Cosmology with cosmic void statistics in galaxy surveys

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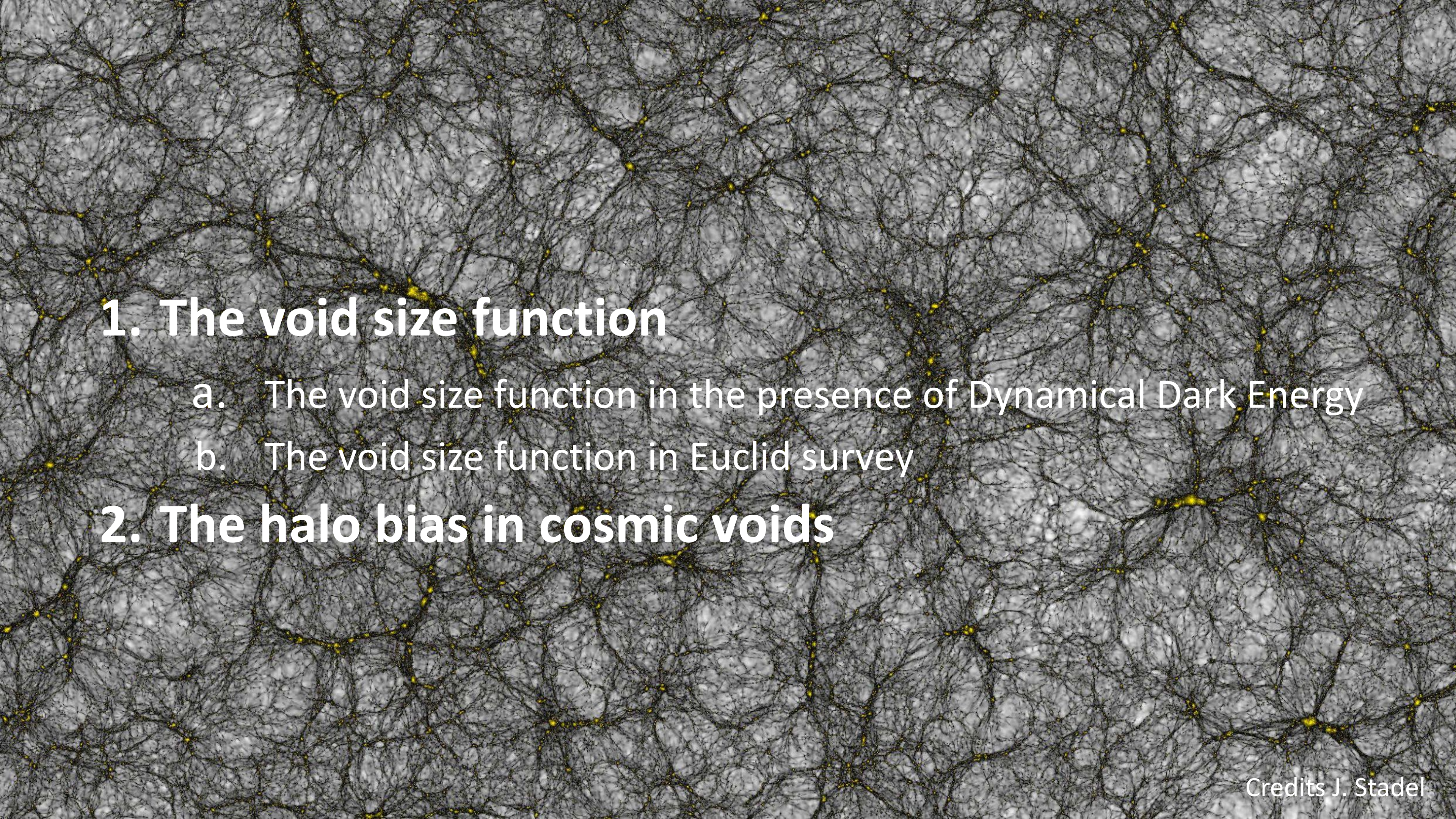


1. **The void size function**
    a. The void size function in the presence of Dynamical Dark Energy
    b. The void size function in Euclid survey
2. **The halo bias in cosmic voids**

Credits J. Stadel

Cosmic voids ID & features

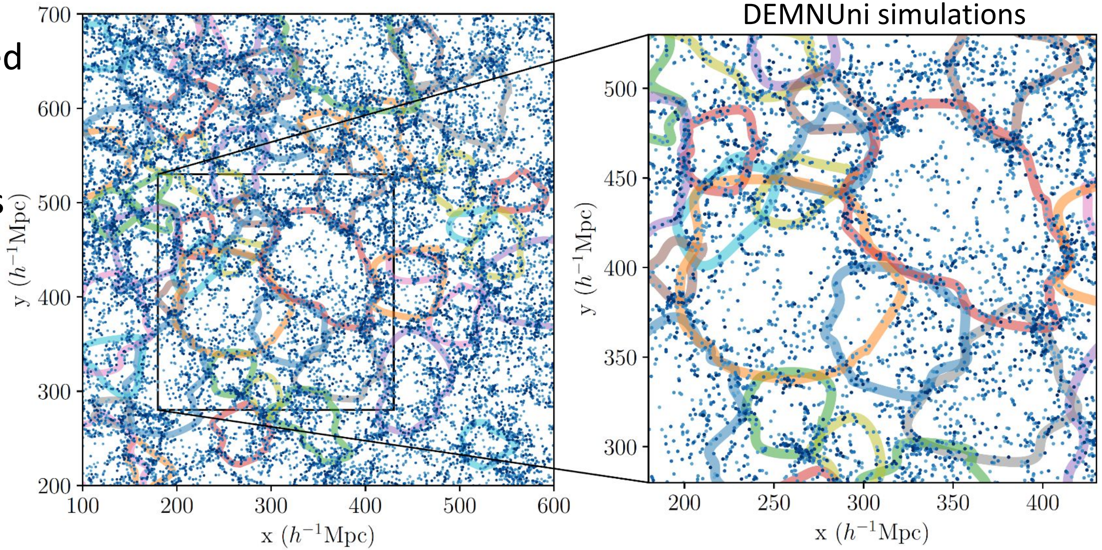
- Under-dense regions
- They span a large range of scales and are the largest observable structures in the cosmic web (from tens to hundreds of Mpc)

○ Suited to study dark energy and modified gravity, massive neutrinos, primordial non-Gaussianity, etc.

○ From linear to mildly non-linear regimes (do not experience shell-crossing, virialization, collapse...)

○ Studying voids requires redshift surveys with very large volume e.g. Euclid, Roman, SphereX, PFS, DES, DESI, Vera Rubin Observatory, BOSS

A void snapshot from the DEMNUni simulations



GV et al., 2019
JCAP12(2019)040

The void size function

$$\frac{\mathrm{d}n(M)}{\mathrm{d}M} = \frac{\rho}{M} f(\sigma, \delta_{\mathrm{v}}, \delta_{\mathrm{c}}) \frac{\mathrm{d}\sigma}{\mathrm{d}M}$$

- Number density
- The multiplicity function:
  fraction of fluctuations that first reach the linear threshold for void formation, δ_v, without having reached the threshold of halo collapse, δ_c, at larger scales
- Jacobian: from σ to mass interval

From Lagrangian to Eulerian space:

$$\frac{\mathrm{d}n_{\mathrm{L}}}{\mathrm{d}R_{\mathrm{L}}} = \frac{f(\sigma, \delta_{\mathrm{v}}, \delta_{\mathrm{c}})}{V(R_{\mathrm{L}})} \frac{\mathrm{d}\sigma}{\mathrm{d}R_{\mathrm{L}}}$$

Void expansion

$$R = (1 + \delta_{\mathrm{v}}^{\mathrm{NL}})^{-1/3} R_{\mathrm{L}}$$

$$\frac{\mathrm{d}n}{\mathrm{d}R} = \frac{f(\sigma, \delta_{\mathrm{v}}, \delta_{\mathrm{c}})}{V(R)} \frac{\mathrm{d}\sigma}{\mathrm{d}R_{\mathrm{L}}}\Big|_{R_{\mathrm{L}}=R(R_{\mathrm{L}})}$$

volume conserving model

$$\mathrm{d}n(R)V(R) = \mathrm{d}n(R_{\mathrm{L}})V(R_{\mathrm{L}})|_{R_{\mathrm{L}}=R(R_{\mathrm{L}})}$$

Sheth & Van de Weygaert 2004
Jennings et al. 2013

The void size function in the presence of Dynamical Dark Energy

Based on **GV**, Pisani, Carbone, Hamaus, and Guzzo 2019, The Void Size Function in Dynamical Dark Energy Cosmologies, JCAP12(2019)040

"Dark Energy and Massive Neutrino Universe" (DEMNUni) set of simulations (Carbone et al. 2016)

- Simulation box: Vol. $(2h^{-1}\text{Gpc})^3$, 2048^3 dark matter part., $M = 8 \times 10^{10} h^{-1} M_\odot$
- 2048^3 neutrino particles: $\sum m_\nu = 0, 0.16, 0.32\,\text{eV}$ for each EoS

