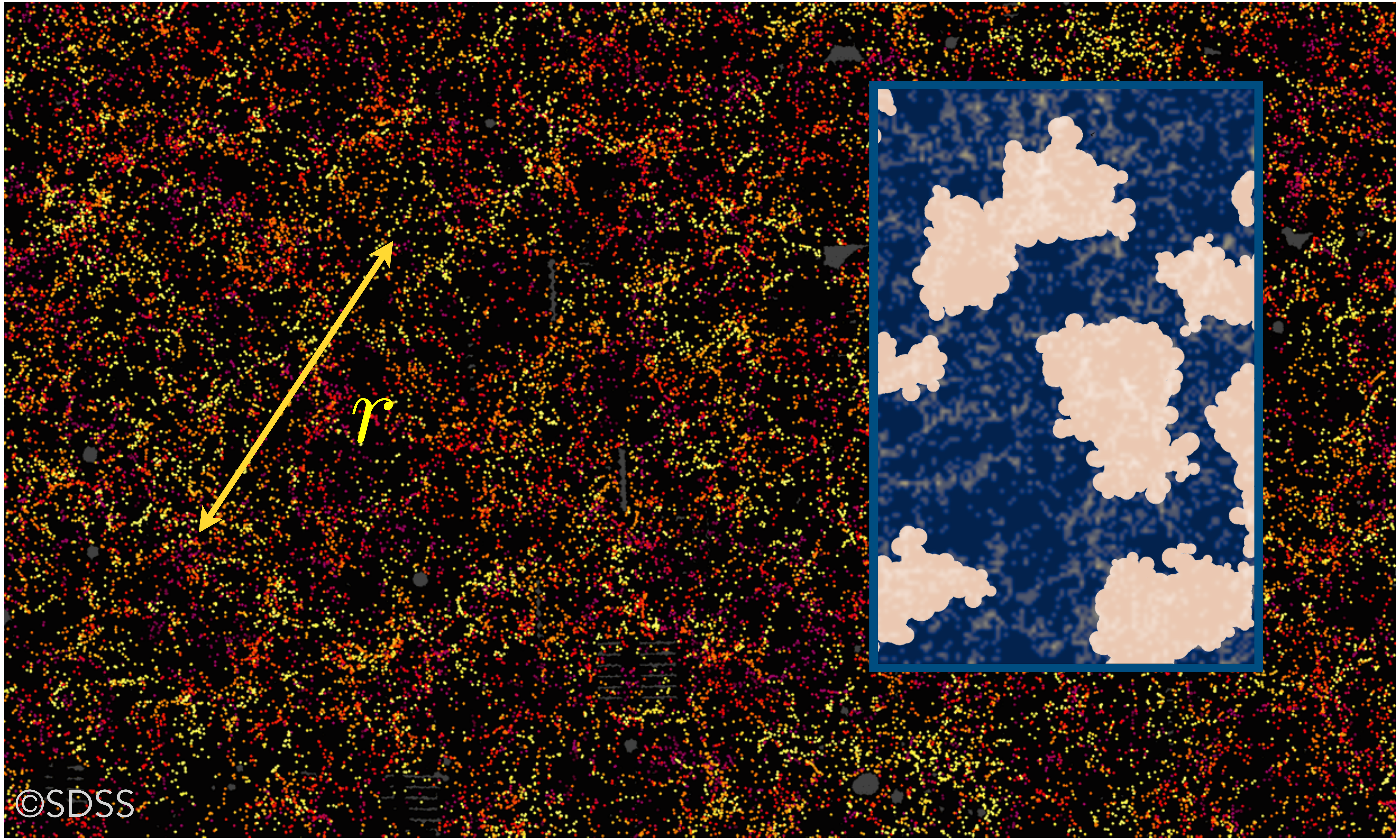
Unraveling cosmology with cosmic voids

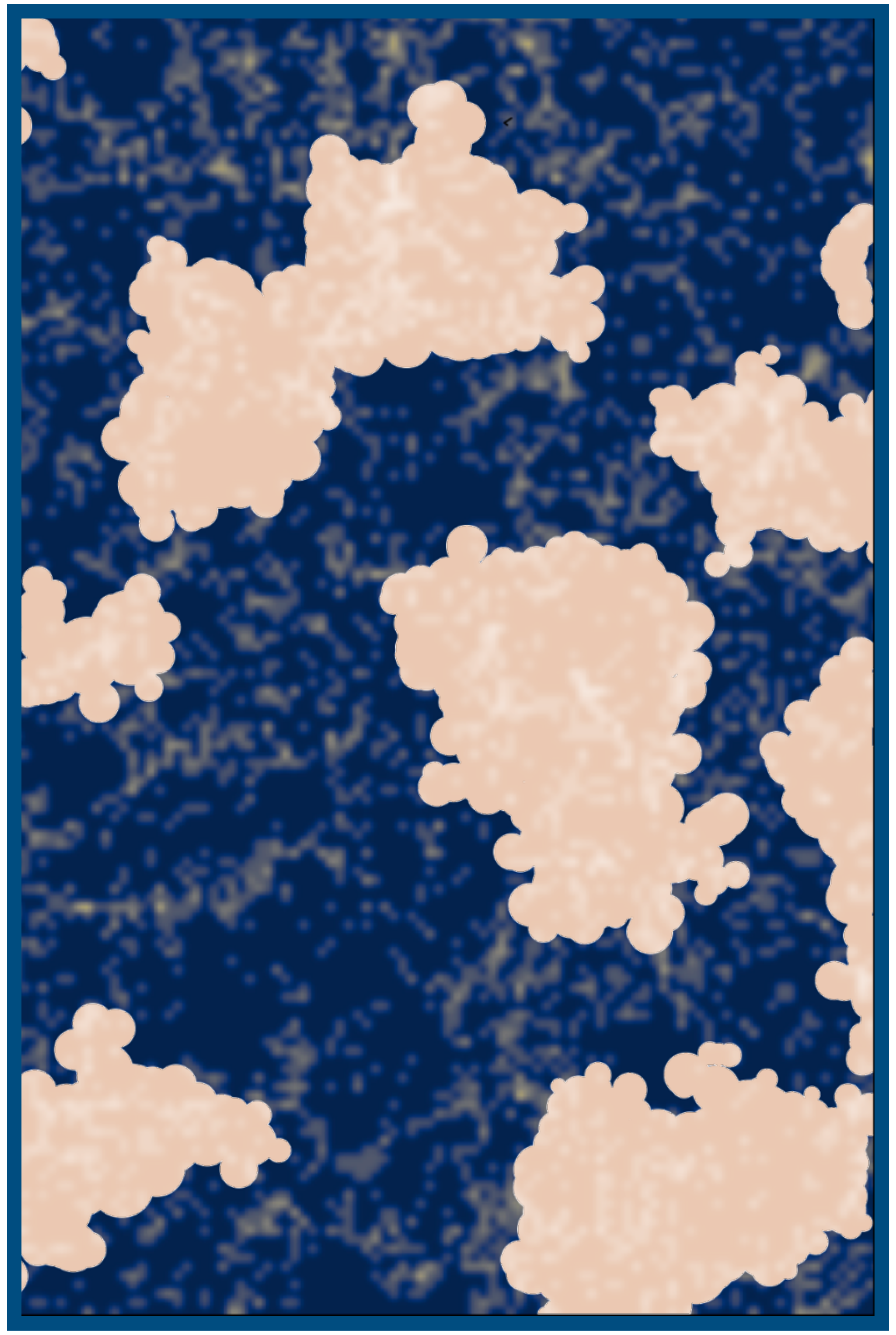
+ many collaborators, highlights: N. Hamaus (LMU, Munich), S. Contarini (MPE), G. Verza (CCA, NYU), B. Y. Wang (CMU), D. Spergel (Princeton, Flatiron), B. Wandelt (IAP), C. Kreisch (Princeton), L. Thiele (Princeton, IPMU), R. Panchal (Princeton), M. Aubert (LPC), M.-C. Cousinou (CPPM), S. Escoffier (CPPM),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

Alice Pisani

Galaxy maps contain information beyond the 2-point correlation function.



Voids have a unique sensitivity to cosmology.



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

Dark energy dominated (first!)

Sensitive to diffuse components Σm_ν

Sweet spots to test gravity

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

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

Keep memory of initial conditions

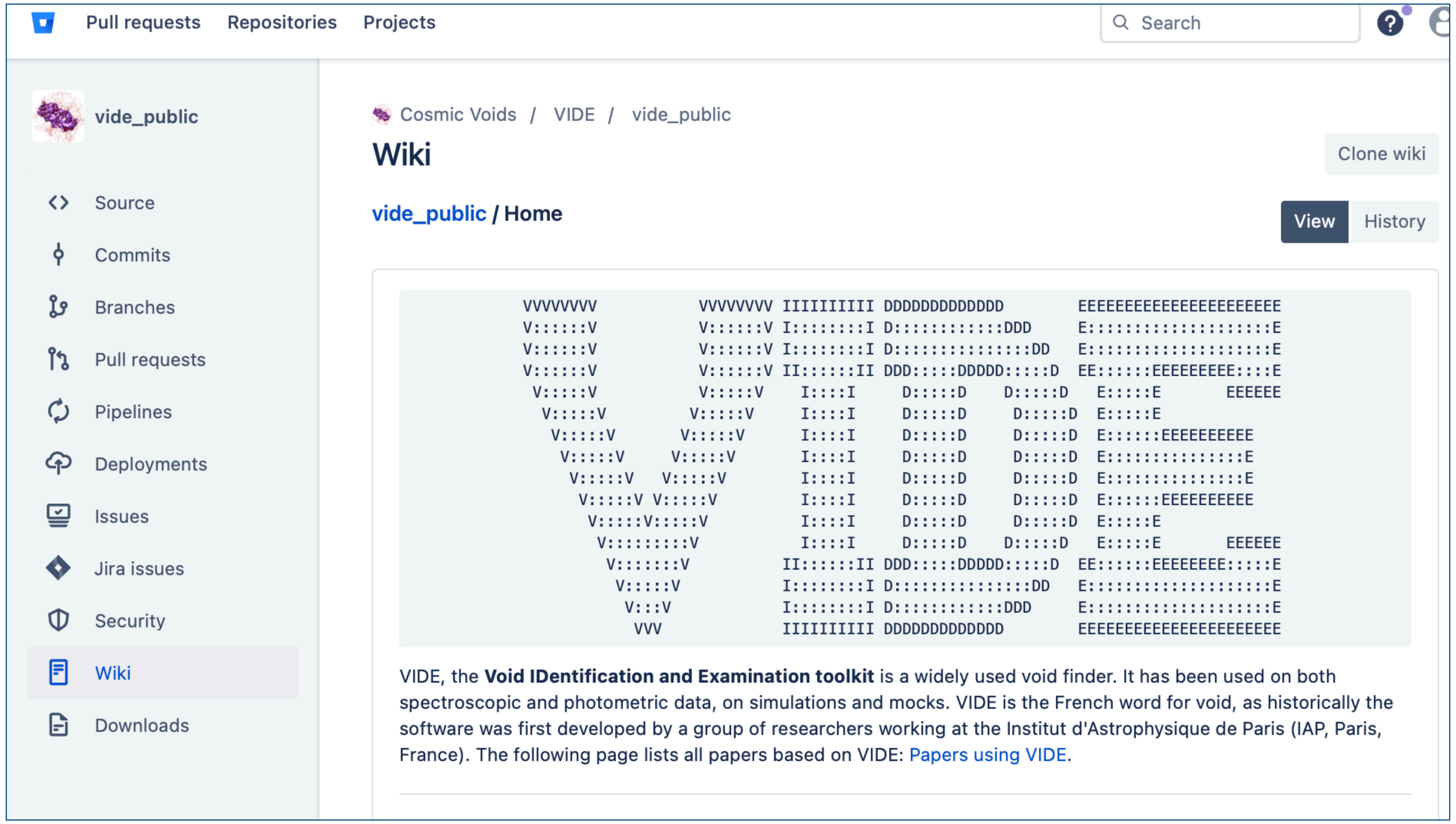
High signal-to-noise for dark matter

Arcari, Pinetti, Fornengo 2022 JCAP Arxiv: 2205.03360

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!

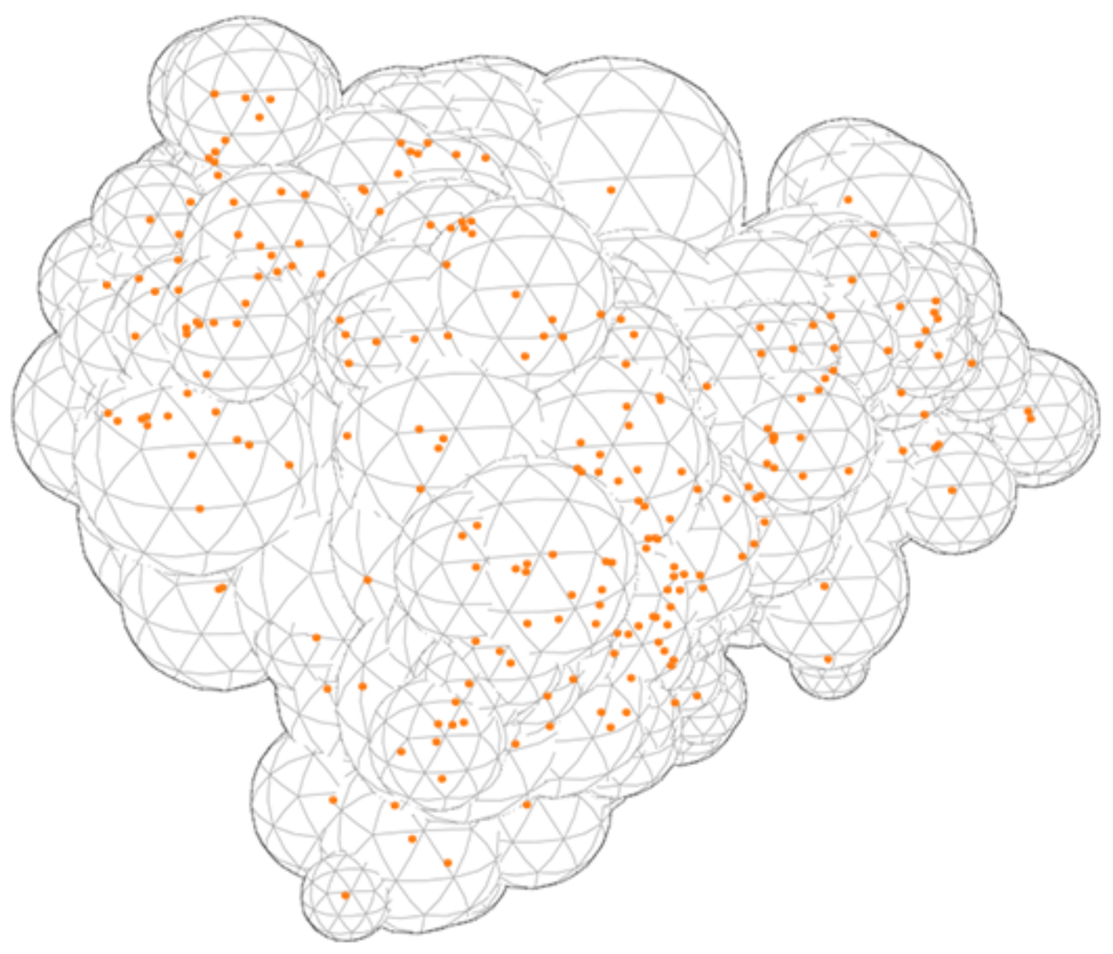
Void IDentification and Examination



- ☑ 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)



