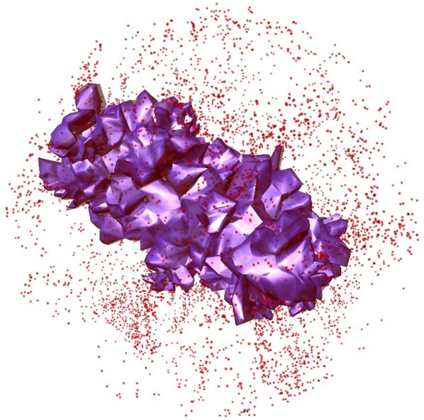
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

LMU USM

Nico Hamaus

Fundamental Physics from the Unexplored Universe

Cosmology with Cosmic Voids



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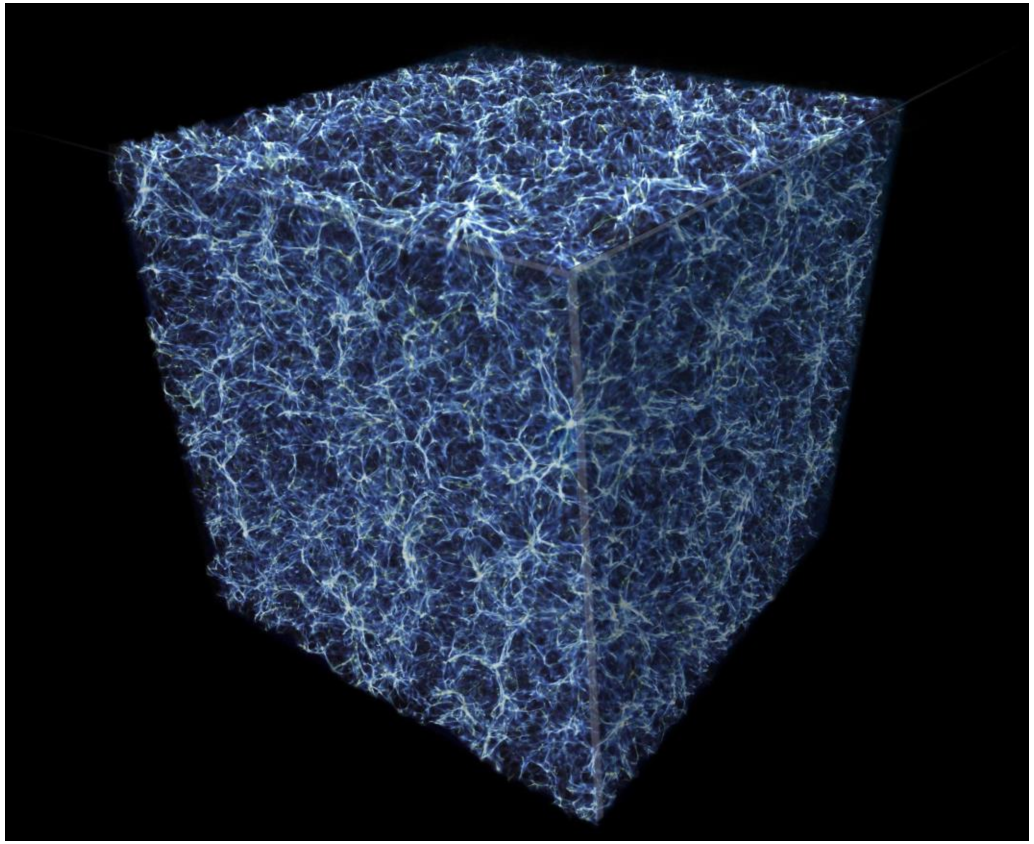
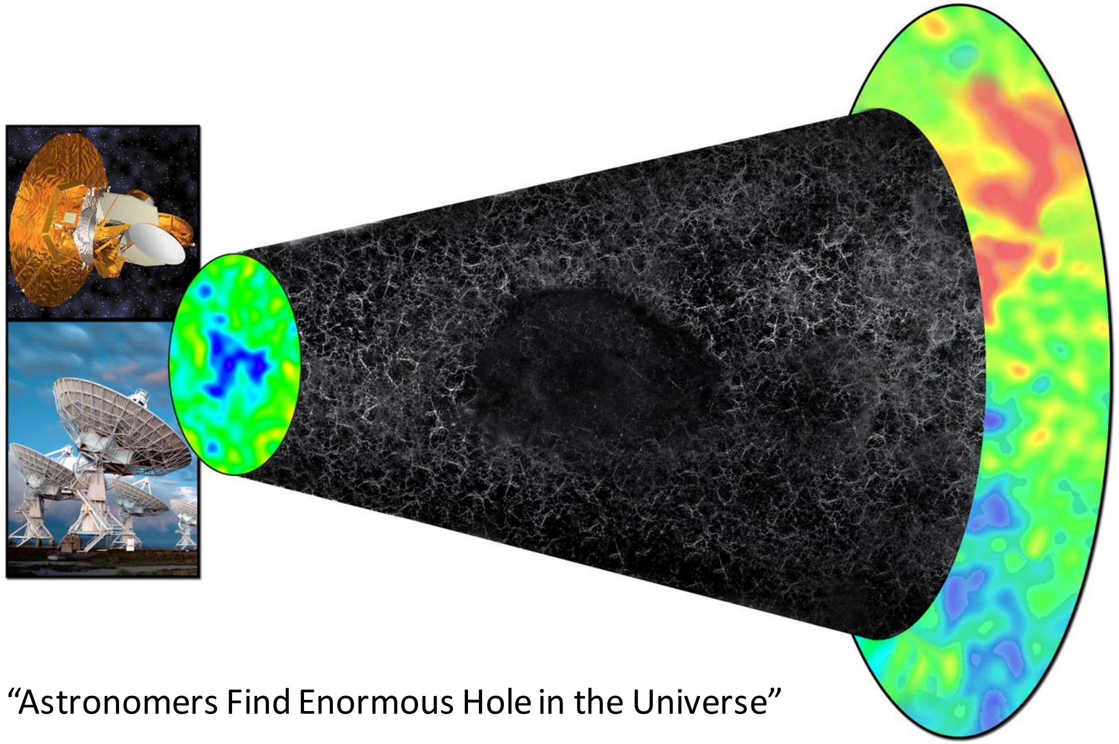
WHAT ARE “COSMIC VOIDS”?

Universe Today



Wikipedia

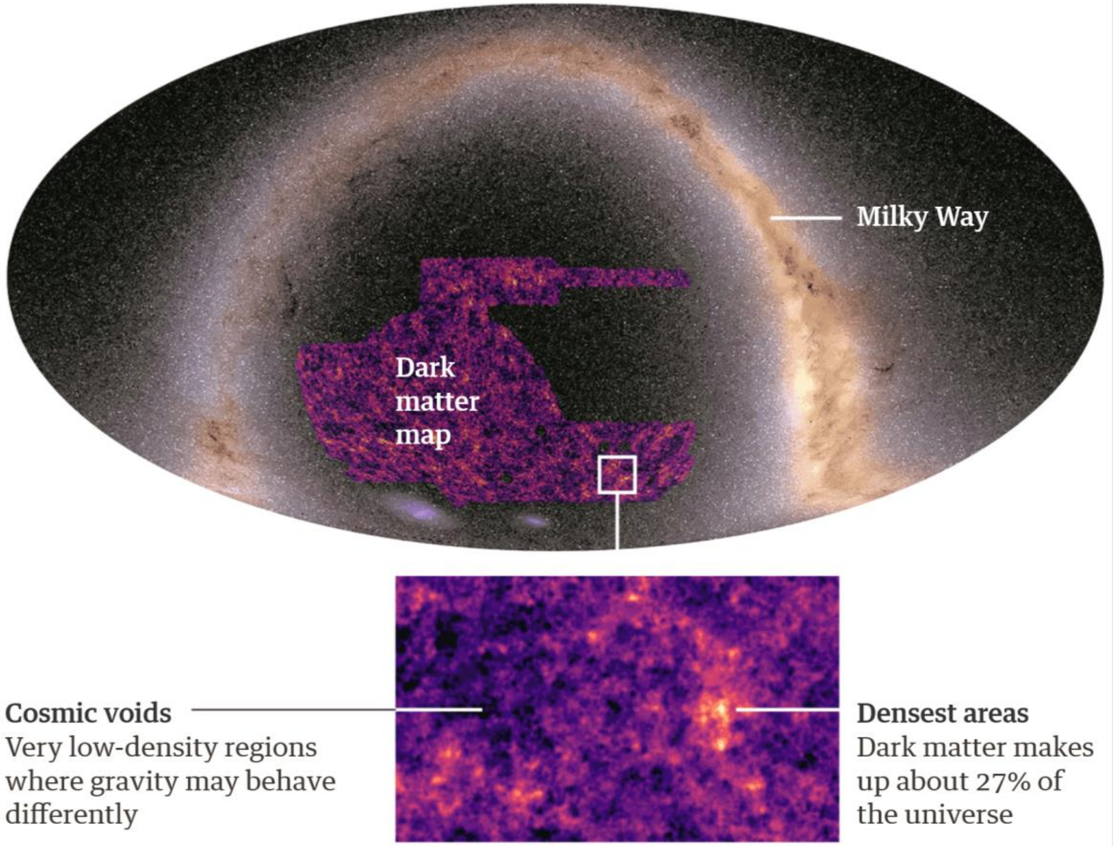
WHAT ARE “COSMIC VOIDS”?



“Astronomers Find Enormous Hole in the Universe”

“Astronomers Puzzled by Massive Blank Spot in Universe”

NRAO, Fox News

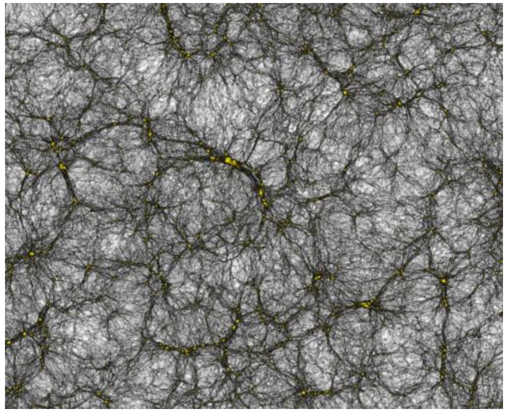


Guardian graphic. Source: DES Observations, N Jeffrey, Dark Energy Survey Collaboration

The Guardian

HOW DO WE DEFINE COSMIC VOIDS?

Cosmic web



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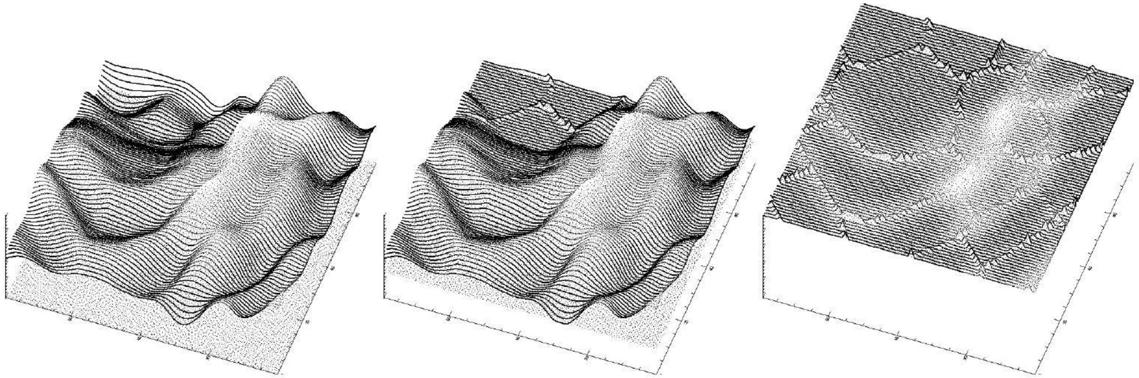
Watershed transform



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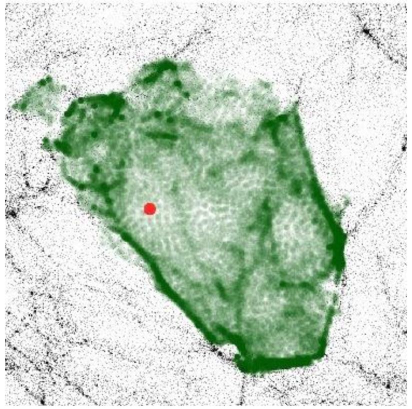
Void hierarchy

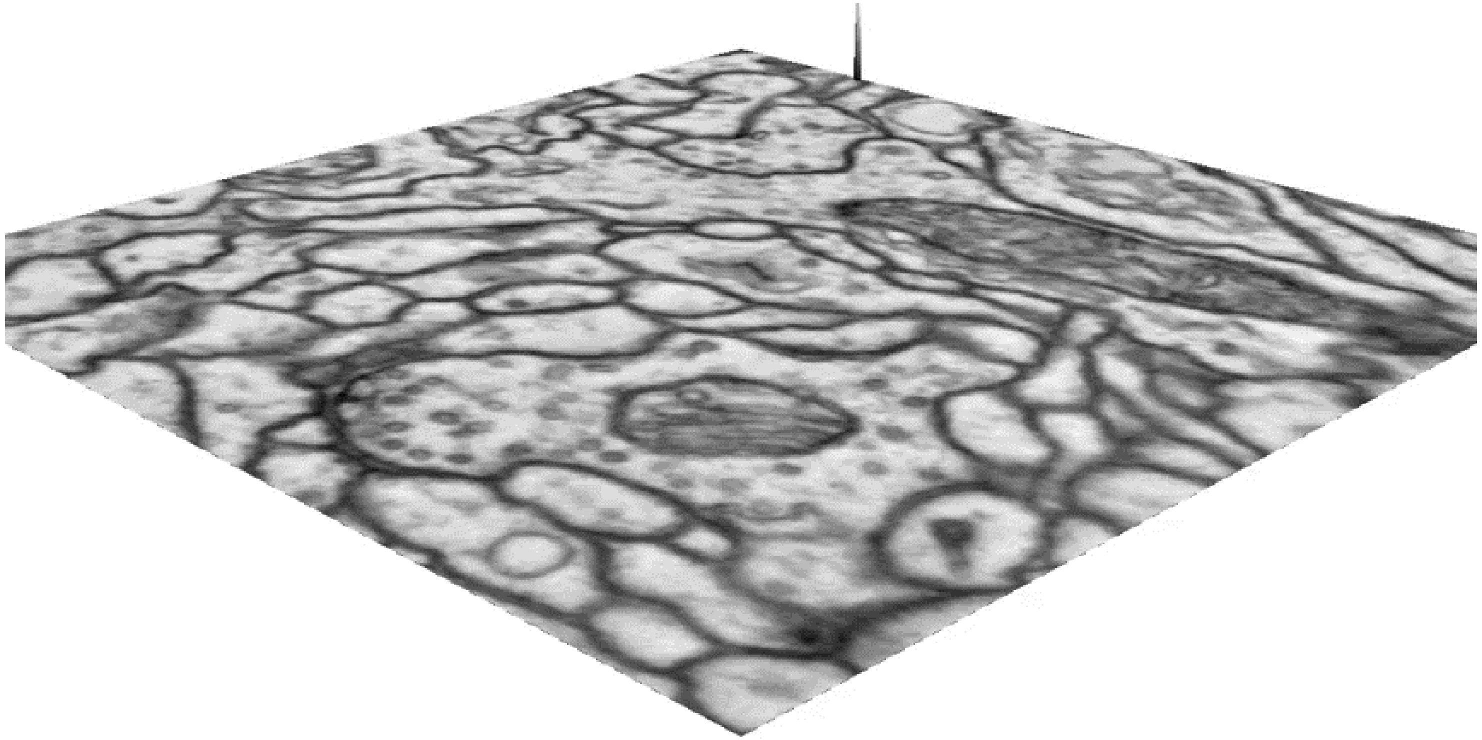


Potter er al. (ComAC 2017)

Platen, Van De Weygaert & Jones (MNRAS 2007)

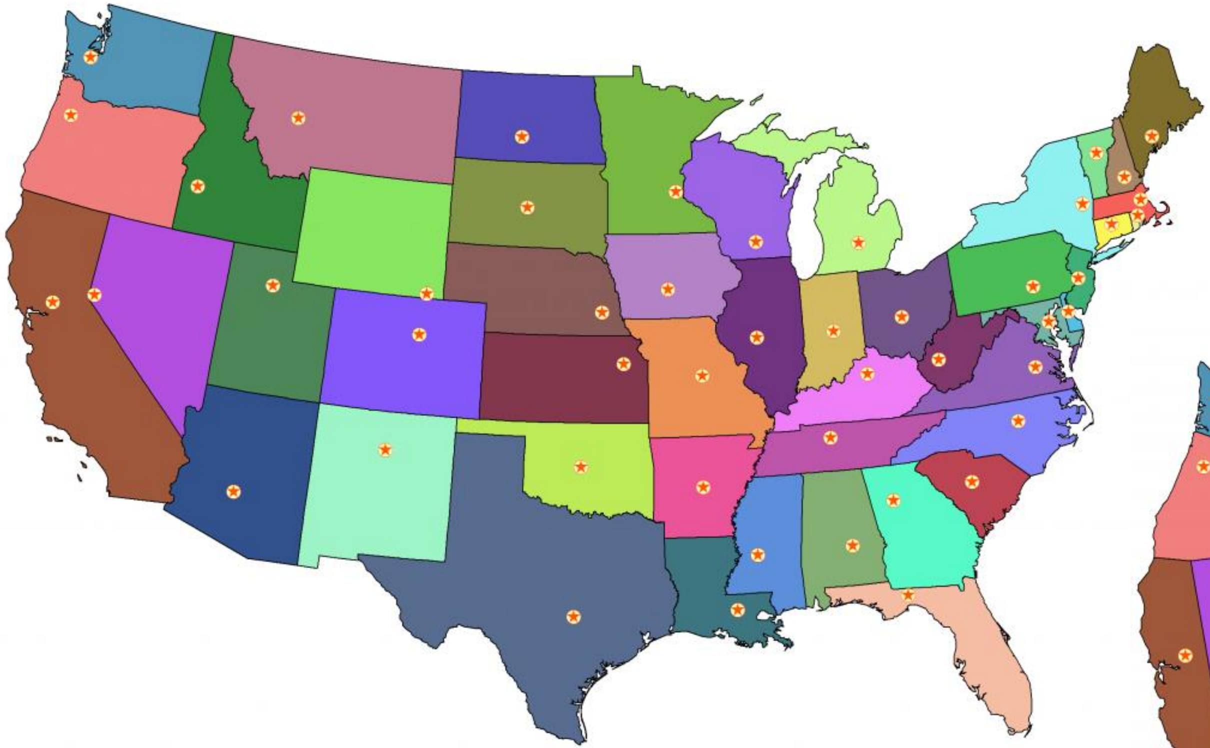
Neyrinck (MNRAS 2008)