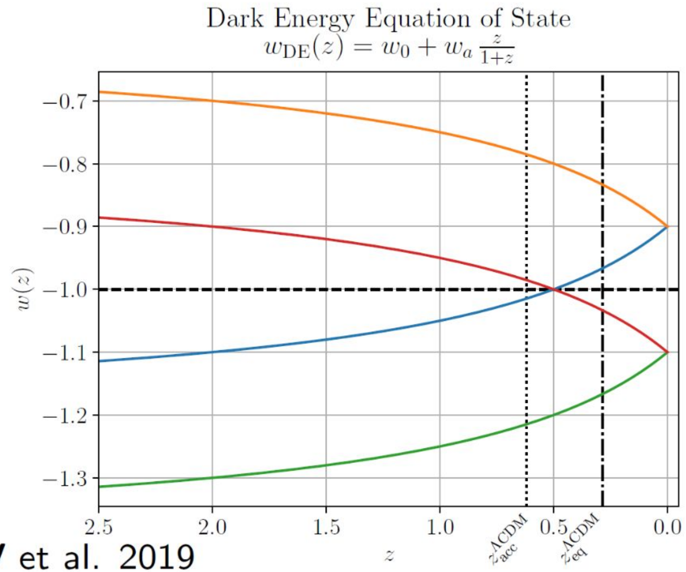
- Dark energy equation of state (EoS)

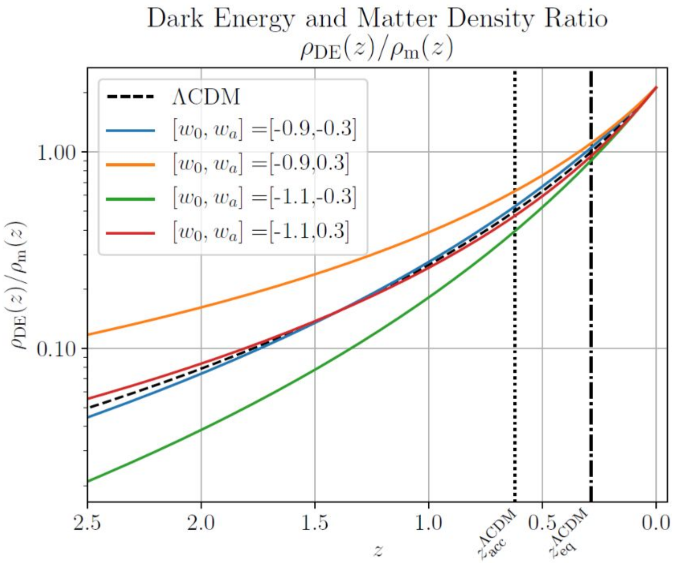
  Chevallier-Polarski-Linder (CPL) parametrisation:

  $$w(a) = w_0 + w_a(1-a)$$

  $w_0 = -1;\ w_a = 0$ (ΛCDM)

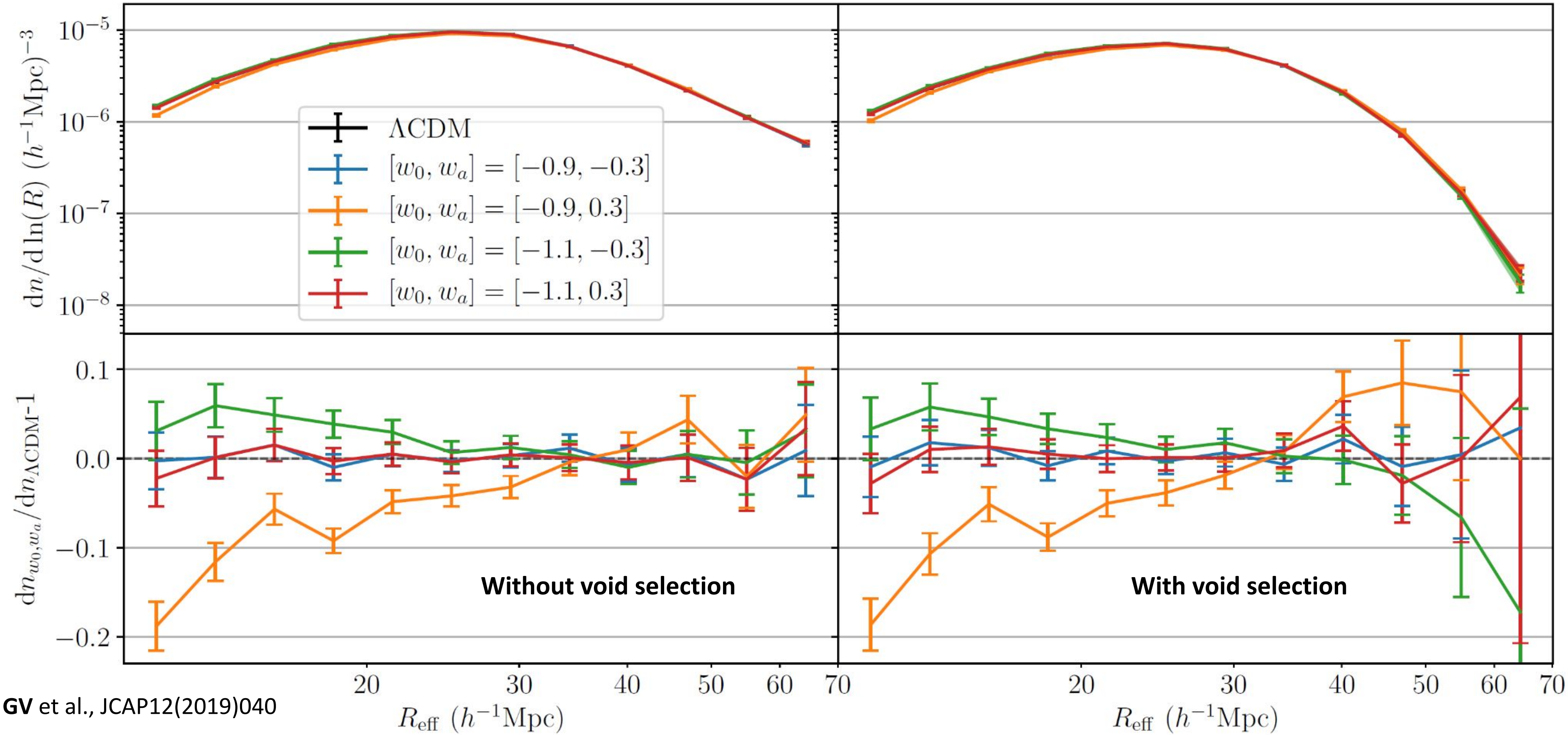
  $w_0 = -0.9, -1.1;\ w_a = -0.3, 0.3$





GV et al. 2019

Void abundances in the DEMNUni simulations



GV et al., JCAP12(2019)040

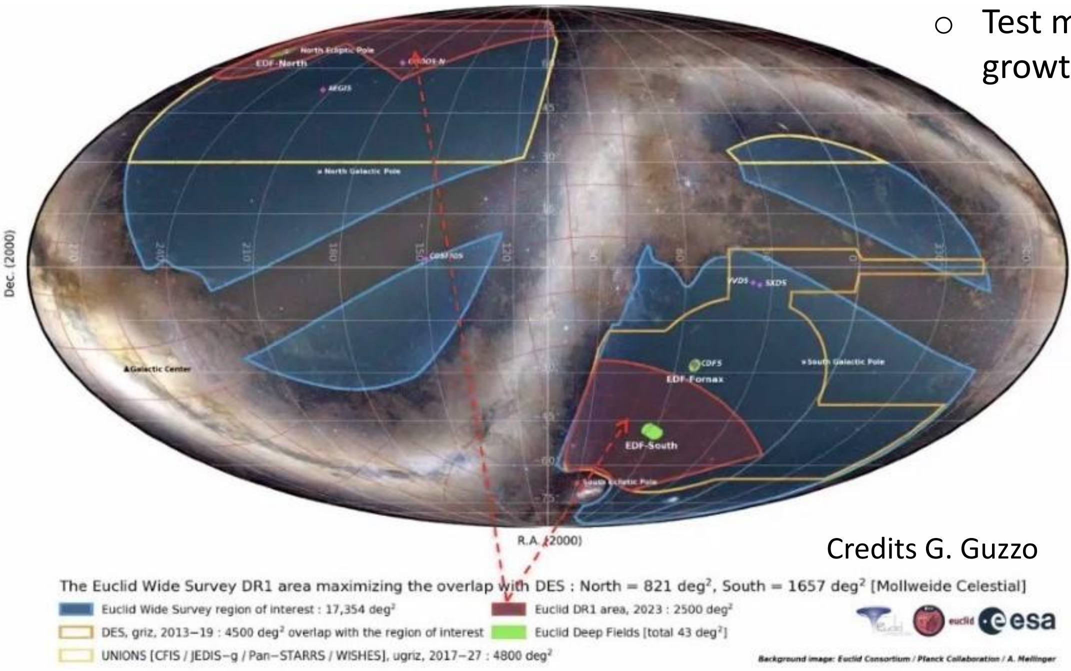
The void size function in Euclid survey

Based on Contarini, **GV**, Pisani, Hamaus, et al. 2022, Euclid: Cosmological forecasts from the void size function, A&A, Forthcoming article

