The Nature of Voids:
theory and simulation

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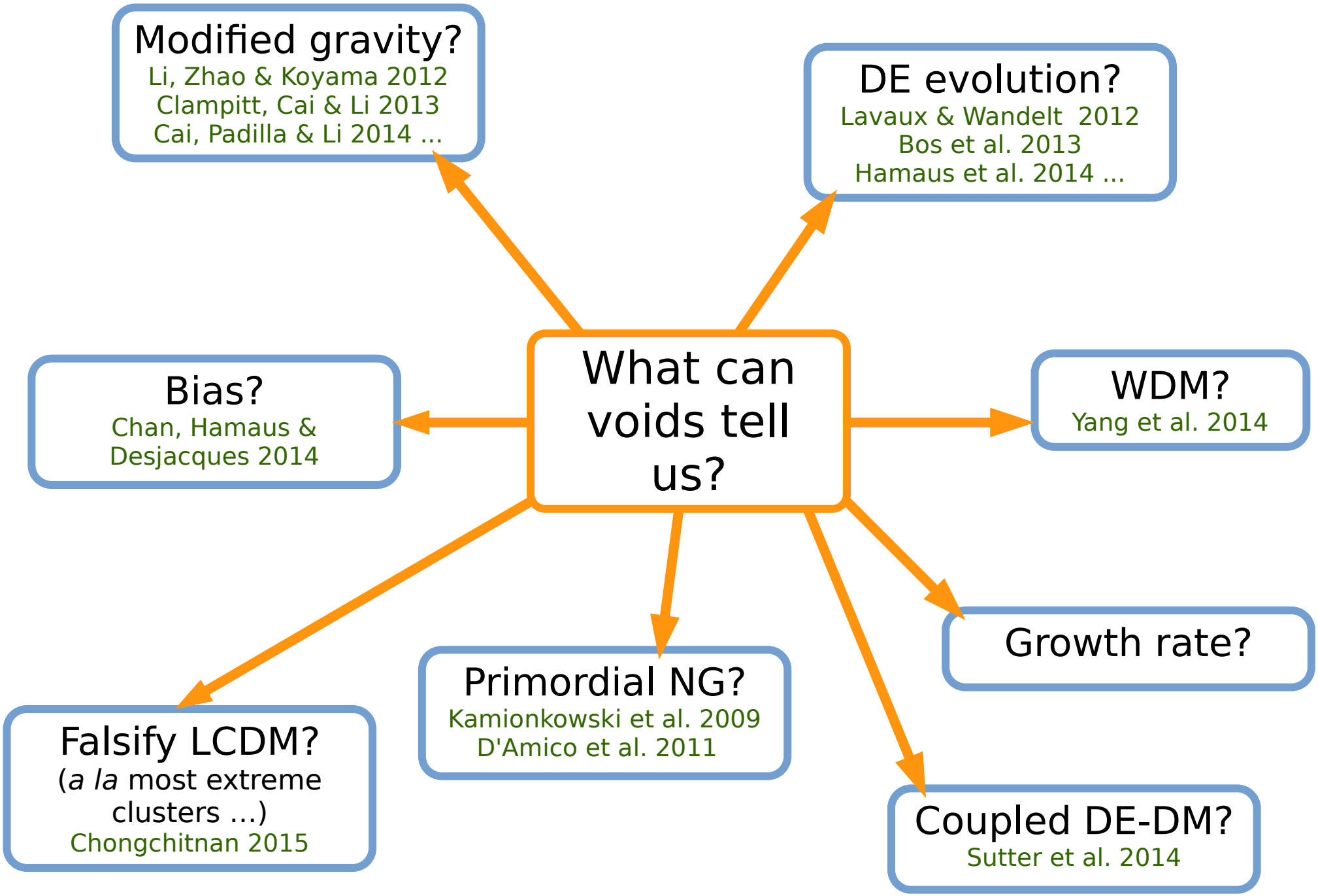
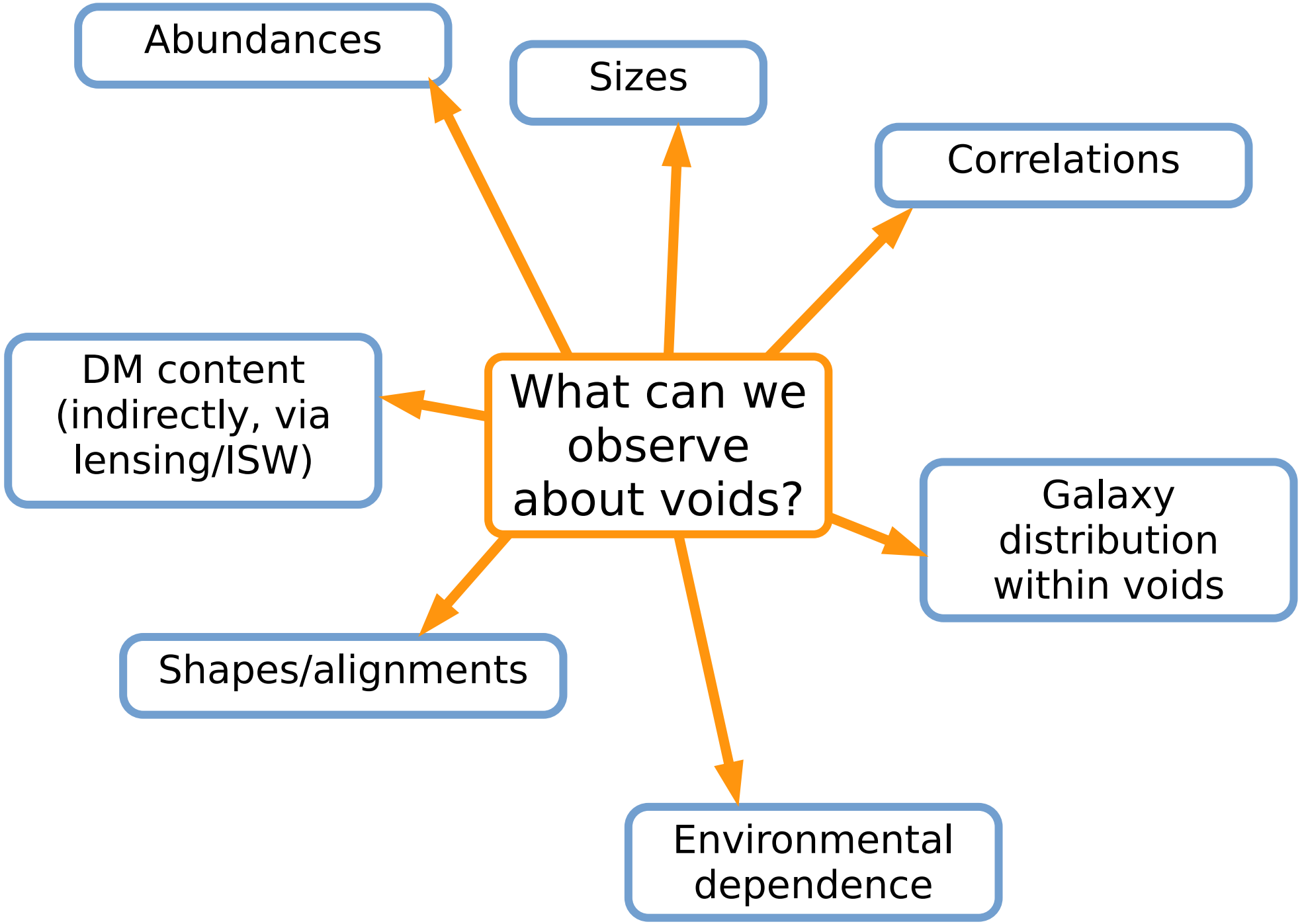
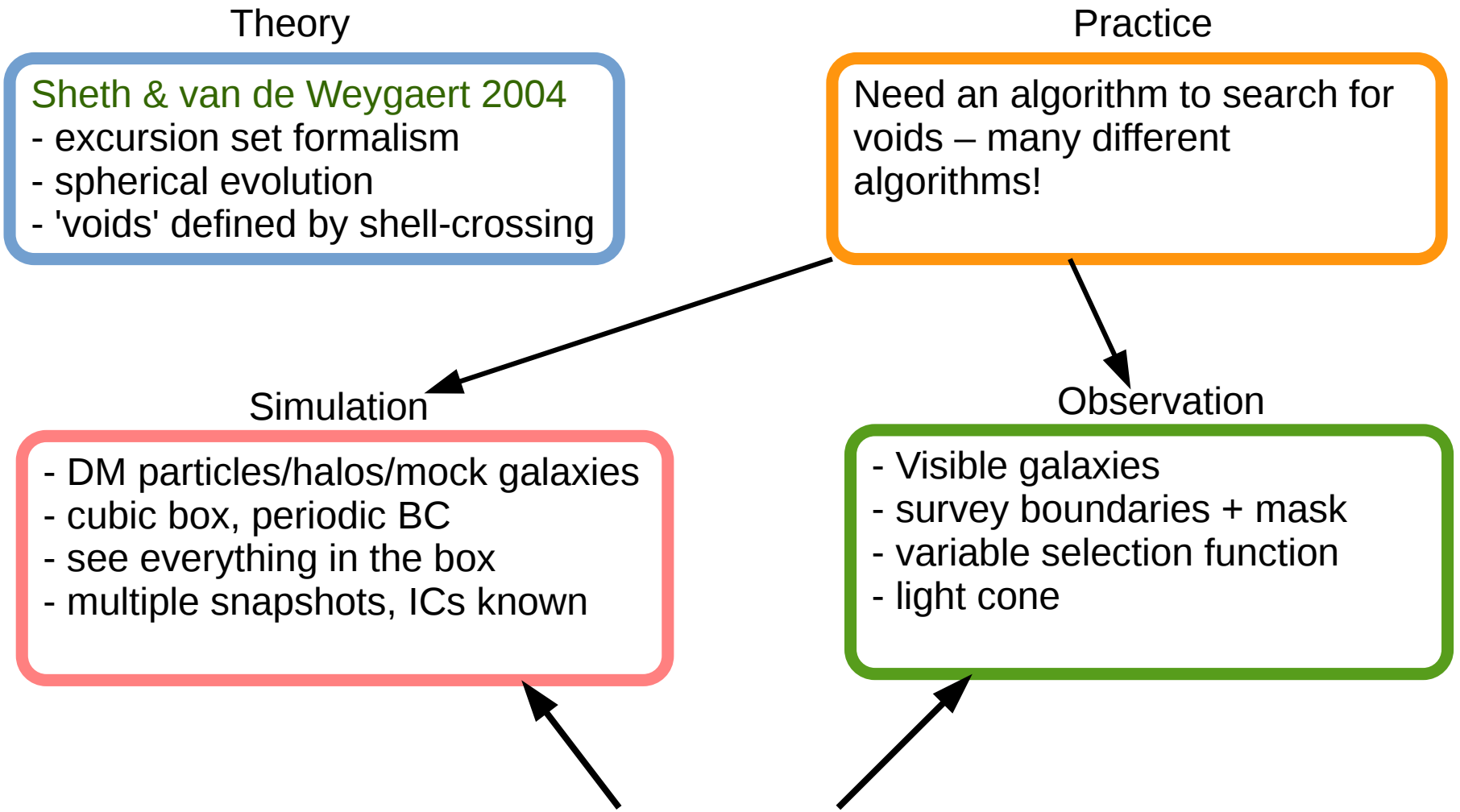
What can voids tell us?


