PRINCETON UNIVERSITY

Cosmology with Cosmic Voids

Alice Pisani

+many collaborators, highlights: **G. Verza**, **C. Kreisch**, D. Spergel, N. Hamaus, M.-C. Cousinou, B. Wandelt, A. Hawken,....

Outline

- Cosmology and Large Scale Structure
- Why are voids great for cosmology?
- How do we find voids?
- Void-galaxy correlation function [shape]
- Void size function [numbers]
- Void-void correlation function [clustering]
- Take home messages

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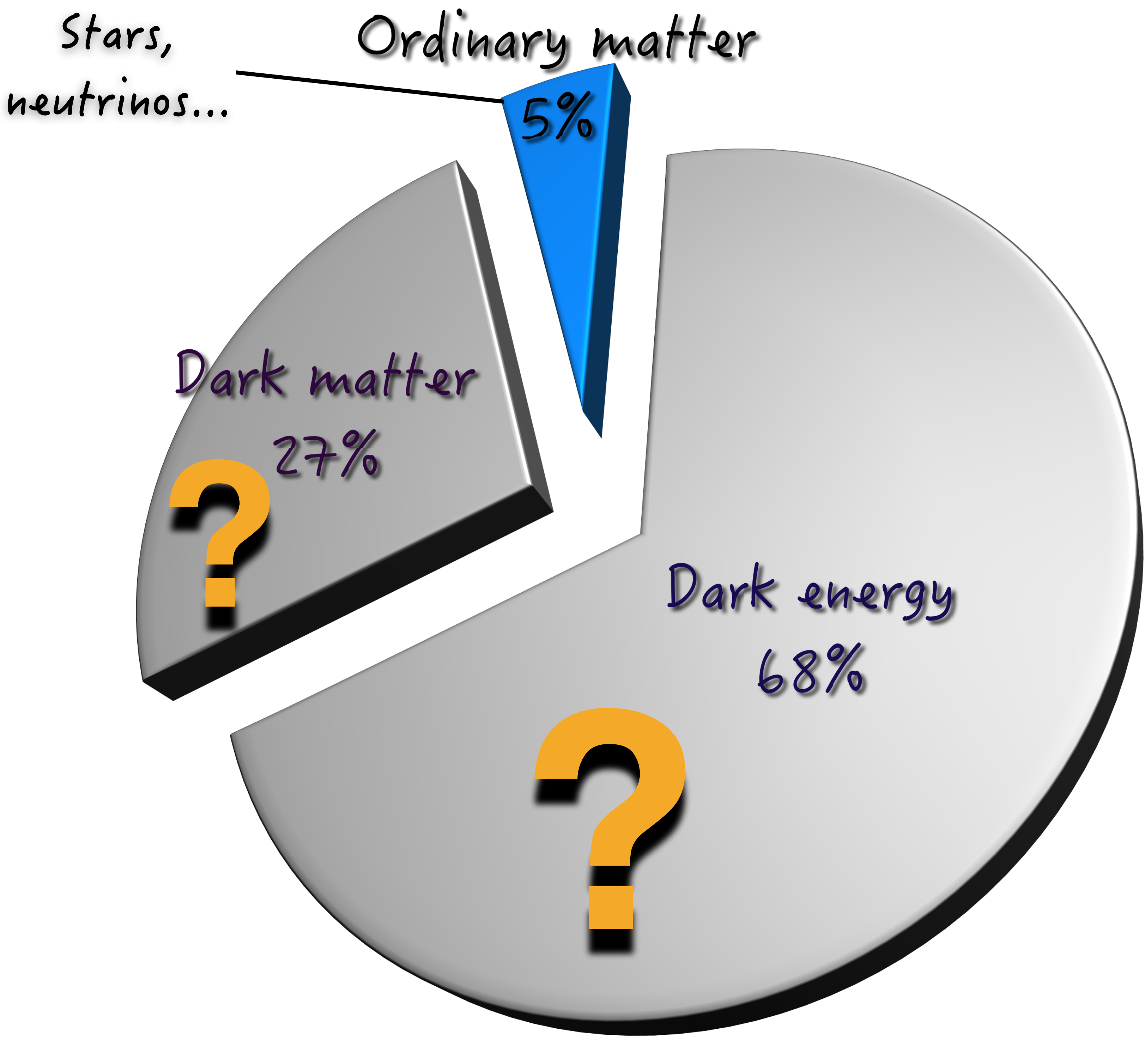
A well established model

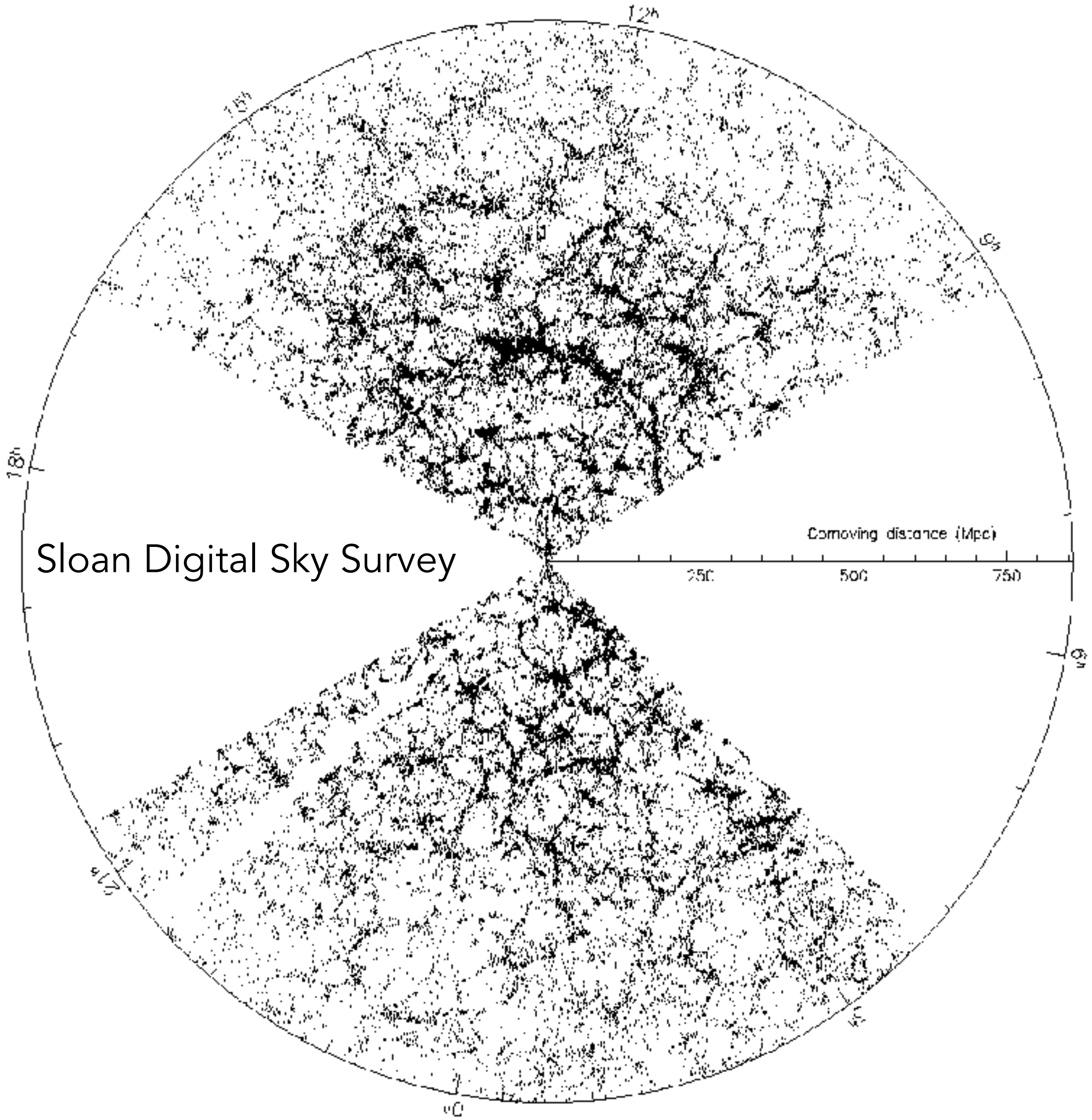
ΛCDM



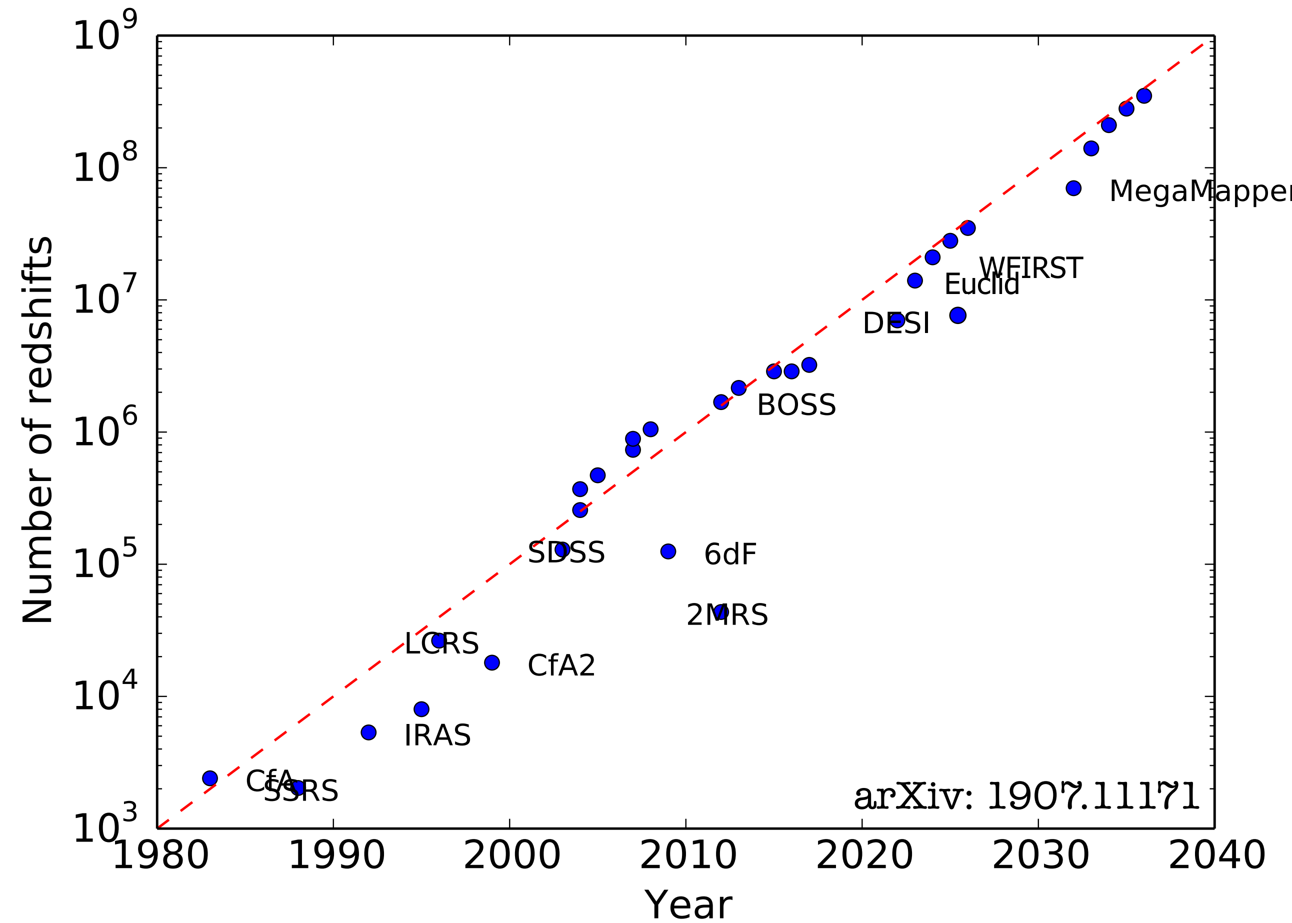
Precision Cosmology

We don't understand most of our Universe!

Large Scale Structure



Sloan Digital Sky Survey



THE DARK ENERGY SURVEY

WFIRST — Wide-Field Infrared Survey Telescope — Astrophysics • Dark Energy • Exoplanets

SuMIRe Prime Focus Spectrograph

SPHEREx

LSST — Large Synoptic Survey Telescope

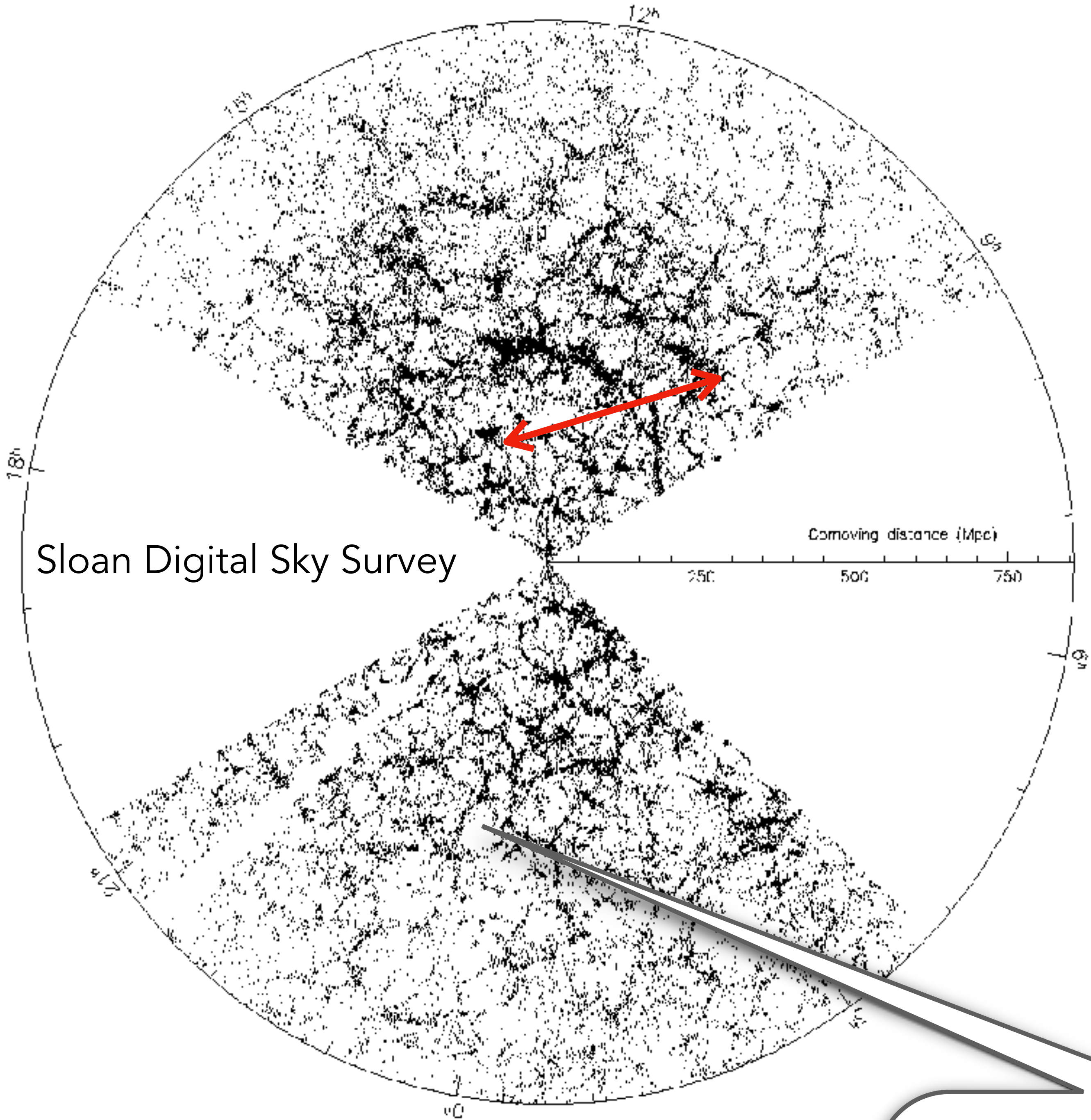
HSC

Dark Energy Spectroscopic Instrument

Euclid consortium

the golden era

Large Scale Structure



- Cosmological information mostly focuses on the two point correlation function: *take one random galaxy, how likely is it to find another galaxy xMpc away?*
- A wealth of information that we are not using!