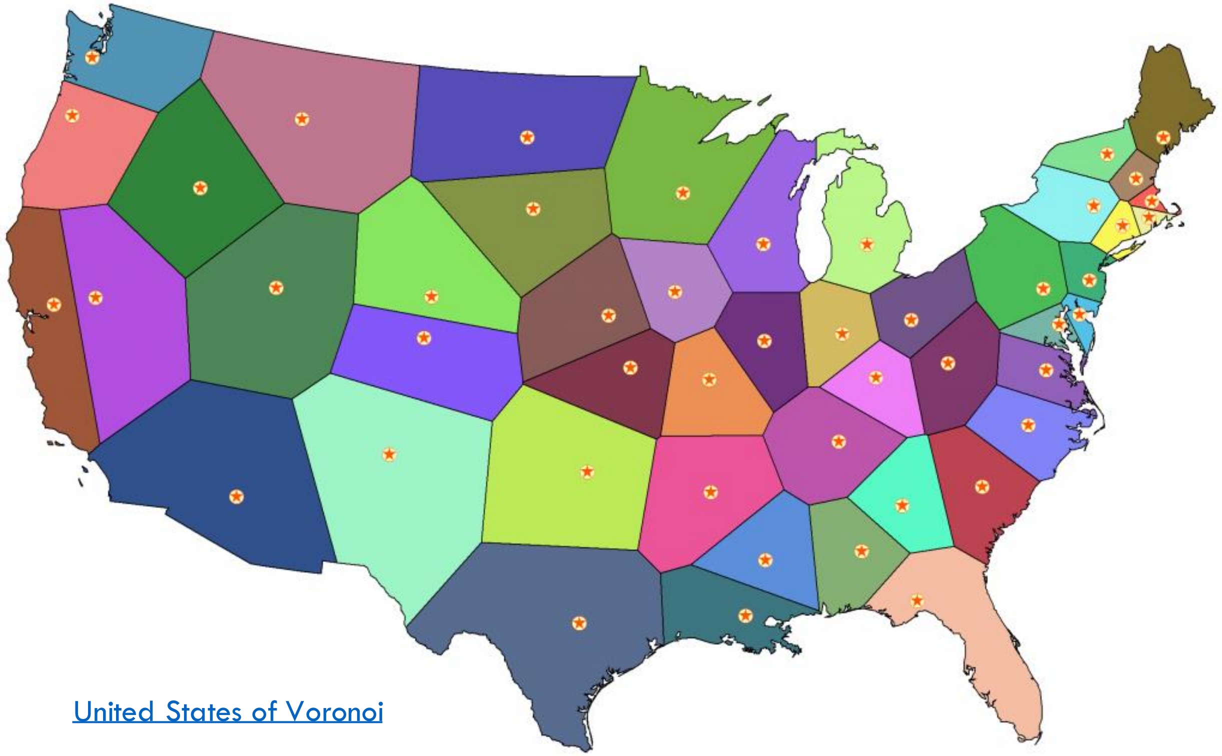
Watershed transform



Steffen Wolf

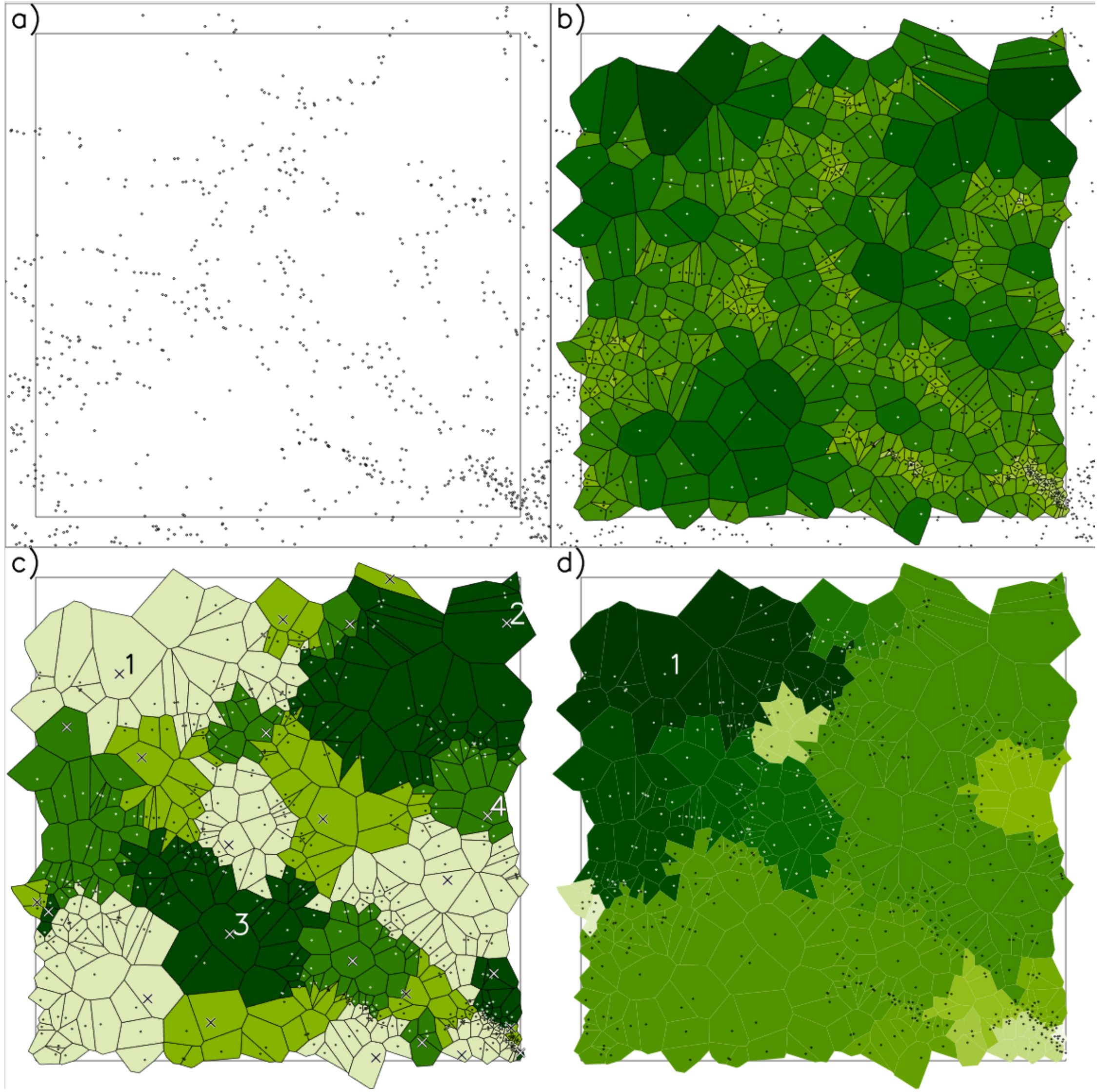
Density field via Voronoi tessellation



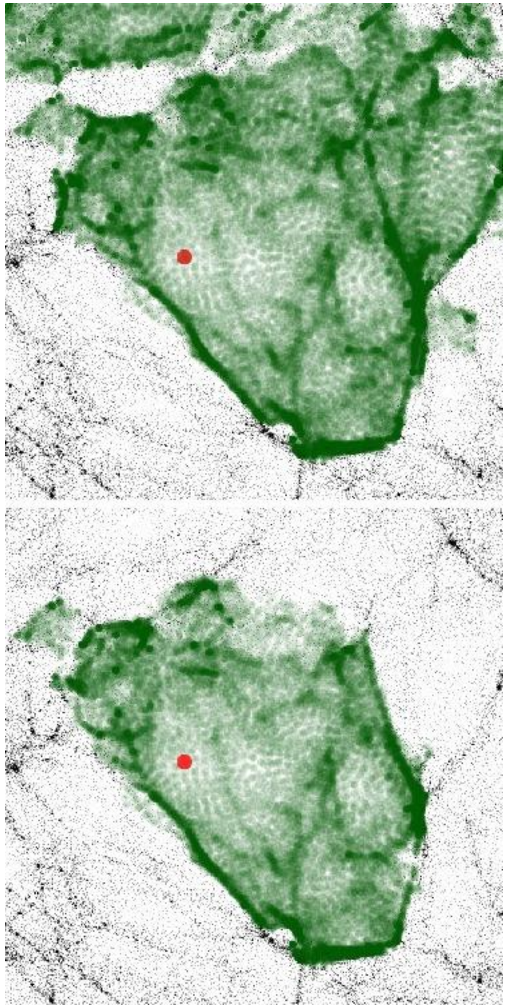


United States of Voronoi

Voronoi tessellation

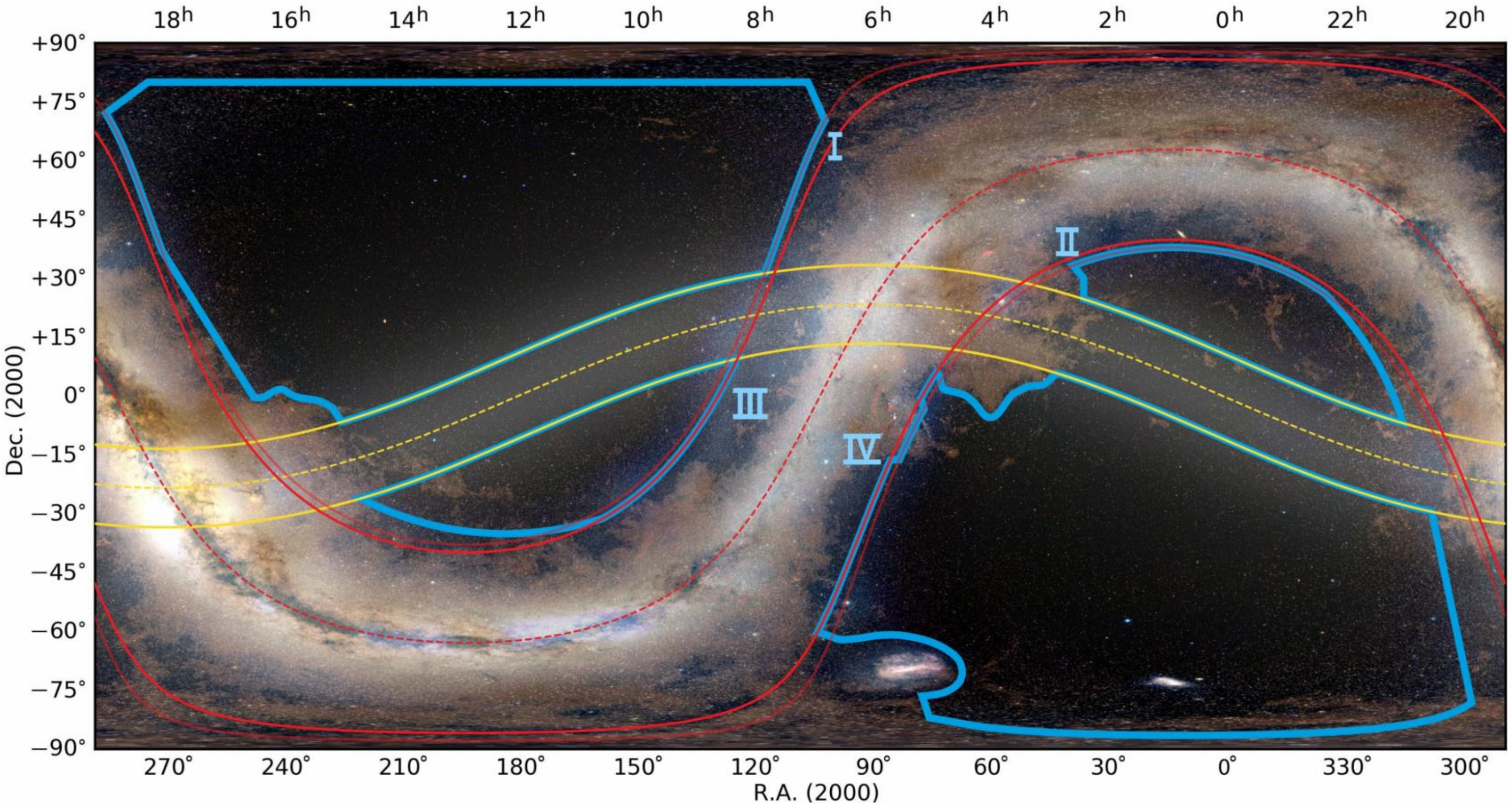


ZOBOV

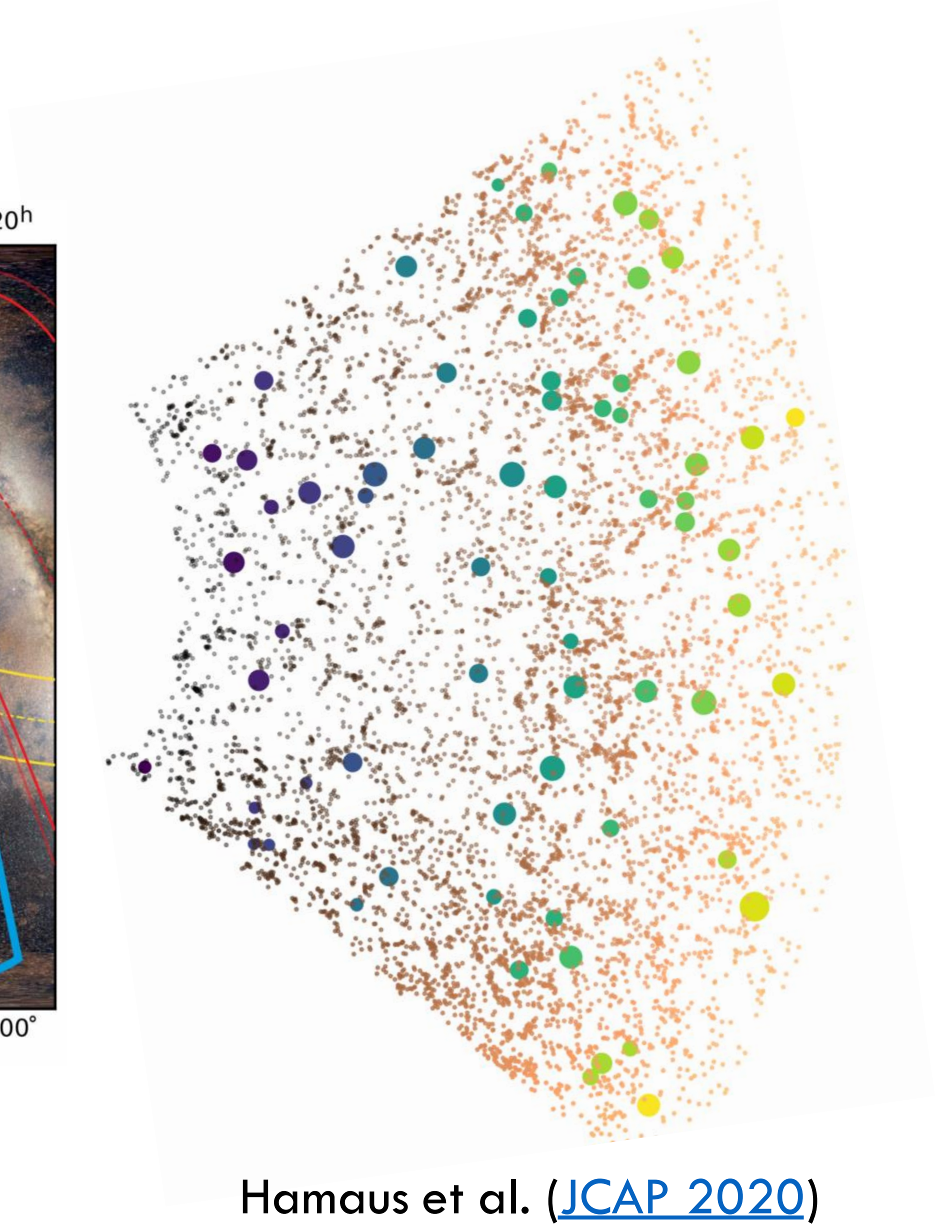


Neyrinck (MNRAS 2008)

Complication with observations: foregrounds & light cone



Euclid Collaboration: Scaramella et al. ([A&A 2022](https://www.aanda.org/))



Hamaus et al. ([JCAP 2020](https://iopscience.iop.org/))

Handle survey mask and selection function

https://bitbucket.org/cosmicvoids/vide_public

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VVVVVVVV           VVVVVVVV IIIIIIIIII DDDDDDDDDDDDD        EEEEEEEEEEEEEEEEEEEEEE
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        EEEEEEEEEEEEEEEEEEEEEE
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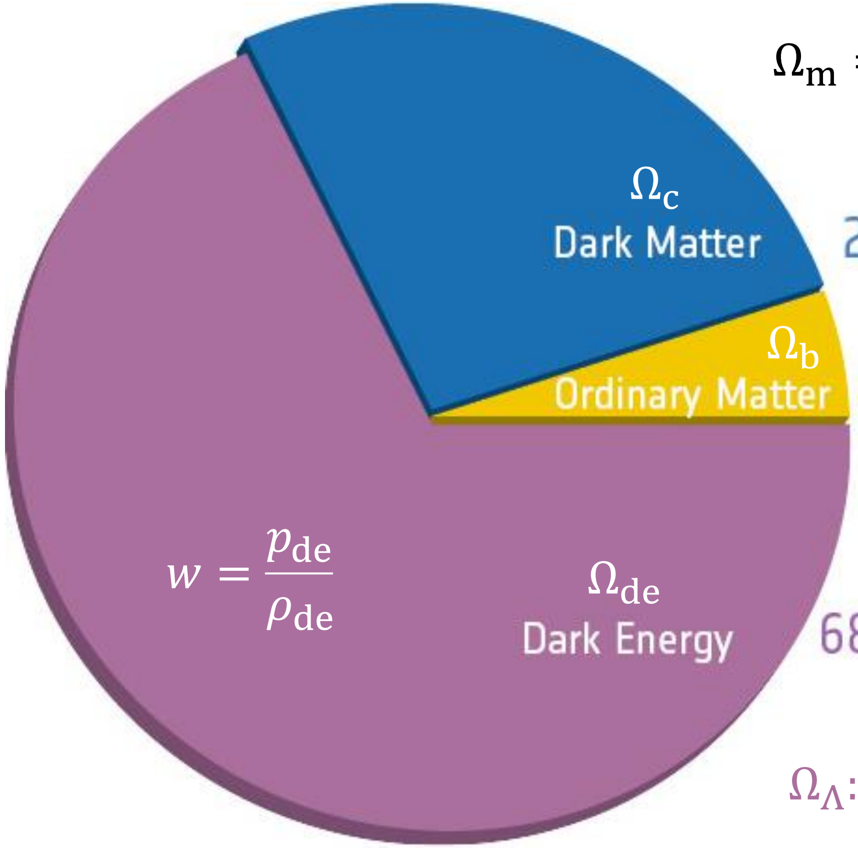
VIDE, the **Void IDentification and Examination toolkit** is a widely used void finder. It has been used on both spectroscopic and photometric data, on simulations and mocks. VIDE is the French word for void, as historically the software was first developed by a group of researchers working at the Institut 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

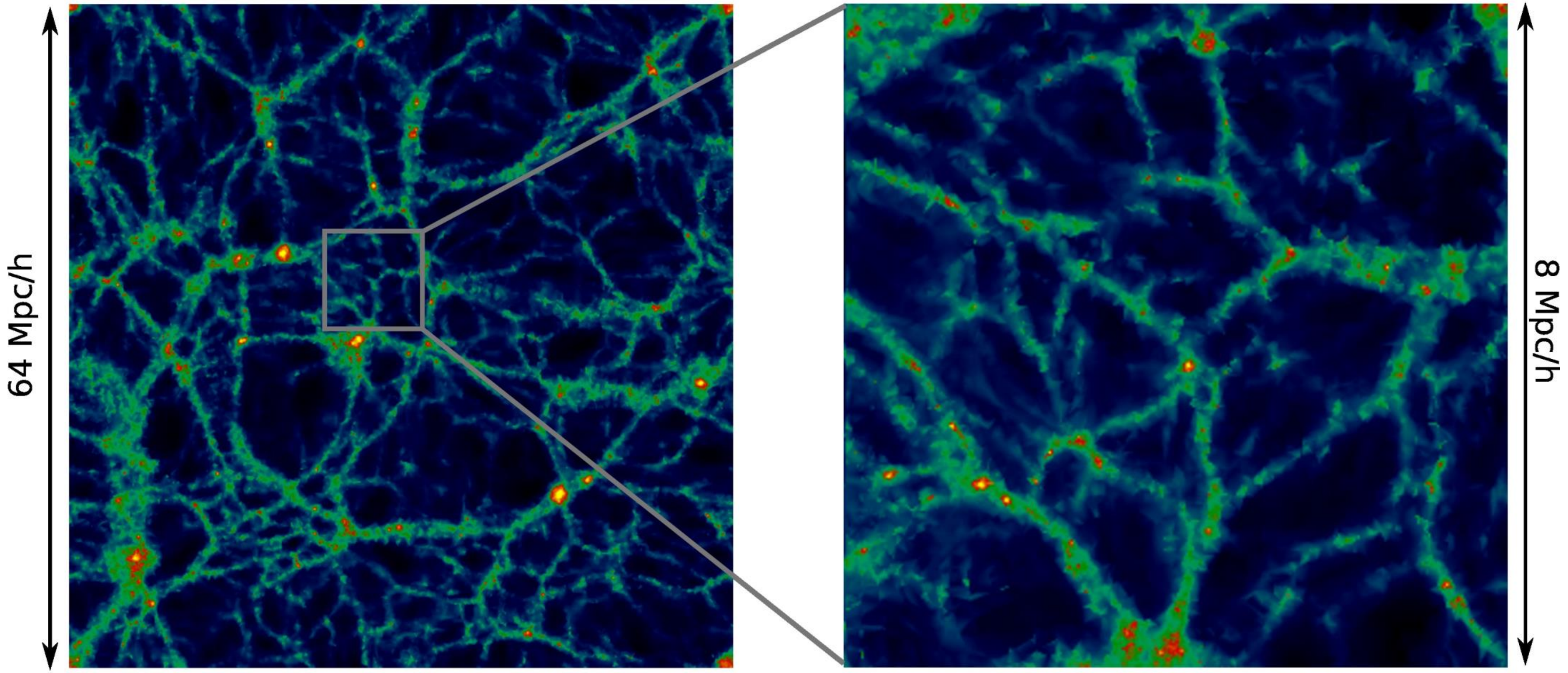
$\Omega_\mathrm{m} = \Omega_\mathrm{c} + \Omega_\mathrm{b}$



Ω_Λ: $w = -1$

esa Planck mission

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

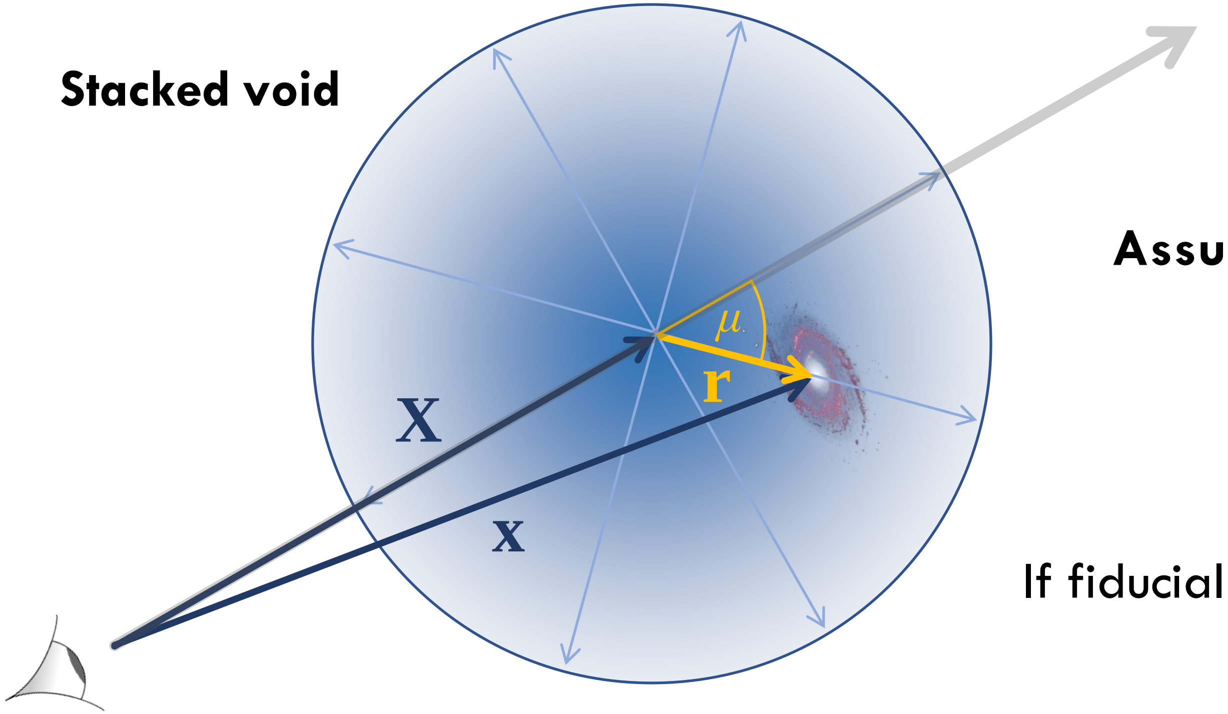
1. Hand-eye coordination
2. Problem solving skills
3. Cause and effect understanding
4. **Shape identification**
5. Color recognition
6. Gross motor skill development
7. Fine motor skill development
8. Goal setting

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, e.g. 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):

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

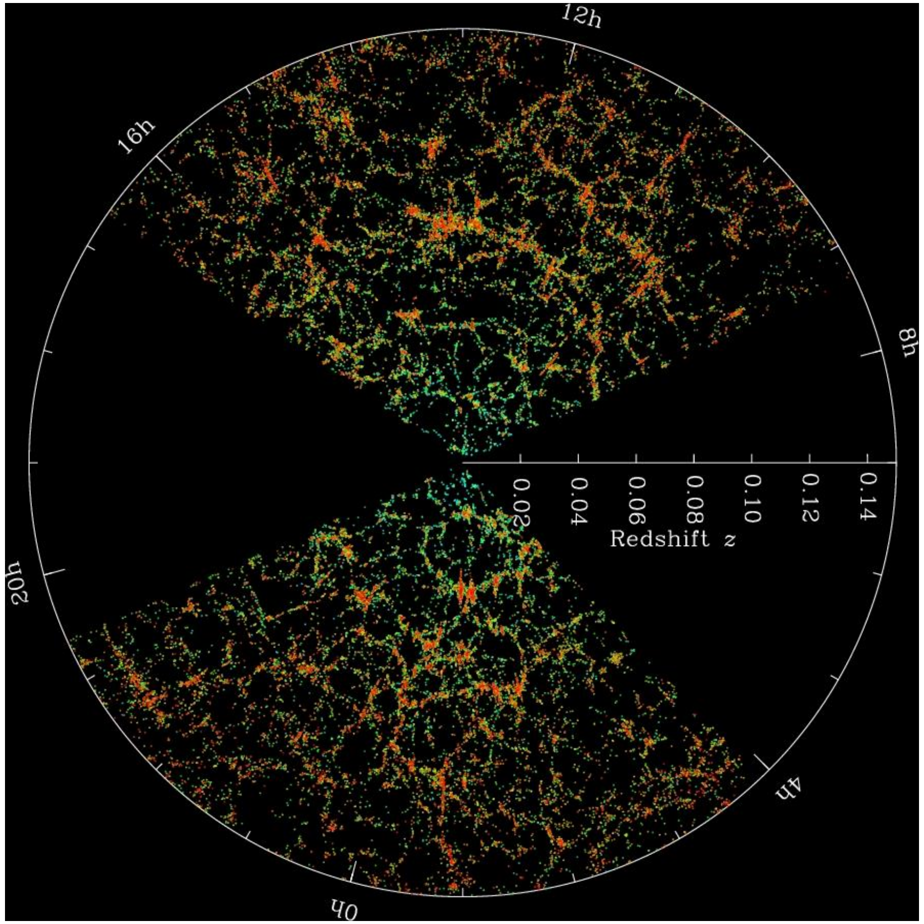
Assume statistical isotropy $(r_\parallel^* = r_\perp^*)$ and measure:

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

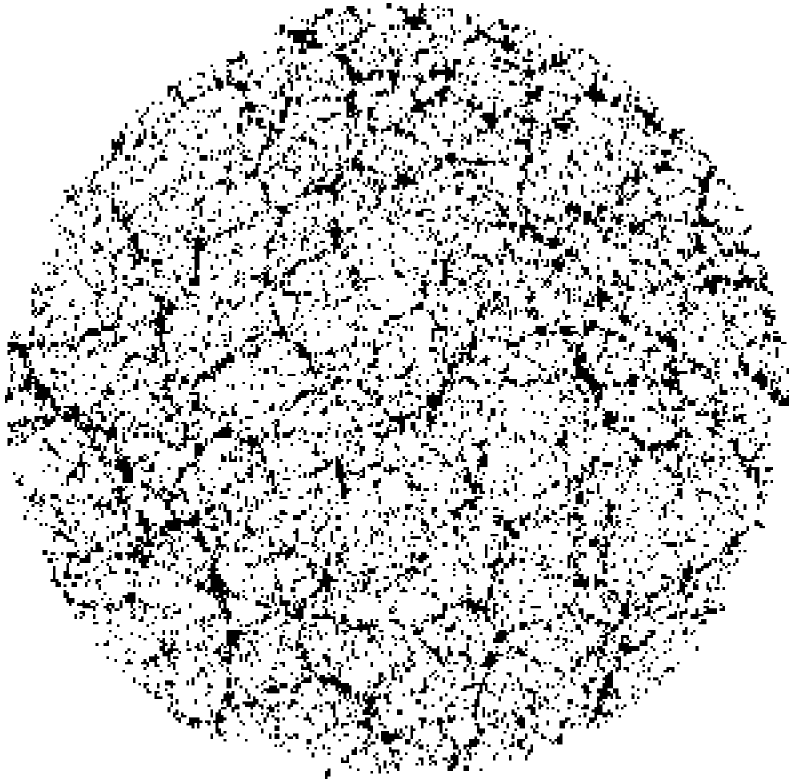
If fiducial cosmology = true cosmology (**Alcock-Paczynski test**):

$$\varepsilon = 1$$

DYNAMIC DISTORTIONS SPOIL SYMMETRY



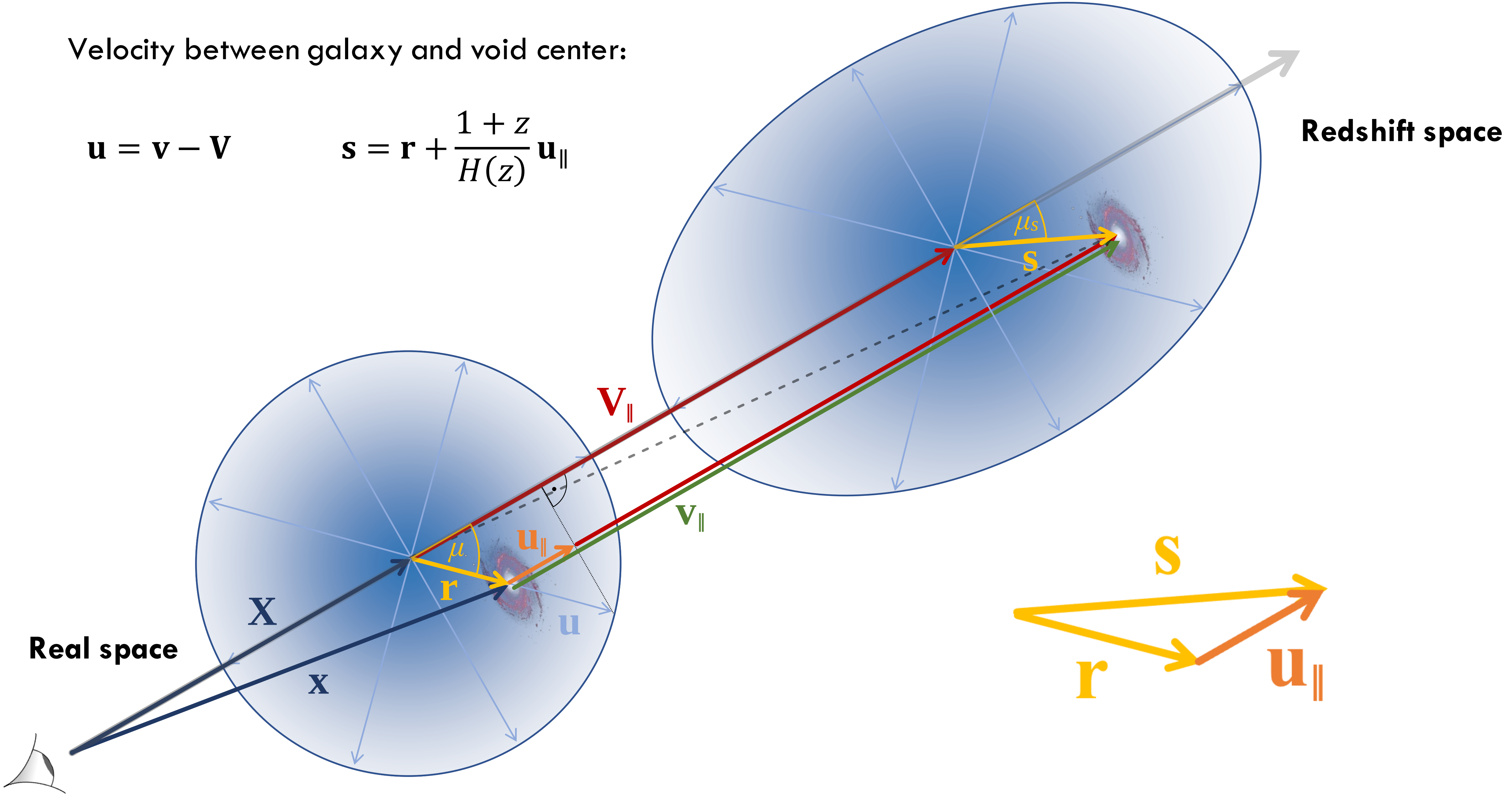
SDSS DR7 (ApJS 2009)