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

Yue Bonny Wang

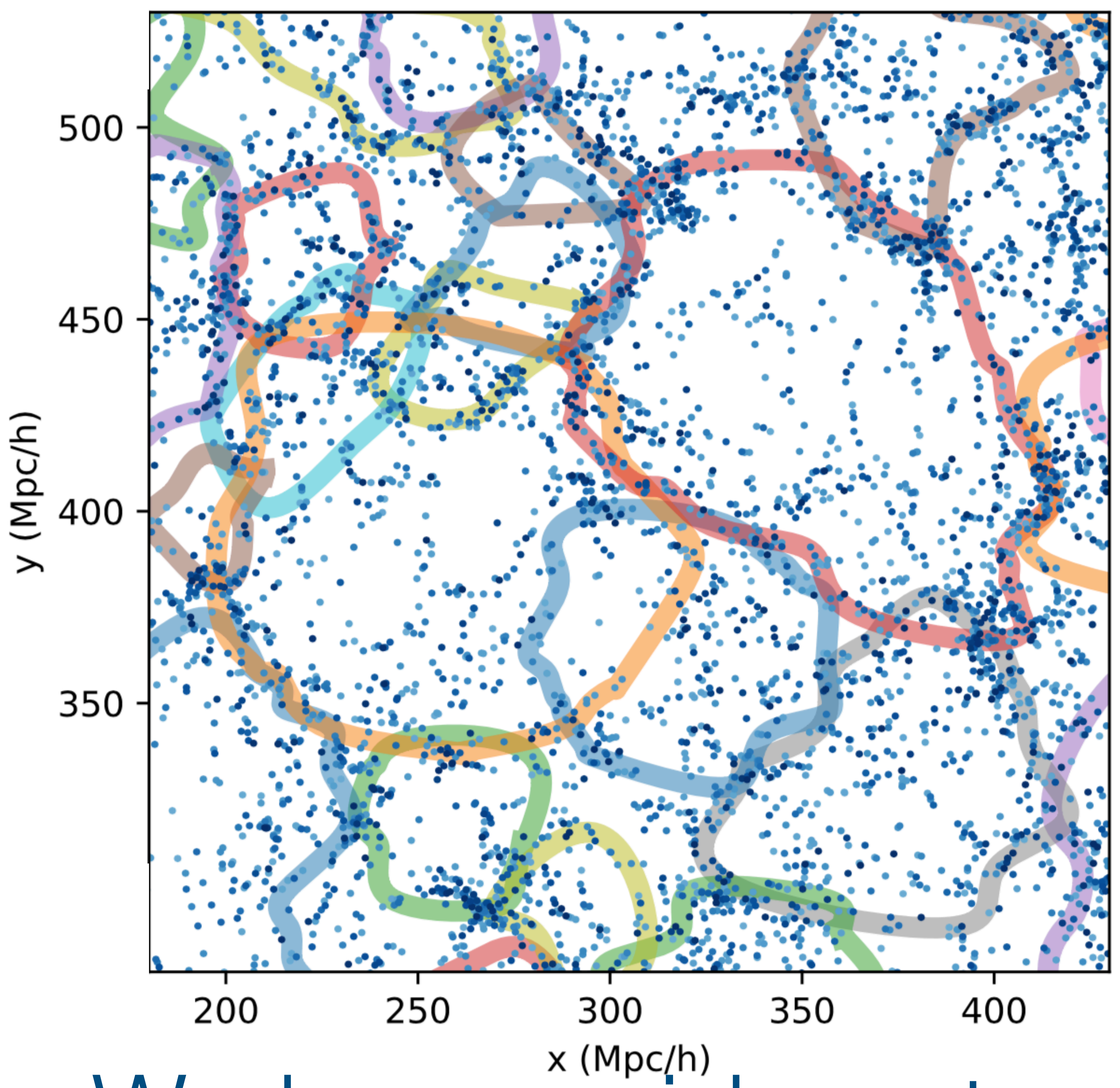
Giovanni Verza

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

Wang, Pisani et al. 2023, ApJ 955 131, Arxiv: 2212.06860

Ryden, B. S. 1995, ApJ, 452, 25

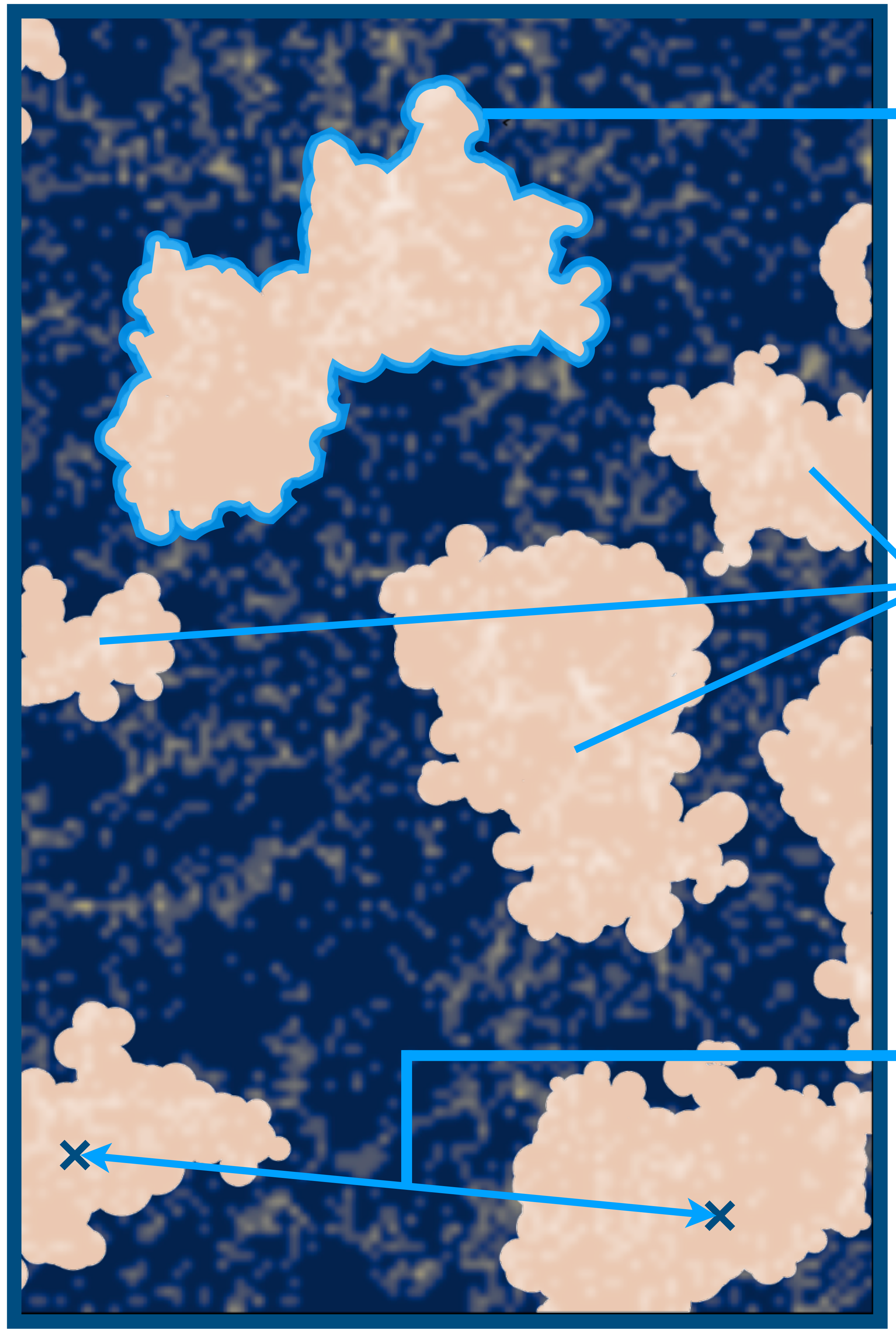
Lavaux & Wandelt 2011; ArXiv: 1110.0345 ApJ



We have void centers, void radii, and tracers!

Using voids means more than one application!

Many different void statistics



Shape

$\xi_{\rm vg}$

Numbers

$N_{\rm v}$

Clustering

$\xi_{\rm vv}$

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

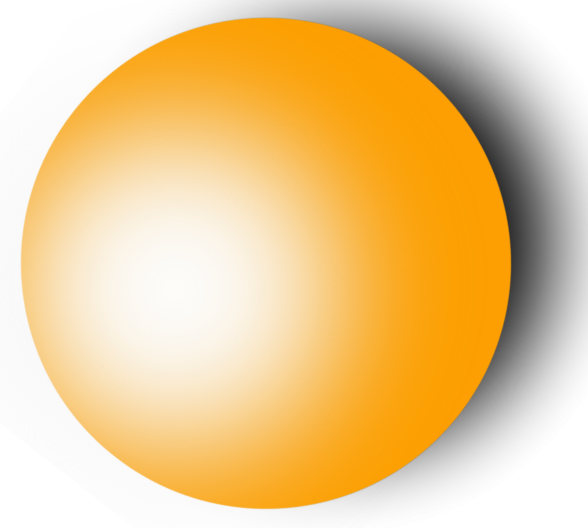
Neutrinos

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 ξ_{vg}

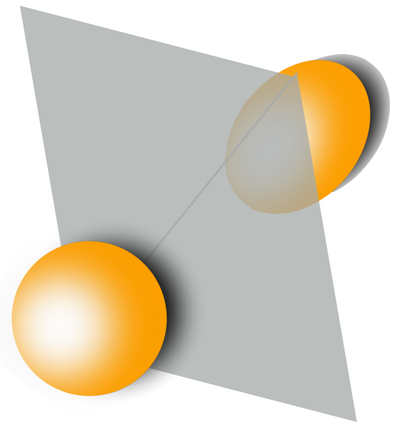
1. Stacked void density profile in real space



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 $\quad r_{\perp} = r_{\parallel}$

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

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

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

$$\varepsilon = 1$$

+

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

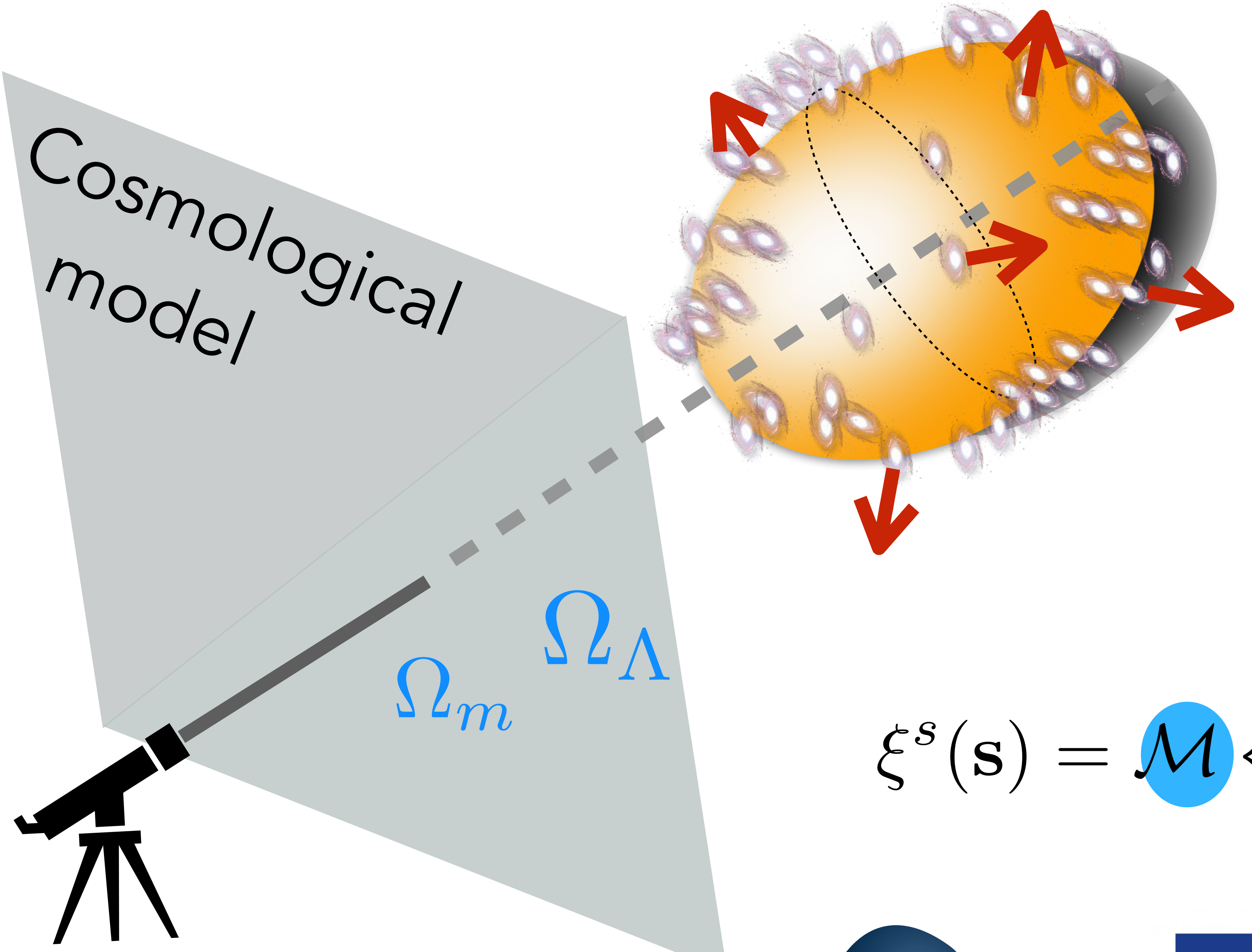
$$cz = H_0 d + v cos\theta$$

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

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

=

Void stack in redshift space

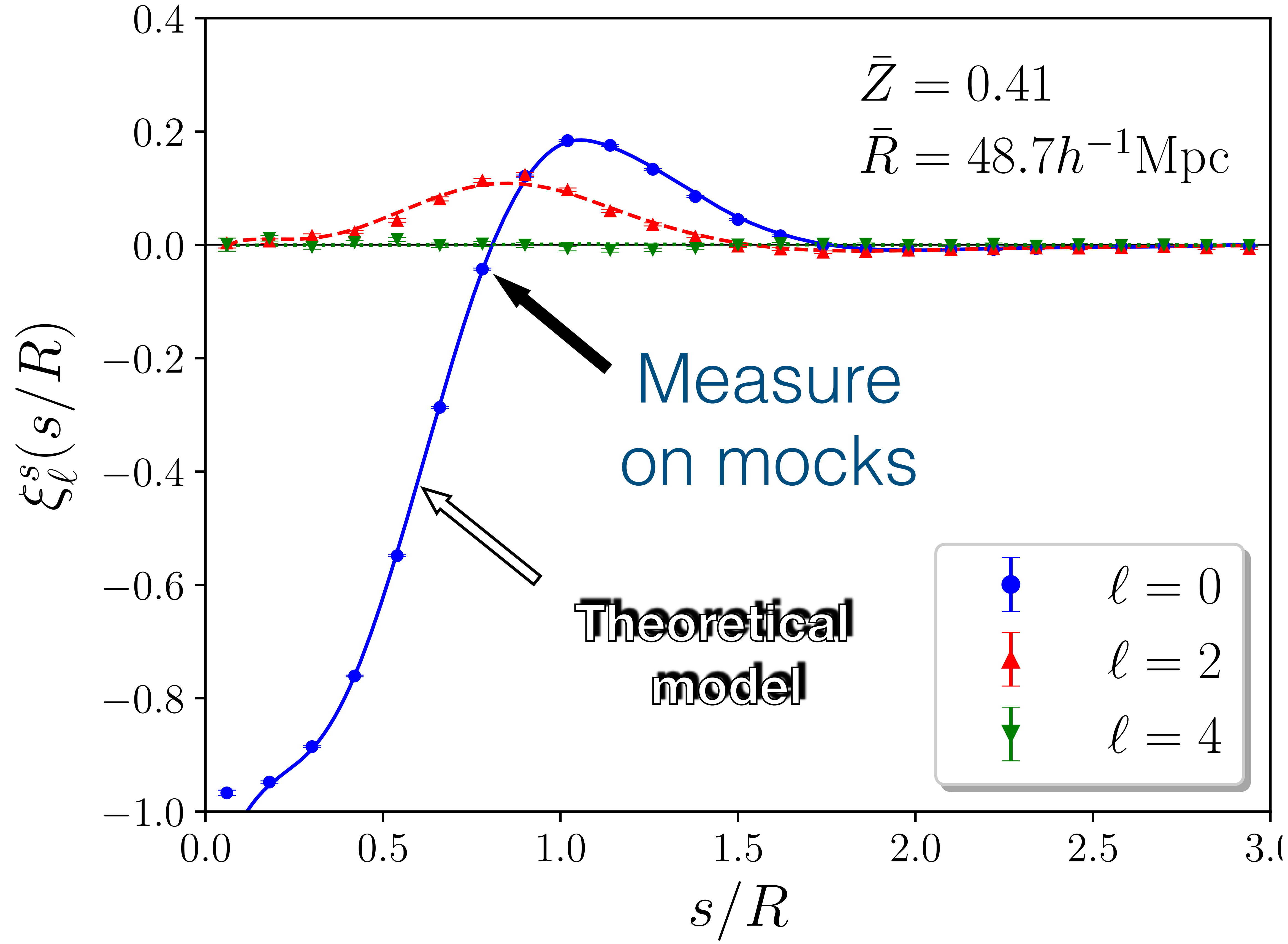


$$\xi^s(\mathbf{s}) = \mathcal{M}\left\{\xi(r) + \frac{1}{3}\frac{f}{b}\bar{\xi}(r) + \frac{f}{b}\mathcal{Q}\mu_r^2\left[\xi(r) - \bar{\xi}(r)\right]\right\}$$

