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New Insight into the Void-in-Cloud Process

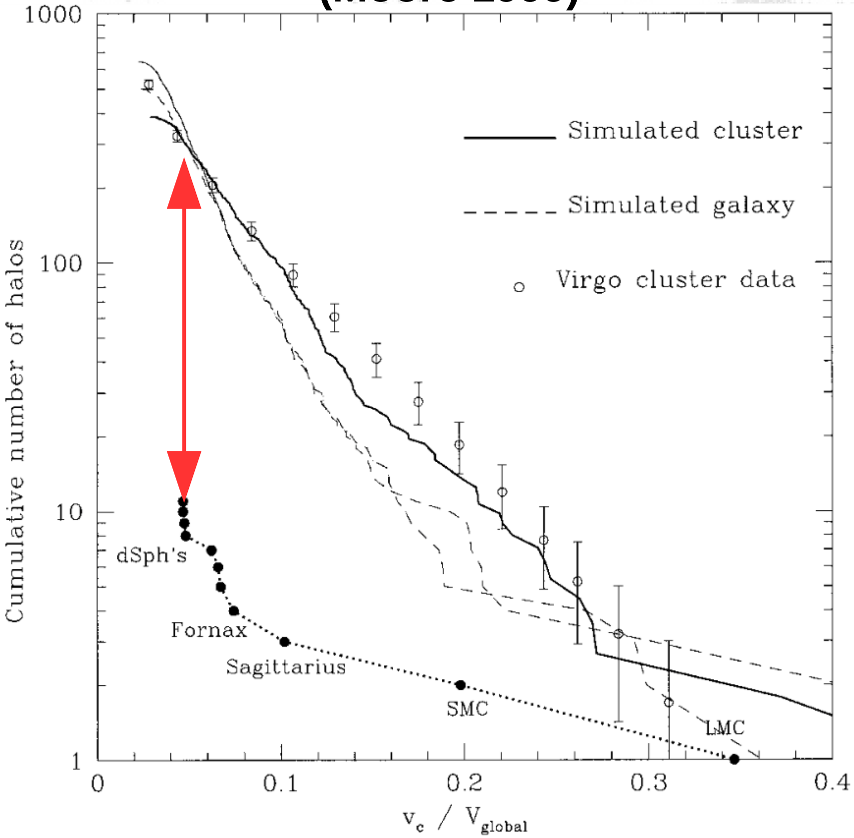
Hei Yin Jowett Chan (Tohoku University), Masashi Chiba (Tohoku University),
Tomoaki Ishiyama (Chiba University)

TOHOKU UNIVERSITY

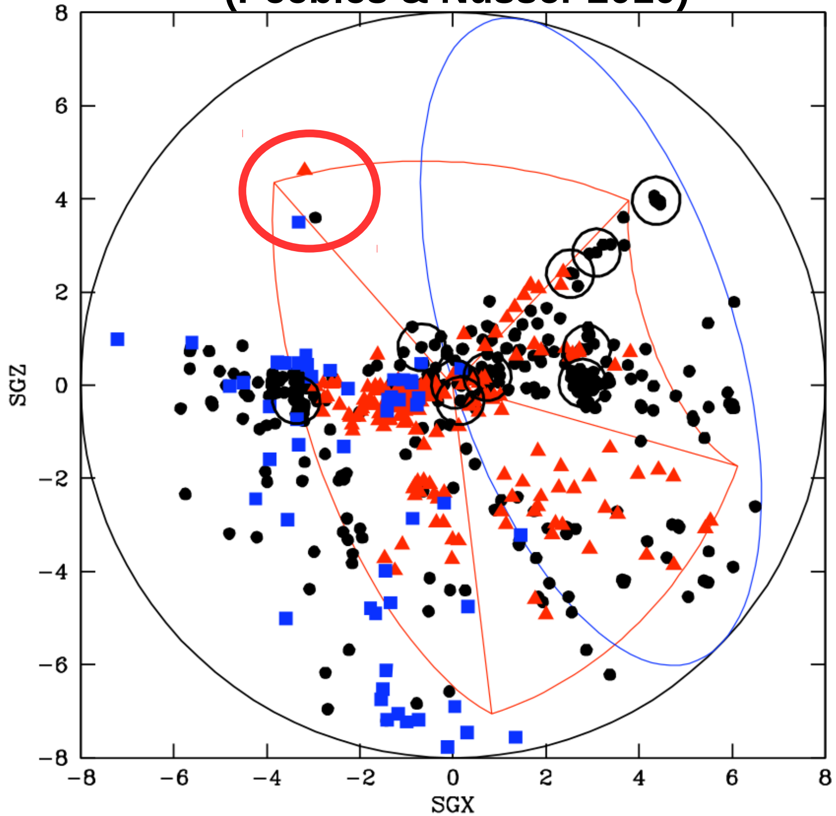
Paper:
Chan, Chiba, & Ishiyama, 2019, MNRAS, 490, 2, 2405

LCDM Problems on Small Scale (Halo & Void)

(Moore 1999)



(Peebles & Nusser 2010)