Melott et al. (ApJ 1998)

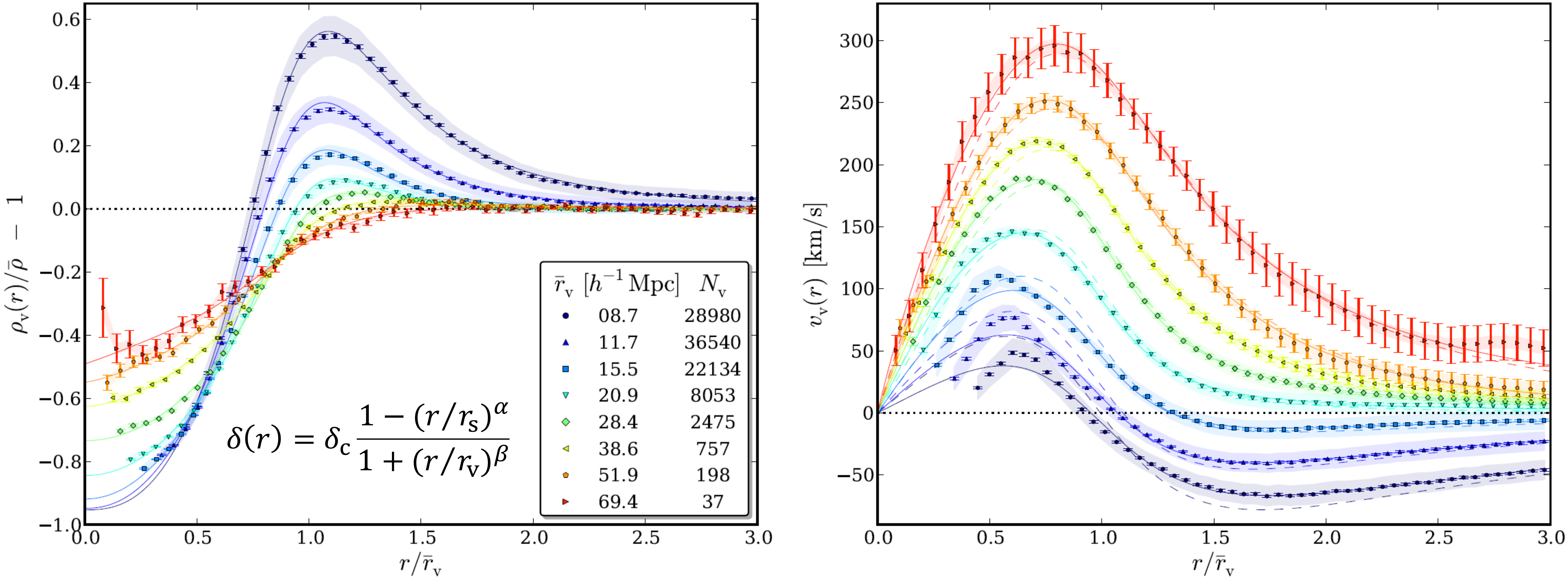
Velocity between galaxy and void center:

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



Pairwise velocity profile: assume local mass conservation at linear order with growth rate $f \equiv \frac{d\ln\delta}{d\ln a}$

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



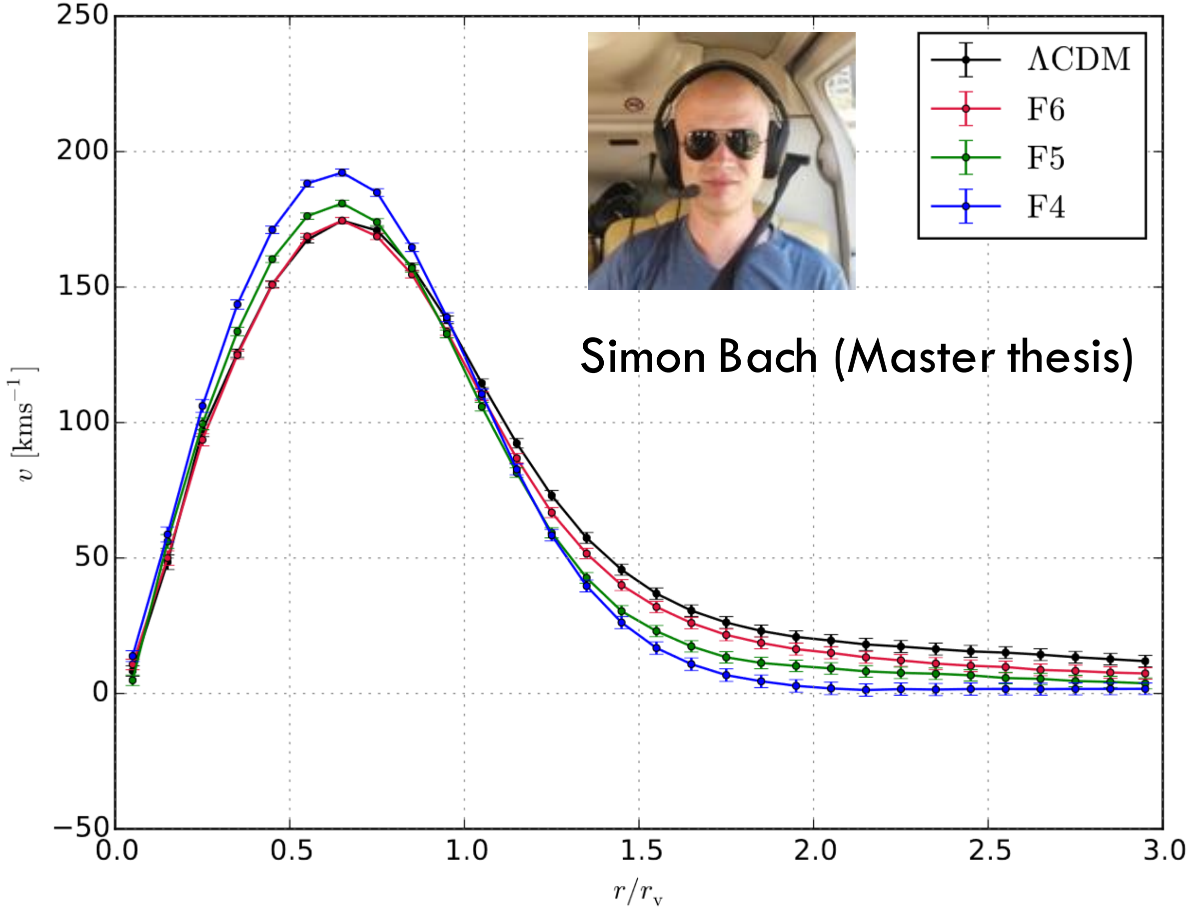
$$\delta(r) = \delta_\mathrm{c}\frac{1-(r/r_\mathrm{s})^\alpha}{1+(r/r_\mathrm{v})^\beta}$$

	$\bar{r}_\mathrm{v}$ $[h^{-1}\mathrm{Mpc}]$	N_v
●	08.7	28980
▲	11.7	36540
■	15.5	22134
▼	20.9	8053
◆	28.4	2475
◀	38.6	757
⬟	51.9	198
▶	69.4	37

Hamaus, Sutter & Wandelt (PRL 2014)

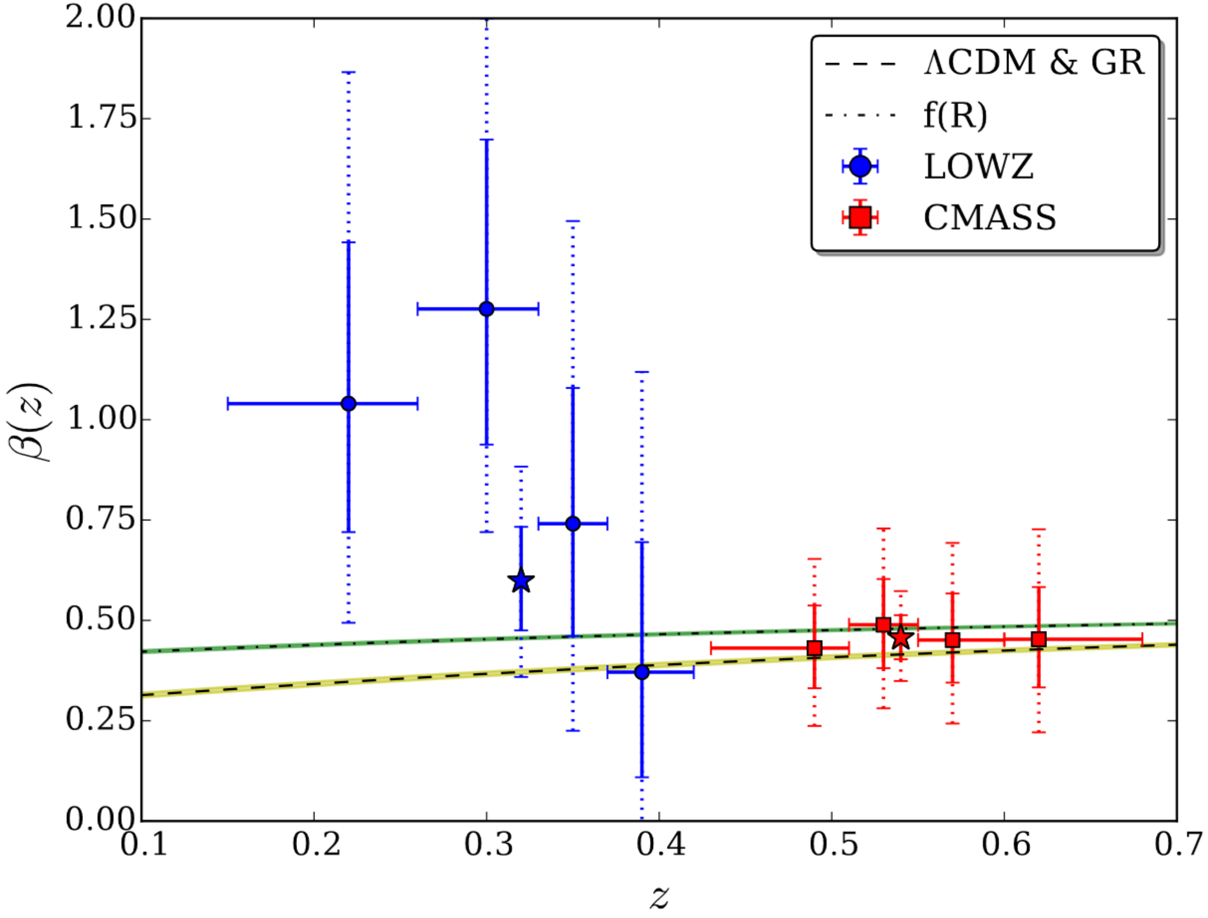
Gravity: Explore alternatives to *General Relativity* (GR)

$f(z) \approx [\Omega_\mathrm{m}(z)]^\gamma$ in GR: $\gamma \approx 0.55$ "growth index"



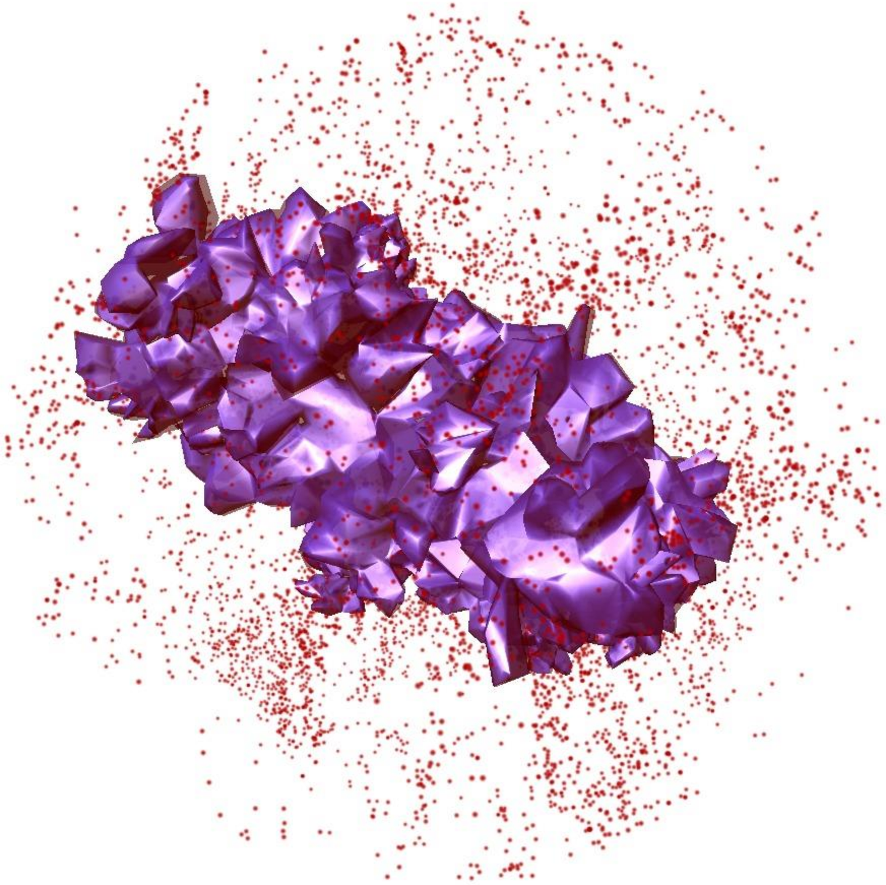
Simon Bach (Master thesis)

$\beta(z) = f(z)/b(z)$ "galaxy bias" $b(z)$

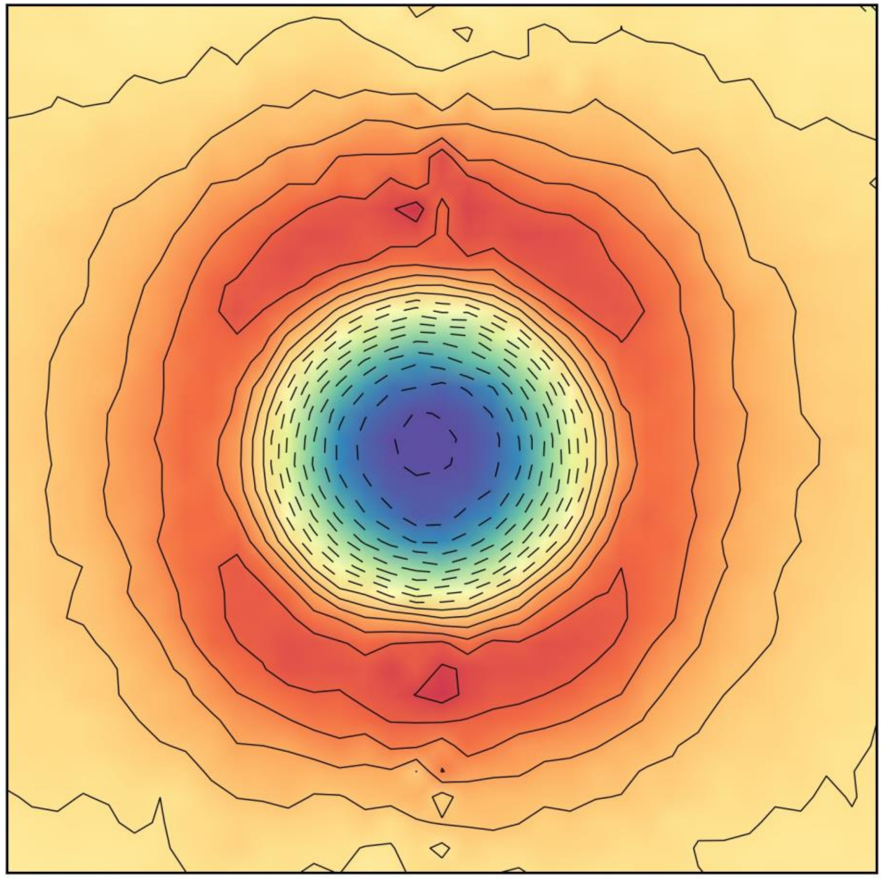


Hamaus et al. (JCAP 2017)

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:

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

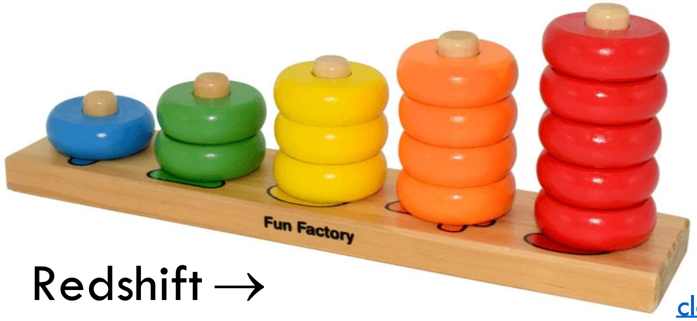
Landy-Szalay estimator for cross-correlations:

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

$\mathcal{D}$: 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)

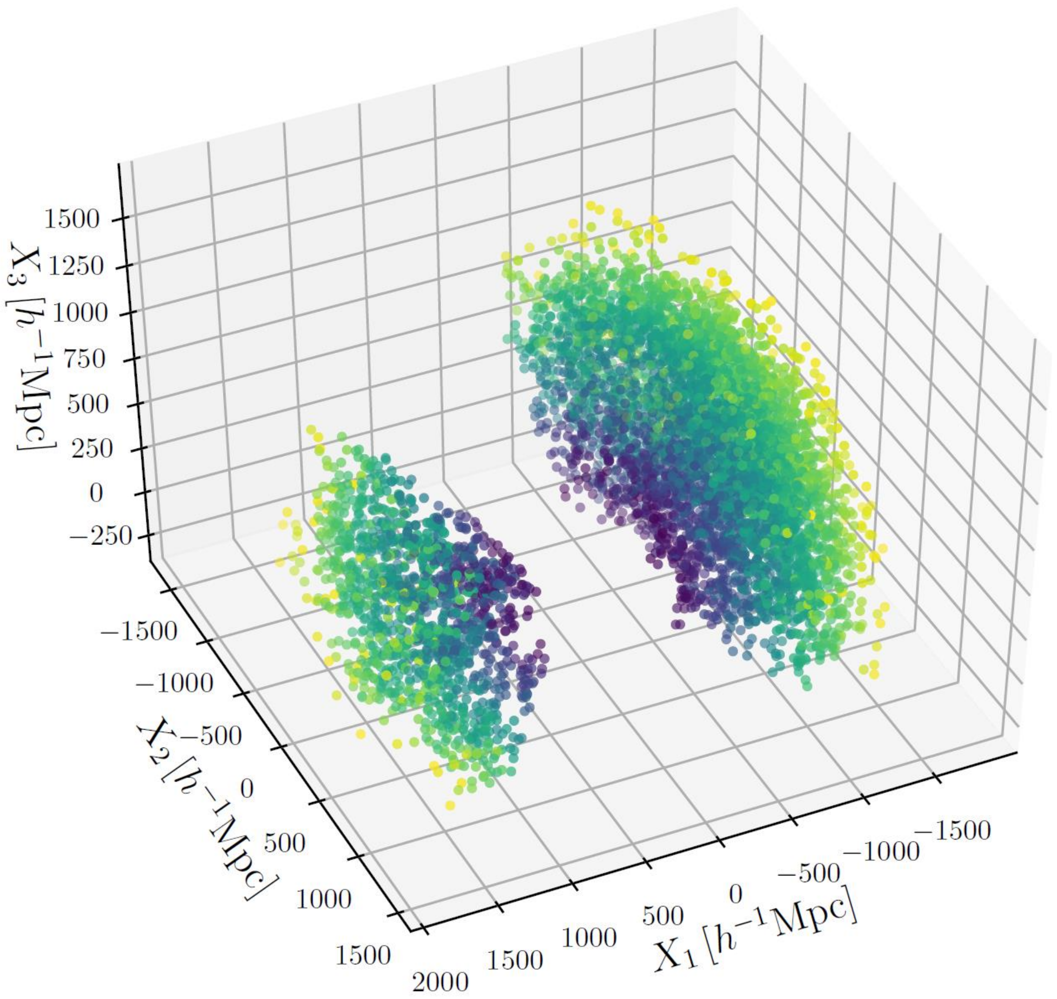
$$1+\xi^s(\mathbf{s}) = \int [1+\xi(r)]\,\mathcal{P}(u_\parallel, r, \mu)\mathrm{d}u_\parallel \qquad \mathcal{P}(u_\parallel, r, \mu) = \frac{1}{\sqrt{2\pi}\sigma_\parallel(r,\mu)}\exp\left\{-\frac{[u_\parallel - u(r)\mu]^2}{2\sigma_\parallel^2(r,\mu)}\right\}$$

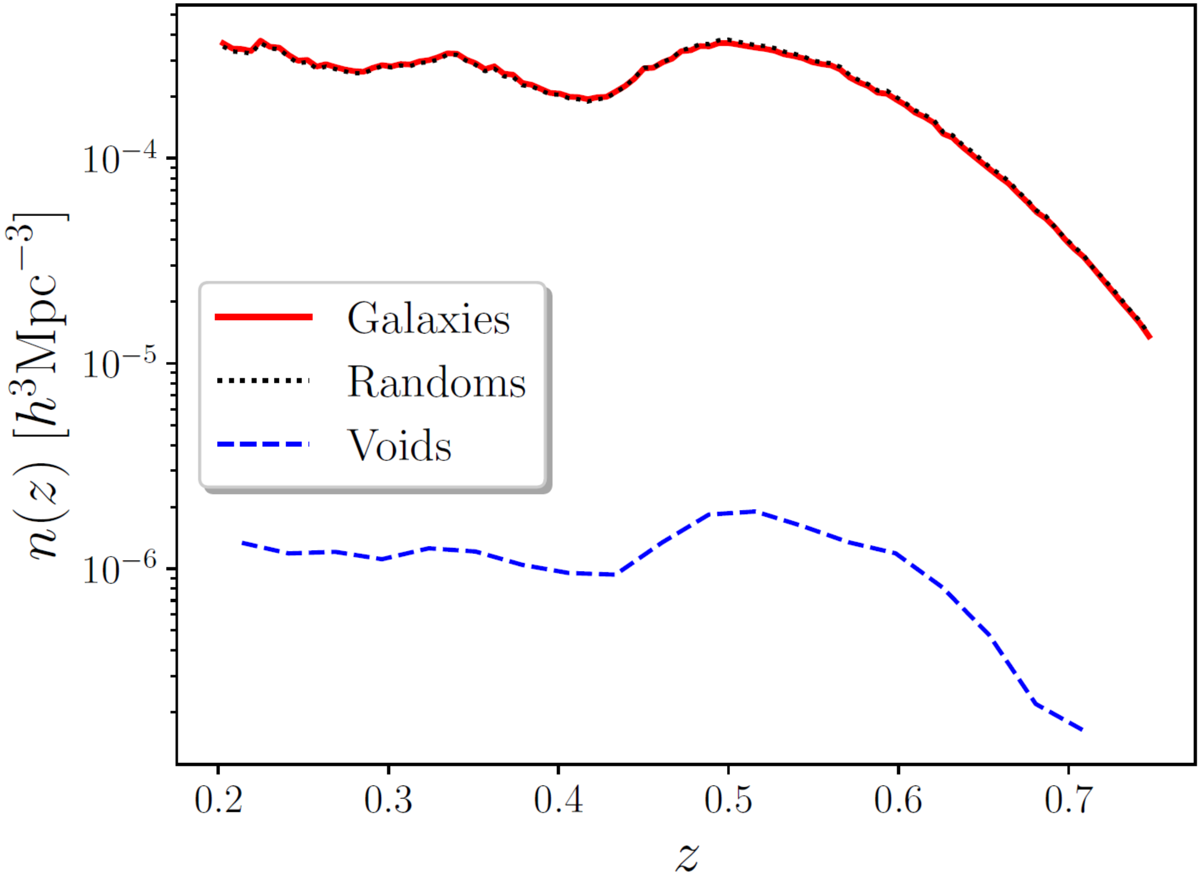
Linear Kaiser-like model: Cai et al. (MNRAS 2016), Hamaus et al. (JCAP 2017)