The Euclid mission

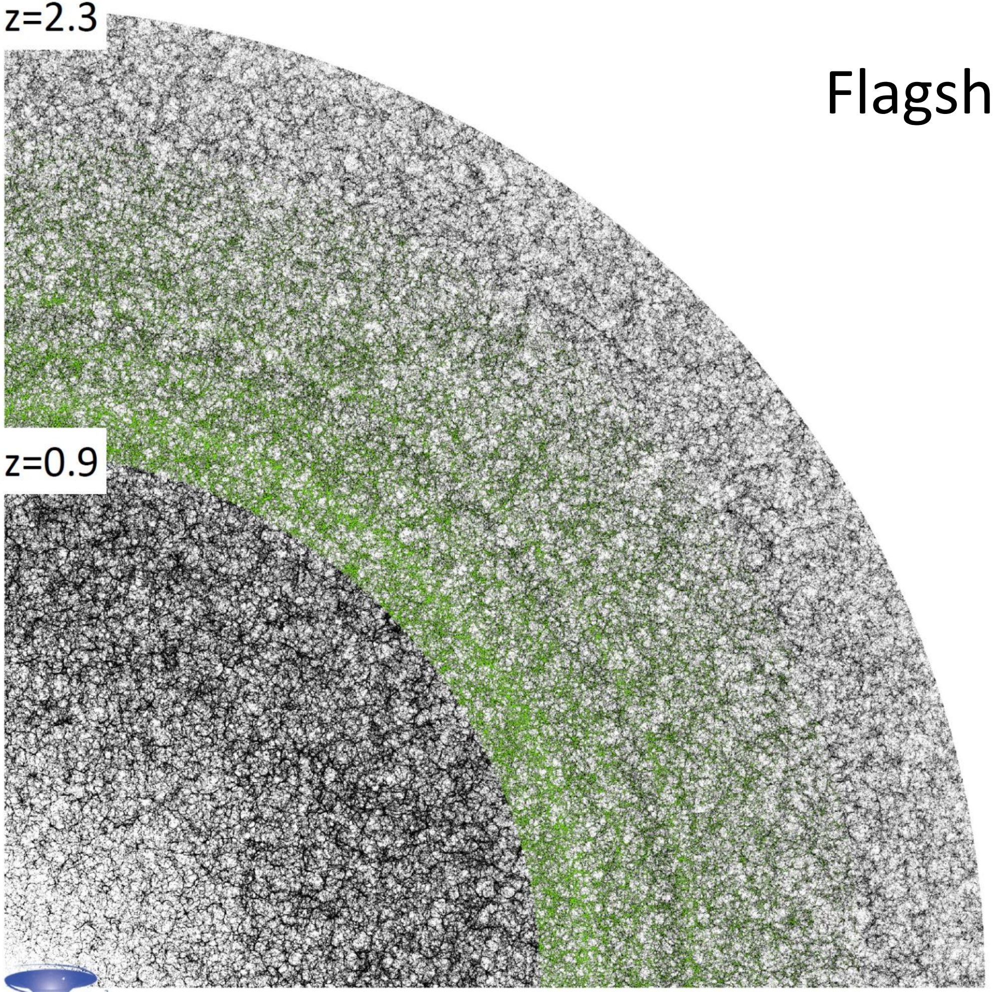
- ESA space mission, launch of satellite in 2023
- Foreseen duration of the mission: 6 years
- Euclid will probe the last 10 billion years of Universe expansion history

- The mission will observe 15 000 deg^2 (~36%) of the sky
- Scientific objectives:
  - Nature of dark energy and dark matter
  - Measure neutrino mass scale
  - Test modified gravity theories by growth of structures



Credits G. Guzzo

Flagship simulation and lightcone



Credits B. Granett

Simulation box:

- $(3780\ h^{-1}\mathrm{Mpc})^3$, 2×10^{12} DM part, M_p=$2.4{\times}10^9 M_\odot$
- ΛCDM - Plack baseline cosmology

Simulated data used:

- Lightcone: z from 0.9 to 1.8 in one octant
- Galaxy properties by HOD
- 60% of completeness simulated: $6.5{\times}10^6$ galaxies.

The void size function

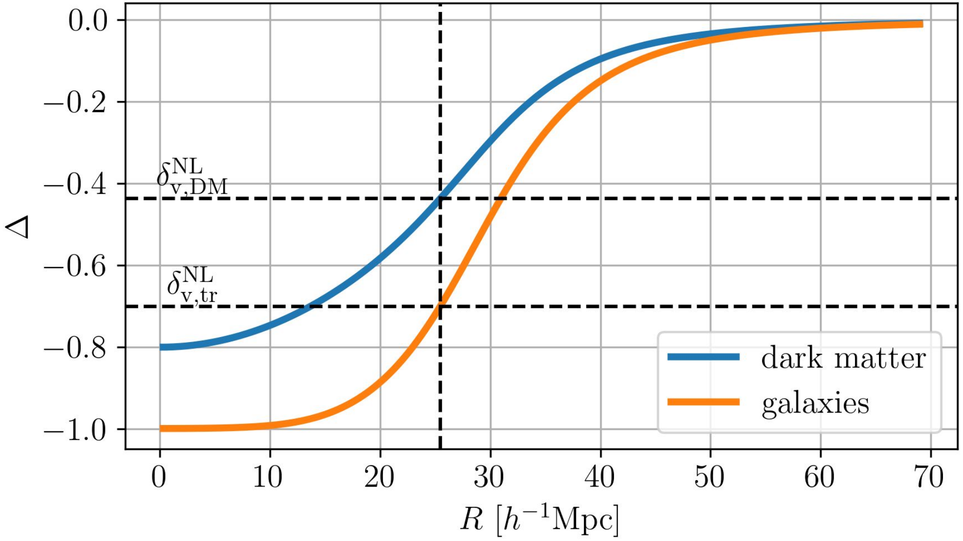
$$\frac{\mathrm{d}n(R)}{\mathrm{d}\ln R} = \frac{f(\ln\sigma, \delta_\mathrm{v}, \delta_\mathrm{c})}{V(R)} \left.\frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}R_\mathrm{L}}\right|_{R_\mathrm{L}=R_\mathrm{L}(R)}$$

Sheth & Van de Weygaert 2004
Jennings et al. 2013

Watershed voids from the void finder

↕

Spherical fluctuations in the matter field with fixed density contrast.

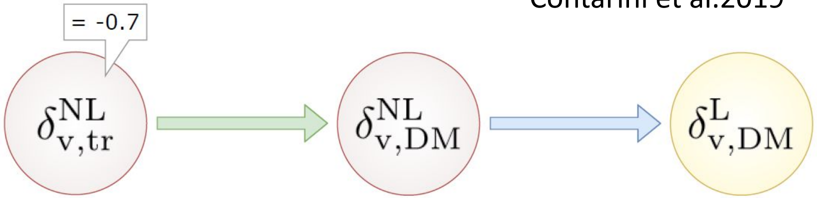


We assume a linear bias relation:

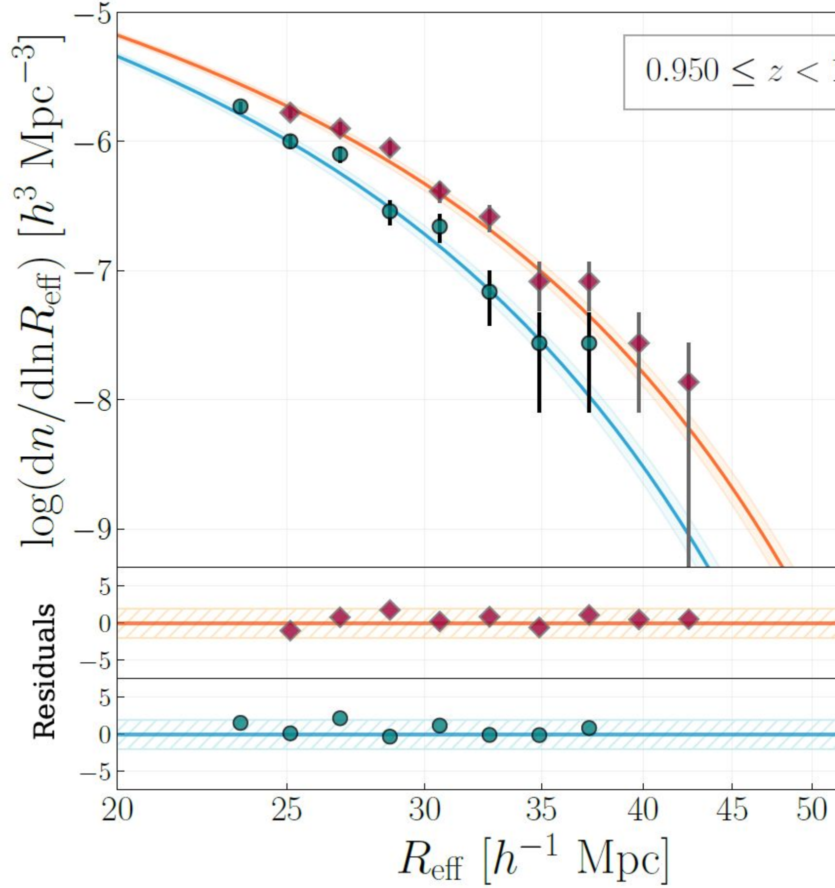
$$\delta^{\mathrm{NL}}_{\mathrm{v,g}} = \mathcal{F}(b_\mathrm{eff})\delta^{\mathrm{NL}}_{\mathrm{v,m}}$$

