Unraveling the Universe with Cosmic Voids

New Strategies for Extracting Cosmology from Galaxy Surveys, 2nd edition, Sexten Workshop

+ many collaborators, highlights: N. Hamaus (LMU, Munich), S. Contarini (MPE), G. Verza (CCA, NYU), B. Y. Wang (CMU), D. Spergel (Princeton, Flatiron), B. Wandelt (IAP), C. Kreisch (Princeton), R. Panchal (Princeton), M. Aubert (LPC), M.-C. Cousinou (CPPM), S. Escoffier (CPPM), G. Lavaux (IAP), M. Habouzit (MPIA), E. Massara (Waterloo),….

Aix*Marseille université

cnrs dépasser les frontières IN2P3 Les deux infinis

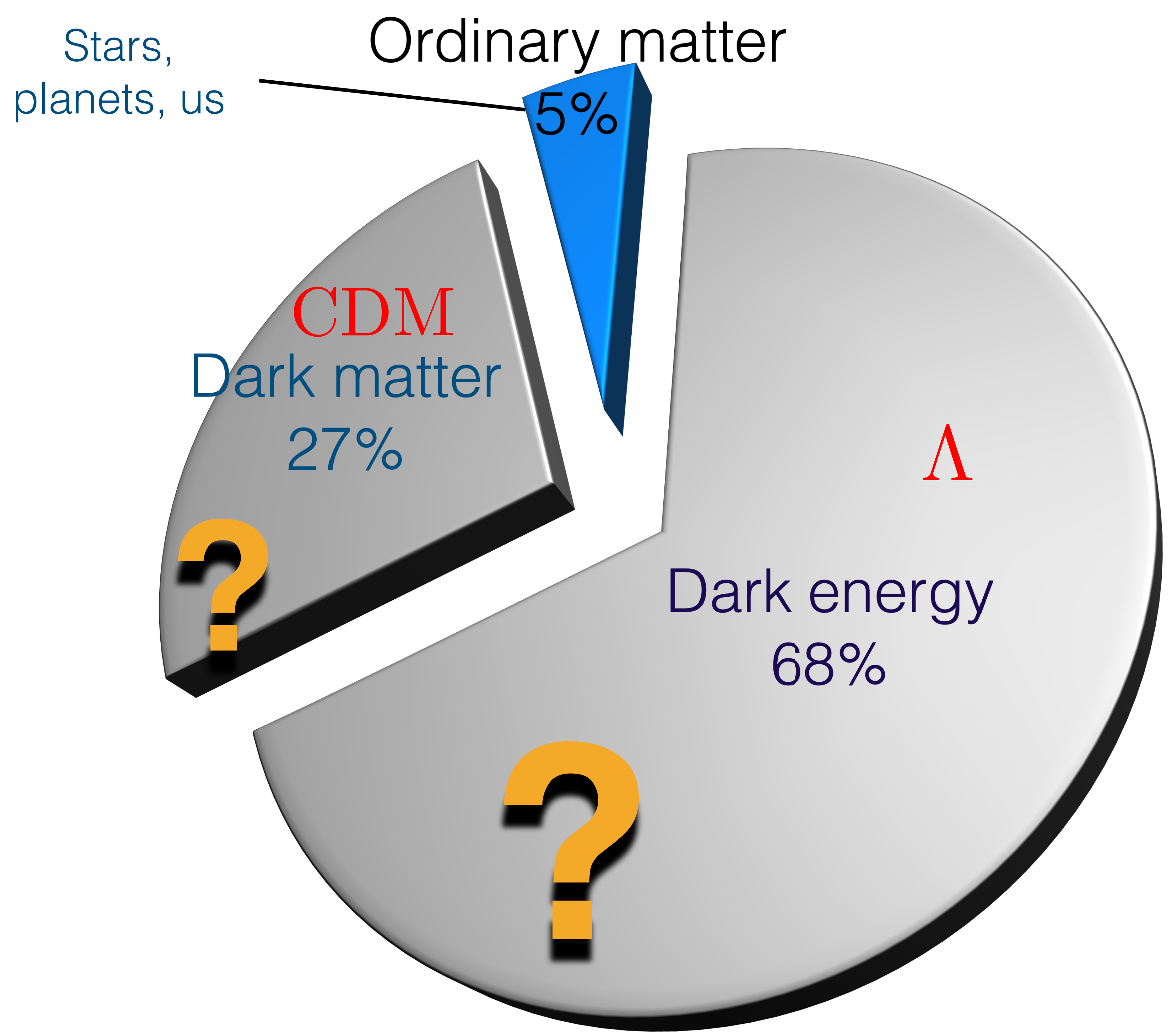
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

erc European Research Council Established by the European Commission

A*Midex Initiative d'excellence Aix-Marseille

Alice Pisani

Precision cosmology



A standard model $\Lambda\mathrm{CDM}$, to explain the accelerated expansion of the Universe.

New Physics!

Outline

- Large Scale Structure, Voids and Cosmology
- How do we find voids?
- Void-galaxy cross-correlation function
- Void size function
- Voids and the rising tensions
- Void-void auto-correlation function and neutrinos
- Challenges
- Take home messages

Outline

- **Large Scale Structure, Voids and Cosmology**
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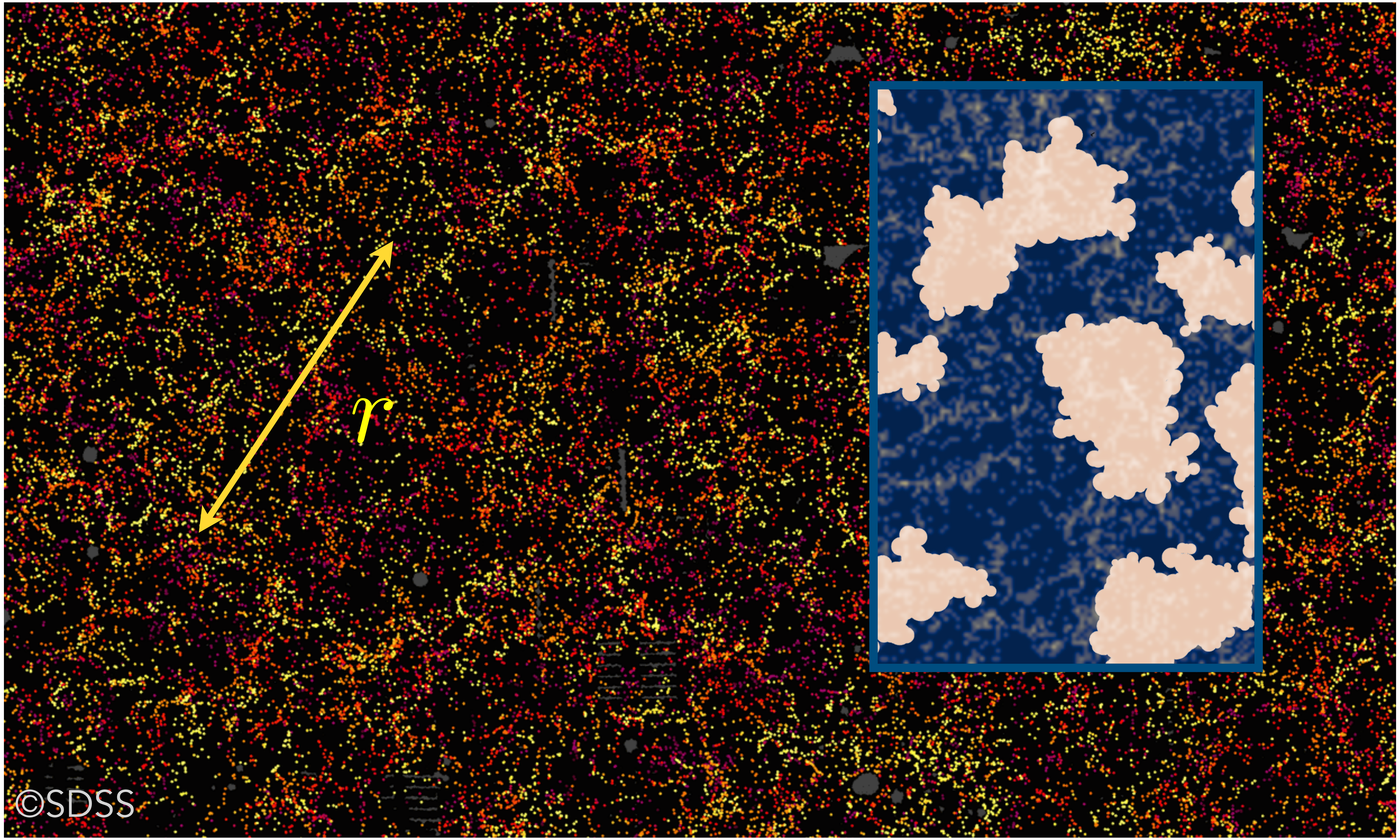
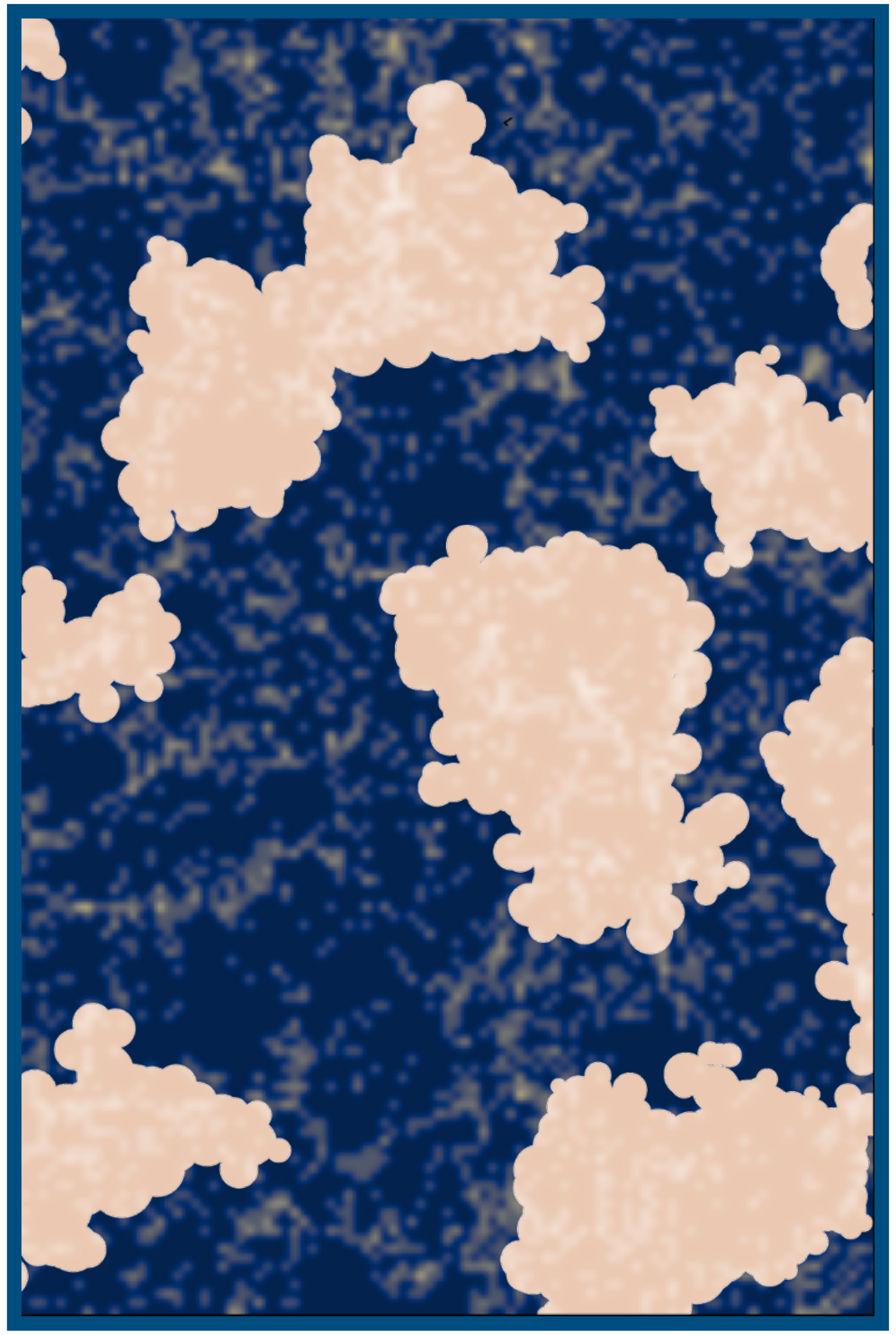
Galaxy maps contain information beyond the 2-point correlation function.



Voids have a unique sensitivity to cosmology.



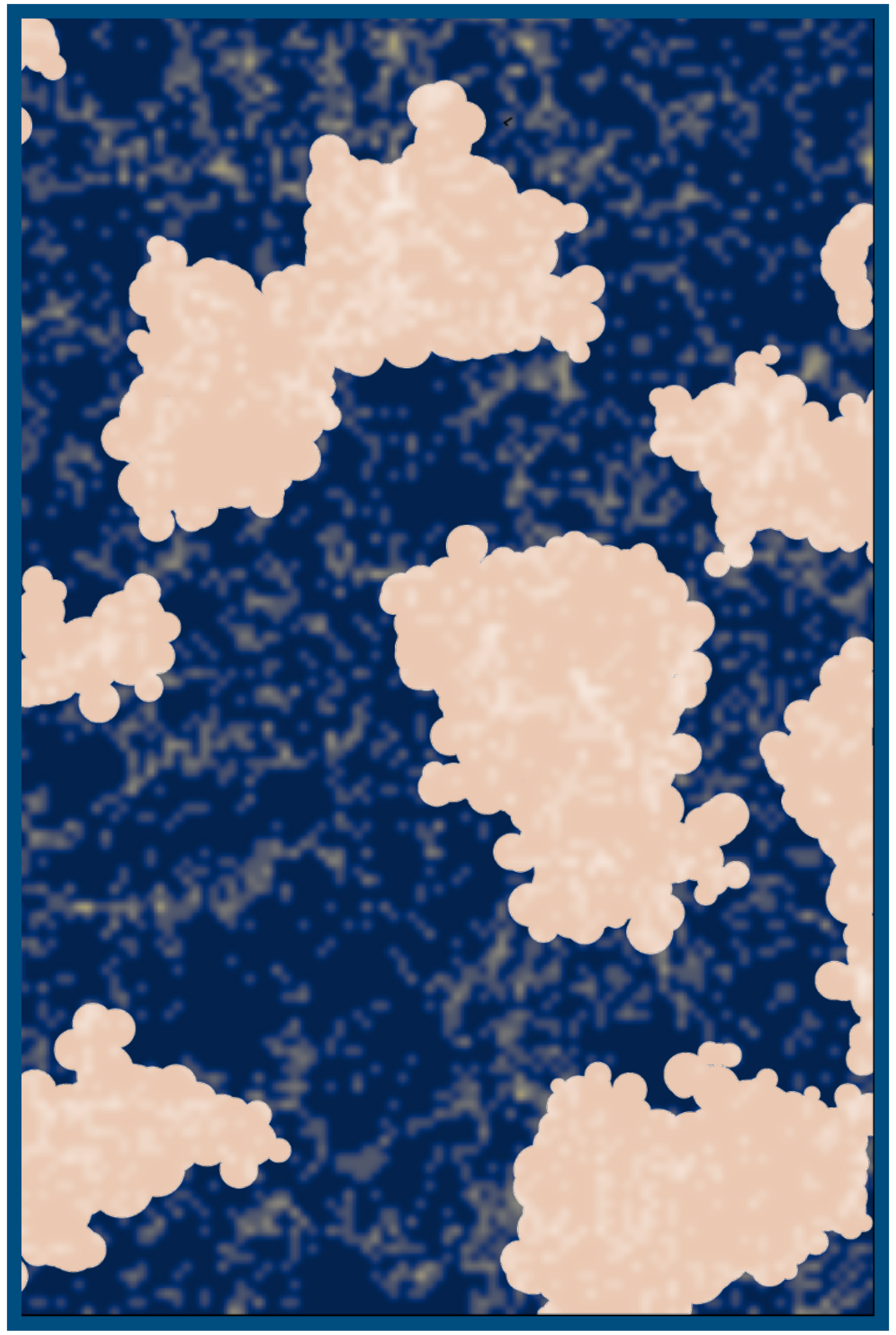
Dark energy dominated (first!)

Sensitive to diffuse components Σm_ν

Sweet spots to test gravity

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

Voids have a unique sensitivity to cosmology.



Multi-scale sensitivity (sizes 10 - 100 Mpc/h)

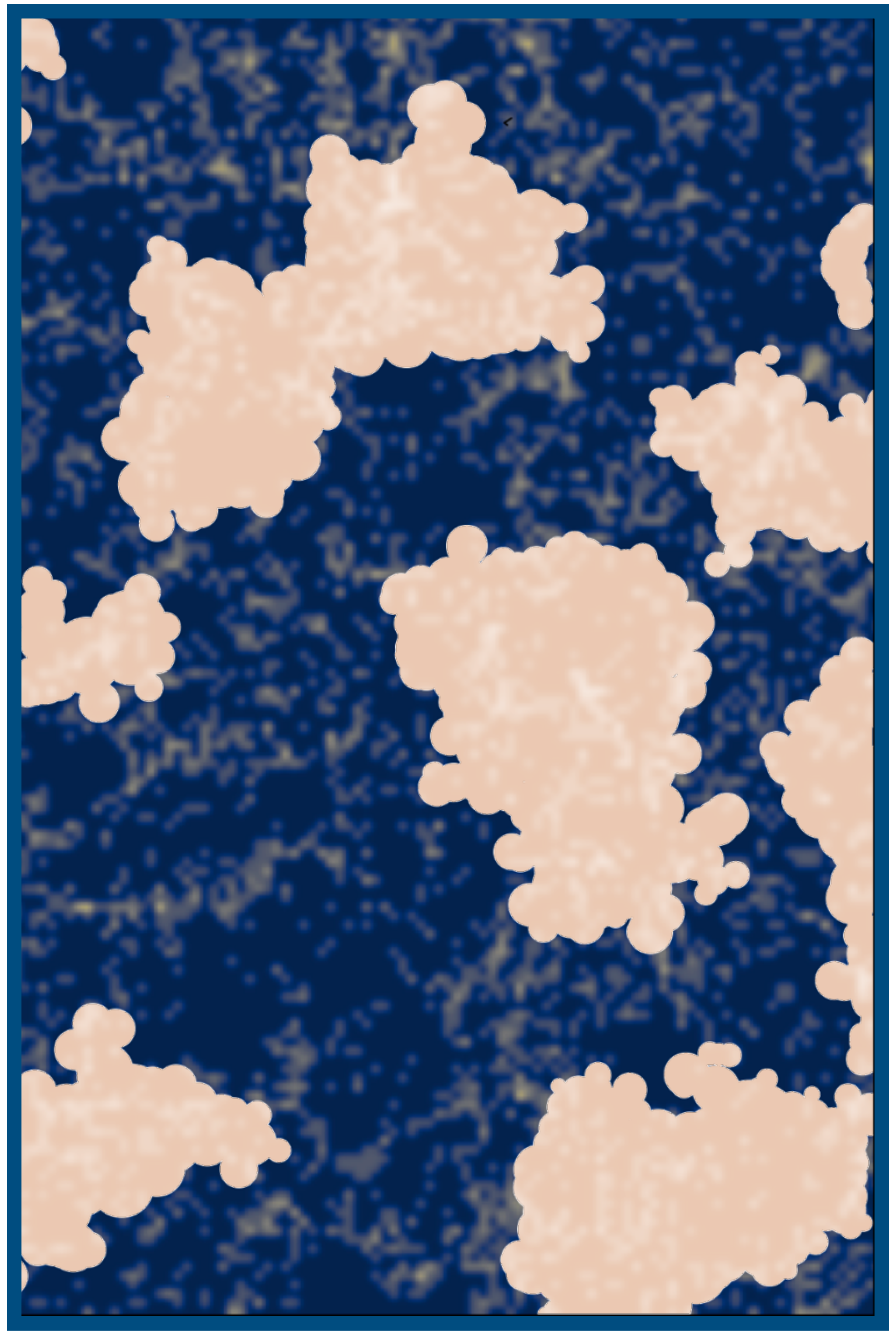
Easier to model (traditional techniques, models valid down to small scales)

Keep memory of initial conditions

High signal-to-noise for dark matter

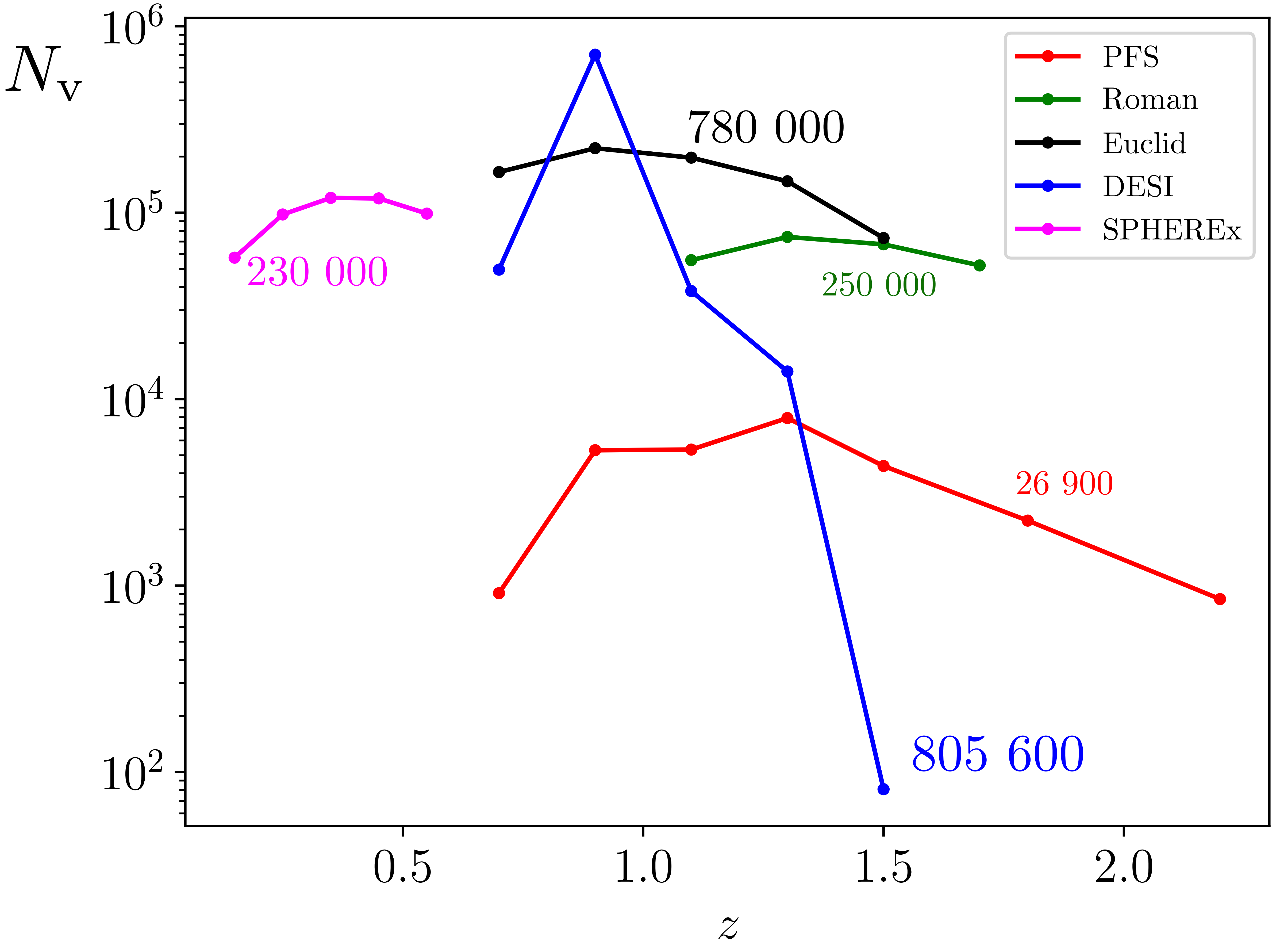
Arcari, Pinetti, Fornengo 2022
JCAP Arxiv: 2205.03360

It's the golden age for void cosmology!



Voids need large volume <u>and</u> deep, detailed maps!

Hundreds of thousands of voids



Number density also plays a role!

From a practical perspective: quantities we wish to constrain

Ω_m, Ω_Λ Content of the Universe

σ_8 Amplitude of density fluctuations

$f = \frac{d\ln\Delta}{d\ln a}$ Growth rate of structure

$\frac{f}{b}$ Bias $b = \frac{\delta_{\rm gal}}{\delta}$

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

Σm_ν Sum of neutrino masses

H_0 Hubble constant

- Large Scale Structure, Voids and Cosmology
- **How do we find voids?**
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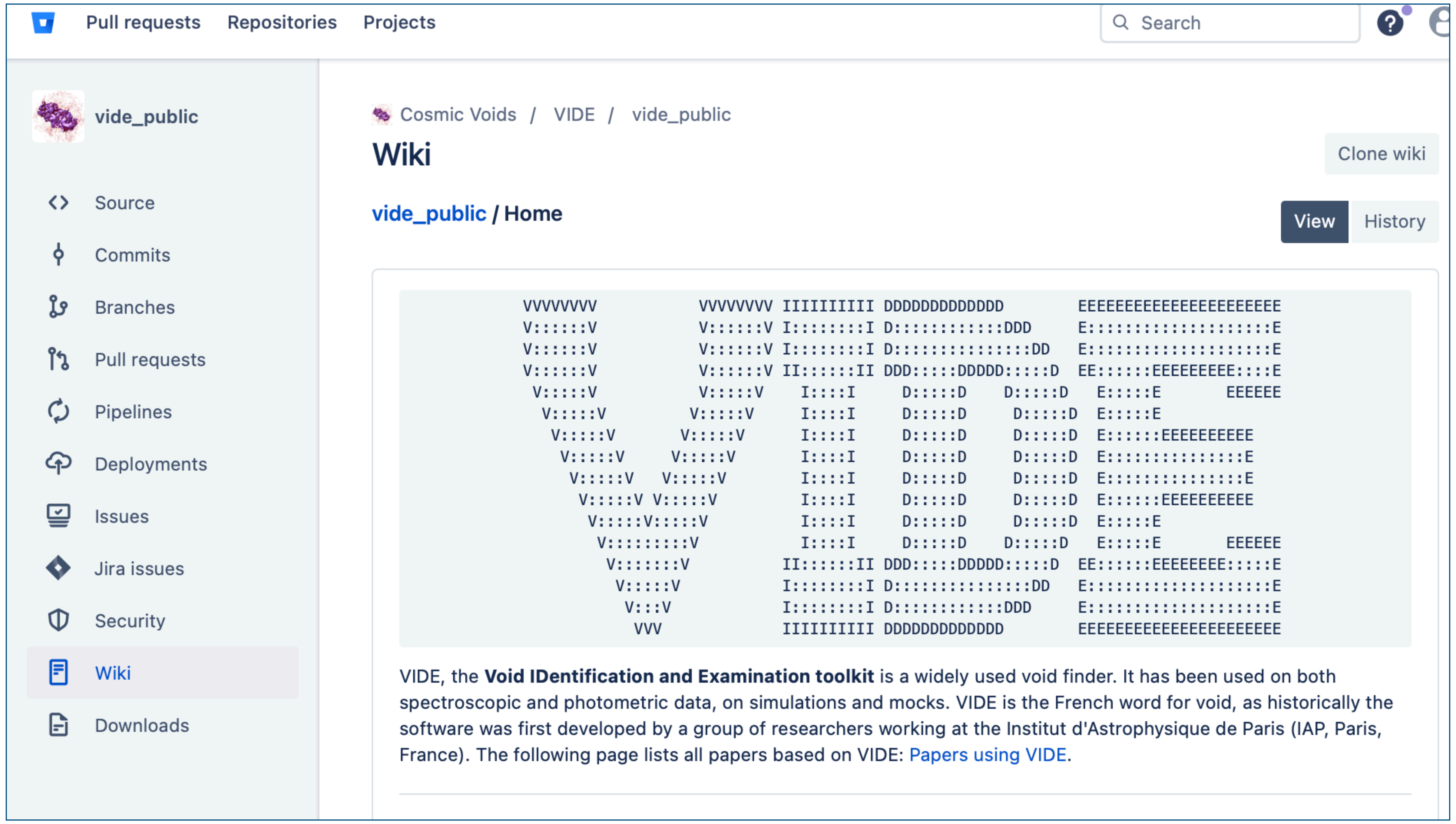
Void definition

A void definition must be well **tested**, suitable to your dataset and should enhance the S/N of the measurement we wish to do. We also wish to link it to theory!