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

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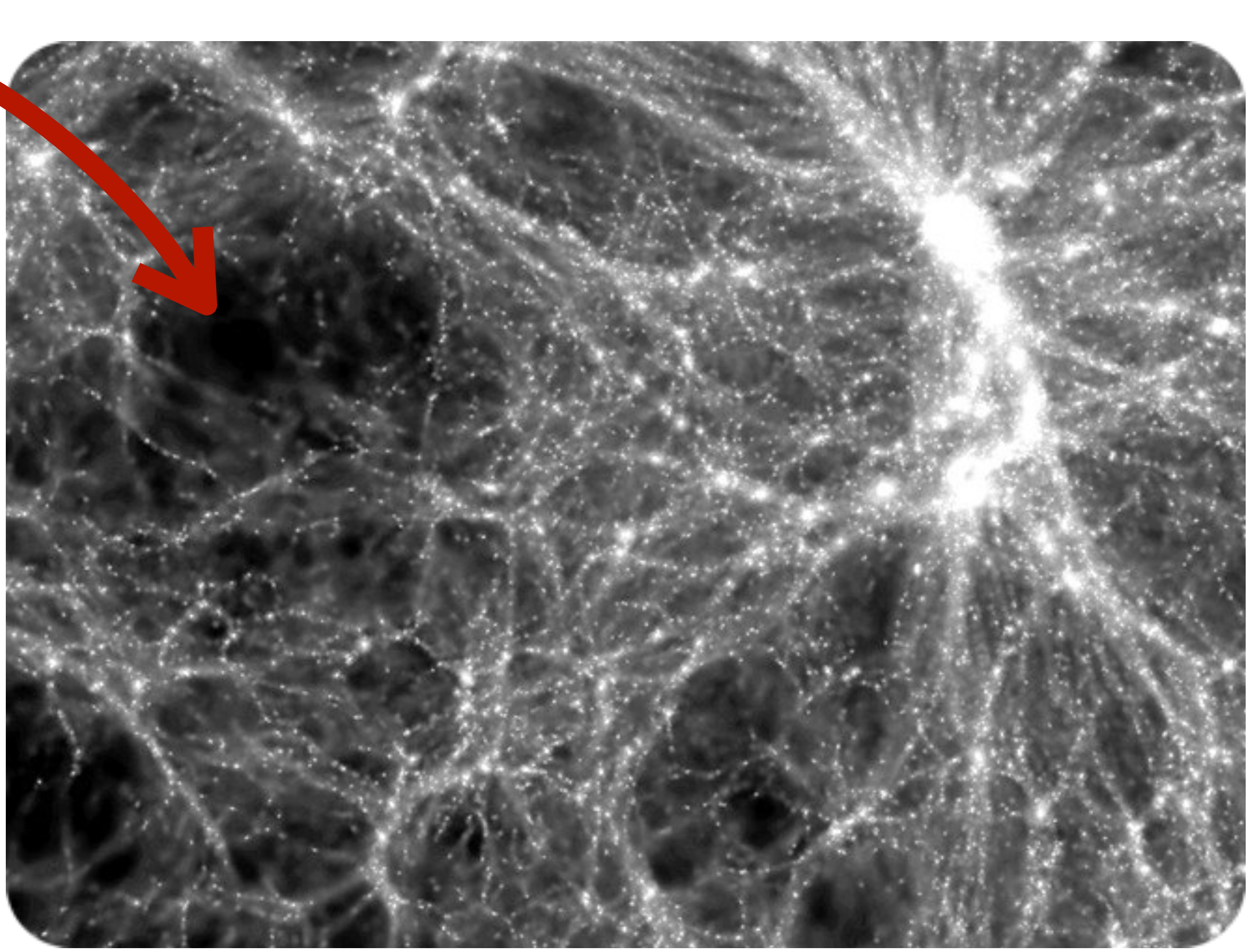
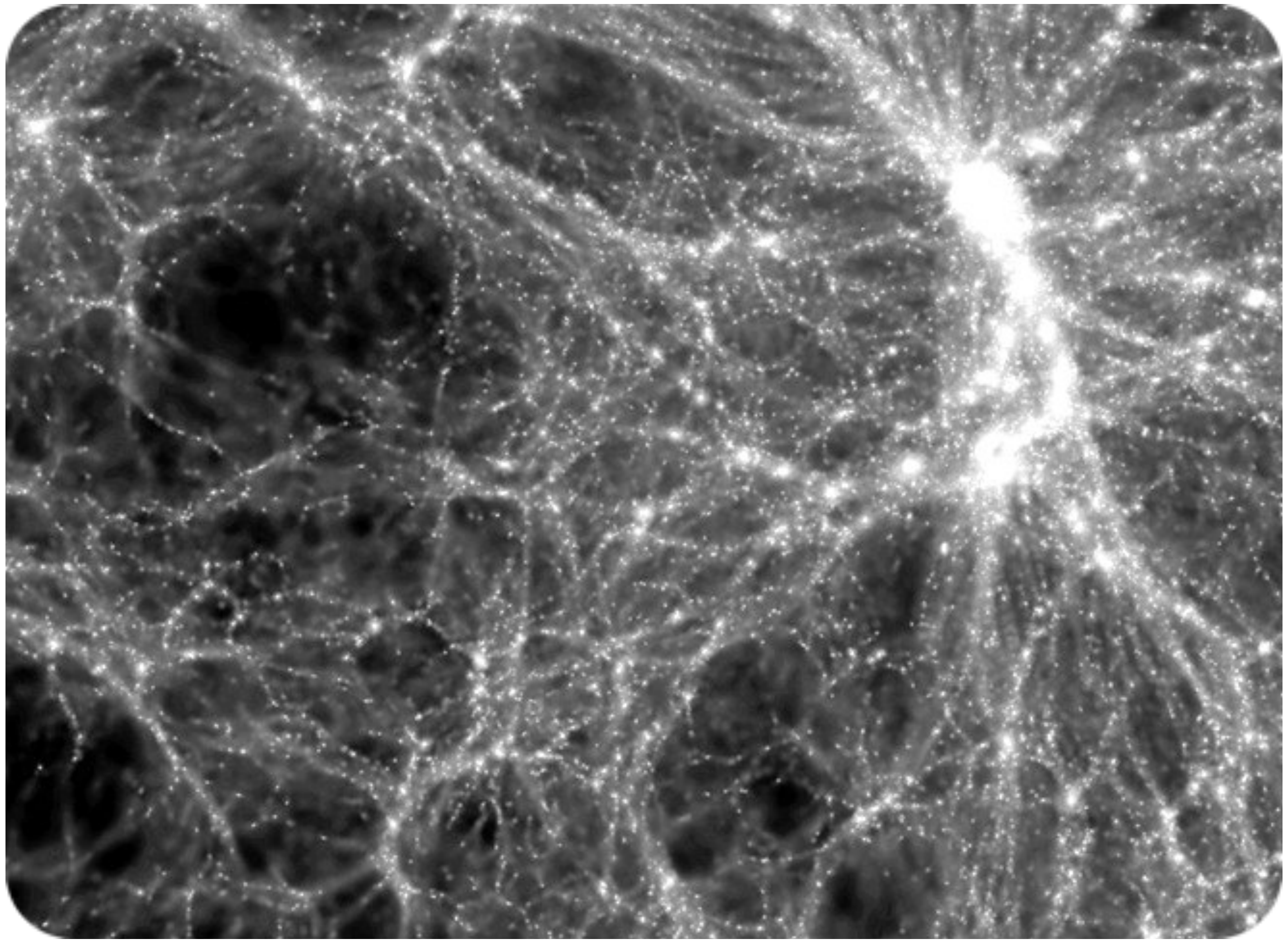
Why are voids great for cosmology?

- By definition dark energy dominated objects
- Low density + large scale= mimic current accelerated expansion status

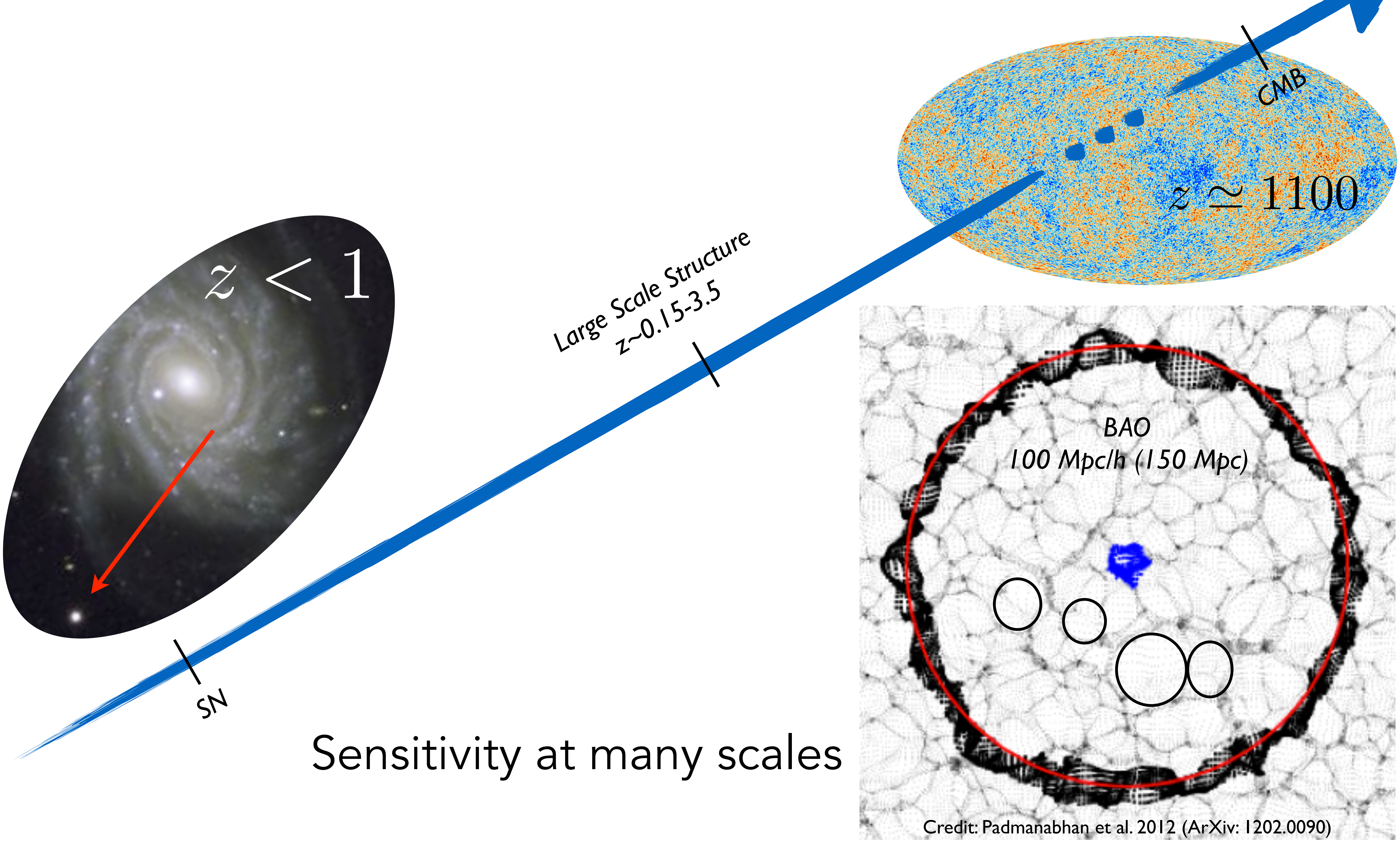


Why are voids great for cosmology?

- Sweet spot: potential deviations from General Relativity more prominent
- Generically sensitive to diffuse components (Σm_ν)



Why are voids great for cosmology?



Sensitivity at many scales

Why are voids great for cosmology?

- (hopefully) easy(-ier) to model
- We will have plenty anyway with upcoming surveys
- There is still a lot of work to be done!

  =>benefit of being a recent field; in the broader field of *galaxy clustering*, exploit knowledge we already have!

Quantities we wish to constrain

Ω_m Matter content of the Universe

$$\beta = \frac{f}{b} = \frac{\Omega_m(z)^\gamma}{b}$$ Growth rate of structure

$$w(z) = w_0 + w_a \frac{z}{z+1}$$ Dark energy equation of state

But first we need to find voids...

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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 → ? → voids

VIDE: Void IDentification and Examination

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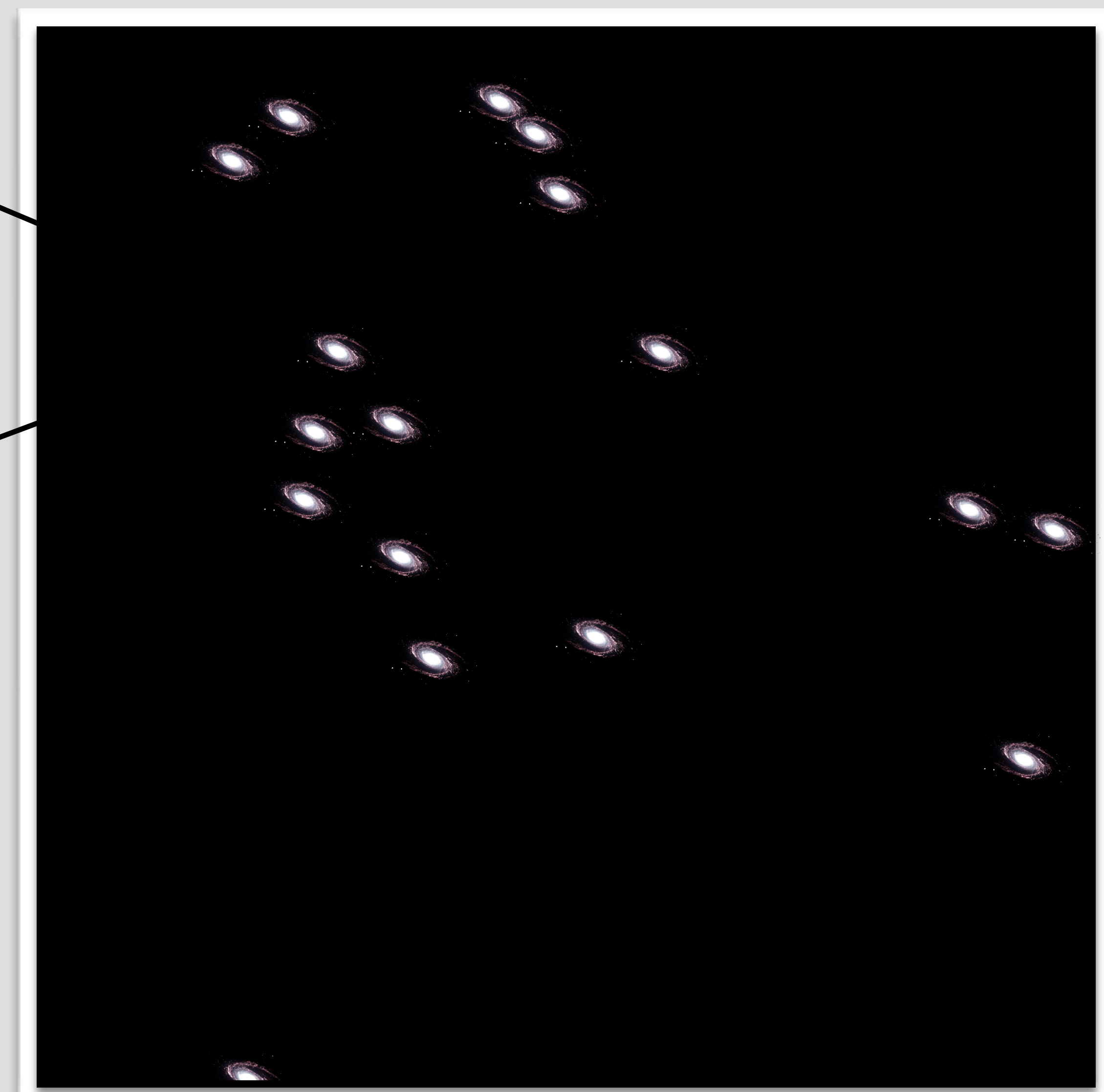
galaxies → Voronoi tessellation

A tessellation 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)

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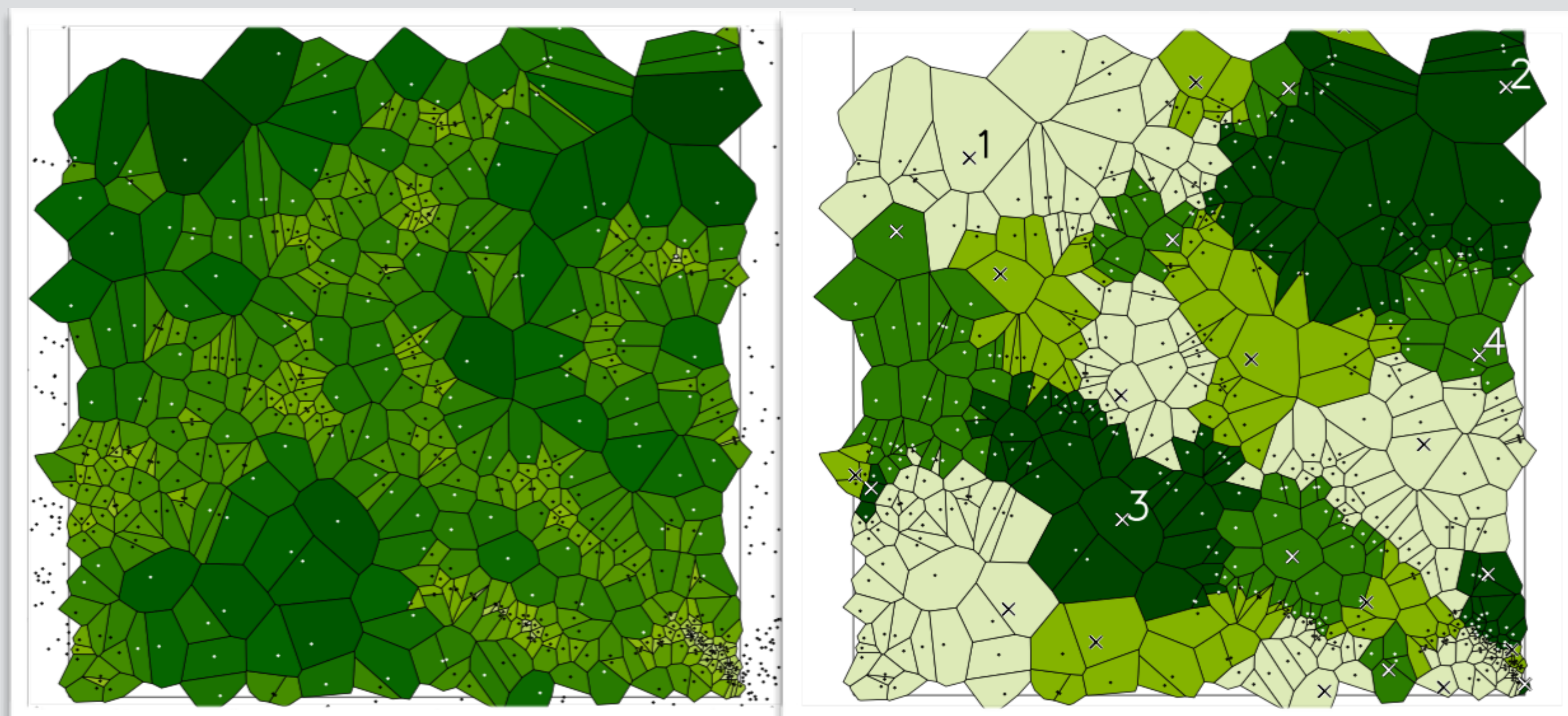
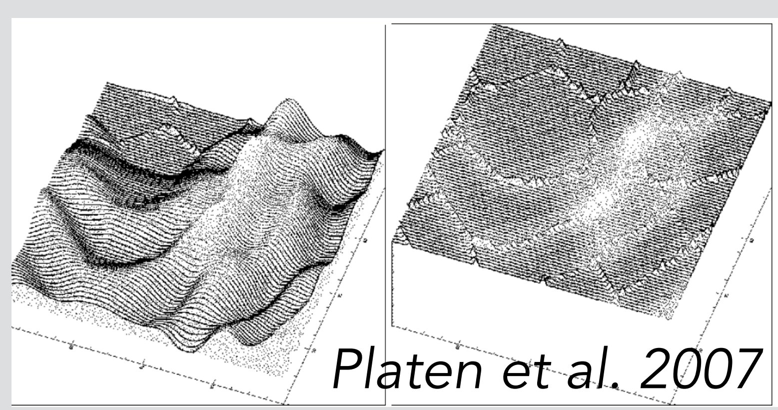
Sutter, P. M., Lavaux G., Hamaus N., **Pisani A.**, Wandelt B. D. et al., **Astronomy & Computing** (1406.1191) (ZOBOV, Neyrinck 2008)

