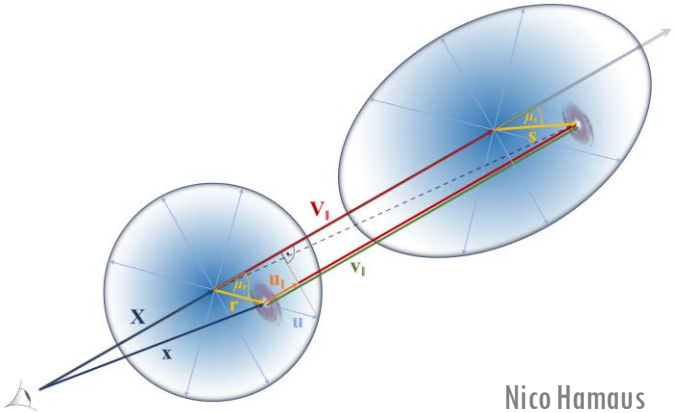
Nico Hamaus

Cosmology with Cosmic Voids

with M. Aubert, M. Biagetti, M. Bonici, C. Carbone, K.C. Chan, S. Contarini, M.-C. Cousinou, K. Dolag, J. Fang, B. Jain, A. Kovacs, C. Kreisch, G. Lavaux, A. Pisani, G. Pollina, N. Schuster, G. Verza, B. Wandelt, J. Weller, et al.

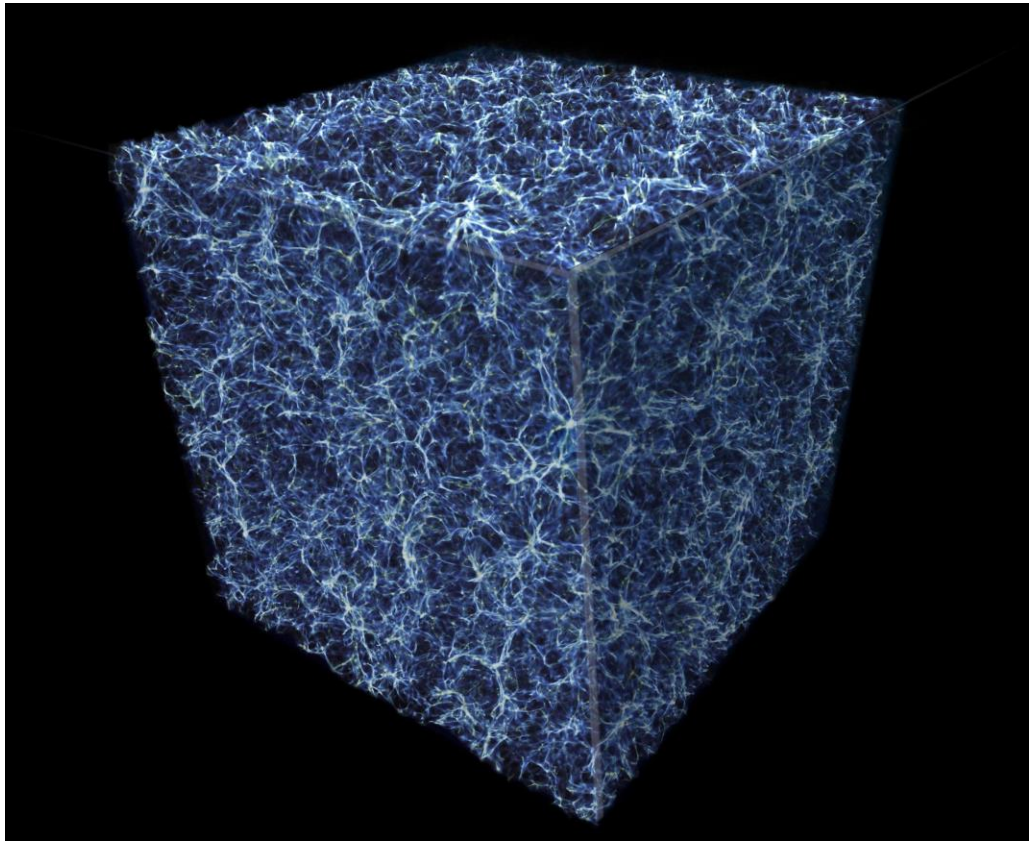


CONTENTS

- Void definition / identification
- Geometric distortions and the Alcock-Paczynski test
- Dynamic distortions and the growth rate of structure
- Void lensing and the density profile
- Void clustering and
  - Primordial non-Gaussianity
  - Massive Neutrinos
  - Baryon Acoustic Oscillations

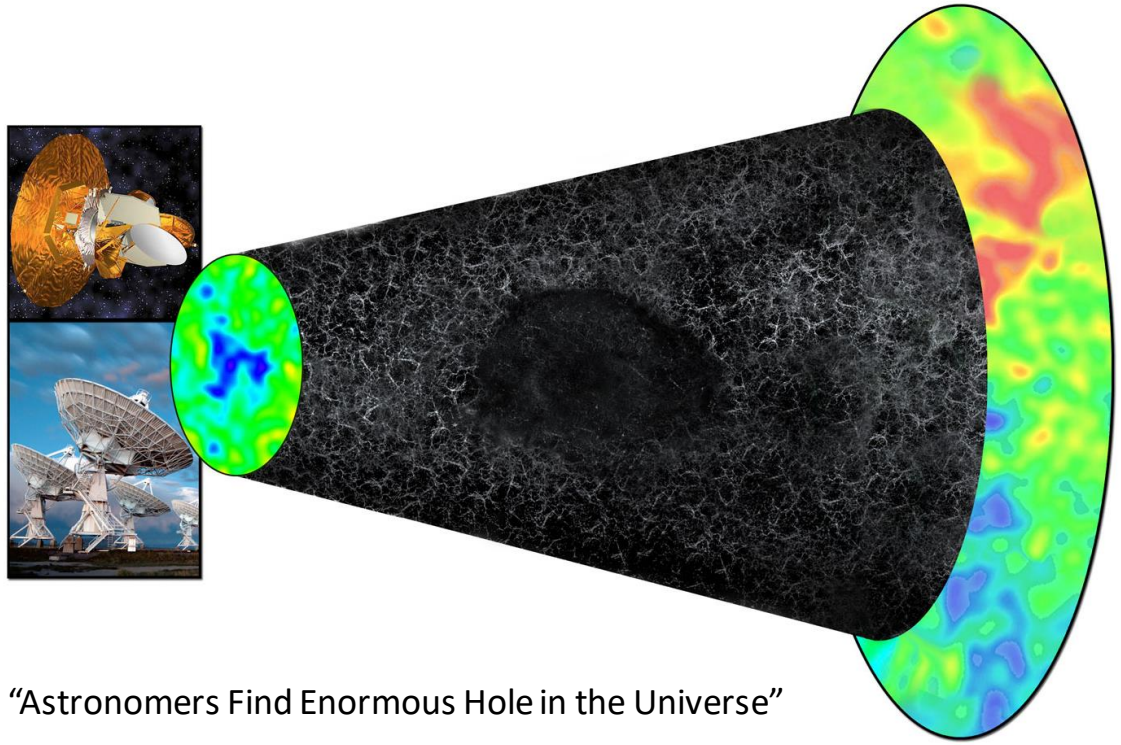
WHAT ARE "COSMIC VOIDS"?

Universe Today



Wikipedia

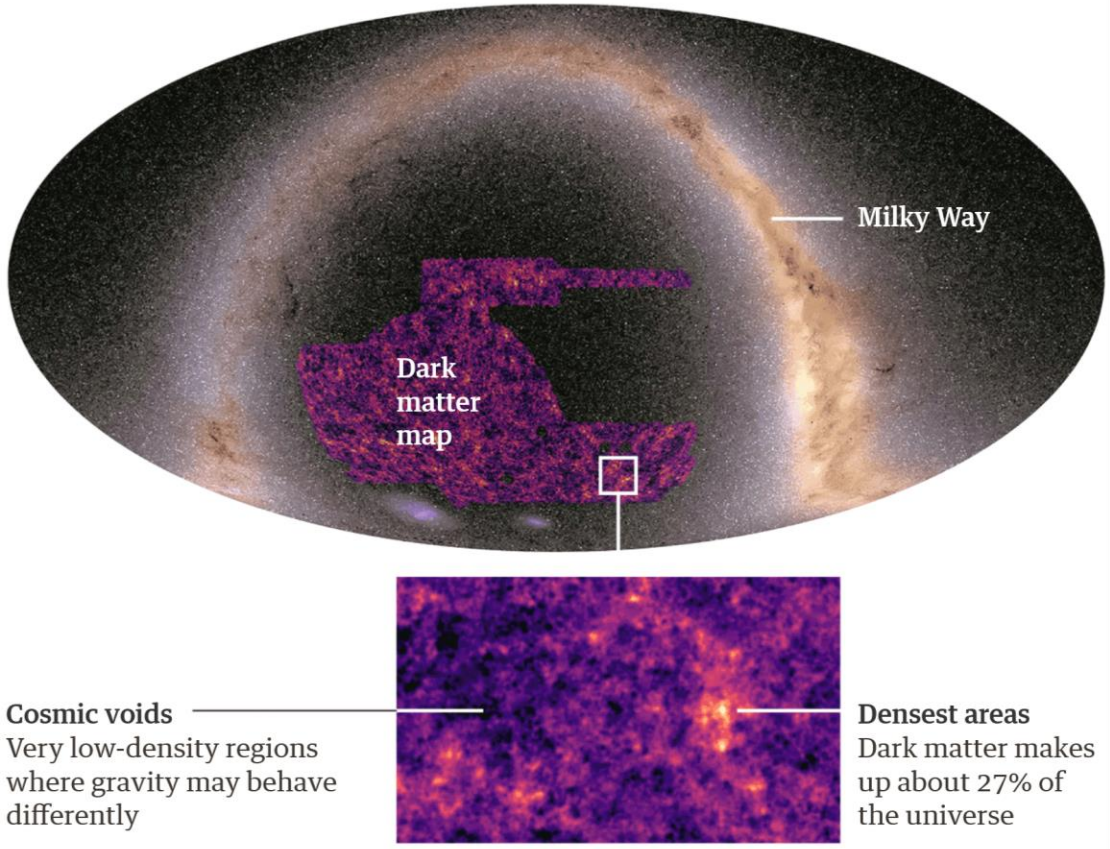
WHAT ARE "COSMIC VOIDS"?



"Astronomers Find Enormous Hole in the Universe"

"Astronomers Puzzled by Massive Blank Spot in Universe"

NRAO, Fox News

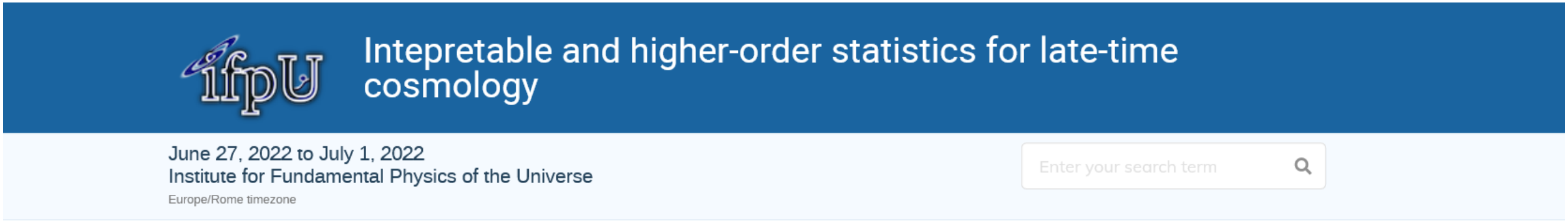


Guardian graphic. Source: DES Observations, N Jeffrey, Dark Energy Survey Collaboration

The Guardian

WHY BOTHER?

- **Interpretable** as spatially distinct components of the cosmic web (individual objects)
- Contain **higher-order statistics**
- Probe of **late-time cosmology**

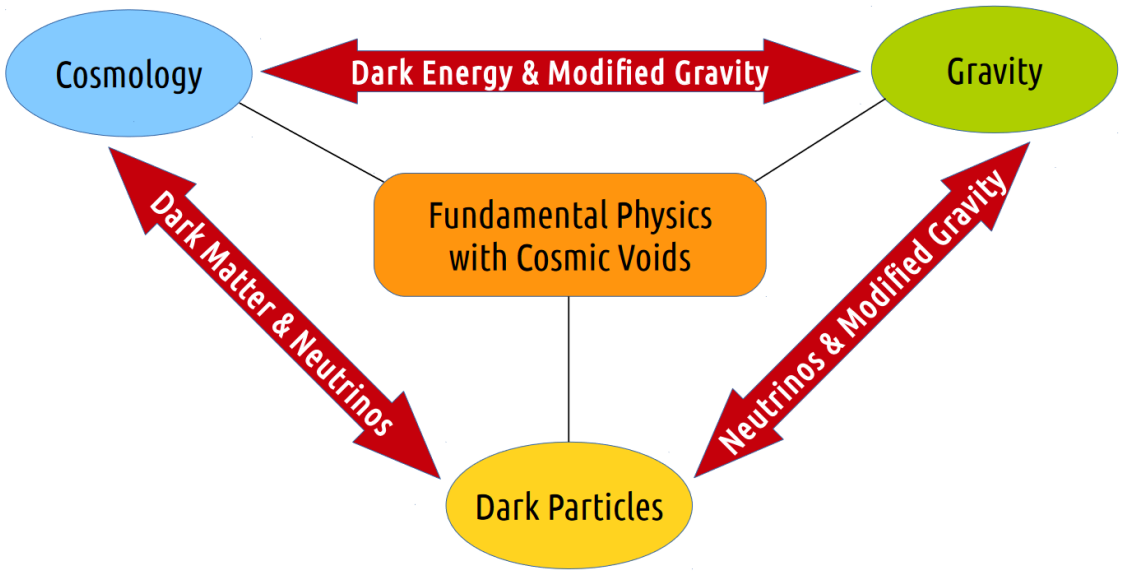


WHY BOTHER?

- Constrain competing theories of cosmology and gravity in the **underdense Universe,** where:
  - **Dark energy dominates** the cosmic mass-energy budget for the longest time
  - **Neutrinos** and potentially other **dark particles** have a **higher** relative **abundance / impact**
  - **Modifications to General Relativity** are expected most severe due to the **lack of screening**
- A relatively young, **emerging field**

(e.g., compared to galaxy clusters)

  - Expect the **unexpected**
  - Reveal unknown **unknowns**
  - Lots of **potential for discovery**

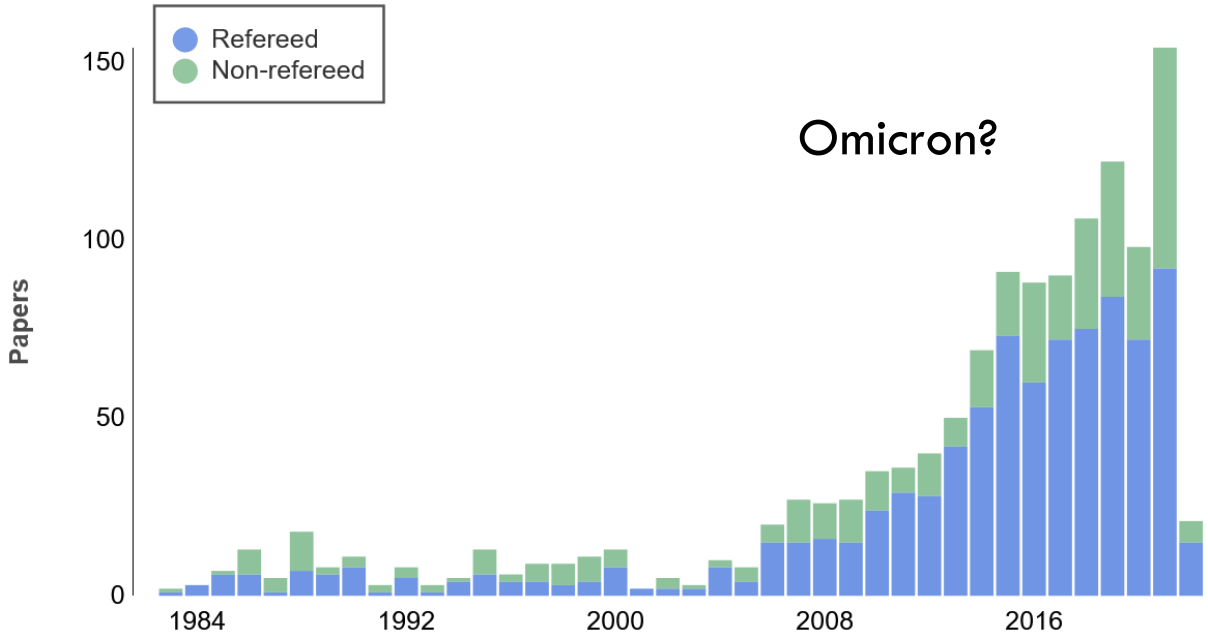


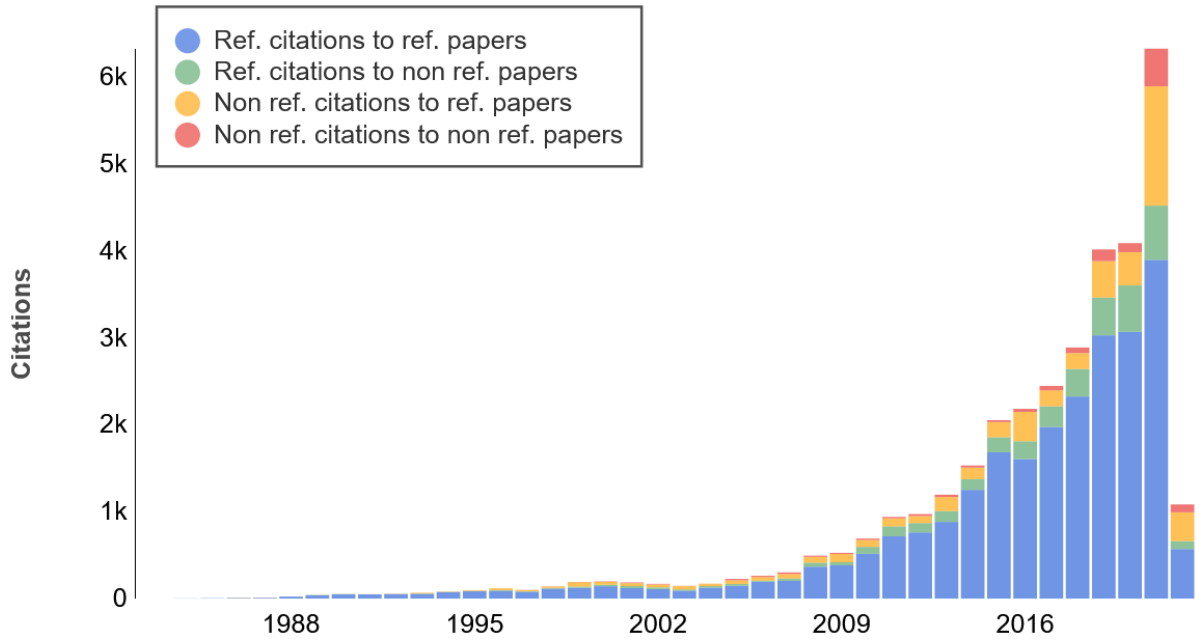
WHY NOW?

- Current generation of galaxy surveys (e.g., 6dFGS, SDSS, BOSS, eBOSS, DES, KiDS, VIPERS):
  - **Large** enough to detect significant **sample sizes** of voids (1 void defined by 100s of galaxies)
  - **Deep** enough to detect **fainter** galaxies inside voids / **smaller** voids and sub-voids
- Observational cosmology with voids is still a **teenager**, about to grow to adulthood
  - Very **active** / **energetic** with lots of low-hanging fruit to be harvested
  - Rapidly **growing** / **expanding** (as expected for voids)
- Golden age of next-generation surveys is beginning (e.g., DESI, Euclid, PFS, Roman, Rubin, SPHEREx)
  - Urgent need for **experience** and **robustness** in void analysis (post teenager stage)
  - Lots of **science** to be done, many **lessons** to be learned, numerous **discoveries** to be made!

WHY NOW?

Papers containing “cosmic voids” with full text search on NASA/ADS





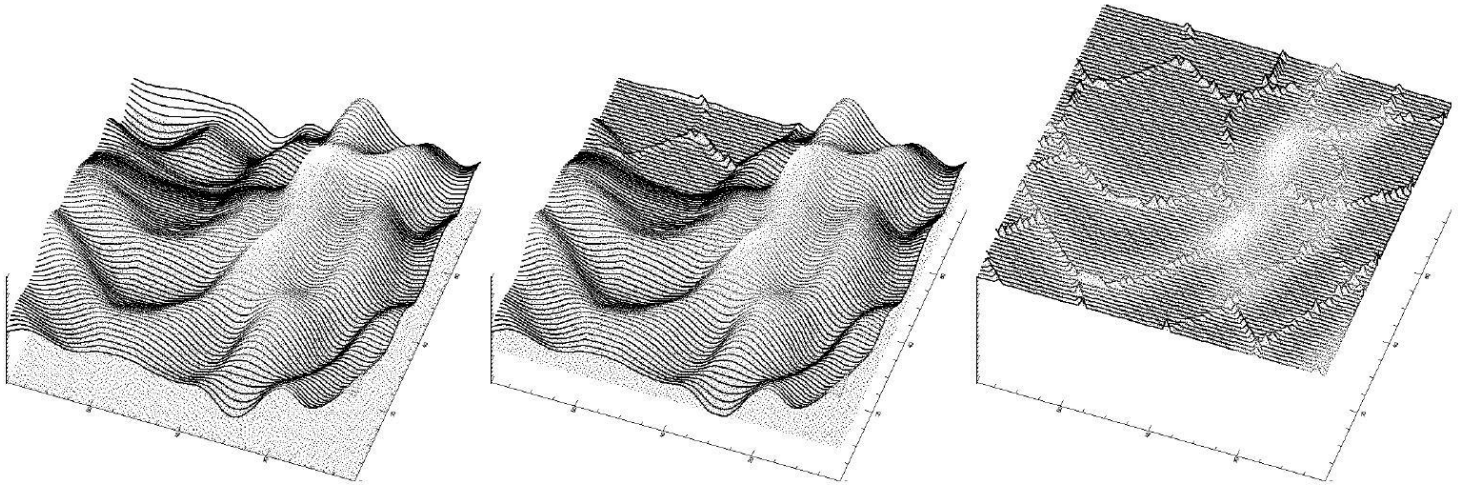
HOW DO WE DEFINE COSMIC VOIDS? WITH WATER!

Cosmic web

Gregory Massal

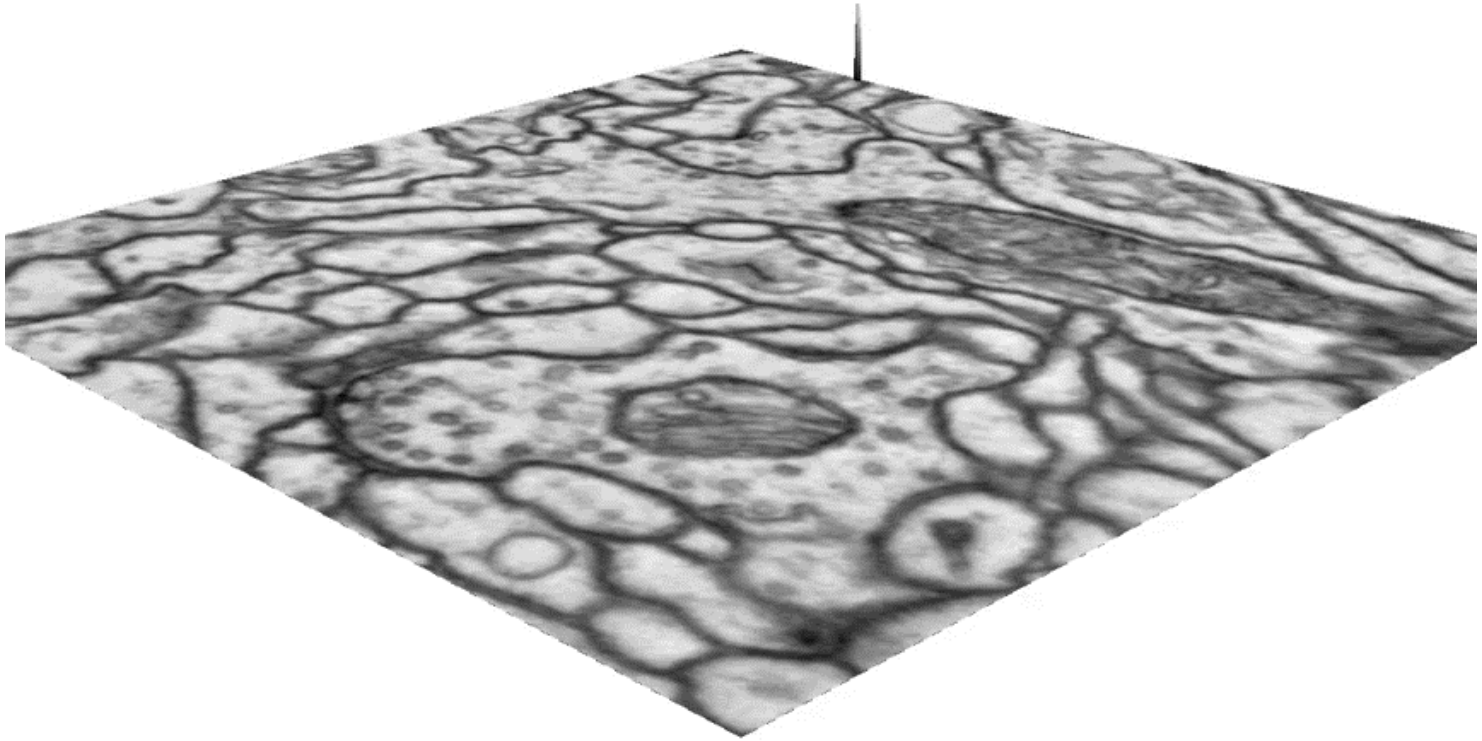
+

Watershed transform



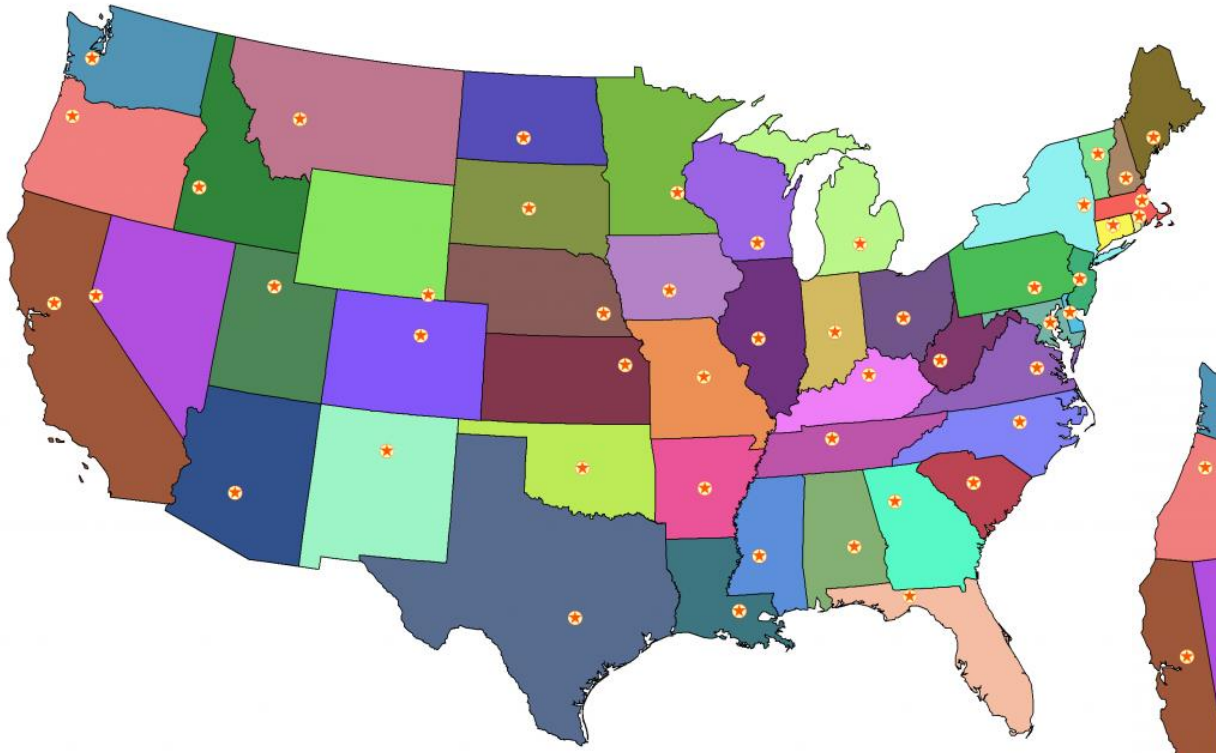
Platen, Van De Weygaert & Jones (MNRAS 2007)

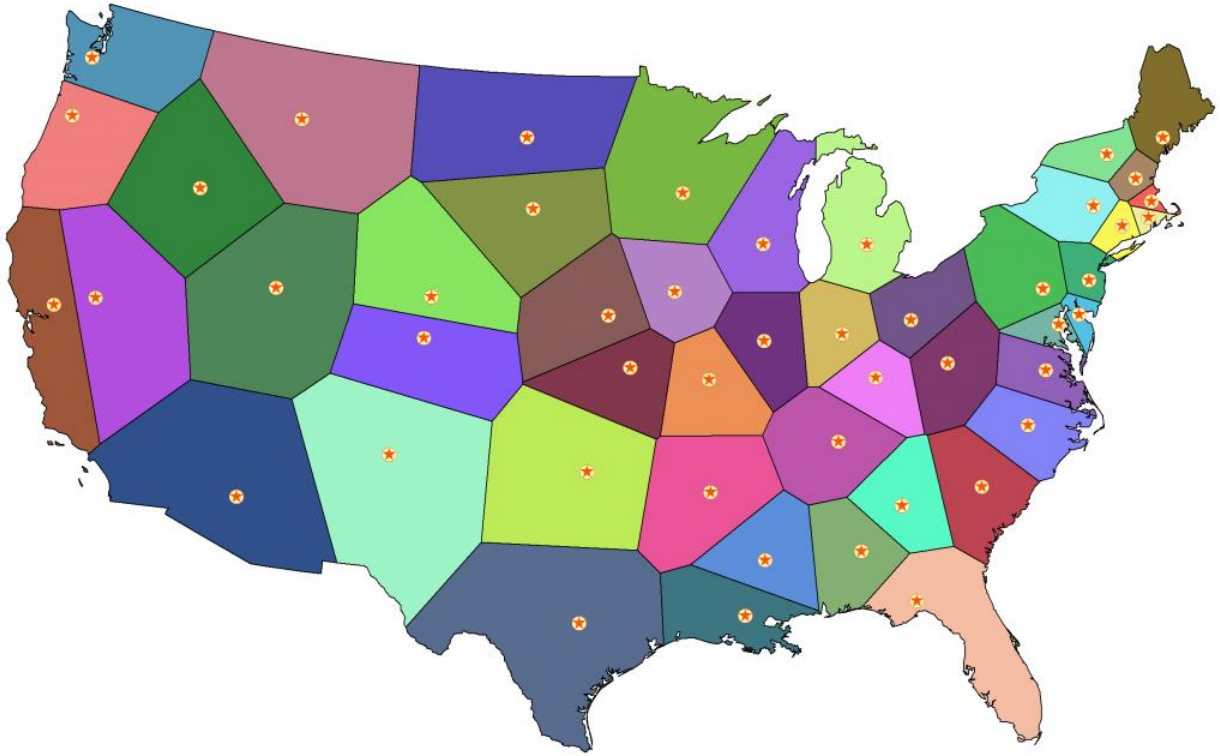
Watershed transform



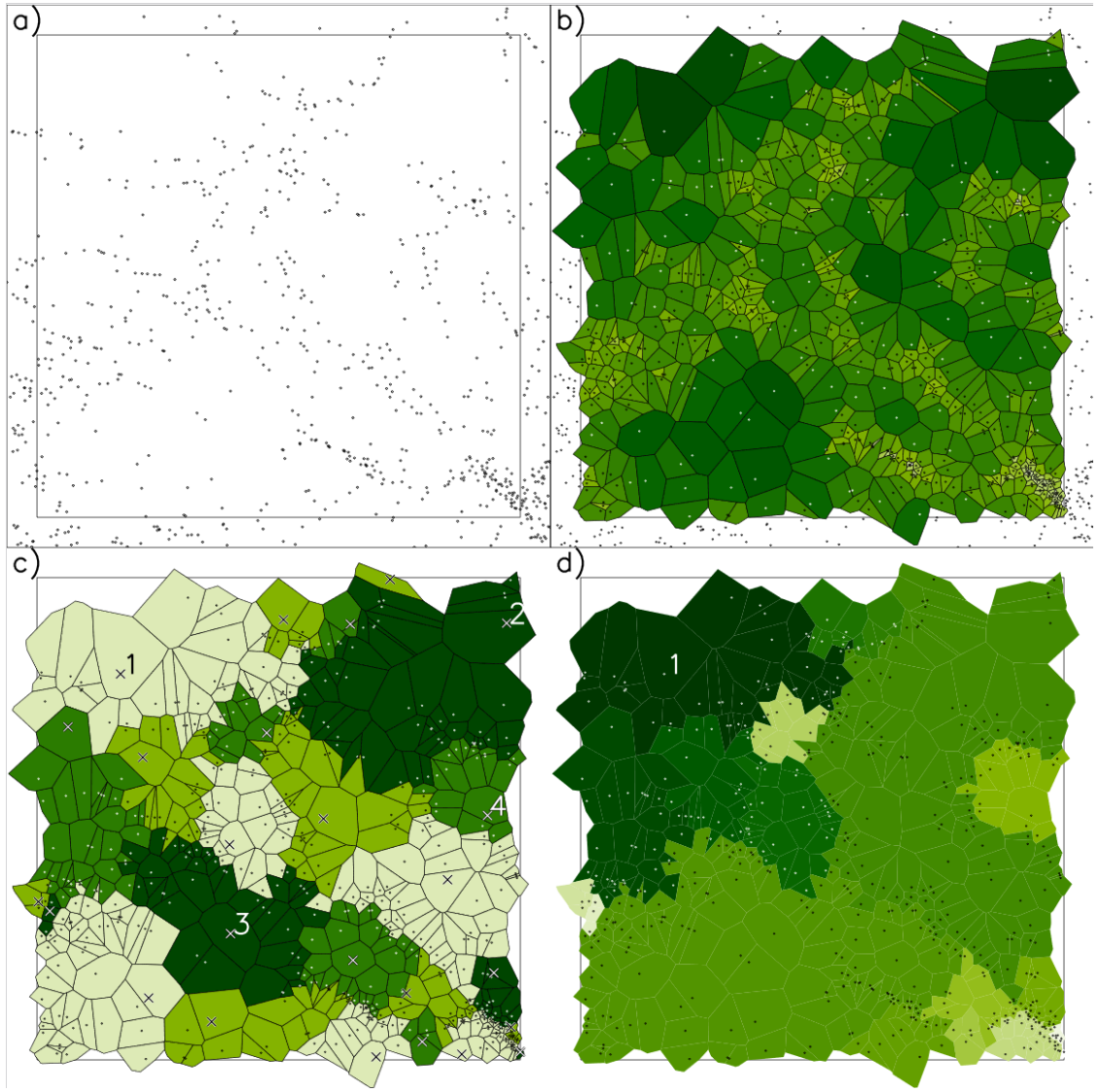
Steffen Wolf (YouTube)