Void IDentification and Examination

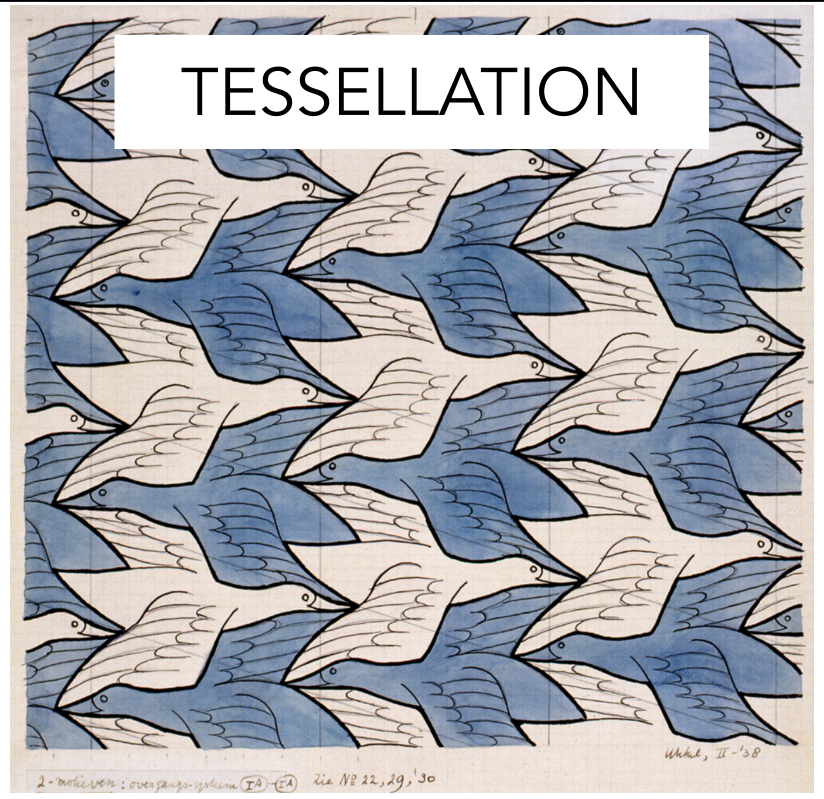


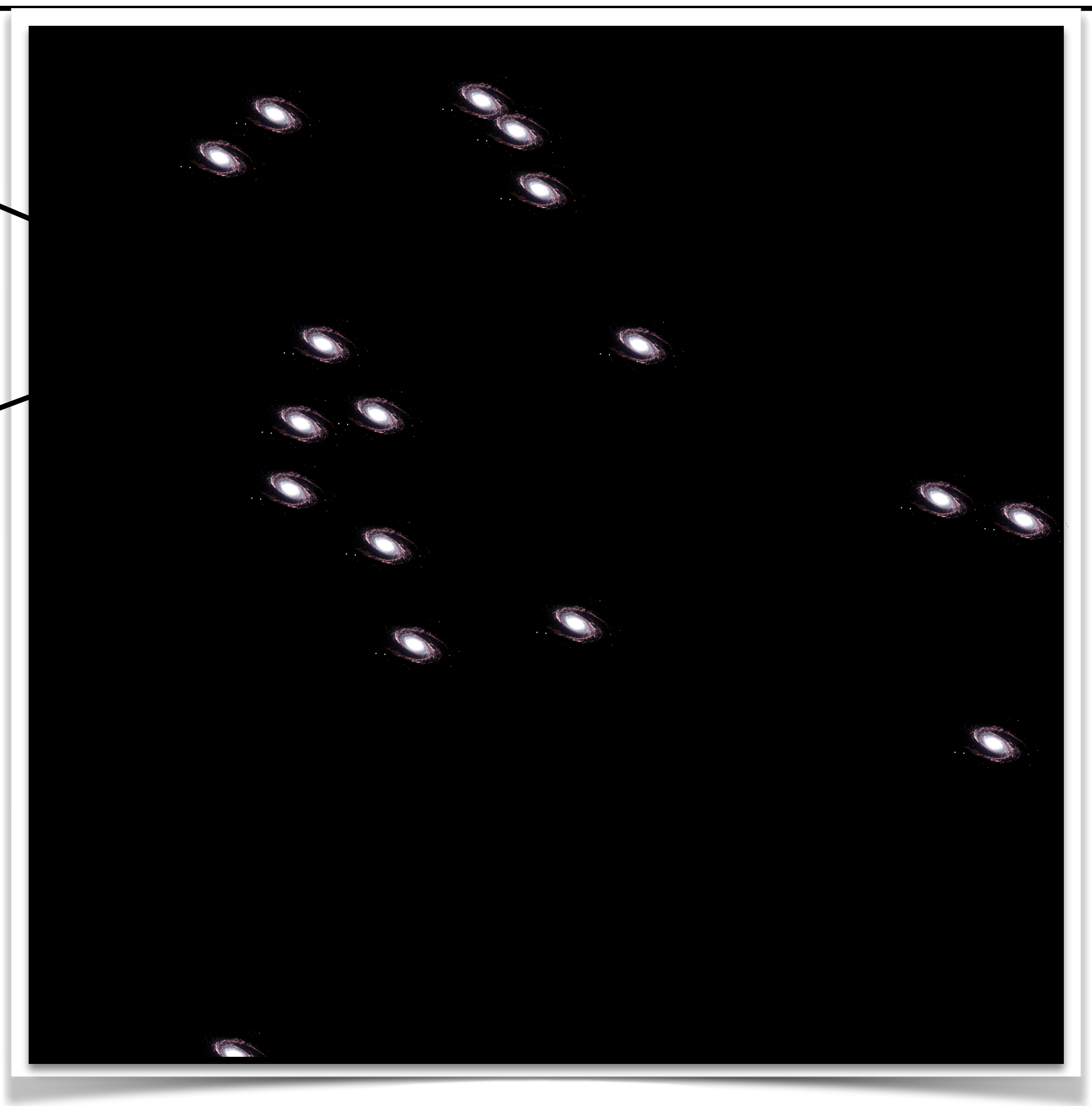
- ☑ Provides void detailed shape.
- ☑ Suitable for both simulations and surveys (accounts for mask).
- ☑ Widely used: BOSS (DR7, DR10, DR11, DR12), eBOSS (DR14), DES, Euclid, Roman, PFS.

https://bitbucket.org/cosmicvoids/vide_public/src/master/, Sutter et al. 2015 A&C
based on ZOBOV (Neyrinck 2008)

Void definition: VIDE (Void IDentification and Examination)

galaxies → Voronoi tessellation → ? → Watershed transform → voids





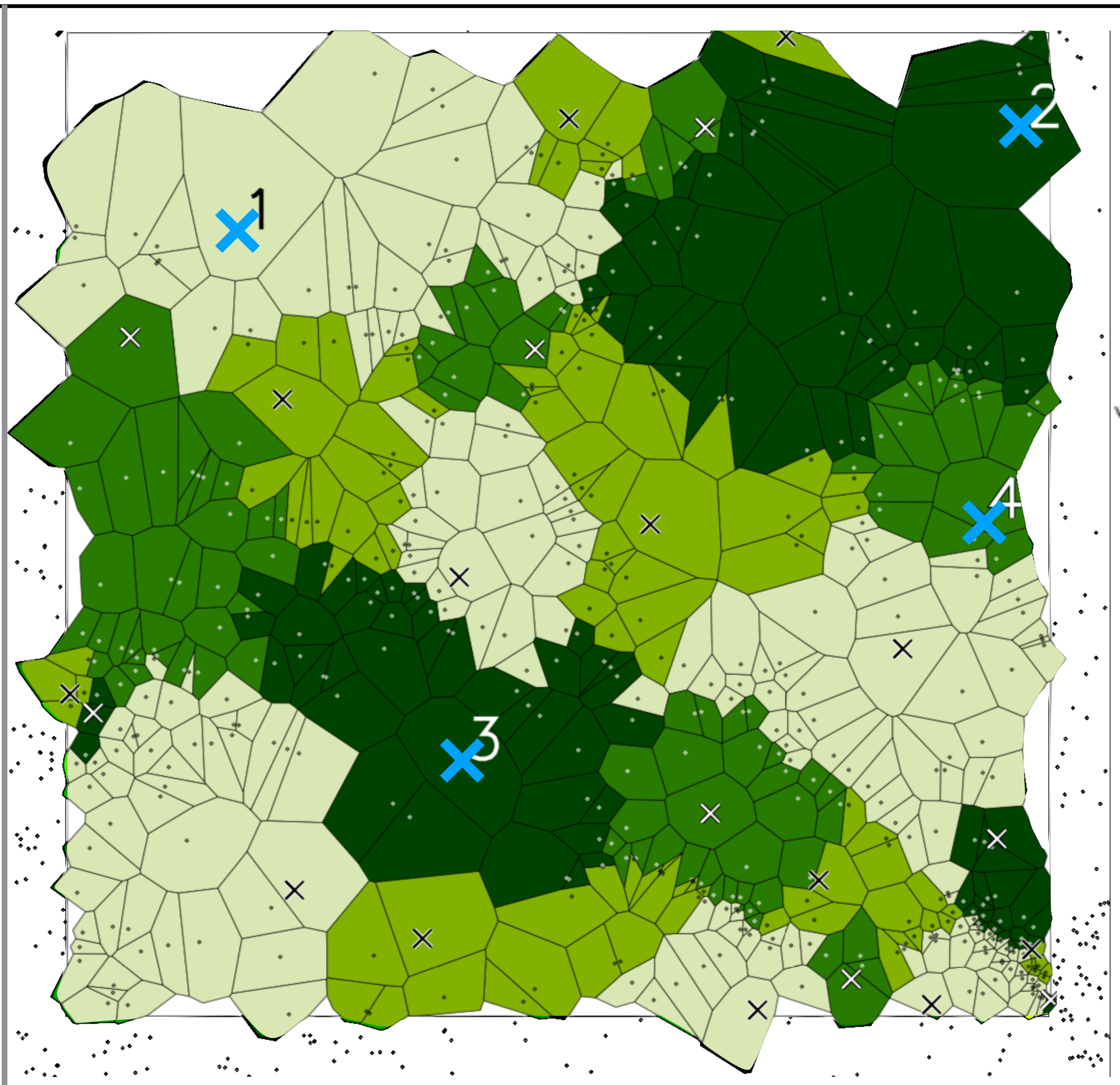
Galaxy

All points closer to the tracer than to any other point

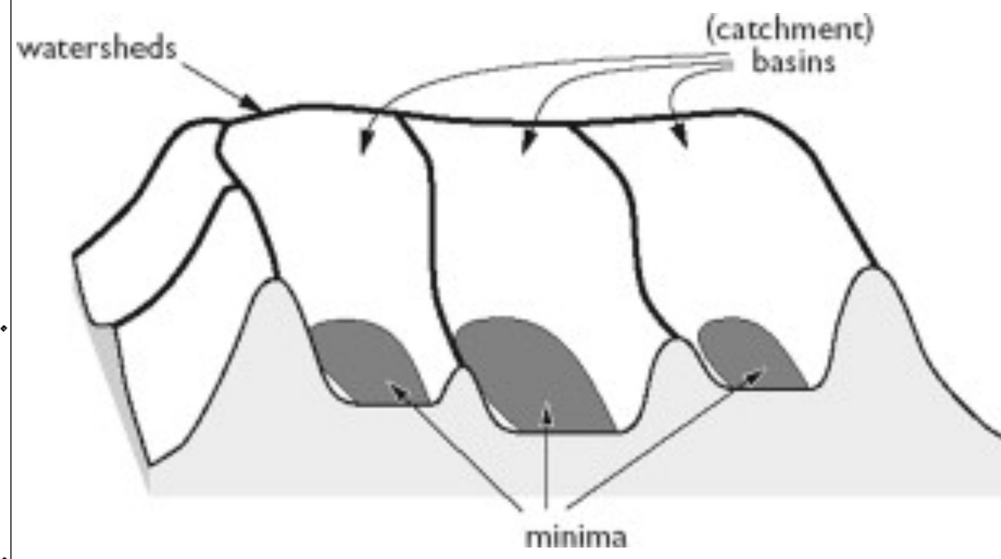
Local density estimation

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

A tessellation with a physical meaning



Neyrinck 2008



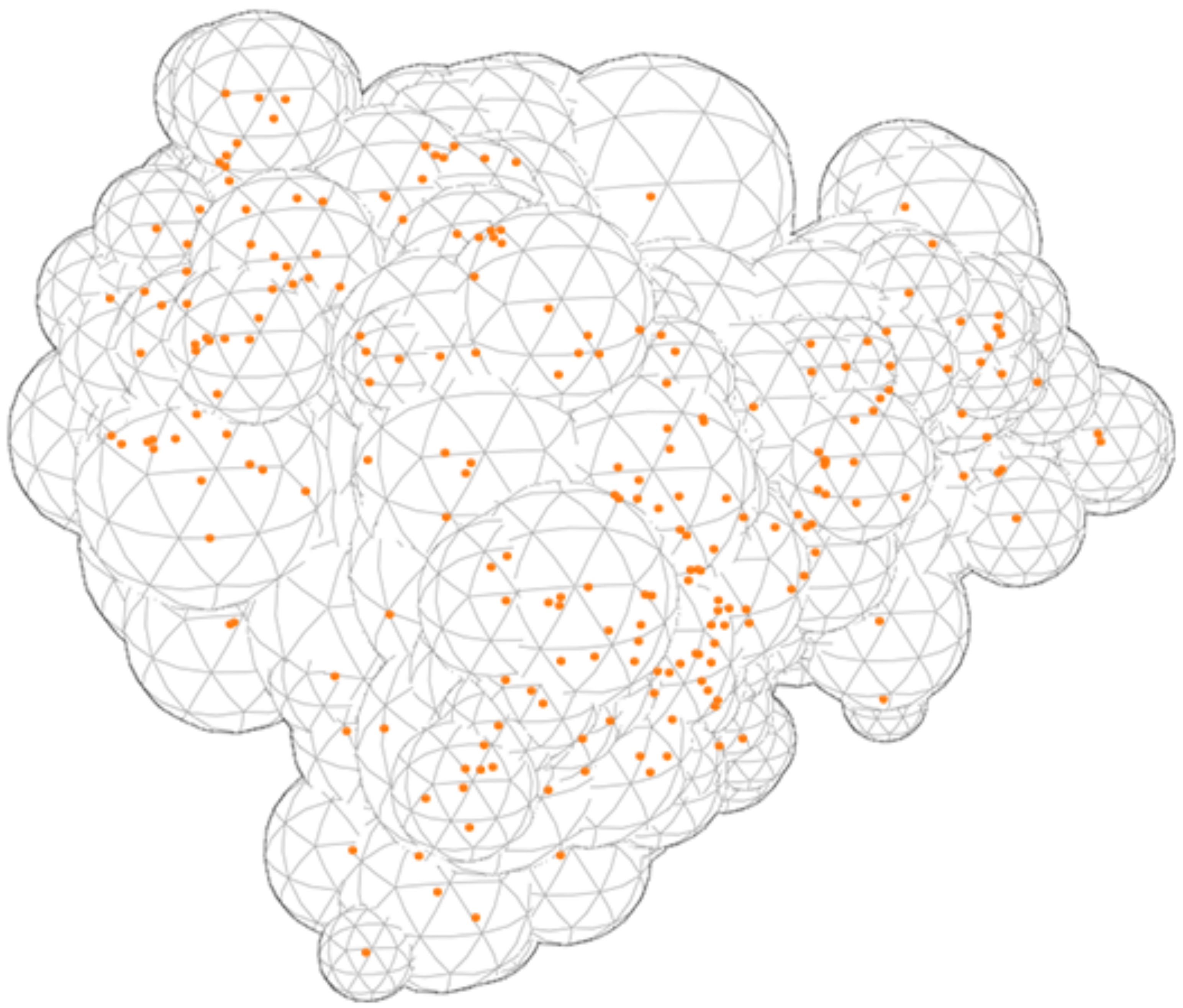
Preim, Botha 2014

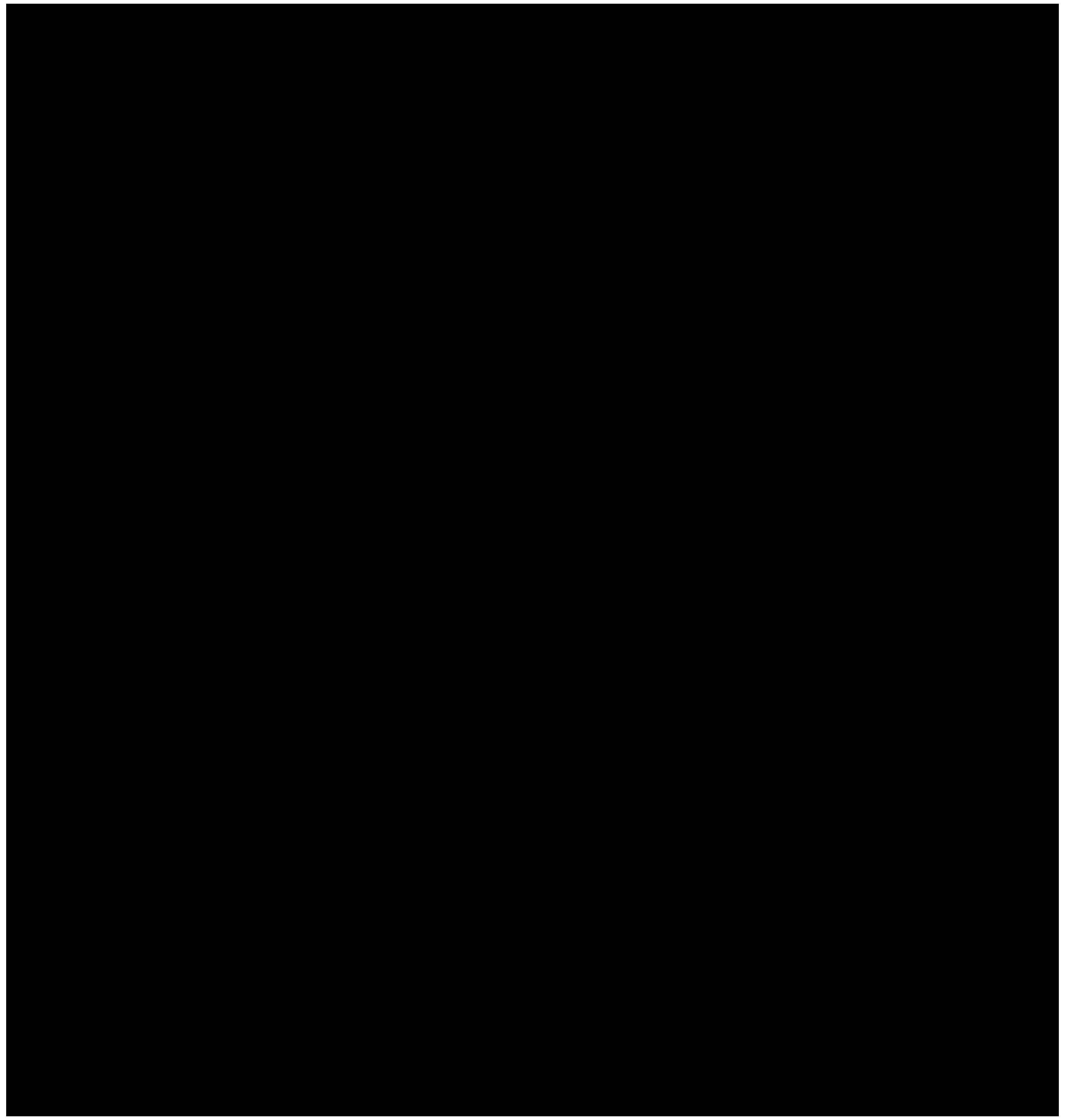
VIDE:https://bitbucket.org/cosmicvoids/vide_public/src/master/, Sutter, Lavaux, Hamaus, Pisani, Wandelt, Warren, Villaescusa-Navarro, Zivick, Mao, and Thompson 2015 A&C ArXiv: 1406.1191
Icke & Van de Weygaert (1987)
Platen et al. 2007

Void finding in 3D!

Void definition: VIDE (Void IDentification and Examination)

No a priori on the shape.
Void's shape is not regular on a one-to-one basis!



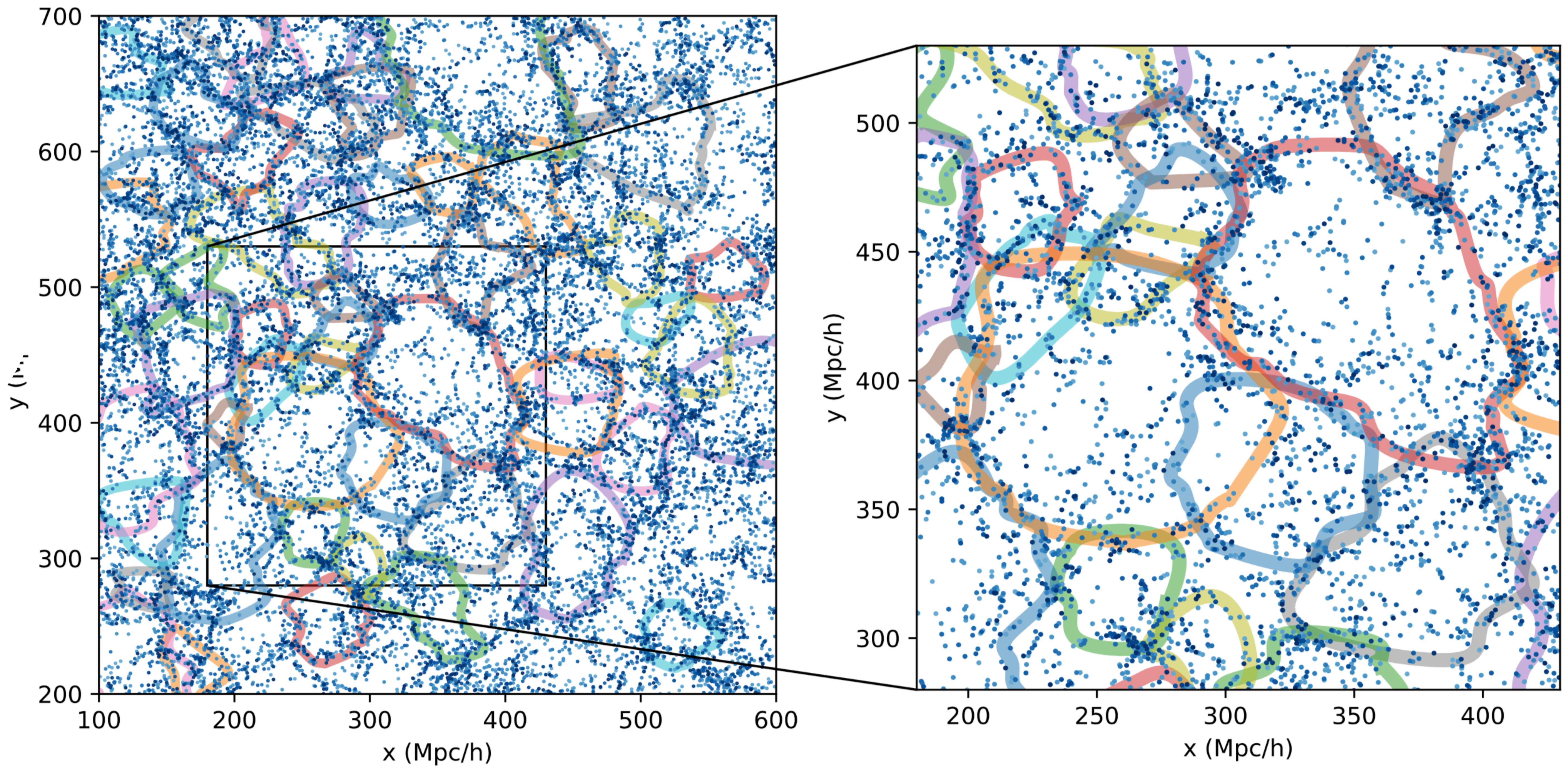


Yue Bonny Wang

Wang, Pisani, Villaescusa-Navarro and Wandelt 2023, ApJ 955 131, Arxiv: 2212.06860

Void definition: VIDE   (Void IDentification and Examination)

Giovanni
Verza

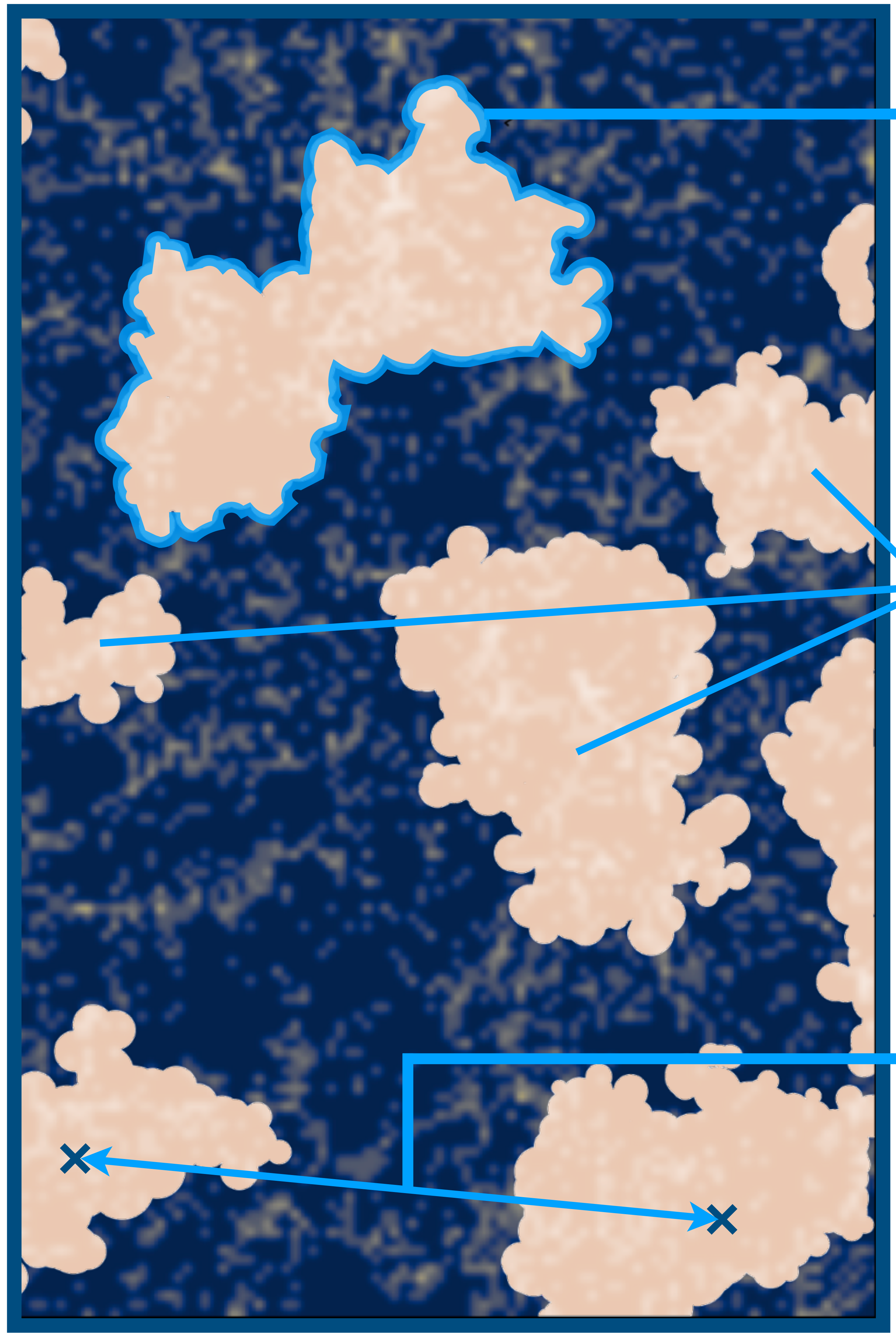


We have void centers, void radii, and tracers!