What can voids tell us?
Modified gravity?
Li, Zhao & Koyama 2012
Clampitt, Cai & Li 2013
Cai, Padilla & Li 2014 ...
DE evolution?
Lavaux & Wandelt 2012
Bos et al. 2013
Hamaus et al. 2014 ...
Bias?
Chan, Hamaus & Desjacques 2014
WDM?
Yang et al. 2014
Falsify LCDM?
(*a la* most extreme clusters ...)
Chongchitnan 2015
Primordial NG?
Kamionkowski et al. 2009
D'Amico et al. 2011
Growth rate?
Coupled DE-DM?
Sutter et al. 2014

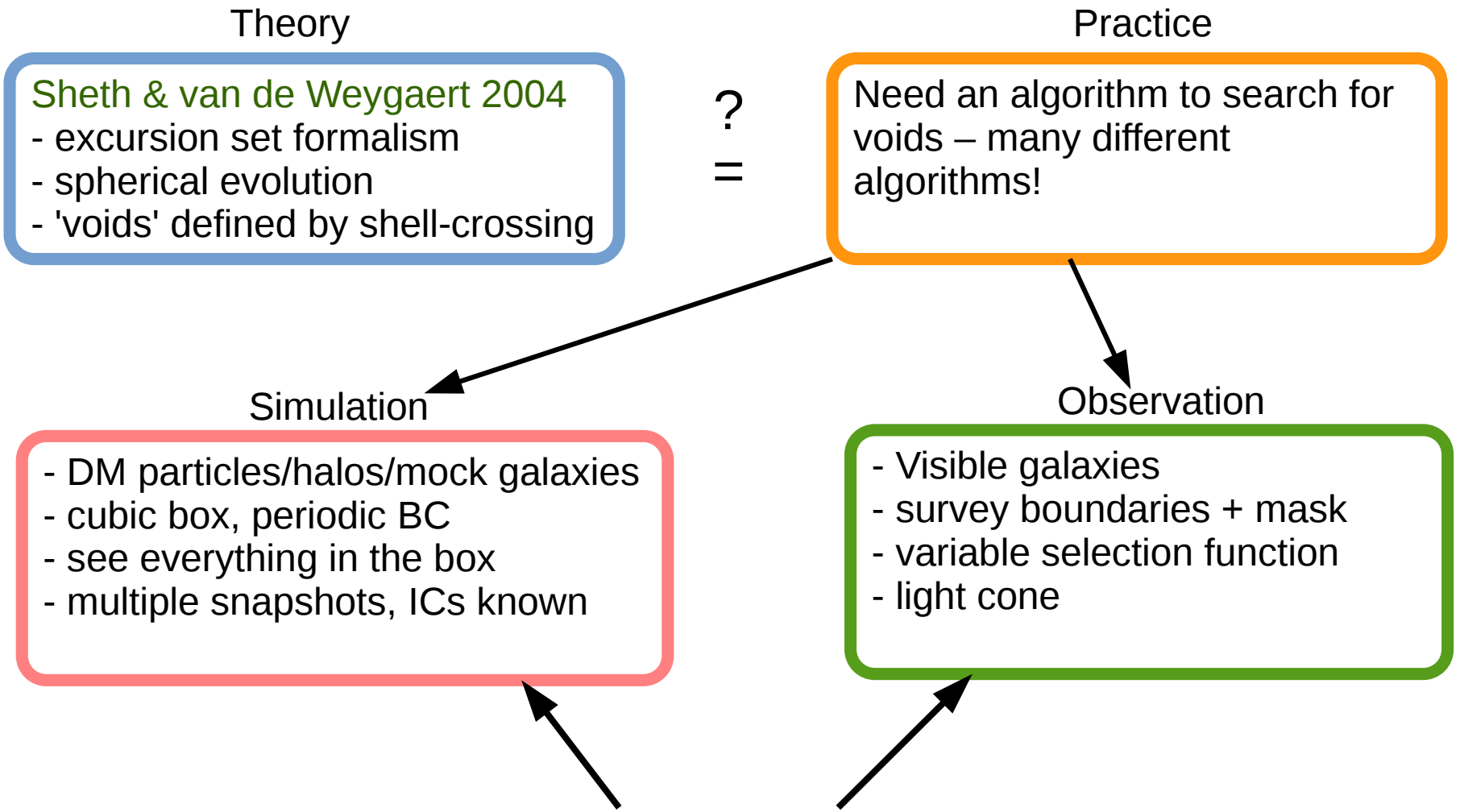

Abundances
Sizes
Correlations
DM content (indirectly, via lensing/ISW)
What can we observe about voids?
Galaxy distribution within voids
Shapes/alignments
Environmental dependence

What is a 'void'?



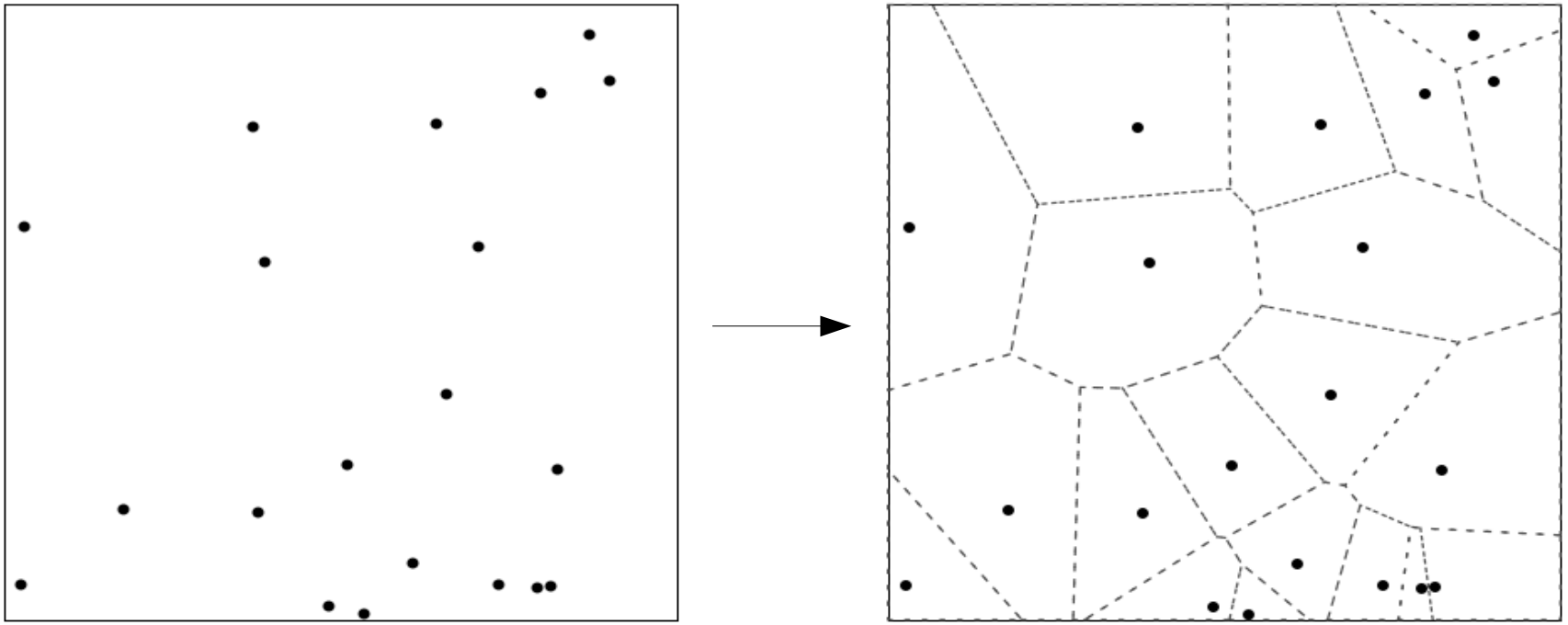
but be careful in applying ZOBOV to survey data! (see Nadathur & Hotchkiss 2014)

What is a 'void'?



but be careful in applying ZOBOV to survey data! (see Nadathur & Hotchkiss 2014)