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

Contarini et al.2019

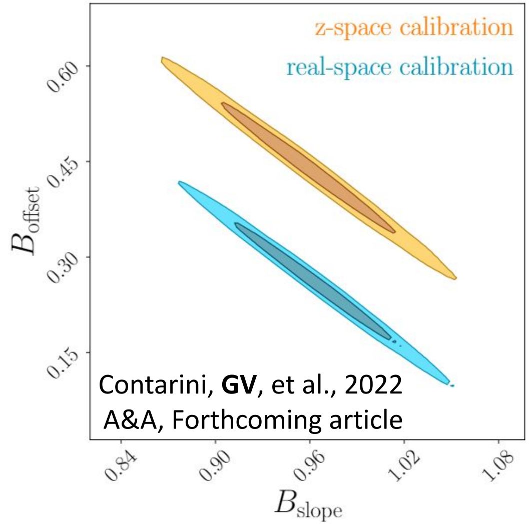


Model Validation



Contarini, **GV**, et al., 2022
A&A, Forthcoming article

Bias parameters calibration:



Contarini, **GV**, et al., 2022
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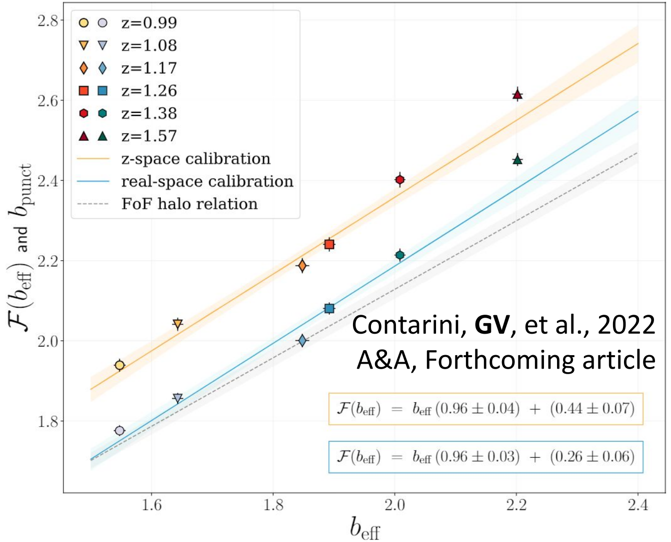


Contarini, **GV**, et al., 2022
A&A, Forthcoming article

Forecasts with MCMC

- Flagship simulation cover ~ 1/3 of the sky area of Euclid survey

  We perform MCMC analysis using as data the expected void size function with corresponding errors

- Poissonian likelihood

$$\mathcal{L}(\mathcal{D}|\Theta) = \prod_{i,j} \frac{N(r_i, z_j|\Theta)^{N(r_i, z_j|\mathcal{D})} \exp\left[-N(r_i, z_j|\Theta)\right]}{N(r_i, z_j|\mathcal{D})!}$$

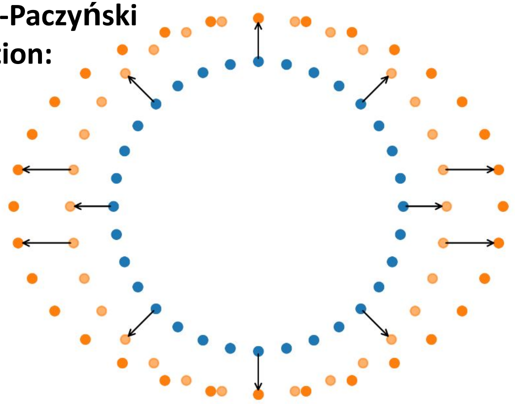
$\mathcal{D} =$ Data

$\Theta =$ Set of parameters

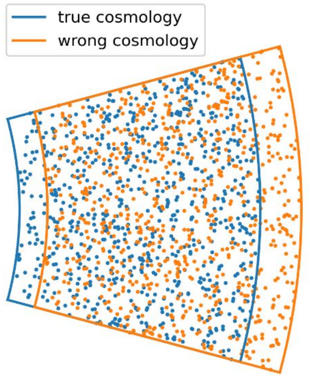
- Geometrical & dynamical distortions included.

  Cosmic voids are extended object: they are impacted by geometric effect, together with dynamic effects

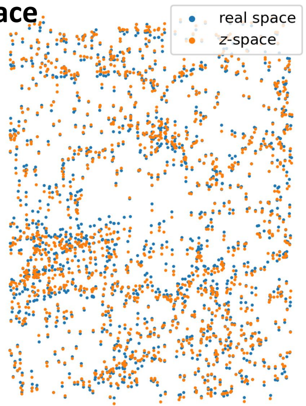
1. Alcock-Paczyński distortion:



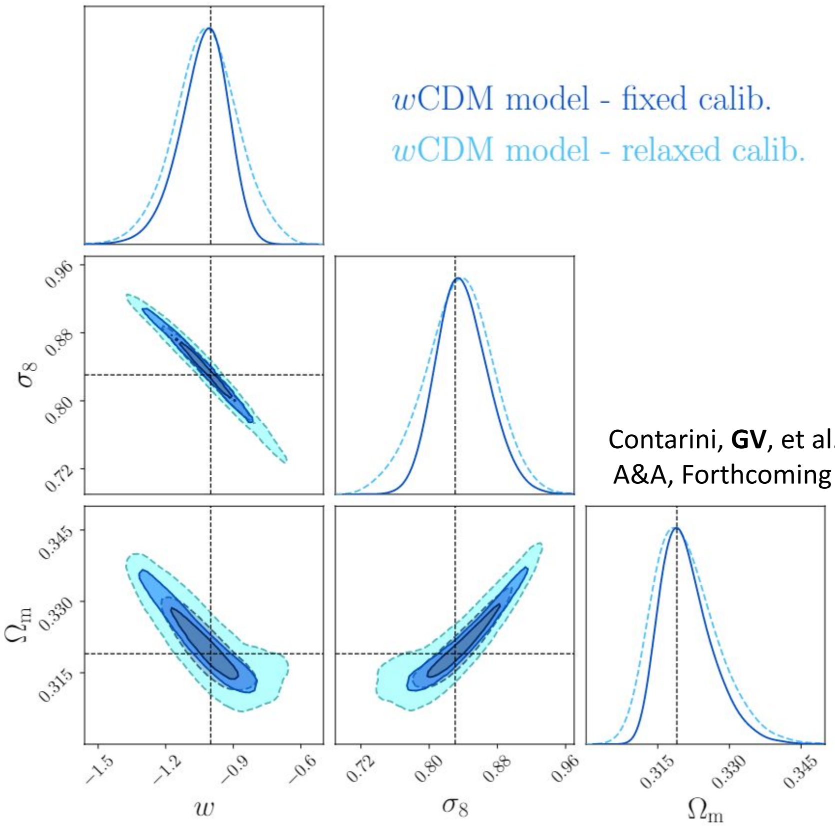
2. Volume effect:



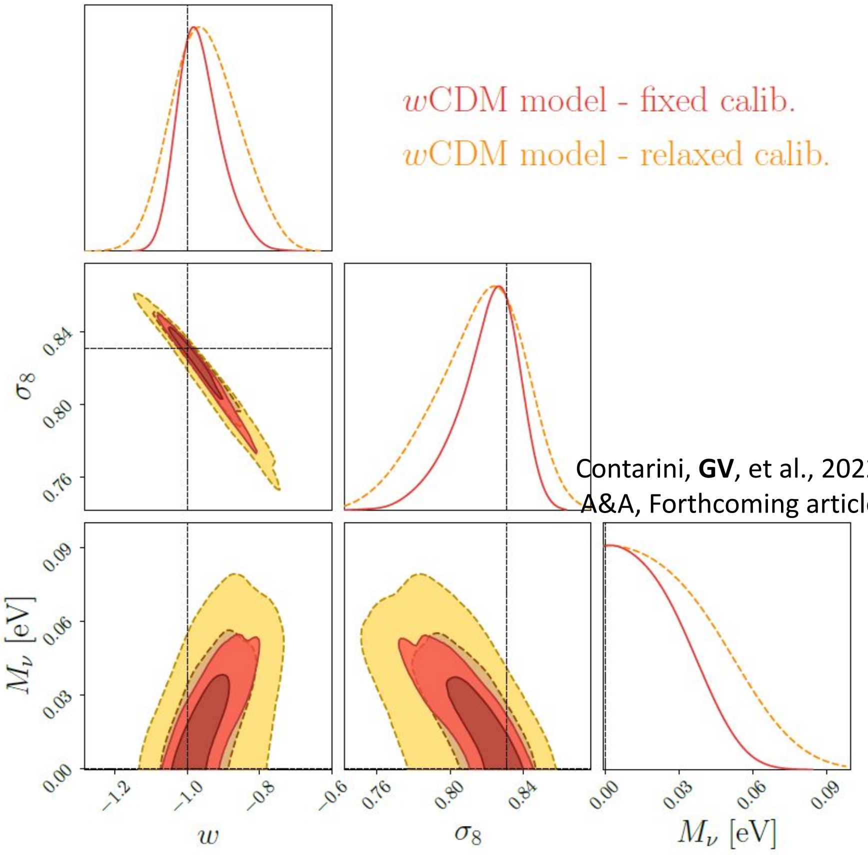
3. Redshift-space distortions:



Cosmological parameter constraints: Ω_m, M_ν, w



Contarini, **GV**, et al., 2022
A&A, Forthcoming article



Contarini, **GV**, et al., 2022
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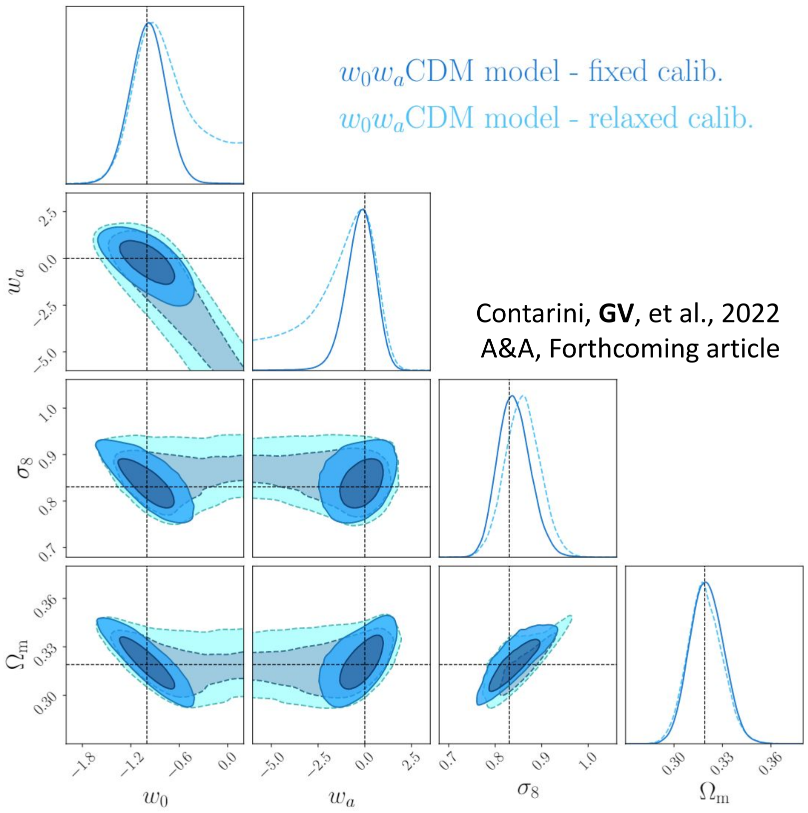
Cosmological parameter constraints: Ω_m, M_ν, w_0 , w_a



Contarini, **GV**, et al., 2022
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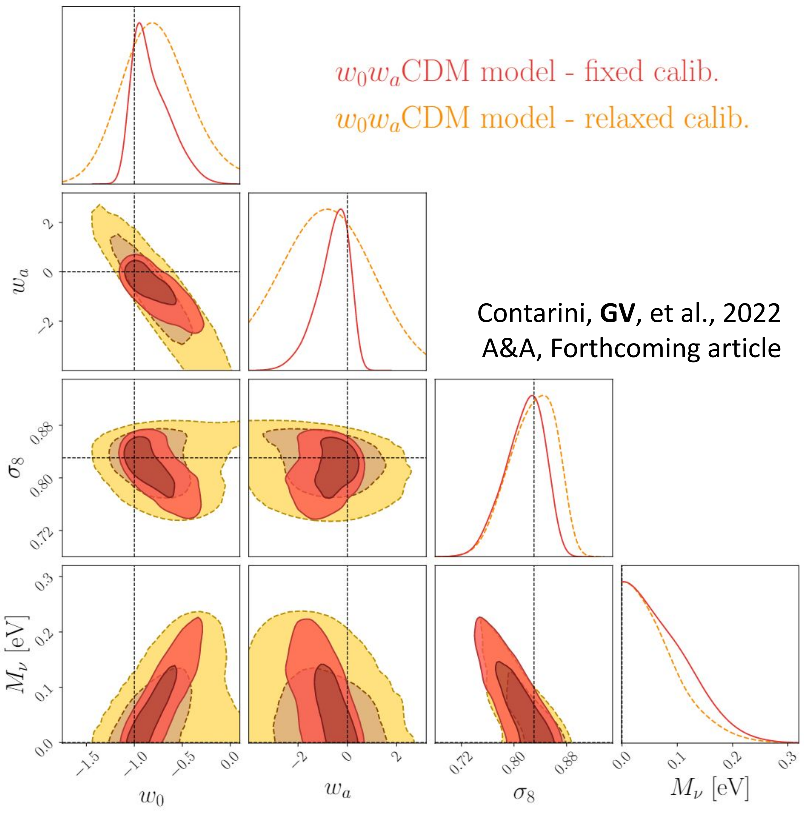
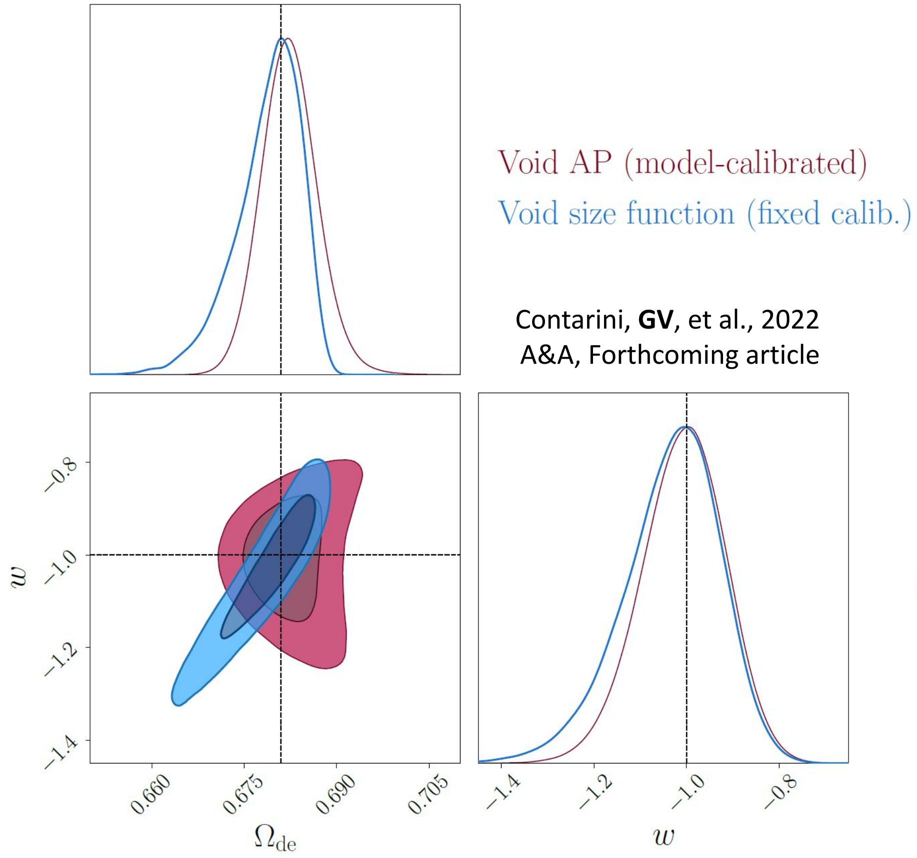


Contarini, **GV**, et al., 2022
A&A, Forthcoming article

Parameters constraints: breaking degeneracies



Contarini, **GV**, et al., 2022
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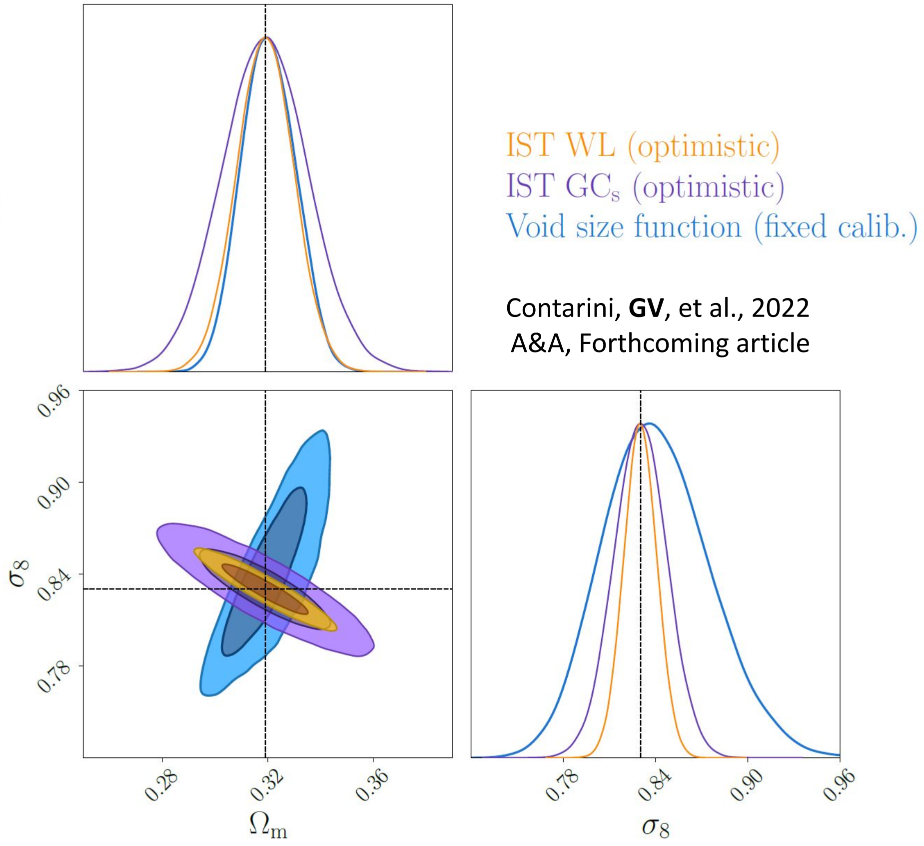