Using voids means more than one application!

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

Many different void statistics



Shape

ξ_{vg}

Numbers

N_{v}

Clustering

ξ_{vv}

Pisani et al. 2014 MNRAS
Hamaus, Aubert, Pisani et al. 2021 A&A

Pisani et al. 2015 PRD
Verza, Pisani et al. 2019 JCAP

Massara et al. JCAP 2015
Kreisch, Pisani et al. 2019 MNRAS
Contarini, Verza, Pisani et al. 2022 A&A

Kreisch, Pisani et al. 2021 ApJ

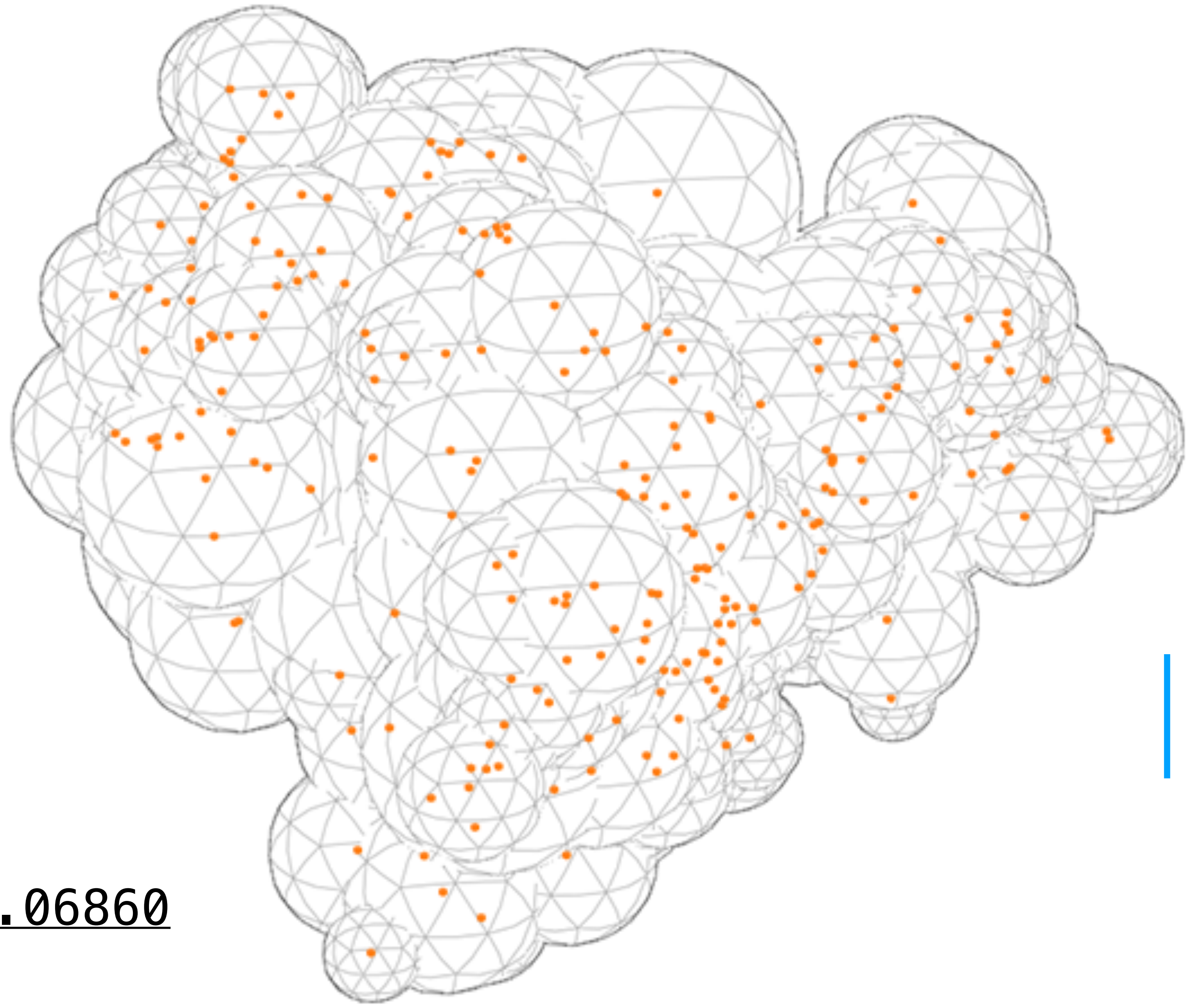
Dark energy
Modified gravity

Neutrinos

Not at the same degree of maturity !

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

The *observed* void-galaxy cross-correlation function $\xi_{\rm vg}$



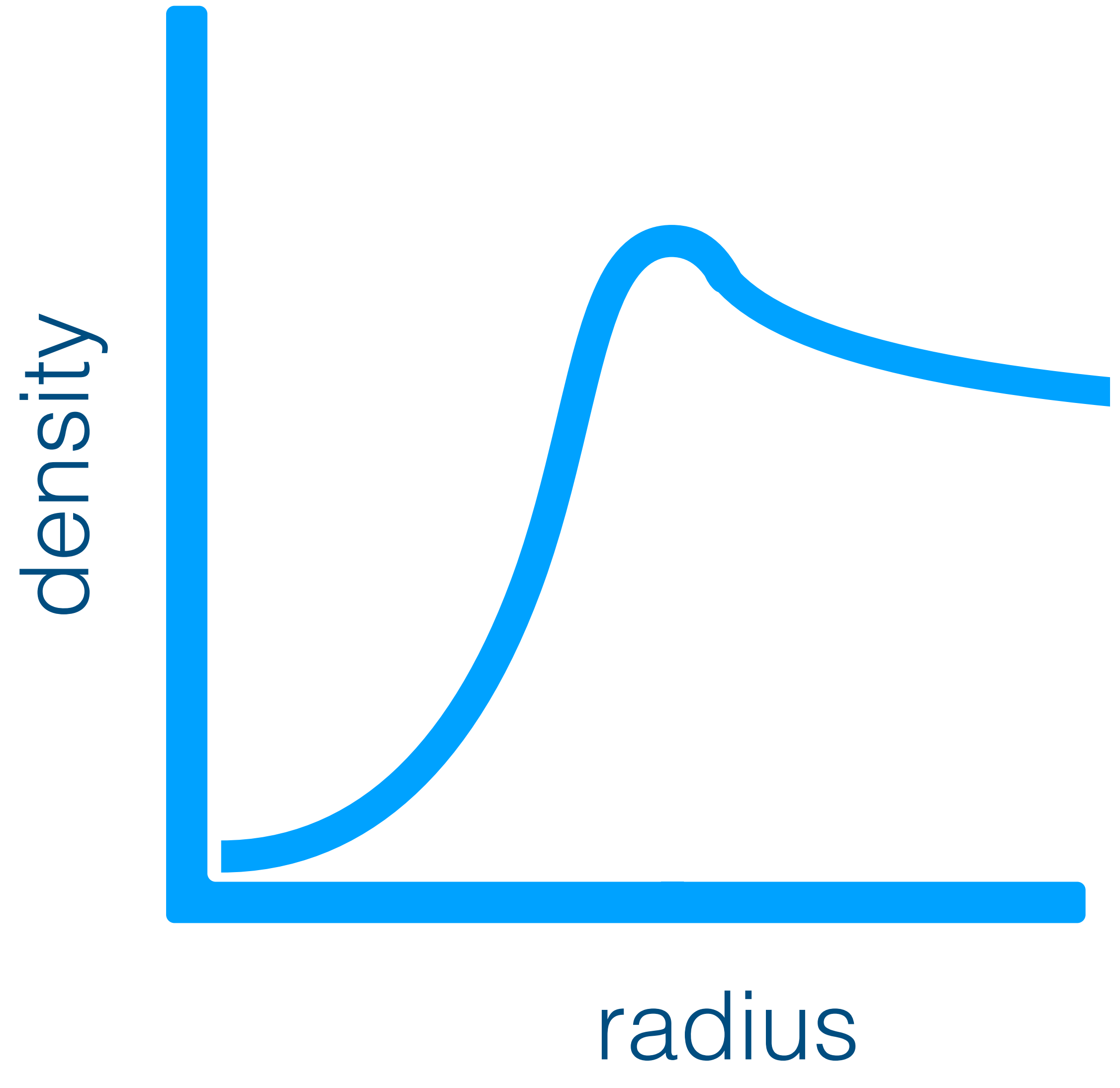
Void's shape is not regular on a one-to-one basis!

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

Wang, Pisani, Villaescusa-Navarro and Wandelt 2023, ApJ 955 131, Arxiv: 2212.06860

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

The *observed* void-galaxy cross-correlation function ξ_{vg}



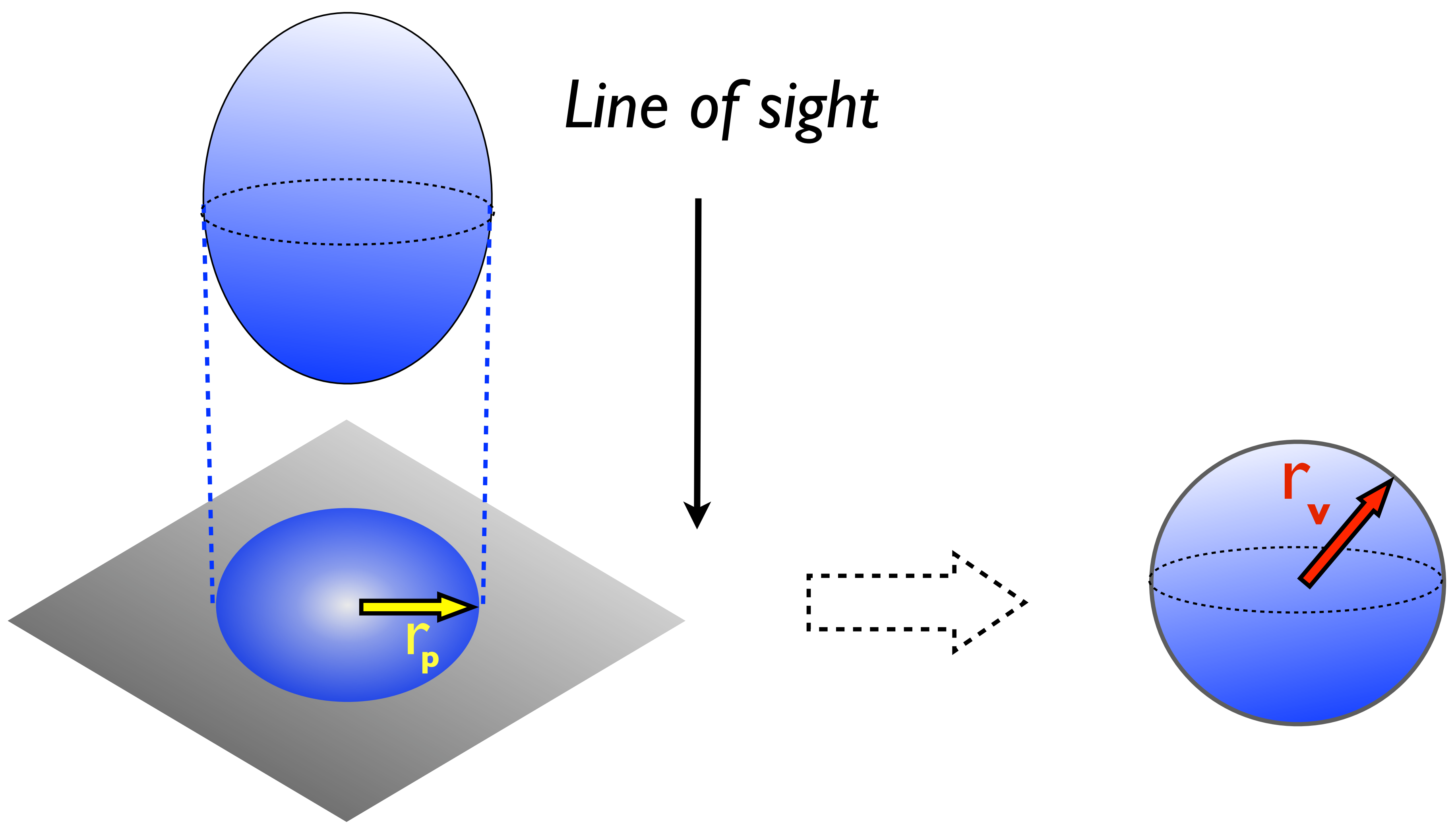
But… we observe voids in redshift space!

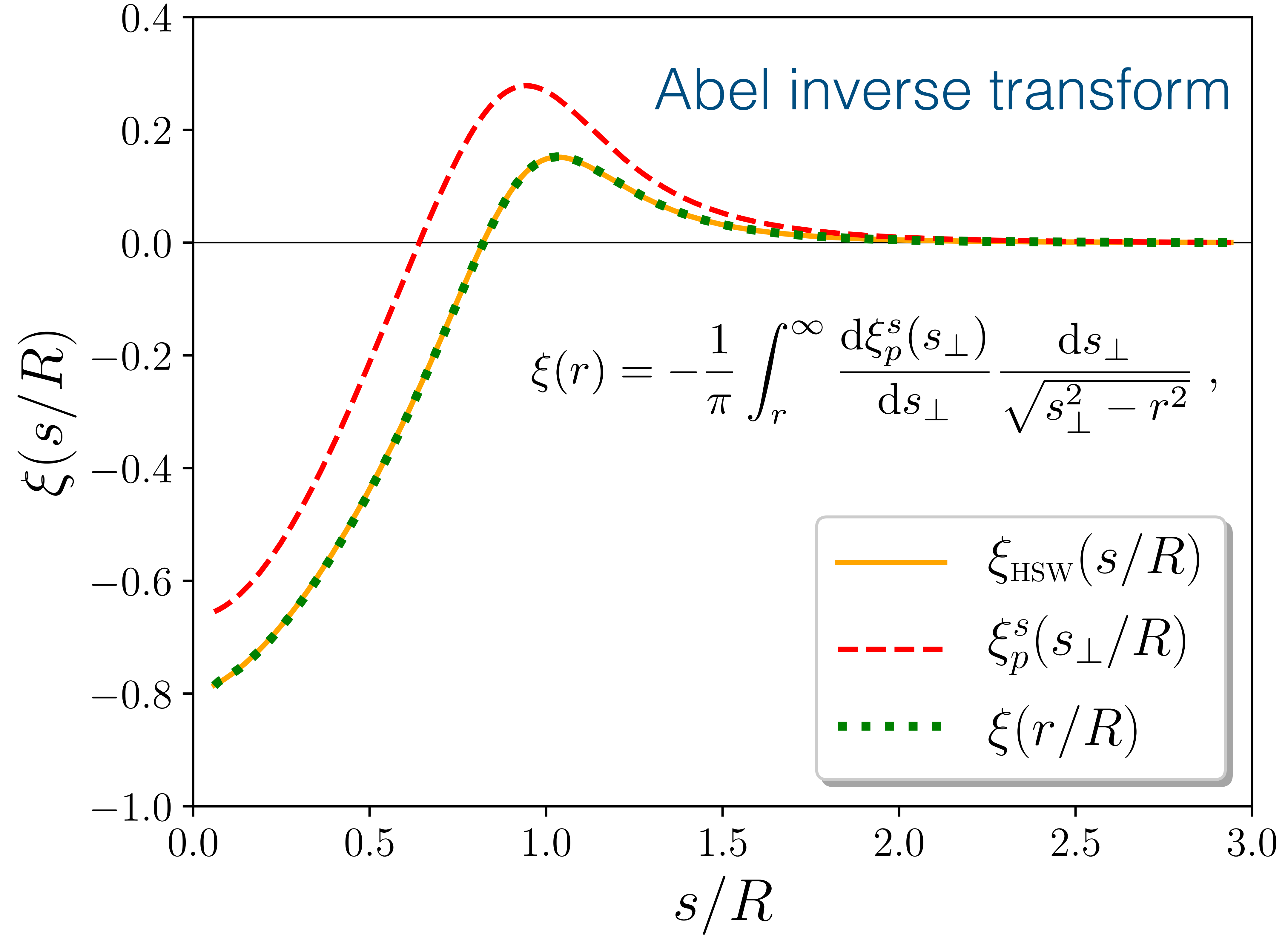
Our model needs many ingredients:

- Density profile modeling
- Alcock-Paczynski (AP) distortions
- Redshift space distortion modeling

The *observed* void-galaxy cross-correlation function $\xi_{\rm vg}$

Models the profile from data



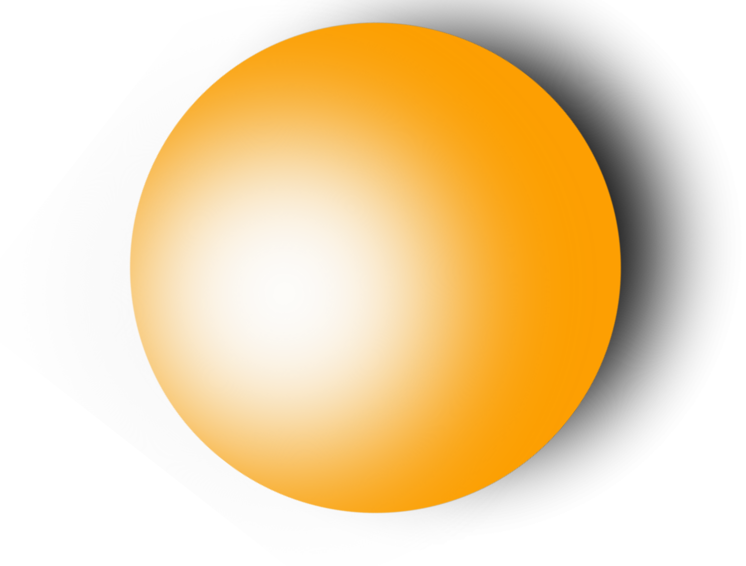


Other prescriptions model the profile from simulations(fit).
Caveat: introduces simulation bias!

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

The *observed* void-galaxy cross-correlation function ξ_{vg}

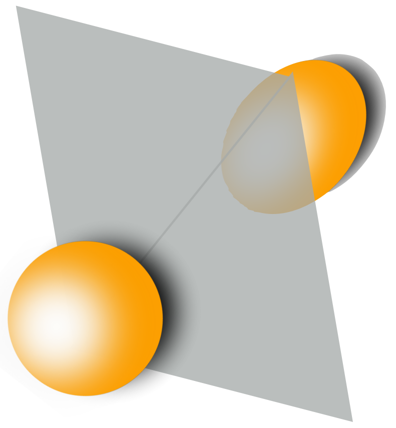
1. Stacked void density profile in real space



Pisani, Lavaux, Sutter, Wandelt 2014; ArXiv: 1306.3052 MNRAS

+

2. Alcock-Paczynski (AP) distortions: Relationship between measured quantities and physical sizes



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

AP test $r_{\perp} = r_{\parallel}$

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

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

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

$$\varepsilon = 1$$

+

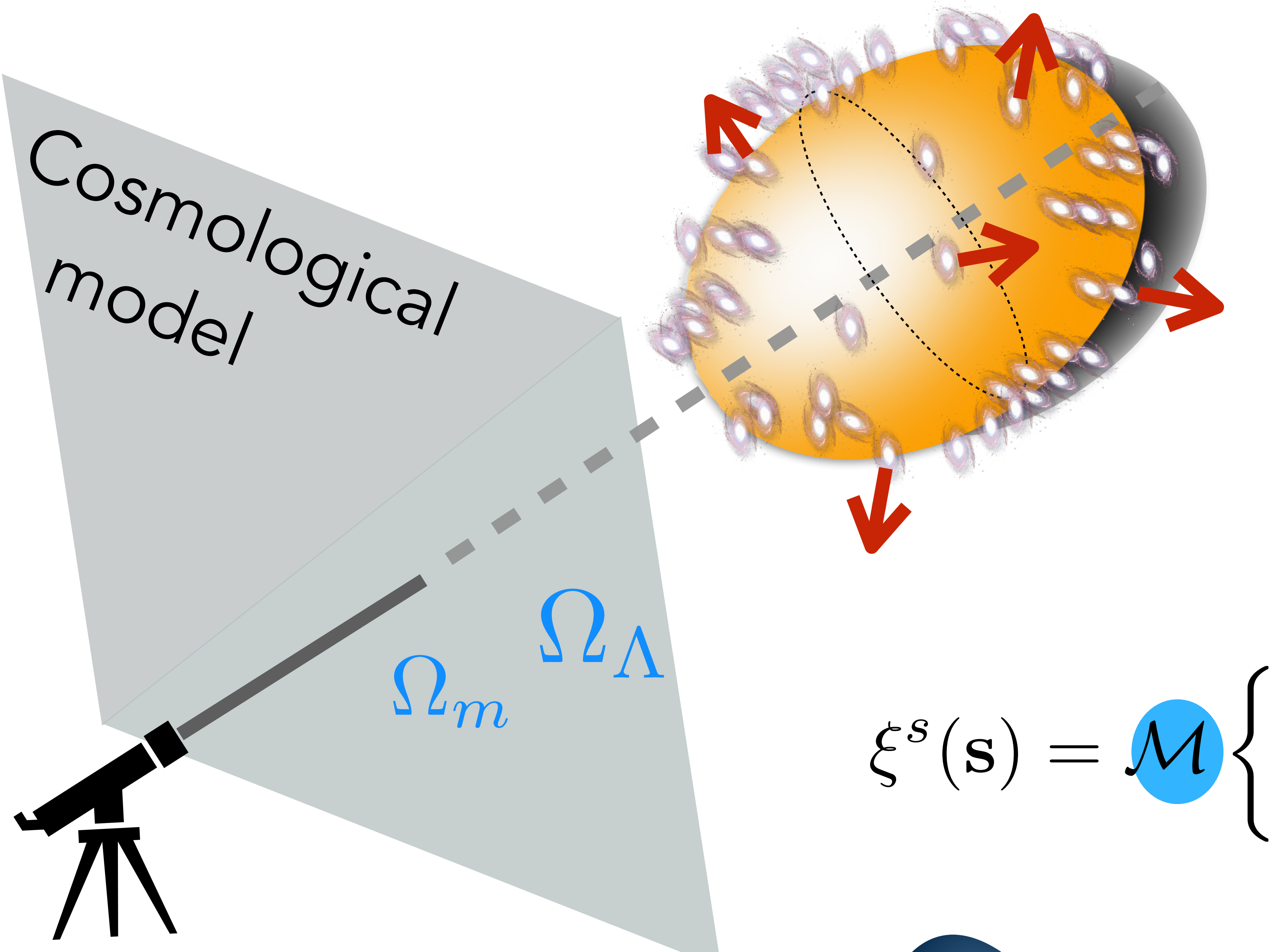
3. Redshift-space distortions (RSD) modeling due to galaxies peculiar velocities

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

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

Peebles (1980)
Schuster et al. 2022; ArXiv:2210.02457

= Void stack in redshift space

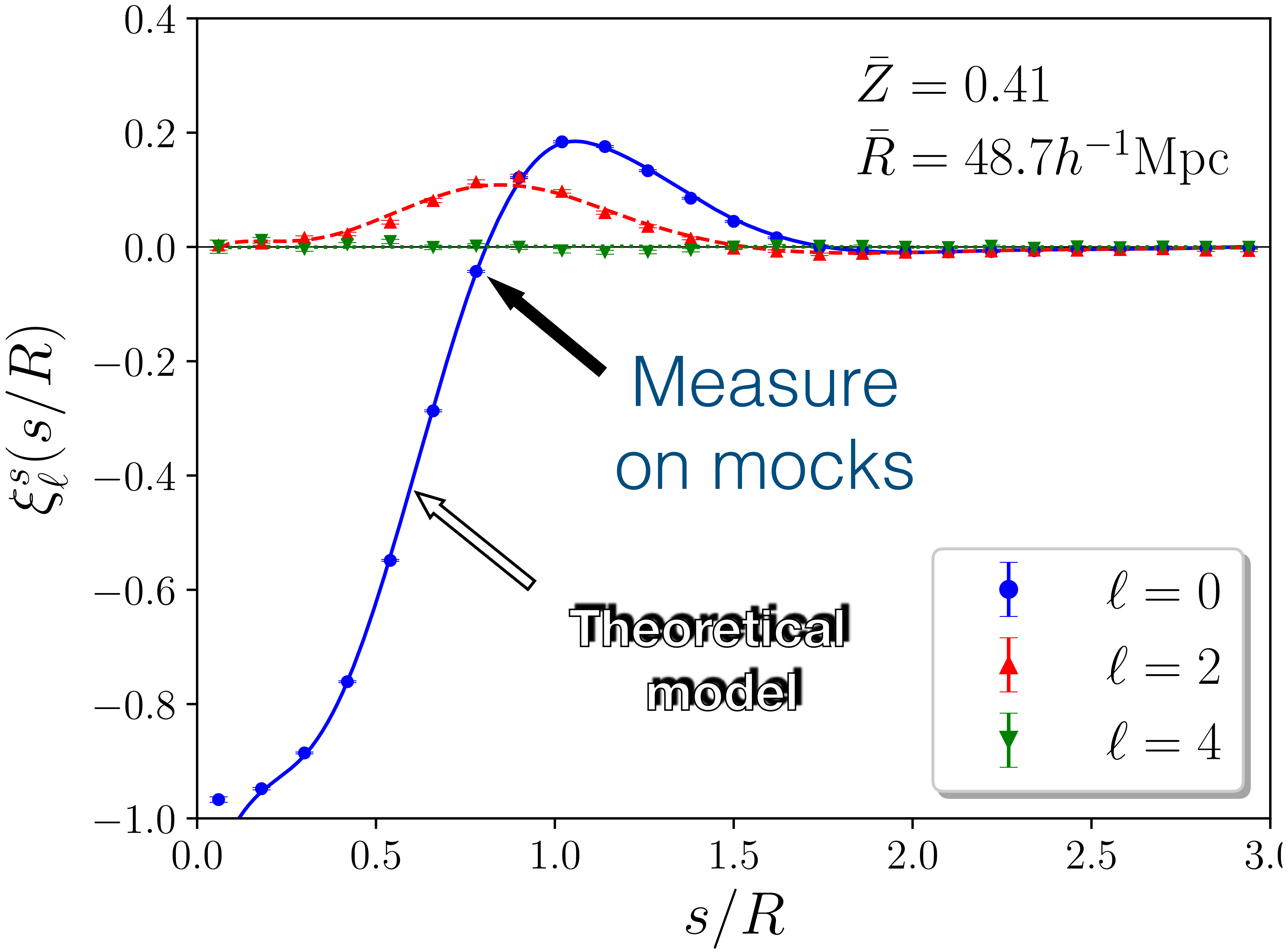


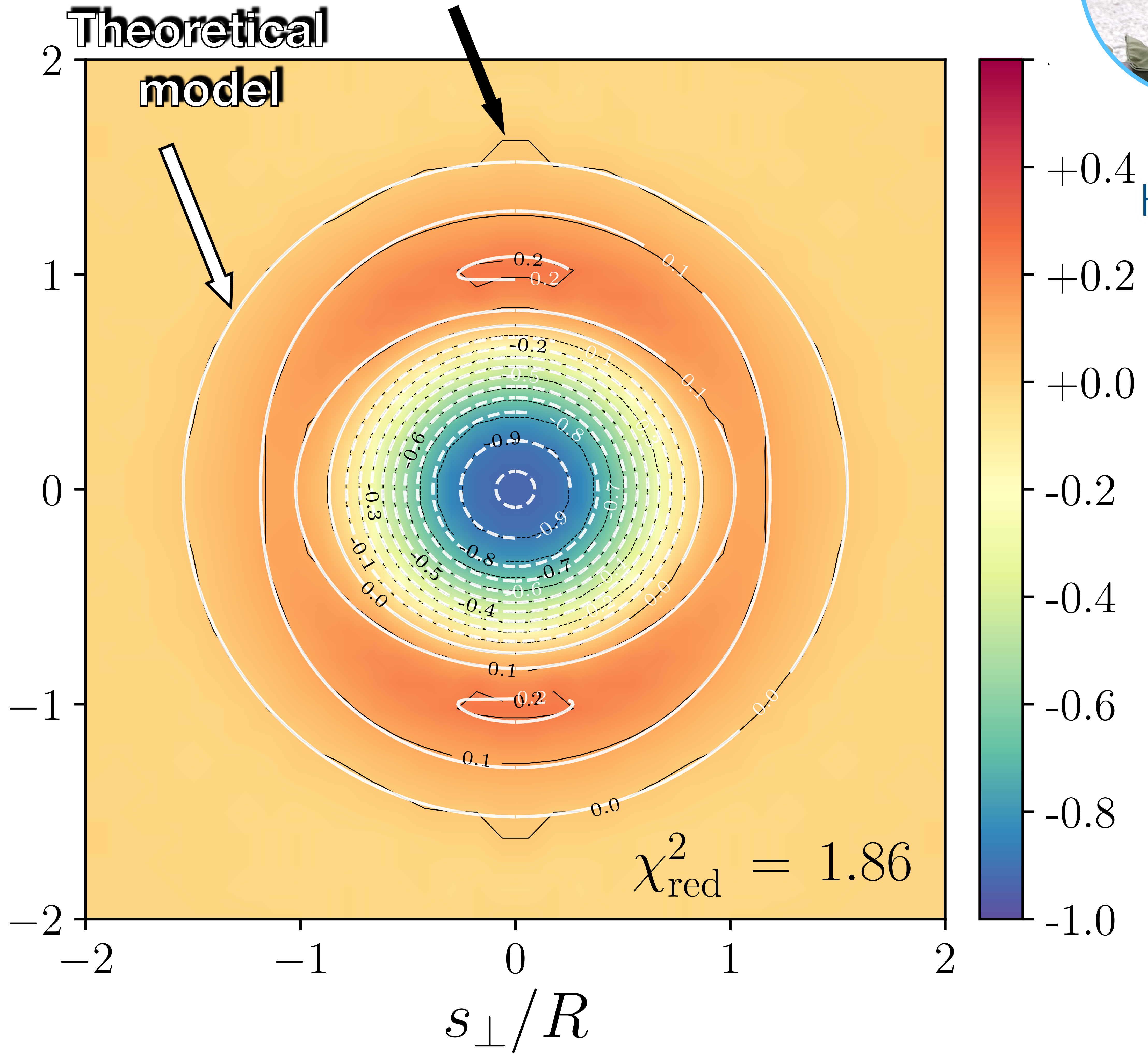
$$\xi^s(\mathbf{s}) = \mathcal{M}\left\{\xi(r) + \frac{1}{3}\frac{f}{b}\bar{\xi}(r) + \frac{f}{b}\mathcal{Q}\mu_r^2\left[\xi(r) - \bar{\xi}(r)\right]\right\}$$