ZOBOV uses Voronoi tessellation to reconstruct density



$$\rho_i = \frac{1}{V_i}$$

Self-adaptive scaling – more resilient to shot noise

ZOBOV is a watershed algorithm

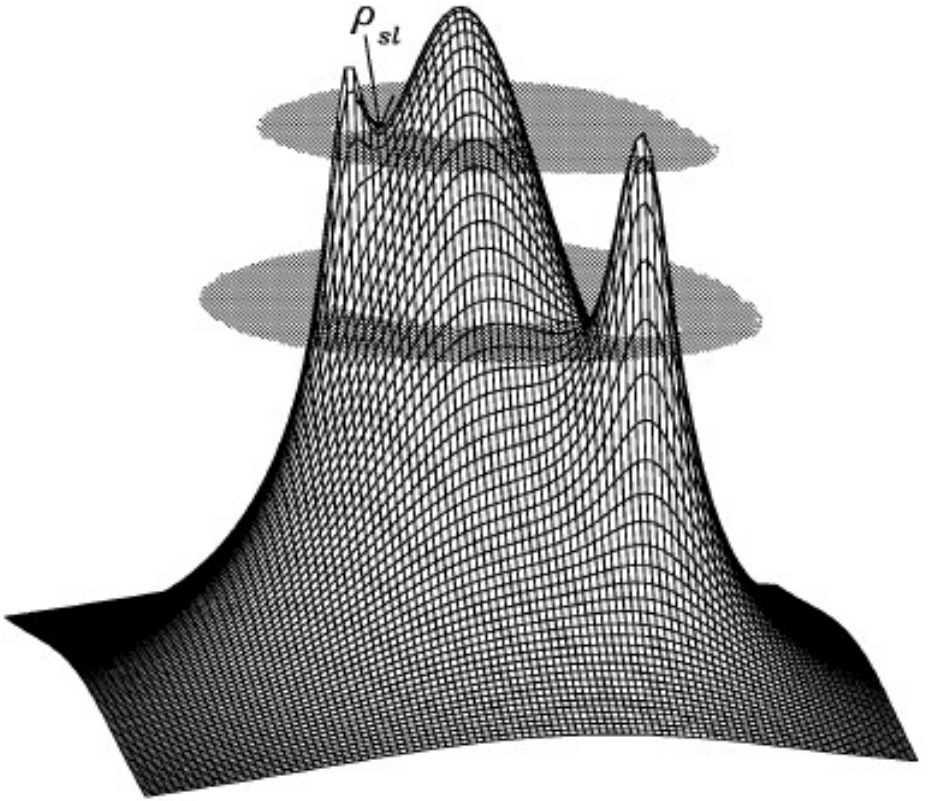


figure from Mark Neyrinck

ZOBOV is a watershed algorithm

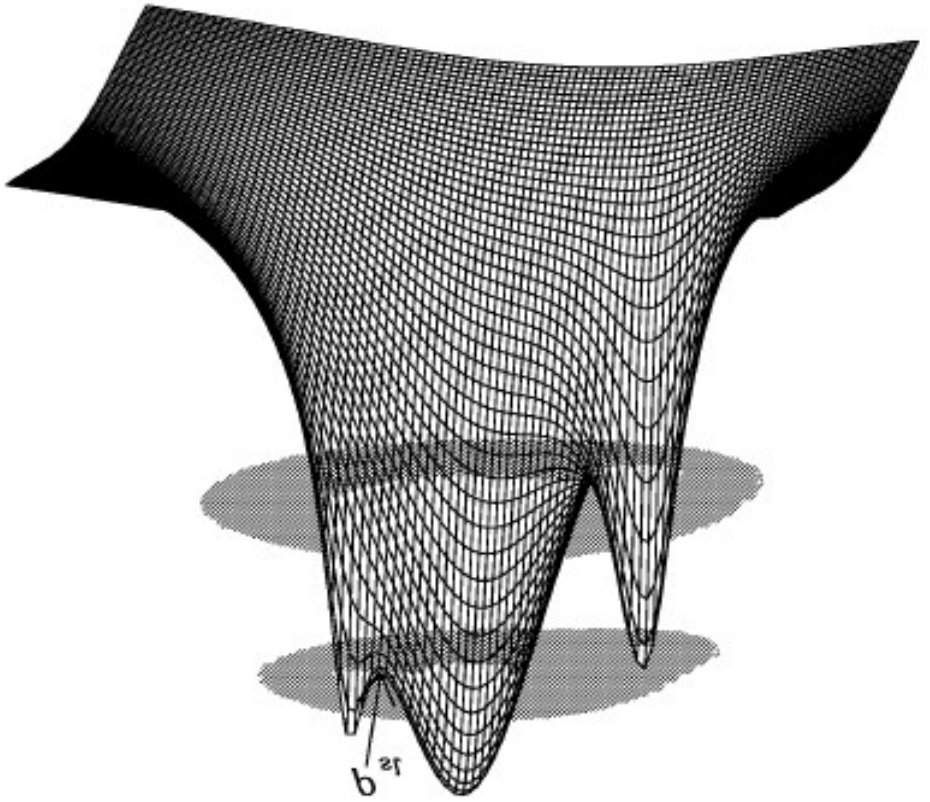


figure from Mark Neyrinck

To identify voids, ZOBOV requires a set of ***tracers*** of the DM density field in a simulation

DM particles as tracers – ok, but *unobservable* (we see galaxies)

Strategy 1

Use random subset of DM particles in simulation
– match $\overline{n}$ to mean galaxy density in surveys

Strategy 2

Use mock galaxies
– HOD/SHAM/semi-analytic
– match mock clustering properties to surveys

Strategy 2 appears more realistic, but let's start with Strategy 1.

Theoretical model of voids: main features

– Shell-crossing occurs when (for all voids)

$$\Delta = \frac{\rho(< R_v)}{\overline{\rho}} - 1 \simeq -0.8$$

– Lin. extrapolated $\Delta_{\rm lin} = \delta_{\rm v} \simeq -2.7$

– Void distribution

$$\frac{dn}{dR_v} = \frac{f(\nu)}{V(R_L)} \frac{d\nu}{dR_L}\bigg|_{R_L = 0.58 R_v} \; ; \; \nu \equiv \frac{\delta_{\rm v}^2}{\sigma^2}$$