galaxies → Voronoi tessellation → Watershed transform



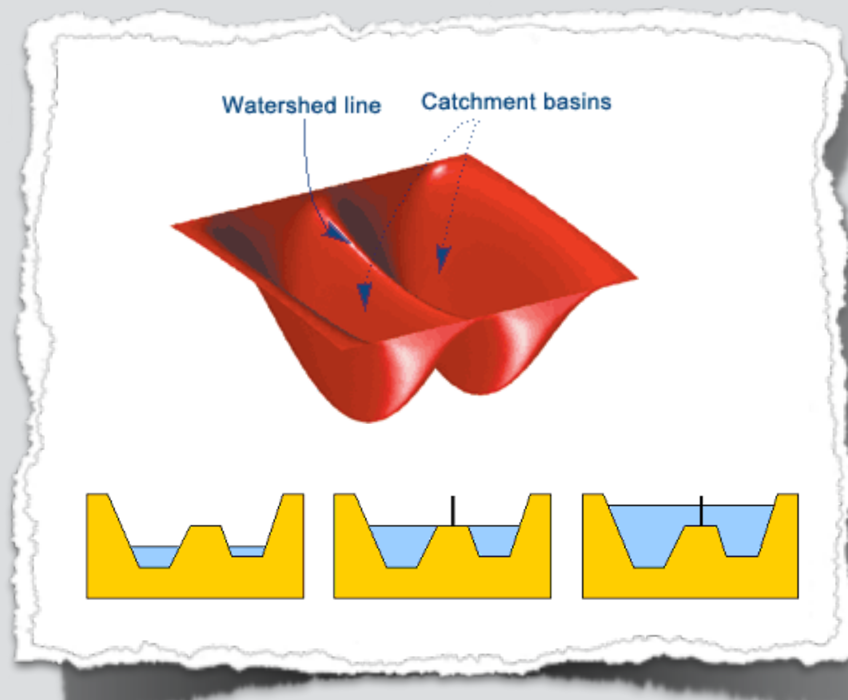
Neyrinck 2008



Platen et al. 2007

Merge cells into local basins

Merge basins



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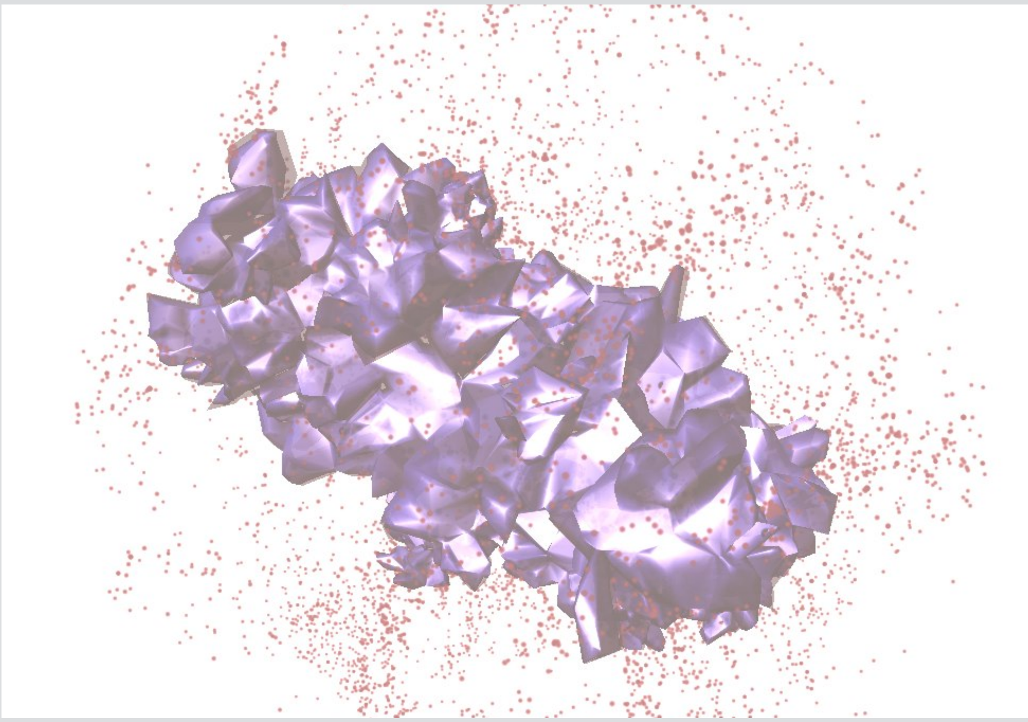
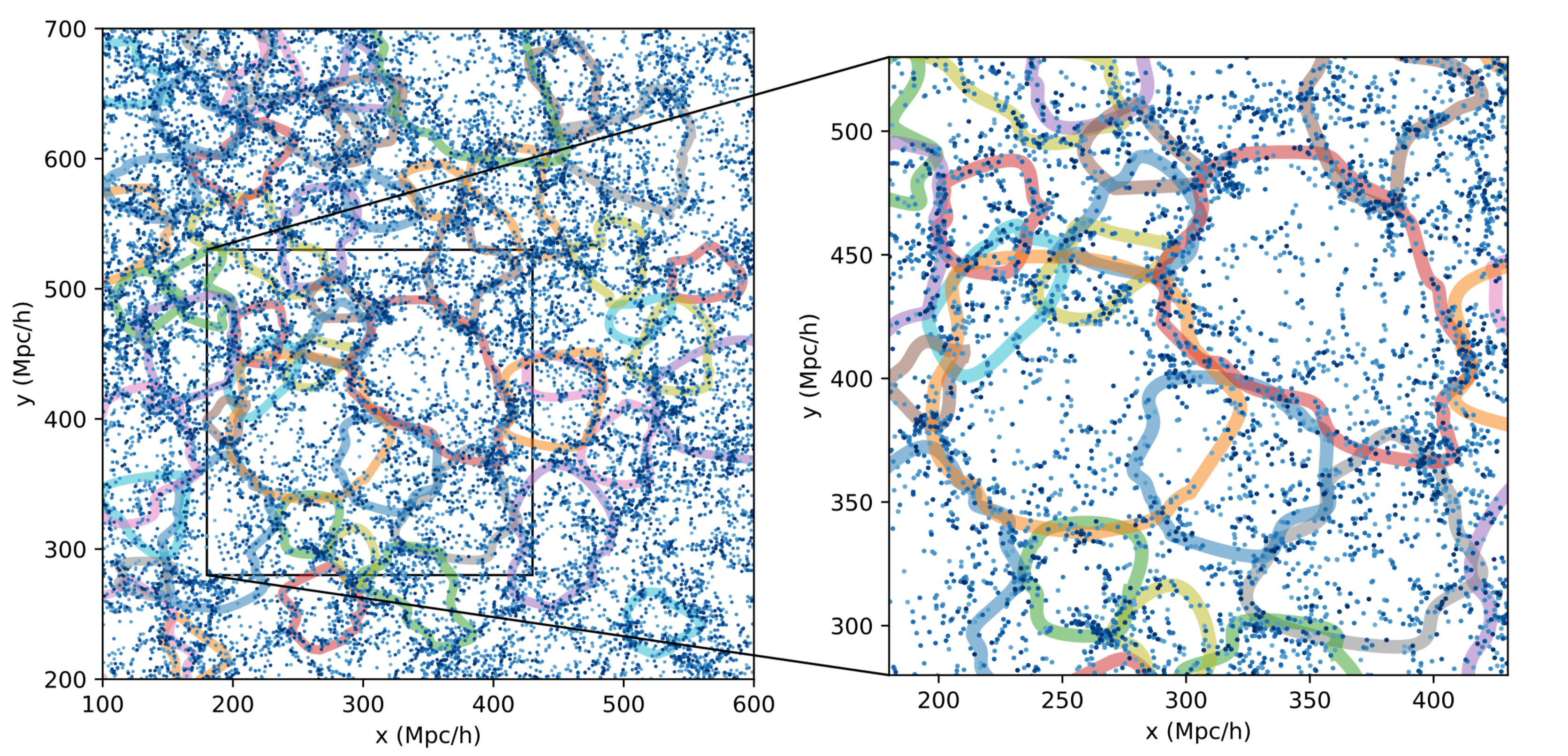
galaxies → Voronoi tessellation → Watershed transform → voids



Sutter et al. 2012



arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

- Captures the shape of voids in detail
- Takes mask into account
- Captures hierarchical pattern of cosmic web
- BOSS, eBOSS, DES, Euclid,WFIRST

Take home message:

Definition is not an issue => consistency is

A definition needs to be:

- **Suitable** for the observable quantity
- Tested on **mocks**
- Enhances S/N

UNDERSTAND YOUR DEFINITION

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What quantities do we measure to extract cosmological information ?

We have void centers, void radii, and tracers!

↓

Void-galaxy correlation function	$\xi_{\rm vg}$
Void size function	$N_{\rm v}$
Void-void correlation function	$\xi_{\rm vv}$

Pisani, Massara, Spergel et al. 2019; ArXiv: 1903.05161

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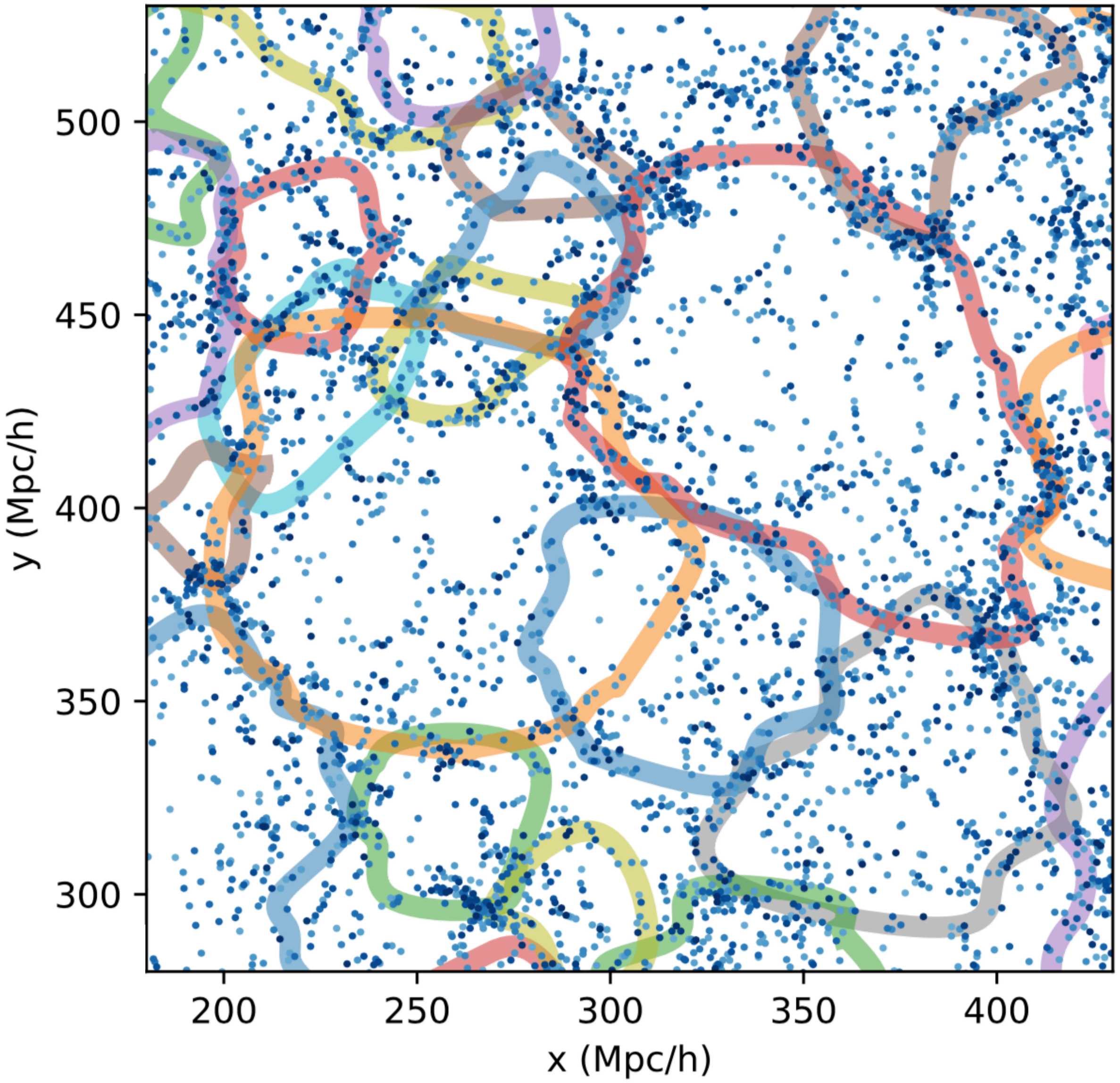
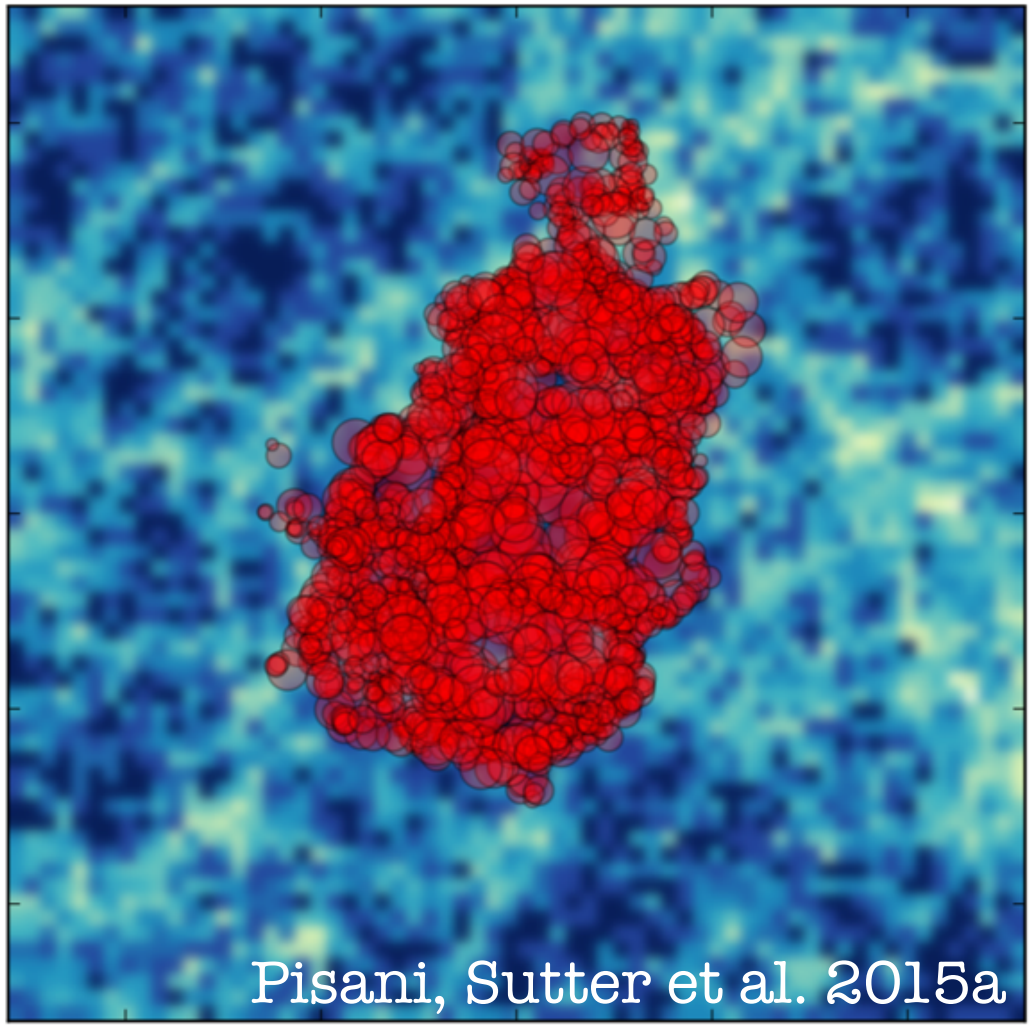
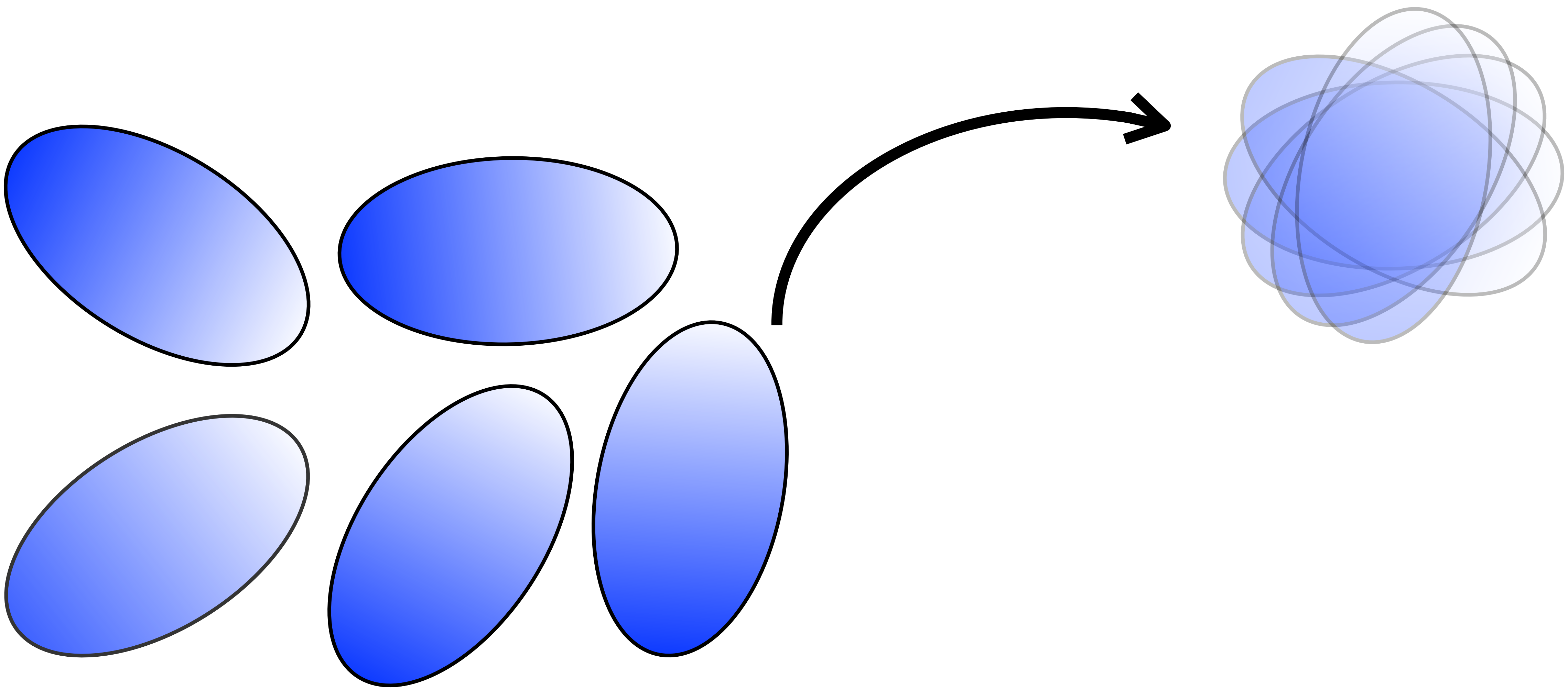
Void have irregular shapes on a one to one basis.