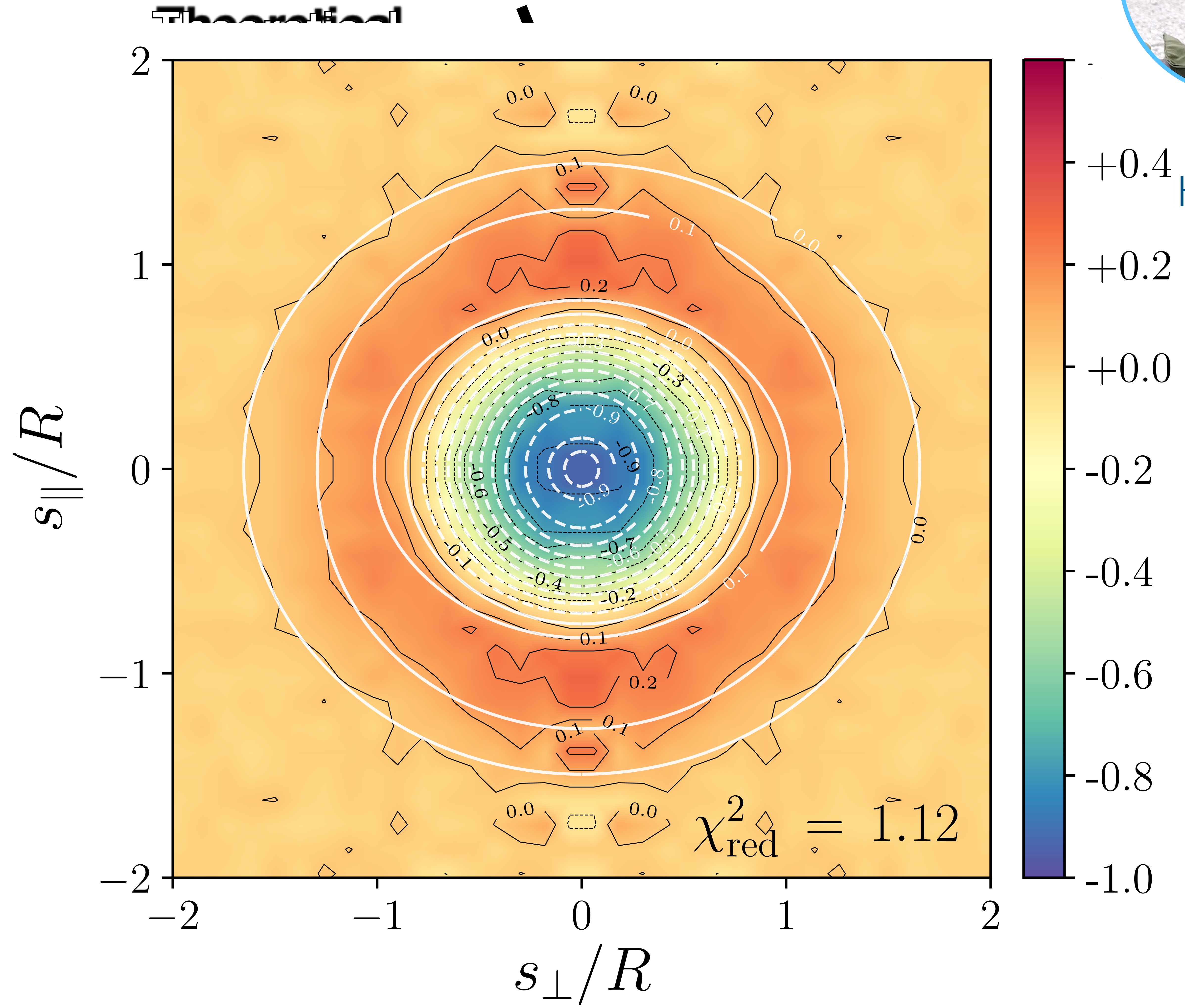
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP

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

Tested on mocks

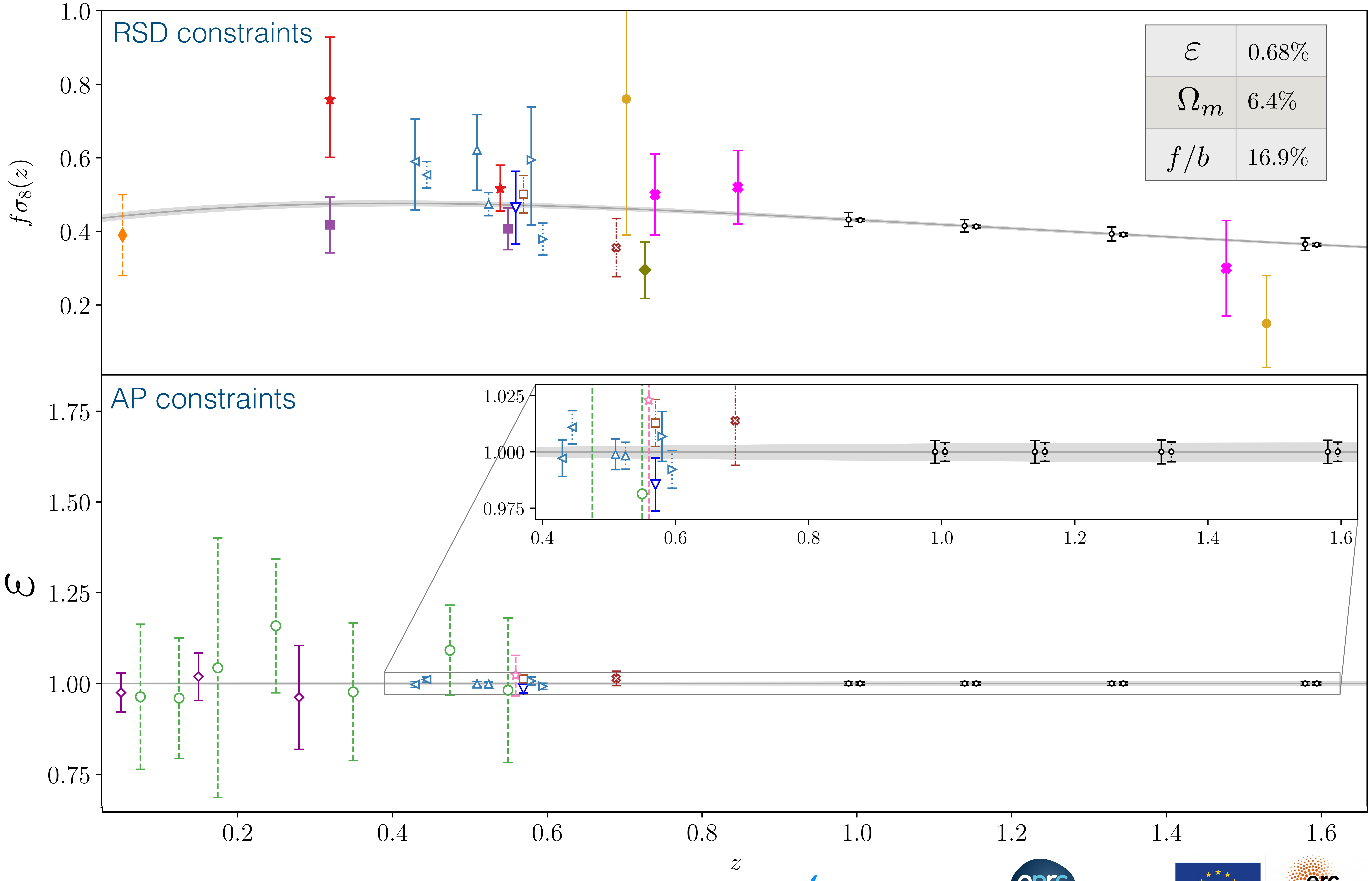


Measure on mocks



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

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

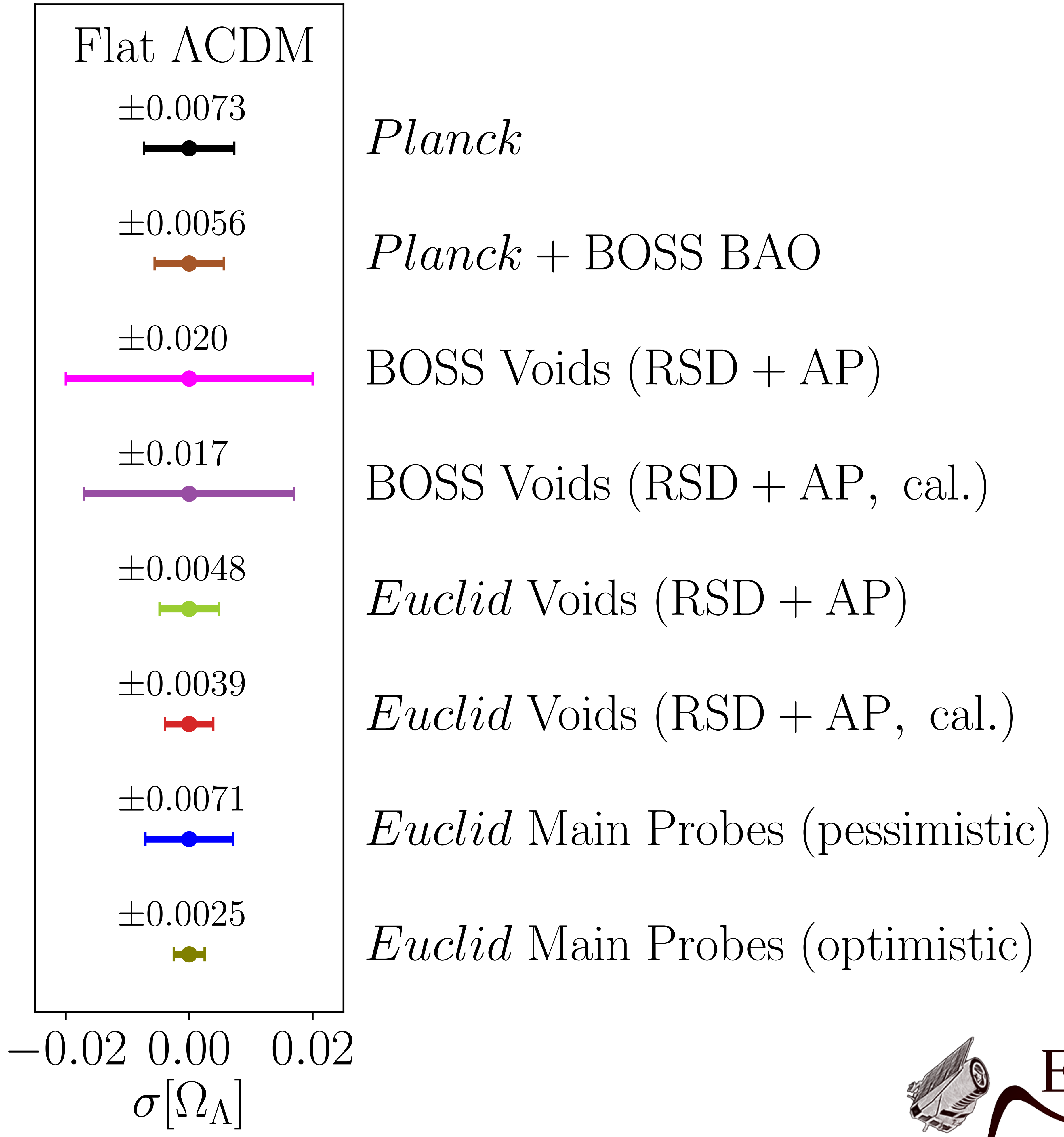
Hamaus, Aubert, Pisani et al. 2022 Euclid collaboration paper ArXiv: 2108.10347 A&A

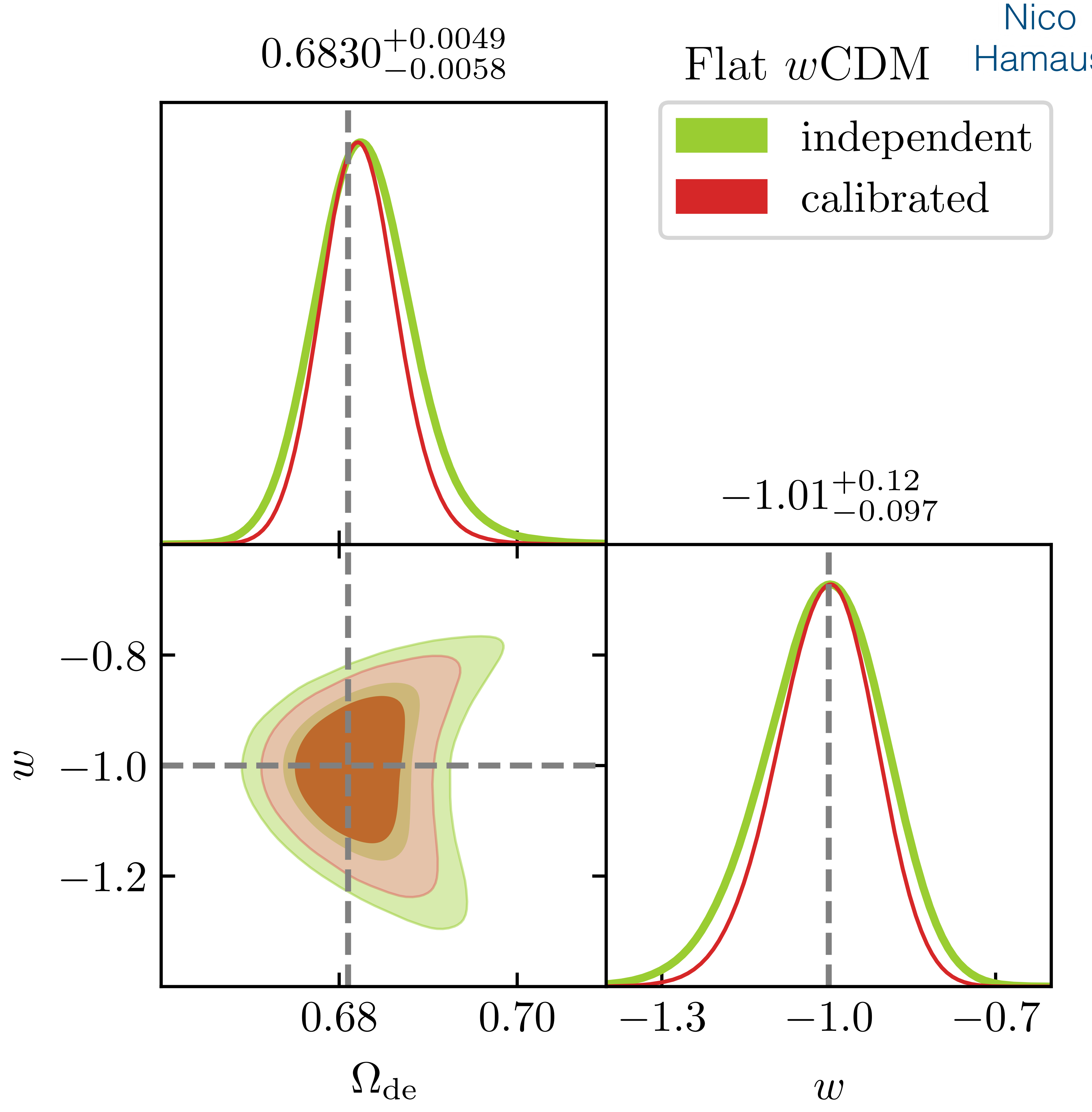
The *observed* void-galaxy cross-correlation function ξ_{vg}

How will it perform with future surveys?