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

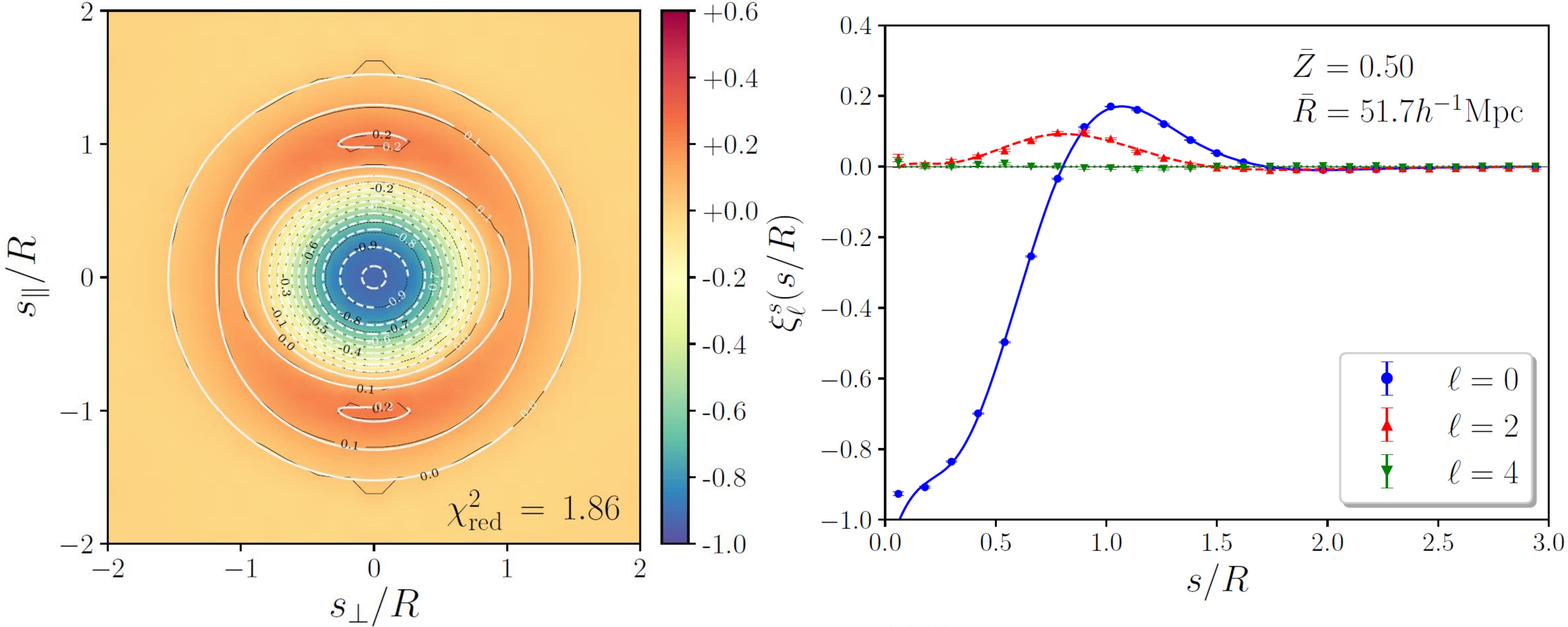
Model ingredients: $\xi(r), u(r), \sigma_\parallel(r,\mu)$

SDSS BOSS DR12 VOIDS



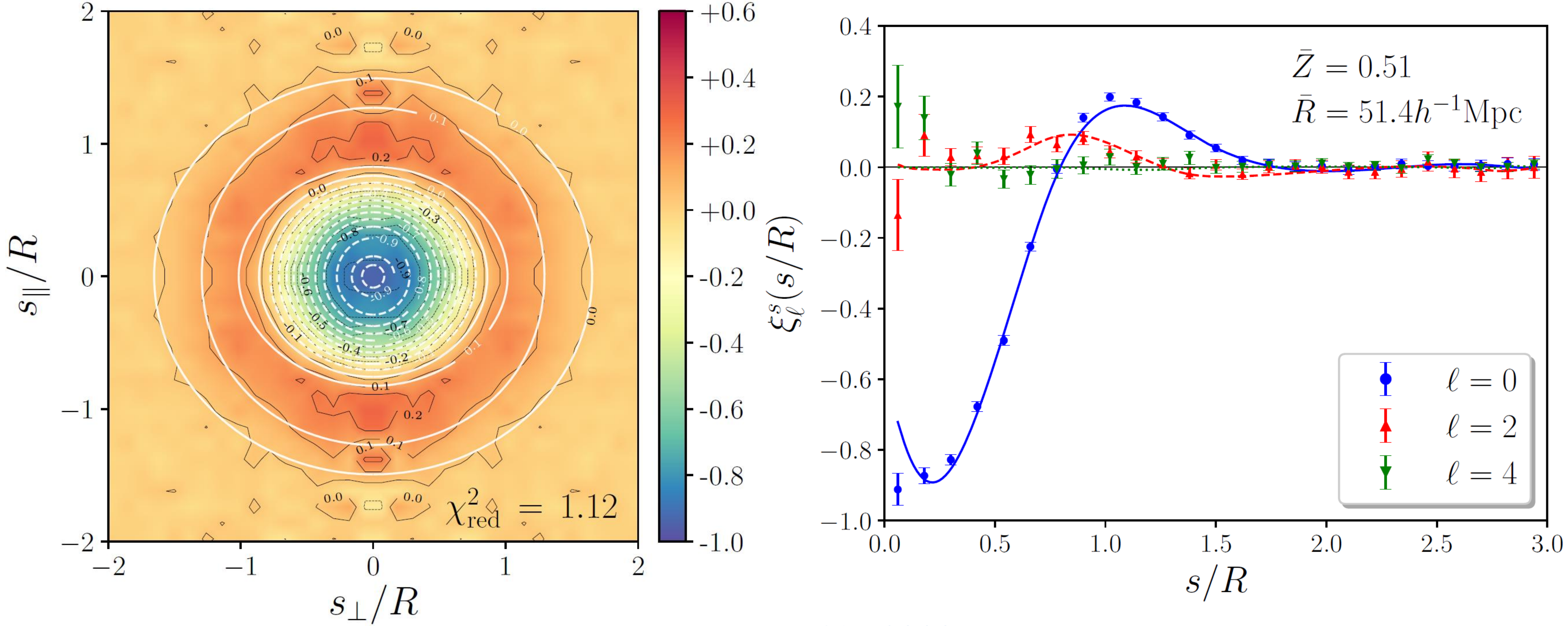


Model validation on 30 PATCHY mocks



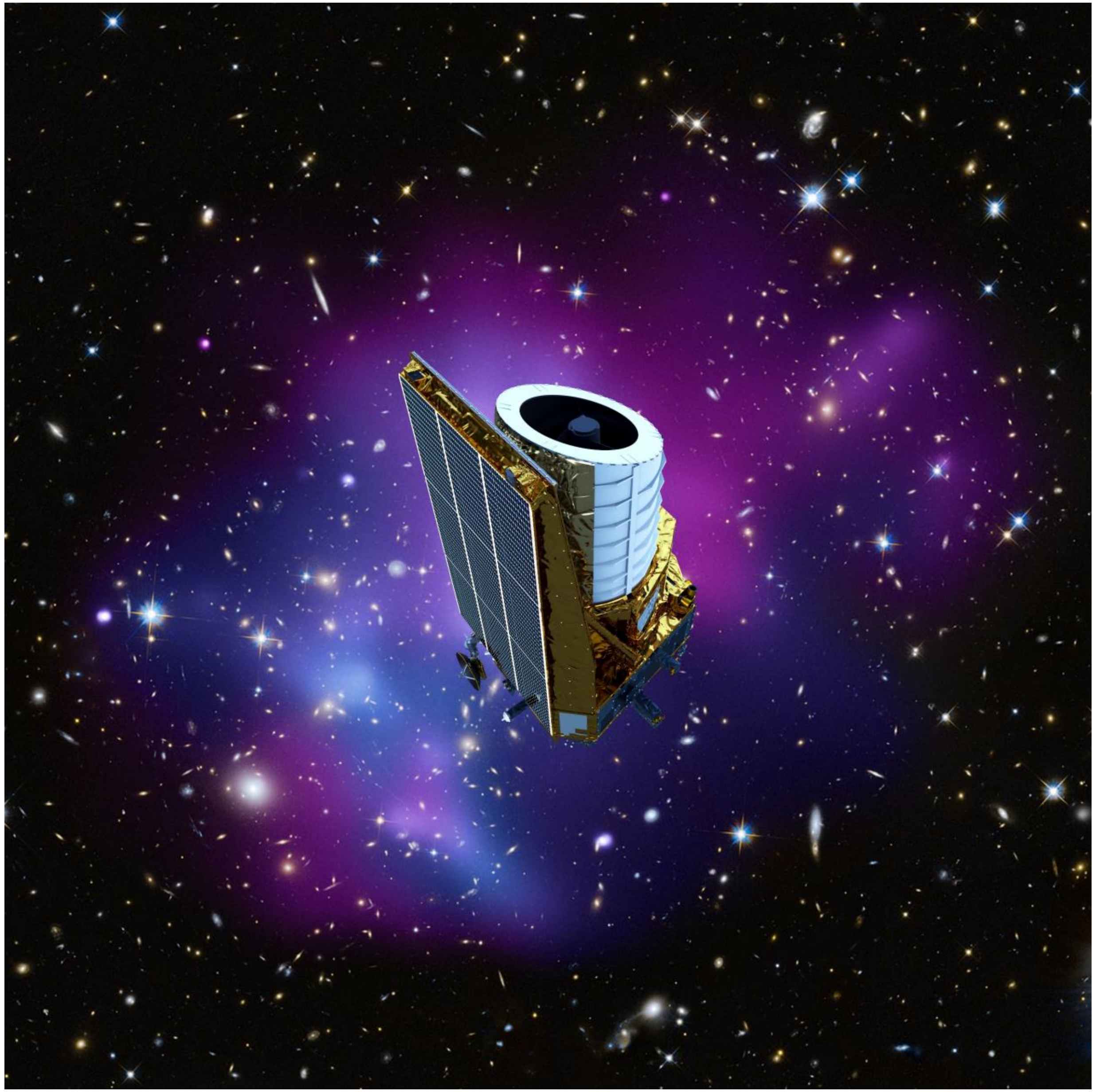
Hamaus et al. (JCAP 2020)

BOSS DR12 data



Hamaus et al. (JCAP 2020)

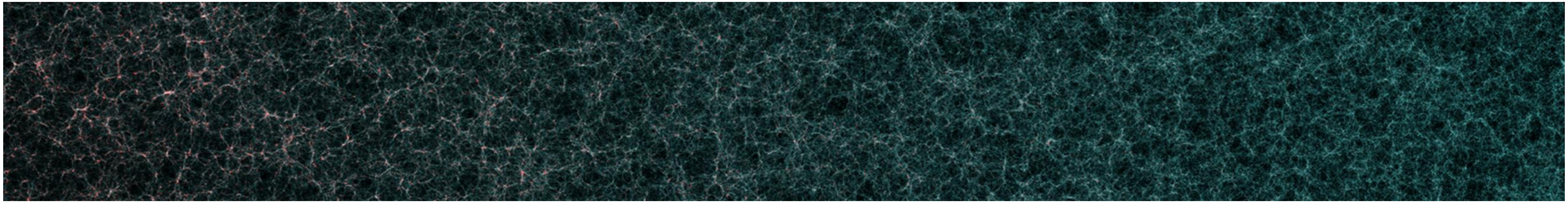
EUCLID VOIDS



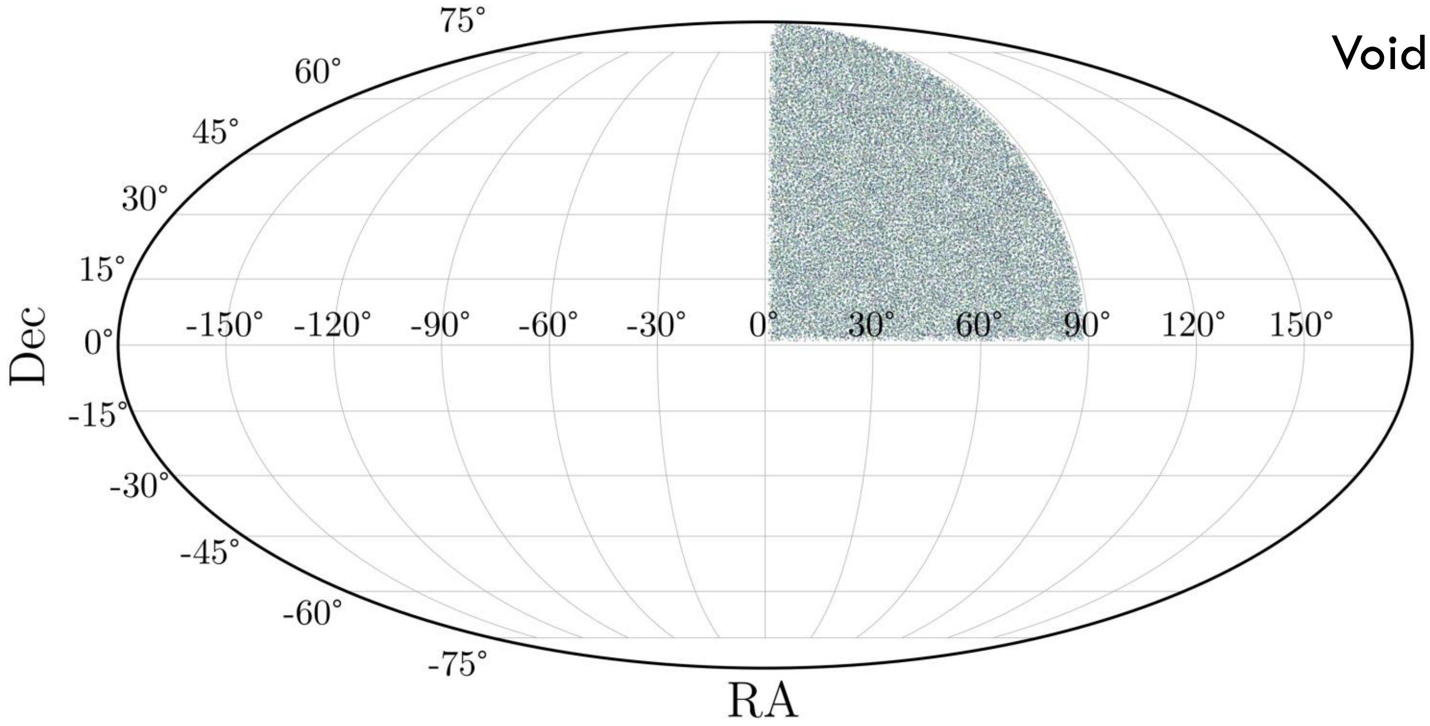
- Space-satellite mission to survey 35% of the sky
- Launch to Lagrange point 2 (L2) in 2023
- $\sim 10^9$ galaxies with $\sim 10^7$ spectra: **$\sim 10^5$ voids**
- Redshift range:
  - $0.0 < z < 2.5$ (photo-z)
  - $0.9 < z < 1.8$ (spec-z)

esa Euclid mission

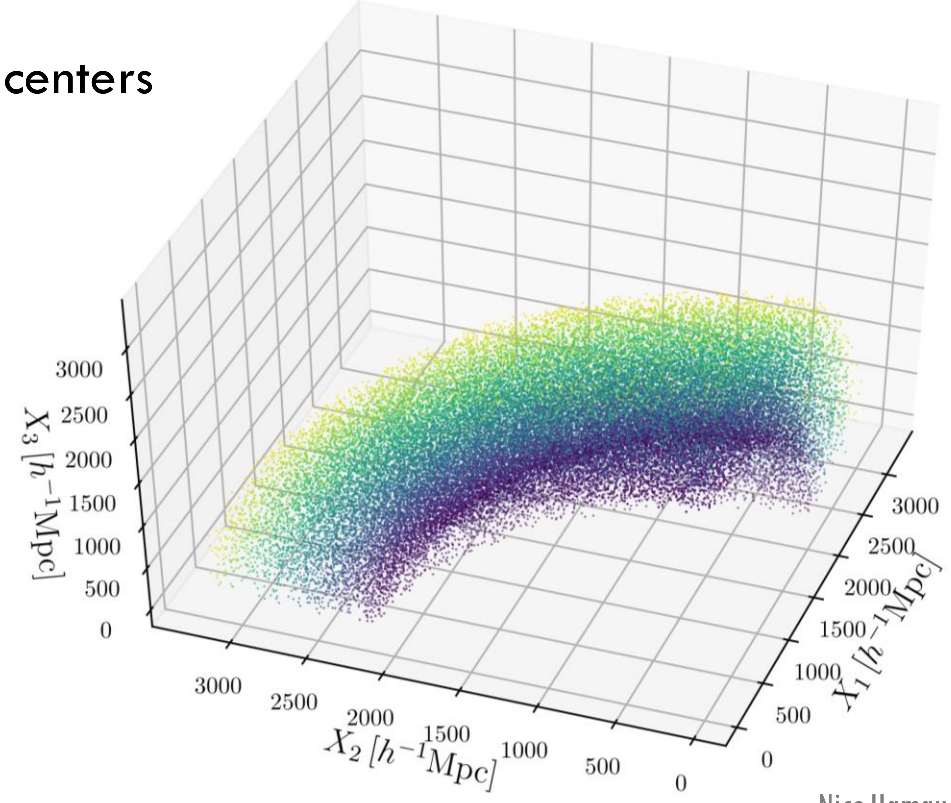
VIDE voids in *Euclid* **Flagship** mock (based on N-body simulation with 2 trillion particles).