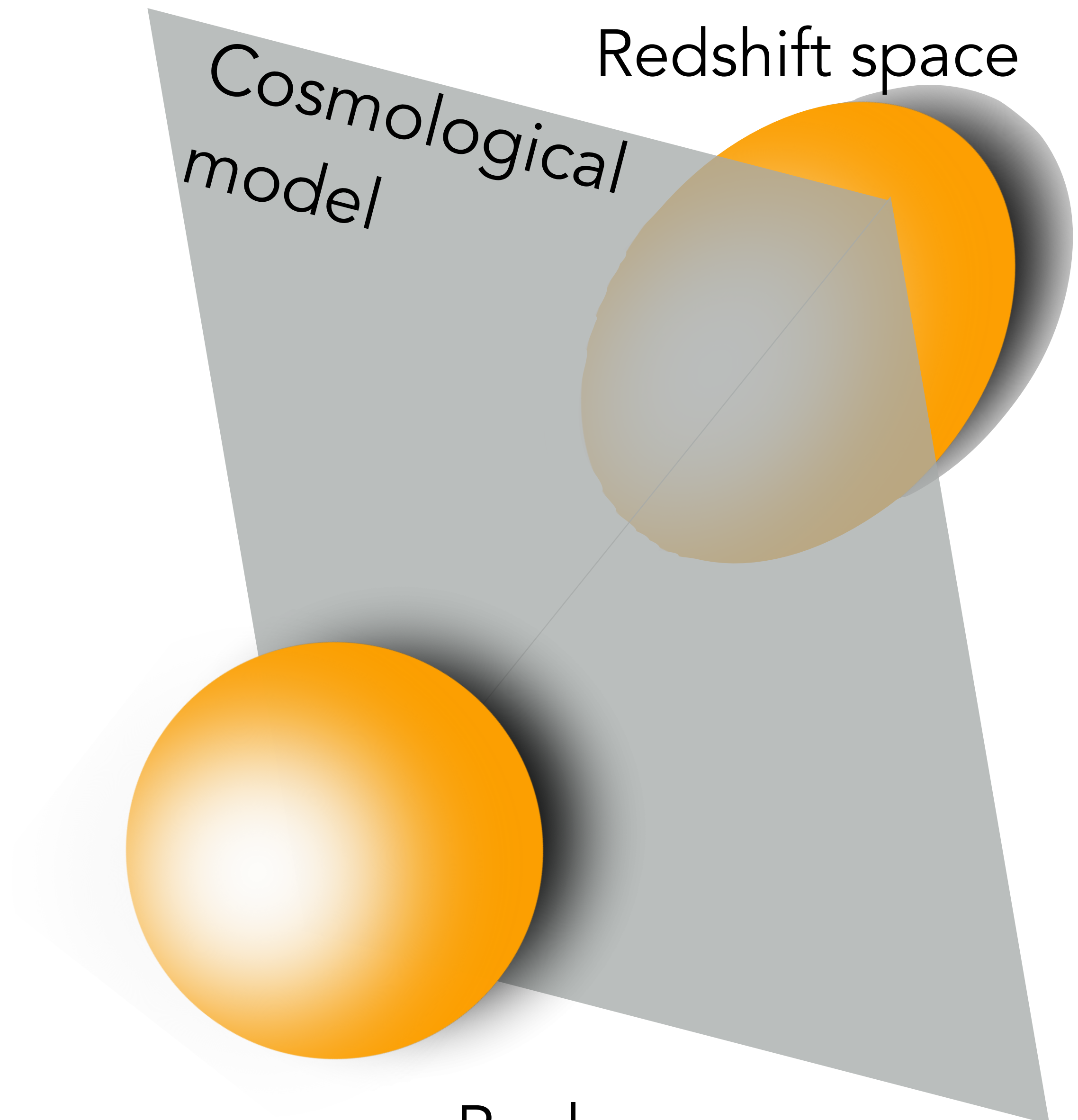
arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

Void **stacks** are spherical in **real** space (in a *homogeneous and isotropic* universe).



Lavaux and Wandelt 2012

Unfortunately (or maybe not so unfortunately) we observe objects in **redshift space**

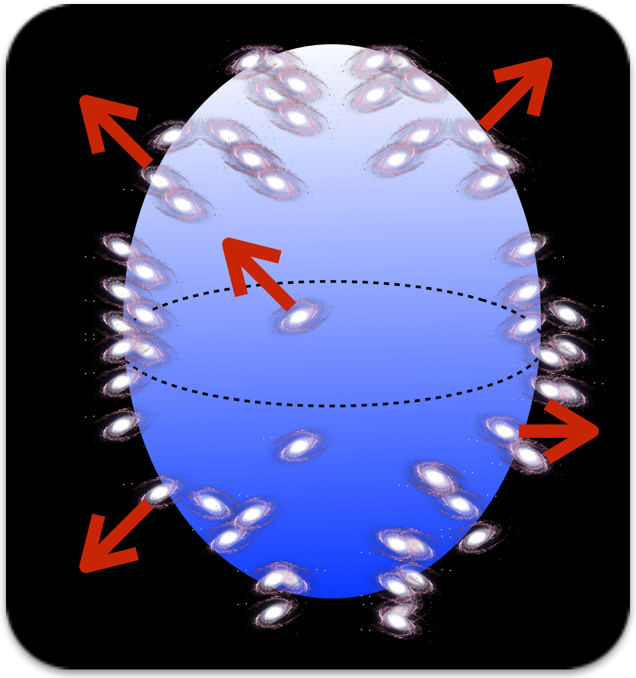


Observed shape =

the relationship between angular diameter distance and redshift (Alcock-Paczynski effect)

+

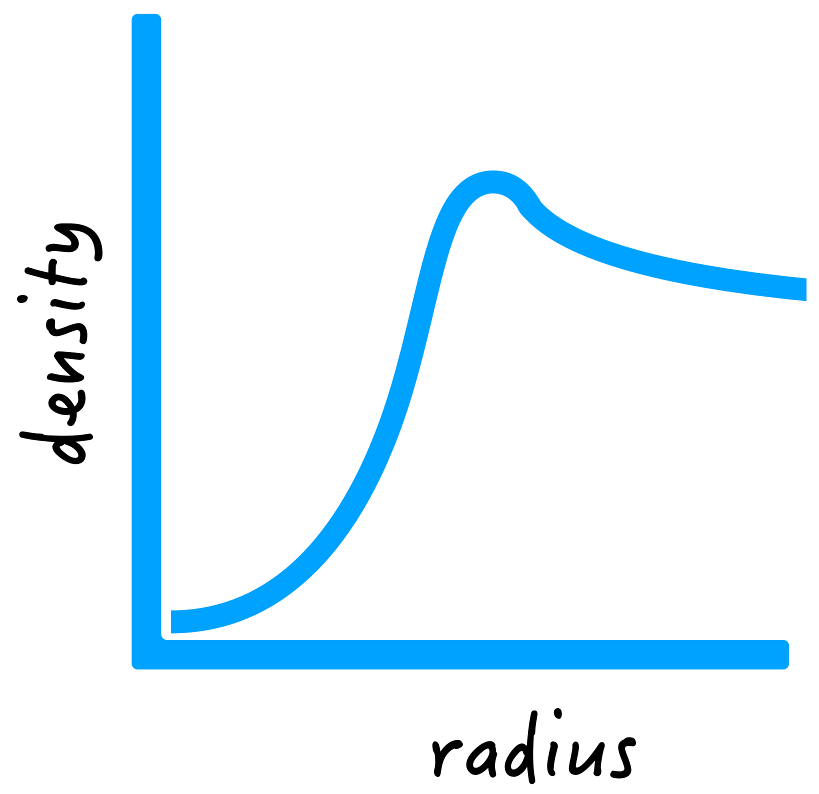
redshift-space distortions (deviation from the Hubble flow)



Lavaux and Wandelt 2012; **Pisani** el al. 2013; **Pisani** et al. 2015

Void "shape": the density profile (void-galaxy correlation function)

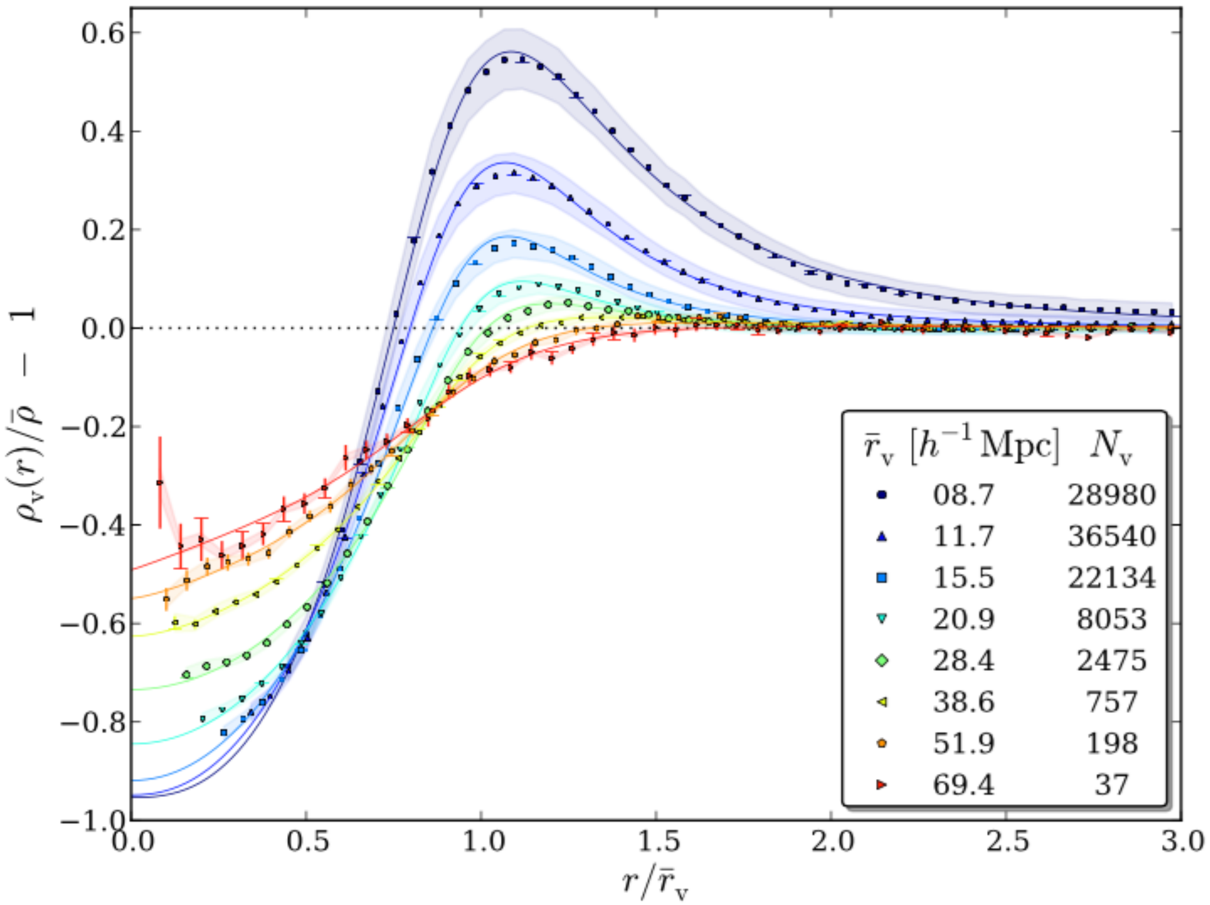
Ingredients { Density profile modelling / RSD modelling



$$\xi_{\rm vg}$$

Void density profile (void-galaxy correlation function) $\xi_{\rm vg}$

- Is there a robust theoretical prediction for the void density profile? Are there commonly used prescriptions?



- Real-space density profile reconstruction (Pisani et al. MNRAS 2014)
- Fitting function (Hamaus et al. 2014, Phys. Rev. Letters, arXiv: 1403.5499)

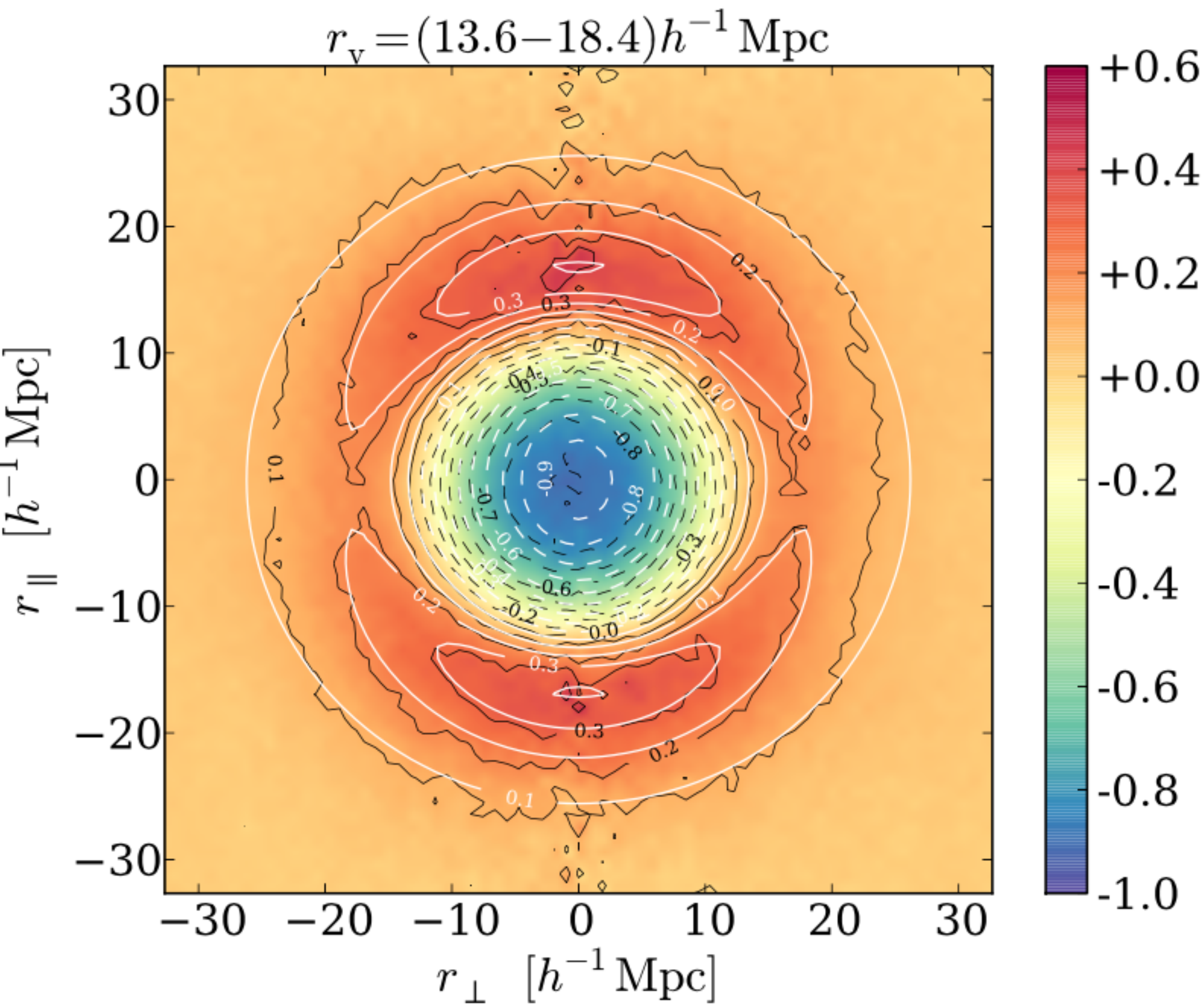
$$\frac{\rho_{\rm vm}(r)}{\bar{\rho}_{\rm m}} - 1 = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_{\rm v})^{\beta}}$$

density contrast
R : $\rho = \bar{\rho}$
slopes before/after wall
linear fxs of $r_s/r_{\rm v}$

Void density profile (void-galaxy correlation function) ξ_{vg}

- RSD: two 'mainstream' prescriptions
    - Gaussian streaming model
    - Multipoles

Modeling the void-galaxy cross correlation function (vel+AP)



Gaussian streaming model

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

P. J. E. Peebles, The large-scale structure of the universe (1980), mass conservation.

$$\Delta_{vm}(r) = \frac{3}{r^3}\int_0^r \left(\frac{\rho_{vm}(q)}{\bar{\rho}_m} - 1\right) q^2 dq$$

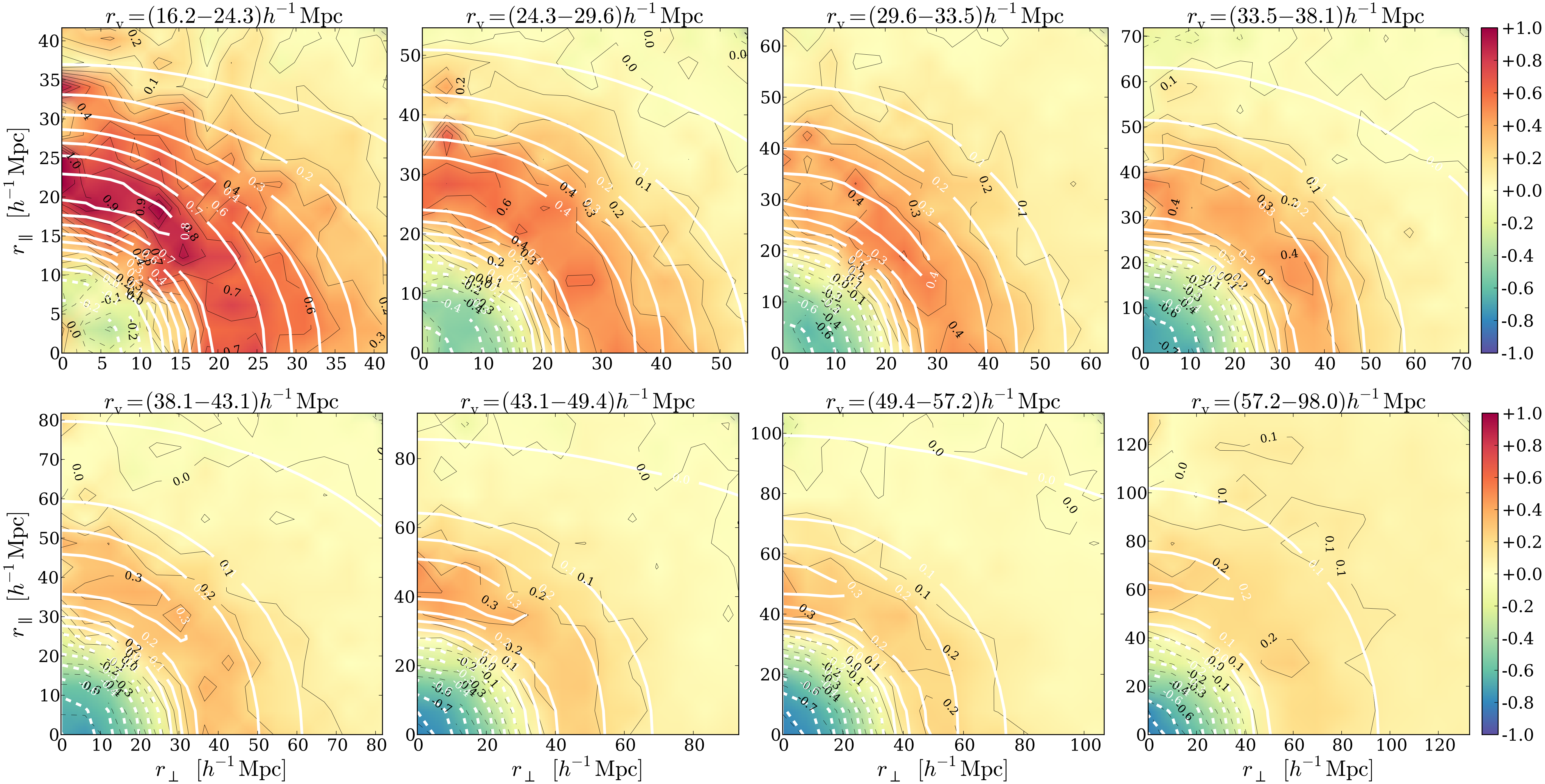
Cumulative density profile

$$1 + \tilde{\xi}_{vg}(\tilde{\mathbf{r}}) = \int P(\mathbf{v}, \mathbf{r})[1 + \xi_{vg}(\mathbf{r})]d^3v = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_v(\mathbf{r})} \exp\left[-\frac{(v_\parallel - v_v(r)\frac{r_\parallel}{r})^2}{2\sigma_v^2(\mathbf{r})}\right] \frac{\rho_v(r)}{\bar{\rho}} dv_\parallel$$