Currently ~50 dwarfs are observed but we expected ~1000 in simulation

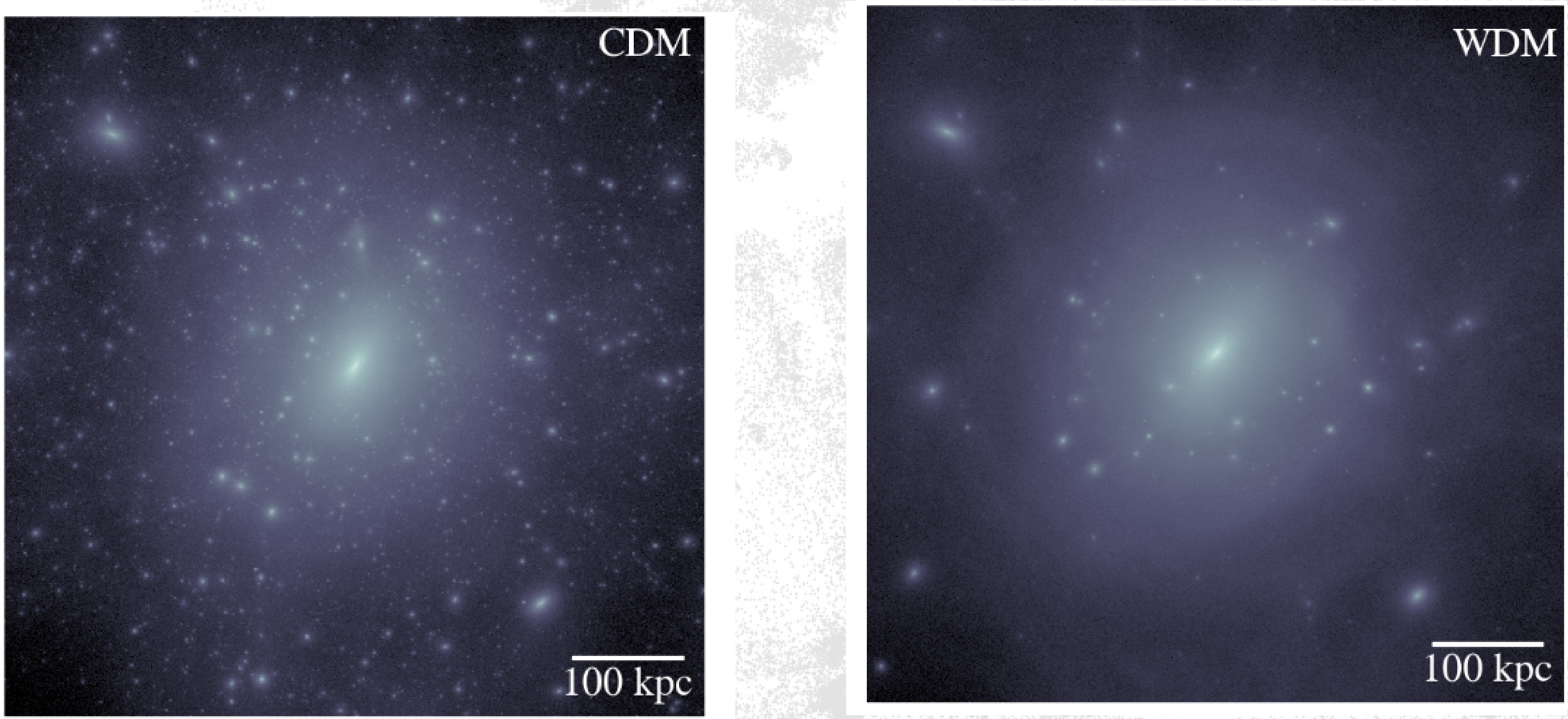
Simulation predicts ~ 19 galaxies in void but we observe only 3 in the Local Void

Missing Satellite Problem
lack of dwarfs in halo

Void Phenonmenon
lack of dwarf/galaxies in void

Alternative Dark Matter Model

(Bullock & Boylan-Kolchin 2017)



$$T_{\mathrm{WDM}}(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

$$\alpha = 0.048 \left(\frac{\Omega_m}{0.4}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} \left(\frac{m}{\mathrm{keV}}\right)^{1.15} \left(\frac{1.5}{g}\right)^{0.29},$$

~ 2keV (Hayashi & Chiba 2015; Viel et al. 2005)

Halo abundance on small scale is suppressed in the WDM cosmology

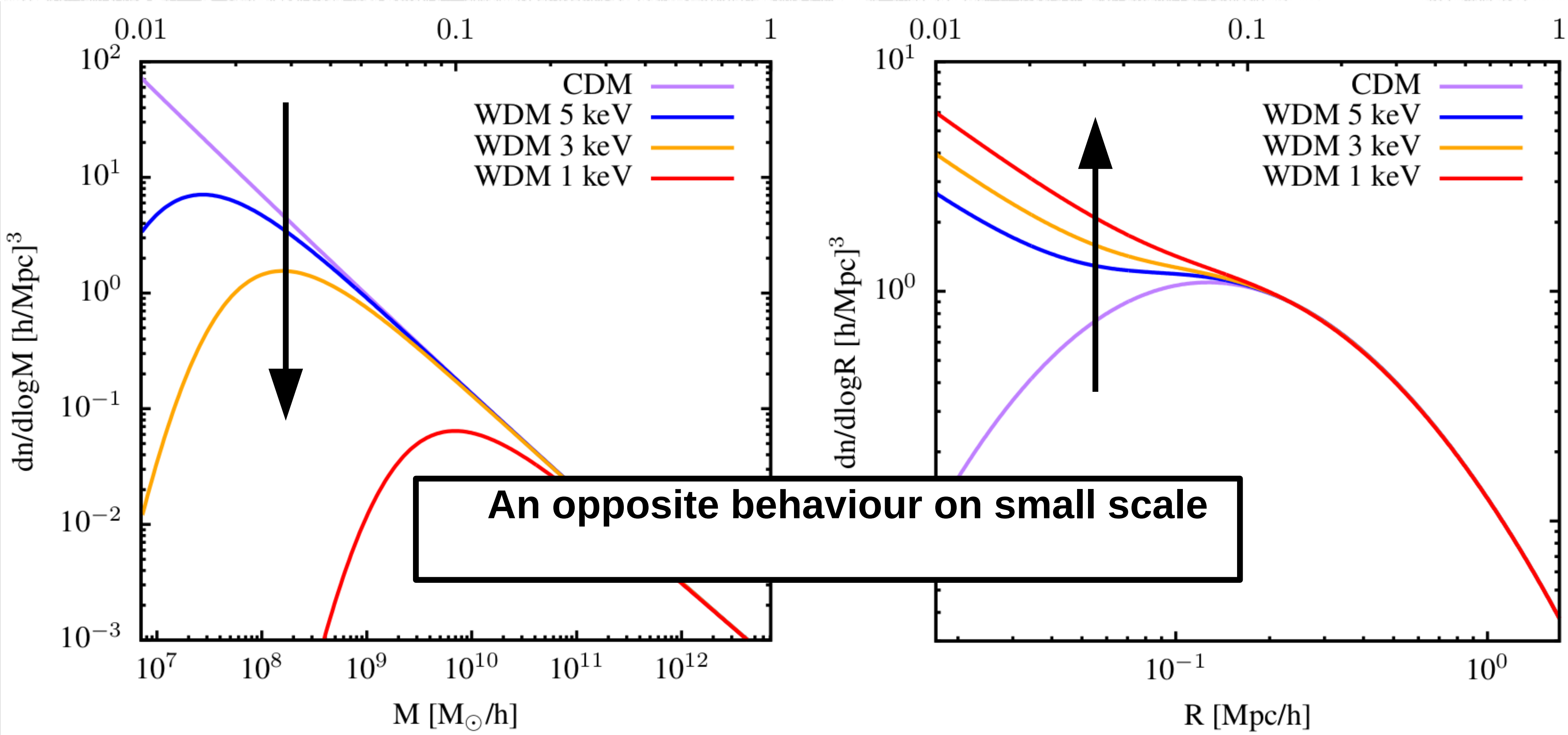
Analytical Models

Halo mass function (EPS)

EPS: Extended Press-Secheter Model

Void size function (Svdw)