Nico Hamaus

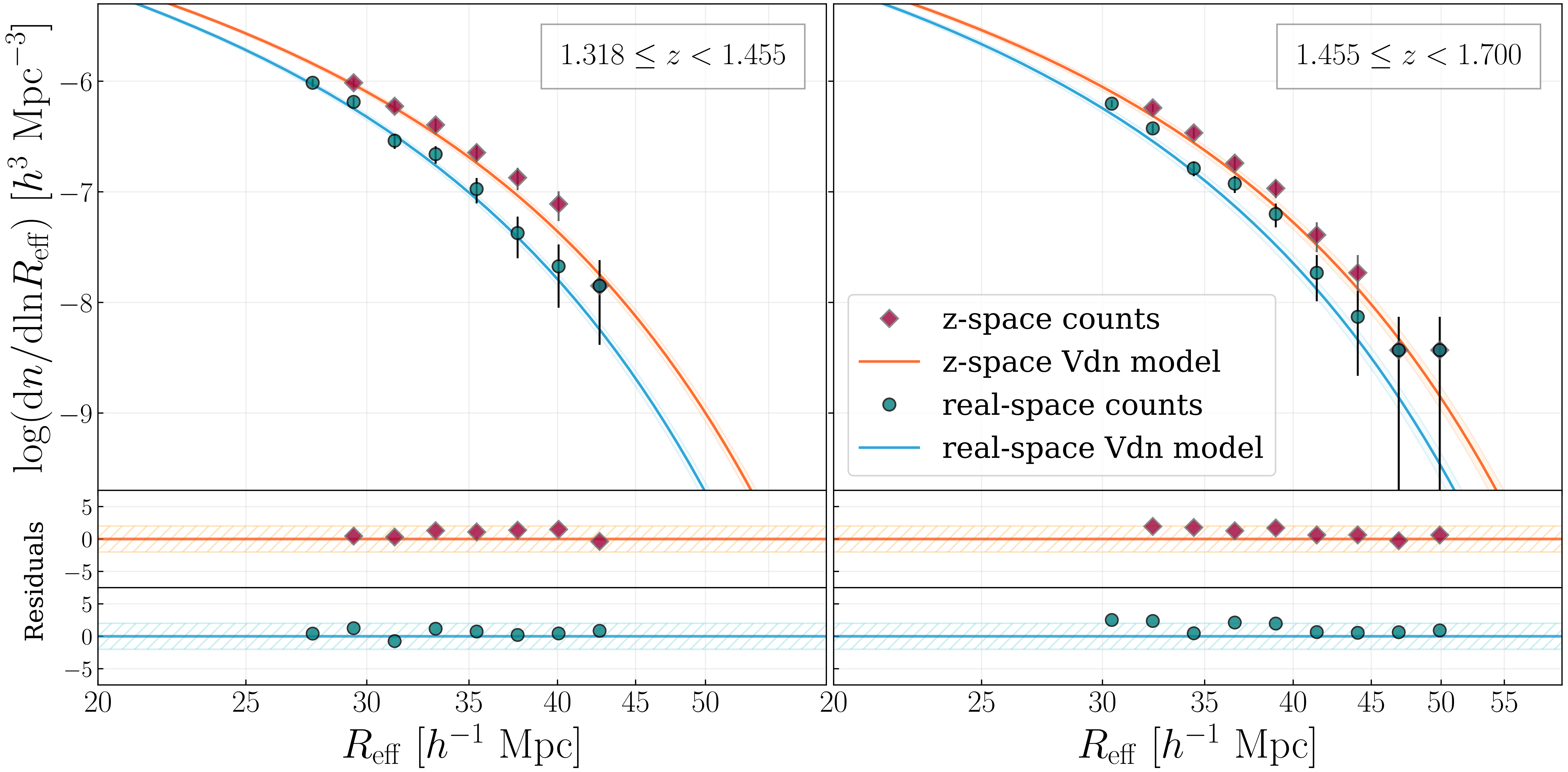
Marie Aubert





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

The void size function



Sofia Contarini

Giovanni Verza

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

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

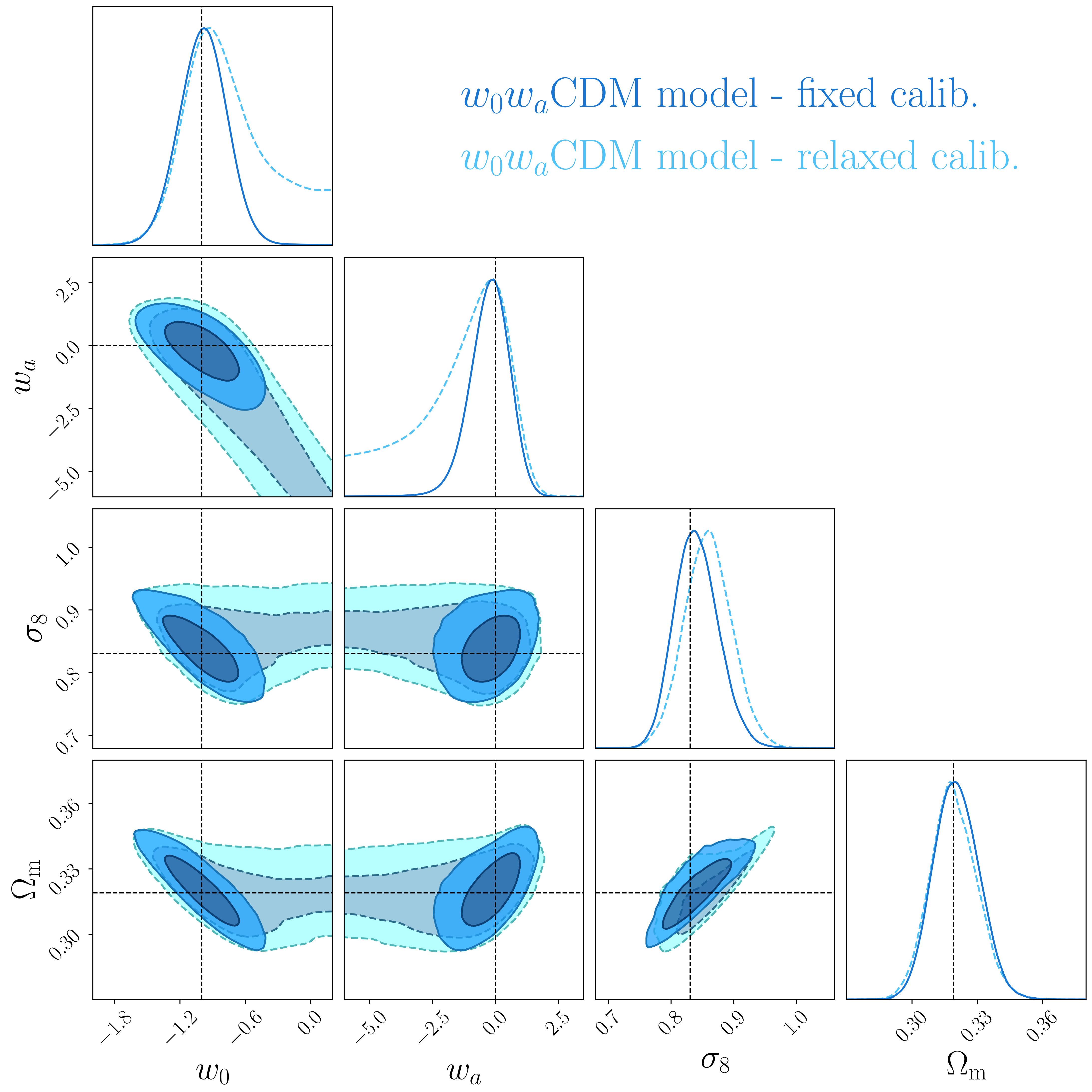
$$\delta^{\mathrm{NL}}_{\mathrm{v,DM}} = \frac{\delta^{\mathrm{NL}}_{\mathrm{v,tr}}}{\mathcal{F}(b_{\mathrm{eff}}, z)}, \quad \text{with}$$

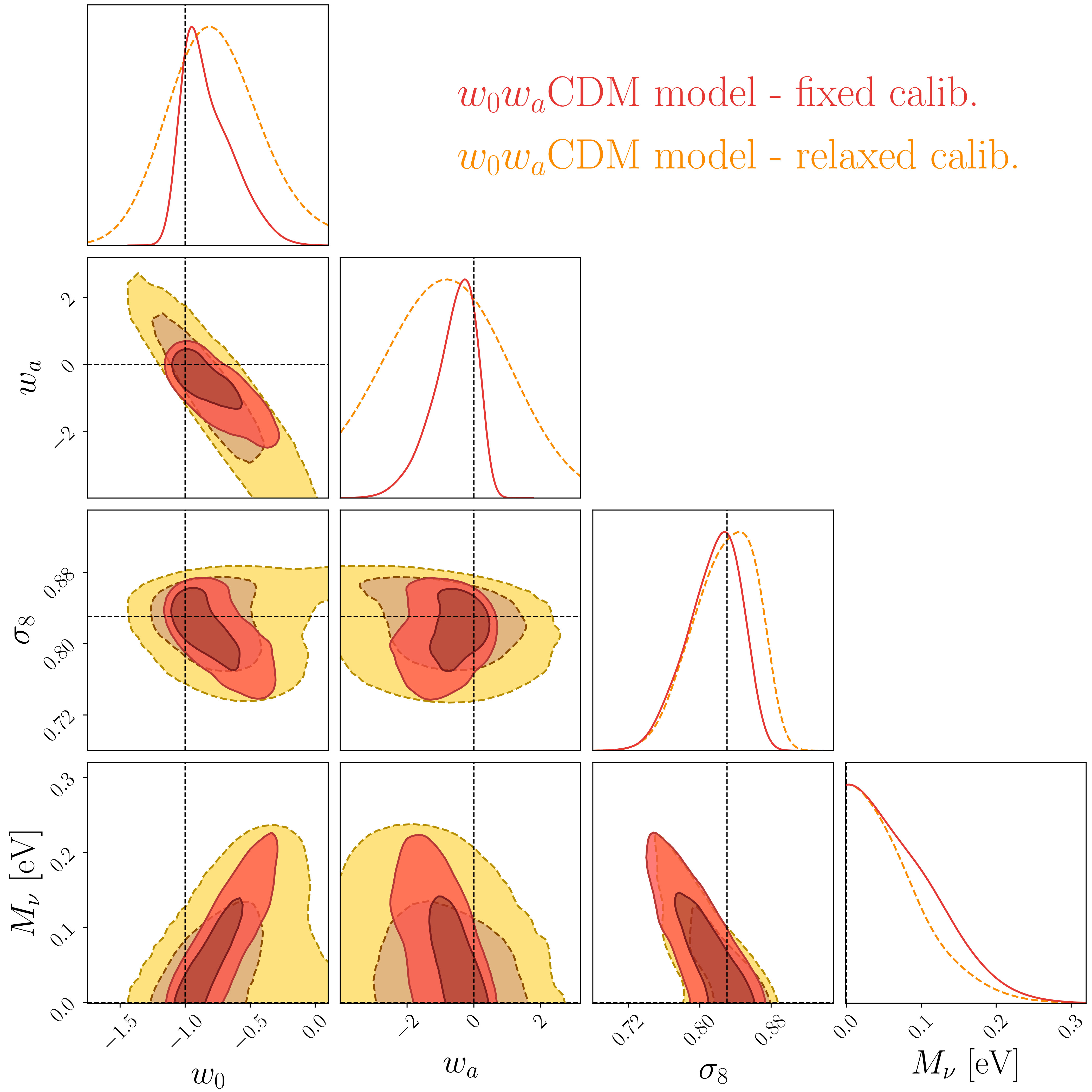
$$\mathcal{F}(b_{\mathrm{eff}}, z) = B_{\mathrm{slope}}\, b_{\mathrm{eff}}(z) + B_{\mathrm{offset}}$$

Large scale effective bias

Euclid Voids

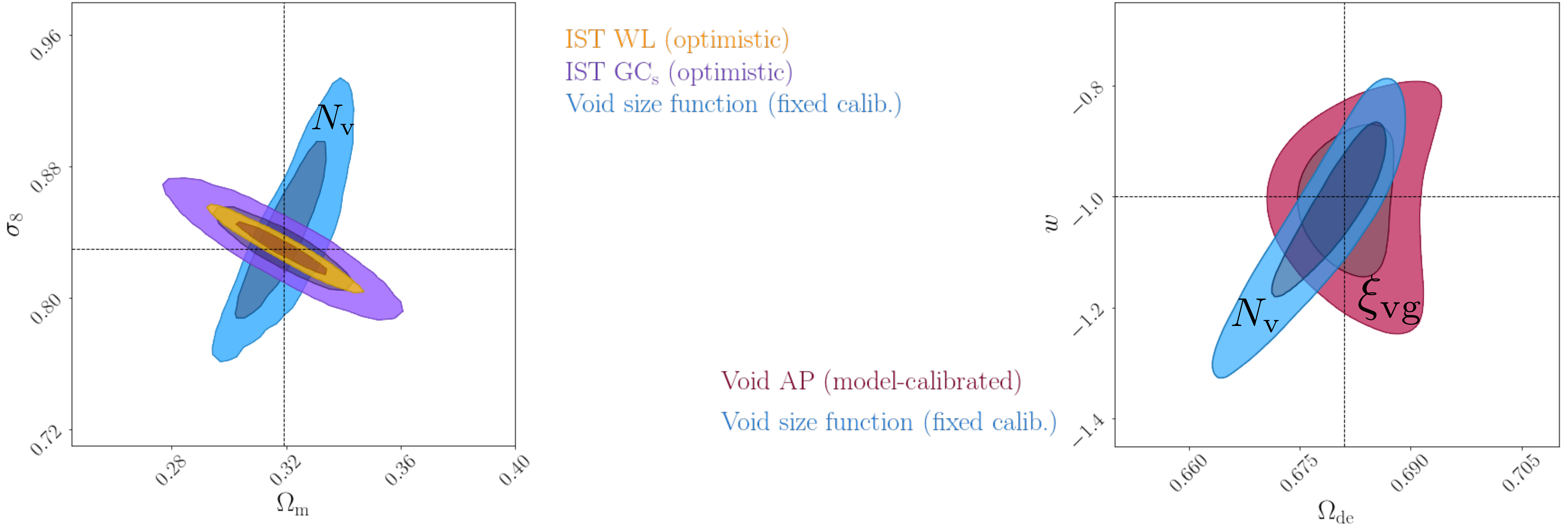
The void size function: Euclid forecasted constraints