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

The *observed* void-galaxy cross-correlation function ξ_{vg}

Tested on mocks

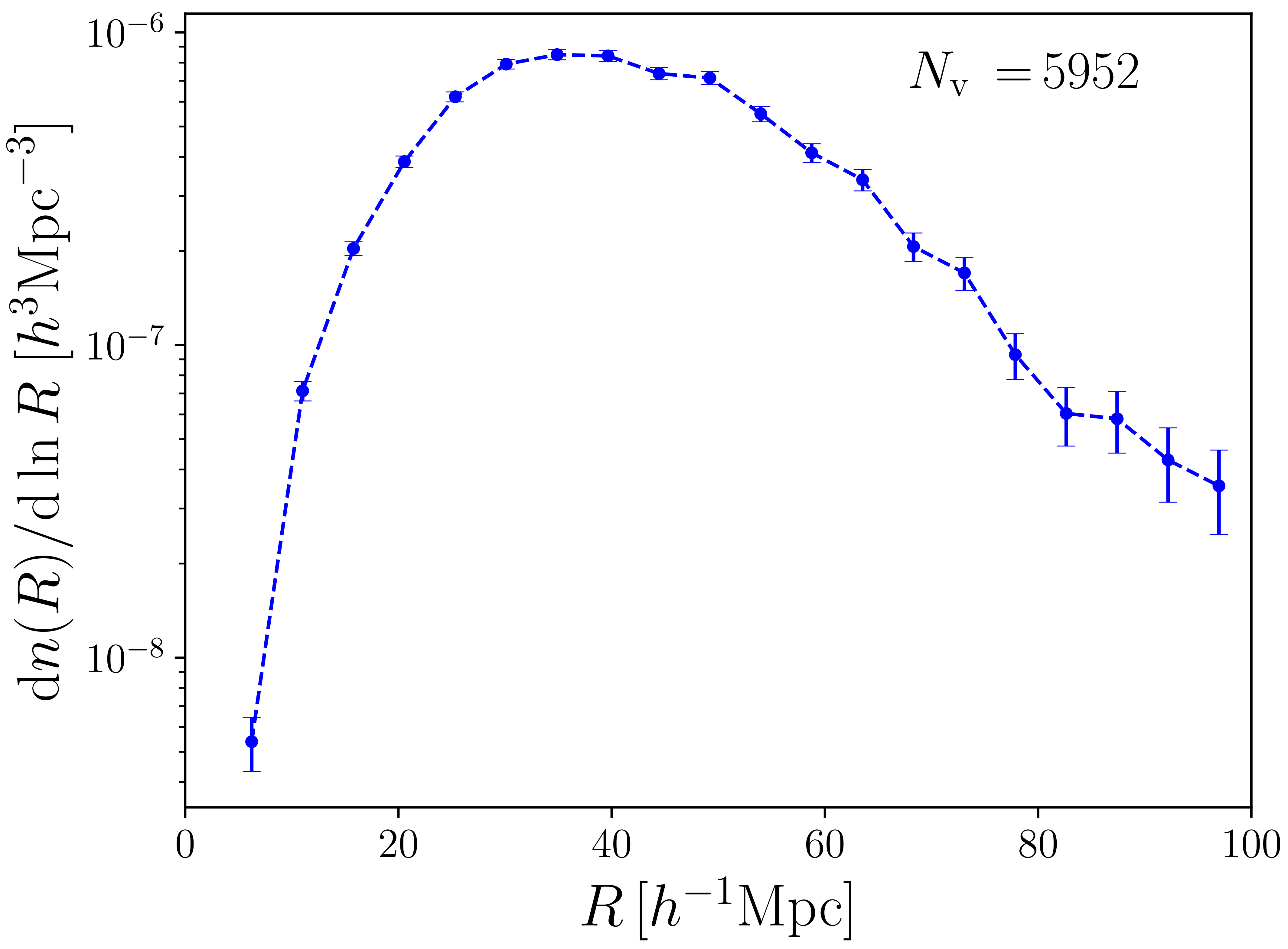


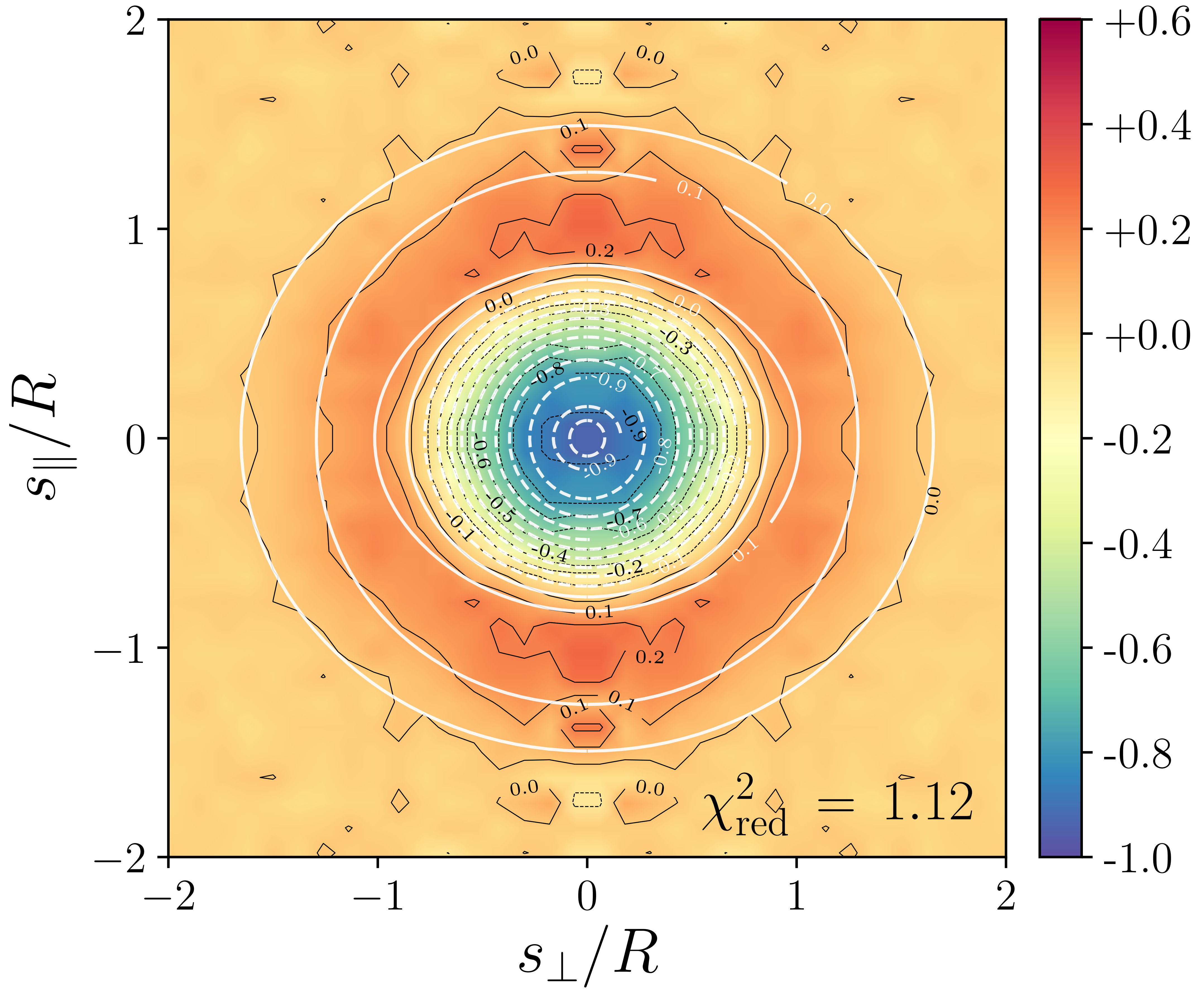


Nico Hamaus

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

The *observed* void-galaxy cross-correlation function ξ_{vg}





Nico Hamaus

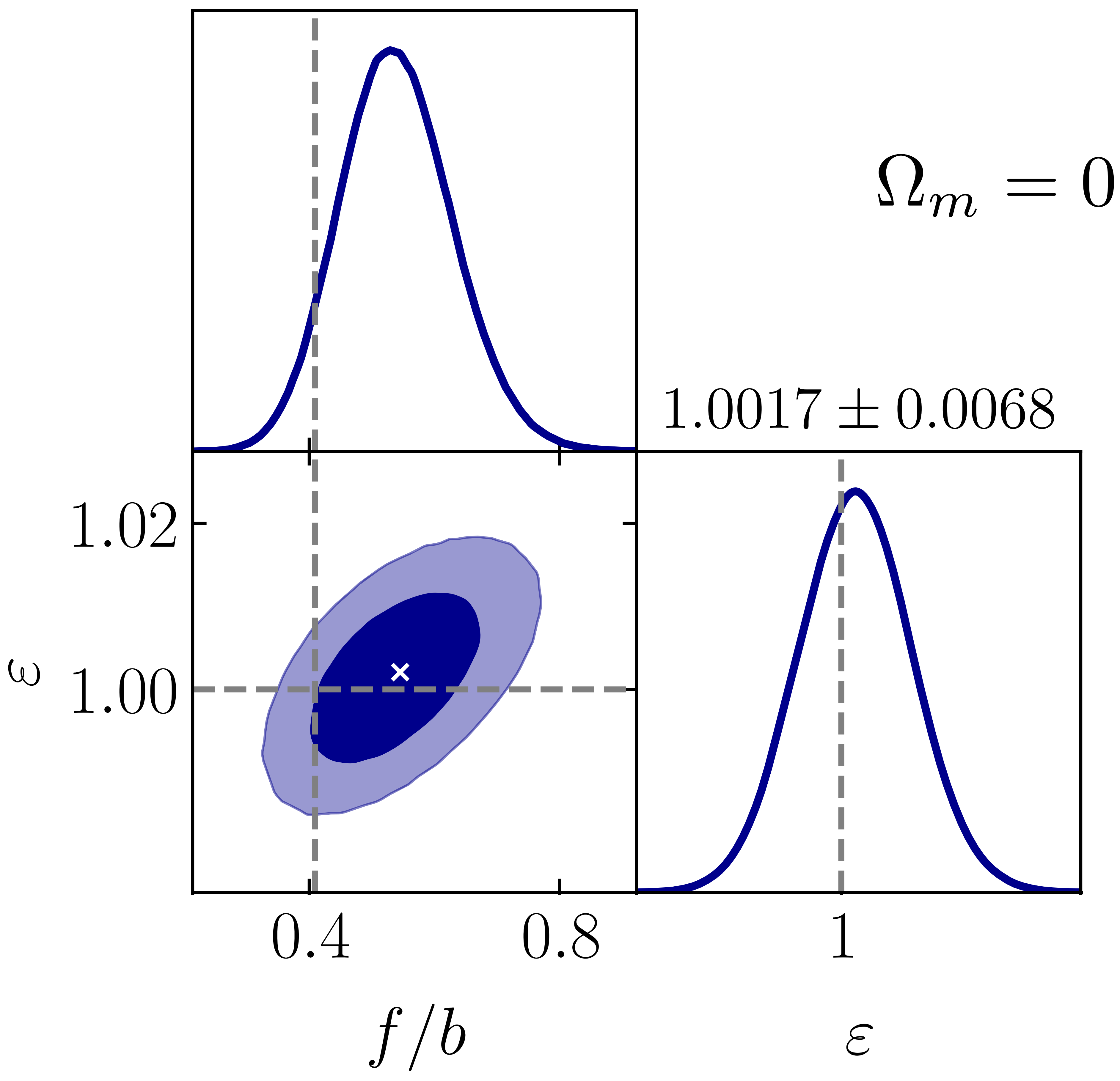
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP

The *observed* void-galaxy cross-correlation function $\xi_{\rm vg}$

Nico Hamaus

Results

$$\beta = \frac{f}{b} \qquad \varepsilon = \frac{[D_A(z)H(z)]_{\rm meas}}{[D_A(z)H(z)]_{\rm fid}}$$



$$\Omega_m = 0.312 \pm 0.020$$

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

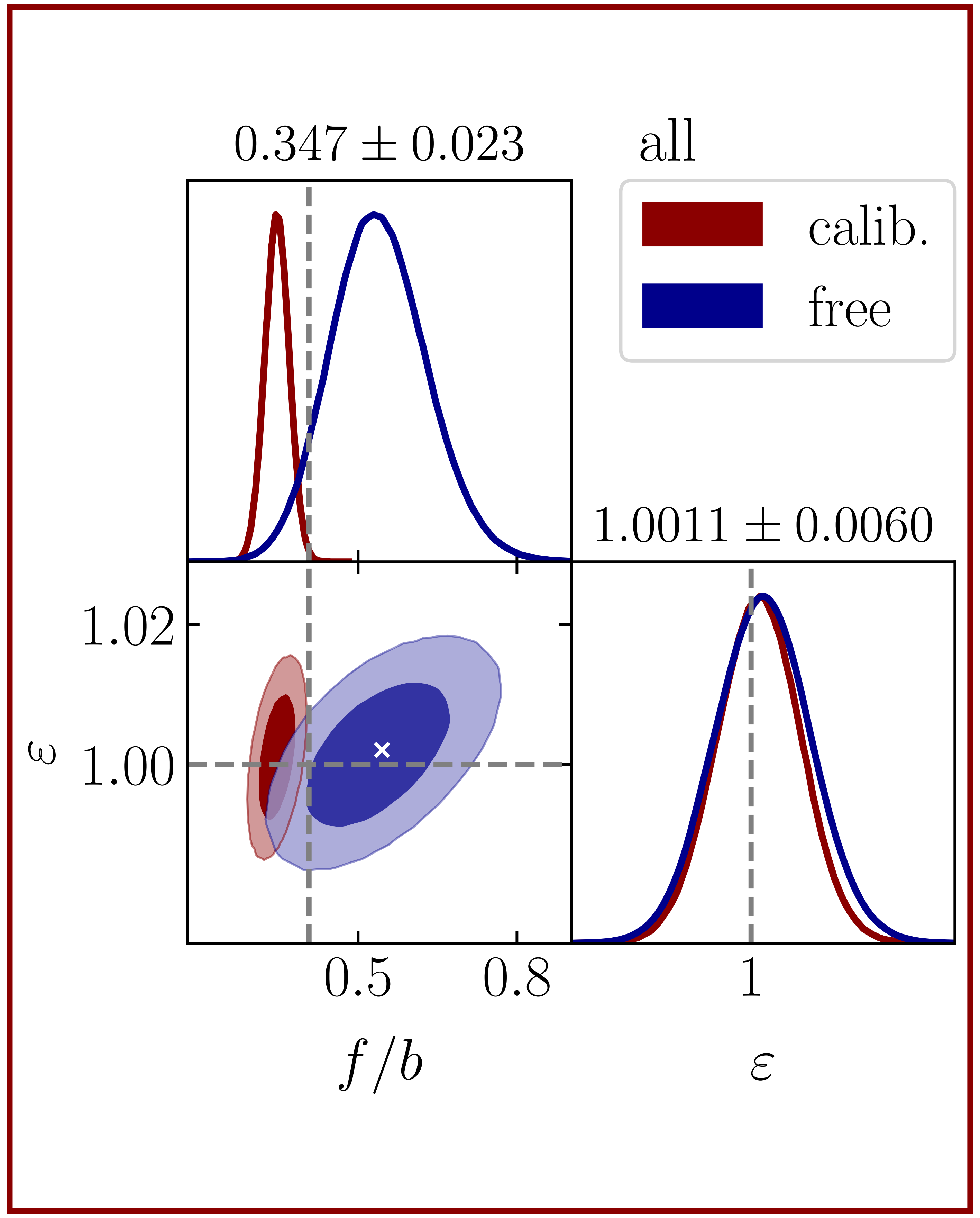
The *observed* void-galaxy cross-correlation function

Two nuisance parameters:

Amplitude { monopole, quadrupole

Precision

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



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

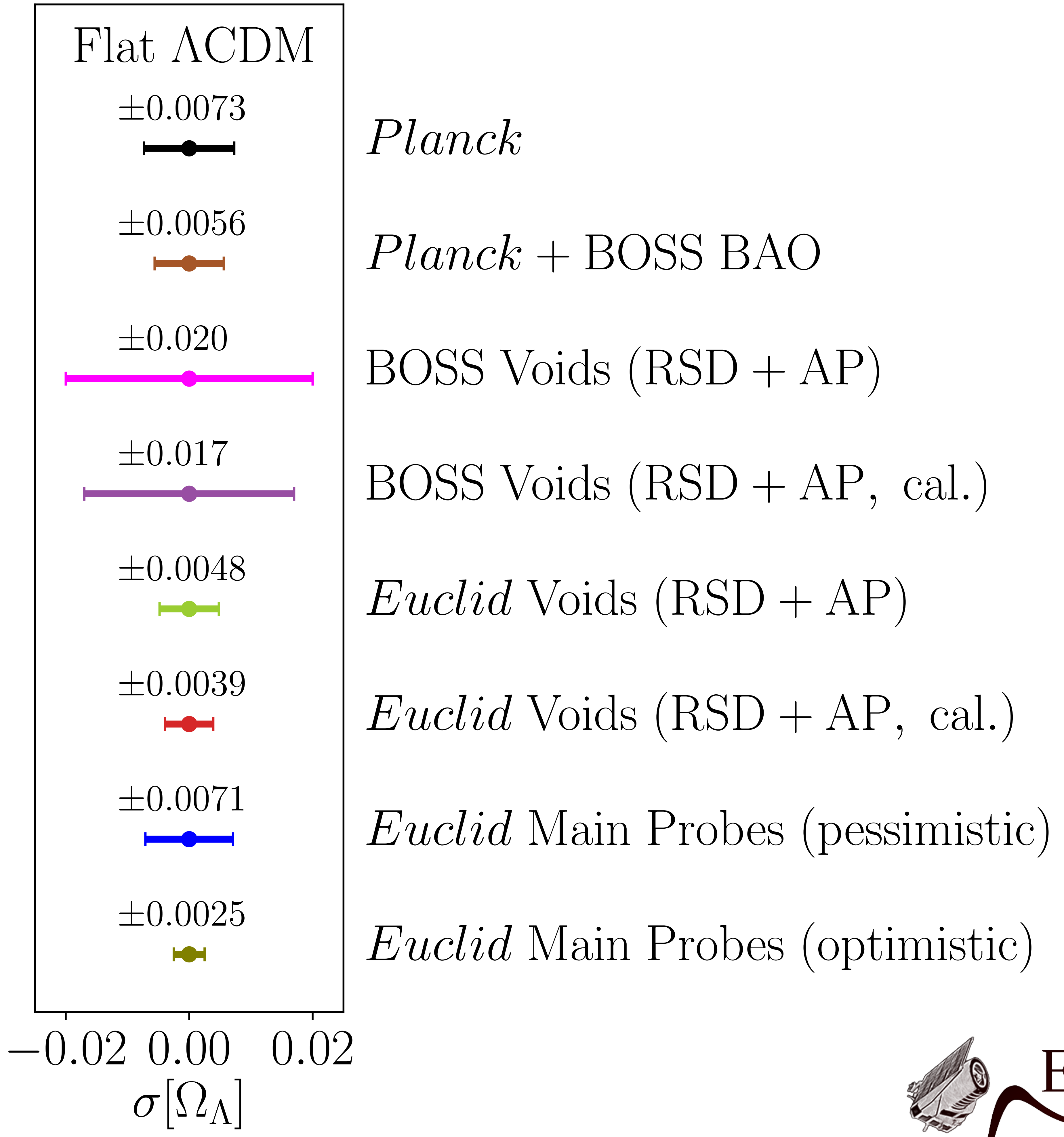
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP

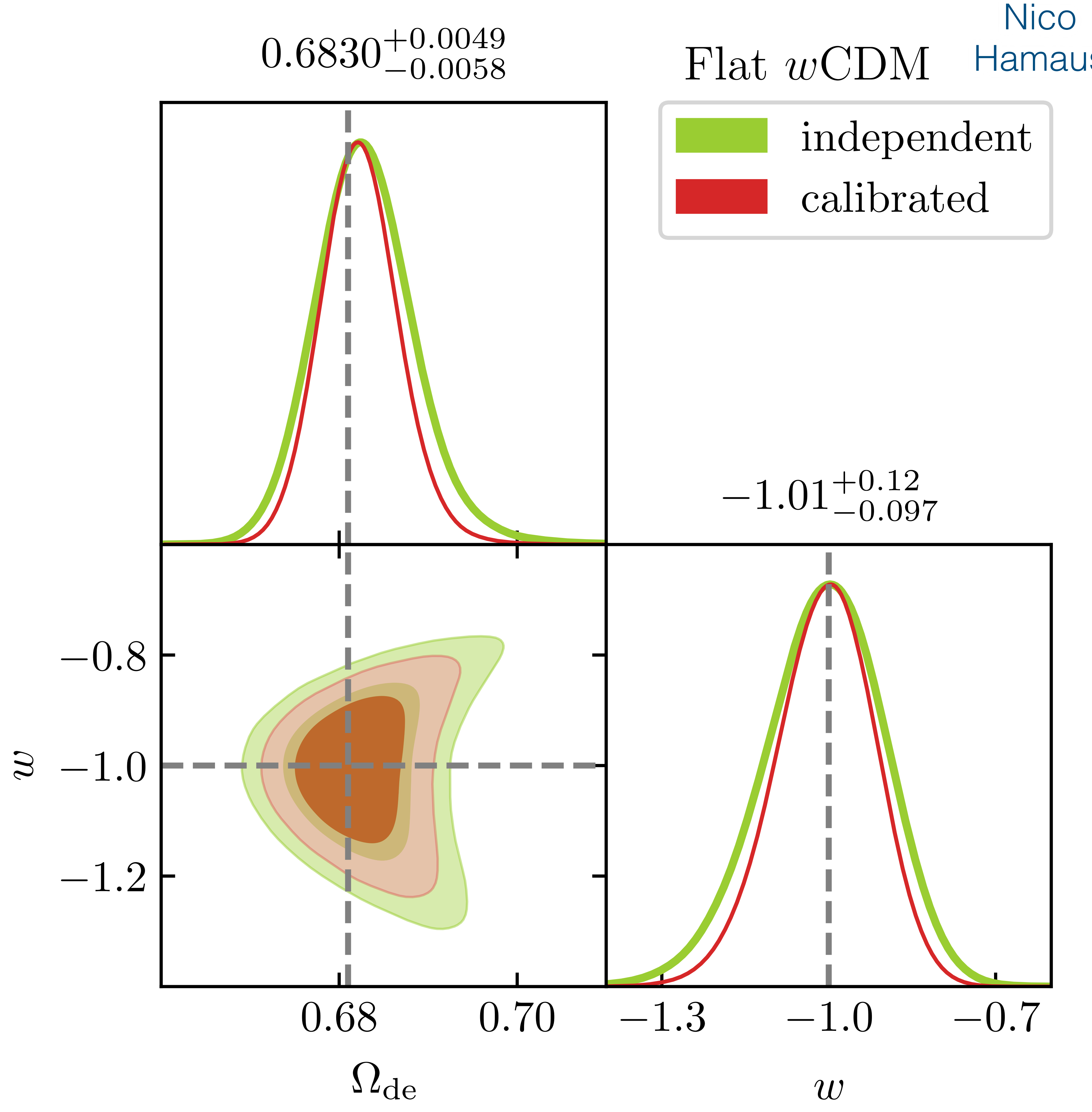
The *observed* void-galaxy cross-correlation function ξ_{vg}

How will it perform with future surveys?

