Unraveling the Universe with cosmic voids

+ many collaborators, highlights: N. Hamaus (Munich), G. Verza (Padova), C. Kreisch (Princeton), S. Contarini (Bologna), R. Panchal (Princeton), D. Spergel (Princeton, Flatiron), B. Wandelt (IAP), G. Lavaux (IAP), M. Habouzit (MPIA), E. Massara (Waterloo), M.-C. Cousinou (CPPM),….

PRINCETON UNIVERSITY

Alice Pisani

Outline

- Cosmology and Large Scale Structure
- Why are voids great for Cosmology?
- How do we find voids?
- Void-galaxy cross-correlation function (constraints so far)
- Void-size function
- Void-void auto-correlation function
- Take home messages

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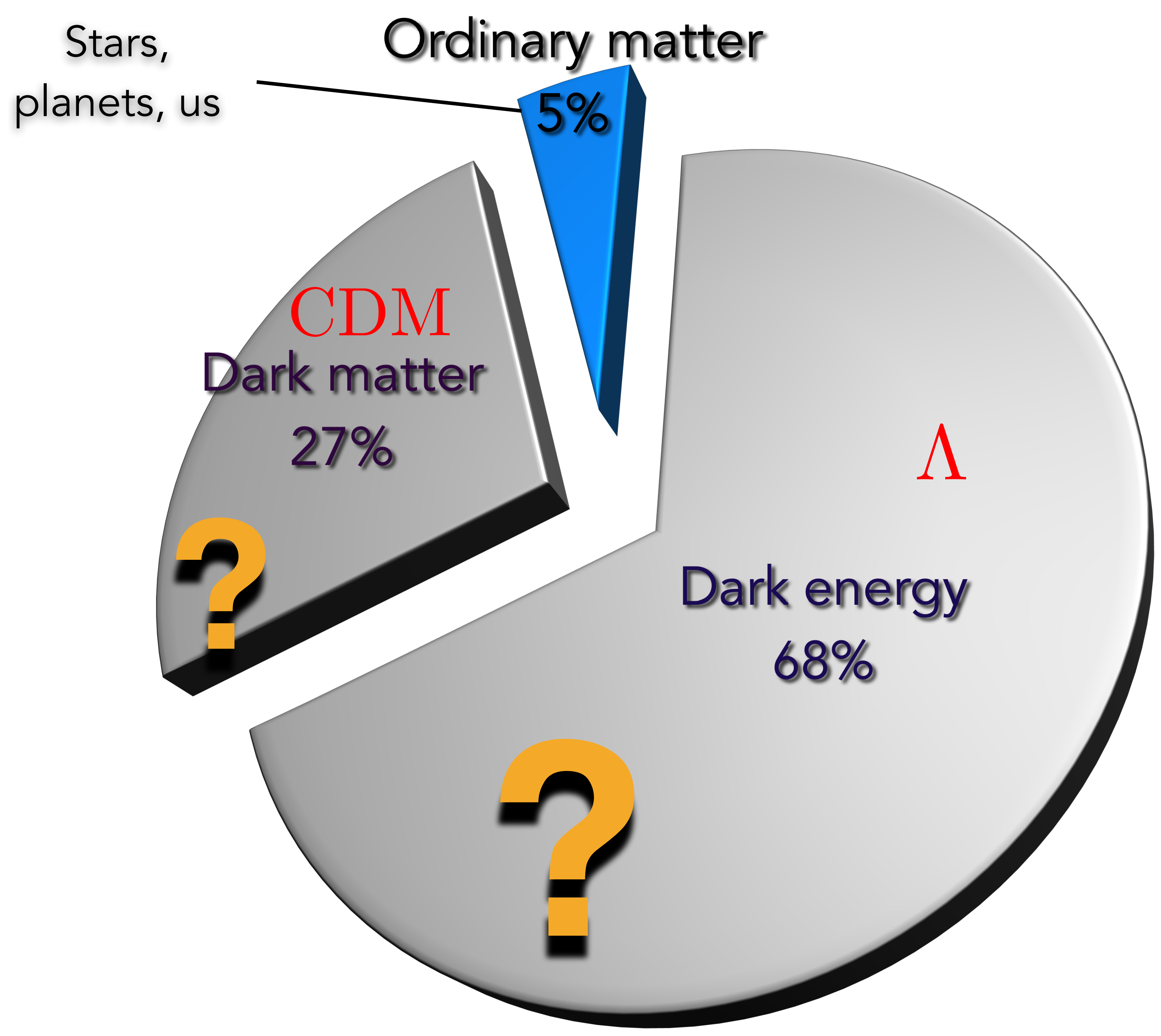


Precision Cosmology

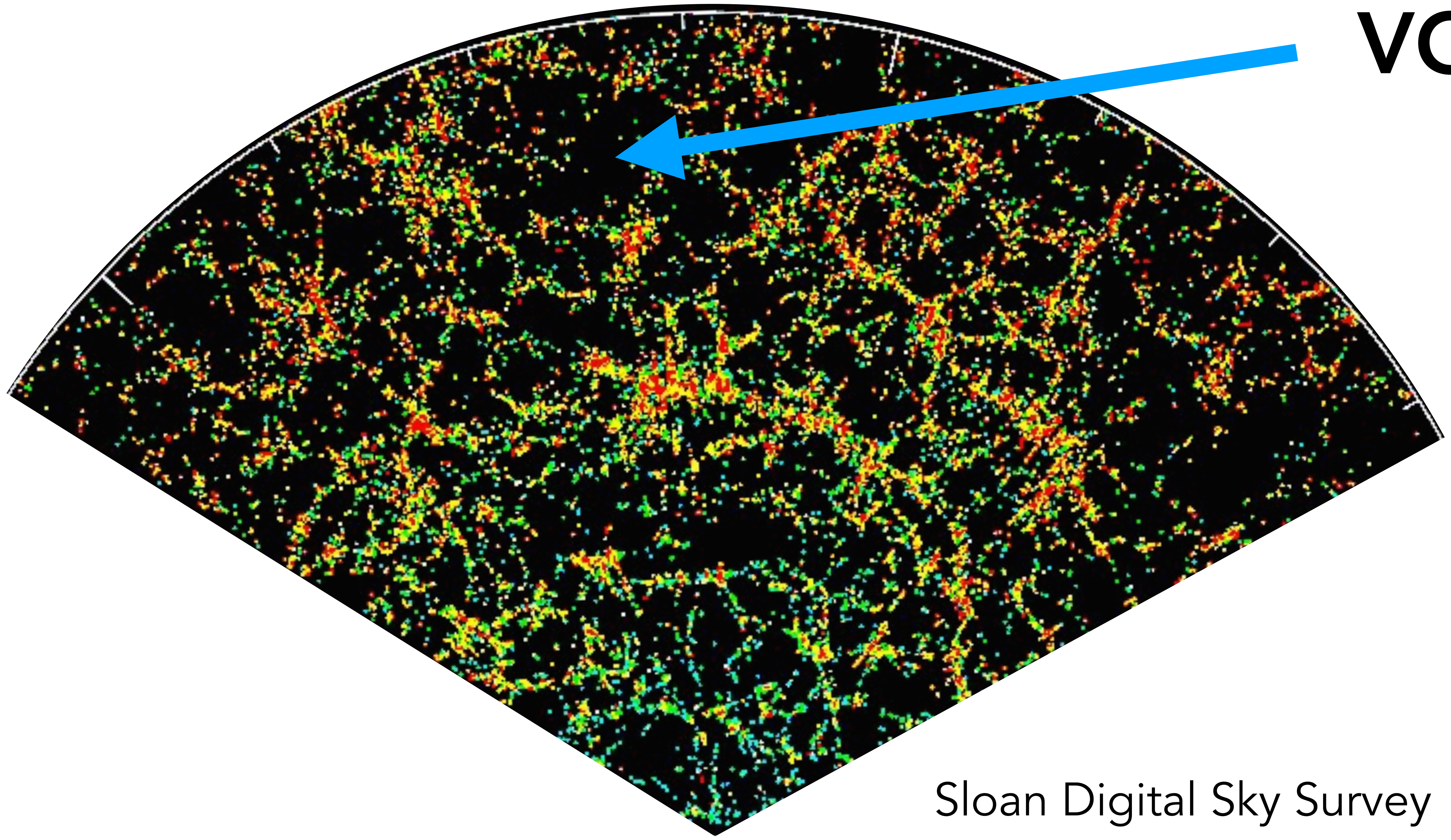
A standard model ΛCDM, to explain the accelerated expansion of the Universe.

New physics!

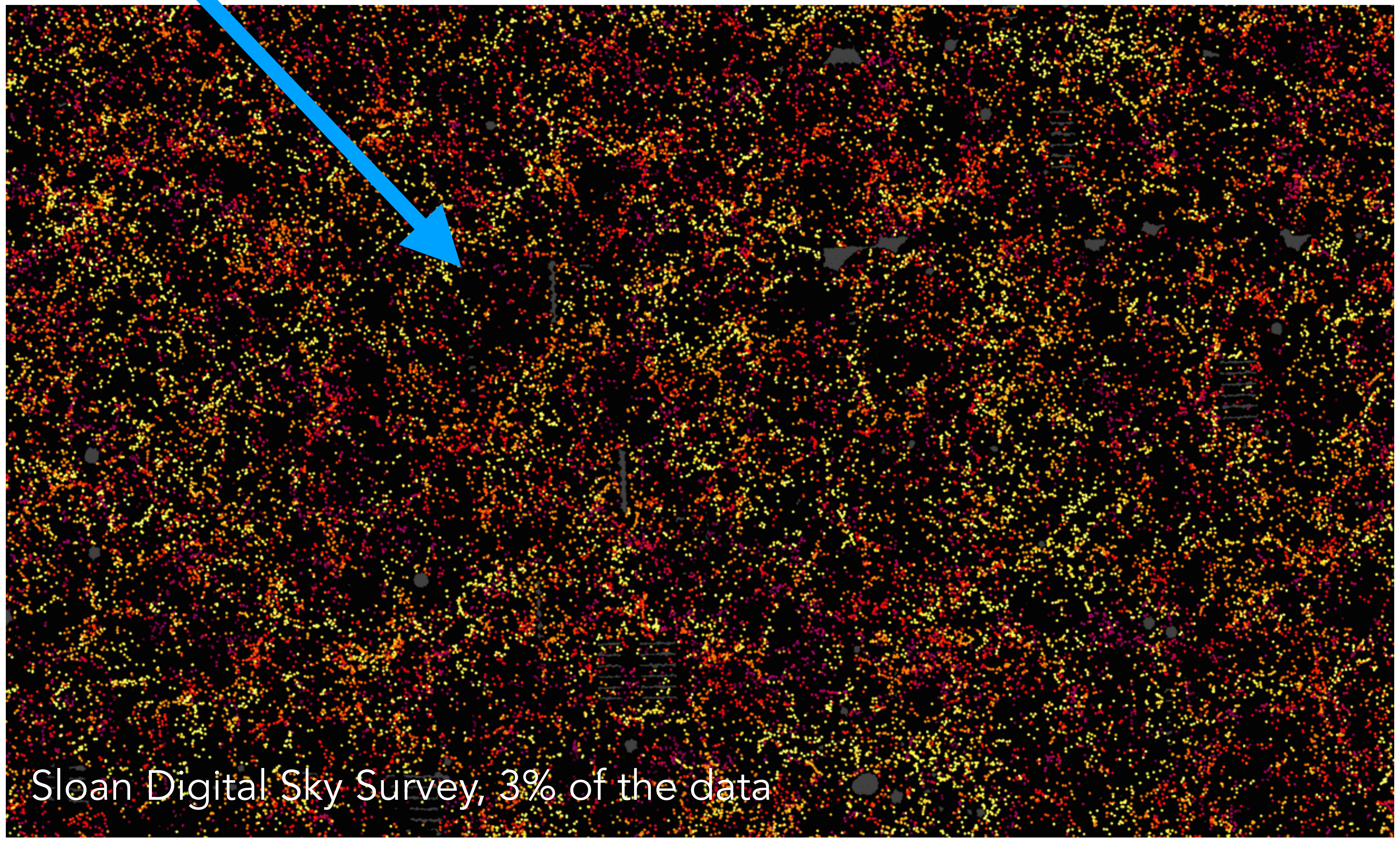
Large Scale Structure of the Universe

Modern surveys = access to large volume + detailed map

VOIDS



Sloan Digital Sky Survey



Sloan Digital Sky Survey, 3% of the data

Voids **need** large volume and deep, detailed maps!

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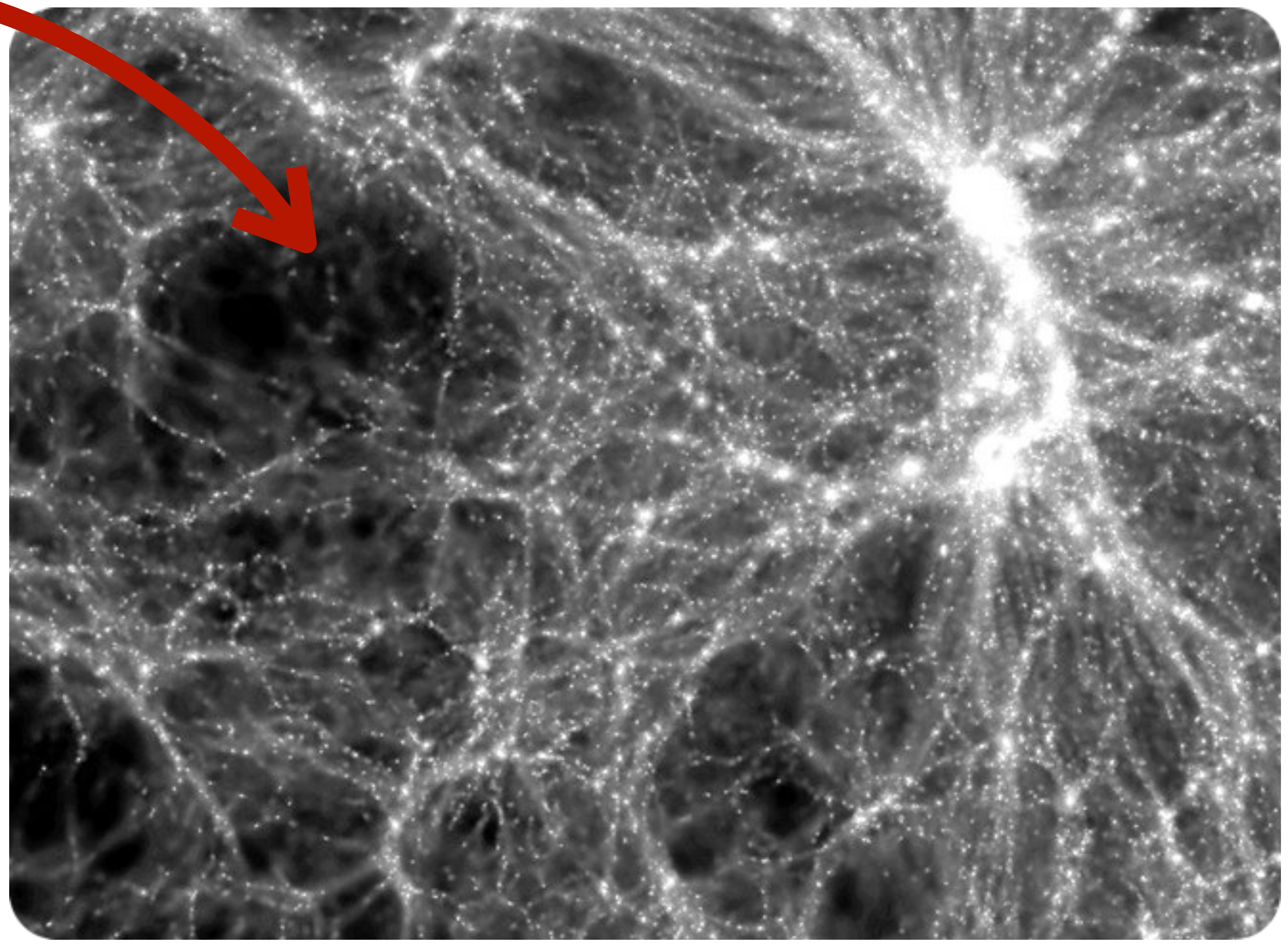
Why are voids great for Cosmology?

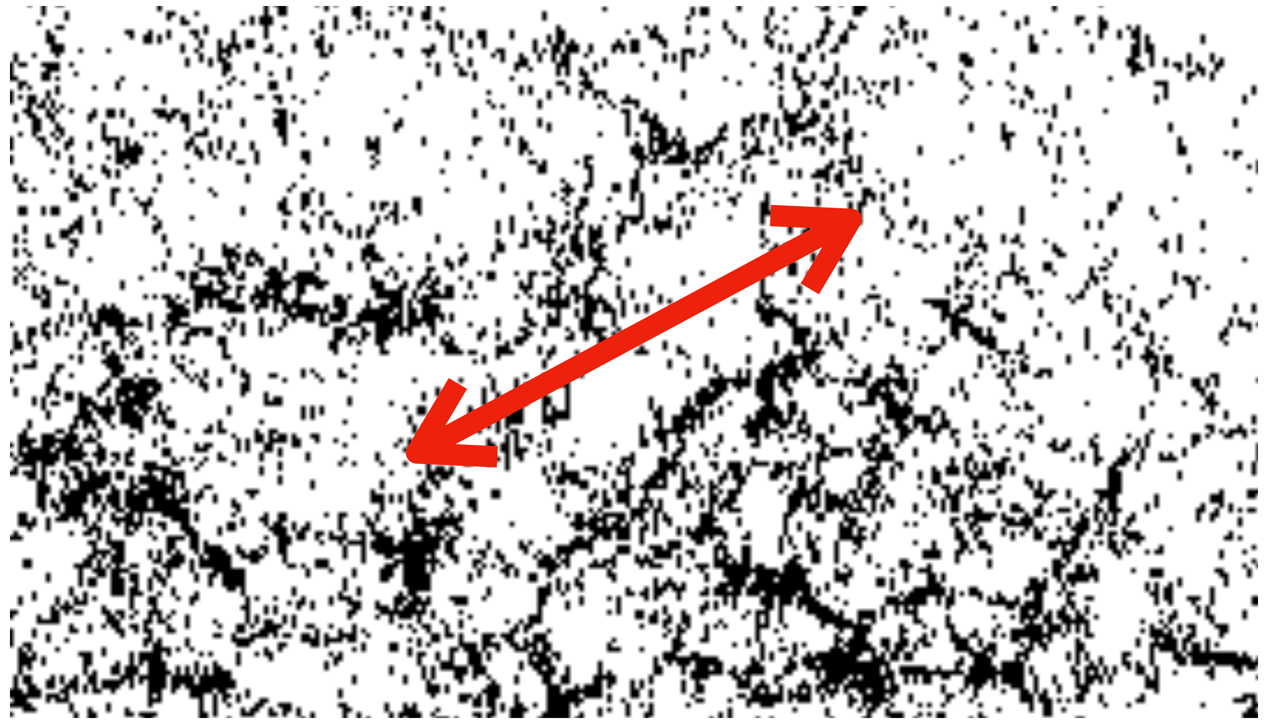
- By definition dark energy dominated objects (first regions to be dominated).
- Low density + large scale= mimic current accelerated expansion status.
- Sweet spot: potential general relativity deviations more prominent!
- Generically sensitive to diffuse components Σm_ν



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

Why are voids great for Cosmology?

- Allow to go beyond 2 pt correlation function
- Multi-scale sensitivity (span sizes from 10-100 Mpc/h)
- Easier to model (exploit traditional techniques, models valid down to small scales)
- Keep memory of initial conditions



Take one random galaxy, how likely is it to find another galaxy x Mpc away?

Lots of large scale structure data!
Golden era for voids!

Quantities we wish to constrain

Ω_m, Ω_Λ Content of the Universe

Bias

$f = \frac{d\ln\Delta}{d\ln a}$ Growth rate of structure $\frac{f}{b}$ $b = \frac{\delta_{\rm gal}}{\delta}$

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

Σm_ν Sum of neutrino masses

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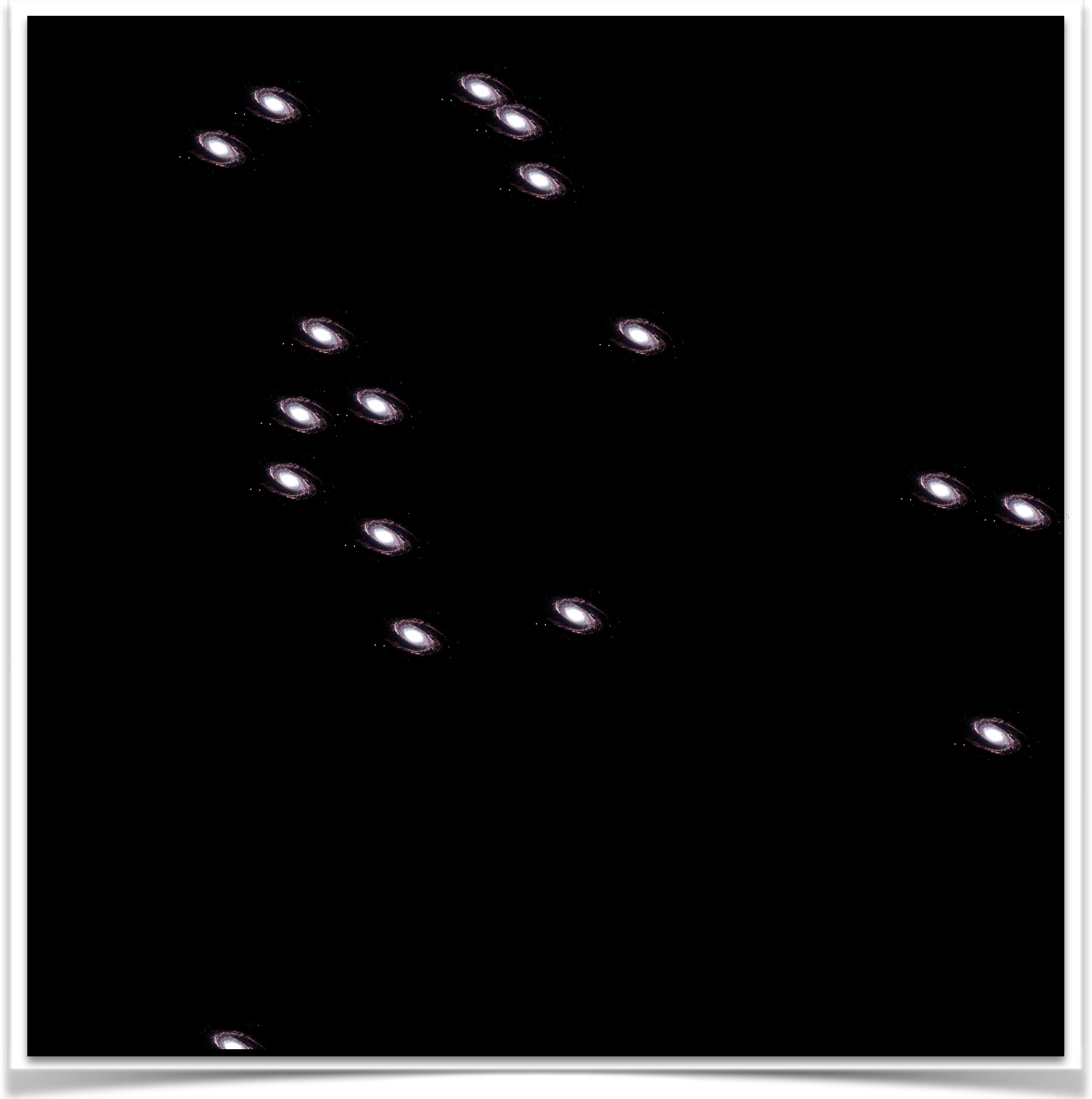
Void definition: VIDE (Void IDentification and Examination)

galaxies → ? → voids



VIDE:https://bitbucket.org/cosmicvoids/vide_public/src/master/, Sutter, Lavaux, Hamaus, Pisani, Wandelt, Warren, Villaescusa-Navarro, Zivick, Mao, and Thompson 2015 A&C ArXiv: 1406.1191
Icke & Van de Weygaert (1987)
Platen et al. 2007

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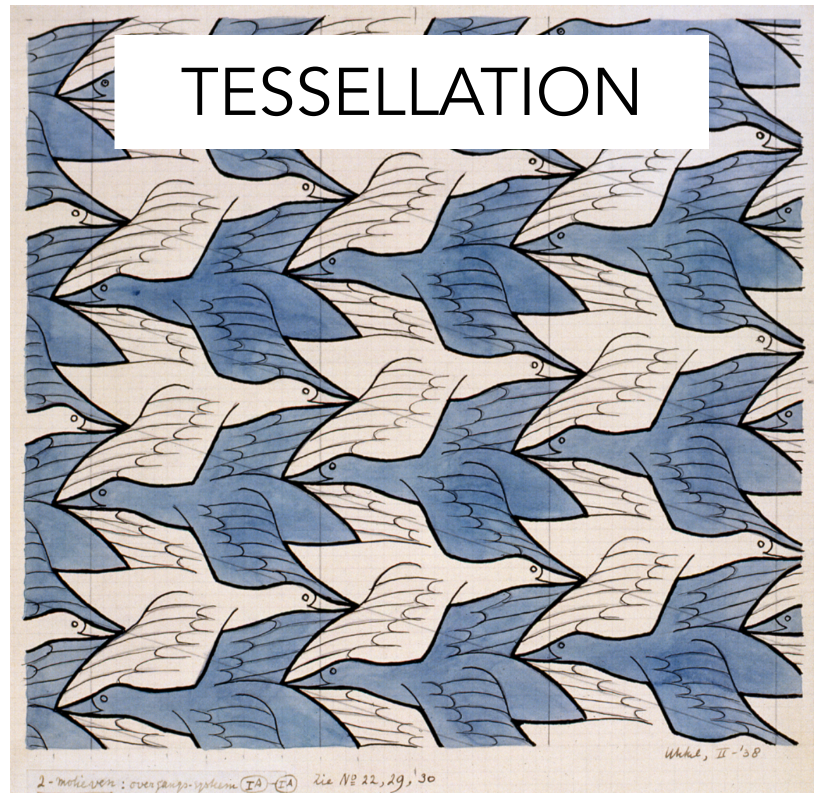