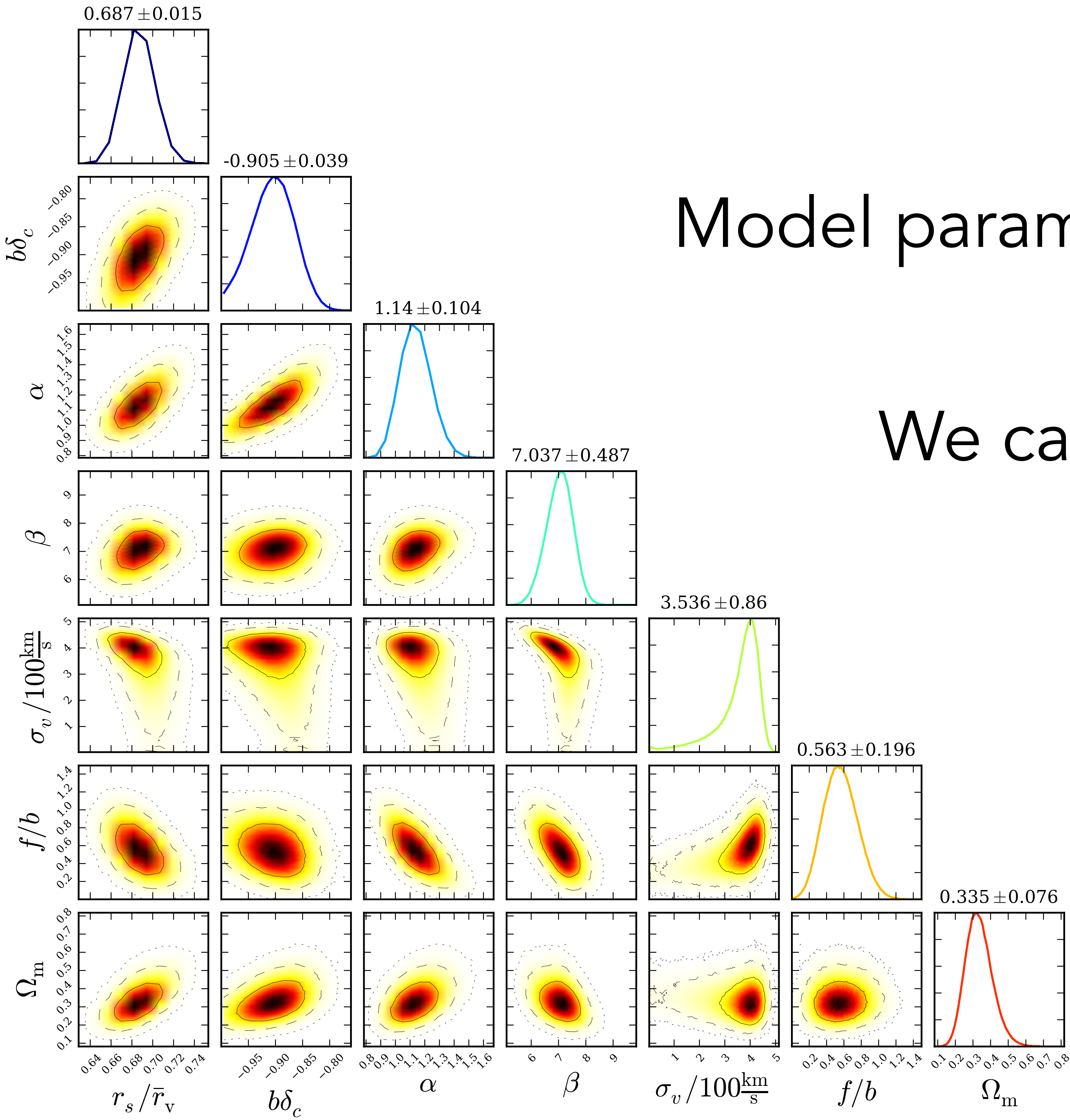
Gaussian probability distribution function for velocities
(Gaussian streaming model, Fisher 1995)

Hamaus et al 2015 ArXiv: 1507.04363; **Pisani**, Massara, Spergel et al. 2019; ArXiv: 1903.05161

Tested on mocks, applied to data: SDSS BOSS voids (CMASS DR11)



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

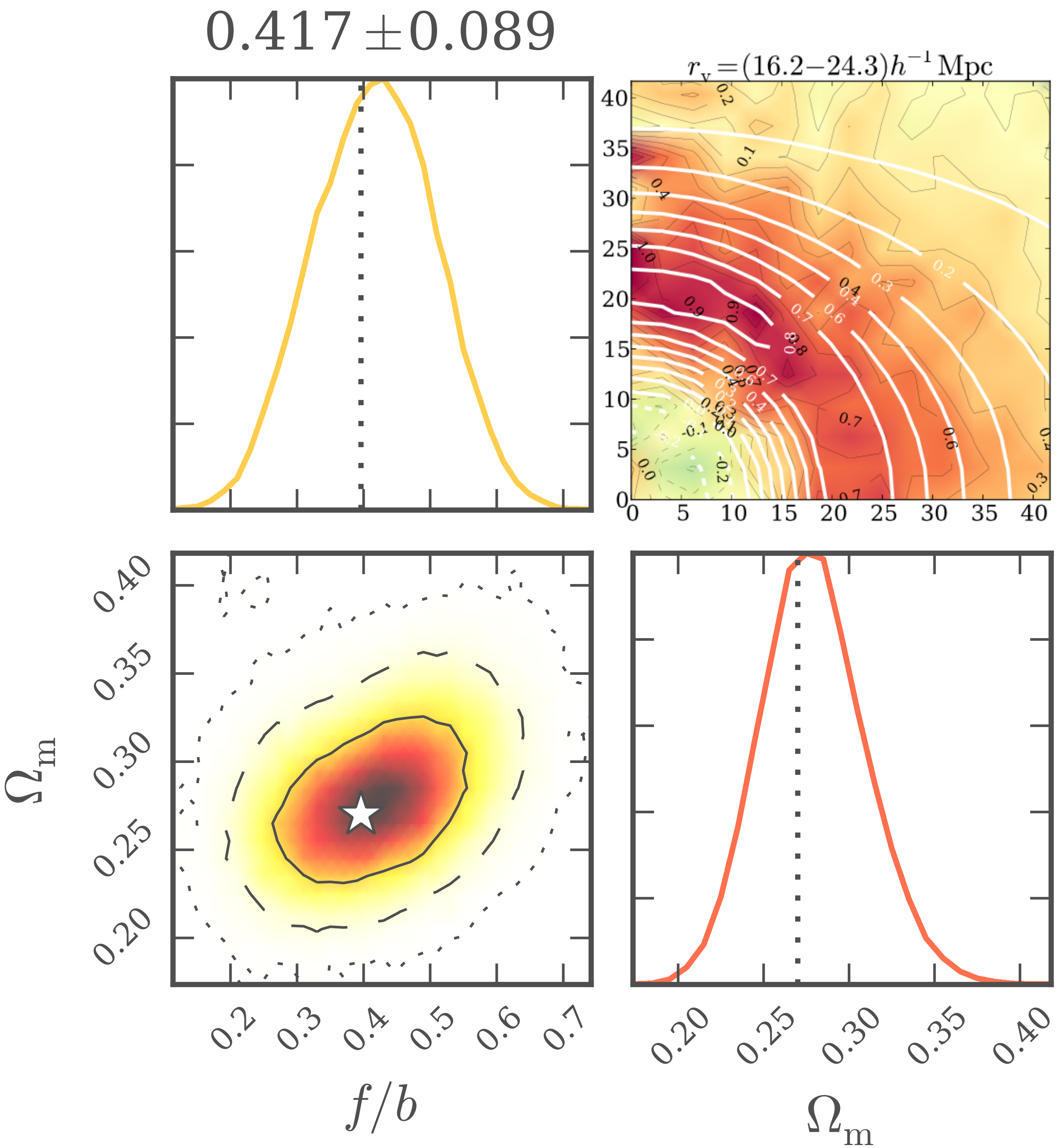


Model parameters (profile+velocities)

We can model everything …

Note that this marginalizes over profile uncertainty…

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



SDSS BOSS voids (CMASS DR11)

… and get constraints!

Shape measured at **1%** precision level

(~AP 4 times better than traditional clustering).

Constraints accuracy:

Ω_m =>**10%**

$\beta = \frac{f}{b}$ =>**21%**

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

Multipole analysis of RSD

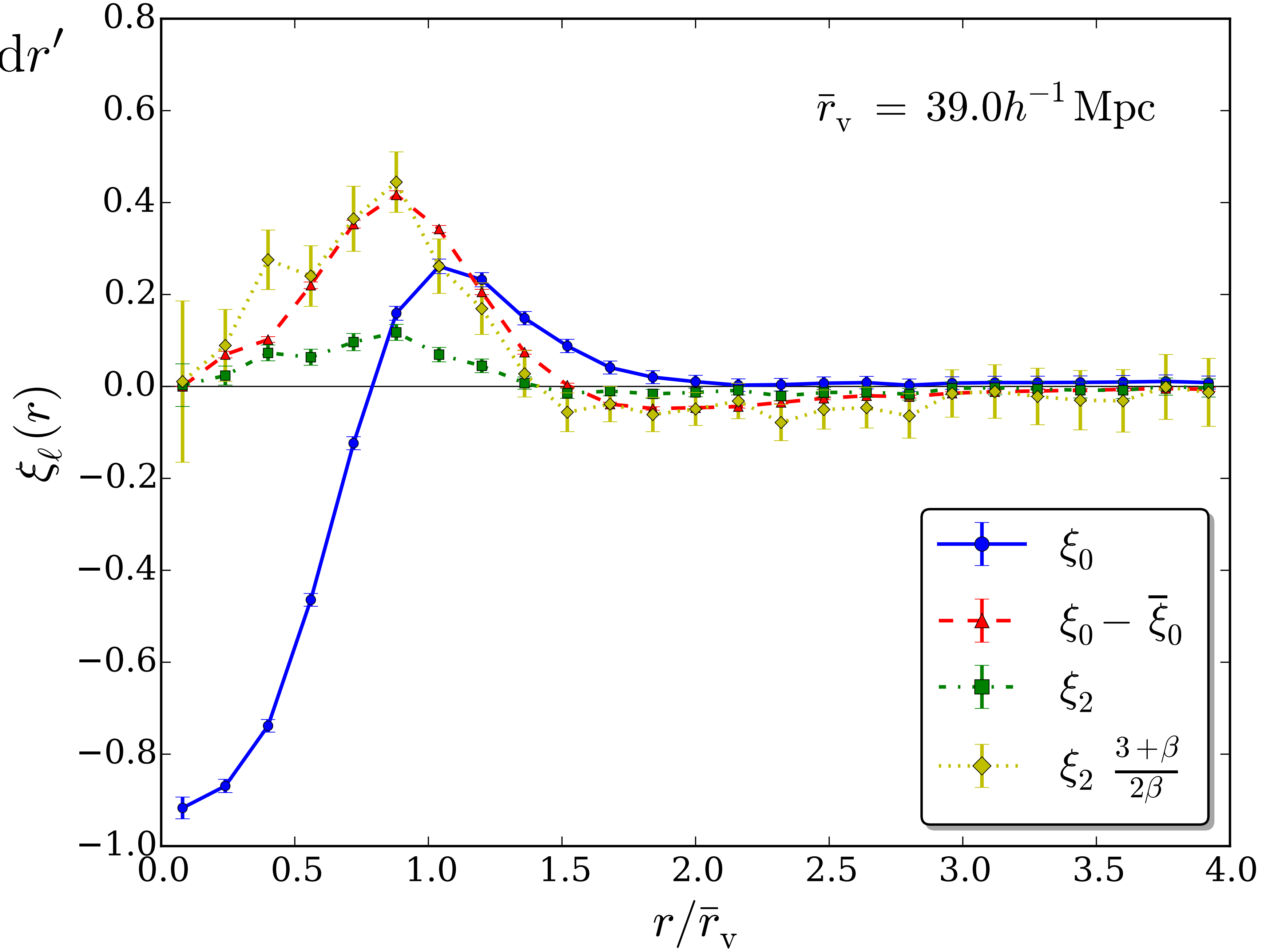
$$\xi_\ell(r) = \int_0^1 \tilde{\xi}_{\mathrm{vg}}(r,\mu)(1+2\ell)P_\ell(\mu)\mathrm{d}\mu \qquad \mu = r_\parallel / r$$

$$\bar{\xi}_{\mathrm{vg}}(r) = \frac{3}{r^3}\int_0^r \xi_{\mathrm{vg}}(r')r'^2\mathrm{d}r'$$

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

direct constraint on

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



Cai et al. 2016 , ArXiv: 1603.05184;

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

Test of ΛCDM + GR at large scales and in the under-dense regime

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

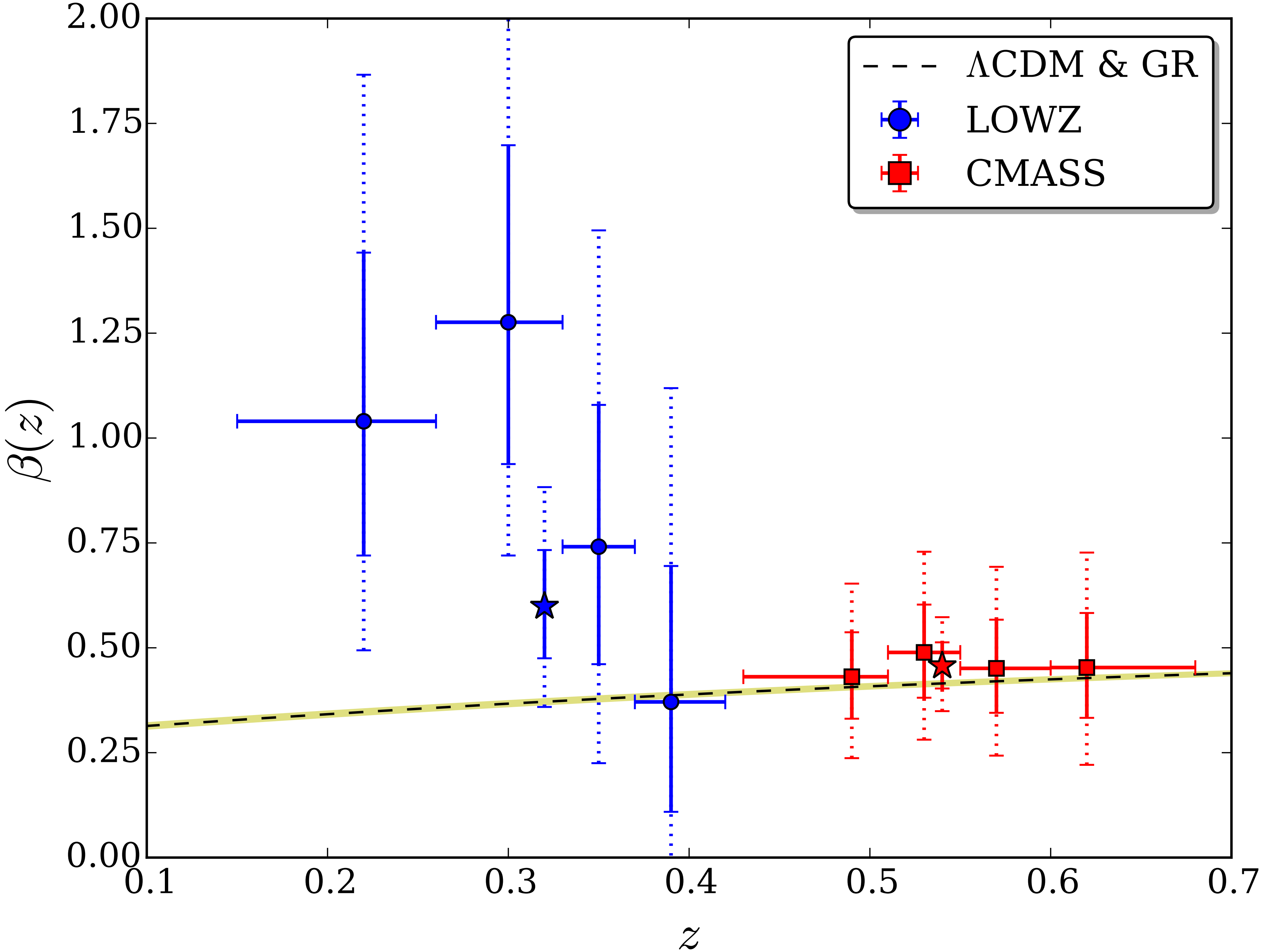
1σ solid errorbars
2σ dashed errorbars

Constraints accuracy:

$\beta = \frac{f}{b}$ => **12%**

$$\gamma \simeq 0.55$$

ΛCDM + GR



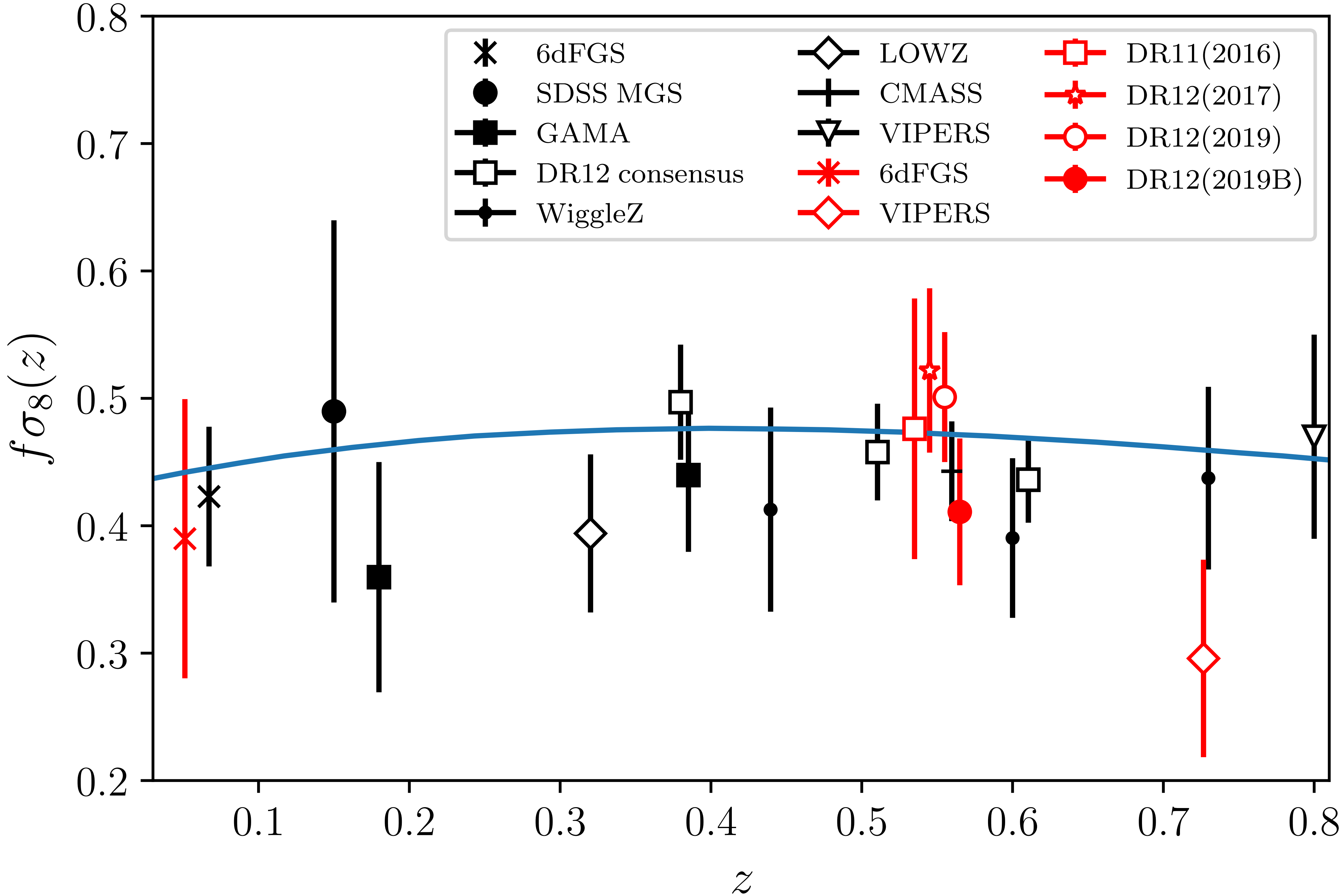
Hamaus, Cousinou, **Pisani**, Aubert, Escoffier, Weller 2017 ArXiv:1705.05328 JCAP 2017

- Nonlinear RSDs from virial motions of close-by galaxy pairs, causing the *Fingers-of-God* effect [24, 59, 72, 73].
- Nonlinear clustering on small scales and at high densities [74–76].
- Nonlinear and scale-dependent galaxy bias [47].
- Impact of baryonic physics [77].