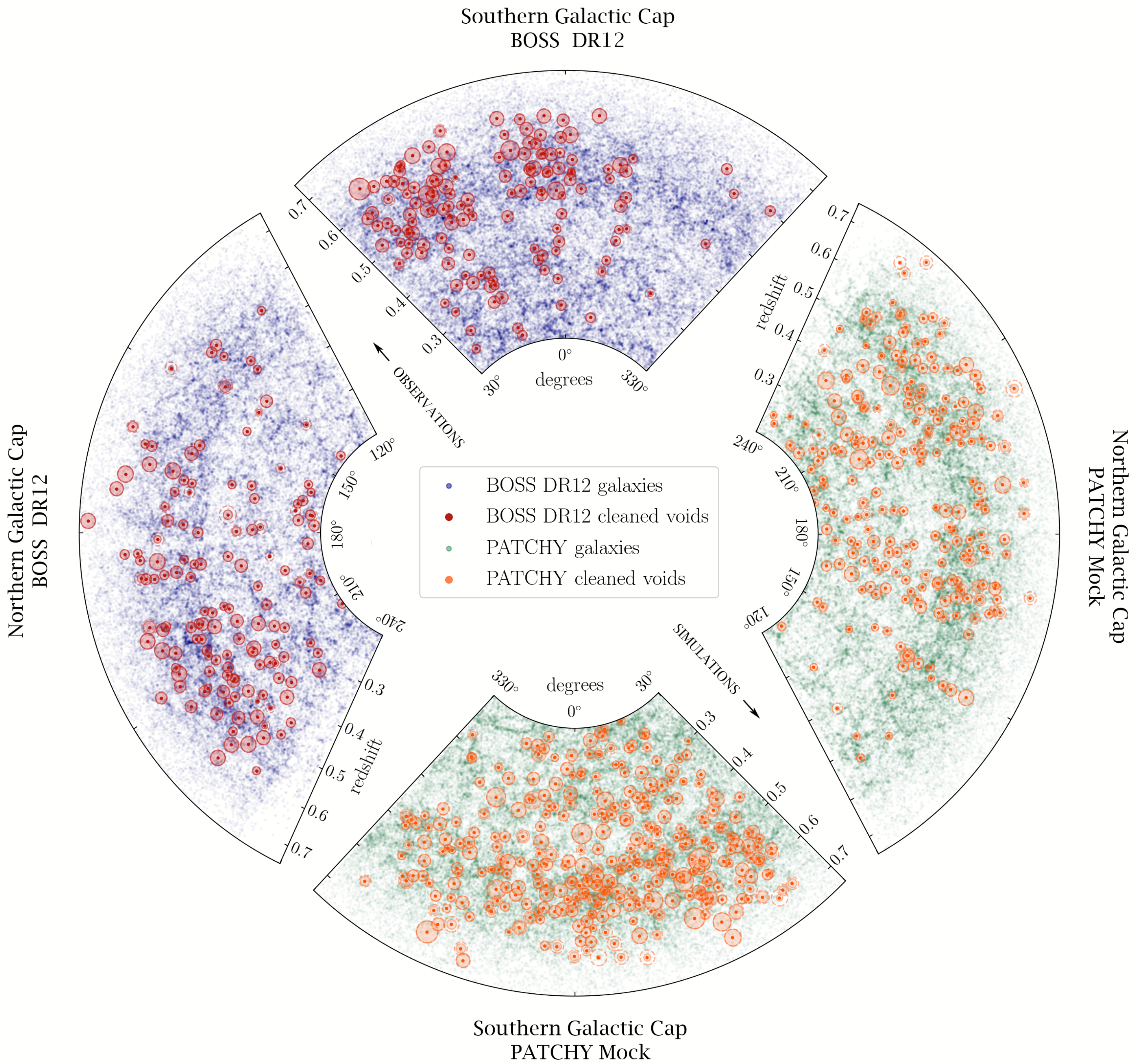
Contarini, Verza, Pisani et al.
2022 Euclid collaboration paper
A&A, ArXiv: 2205.11525

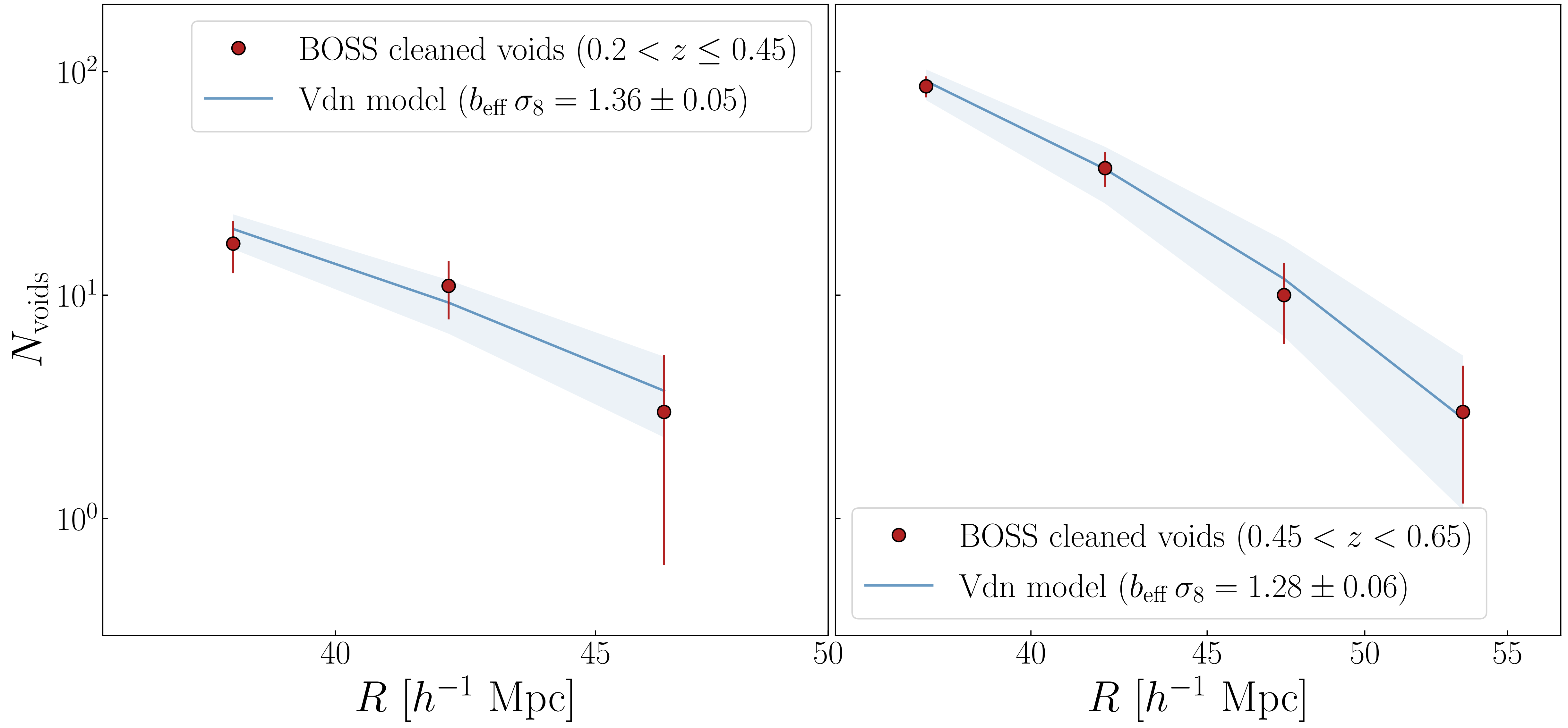
The void size function: forecasted constraints *combined*



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

The void size function: first data application





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

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

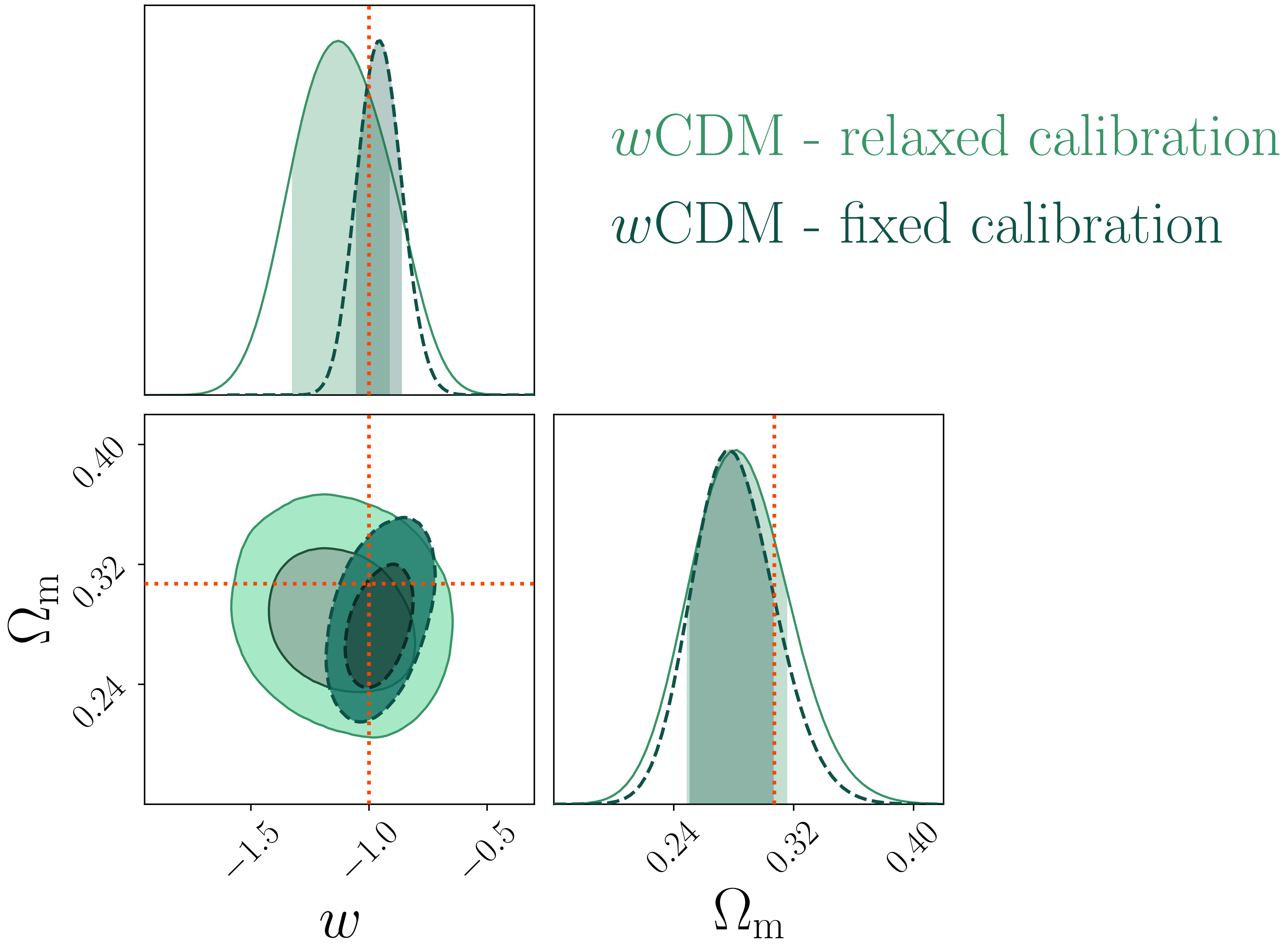
$$\mathcal{F}(b_{\rm eff}, z) = B_{\rm slope}\, b_{\rm eff}(z) + B_{\rm offset}$$

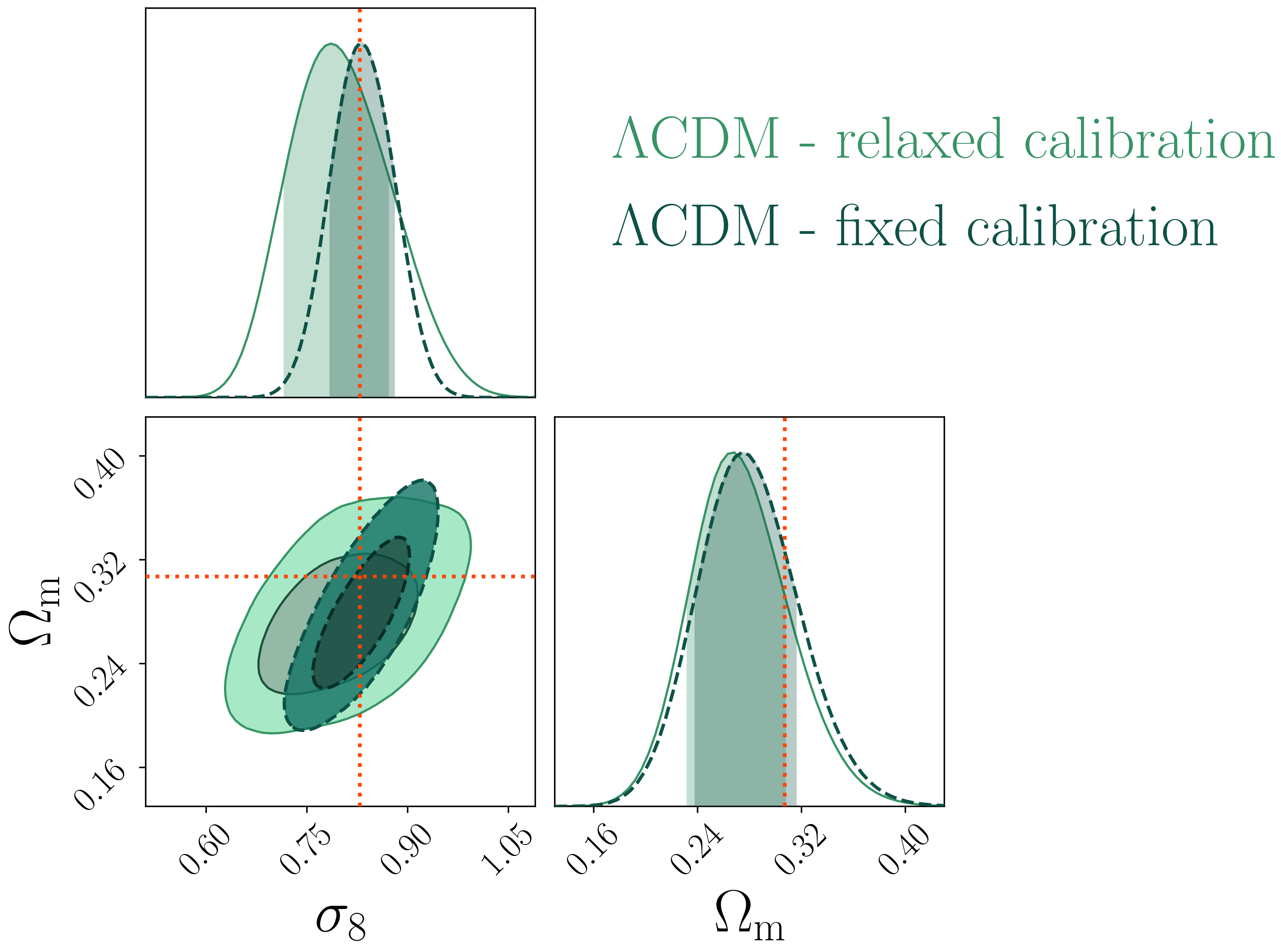
Large scale effective bias

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

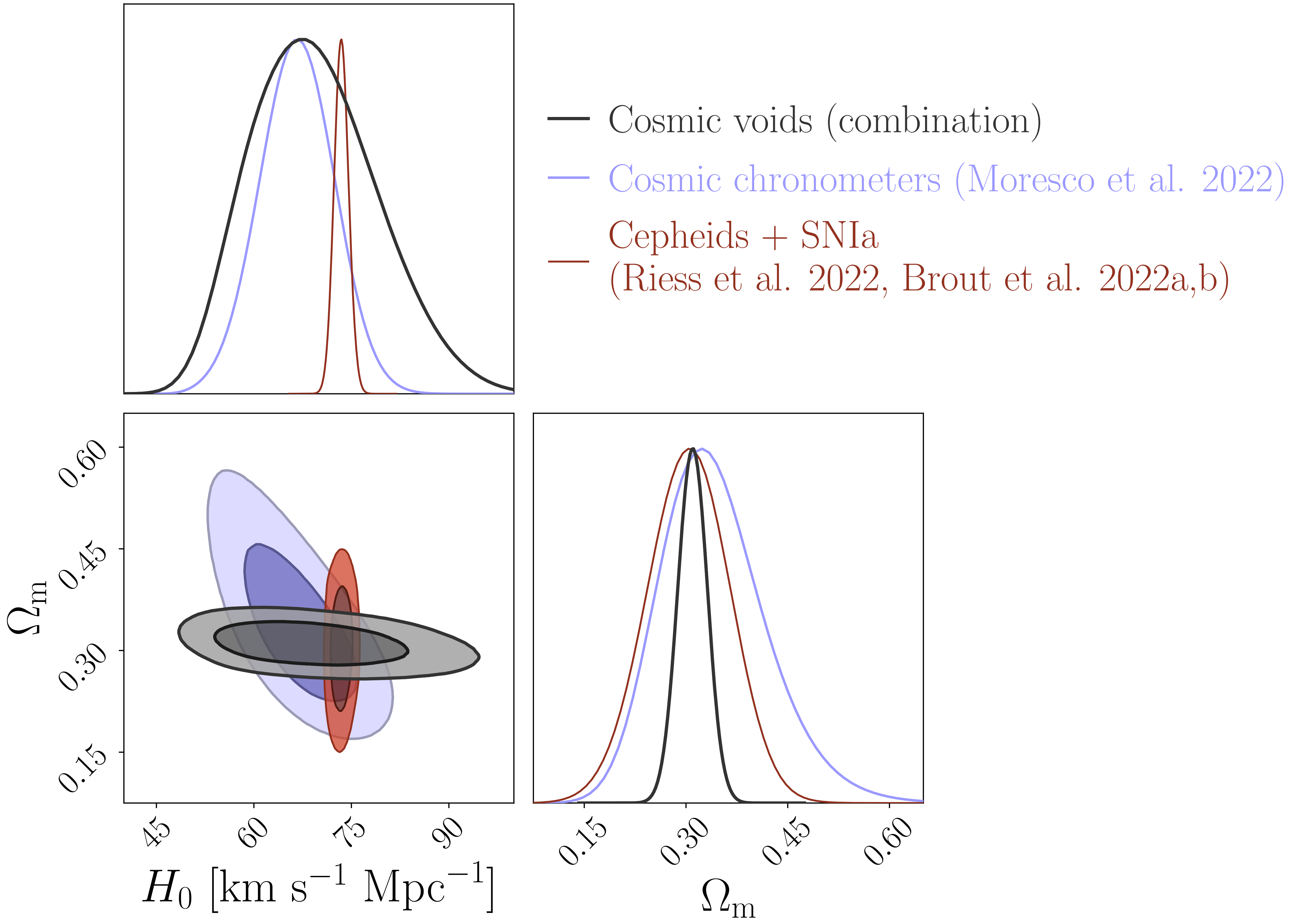
The void size function: first data application