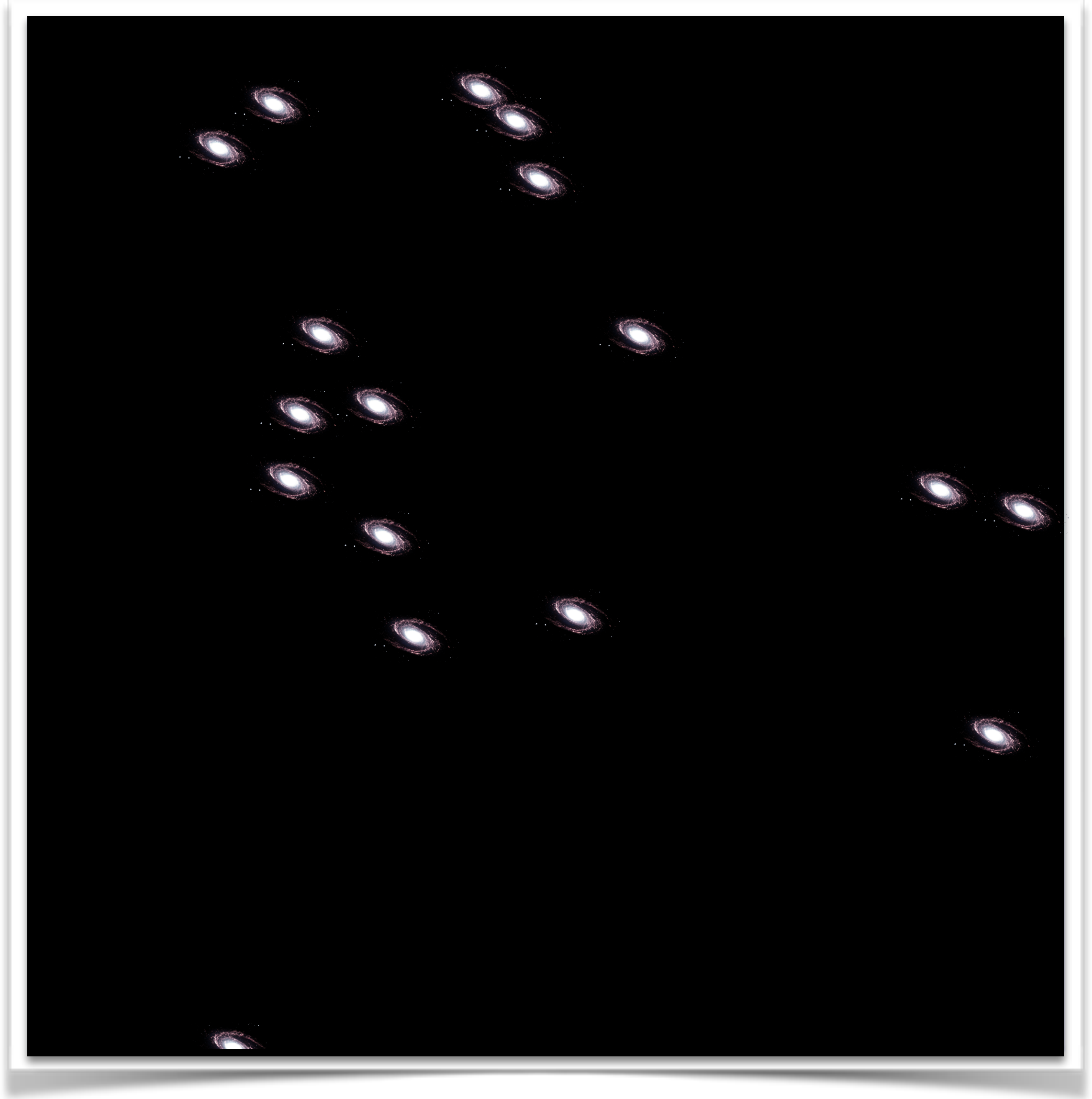

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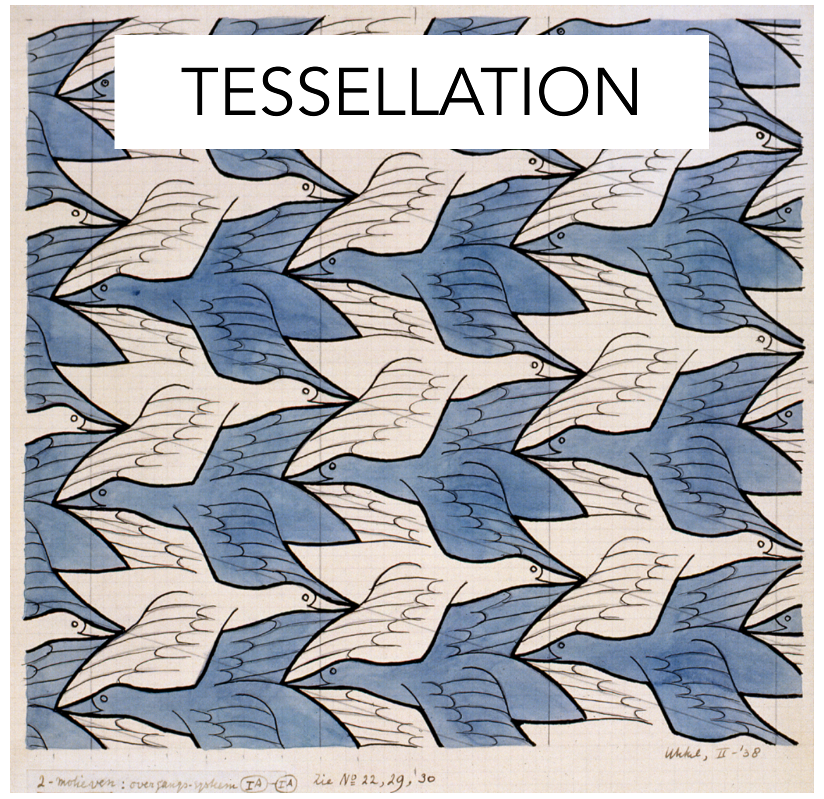
galaxies ➡ Voronoi tessellation | voids



Galaxy

All points closer to the tracer than to any other point

Local density estimation

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

A tessellation with a physical meaning

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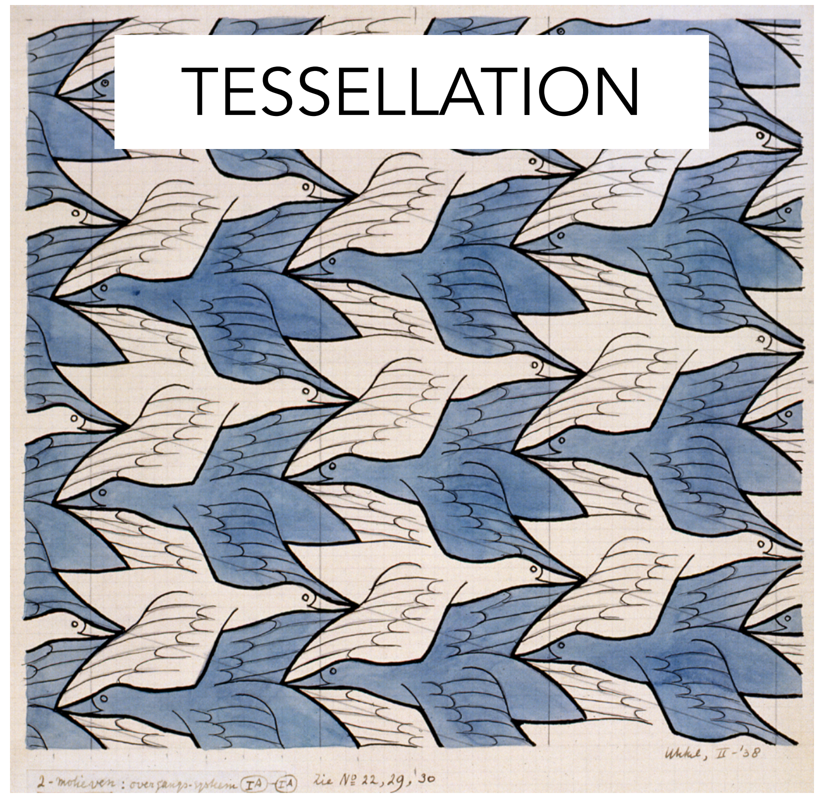

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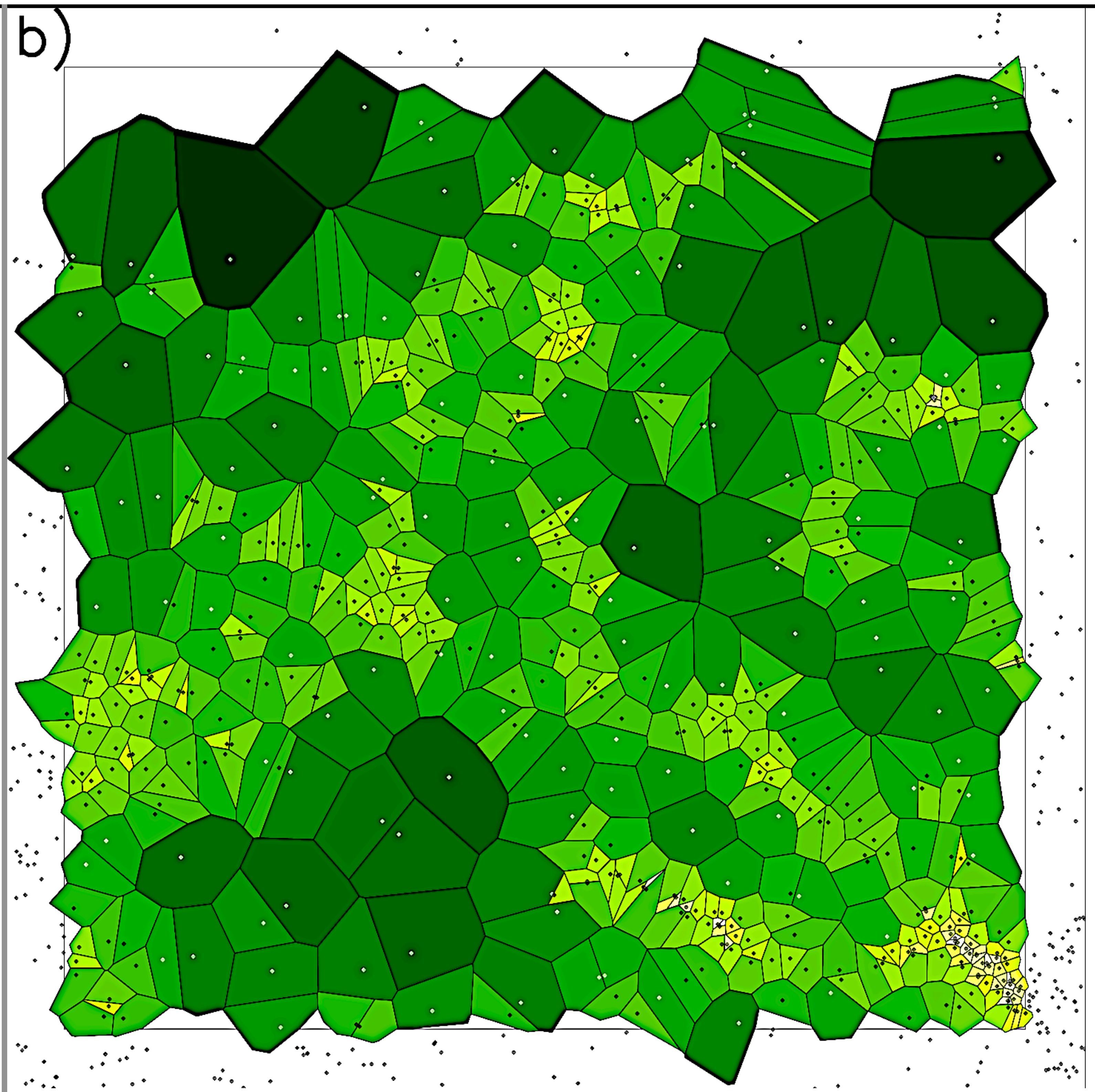

Neyrinck 2008

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

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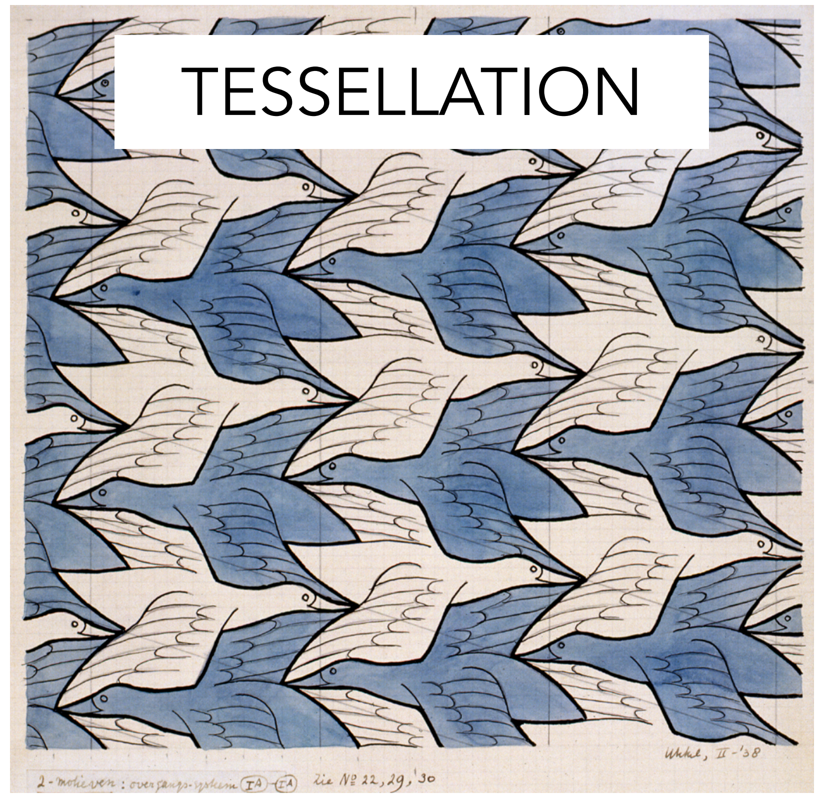
galaxies → Voronoi tessellation → voids



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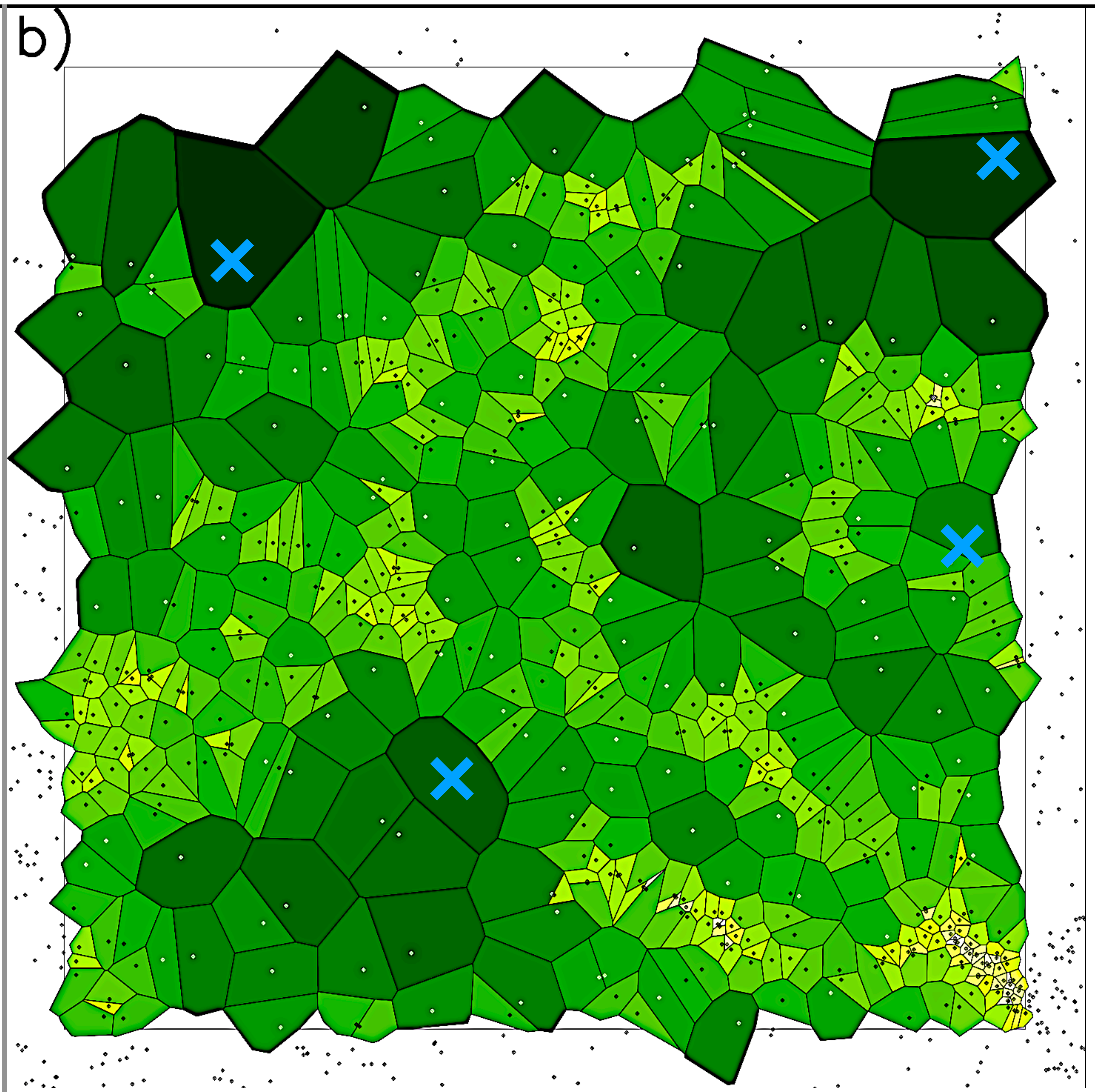

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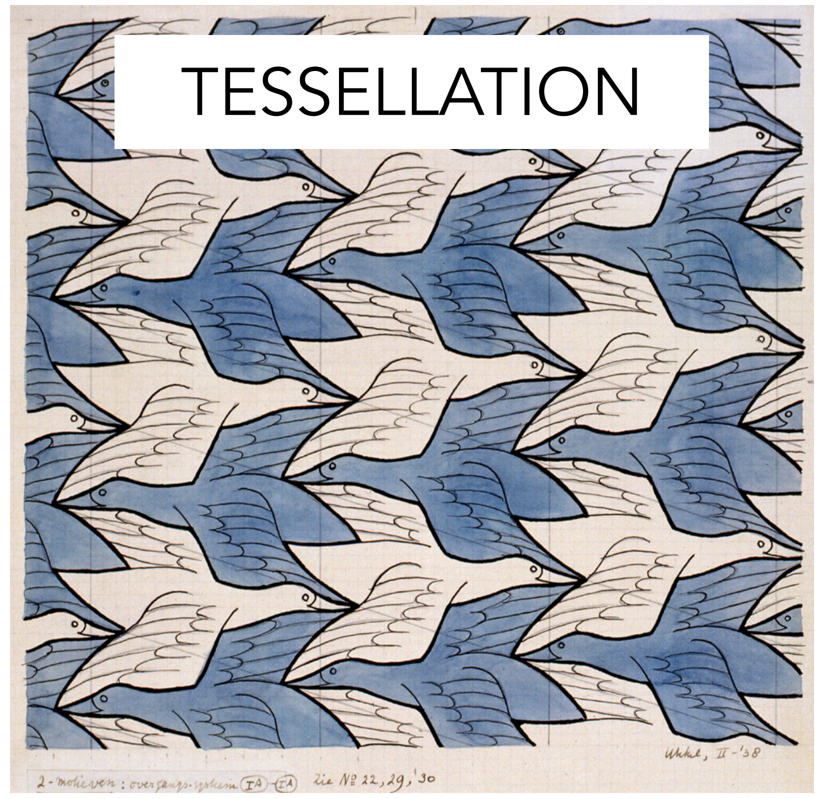
Void definition: VIDE (Void IDentification and Examination)

galaxies → Voronoi tessellation → Watershed transform → voids



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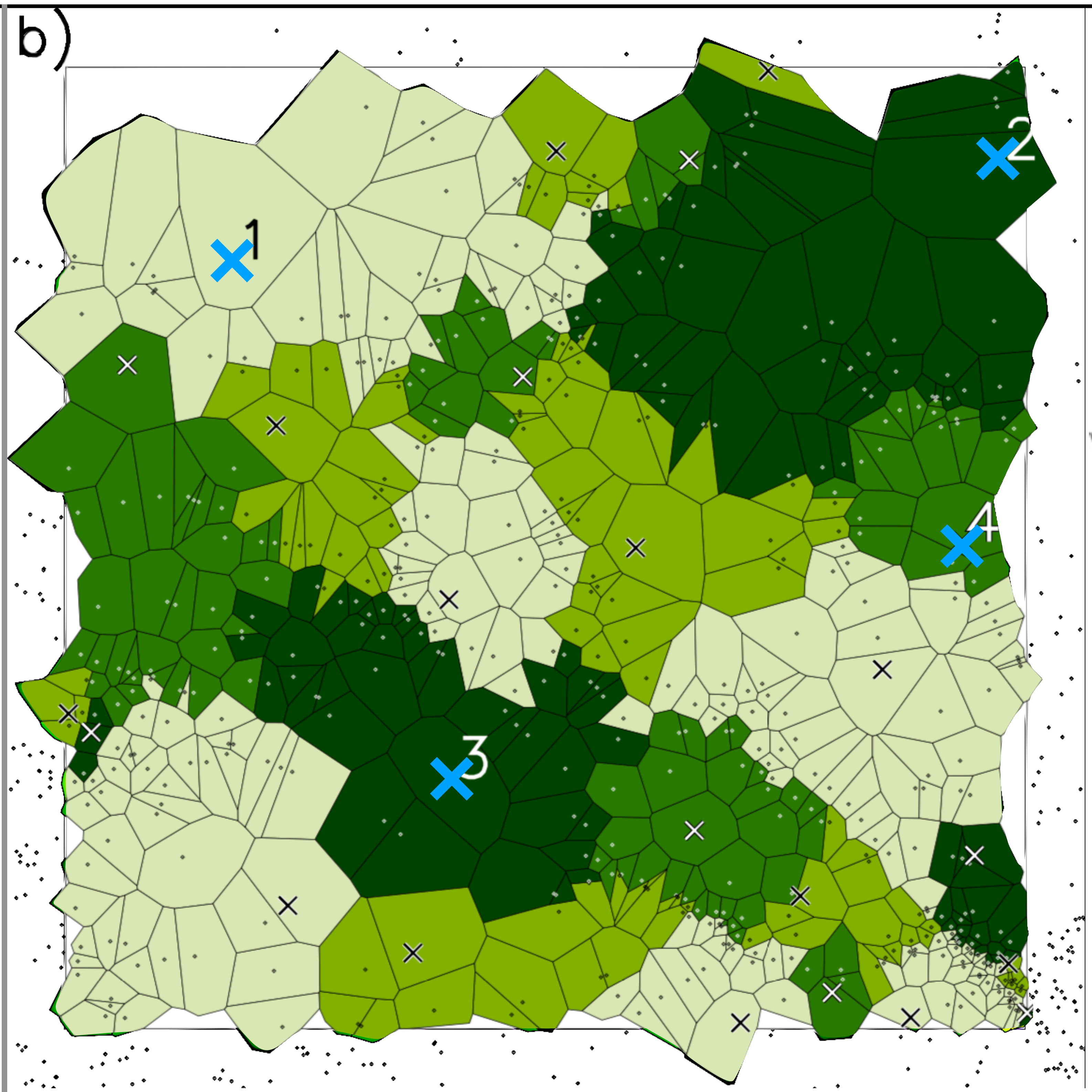

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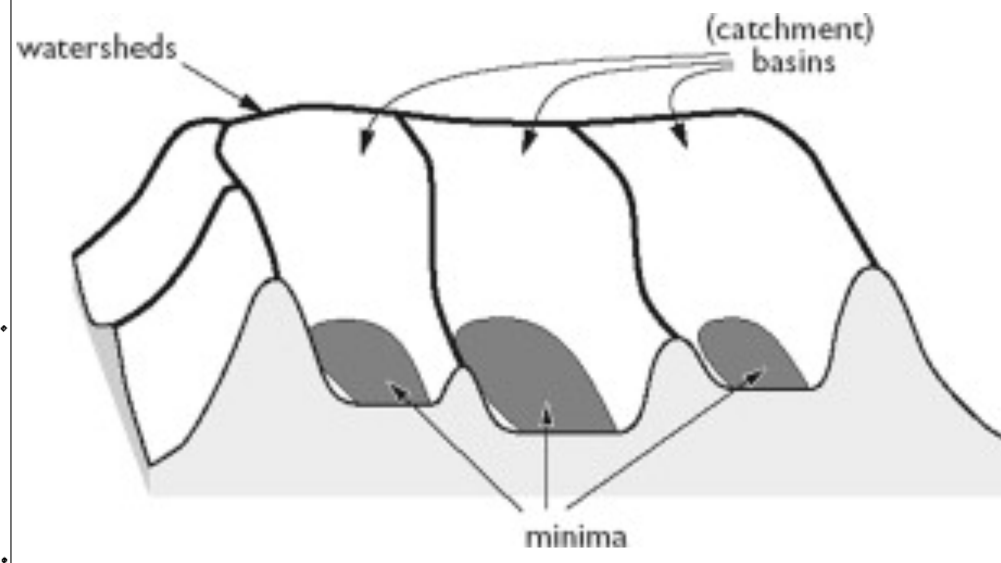