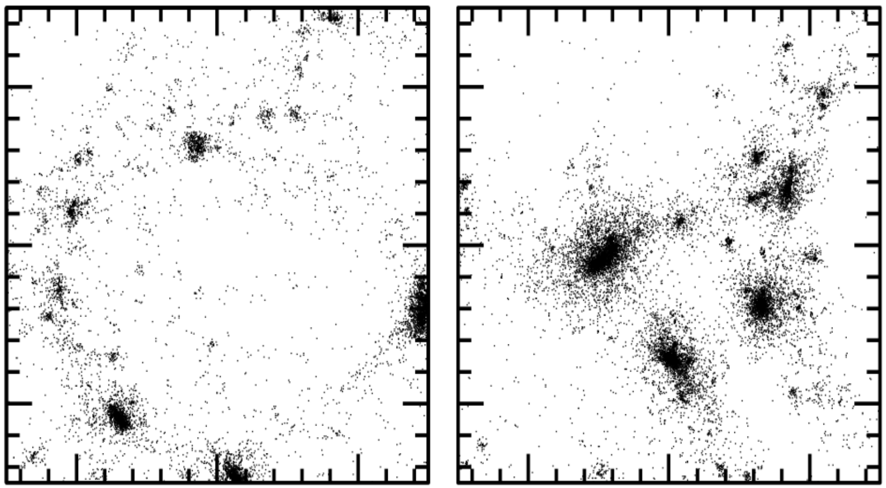
(Sheth & van de Weygaert 2004)



(Schneider et al. 2013)

The void-in-cloud process

CDM **WDM**



Free streaming suppresses small halo

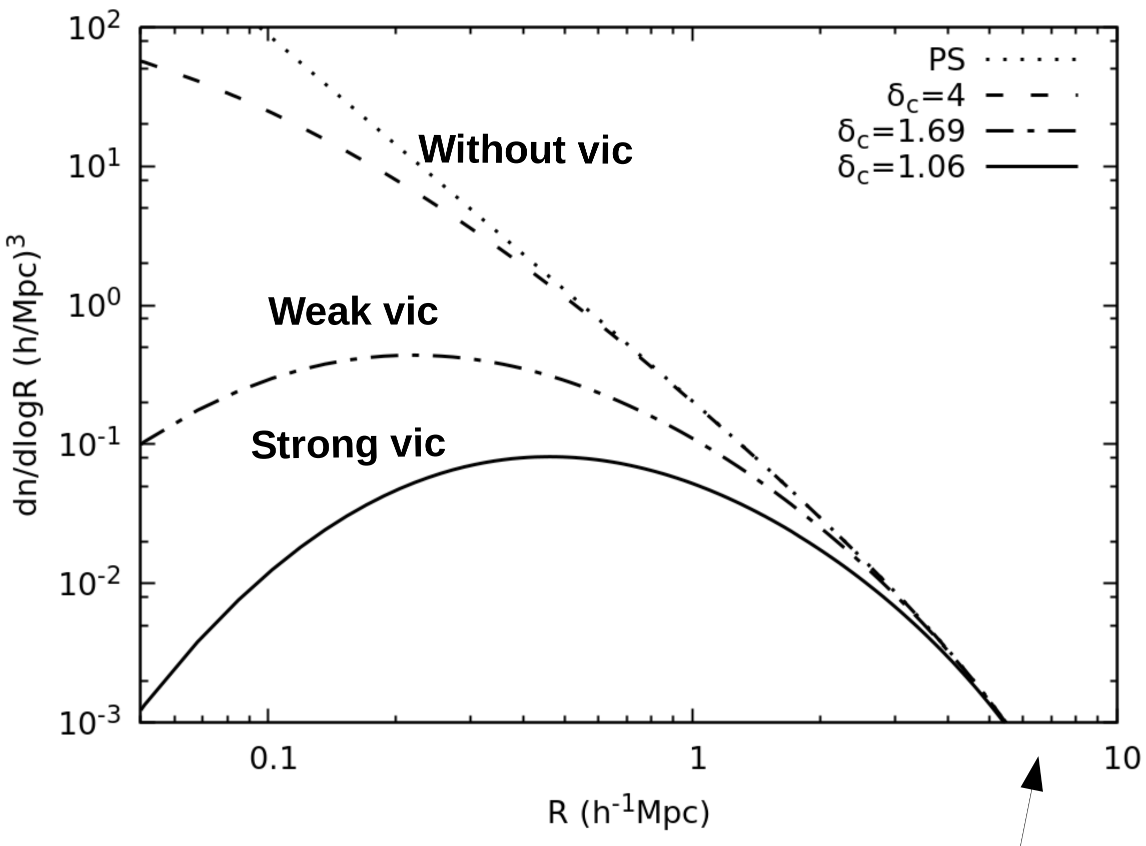
=> fewer vic process

=> more formation of void !

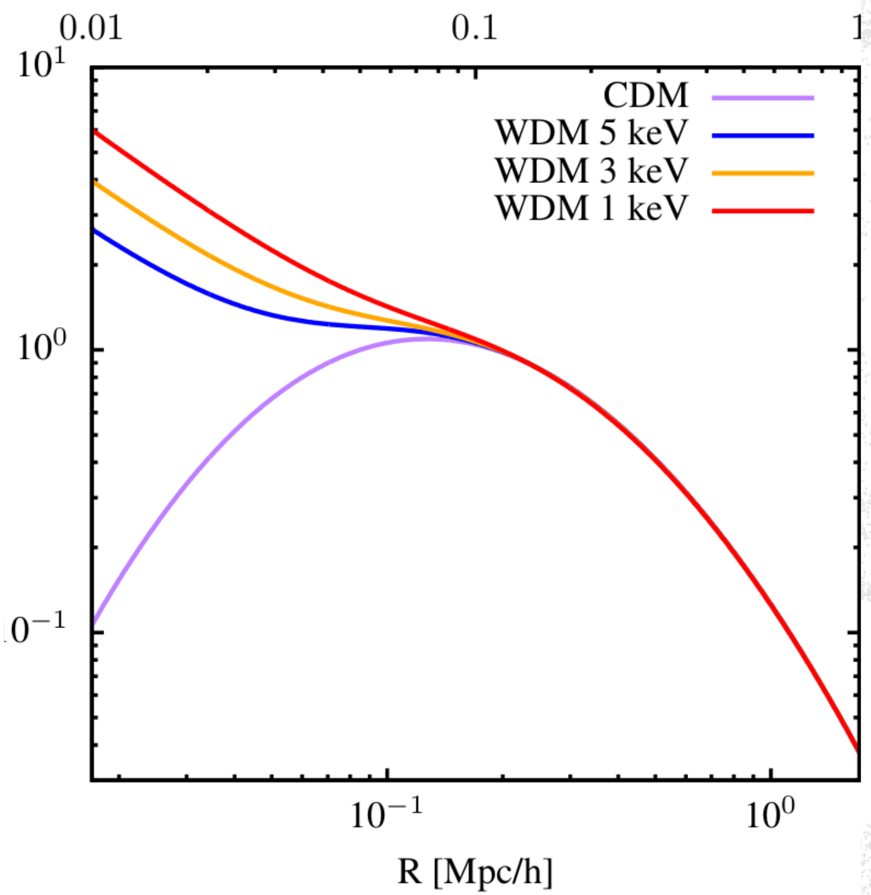
(Sheth & van de Wagaert 2004).