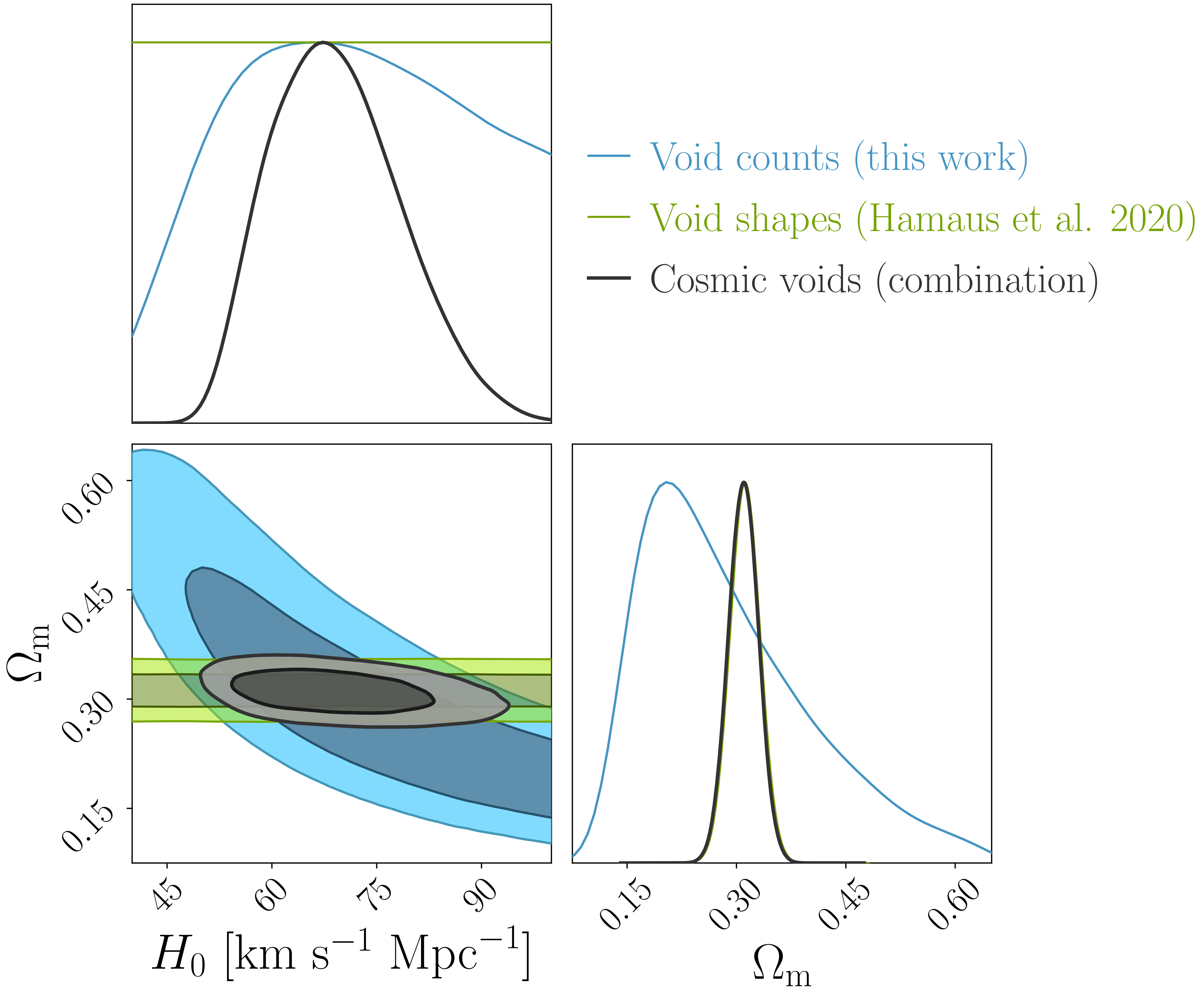




Contarini, Pisani, Hamaus et al.
2022a ArXiv: 2212.03873 , JCAP

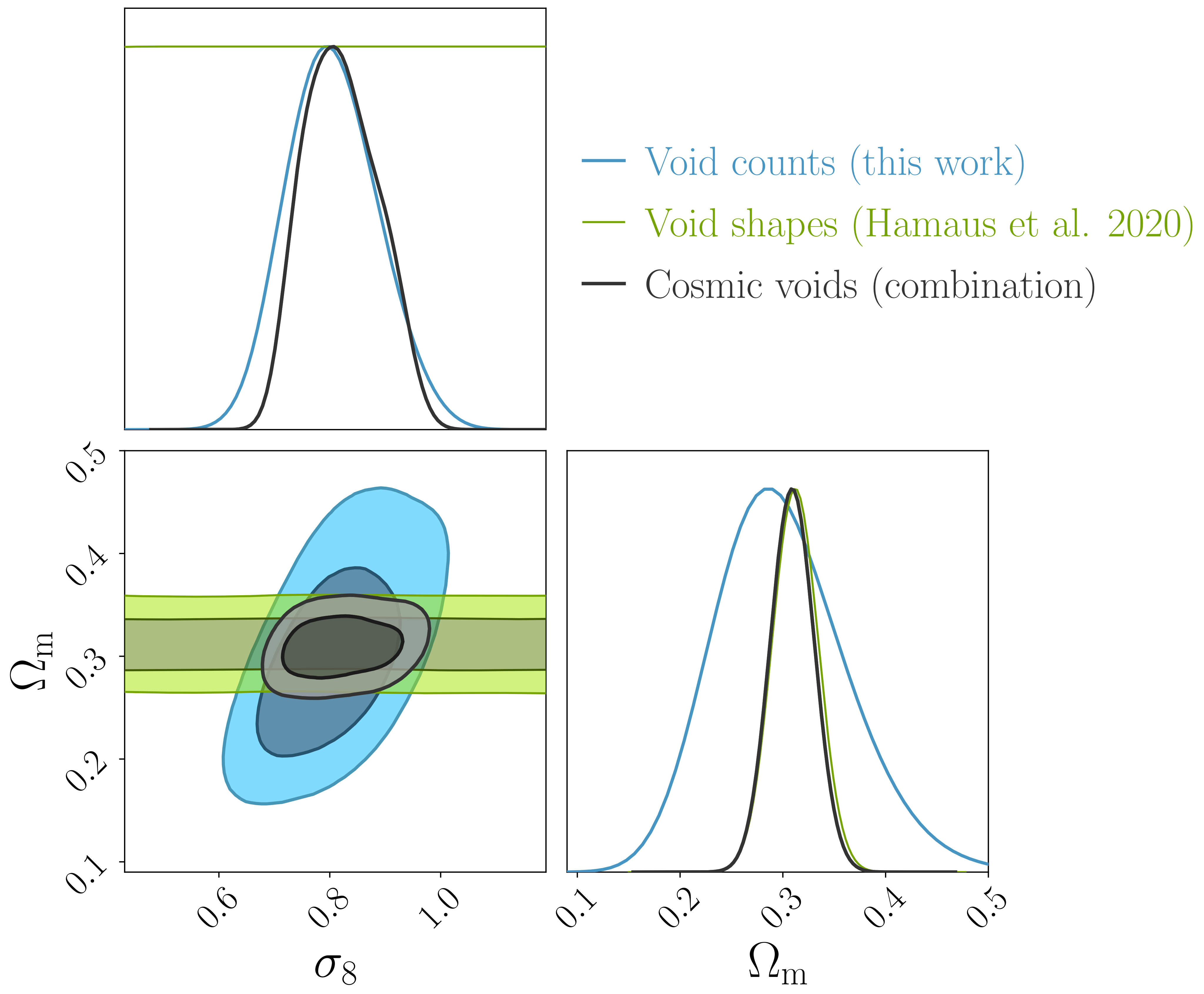
Voids can fill us in on rising cosmology tensions

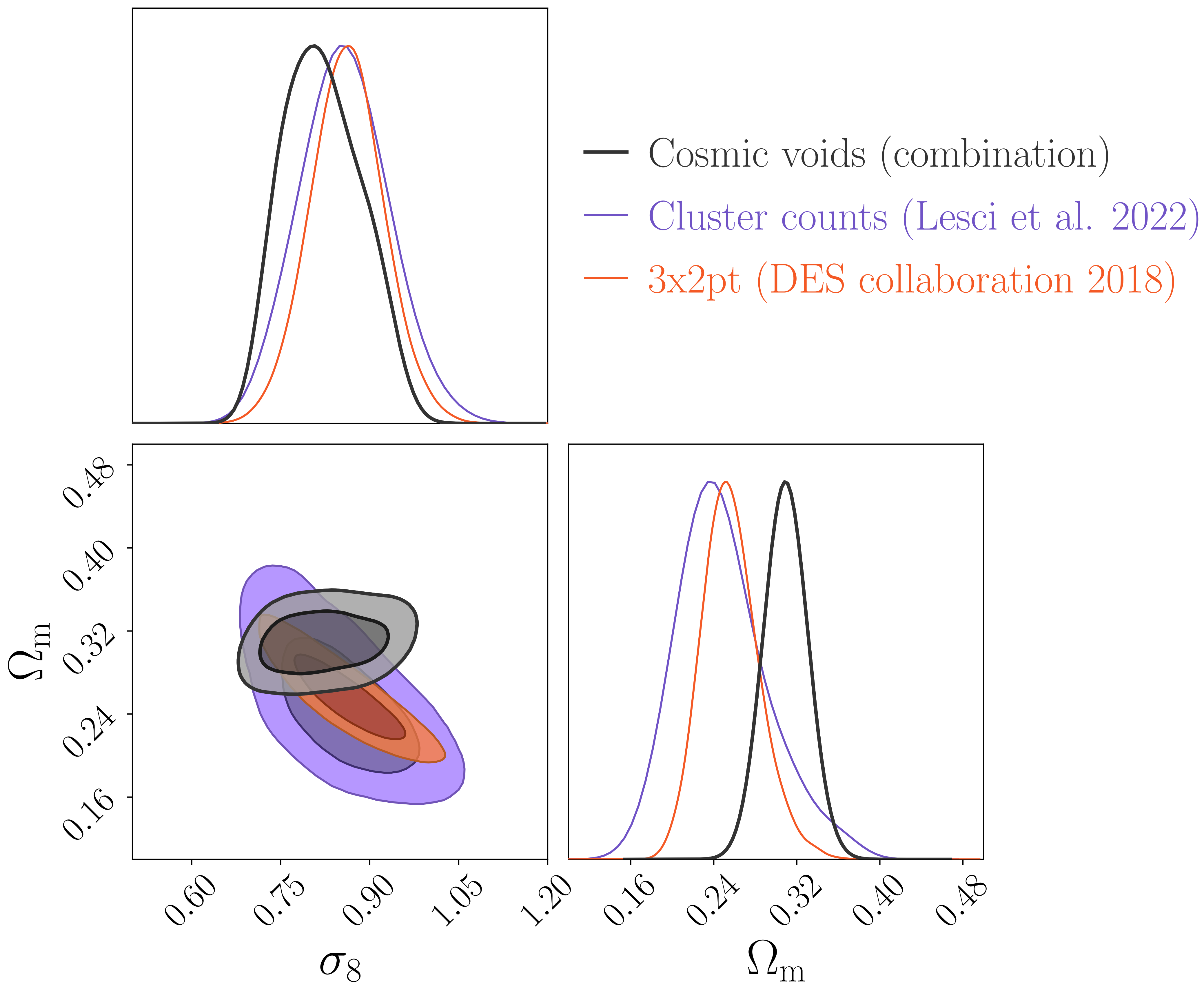




Contarini, Pisani, Hamaus et al.
2022b ArXiv: 2212.07438 A&A

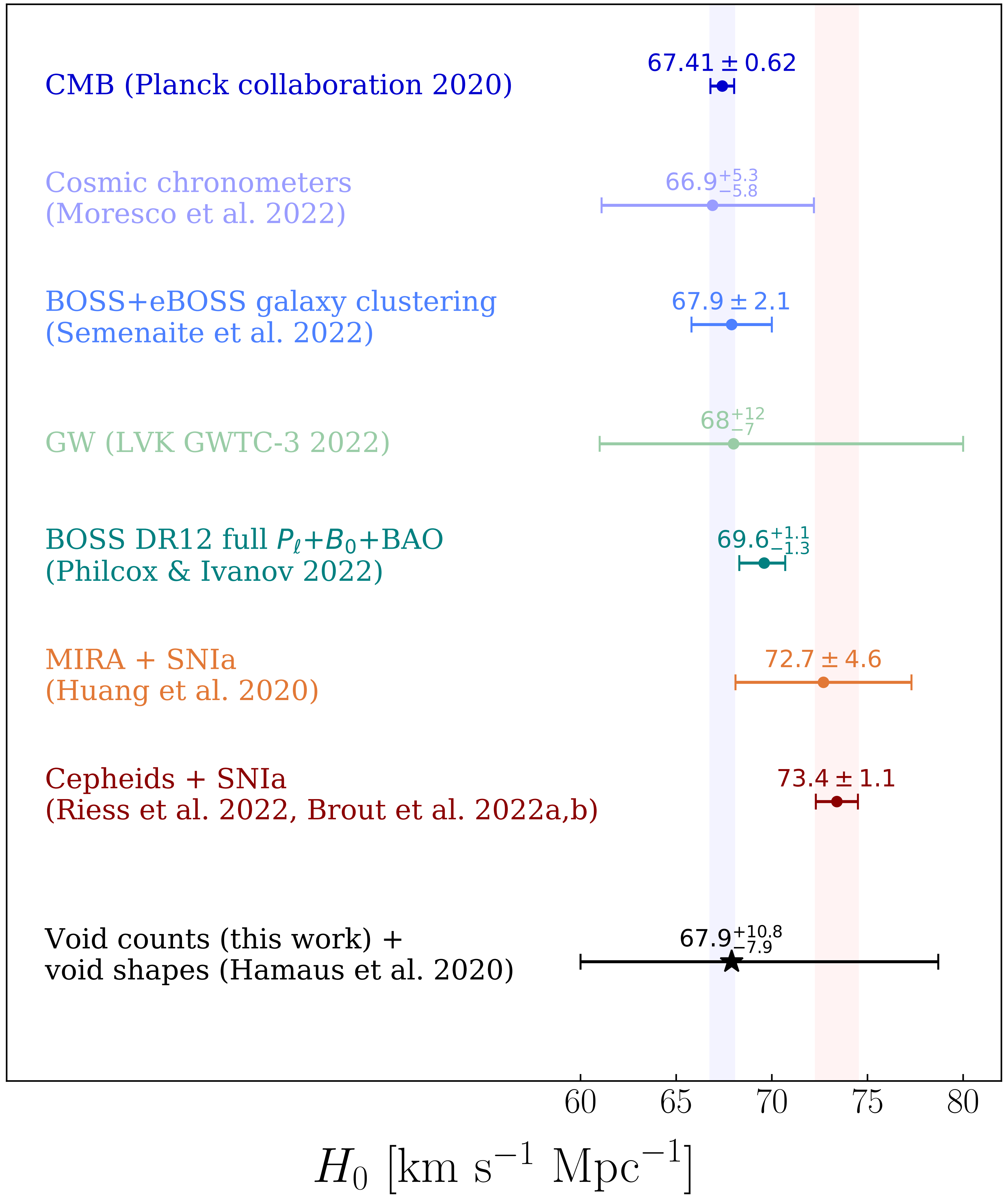
Voids can fill us in on rising cosmology tensions