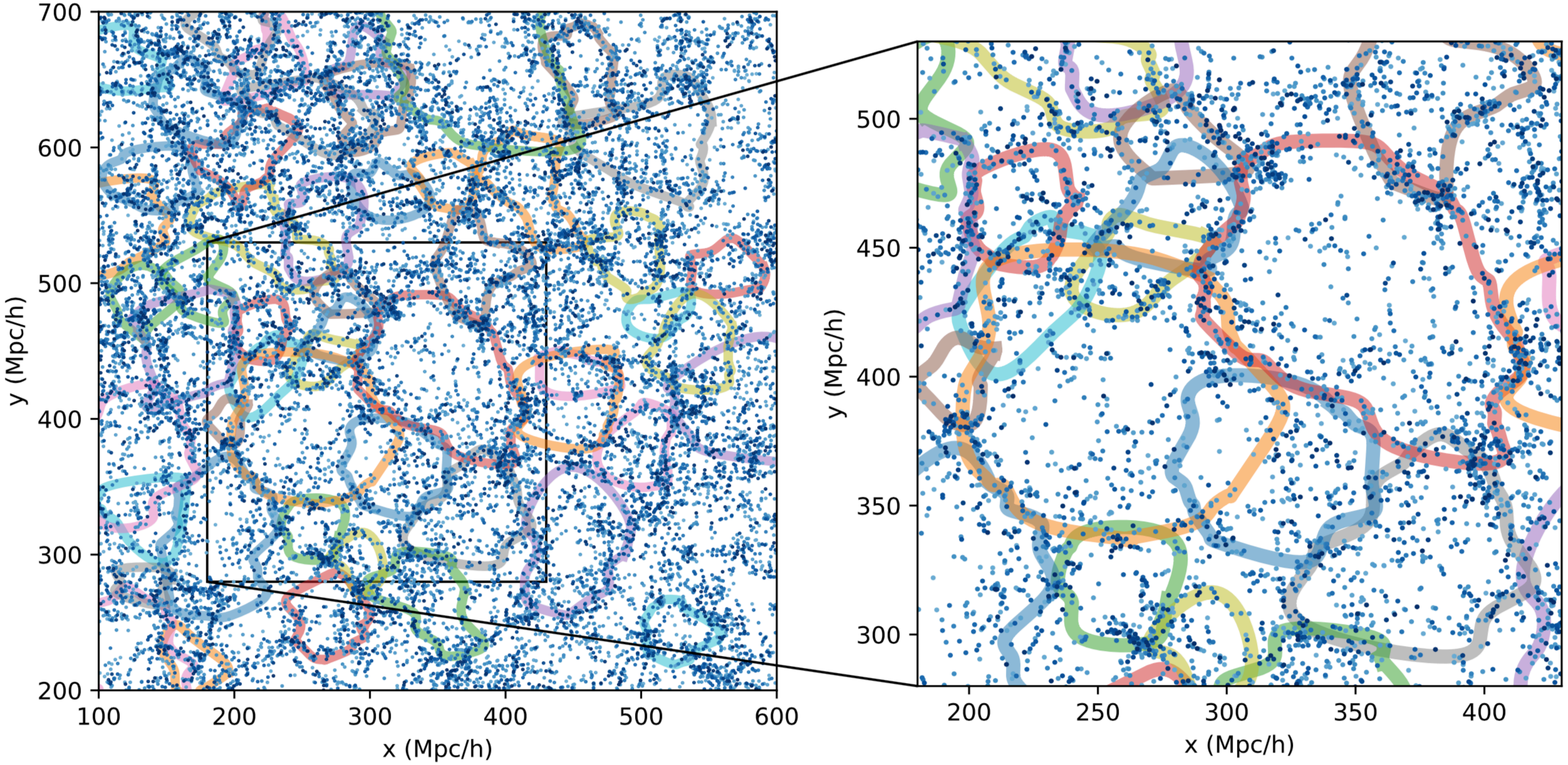
Preim, Botha 2014

VIDE: https://bitbucket.org/cosmicvoids/vide_public/src/master/, Sutter, Lavaux, Hamaus, Pisani, Wandelt, Warren, Villaescusa-Navarro, Zivick, Mao, and Thompson 2015 A&C ArXiv: 1406.1191
Icke & Van de Weygaert (1987)
Platen et al. 2007

Void definition: VIDE (Void IDentification and Examination)

- Widely used: BOSS (DR7, DR10, DR11, DR12), eBOSS (DR14), DES, Euclid, Roman, PFS, DESI.

https://bitbucket.org/cosmicvoids/vide_public/src/master/, Sutter et al. 2015 A&C



- Provides void **detailed** shape, takes mask into account.
- Enhances S/N, suitable, **tested**

Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP

What quantities do we measure to extract cosmological information ?

We have void centers, void radii, and tracers!

↓

Void-galaxy cross-correlation function	ξ_{vg}
Void-size function	N_{v}
Void-void auto-correlation function	ξ_{vv}

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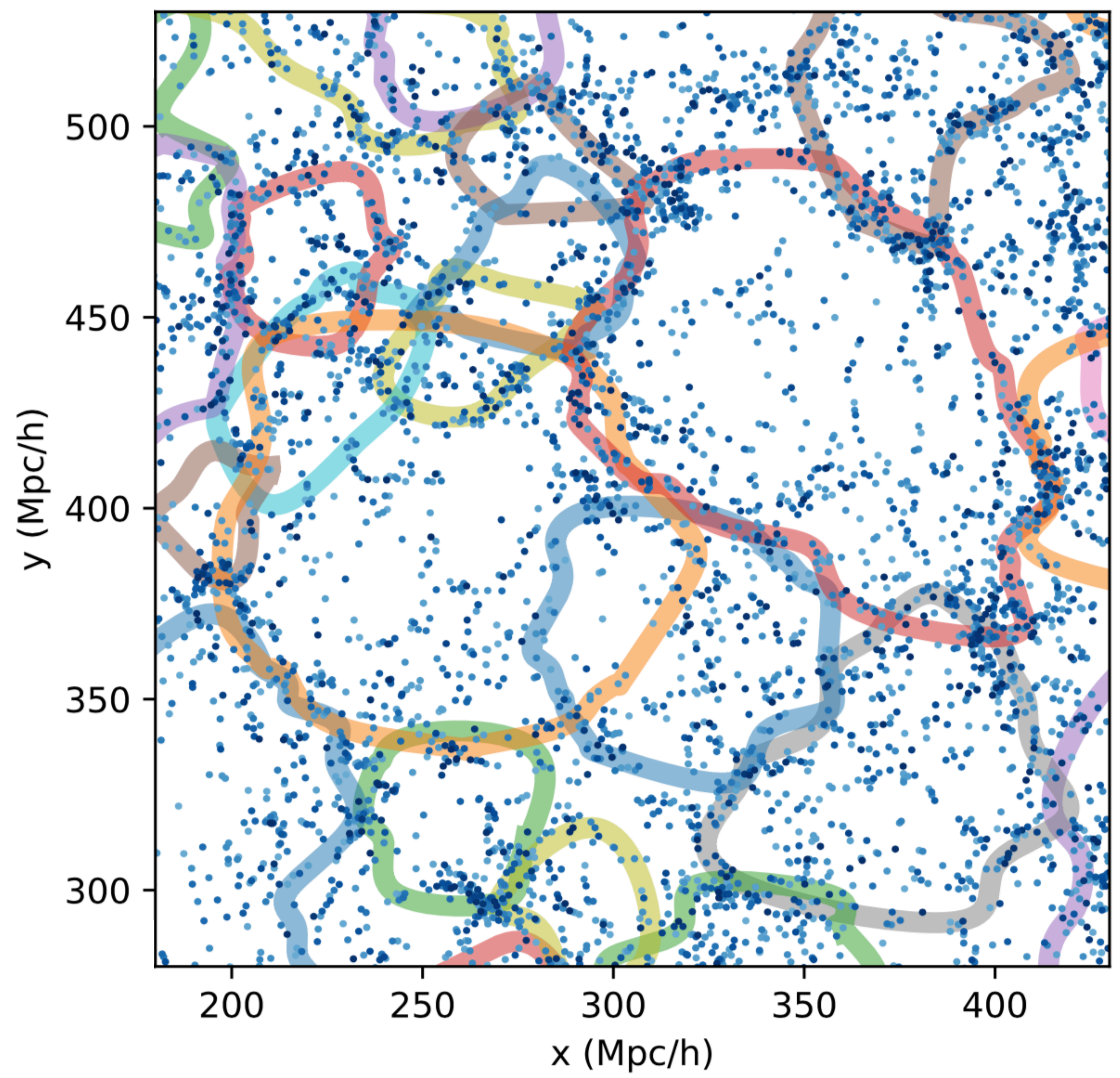
ξ_{vg} A theoretical model to predict observed void density profiles

Voids are irregular on a one-to-one basis



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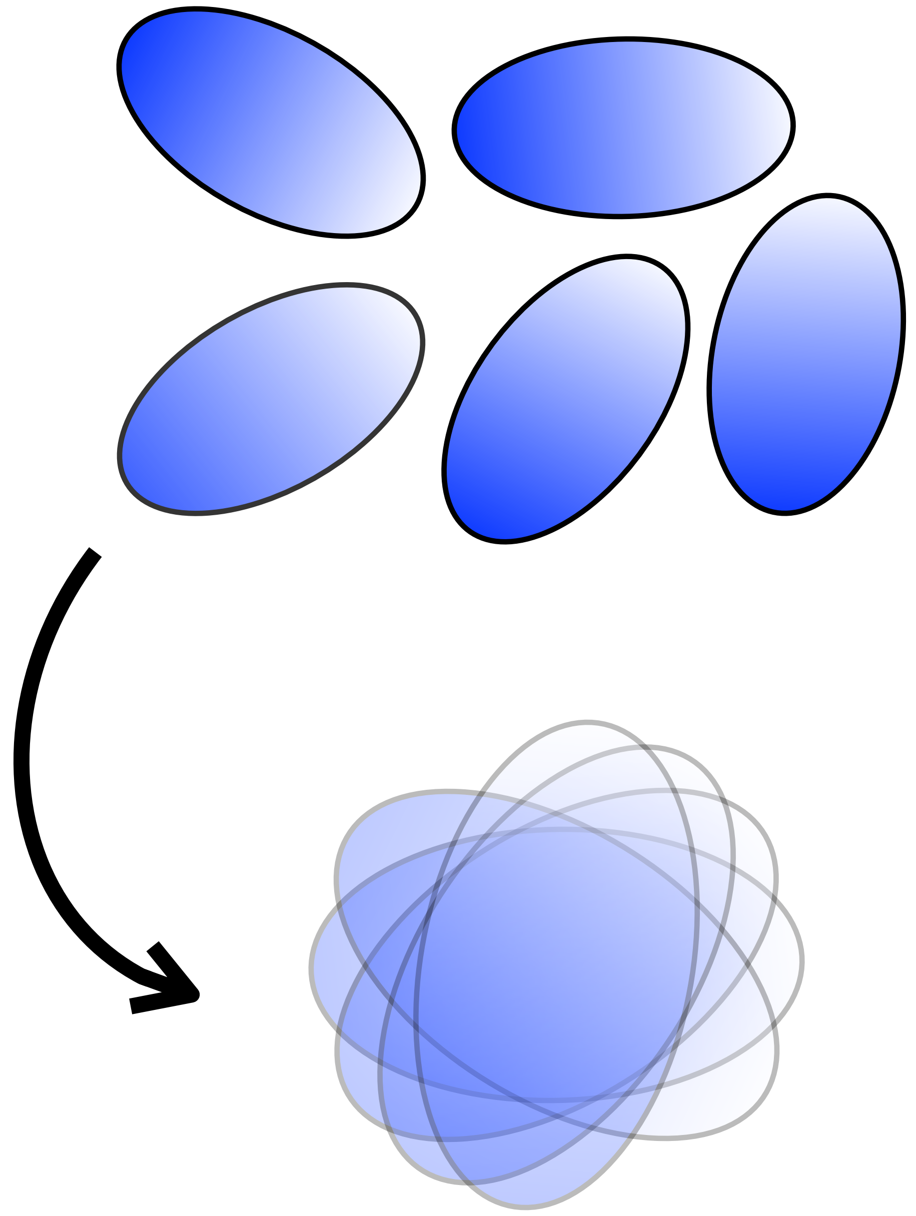
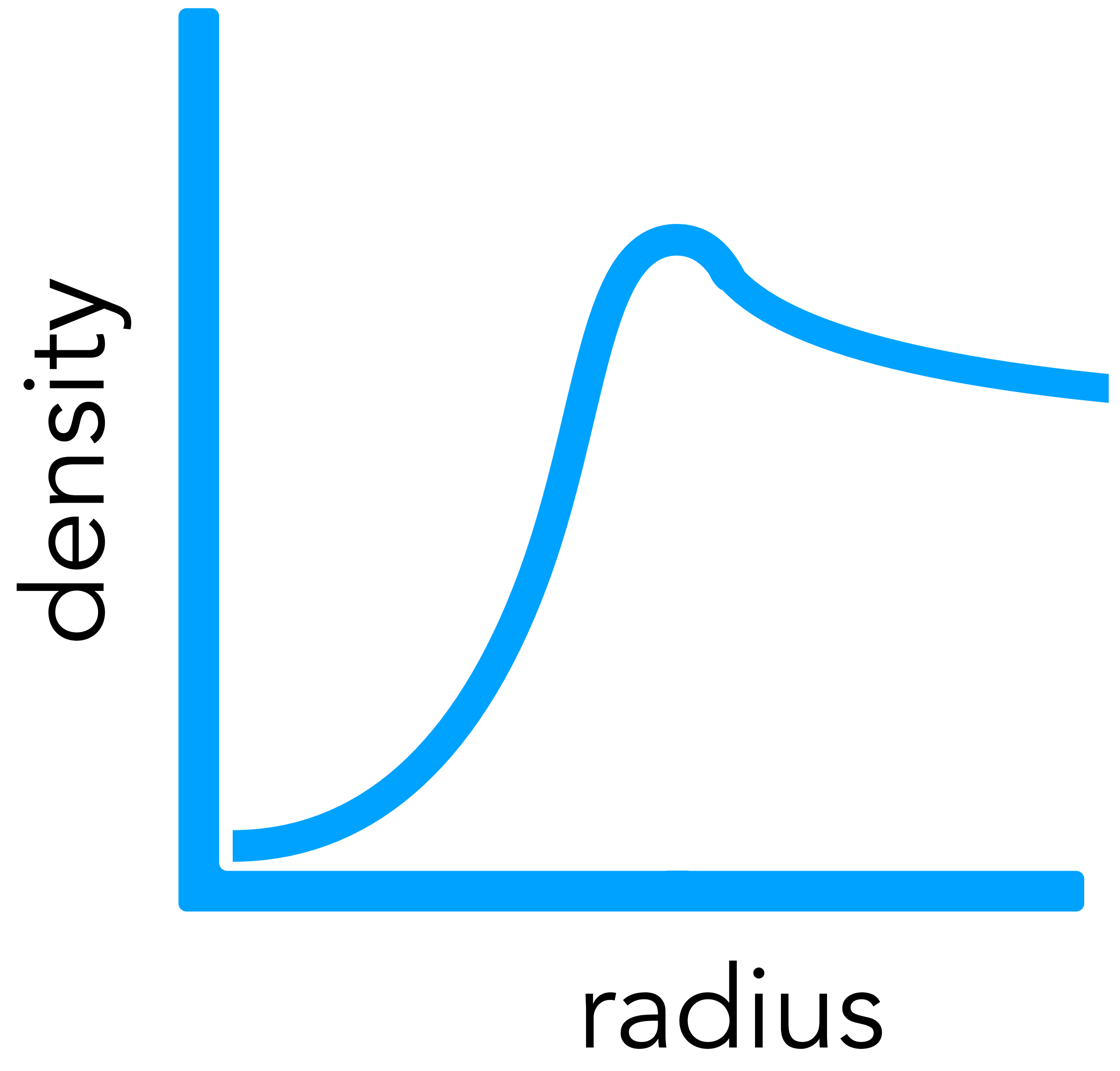


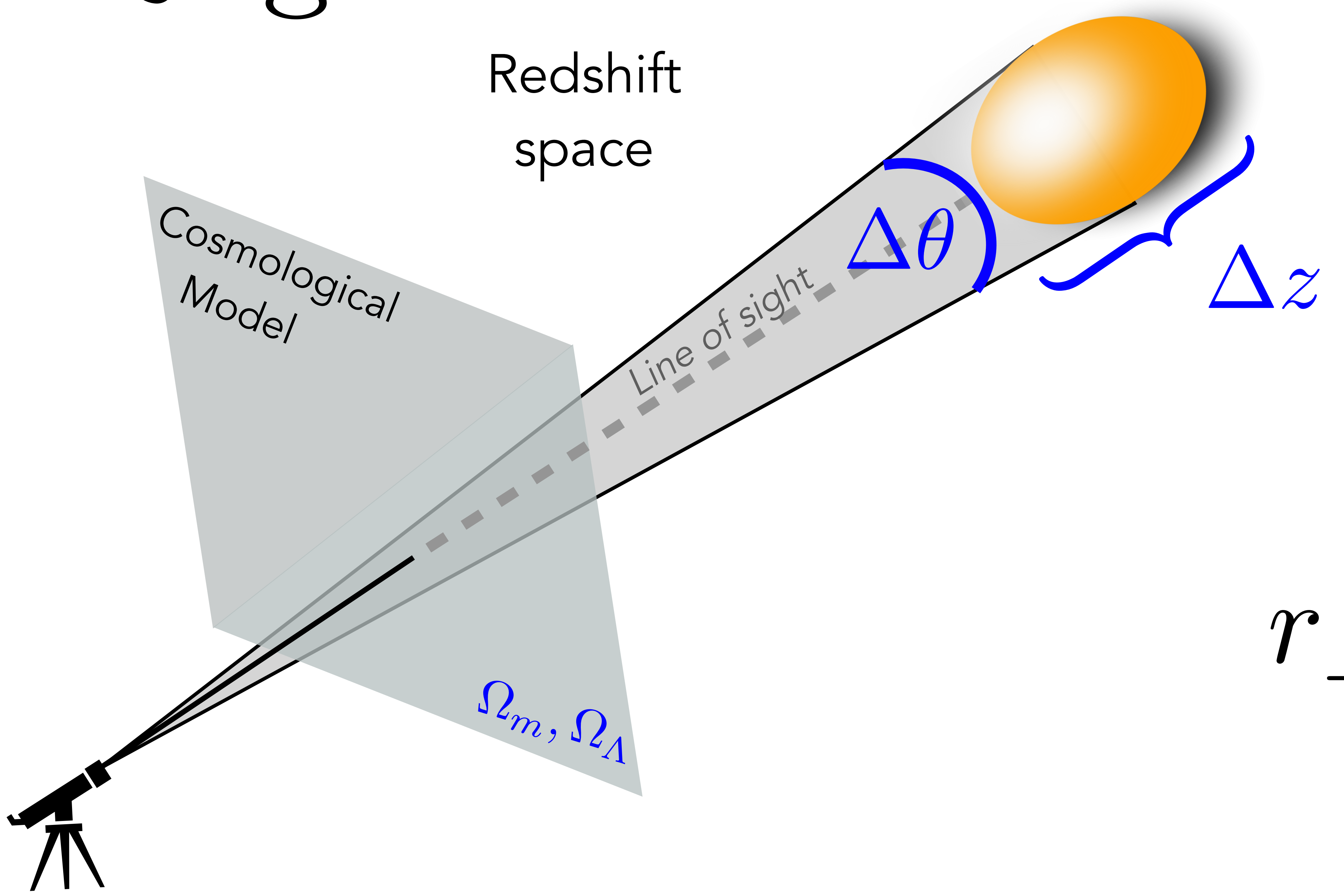


In a *homogeneous and isotropic* universe void **stacks** are spherically symmetric in **real** space.

But we observe voids in redshift space!

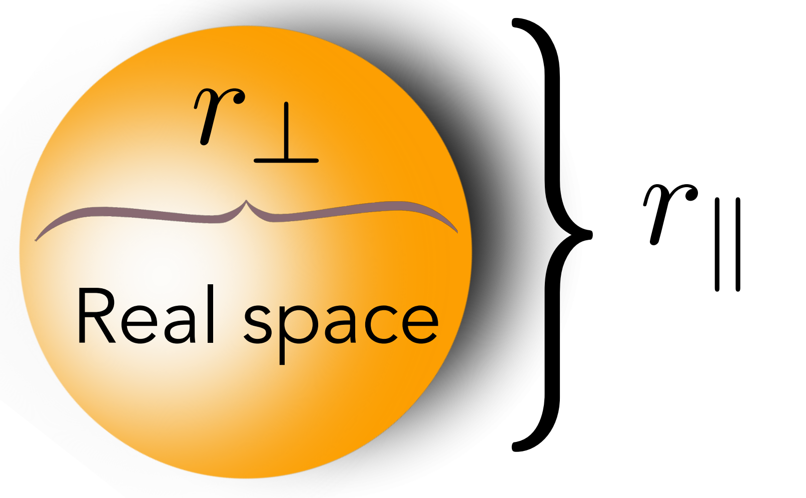
Ryden, B. S. 1995, ApJ, 452, 25
Lavaux & Wandelt 2011; ArXiv: 1110.0345 ApJ

ξ_{vg} A theoretical model to predict observed void density profiles



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

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



$$r_\perp = r_\parallel \quad \Leftrightarrow \quad \frac{c\Delta z}{\Delta\theta} = D_A H(z)$$

function$(\Omega_m, \Omega_\Lambda)$

$$\varepsilon = \frac{[D_A H(z)]_{\rm meas}}{[D_A H(z)]_{\rm fid}} \Rightarrow$$

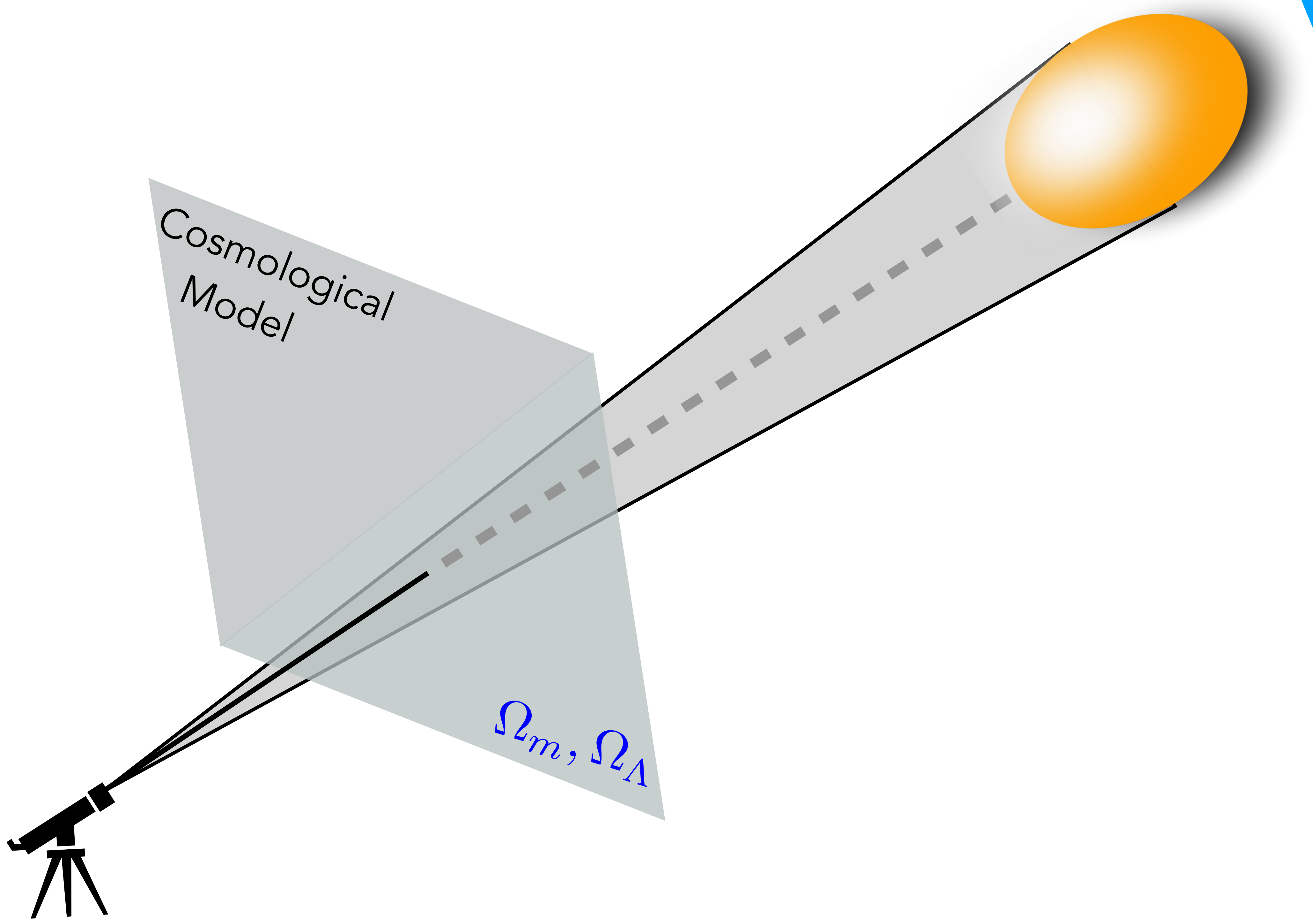
pick $[\Omega_m, \Omega_\Lambda]$, calculate

