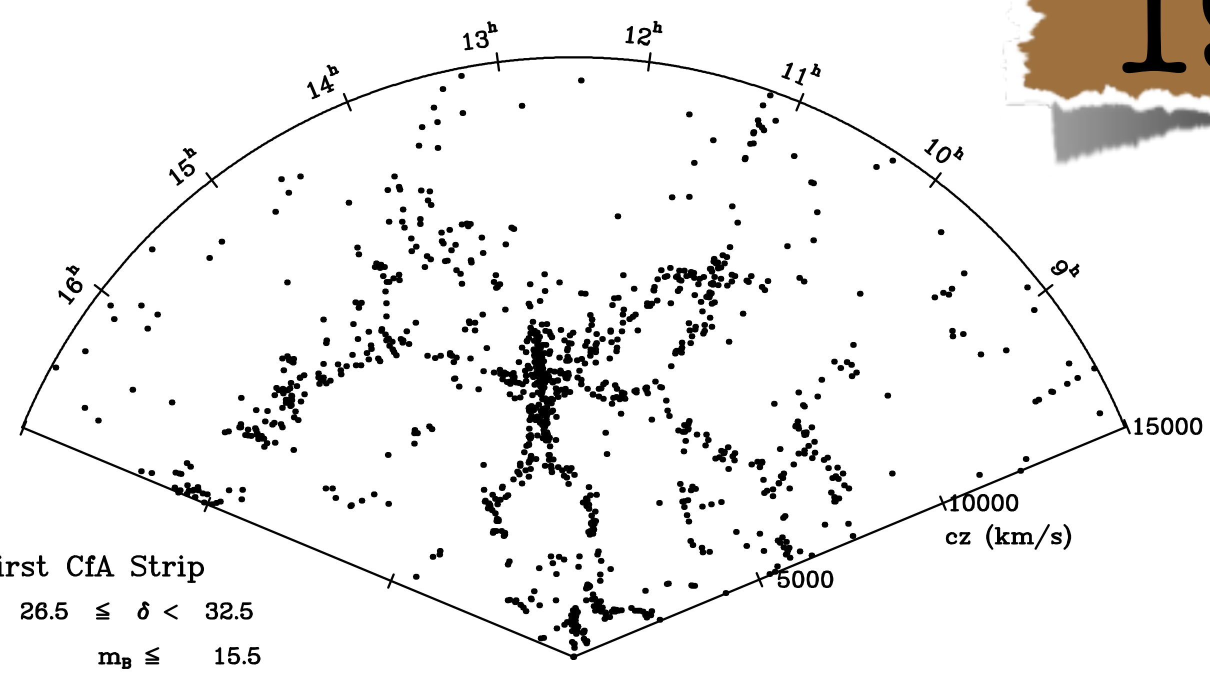
Credit: Thompson and Gregory 1977

Peebles Abell Longair Einasto

Are voids there?

A first look to the cosmic web

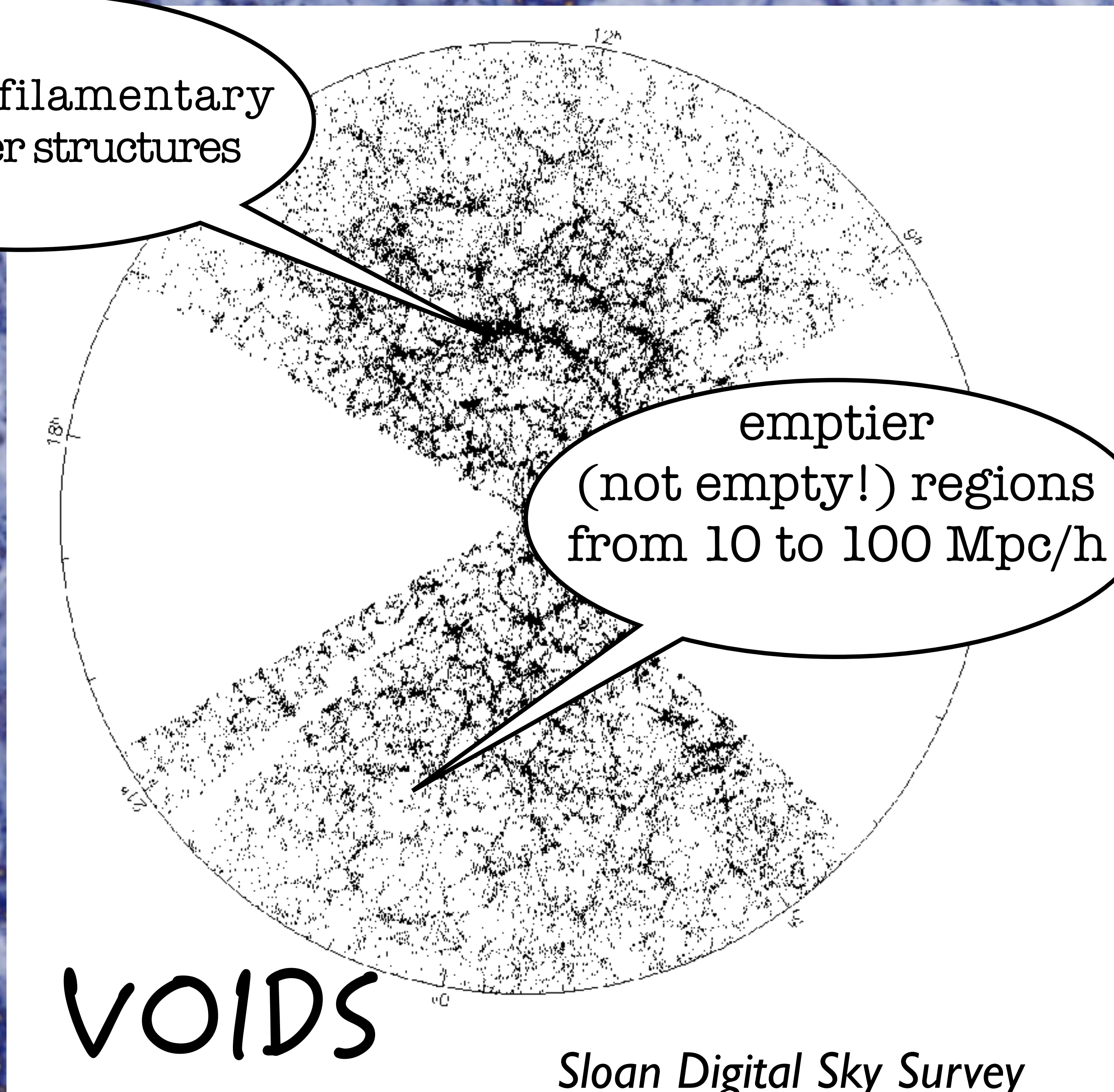
1986



Credit: de Lapparent et al. 1986

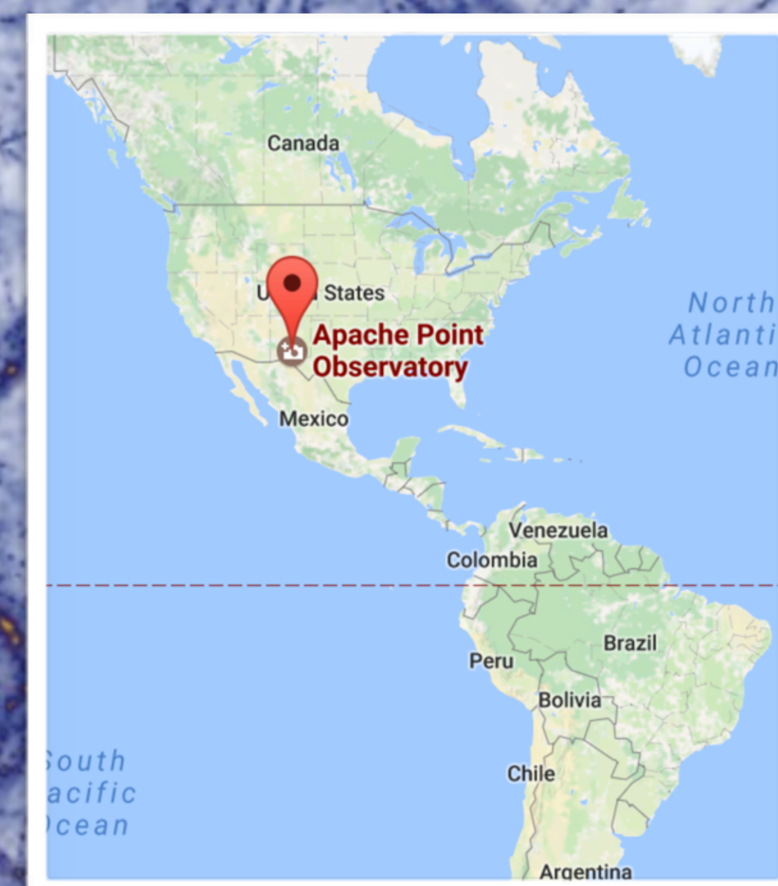
Yes, voids do exist!

The cosmic web



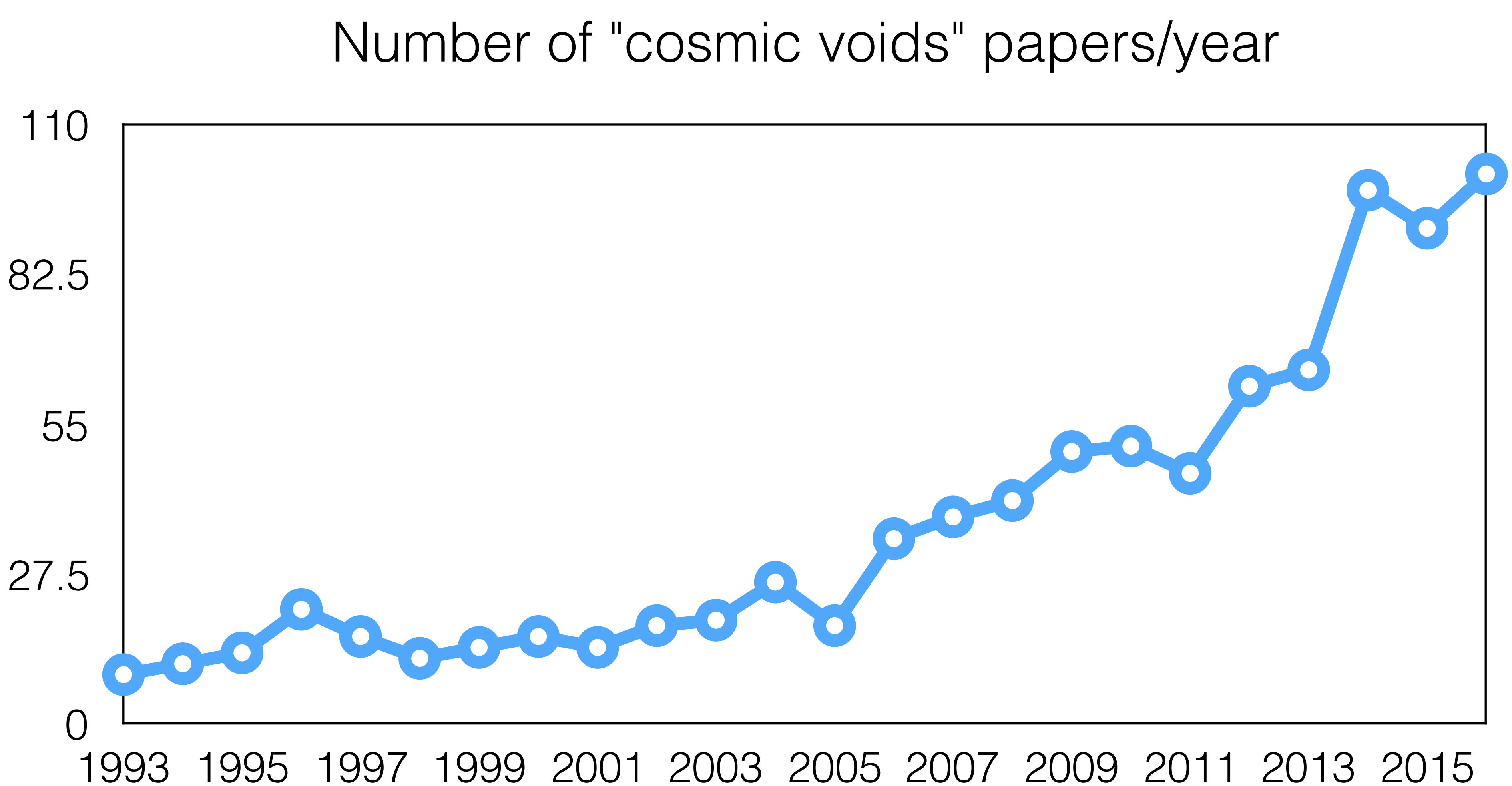
complex filamentary supercluster structures

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



A recent field of Cosmology

- needs large volumes
- huge development in recent years



Source ADS – just to have an idea

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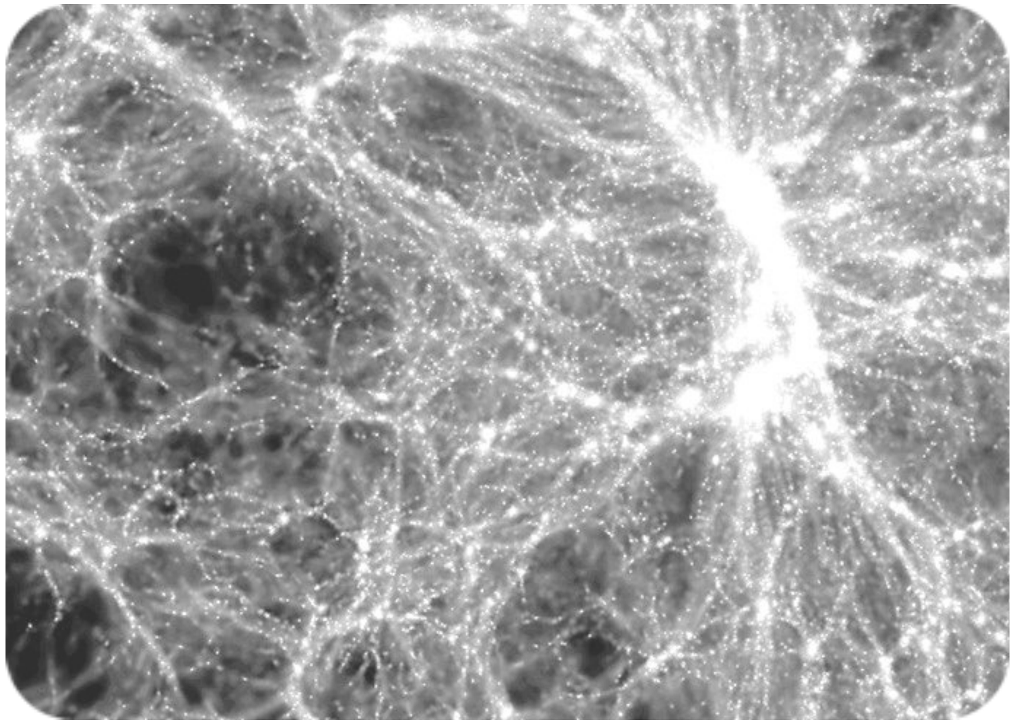
Can we use cosmic voids to get cosmological information?

Voids to understand Dark Energy

Voids are emptier by definition



Because there is few matter we can expect to have information on dark energy

If dark energy exists it will rule the evolution of voids and their properties.

If dark energy does not exist ?

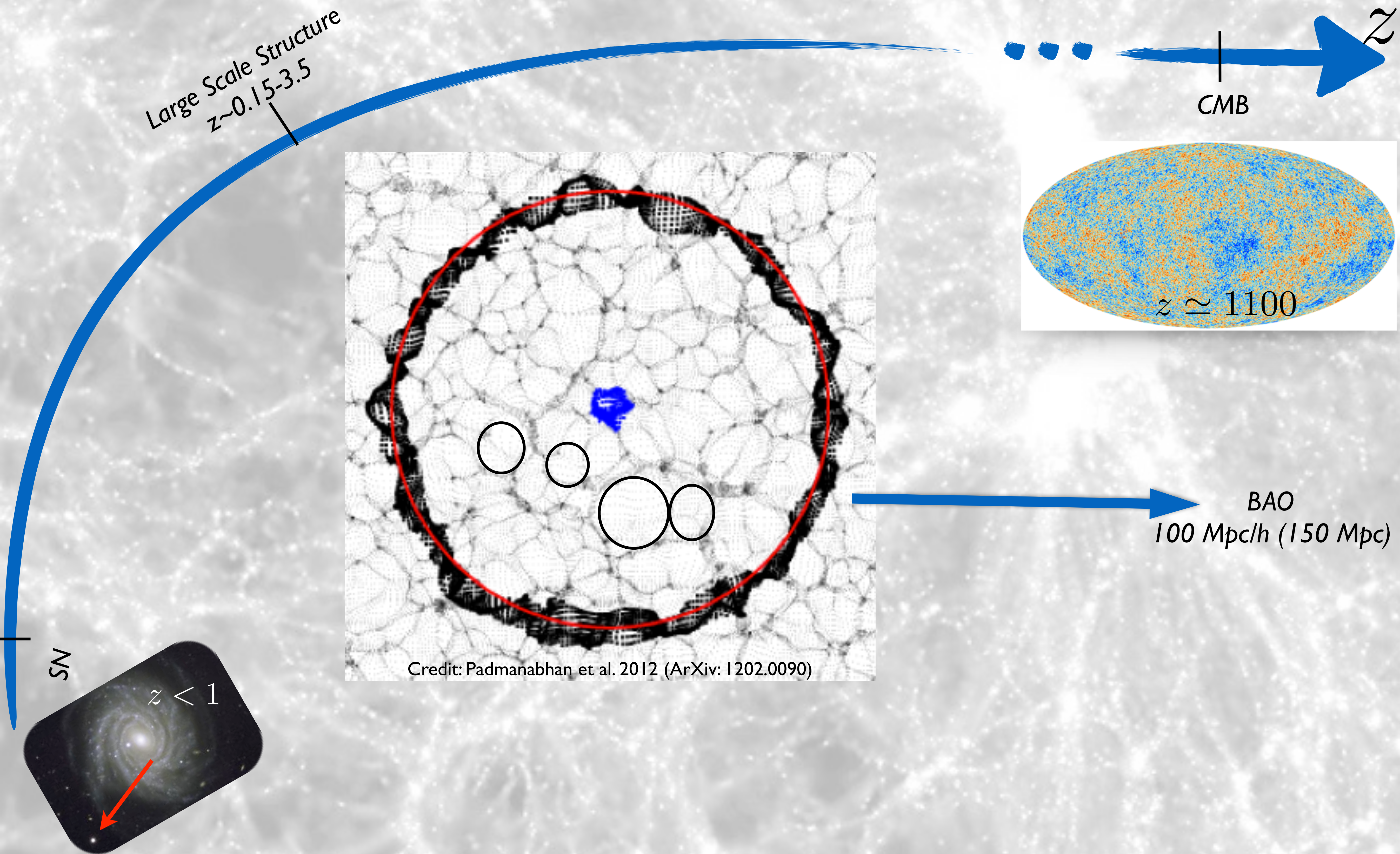
We need another way to explain the accelerated expansion of the Universe.

One possibility is to modify General Relativity at large scales.

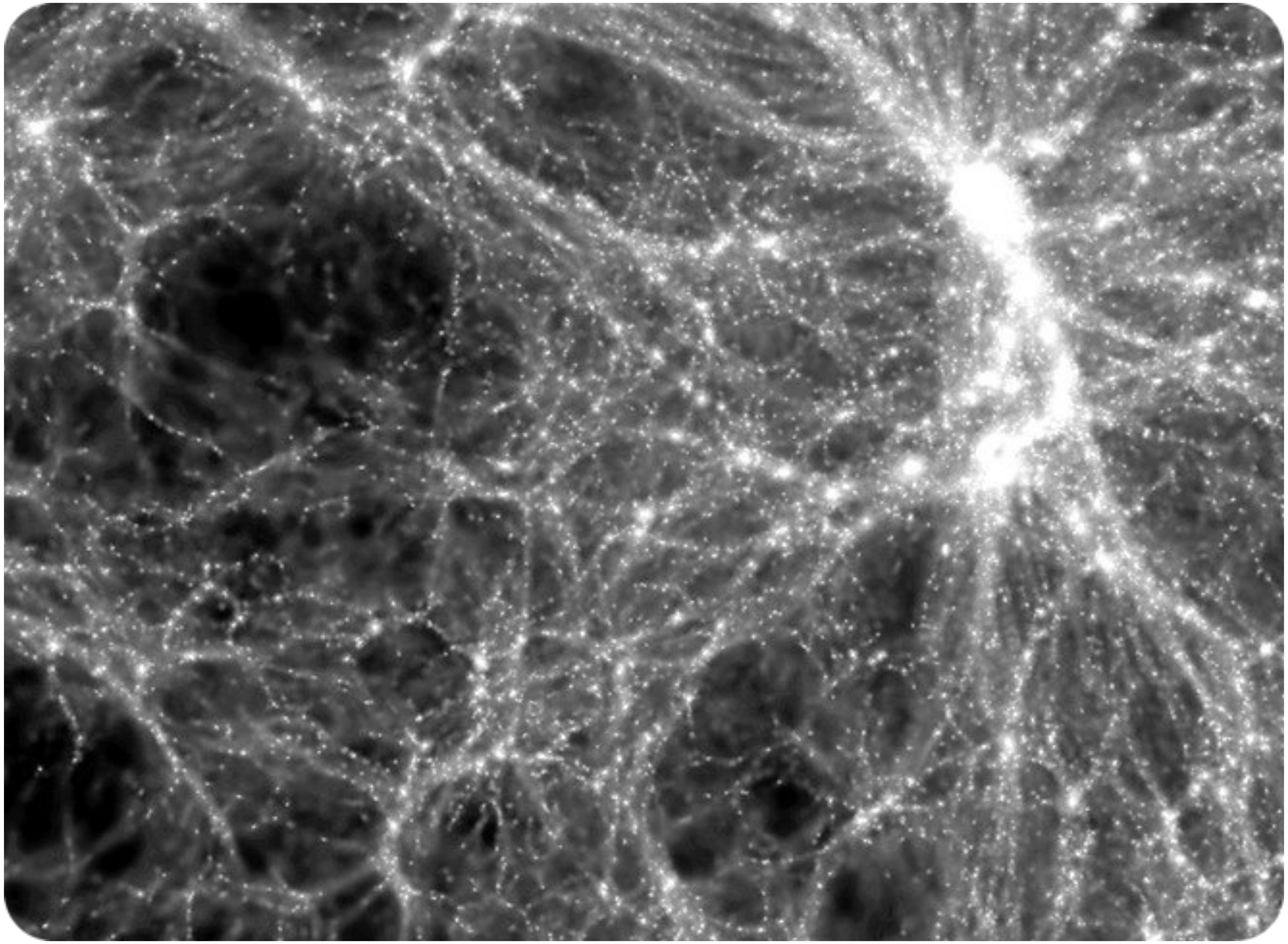
We know that General Relativity is very well constrained in high density environments (e.g. solar system) and at small scales. We thus try to modify it in the case of a low density (such as the current one) and at large scales to explain observations.

Thus it is in a low density regime and at cosmological scales that the models of Modified Gravity can be optimally tested => voids present both these features.

Voids are sensitive at different scales



Studying voids gives a window on dark energy



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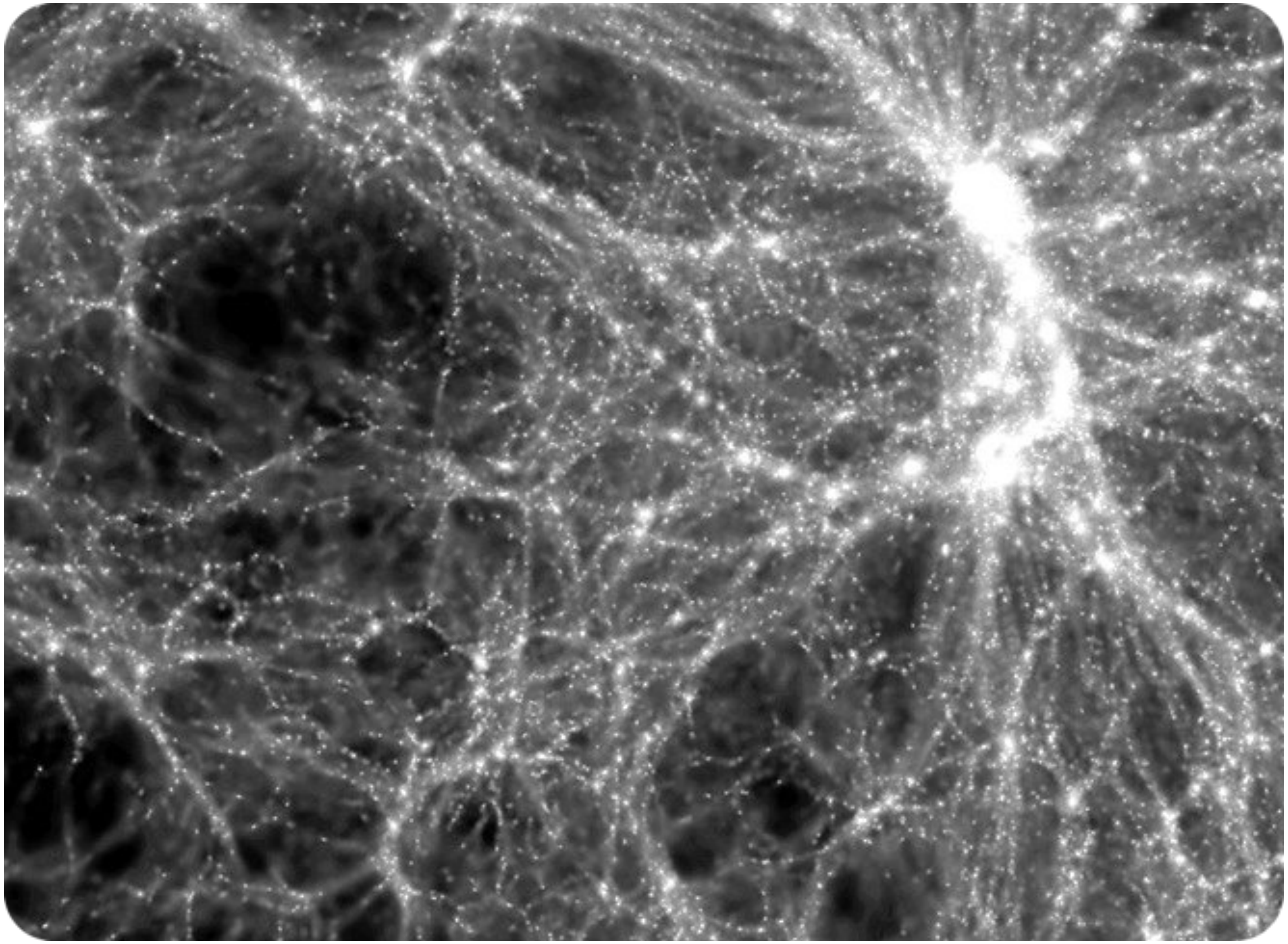

But first we need to **find voids** !

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How do we find voids?