Contarini, **GV**, et al., 2022
A&A, Forthcoming article

The void size function: results summary

1. We forecast the void size function in Euclid

2. We validate the theoretical model

3. We show the power of the void size function and its complementarity to other probes in constraining cosmological parameters

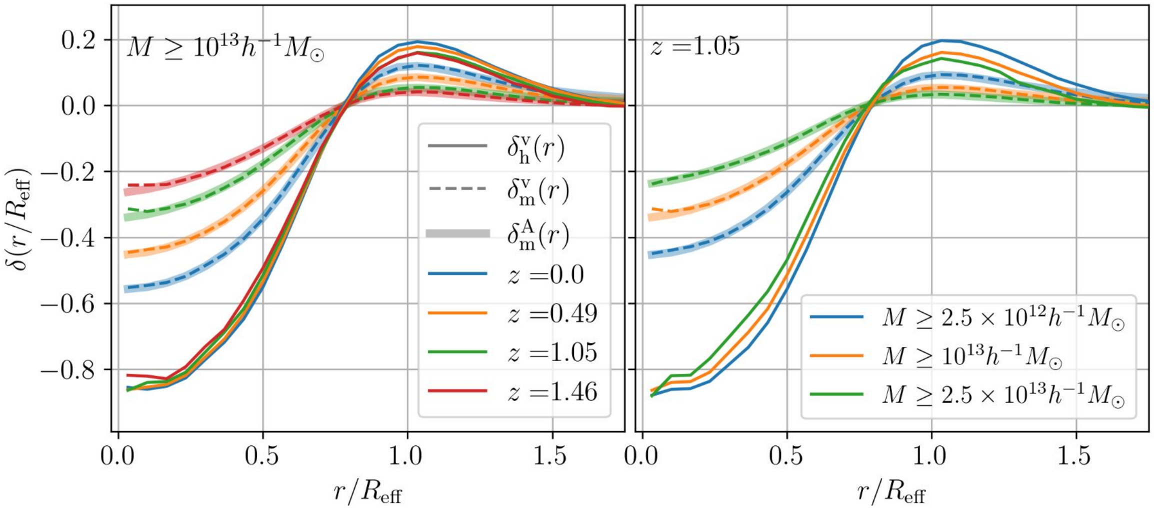
The halo bias in cosmic voids

Based on **GV**, Carbone, Renzi, 2022, The halo bias inside cosmic voids, ArXiv:2207.04039

The void density profile and bias: ΛCDM analysis from the DEMNuni simulations

The stacked void density profile:

- It is the mean density contrast in spherical shells at a distance *r* from the void center
- In the averaging procedure, we normalize the distance from the void center with respect to the void radius R_{eff}



GV, Carbone, Renzi, 2022
ArXiv:2207.04039

The halo bias inside cosmic voids: the relation between the void density profiles in the halo distributions, $\delta_{\mathrm{v}}^{\mathrm{h}}(r)$, and in the underlying matter distributions, $\delta_{\mathrm{m}}^{\mathrm{h}}(r)$.

- Go beyond the linear bias model
- Halo bias is in one-to-one correspondence with the halo mass function

The halo mass function in cosmic voids

Halo mass function (HMF):

$$\frac{\mathrm{d}n_\mathrm{h}}{\mathrm{d}M} = \frac{\bar{\rho}_\mathrm{m}}{M} f[\nu(z), p, q] \left| \frac{\mathrm{d}\nu(z)}{\mathrm{d}M} \right|$$

Ellipsoidal collapse (Sheth & Tormen 1999)

$$f(\nu, p, q) = \sqrt{\frac{2}{\pi}} A \left[1 + (q\nu^2)^{-p}\right] \sqrt{q} e^{-q\nu^2/2}$$

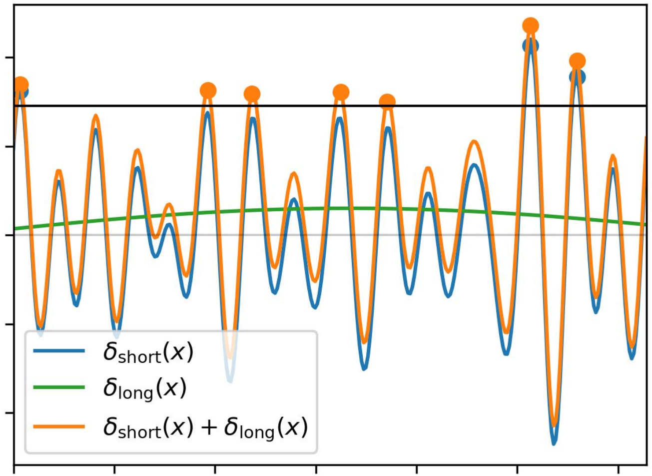
$$\nu = \delta_\mathrm{c}/\sigma(M), \; A = \left[1 + \Gamma(1/2 - p)/(2^p\sqrt{\pi})\right]^{-1}$$

The peak-background split (PBS) approach:

Halo formation modified by a long-wavelength density perturbation δ_lw acting like a local modification of the background density

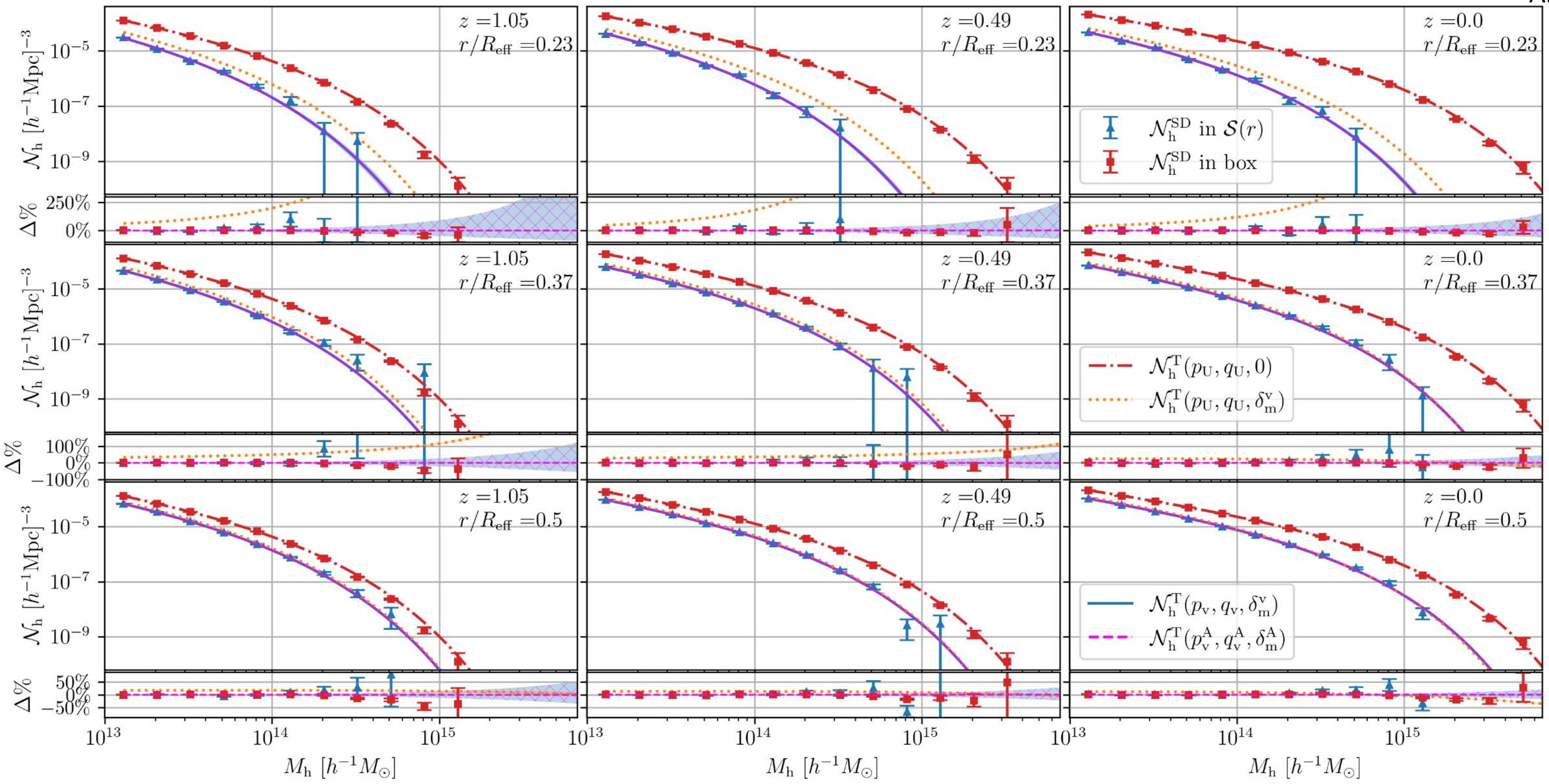
$$\frac{\mathrm{d}n_\mathrm{h}}{\mathrm{d}M} = [1+\delta_\mathrm{lw}(z)] \frac{\bar{\rho}_\mathrm{m}}{M} f[\tilde{\nu}(z), p, q] \frac{\mathrm{d}\tilde{\nu}(z)}{\mathrm{d}M}$$

$$\nu \to \tilde{\nu} = [\delta_\mathrm{sc}(z) - \delta^\mathrm{L}_\mathrm{lw}(z))]/\sigma(M)$$