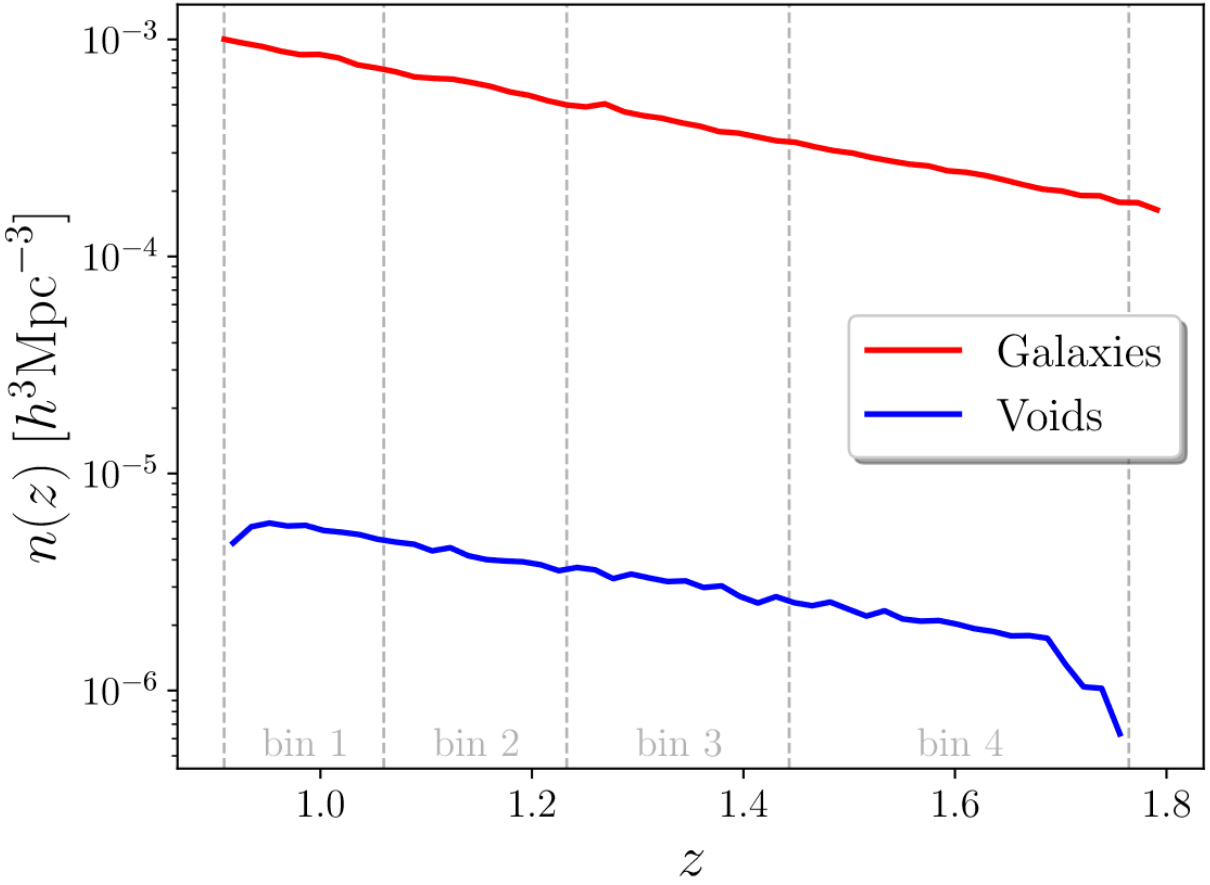
Redshift →



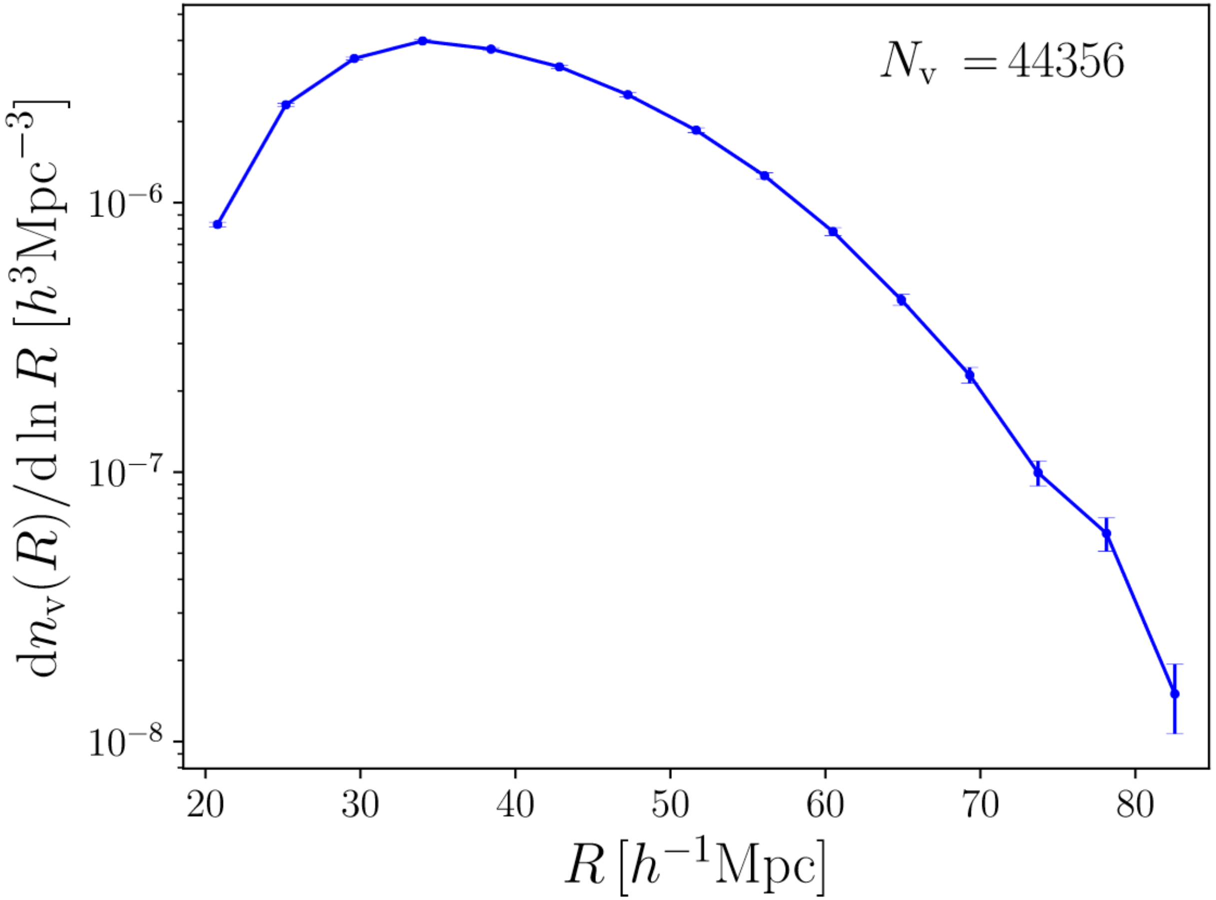
Void centers



Number density of tracers and voids

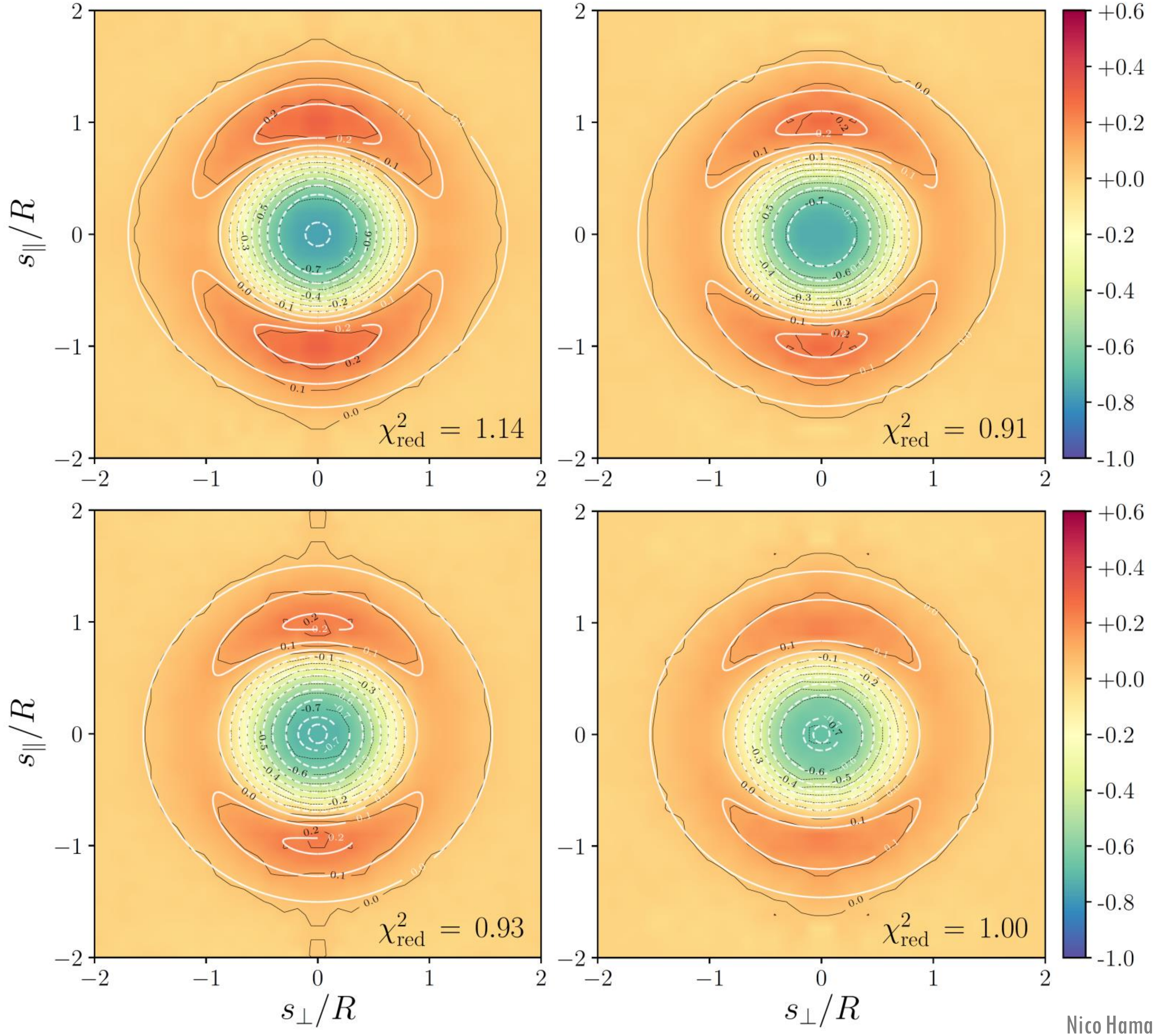


Void size function

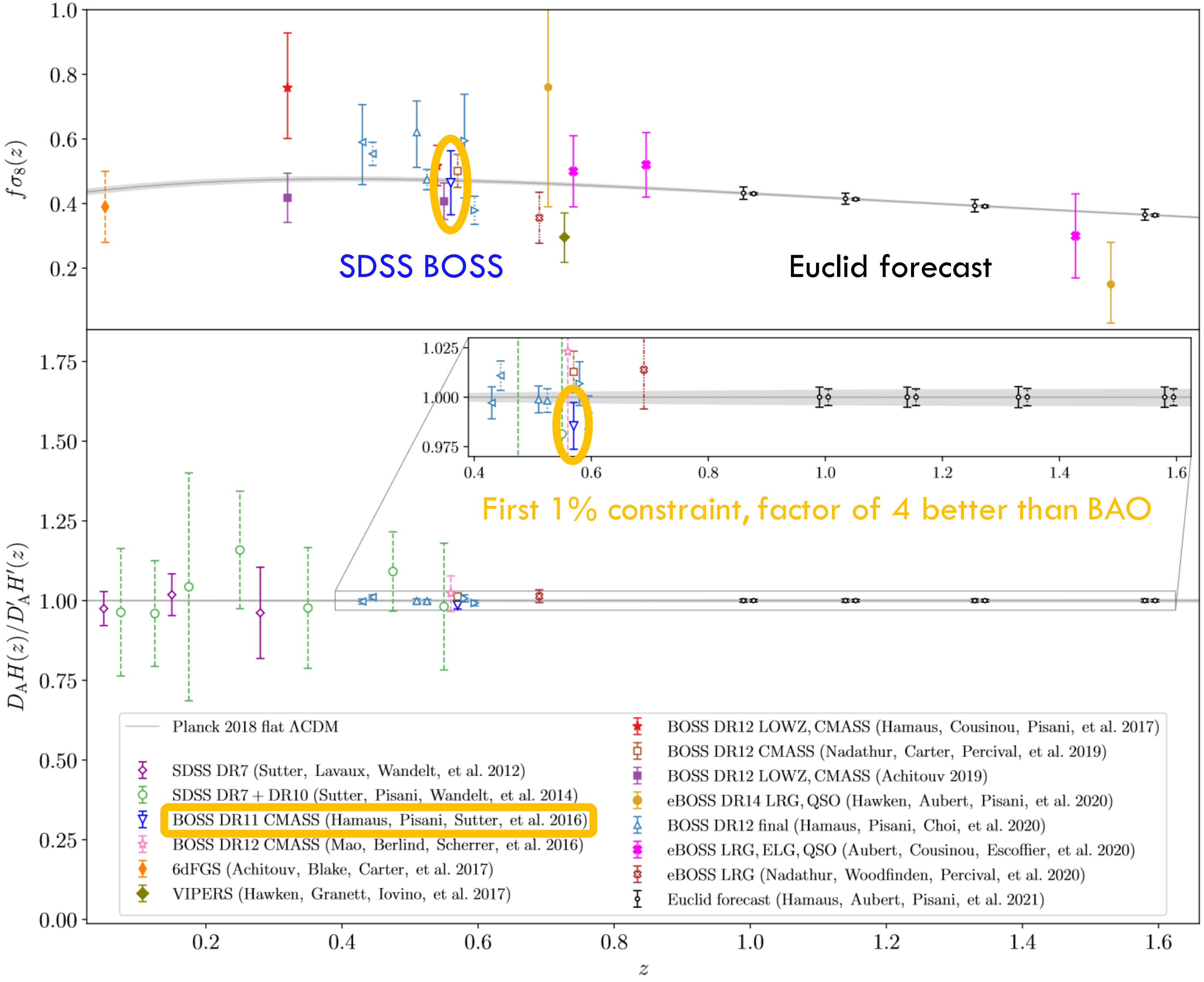


Purity cut on void size: $R > N_\mathrm{s}\left(\frac{4\pi}{3}n_\mathrm{g}(Z)\right)^{-1/3}$ $\quad N_\mathrm{s} = 3$

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



Overview of constraints from various galaxy surveys



SDSS BOSS

Euclid forecast

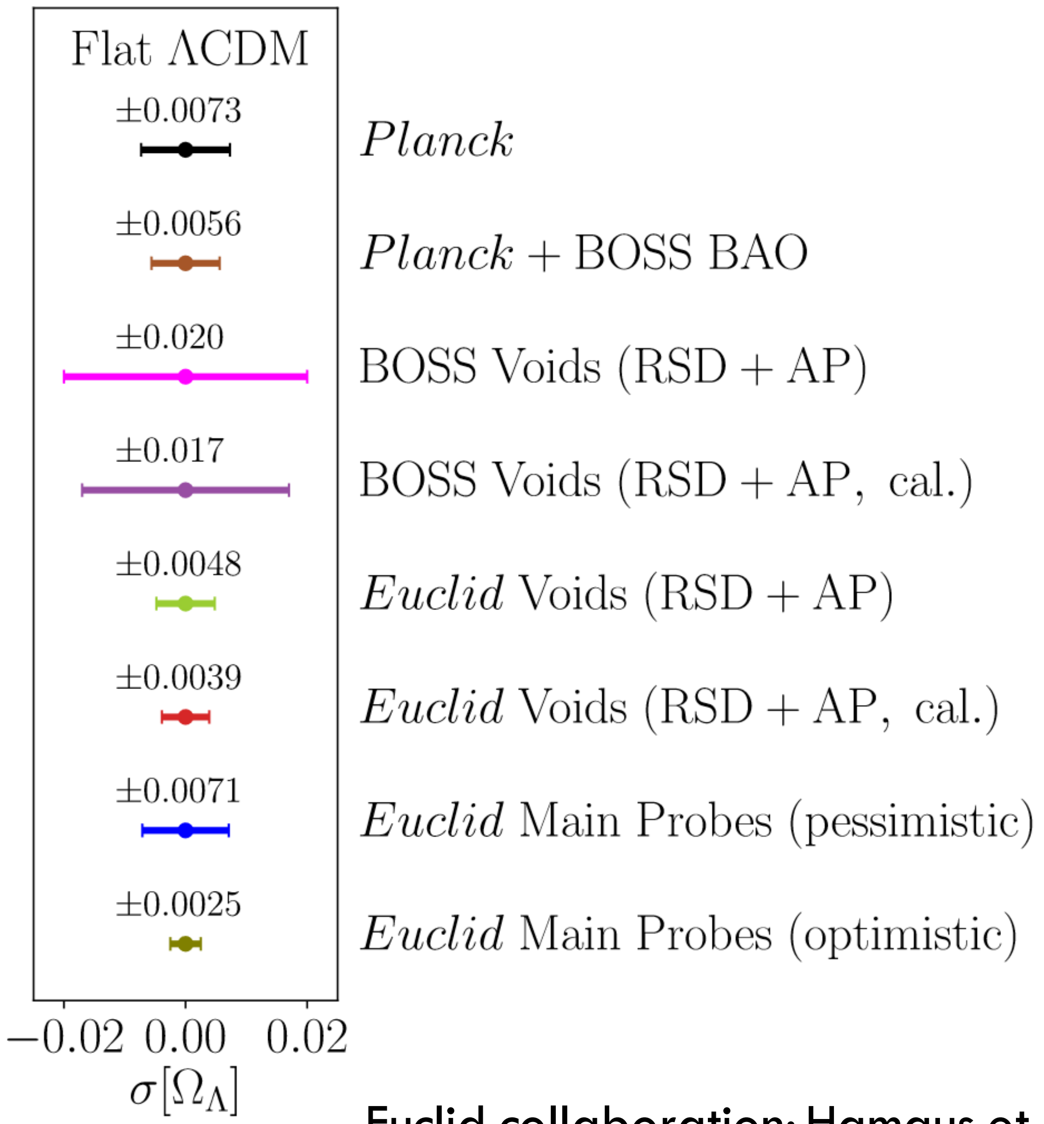
First 1% constraint, factor of 4 better than BAO

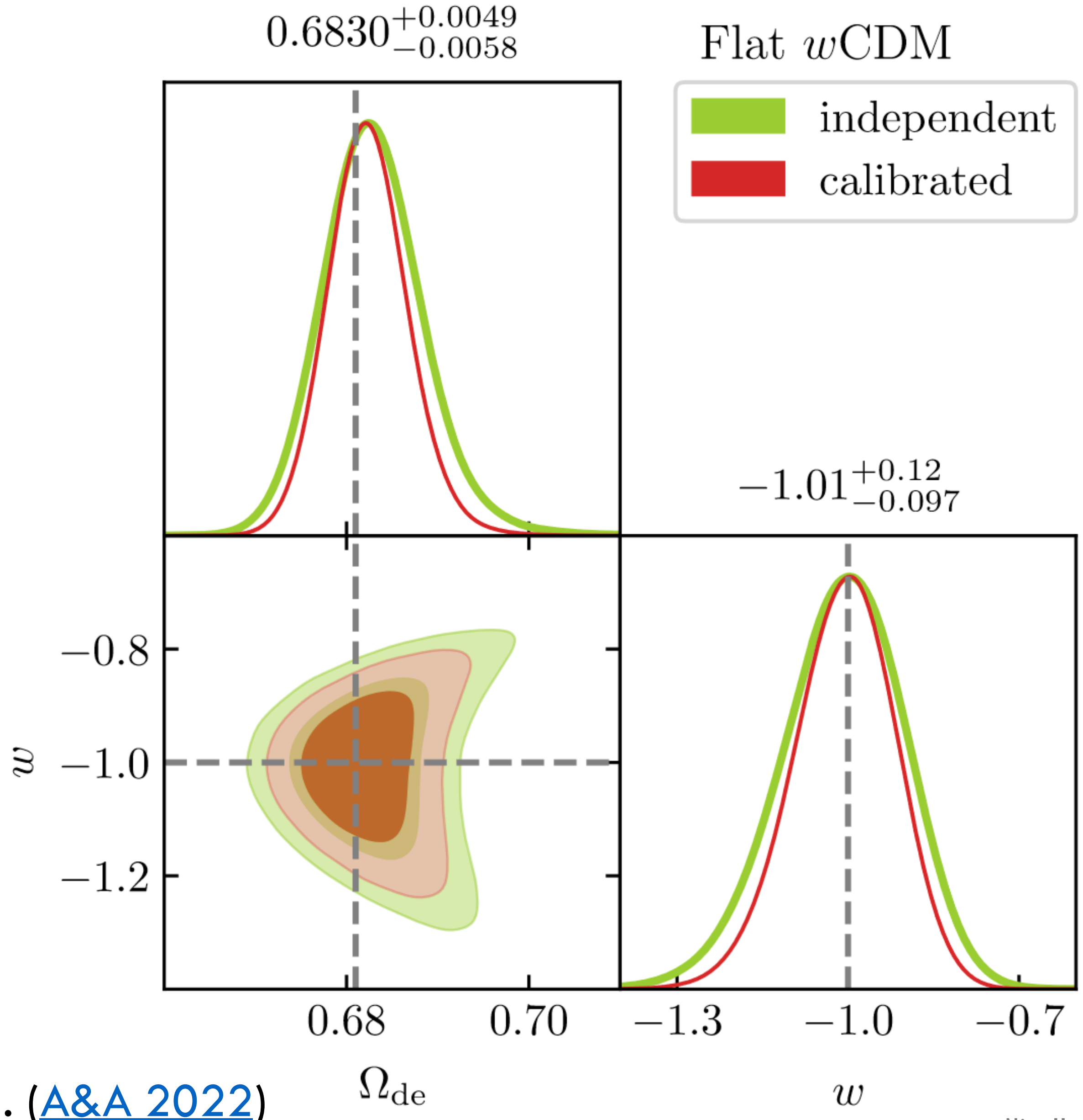
Method:
RSD only (filled symbols)
RSD+AP (open symbols)

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

Reference:
Planck 2018 (gray line)

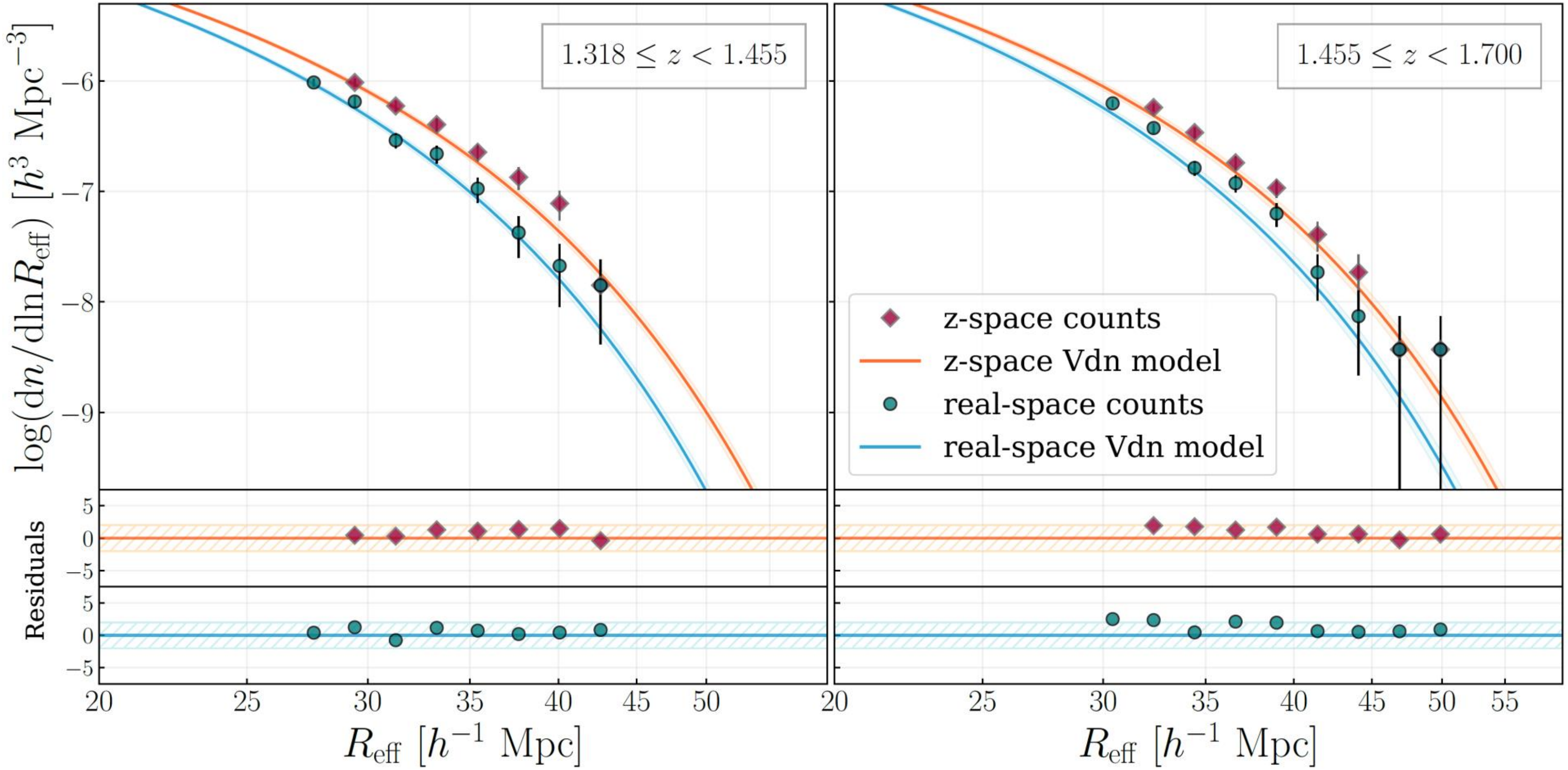
Constraints on dark energy as stand-alone probe, extrapolated to full *Euclid* footprint of 15 000 sq. deg.





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

VOID SIZE FUNCTION

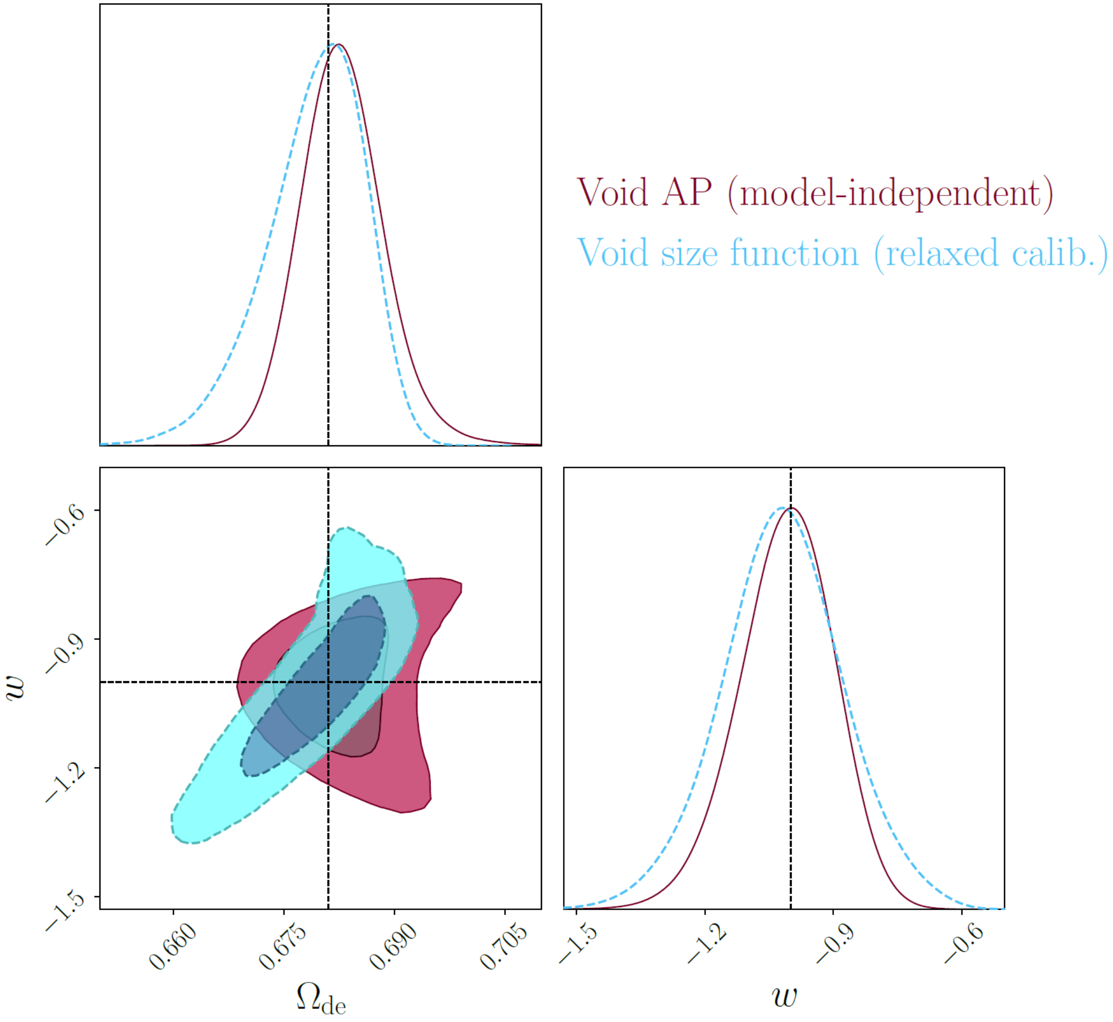


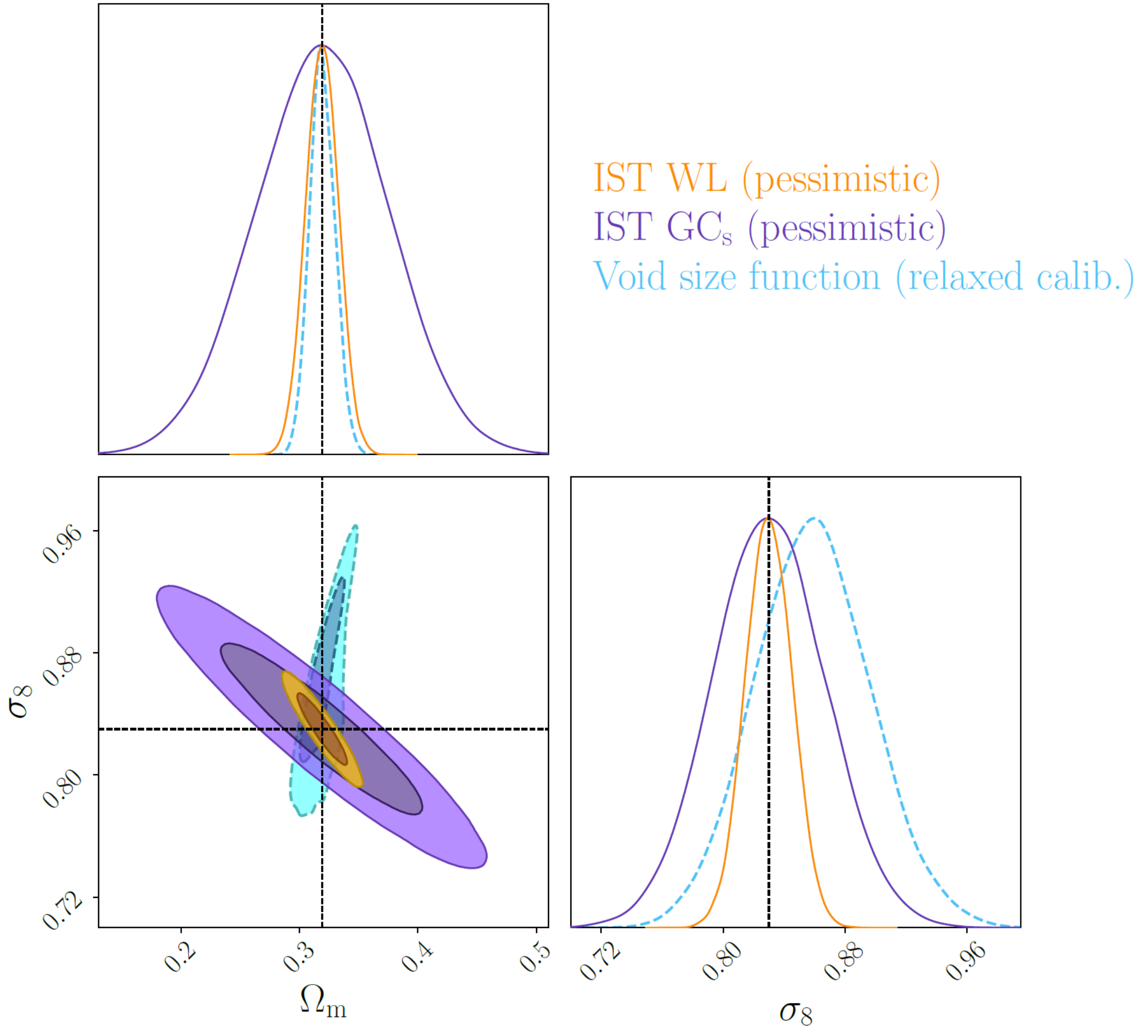
Sofia Contarini

Giovanni Verza

Euclid collaboration: Contarini, Verza et al. incl. Hamaus (A&A 2022)