Alcock-Paczynski test

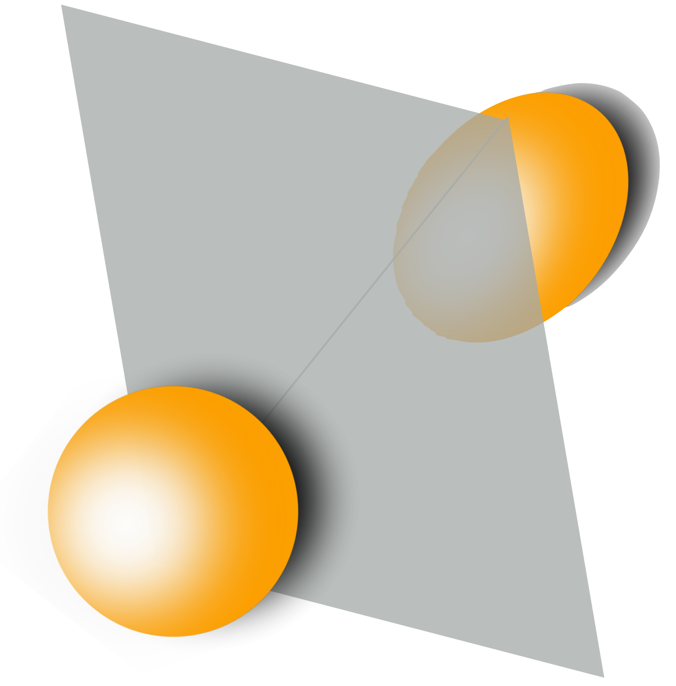
If the proposed cosmology is correct

$\varepsilon = 1$

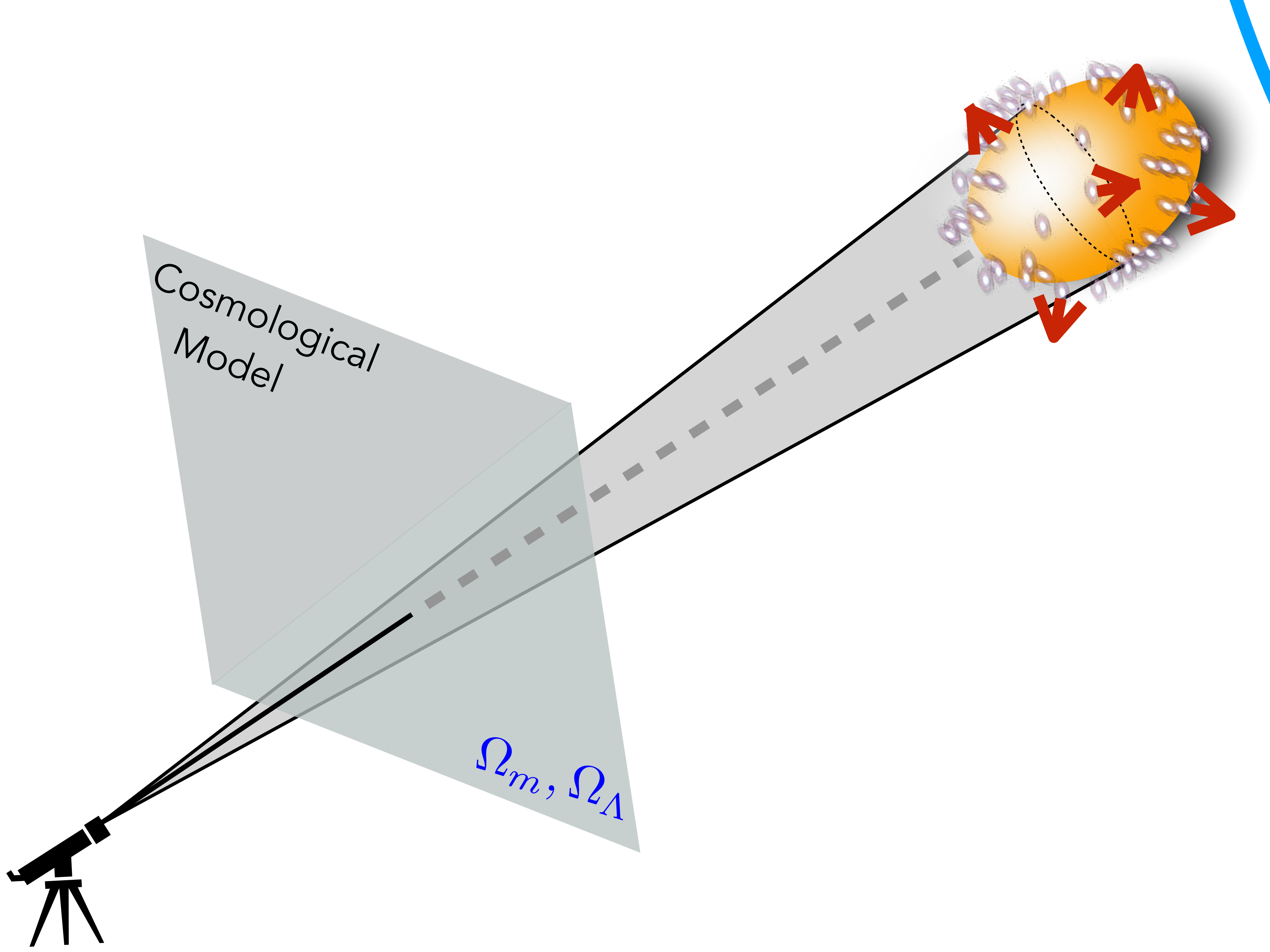
Ryden, B. S. 1995, ApJ, 452, 25
Lavaux & Wandelt 2011; ArXiv: 1110.0345 ApJ



Observed shape =



Real space profile
& AP



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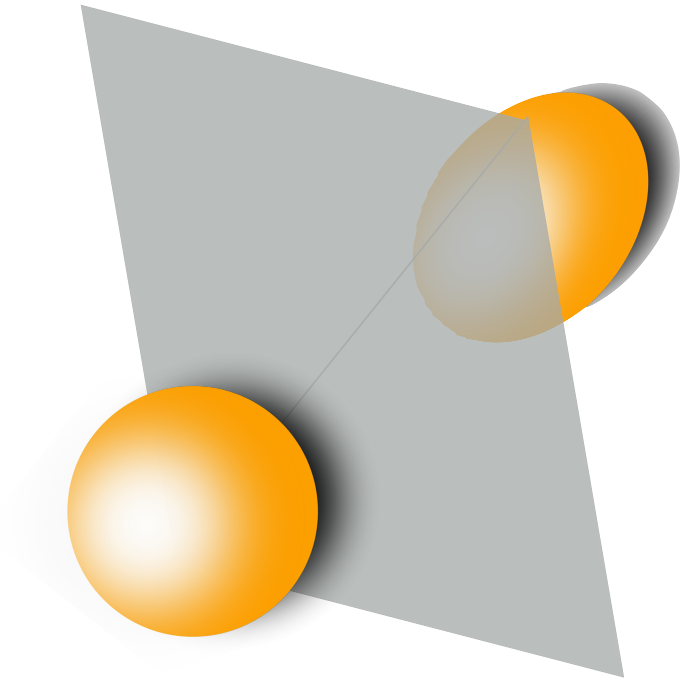
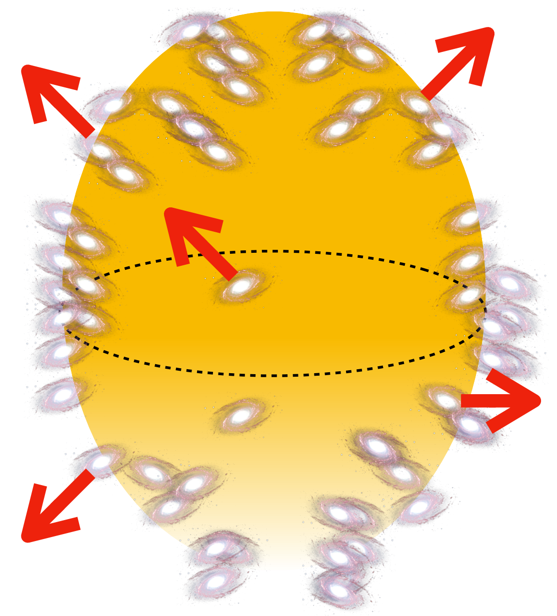


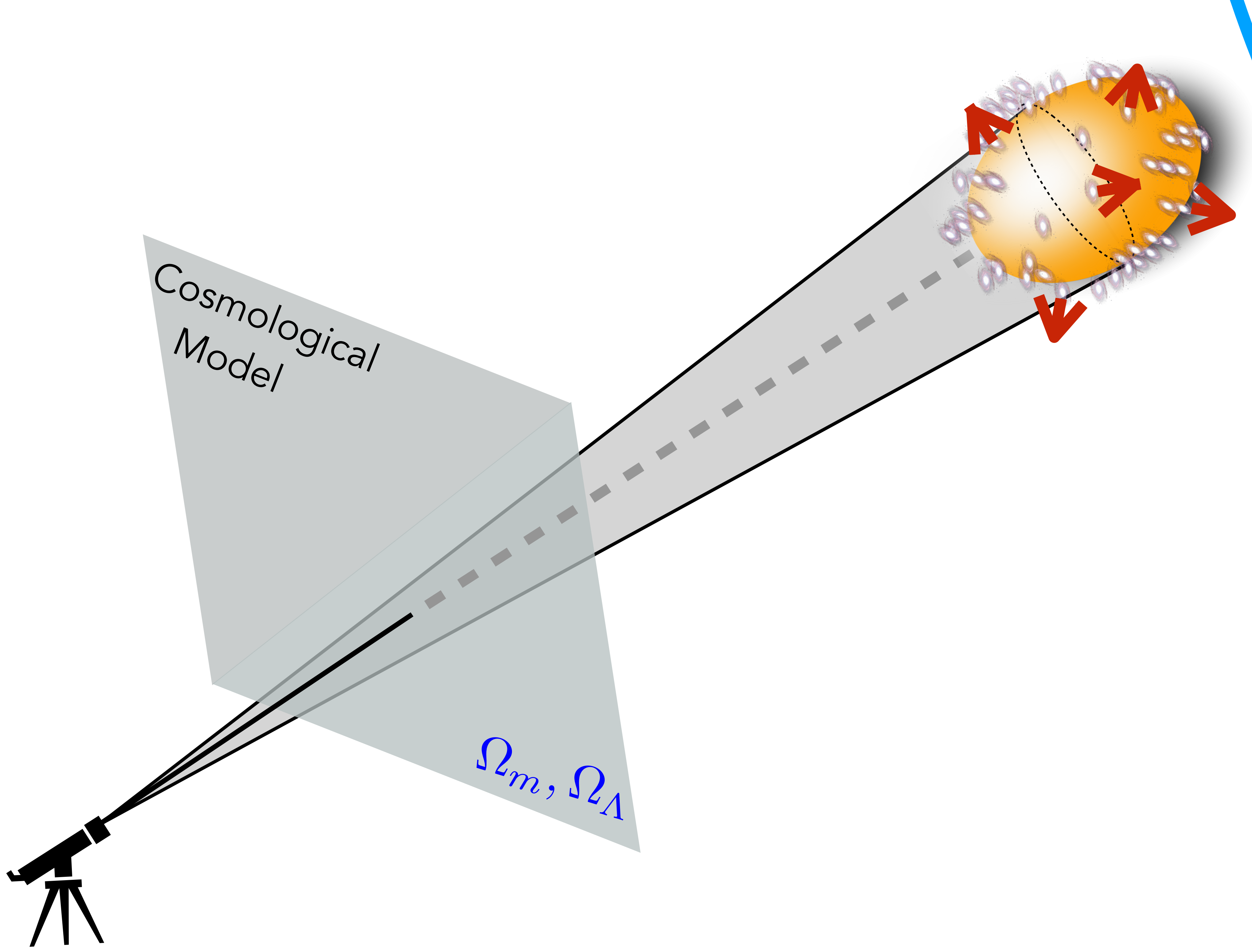
Real space profile & AP

+

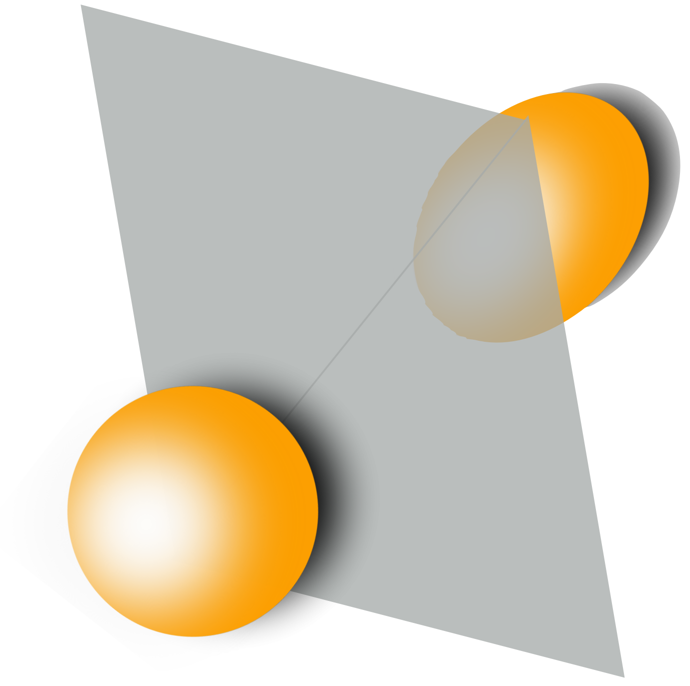


Redshift-space distortions (**RSD**) (deviations from the Hubble flow) due to **galaxies peculiar velocities**

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



Observed shape =



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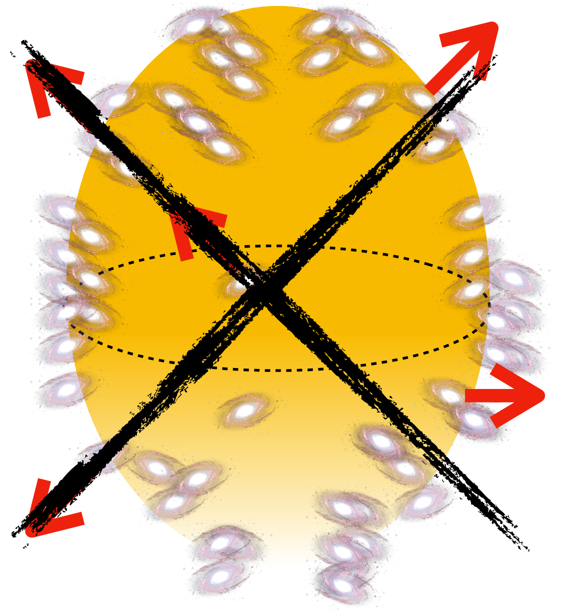


Real space profile & AP

Redshift-space distortions (**RSD**) (deviations from the Hubble flow) due to **galaxies peculiar velocities**

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

Very first papers in the field would try to mitigate the effect of peculiar velocities to measure the AP information.

Sutter, Lavaux, Wandelt, Weinberg 2012; ArXiv: 1208.1058 ApJ
Sutter, Pisani, Wandelt, Weinberg 2014; ArXiv: 1404.5618 MNRAS

…but velocities **embed** information!

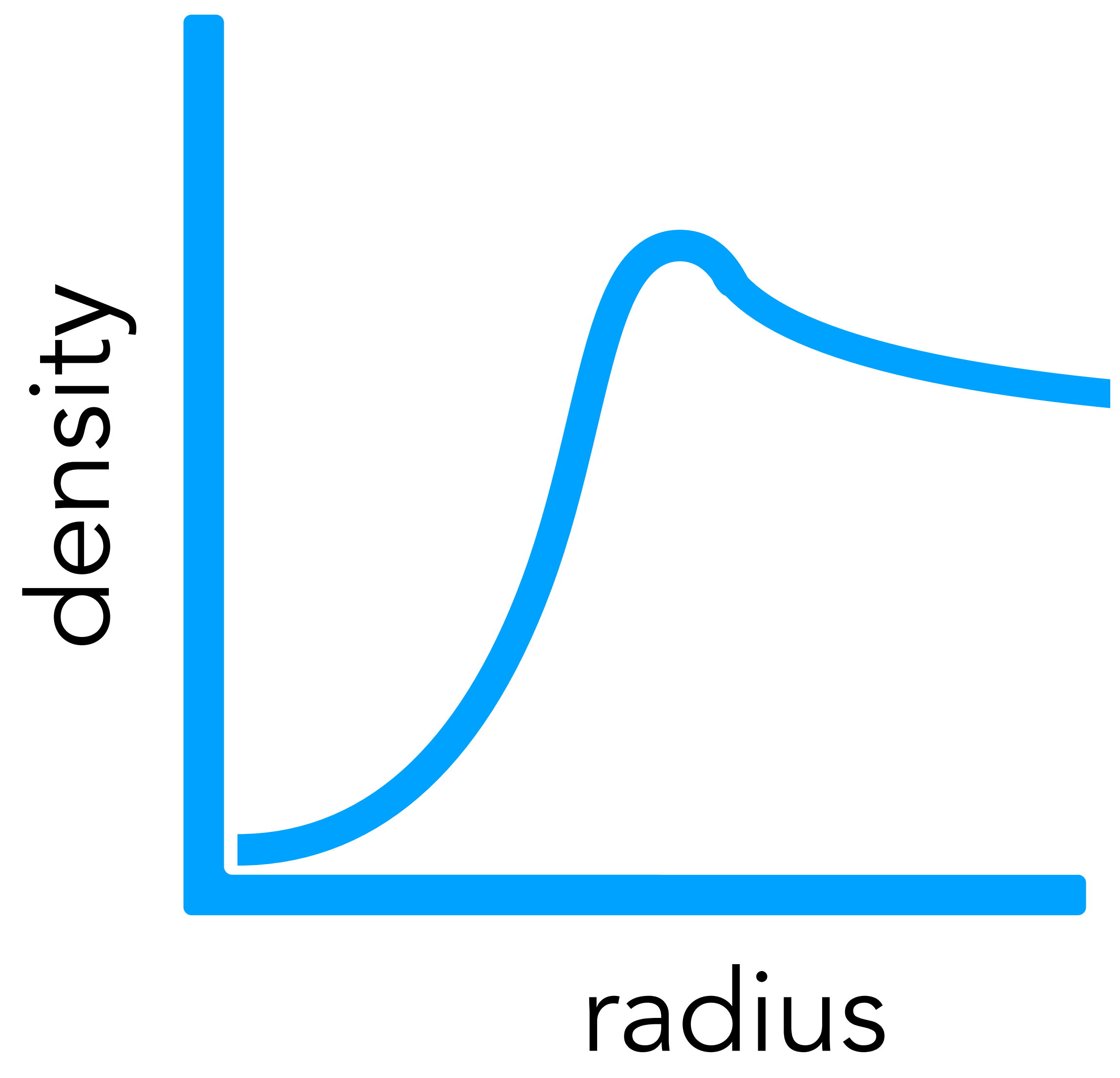
$$\mathrm{v}(r) \simeq -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta(r)$$

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

$$\Delta(r) = \frac{3}{r^3}\int_0^r \delta(r')r'^2 dr'$$

Incredible gain in **modeling** redshift-space distortions!

ξ_{vg} A theoretical model to predict observed void density profiles

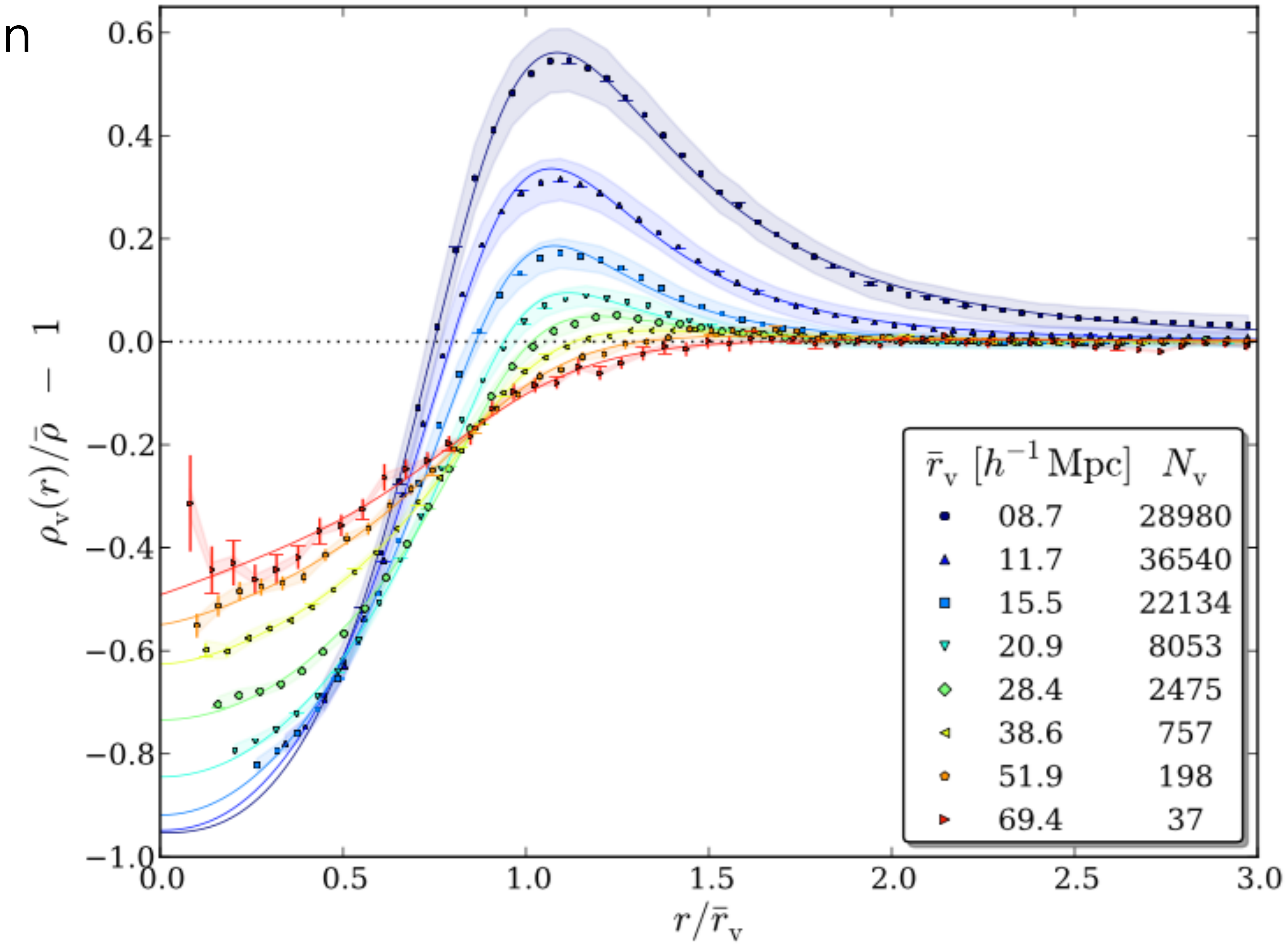


Ingredients $\left\{ \begin{array}{l} \text{Density profile modeling} \\ \text{RSD modeling} \end{array} \right.$

ξ_{vg} A theoretical model to predict observed void density profiles

Density profile modeling: No robust theoretical prediction, rely on commonly used prescriptions

- Fitting function



$$\frac{\rho_{vm}(r)}{\bar{\rho}_m} - 1 = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_v)^{\beta}}$$