Voronoi tessellation

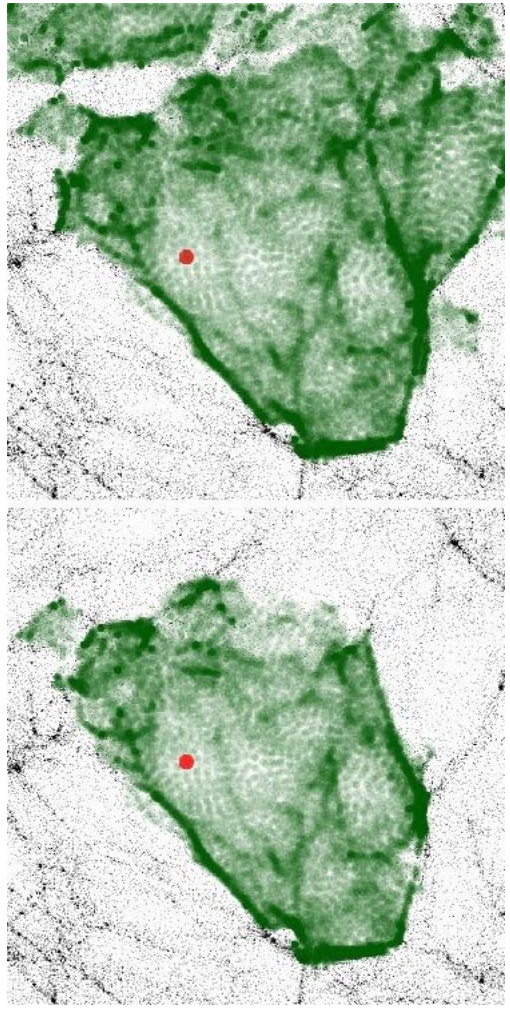




Voronoi tessellation

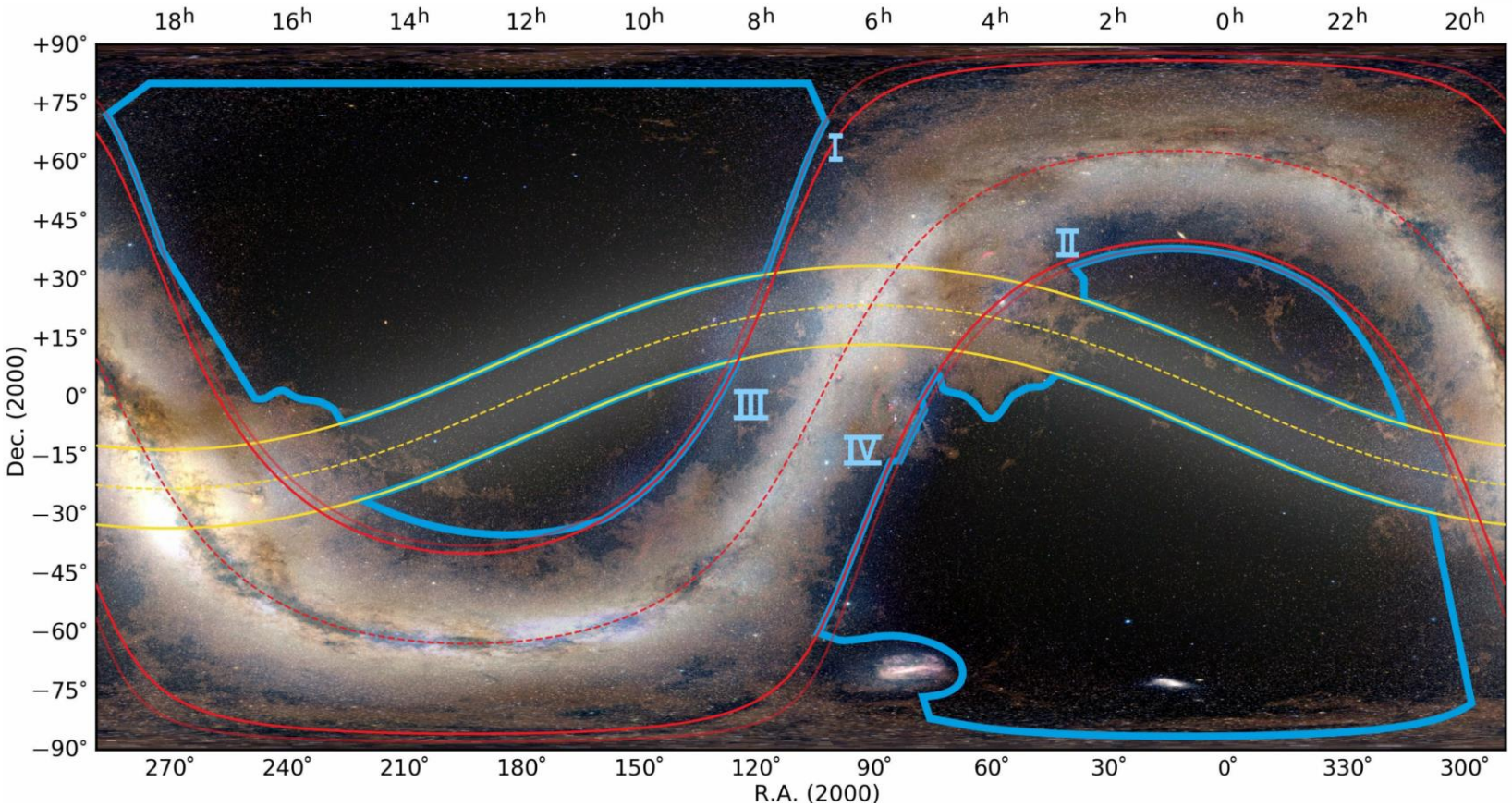


ZOBOV

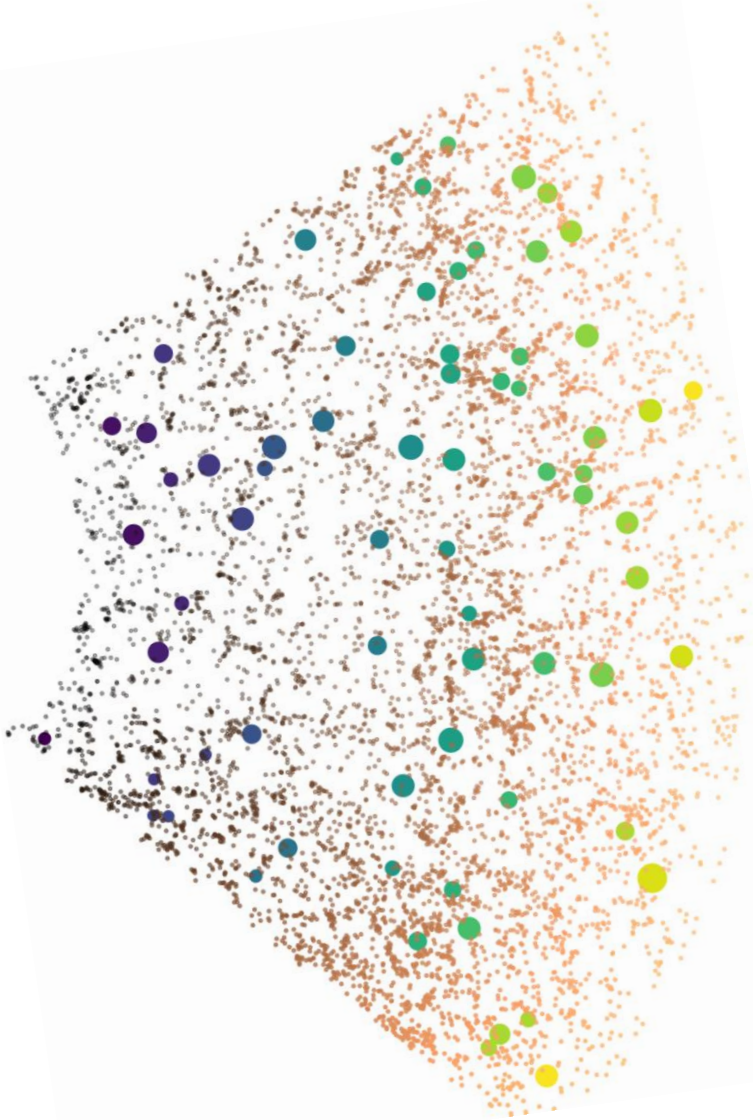


Neyrinck (MNRAS 2008)

Complication with observations: foregrounds & light cone



Euclid Collaboration: Scaramella et al. (arXiv 2108.01201)



Hamaus et al. (JCAP 2020)

Handle survey mask and selection function

https://bitbucket.org/cosmicvoids/vide_public

vide_public

- Source
- Commits
- Branches
- Pull requests
- Pipelines
- Deployments
- Issues
- Jira issues
- Security
- Wiki
- Downloads

Cosmic Voids / VIDE / vide_public

Wiki

Clone wiki

vide_public / Home

View History

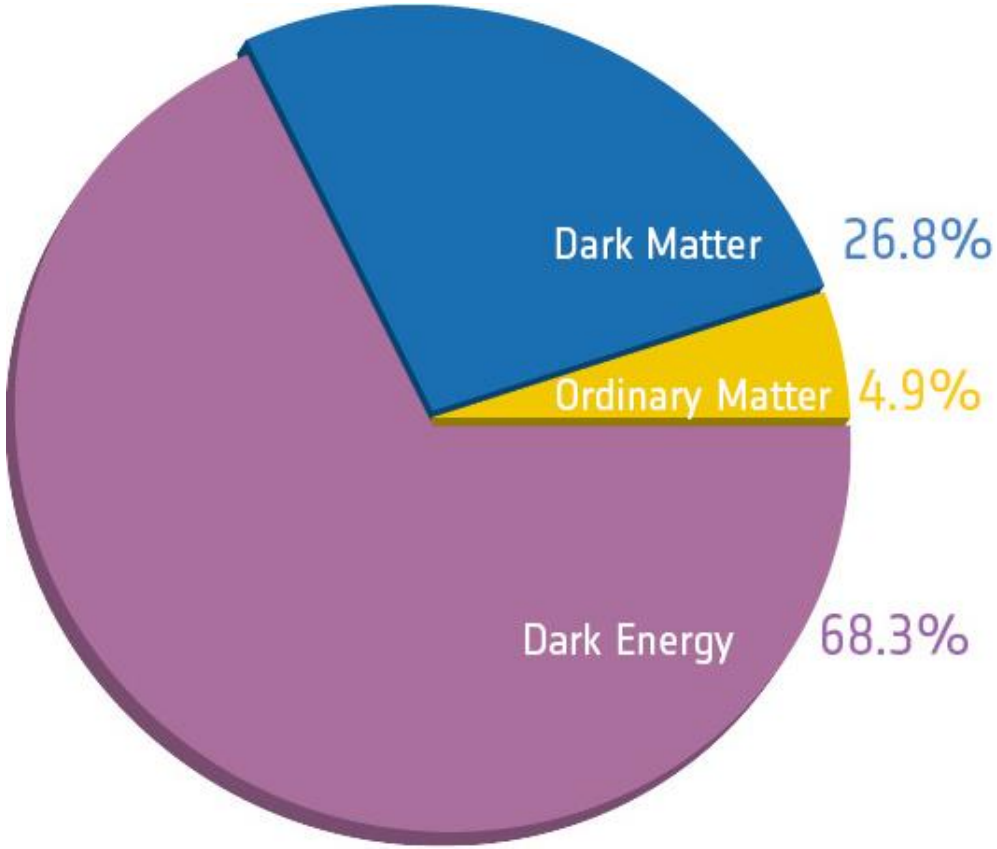
```
VVVVVVVV           VVVVVVVV IIIIIIIIII DDDDDDDDDDDDD        EEEEEEEEEEEEEEEEEEEEE
V:::::V            V:::::V I::::::::I D::::::::::::DDD     E::::::::::::::::::::E
V:::::V            V:::::V I::::::::I D:::::::::::::::DD   E::::::::::::::::::::E
V:::::V            V:::::V II::::::II DDD:::::DDDDD:::::D  EE::::::EEEEEEEEE:::E
 V:::::V           V:::::V   I::::I     D:::::D    D:::::D   E:::::E       EEEEEE
  V:::::V         V:::::V    I::::I     D:::::D     D:::::D  E:::::E
   V:::::V       V:::::V     I::::I     D:::::D     D:::::D  E::::::EEEEEEEEEE
    V:::::V     V:::::V      I::::I     D:::::D     D:::::D  E::::::::::::::E
     V:::::V   V:::::V       I::::I     D:::::D     D:::::D  E::::::::::::::E
      V:::::V V:::::V        I::::I     D:::::D     D:::::D  E::::::EEEEEEEEEE
       V:::::V:::::V         I::::I     D:::::D     D:::::D  E:::::E
        V:::::::::V          I::::I     D:::::D    D:::::D   E:::::E       EEEEEE
         V:::::::V         II::::::II DDD:::::DDDDD:::::D  EE::::::EEEEEEEE:::::E
          V:::::V          I::::::::I D::::::::::::::DD   E::::::::::::::::::::E
           V:::V           I::::::::I D::::::::::::DDD     E::::::::::::::::::::E
            VVV            IIIIIIIIII DDDDDDDDDDDDD        EEEEEEEEEEEEEEEEEEEEE
```

VIDE, the **Void IDentification and Examination toolkit** is a widely used void finder. It has been used on both spectroscopic and photometric data, on simulations and mocks. VIDE is the French word for void, as historically the software was first developed by a group of researchers working at the Institut d'Astrophysique de Paris (IAP, Paris, France). The following page lists all papers based on VIDE: Papers using VIDE.

Sutter, Lavaux, Hamaus et al. (A&C 2015)

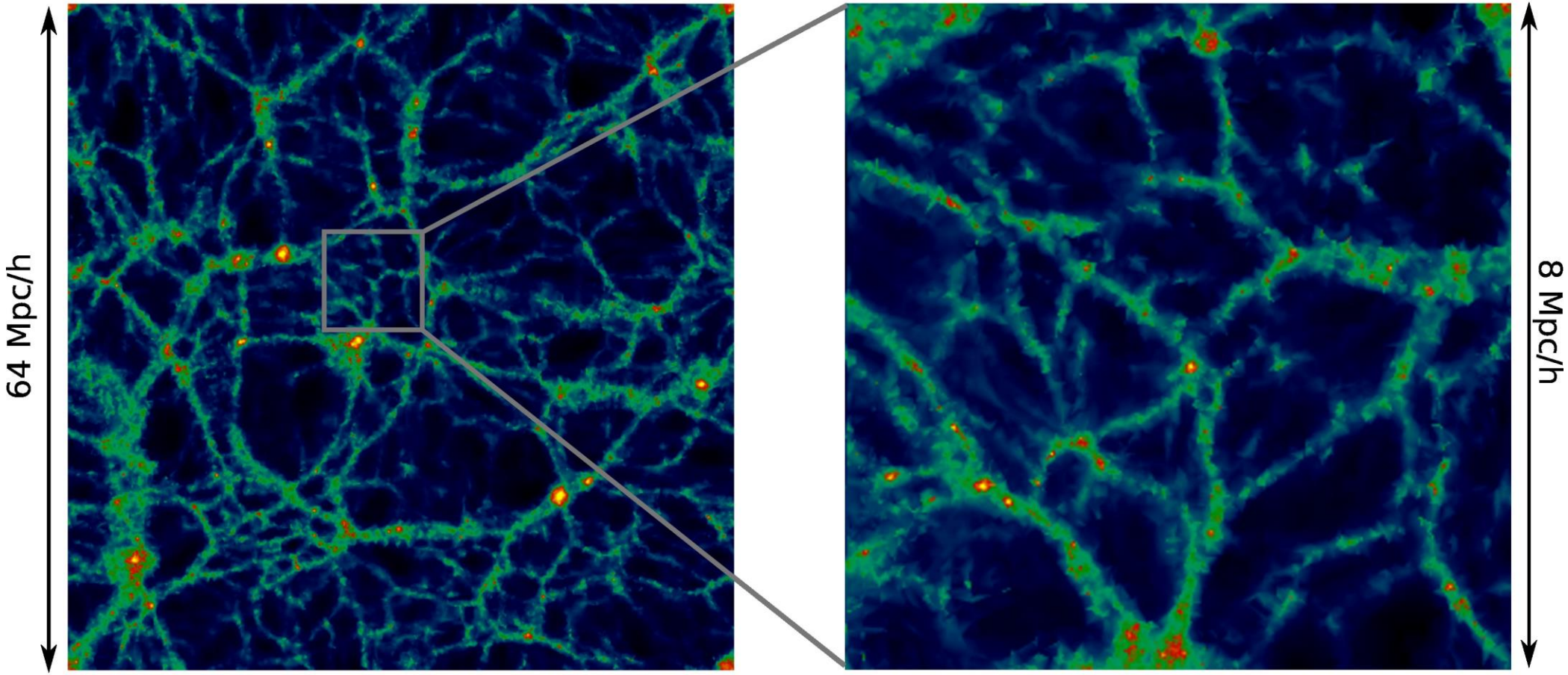
HOW DO WE DO COSMOLOGY WITH VOIDS?

Wikimedia Commons



ESA/Planck

MEASURE GEOMETRIC DISTORTIONS! HOW?



Aragon-Calvo & Szalay (MNRAS 2013)

STACKING

According to the cosmological principle the Universe is statistically isotropic, and so are voids!

Hauser-Optik: Standard Kilogram

- Use stacked voids as **"Standard Sphere"**

cleverstuff

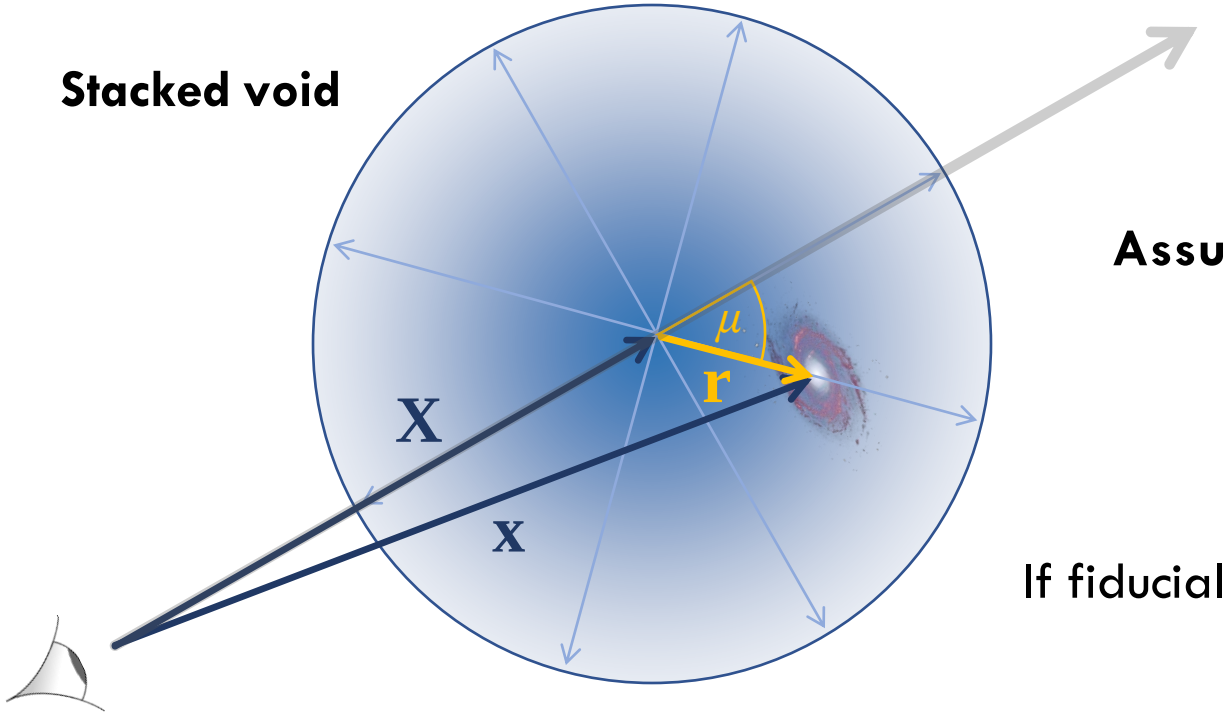
1. Hand-eye coordination
2. Problem solving skills
3. Cause and effect understanding
4. **Shape identification**
5. Color recognition
6. Gross motor skill development
7. Fine motor skill development
8. Goal setting

Invoke the **Cosmological Principle**

$$\mathbf{r} = \mathbf{x} - \mathbf{X} \qquad r = \sqrt{r_\parallel^2 + r_\perp^2} \qquad \mu = \frac{r_\parallel}{r}$$

$$r_\parallel = \frac{c}{H(z)}\delta z \qquad r_\perp = D_\mathrm{A}(z)\delta\theta$$

Stacked void



Fiducial cosmology, flat ΛCDM:

$$H(z) = H_0\sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda} \qquad D_\mathrm{A}(z) = \int_0^z \frac{c}{H(z')}\,\mathrm{d}z'$$

True cosmology, unknown (indicated by asterisk):

$$H^*(z) = H(z)\frac{r_\parallel}{r_\parallel^*} \qquad D_\mathrm{A}^*(z) = D_\mathrm{A}(z)\frac{r_\perp^*}{r_\perp}$$

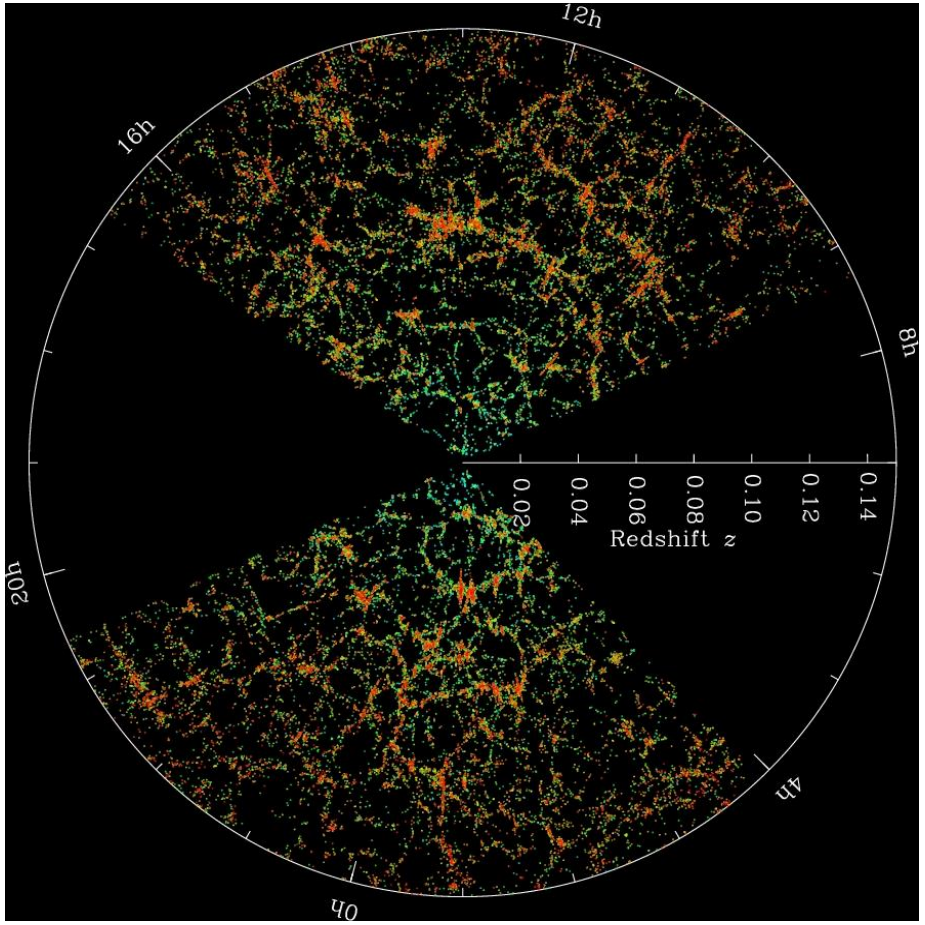
Assume statistical isotropy $(r_\parallel^* = r_\perp^*)$ and measure:

$$\varepsilon = \frac{r_\parallel}{r_\perp} = \frac{D_\mathrm{A}^*(z)H^*(z)}{D_\mathrm{A}(z)H(z)}$$

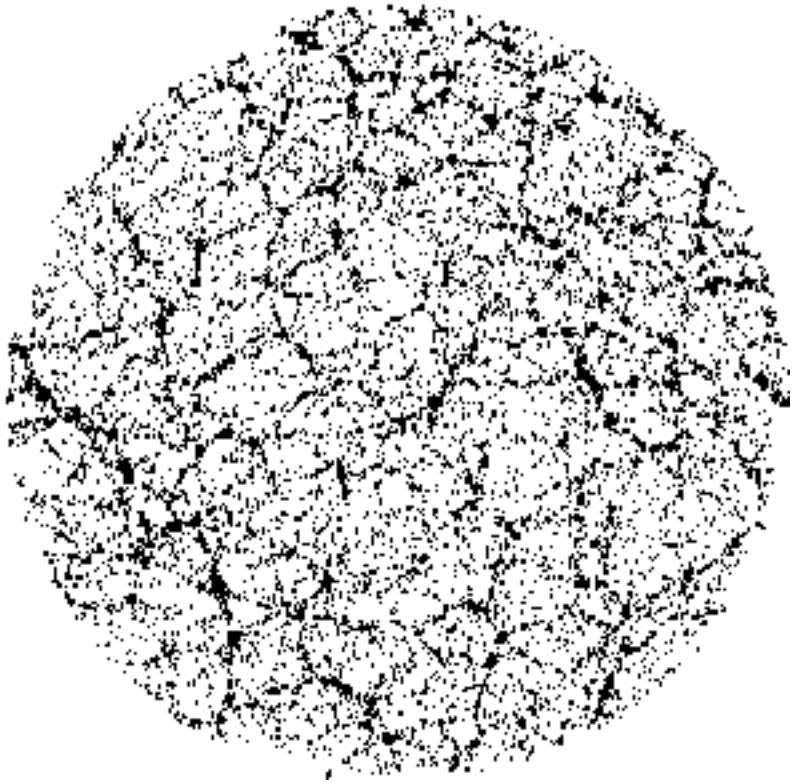
If fiducial cosmology = true cosmology (**Alcock-Paczynski test**):

$$\varepsilon = 1$$

DYNAMIC DISTORTIONS SPOIL SYMMETRY



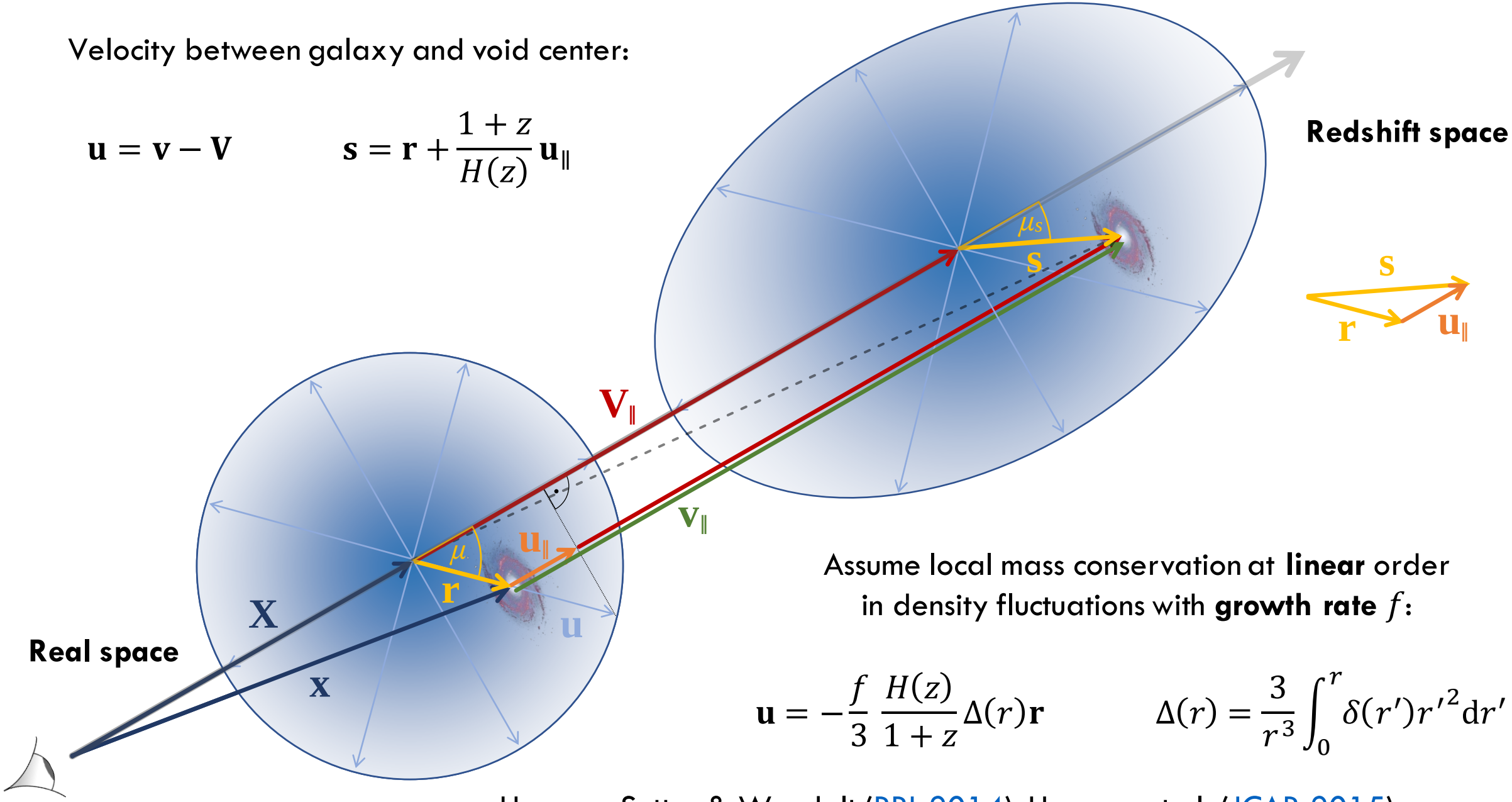
SDSS DR7 (ApJS 2009)



Melott et al. (ApJ 1998)

Velocity between galaxy and void center:

$$\mathbf{u} = \mathbf{v} - \mathbf{V} \qquad \mathbf{s} = \mathbf{r} + \frac{1+z}{H(z)}\mathbf{u}_\parallel$$

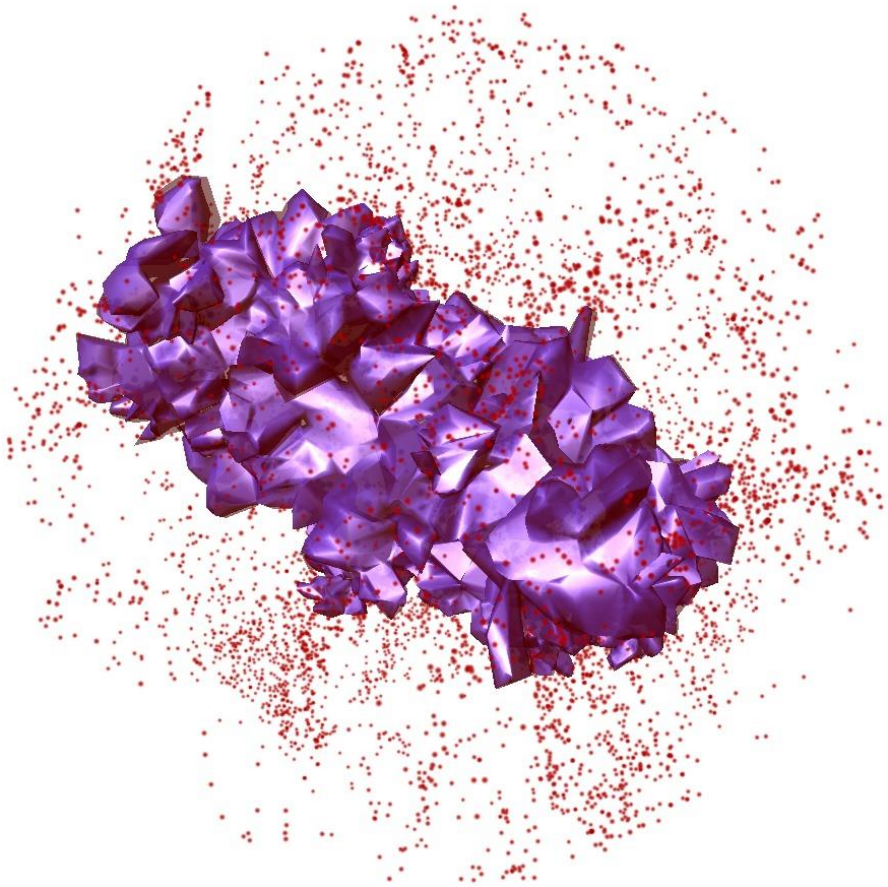


Assume local mass conservation at **linear** order in density fluctuations with **growth rate** f:

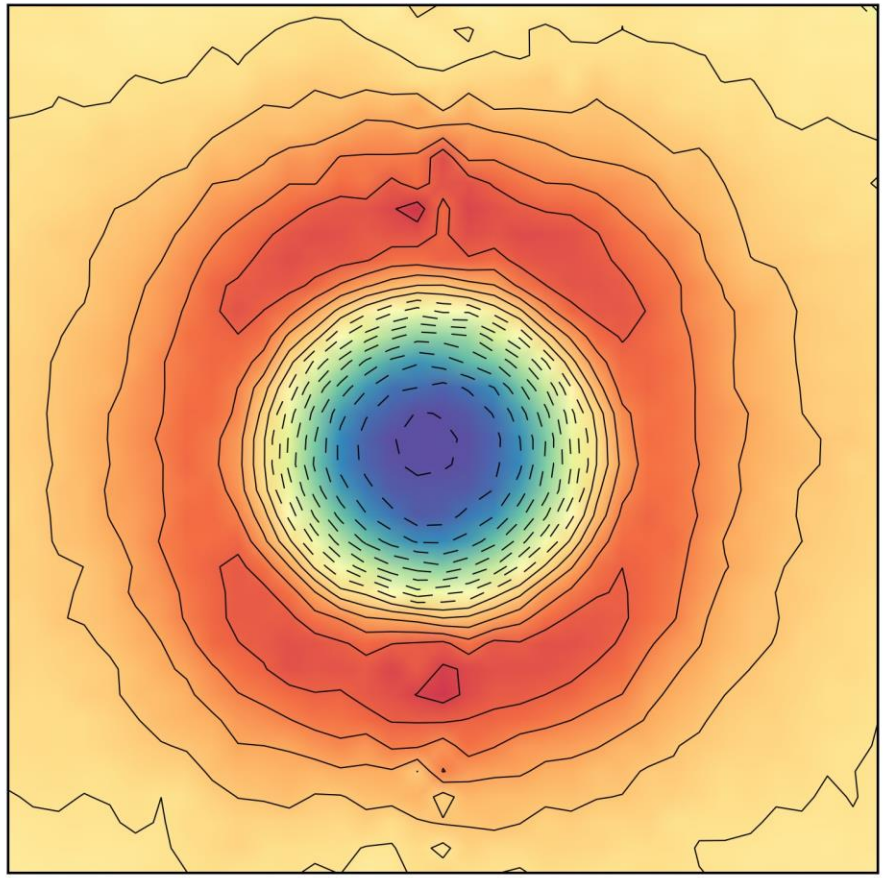
$$\mathbf{u} = -\frac{f}{3}\frac{H(z)}{1+z}\Delta(r)\mathbf{r} \qquad \Delta(r) = \frac{3}{r^3}\int_0^r \delta(r')r'^2 \mathrm{d}r'$$

Hamaus, Sutter & Wandelt (PRL 2014), Hamaus et al. (JCAP 2015)

HOW CAN WE MEASURE THIS?