None of these seem to play a major role in the void-galaxy cross-correlation function

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

Constraints on $f\sigma_8$



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How to estimate void numbers?

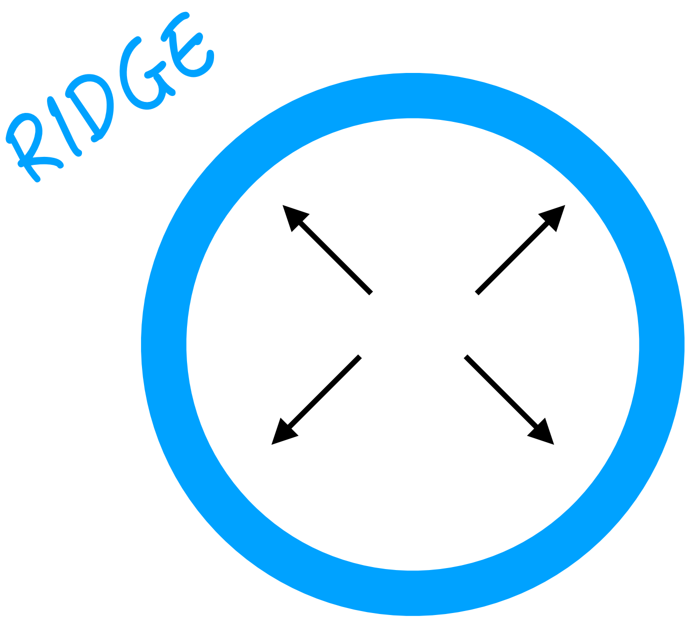
- Number are increasing quickly… my very first work on voids (2014) had ~200 voids
- Results presented above had ~ 4000 voids **GOLDEN ERA**

What's next?

upcoming **constraining power** from voids?

SPHEREx

How to estimate void numbers?



Void evolve emptying themselves

Void formation=shells undergo shell-crossing

Critical under-density: $\delta_{\rm v}^{NL} = -0.8$

Prediction for void numbers!

It is a two barrier model, it explains how the voids population divides into void-in-cloud and void-in-void.

$\delta_{\rm v}$ $\delta_{\rm c}$

Sheth and van de Weygaert 2004

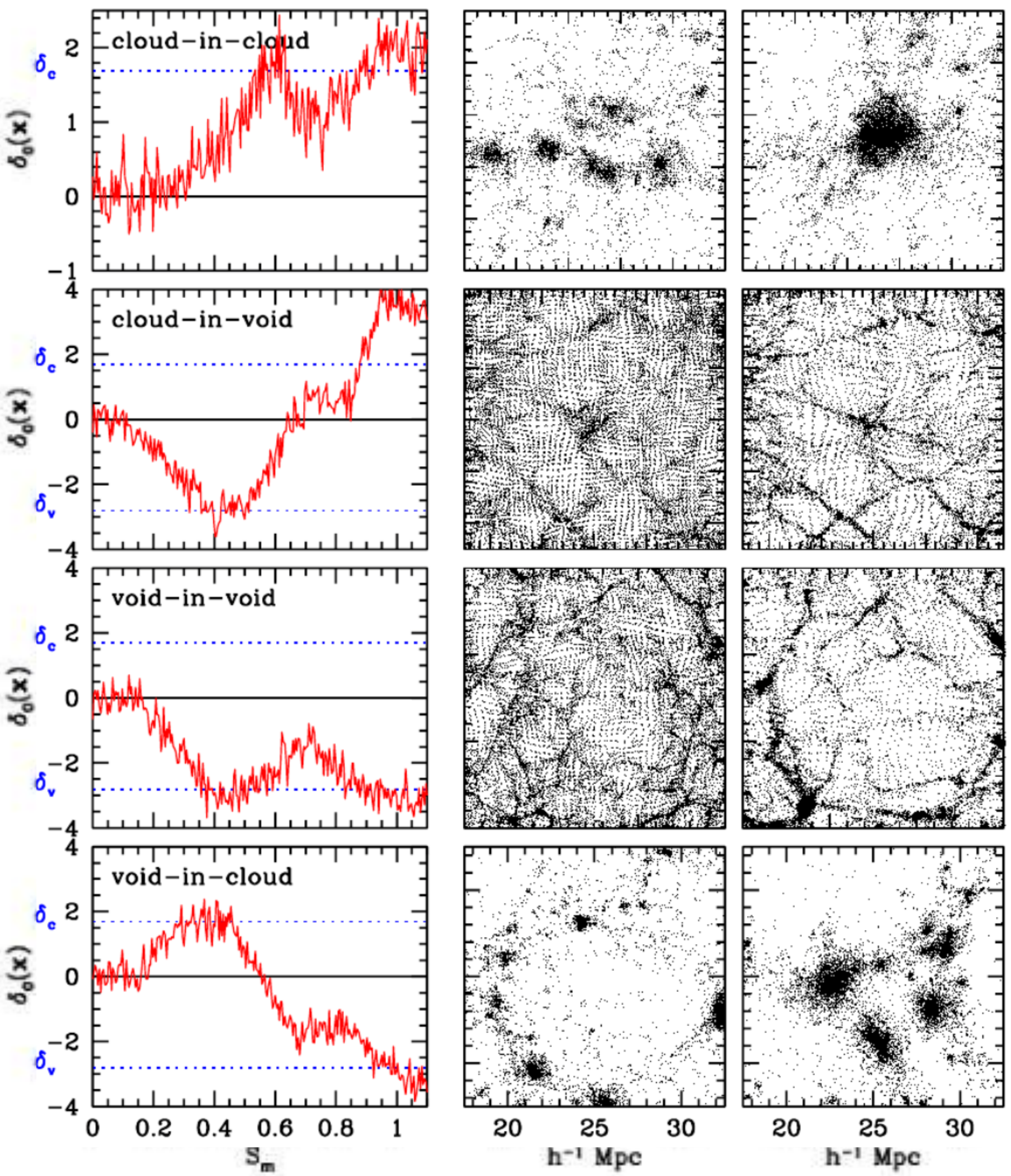


Figure 6. Four mode (extended) excursion set formalism. Each row illustrates one of the four basic modes of hierarchical clustering: the *cloud-in-cloud* process, *cloud-in-void* process, *void-in-void* process and *void-in-cloud* process (from top to bottom). Each mode is illustrated using three frames. 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 and van de Weygaert 2004

- An excursion set model to predict the number of voids

$$n(R,z) \propto \nu f(\nu) \approx \sqrt{\frac{\nu}{2\pi}} \exp(-\nu/2)$$

Fraction of mass evolved into voids

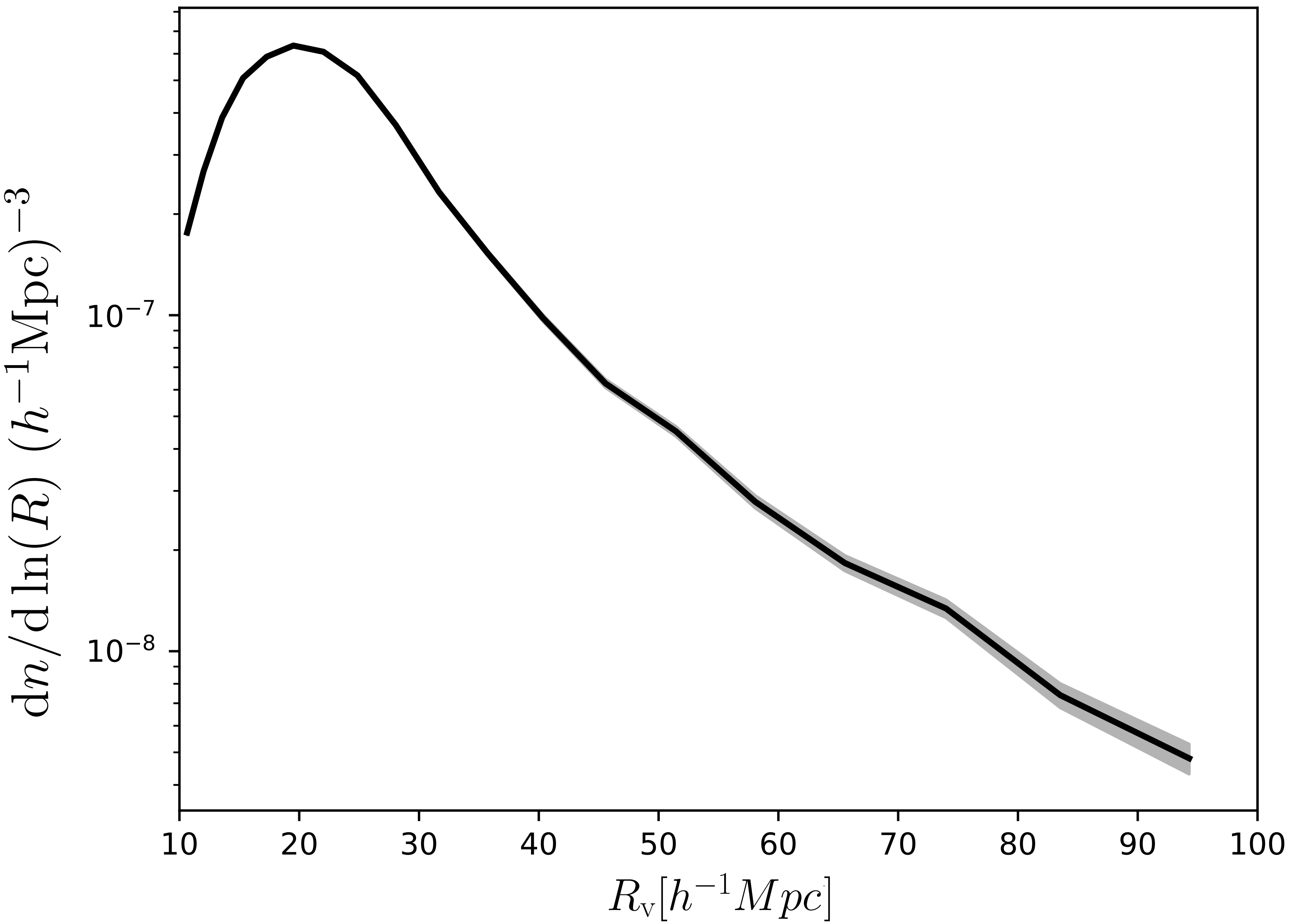
$$\nu = \frac{\delta_v^2}{\sigma^2},$$

Density variance inside a sphere with given mass

$$N_e = \int_z^{z+\Delta z} \mathrm{d}z \int_{R_{\min}}^{\infty} \mathrm{d}R \int_{\Omega_{\mathrm{survey}}} \mathrm{d}\Omega \, n(R,z) \frac{\mathrm{d}V}{\mathrm{d}z \mathrm{d}\Omega}$$

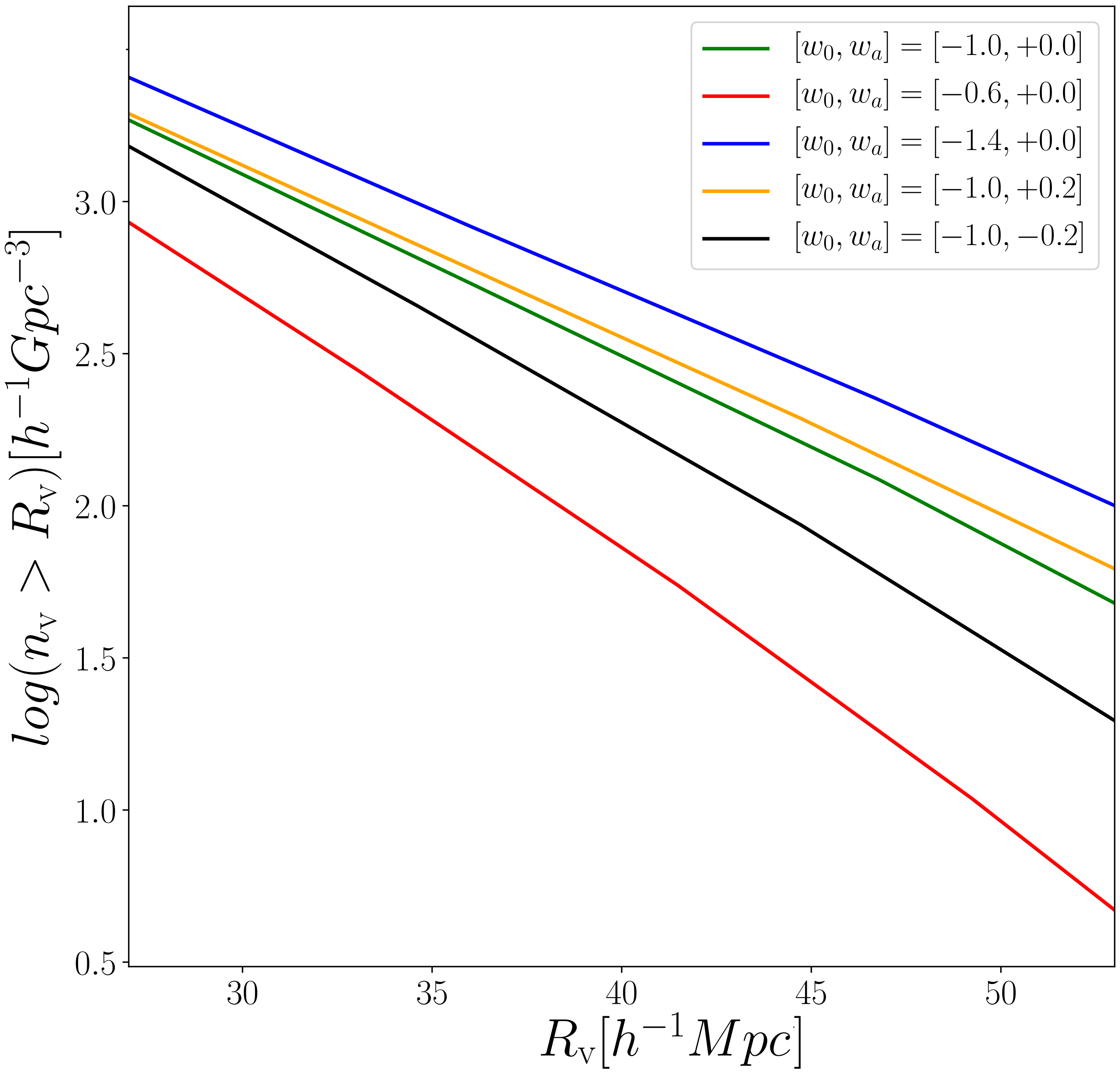
- Void-in-cloud can often be neglected! (Mean particle separation is the limit!)

The void size function



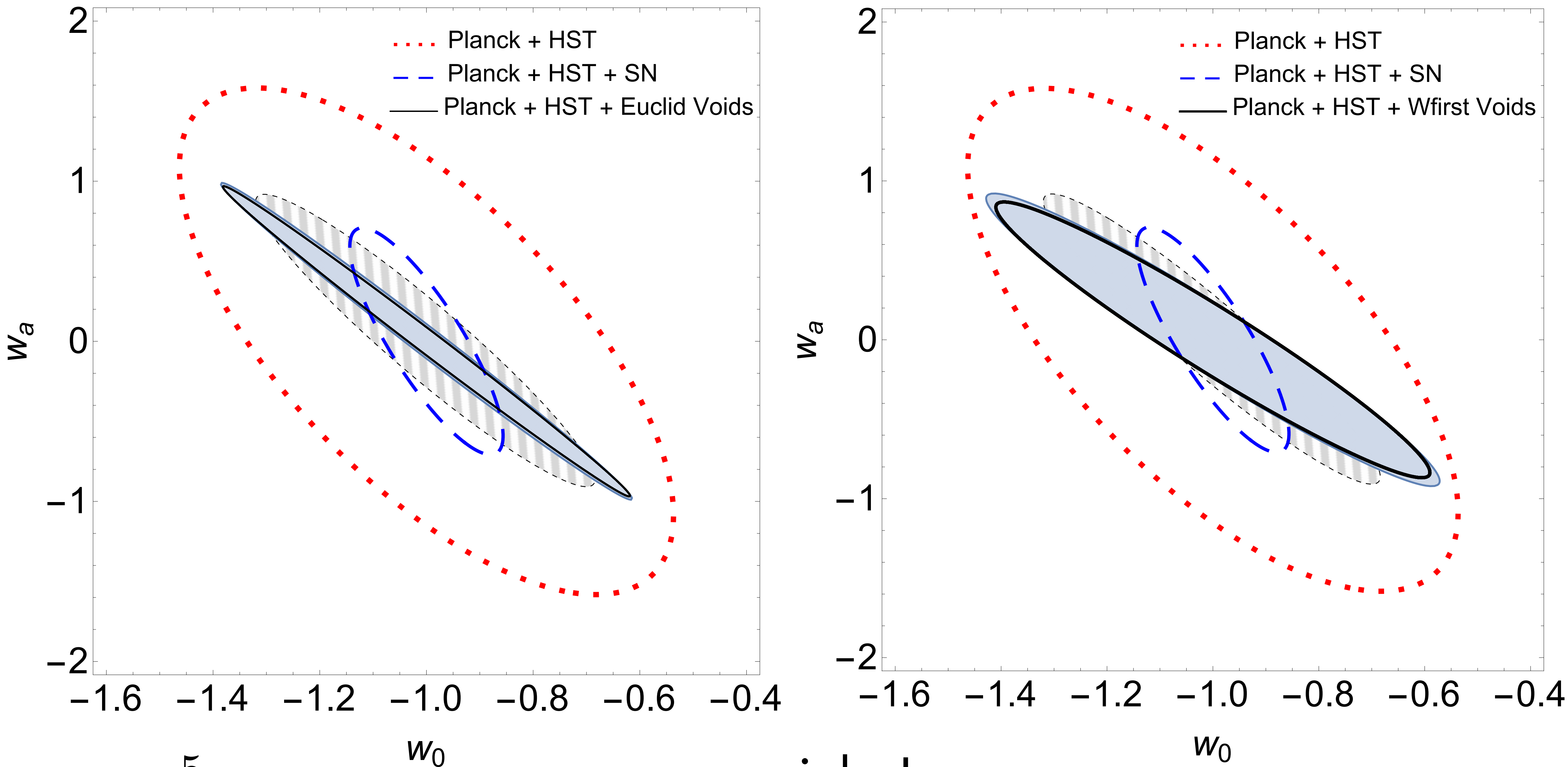
A conservative estimate of void numbers

- The model *as is* over-estimates void numbers in DM sims
- Predictions, with 2 caveats
  - Exclude small voids
  - δ_v = free parameter (watershed voids ≠ theoretical objects)+ marginalize