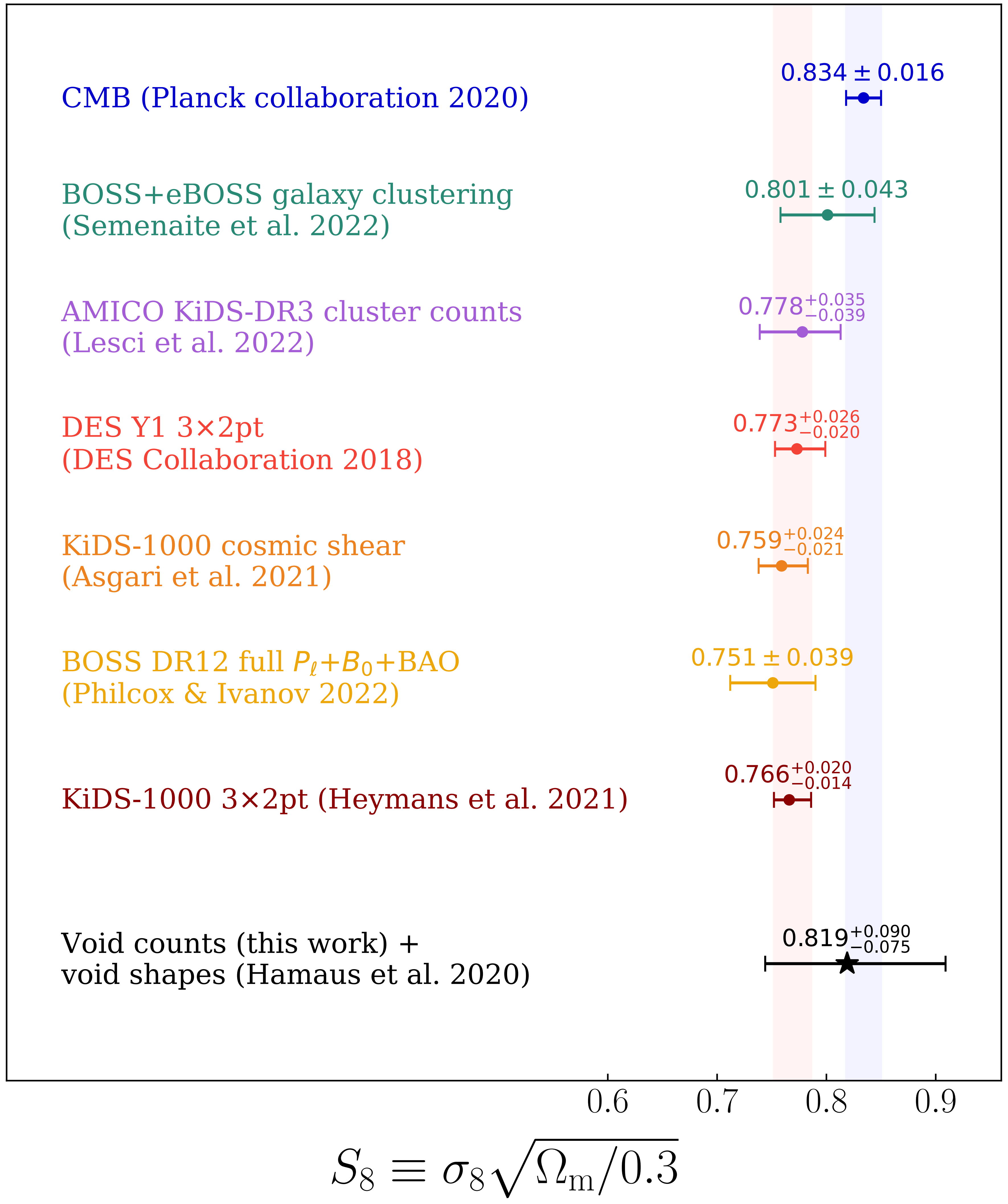




Contarini, Pisani, Hamaus et al.
2022b ArXiv: 2212.07438 A&A

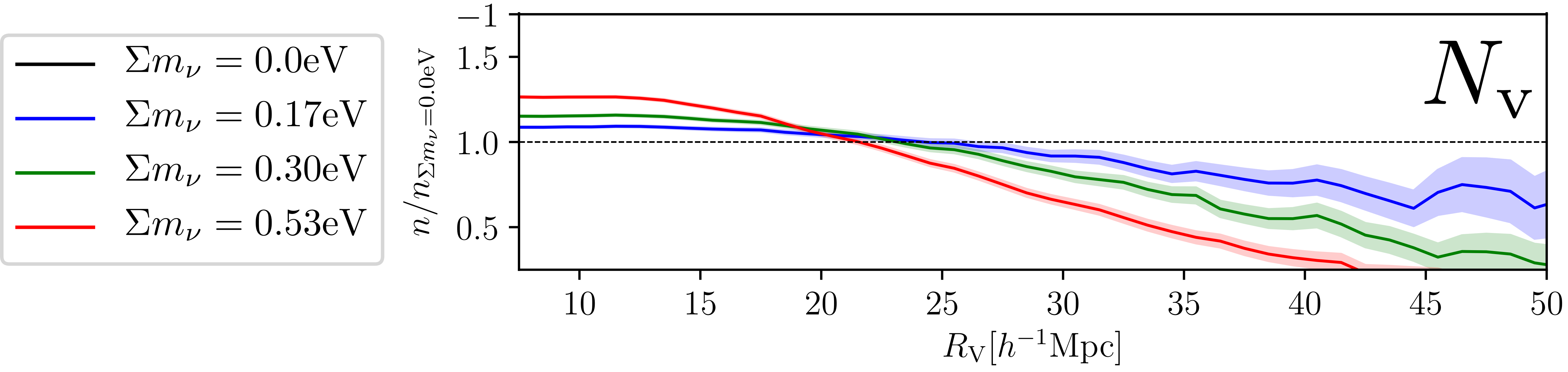
Voids can fill us in on rising cosmology tensions

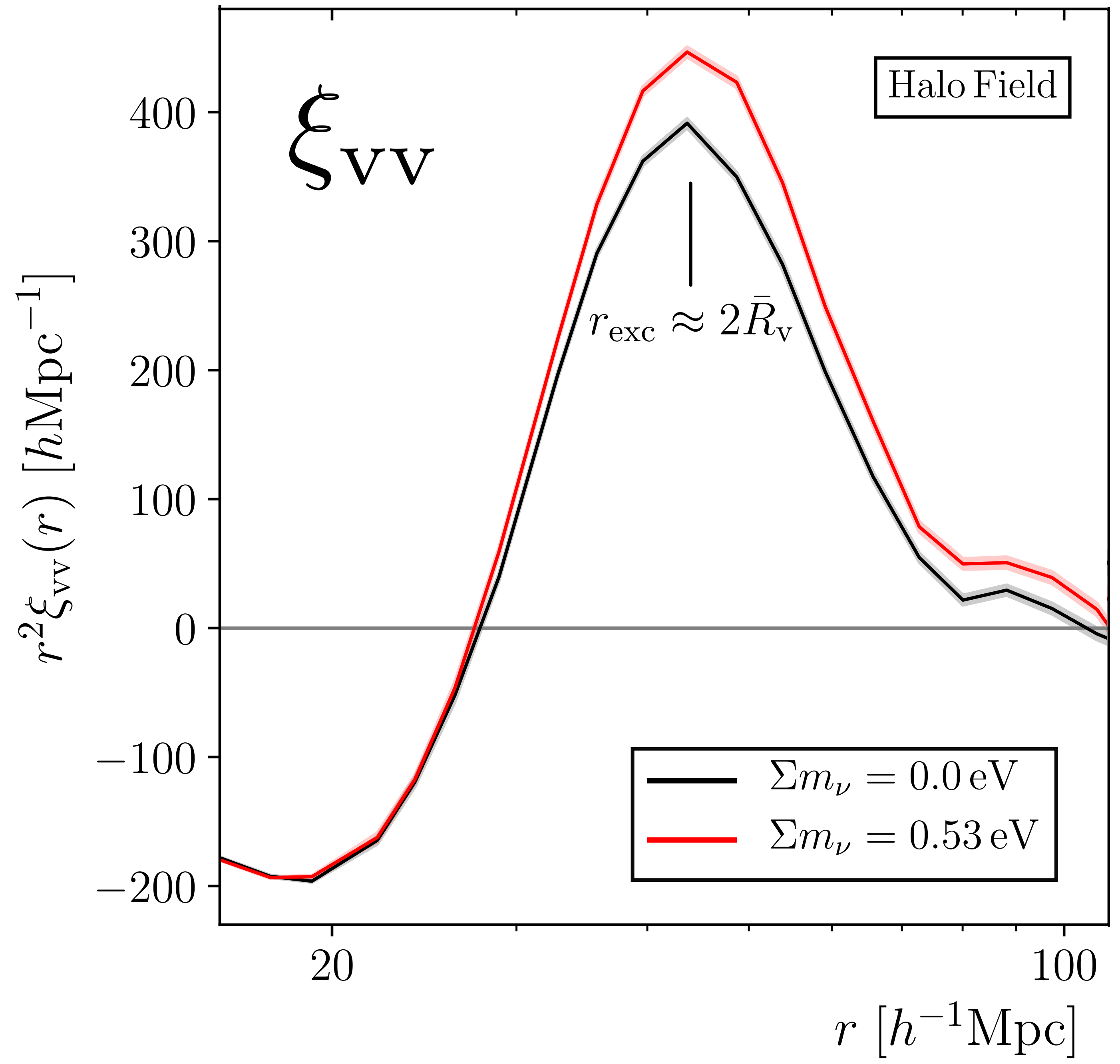




Contarini, Pisani, Hamaus et al. 2022b ArXiv: 2212.07438 A&A

What about 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

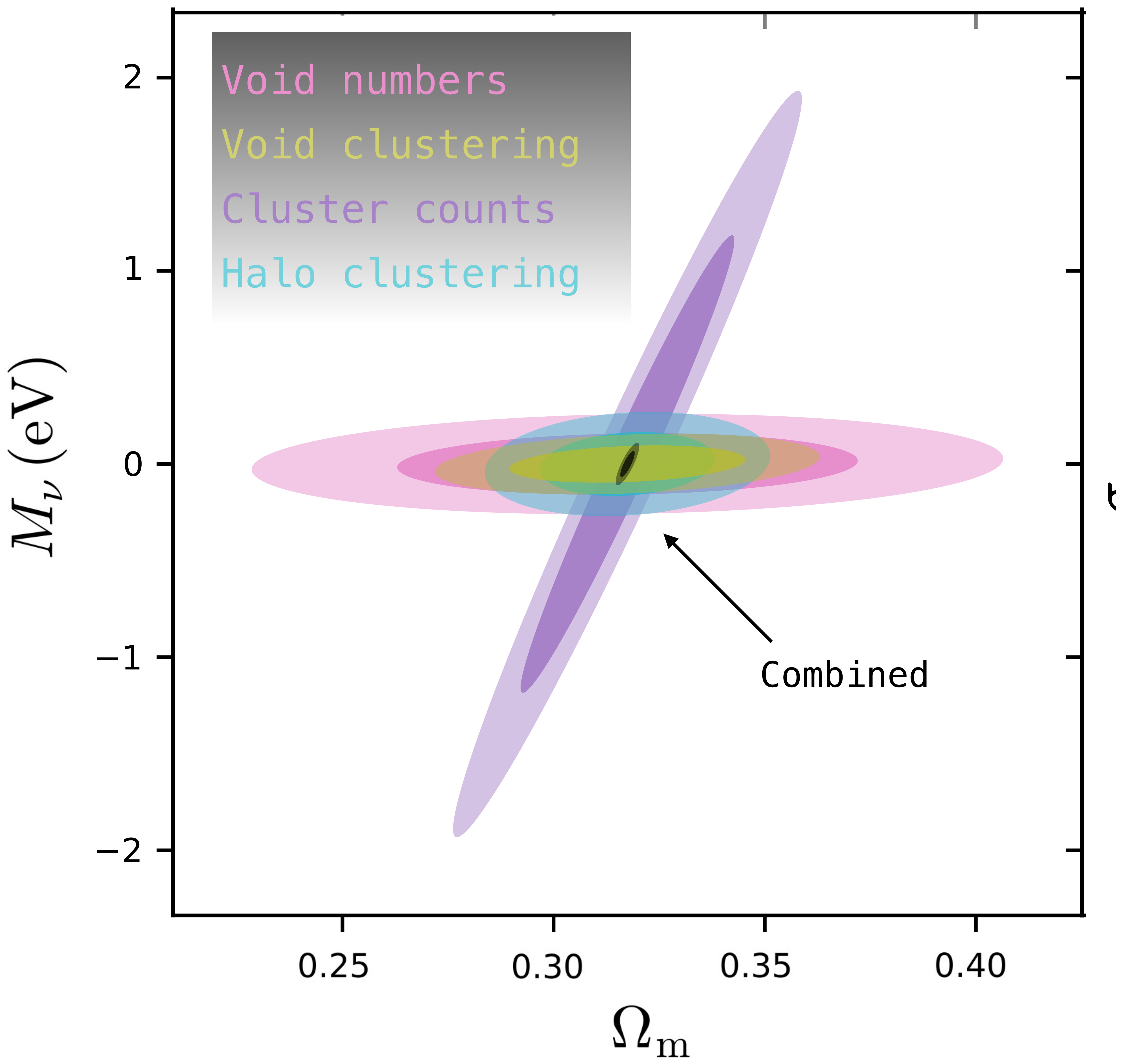
Code:
Gadget-2
1024^3 DM particles
512Mpc/h box
+ kspace-neutrino
+ LensTools
+ Rockstar
+ Consistent Tree

Liu et al. 2018

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

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

What about neutrinos?



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

The GIGANTES void catalogs suite:
15000 VIDE void catalogs ΛCDM
+ 7000 cosmologies

https://gigantes.readthedocs.io/

But for neutrinos the theoretical aspect needs development, and modelling all the statistics together is a challenge…

What about neutrinos?