Nico Hamaus

Marie Aubert





Hamaus, Aubert, Pisani et al.
2022 Euclid collaboration paper
ArXiv: 2108.10347 A&A

The *observed* void-galaxy cross-correlation function ξ_{vg}

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

Moresco et al. 2022, Living Reviews in Relativity; ArXiv: 2201.07241

Hamaus, Aubert, Pisani et al. 2022 Euclid collaboration paper ArXiv: 2108.10347 A&A

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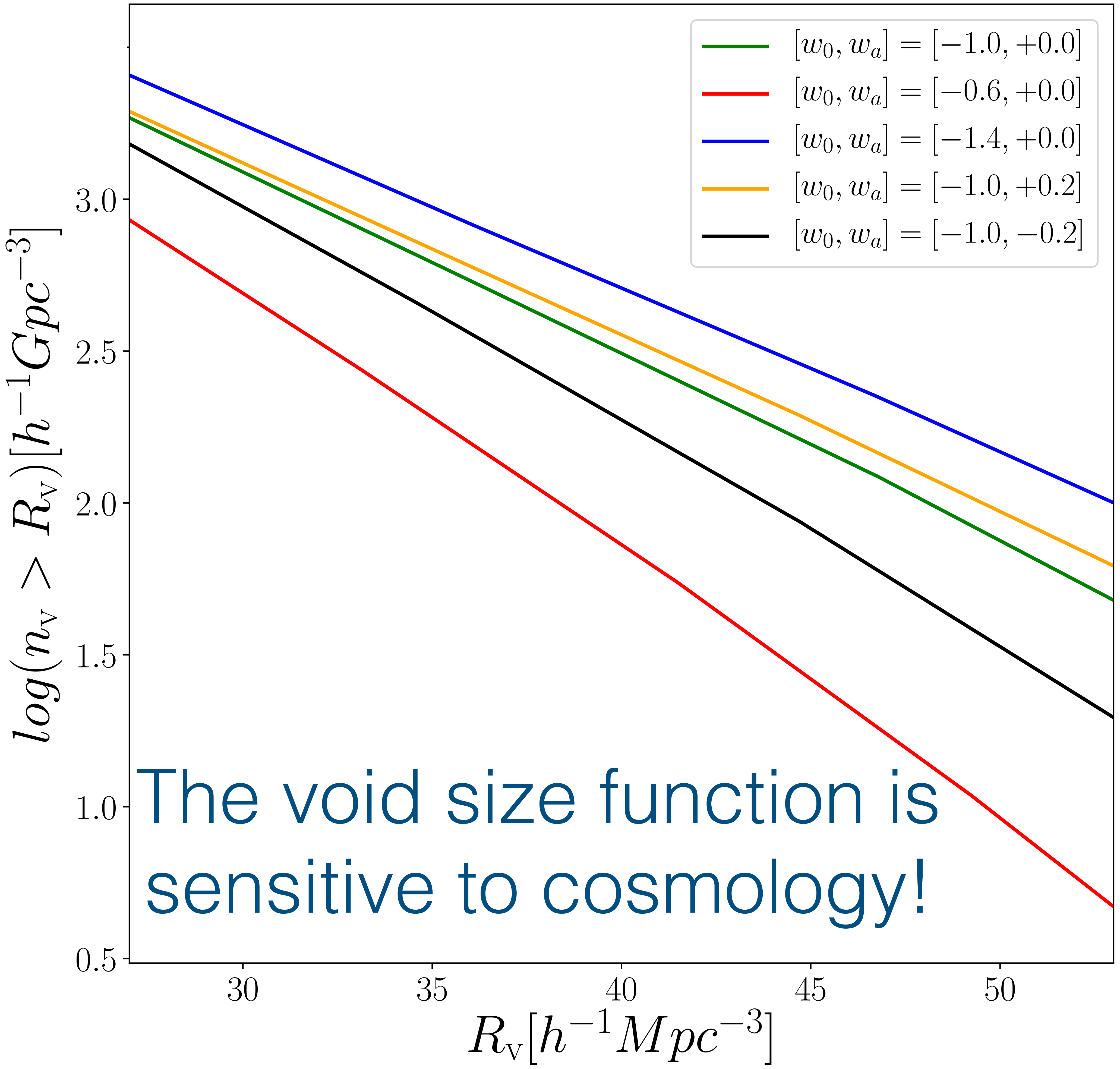
The void size function

An excursion set model to predict void numbers.

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



The void size function is sensitive to cosmology!

Sheth and van de Weygaert 2004; Arxiv: 0311260
Jennings, Li & Hu ArXiv: 1304.6087 MNRAS; DM

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

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

The void size function

Predicts void numbers as spherical non-overlapping regions embedding a fixed density contrast in the biased tracer field.

$$\left.\frac{\mathrm{d}n}{\mathrm{d}\ln r}\right|_{\mathrm{lin}} = \frac{f_{\ln\sigma}(\sigma)}{V(r)}\frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}\ln r}$$

$$f_{\ln\sigma} = 2\sum_{j=1}^{\infty}\exp\left(-\frac{(j\pi x)^2}{2}\right) j\pi x^2\,\sin(j\pi\mathcal{D})$$

Multiplicity function (volume fraction of the Universe by cosmic voids)

$$\mathcal{D} = \frac{|\delta_{\mathrm{v}}^{\mathrm{L}}|}{\delta_{\mathrm{c}}^{\mathrm{L}} + |\delta_{\mathrm{v}}^{\mathrm{L}}|}\,, \qquad x = \frac{\mathcal{D}}{|\delta_{\mathrm{v}}^{\mathrm{L}}|}\sigma(r)\,,$$

Density contrasts for the formation of dark matter halos and cosmic voids

$\sigma(r)$ Root mean square variance of linear matter perturbations

$$\left.\frac{\mathrm{d}n}{\mathrm{d}\ln r}\right|_{\mathrm{Vdn}} = \left.\frac{\mathrm{d}n}{\mathrm{d}\ln r}\right|_{\mathrm{lin}}\frac{V(r^{\mathrm{L}})}{V(r)}\frac{\mathrm{d}\ln r^{L}}{\mathrm{d}\ln r}$$

Vdn model

$$\delta^{\mathrm{NL}}_{\mathrm{v,DM}} = \frac{\delta^{\mathrm{NL}}_{\mathrm{v,tr}}}{\mathcal{F}(b_{\mathrm{eff}}, z)}\,, \quad \text{with}$$

$$\mathcal{F}(b_{\mathrm{eff}}, z) = B_{\mathrm{slope}}\, b_{\mathrm{eff}}(z) + B_{\mathrm{offset}}$$

Large scale effective bias

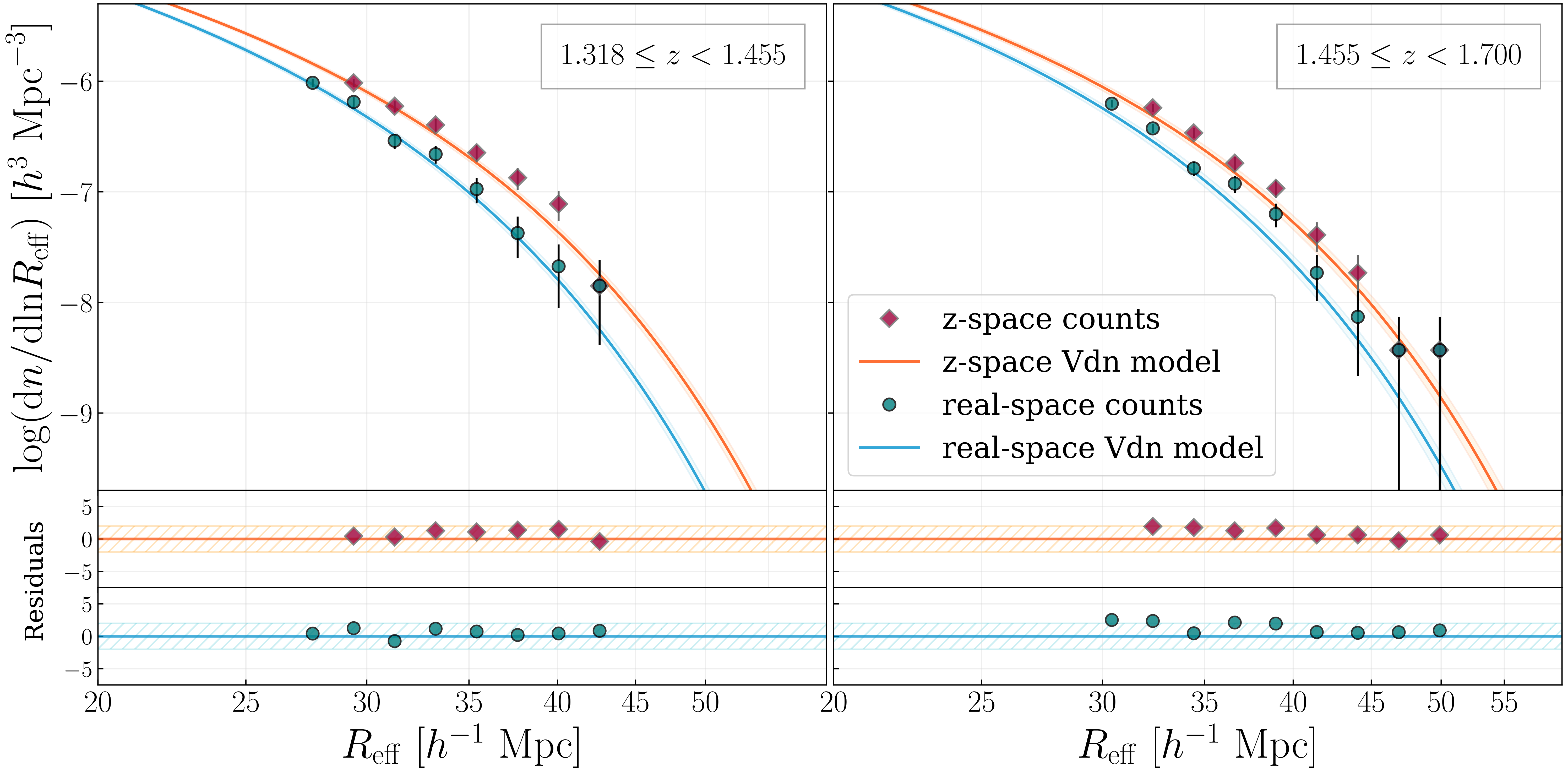
Sheth and van de Weygaert 2004; Arxiv: 0311260
Jennings, Li & Hu ArXiv: 1304.6087 MNRAS; DM
Pollina, Hamaus et al. ArXiv: 1806.06860 MNRAS

Contarini, Ronconi, Marulli, Moscardini, Veropalumbo, Baldi ArXiv: 1904.01022 MNRAS

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

Contarini, Marulli, Moscardini, Veropalumbo, Giocoli, Baldi ArXiv: 2009.03309 MNRAS

The void size function



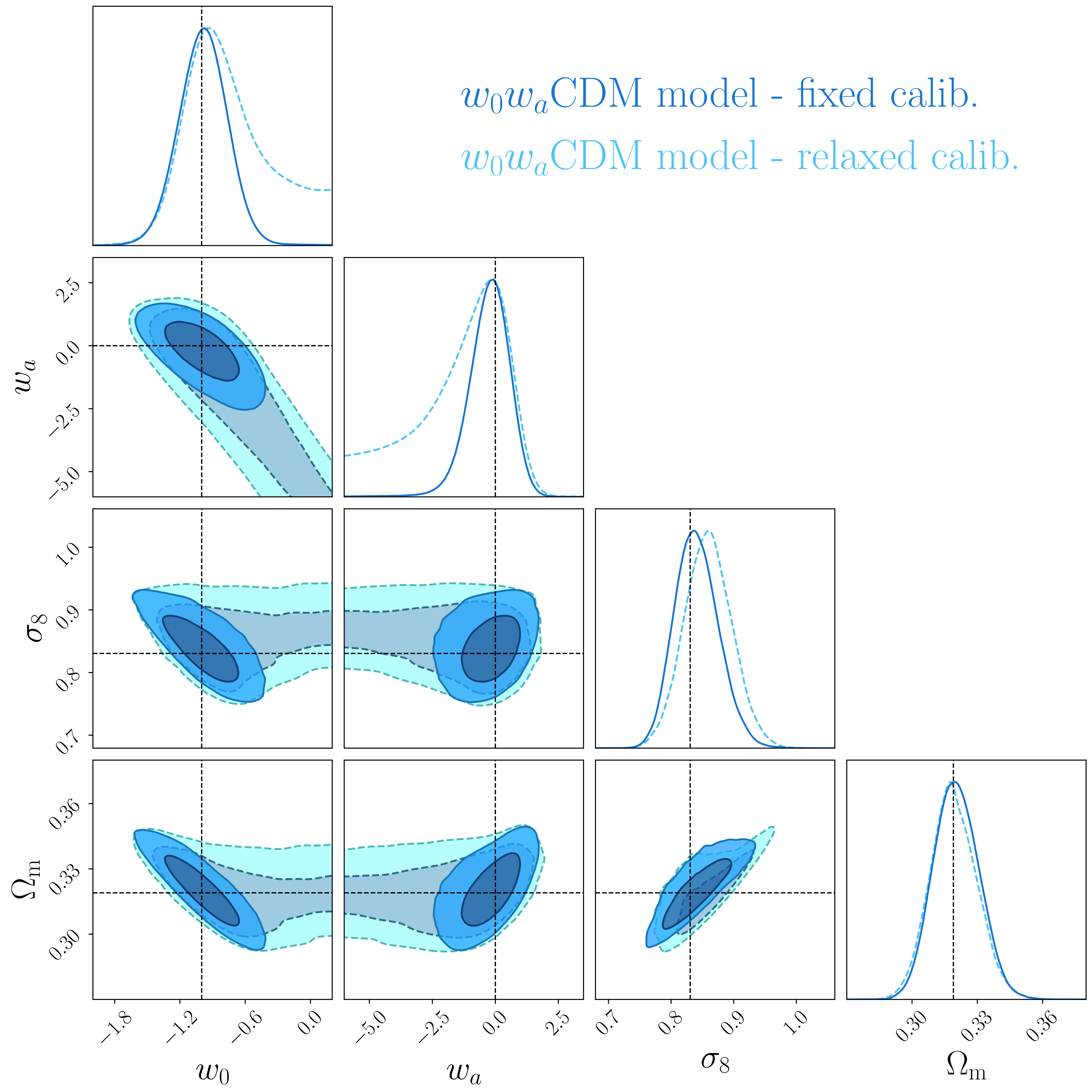
Sofia Contarini

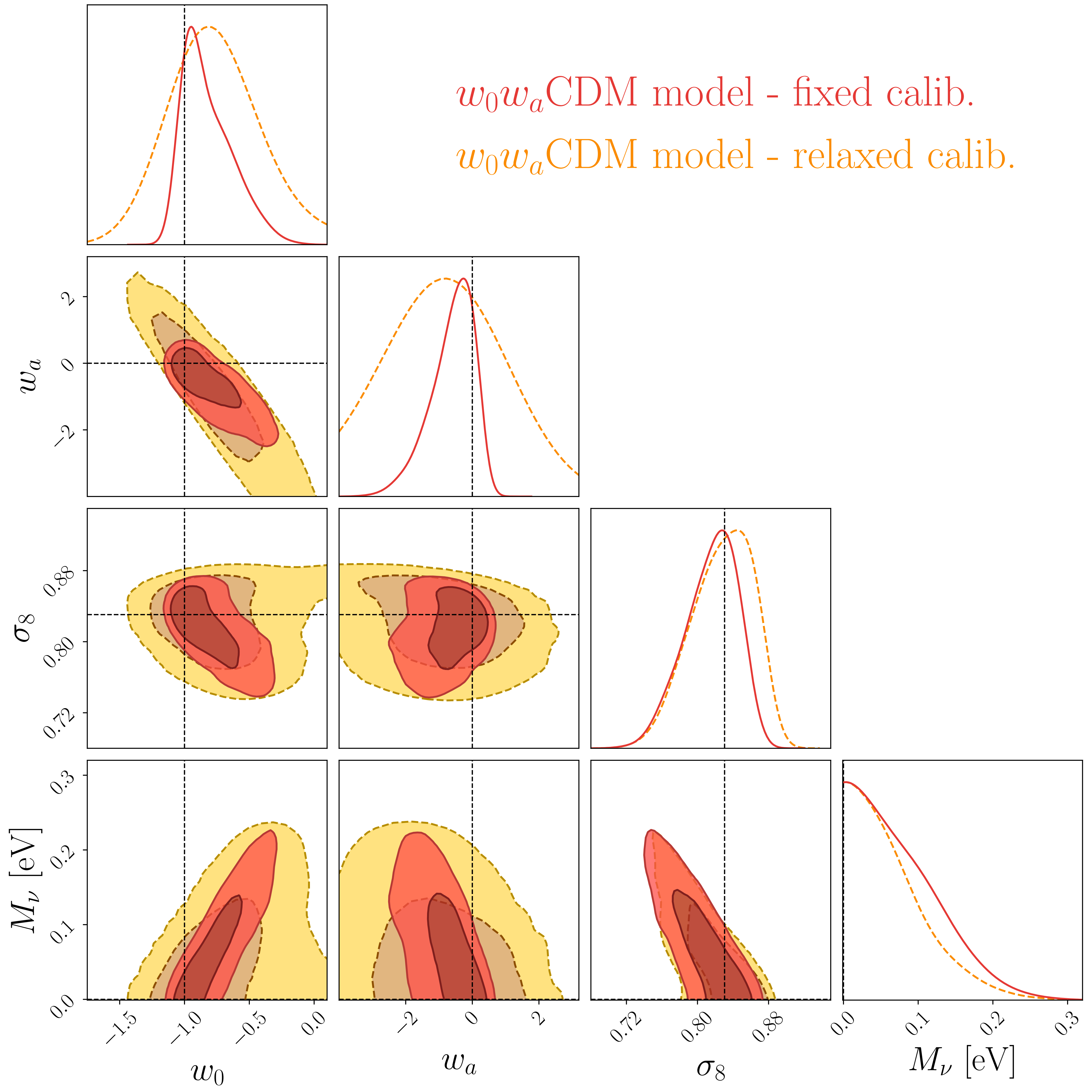
Giovanni Verza

Contarini, Verza, Pisani et al.
2022 Euclid collaboration paper
A&A, ArXiv: 2205.11525

Euclid Voids

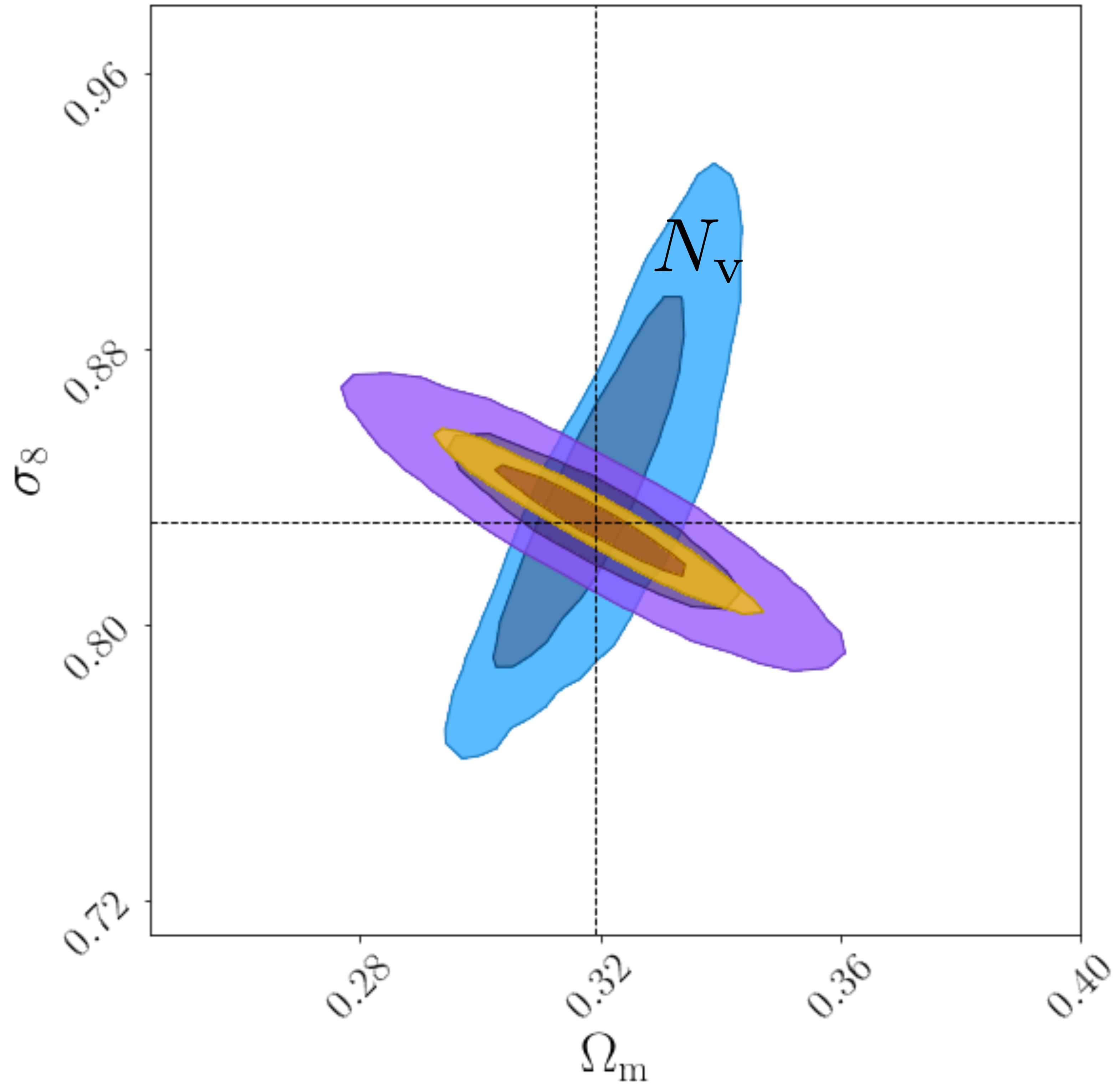
The void size function: Euclid forecasted constraints

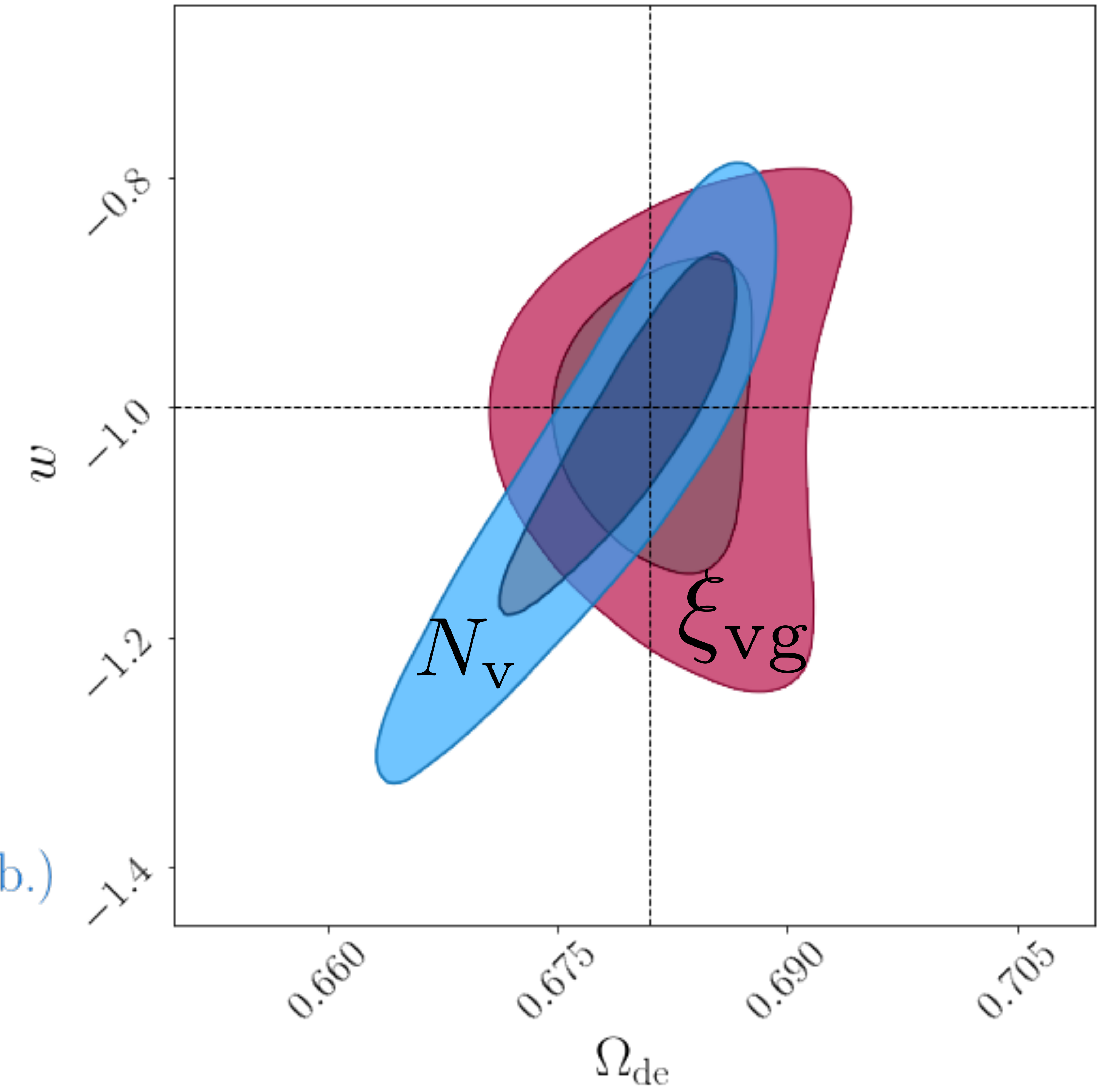




Contarini, Verza, Pisani et al.
2022 Euclid collaboration paper
A&A, ArXiv: 2205.11525