The void-in-cloud process

Varying strength of void-in-cloud



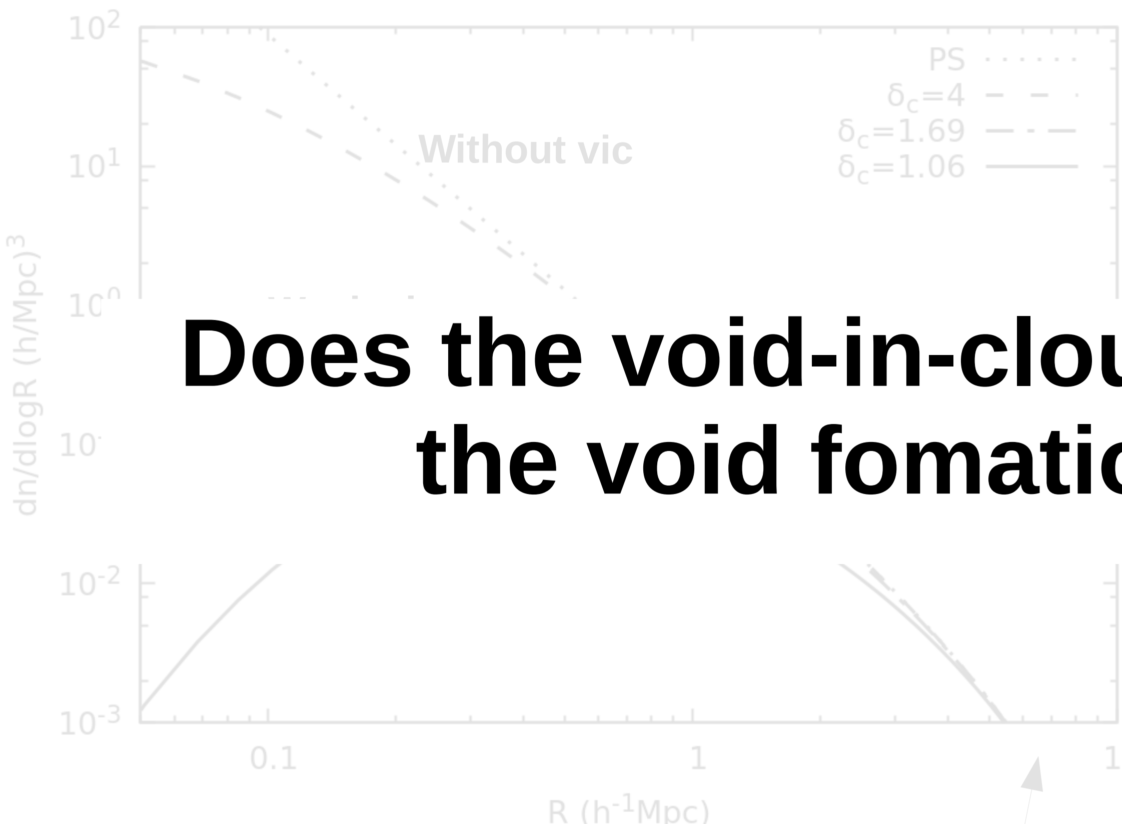
Varying mass of WDM particle



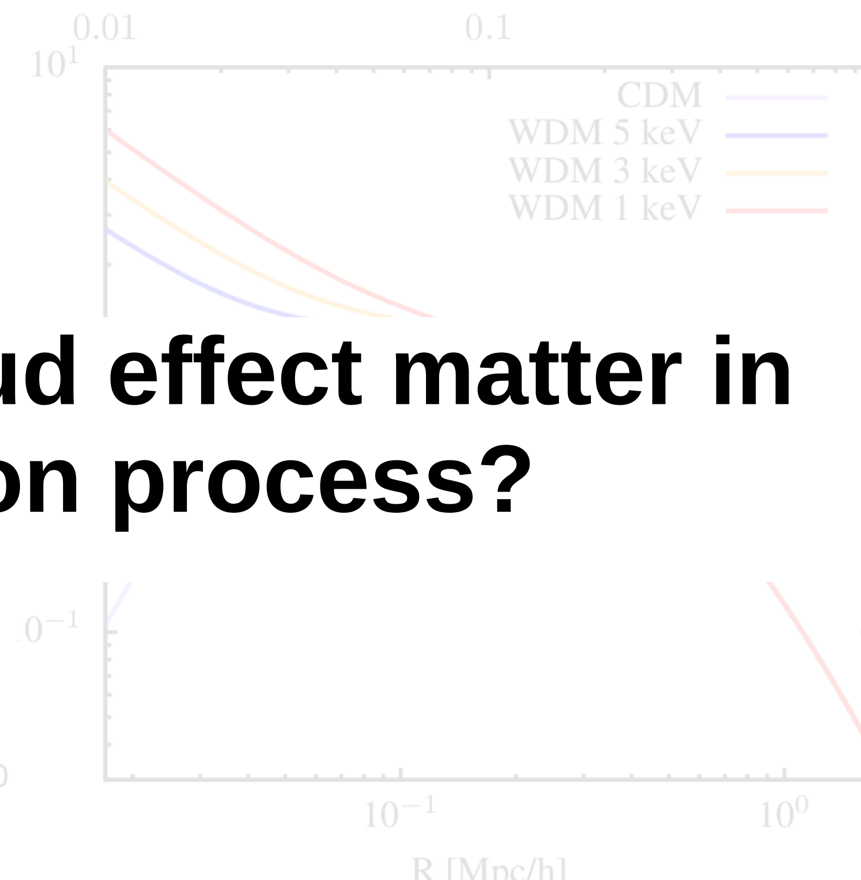
Can we trust it?

The void-in-cloud process

Varying strength of void-in-cloud



Varying mass of WDM particle



Does the void-in-cloud effect matter in the void fomation process?

Can we trust it?

(Sheth & van de Wagaert 2004).