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

Hamaus, Sutter, Wandelt 2014; ArXiv: 1403.5499 PRL

Modeling velocities with the **Gaussian streaming model**

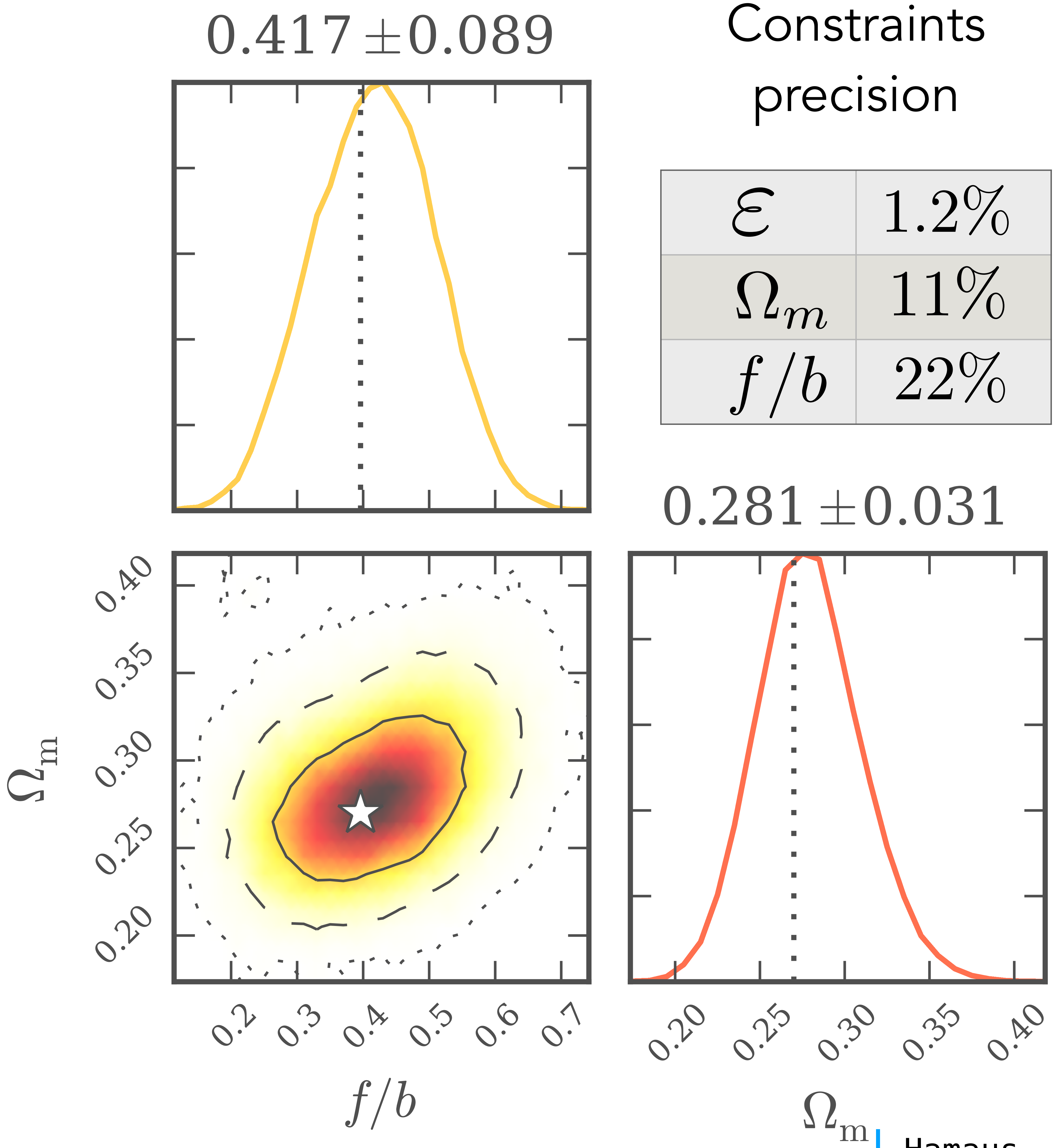
Gaussian probability distribution function for velocities
Gaussian streaming model, Fisher 1995

$$1 + \xi^s(\mathbf{s}) = \int P(\mathbf{v}, \mathbf{r})[1 + \xi(\mathbf{r})]\mathrm{d}^3 v = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_v(\mathbf{r})} \exp\left[- \frac{(v_\parallel - \mathrm{v}(r)\frac{r_\parallel}{r})^2}{2\sigma_v^2(\mathbf{r})} \right] \frac{\rho_\mathrm{v}(r)}{\bar{\rho}} \mathrm{d}v_\parallel$$

Paz, Lares, Ceccarelli, Padilla, Lambas 1306.5799 MNRAS
Hamaus, Sutter, Lavaux, Wandelt, 2015 ArXiv: 1507.04363 JCAP

Hamaus, Pisani, Sutter, Lavaux, Escoffier, Wandelt, Weller 2016; ArXiv: 1602.01784 PRL

Modeling velocities with the **Gaussian streaming model**



Constraints precision

$\mathcal{E}$	1.2%
Ω_m	11%
f/b	22%

Theoretical model

Profile from fitting function and marginalization
Gaussian streaming model
RSD & AP

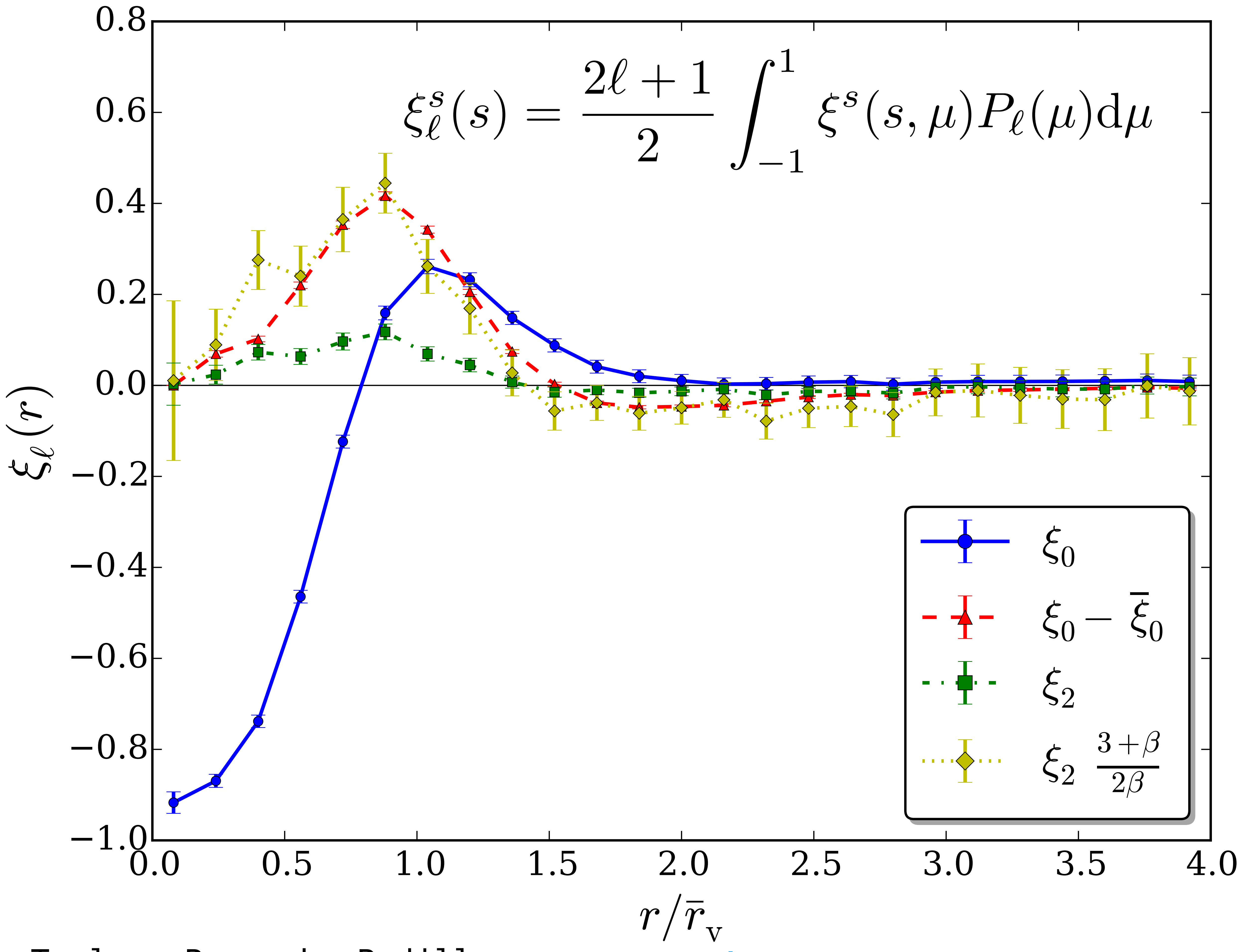
New standard tool!

Hamaus, Pisani, Sutter, Lavaux, Escoffier, Wandelt, Weller 2016; ArXiv: 1602.01784 PRL

Modeling velocities with the **linear model**, multipole analysis of RSD

$$\boxed{\xi^s(\mathbf{s})} = \xi(r) - \frac{1+z}{H(z)}\frac{\mathrm{d}v_{\parallel}(r)}{dr} = \xi(r) + \frac{f}{3}\Delta(r) + f\mu^2[\delta(r) - \Delta(r)] \boxed{= \xi(r) + \frac{f}{3b}\bar{\xi}(r) + \frac{f}{b}\mu^2[\xi(r) - \bar{\xi}(r)]}$$

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



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

Theoretical model

Linear model
Only RSD, No AP

Cai, Taylor, Peacock, Padilla 2016; ArXiv: 1603.05184; MNRAS

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

Modeling velocities with the **linear model**, multipole analysis of RSD

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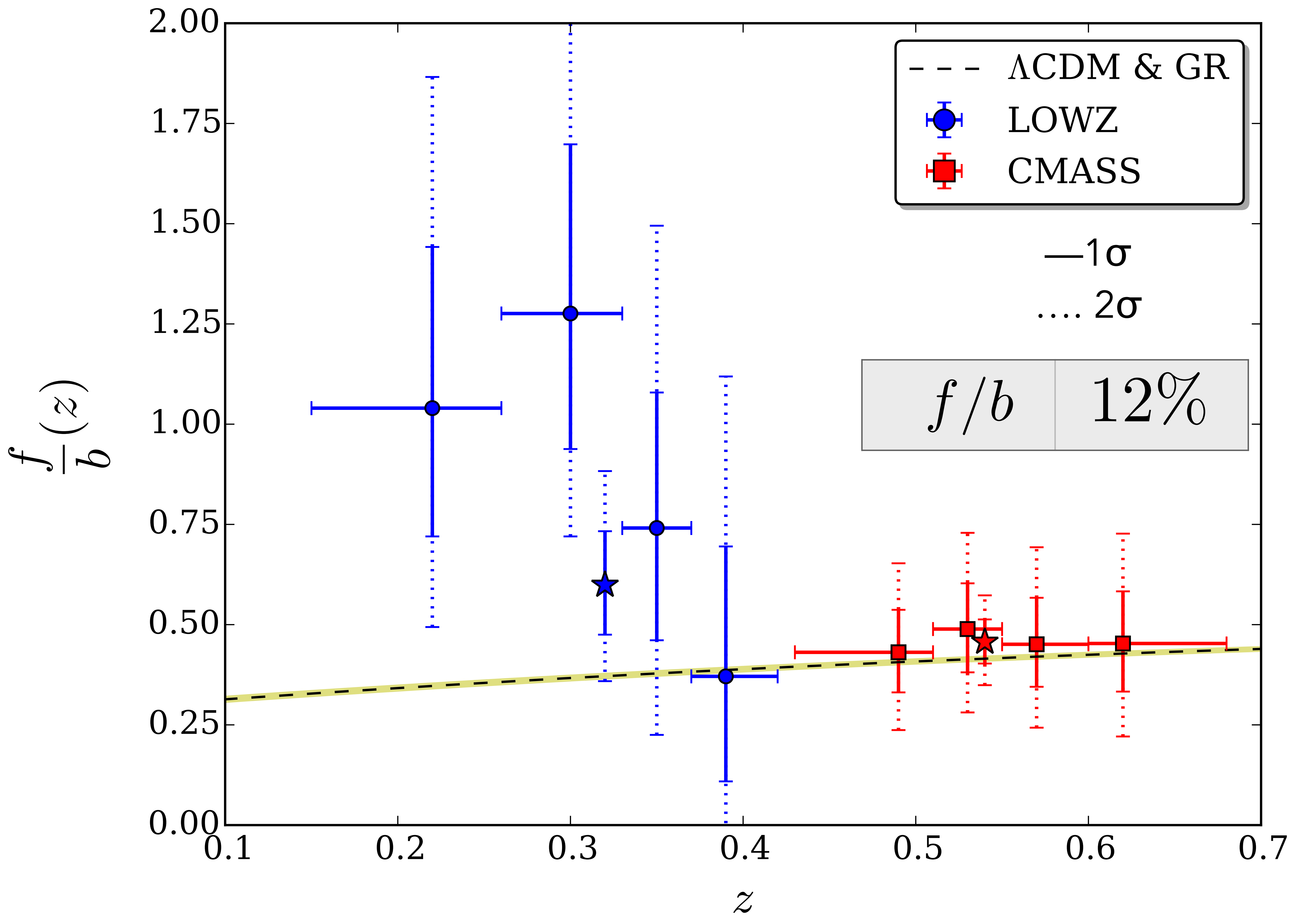

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Void-galaxy cross-correlation: Final analysis from the combined BOSS sample

~~Profile from fitting function~~

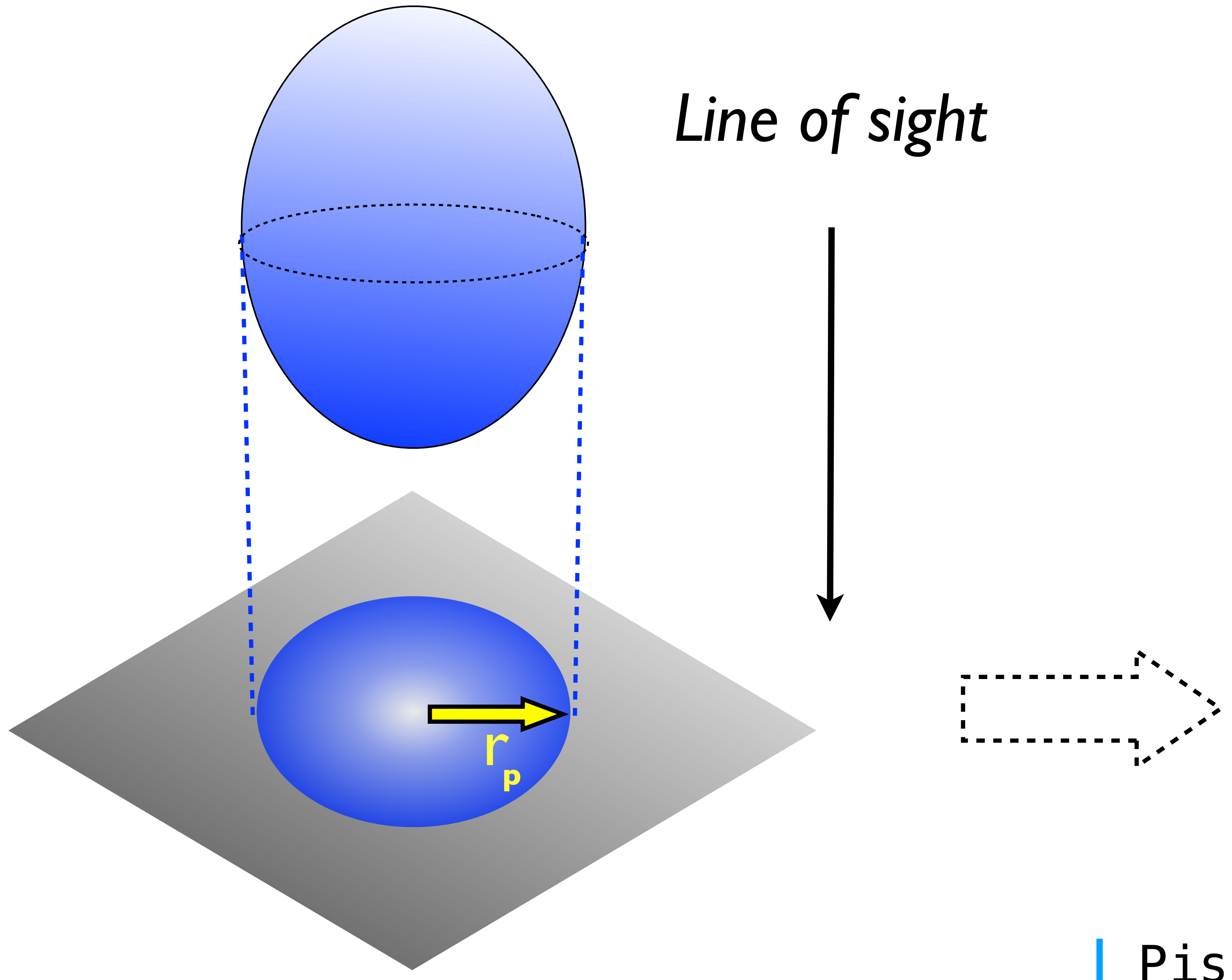
~~Velocities (Gaussian streaming model)~~

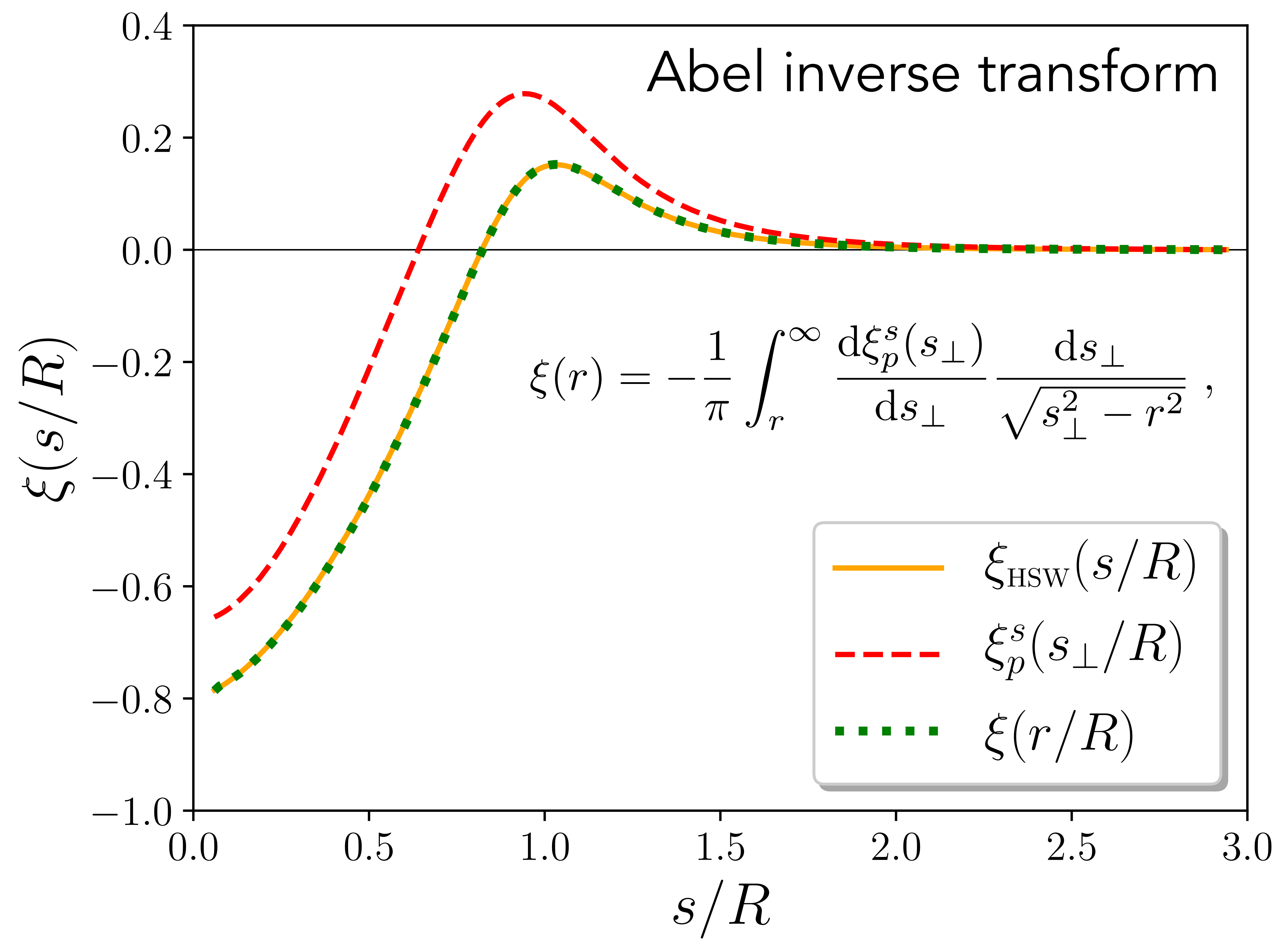
Alcock-Paczynski

Only velocities (linear model)

+

Models the profile from the de-projection (model-independent)



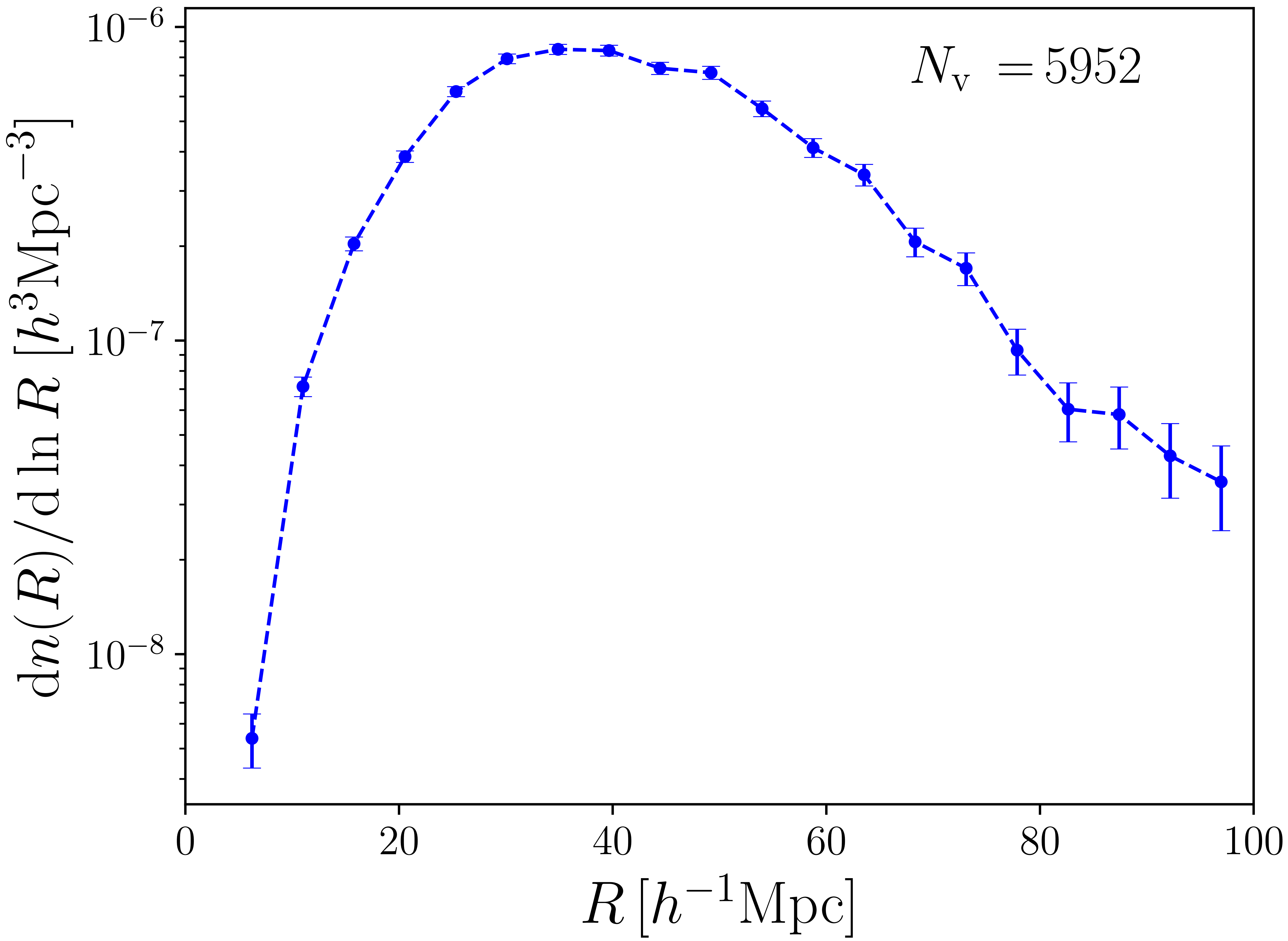


Pisani, Lavaux, Sutter, Wandelt 2014; ArXiv: 1306.3052 MNRAS
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP

Void-galaxy cross-correlation: Final analysis from the combined BOSS sample

State-of-the-art theoretical model

Models AP & velocities (linear model)
Models the profile from the de-projection (model-independent)