– Smaller voids ◄► deeper density minima

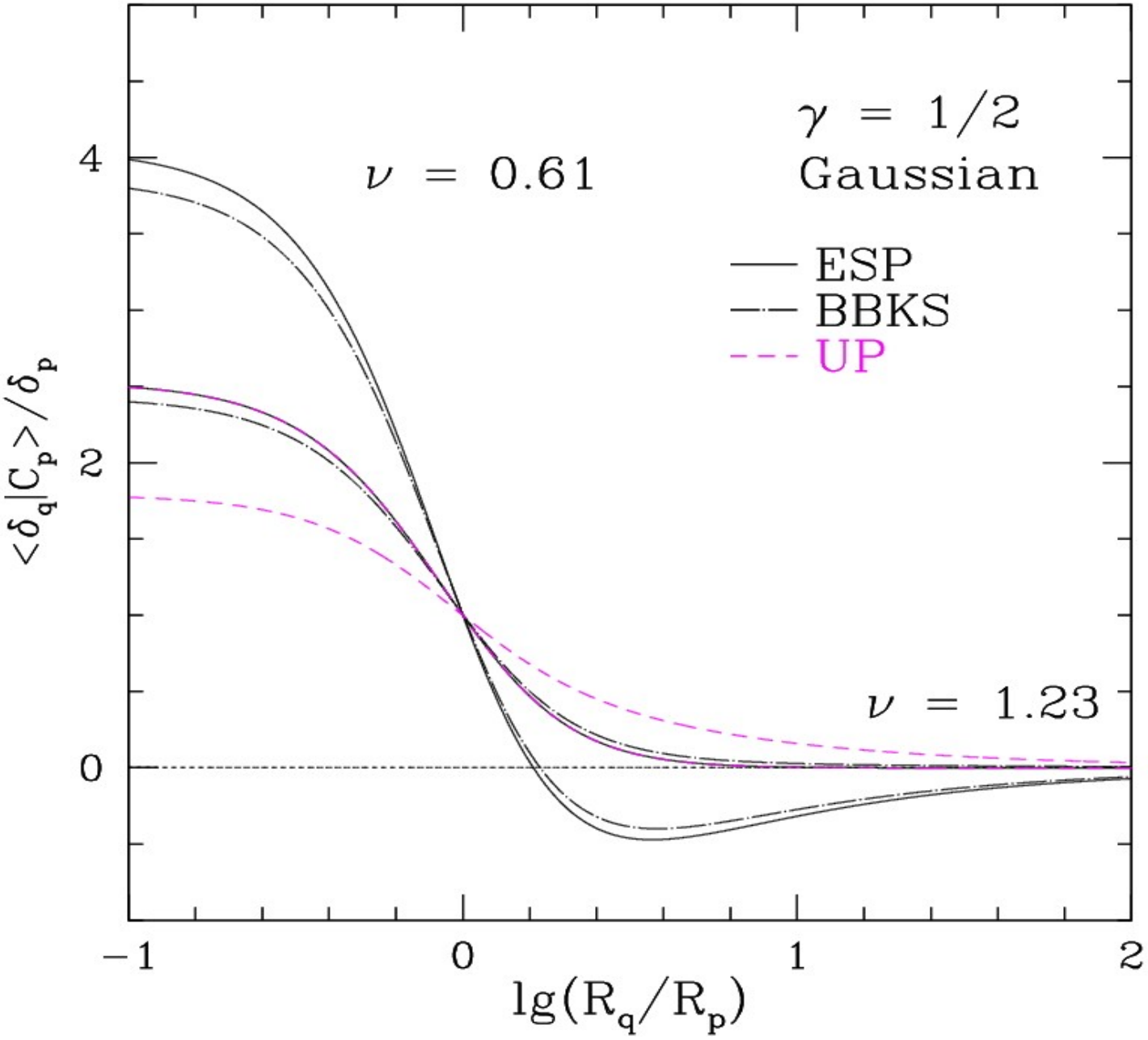


figure courtesy Elena Massara & Ravi Sheth

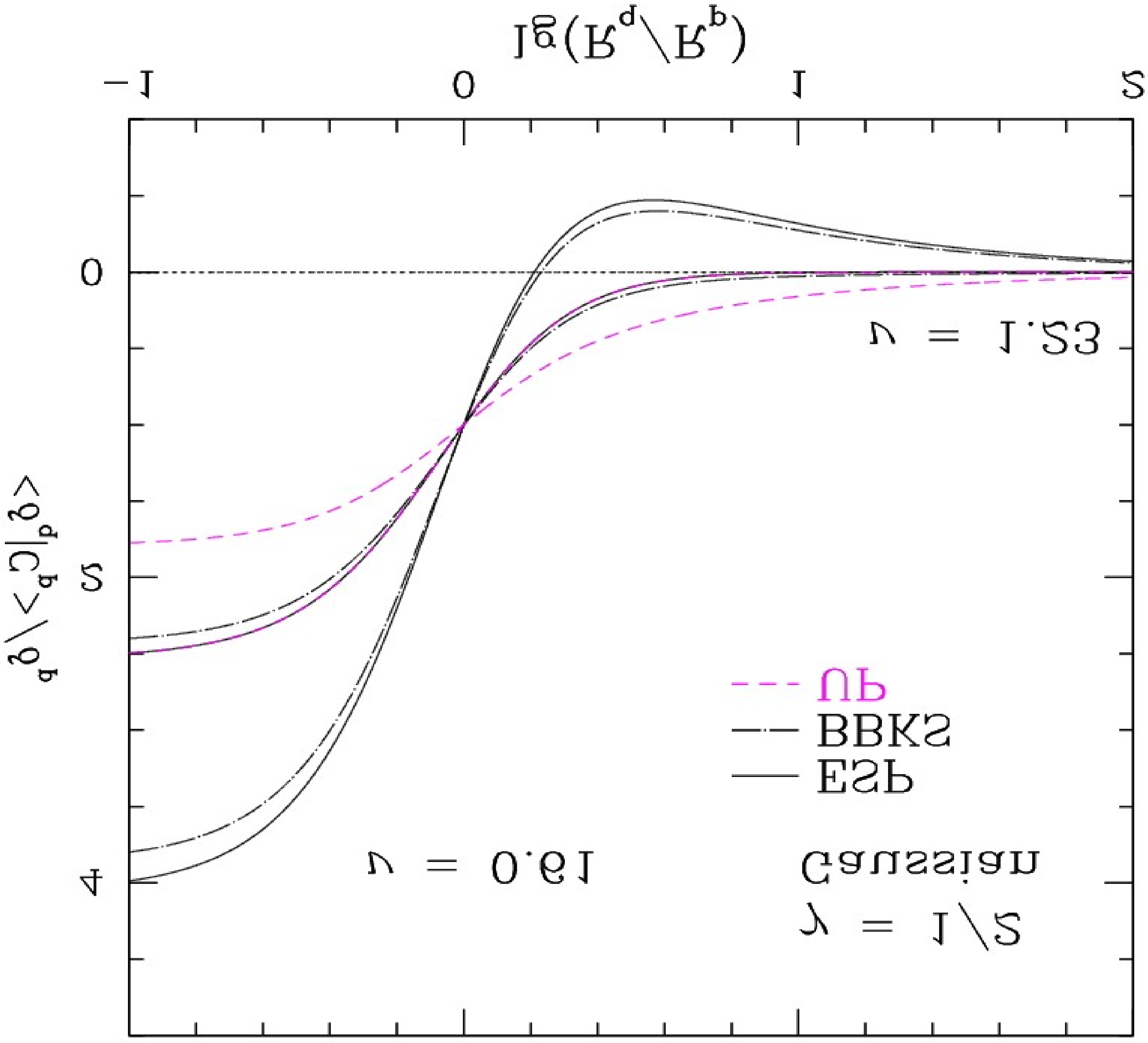
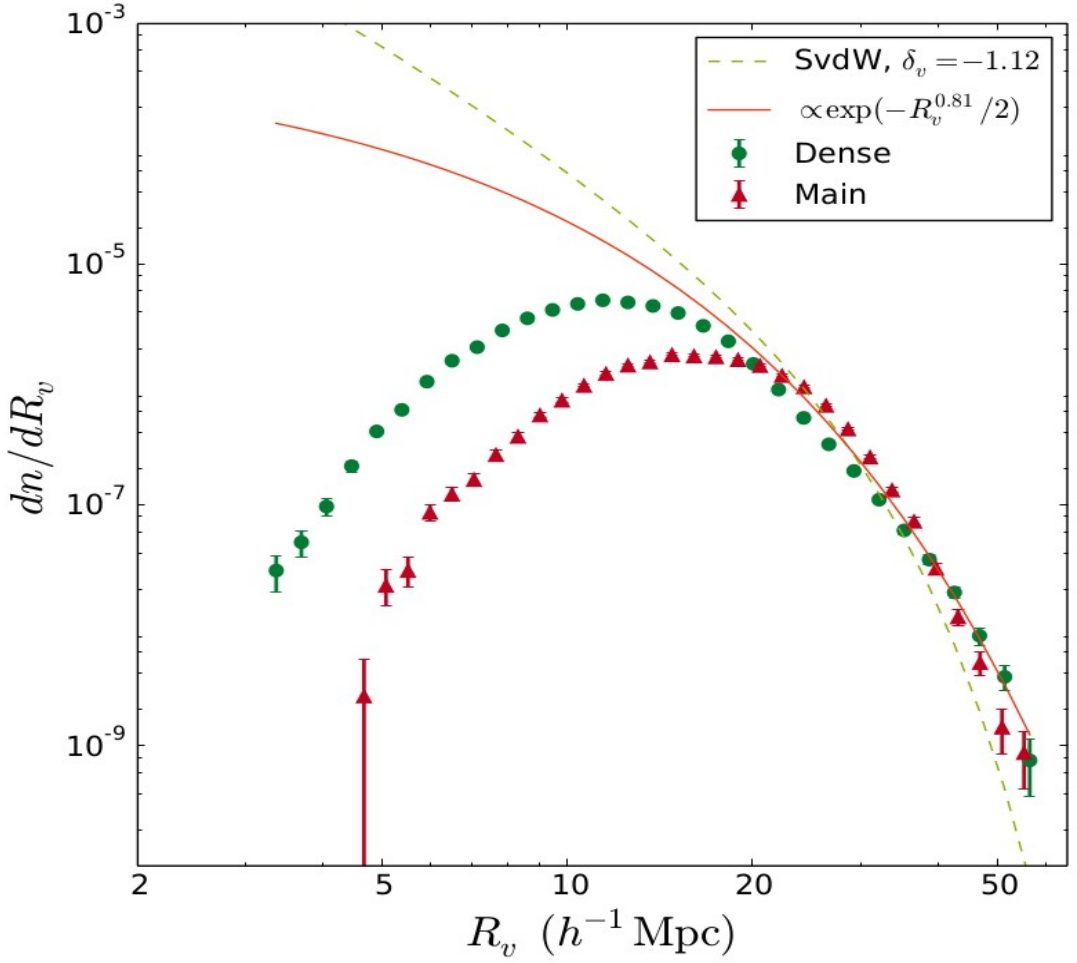


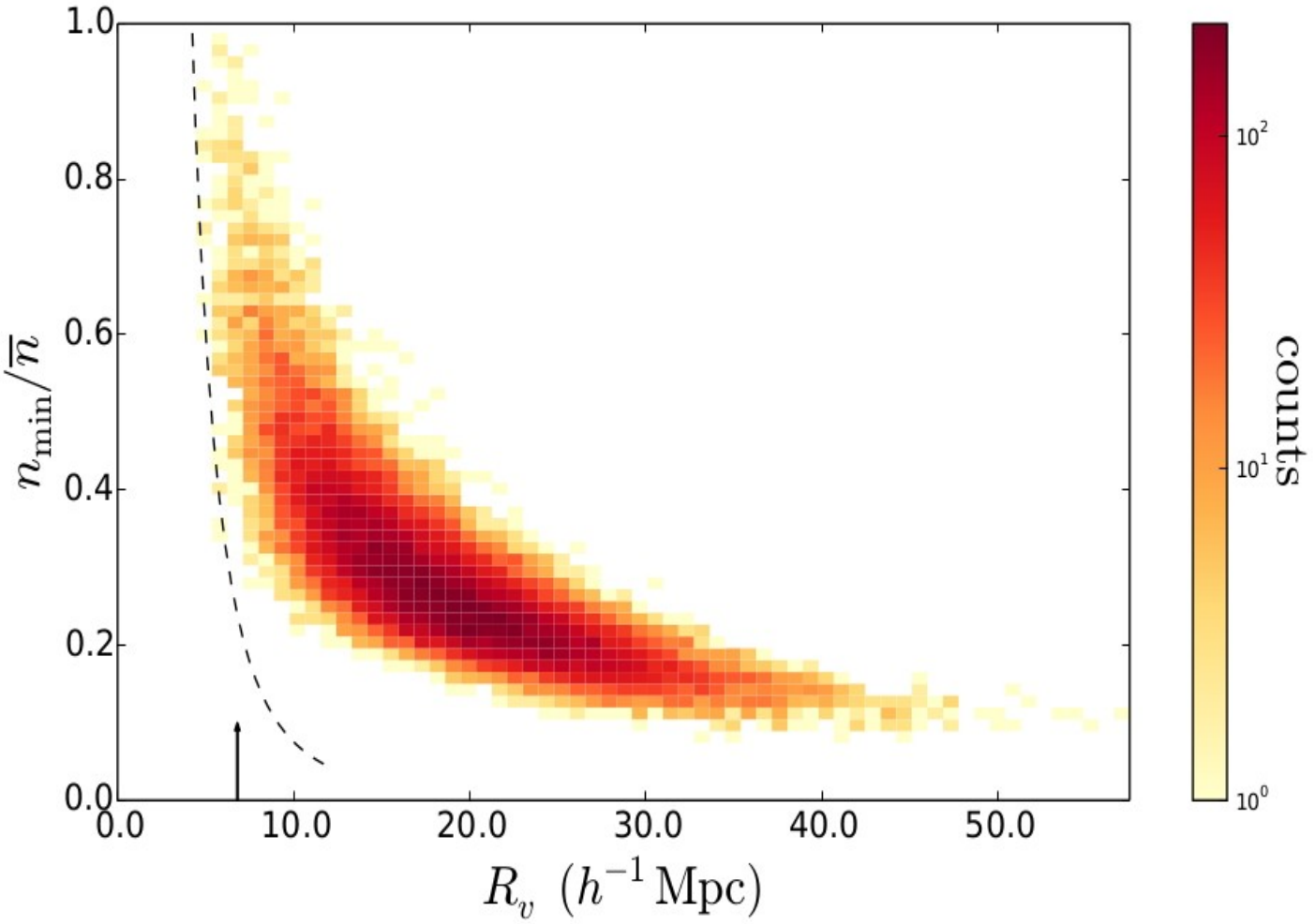
figure courtesy Elena Massara & Ravi Sheth

We already know void distribution in simulations doesn't fit well ...