Theoretical HMF against measurements from the DEMNUni simulations in the ΛCDM case

GV, Carbone, Renzi, 2022
ArXiv:2207.04039



$\mathcal{N}_{\rm h}^{\rm T}(p_{\rm U}, q_{\rm U}, \delta_{\rm m}^{\rm v})$: $p_{\rm U}, q_{\rm U}$ **fixed,** $\delta_{\rm m}^{\rm v}(r, z)$

$\mathcal{N}_{\rm h}^{\rm T}(p_{\rm v}, q_{\rm v}, \delta_{\rm m}^{\rm v})$: $p_{\rm v}(r, z), q_{\rm v}(r, z), \delta_{\rm m}^{\rm v}(r, z)$

$p_{\rm v}$(r, z) and $q_{\rm v}$(r, z) account for the impact of the internal dynamic of voids on the HMF

$$\frac{{\rm d}n_{\rm h}}{{\rm d}M}(\tilde{\nu}, p_{\rm v}, q_{\rm v}, \delta_{\rm m}^{\rm v}) = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}_{\rm m}}{M}(1+\delta_{\rm m}^{\rm v})\times\left\{A_{\rm v}[1+(q_{\rm v}\tilde{\nu}^2)^{-p_{\rm v}}]\sqrt{q_{\rm v}}e^{-q_{\rm v}\tilde{\nu}^2/2}\frac{{\rm d}\tilde{\nu}}{{\rm d}M}\right\}$$

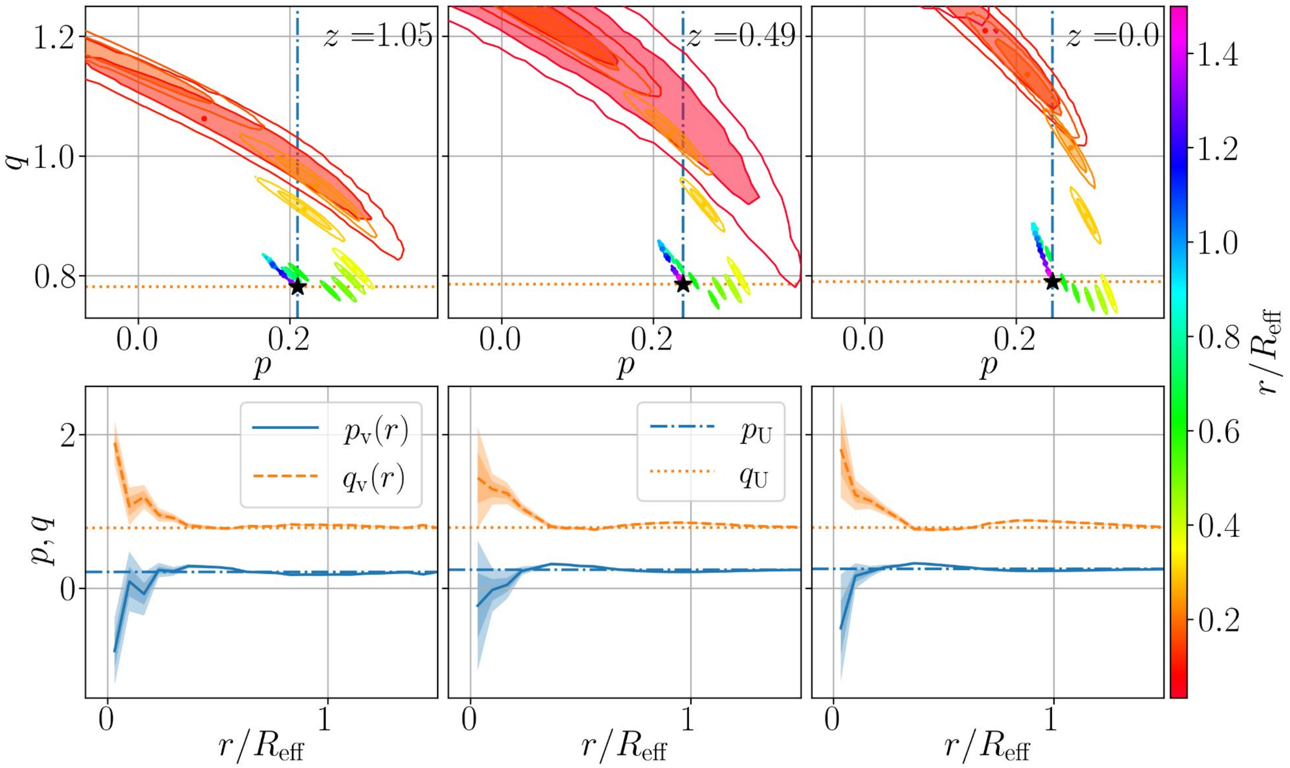
The p_v and q_v evolution

GV, Carbone, Renzi, 2022
ArXiv:2207.04039

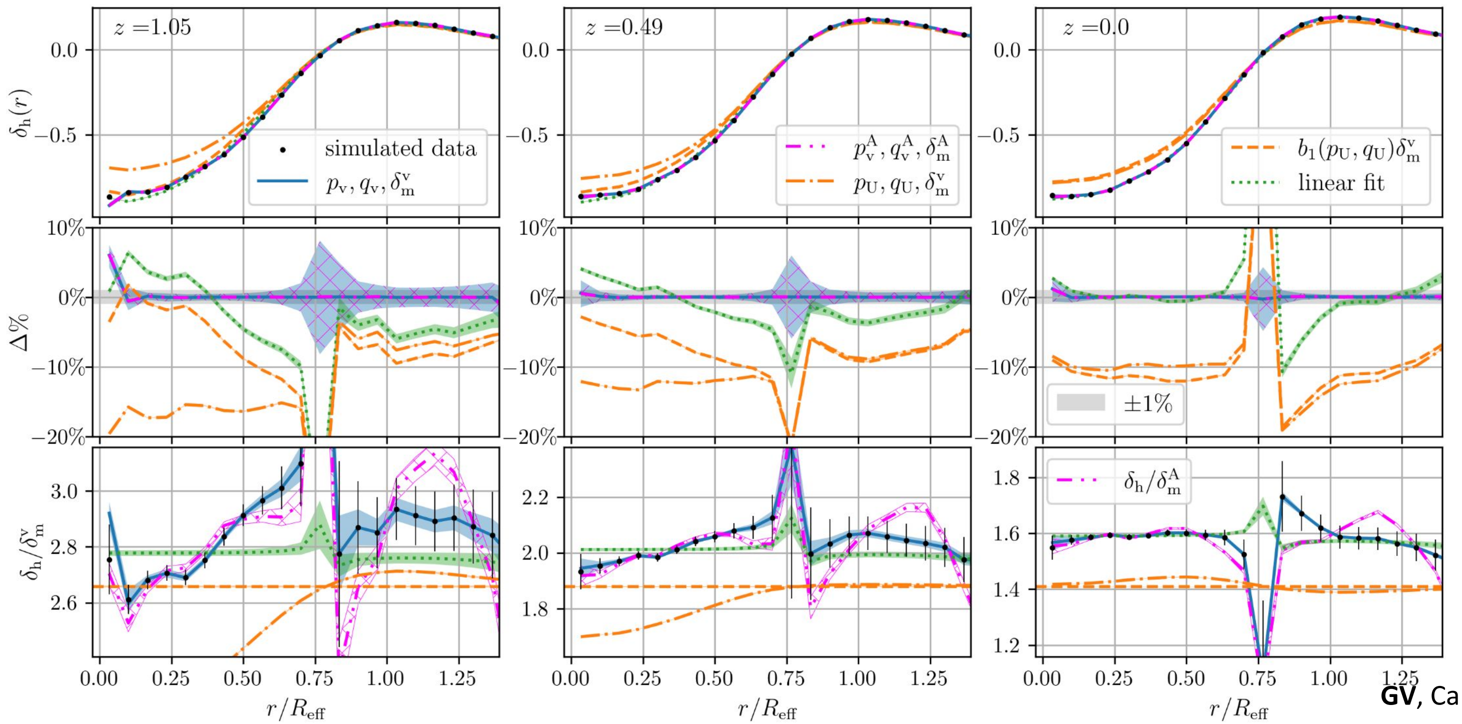
The $p_v(r)$ and $q_v(r)$ parameters, along the void profile, of the multiplicity function associated to our HMF model, fitted to simulated measurements.

Upper panels: 68% and 95% CL in the p-q plane. The contour colors denote the distance from the void center, the black stars, together with the dot-dashed blue and dotted orange lines, represent p_U and q_U.

Lower panels: same quantities as a function of r: $p_v(r)$ (blue solid), $q_v(r)$ (orange dashed), p_U (blue dash-dotted horizontal), and q_U (orange dotted horizontal).