Sutter, Lavaux, Hamaus et al. (A&C 2015)



Hamaus et al. (PRL 2016)

Void-galaxy cross-correlation function in redshift space and its multipoles:

$$\xi^s(\mathbf{s}) = \xi^s(s_\parallel, s_\perp) = \xi^s(s, \mu_s) \qquad \xi^s_\ell(s) = \frac{2\ell+1}{2}\int_{-1}^{1} \xi^s(s,\mu_s) P_\ell(\mu_s) \mathrm{d}\mu_s$$

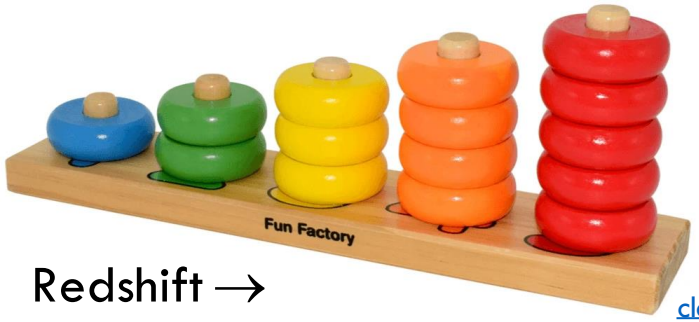
Landy-Szalay estimator for cross-correlations:

$$\hat{\xi}^s(\mathbf{s}) = \frac{\langle \mathcal{D}_\mathrm{v}\mathcal{D}_\mathrm{g}\rangle - \langle \mathcal{D}_\mathrm{v}\mathcal{R}_\mathrm{g}\rangle - \langle \mathcal{R}_\mathrm{v}\mathcal{D}_\mathrm{g}\rangle + \langle \mathcal{R}_\mathrm{v}\mathcal{R}_\mathrm{g}\rangle}{\langle \mathcal{R}_\mathrm{v}\mathcal{R}_\mathrm{g}\rangle}$$

$\mathcal{D}$: data, $\mathcal{R}$: randoms

Randoms: drawn from redshift distribution of data with much higher density, but no clustering

Stacking: express all distances in units of the effective radius of each void to align void boundaries.



Redshift →

cleverstuff

Models for void-galaxy cross-correlation function

Basic assumptions:

- Spherical symmetry in real space (cosmological principle)
- Conservation of voids and galaxies between real and redshift space
- Voids evolve individually, the impact of neighbors can be neglected

Gaussian streaming model (GSM): Paz et al. (MNRAS 2013), Hamaus et al. (JCAP 2015, PRL 2016)

$$1 + \xi^s(\mathbf{s}) = \int [1 + \xi(r)]\, \mathcal{P}(u_\parallel, r, \mu) \mathrm{d}u_\parallel \qquad \mathcal{P}(u_\parallel, r, \mu) = \frac{1}{\sqrt{2\pi}\sigma_\parallel(r,\mu)} \exp\left\{-\frac{[u_\parallel - u(r)\mu]^2}{2\sigma_\parallel^2(r,\mu)}\right\}$$

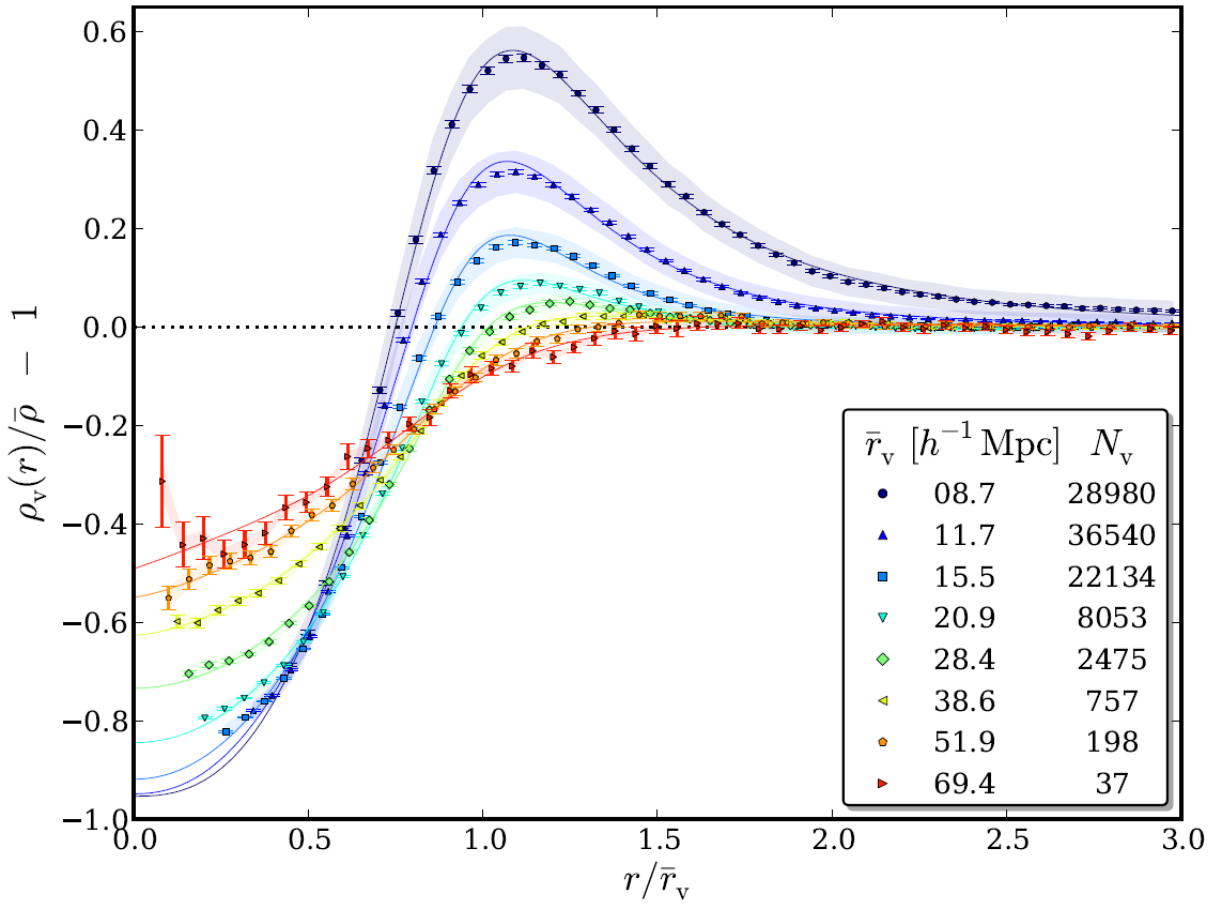
Linear Kaiser-like model: Cai et al. (MNRAS 2016), Hamaus et al. (JCAP 2017)

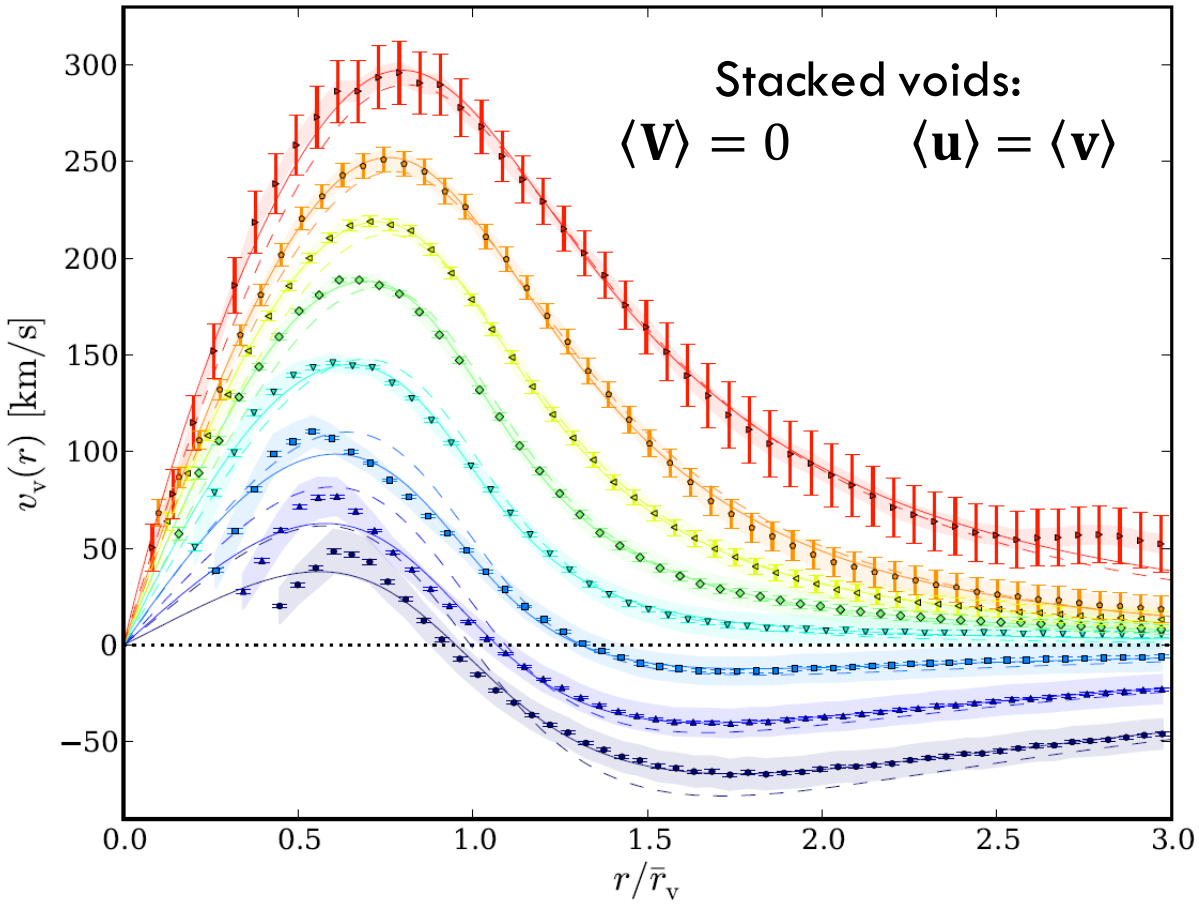
$$\xi^s(\mathbf{s}) = \xi(r) - \frac{1+z}{H(z)} \frac{\mathrm{d}u_\parallel(r)}{\mathrm{d}r}$$

Model ingredients: $\xi(r), u(r), \sigma(r,\mu)$

Pairwise velocity profile: assume local mass conservation at linear order with growth rate f

$$\mathbf{u} = -\frac{f}{3}\frac{H(z)}{1+z}\Delta(r)\mathbf{r} \qquad \Delta(r) = \frac{3}{r^3}\int_0^r \delta(r')r'^2\mathrm{d}r' \qquad \delta(r) = \delta_\mathrm{c}\frac{1-(r/r_\mathrm{s})^\alpha}{1+(r/r_\mathrm{v})^\beta}$$





Hamaus, Sutter & Wandelt (PRL 2014)

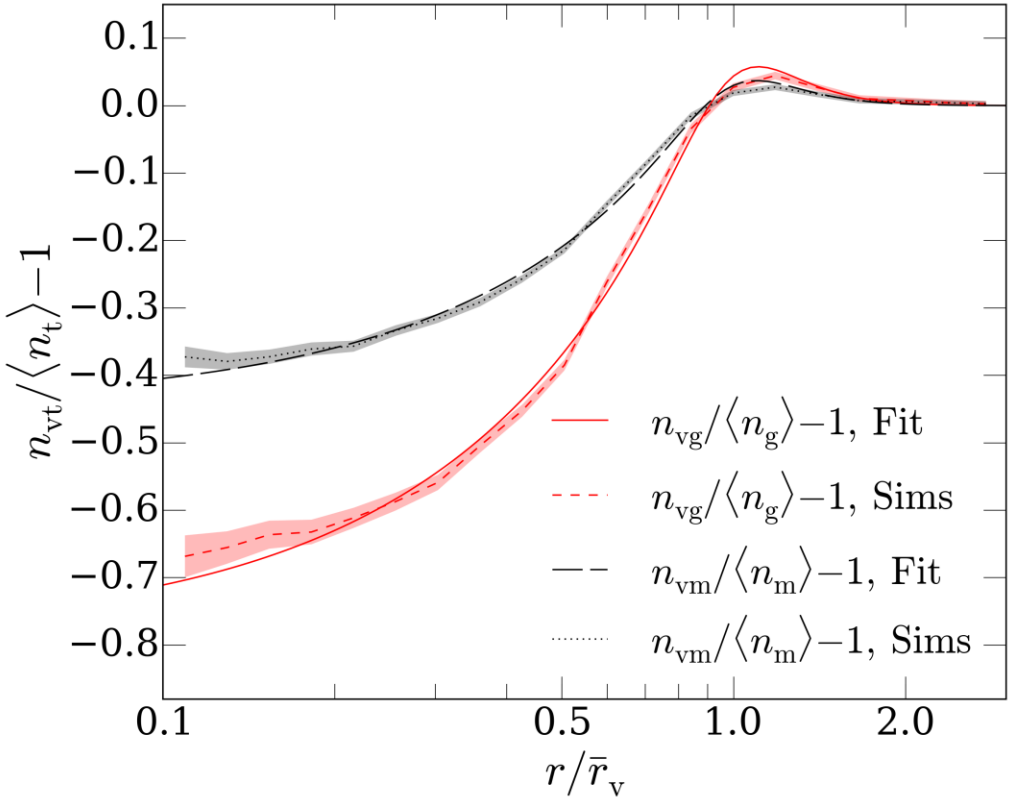
Density profile: assume linear bias relation

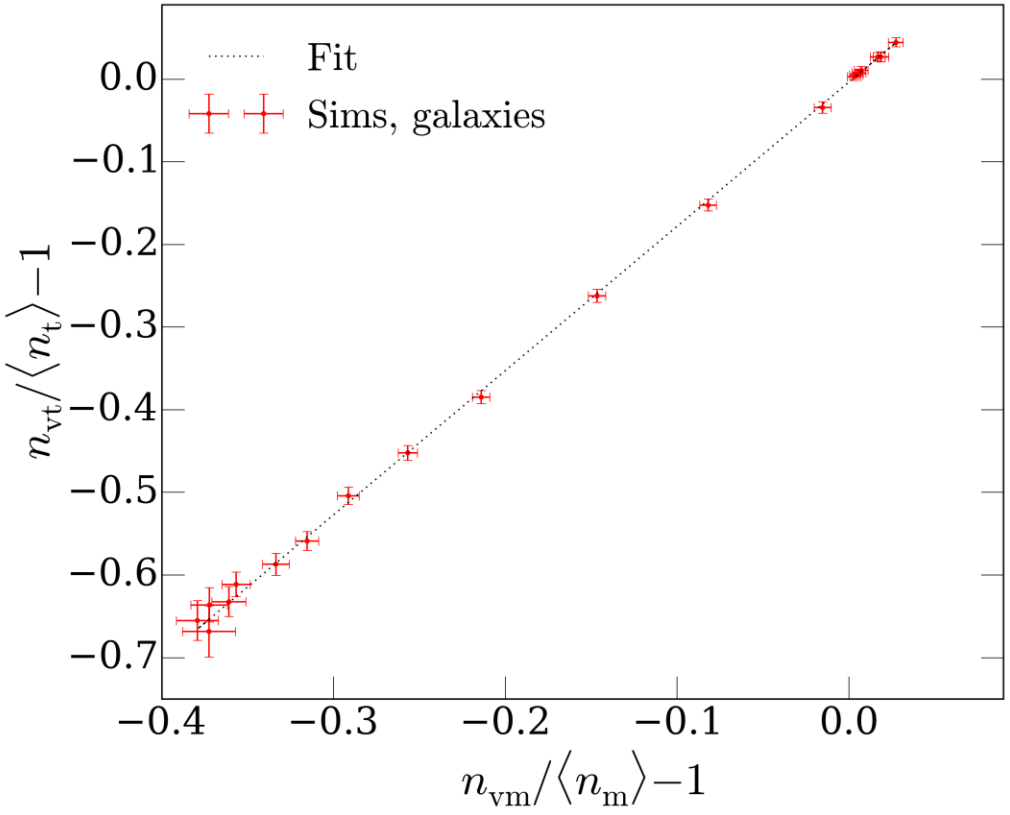
$$\xi(r) = b\delta(r)$$

Replace:

$$\delta(r) \longrightarrow \xi(r), \qquad \Delta(r) \longrightarrow \bar{\xi}(r)$$

$$f \longrightarrow f/b$$





Pollina, Hamaus et al. (MNRAS 2017, 2019)

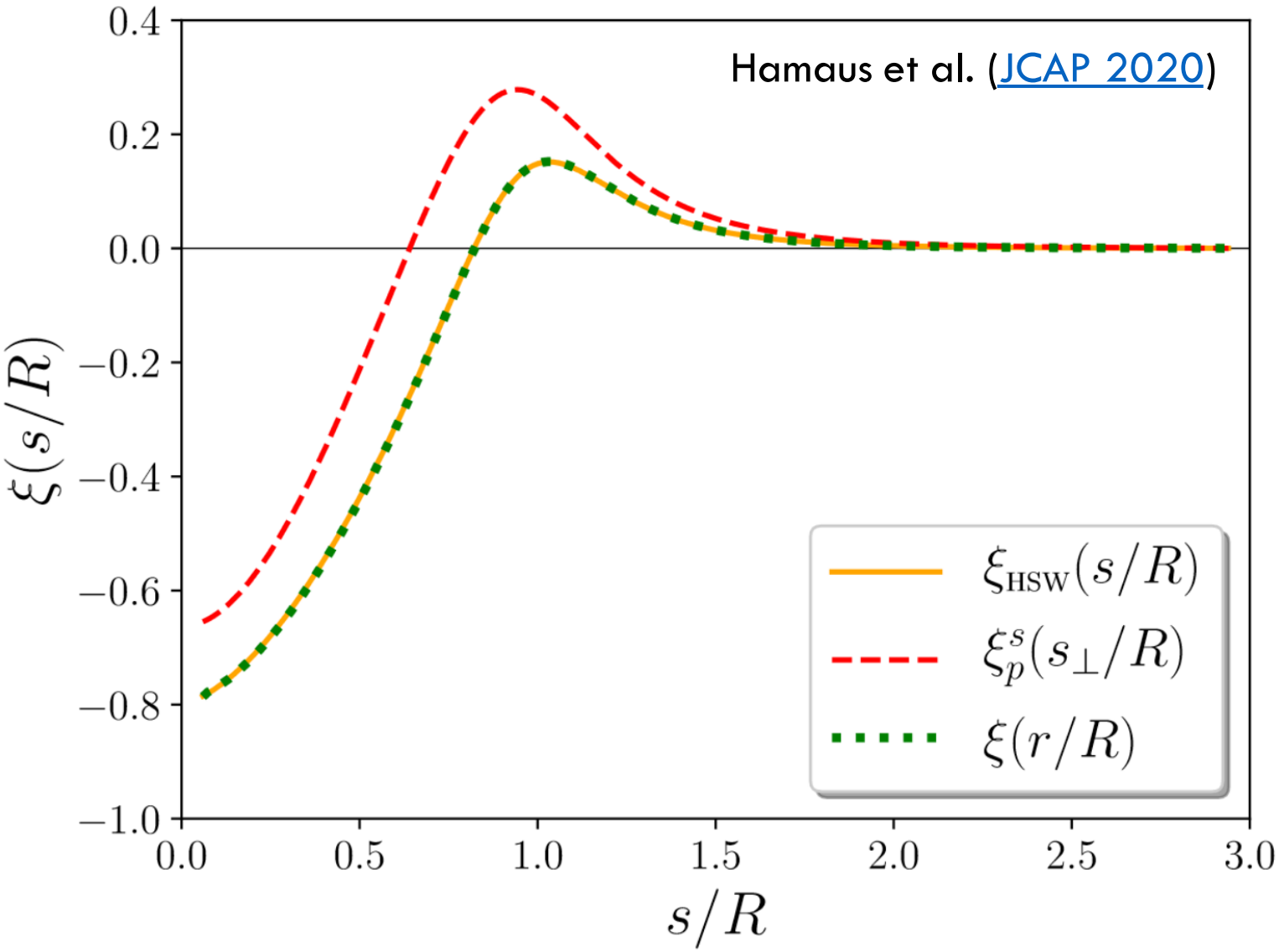
Real-space correlation: inverse Abel transform of projected correlation (N. H. Abel, 1842)

$$\xi(r) = -\frac{1}{\pi}\int_r^\infty \frac{\mathrm{d}\xi_\mathrm{p}^s(s_\perp)}{\mathrm{d}s_\perp}\frac{\mathrm{d}s_\perp}{\sqrt{s_\perp^2 - r^2}}$$

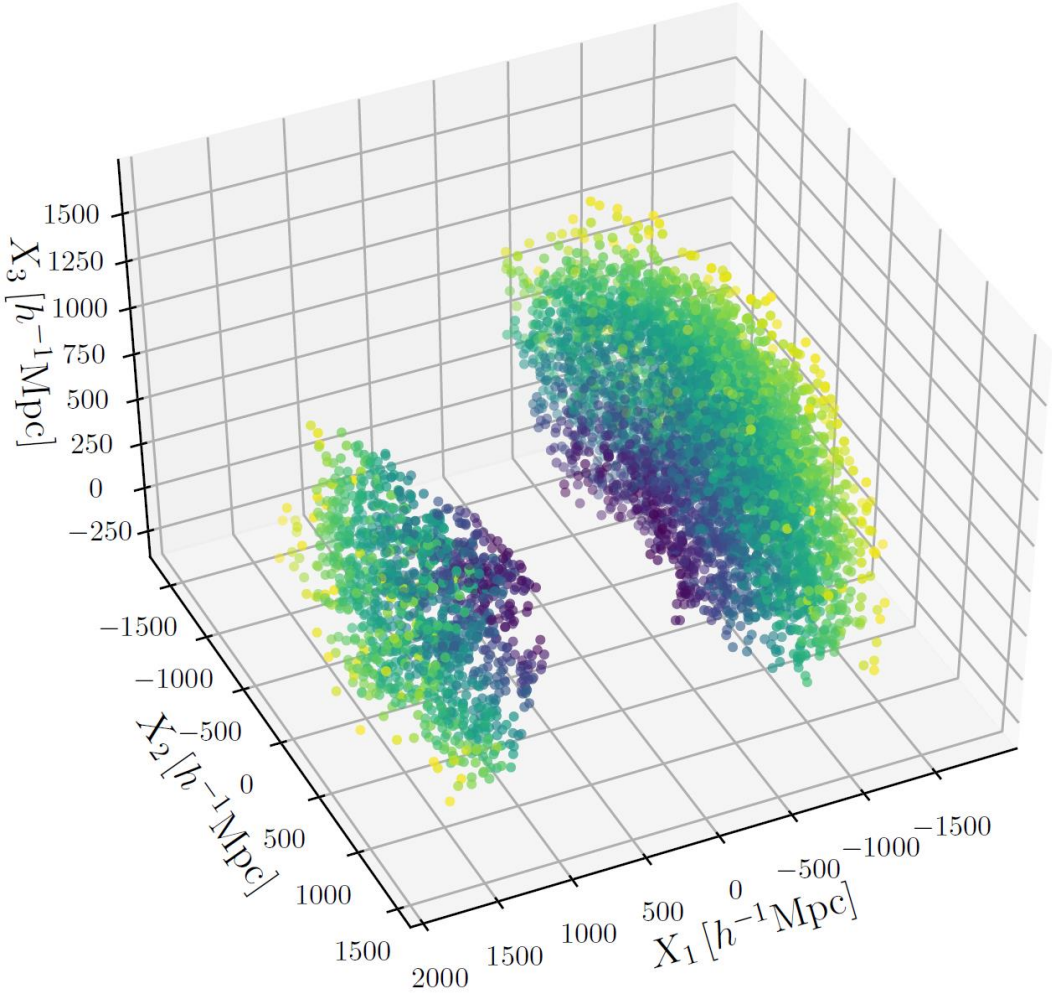
Pisani et al. (MNRAS 2014)
Hawken et al. (A&A 2017)

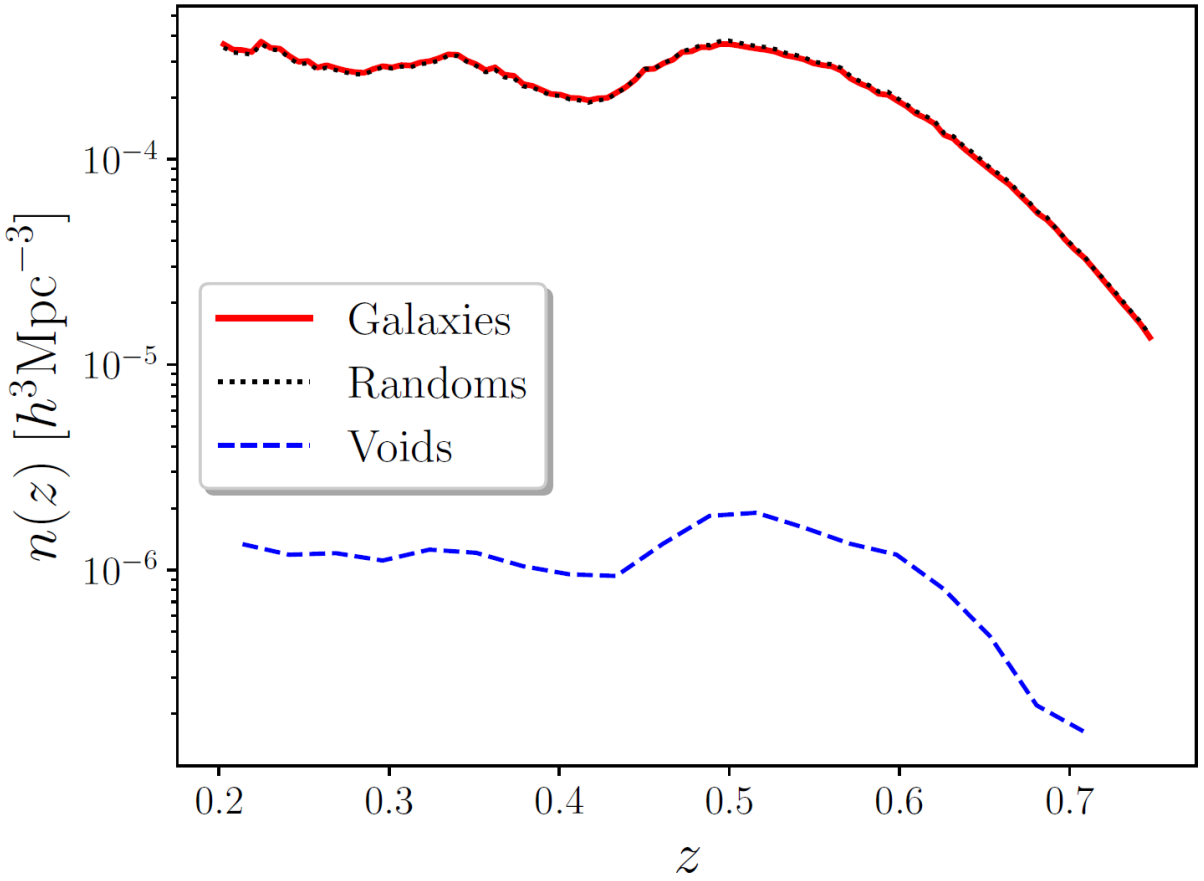
Test with template:

$$\xi_\mathrm{HSW}(r) = b\delta_\mathrm{c}\frac{1-(r/r_\mathrm{s})^\alpha}{1+(r/r_\mathrm{v})^\beta}$$

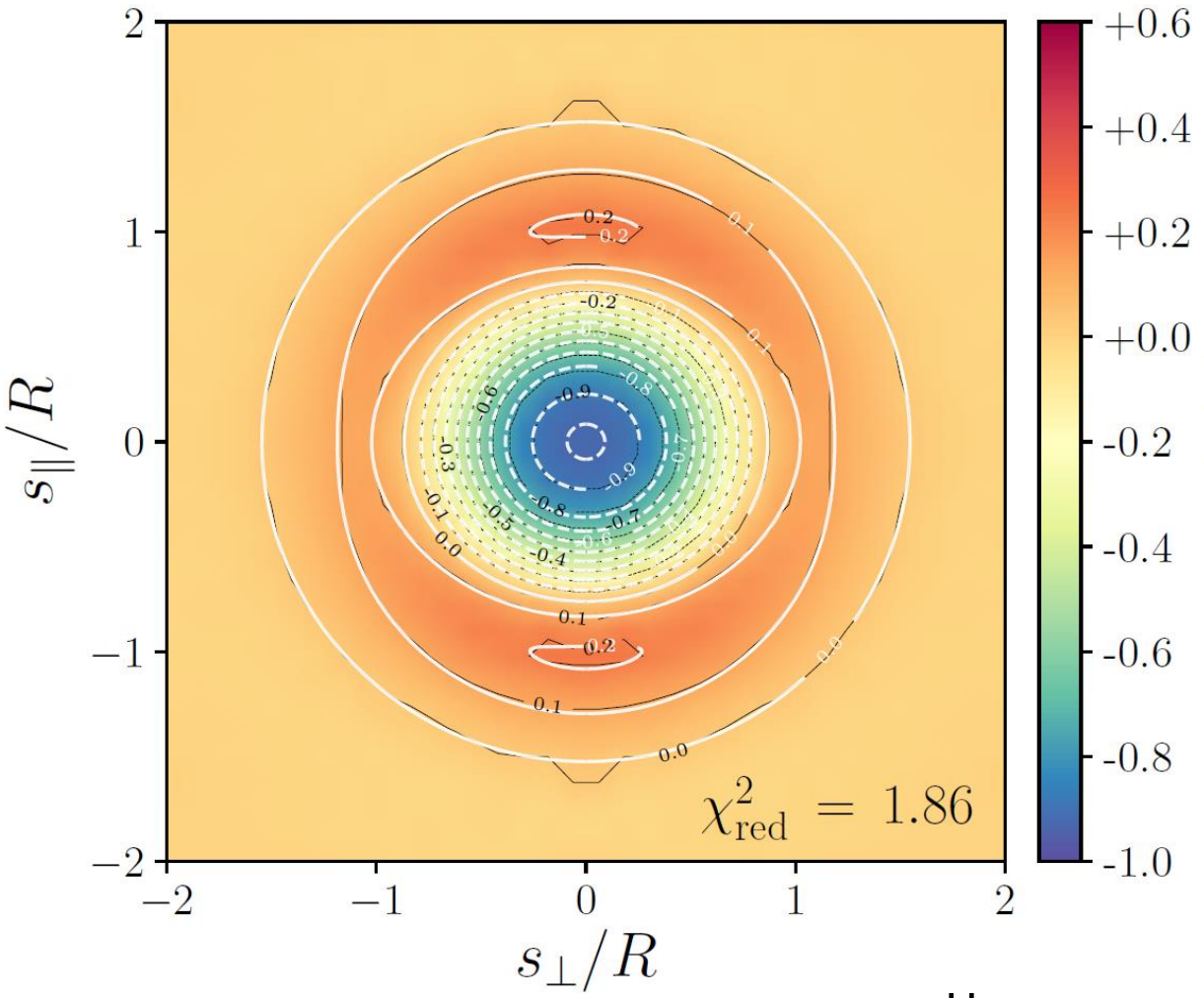


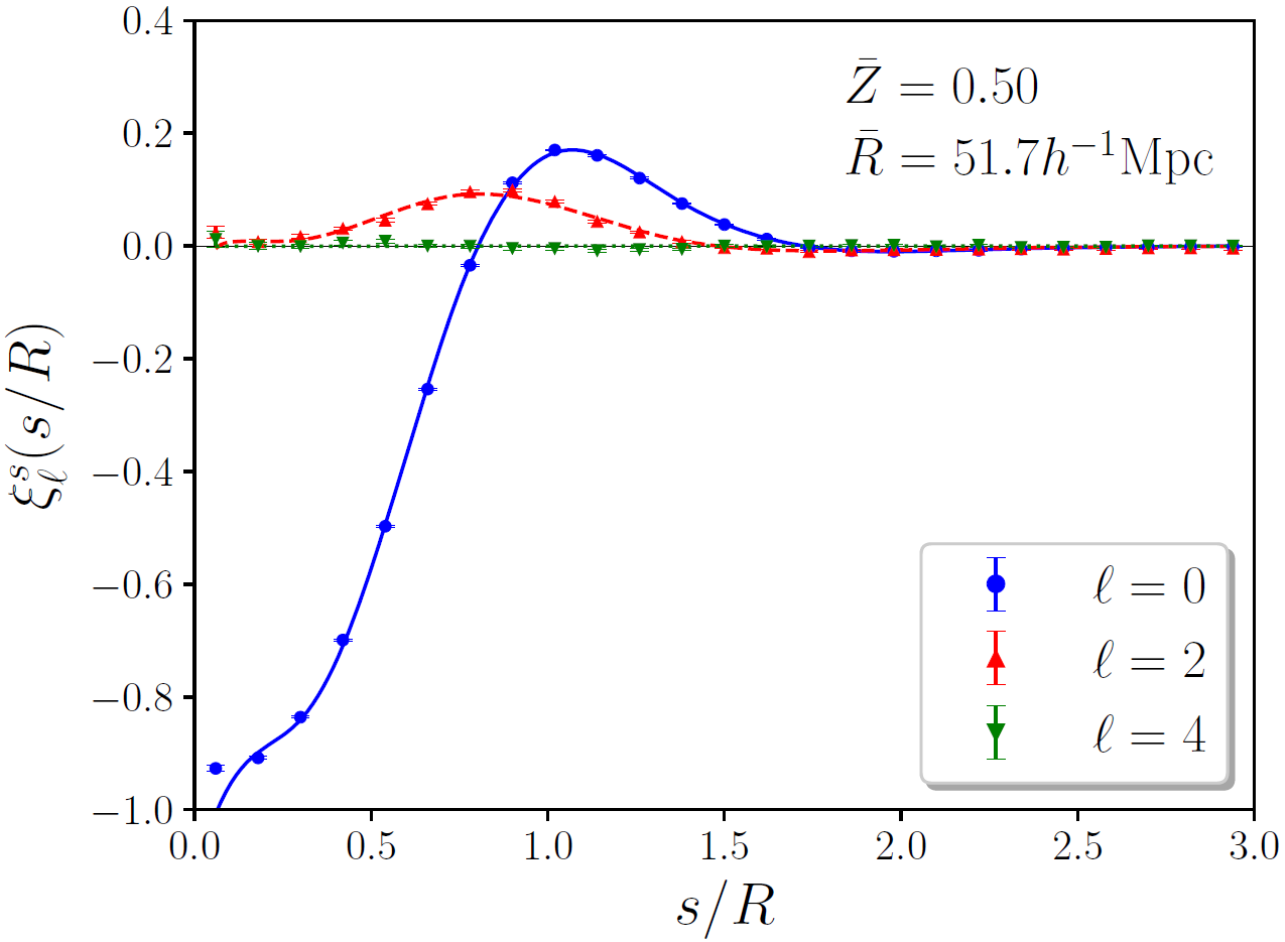
SDSS BOSS DR12 VOIDS





Model validation on PATCHY mocks





Hamaus et al. (JCAP 2020)