VIDE: Void IDentification and Examination

Sutter, P. M., Lavaux G., Hamaus N., **Pisani A.**, Wandelt B. D. et al., **Astronomy & Computing** (1406.1191) (ZOBOV, Neyrinck 2008)

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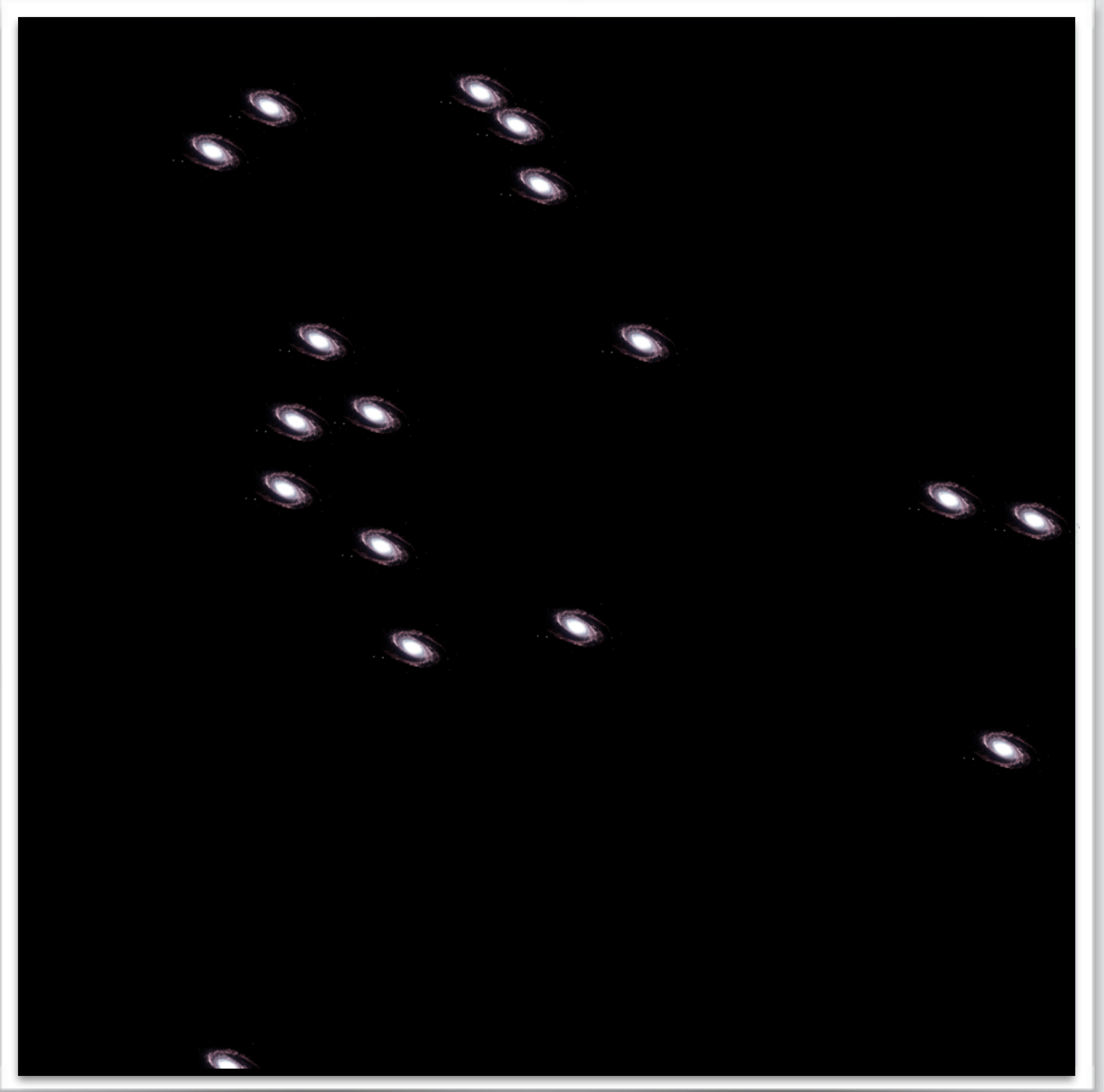
galaxies



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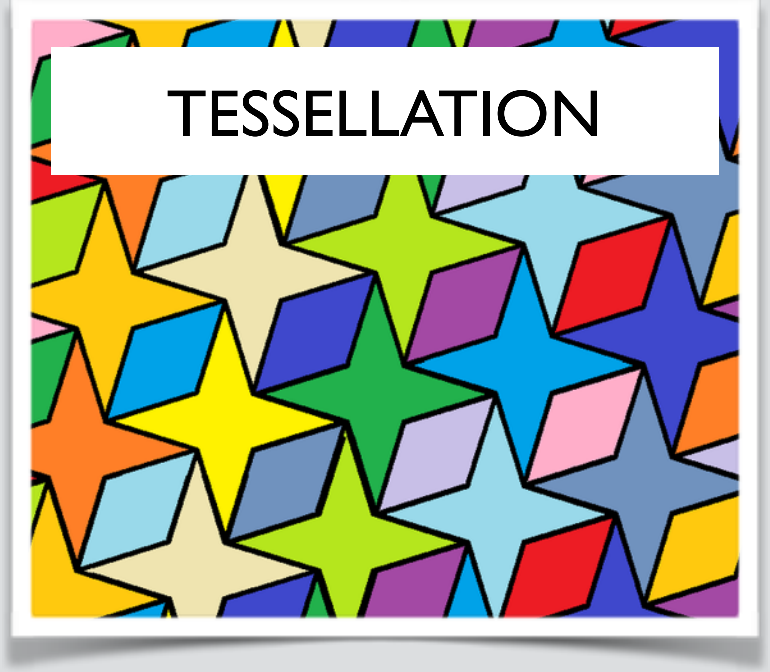

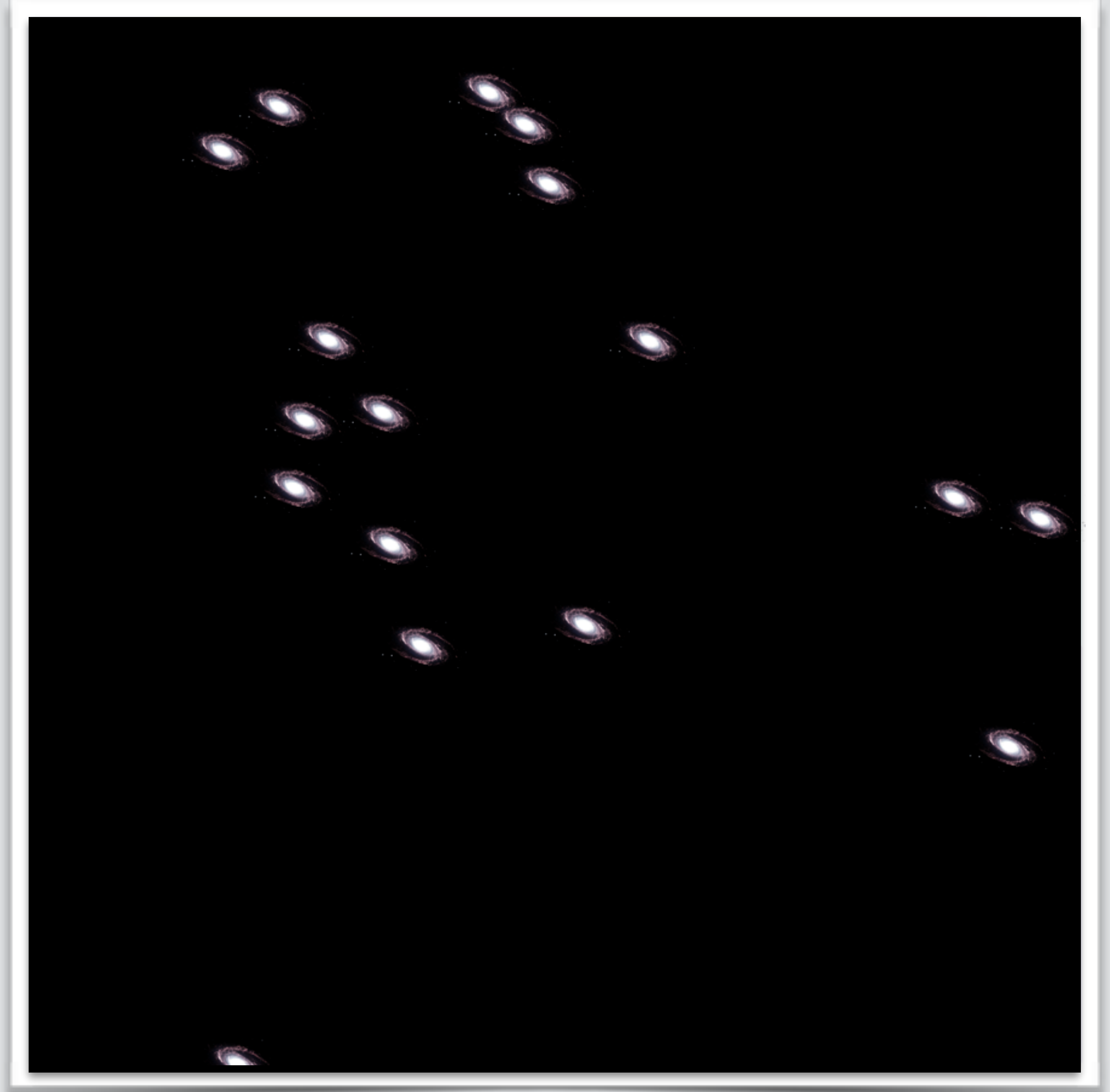

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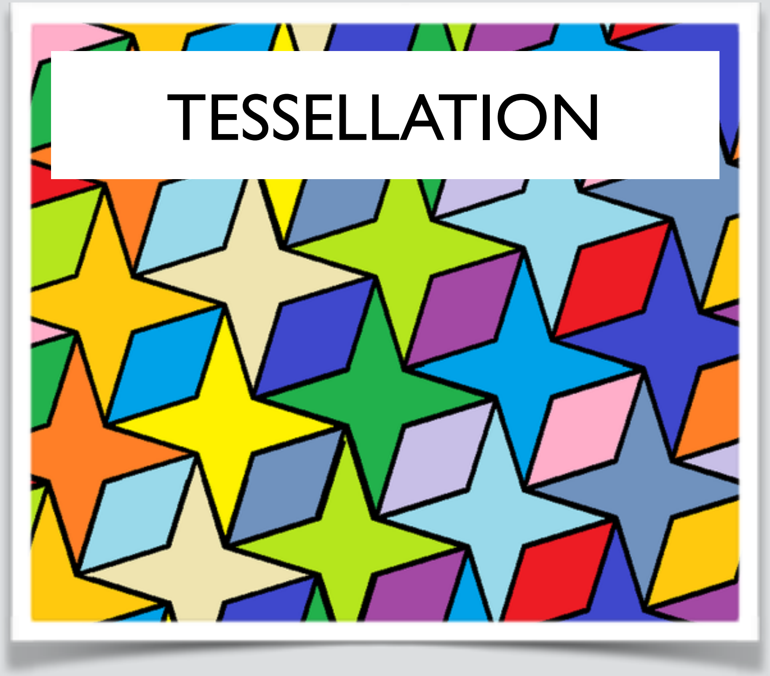
galaxies → Voronoi tessellation



A tesselation with a physical meaning

Galaxy

All points closer to the tracer than to any other point

Local density estimation

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

Icke & Van de Weygaert (1987)

VIDE: Void IDentification and Examination

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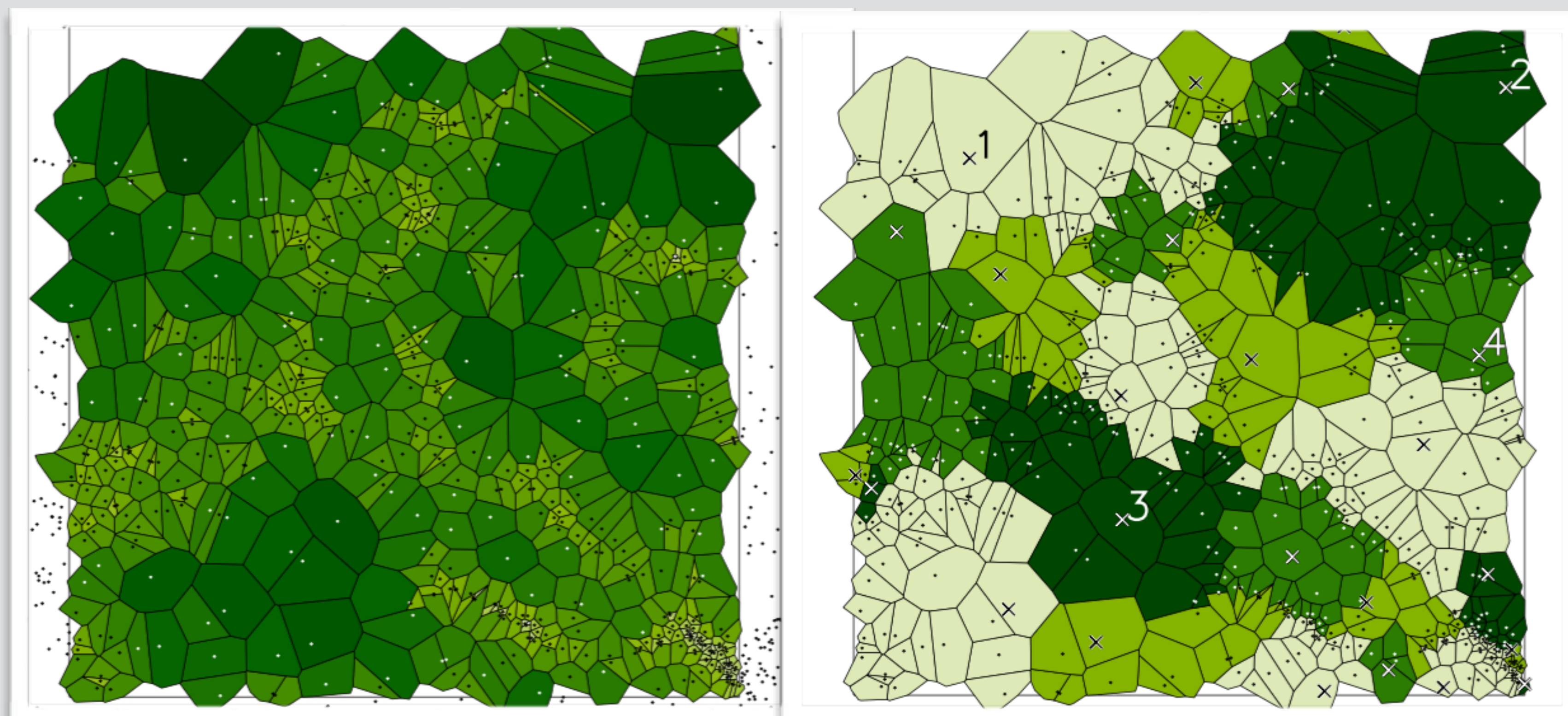
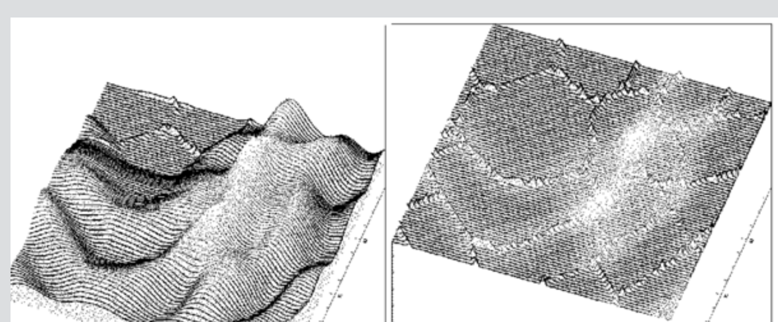
galaxies → Voronoi tessellation → Watershed transform

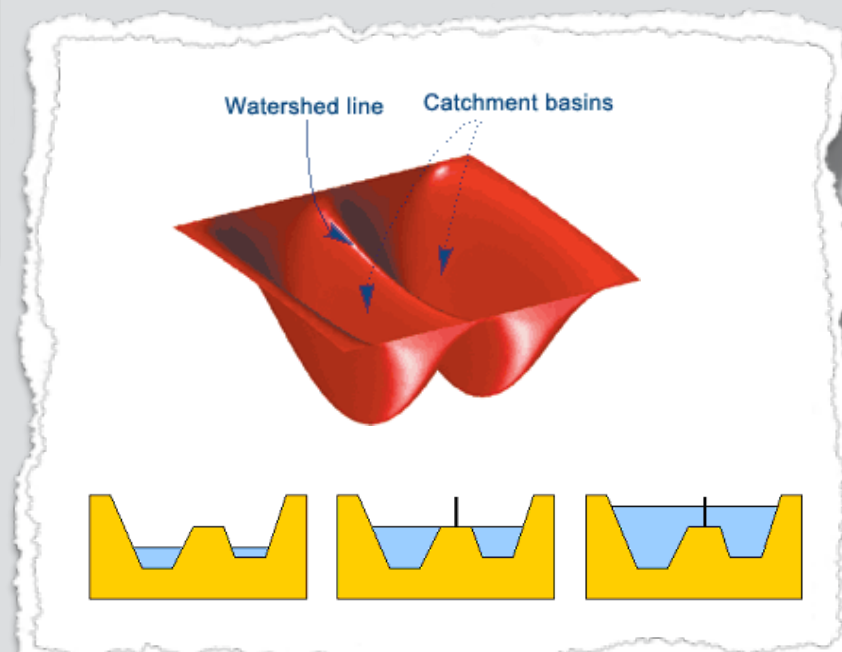


Neyrinck 2008

Merge basins if the wall between then is at a lower density.



Platen et al. 2007



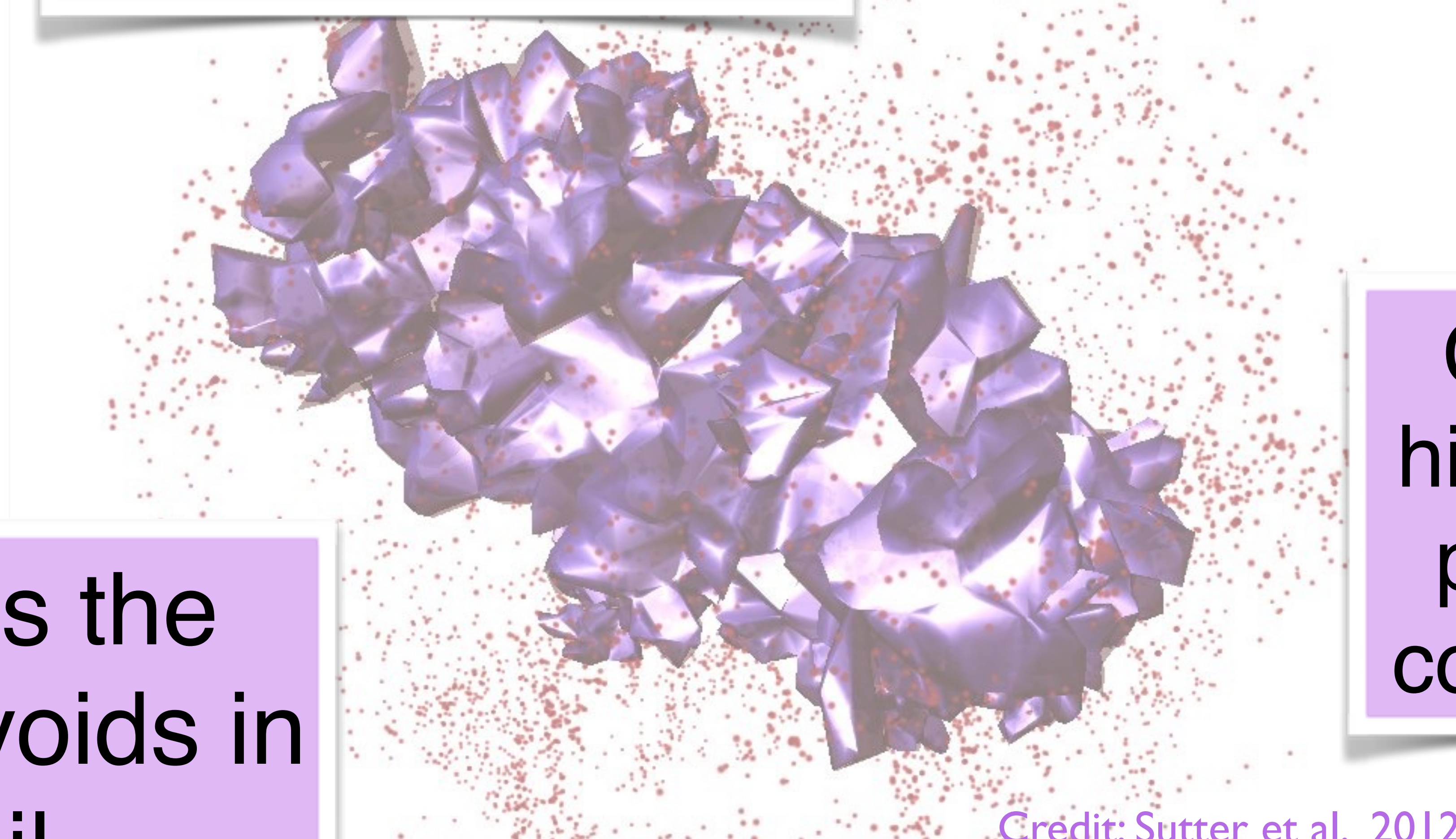
Merge cells

VIDE: Void IDentification and Examination

Sutter, P. M., Lavaux G., Hamaus N., **Pisani A.**, Wandelt B. D. et al., **Astronomy & Computing** (1406.1191) (ZOBOV, Neyrinck 2008)

galaxies → Voronoi tessellation → Watershed transform → voids

A VOID



Credit: Sutter et al. 2012

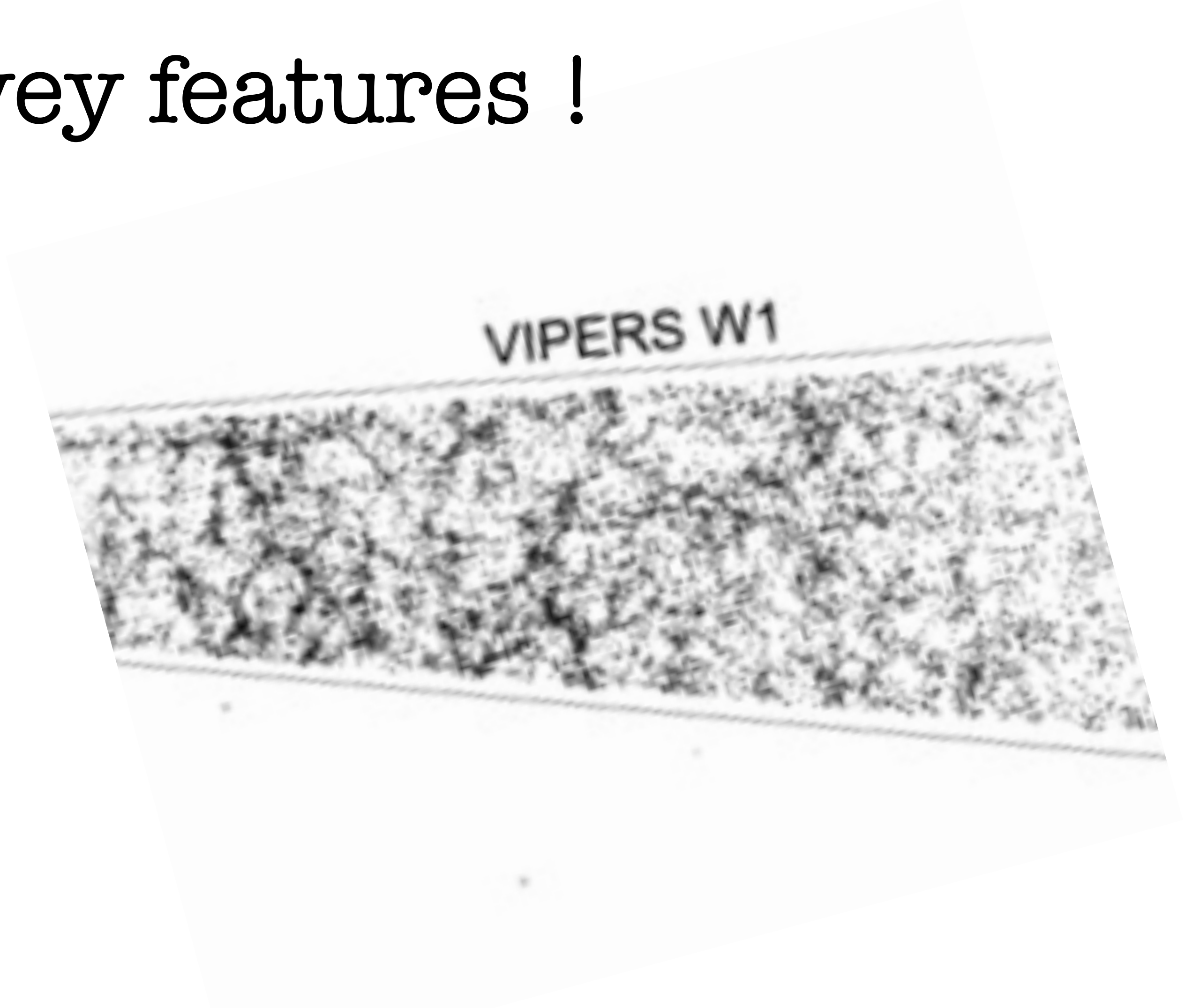
Takes mask into account

Captures the shape of voids in detail

Captures hierarchical pattern of cosmic web

Void finder choice

- Depends on application (on what we wish to measure)
- Depends on the survey features !
- Ex: VIPERS



Take Home Message: Definition is not a problem, consistency is.