Phi0, Phi1 & Multi-dark Planck

	Name	box size (h^{-1}Mpc)	N	$N_{\rm sub}$	$m_{\rm p}$ ($h^{-1}{\rm M}_\odot$)	ϵ (h^{-1}kpc)	Ref
Small Scale	Phi-0	8	2048^3	$[1.07, 8.59] \times 10^7$	5.13×10^3	0.12	1
	Phi-1	32	2048^3	8.59×10^7	3.28×10^5	0.48	2
Large Scale	VSMDPL	160	3840^3	5.66×10^7	6.20×10^6	1	3
	SMDPL	400	3840^3	5.66×10^7	9.63×10^7	1.5	3
	MDPL2	1000	3840^3	5.66×10^7	1.51×10^9	5	3

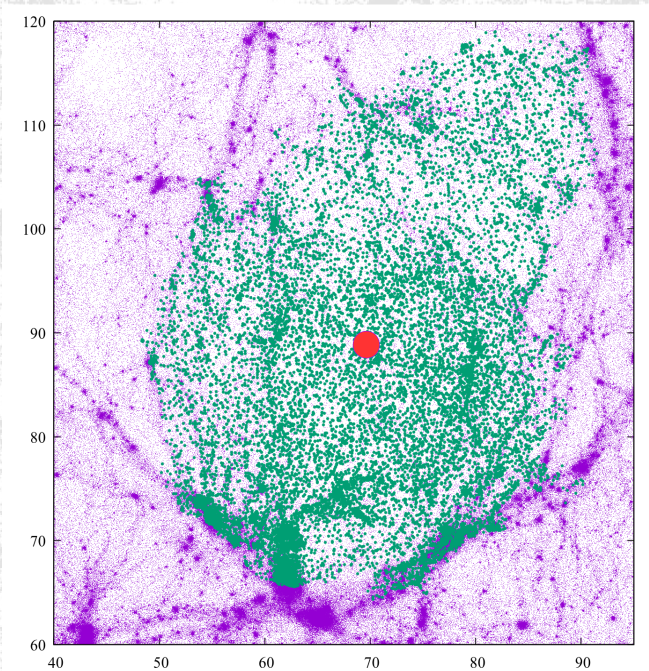
Note. — Here N, $N_{\rm sub}$, $m_{\rm p}$ and ϵ are the number of particles, the subsample, mass resolution and gravitational softening length respectively.

References. — (1) Ishiyama et al. 2016 (2) Ishiyama et al. 2015 (3) Klypin et al. 2016

Void Finding Process

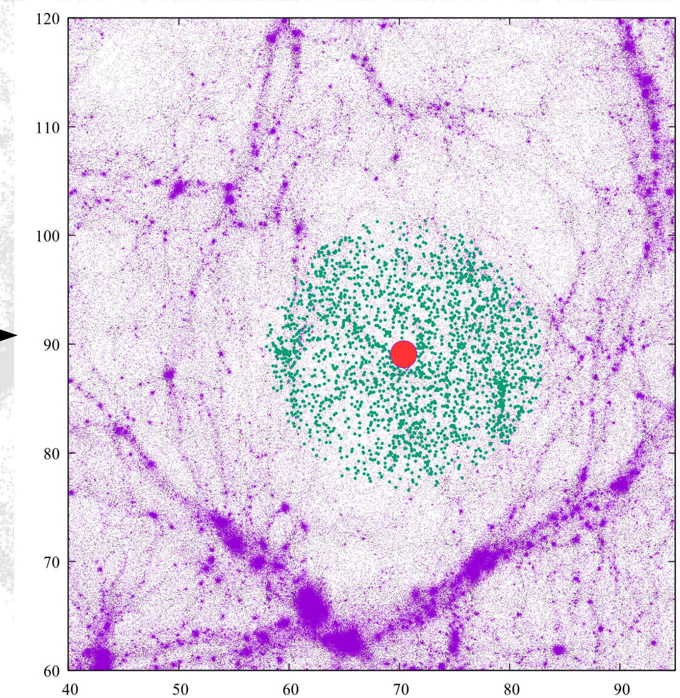
ZOBOV:
- Voronoi Tessellation based
- closely follow geometry of void

Aspherical Void



Growing Sphere →

Spherical Void



Zone merging criteria

$$\rho_{\rm link} < [0.032, 0.04, 0.1, 0.15, 0.24]\bar{\rho}$$

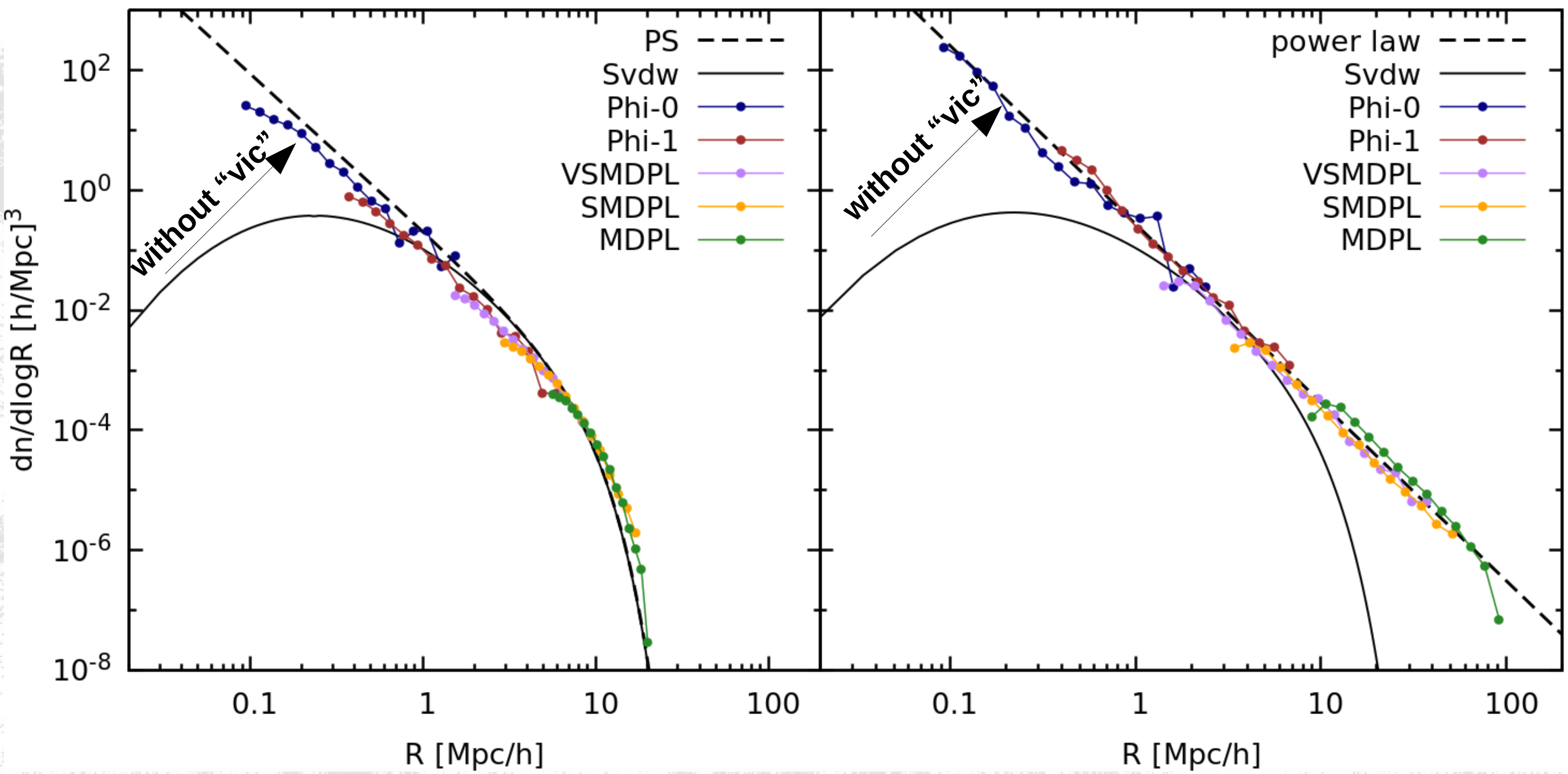
for Phi–0, Phi–1, VSMDPL, SMDPL and MDPL2

Non-linear denstiy threshold

$$\rho_v = 0.2\bar{\rho}.$$

RESULTS

Void Size Distributions



Directly use the EPS model but replacing δc with δv -> Agreement!