Simulation Based Inference: Learn the likelihood from simulated samples

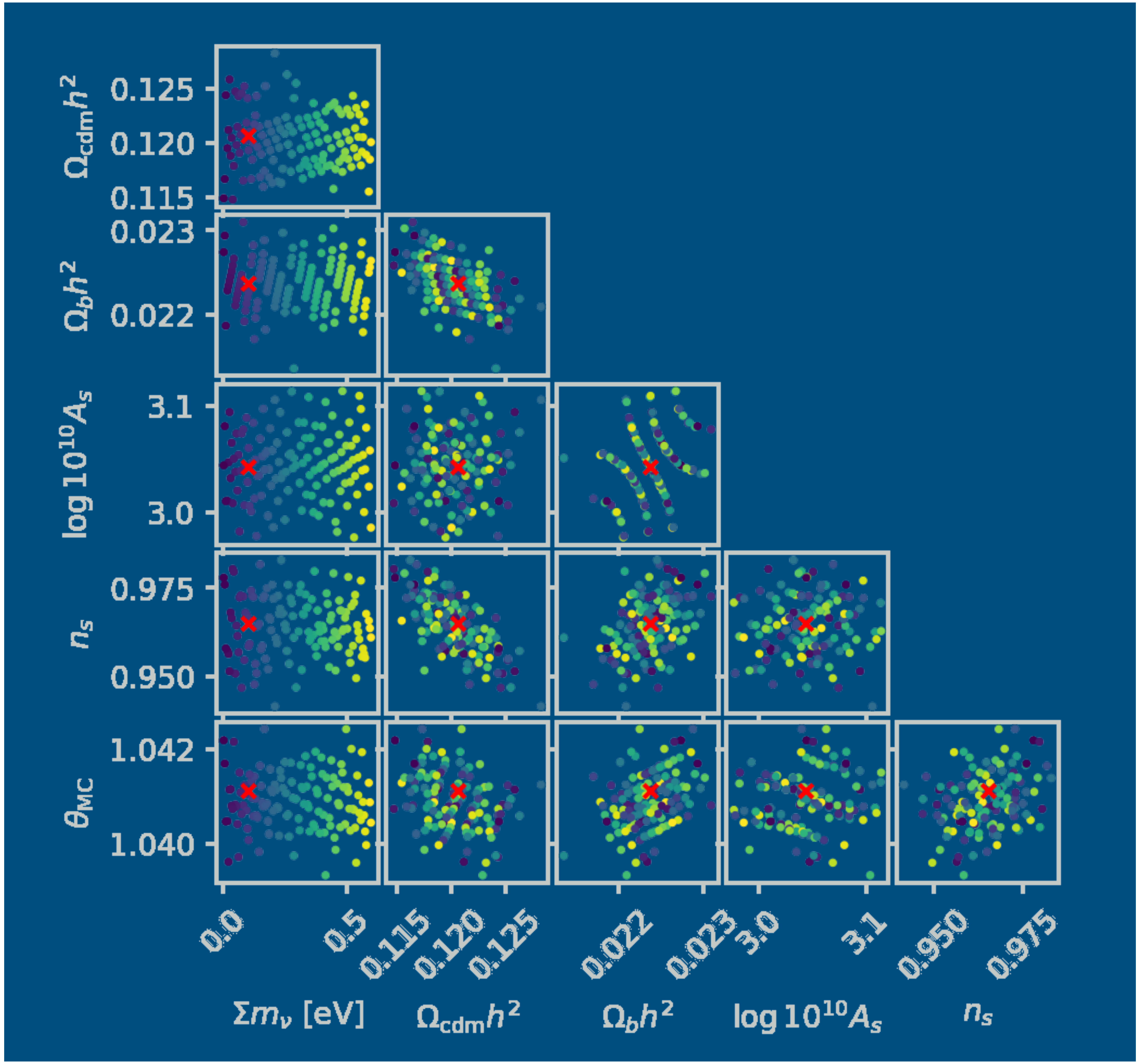
Leander Thiele

1) Building the simulations

- Using halo occupation distribution, tuned on preliminary tests with QUIJOTE sims and data.
- Standard 5-dim HOD plus
- velocity biases
- linear redshift evolution
- secondary/assembly bias

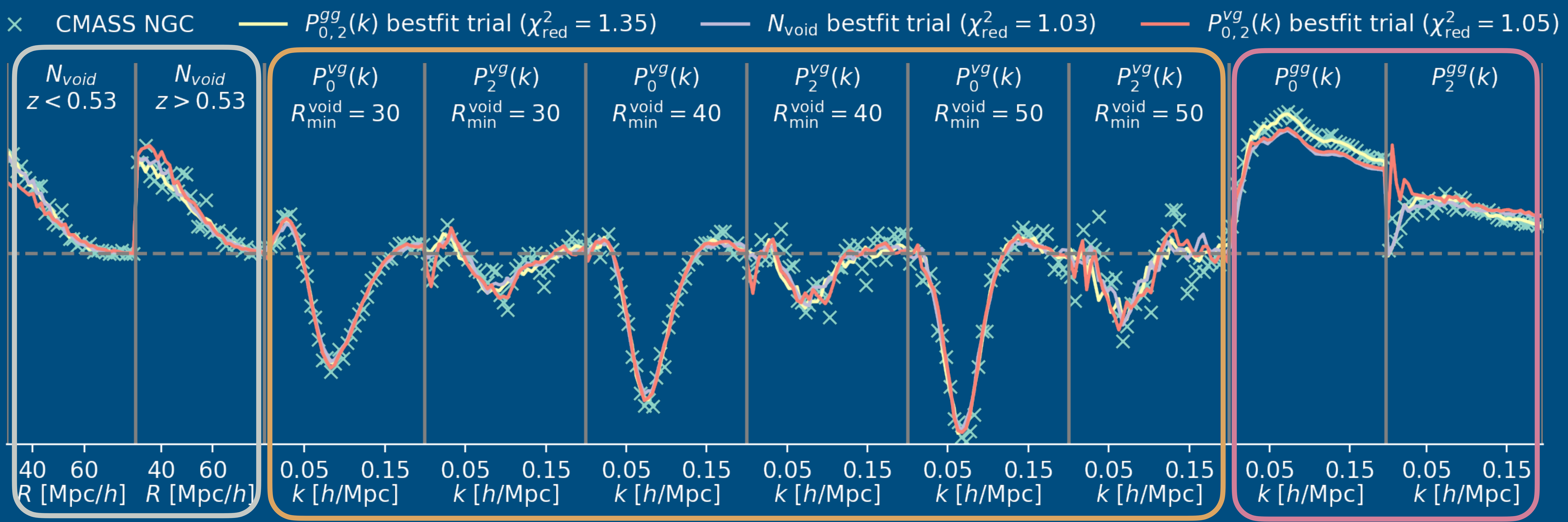
2) Create a light-cone

- mask
- fiber collisions
- n(z)



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

What about neutrinos?

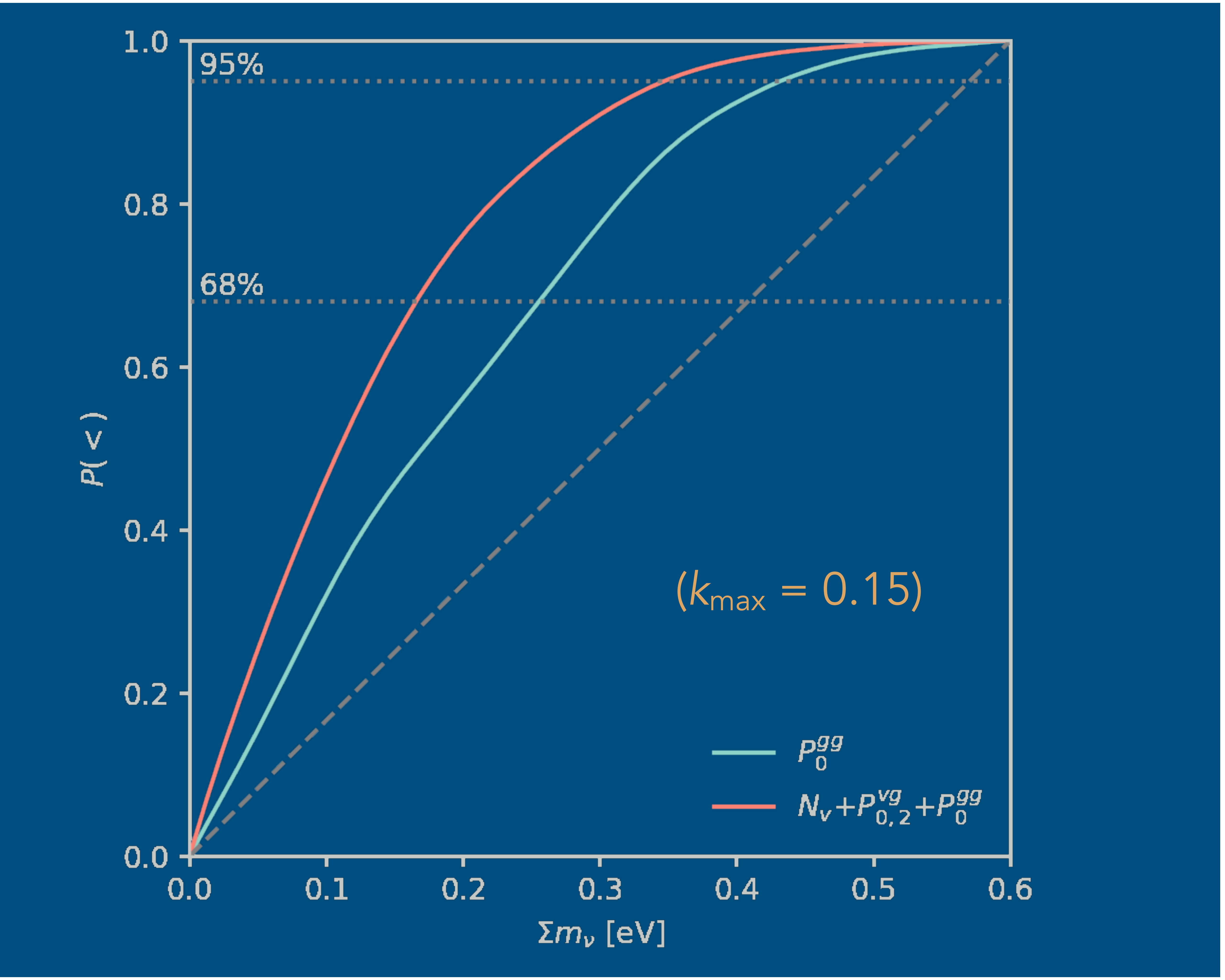


Leander Thiele

- galaxy auto power spectrum
- void size function
- void galaxy cross power spectrum

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

Hints of neutrinos constraints!



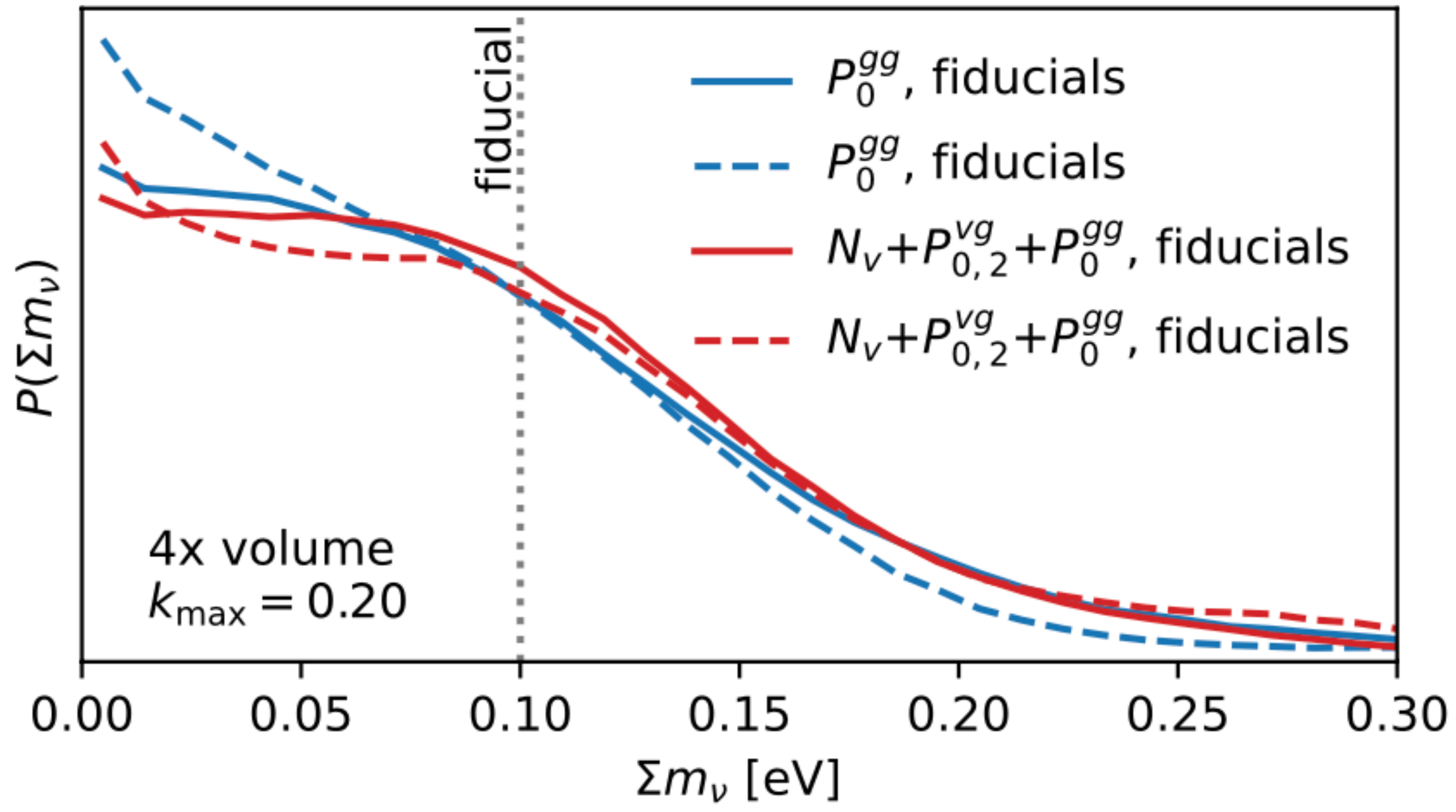


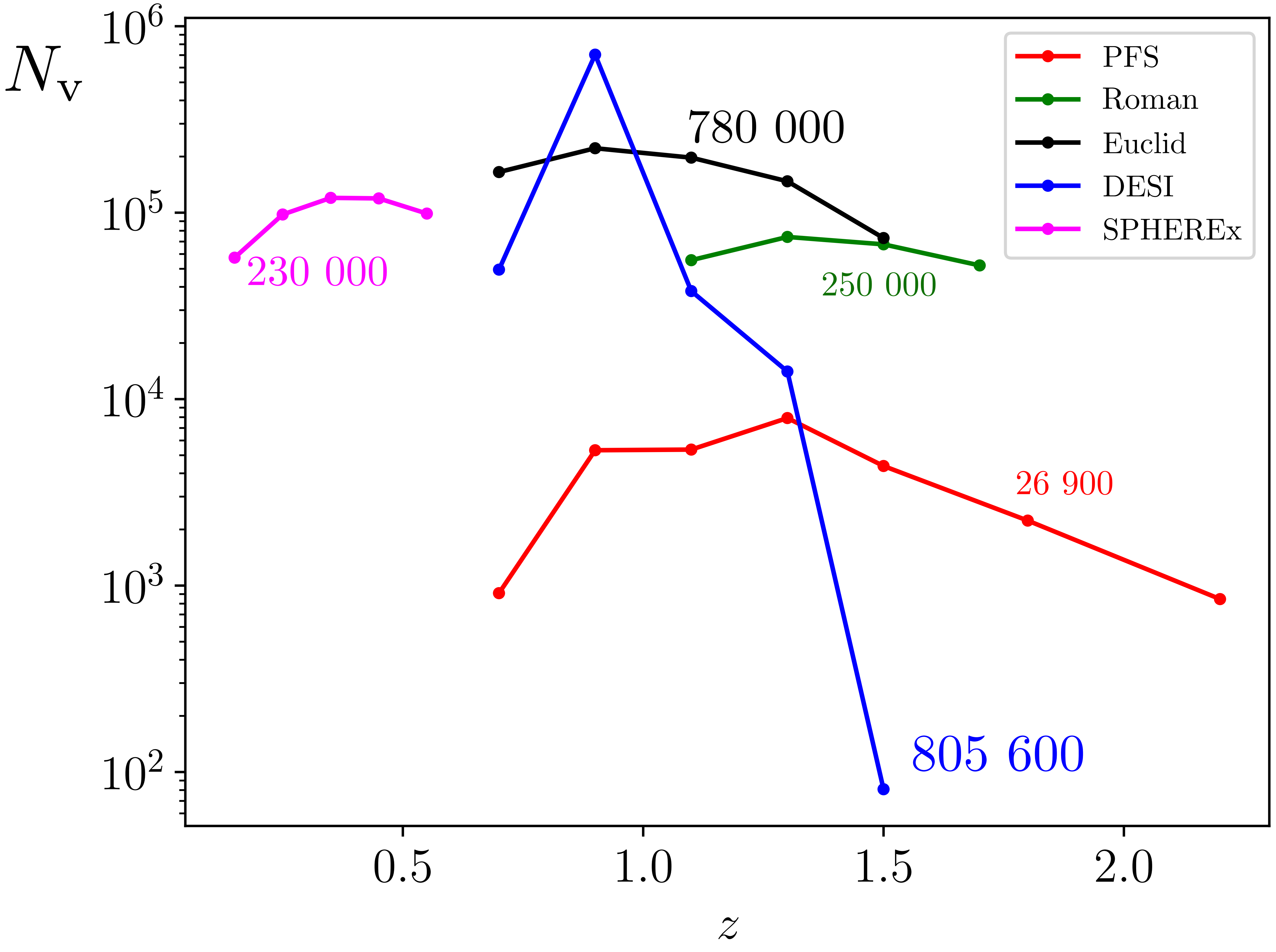
Figure 14. Posteriors on joint analyses of four randomly chosen fiducial mocks, averaged over ∼ 30 groups. The solid and dashed lines correspond to likelihoods with two different sets of five nuisance parameters kept explicit. We see that the posteriors where void statistics are included have a slightly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

Leander Thiele

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

Hundreds of thousands of voids



Number density also plays a role!

Take home messages

- Void analysis: active field of galaxy clustering!
- Many statistics, not at the same degree of maturity
- DESI, Euclid, Rubin, Roman, SPHEREx, PFS : 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!