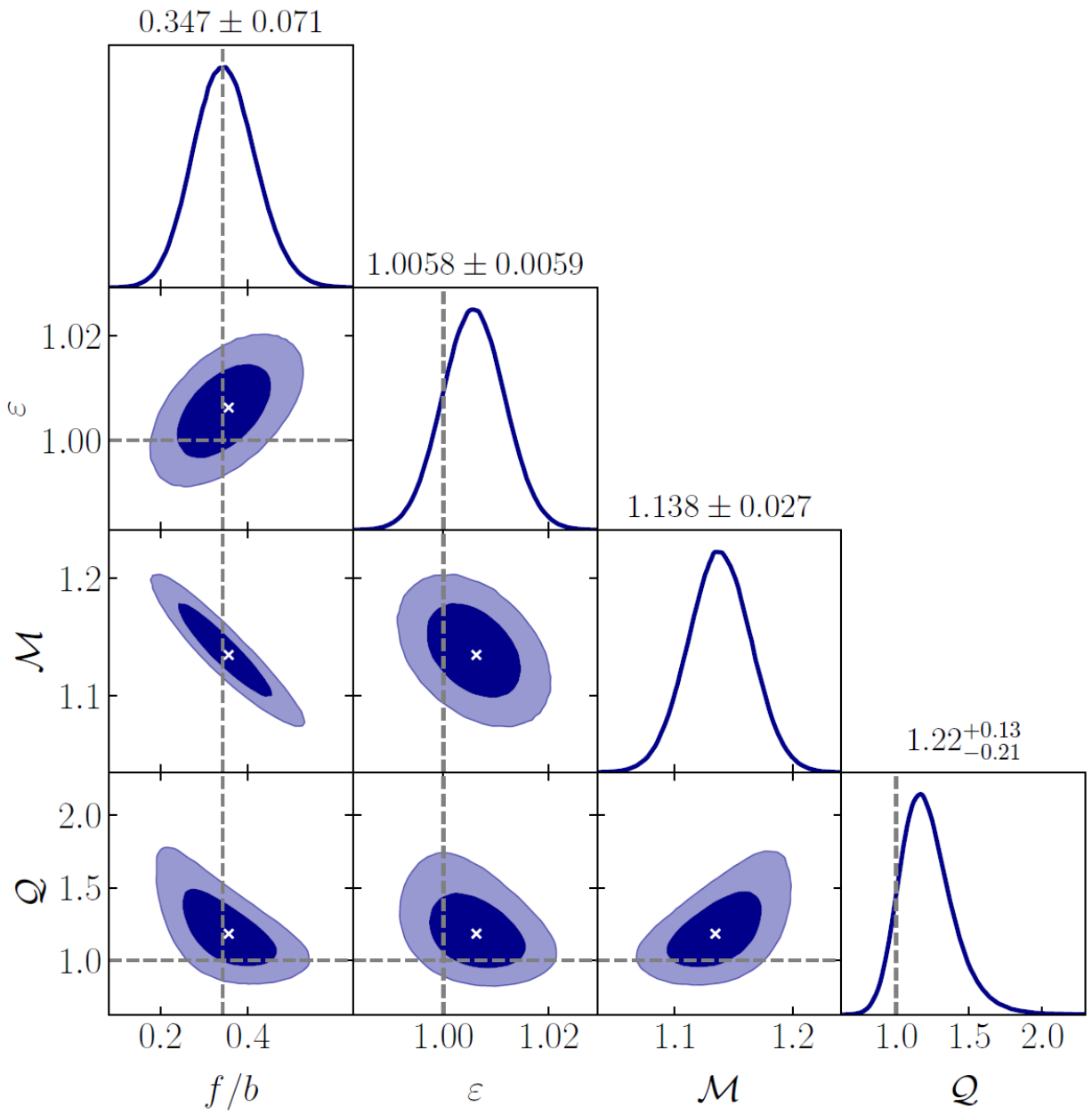
Model validation on PATCHY mocks

2 additional nuisance parameters for systematics:

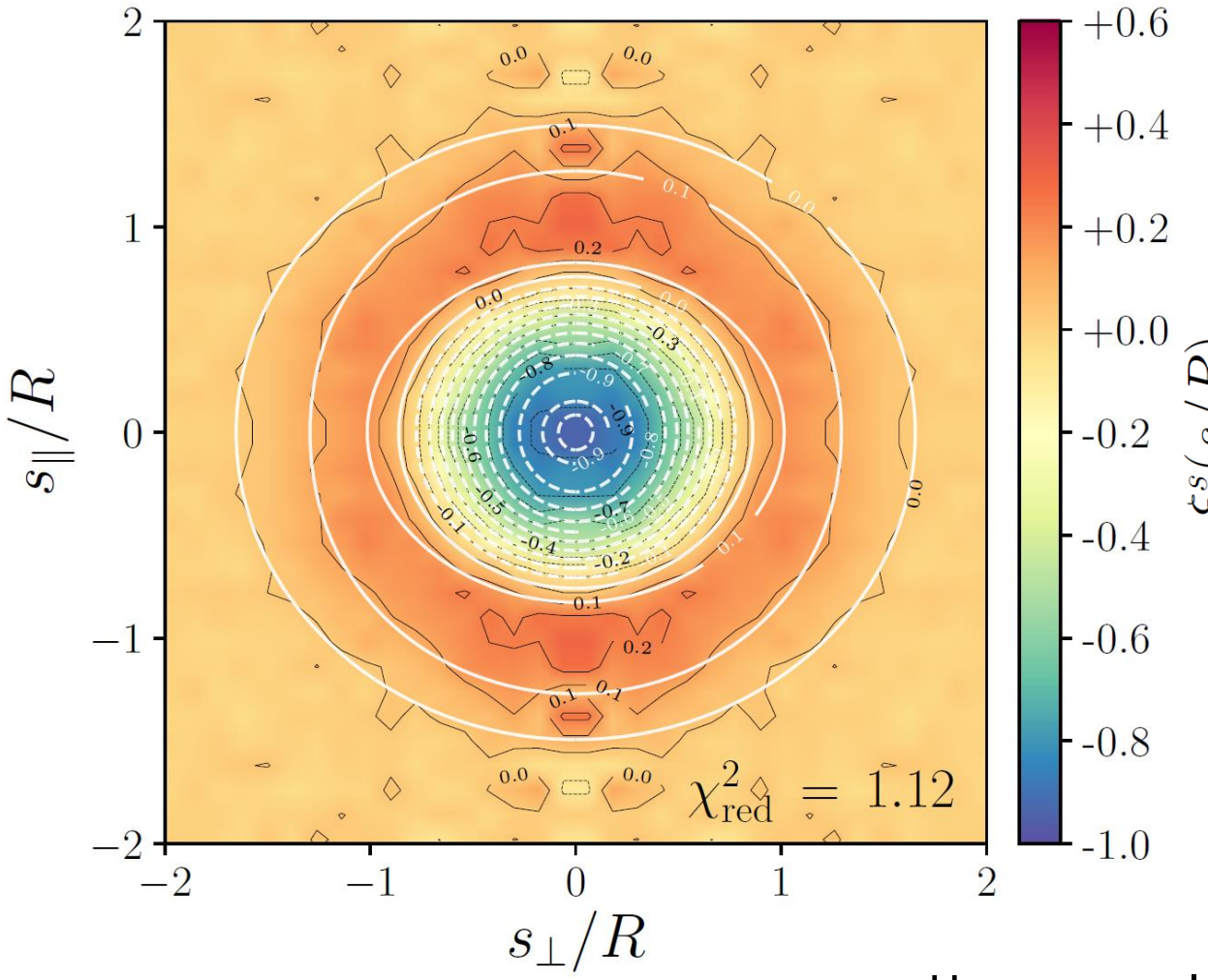
$\mathcal{M}$: Monopole amplitude after deprojection
$\mathcal{Q}$: Quadrupole amplitude

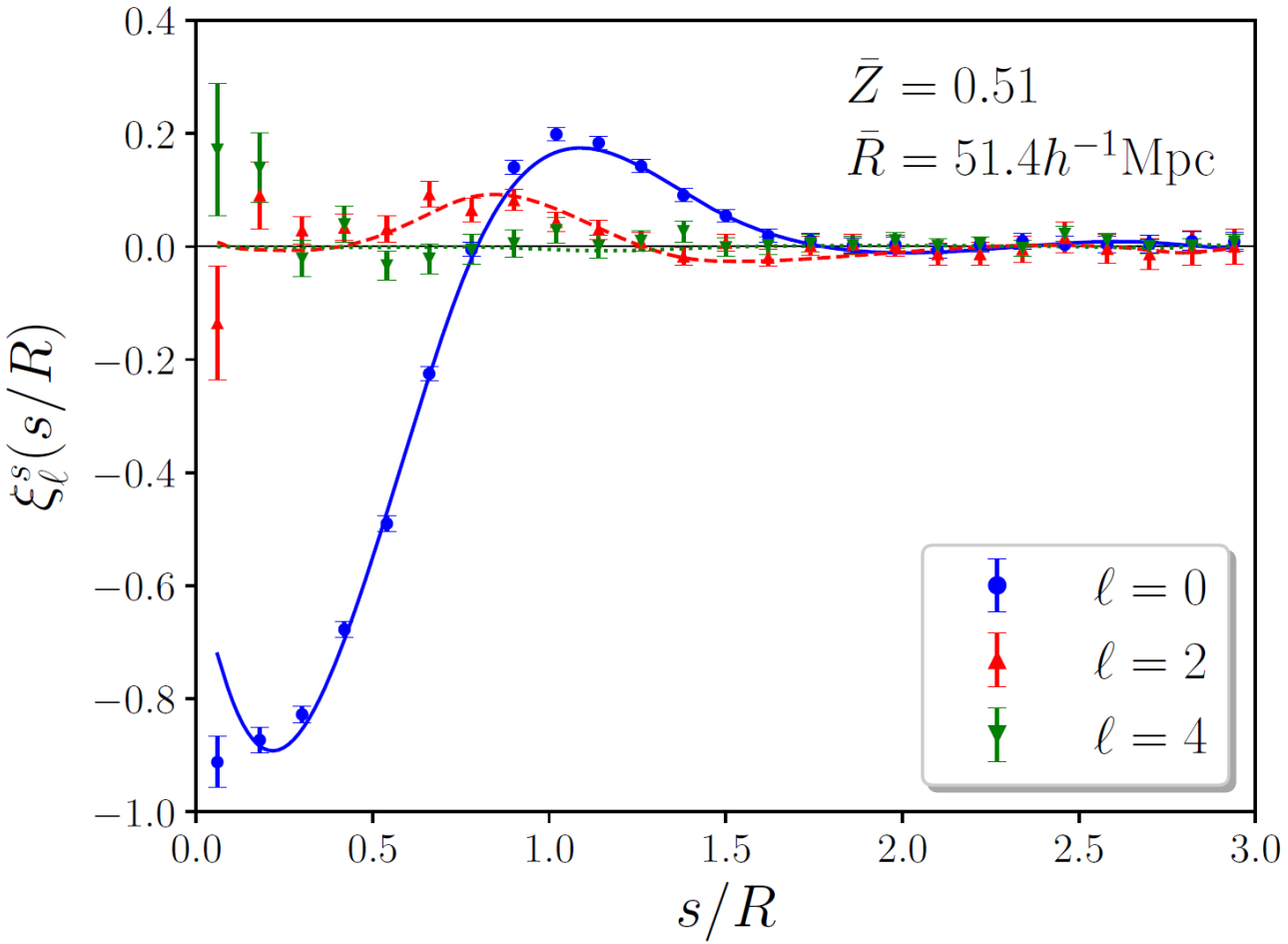
$$\xi^s(\mathbf{s}) = \mathcal{M}\left\{\xi(r) + \frac{1}{3}\frac{f}{b}\bar{\xi}(r) + \frac{f}{b}\mathcal{Q}\mu_r^2\left[\xi(r) - \bar{\xi}(r)\right]\right\}$$

$$r_\parallel = \frac{s_\parallel}{1 - \frac{\mathcal{M}}{3}\frac{f}{b}\bar{\xi}(r)} \qquad r_\perp = s_\perp \qquad r = \sqrt{r_\parallel^2 + r_\perp^2}$$



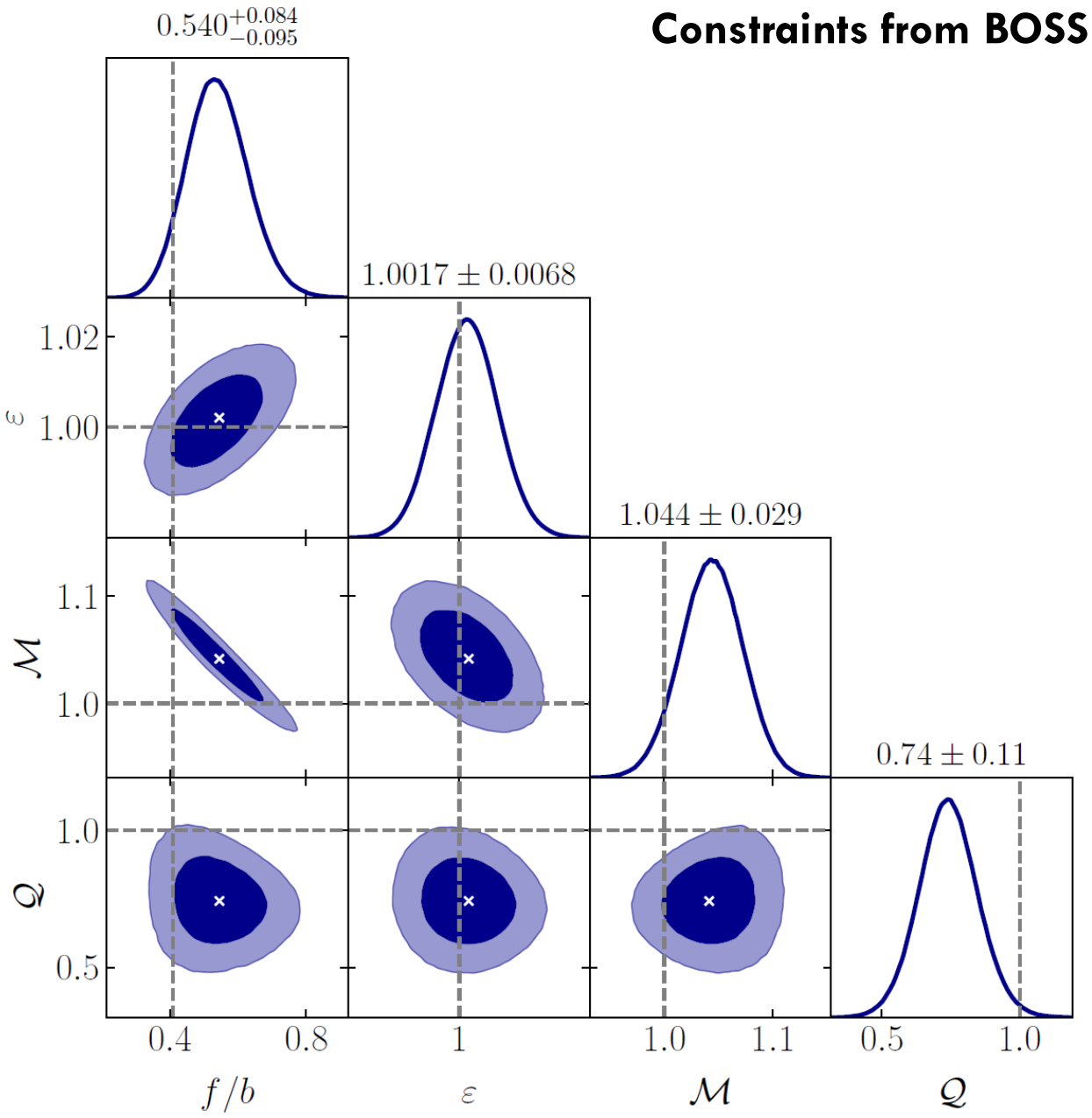
BOSS DR12 data (all voids)

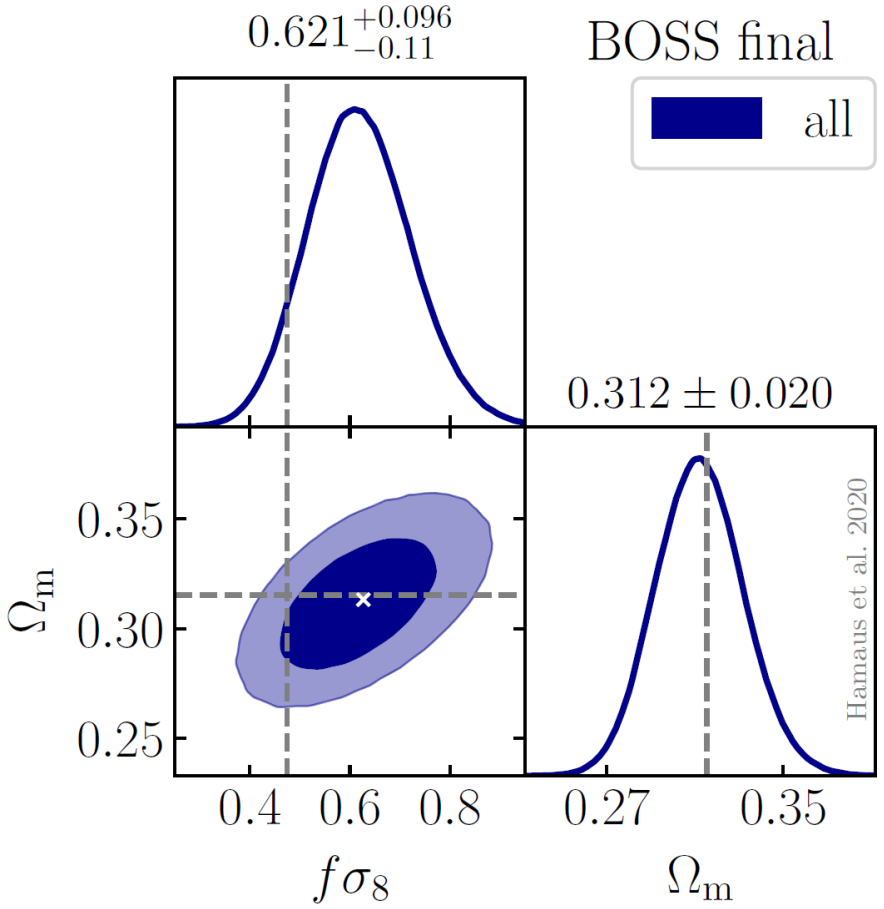




Hamaus et al. (JCAP 2020)

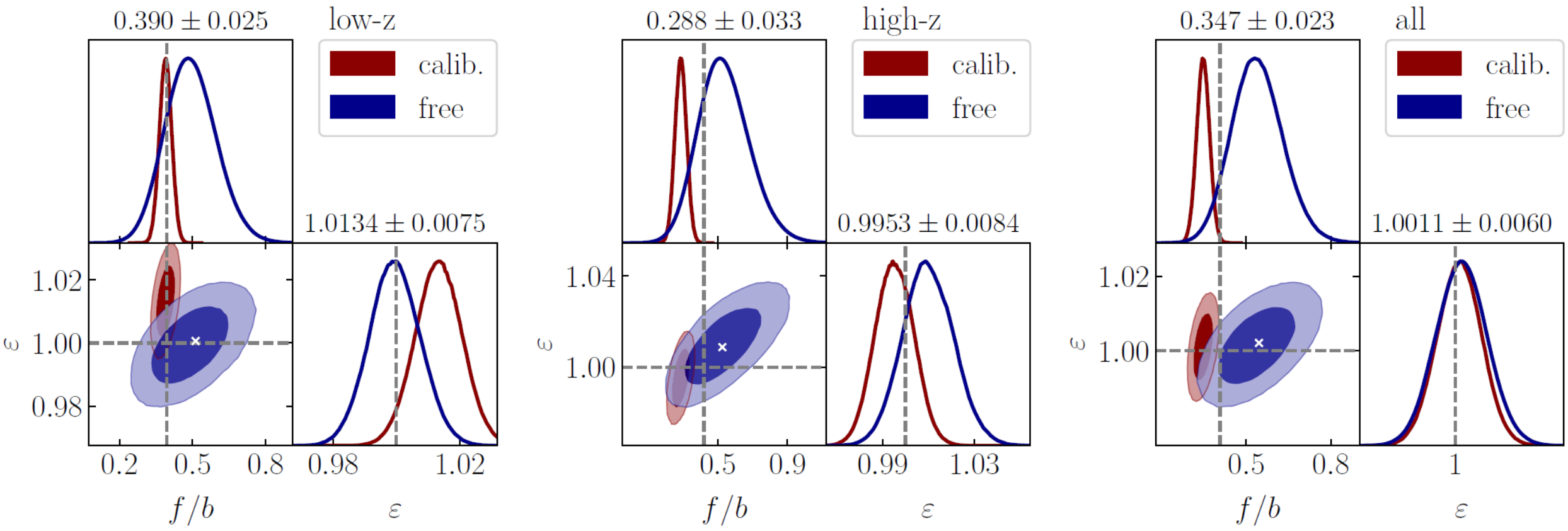
Constraints from BOSS DR12



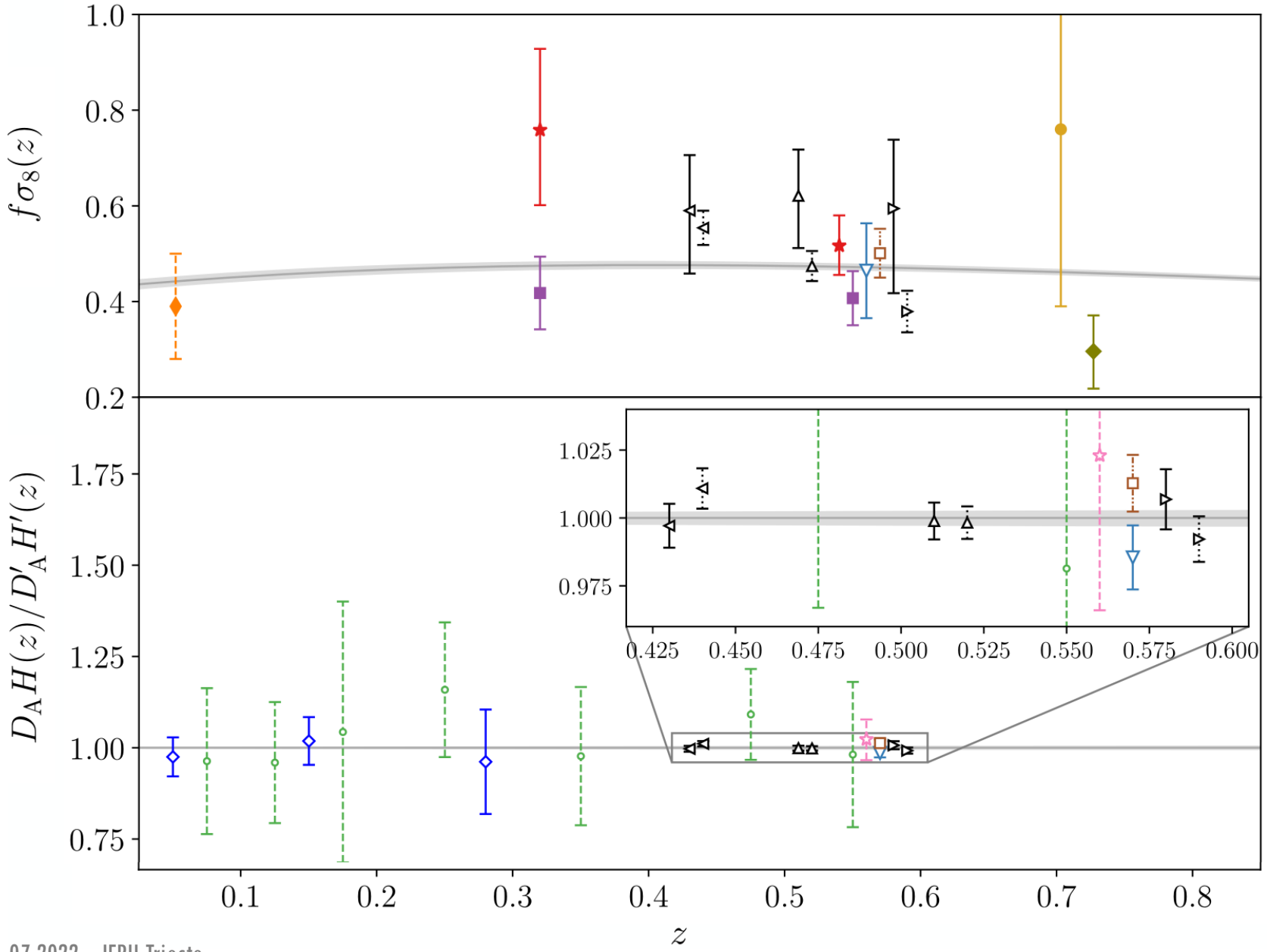


BOSS DR12 constraints (redshift bins & all voids)

Model calibration: determine $\mathcal{M}$, $\mathcal{Q}$, $\xi(r)$ from PATCHY mocks



Comparison of void constraints



Method:
RSD only (filled symbols)
RSD+AP (open symbols)

Model calibration:
none (solid)
with mocks (dotted)
with sims & mocks (dot-dashed)

Reference:
Planck 2018 (gray line)

A&A 658, A20 (2022)
https://doi.org/10.1051/0004-6361/202142073

Astronomy & Astrophysics

arxiv.org/abs/2108.10347

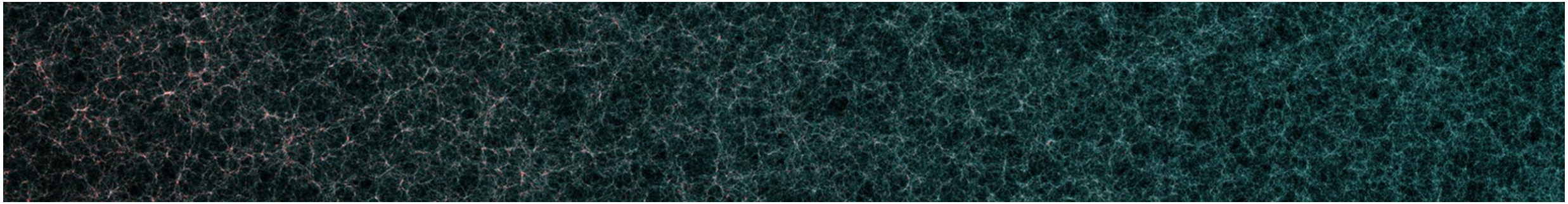
Euclid: Forecasts from redshift-space distortions and the Alcock–Paczynski test with cosmic voids★

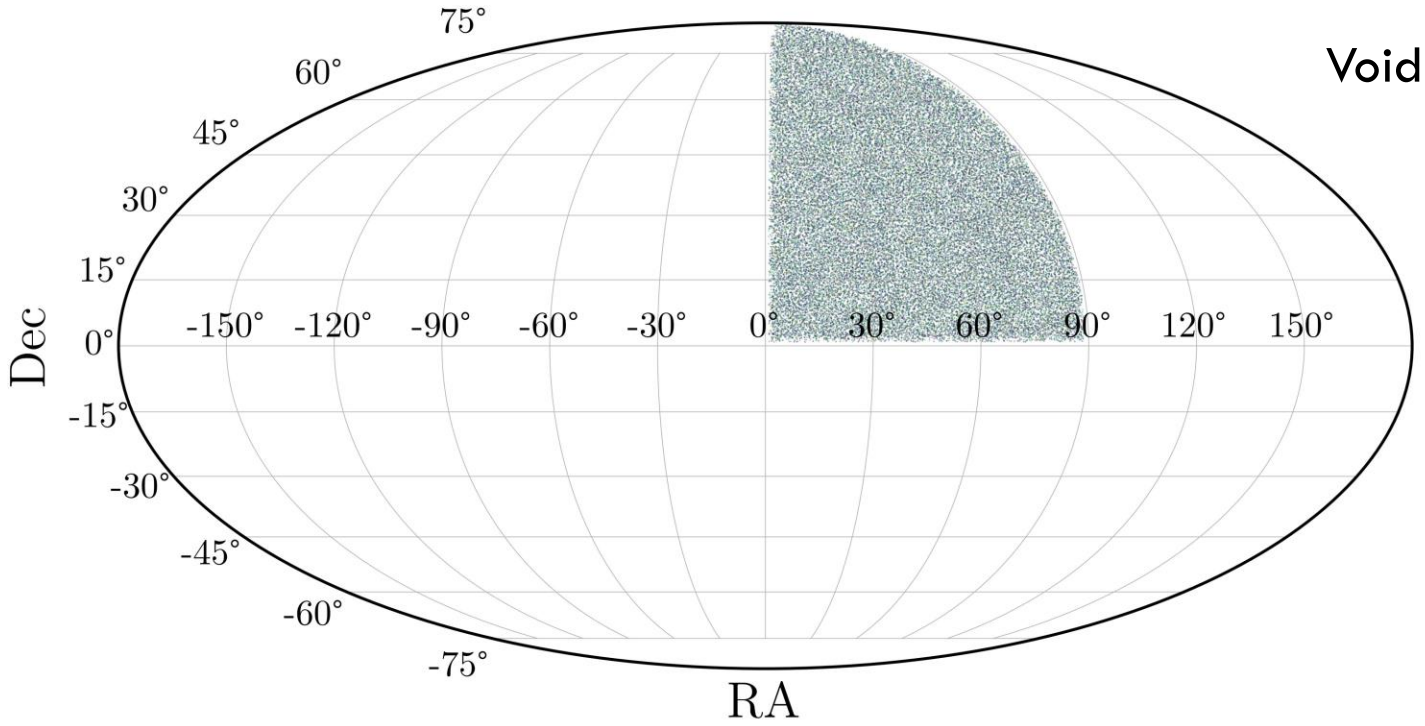
N. Hamaus[1], M. Aubert[2,3], A. Pisani[4], S. Contarini[5,6,7], G. Verza[8,9], M.-C. Cousinou[3], S. Escoffier[3], A. Hawken[3], G. Lavaux[10], G. Pollina[1], B. D. Wandelt[10], J. Weller[1,11], M. Bonici[12,13], C. Carbone[14,15], L. Guzzo[14,16,17], A. Kovacs[18,19], F. Marulli[6,20,21], E. Massara[22,23], L. Moscardini[6,20,21], P. Ntelis[3], W. J. Percival[22,23,24], S. Radinović[25], M. Sahlén[26,27], Z. Sakr[28,29], A. G. Sánchez[11], H. A. Winther[25], N. Auricchio[21], S. Awan[30], R. Bender[1,11], C. Bodendorf[11], D. Bonino[31], E. Branchini[32,33], M. Brescia[34], J. Brinchmann[35], V. Capobianco[31], J. Carretero[36,37], F. J. Castander[38,39], M. Castellano[40], S. Cavuoti[34,41,42], A. Cimatti[5,43], R. Cledassou[44,45], G. Congedo[46], L. Conversi[47,48], Y. Copin[49], L. Corcione[31], M. Cropper[30], A. Da Silva[50,51], H. Degaudenzi[52], M. Douspis[53], F. Dubath[52], C. A. J. Duncan[54], X. Dupac[48], S. Dusini[8], A. Ealet[49], S. Ferriol[49], P. Fosalba[38,39], M. Frailis[55], E. Franceschi[21], P. Franzetti[15], M. Fumana[15], B. Garilli[15], B. Gillis[46], C. Giocoli[56,57], A. Grazian[58], F. Grupp[1,11], S. V. H. Haugan[25], W. Holmes[59], F. Hormuth[60,61], K. Jahnke[61], S. Kermiche[3], A. Kiessling[59], M. Kilbinger[62], T. Kitching[30], M. Kümmel[1], M. Kunz[63], H. Kurki-Suonio[64], S. Ligori[31], P. B. Lilje[25], I. Lloro[65], E. Maiorano[21], O. Marggraf[66], K. Markovic[59], R. Massey[67], S. Maurogordato[68], M. Melchior[69], M. Meneghetti[6,21,70], G. Meylan[71], M. Moresco[20,21], E. Munari[55], S. M. Niemi[72], C. Padilla[37], S. Paltani[52], F. Pasian[55], K. Pedersen[73], V. Pettorino[62], S. Pires[62], M. Poncet[45], L. Popa[74], L. Pozzetti[21], R. Rebolo[19,75], J. Rhodes[59], H. Rix[61], M. Roncarelli[20,21], E. Rossetti[20], R. Saglia[1,11], P. Schneider[66], A. Secroun[3], G. Seidel[61], S. Serrano[38,39], C. Sirignano[8,9], G. Sirri[6], J.-L. Starck[62], P. Tallada-Crespí[36,76], D. Tavagnacco[55], A. N. Taylor[46], I. Tereno[50,77], R. Toledo-Moreo[78], F. Torradeflot[36,76], E. A. Valentijn[79], L. Valenziano[6,21], Y. Wang[80], N. Welikala[46], G. Zamorani[21], J. Zoubian[3], S. Andreon[17], M. Baldi[6,21,81], S. Camera[31,82,83], S. Mei[84], C. Neissner[36,37], and E. Romelli[55]

(Affiliations can be found after the references)

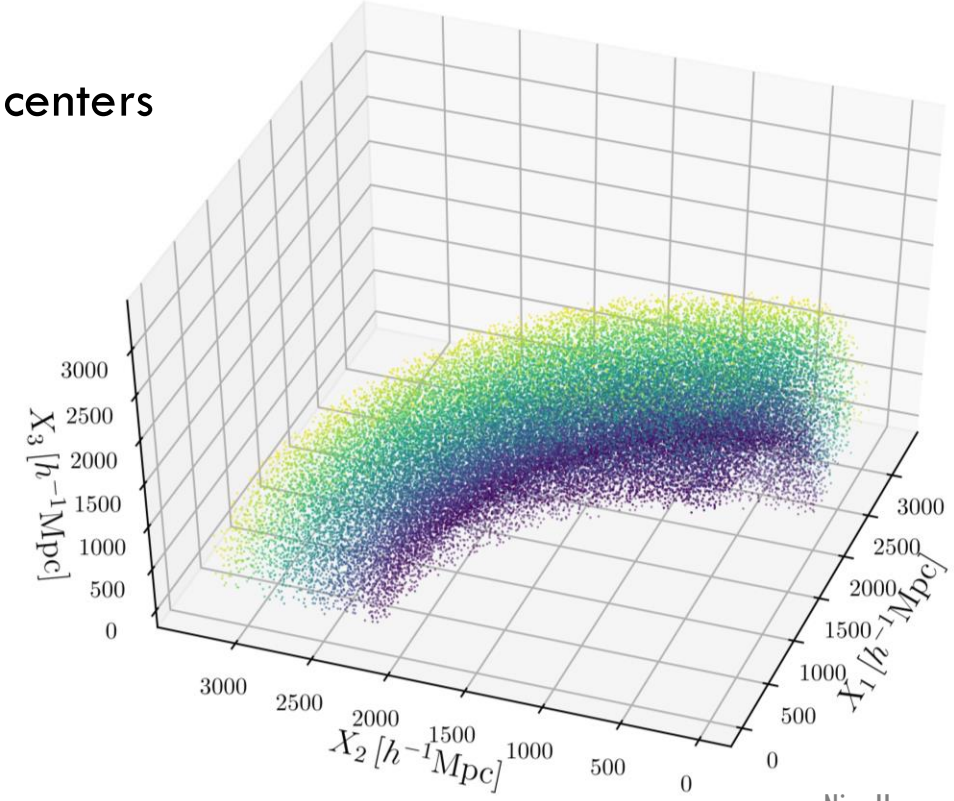
Received 23 August 2021 / Accepted 31 October 2021

VIDE voids in *Euclid* **Flagship mock** light-cone octant (version 1.8.4, $0.9 < z < 1.8$, redshift space) with completeness cut of 60% and added Gaussian redshift error of $\sigma_z = 1‰$