Voids in simulation rarely experience the void-in-cloud effect

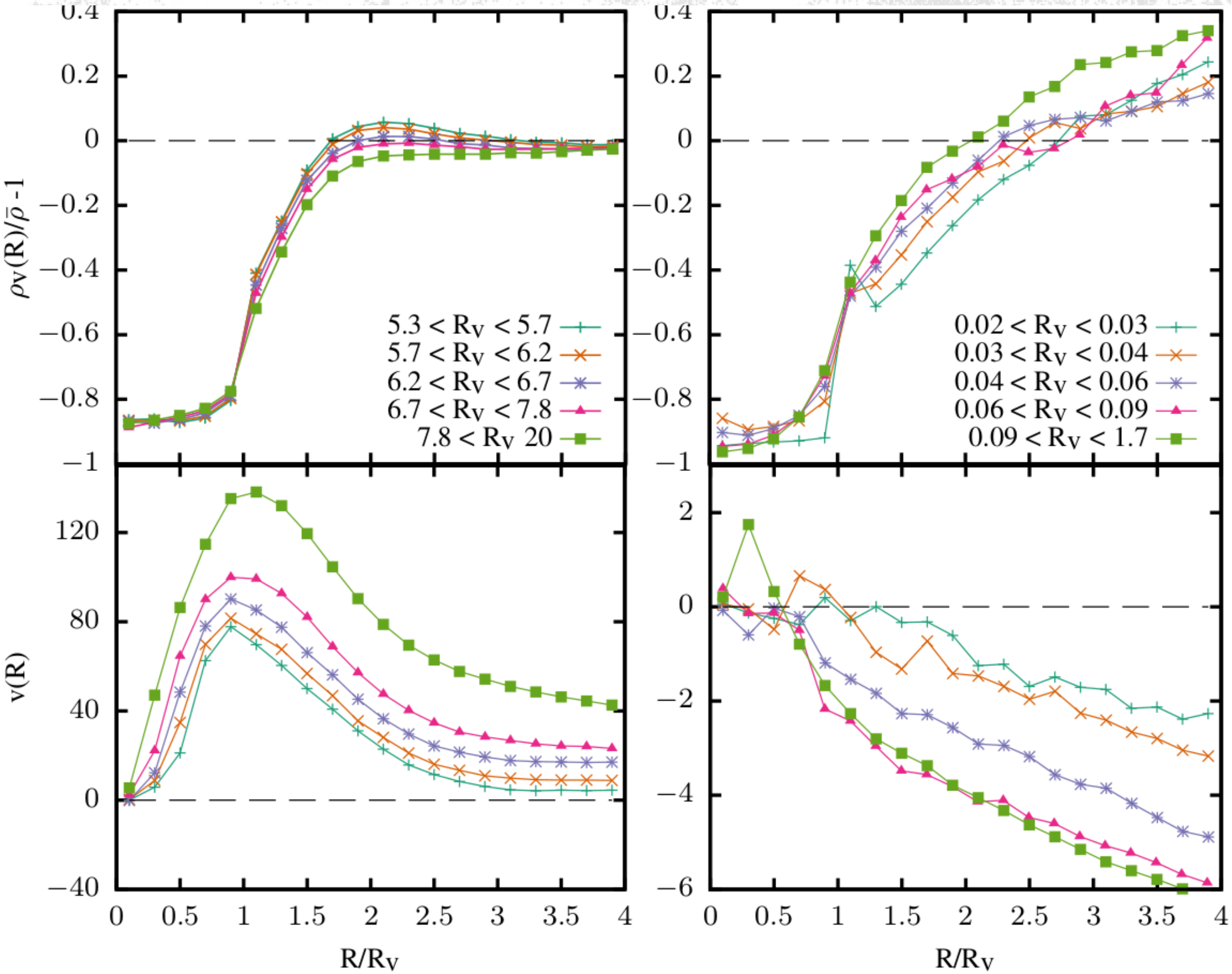
Density & Velocity Profile of Void

MDPL2
(Large void)

Phi-0
(Small void)

Density profile

Velocity Profile

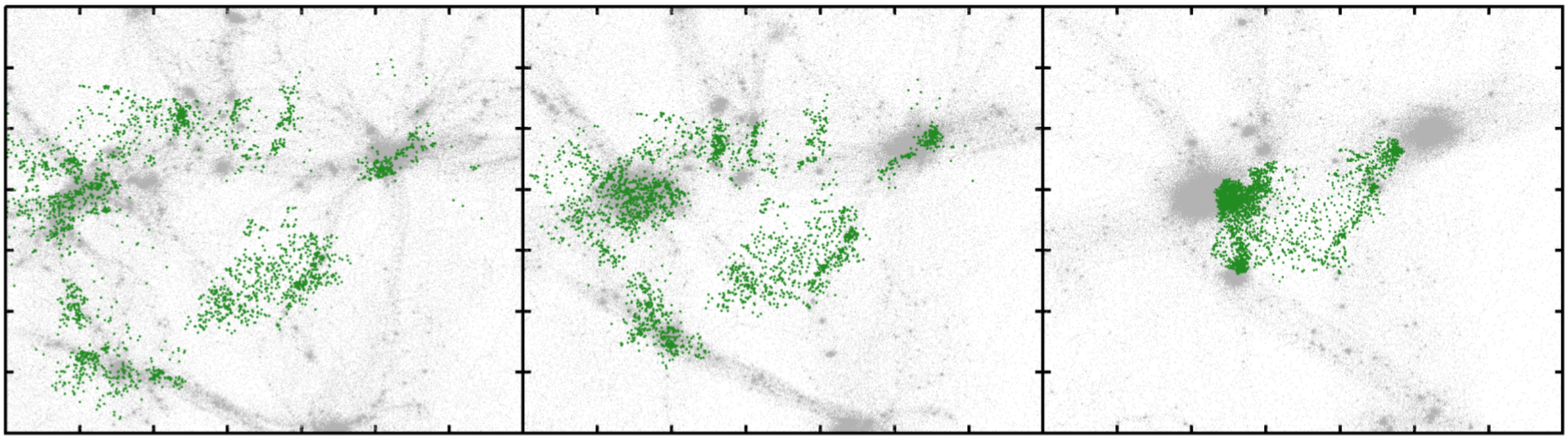


Small void is still underdense at center

Slowly collapsing at r > 1

- **Dependence on void size** (in consistent with Hamaus et al., 2014)
- **Small voids are partially collapsing structure**