The halo bias inside cosmic voids: new theoretical model



GV, Carbone, Renzi, 2022
ArXiv:2207.04039

Bias model: $$\delta_h(r) = \frac{\int_{M_{min}}^{\infty} \frac{dn_h}{dM}\left[\tilde{\nu}, p_v(r), q_v(r), \delta_m^v(r)\right] dM}{\int_{M_{min}}^{\infty} \frac{dn_h}{dM}\left(\nu, p_U, q_U, 0\right) dM} - 1$$

(**GV**, Carbone, Renzi, 2022)

Linear fit: $$\delta_h(r) = b_{slope}\, \delta_m^v(r) + c_{offset}$$

(Pollina et al. 2017)

The halo bias in cosmic voids: results summary

- For the first time to date, we show that the halo mass function inside cosmic voids is not universal, rather it depends on the distance, *r*, from the void center;

- We provide theoretical model able to describe the halo mass function along void profiles;

- Applying the peak-background split technique we are able to obtain a theoretical prediction of the halo bias within voids.

- Several possible applications:
  - Analysis involving the void size function.
  - Analysis involving redshift-space distortions around voids.
  - Extend our modeling to cosmologies alternative to the ΛCDM model, i.e. in the presence of massive neutrinos and dynamical dark energy which may alter halo formation inside voids;

Thank you for your attention

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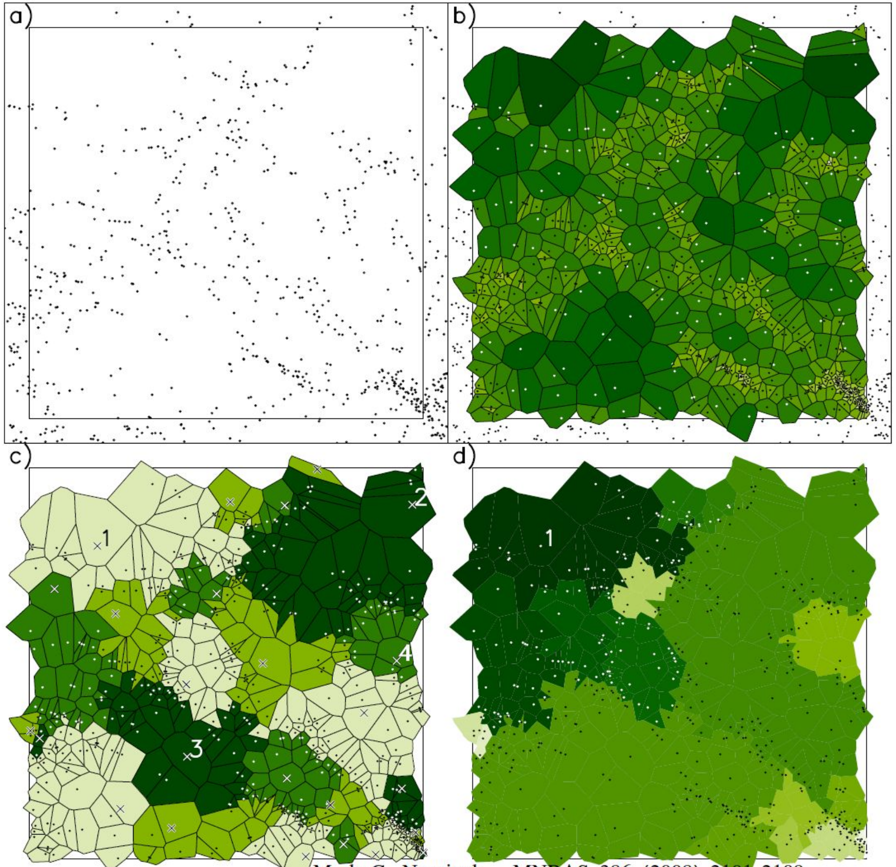
Backup slides

Void finder: VIDE 2.0 (Sutter et al. 2015)

- Voronoi tessellation
- Relative minima
- Watershed algorithm



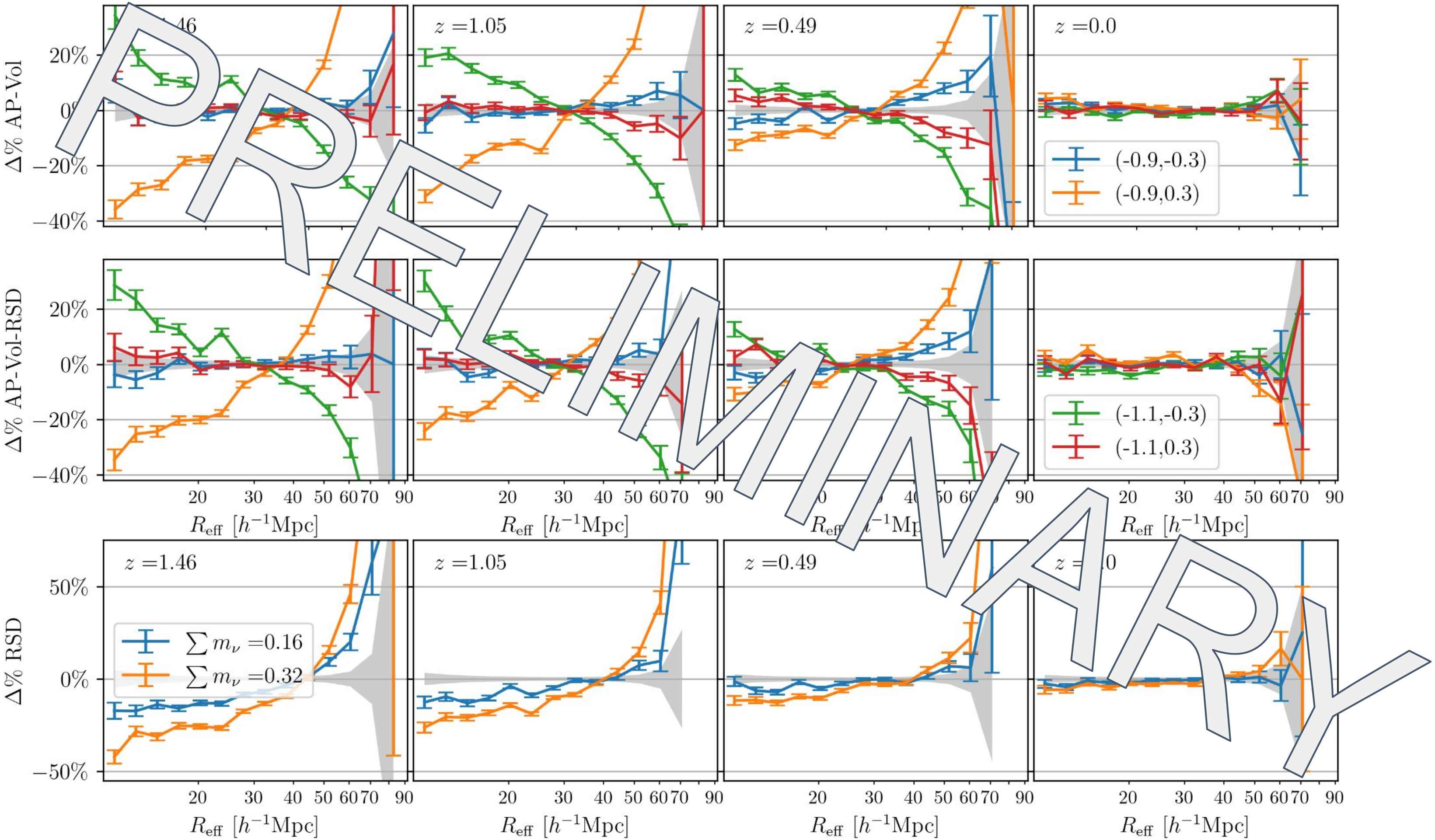
Mark C. Neyrinck - MNRAS 386 (2008) 2101-2109

Constraints from the void size function

Model	w_0	w_a	σ_8	Ω_m	M_ν [eV]	B_{slope}	B_{offset}	FoM_{w_0,w_a}
fixed calib.	-1.0 ± 0.2	$-0.1^{+0.7}_{-0.9}$	$0.84^{+0.04}_{-0.03}$	0.32 ± 0.01	0	0.96	0.44	4.9
	$-1.0^{+0.2}_{-0.6}$	$-0.1^{+0.3}_{-0.8}$	$0.83^{+0.02}_{-0.03}$	0.319	< 0.08	0.96	0.44	17
relaxed calib.	$-0.8^{+1.6}_{-0.6}$	$-0.9^{+3.6}_{-9.6}$	0.86 ± 0.04	0.32 ± 0.01	0	$1.01^{+0.03}_{-0.04}$	$0.35^{+0.08}_{-0.05}$	0.78
	$-0.9^{+0.3}_{-0.2}$	$-0.5^{+0.9}_{-1.3}$	$0.86^{+0.02}_{-0.05}$	0.319	< 0.08	$0.99^{+0.01}_{-0.04}$	$0.38^{+0.07}_{-0.01}$	2.3

Model	w	σ_8	Ω_m	M_ν [eV]	B_{slope}	B_{offset}
fixed calib.	$-1.01^{+0.09}_{-0.11}$	0.83 ± 0.03	$0.319^{+0.005}_{-0.004}$	0	0.96	0.44
	$-0.99^{+0.06}_{-0.04}$	$0.83^{+0.1}_{-0.2}$	0.319	< 0.03	0.96	0.44
relaxed calib.	-1.0 ± 0.1	0.84 ± 0.04	$0.318^{+0.008}_{-0.005}$	0	0.96 ± 0.02	0.44 ± 0.04
	$-0.98^{+0.10}_{-0.07}$	$0.83^{+0.02}_{-0.03}$	0.319	< 0.06	0.95 ± 0.02	0.46 ± 0.04

Void abundances in the DEMNUni simulations



Void abundances in the DEMNUni simulations