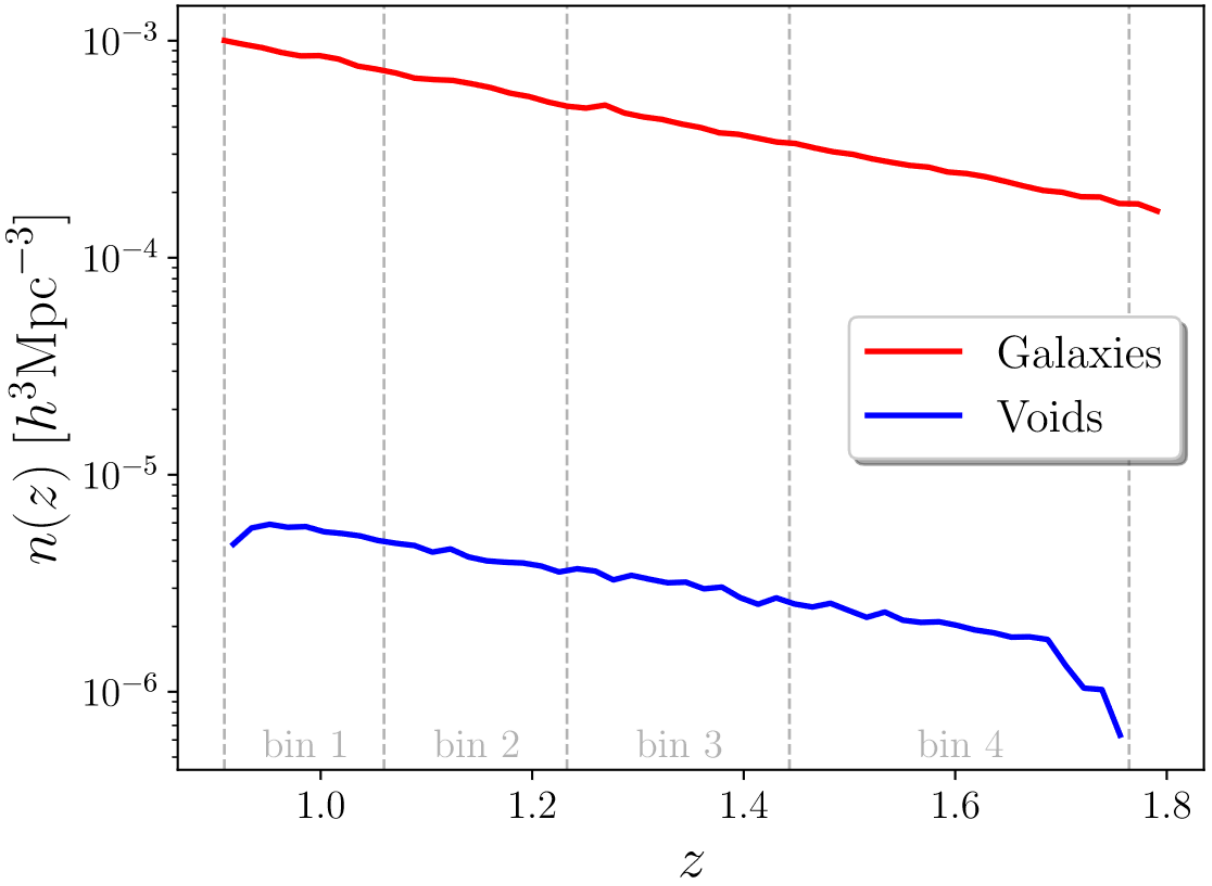




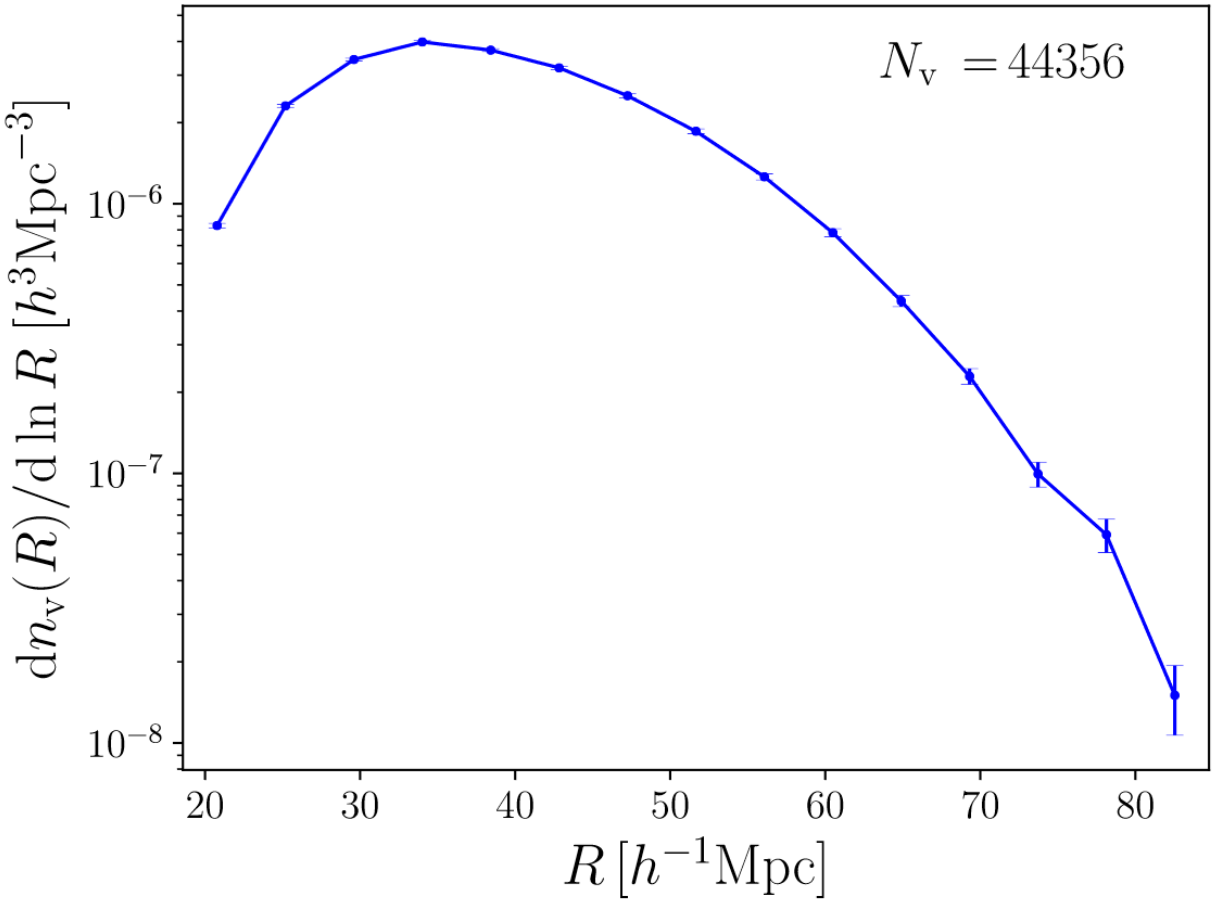
Void centers



Number density of tracers and voids



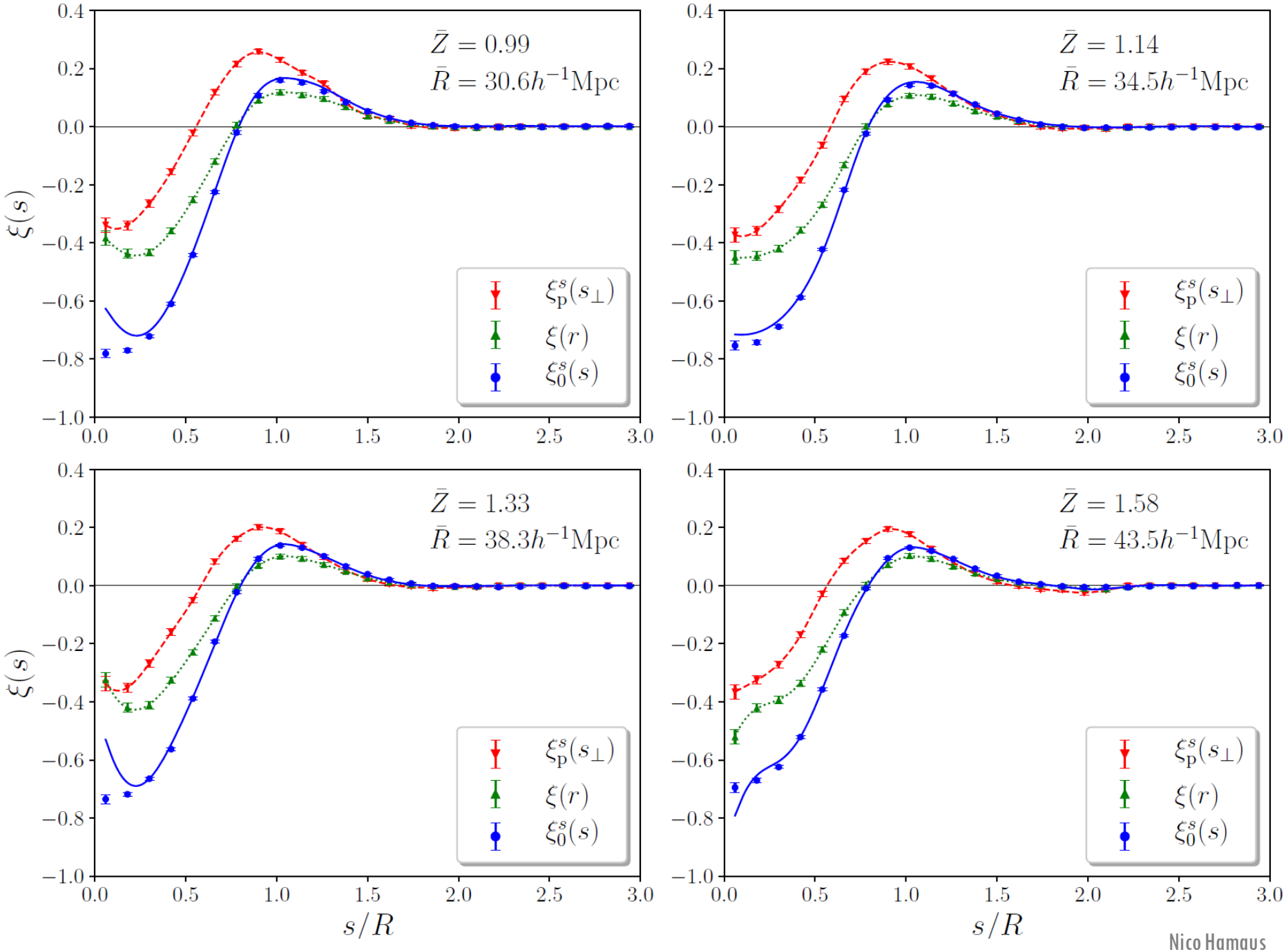
Void size function



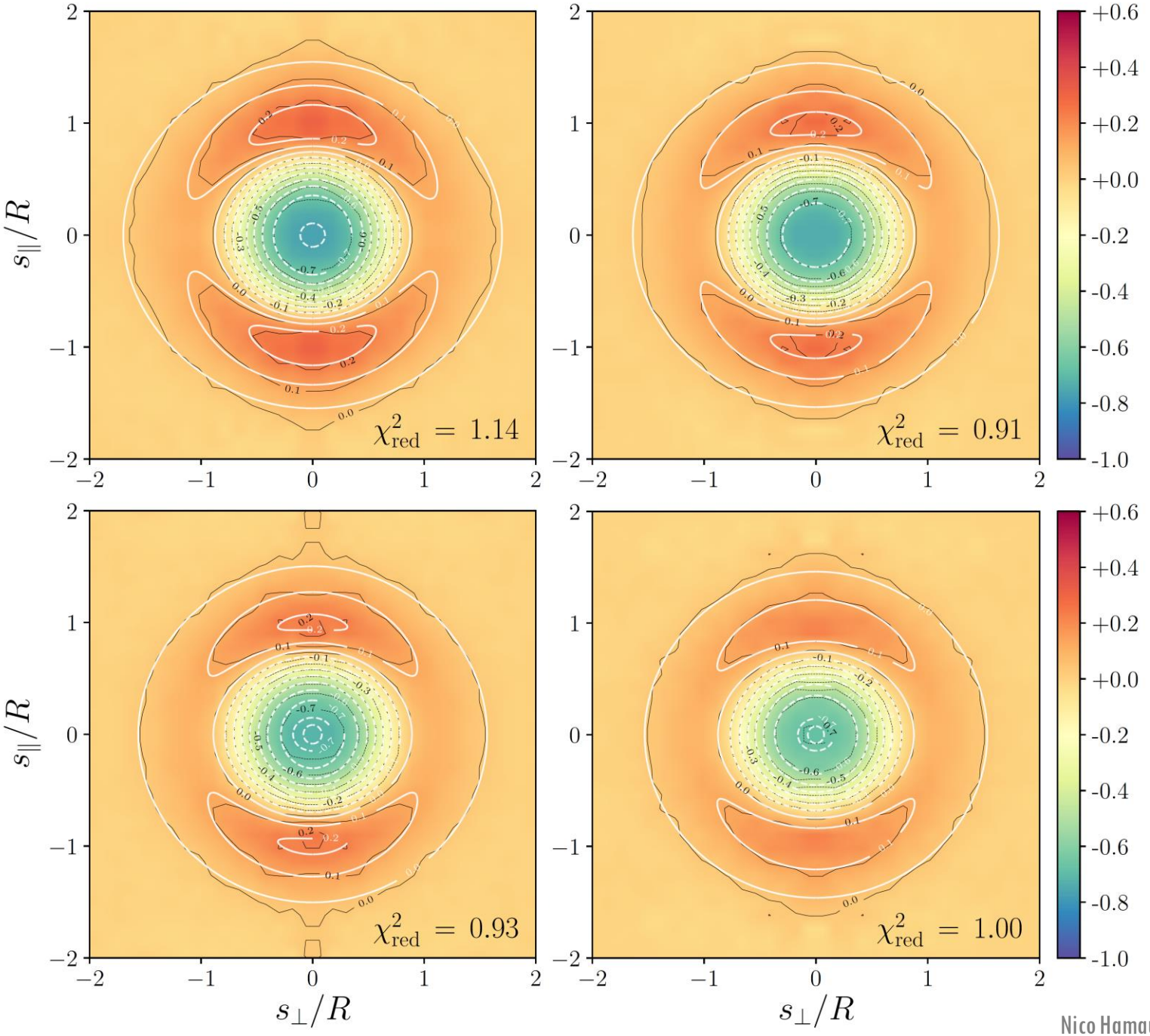
Purity cut on void size: $R > N_\mathrm{s}\left(\frac{4\pi}{3} n_\mathrm{g}(Z)\right)^{-1/3}$ $N_\mathrm{s} = 3$

Projected void-galaxy correlation function

Deprojection via inverse Abel transform

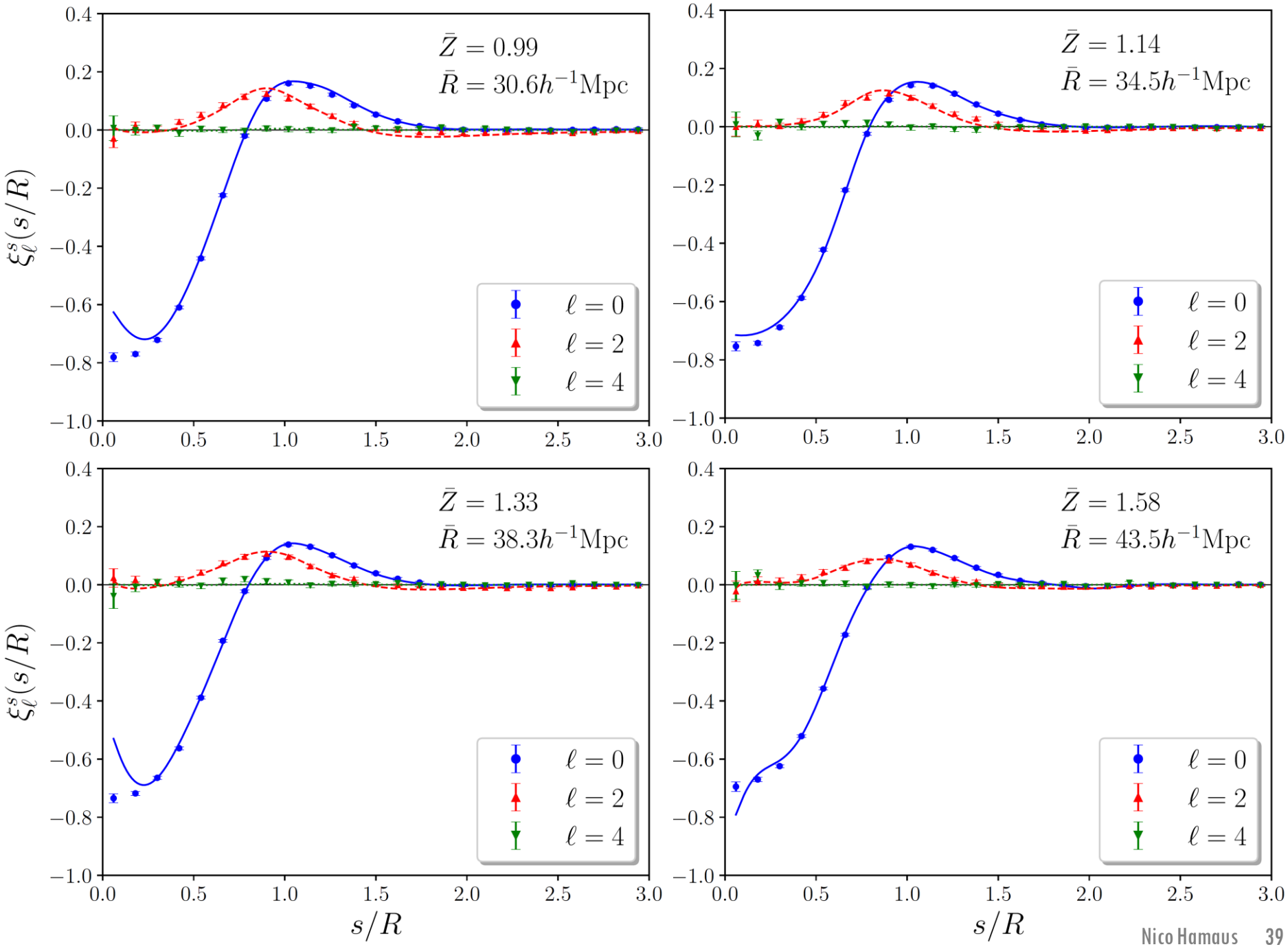


Plane-of-sky vs. line-of-sight 2D void-galaxy correlation function

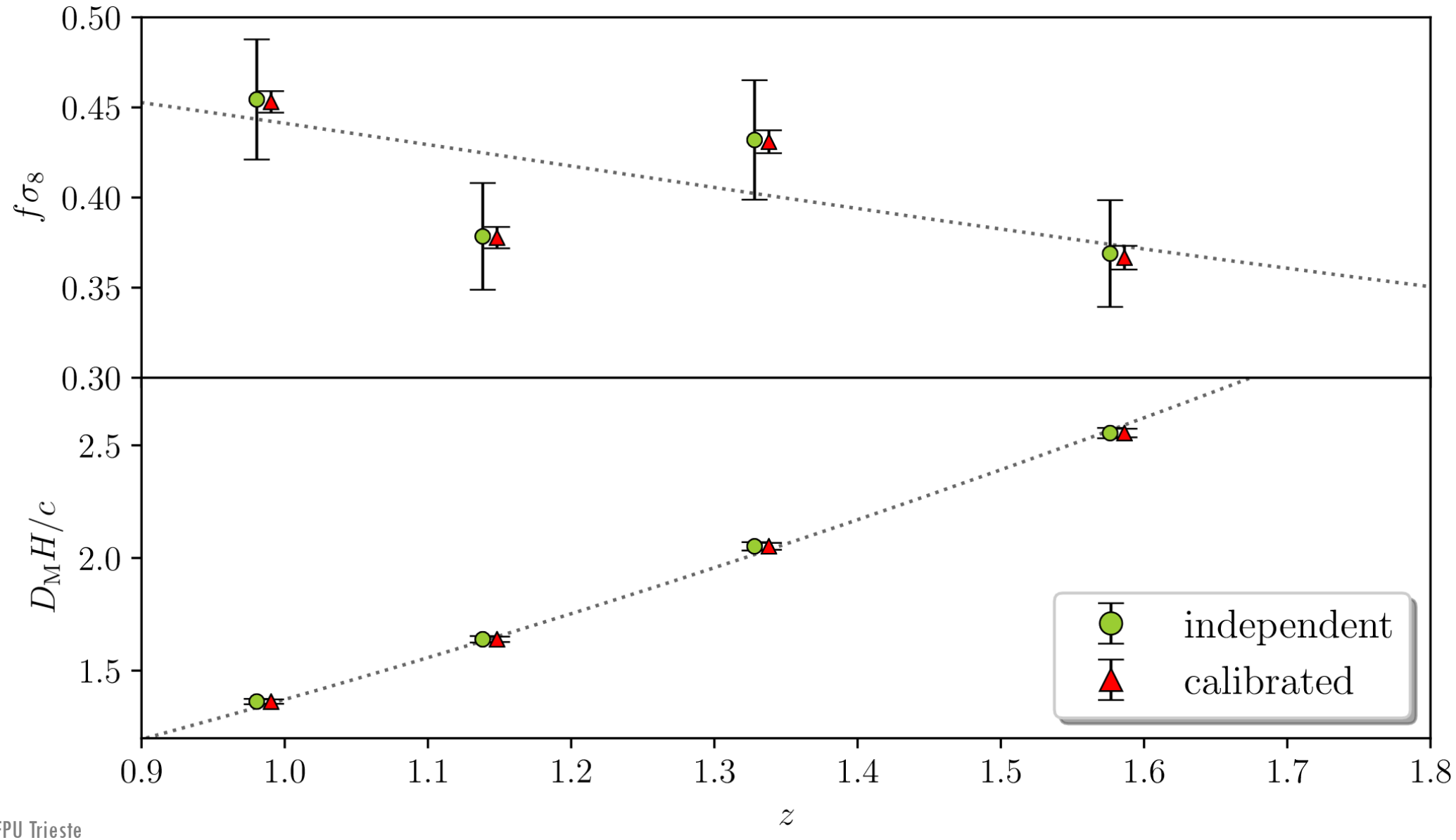


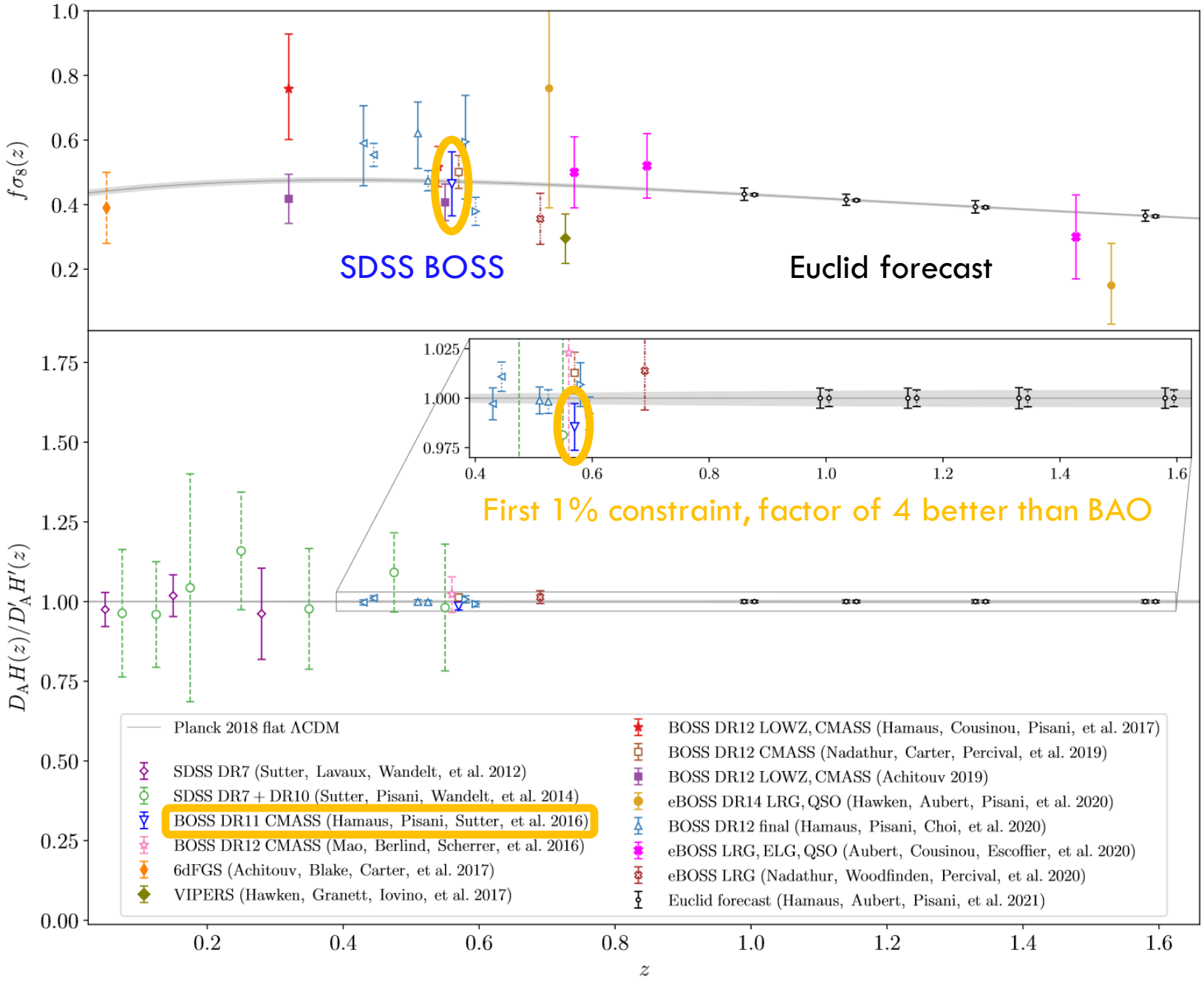
Multipoles

$$\xi_\ell^s(s) = \frac{2\ell+1}{2}\int_{-1}^{1} \xi^s(s,\mu_s)P_\ell(\mu_s)\mathrm{d}\mu_s$$



Constraints on growth and expansion history (forecast from one octant)





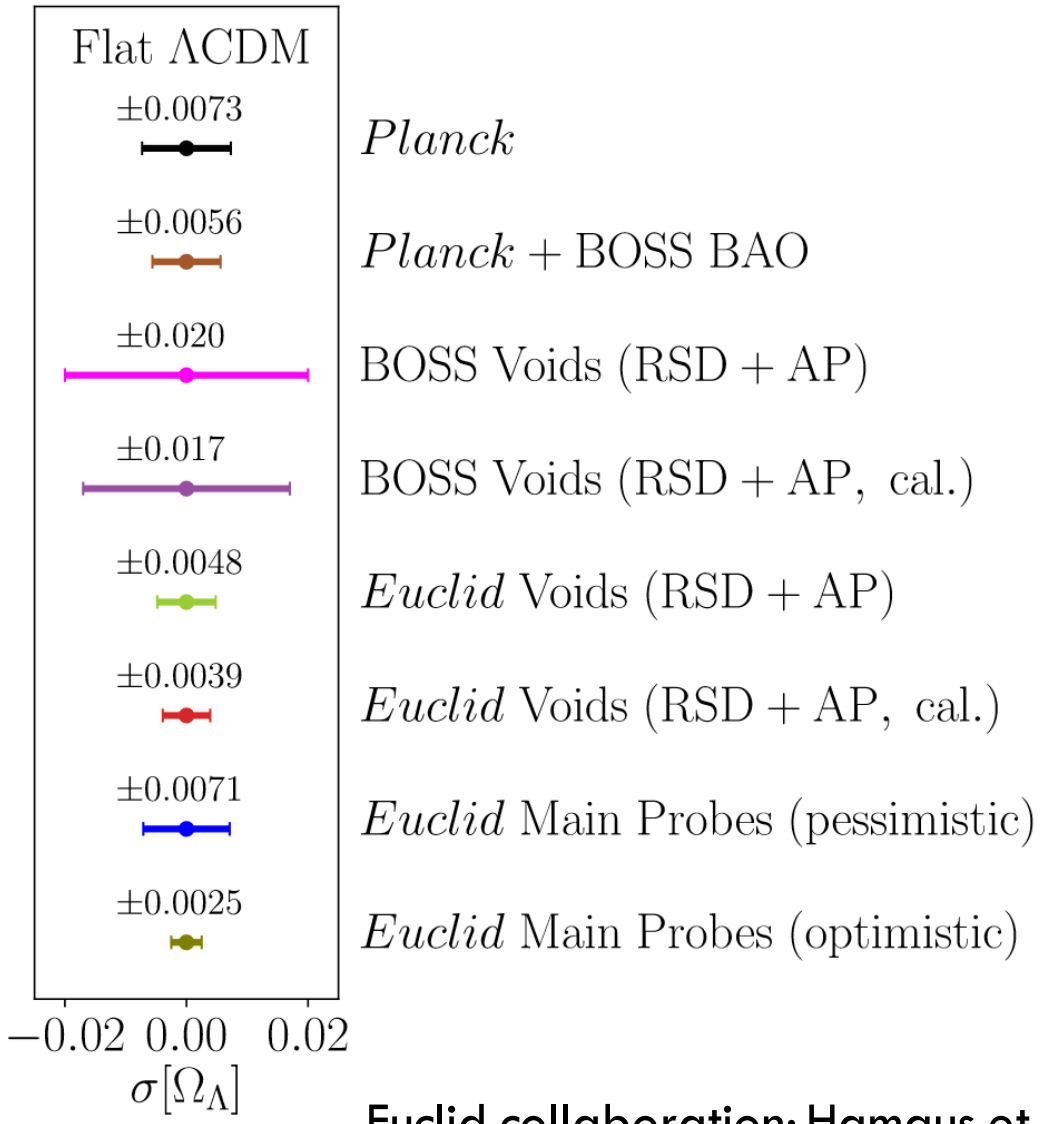
Overview of constraints from various galaxy surveys

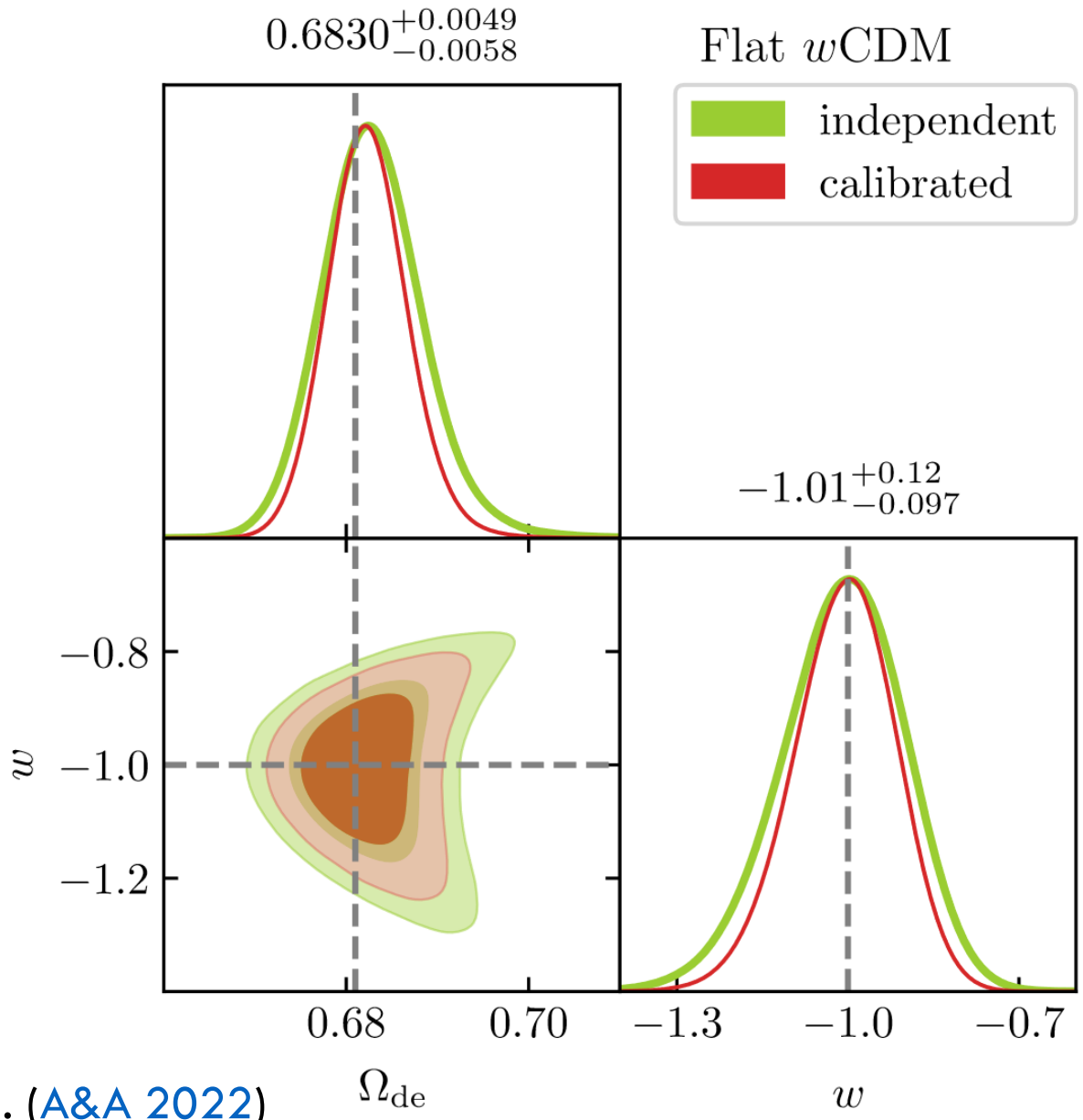
Method:
RSD only (filled symbols)
RSD+AP (open symbols)

Model calibration:
none (solid)
with mocks (dotted)
with sims & mocks (dot-dashed)

Reference:
Planck 2018 (gray line)

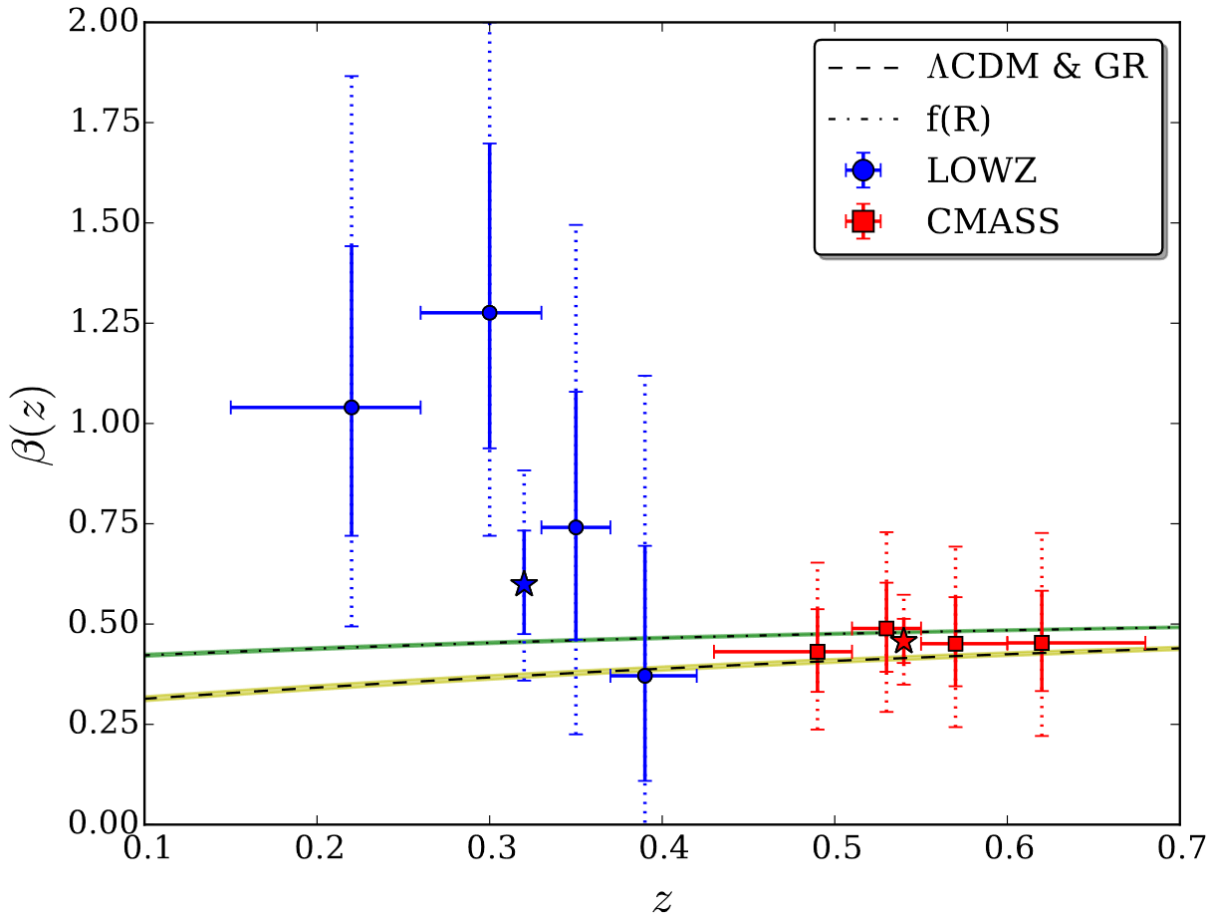
Constraints on cosmology as stand-alone probe, extrapolated to full *Euclid* footprint of 15 000 sq. deg.