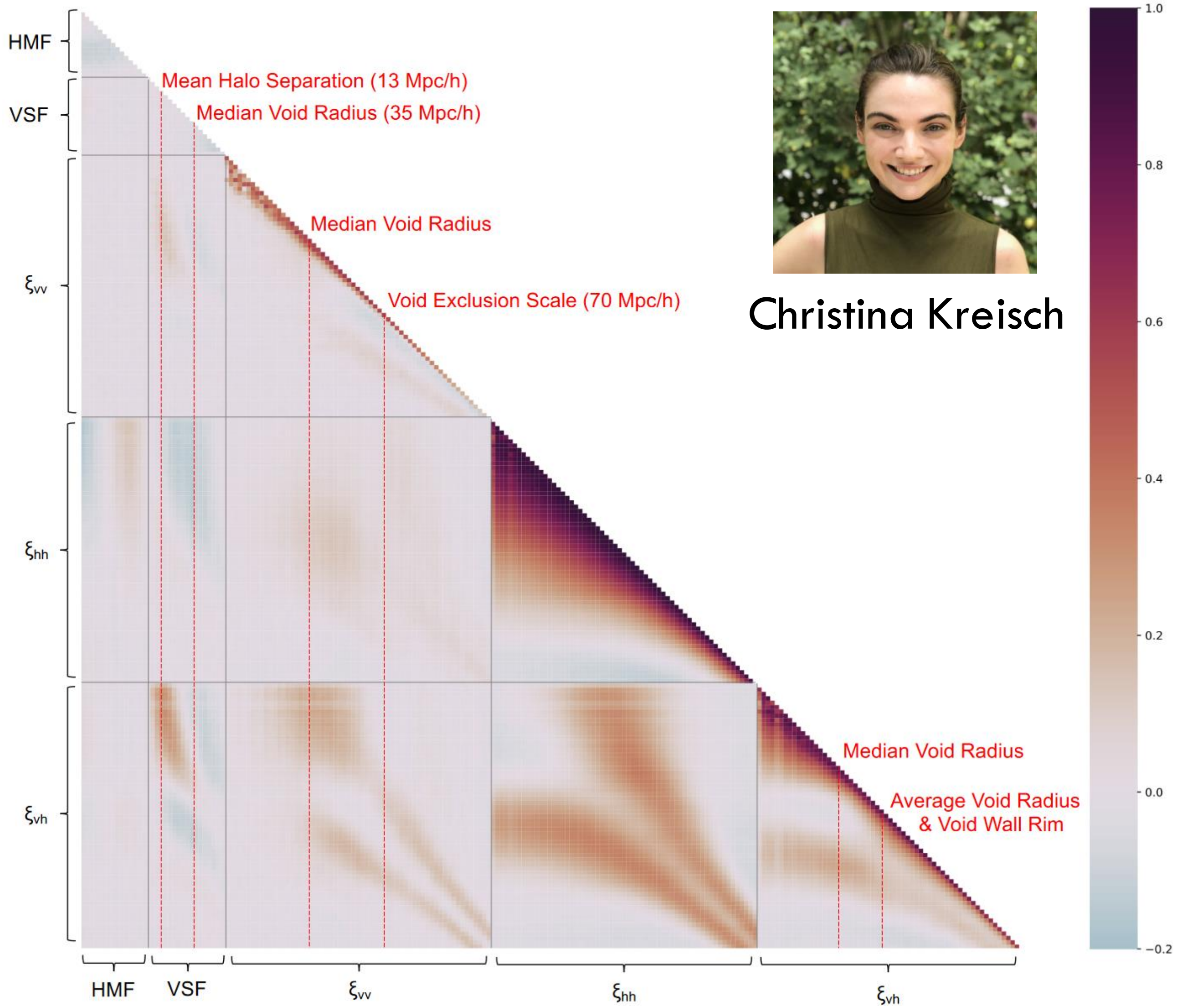
Let’s break degeneracies!



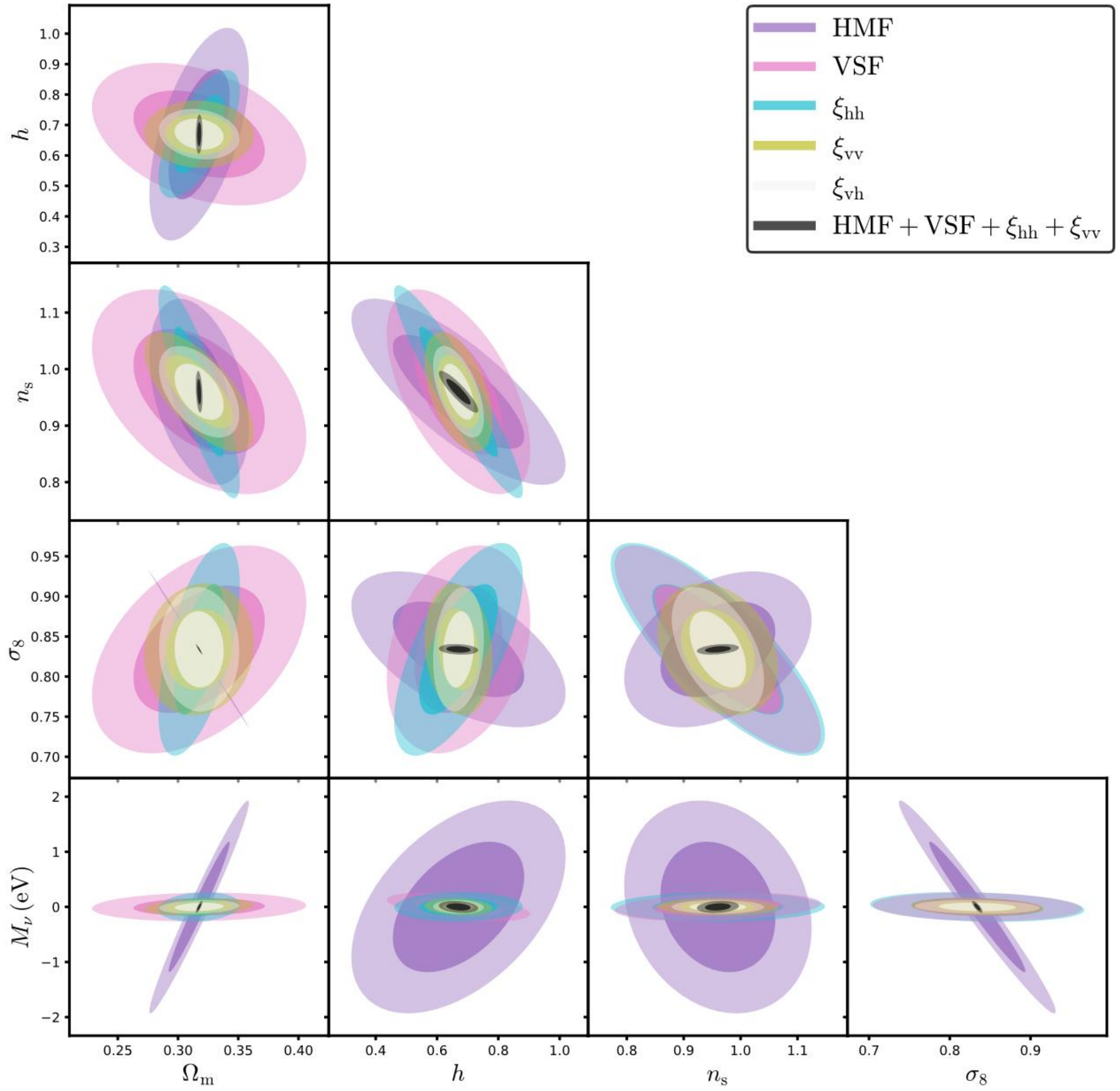


Euclid collaboration: Contarini, Verza et al. incl. Hamaus (A&A 2022)

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

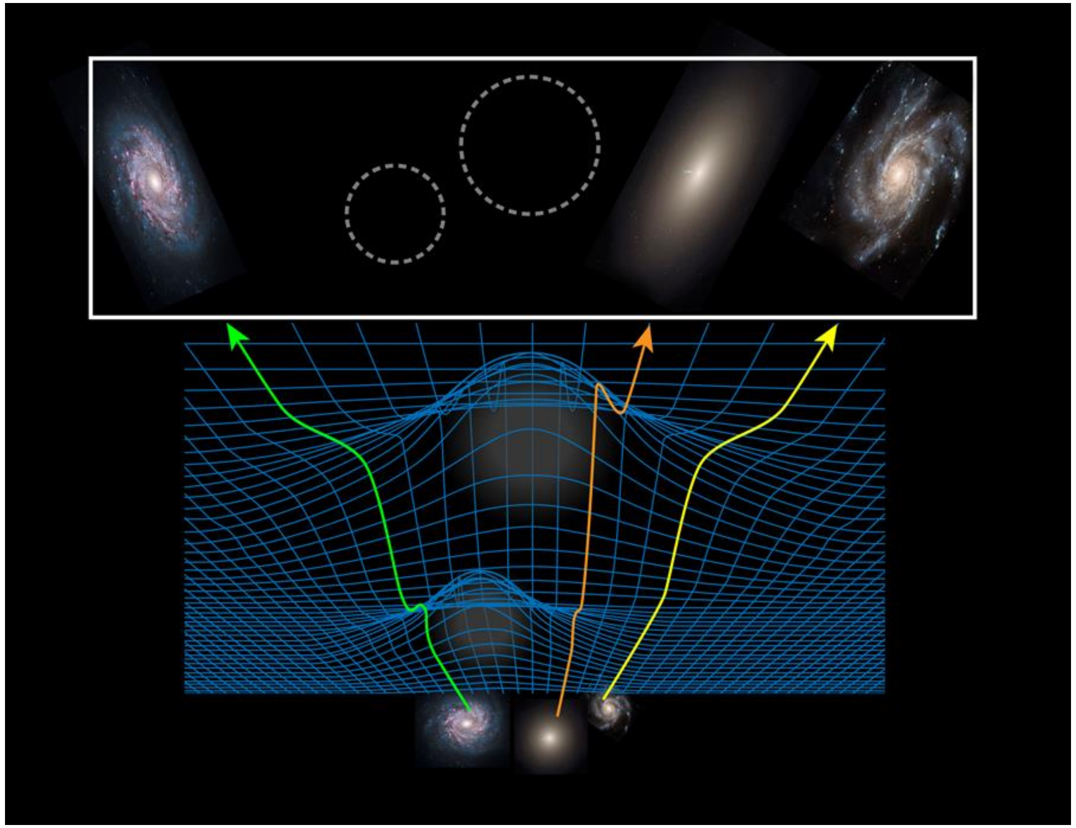


Christina Kreisch

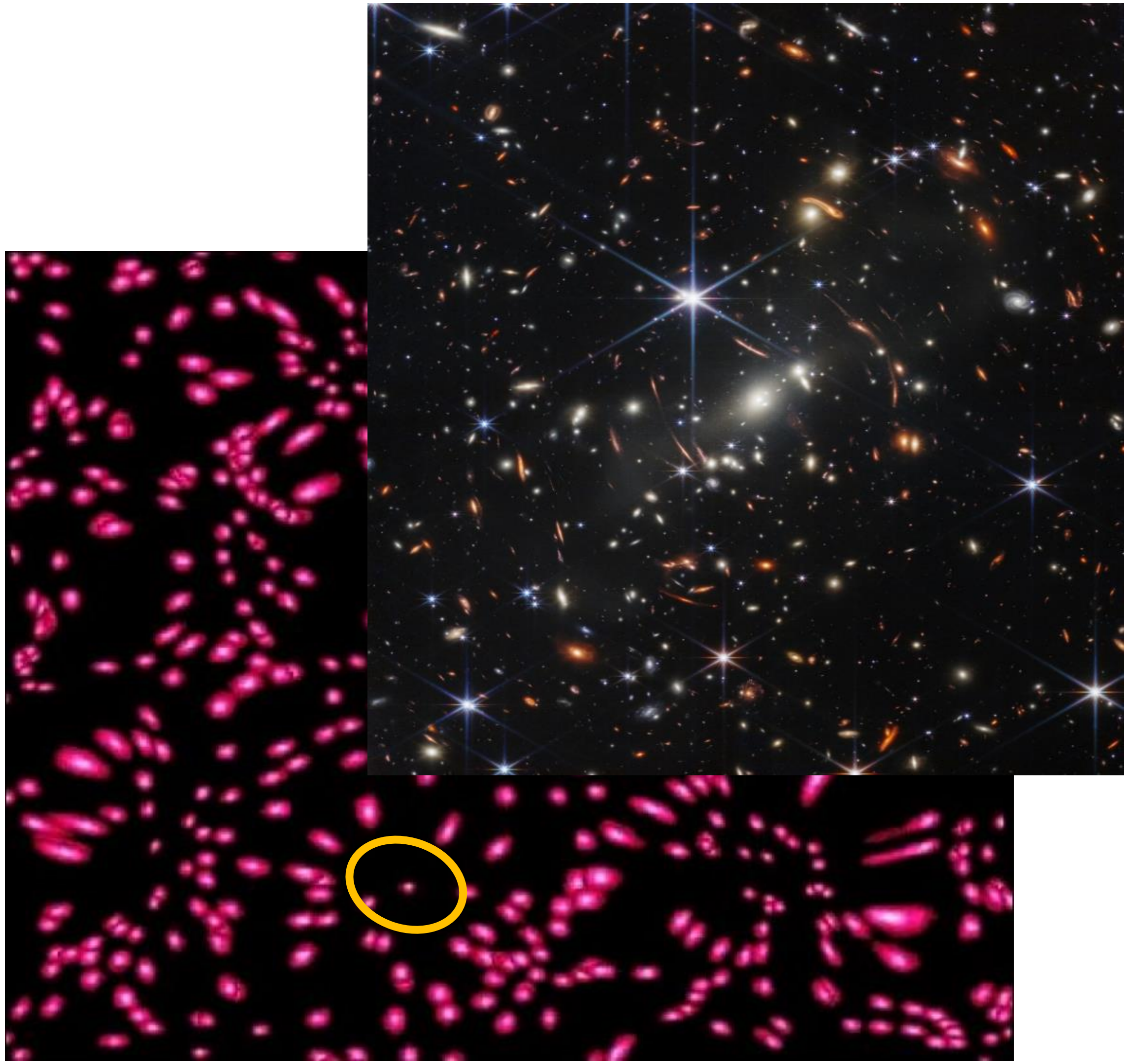


Kreisch et al. incl. Hamaus ([ApJ 2022]())

VOID LENSING



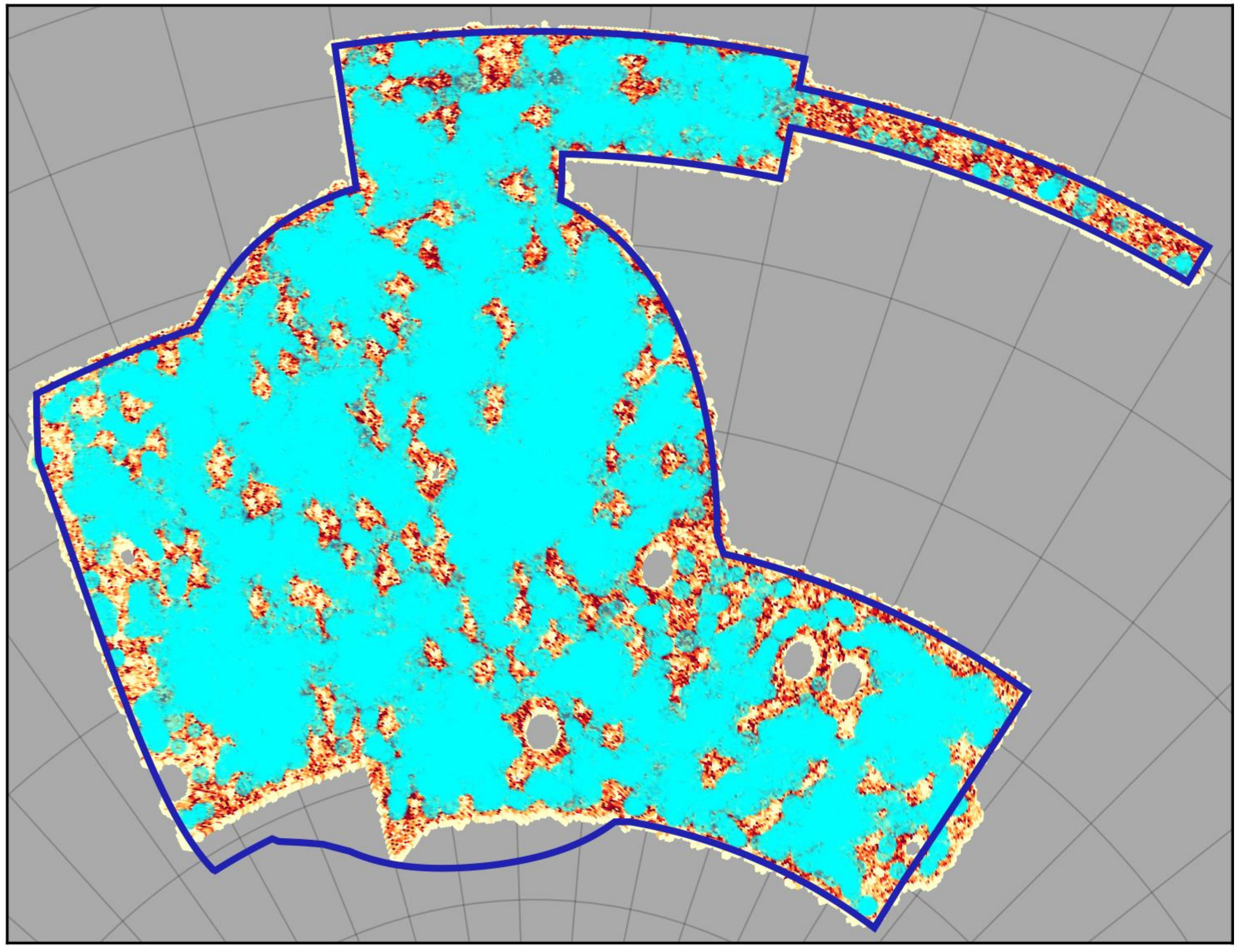
APS (Alan Stonebraker)

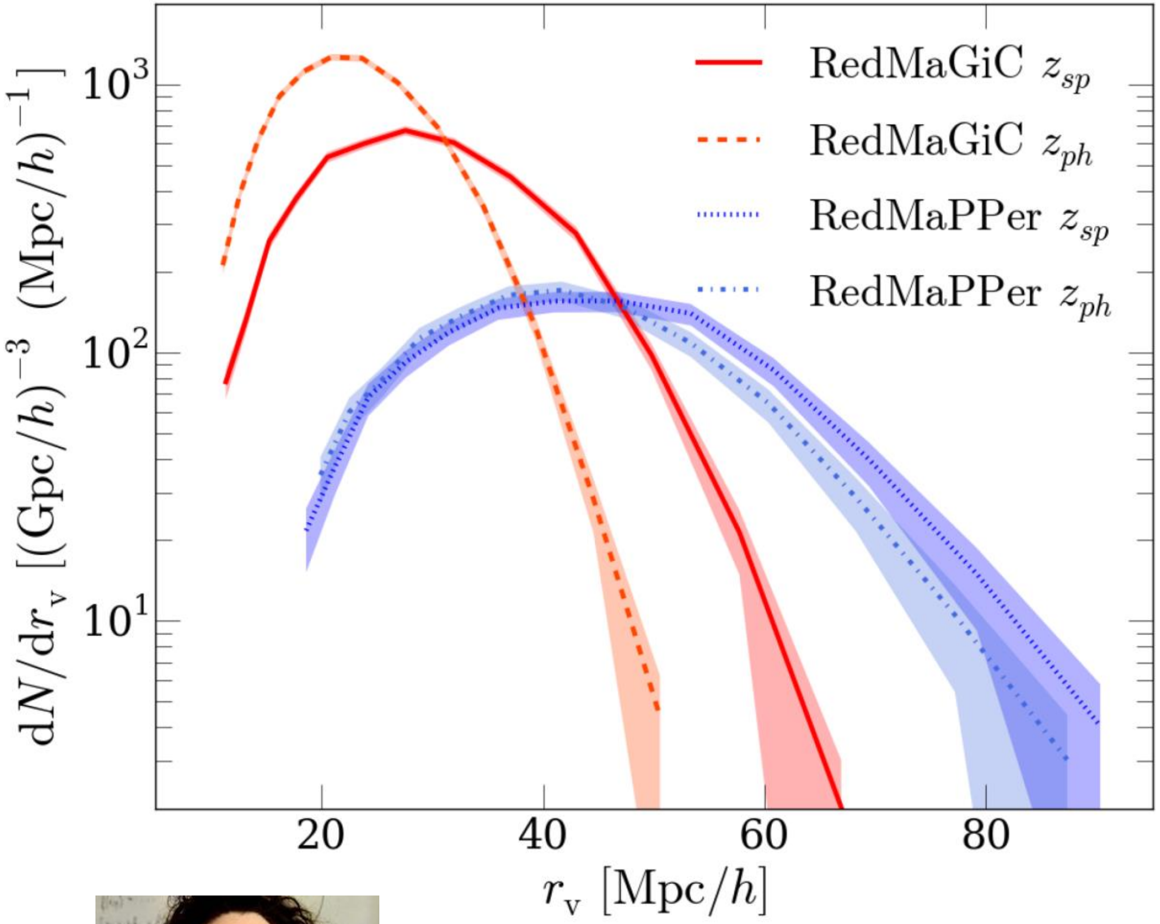


LSST (Rubin) / JWST (NASA)

Magnification and tangential shear

Voids in the Dark Energy Survey (DES)