The void size function: forecasted constraints *combined*





Contarini, Verza, Pisani et al.
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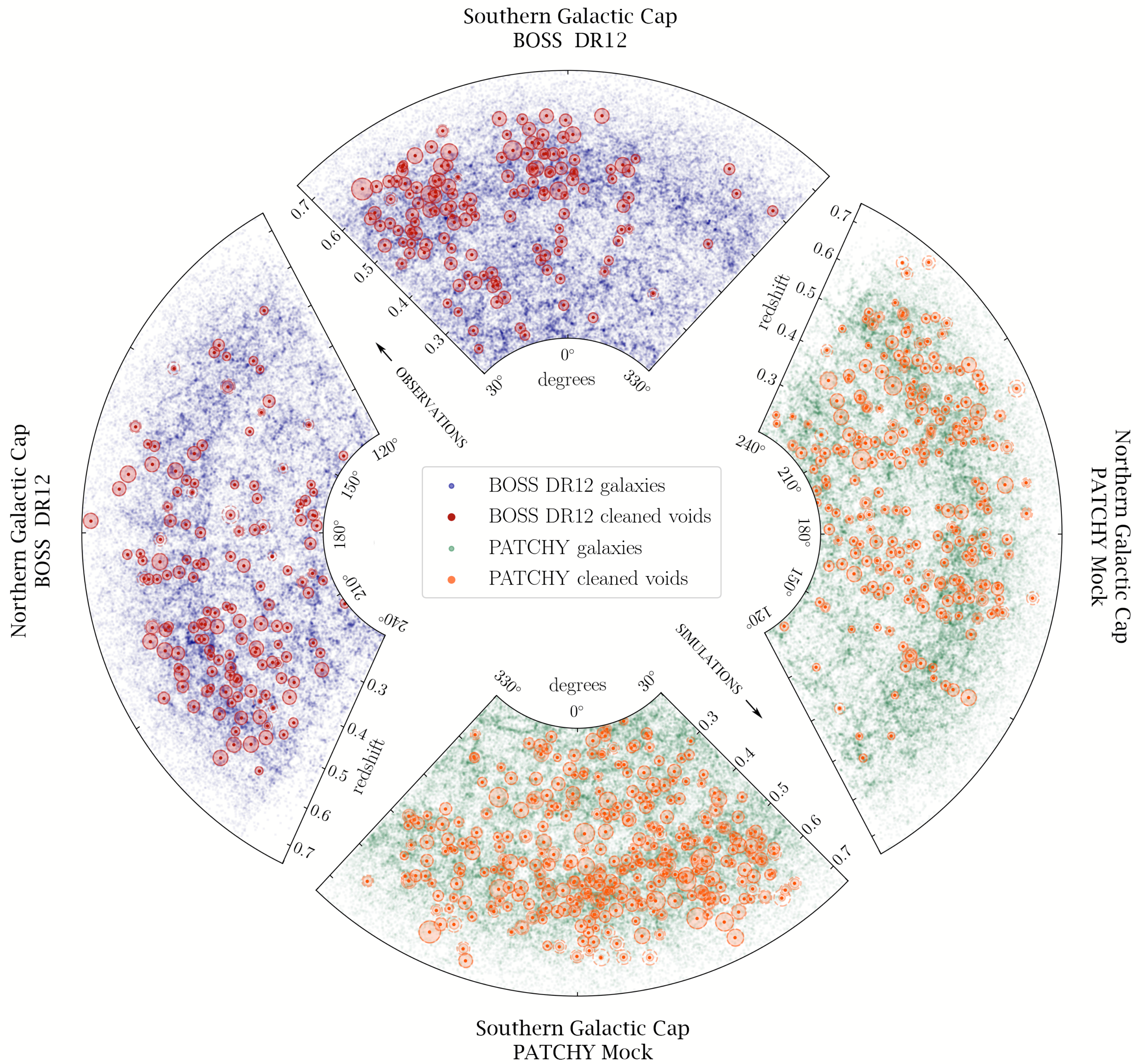
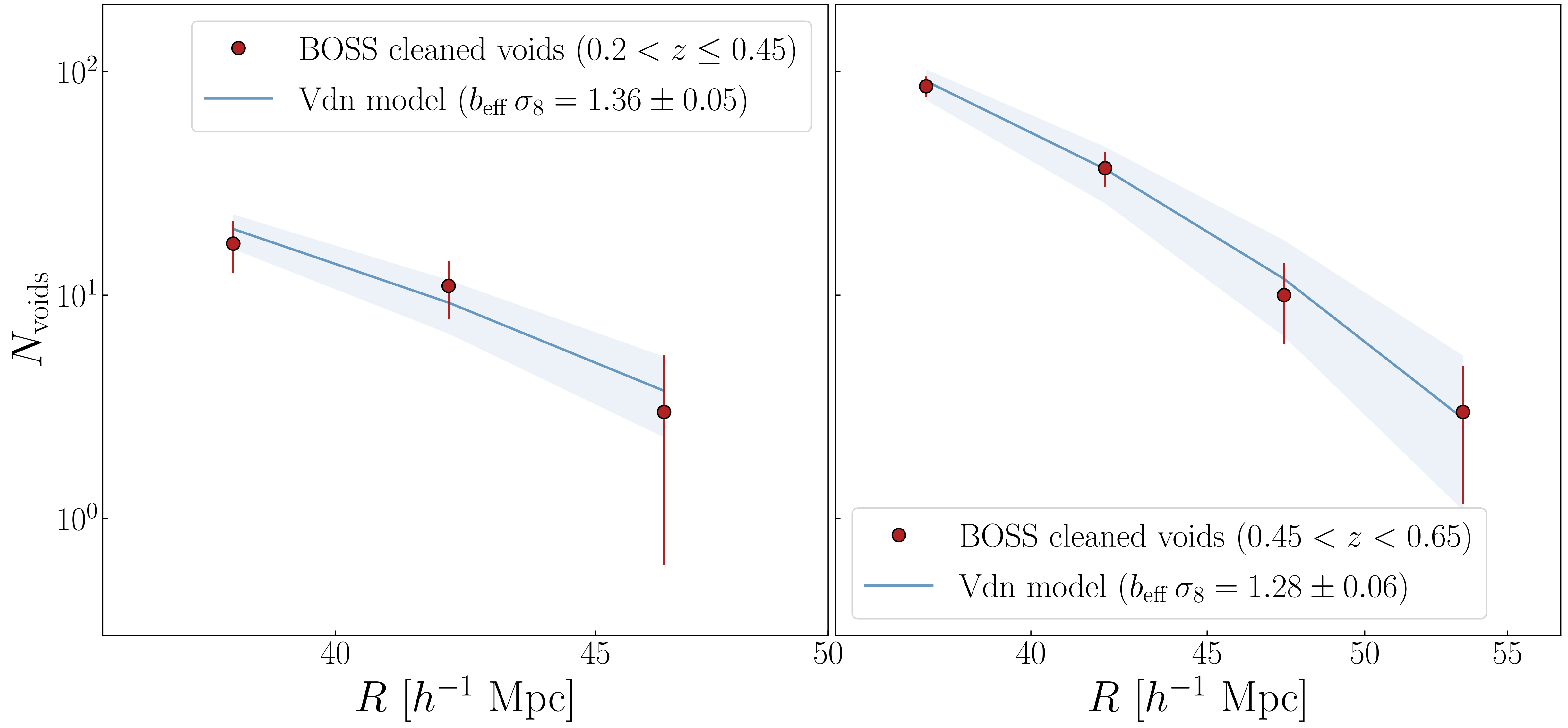
A&A, ArXiv: 2205.11525

The void size function: first data application

Sofia
Contarini





$$\left.\frac{\mathrm{d}n}{\mathrm{d}\ln r}\right|_{\mathrm{Vdn}} = \left.\frac{\mathrm{d}n}{\mathrm{d}\ln r}\right|_{\mathrm{lin}} \frac{V(r^{\mathrm{L}})}{V(r)} \frac{\mathrm{d}\ln r^{L}}{\mathrm{d}\ln r}$$

Sheth and van de Weygaert 2004; Arxiv: 0311260
Jennings, Li & Hu ArXiv: 1304.6087 MNRAS; DM

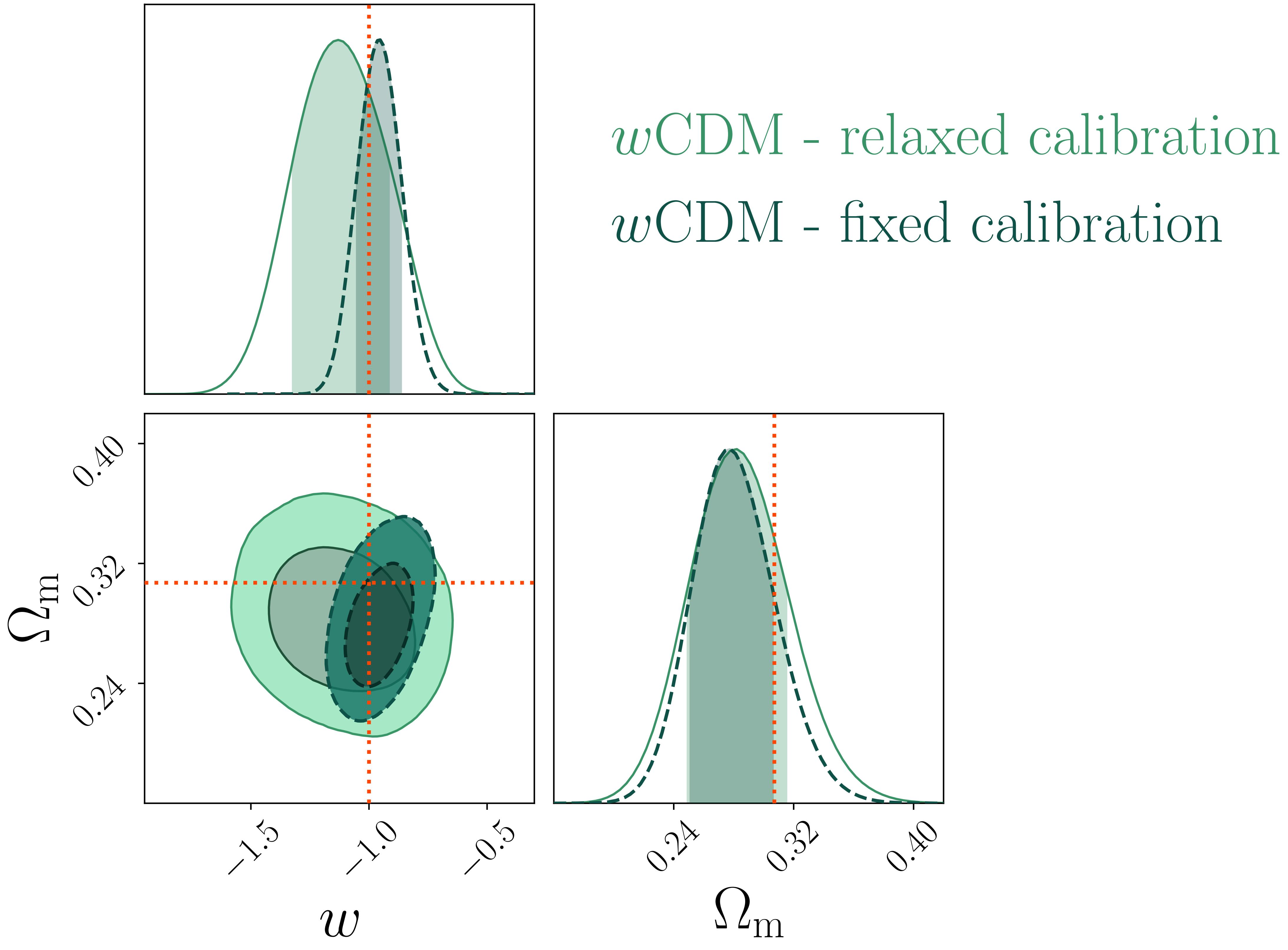
Contarini, Pisani, Hamaus et al. 2022a ArXiv: 2212.03873 JCAP

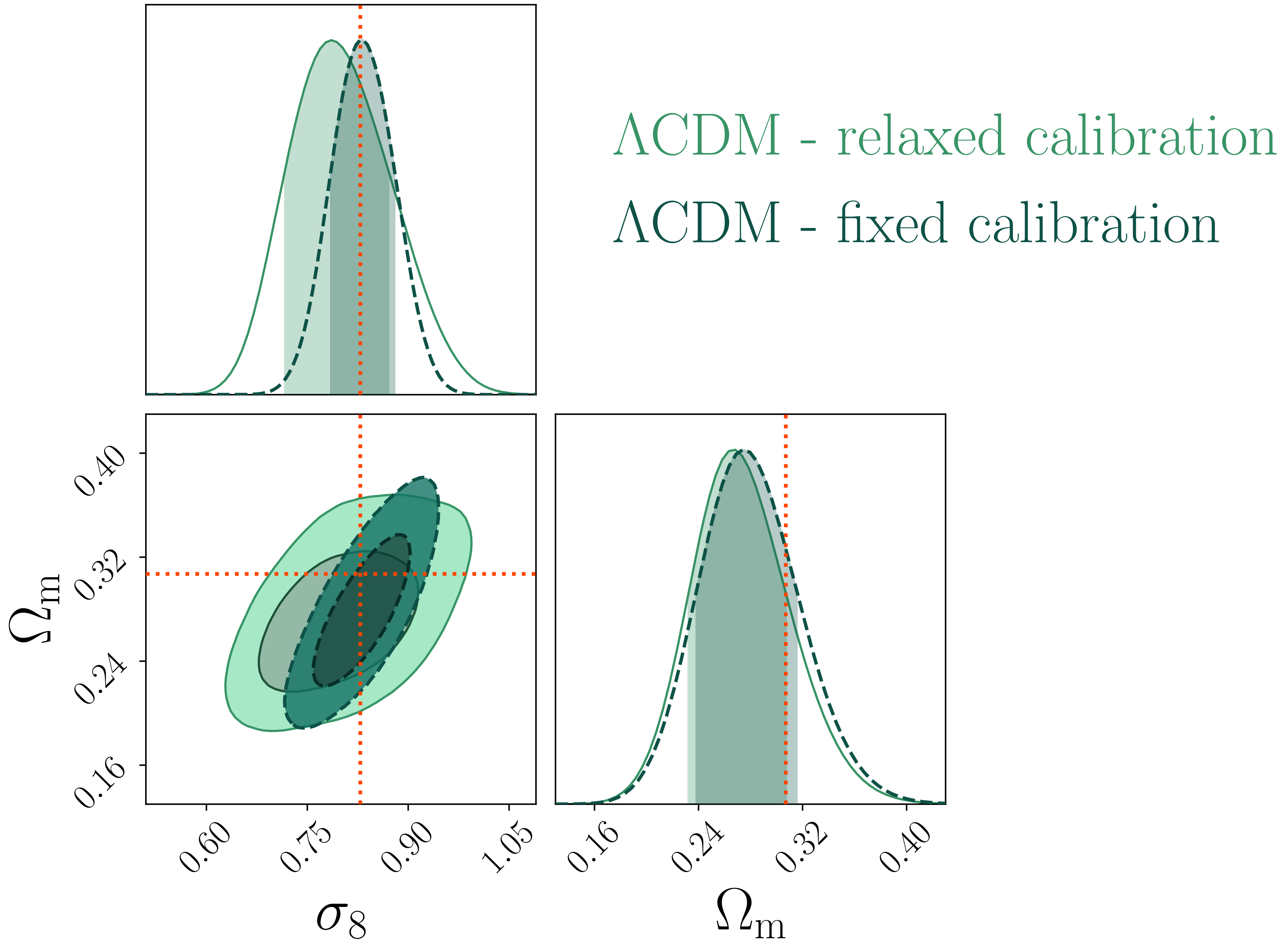
$$\delta^{\mathrm{NL}}_{\mathrm{v,DM}} = \frac{\delta^{\mathrm{NL}}_{\mathrm{v,tr}}}{\mathcal{F}(b_{\mathrm{eff}}, z)}, \text{ with}$$

$$\mathcal{F}(b_{\mathrm{eff}}, z) = B_{\mathrm{slope}}\, b_{\mathrm{eff}}(z) + B_{\mathrm{offset}}$$

Large scale effective bias

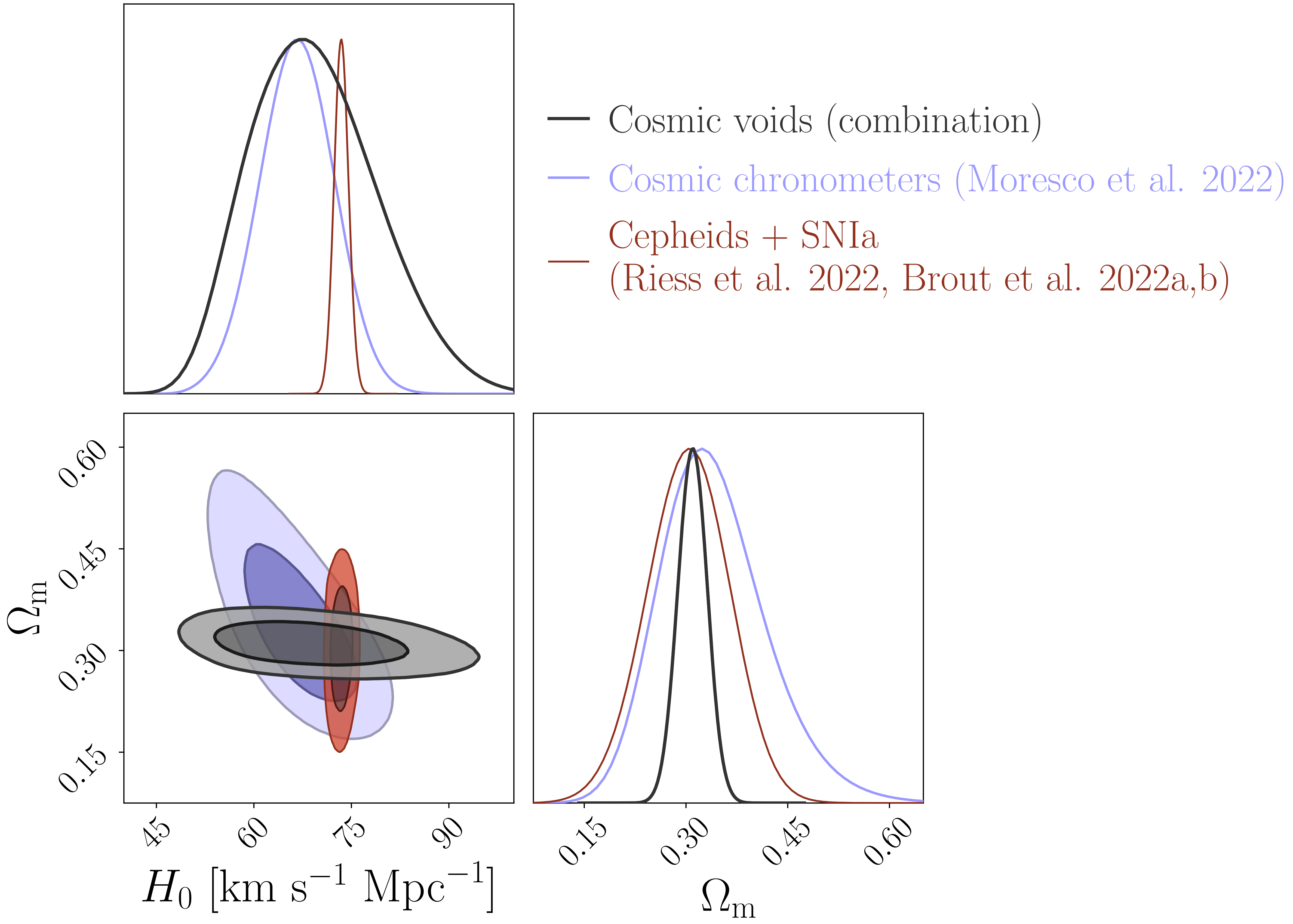
The void size function: first data application

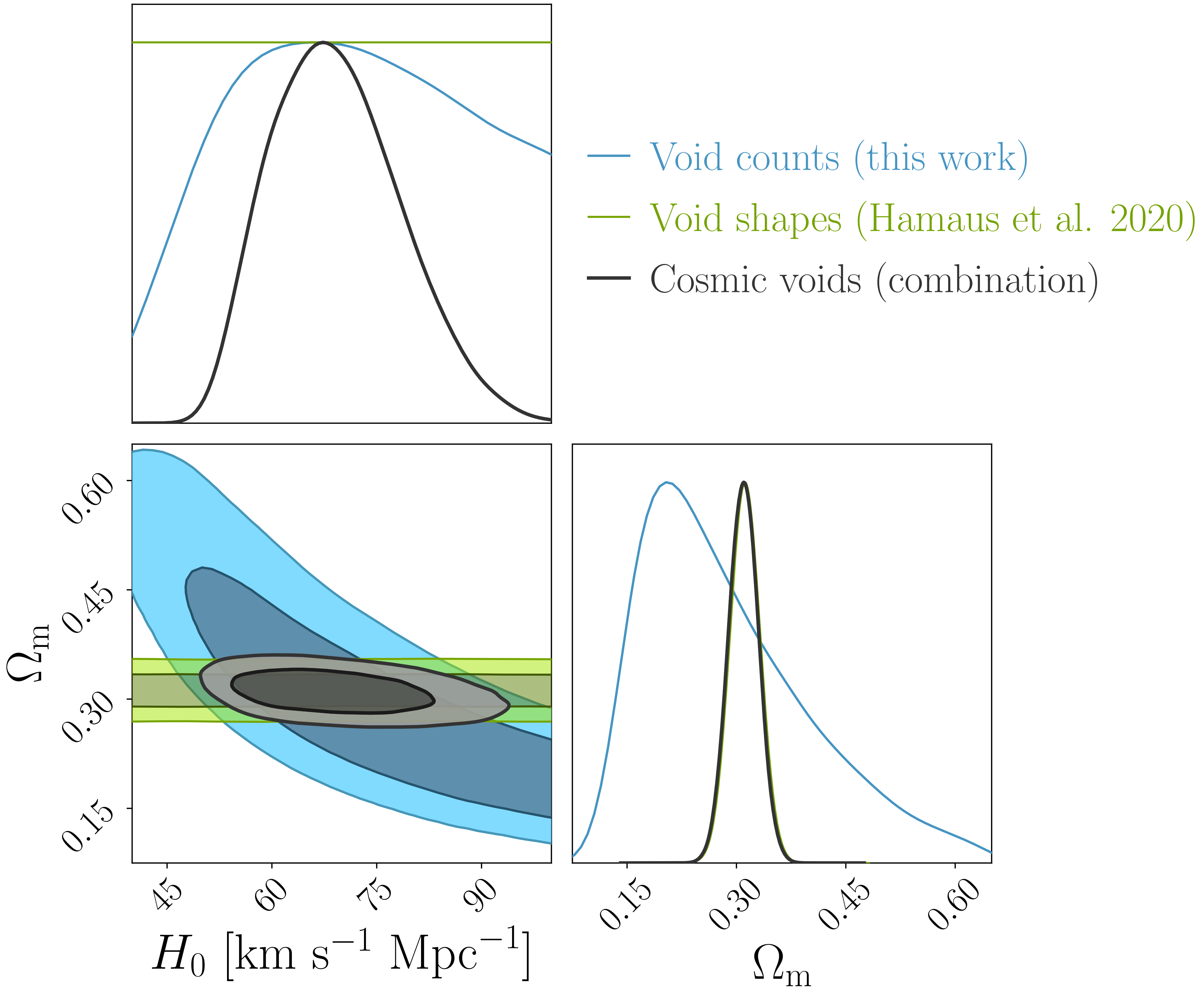




Contarini, Pisani, Hamaus et al.
2022a ArXiv: 2212.03873 , JCAP

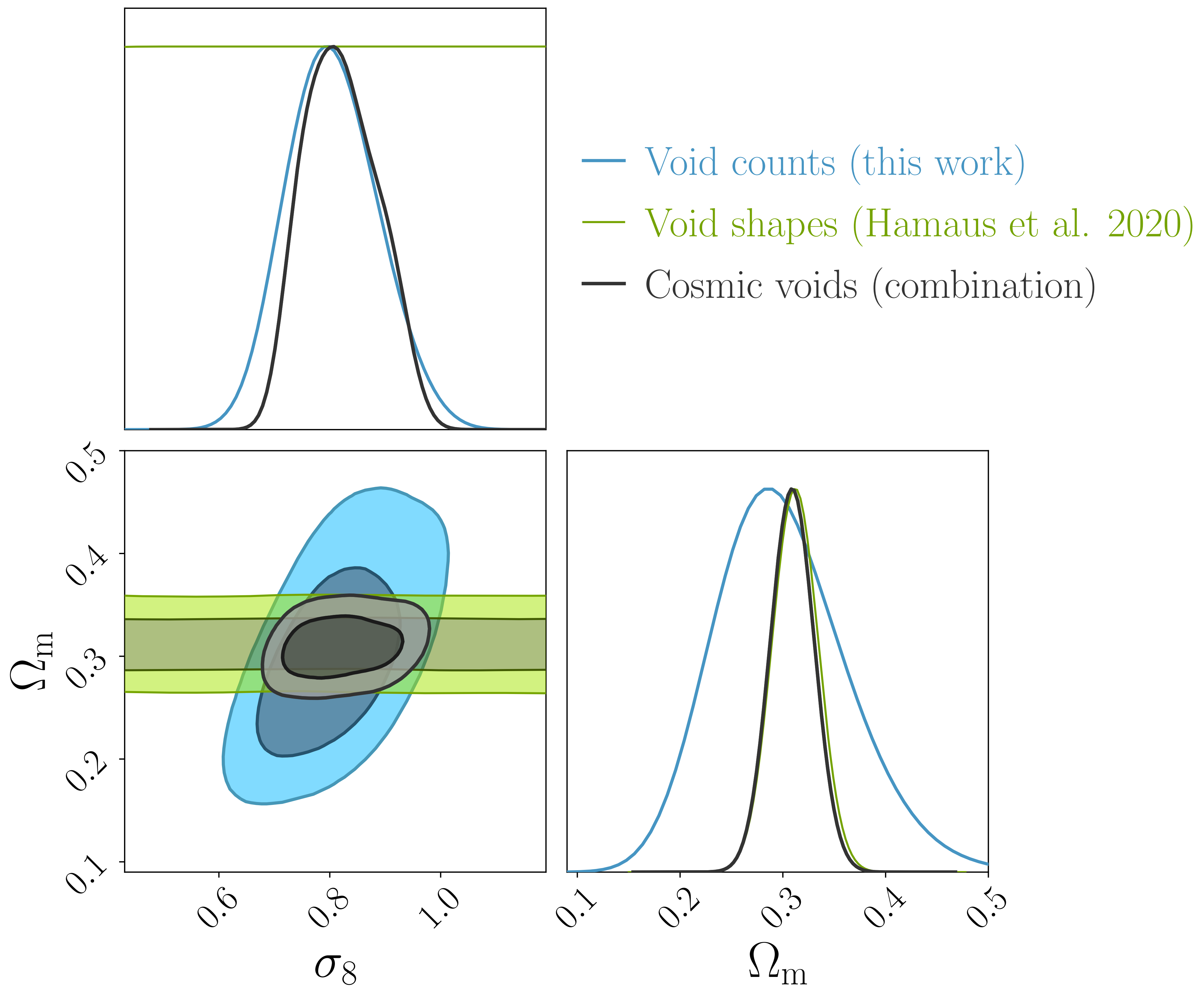
Voids can fill us in on rising cosmology tensions