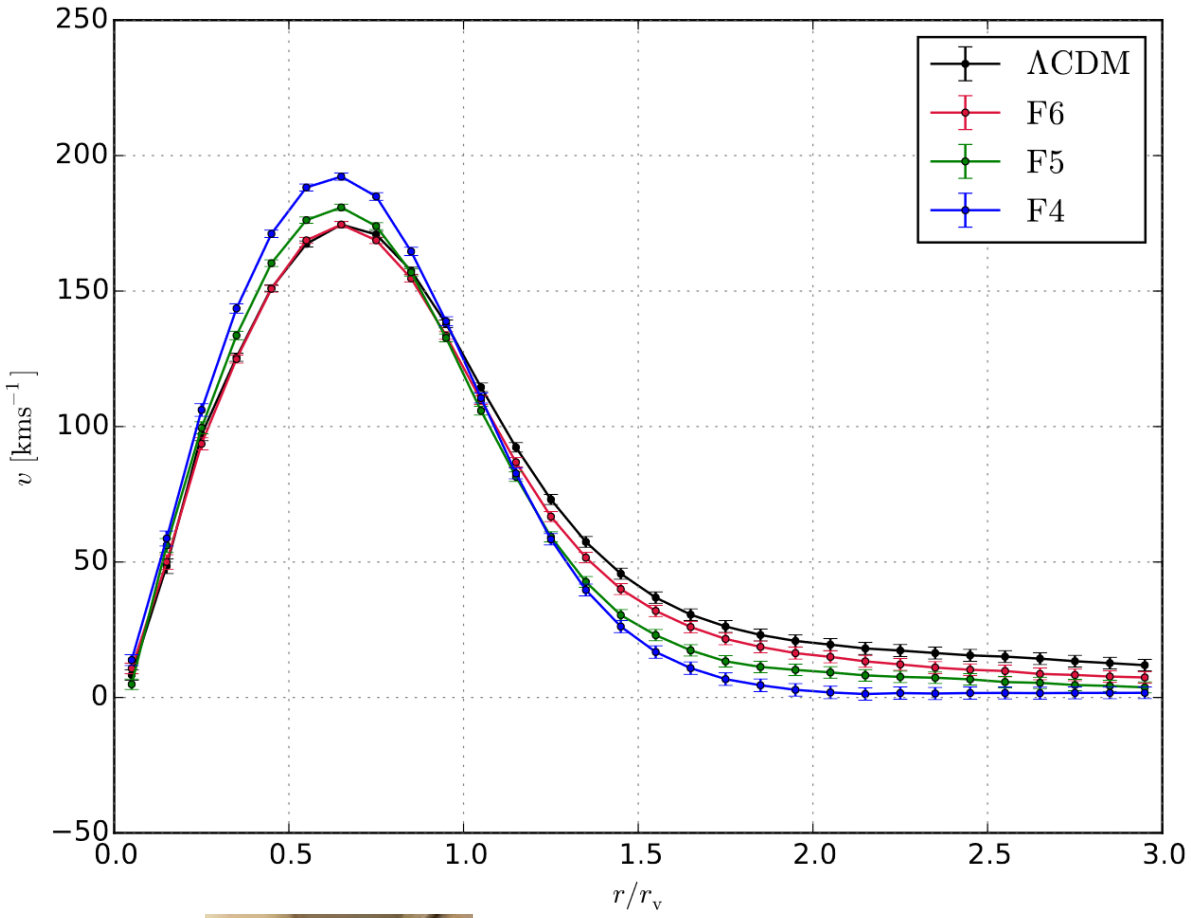


Euclid collaboration: Hamaus et al. ([A&A 2022](#))

Gravity: Exploring alternatives to GR

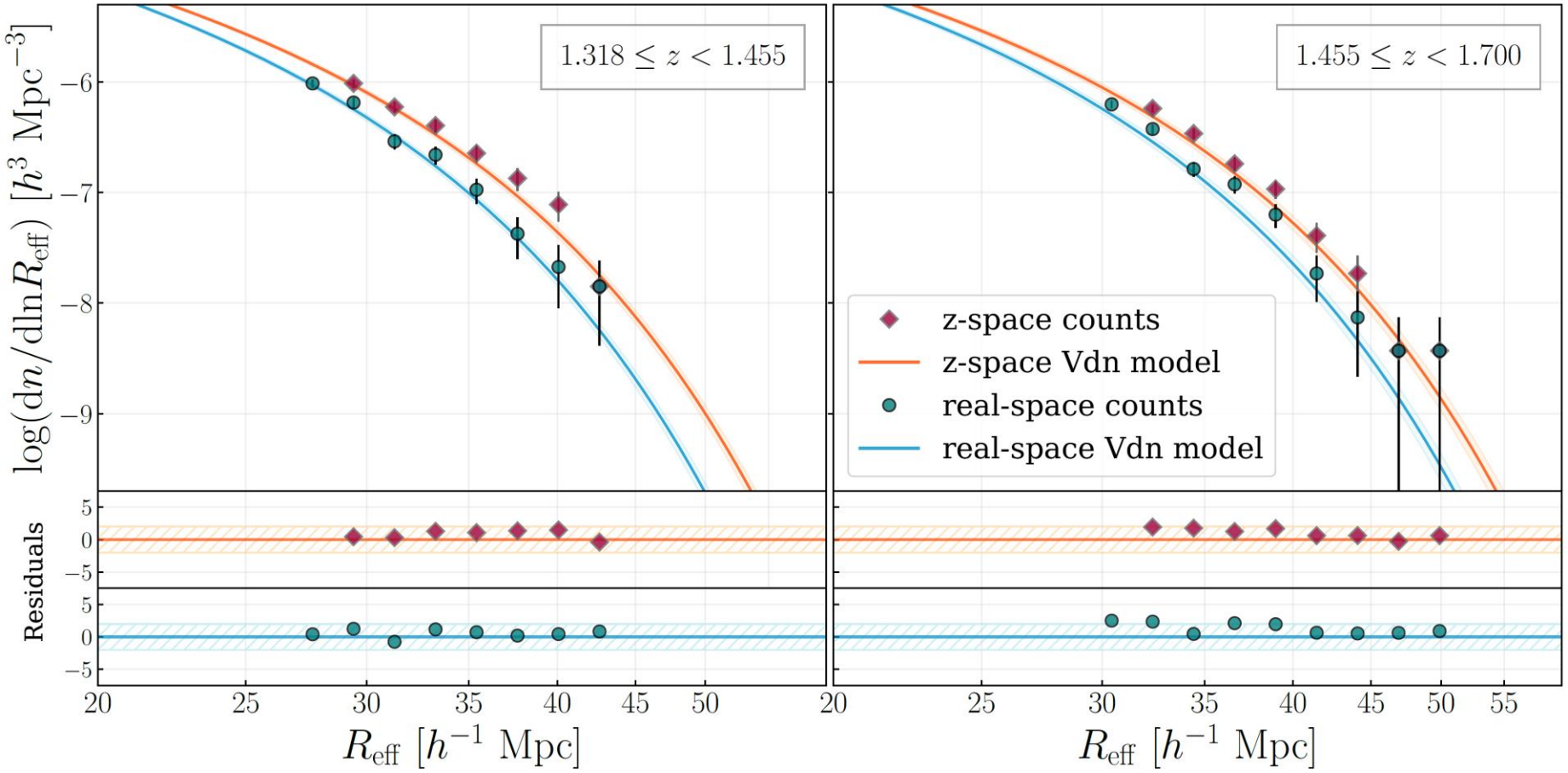


Hamaus et al. (JCAP 2017)



Simon Bach (Master thesis)

VOID SIZE FUNCTION

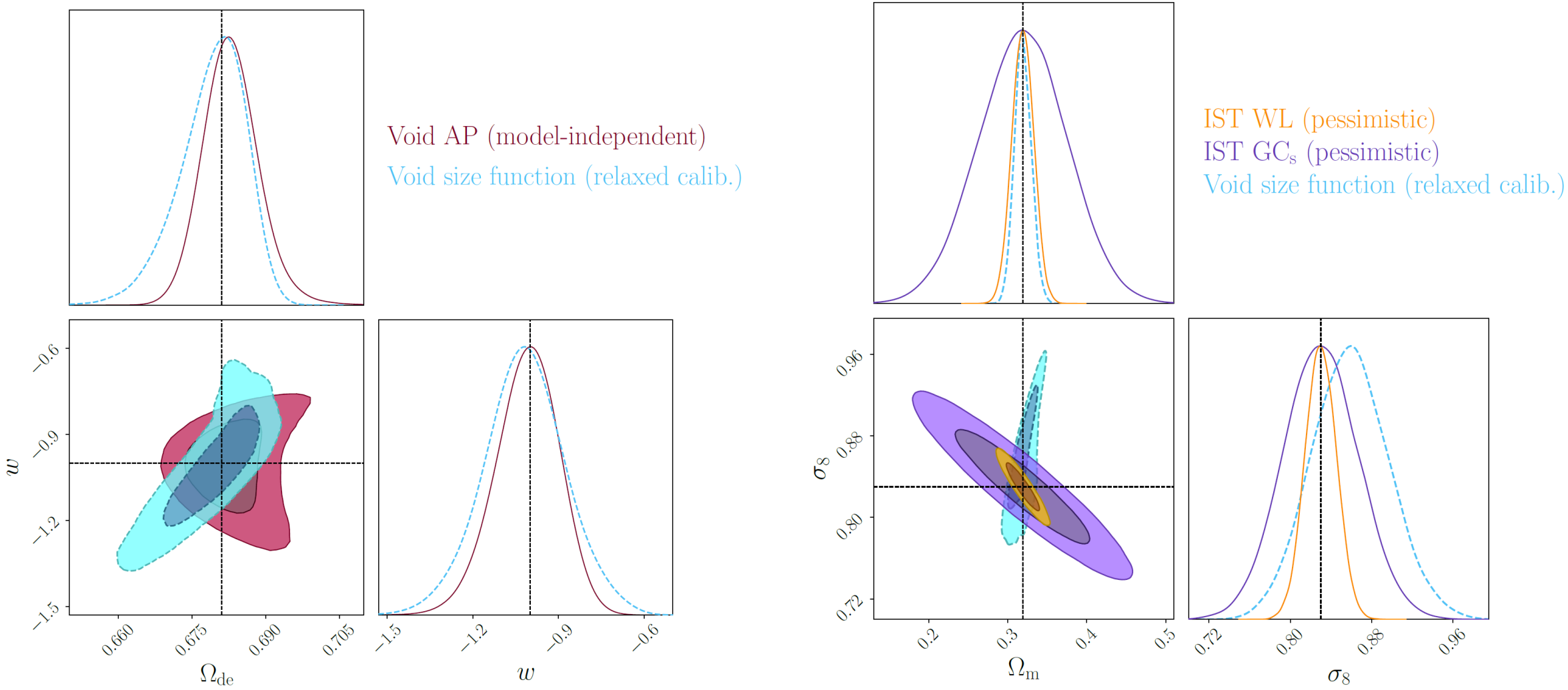


Sofia Contarini

Giovanni Verza

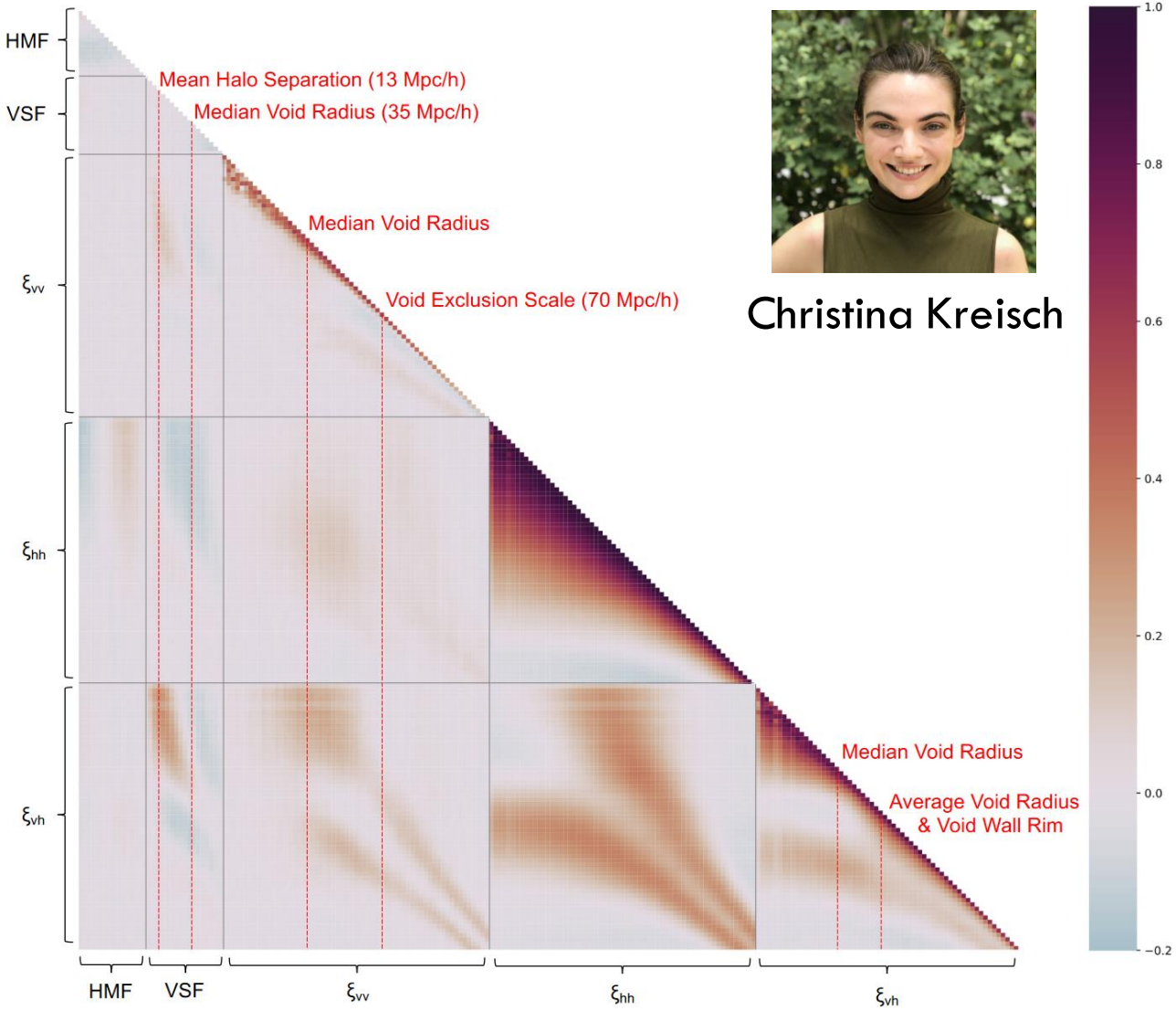
Euclid collaboration: Contarini, Verza et al. (arXiv 2205.11525)

Let's break degeneracies!

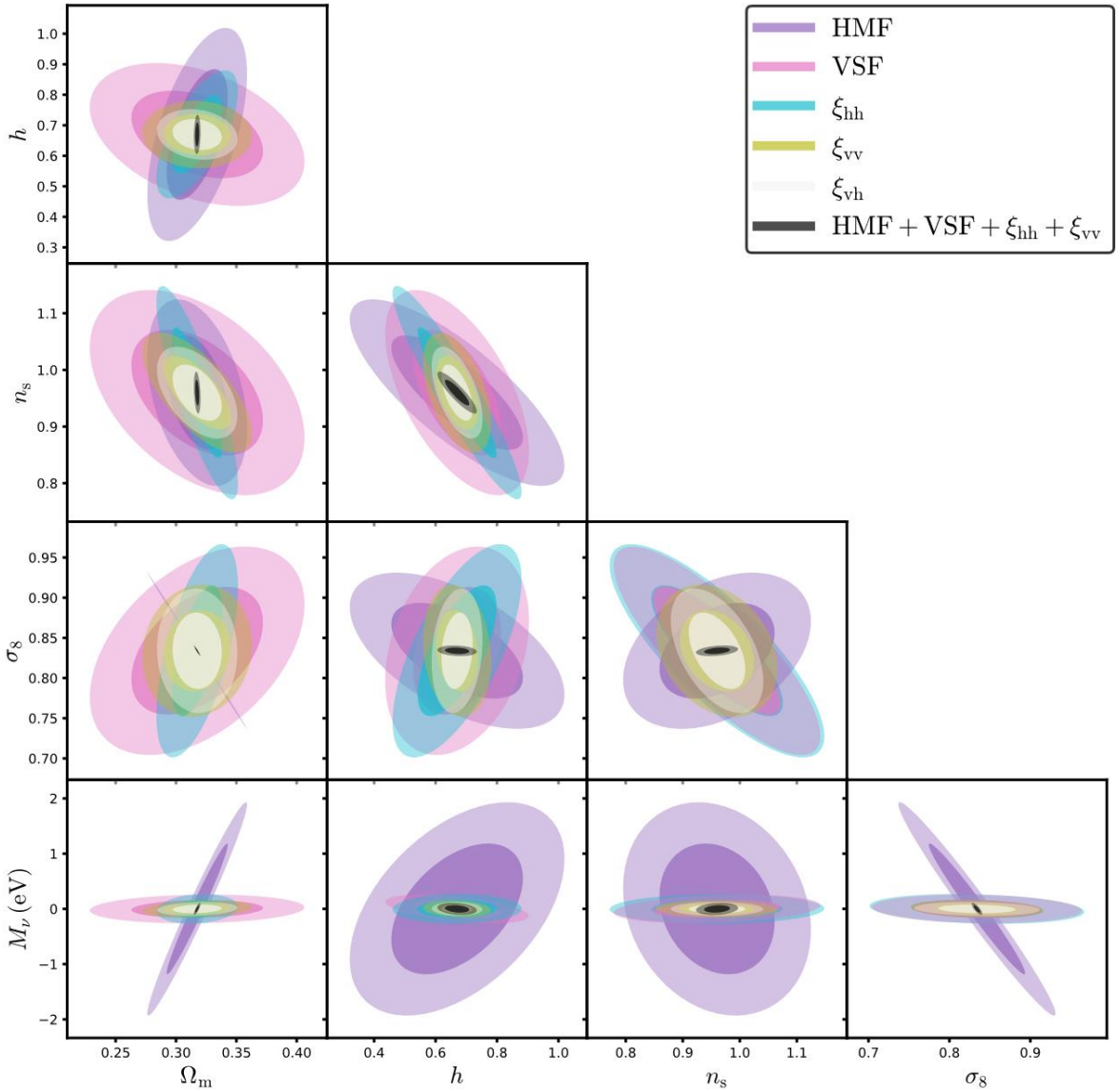


Euclid collaboration: Contarini, Verza et al. (arXiv 2205.11525)

Complementarity / **Orthogonality** with other probes (Fisher forecast with Quijote)

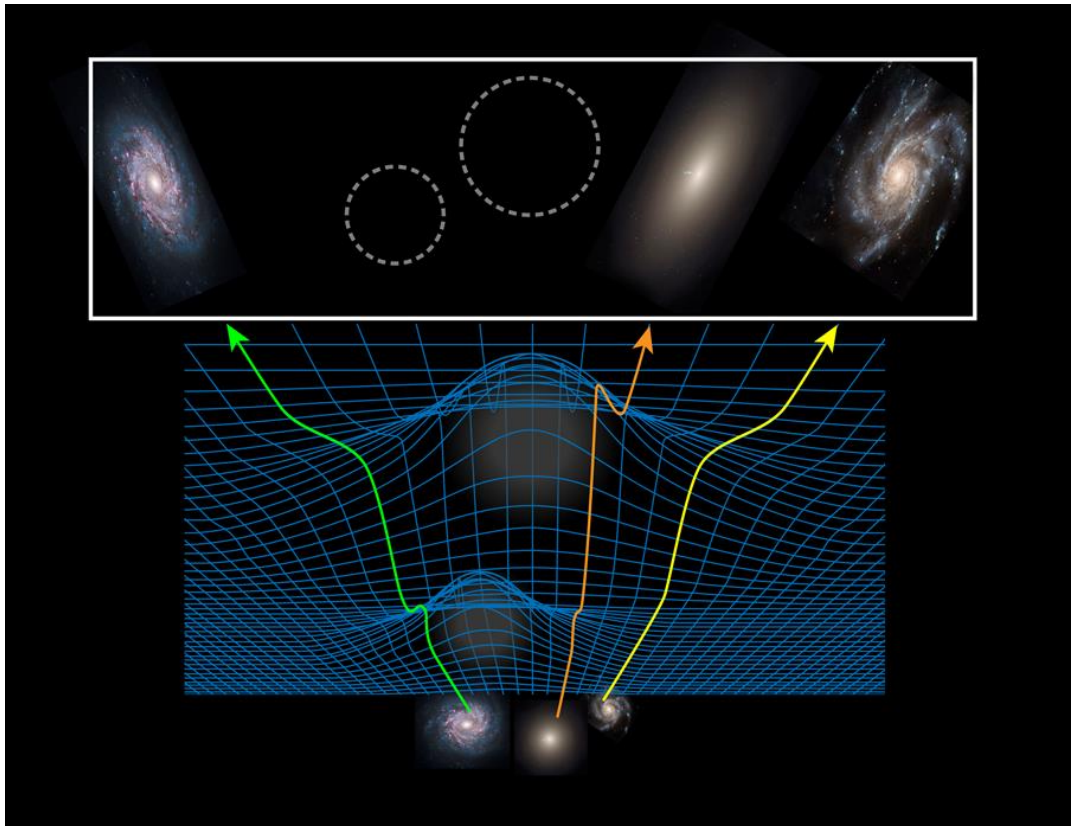


Christina Kreisch

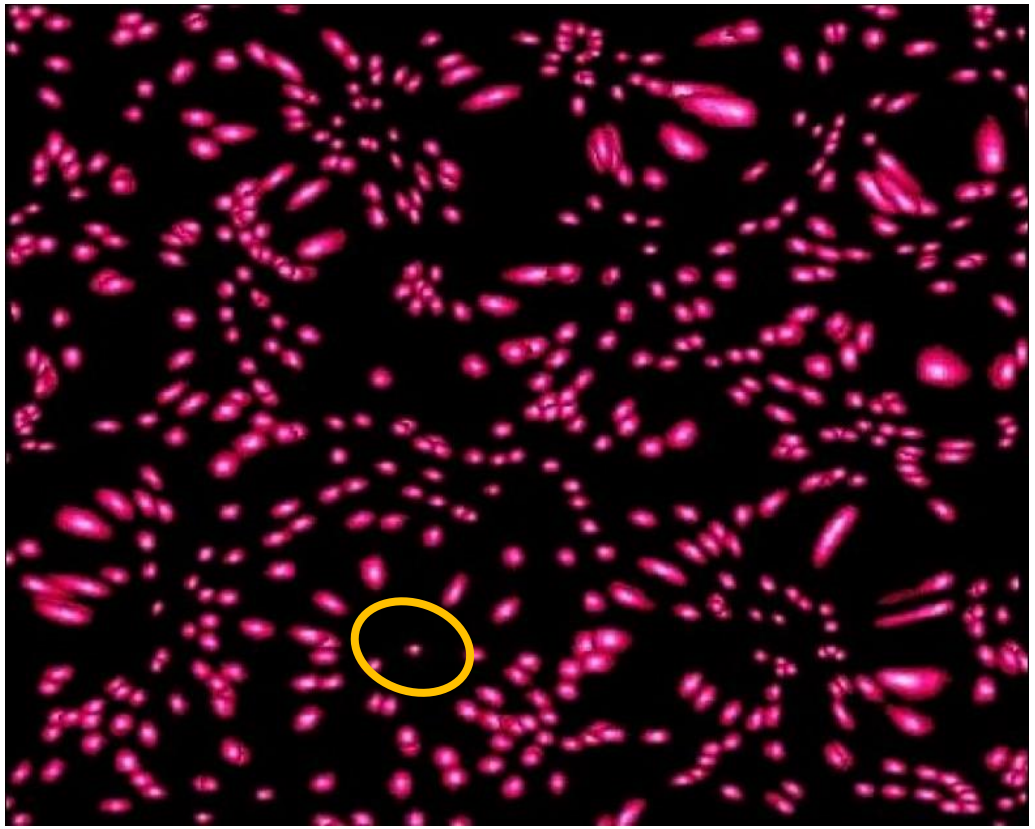


Kreisch, Pisani et al. (arXiv 2107.02304)

VOID LENSING



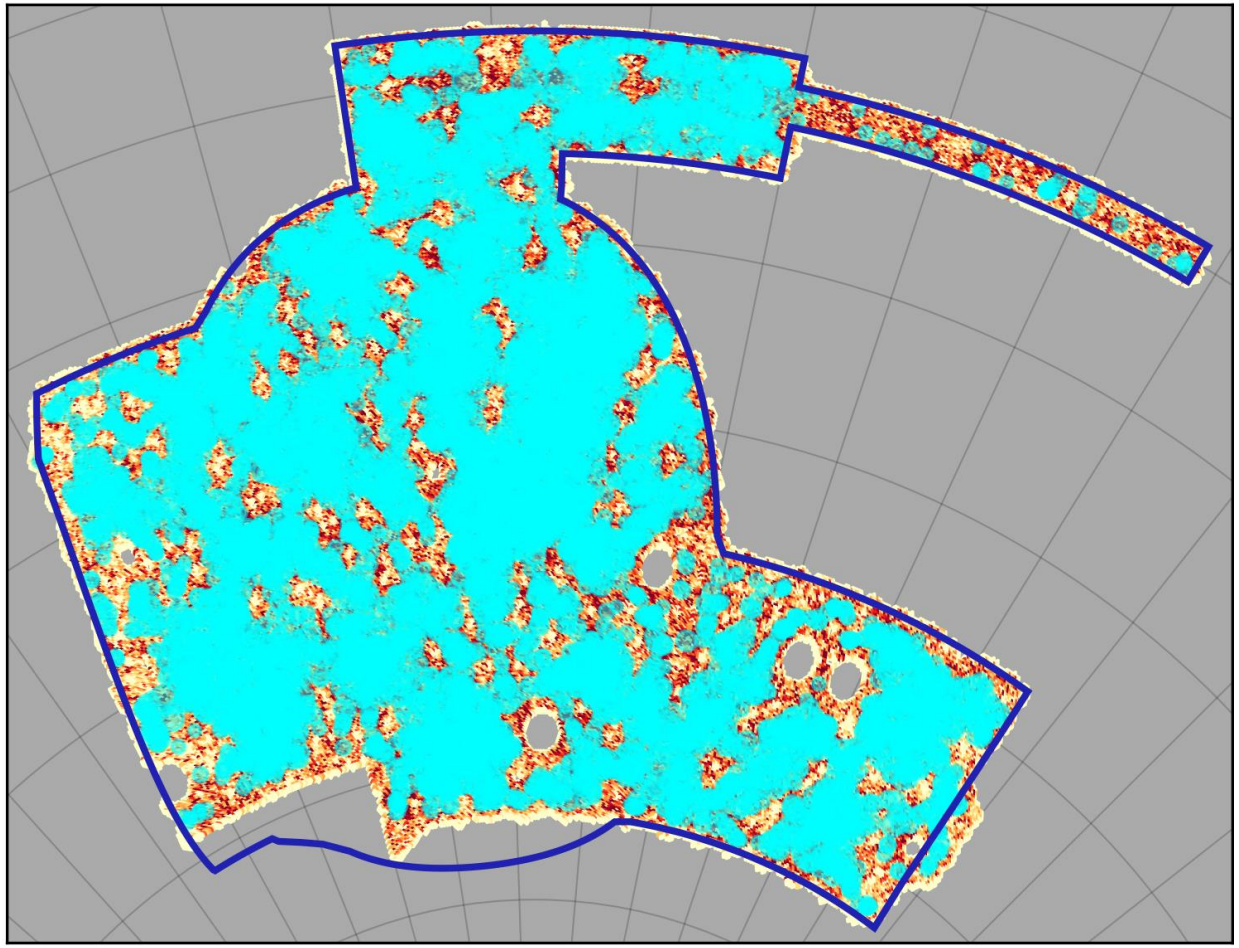
APS / Alan Stonebraker

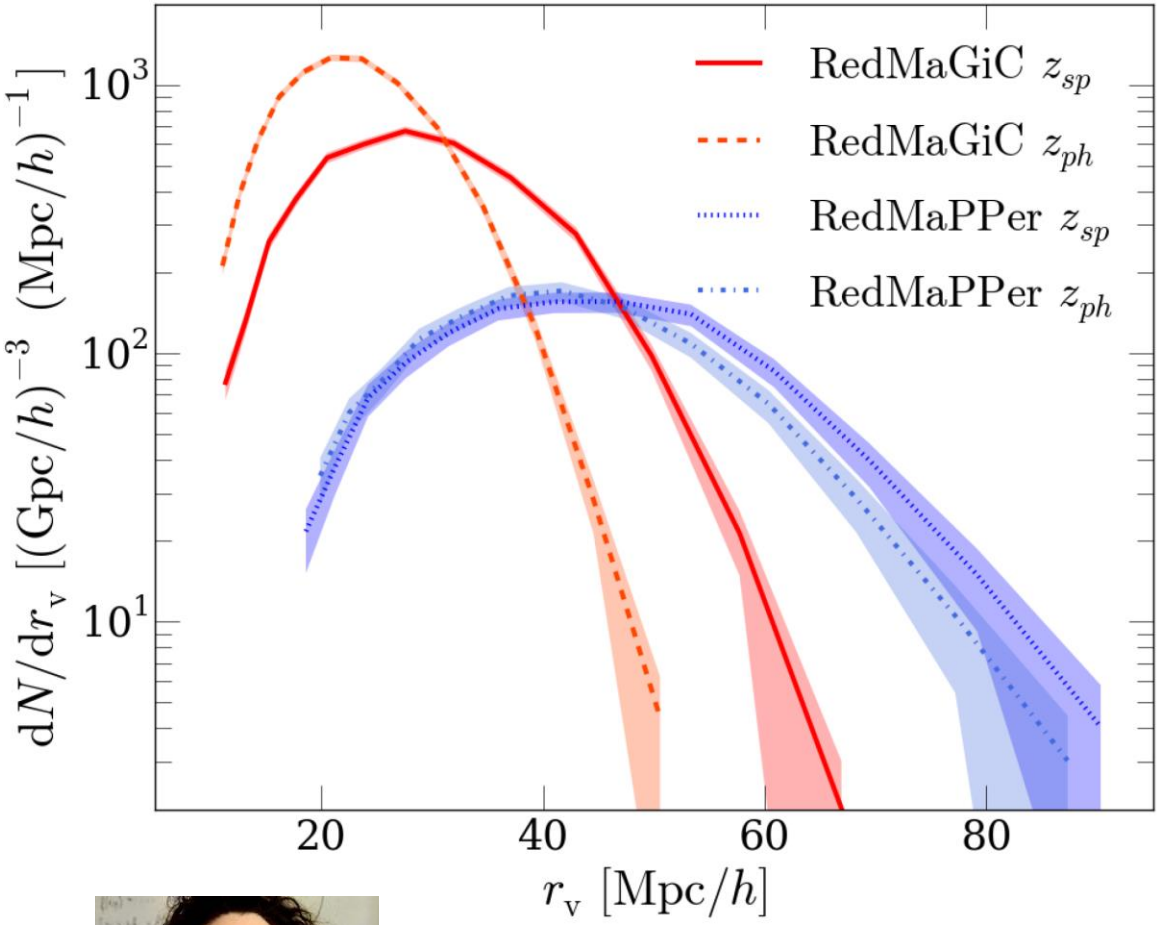


LSST / Rubin

Magnification and tangential shear

Voids in the Dark Energy Survey (DES)

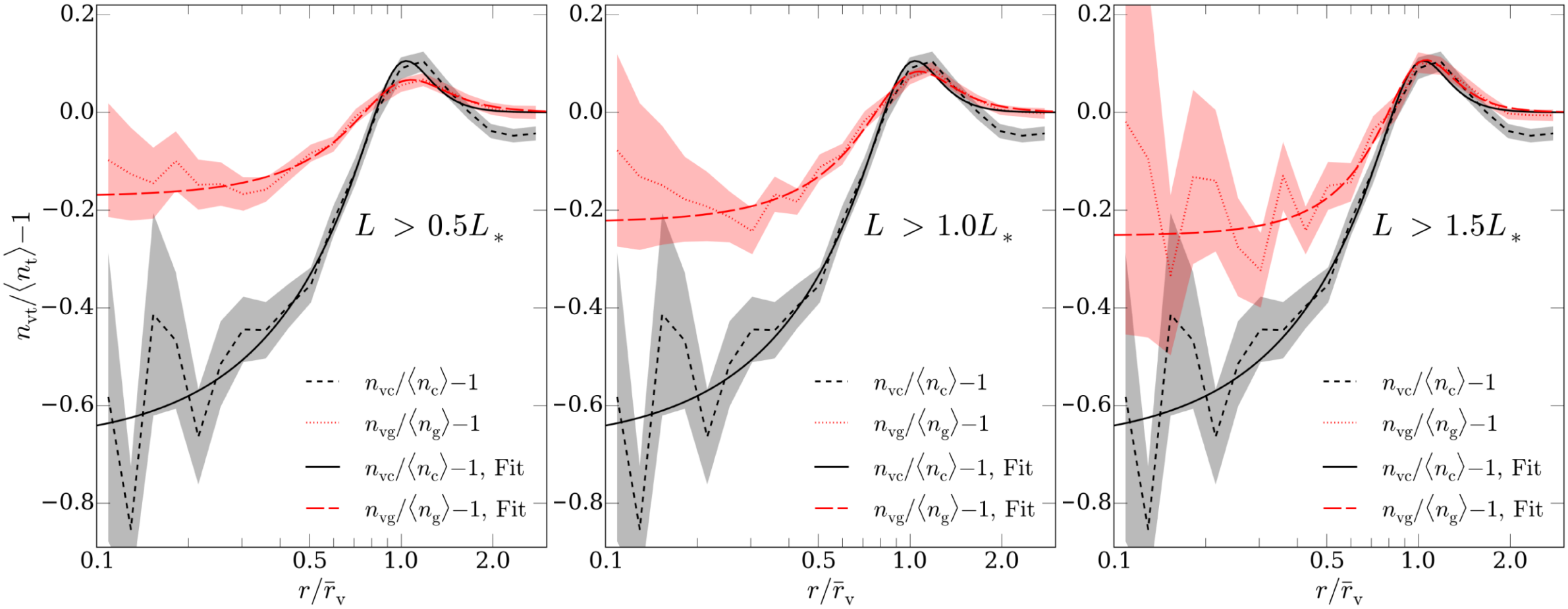




Pollina, Hamaus et al. (MNRAS 2019)