Nadathur & Hotchkiss 2015a

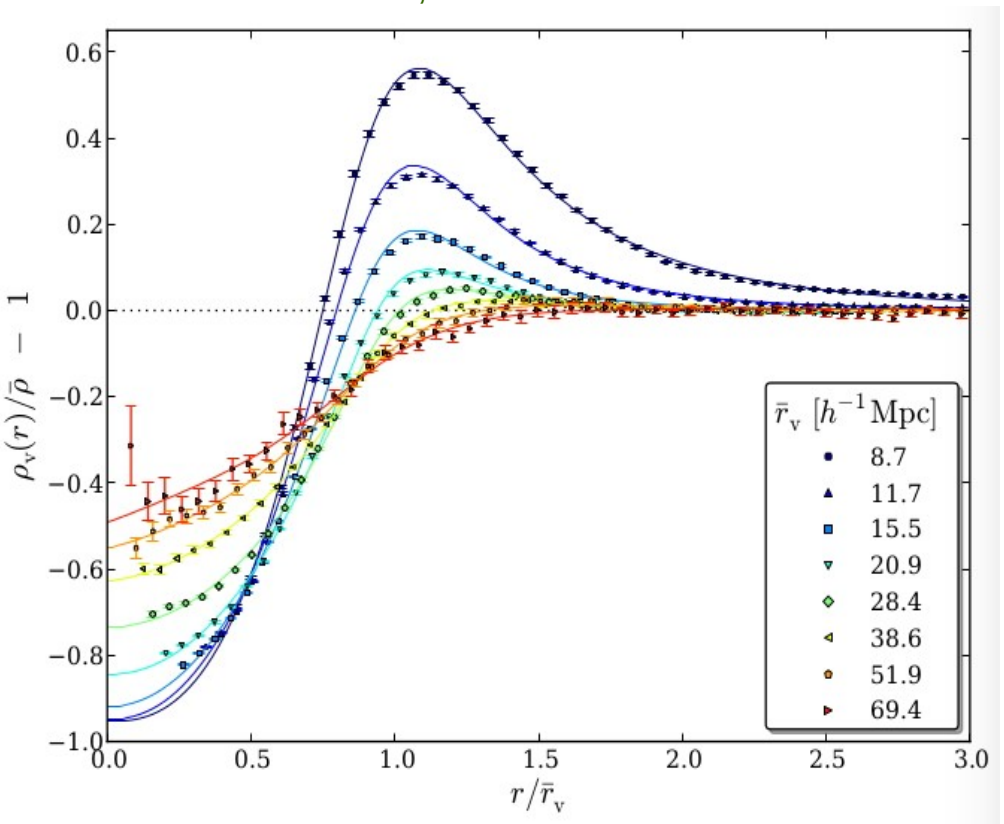
So what about other features?



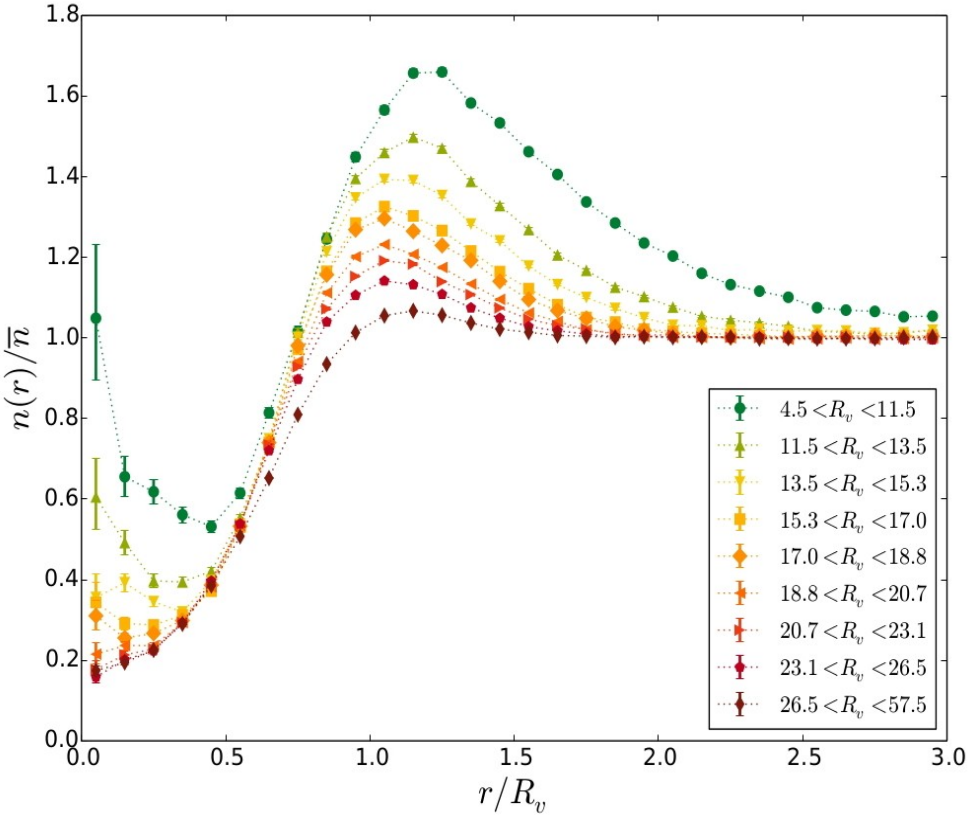
Larger voids are deeper – generic feature of ZOBOV (and all watershed void finders!)

'Universal' density profile?

Hamaus, Sutter & Wandelt 2014



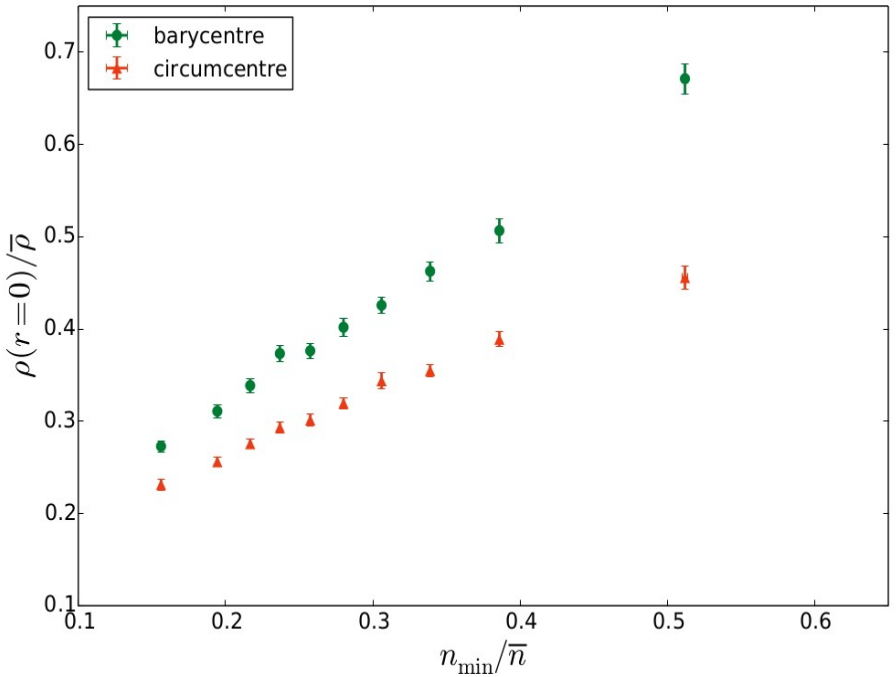
Nadathur & Hotchkiss 2015a

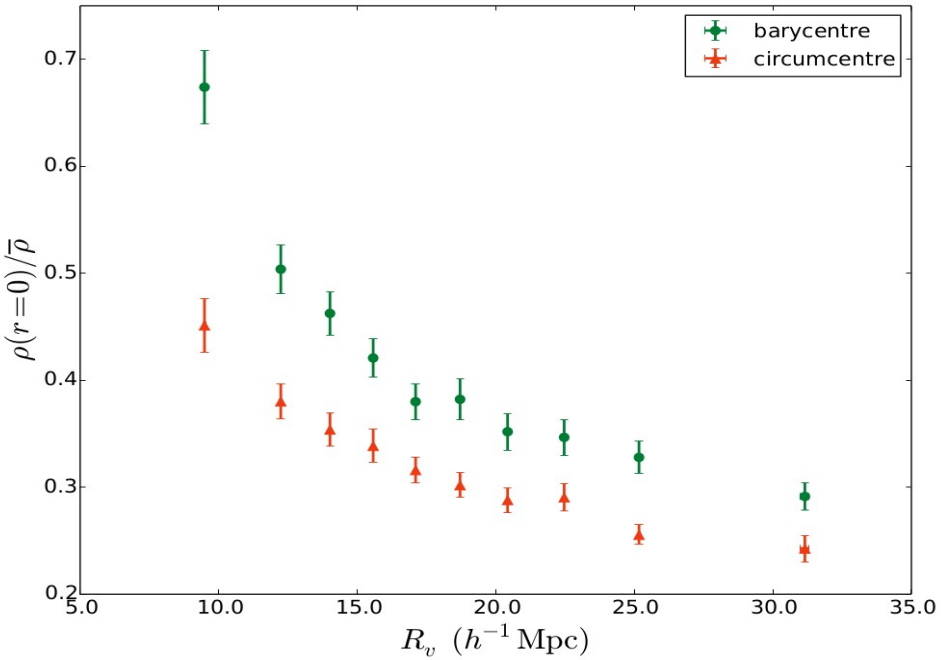


We don't agree.