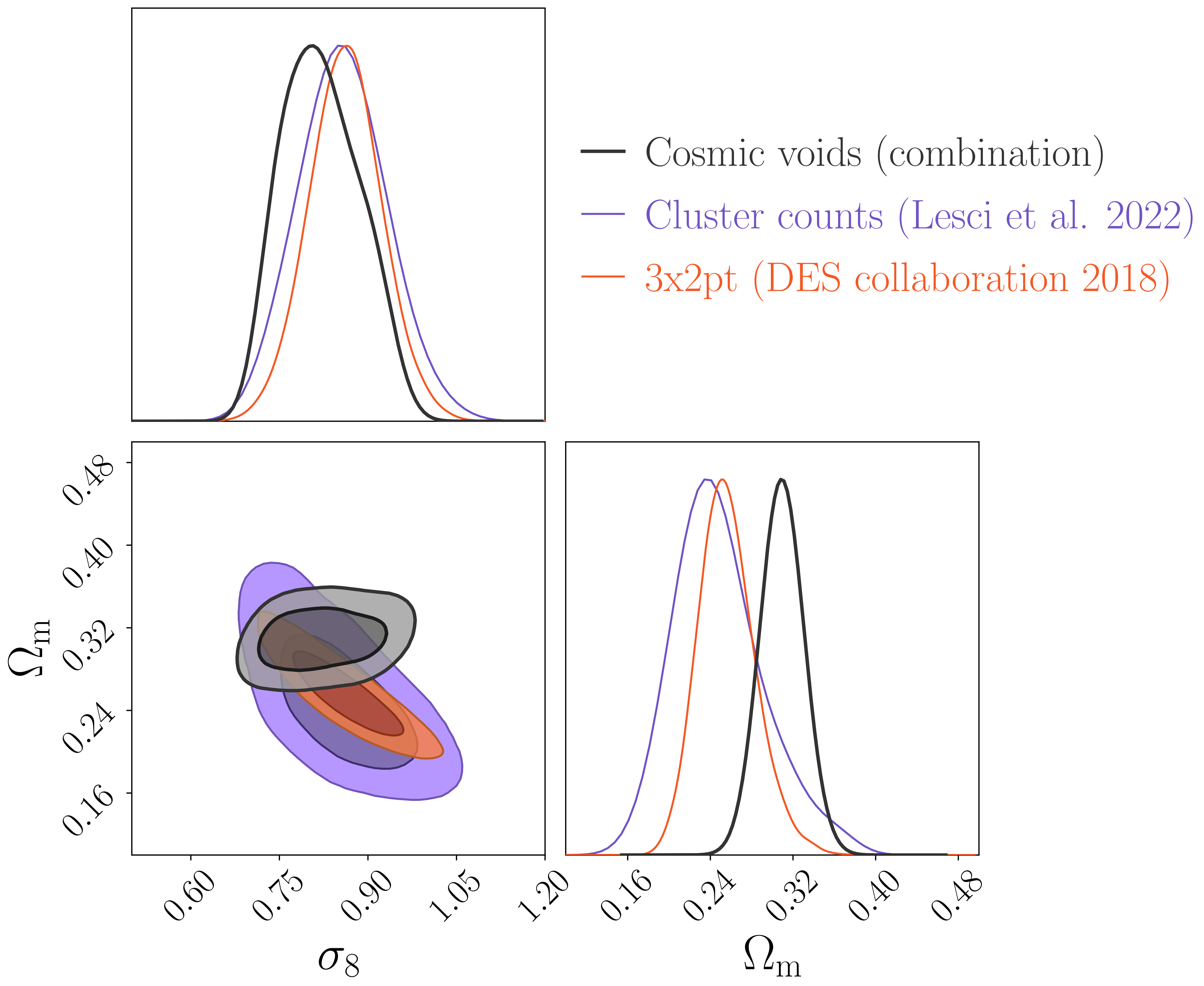




Contarini, Pisani, Hamaus et al.
2022b ArXiv: 2212.07438 A&A

Voids can fill us in on rising cosmology tensions





Contarini, Pisani, Hamaus et al.
2022b ArXiv: 2212.07438 A&A

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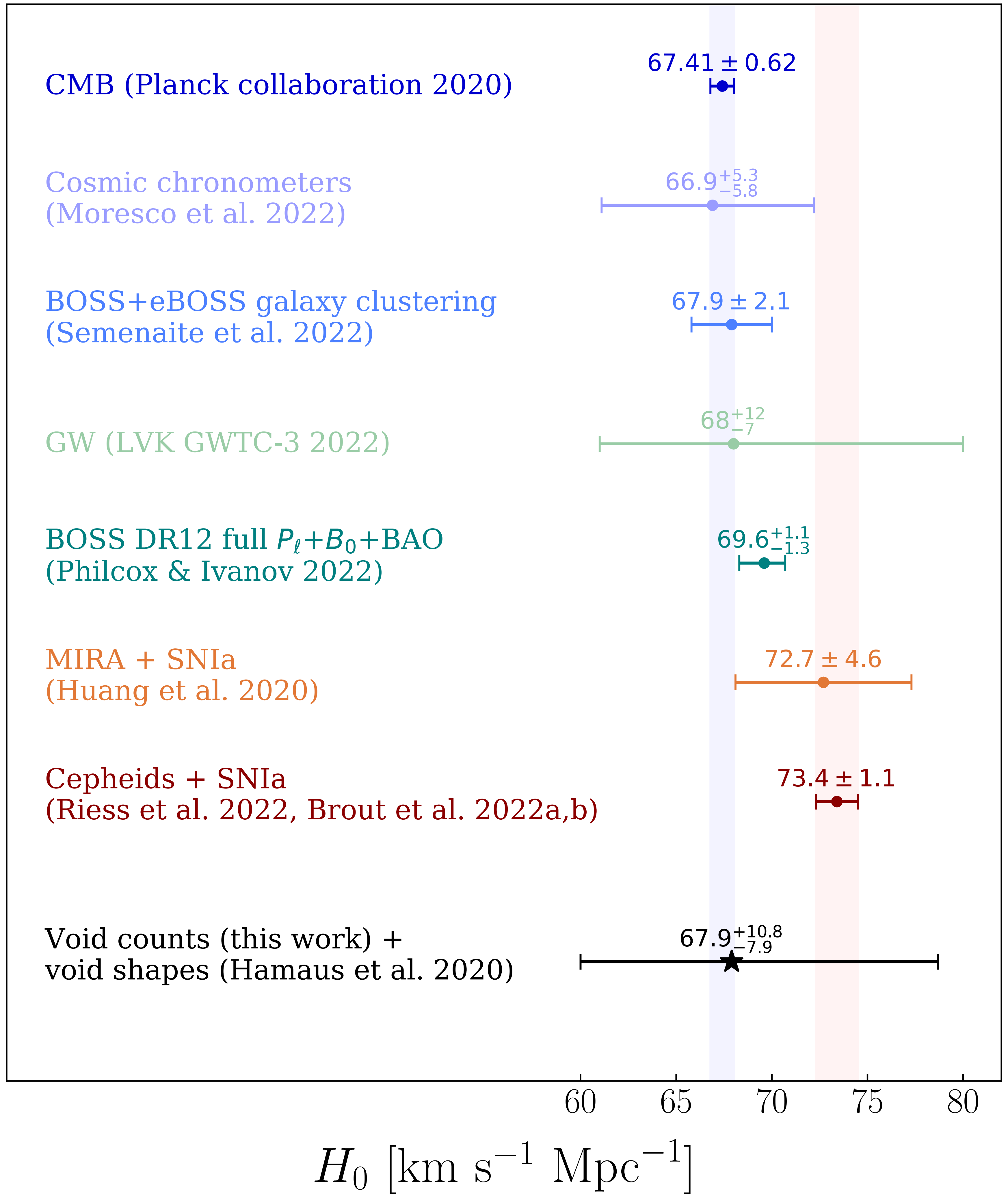
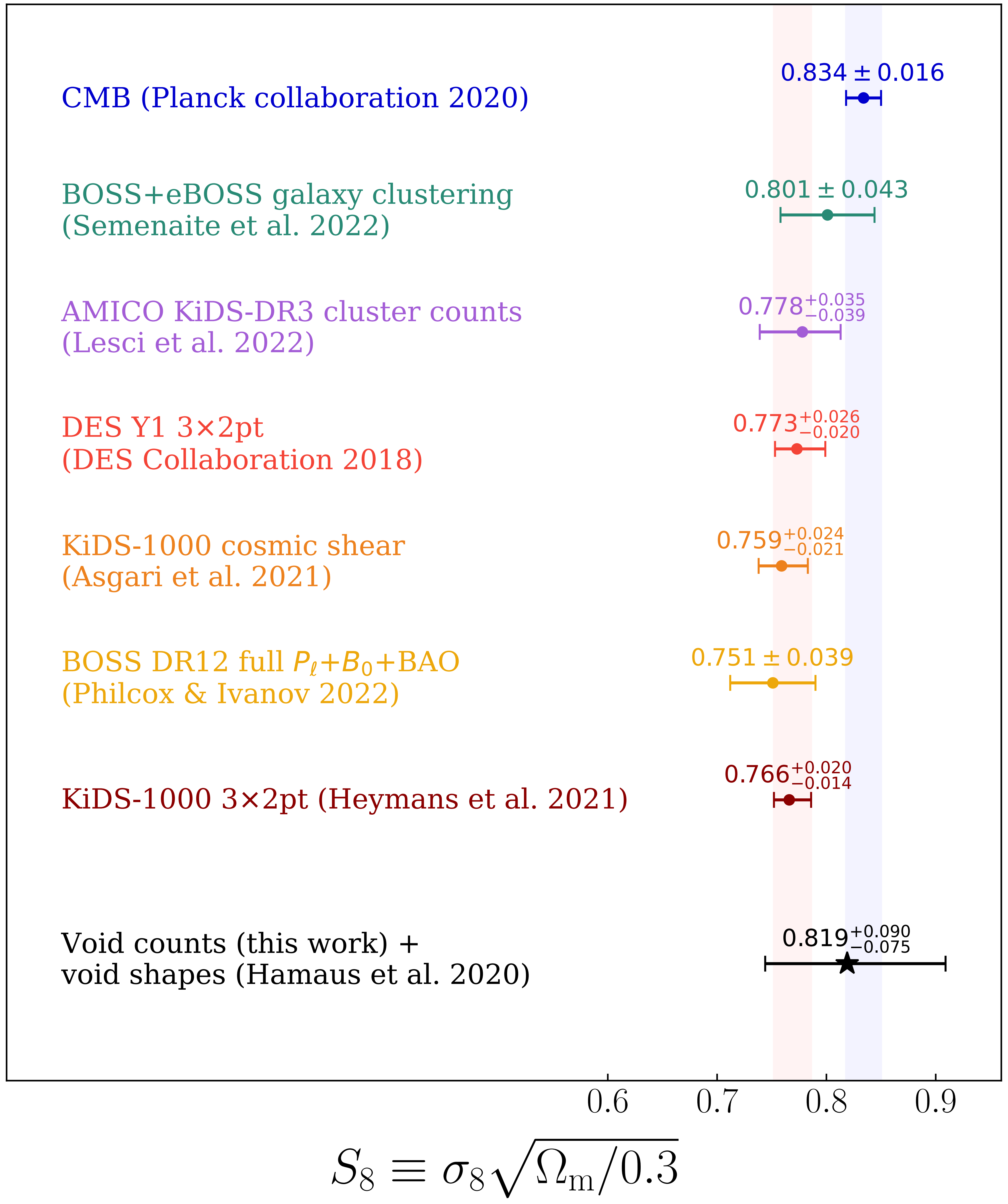


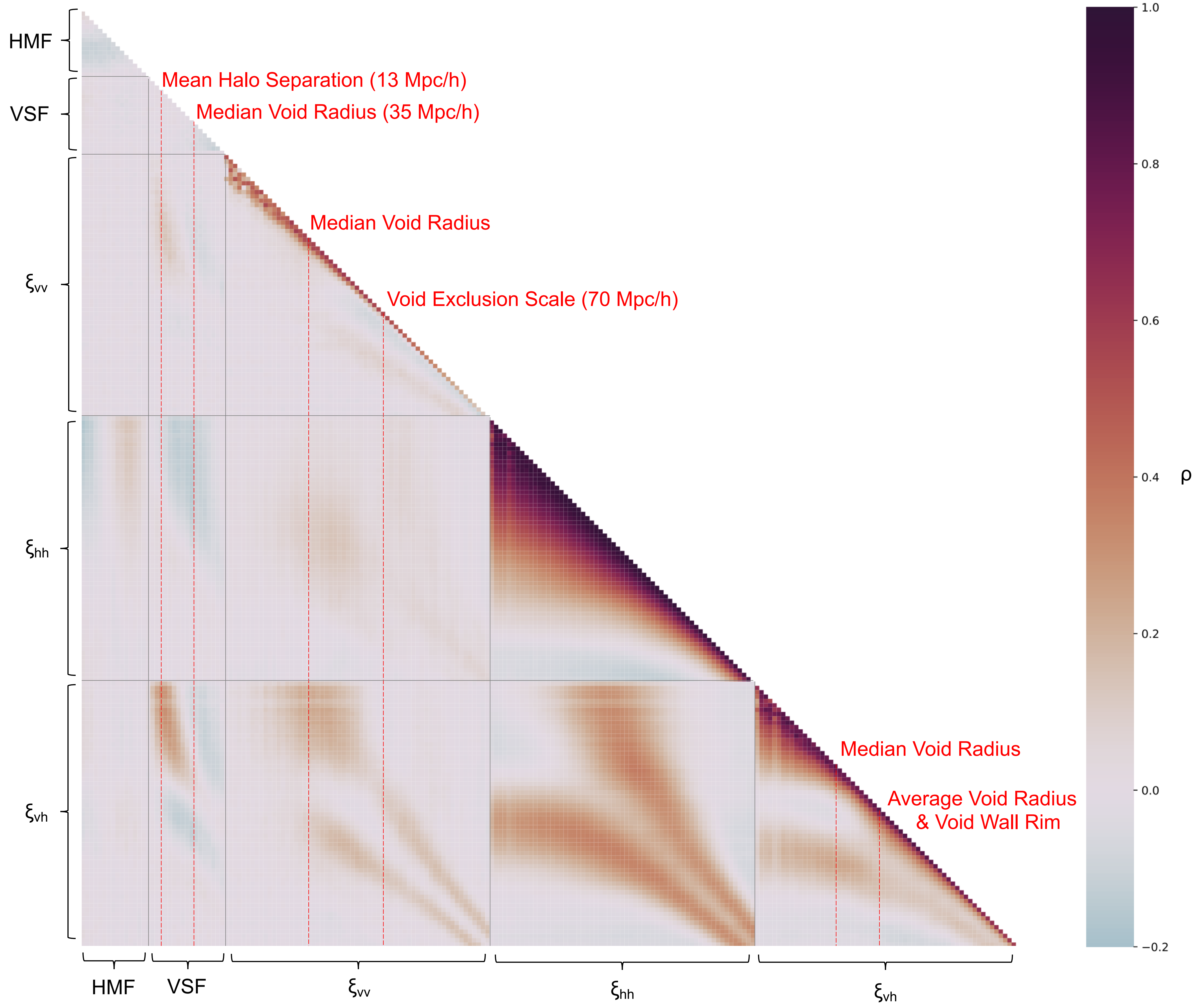


Contarini, Pisani, Hamaus et al. 2022b ArXiv: 2212.07438 A&A

A billion voids: GIGANTES void catalogs suite

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

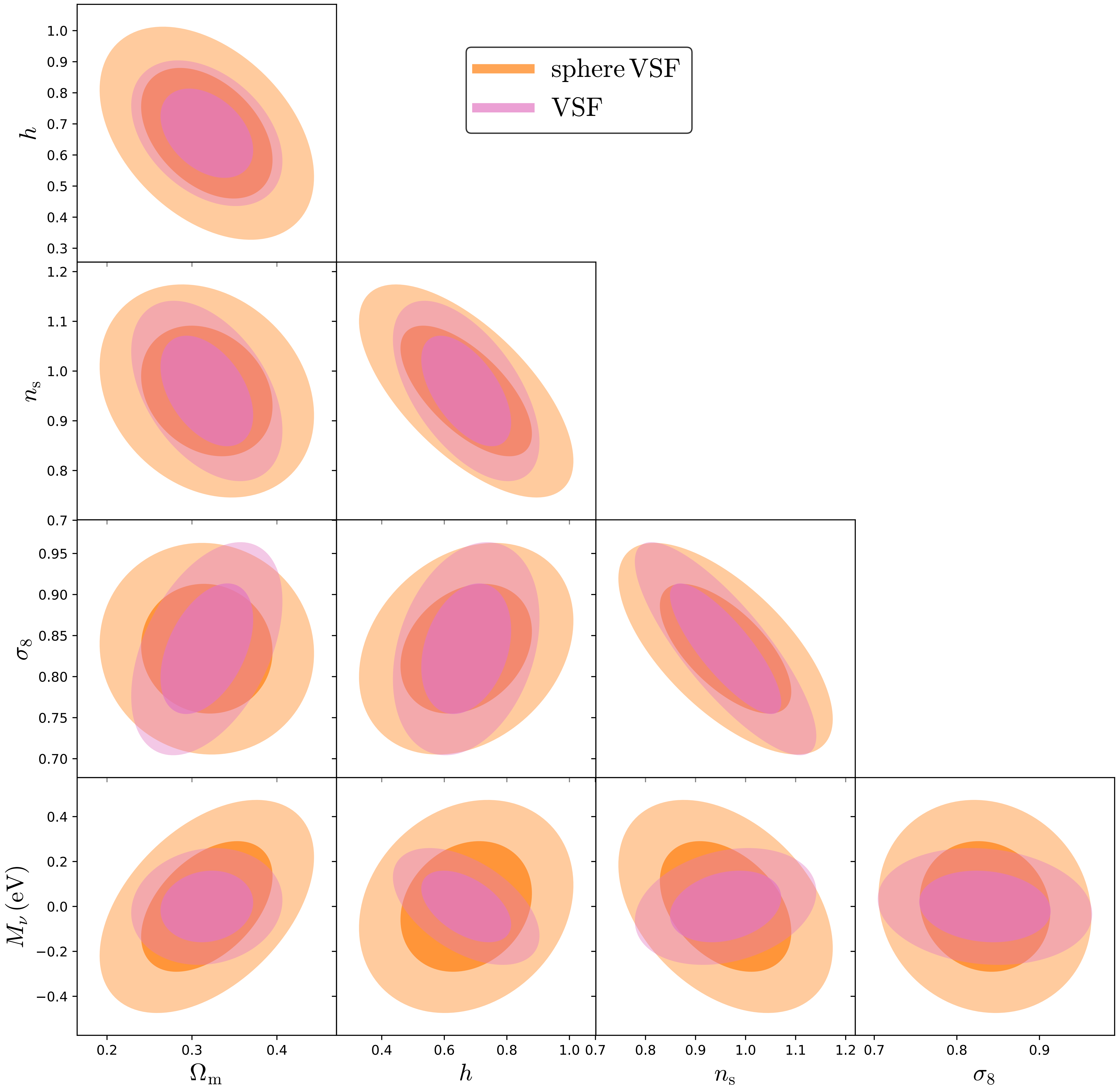
A massive dataset for ML



Kreisch, Pisani, Villaescusa-Navarro, Spergel, Wandelt, Hamaus and Bayer ApJ, ArXiv: 2107.02304

https://gigantes.readthedocs.io/

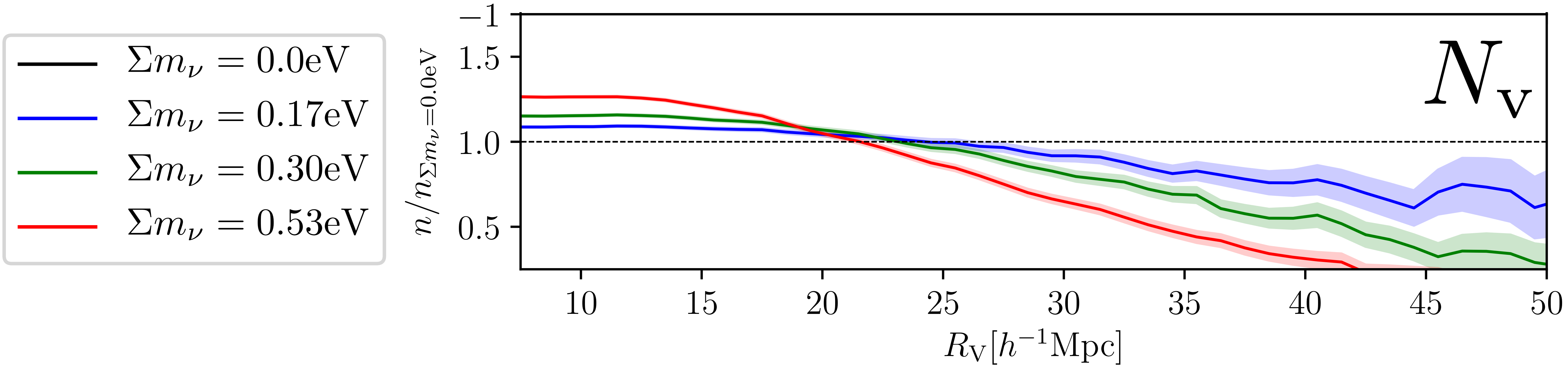
The void size function: void shape matters!

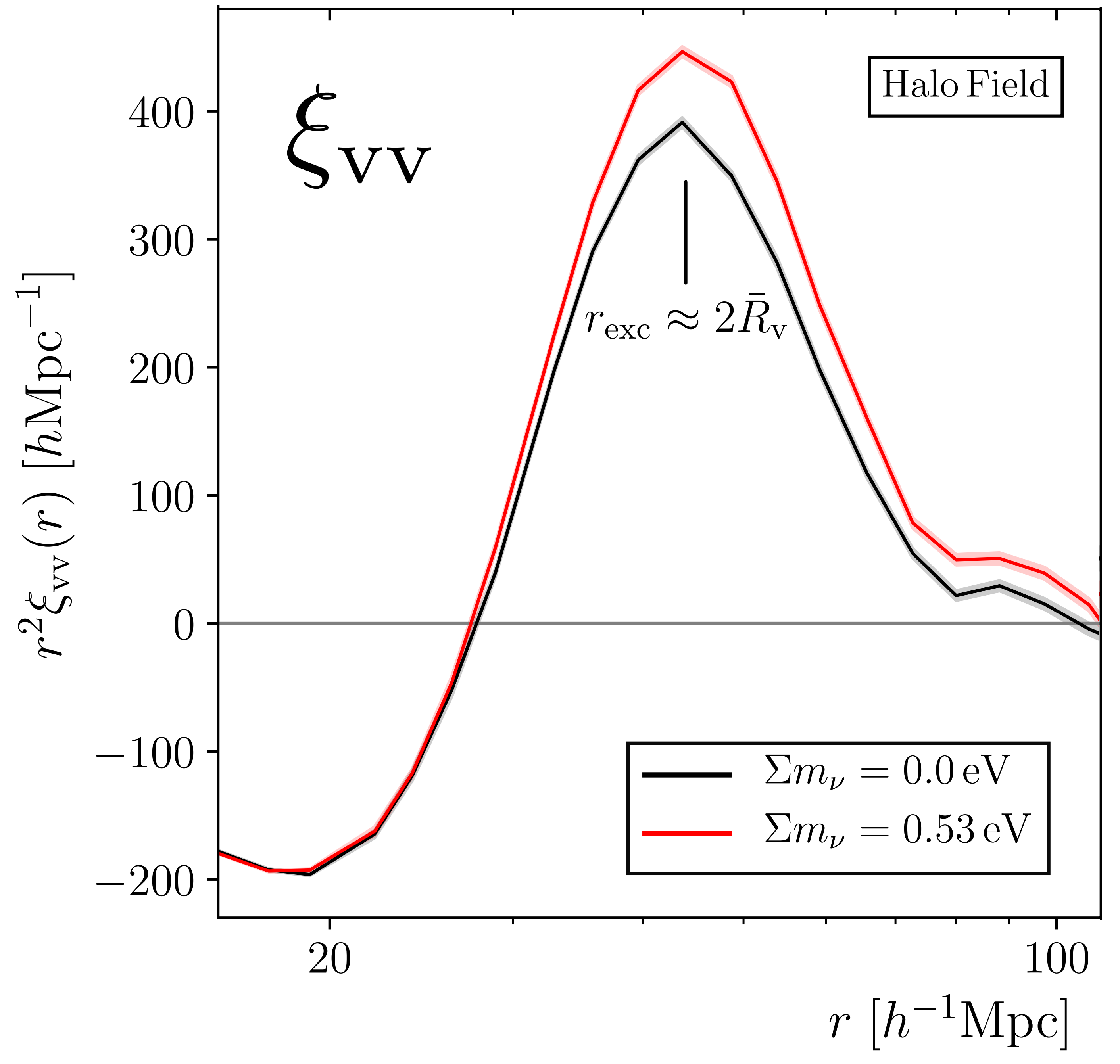


Kreisch, Pisani, Villaescusa-Navarro, Spergel, Wandelt, Hamaus and Bayer ApJ, ArXiv: 2107.02304

- Large Scale Structure, Voids and Cosmology
- How do we find voids?
- Void-galaxy cross-correlation function
- Void size function
- Voids and the rising tensions
- **Void-void auto-correlation function and neutrinos**
- Challenges
- Take home messages

The void-void autocorrelation function & neutrinos





Christina Kreisch

There is a signal in void statistics.

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

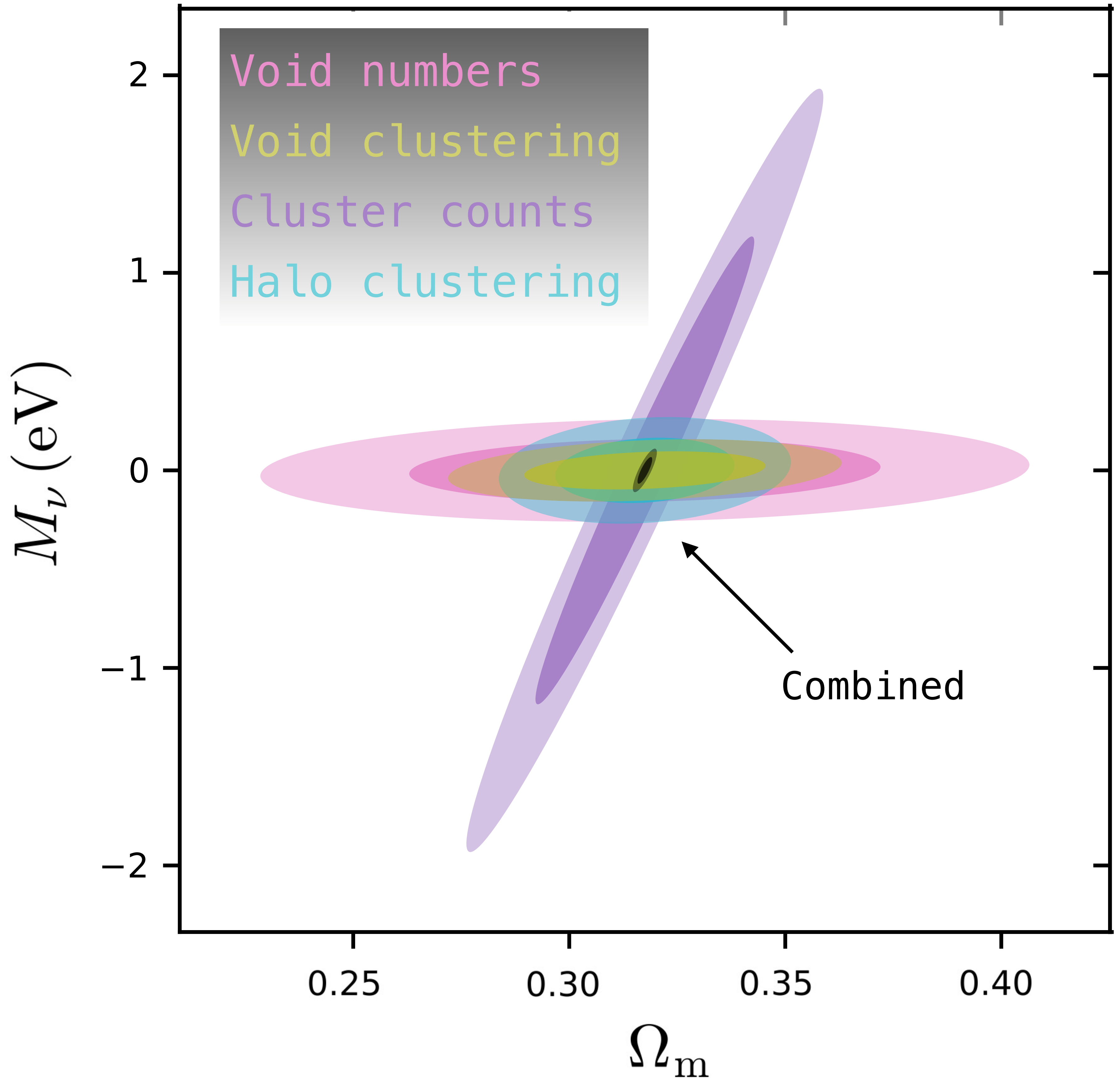
Liu et al. 2018

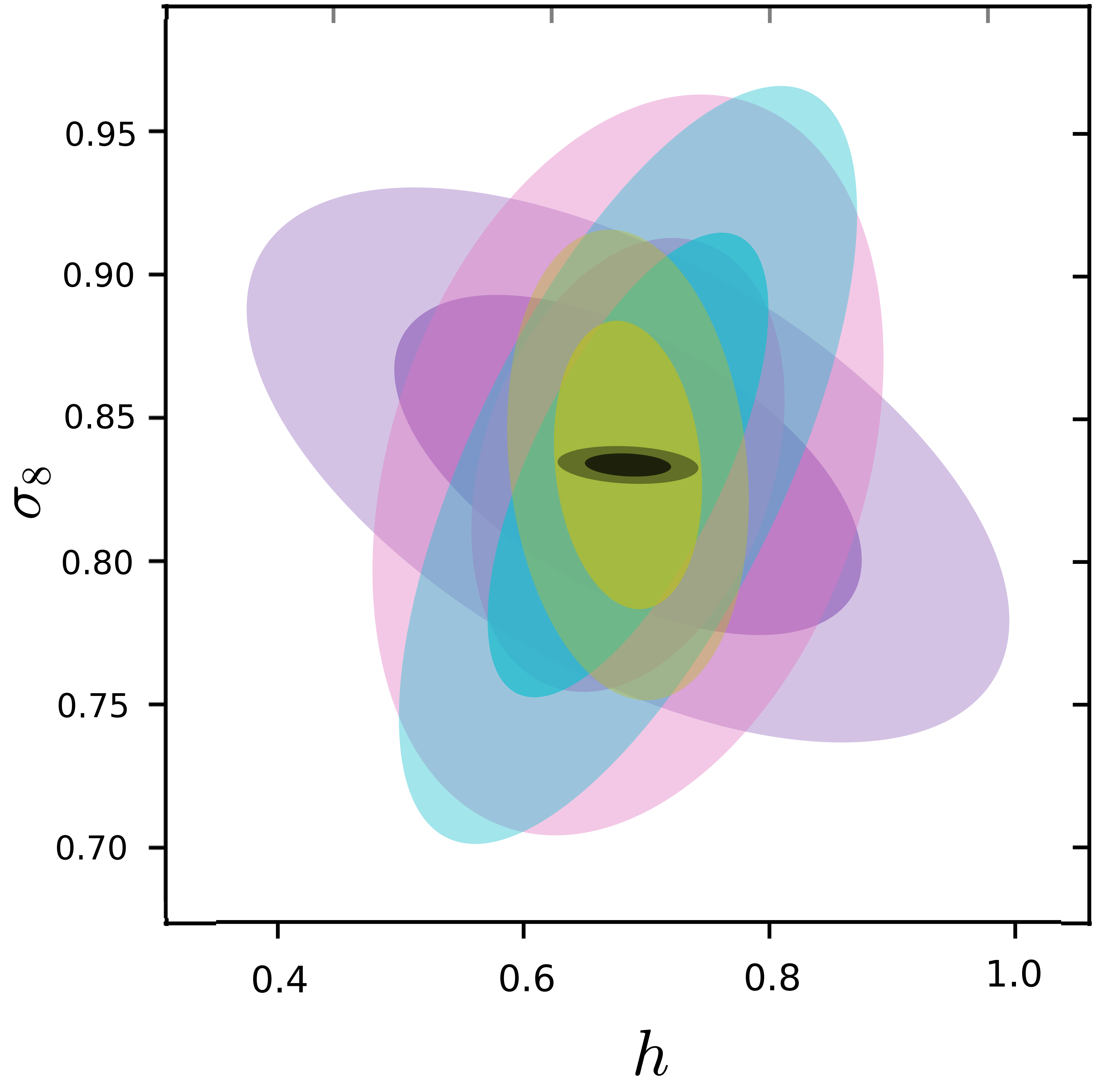
DEMNUni Simulation Suite
Carbone et al. 2016
$L = 2\,h^{-1}\mathrm{Gpc}$ 2048^3 DM part.