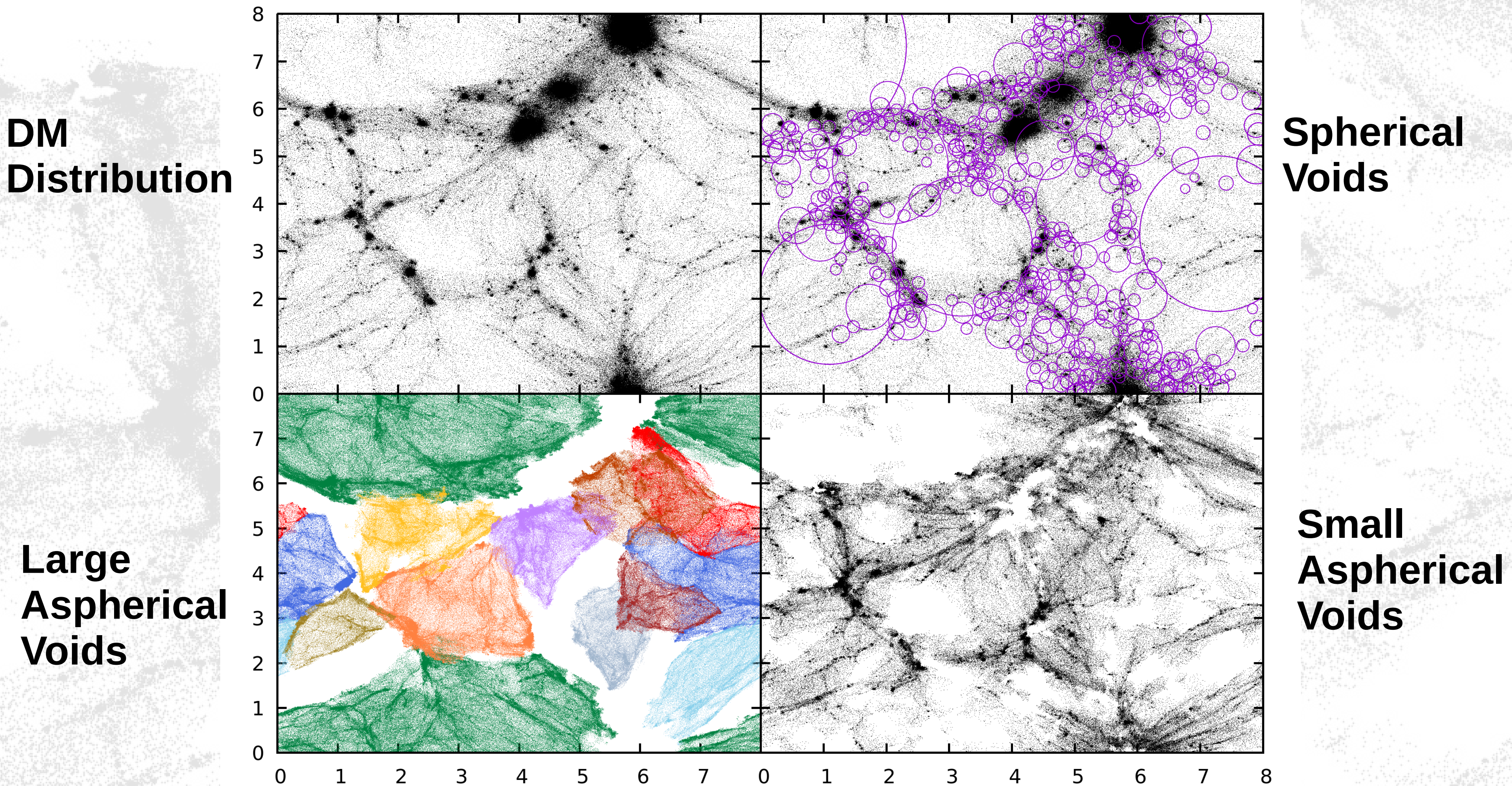
Evolution of Small Void



A void with $R_{\rm eff} = 0.2\,h^{-1}$Mpc in Phi–0 simulation at redshift $z = 2, 1, 0$ from left to right.

Support the void model in the Eulerian framwork **(Paranjape, Sheth & Iam, 2012)**

Environmental Dependence of Void Distribution



Both small spherical & aspherical voids tend to reside close to the filament and overdense regions.

Classification of Voids' Environment (Phi-0)

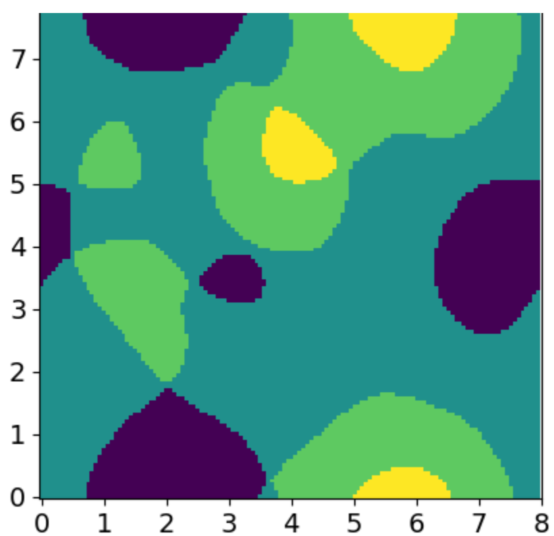
(Hahn et al., 2007)