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

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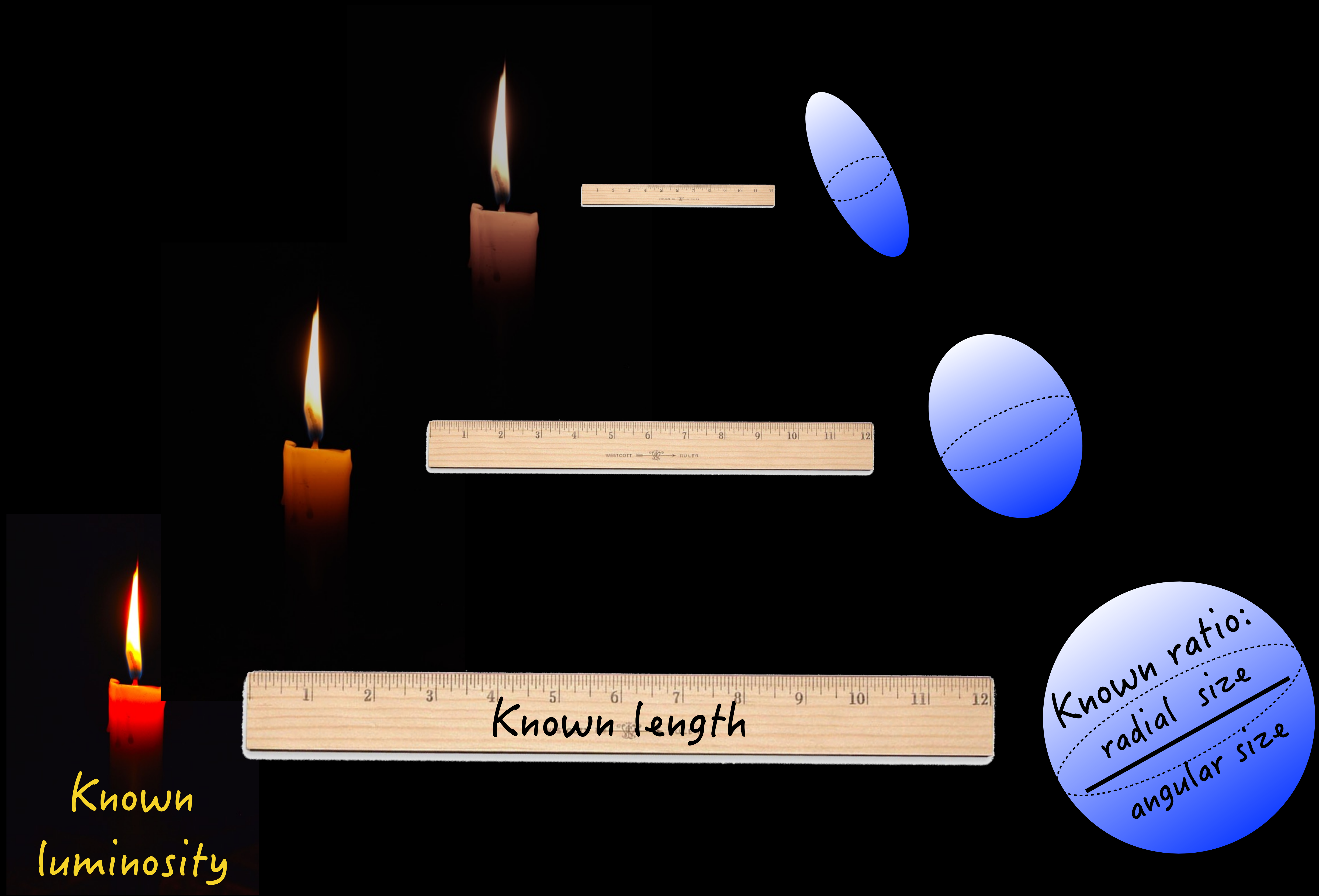
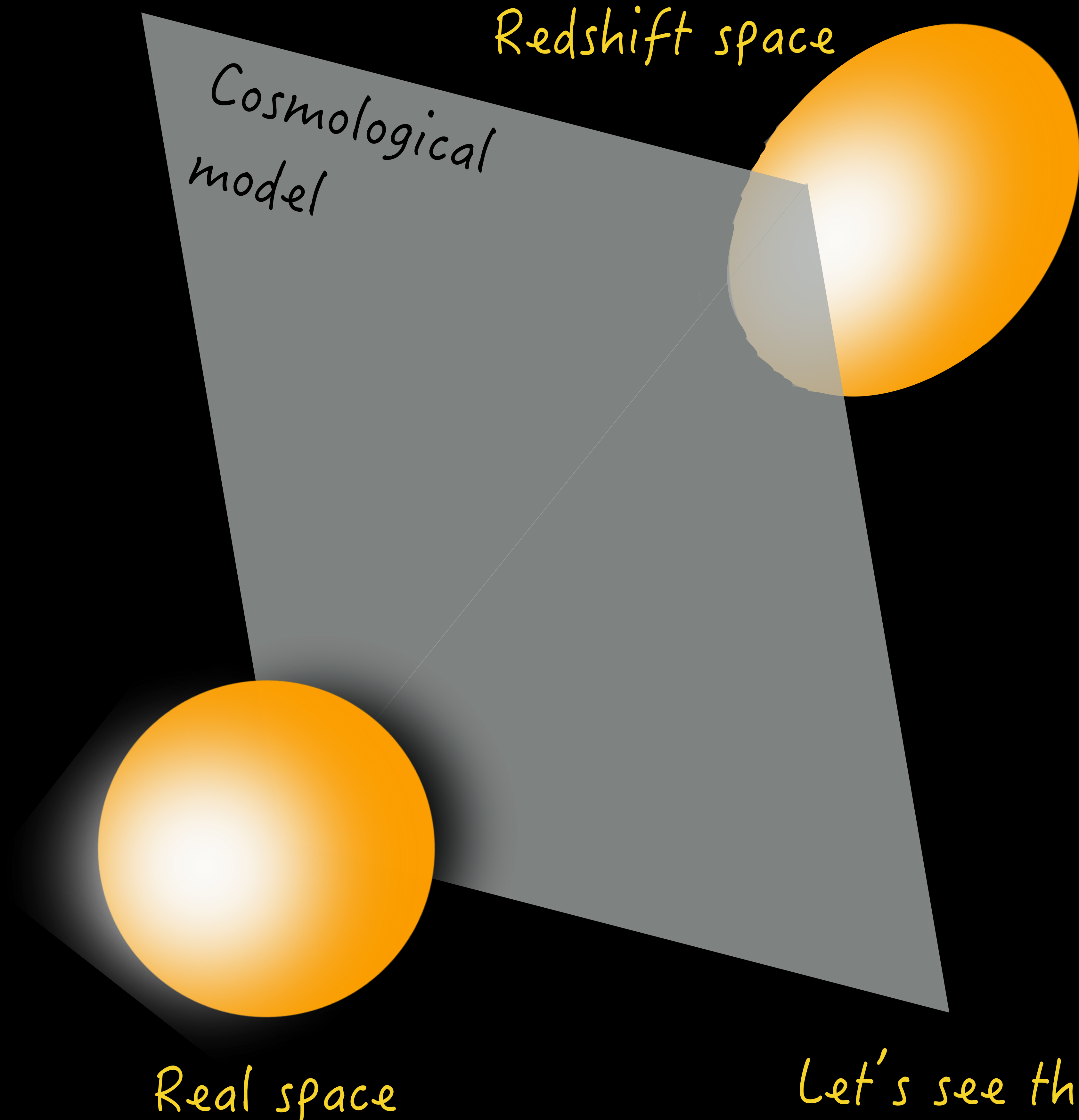
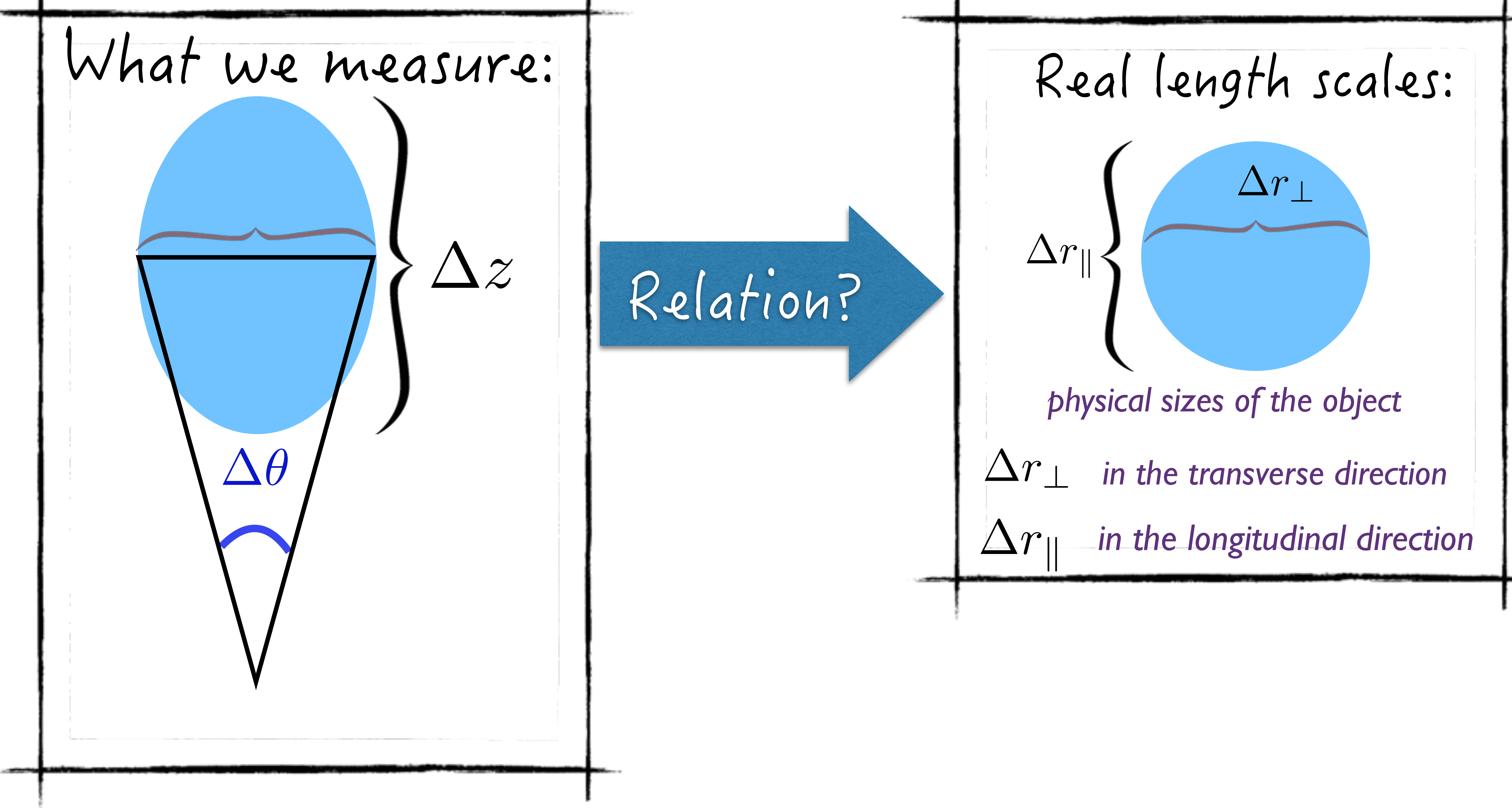
Standard objects

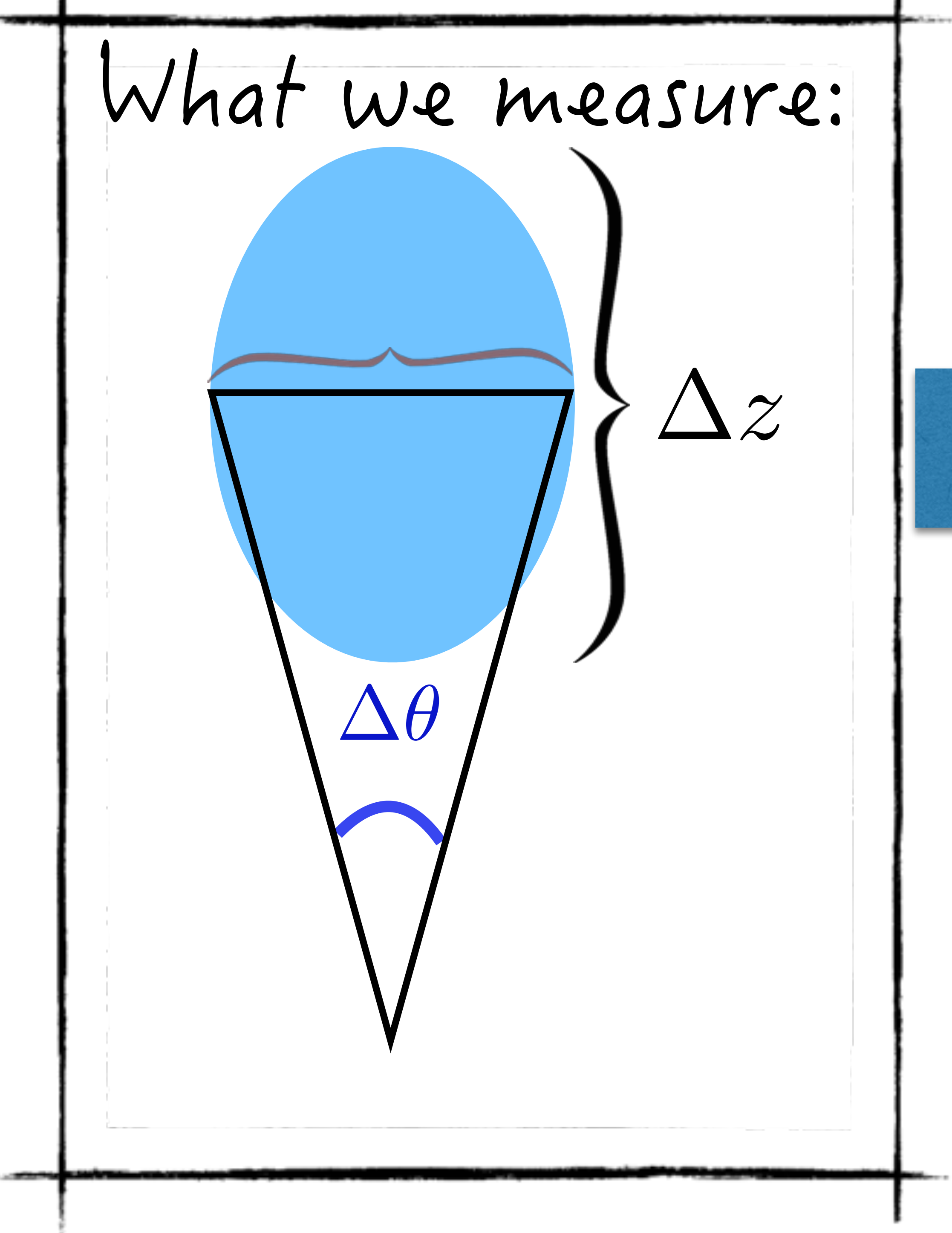


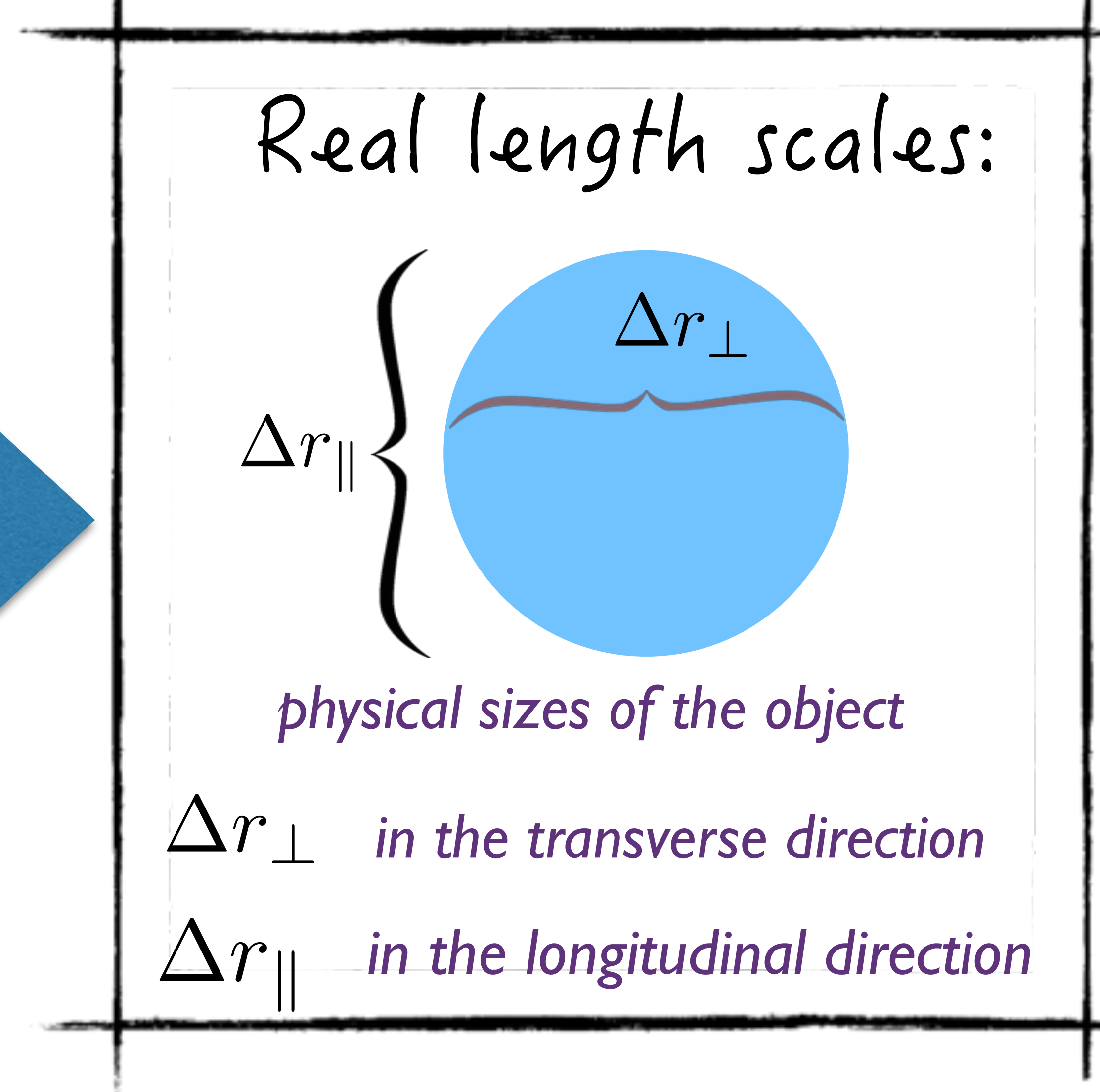


Observing standard spheres allows to test the model

Let's see this more in detail


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





Cosmology, of course !

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

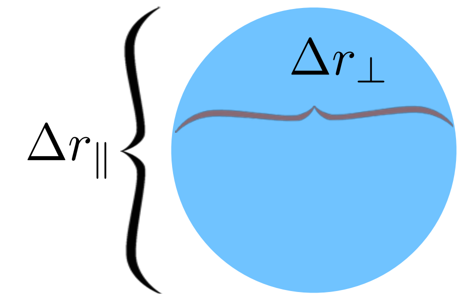
angular diameter distance

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

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.

Flat Universe $D_A(z) = \int_0^z \frac{cdz}{H(z)}$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

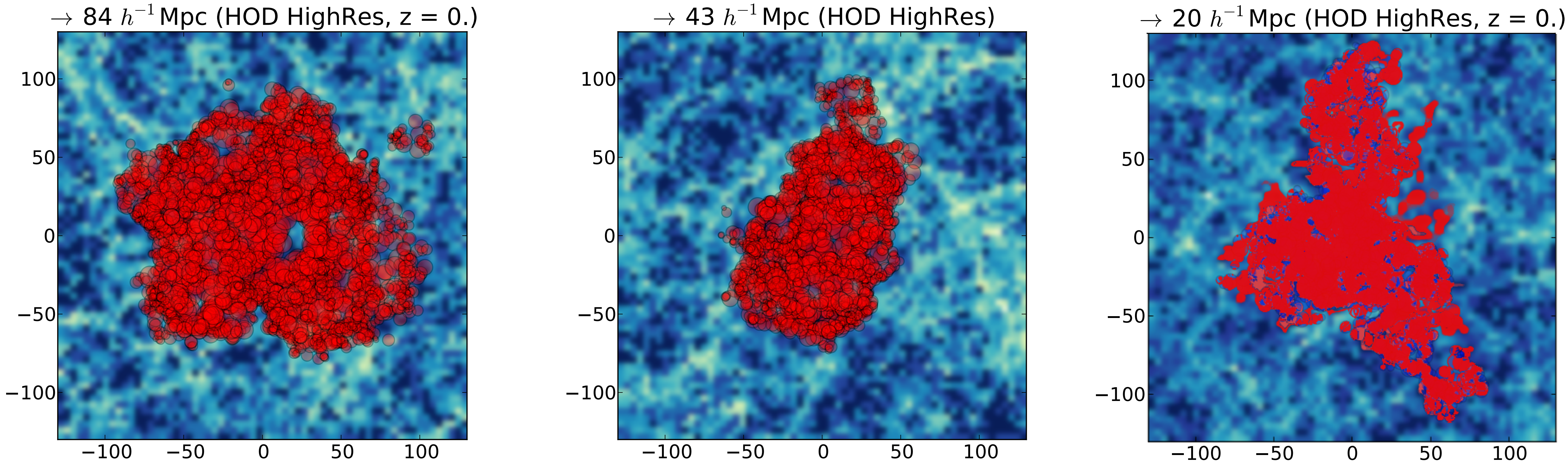
We need spheres in the Universe to perform the test

Barbara Ryden

We can use voids for the test.

But: "The accuracy of the estimated values[..] is limited by the intrinsic scatter in the size and shape of the voids." [tests with a toy model of the Universe]
ArXiv: 9506028,9510108

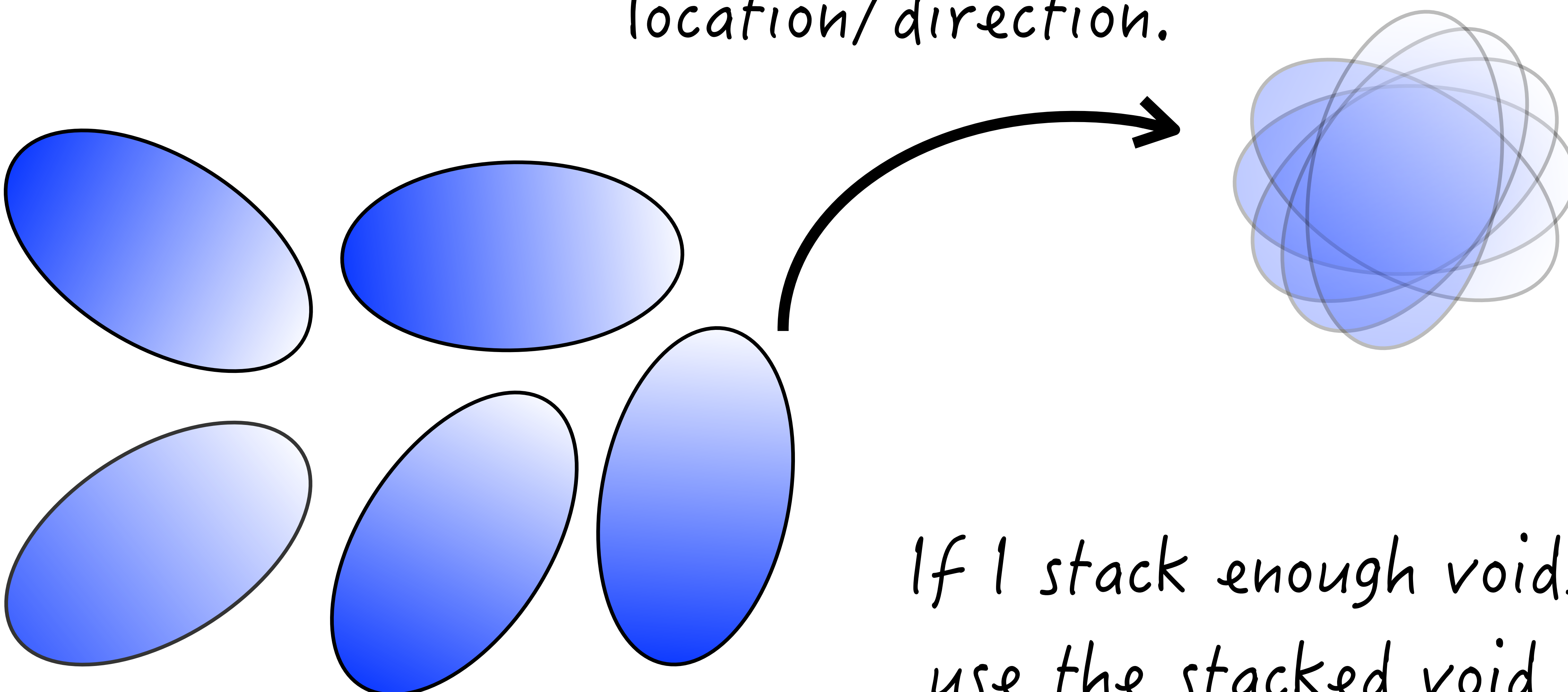
Voids have very different shapes



How do we apply the test?

How do we apply the AP test with voids?

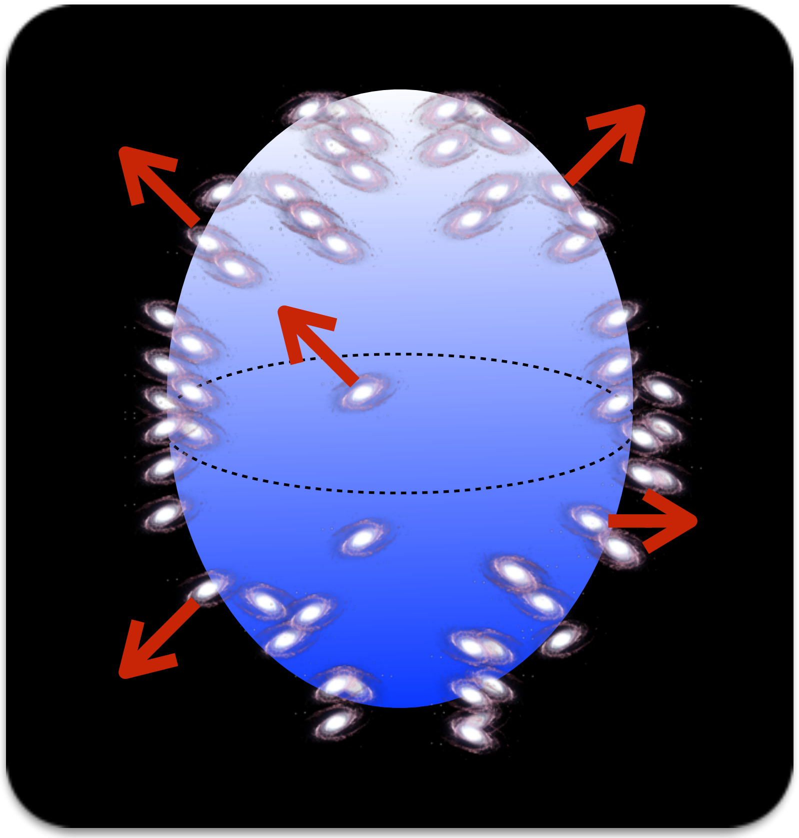
Cosmological principle says there is no preferential location/direction.

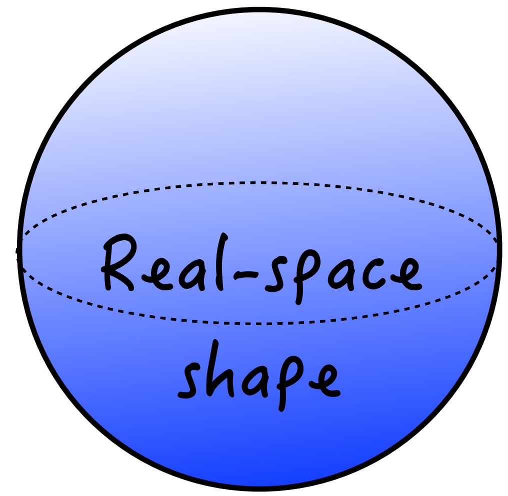


If I stack enough voids I can use the stacked void as my standard sphere.

Lavaux & Wandelt 2012

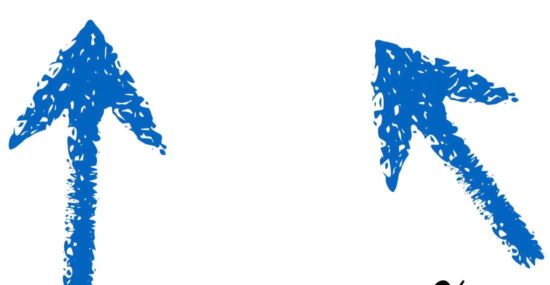
A stacked void is a standard sphere: the void shape tells us the cosmology





But… the velocities of galaxies also affect that shape.

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



$z_{measured}$ z_{cosmo}

They add **distortions** to the large-scale structures, the redshift-space distortions (RSD).

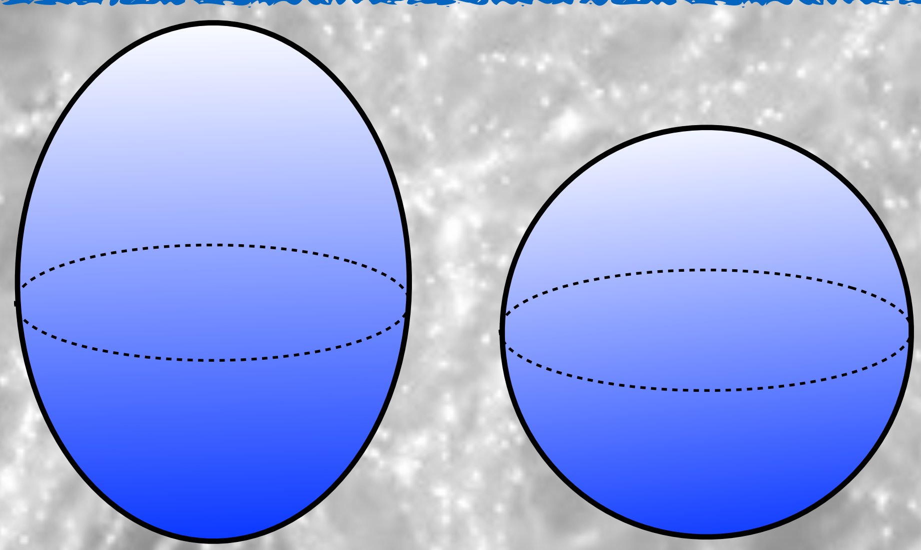
Velocities will be our main source of systematics!