(But our result is consistent with watershed principles)

Tracer number density vs. dark matter density

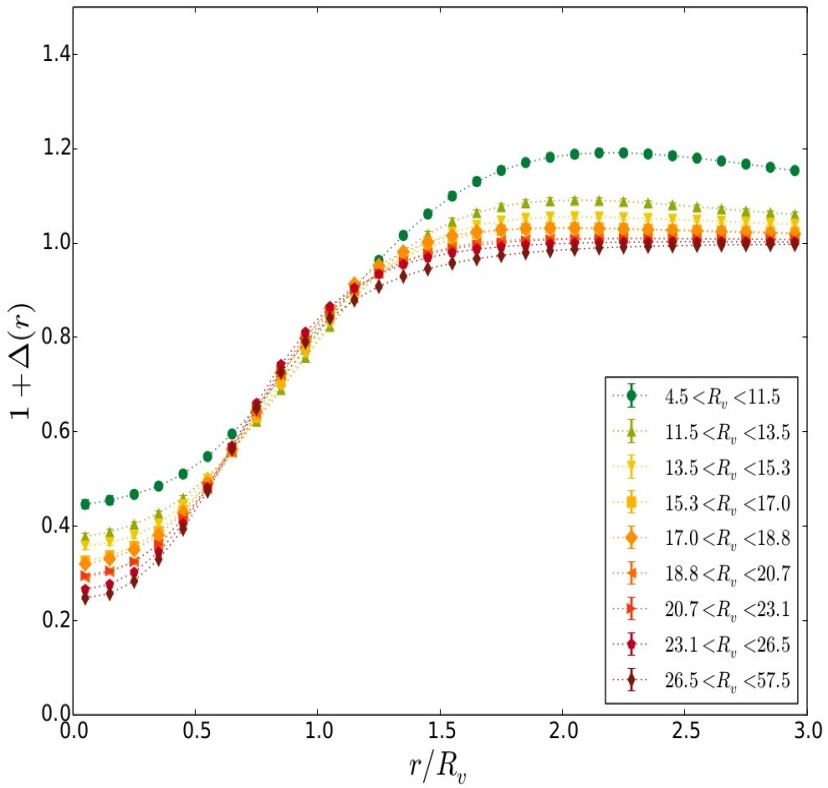




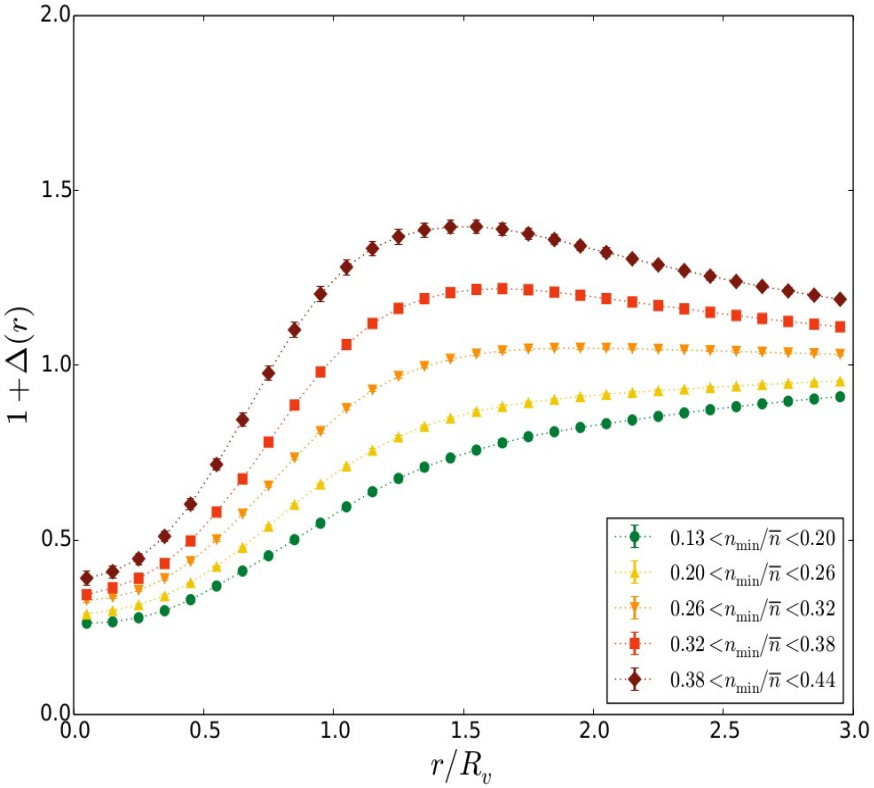
Nadathur & Hotchkiss 2015a

Related, but not the same. Larger voids still have deeper minima.

DM content of voids



different radii



same radius, diff. min. tracer densities

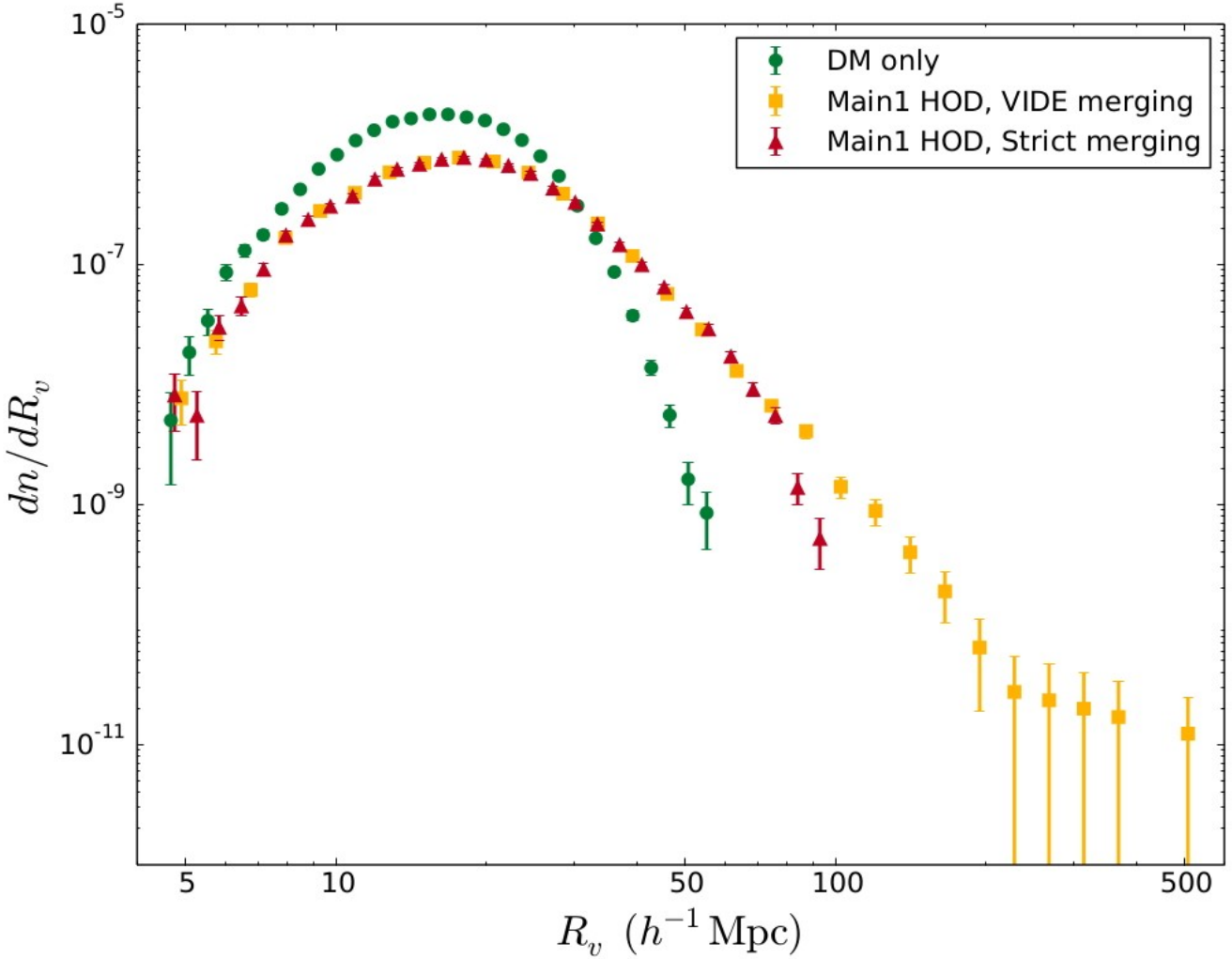
Nadathur & Hotchkiss 2015a

The word 'void' means different things in different contexts!