Eigenvalues of the tidal tensor

$$T_{ij}(\mathbf{x}) = \partial_i \partial_j \psi_R(\mathbf{x})$$

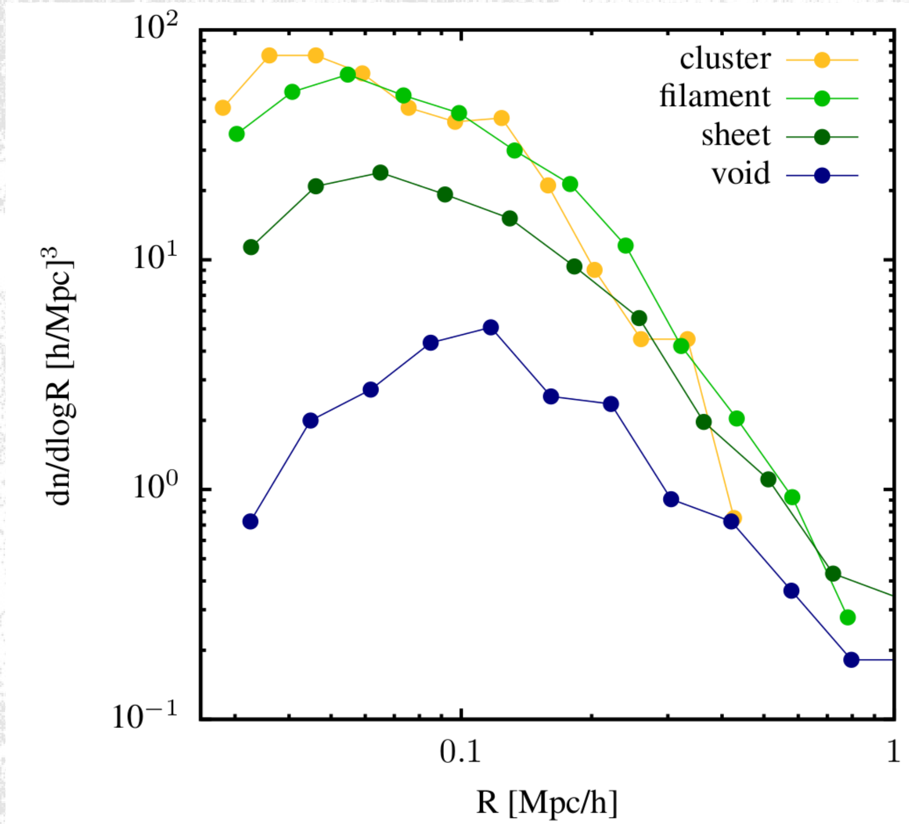
$$\lambda_1 < \lambda_2 < \lambda_3$$

	sign$(\lambda_1, \lambda_2, \lambda_3)$
void	$(-\,,-\,,-)$
sheet	$(-,-,+)$
filament	$(-,+,+)$
cluster	$(+,+,+)$



Smoothing R = 0.6 Mpc/h

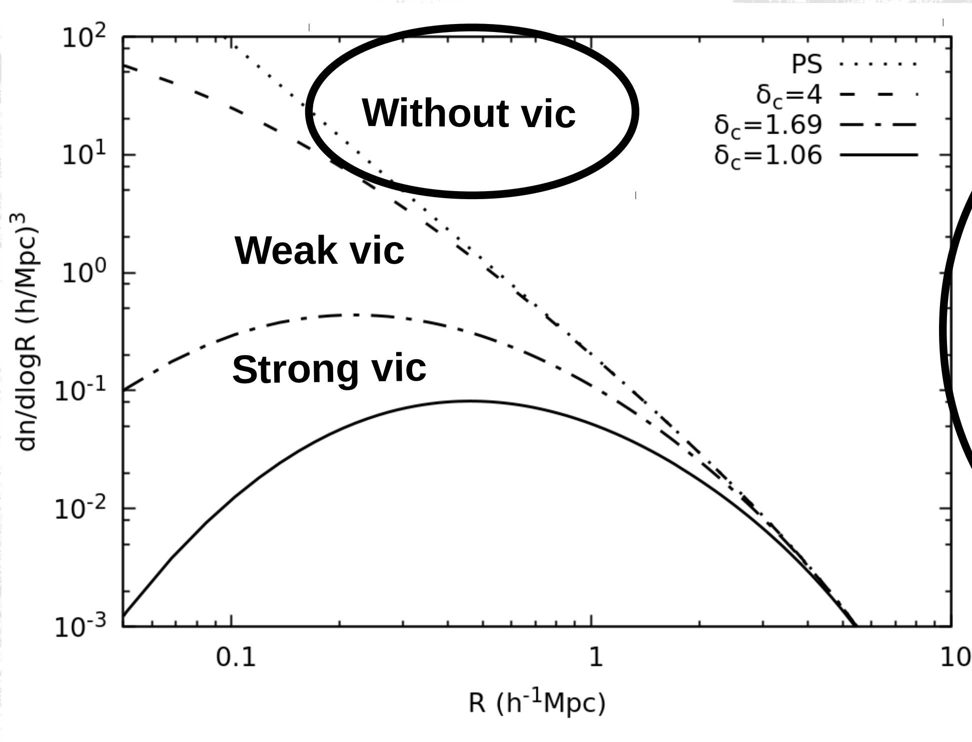
Void size function in various environment

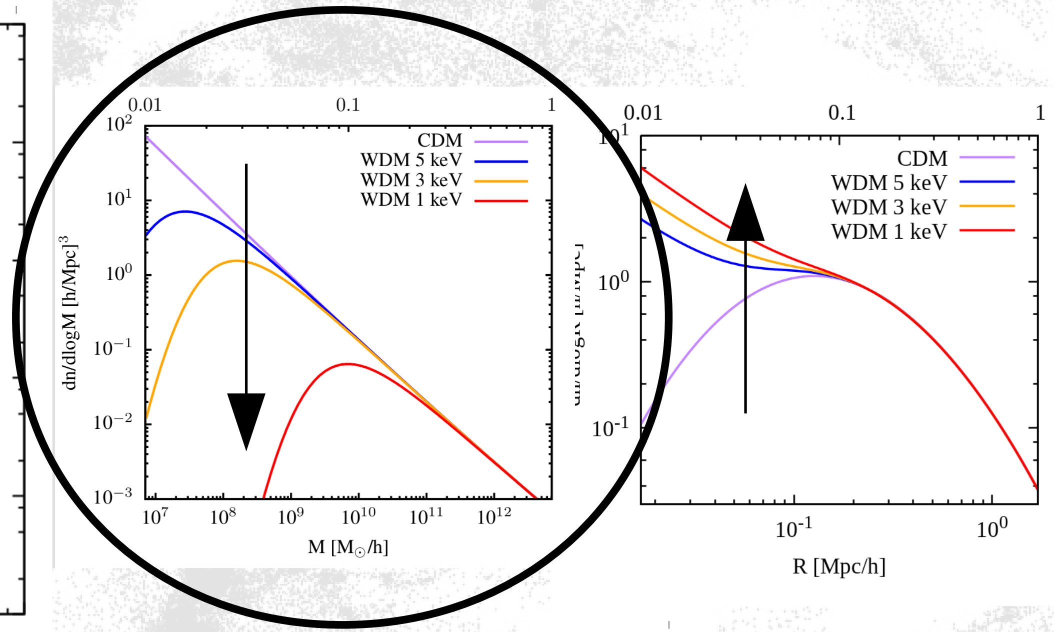


The void–in–void effect alone can explain the correlation between distribution and environments

The void–in–cloud effect is weak even in filaments and clusters.

Uniqueness of Void Distribution





Weak void–in–cloud ⟶ void distribution is less unique in their ability to probe DM

Summary

- **The Svdw model assumes a simplified void-in-cloud scenario.**

  Small voids are

  (i) abundant
  (ii) mostly partially collapsing underdensities
  (iii) even in filaments and clusters

- **Void distribution <u>may not</u> be a unique probe of WDM**

- **Eulerian framework, and alternative void model**

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