We can solve this by:

1) better modeling of the real space shape

2) studying the effect of peculiar velocities

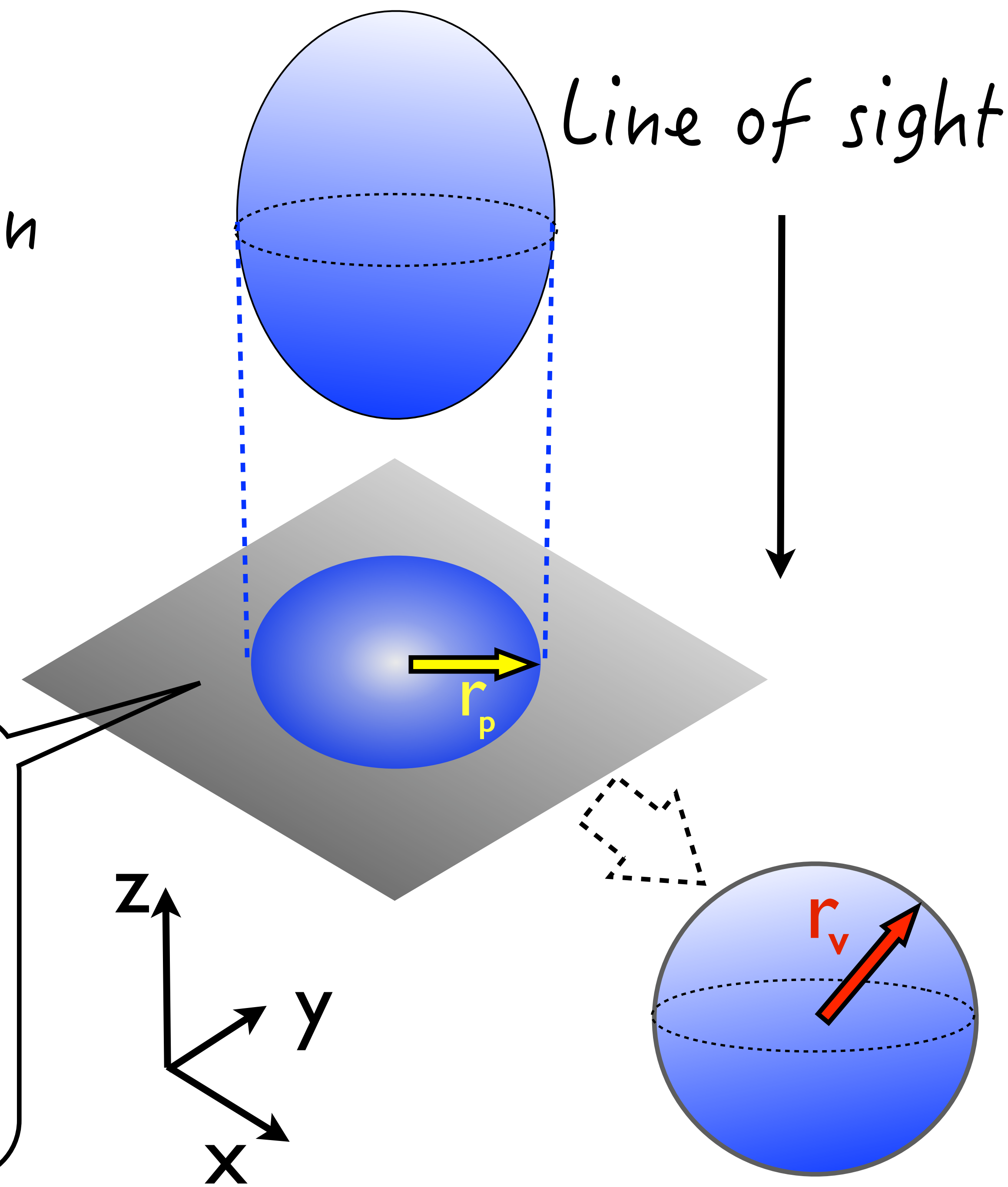
3) using the information embedded in velocities



Getting the real space profile

Key idea

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

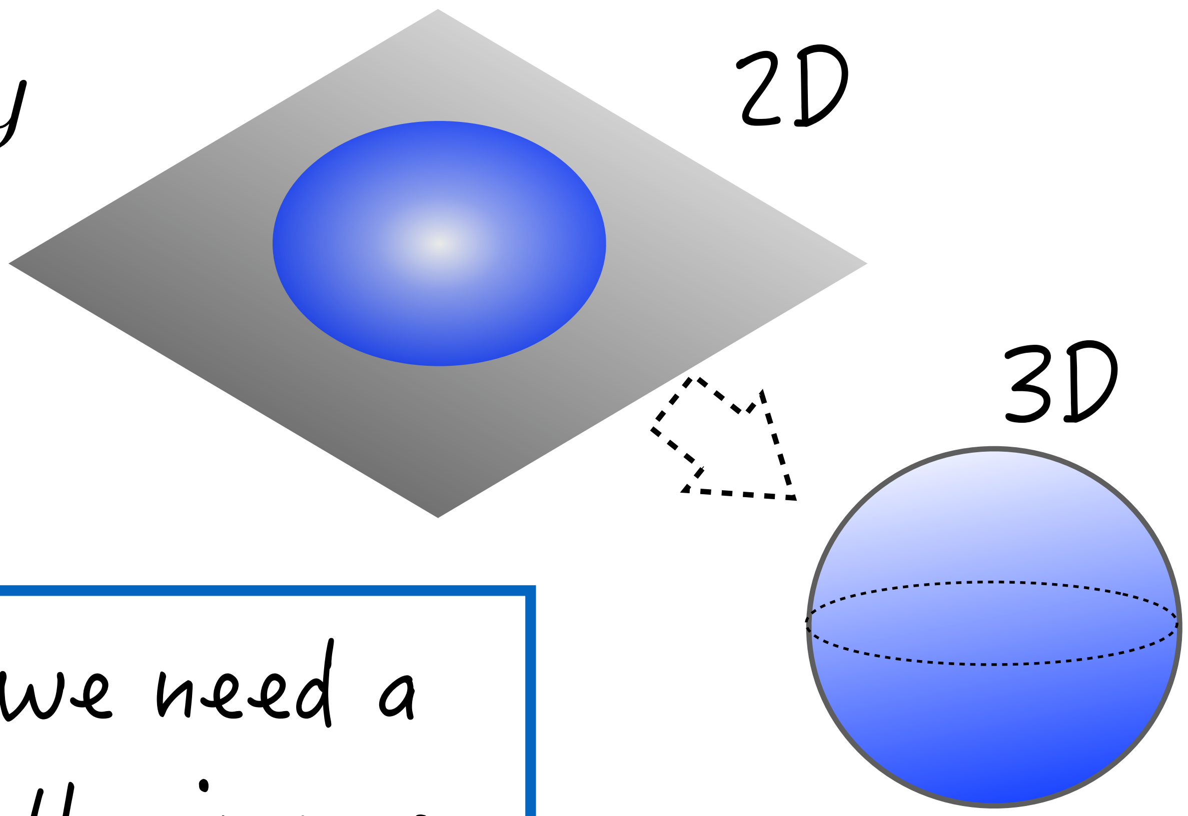


From this projection we reconstruct a 3D profile without the contribution of peculiar velocities.

→ 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

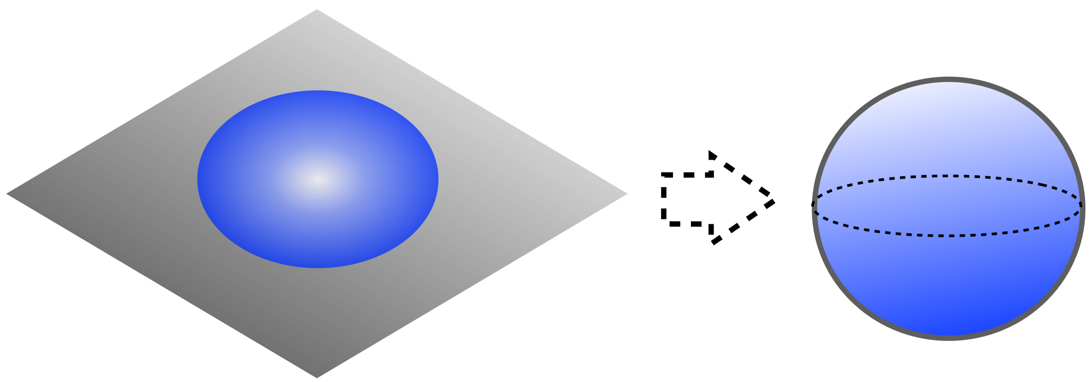
But...

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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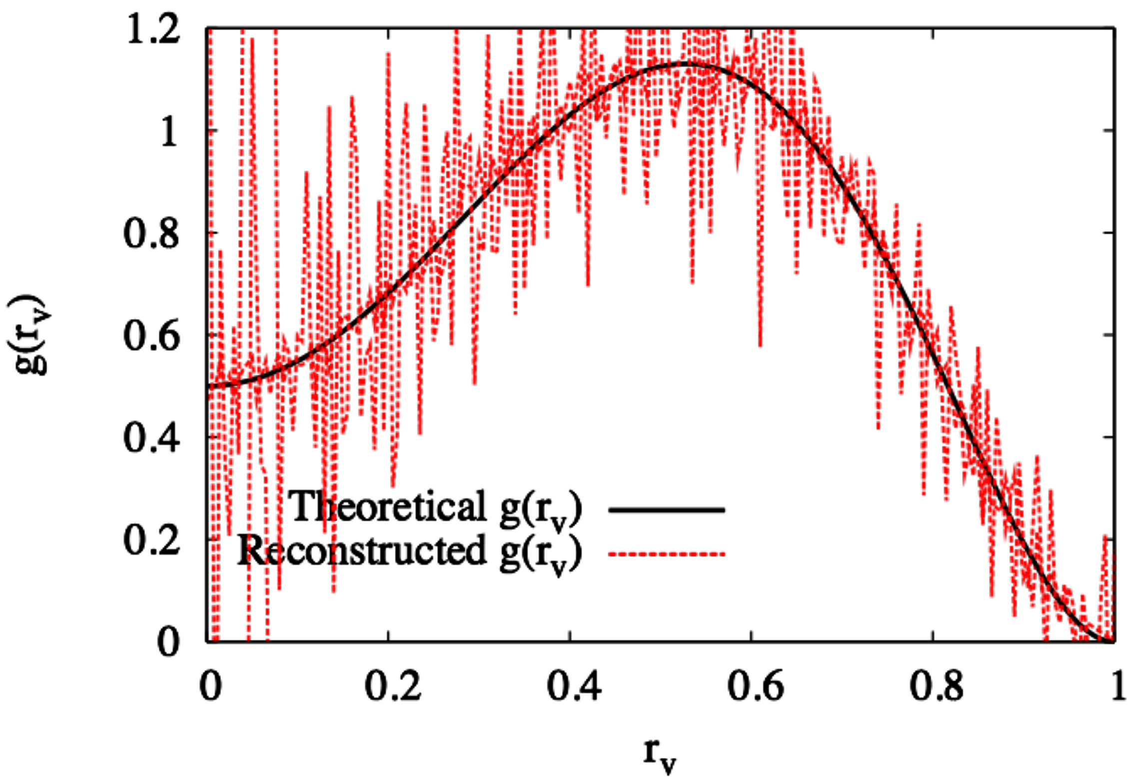

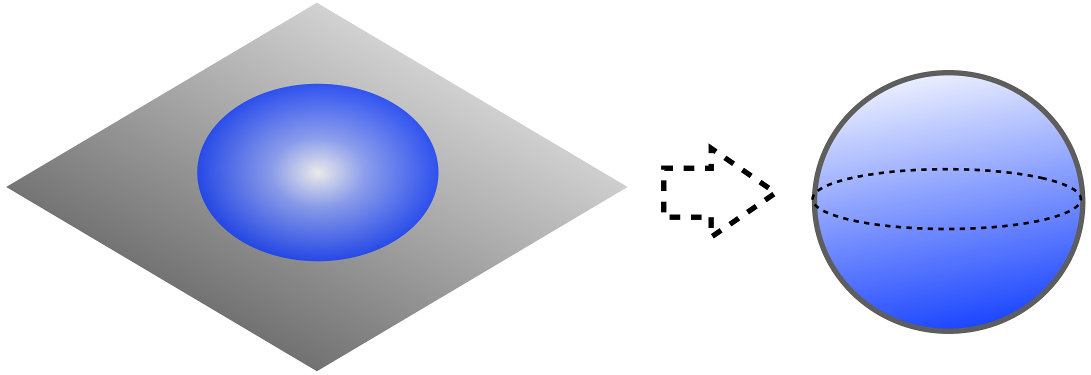

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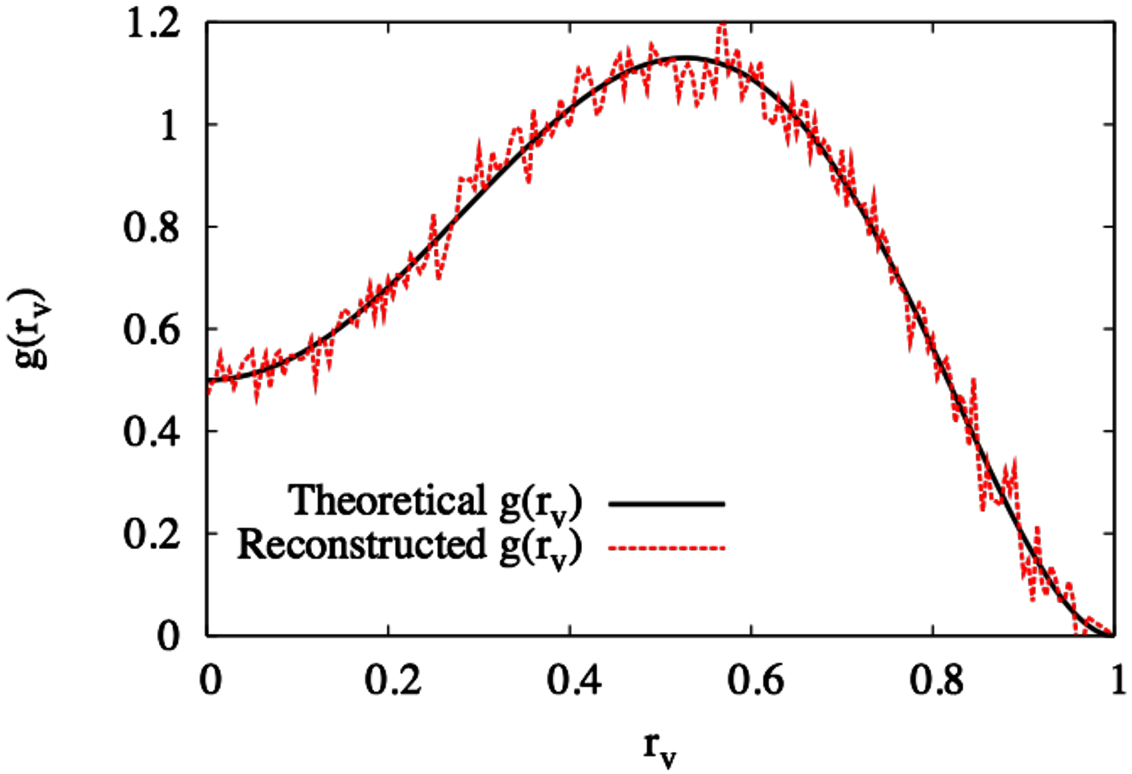
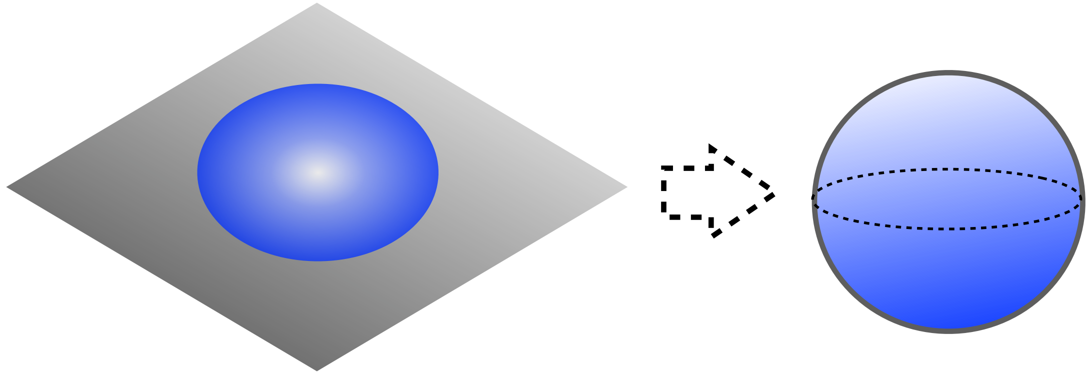
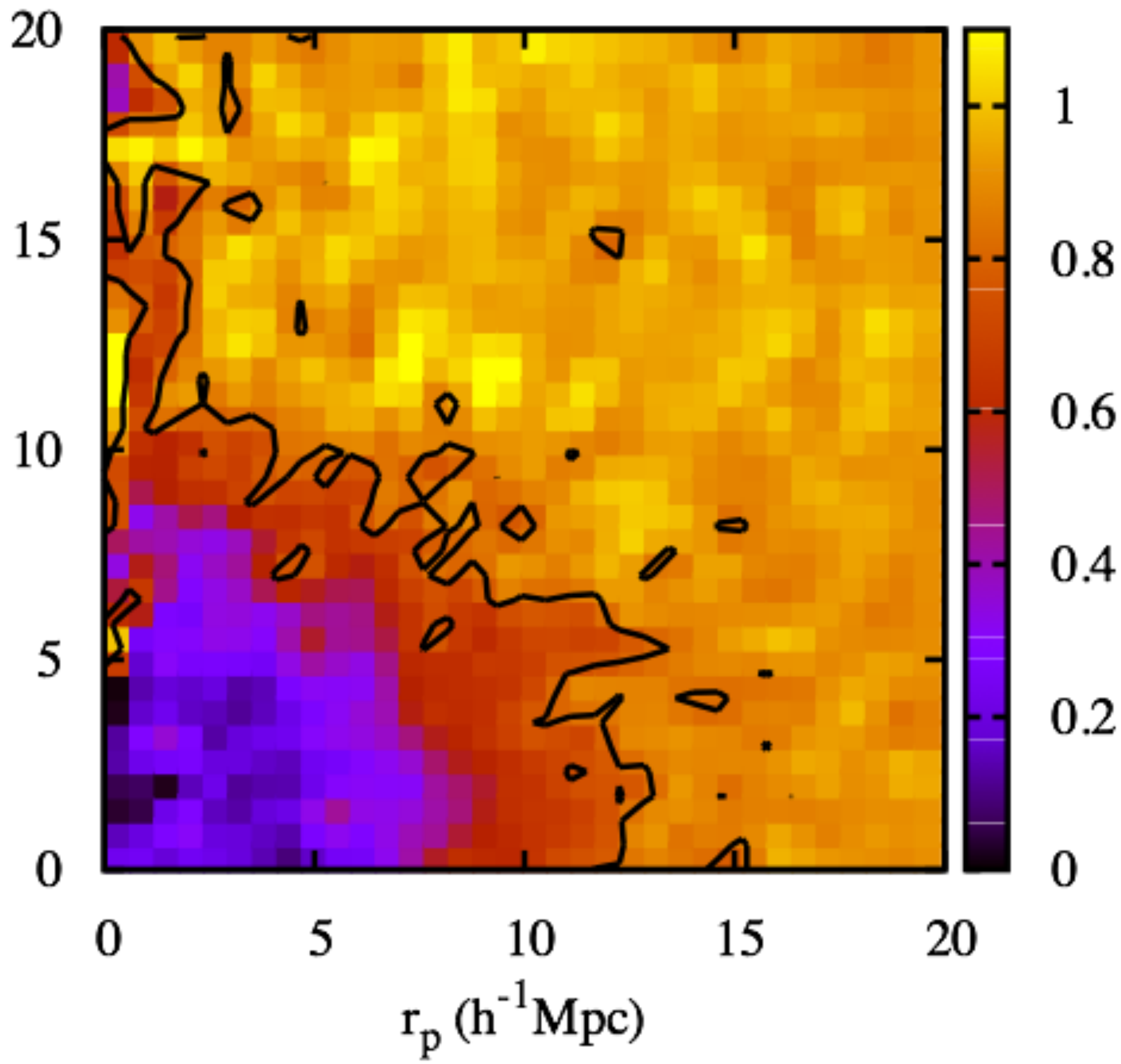


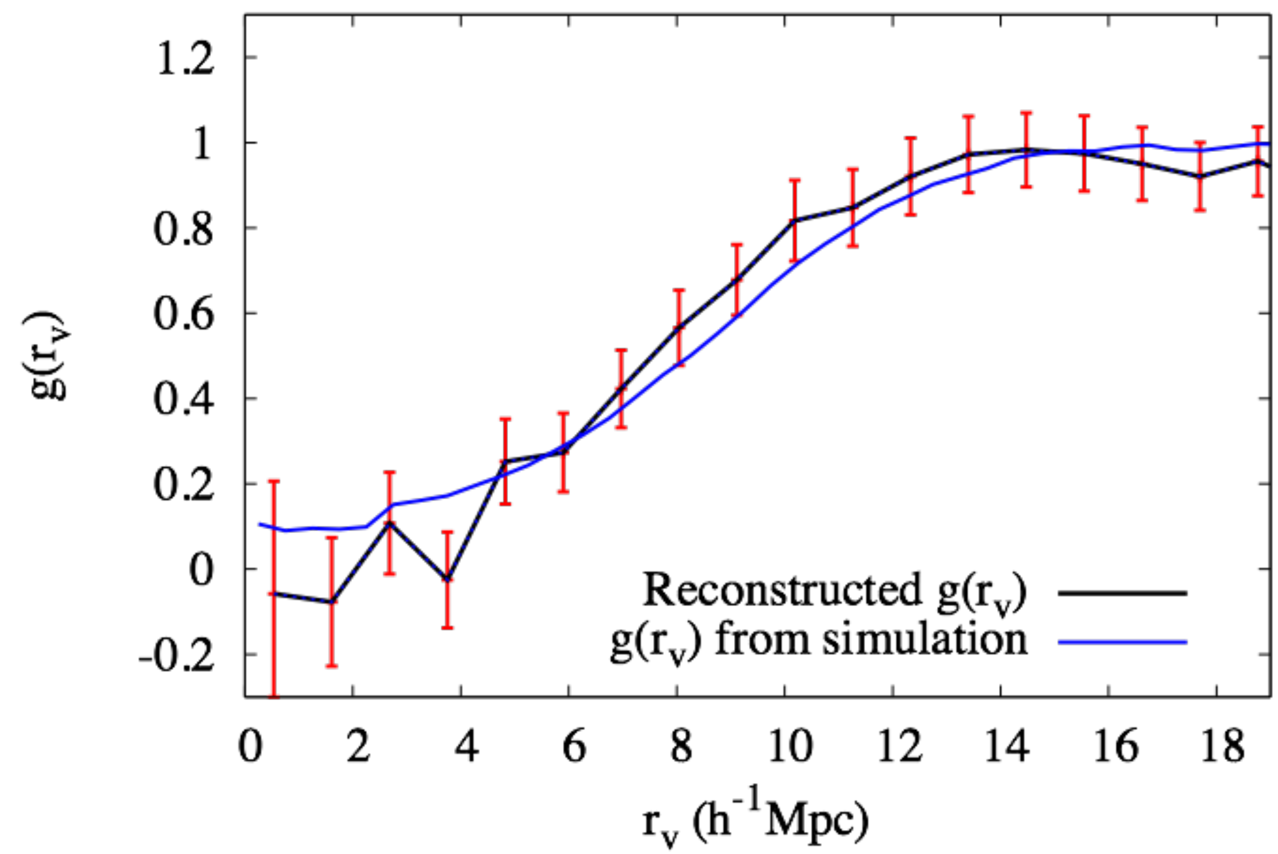


Reconstruction was with an Abel pair,
so it is a particular case

RESULT:
Very good
reconstruction!

Result II

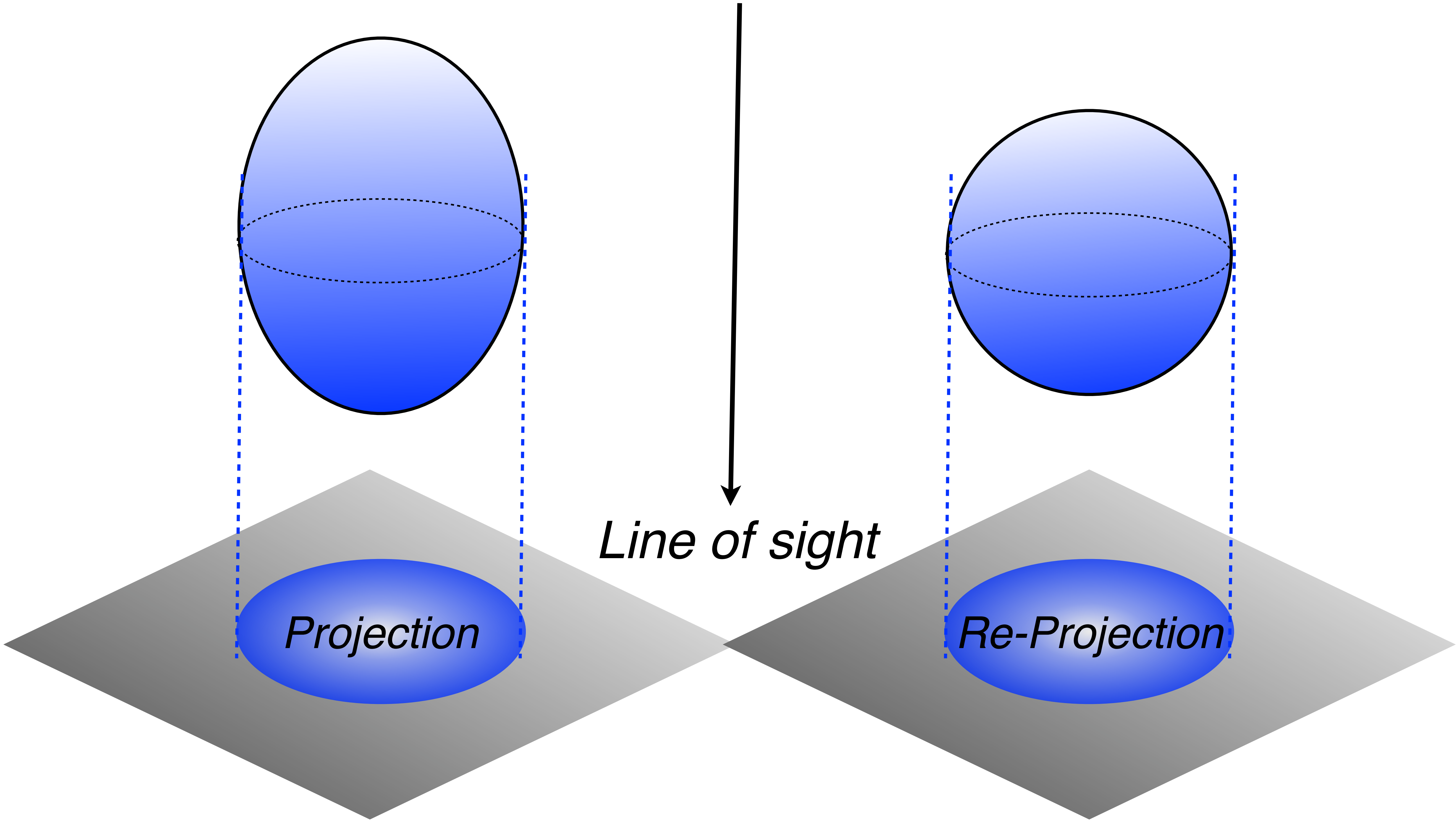




Stacking from 10 to 12 Mpc/h

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

The sanity check for the reconstruction



Check the reconstruction

Reconstruction from stacked void with HOD model

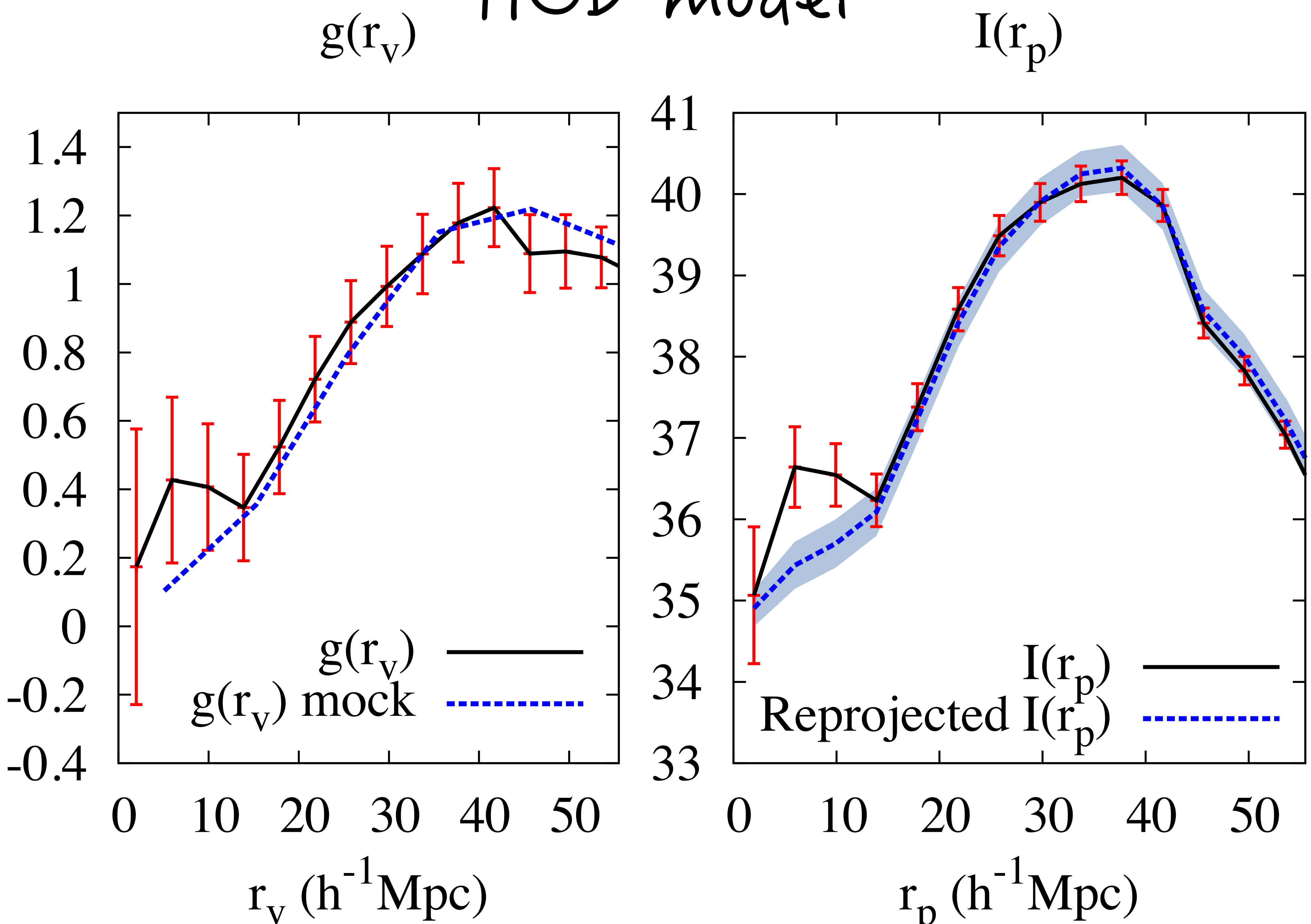
$$\langle N_{\rm cen}(M)\rangle = \frac{1}{2}\left[1+{\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