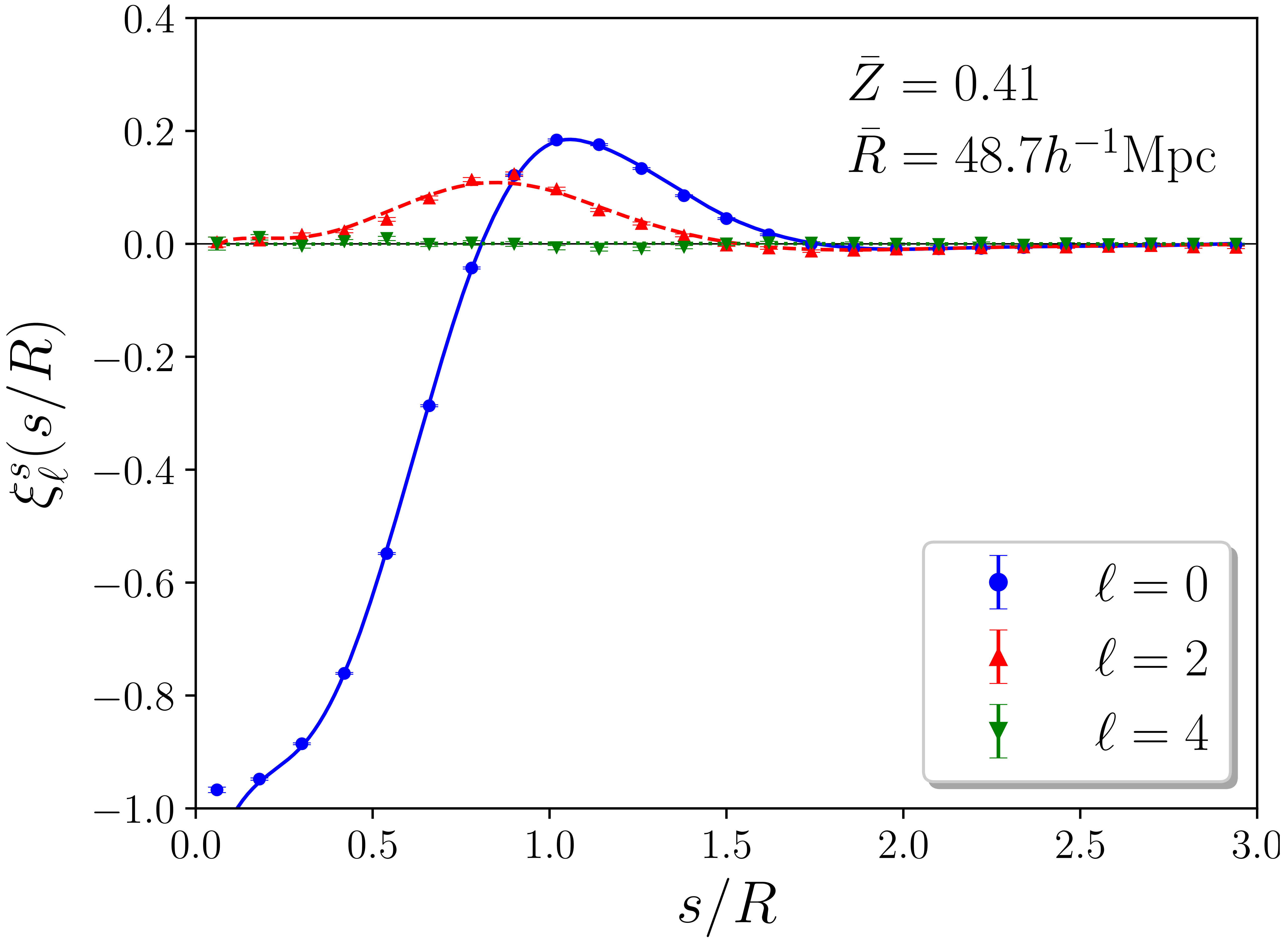


Largest catalog of voids available

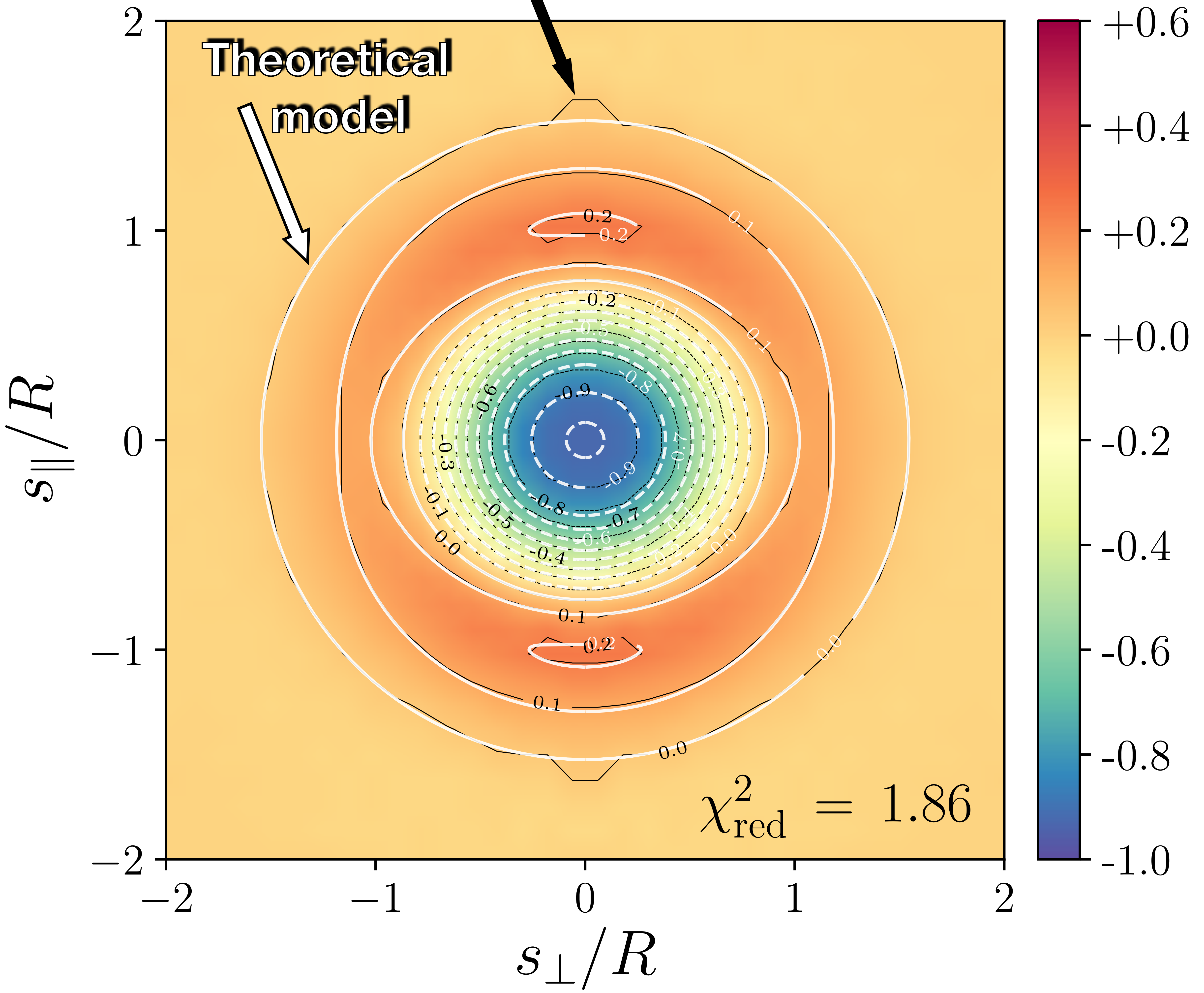
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Void-galaxy cross-correlation: Final analysis from the combined BOSS sample

Tested on mocks



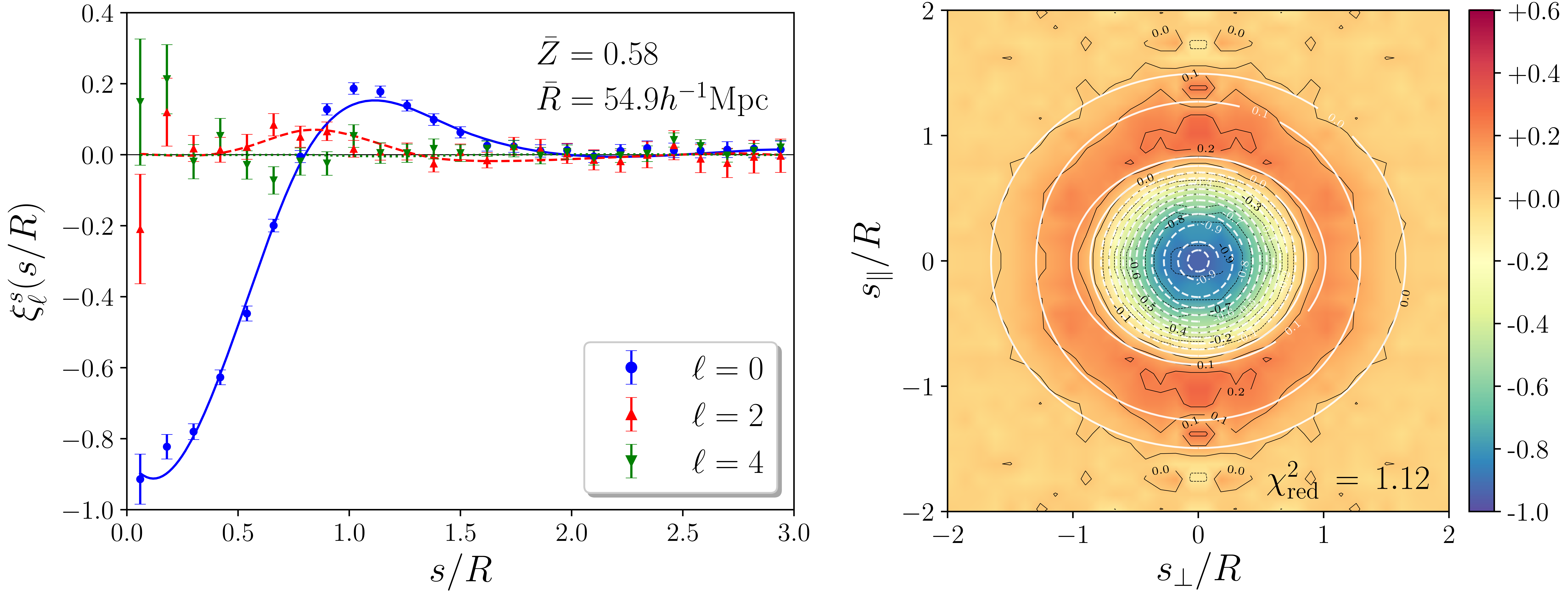
Measure on mocks



Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Void-galaxy cross-correlation: Final analysis from the combined BOSS sample

Applied on data



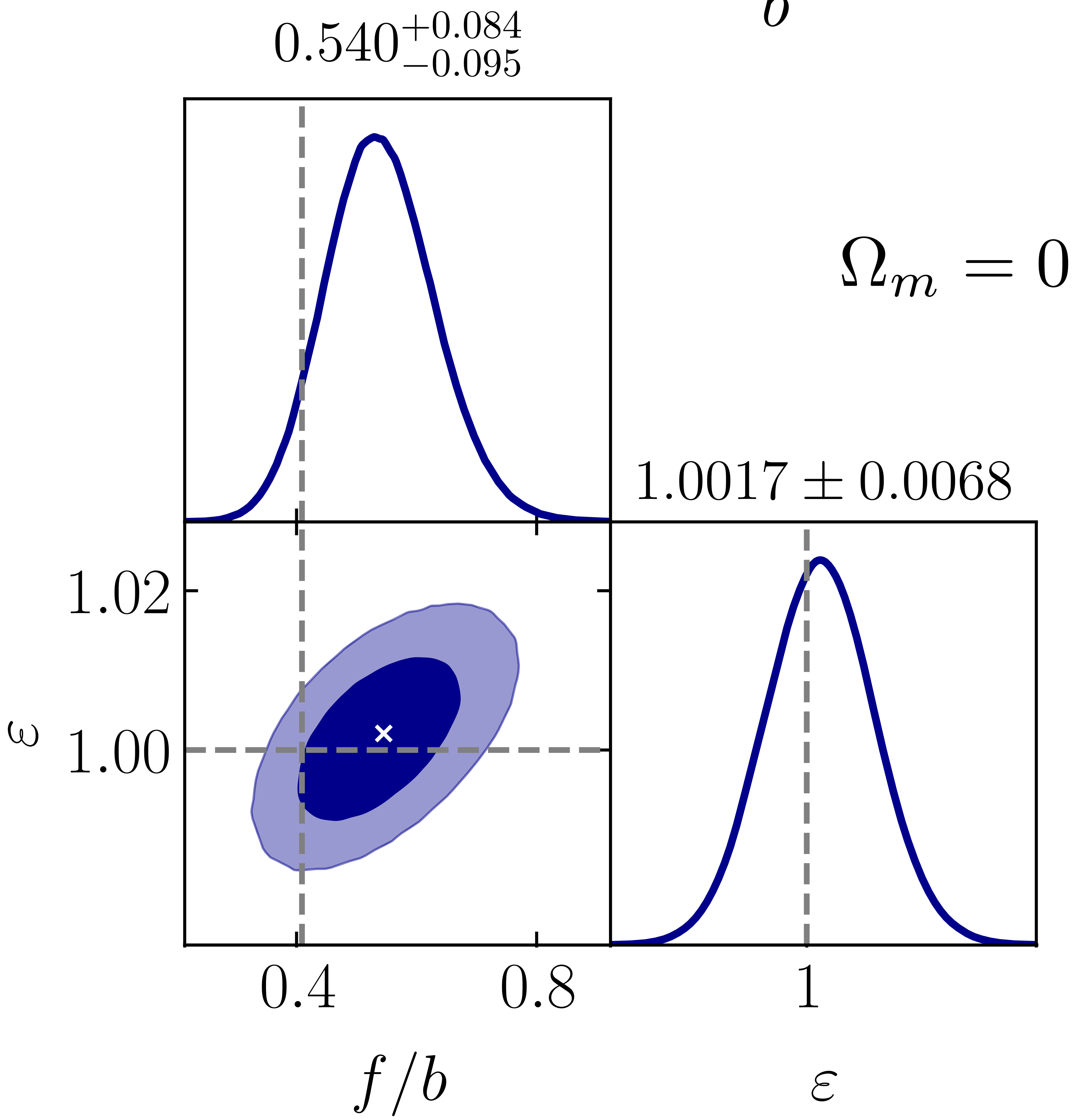
Hamaus, Pisani, Choi, Lavaux, Wandelt,
Weller 2020; ArXiv: 2007.07895 JCAP sub.

Void-galaxy cross-correlation: Final analysis from the combined BOSS sample

Results

$$\beta = \frac{f}{b}$$

$$\varepsilon = \frac{[D_A(z)H(z)]_{\mathrm{meas}}}{[D_A(z)H(z)]_{\mathrm{fid}}}$$



$$\Omega_m = 0.312 \pm 0.020$$

Precision

	indep
ε	0.68%
Ω_m	6.4%
f/b	16.9%

What if we still want to use simulations?

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

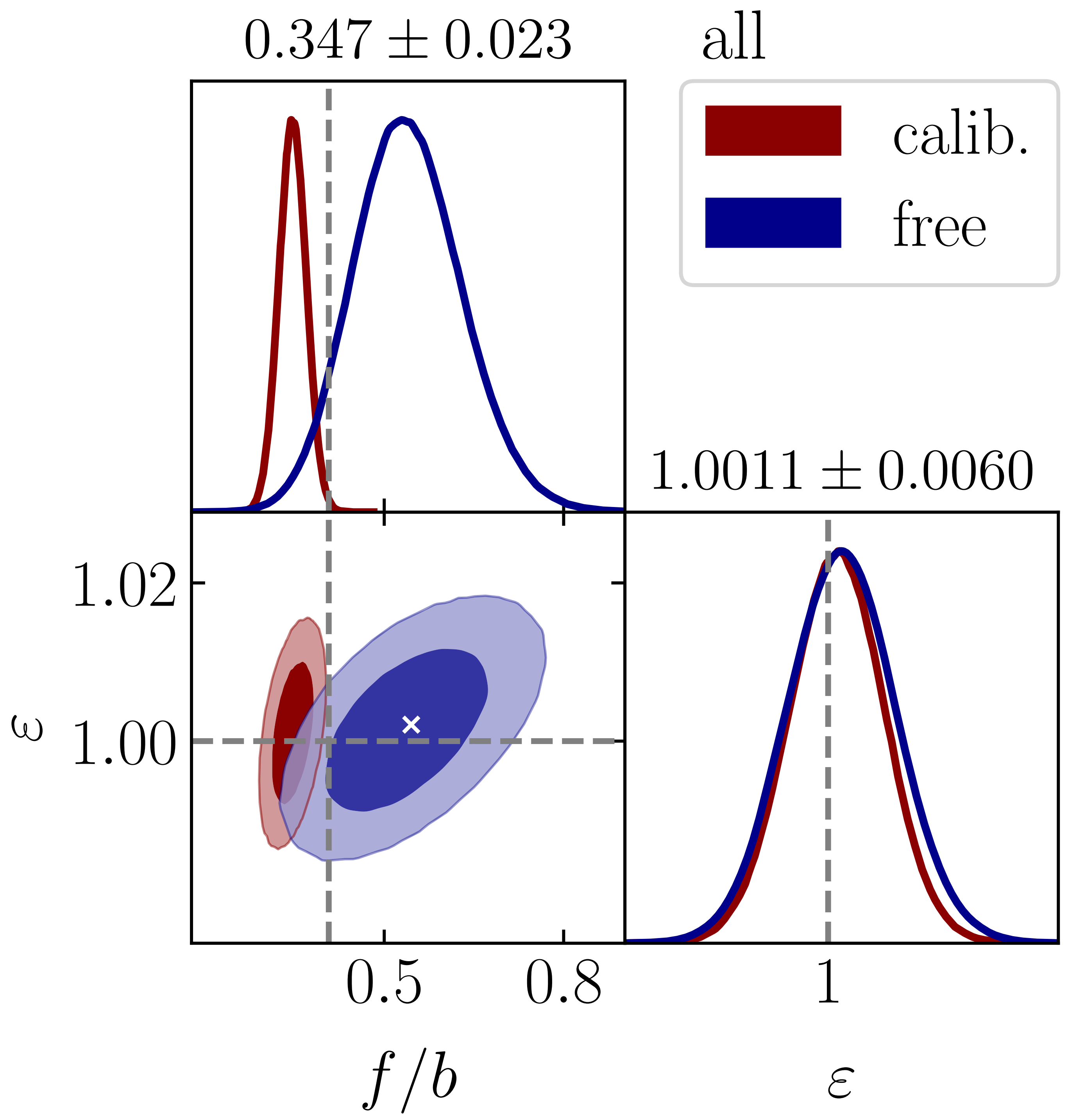
Void-galaxy cross correlation: Final analysis from the combined BOSS sample

Two nuisance parameters:

Amplitude $\begin{cases} \text{monopole} \\ \text{quadrupole} \end{cases}$

Precision

	indep	calib
ε	0.68%	0.60%
Ω_m	6.4%	5.5%
f/b	16.9%	6.6%



$$\xi^s(\mathbf{s}) = \mathcal{M}\left\{\xi(r) + \frac{1}{3}\frac{f}{b}\bar{\xi}(r) + \frac{f}{b}\mathcal{Q}\mu_r^2\left[\xi(r) - \bar{\xi}(r)\right]\right\}$$


RSD constraints
AP constraints
Planck 2018
$f\sigma_8(z)$
$D_A H(z)/D'_A H'(z)$
z
Planck 2018 flat ΛCDM
SDSS DR7 (Sutter, Lavaux, Wandelt, et al. 2012)
SDSS DR7 + DR10 (Sutter, Pisani, Wandelt et al. 2014)
BOSS DR11 CMASS (Hamaus, Pisani, Sutter et al. 2016)
BOSS DR12 CMASS (Mao, Berlind, Scherrer et al. 2016)
6dFGS (Achitouv and Blake 2017)
VIPERS (Hawken, Granett, Iovino et al. 2017)
BOSS DR12 LOWZ, CMASS (Hamaus, Cousinou, Pisani et al. 2017)
BOSS DR12 CMASS (Nadathur, Carter, Percival et al. 2019)
BOSS DR12 LOWZ, CMASS (Achitouv 2019)
eBOSS DR14 LRG (Hawken, Aubert, Pisani et al. 2020)
BOSS final low-z (Hamaus, Pisani, Choi et al. 2020)
BOSS final high-z (Hamaus, Pisani, Choi et al. 2020)
BOSS final all (Hamaus, Pisani, Choi et al. 2020)
eBOSS LRG, ELG, QSO (Aubert, Cousinou, Escoffier et al. 2020)
eBOSS LRG (Nadathur, Woodfinden, Percival et al. 2020)


RSD constraints
GSM
Planck 2018
$f\sigma_8(z)$
Planck 2018 flat ΛCDM
SDSS DR7 (Sutter, Lavaux, Wandelt, et al. 2012)
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eBOSS LRG, ELG, QSO (Aubert, Cousinou, Escoffier et al. 2020)
eBOSS LRG (Nadathur, Woodfinden, Percival et al. 2020)
AP constraints
$D_A H(z)/D'_A H'(z)$
Standard spheres (GSM)
z

RSD constraints
AP constraints
Planck 2018
Linear model for velocities
$f\sigma_8(z)$
$D_A H(z)/D'_A H'(z)$
z
Planck 2018 flat ΛCDM
SDSS DR7 (Sutter, Lavaux, Wandelt, et al. 2012)
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eBOSS LRG, ELG, QSO (Aubert, Cousinou, Escoffier et al. 2020)
eBOSS LRG (Nadathur, Woodfinden, Percival et al. 2020)


RSD constraints
Model-independent
Planck 2018
$f\sigma_8(z)$
Planck 2018 flat ΛCDM
SDSS DR7 (Sutter, Lavaux, Wandelt, et al. 2012)
SDSS DR7 + DR10 (Sutter, Pisani, Wandelt et al. 2014)
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AP constraints
$D_A H(z)/D'_A H'(z)$
z

RSD constraints
AP constraints
Planck 2018
Calibrated on mocks
Planck 2018 flat ΛCDM
SDSS DR7 (Sutter, Lavaux, Wandelt, et al. 2012)
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$f\sigma_8(z)$
$D_A H(z)/D'_A H'(z)$
z

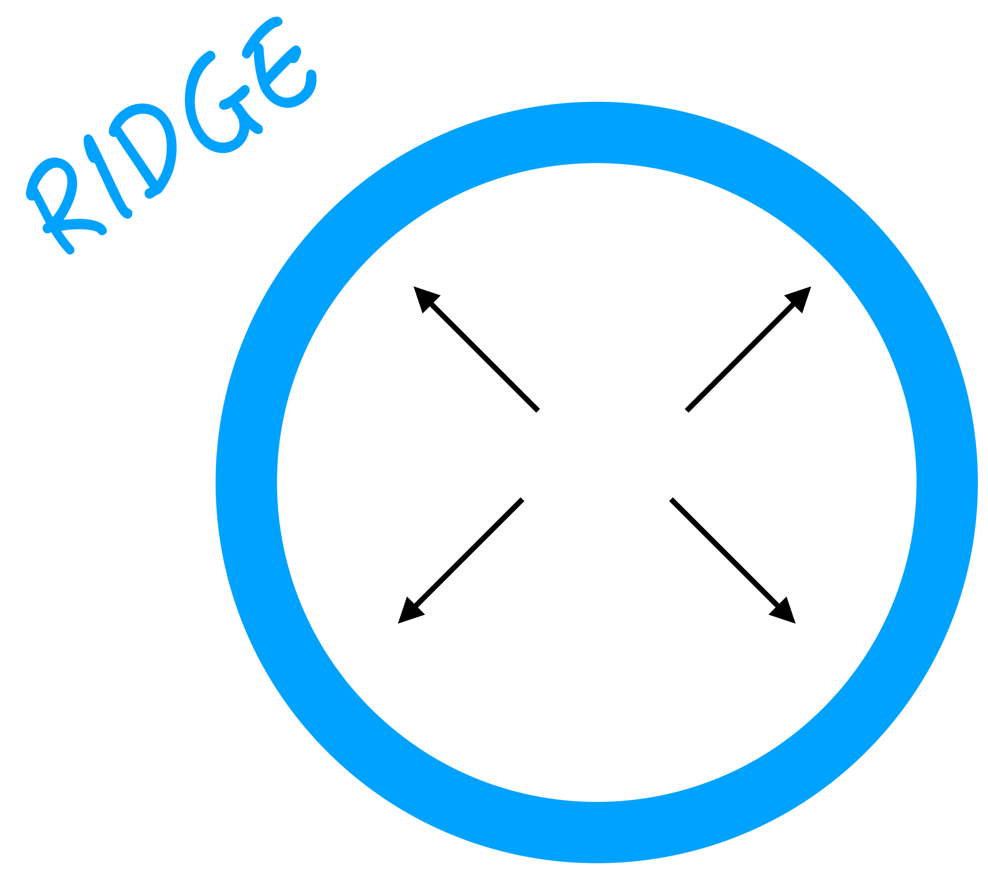
Outline

- Cosmology and Large Scale Structure
- Why are voids great for Cosmology?
- How do we find voids?
- Void-galaxy cross-correlation function (constraints so far)
- **Void-size function**
- Void-void auto-correlation function
- Take home messages

How to estimate void numbers?

Latest AP+RSD results use ~ 6000 voids

=> **GOLDEN ERA**



Void evolve emptying themselves

Void formation=shells undergo shell-crossing

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

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

Fraction of mass evolved into voids

An excursion set model to predict void numbers!