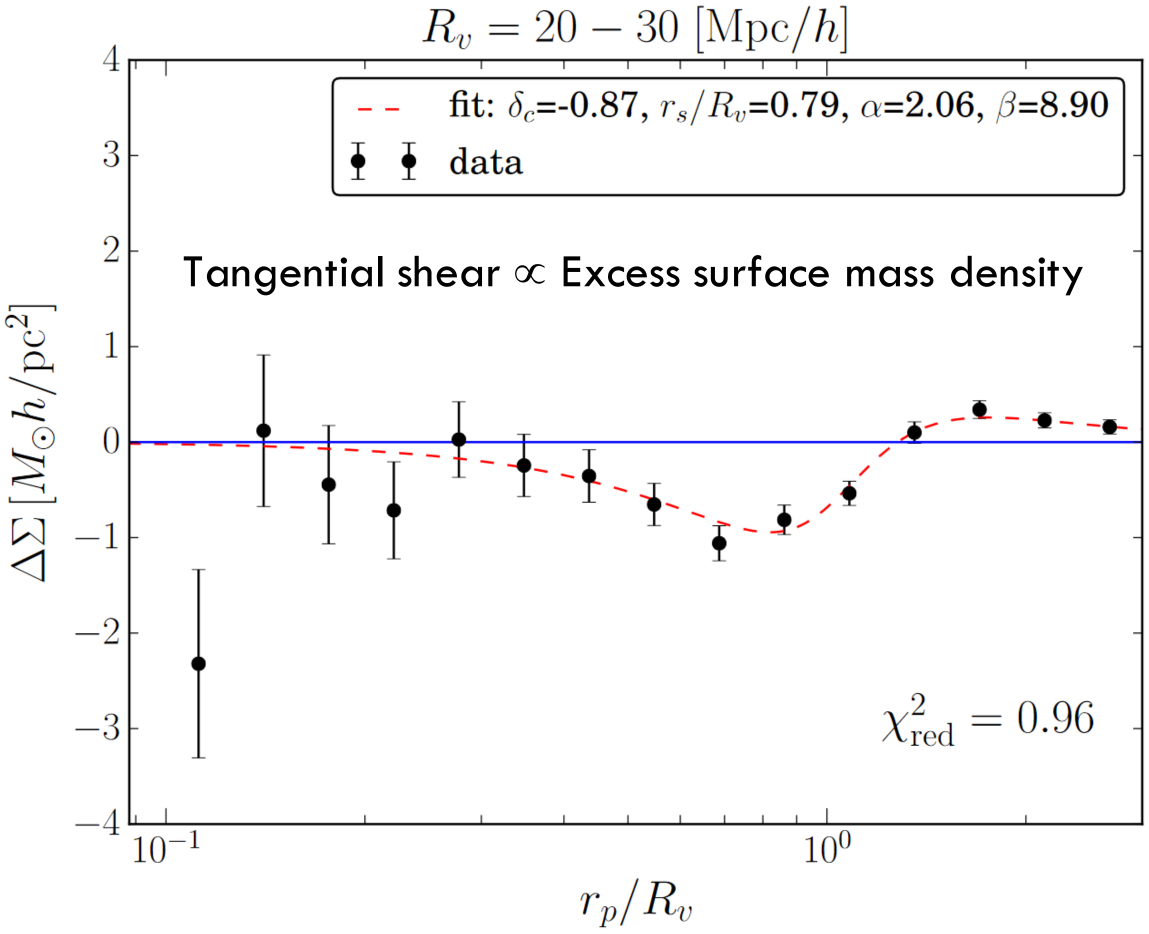




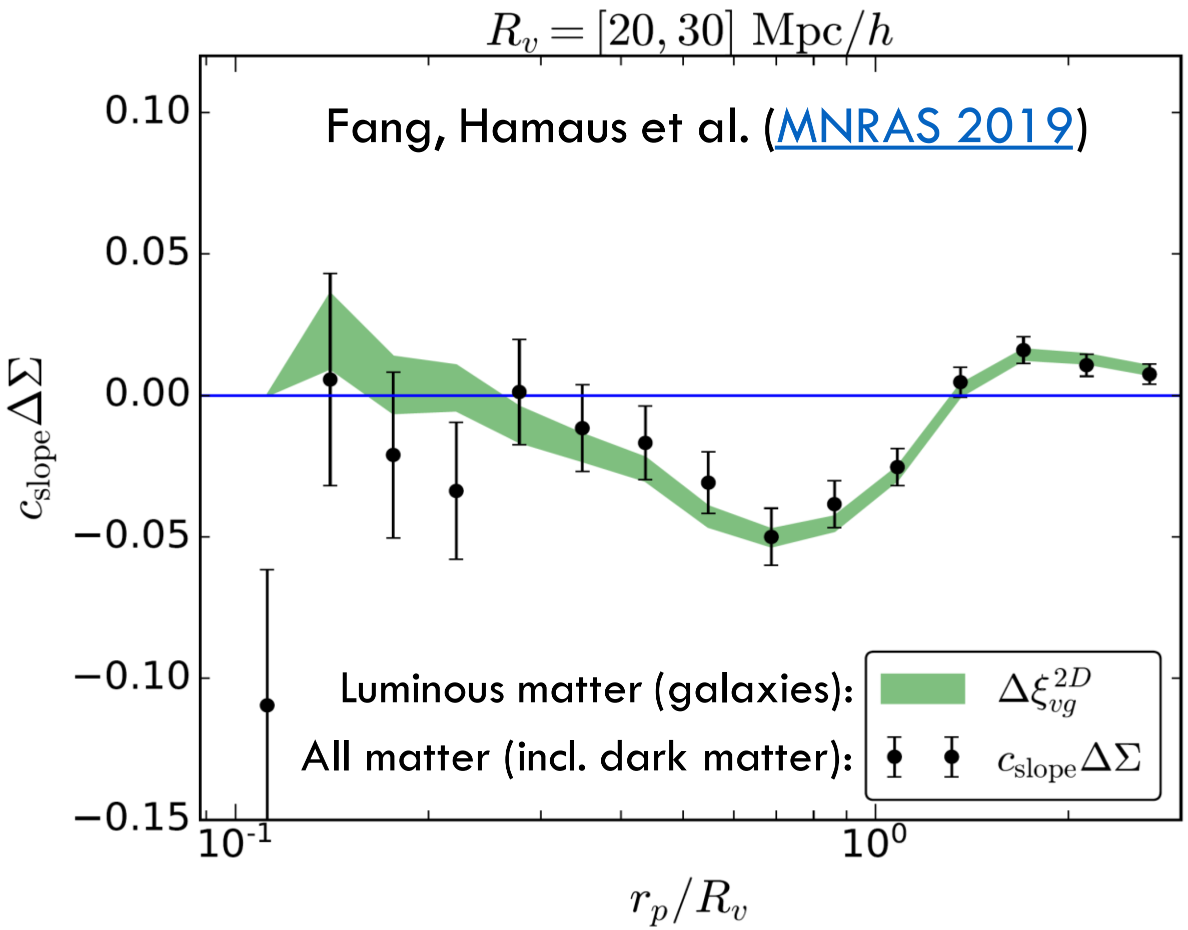
Pollina, Hamaus et al. (MNRAS 2019)

Giorgia Pollina

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



Tangential shear ∝ Excess surface mass density



Fang, Hamaus et al. (MNRAS 2019)

Luminous matter (galaxies): 🟩 $\Delta\xi^{2D}_{vg}$

All matter (incl. dark matter): ● $c_{\mathrm{slope}}\Delta\Sigma$

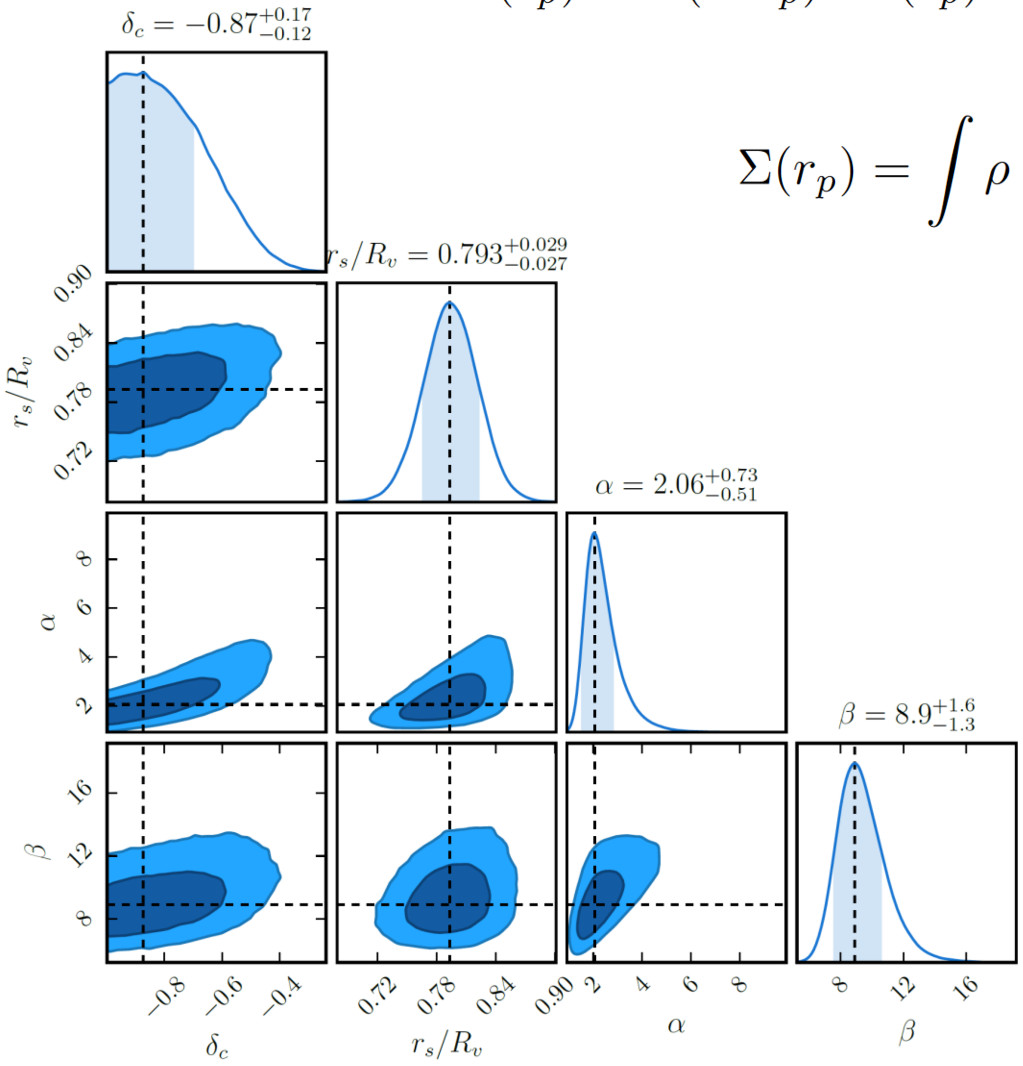
$$\left.\begin{array}{rl} \text{All matter (incl. dark matter):} & \Delta\Sigma(r_p) \equiv \bar{\Sigma}(<r_p) - \Sigma(r_p) \\ \text{Luminous matter (galaxies):} & \Delta\xi^{\mathrm{2D}}_{\mathrm{vg}}(r_p) \equiv \bar{\xi}^{\mathrm{2D}}_{\mathrm{vg}}(<r_p) - \xi^{\mathrm{2D}}_{\mathrm{vg}}(r_p) \end{array}\right\} \Rightarrow \Delta\xi^{\mathrm{2D}}_{\mathrm{vg}}(r_p) = \frac{b_{\mathrm{g}}}{\langle\Sigma_{\mathrm{m}}\rangle}\Delta\Sigma(r_p)$$

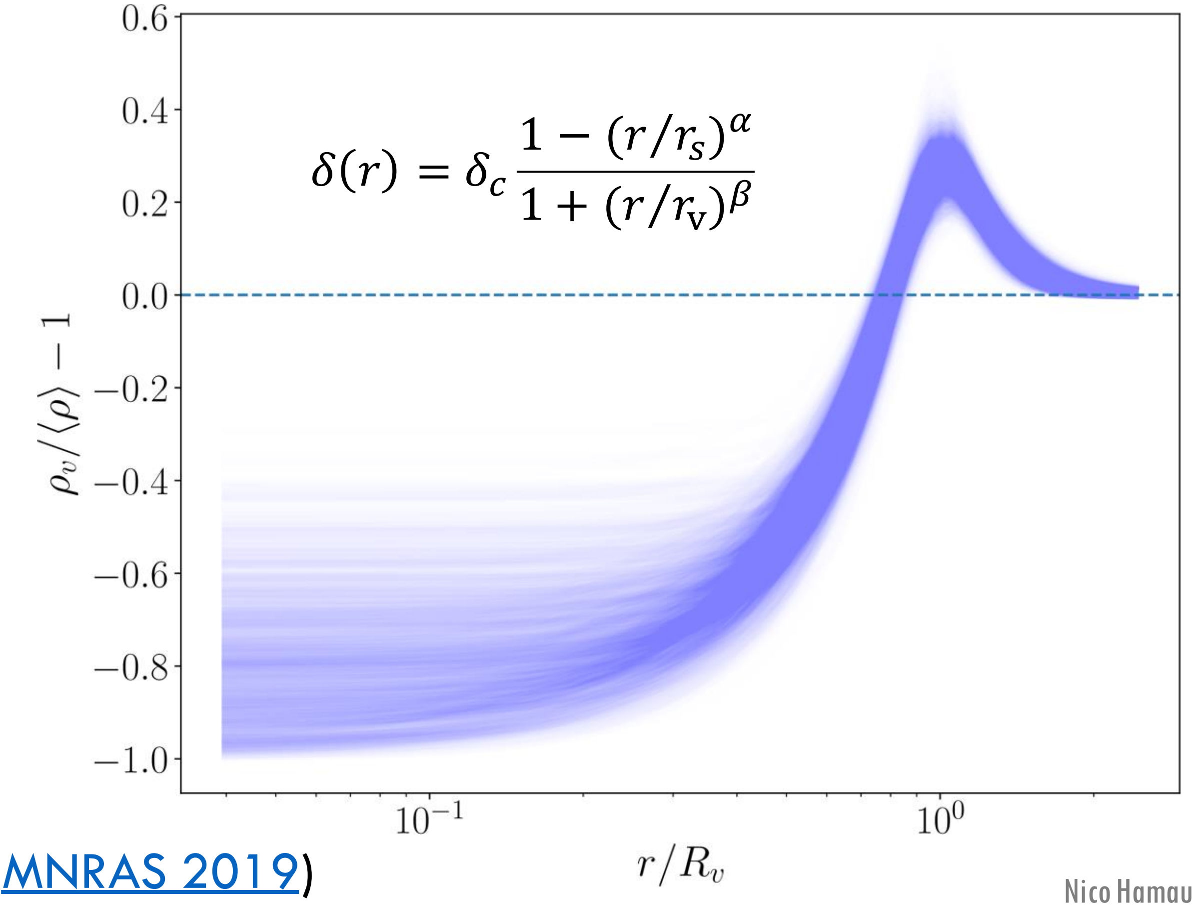
Voids in the Dark Energy Survey (DES) – Inferred (dark) matter density profile

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

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

Yuedong Fang

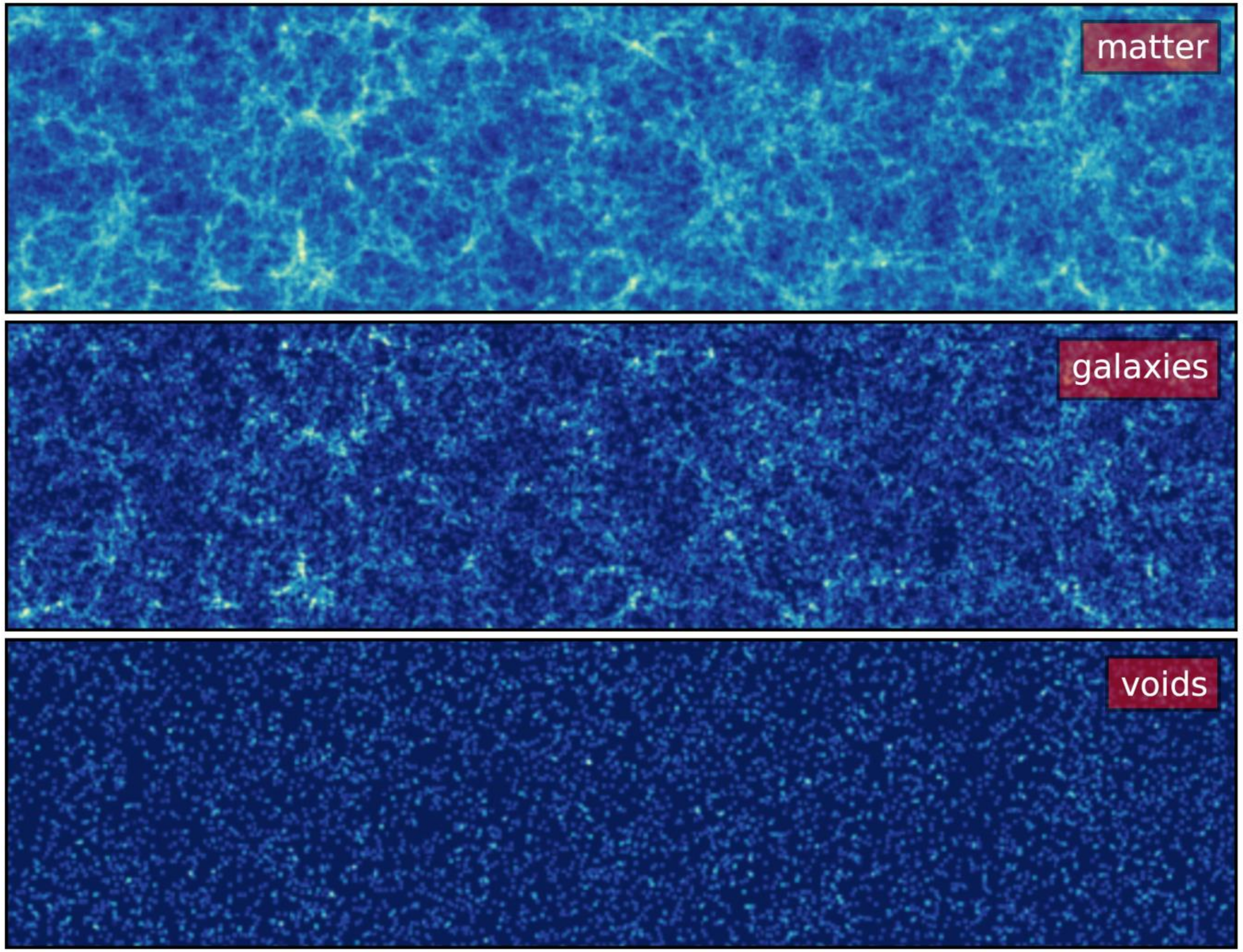




$$\delta(r) = \delta_c \frac{1 - (r/r_s)^\alpha}{1 + (r/r_{\rm v})^\beta}$$

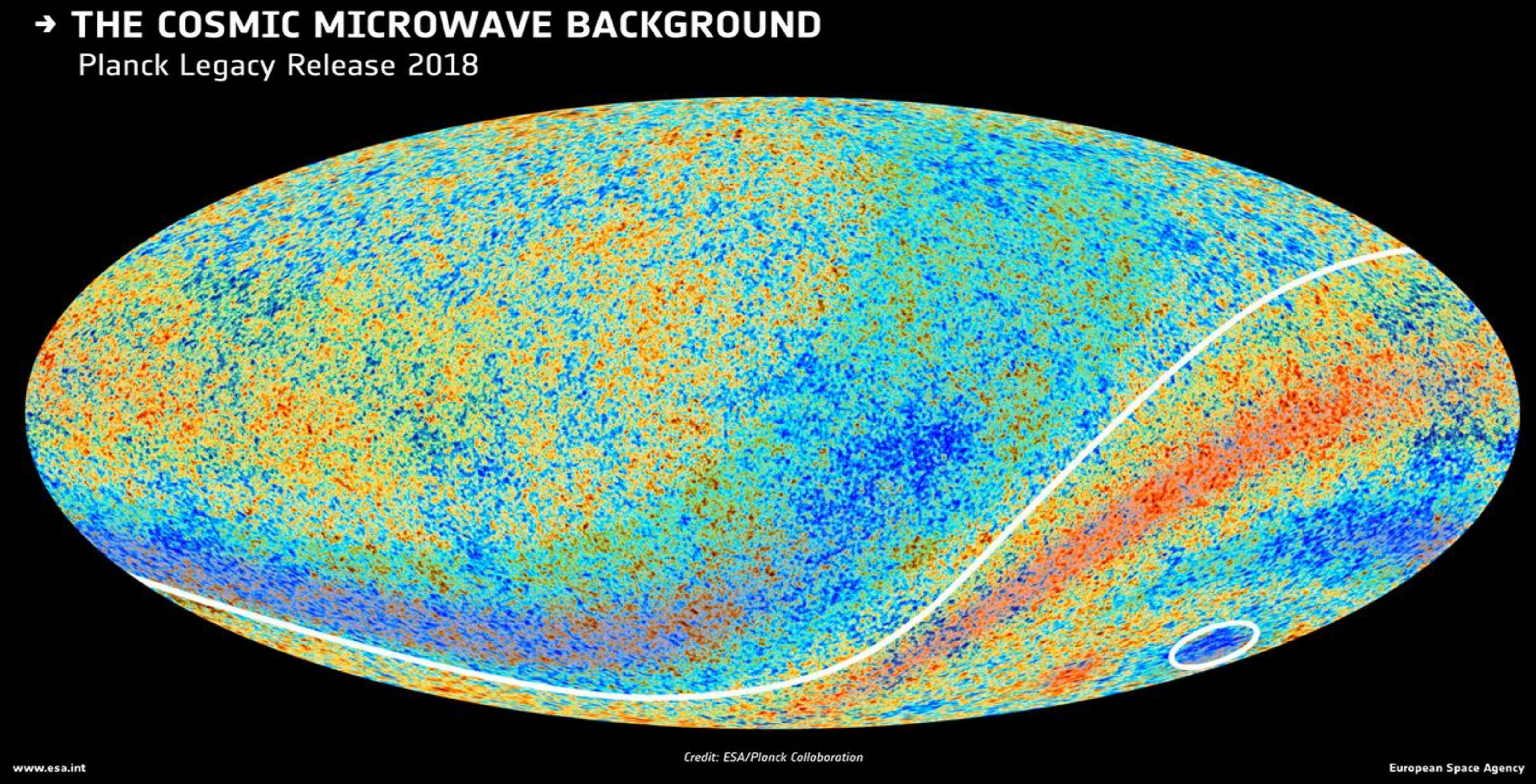
Fang, Hamaus et al. (MNRAS 2019)

VOID CLUSTERING



- Spatial distribution of voids beyond their own extent.
- Voids can be considered as tracers of the large-scale structure.
- Large scales retain information from the initial conditions

Gaussian initial conditions for structure formation?

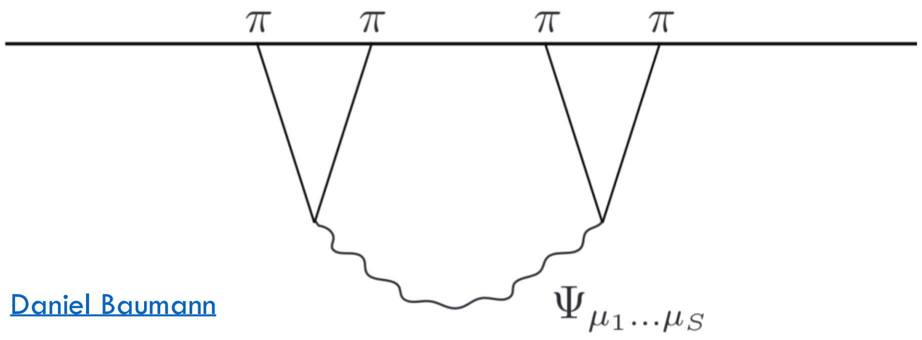


Credit: ESA/Planck Collaboration

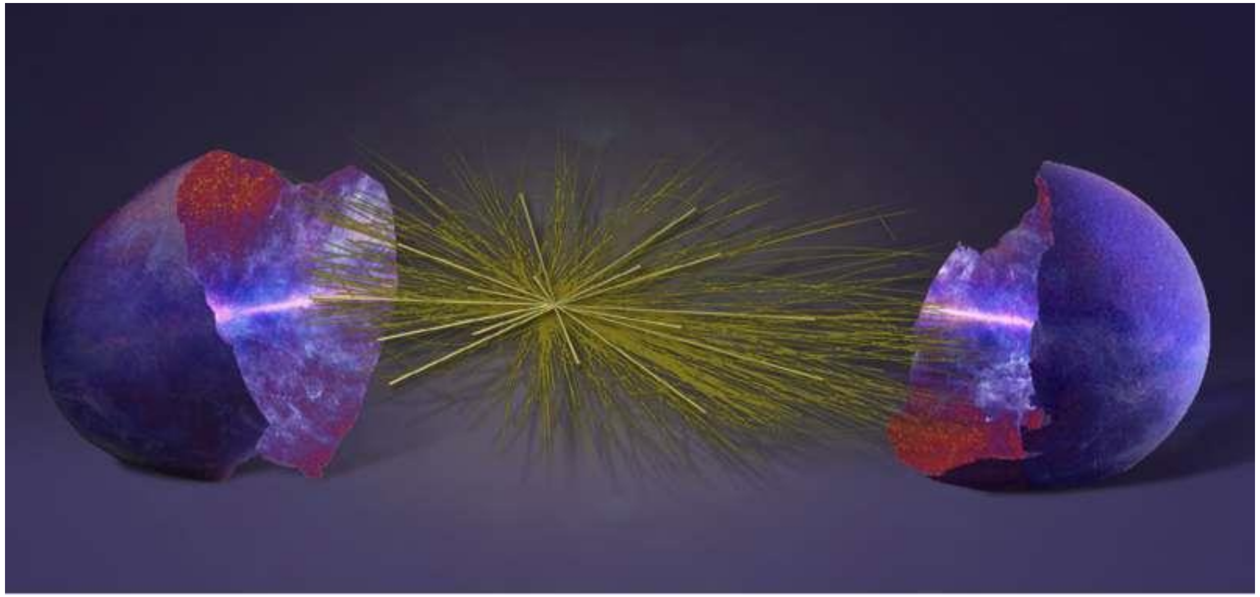
Primordial gravitational potential, expanded around Gaussian:

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

- f_{NL} measures degree of "**Primordial Non-Gaussianity**". Current best limit by Planck: $|f_{\mathrm{NL}}| < 5$
- A detection of $|f_{\mathrm{NL}}| > 1 - n_s \sim \mathcal{O}(10^{-2})$ could hint at **multiple fields** / **particles** interacting during early inflationary phase (in addition to the *inflaton*)
- "**Cosmological Collider Physics**" (Arkani-Hamed & Maldacena, arXiv 1503.08043)