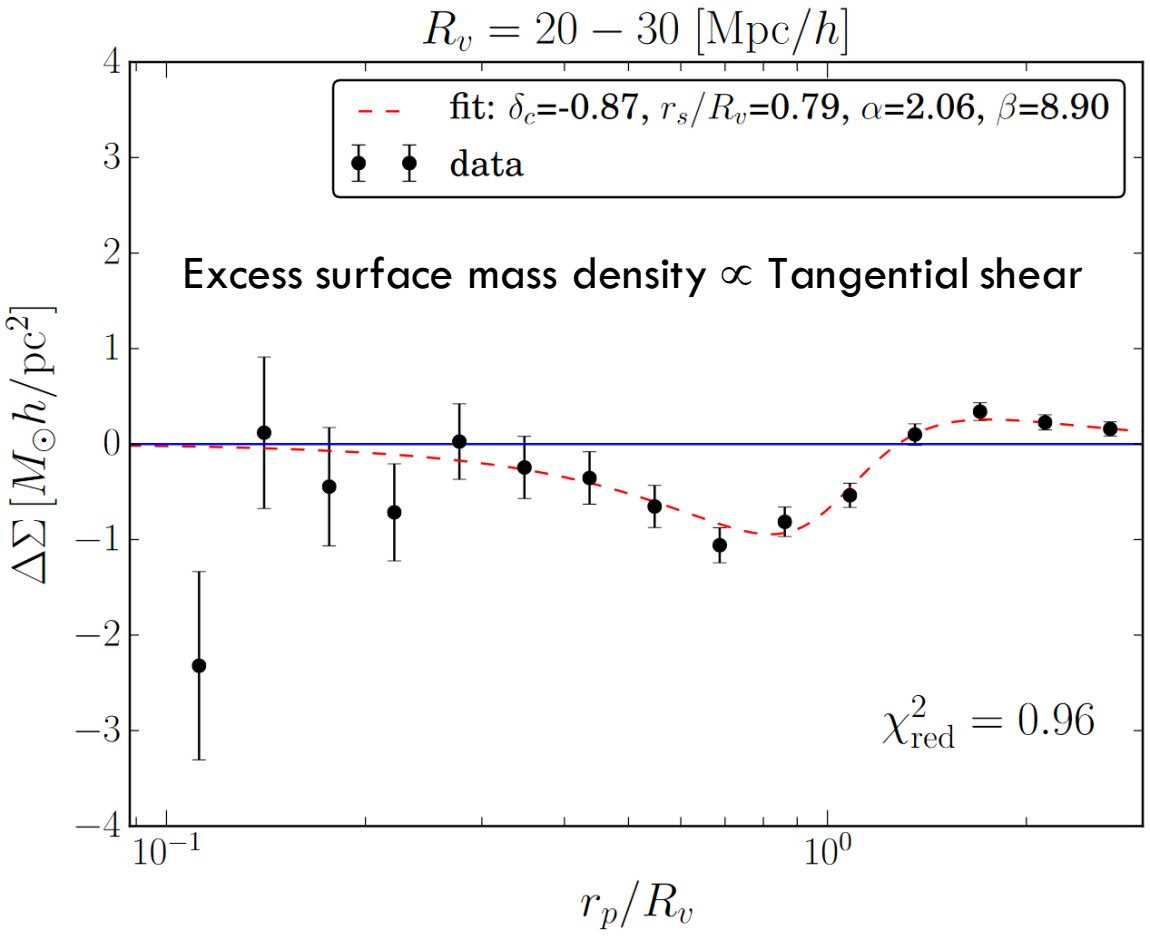
Giorgia Pollina

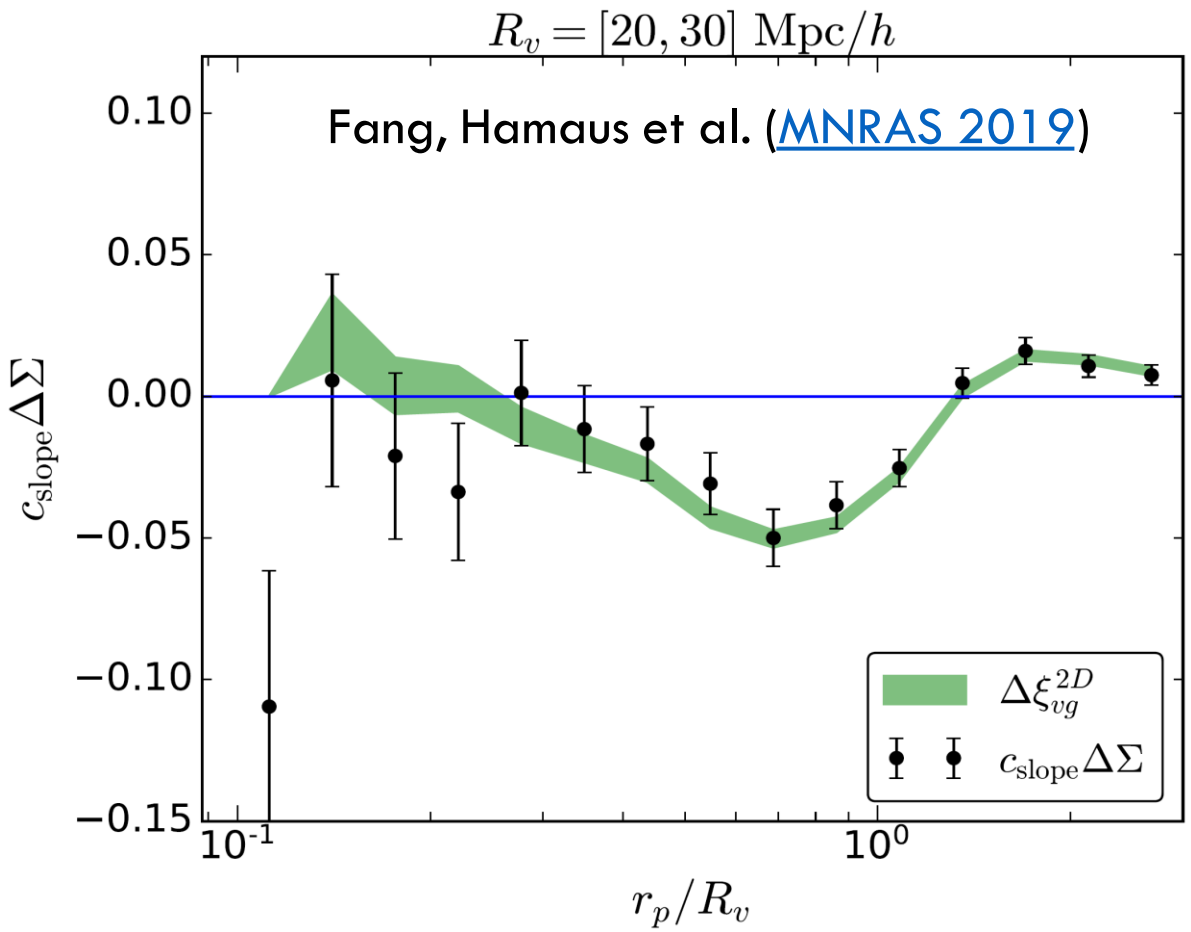
Voids in the Dark Energy Survey (DES) – Tracer-density profiles (RedMapper clusters and RedMagic galaxies)



Pollina, Hamaus et al. (MNRAS 2019)

Voids in the Dark Energy Survey (DES) – Weak-lensing profiles





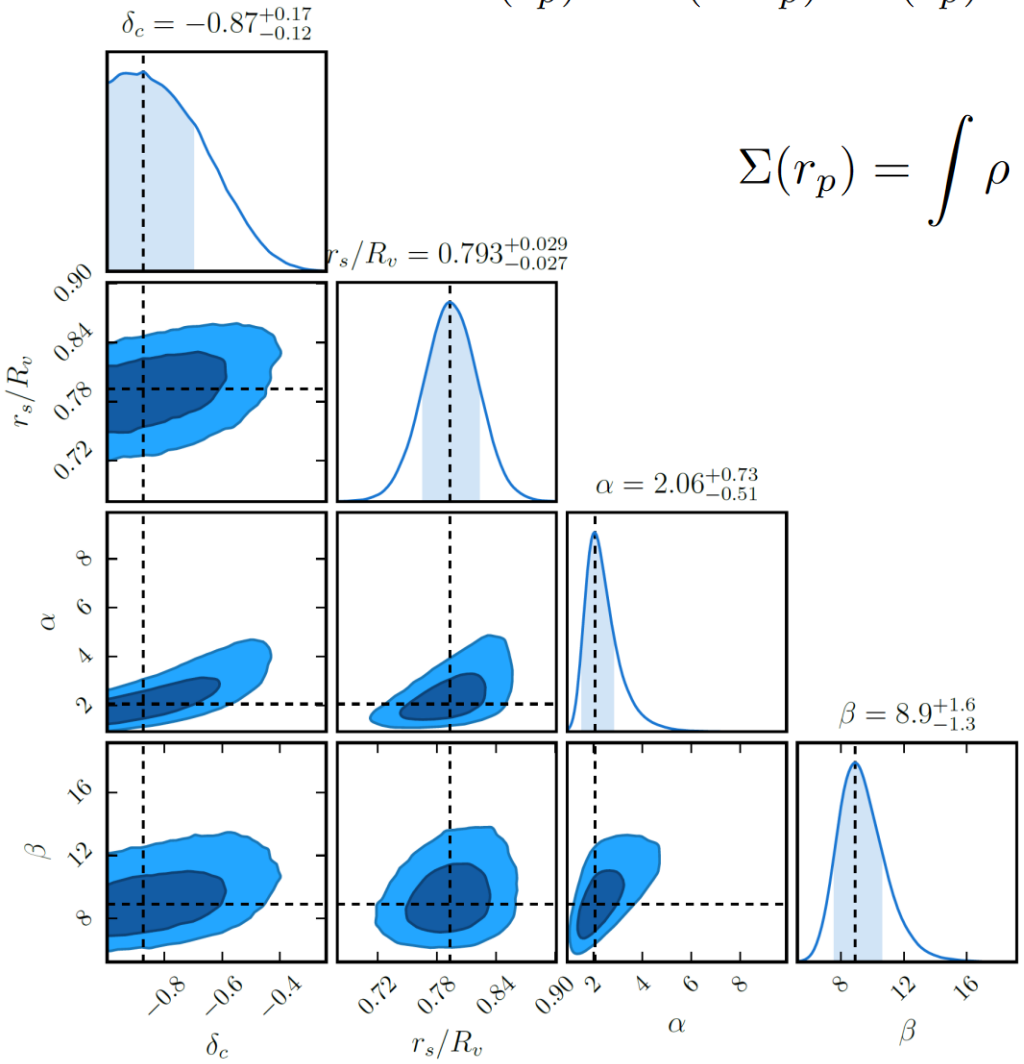
$$\left.\begin{aligned}\Delta\Sigma(r_p) &\equiv \bar{\Sigma}(<r_p) - \Sigma(r_p)\\ \Delta\xi^{\rm 2D}_{\rm vg}(r_p) &\equiv \bar{\xi}^{\rm 2D}_{\rm vg}(<r_p) - \xi^{\rm 2D}_{\rm vg}(r_p)\end{aligned}\right\} \Rightarrow \Delta\xi^{\rm 2D}_{\rm vg}(r_p) = \frac{b_{\rm g}}{\langle\Sigma_{\rm m}\rangle}\Delta\Sigma(r_p)$$

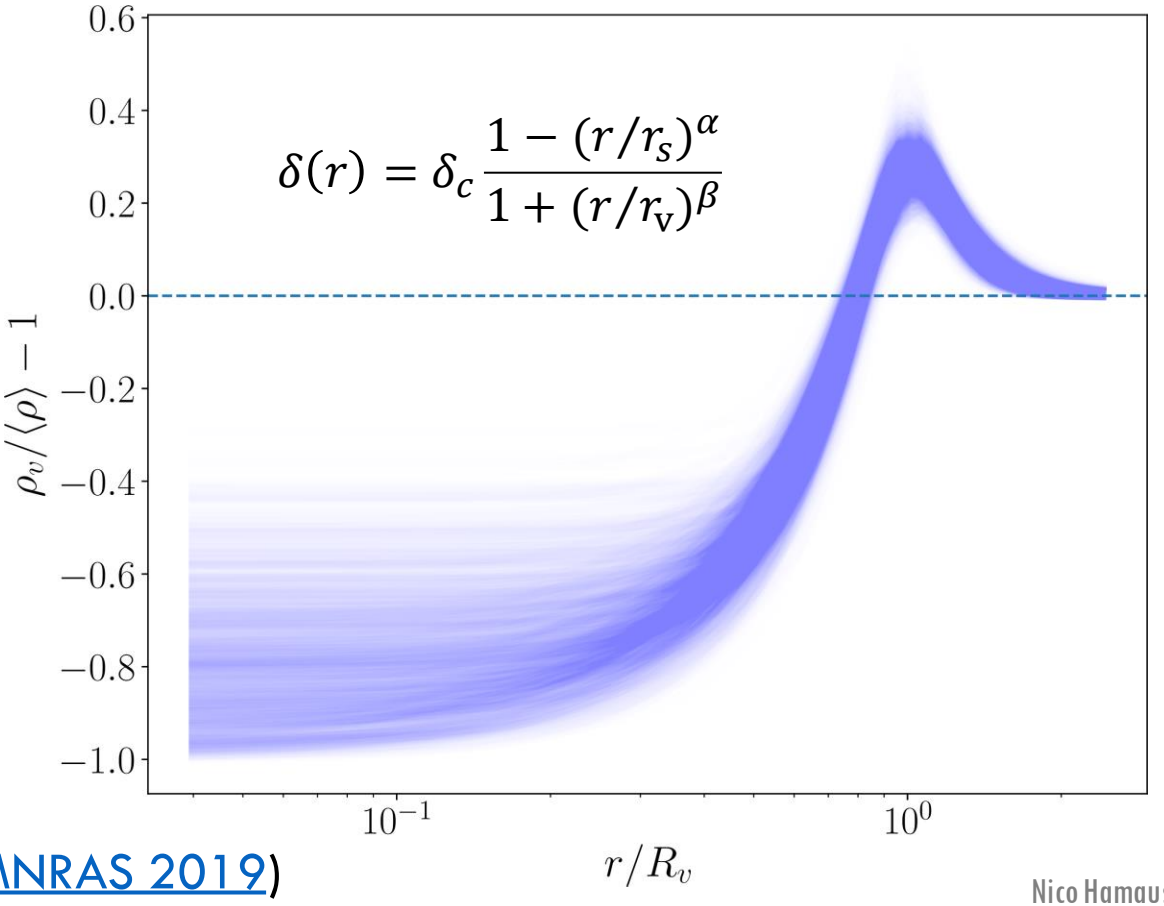
Voids in the Dark Energy Survey (DES) – Inferred density profile

$$\Delta\Sigma(r_p) \equiv \bar{\Sigma}(<r_p) - \Sigma(r_p) = \Sigma_{\rm crit}\gamma_+(r_p)\ , \quad \Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_A(z_{\rm s})}{D_A(z_{\rm l})D_A(z_{\rm l}, z_{\rm s})}$$

Yuedong Fang

$$\Sigma(r_p) = \int \rho\left(\sqrt{[r_z - D_A(z_{\rm l})]^2 + r_p^2}\right) {\rm d}r_z$$

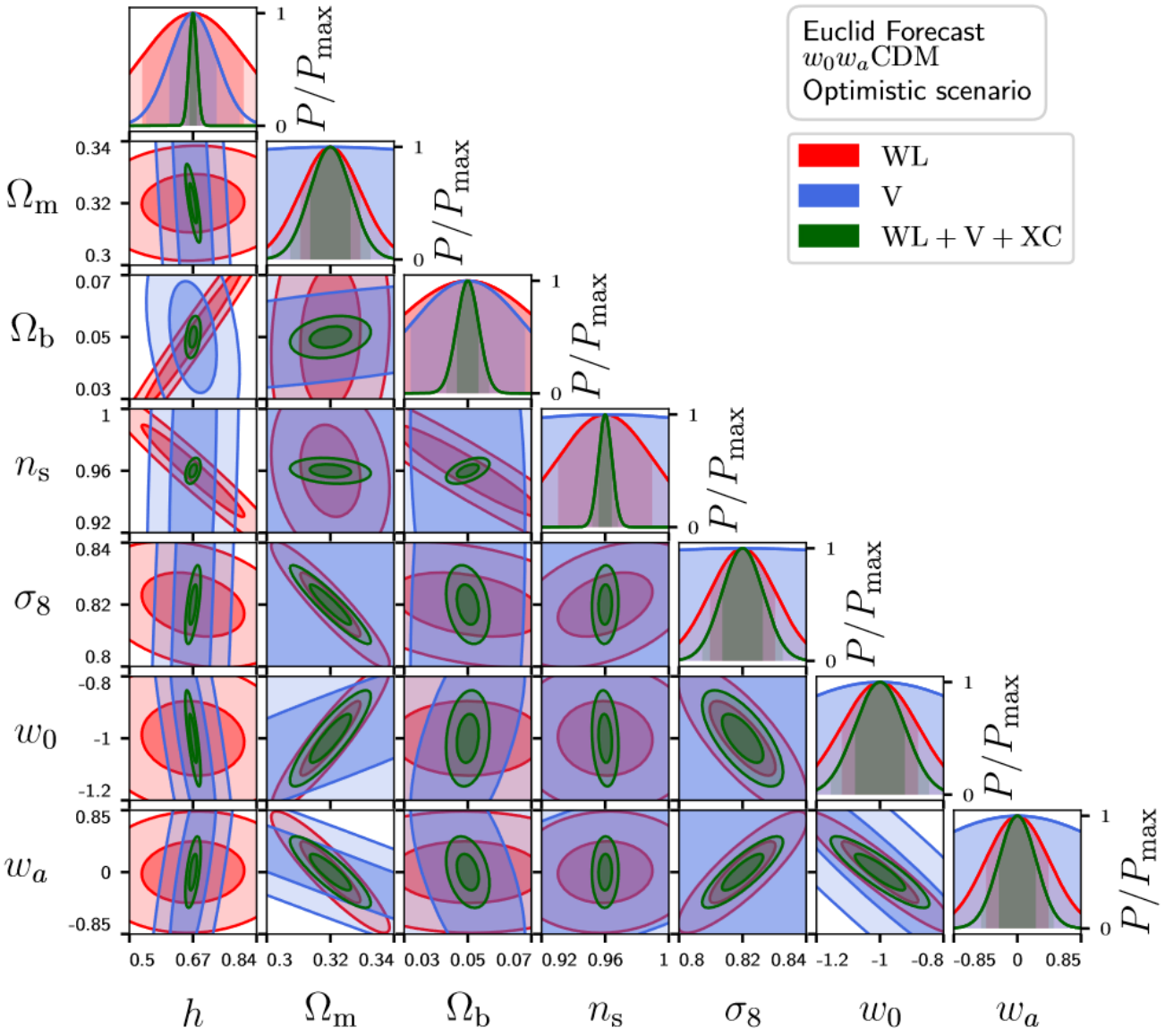


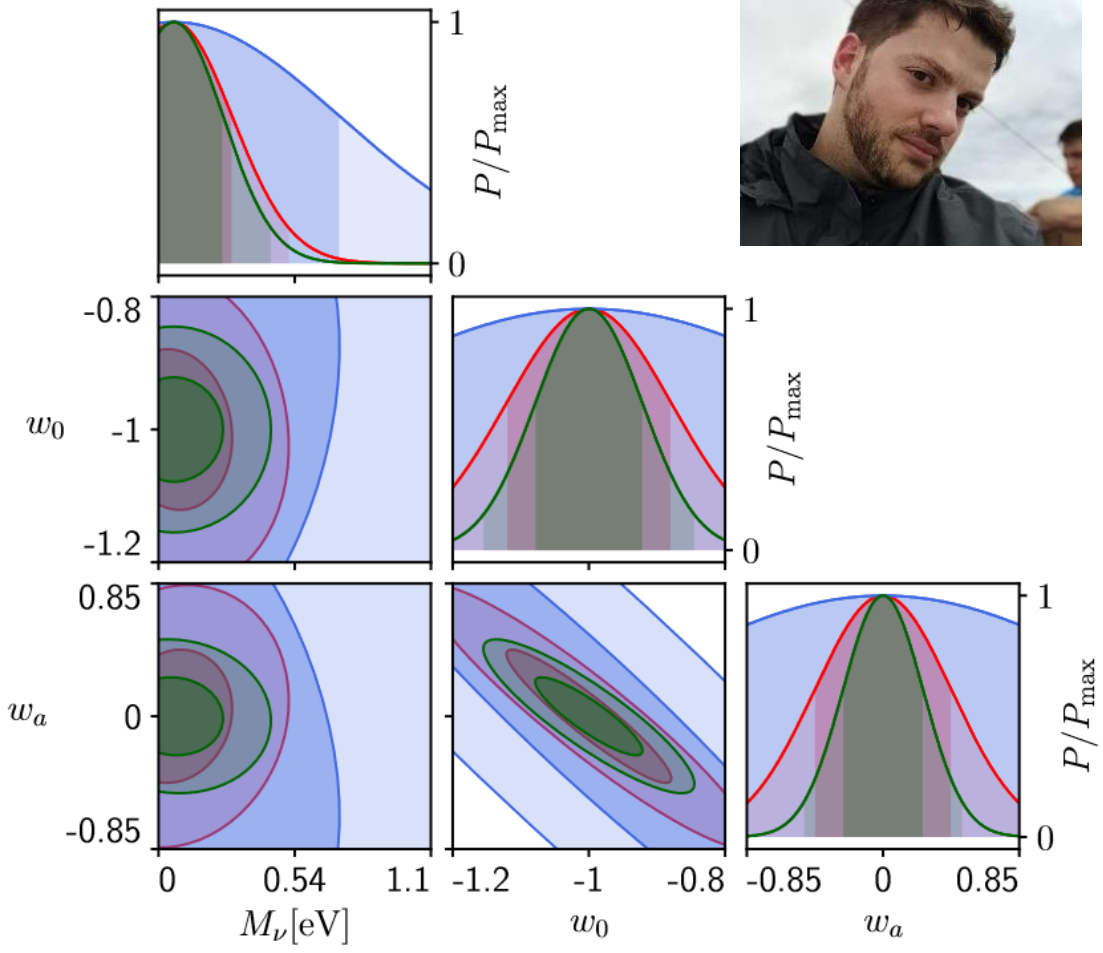


Fang, Hamaus et al. (MNRAS 2019)

Void lensing in Euclid (Fisher forecast)

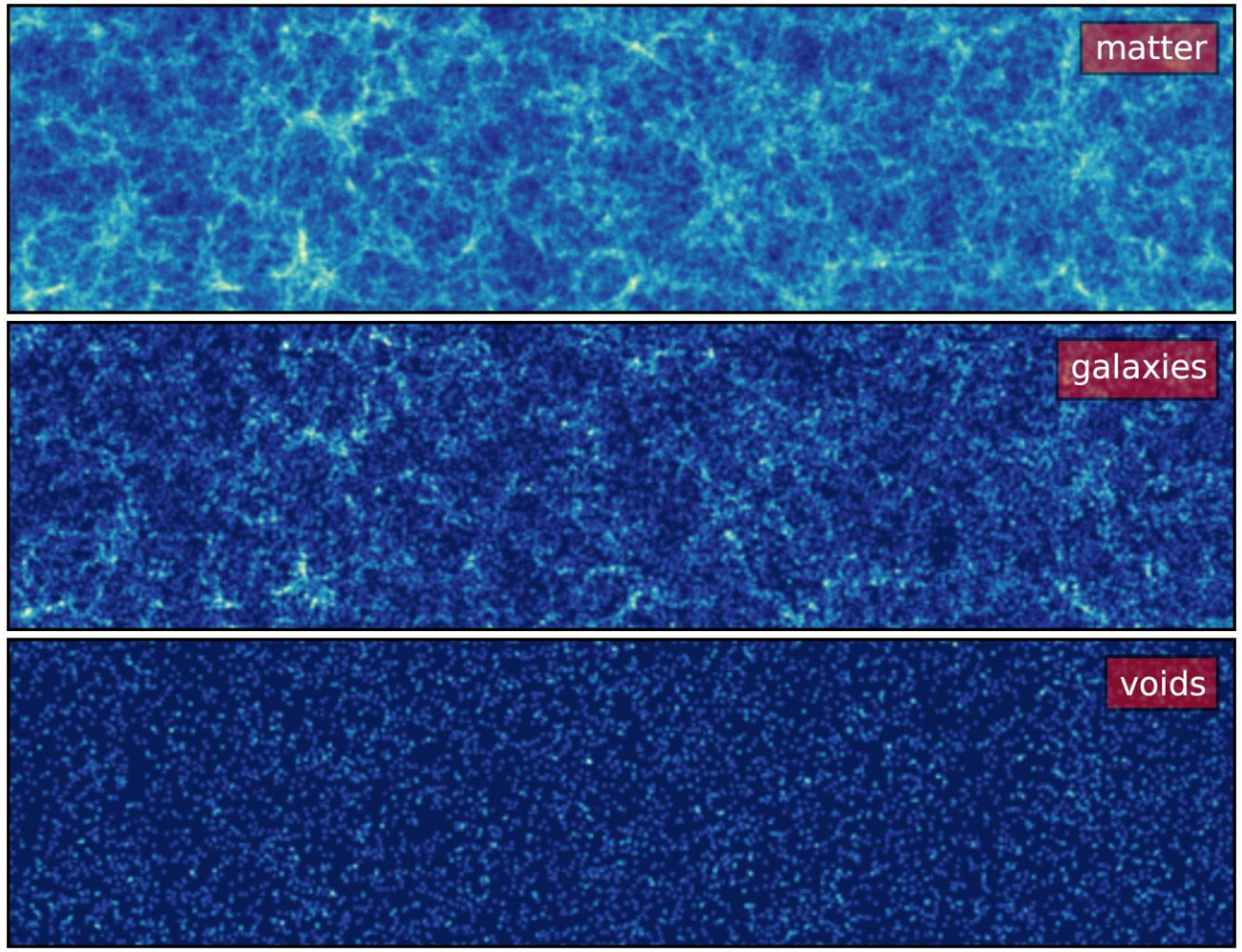
Marco Bonici





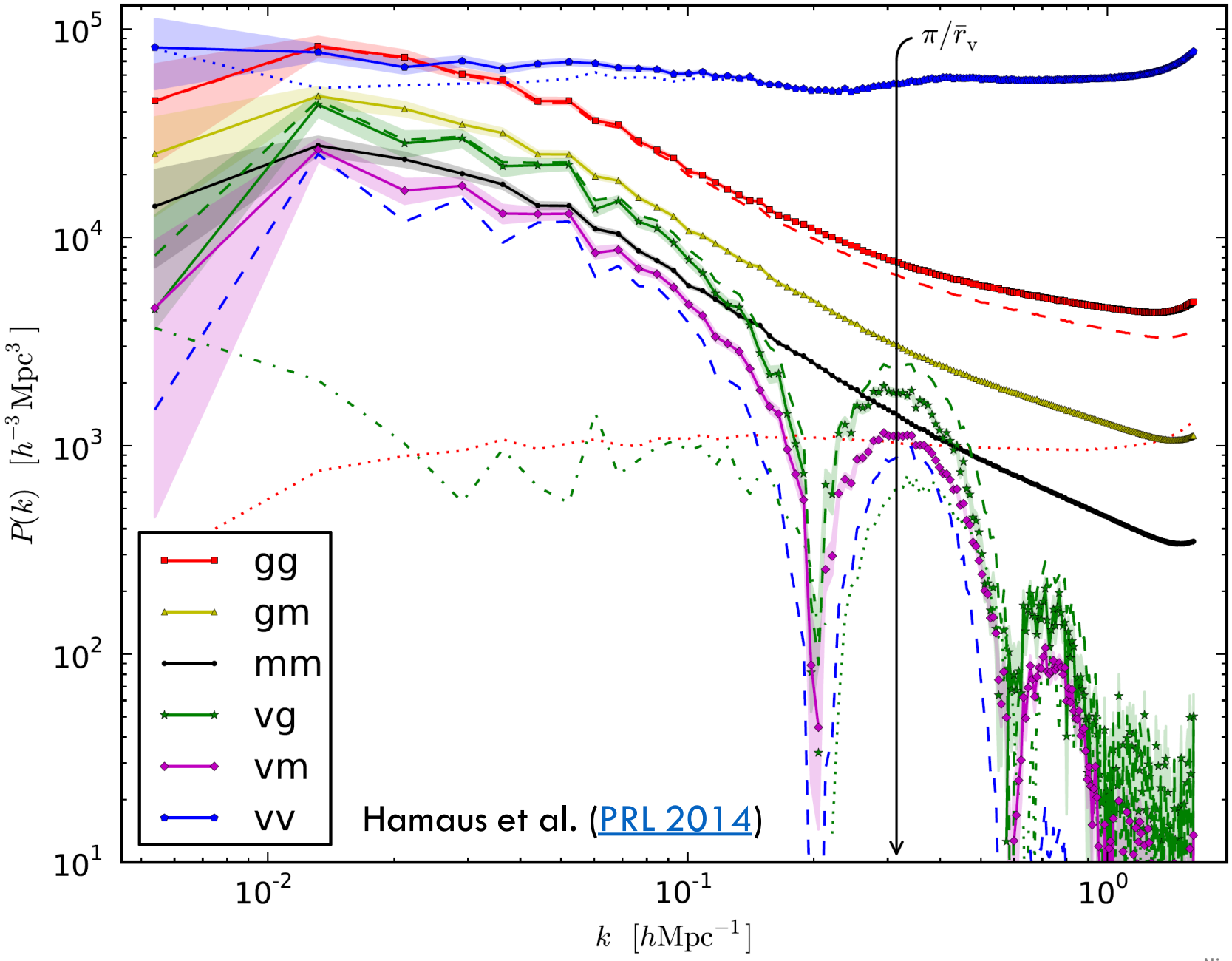
Bonici et al. (arXiv 2206.14211)

VOID CLUSTERING



Voids can be considered as tracers of the large-scale structure !