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

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

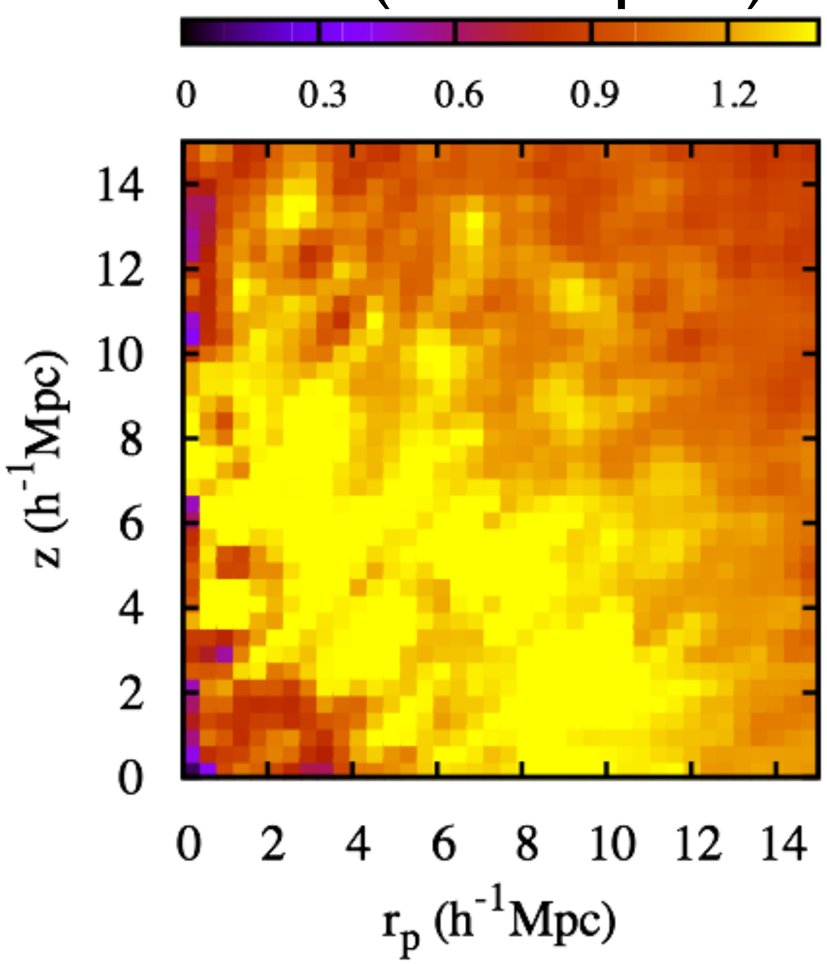
Matching the features of SDSS DR7

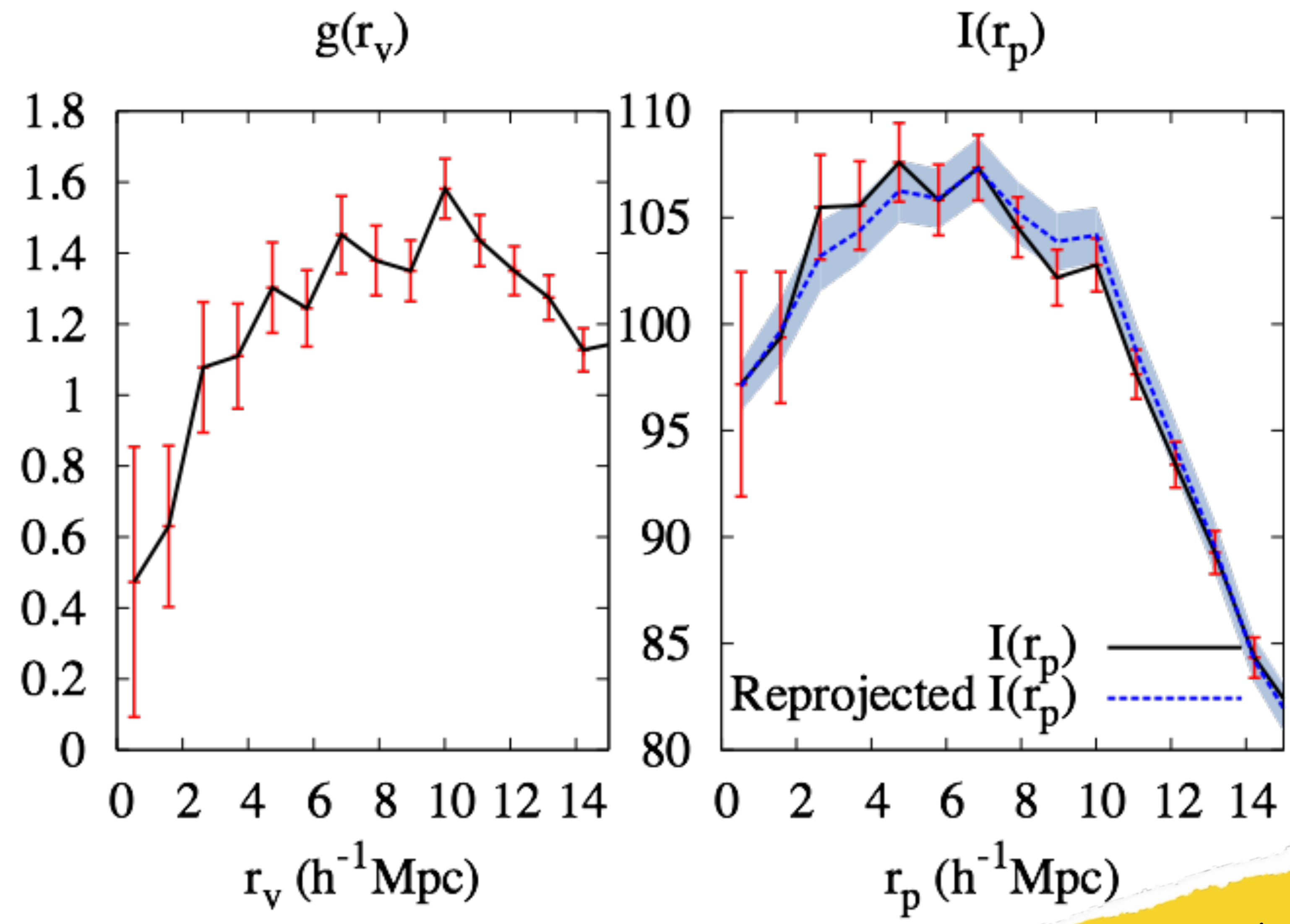
Reconstruction from stacked void of HOD model



Result III

Dim (5-15 Mpc/h)



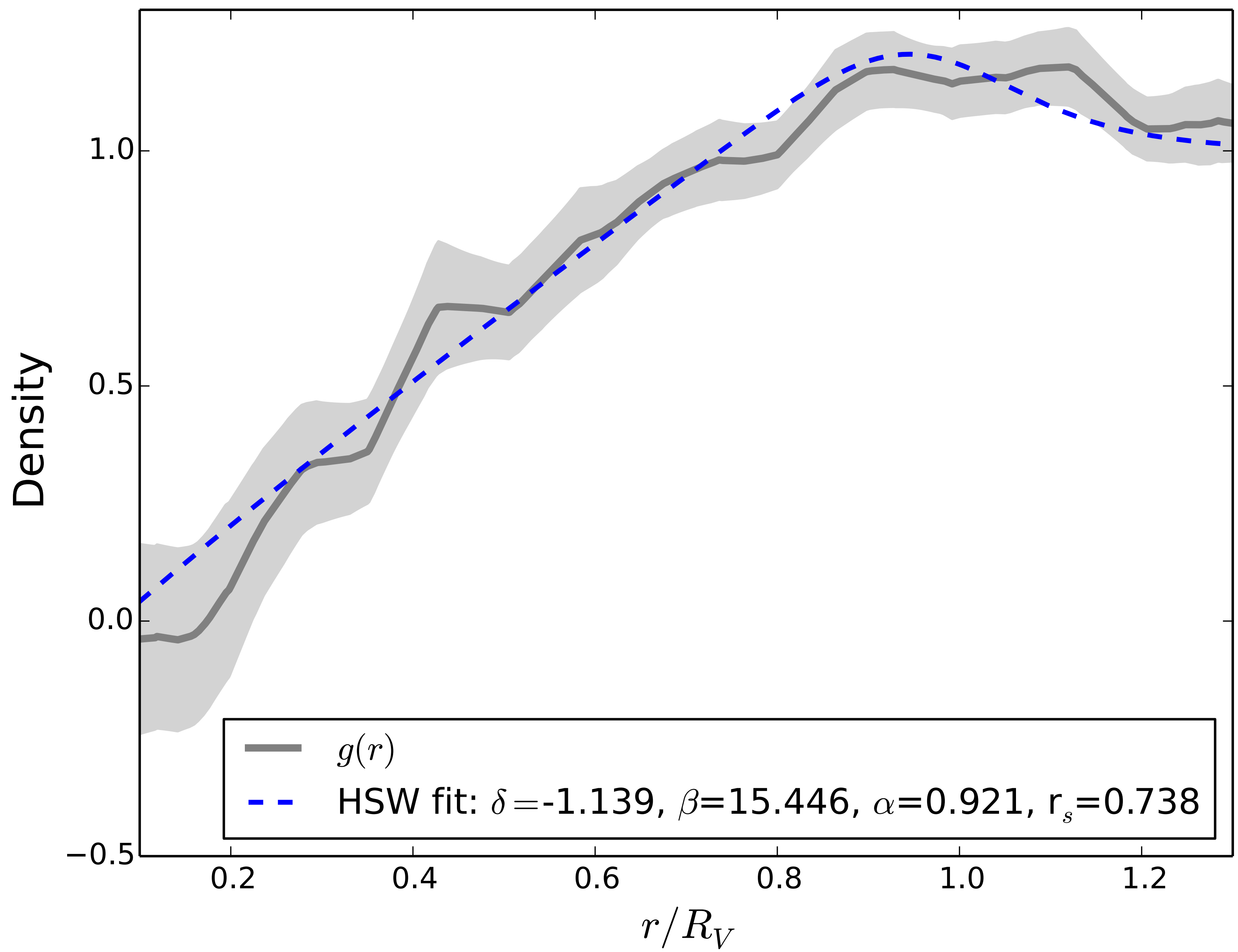


Stack radius	Redshift	Dataset	Galaxies	Voids
5-15	0.05-0.10	dim2	173929	173
10-15	0.05-0.10	dim2	43527	41
20-25	0.10-0.15	bright1	21241	17
25-45	0.15-0.20	bright2	51913	37

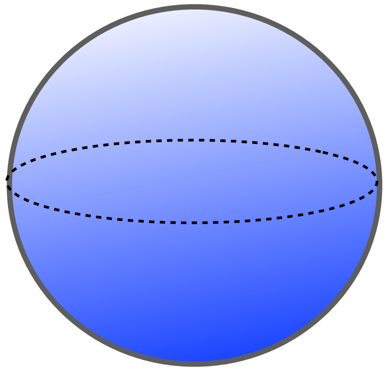
Model independent!
No assumption about RSD

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

Average real space void from SDSS DR7 matches simulations

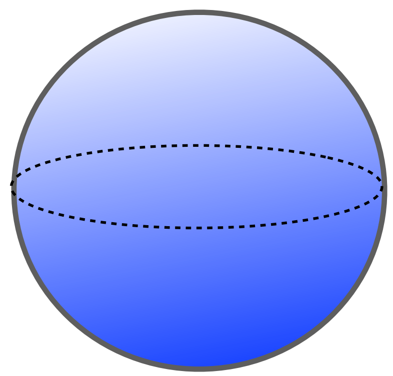


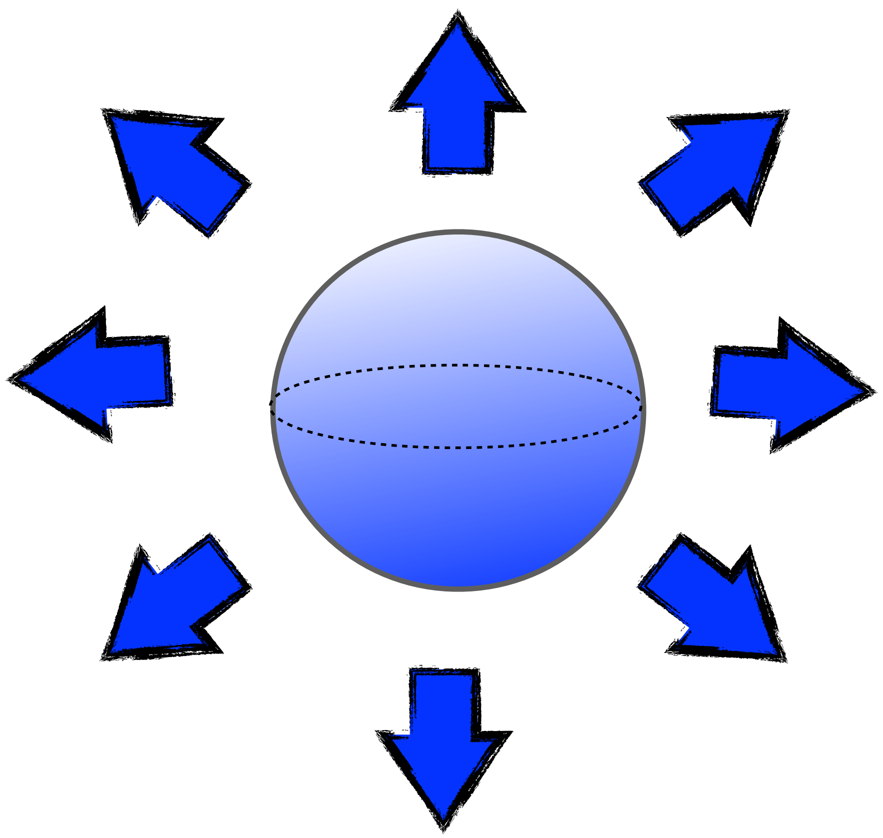
What do we know about voids?



STATIC!!!!

What do we know about voids?





STATIC!!!! DYNAMICS ????

“Really” looking at voids...

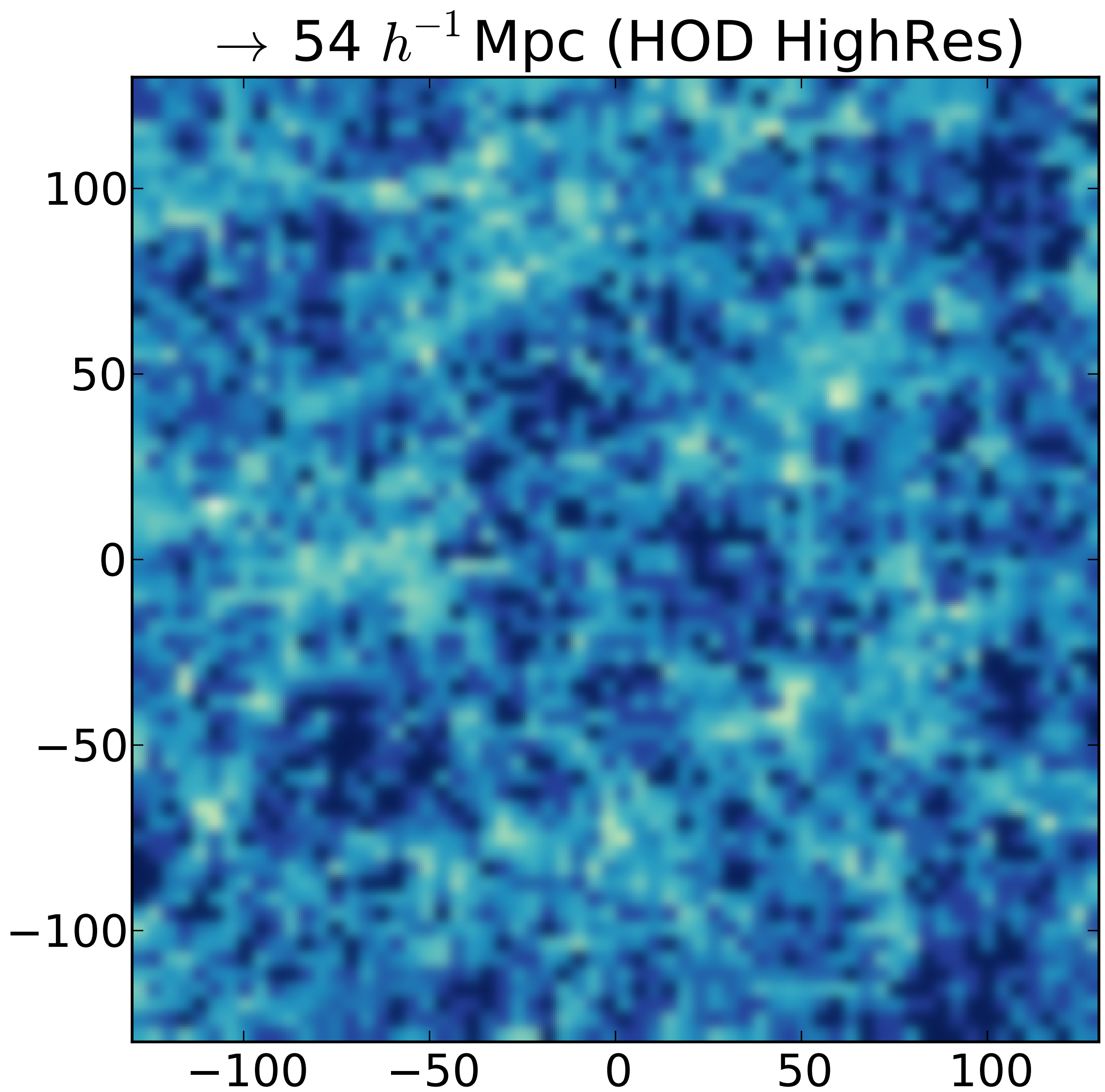
How do velocities impact the way the void finder selects voids?

Let's give a look at voids...

HOD nopv

versus

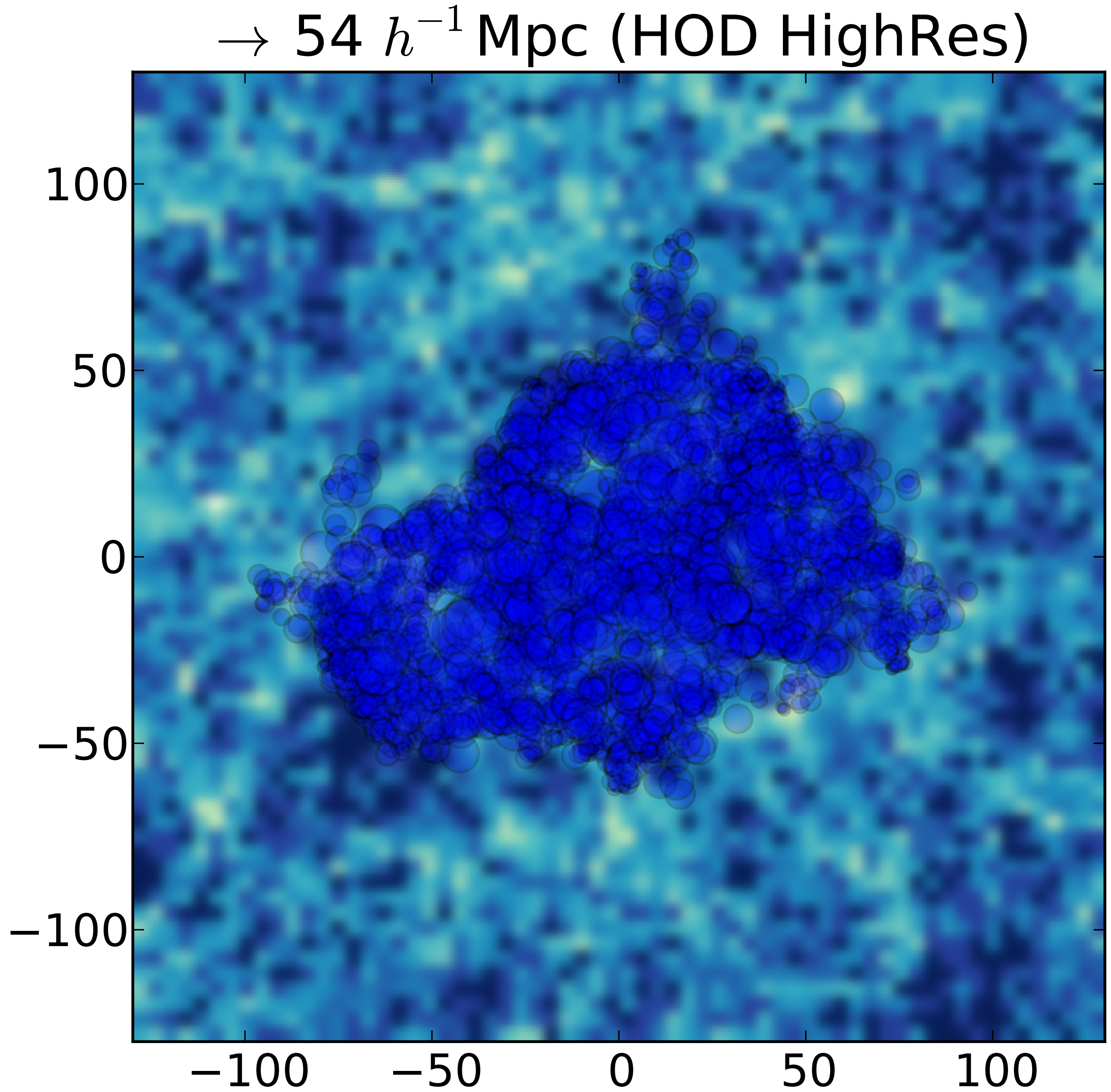
HOD + pv



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

Let's give a look at voids…

HOD nopv
versus
HOD + pv



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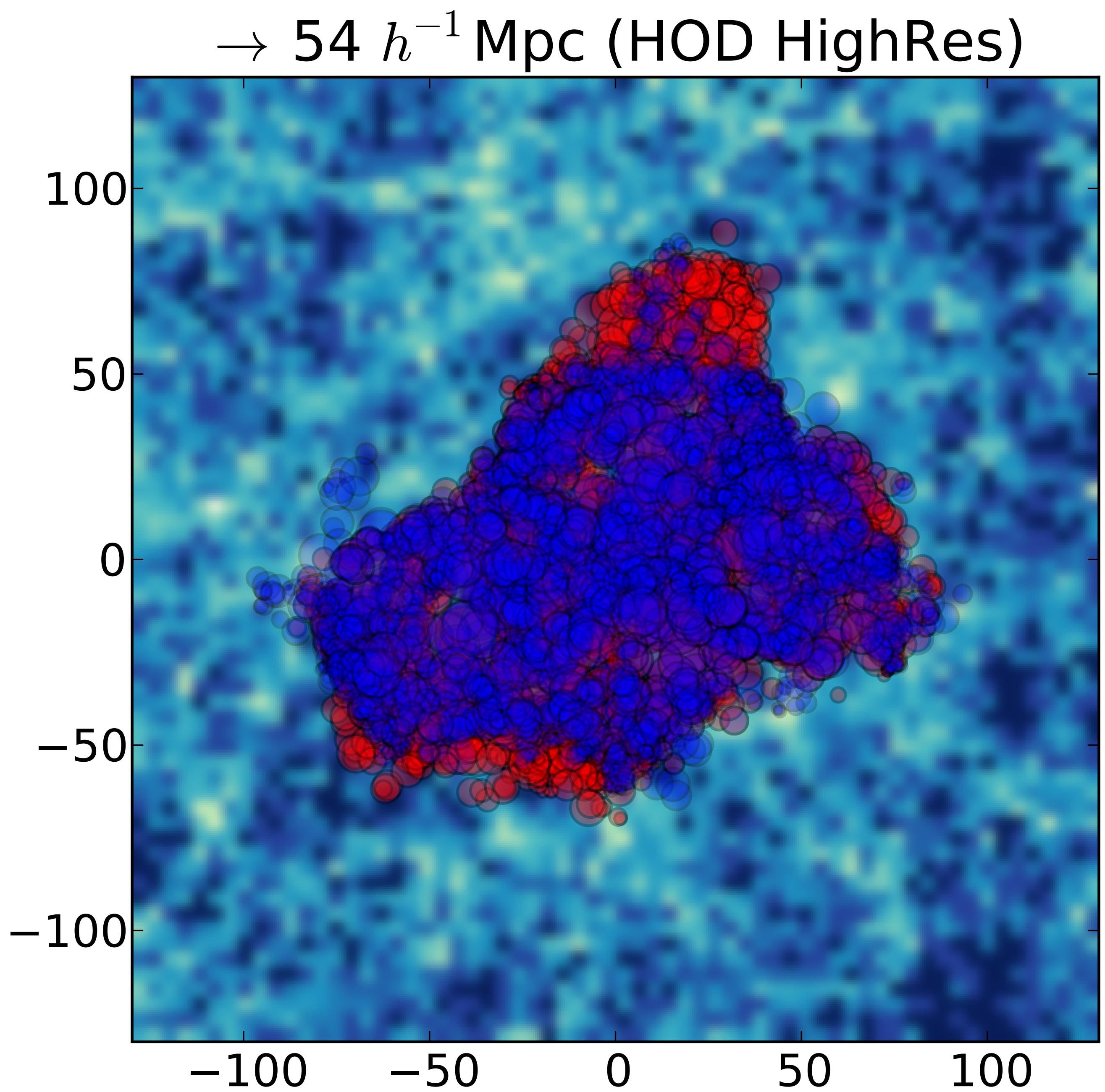
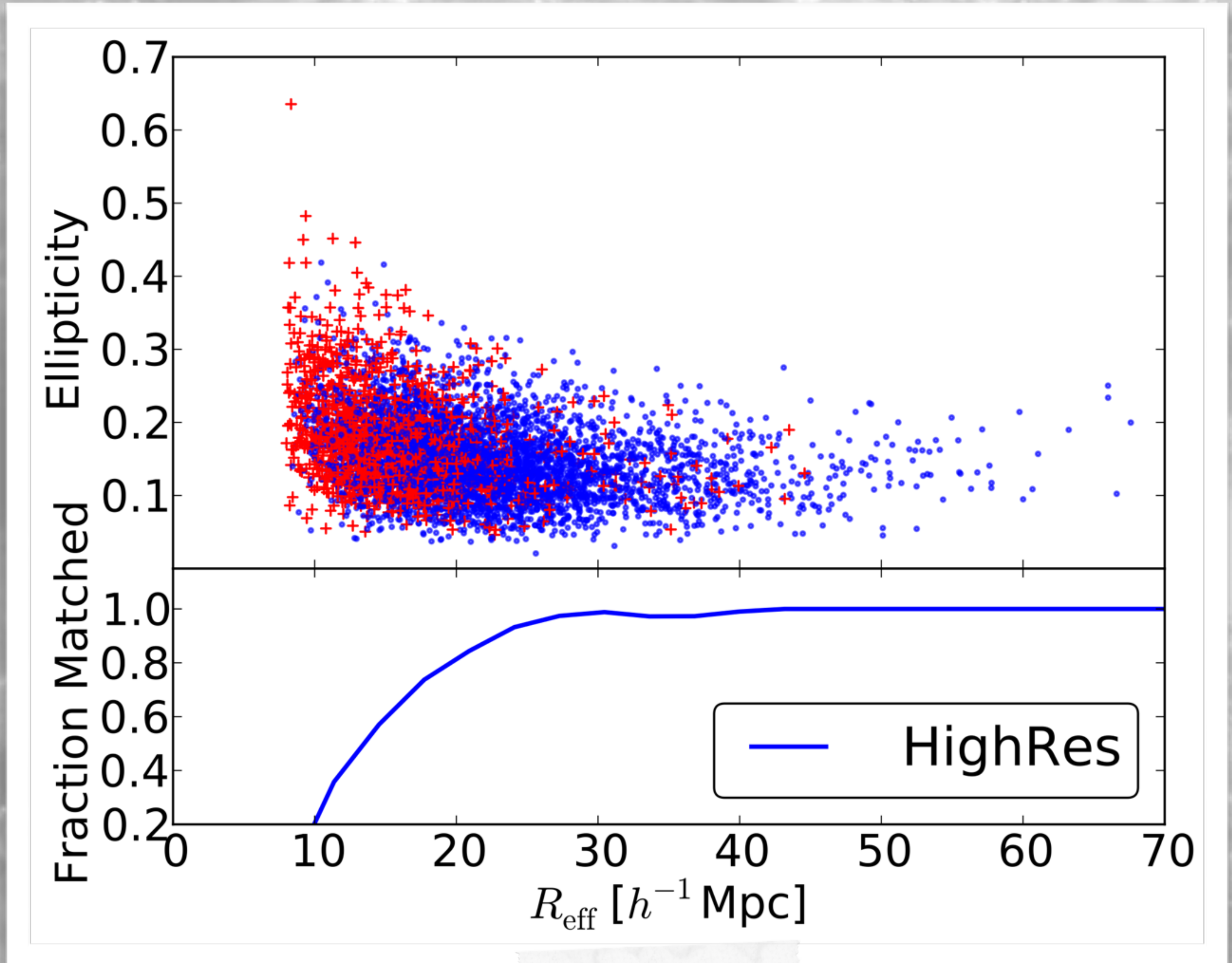


Is the cosmological signal washed out by velocities in a certain kind of voids? Can we identify them and boost the cosmological signal?