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

The great **complementarity** of upcoming surveys for voids

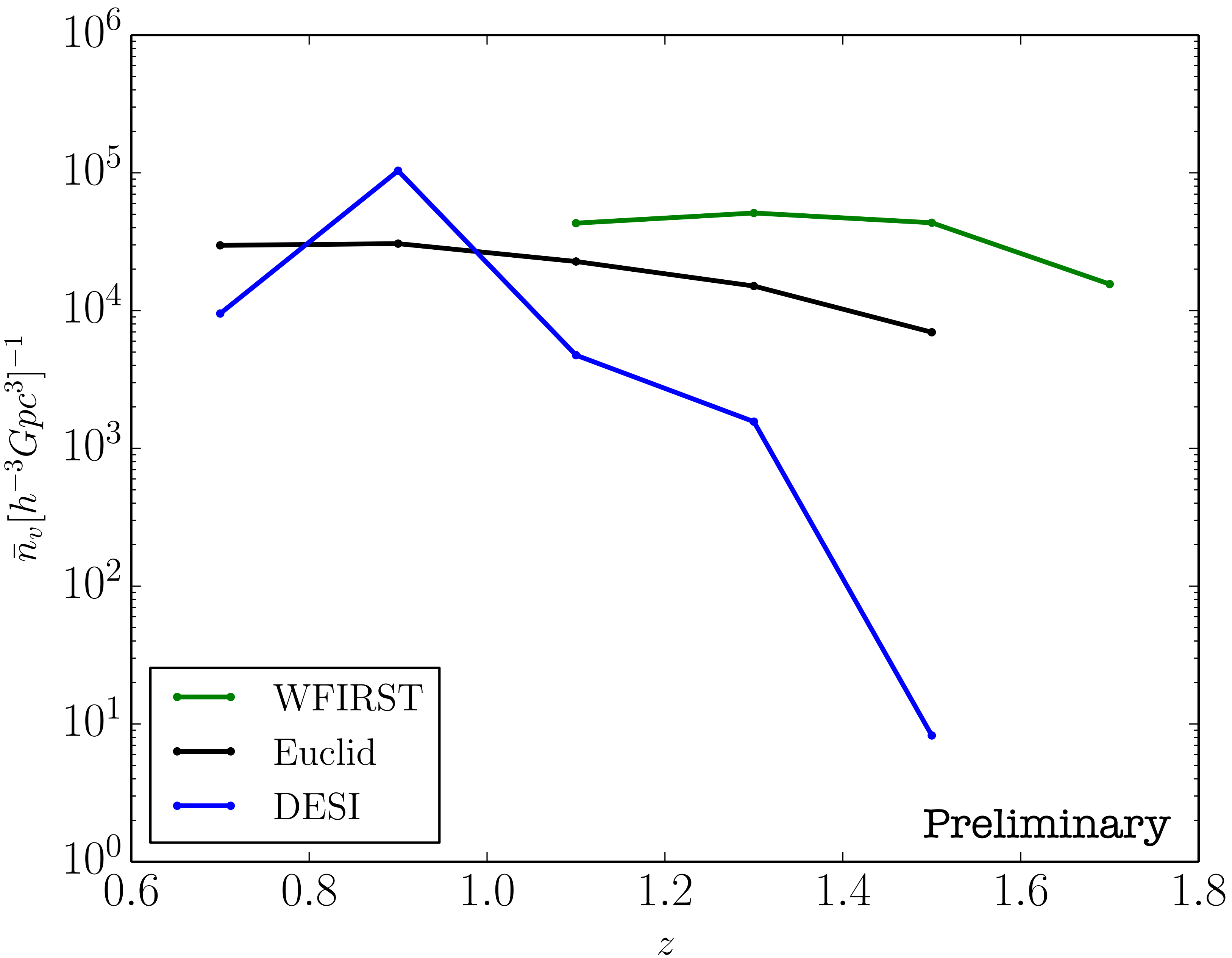


7.8×10^5 $\neq$ voids ! 2.5×10^5

Abundance , huge statistic for AP test and RSD

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

Not only upcoming surveys will provide an impressive number of voids, but they will target **different** voids, scanning the hierarchy of voids at different level.

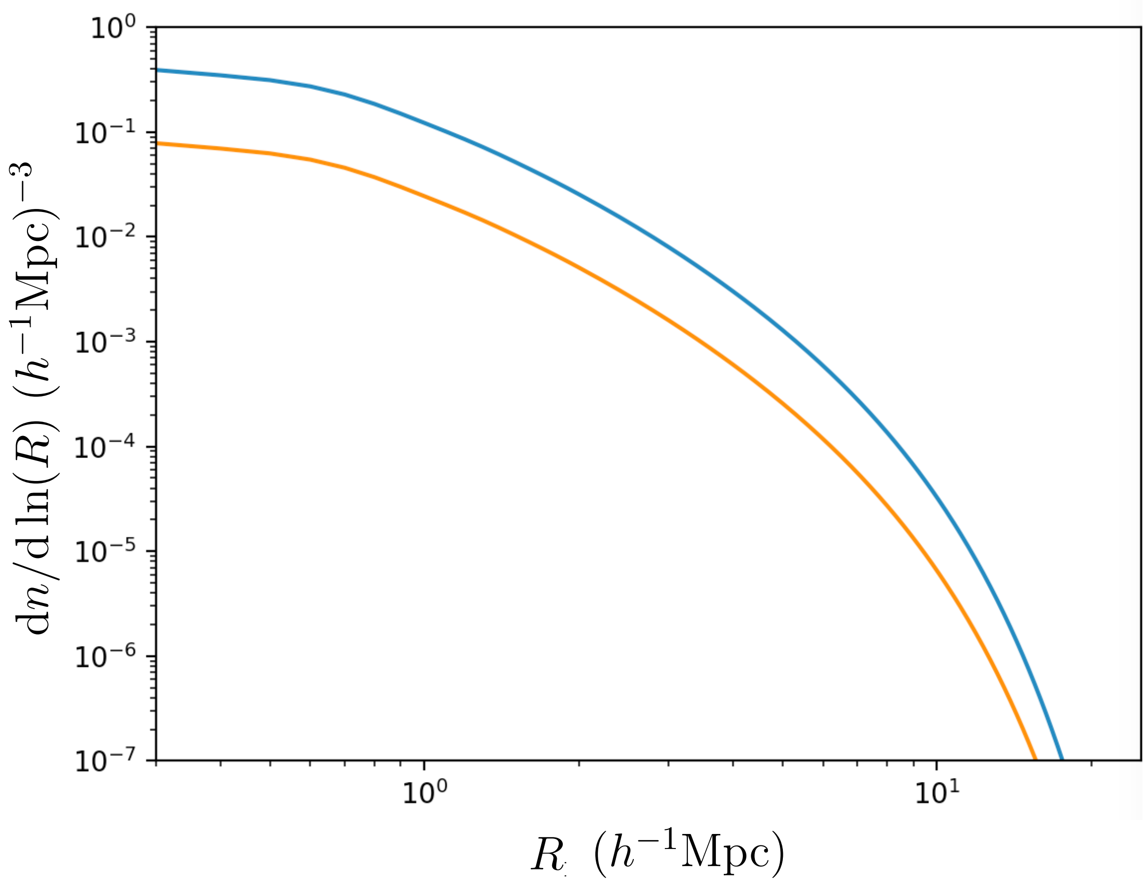


DE properties at ≠ scales

But let's work on bringing "theoretical" voids closer to the real world

Improved model

- Impose conserving the volume fraction of voids (works for DM, Jennings 2013)
- Rescale voids to account for actual under-density
- Consider tracer bias (so far tested only on 'small' sims 256 Mpc/h; 500 Mpc/h, 1 Gpc/h at most, see Pollina et al. 2018, Contarini et al. 2019)
- Only tested on **LCDM**

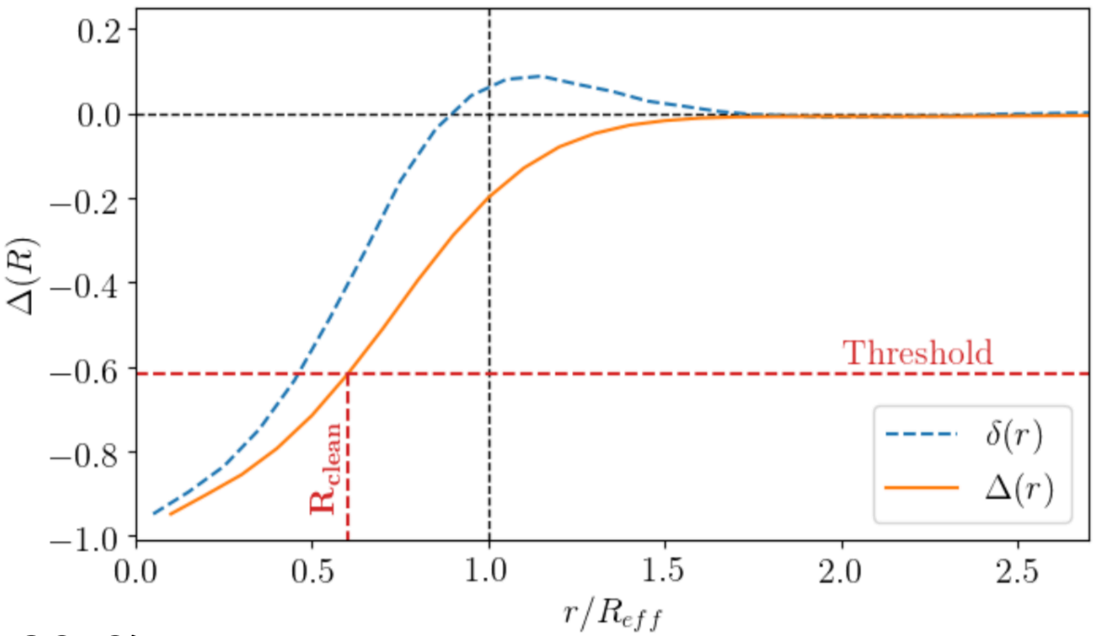


$$V(r)\mathrm{d}n = V(r_L)\mathrm{d}n_L|_{r_L=r_L(r)}$$

$$\frac{\mathrm{d}n}{\mathrm{d}\ln r} = \frac{f_{\ln\sigma}(\sigma)}{V(r)}\frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}\ln r_L}\bigg|_{r_L=r_L(r)}$$

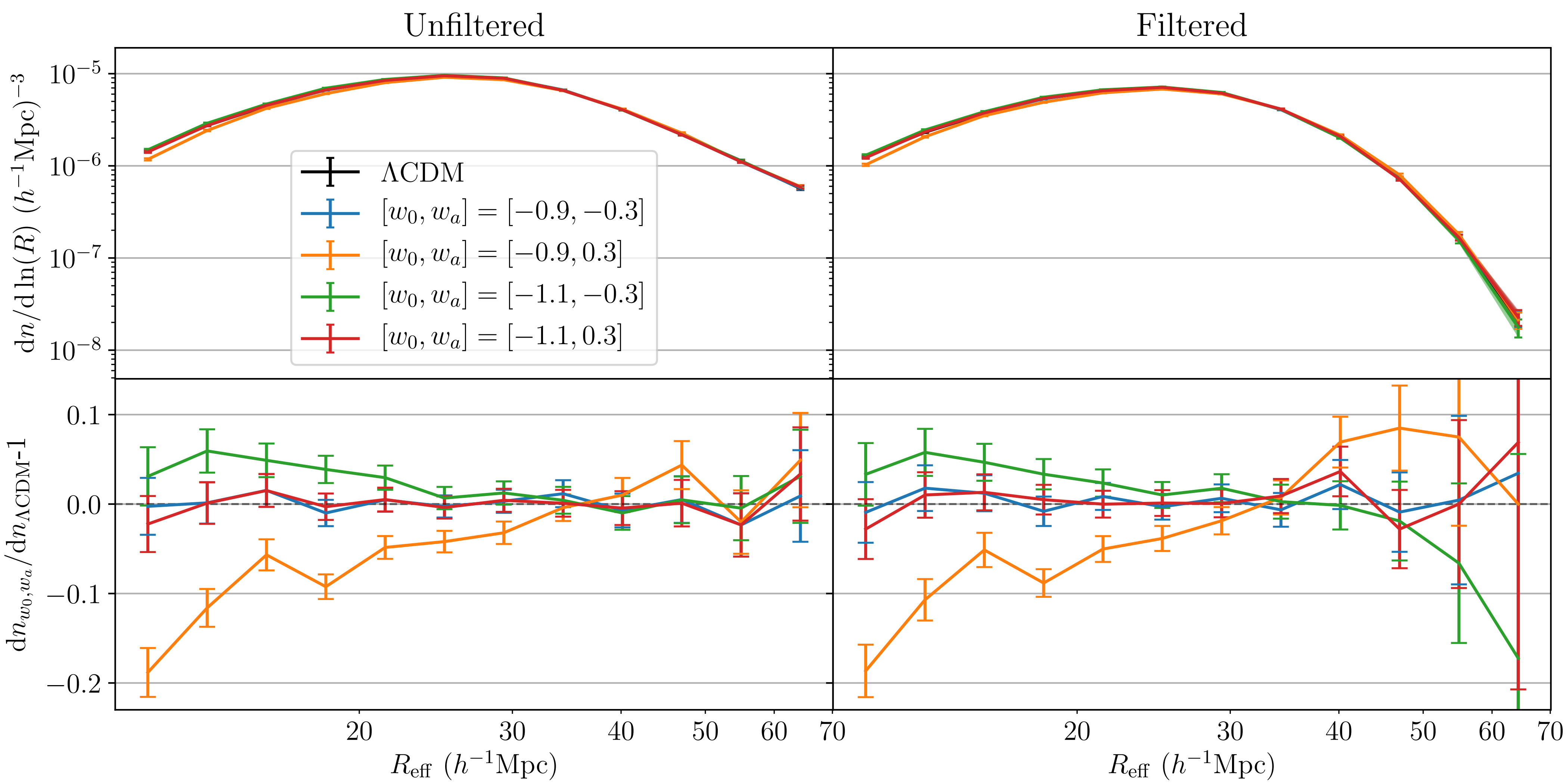
$$\delta^{H}_{v,NL} = b_{\rm eff} \times \delta^{mat}_{v,NL}$$

Giovanni Verza



arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

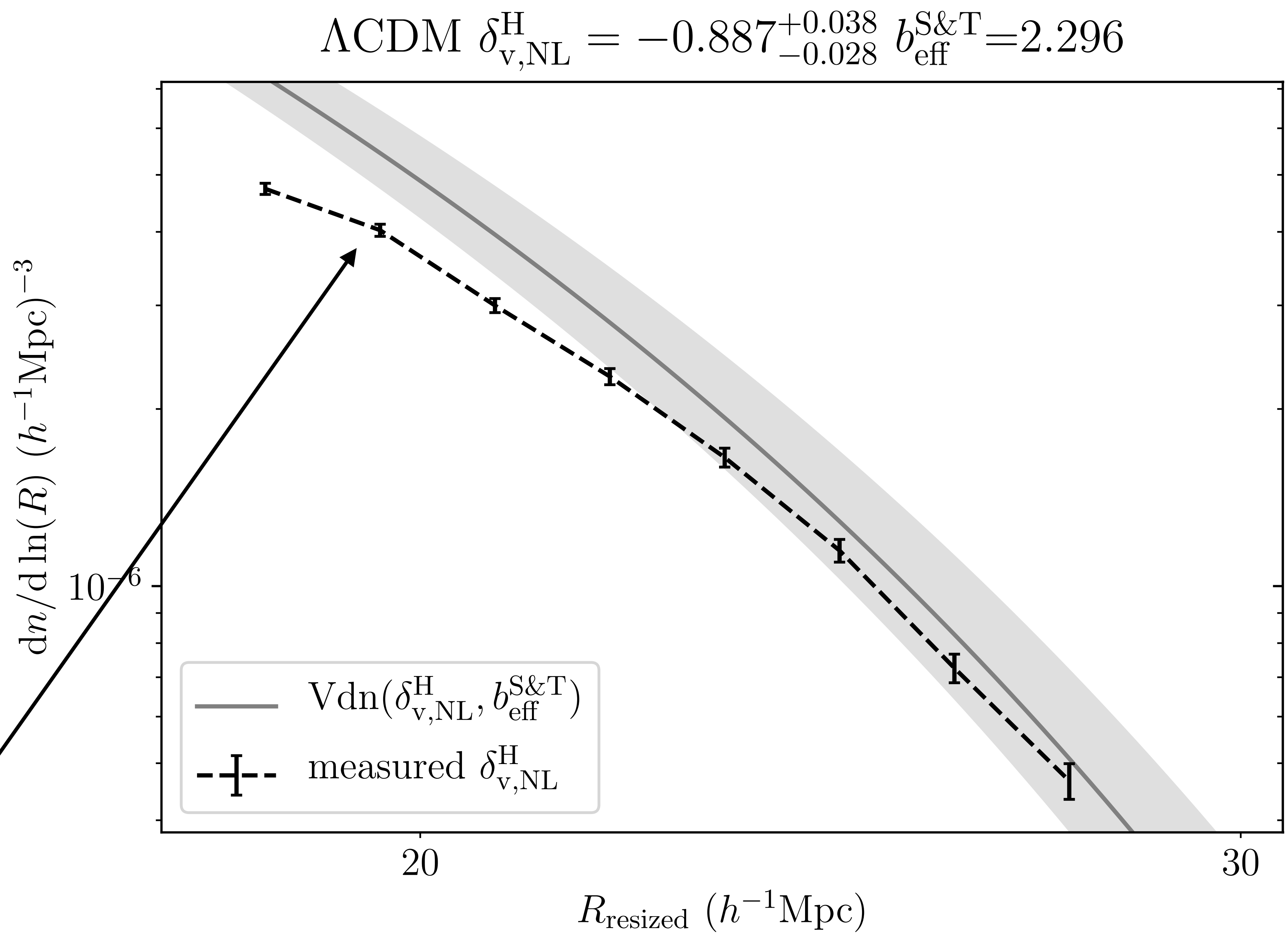
Testing the model



The moment when DE becomes relevant and how 'strong' it is when this happens will have a direct impact on voids.

arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

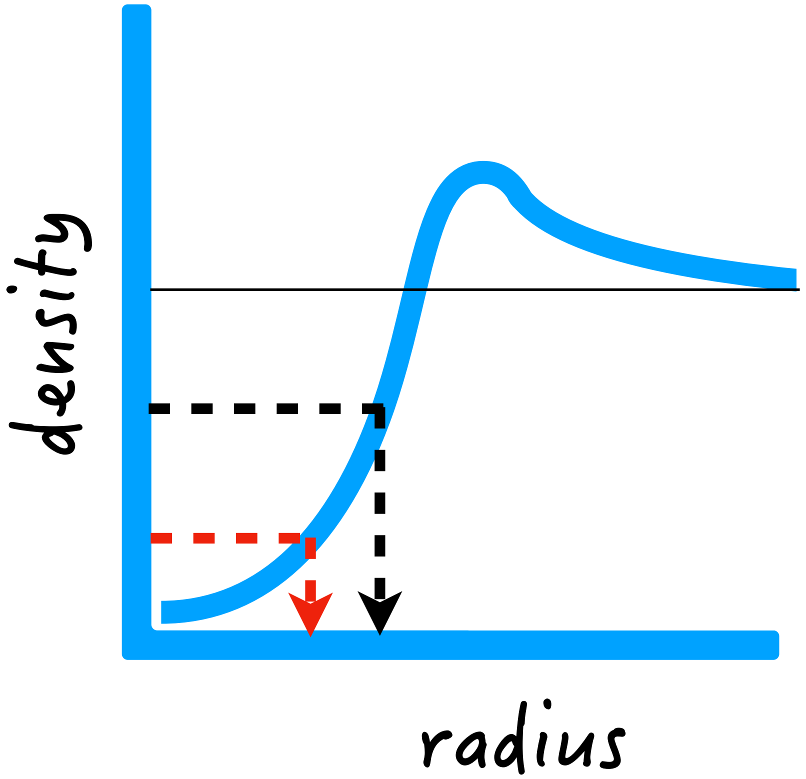
ΛCDM

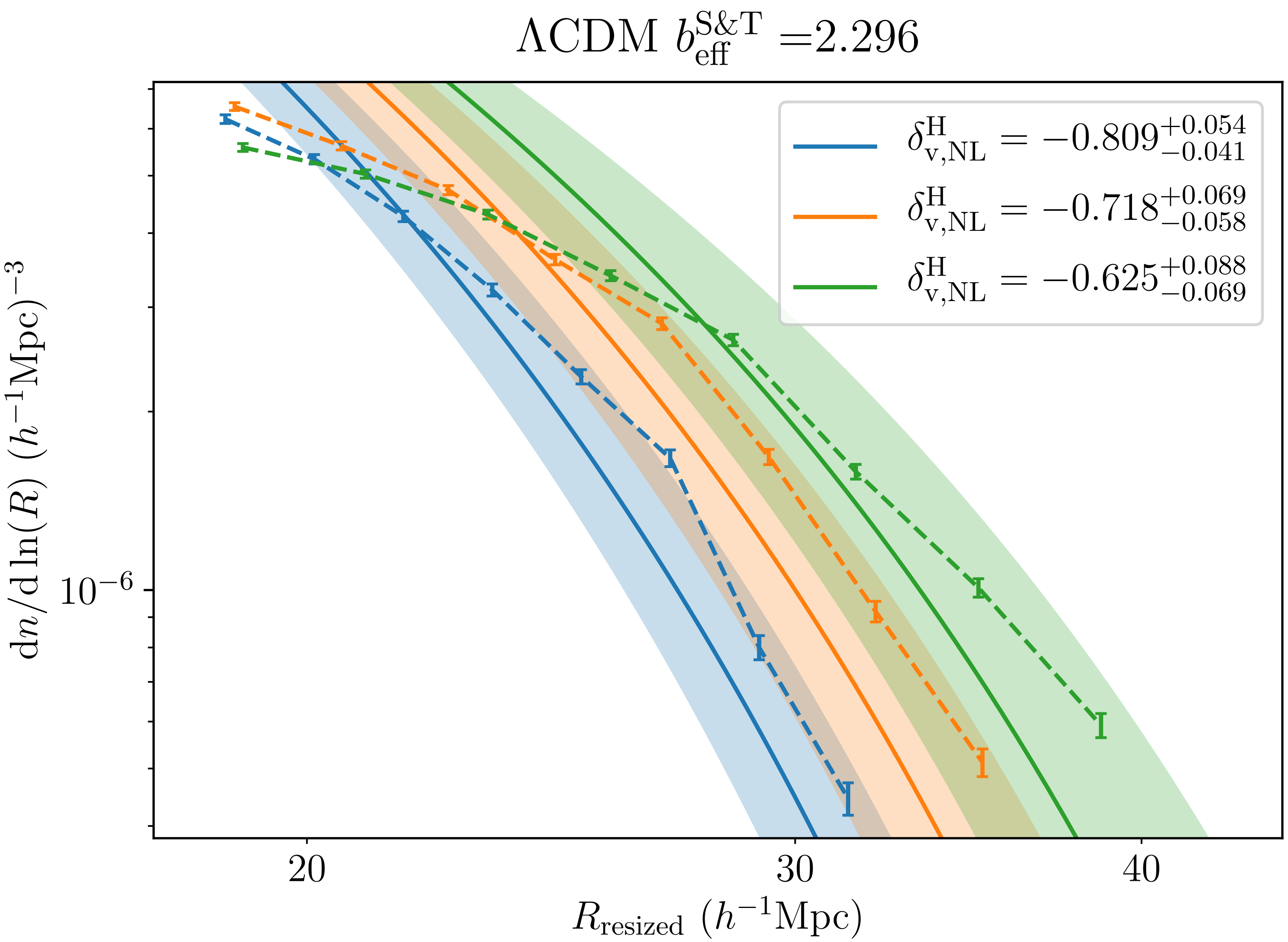


Dense surveys!

arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

ΛCDM





Many thresholds: observationally powerful

arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

DE models, fully theoretical prediction

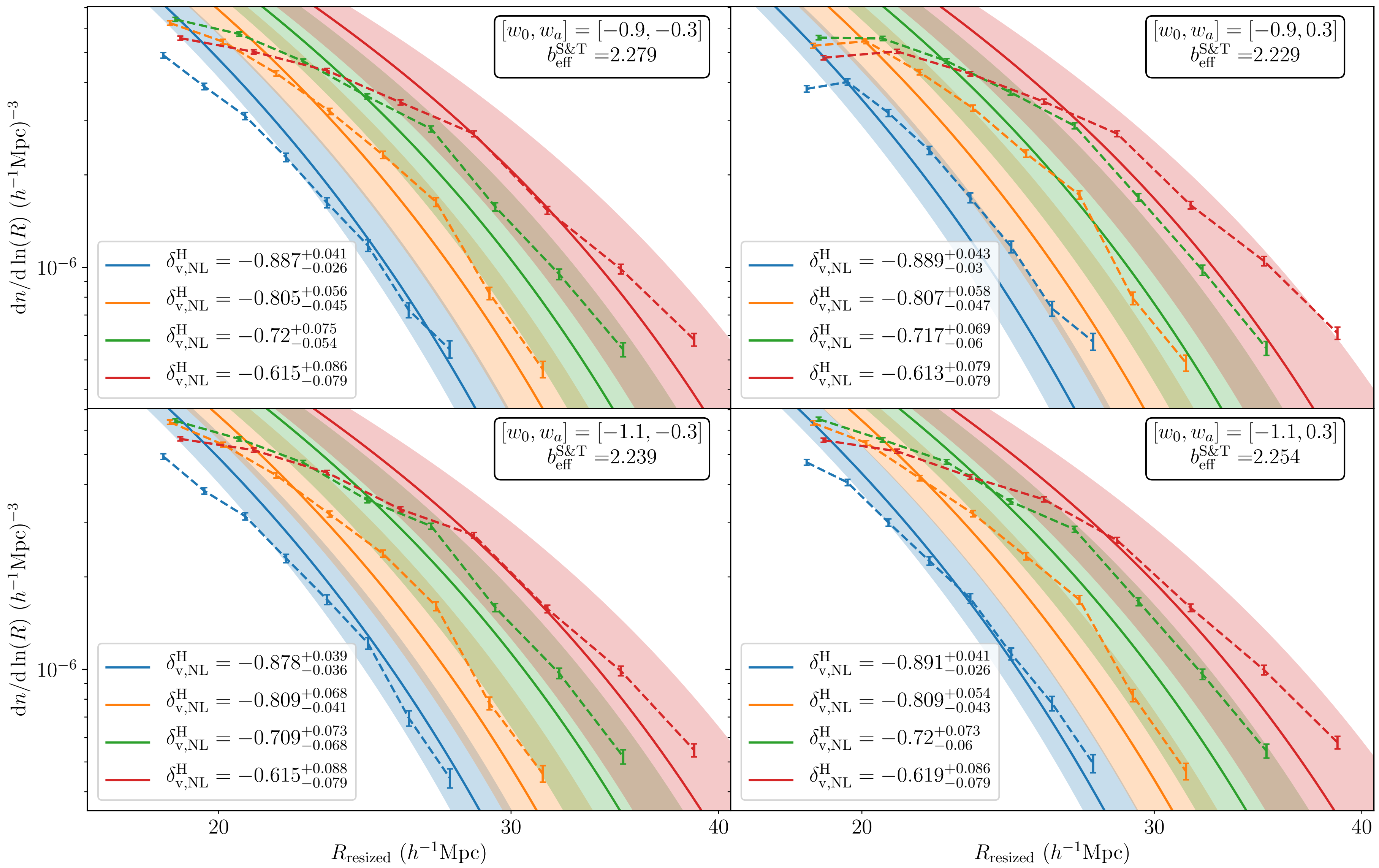


Figure 4: Each panel represents the measured void abundances after applying the resizing procedure (dashed curves), and the corresponding theoretical void size functions (solid curves), for various threshold values $\delta^{\rm H}_{\rm v,NL}$, and for the four sets of parameters of the CPL dark energy EoS. Shaded areas give the uncertainty in the resizing procedure (see text).

arXiv: 1906.00409; JCAP (Verza, **Pisani**, Carbone, Hamaus, Guzzo 2019)

Improvements

- Cleaning !! (based on density profile)
- Estimating bias
- Estimating mask effects, peculiar velocities effects
- Machine learning to enhance void catalogs reliability

All this prepares application to observations!

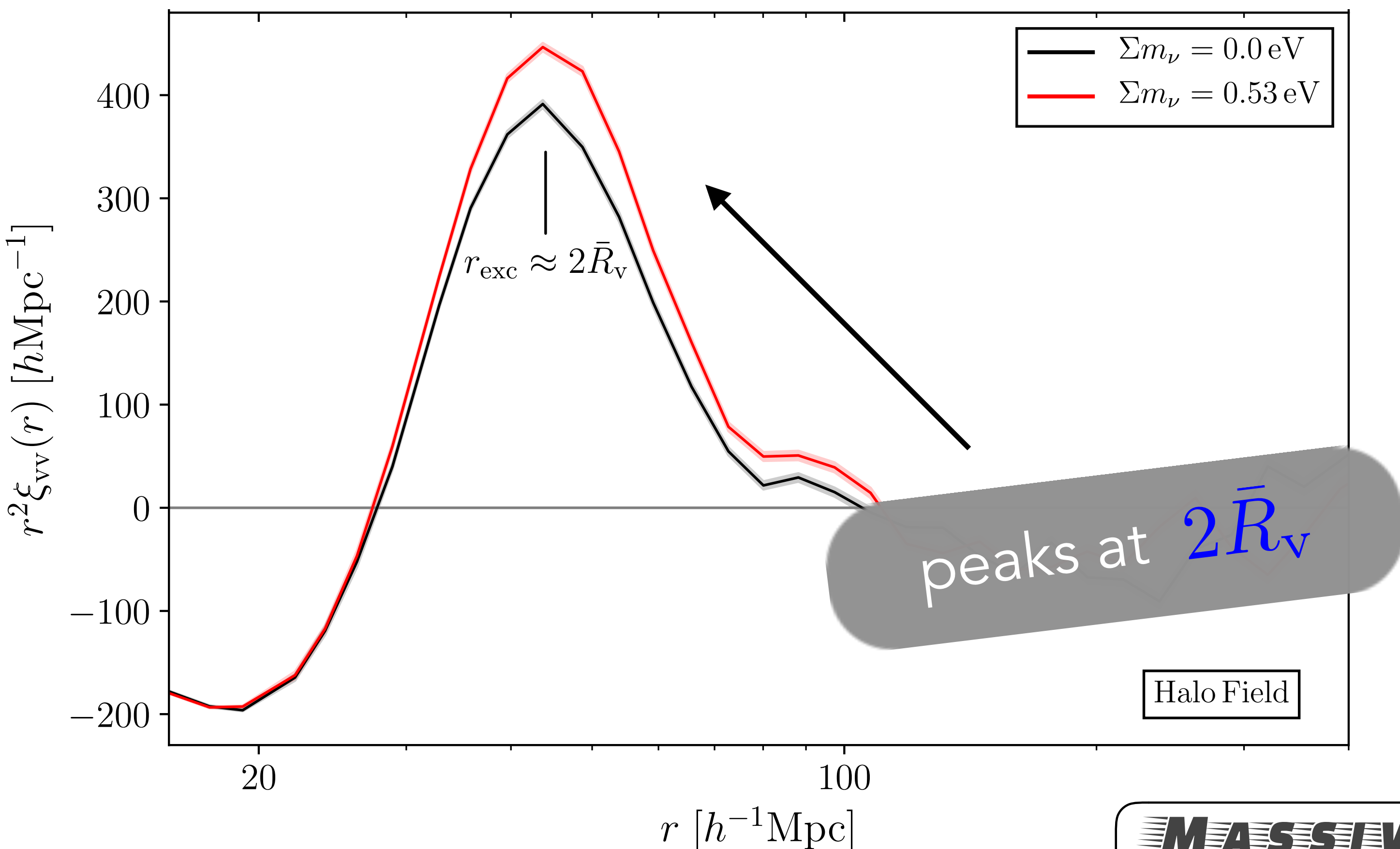
Outline

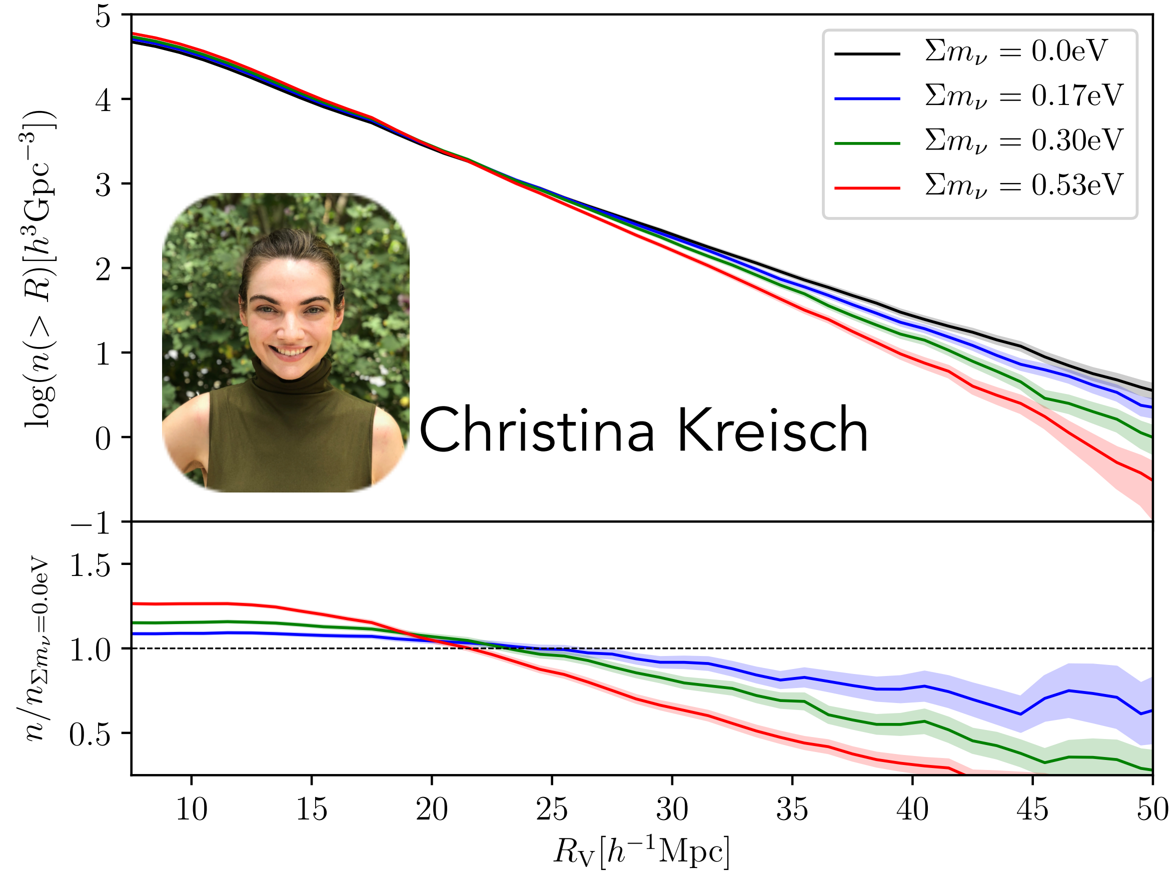
- Cosmology and Large Scale Structure
- Why are voids great for cosmology?
- How do we find voids?
- What do we measure?
- Void-galaxy correlation function [shape] $\xi_{\rm vg}$ ☑
- Void size function [numbers] $N_{\rm v}$ ☑
- **Void-void correlation function [clustering]** $\xi_{\rm vv}$ ☐
- Take home messages

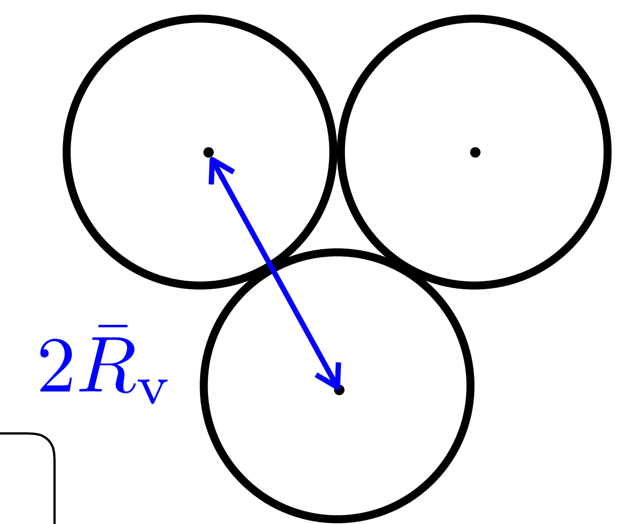
Teaser: 'clustering' of voids

- Massive neutrinos impact LSS (Massara et al 2015)
- Free-streaming length ~voids size

ξ_{VV}







DEMNUni Simulation Suite
Carbone et al. 2016
$L = 2\,h^{-1}\mathrm{Gpc}$ $\quad 2048^3$ DM particles

MASSIVENUS
COSMOLOGICAL MASSIVE NEUTRINO SIMULATIONS
101 cosmological models capturing the full **nonlinear** evolution in massive neutrino cosmologies

Data Fully Public
→ CMB & galaxy lensing maps
→ Halo catalogues
→ Merger trees
→ Snapshots

Code:
Gadget-2
1024^3 DM particles
512Mpc/h box
+ kspace-neutrino
+ LensTools
+ Rockstar
+ Consistent Tree

Liu et al. 2018

Kreisch, **Pisani**, Carbone, Liu, Hawken, Massara, Spergel, Wandelt, MNRAS 2018

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- **Take home messages**

Take home messages

Voids, a **novel tool for Cosmology**.

Void analysis is an active field of galaxy clustering.

Already brings competitive cosmological constraints! $\xi_{\rm vg} \rightarrow \Omega_m \ \beta$

Promising to **constrain DE, massive neutrinos** (theoretical prescription for the void size function! New tool: void-void correlation function).

Huge statistics to come: **large collaborations** are expanding their activity in the sector (PFS, HSC, Euclid, WFIRST, DES), they target ≠ voids

For precision cosmology, theoretical modeling needs to keep the pace with data:

=> theoretical modeling of the density profile
=> impact of peculiar velocities (e.g. on abundance)
=> observational effects (mask, boundaries!)

Thanks!