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

The void-void autocorrelation function & neutrinos $\xi_{\rm vv}$

Significant contribution but… needs large numbers.



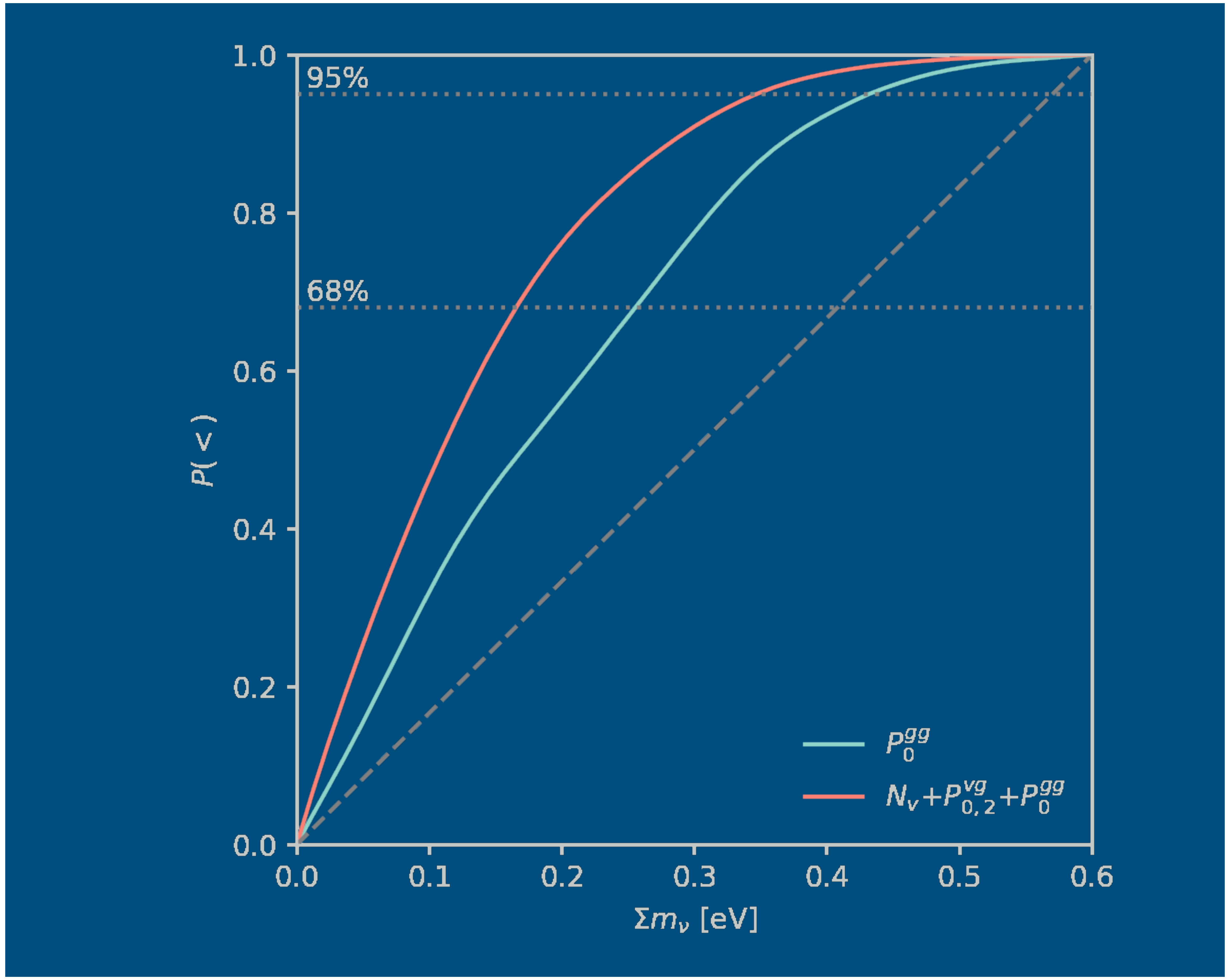


GIGANTES void catalogs suite: power from the combination

But modelling all the statistics together is a challenge…

Kreisch, Pisani, Villaescusa-Navarro, Spergel, Wandelt, Hamaus and Bayer ApJ, ArXiv: 2107.02304

Hints of neutrinos constraints!



Leander Thiele

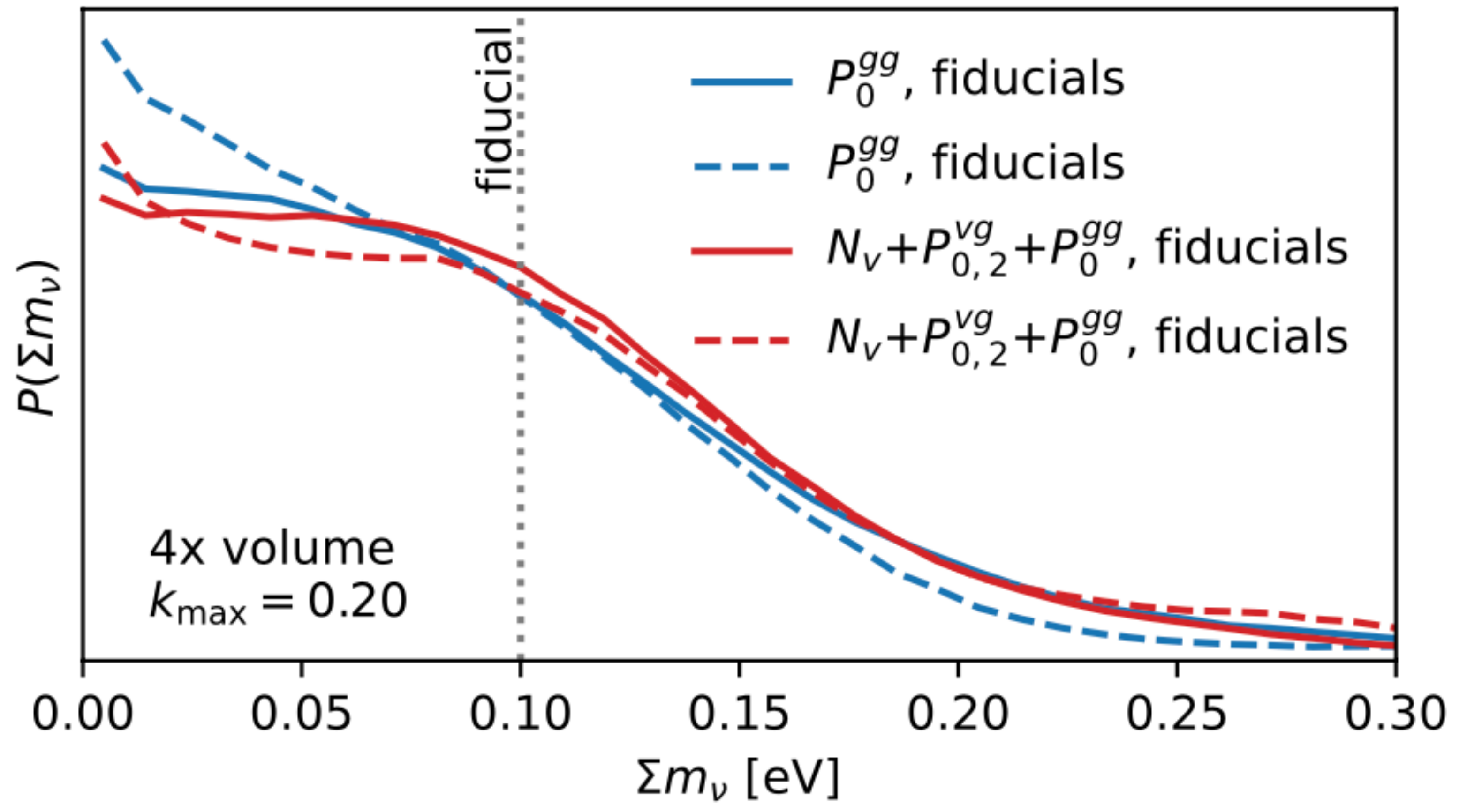
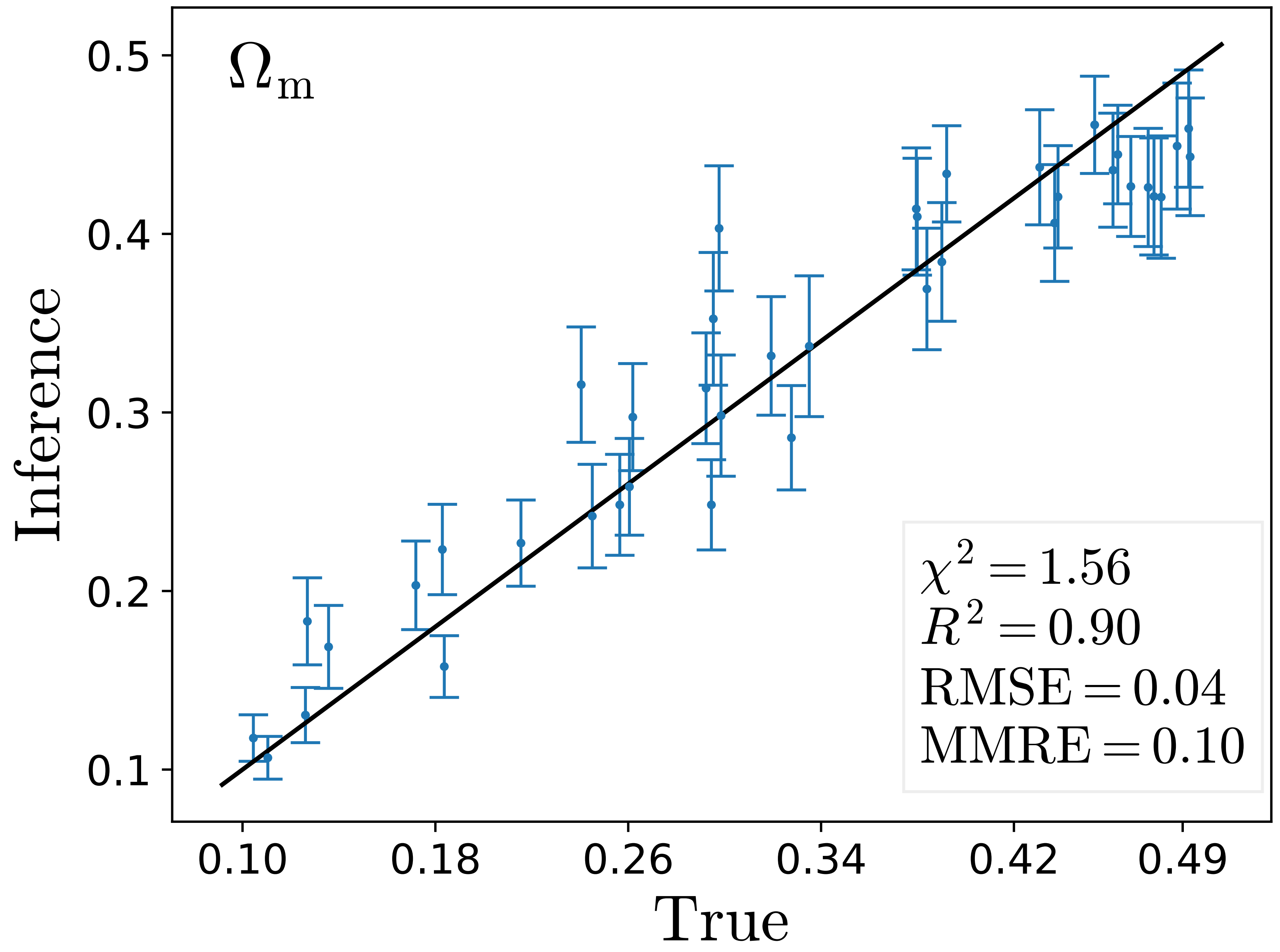


Figure 14. Posteriors on joint analyses of four randomly chosen fiducial mocks, averaged over ~ 30 groups. The solid and dashed lines correspond to likelihoods with two different sets of five nuisance parameters kept explicit. We see that the posteriors where void statistics are included have a slightly more pronounced bump at the true value $\sum m_\nu = 0.1\,\mathrm{eV}$, consistent with the speculative picture in Fig. 13.

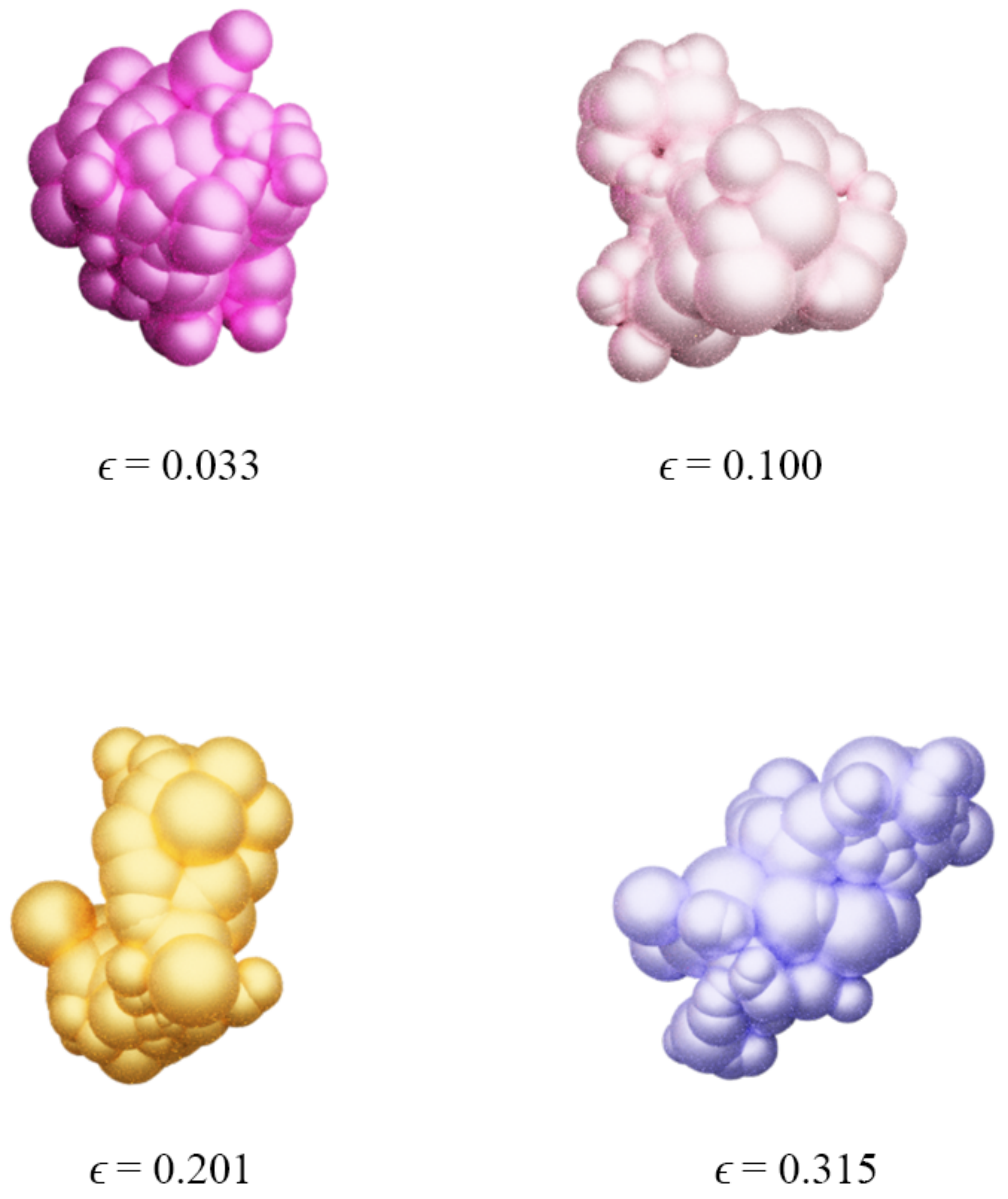
With conservative scale cut of k_{max}=0.15 hMpc^{-1}, voids tighten upper bound on neutrino mass.

Thiele, Massara, Pisani et al. 2023 ArXiv: 2307.07555

Other void statistics deserve attention: ellipticity



Yue Bonny Wang



> Wang, Pisani, Villaescusa-Navarro and Wandelt 2022 ApJ Arxiv: 2212.06860

> Kreisch, Pisani, Villaescusa-Navarro, Spergel, et al. ApJ ArXiv: 2107.02304

> Lavaux and Wandelt 2009 MNRS Arxiv: 0906.4101

GIGANTES: https://gigantes.readthedocs.io

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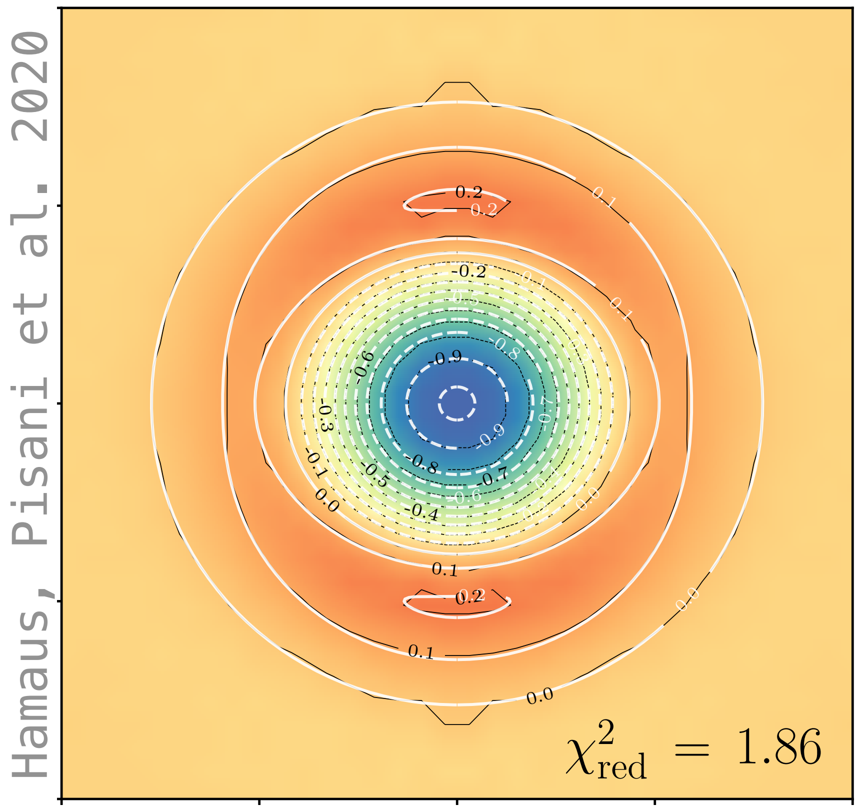
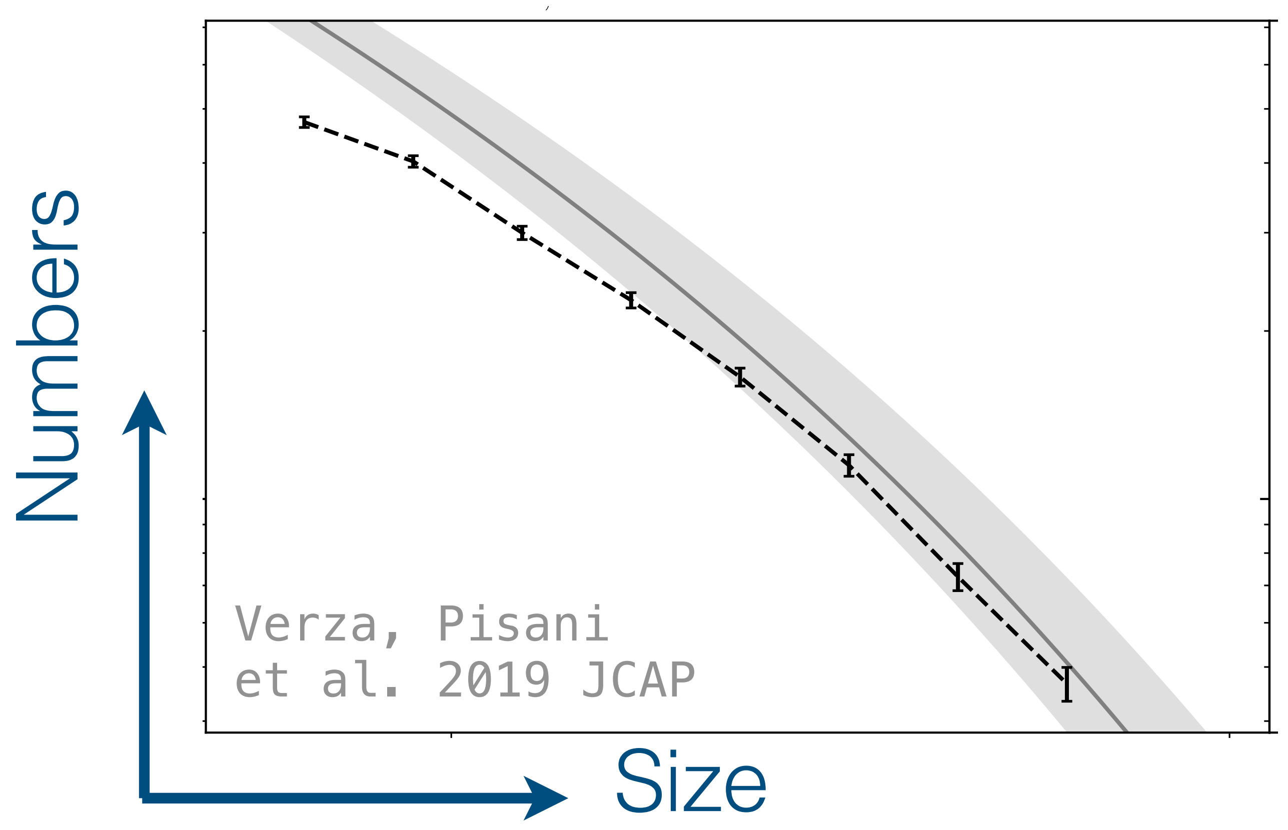
Challenges: Void statistics do not have the same degree of maturity.

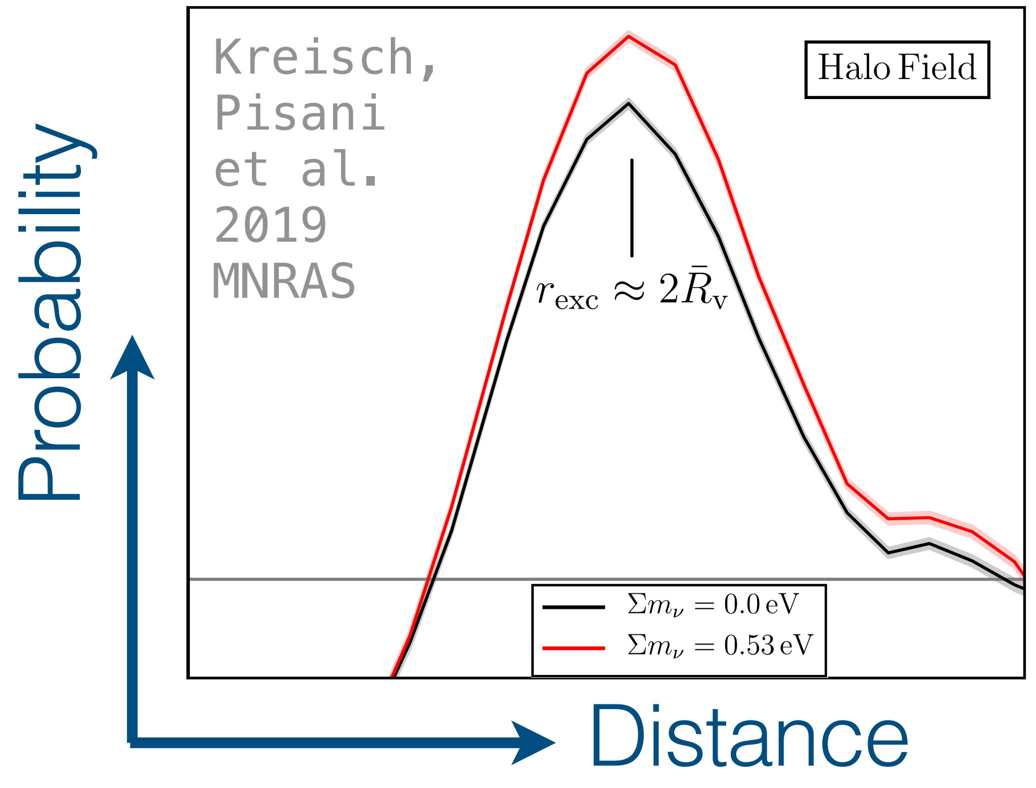
Shape



Numbers



Clustering



	Shape	Numbers	Clustering
Model	✓	✓	✗
Data	✓	✓ (orange)	✗

Spurious voids: very conservative void selection!
Theory: robust **profile** from theory + **bias**
Loss in statistics at **smaller scales**, needs improvement in light of denser surveys.
Controlling **galaxy properties' impact** down to the cosmological constraints.

Verza, Carbone, Pisani et al. 2024
ArXiv: 2401.14451

Take home messages

- Void analysis: active field of galaxy clustering!
- Many statistics, not at the same degree of maturity
- PFS, DESI, Euclid, Rubin, Roman, SPHEREx : a unique set of > $\mathcal{O}(10^5)$ voids per survey!
- Voids can independently constrain $\Omega_m, \Omega_\Lambda, w_0, w_a, f, \Sigma m_\nu, H_0, \sigma_8$
- Voids can contribute to the tension landscape: impressive constraining power coming soon!
- There are challenges that we need to address to exploit voids' power at their best.

Thanks for your attention!