Power spectra with voids



Solid: Signal + Noise

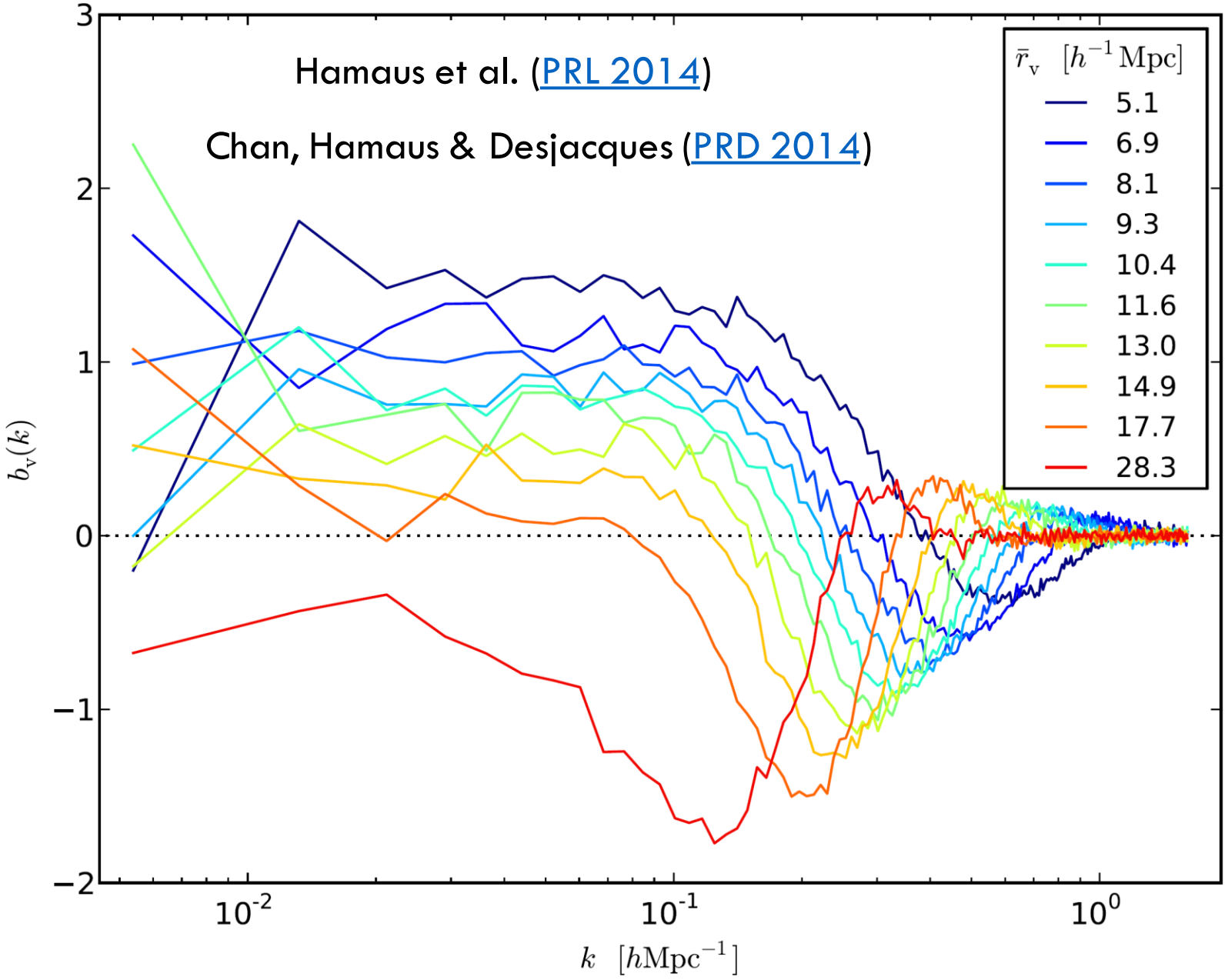
Dotted: Shot Noise

Dashed: Signal

Bias of voids

- Multiplies amplitude of void-density fluctuations

- Constant on large scales
- Modulated by density profile on small scales
- Overcompensated: positive
- Undercompensated: negative



Bias of voids with primordial non-Gaussianity

Primordial potential, expanded around Gaussian:

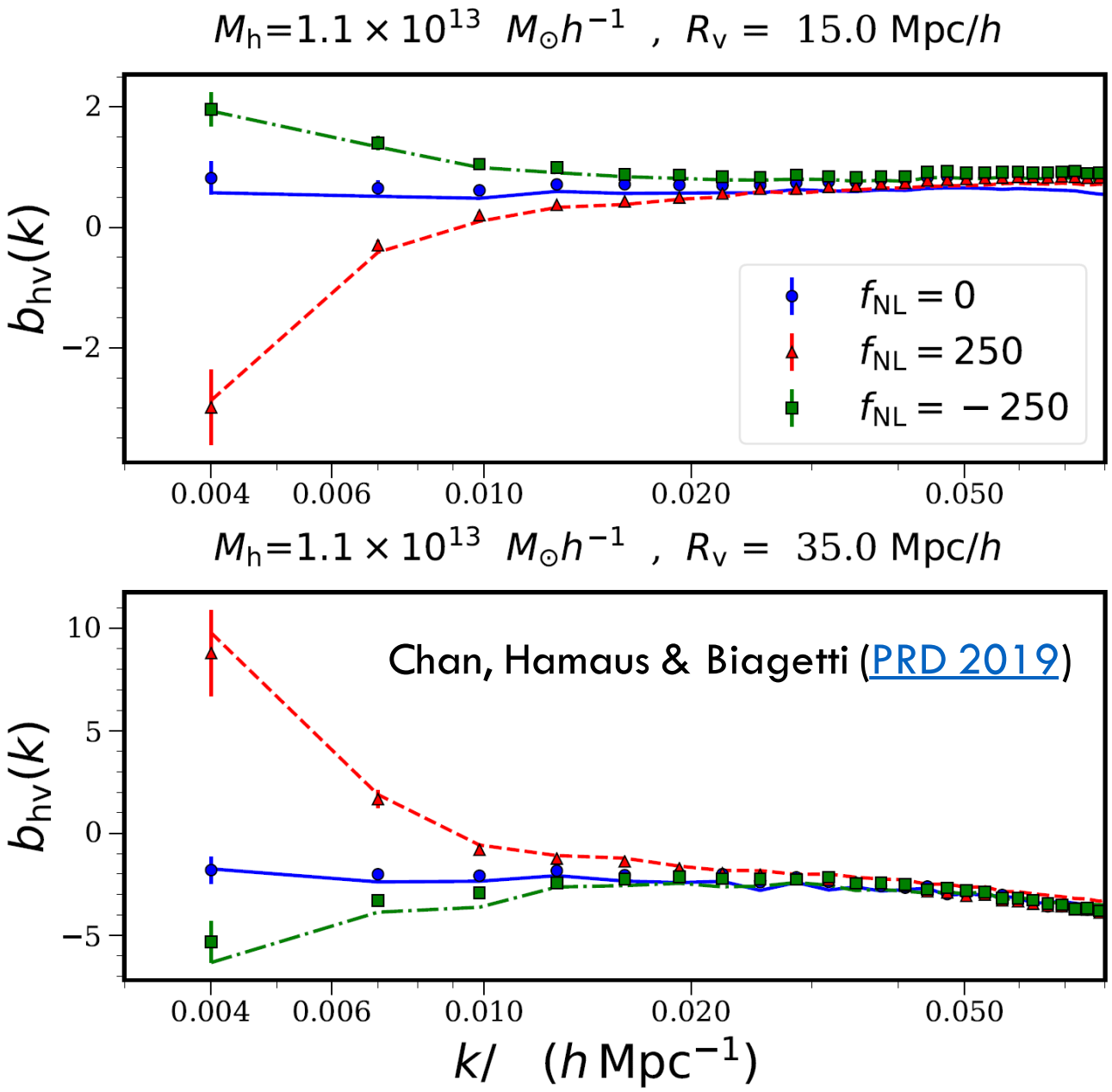
$$\Phi(\mathbf{x}) = \Phi_{\rm G}(\mathbf{x}) + f_{\rm NL}\left[\Phi_{\rm G}^2(\mathbf{x}) - \langle\Phi_{\rm G}^2\rangle\right]$$

Results in scale-dependent bias:

$$b(k, f_{\rm NL}) = b_{\rm G} + f_{\rm NL}(b_{\rm G} - 1)\delta_c \frac{3\Omega_{\rm m}H_0^2}{k^2 T(k) D(z)}$$

Dalal et al. (2008, PRD 77, 123514), Slosar et al. (2008, JCAP 08, 031)

Voids: exchange positive δ_c by negative δ_v

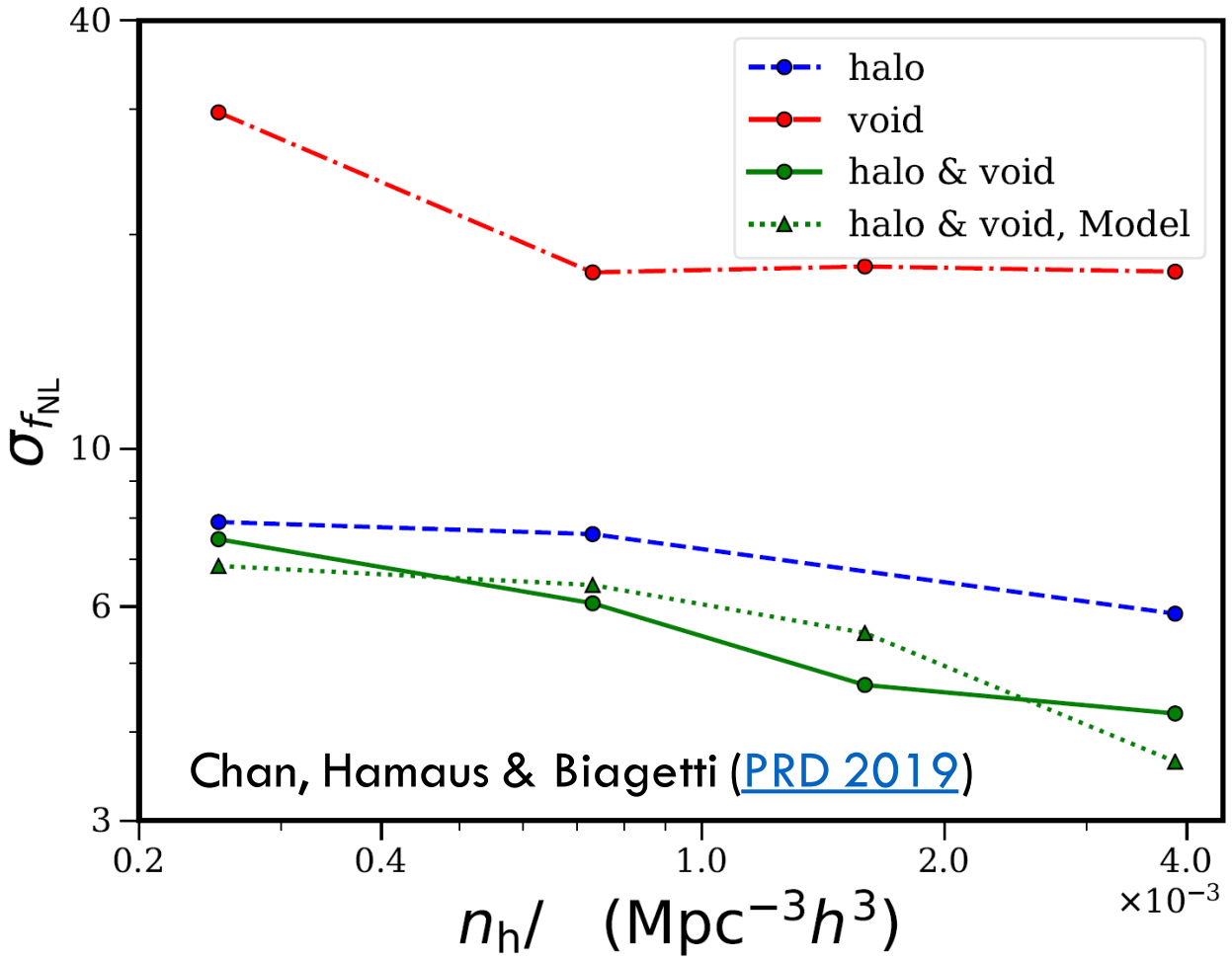


Bias of voids with primordial non-Gaussianity

Fisher forecast with multiple tracers
(5 halo-mass bins, 3 void-size bins):

Improvement of up to factor of 2 !

- Recovers missing information from the troughs in a Gaussian random field

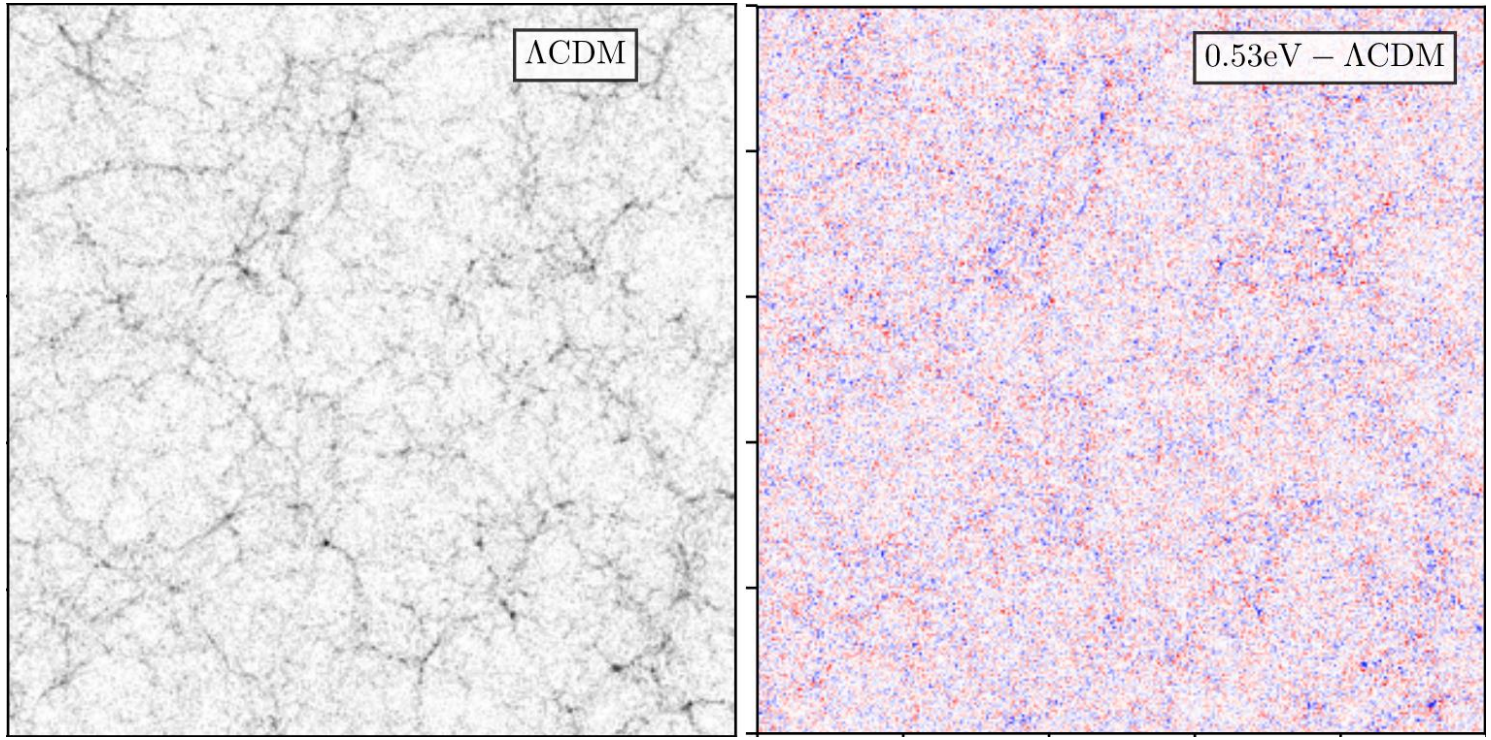


$$F_{f_{\rm NL}f_{\rm NL}} = V \int \frac{\mathrm{d}^3k}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\left(\Sigma^{-1}\frac{\partial\Sigma}{\partial f_{\rm NL}}\Sigma^{-1}\frac{\partial\Sigma}{\partial f_{\rm NL}}\right), \quad \Sigma_{ij} \equiv \langle\delta_i(\boldsymbol{k})\delta_j(\boldsymbol{k})\rangle$$

$$0.004 < k\,[h\mathrm{Mpc}^{-1}] < 0.08$$

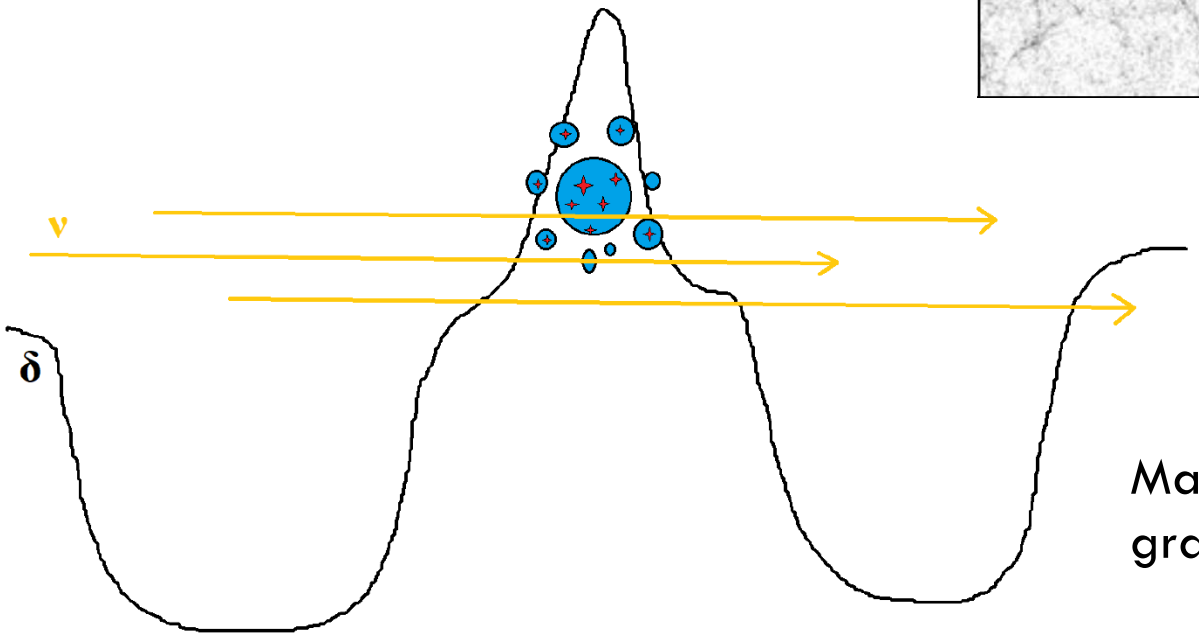
Voids in massive-neutrino cosmologies

Nico Schuster



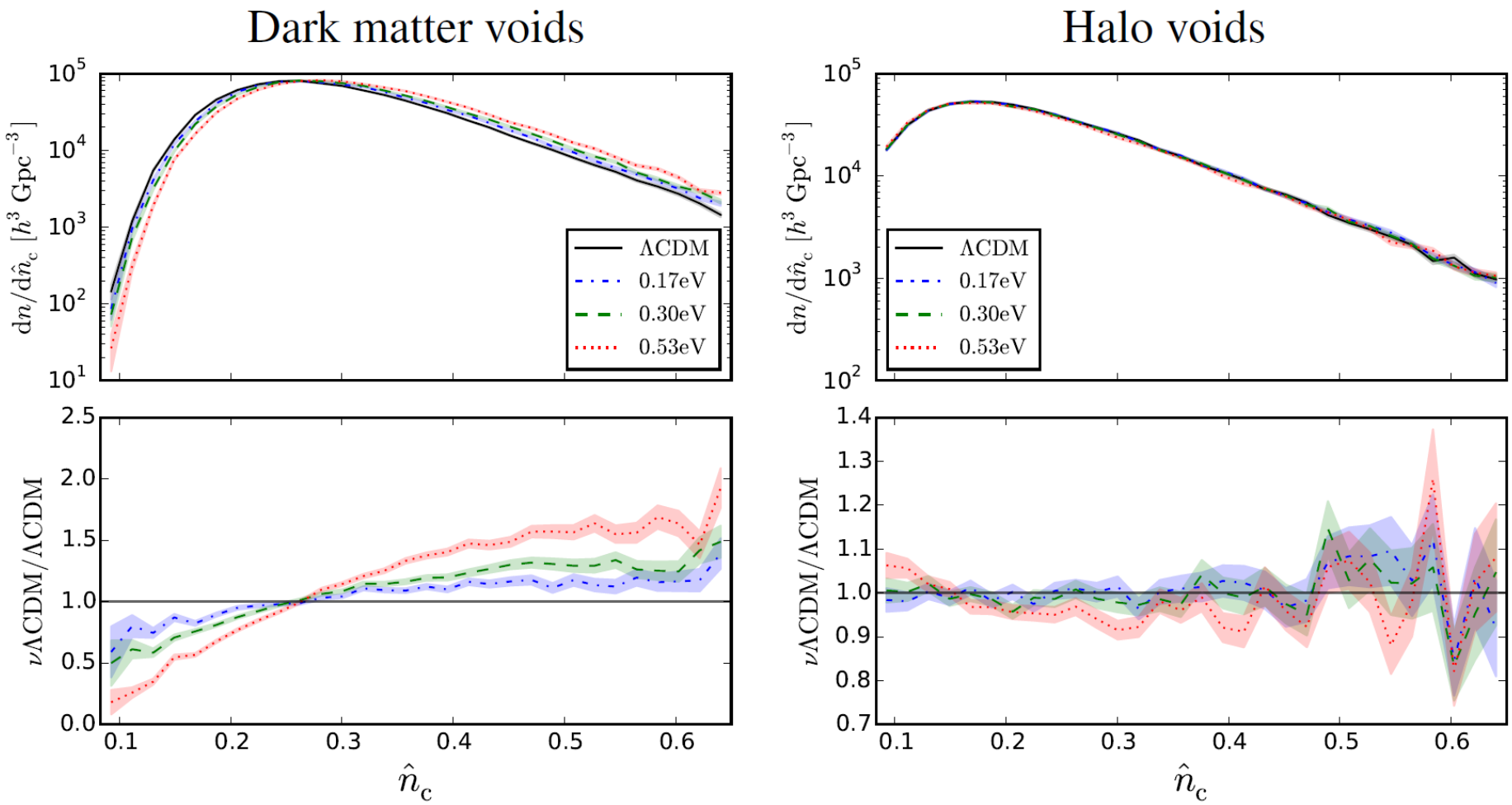
Schuster, Hamaus et al. (JCAP 2019)

DEMNUni simulations, Carbone et al. (JCAP 2016)



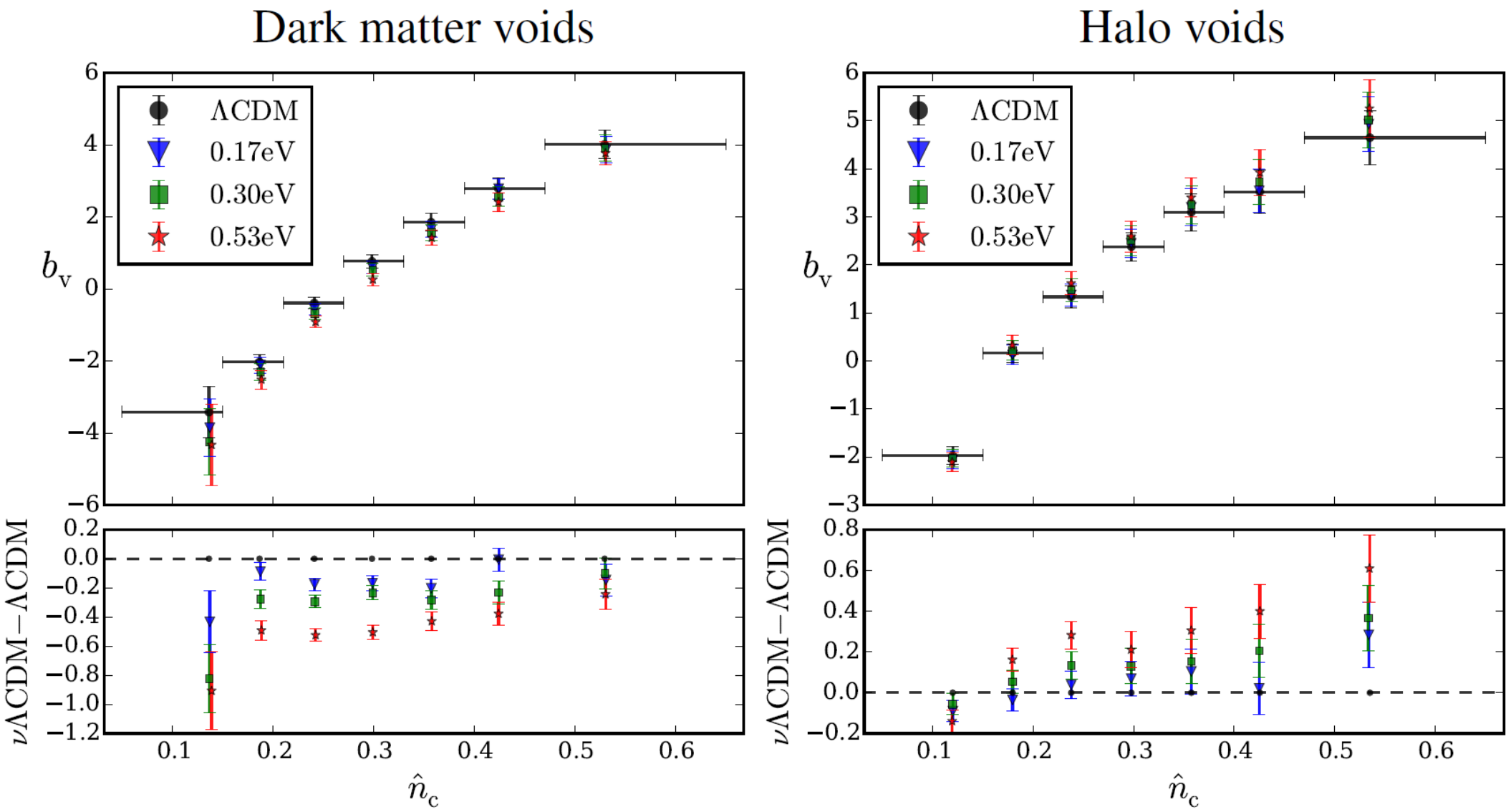
Massive neutrinos freely stream into voids, and gravitationally drag other forms of (dark) matter with them

Voids in massive-neutrino cosmologies: abundance



Schuster, Hamaus et al. (JCAP 2019)

Voids in massive-neutrino cosmologies: bias



Schuster, Hamaus et al. (JCAP 2019)

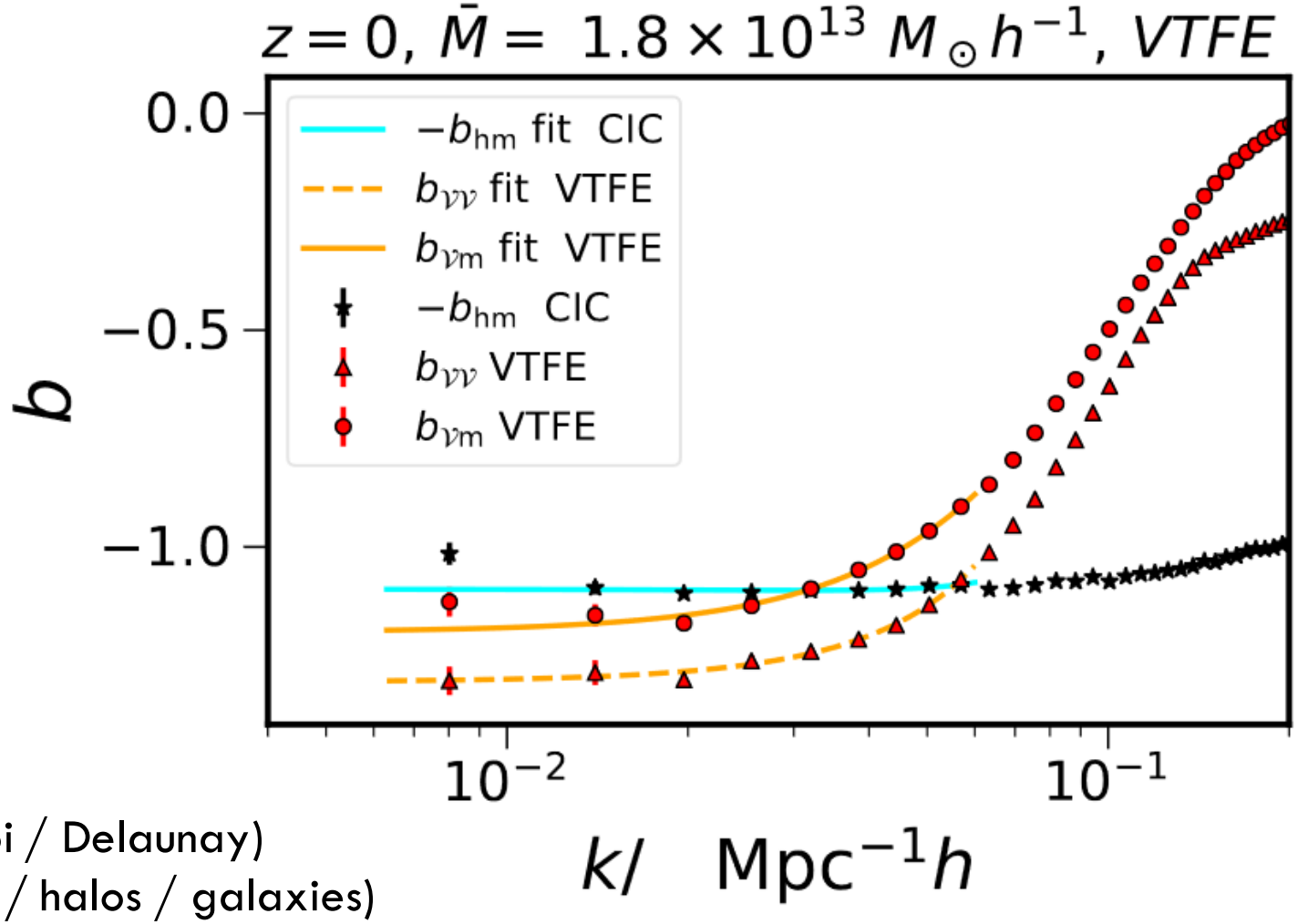
Baryon Acoustic Oscillations (BAOs) from voids

Use the Jacobian between Lagrangian and Eulerian coordinates (volume change)

$$\mathcal{J} \equiv \frac{d^3x}{d^3q} = \frac{1}{1+\delta}$$

And define a "Volume statistic" (in analogy to density contrast)

$$\mathcal{V} \equiv \frac{\mathcal{J}}{\bar{\mathcal{J}}} - 1 = \frac{1}{\bar{\mathcal{J}}(1+\delta)} - 1$$



Chan & Hamaus (PRD 2021)

Advantages:

- Can be estimated via tessellation (Voronoi / Delaunay)
- Possible for any tracer type (dark matter / halos / galaxies)
- Defined for every cell / grid point
- Exhibits negative bias like voids

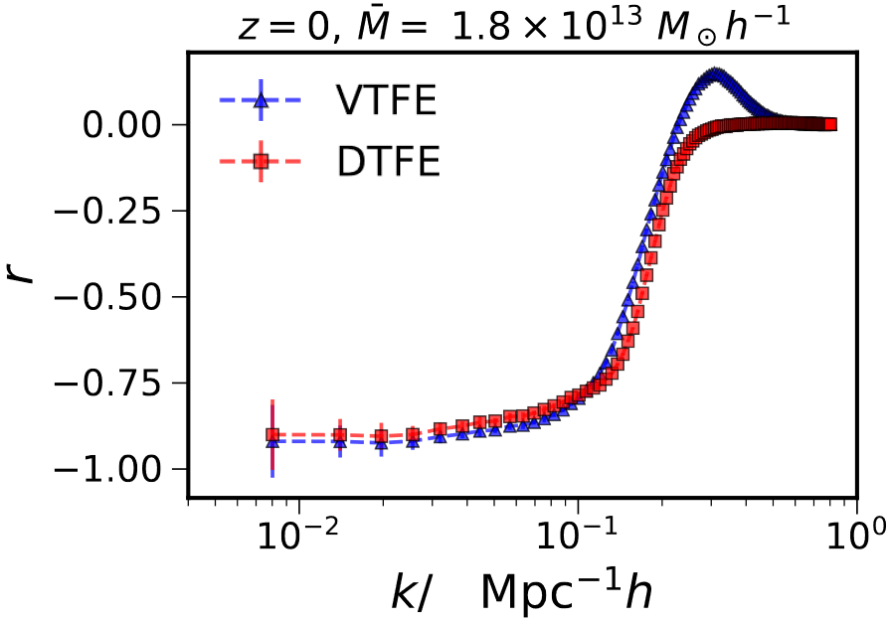
➢ Less prone to shot noise than extended and sparser voids

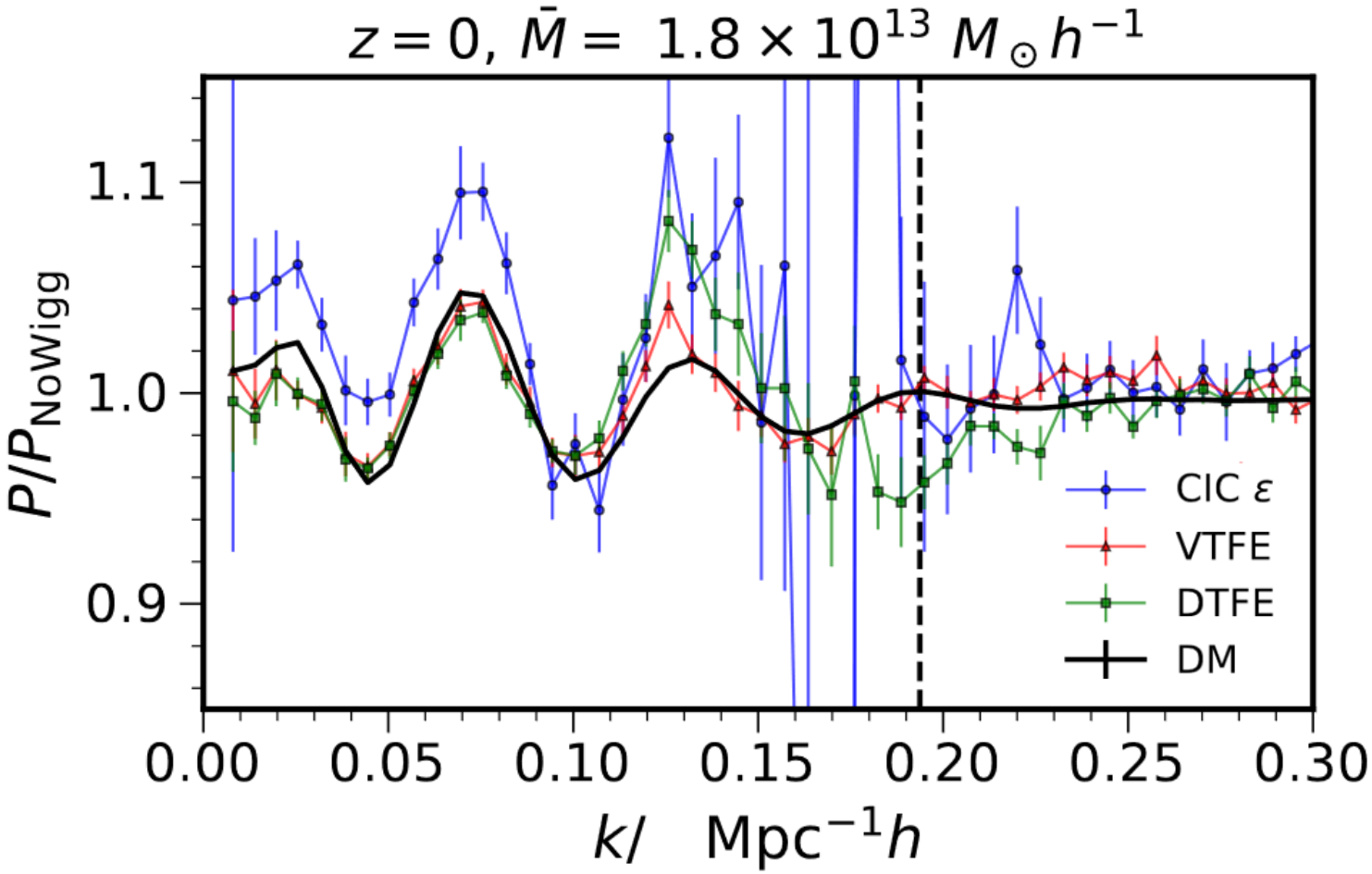
Baryon Acoustic Oscillations (BAOs) from voids

Low amount of shot noise allows estimation of BAOs from the "Volume power spectrum"

Strong anti-correlation with density field

➢ Independent information on cosmology?



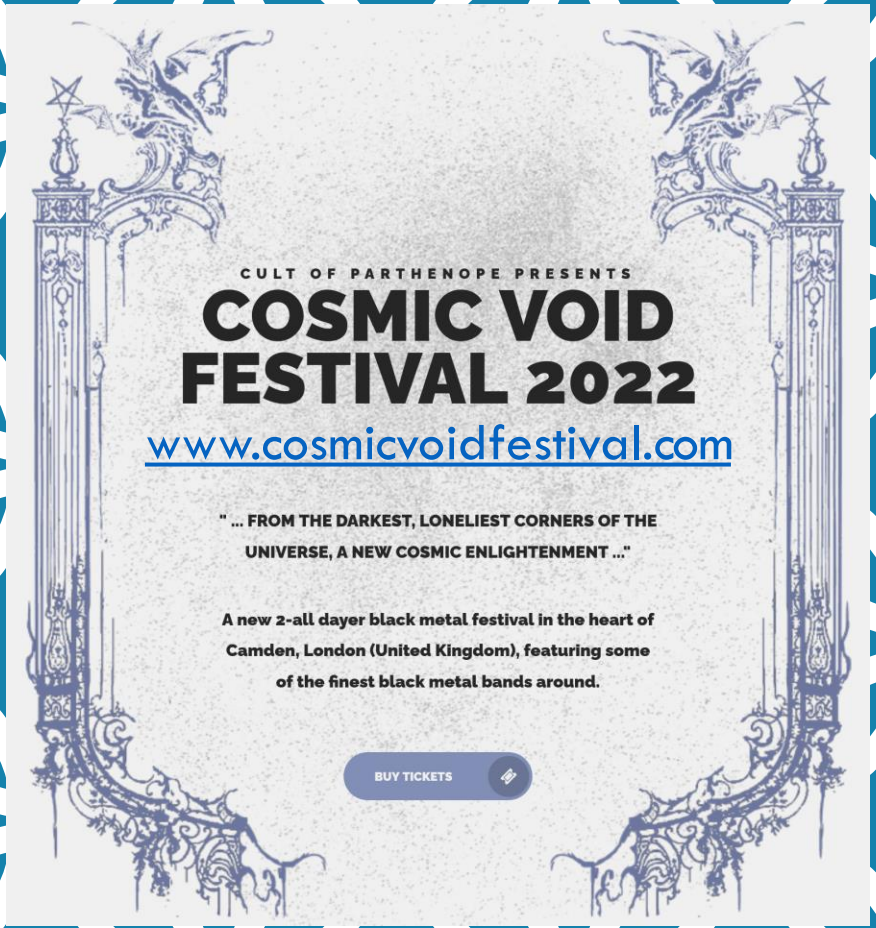


Chan & Hamaus (PRD 2021)

CONCLUSIONS

- Geometric distortions of voids provide powerful AP-test to measure $D_{\mathrm{A}}H(z)$ with sub-percent accuracy
- Dynamic distortions of voids additionally provide $\beta(z) = f(z)/b(z)$
- Weak lensing can be used to infer the 3D density profile of voids
- Undercompensated voids can be regarded as anti-biased tracers of LSS
- Tracers with a negative bias extend the power of a "Multi-tracer analysis"
- Voids provide independent cosmological information on f_{NL} , M_{ν} , BAOs

❖ DESI, Euclid, Roman, … will each provide at least $\mathcal{O}(10^5)$ voids (for free). **<u>We live in the era of voids</u>!**



THANK YOU FOR YOUR ATTENTION!

QUESTIONS?