Daniel Baumann



Paul Shellard

Power spectra with voids

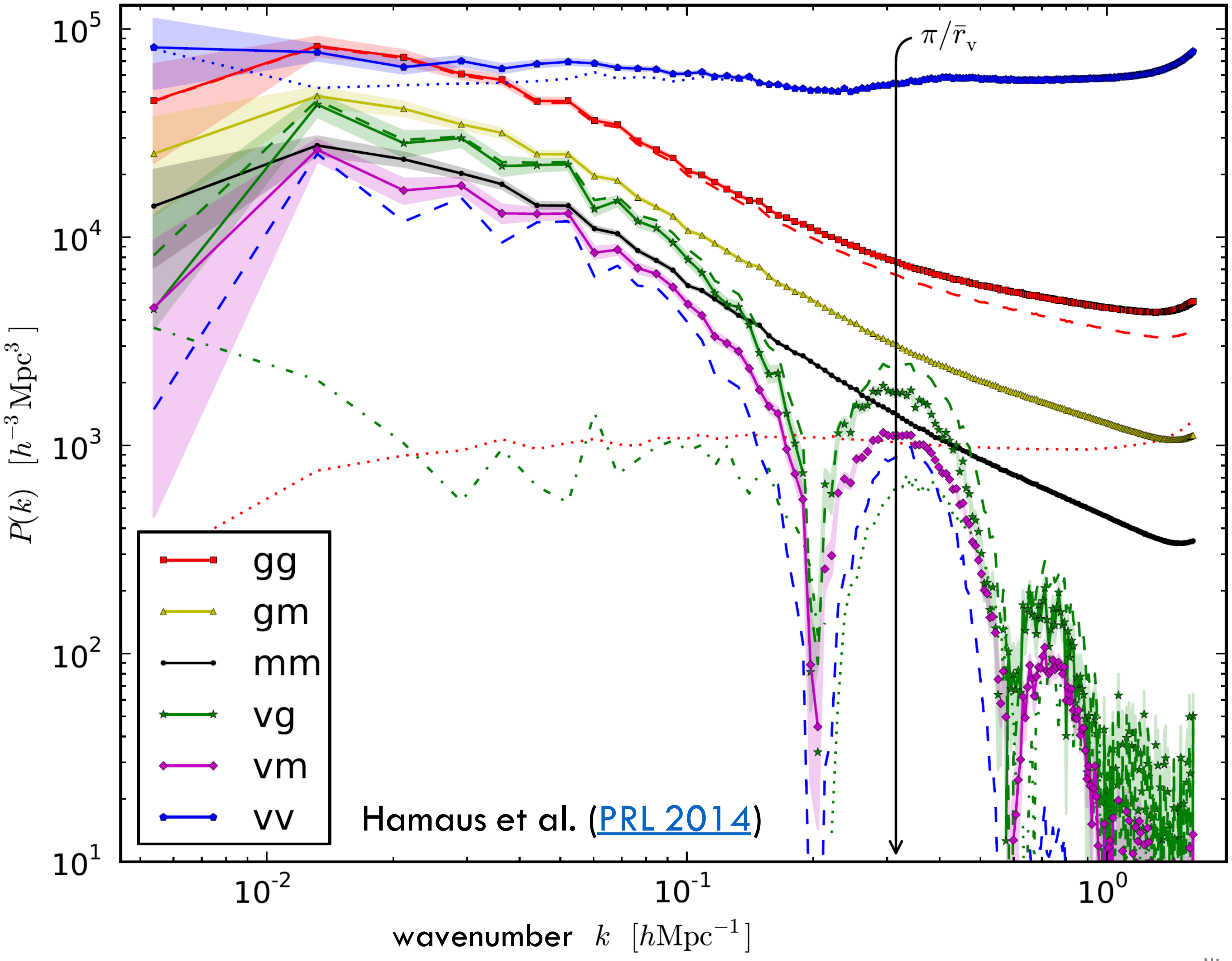
$$P_{xy}(k) = \langle \delta_x(\boldsymbol{k}) \delta_y^*(\boldsymbol{k}) \rangle$$
$$= \frac{1}{(2\pi)^3} \int \xi_{xy}(r) e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} \mathrm{d}^3 r$$

"2-point function" in Fourier space

Solid: Signal + Noise

Dotted: Shot Noise

Dashed: Signal



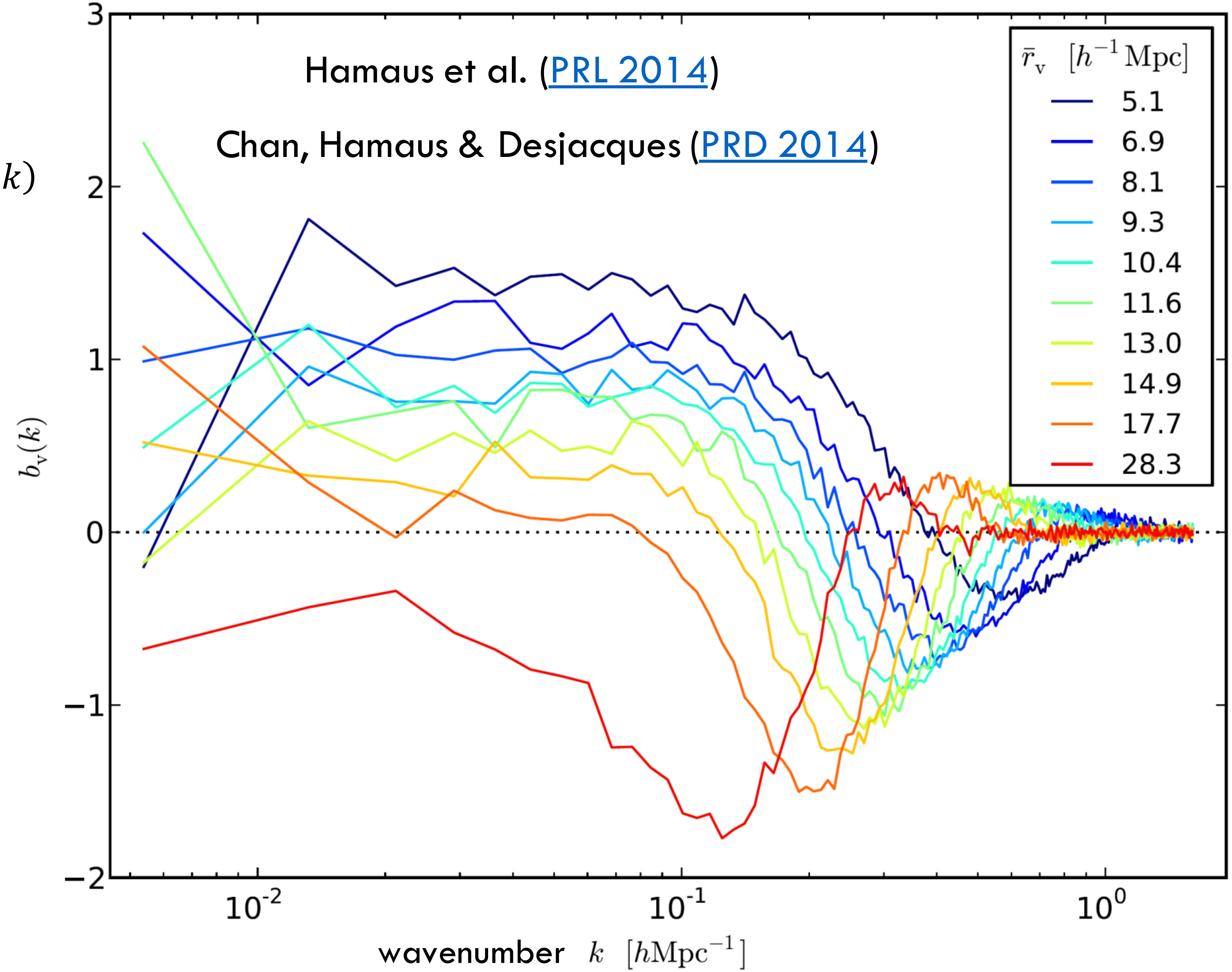
Hamaus et al. (PRL 2014)

Bias of voids

$$P_{\mathrm{vm}}(k) = \langle b_{\mathrm{v}} \delta(\boldsymbol{k}) \delta^*(\boldsymbol{k}) \rangle = b_{\mathrm{v}} P_{\mathrm{mm}}(k)$$

- ➢ Multiplies amplitude of density fluctuations

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


Hamaus et al. (PRL 2014)

Chan, Hamaus & Desjacques (PRD 2014)

Bias of voids with primordial non-Gaussianity

Primordial potential, expanded around Gaussian:

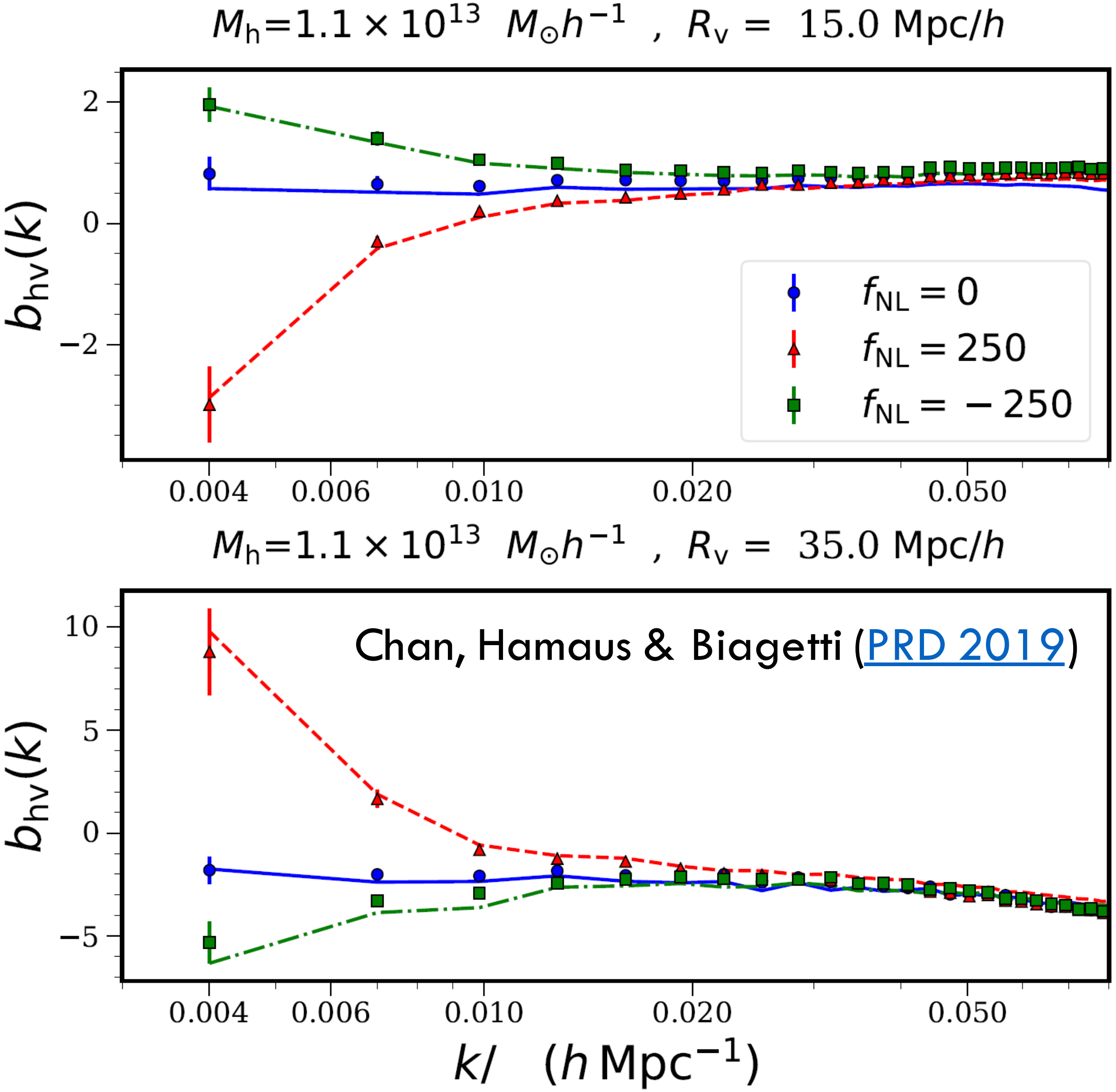
$$\Phi(\mathbf{x}) = \Phi_{\mathrm{G}}(\mathbf{x}) + f_{\mathrm{NL}}\left[\Phi_{\mathrm{G}}^2(\mathbf{x}) - \langle\Phi_{\mathrm{G}}^2\rangle\right]$$

Results in scale-dependent bias (Dalal et al. PRD 2008):

$$b(k, f_{\mathrm{NL}}) \approx b_{\mathrm{G}} + f_{\mathrm{NL}}(b_{\mathrm{G}} - 1)\delta_{\mathrm{c}}\frac{3\Omega_{\mathrm{m}}H_0^2}{k^2 T(k)D(z)}$$

Voids: exchange positive δ_{c} by **negative** δ_{v}

- Error on f_{NL} shrinks by up to factor of **2** incl. voids
- Recovers missing information from troughs in the initial random field

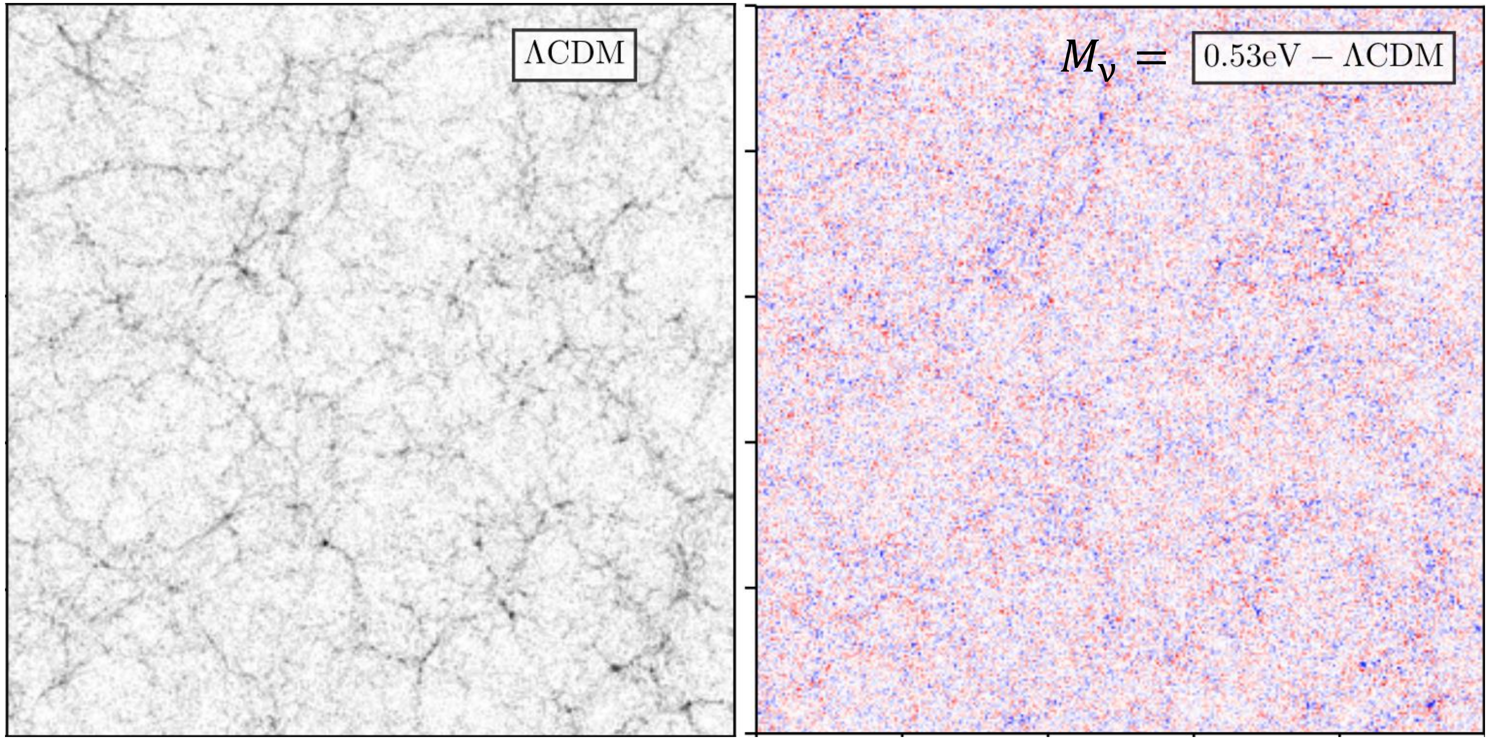


Chan, Hamaus & Biagetti (PRD 2019)

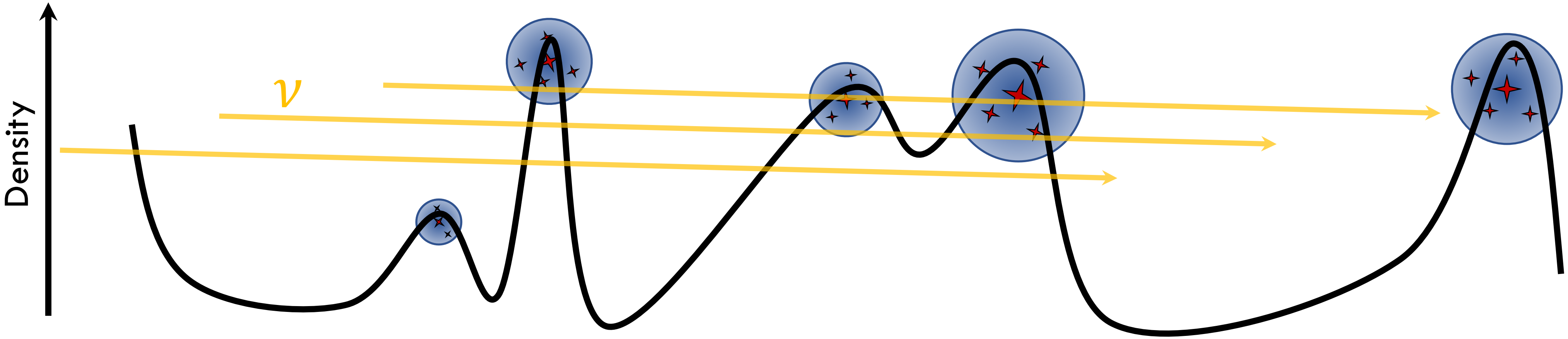
Voids in massive-neutrino cosmologies

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

- ➢ Effect depends on neutrino mass M_ν (sum over species)

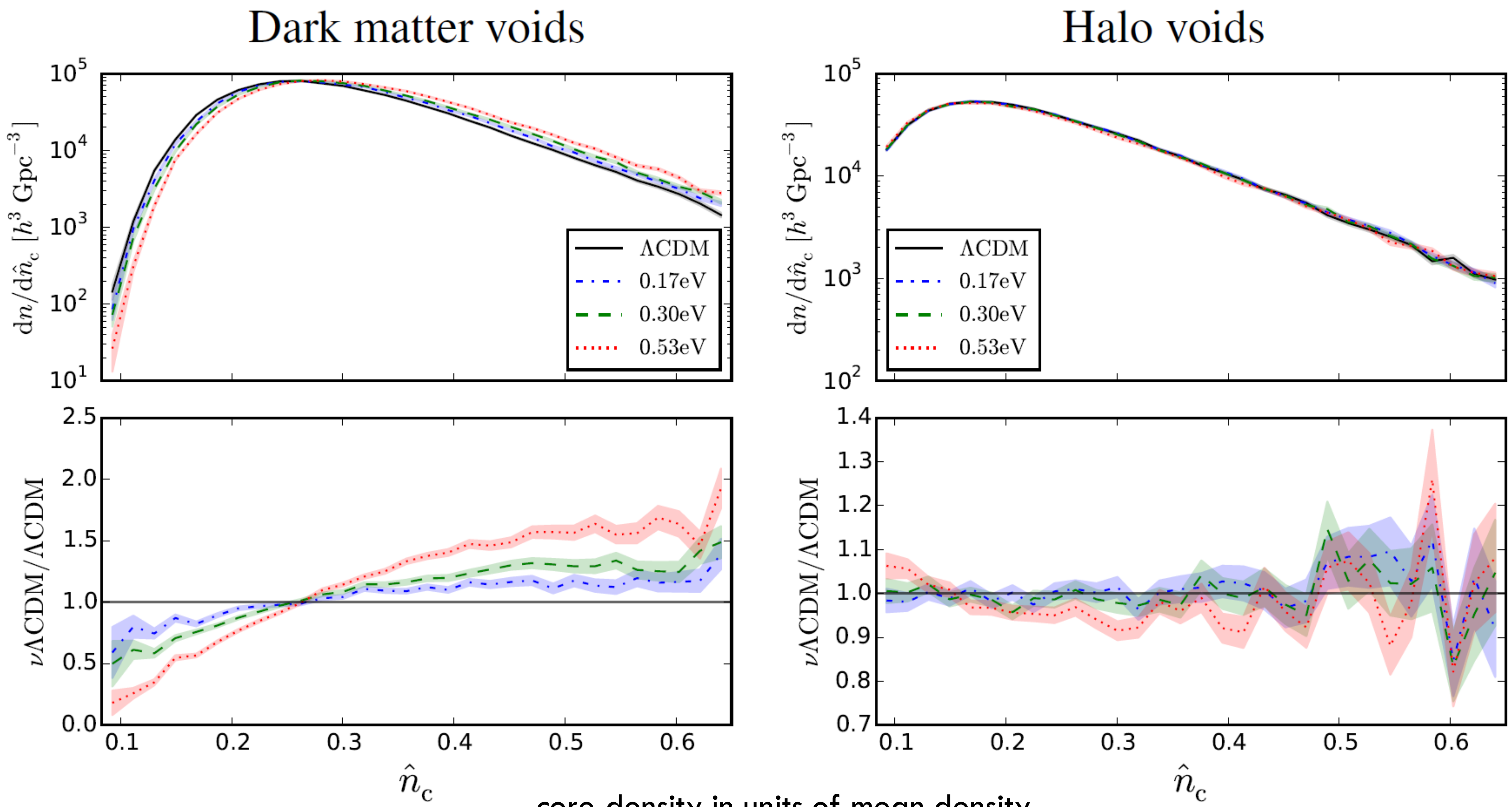


DEMNUni simulations, Carbone et al. (JCAP 2016)



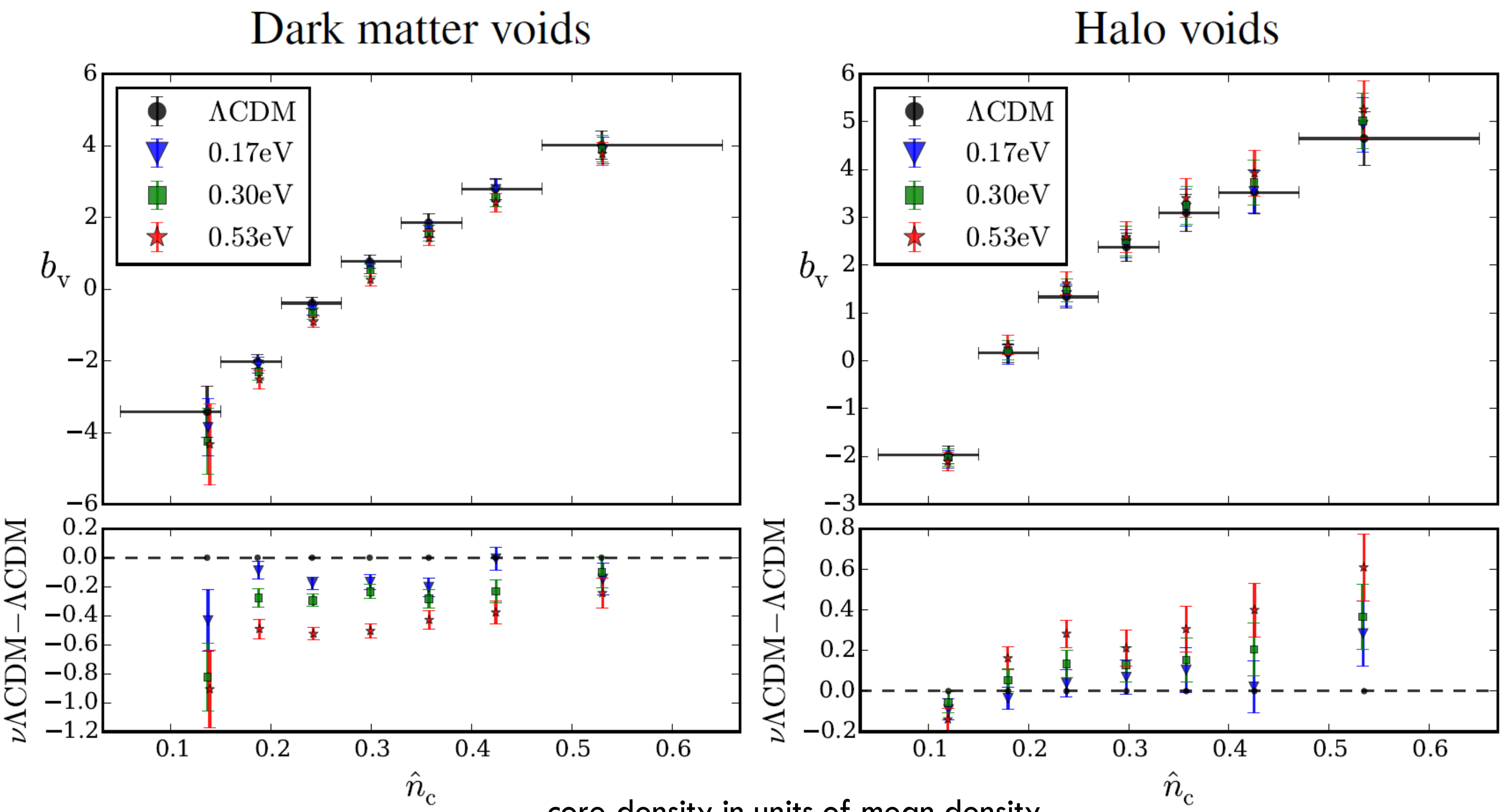
Nico Schuster

Voids in massive-neutrino cosmologies: **abundance** (Schuster, Hamaus et al., JCAP 2019)



core density in units of mean density

Voids in massive-neutrino cosmologies: **bias** (Schuster, Hamaus et al., JCAP 2019)



core density in units of mean density

CONCLUSIONS

- ***Geometric distortions*** of voids measure $D_\mathrm{A}H(z)$ with sub-percent accuracy, constraining ***dark energy***
- ***Dynamic distortions*** of voids additionally provide $\beta(z) = f(z)/b(z)$, facilitating ***tests of gravity***
- ***Gravitational lensing*** can be used to infer the ***dark matter*** density profile of voids
- ***Void clustering*** may reveal insights on the physics of **inflation** (f_NL) and **massive neutrinos** (M_ν)
- DESI, Euclid, PFS, Roman, Rubin, SPHEREx… will each provide at least $\boldsymbol{\mathcal{O}(10^5)}$ **voids** (for free).

We live in the age of exploration for voids!

Waldseemüller (1508)