Excursion set model voids ≠ ZOBOV/watershed voids

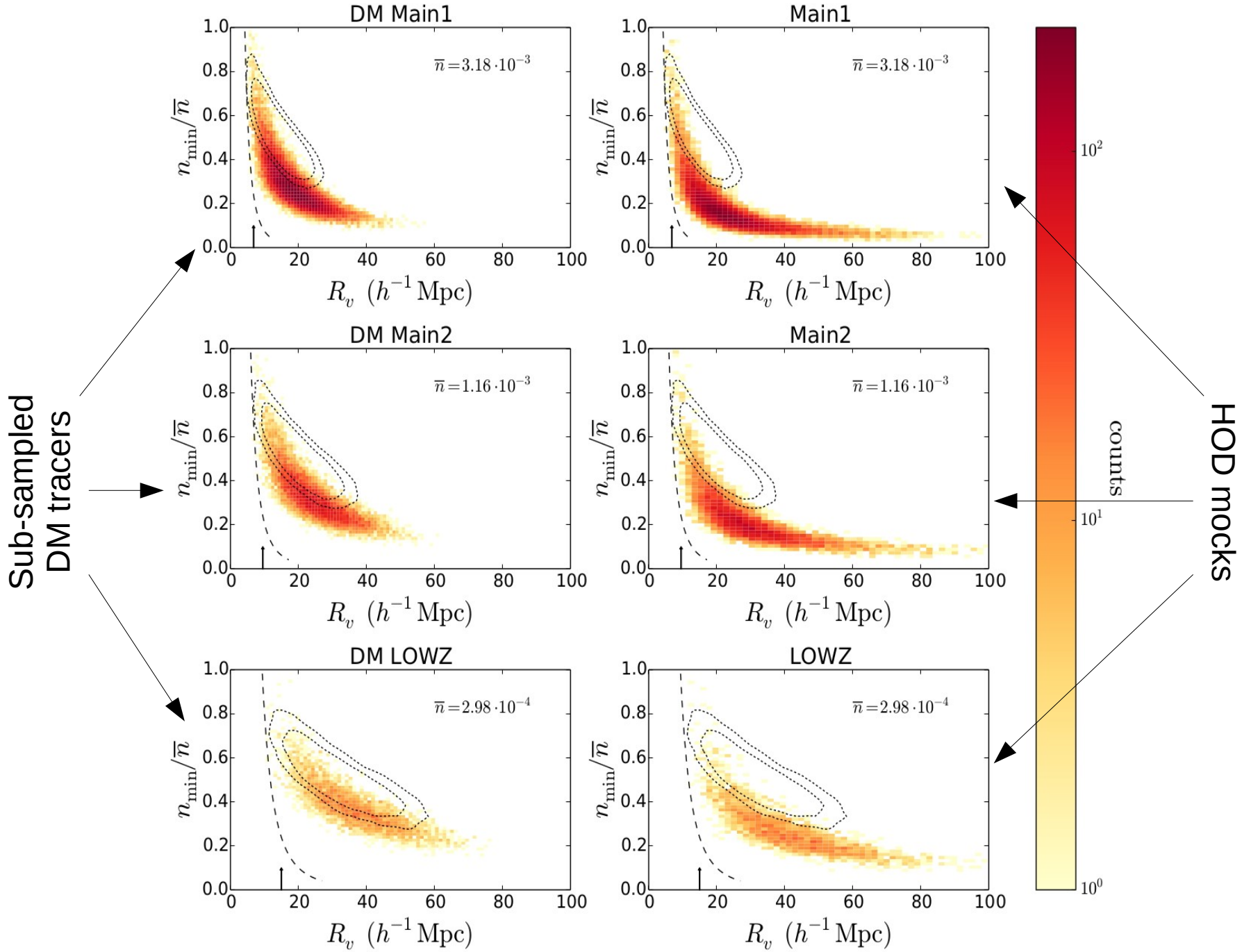
What about voids traced by galaxies?

Galaxies change void abundances and sizes



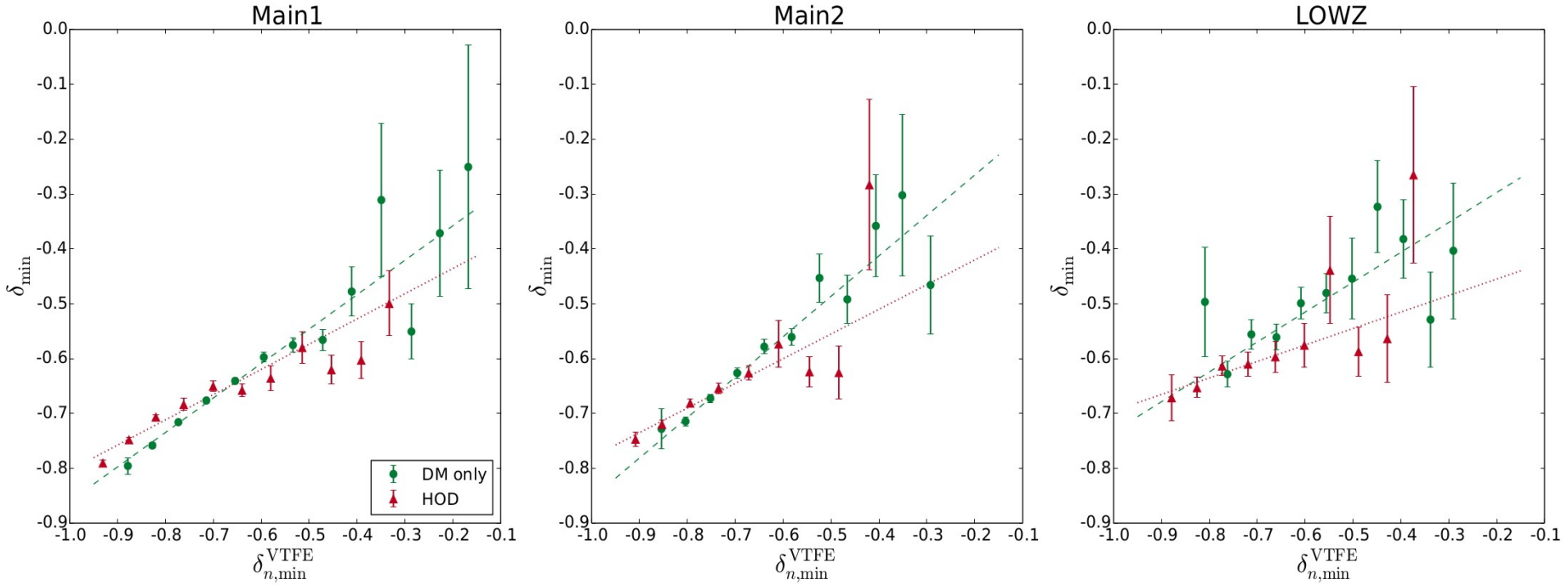
> 50% difference in total numbers!

Nadathur & Hotchkiss 2015b, in prep.



Nadathur & Hotchkiss 2015b, in prep.

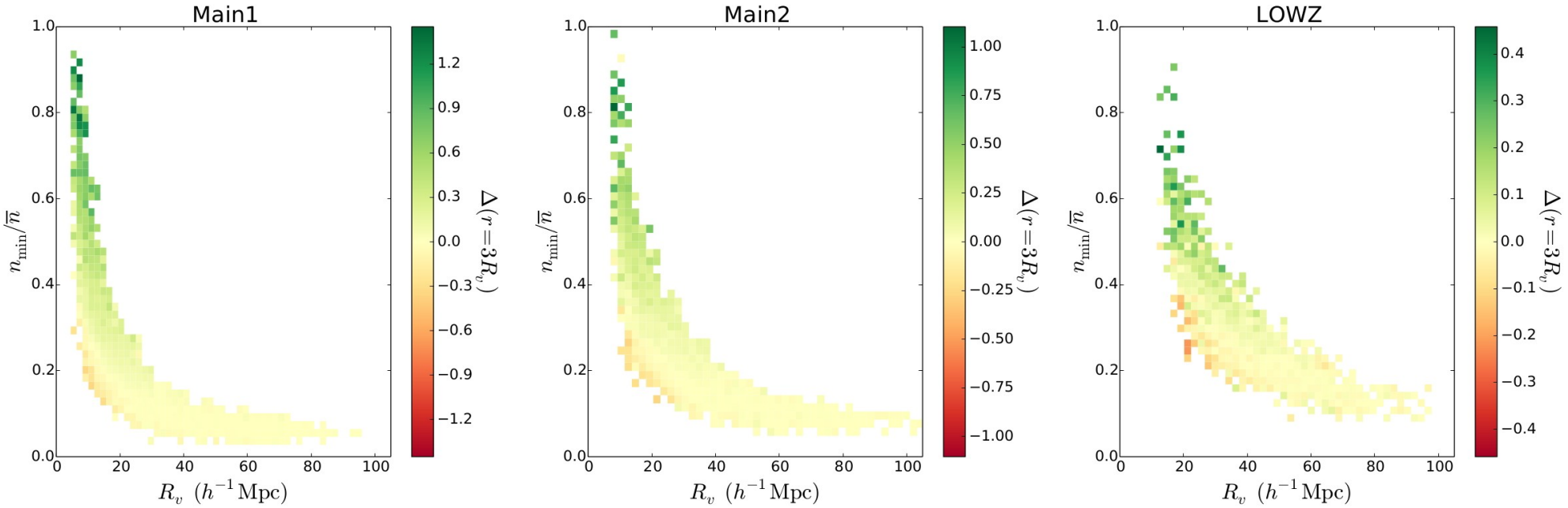
Galaxy voids trace DM underdensities differently



Voids traced by galaxies ≠ voids traced by sub-sampled DM

(obvious, with hindsight?)