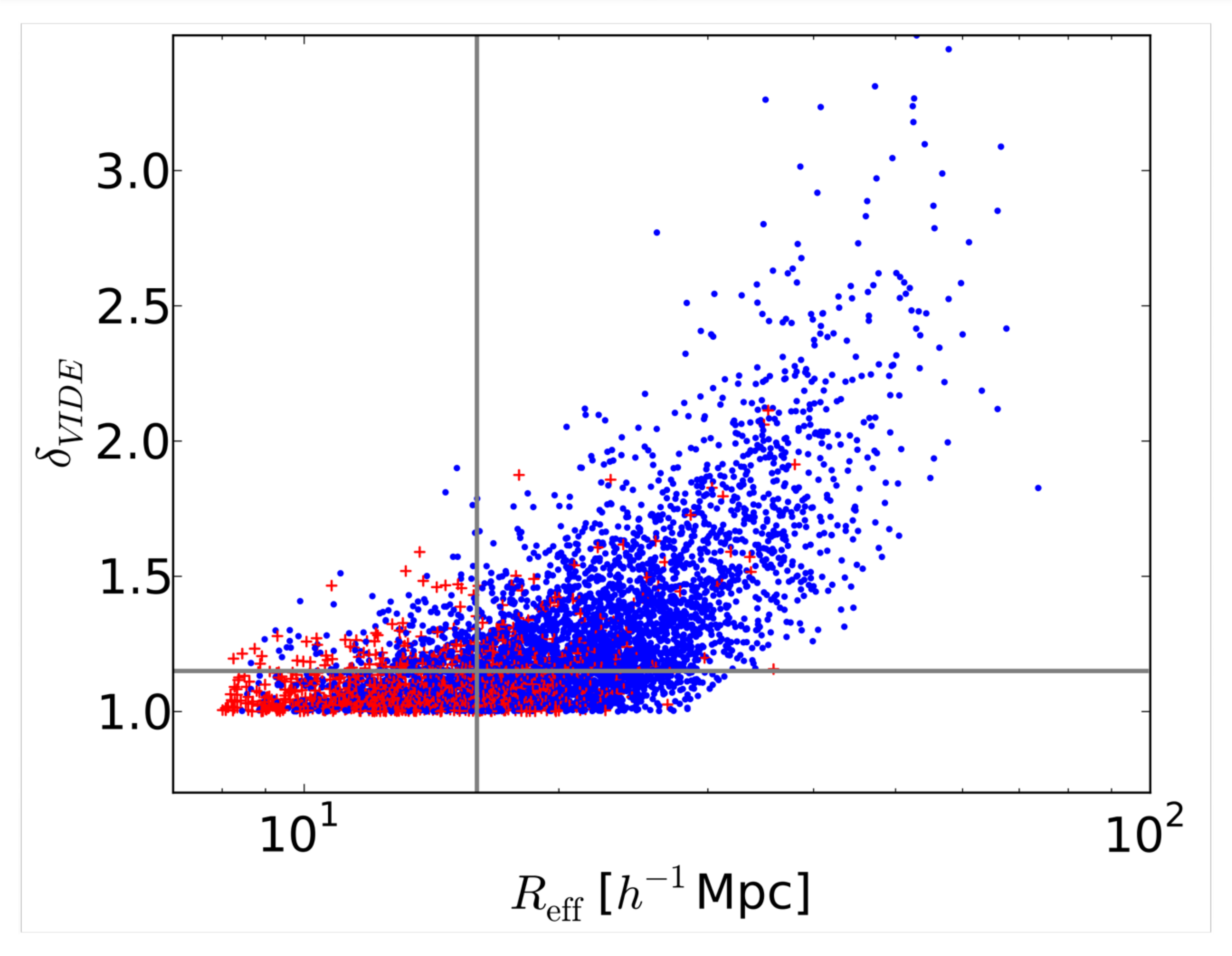
Which voids are affected most?



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

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

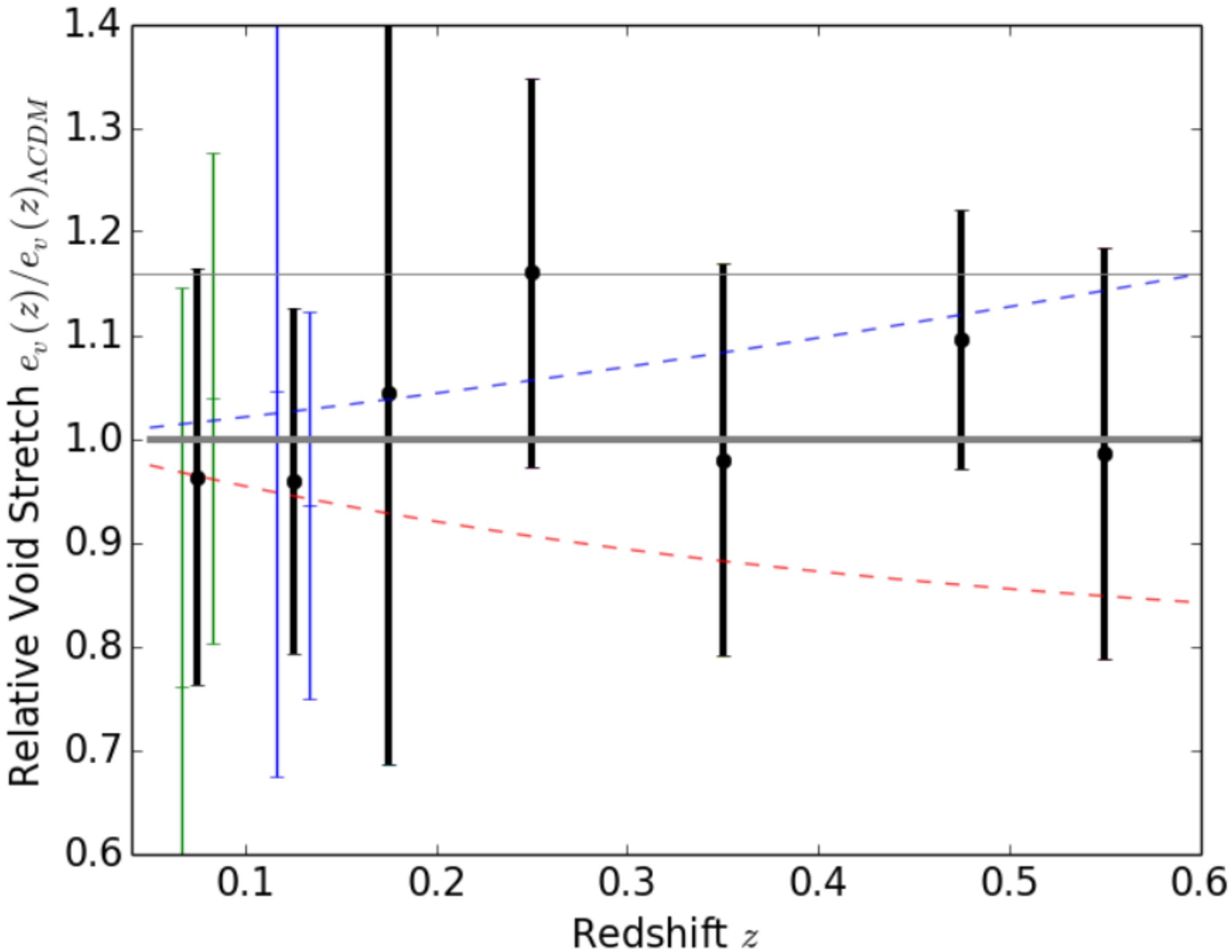
Identify them by properties



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

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

Allows to constrain the matter content of the Universe



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

Flat Universe

$$D_A(z) = \int_0^z \frac{cdz}{H(z)}$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$\Omega_m + \Omega_\Lambda = 1$$

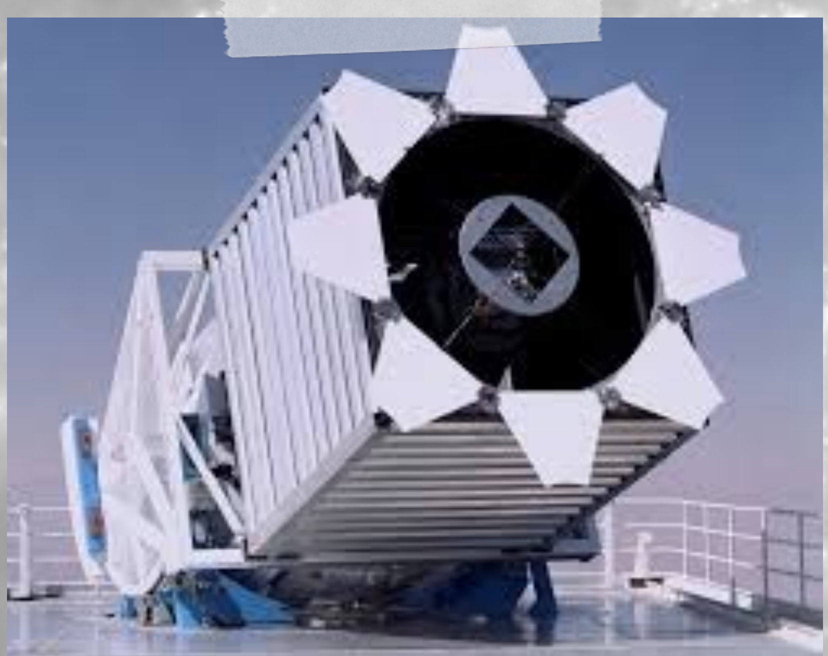
ArXiv: 14045618v2

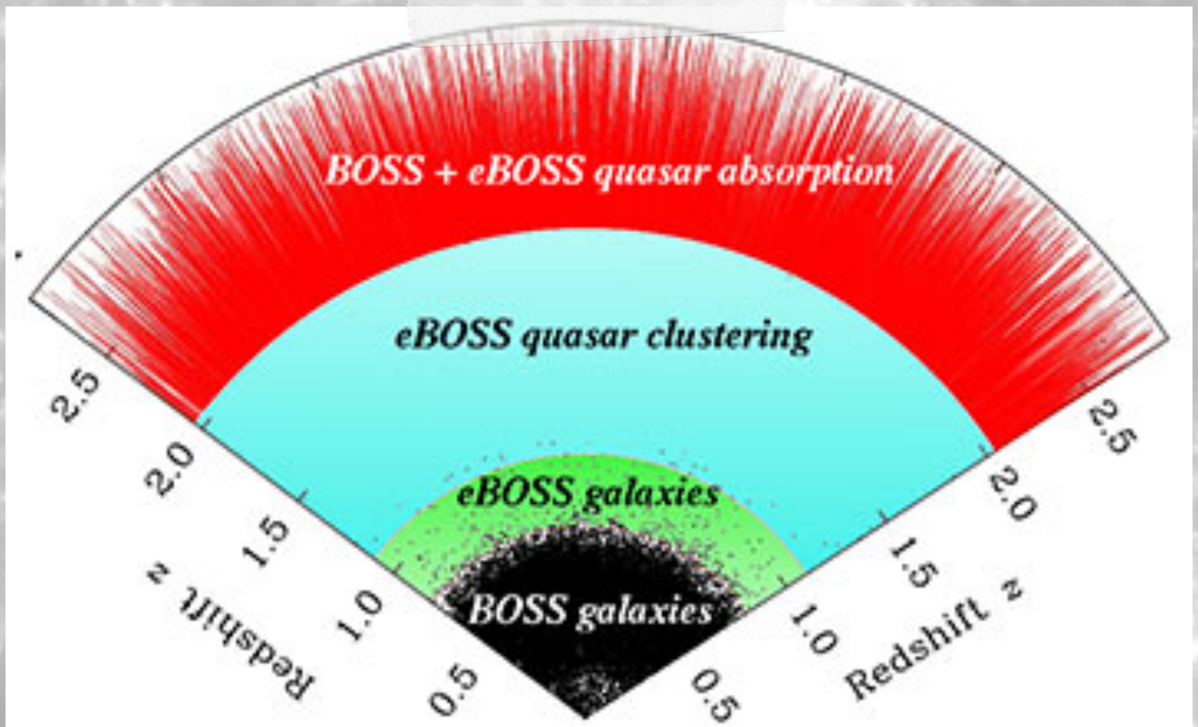
$\Omega_{\rm m} = 0.38^{+0.18}_{-0.15}$ ArXiv: 1602.06306

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.

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





Model the velocities: void-galaxy cross-correlation

$$1 + \tilde{\xi}_{\rm vg}(\tilde{\mathbf{r}}) = \int \mathcal{P}\left(\mathbf{v}, \mathbf{r}\right)\left[1 + \xi_{\rm vg}(\mathbf{r})\right]\, {\rm d}^3 v = \int_{-\infty}^{\infty} \mathcal{P}\left(v_{\parallel}, \mathbf{r}\right) \frac{\rho_{\rm v}(r)}{\bar{\rho}}\, {\rm d}v_{\parallel}$$

We suppose a Gaussian velocity distribution: $v_{\rm v}(r)\frac{r_{\parallel}}{r}$

$$\mathcal{P}\left(v_{\parallel}, \mathbf{r}\right) = \frac{1}{\sqrt{2\pi}\sigma_v(\mathbf{r})} \exp\left[-\frac{\left(v_{\parallel} - v_{\rm v}(r)\frac{r_{\parallel}}{r}\right)^2}{2\sigma_v^2(\mathbf{r})}\right]$$

Gaussian streaming model, Fisher 1995

With $$\sigma_v^2(\mathbf{r}) = \sigma_{\parallel}^2(r)\frac{r_{\parallel}^2}{r^2} + \sigma_{\perp}^2(r)\left(1 - \frac{r_{\parallel}^2}{r^2}\right)$$

(assuming $\sigma_{\parallel,\perp}(r) \equiv \sigma_v = \text{const.}$)

The velocity profile of voids

Imposing mass conservation we can show that

$$v_{\rm v}(r) \simeq -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta_{\rm vm}(r)$$

P. J. E. Peebles, The large-scale structure of the universe. 1980.

$f(z)$ linear growth rate of density perturbations

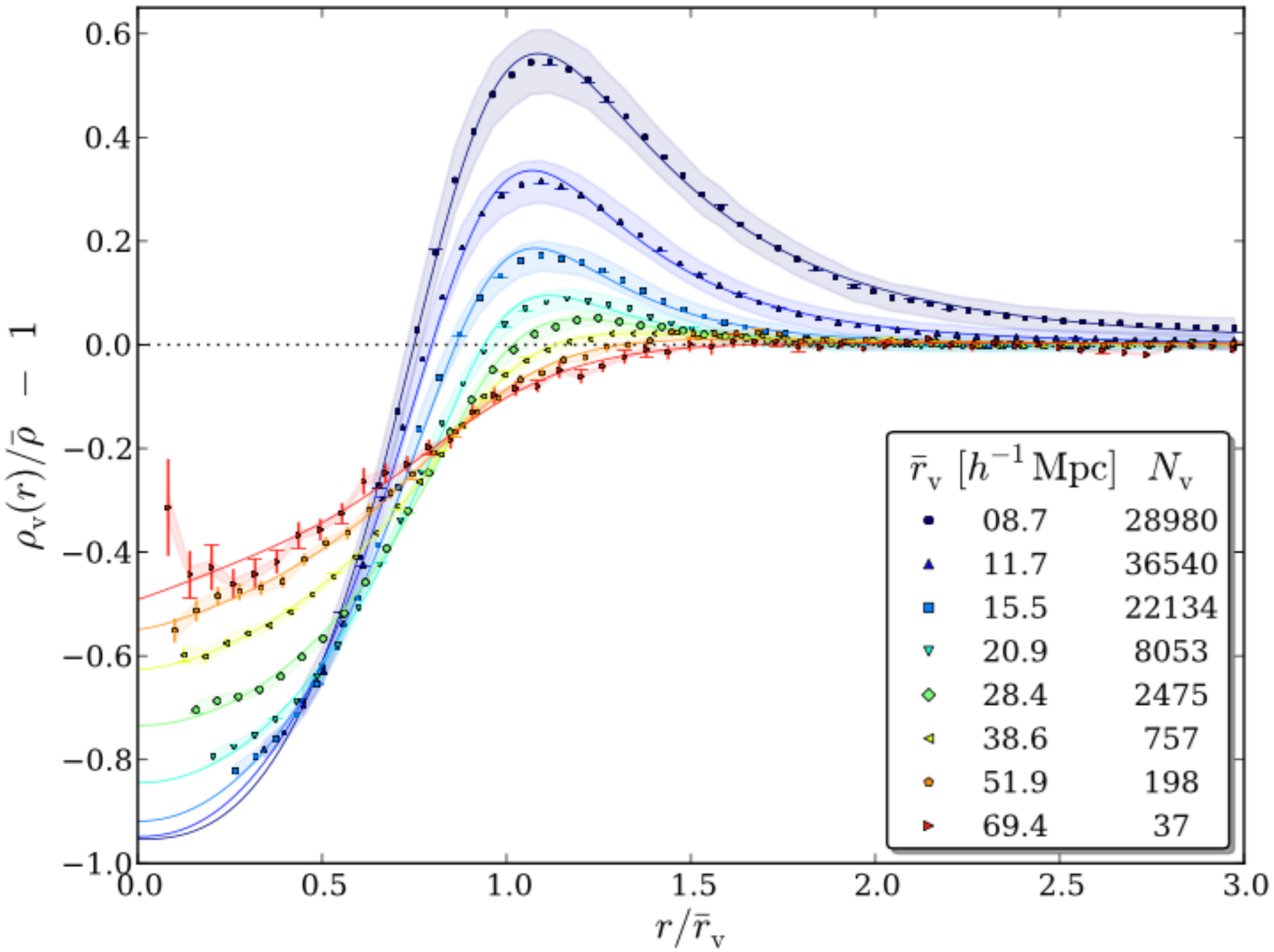
$$\Delta_{\rm vm}(r) = \frac{3}{r^3}\int_0^r \left(\frac{\rho_{\rm vm}(q)}{\bar{\rho}_{\rm m}} - 1\right) q^2 \, {\rm d}q$$

Cumulated density profile

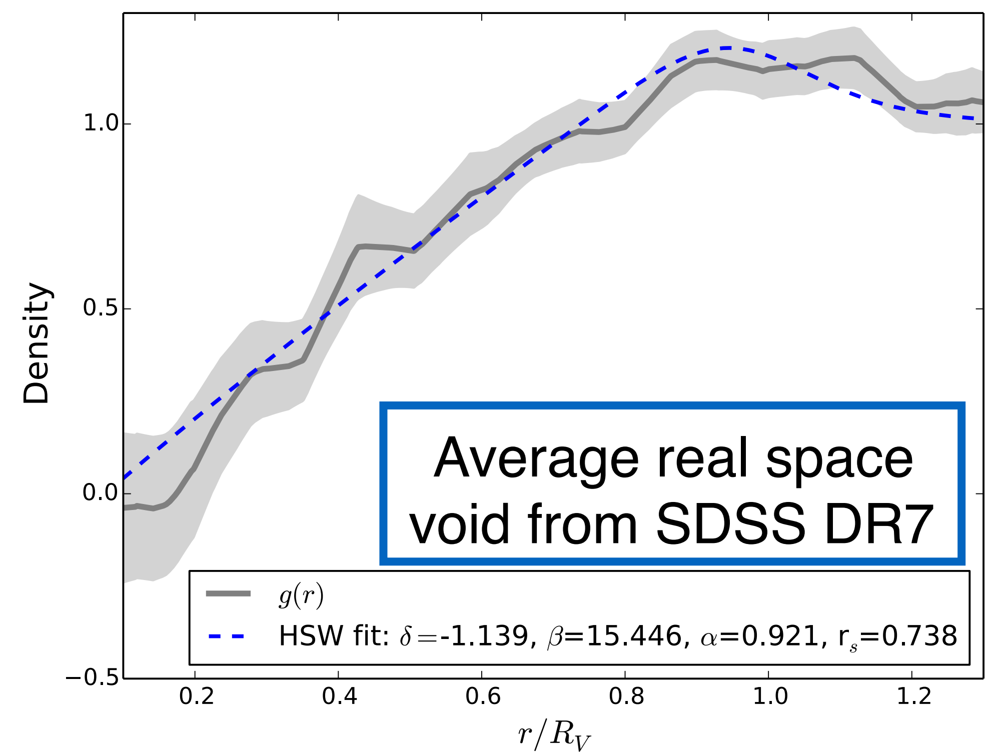
Modeling the density profile

$$\frac{\rho_{\rm vm}(r)}{\bar{\rho}_{\rm m}} - 1 = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_{\rm v})^{\beta}} ,$$

- δ_c density contrast
- r_s radius at which density equal mean density
- α slope before wall
- β slope after wall
- α, β linear functions of $r_s / \bar{r}_{\rm v}$

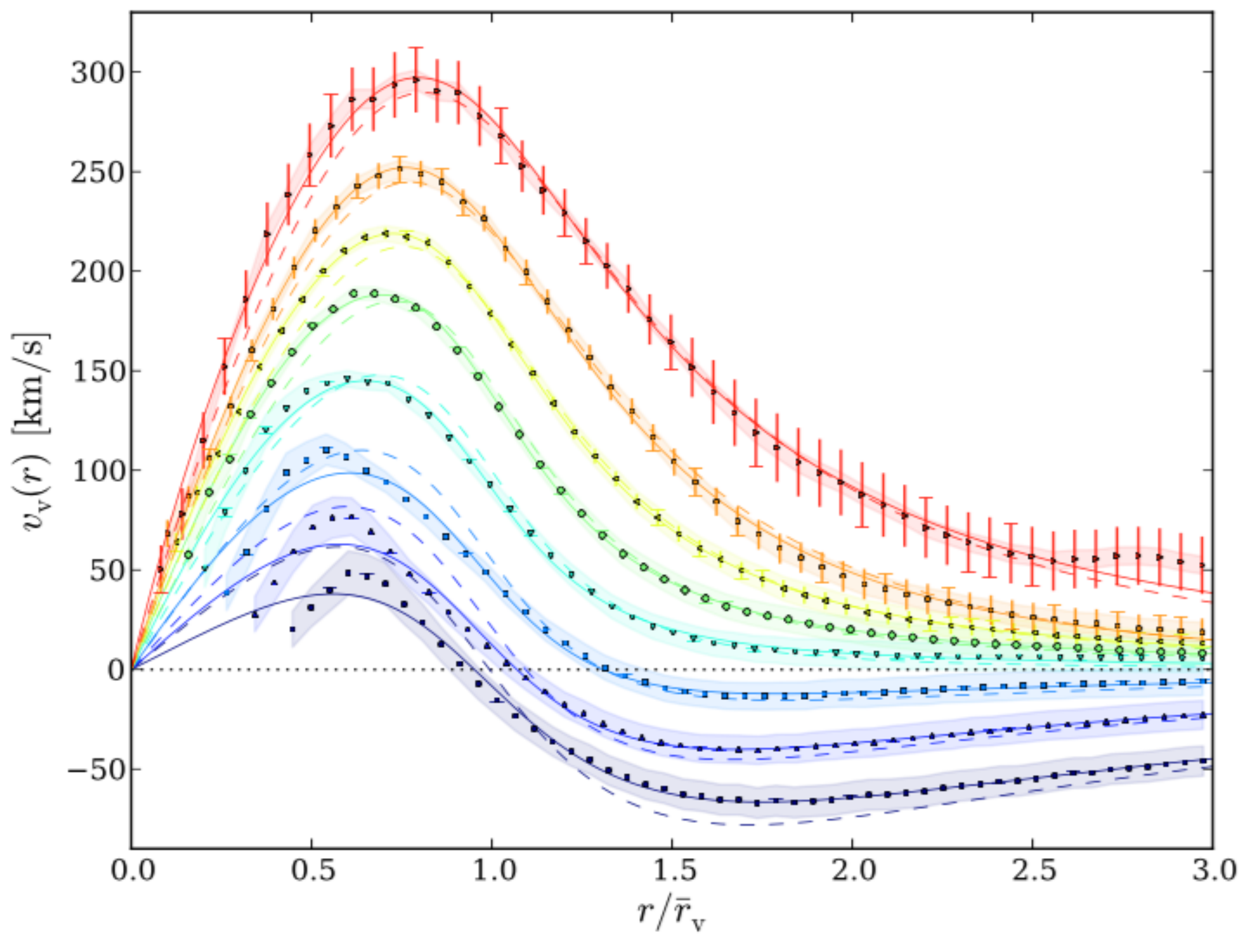


$$R_{\rm V} \equiv \left(\frac{3}{4\pi} V\right)^{1/3}$$

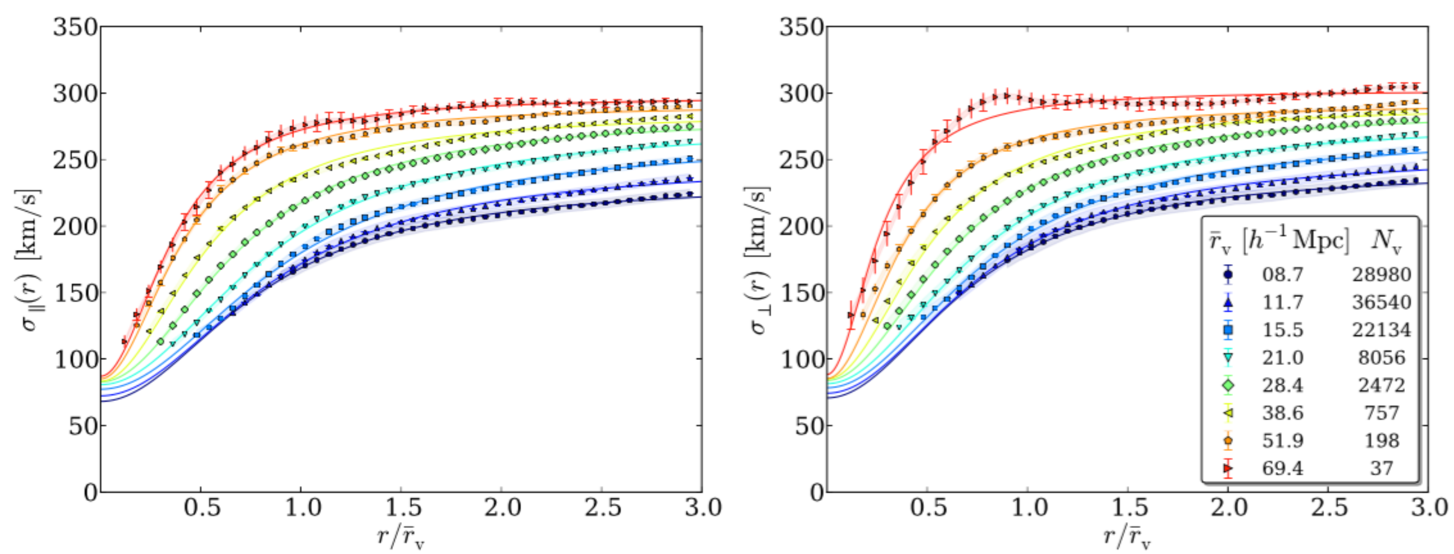


ArXiv: 1403.5499 Hamaus et al. 2014, 1306.3052 Pisani et al. 2014

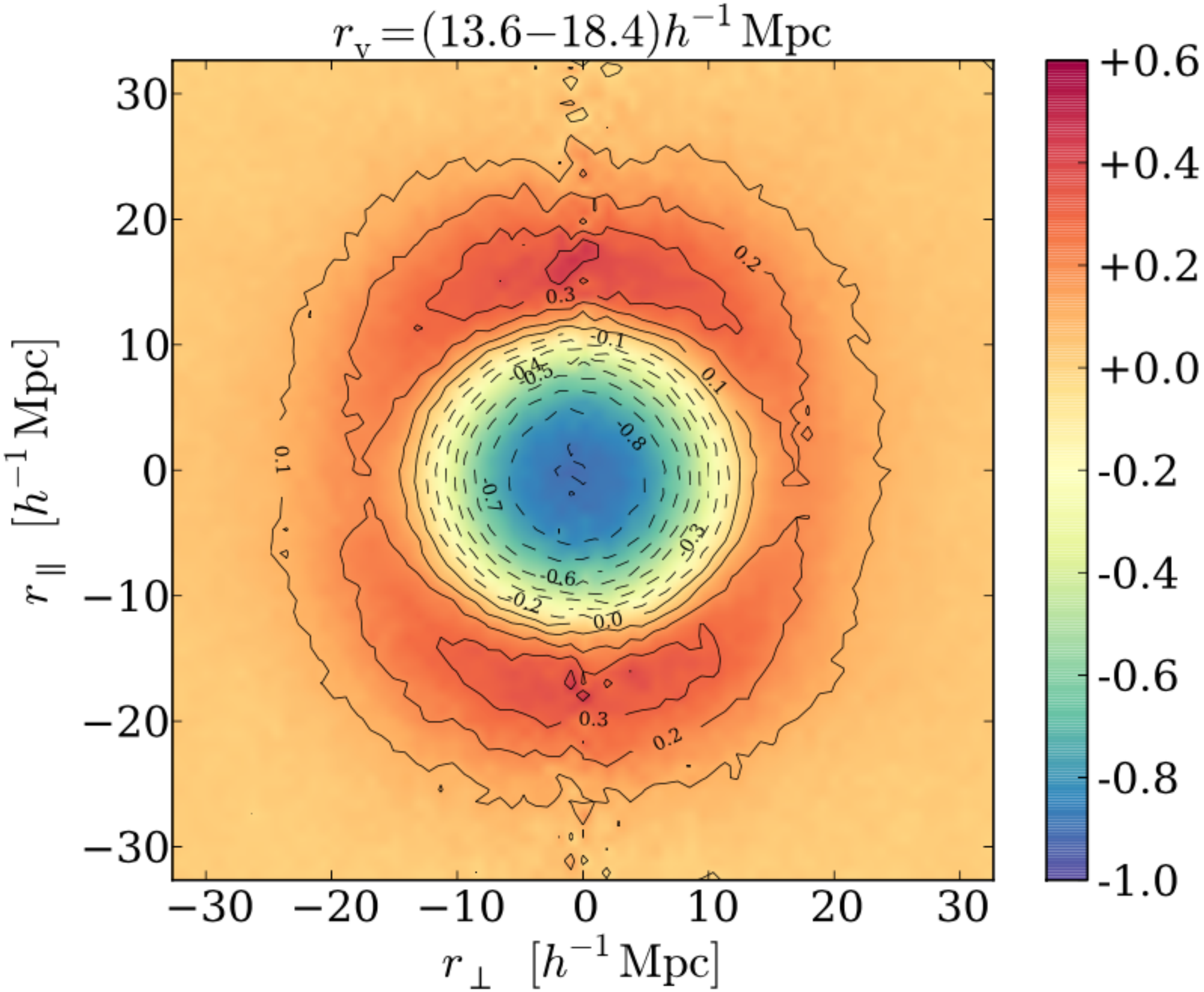
The velocity profile



$$v_{\rm v}(r) \simeq -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta_{\rm vm}(r) \; ,$$