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

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

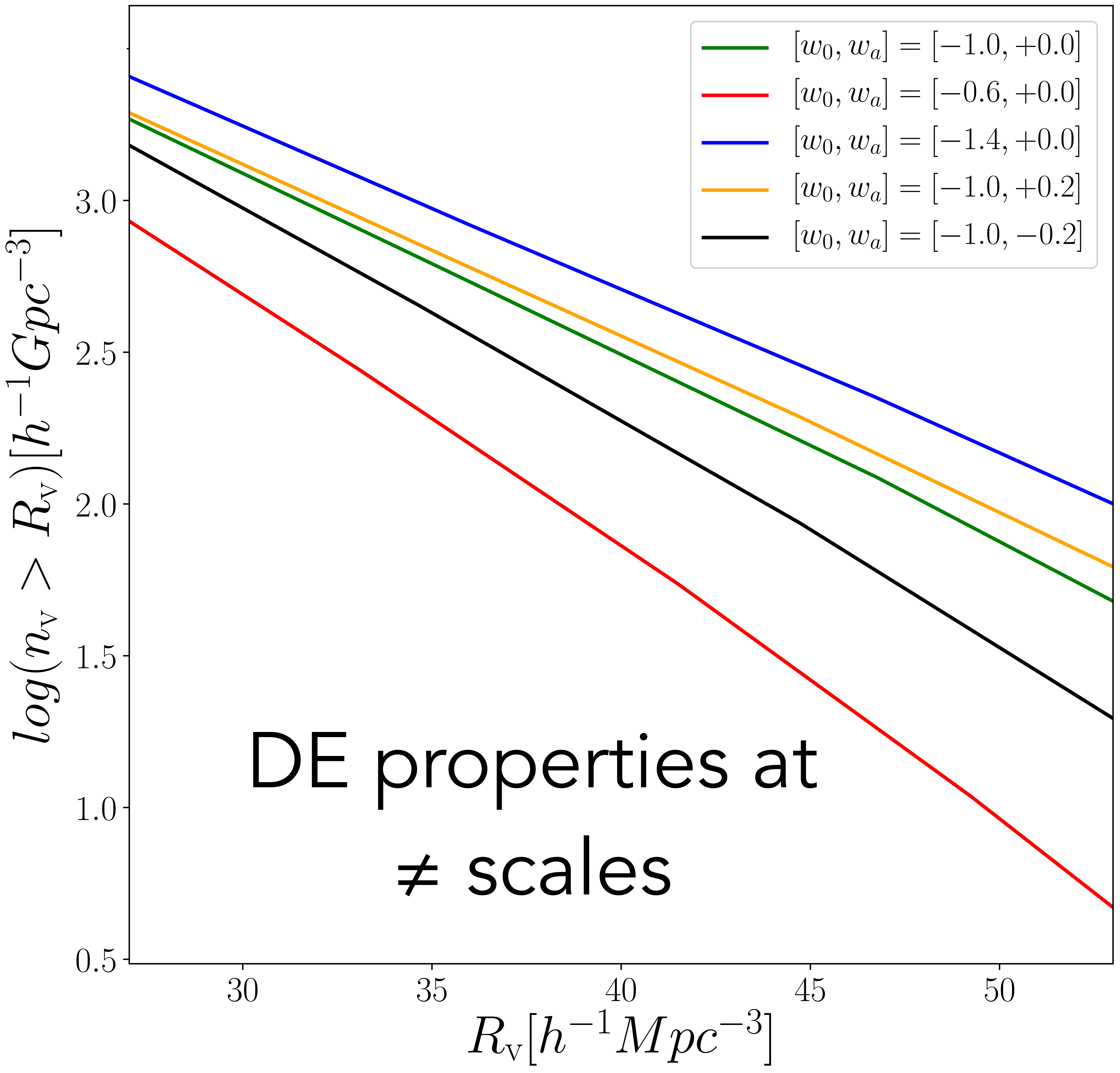
Density variance inside a sphere with given mass

Sheth and van de Weygaert 2004; Arxiv: 0311260

The void-size function is sensitive to DE! $w(z) = w_0 + w_a \frac{z}{z+1}$

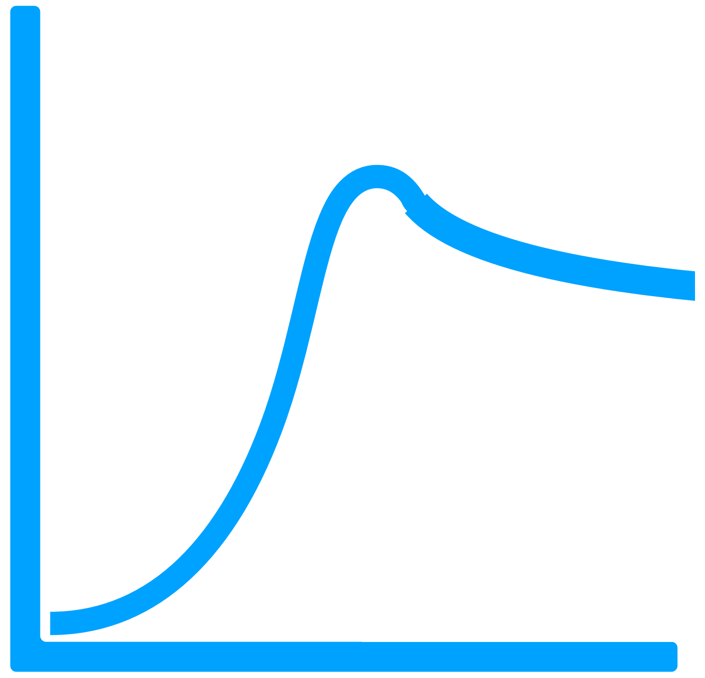
Impact on voids: *when* DE becomes relevant and how '*strong*' it is

Upcoming surveys (DESI, Euclid, LSST, Roman, SPHEREx) will provide $\mathcal{O}(10^5)$ voids per survey!



Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata 2015; ArXiv:1503.07690 PRD

Voids from theory, voids from observations

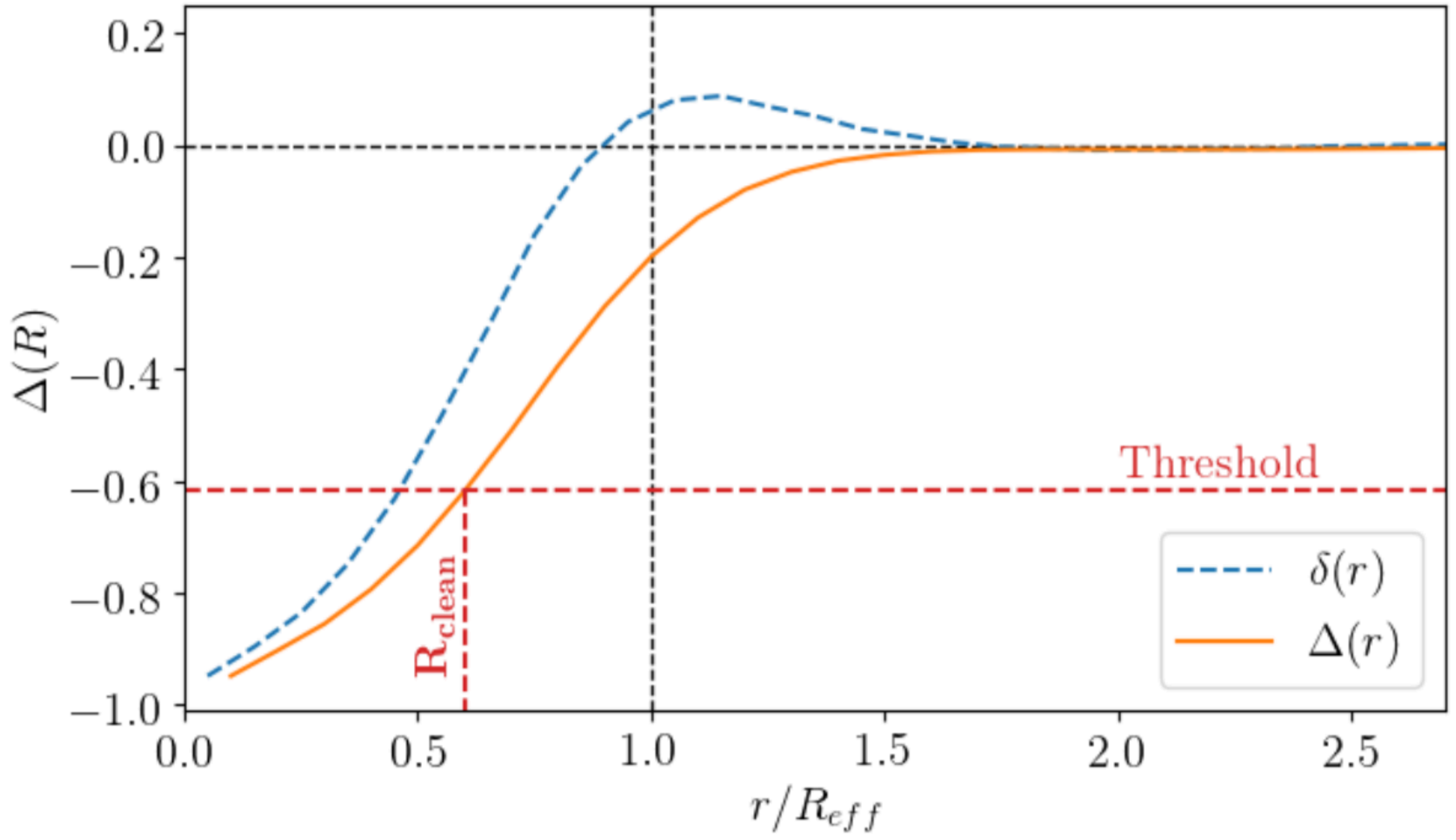


Sofia Contarini

Giovanni Verza

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

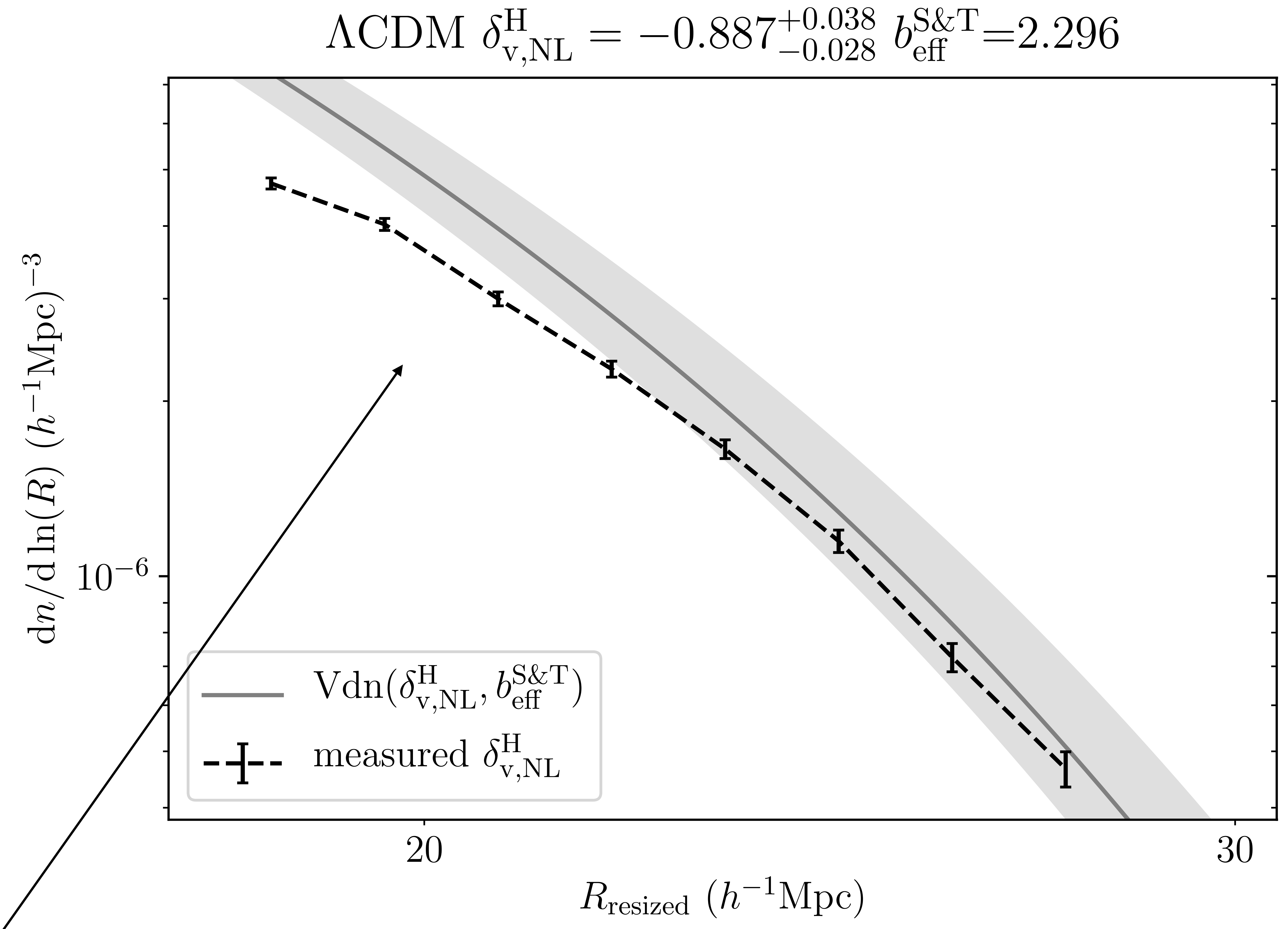
- Account for **tracer bias**
- **Rescale** voids to account for actual under-density



Jennings, Li & Hu ArXiv: 1304.6087 MNRAS; DM
Pollina, Hamaus et al. ArXiv: 1806.06860 MNRAS
Contarini, Ronconi, Marulli, Moscardini, Veropalumbo, Baldi ArXiv: 1904.01022 MNRAS

Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP

ΛCDM

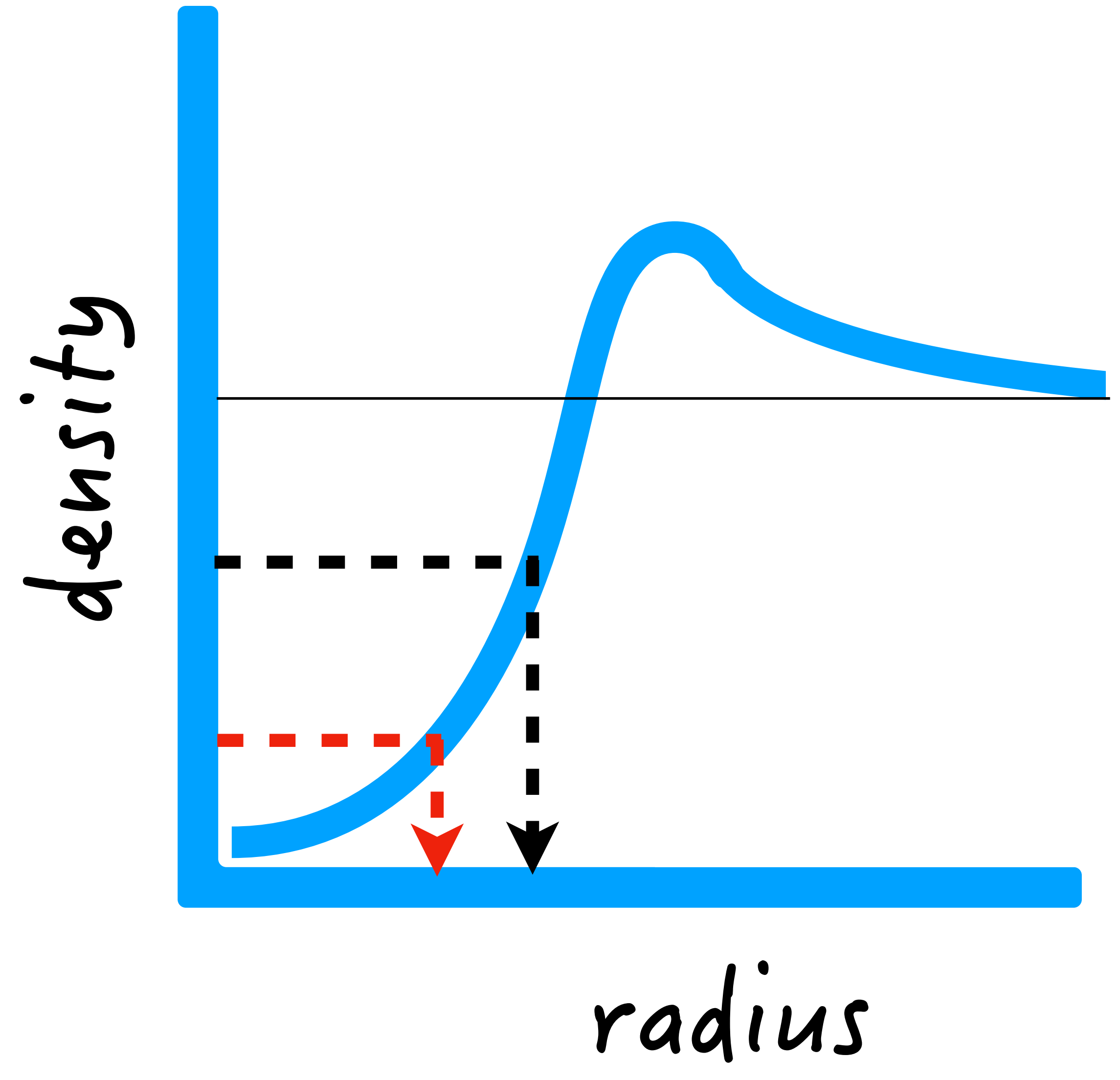


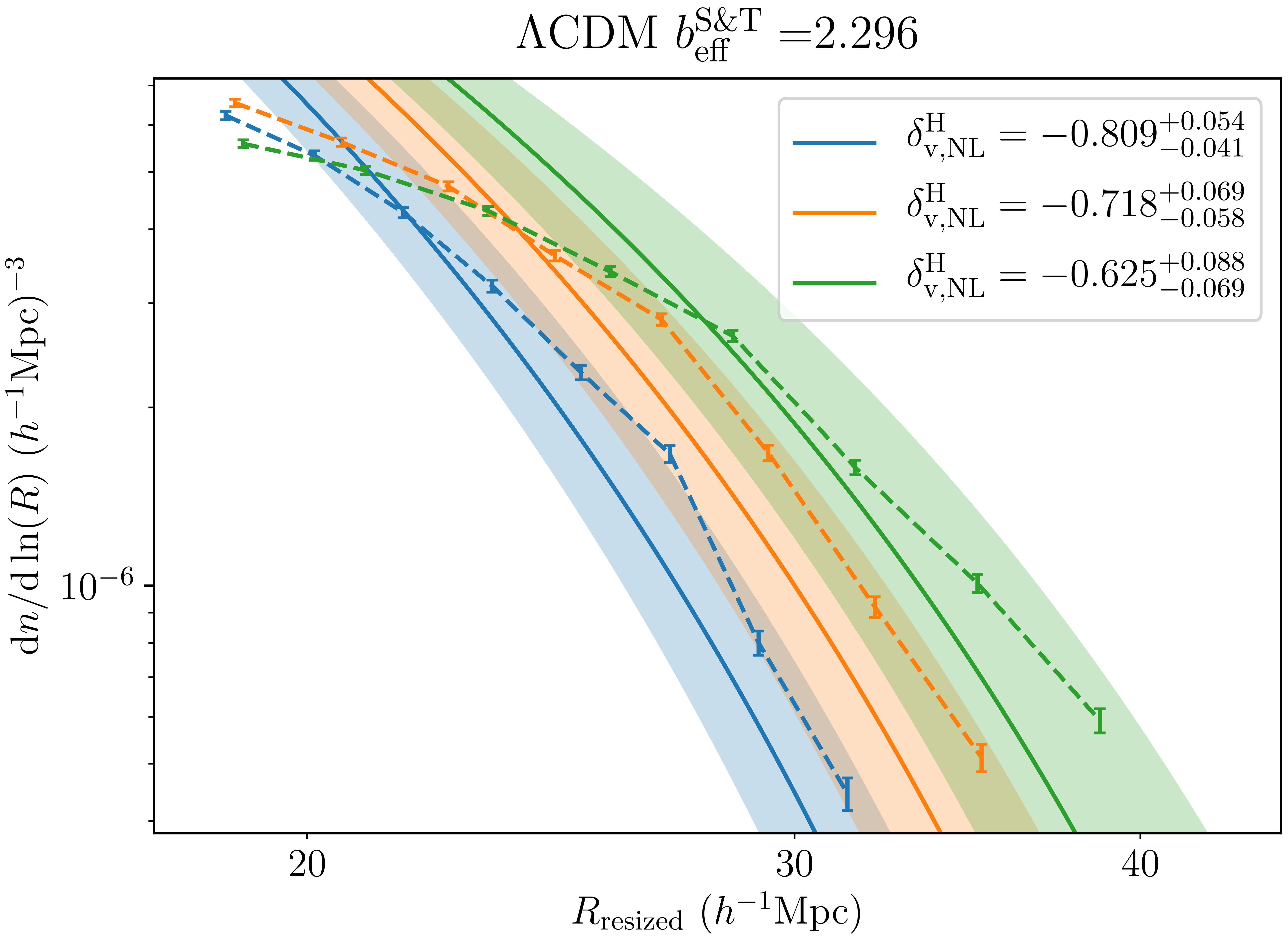
Dense surveys!

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

Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP

ΛCDM



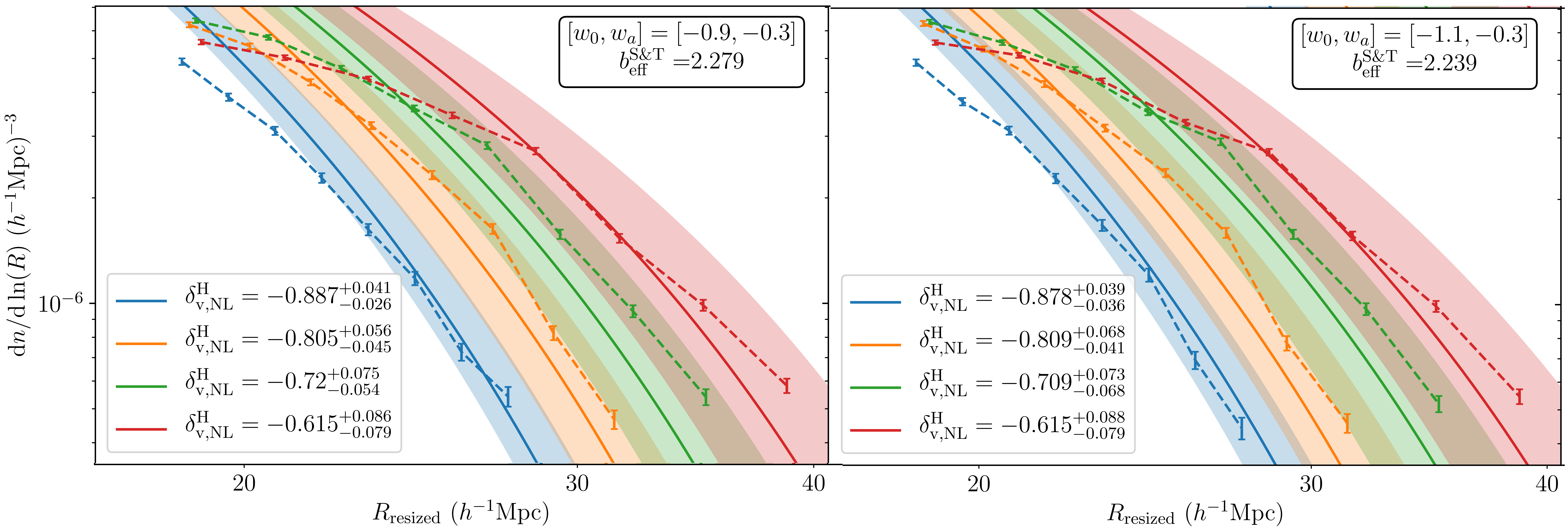


Many thresholds: observationally powerful

Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP

DE models

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



Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP

Future developments for the void-size function

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

- Model with tracer bias | Contarini, Ronconi, Marulli, Moscardini, Veropalumbo, Baldi ArXiv: 1904.01022 MNRAS | Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP
- Test other cosmological models | Contarini, Marulli, Moscardini, Veropalumbo, Giocoli, Baldi ArXiv: 2009.03309 MNRAS
- Estimate observational effects (mask, boundaries!), galaxies properties | Panchal, Pisani, Spergel 2020; ArXiv: 2009.14751 ApJ
- Estimate peculiar velocities effects | Pisani, Sutter, Wandelt 2015, ArXiv: 1506.07982 Correa, Paz, Sánchez, Ruiz, Padilla, Angulo, ArXiv: 2007.12064
- Poisson voids: machine learning to enhance void catalogs reliability | Cousinou, Pisani, Tilquin, Hamaus, Hawken, Escoffier ArXiv: 1805.07181 A&C
- Model the density profile from first principles (and how it changes with cosmology!)

Prepares the application to data!