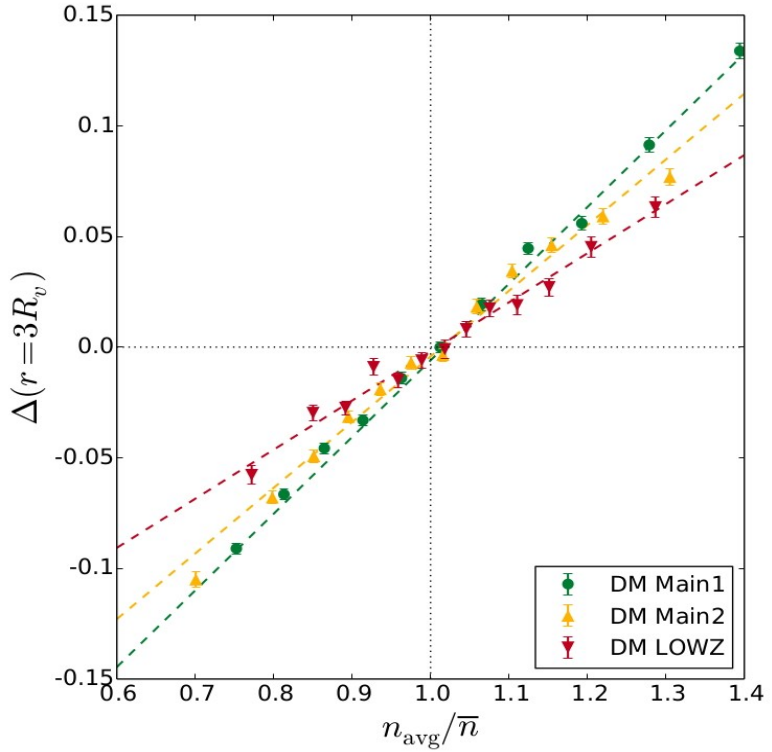
Compensation of mass deficit in voids

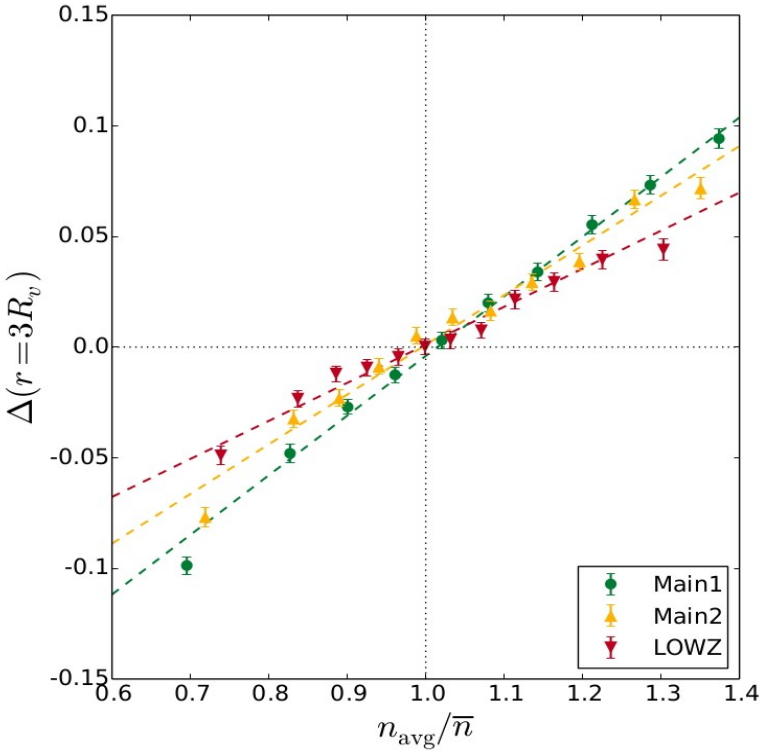


Nadathur & Hotchkiss 2015b, in prep.

Compensation of mass deficit in voids

Sub-sampled DM tracers



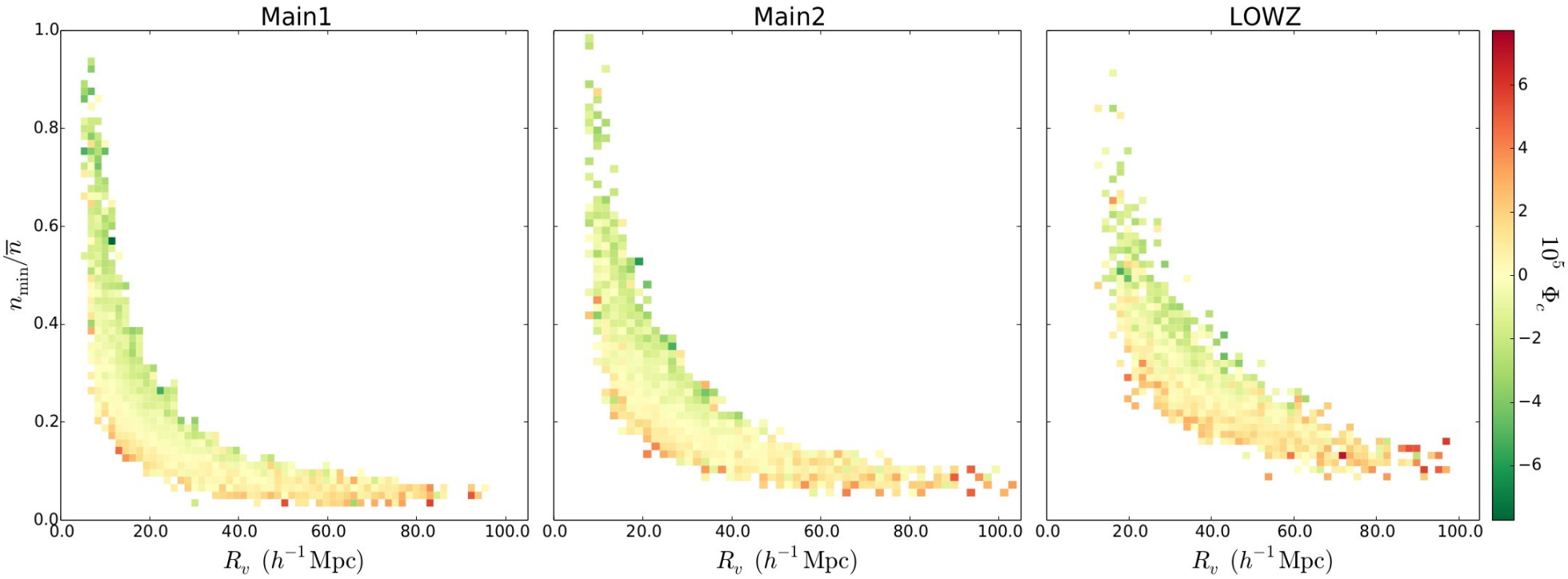


HOD mocks

Linear relationship, universal predictor of compensation

Nadathur & Hotchkiss 2015b, in prep.

Gravitational potential in voids

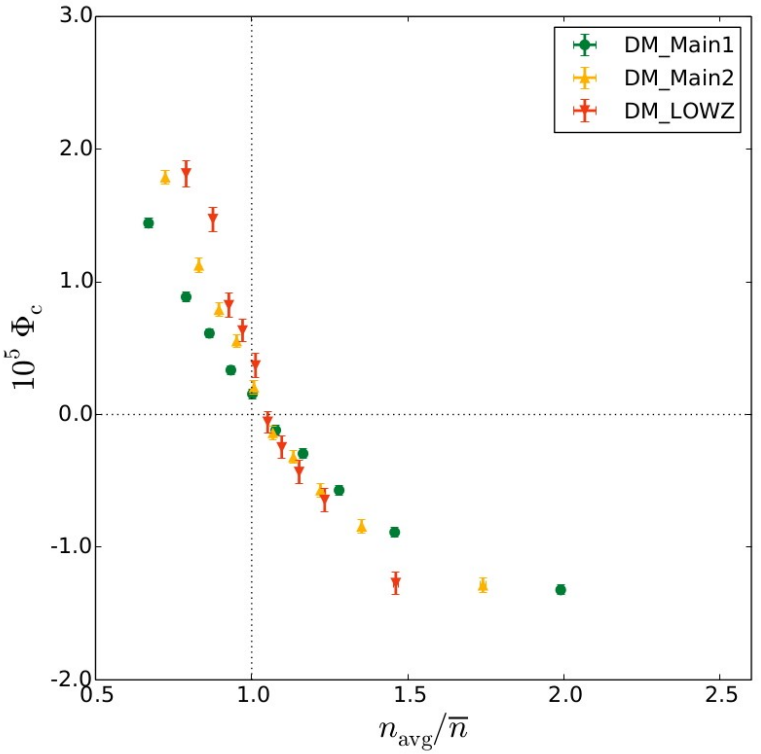


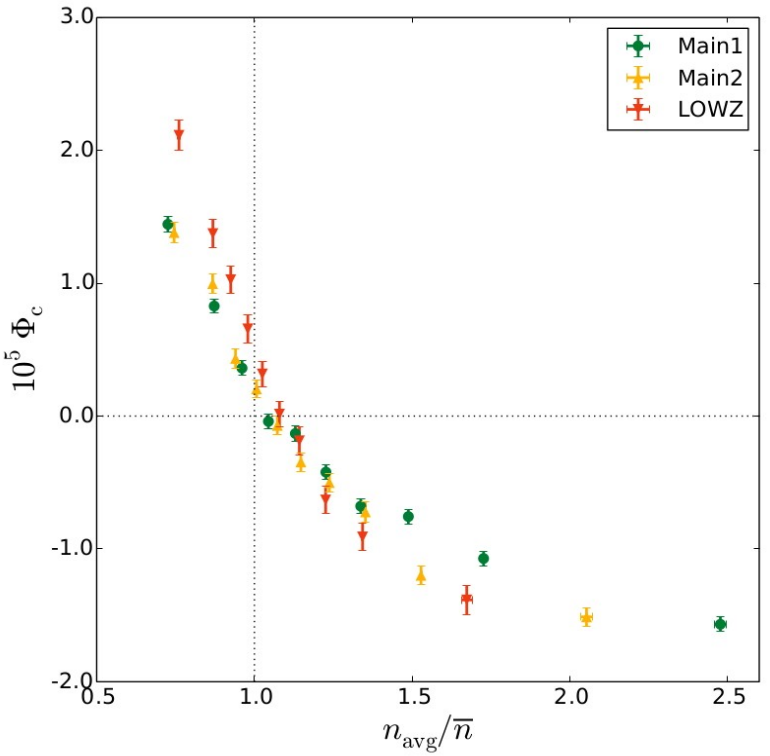
Naturally, $\Phi \leftrightarrow \Delta$

Hotchkiss & Nadathur 2015, in prep.

Gravitational potential in voids

Sub-sampled DM tracers





HOD mocks

Hotchkiss & Nadathur 2015, in prep.

Summary

- Excursion set model does not match (watershed) voids in simulation – because algorithms don't find objects matching model assumptions
- Meaning of the word 'void' context-dependent!
- Need for simulation-led approach/calibration

- In simulations, all void observables depend on tracer properties
- So to be observationally relevant, simulations must use mock galaxy tracers

- There are some nice properties of simulated voids – Δ, Φ – which can be predicted from observable quantities
- Maybe theory should start from here (work for the future...)