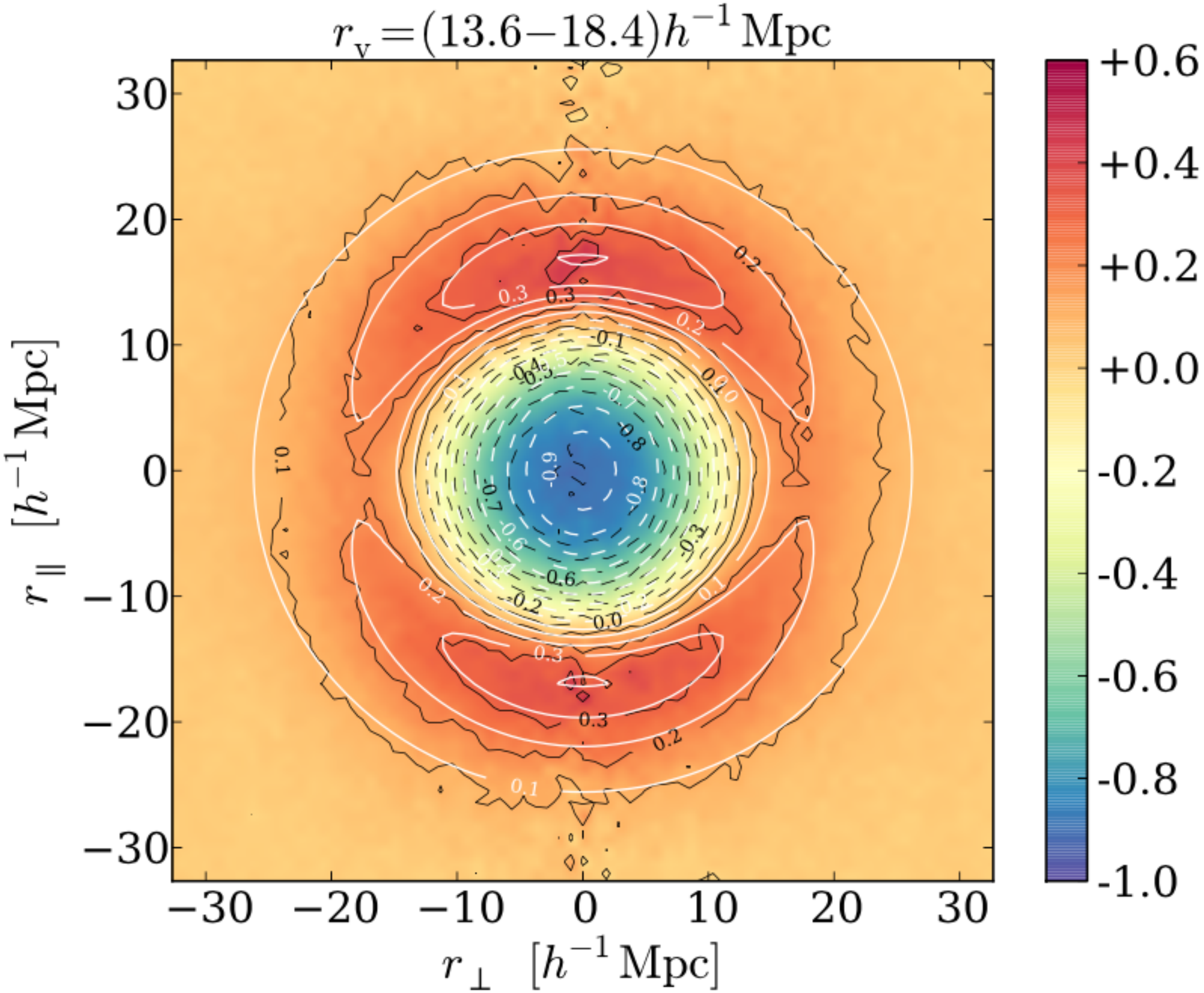
Model velocities around voids



Simulation

Hamaus et al 2015 ArXiv: 1507.04363

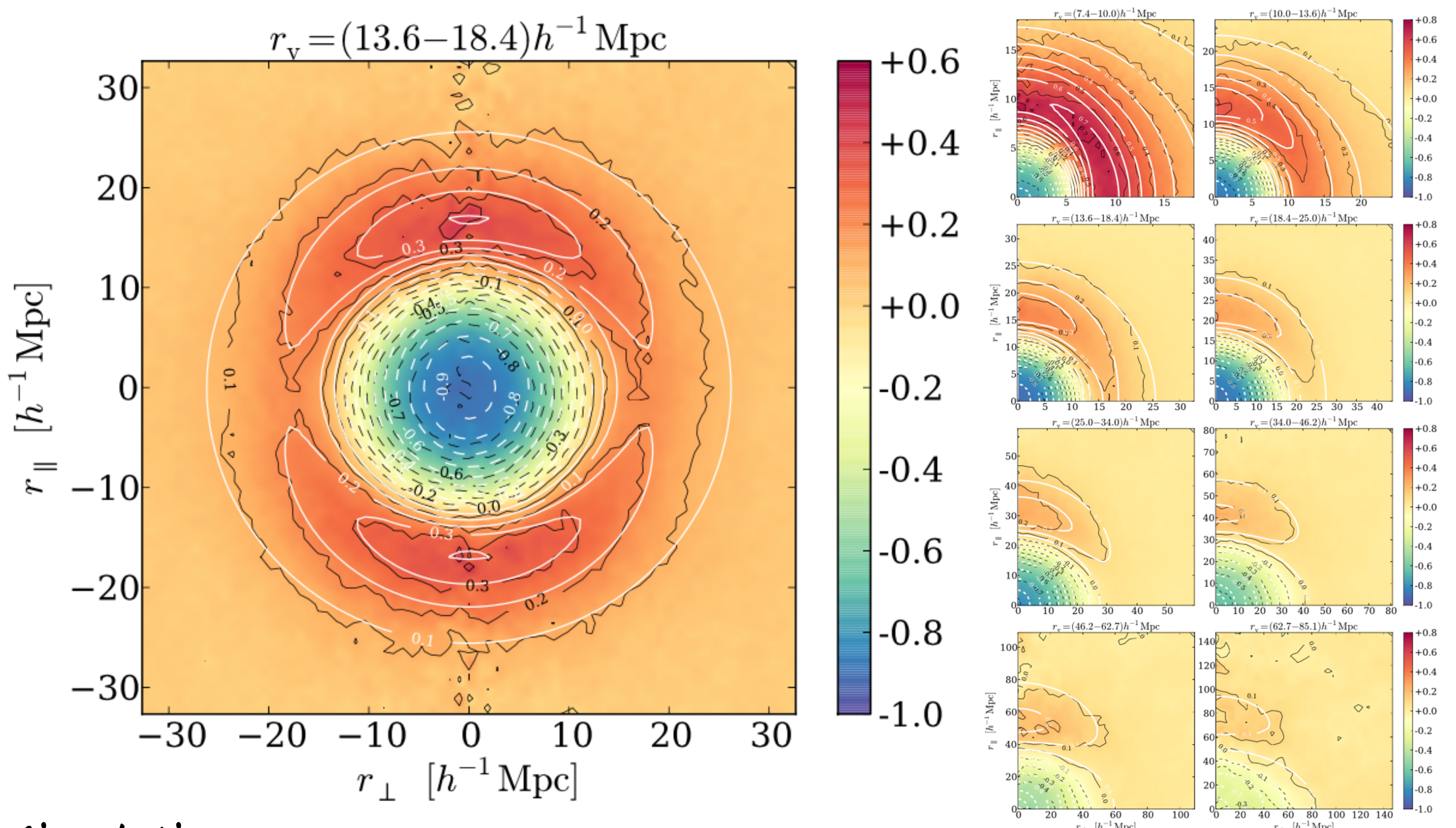
Model velocities around voids



Simulation

Hamaus et al 2015 ArXiv: 1507.04363

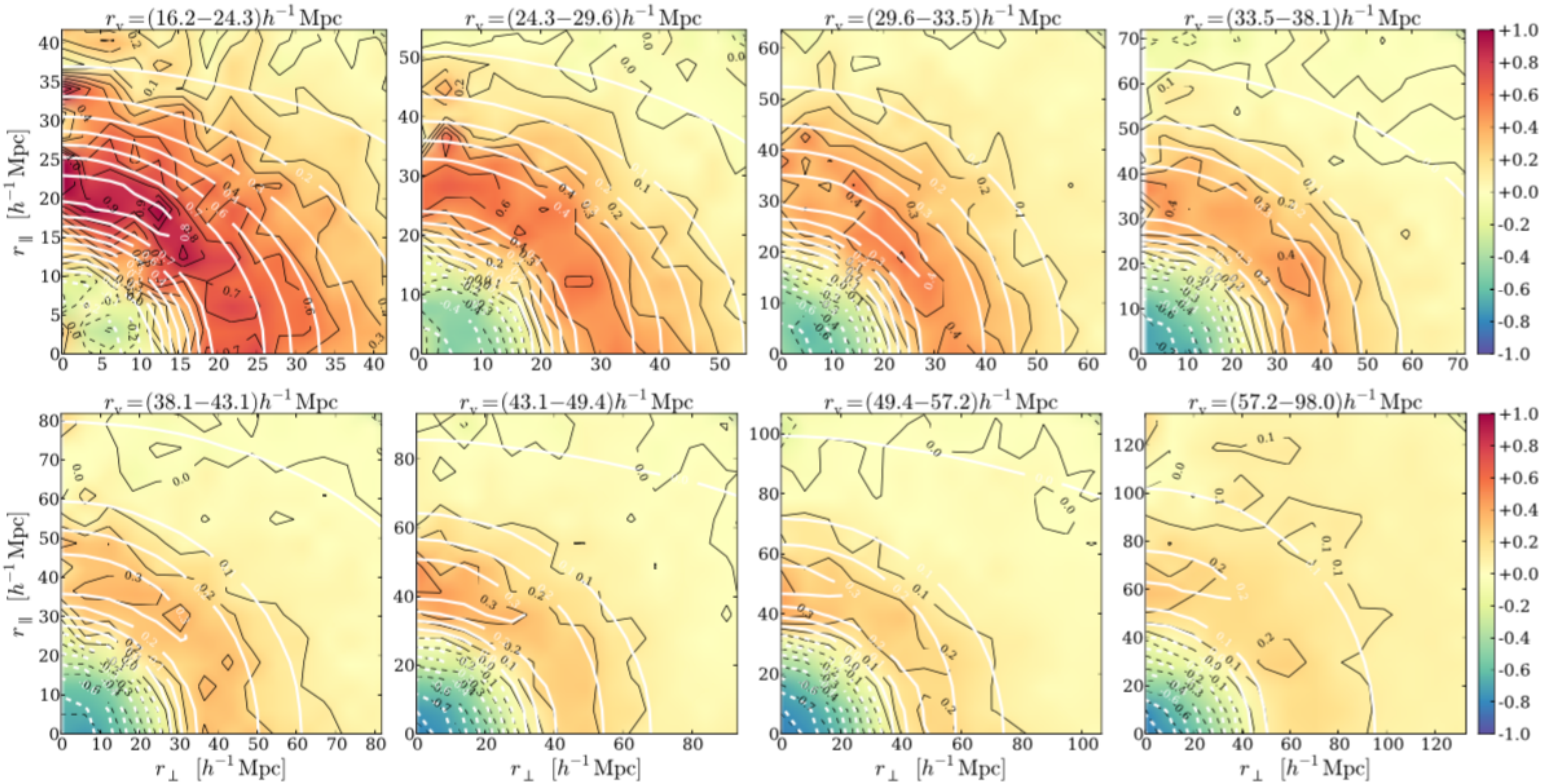
Model velocities around voids



Simulation

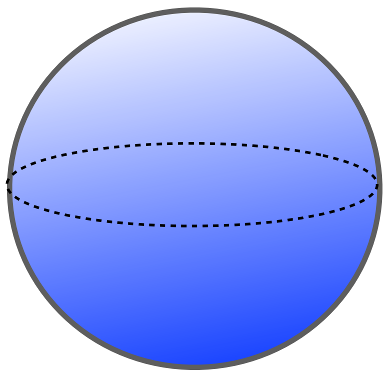
Hamaus et al 2015 ArXiv: 1507.04363

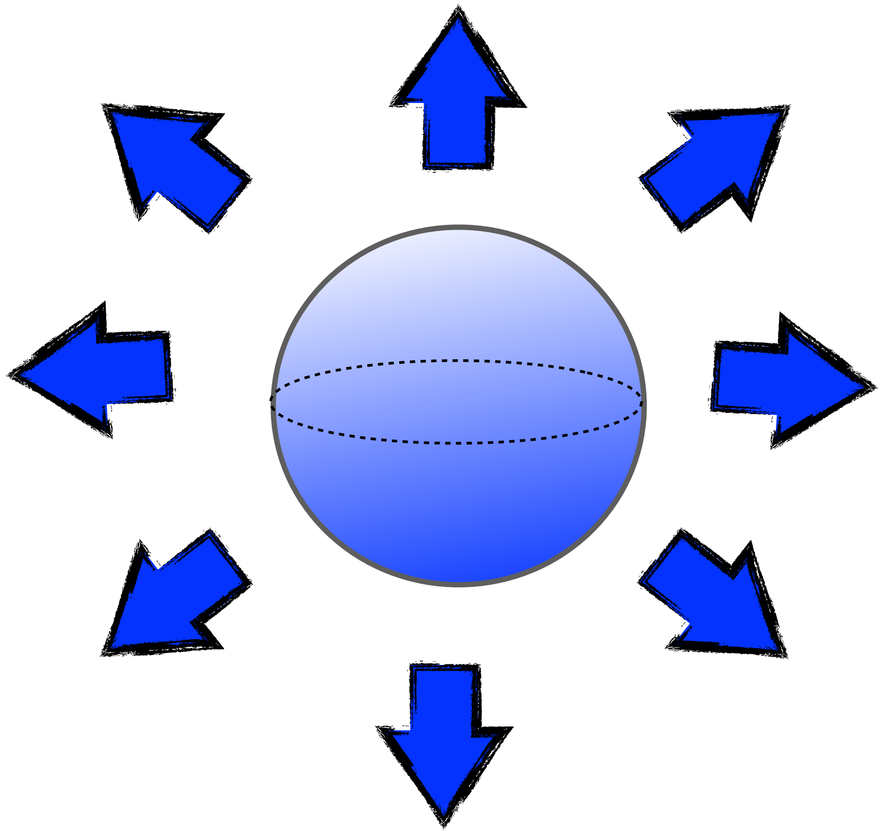
SDSS data (BOSS CMASS)



Hamaus et al 2016 arXiv: 1602.01784

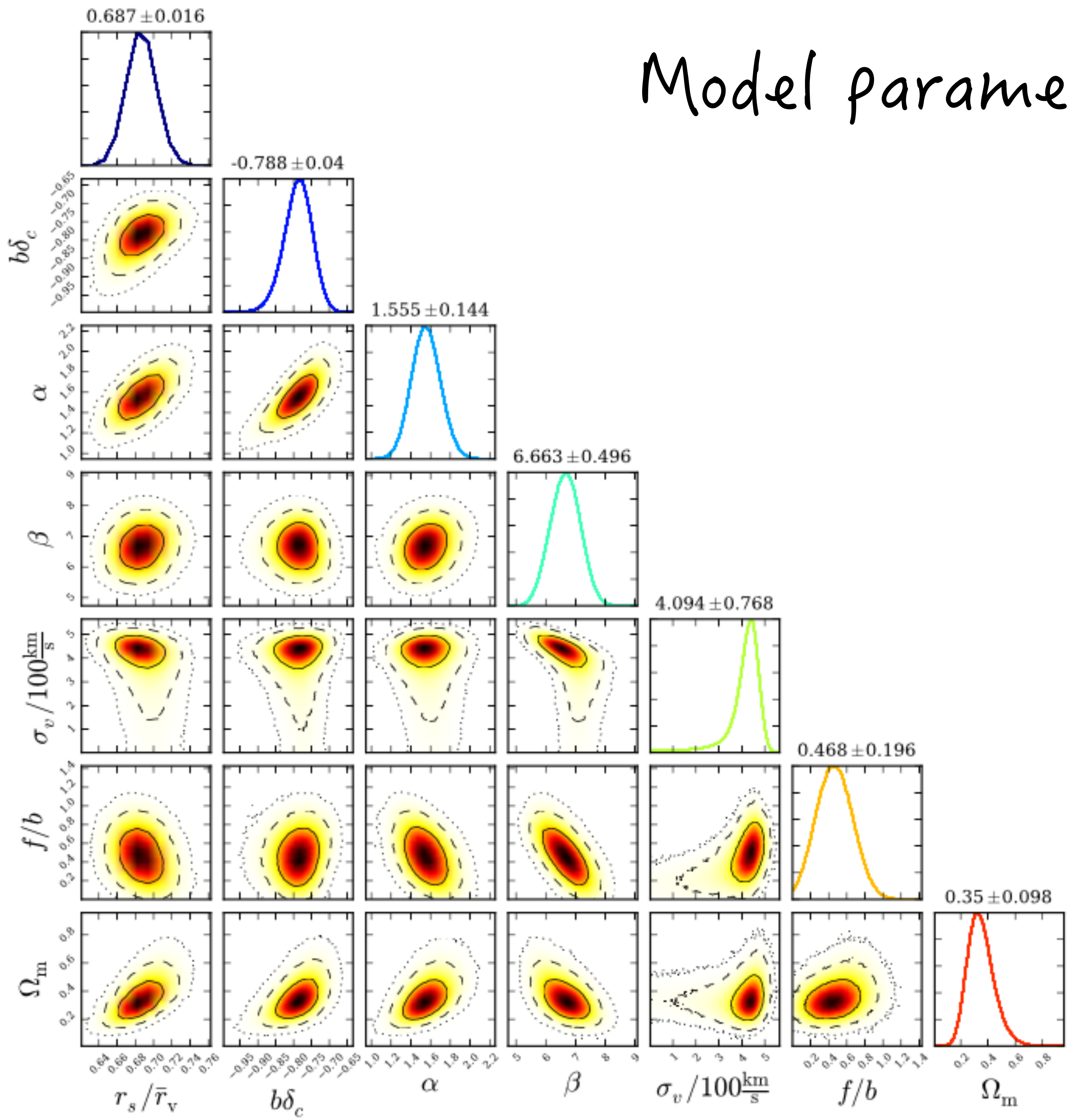
We can model everything now





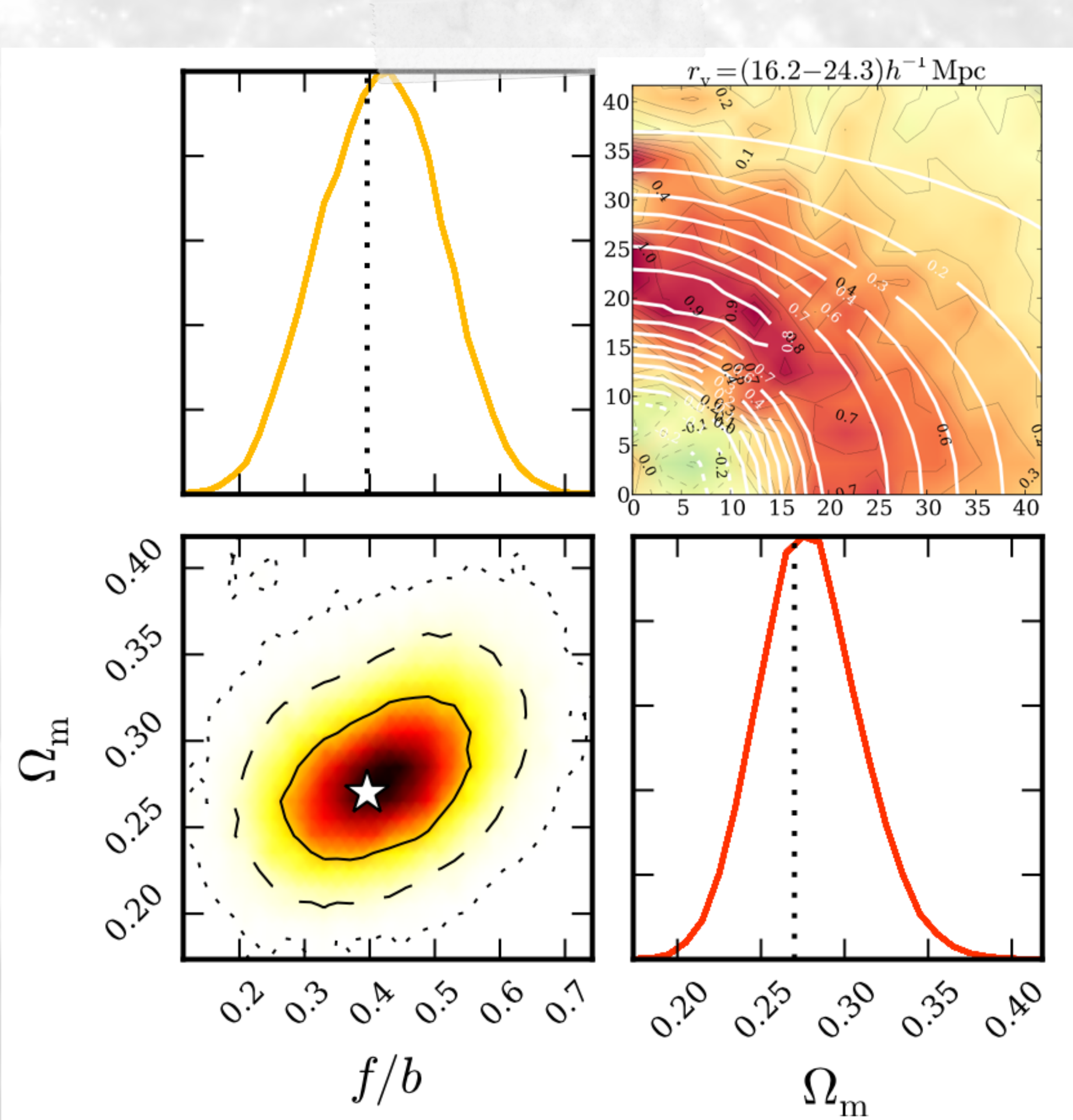
We can model everything now

Model parameters (AP+RSD)



arXiv: 1602.01784

RSD+ AP: competitive constraints



The matter content is constrained at a precision level !

And the model allows to test General Relativity (which still works !)

arXiv: 1602.01784; **Phys. Rev. Lett. 117, 091302** (Hamaus, **Pisani**, Sutter, Lavaux, Escoffier, Wandelt, Weller **2016**)

Summary

- Extremely short cosmology reminder
- Voids, a tool for cosmology
- Finding voids
- The shape of voids
- Constraining General Relativity
- Count to understand Dark Energy

As a bonus: analyzing the velocities around voids allows to constrain General Relativity in an independent way

$f(z)$ linear growth rate of density perturbations

$$\beta = \frac{f}{b} = \frac{\Omega_m(z)^\gamma}{b}$$

In General Relativity γ~0.55, we can predict the theoretical value for f in our cosmological model (LCDM+ RG).