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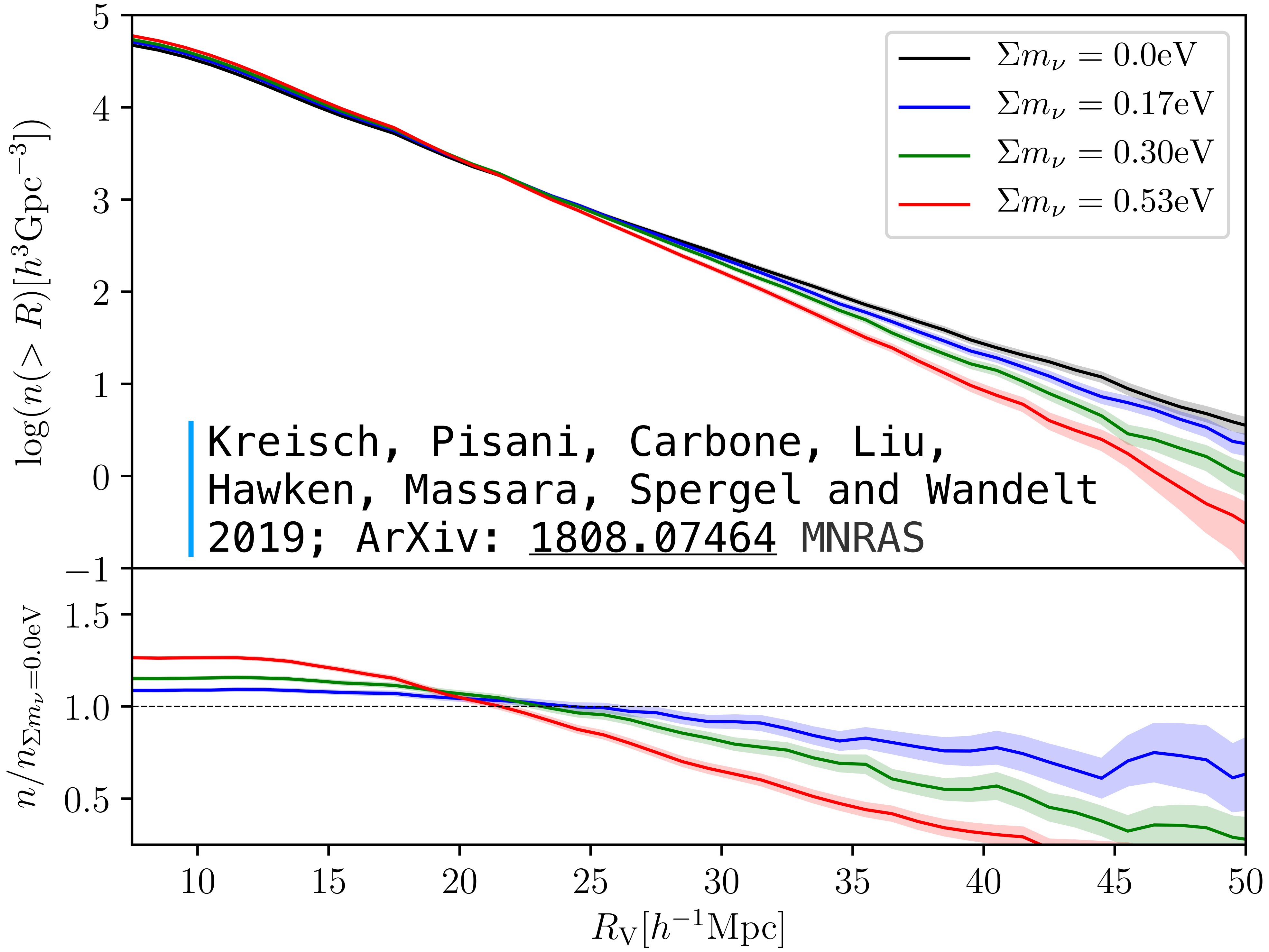
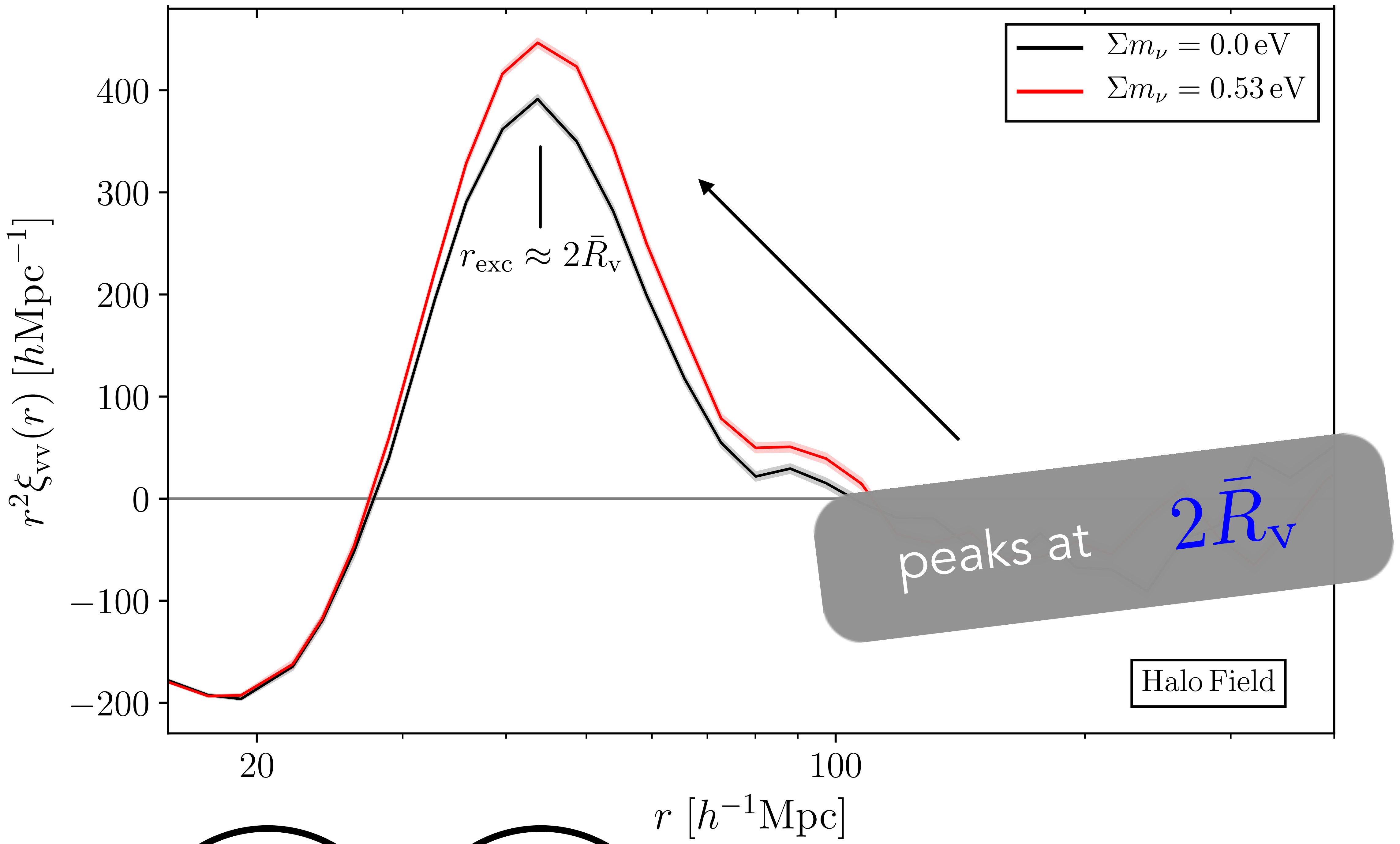
Clustering of voids

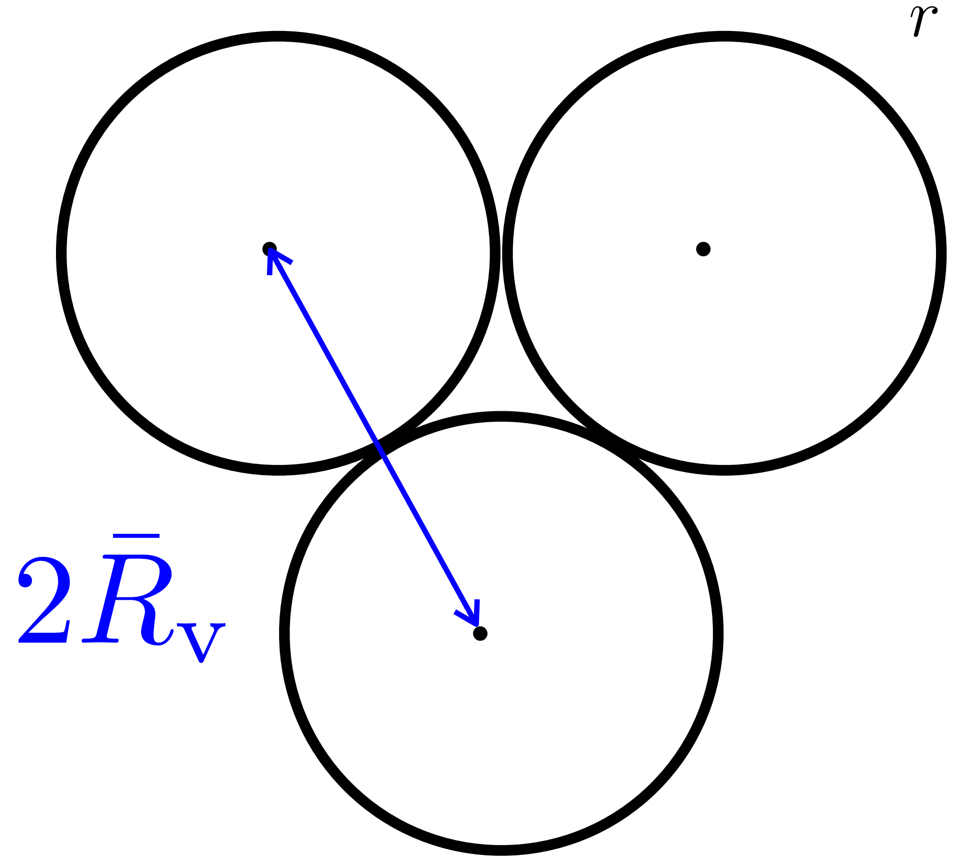
- Massive neutrinos impact LSS ξ_{vv} (Massara et al 2015)
- Free-streaming length ~voids size



Kreisch, Pisani, Carbone, Liu, Hawken, Massara, Spergel and Wandelt 2019; ArXiv: 1808.07464 MNRAS



Christina Kreisch



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

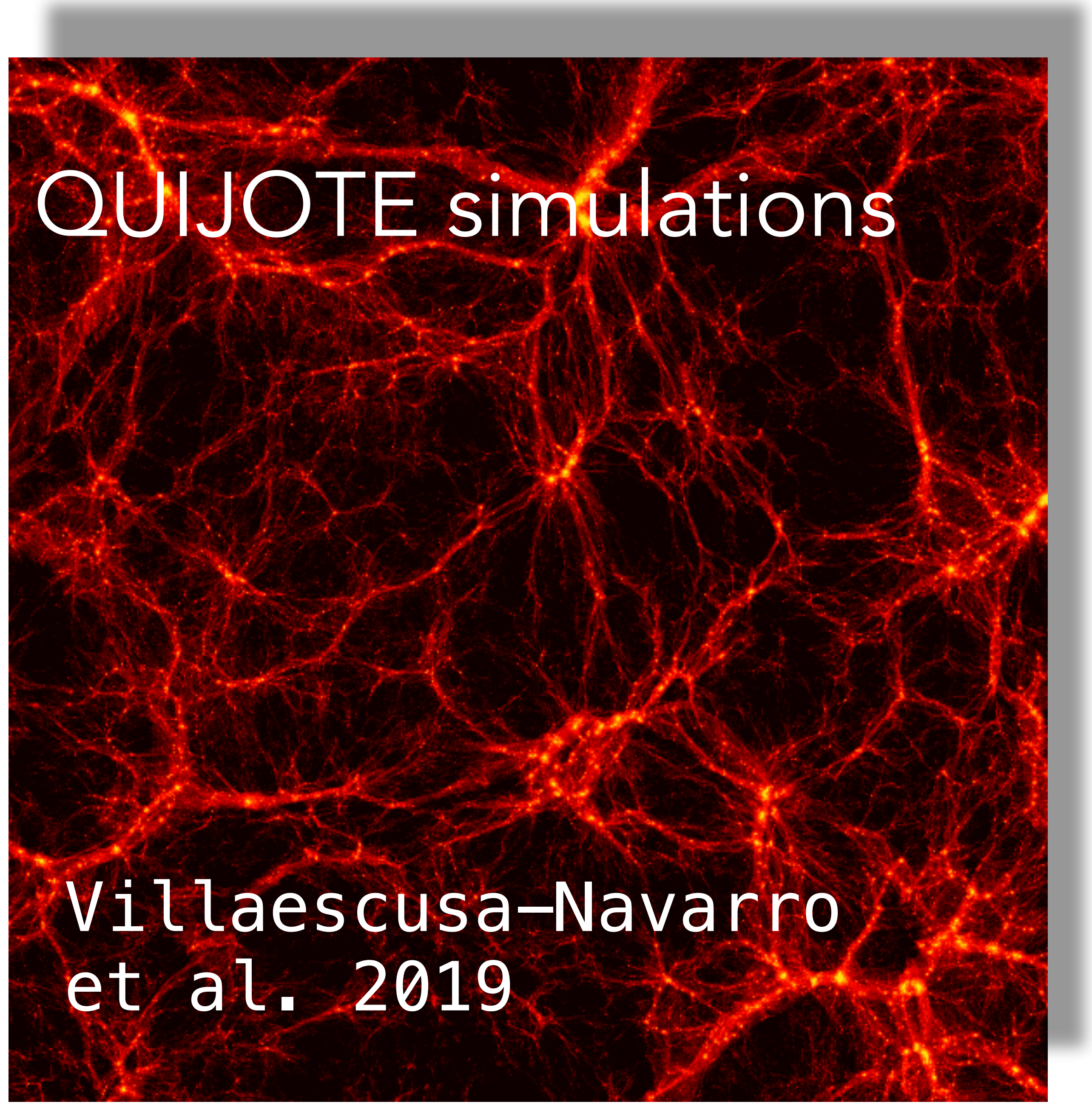
Code:
Gadget-2
1024^3 DM particles
512Mpc/h box
+ kspace-neutrino
+ LensTools
+ Rockstar
+ Consistent Tree

Liu et al. 2018

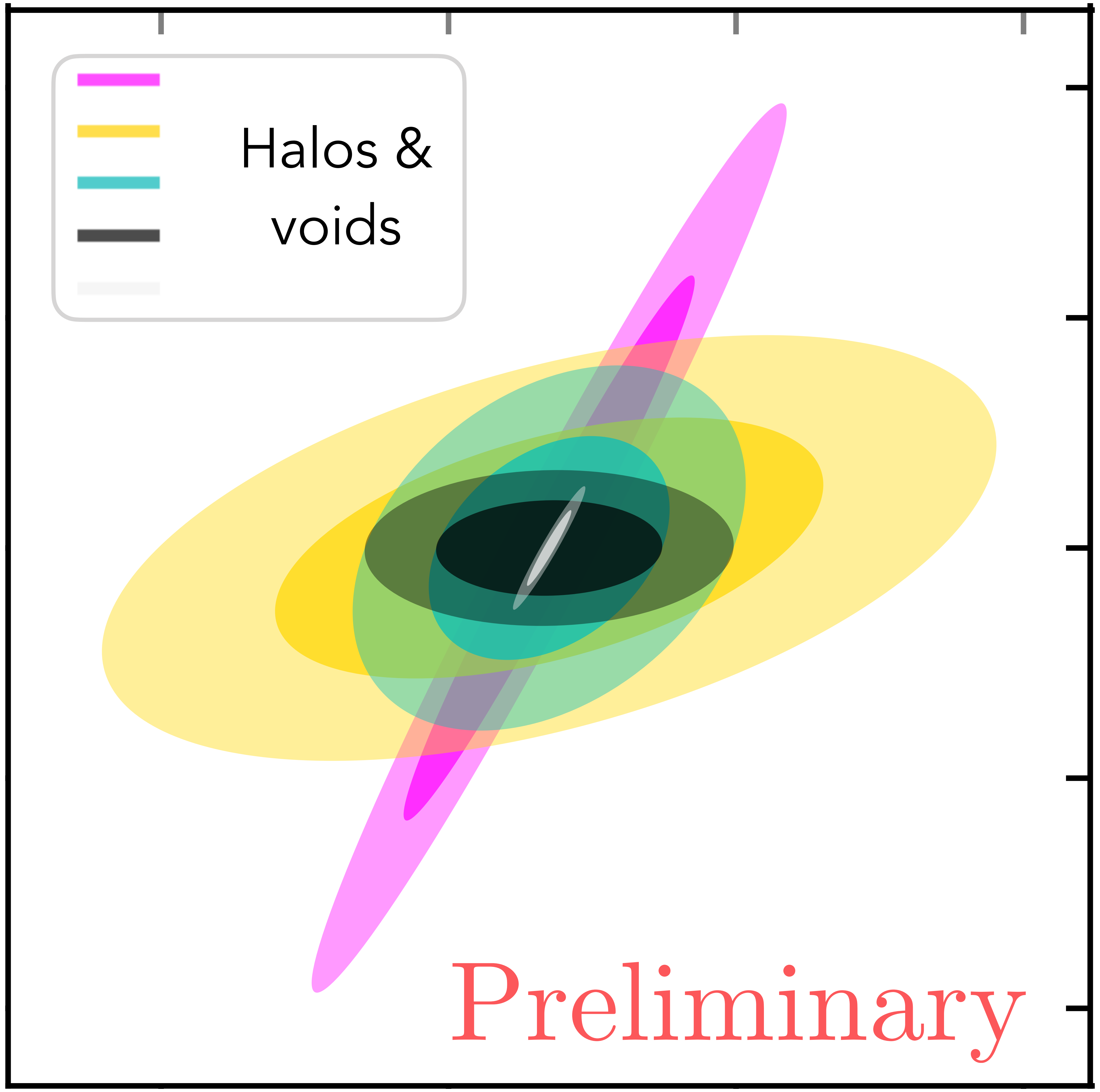
DEMNUni Simulation Suite
Carbone et al. 2016
$L = 2\,h^{-1}\mathrm{Gpc}$ 2048^3 DM part.

Theoretical model for the void-void auto-correlation function?

Power from the combination



15000 VIDE void catalogs $\Lambda\mathrm{CDM}$
+ 7000 cosmologies
$\Omega_m, \Omega_\mathrm{b}, h, n_s, \sigma_8, M_\nu, w$



Christina Kreisch

Kreisch, Pisani, Villaescusa-Navarro, Spergel et al. in prep. (2021)
Bayer et al. 2021 (DM)

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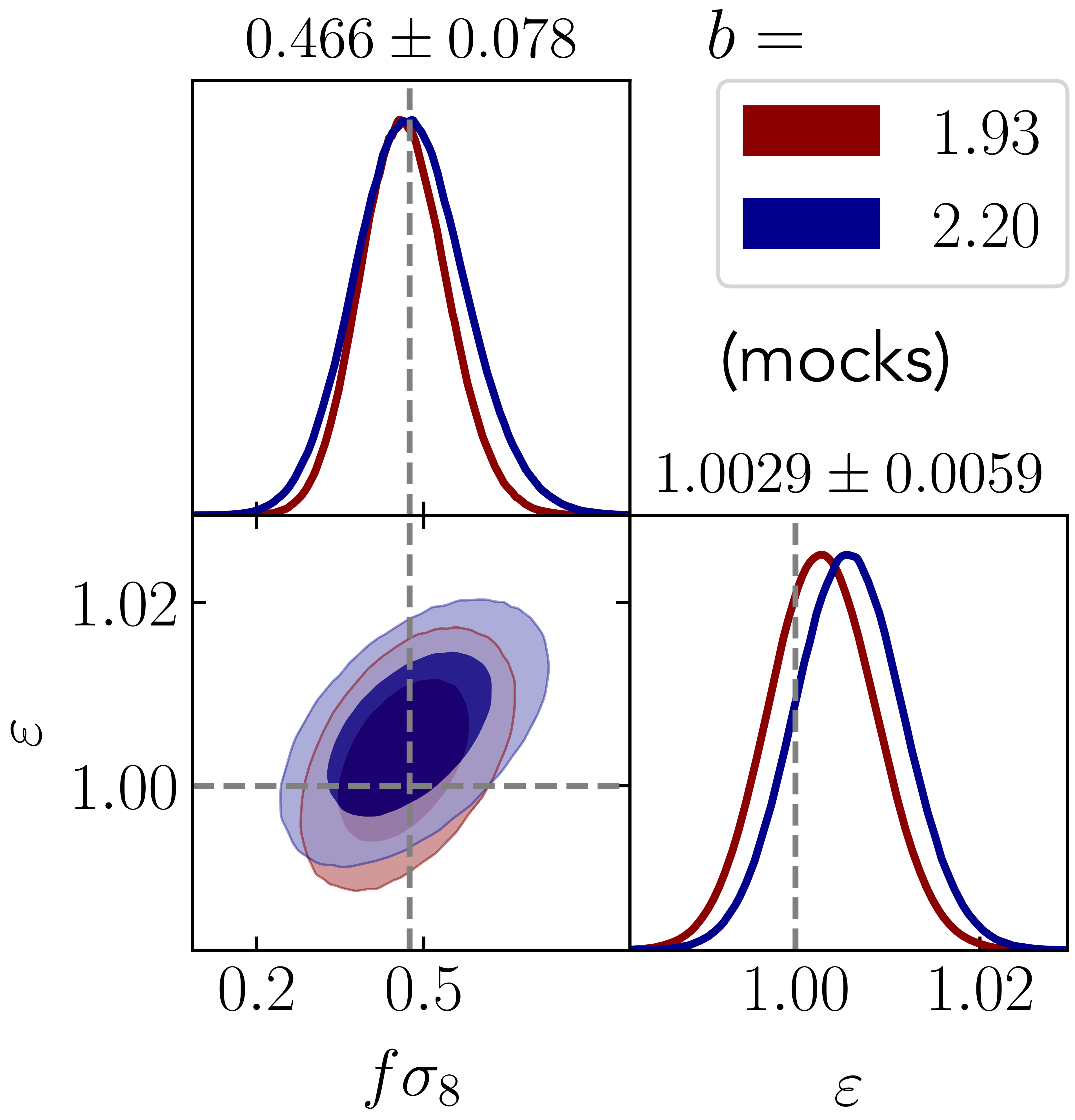
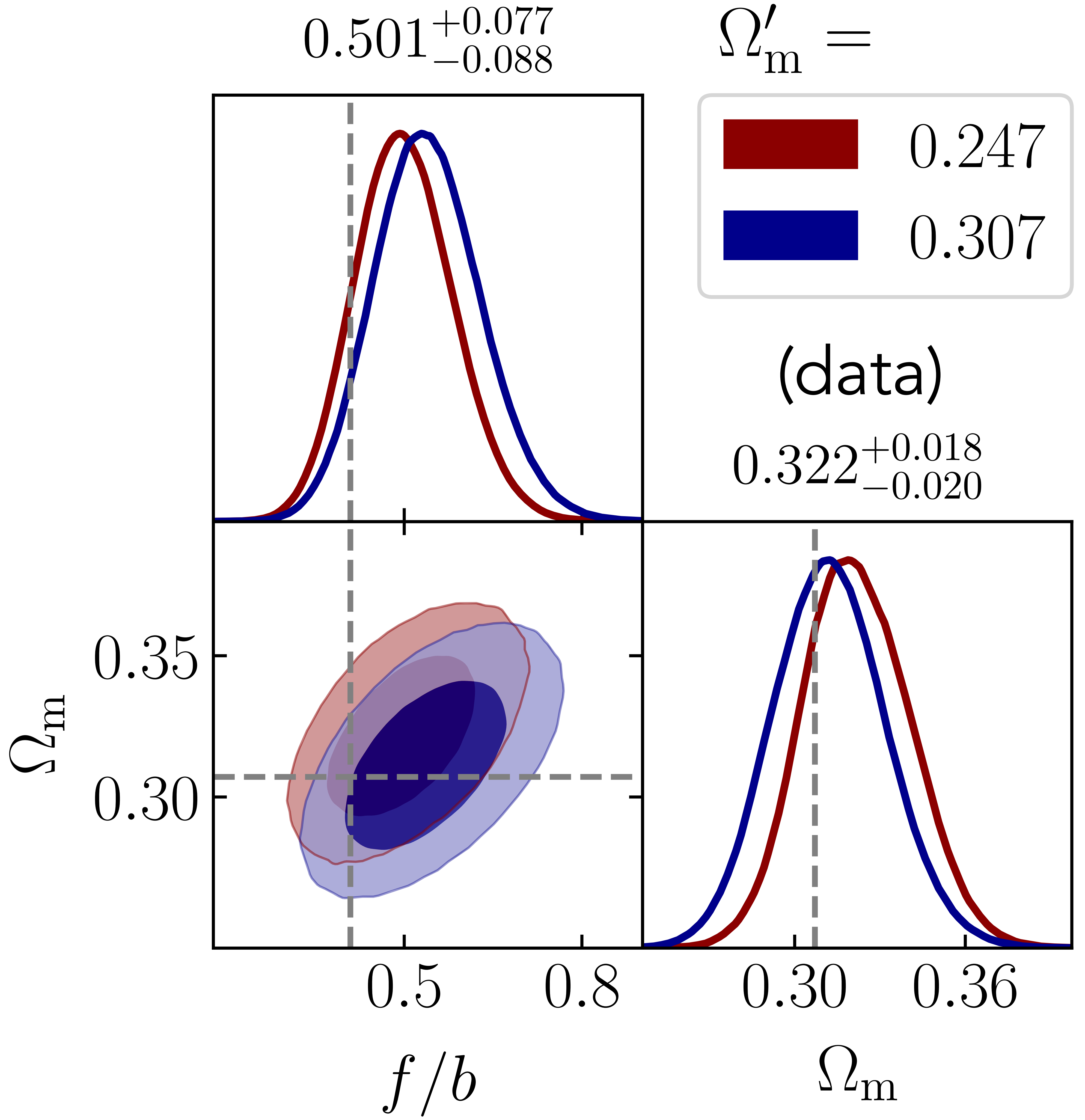
Take home messages

- Void analysis: active field of galaxy clustering=> **competitive sub-percent level constraints.**
- ξ_{vg} is a robust tool for cosmology. Velocities have turned from being a systematic effect into becoming source of information.
- Importance of **model-independent** techniques.
- Robust theoretical modeling of the **void-size function** will lead to application on data.
- The void-void auto-correlation function is a new promising tool to constrain cosmology
- PFS, DESI, Euclid, Rubin, Roman, SPHEREx : a unique set of $> \mathcal{O}(10^5)$ voids per survey!
- Theory needs to keep the pace with data!
- Voids can independently constrain $\Omega_m, \Omega_\Lambda, w_0, w_a, f, \Sigma m_\nu$

Supplementary slides:

Systematic tests: tracer bias and fiducial cosmology





Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.