Measuring multipoles of the void-galaxy correlation function

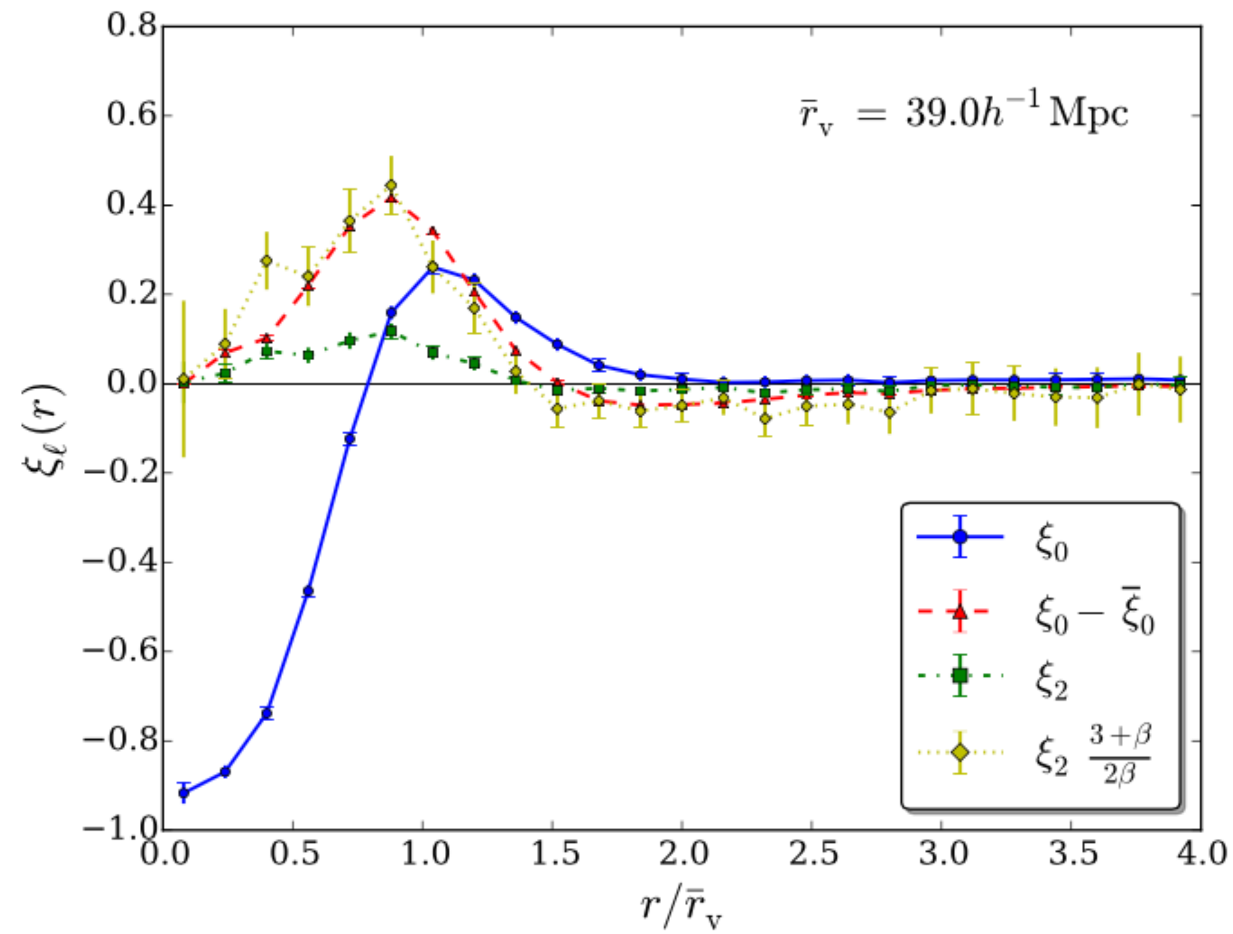
Decomposing them into Legendre's polynomials

$$\xi_\ell(r) = \int_0^1 \xi^s(r,\mu)(1+2\ell)P_\ell(\mu)\mathrm{d}\mu \qquad \beta = \frac{f}{b} = \frac{\Omega_m(z)^\gamma}{b}$$

$$\xi_0(r) = \left(1+\frac{\beta}{3}\right)\xi(r)$$

$$\xi_2(r) = \frac{2\beta}{3}\left[\xi(r) - \bar{\xi}(r)\right]$$

$$\xi_0(r) - \bar{\xi}_0(r) = \xi_2(r)\frac{3+\beta}{2\beta}$$



Cai et al. 2016 , ArXiv: 1603.05184; Hamaus et al. 2017 ArXiv:1705.05328

Updated constraints on General Relativity

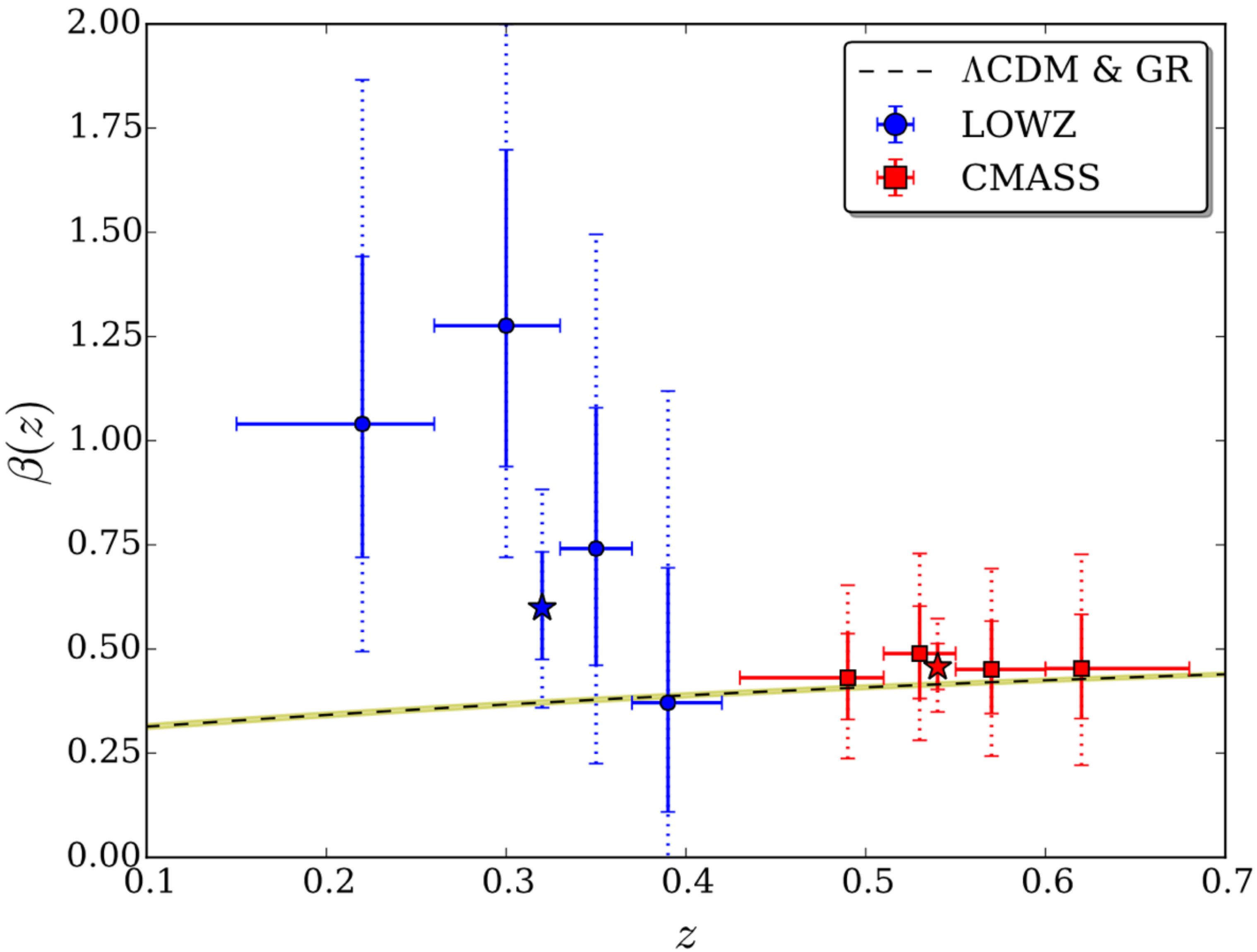


Figure 9. Growth rate constraints as a function of redshift from LOWZ (blue circles) and CMASS (red squares). Stars represent the joint constraint from voids of all redshifts in each sample. Vertical solid lines indicate 1σ, dotted lines 2σ confidence intervals. Horizontal lines delineate redshift bins. The dashed line with yellow shading shows $\beta = \Omega_{\rm m}^{\gamma}(z)/b$, with $\Omega_{\rm m}(z=0) = 0.308 \pm 0.012$ [70], $\gamma = 0.55$ [45], and $b = 1.85$ [52], assuming a flat ΛCDM cosmology and GR.

Hamaus, Cousinou, Pisani, Aubert, Escoffier, Weller 2017 ArXiv:1705.05328

Summary

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- Voids, a tool for cosmology
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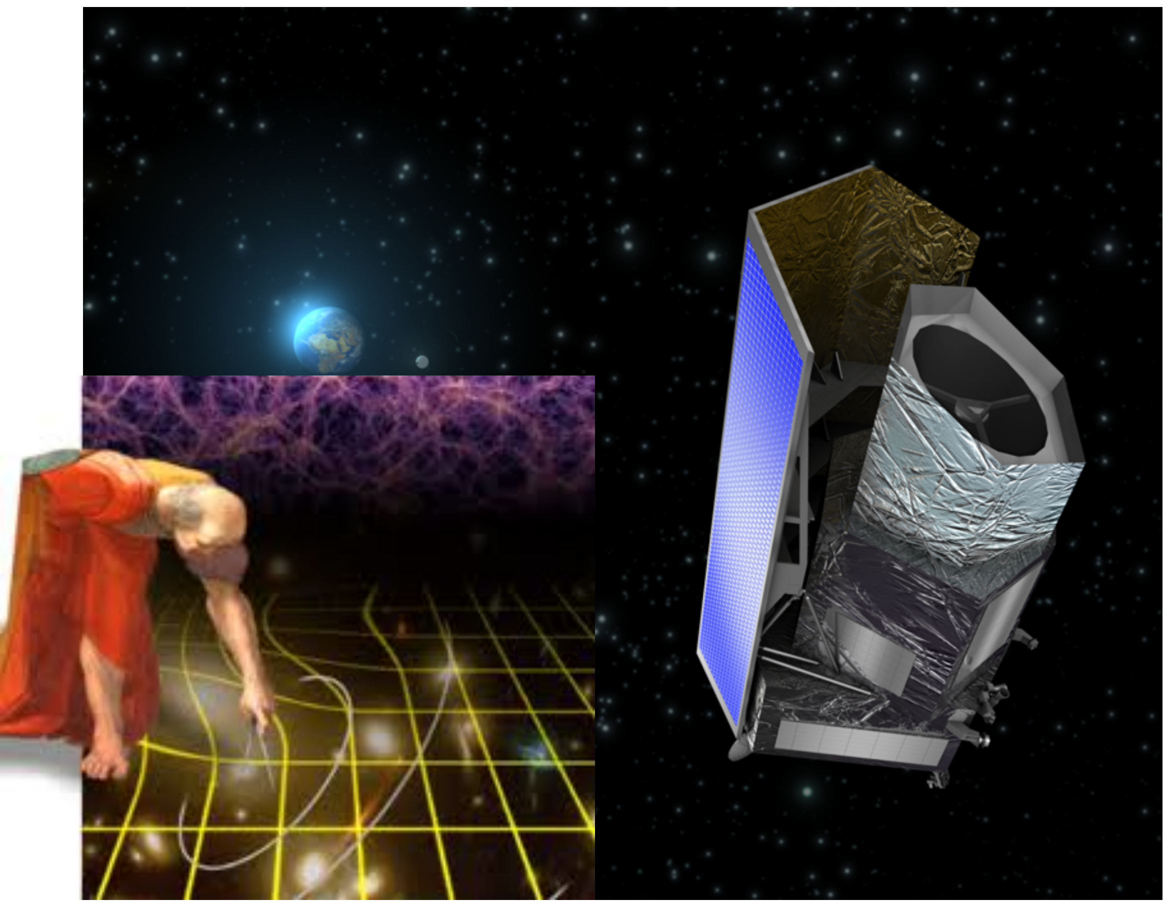
The importance of a large sample

All this work done with ~3000 voids, what can we expect from the future?

Back to the future: betting on LSS with upcoming surveys

Back to the future: betting on LSS with upcoming surveys

SDSS



EUCLID $5.0 \cdot 10^7$

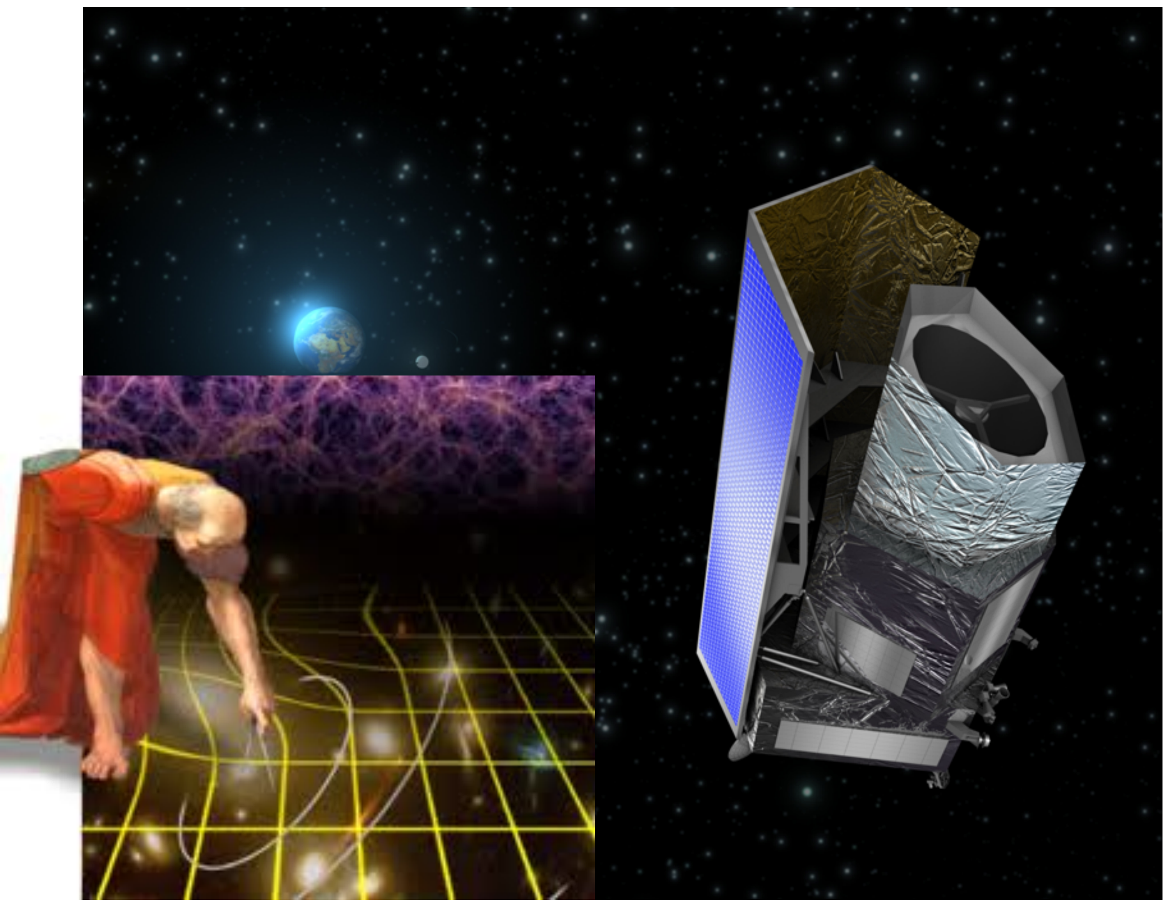
WFIRST

$2.0 \cdot 10^7$

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

Back to the future: betting on LSS with upcoming surveys

SDSS



EUCLID $5.0 \cdot 10^7$

WFIRST $2.0 \cdot 10^7$

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

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

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

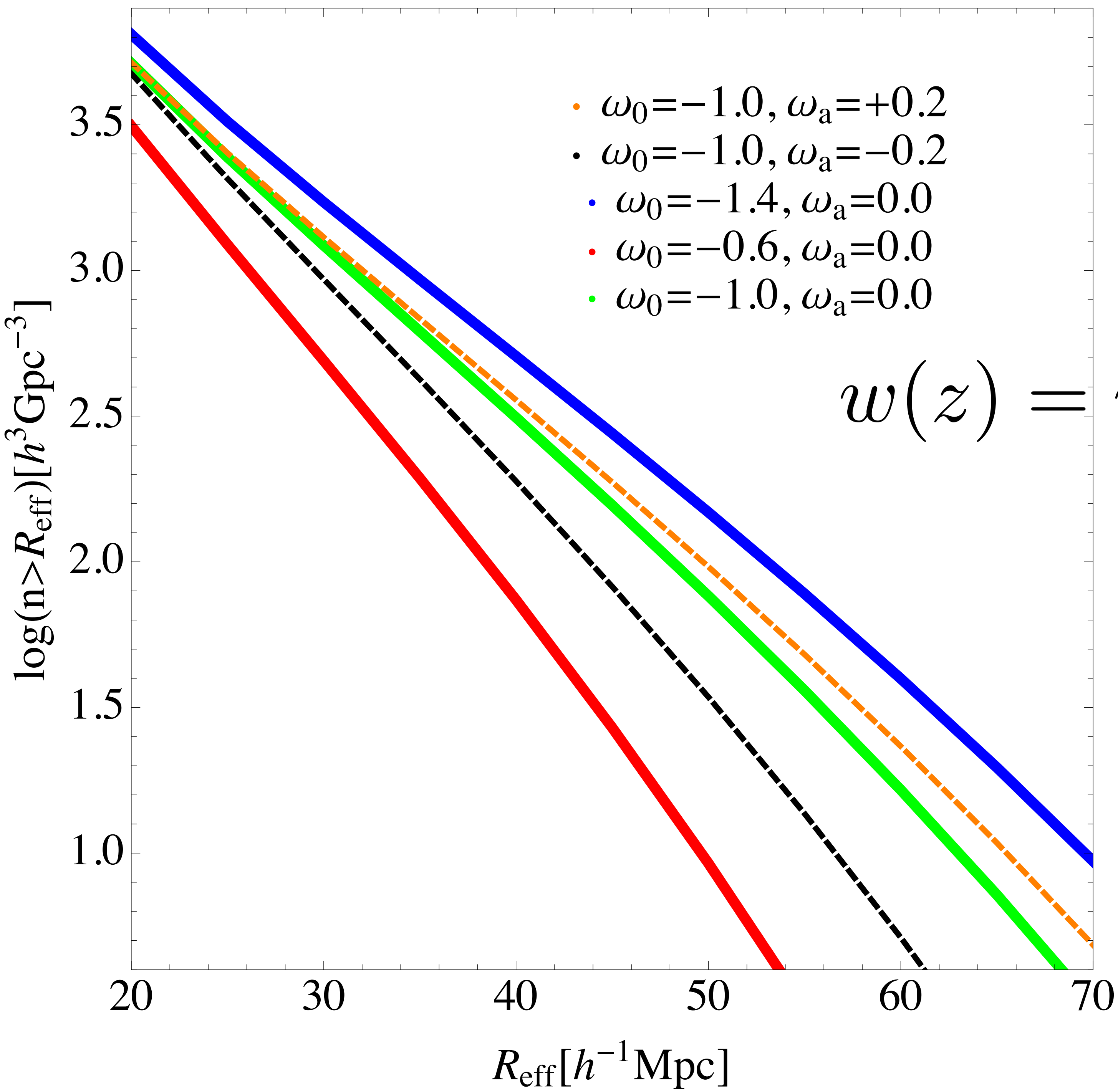
+

Survey

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

Realistic estimation of the number of voids

Void abundance to constrain DE

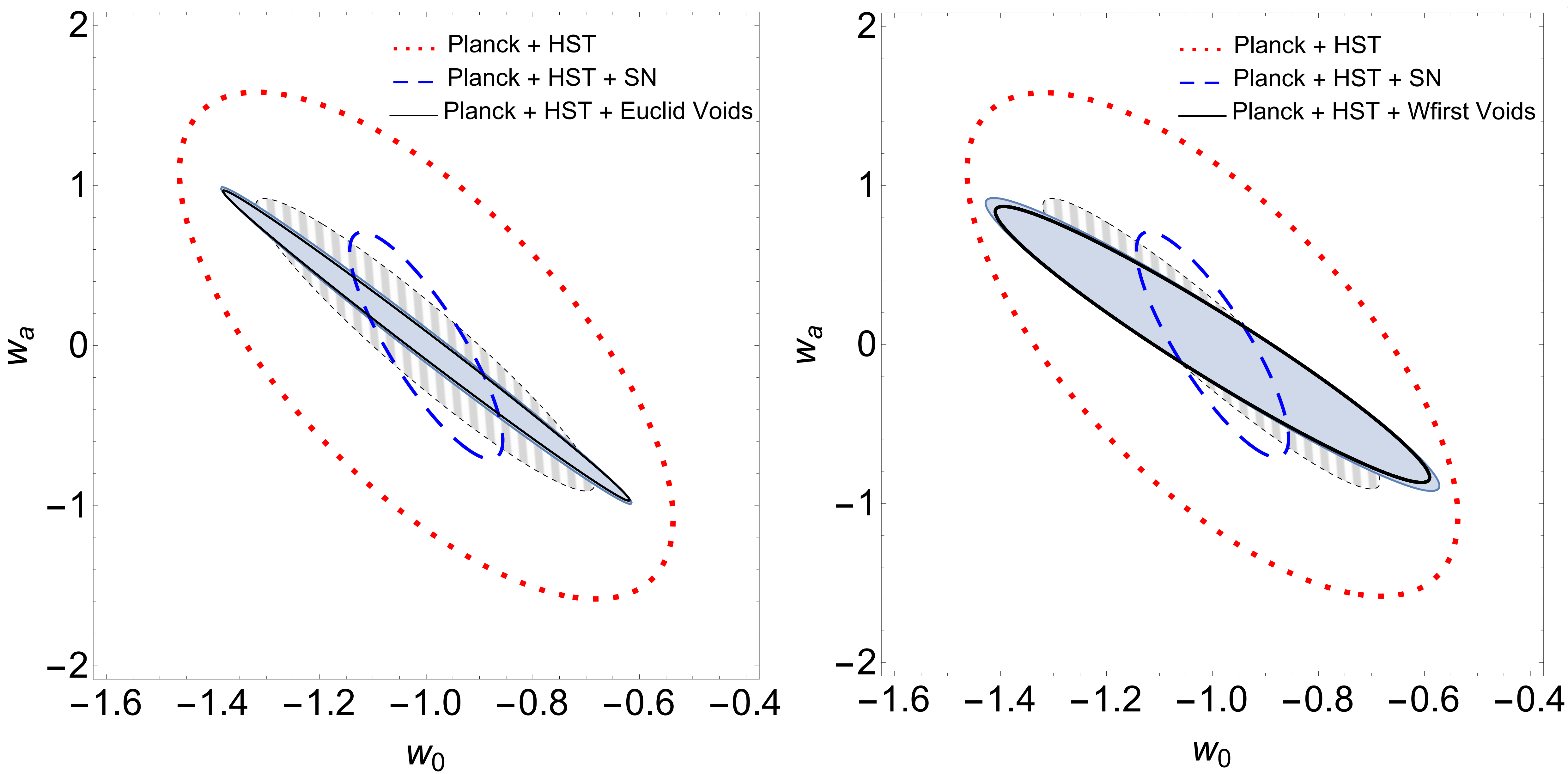


$$w(z) = w_0 + w_a \frac{z}{z+1}$$

time evolution of DE ?

Comparing future surveys:

EUCLID



WFIRST

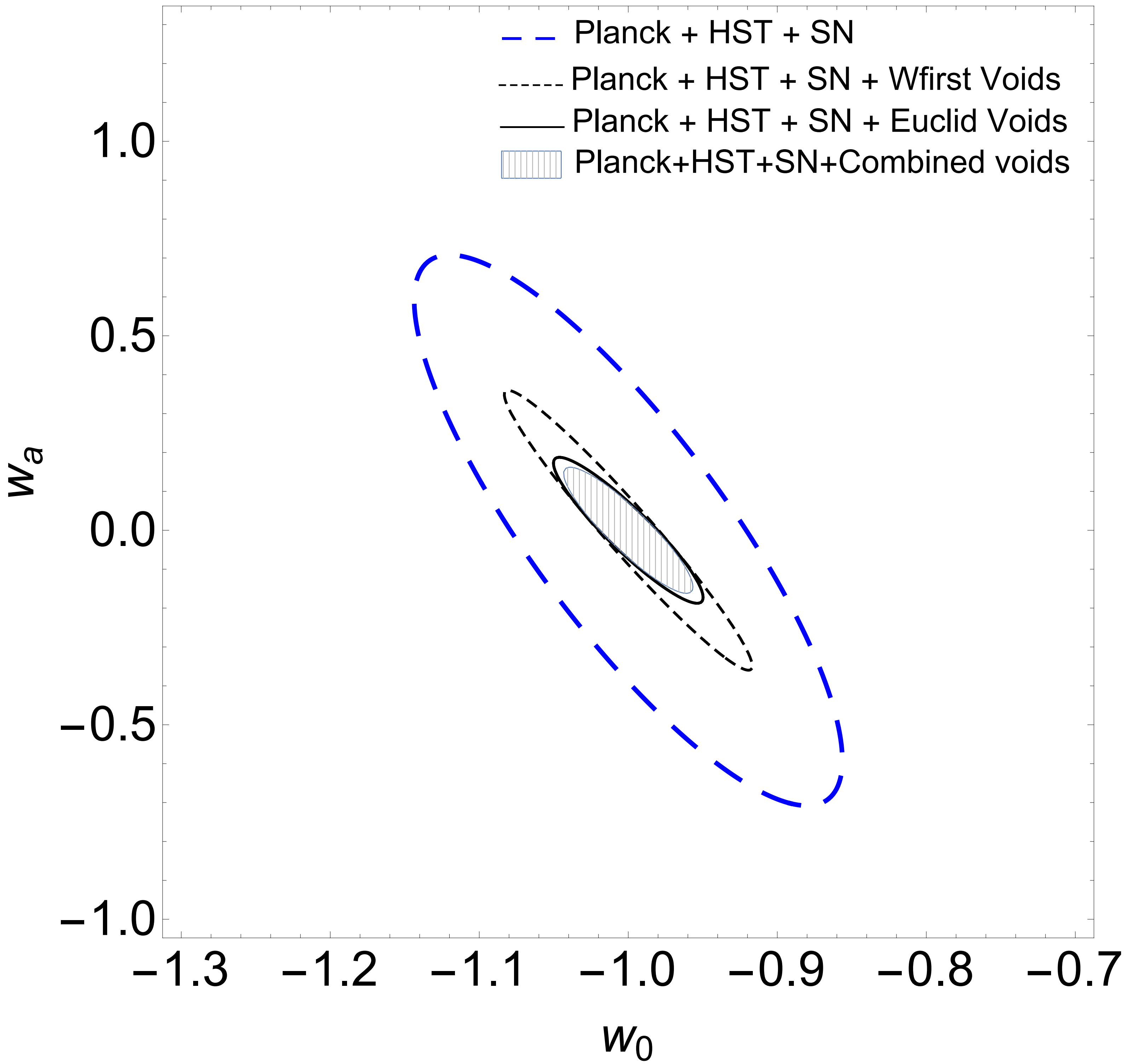
7.8×10^5

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

2.5×10^5

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

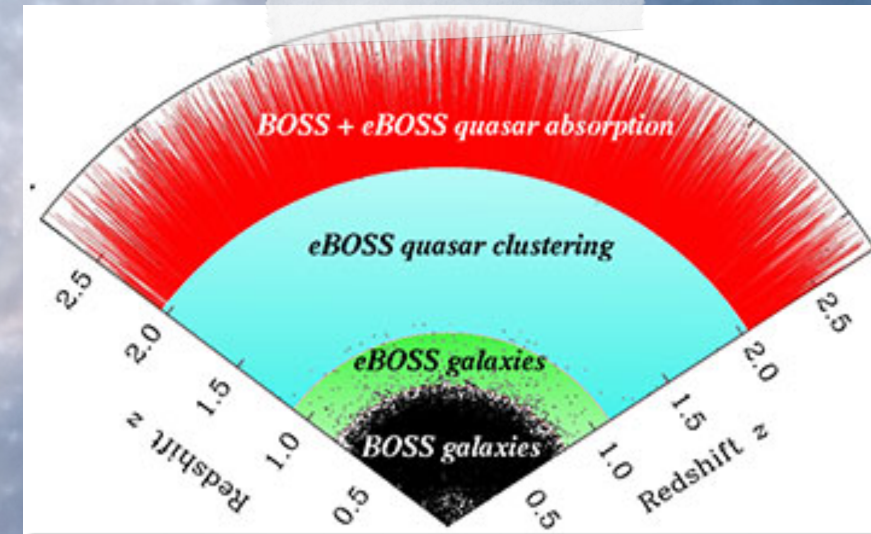
Combining future surveys:



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

Take home messages

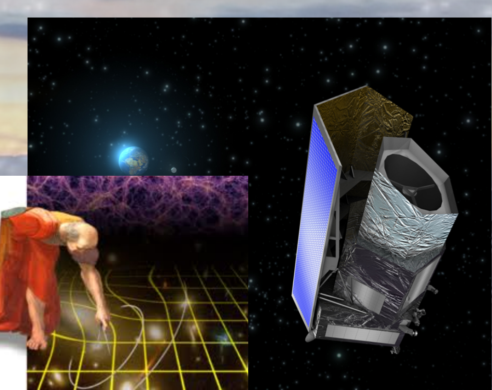
Lots of unknown in the current cosmological model



Voids as a new tool to constrain cosmology

Find voids

shape:AP test, RSD, void number:abundance



Farther and with more voids

Sloan Telescope
Sacramento Mountains, Sunspot