The self-similarity and universality of voids

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Summary

- What is a void, and what isn't
- The density profile around simulated voids is:
  - self-similar
  - independent of redshift (within simulation range)
- Profiles from simulation and SDSS data agree
- Profiles from SDSS are *universal*

What is a void?

- There is no 'Platonic ideal' everybody agrees on!
- But we can set some minimal conditions ...

What is a void?

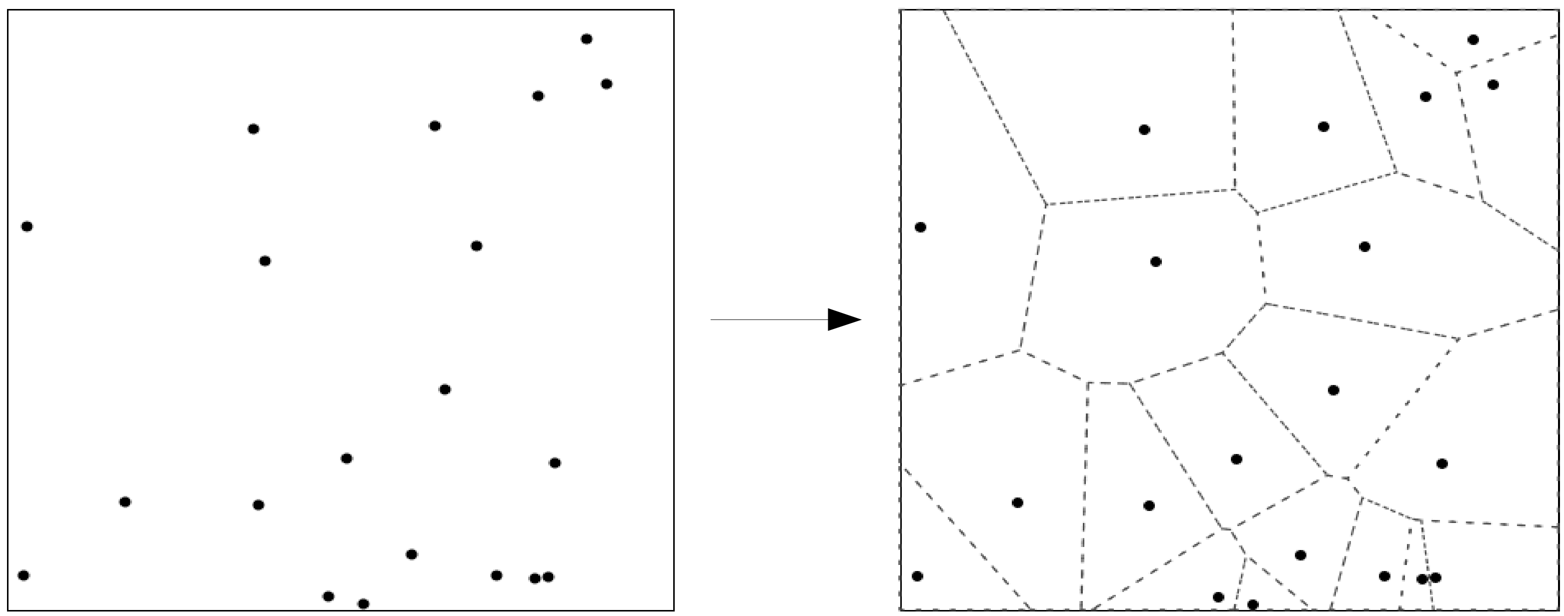
- A “void” should:
  - correspond to a density minimum
  - be underdense (not necessarily empty)
  - not be due to
    - spurious survey edge effects
    - spurious survey selection function effects
    - spurious shot noise effects
  - not be based on a priori shape assumptions

What is a void?

- Our results based on ZOBOV algorithm — Neyrinck, 2008, MNRAS
  - Voronoi tessellation + watershed transform

ZOBOV: density

- Voronoi tessellation field estimator (VTFE)



- Density estimate: $\rho_i = \frac{1}{V_i}$

ZOBOV: watershed

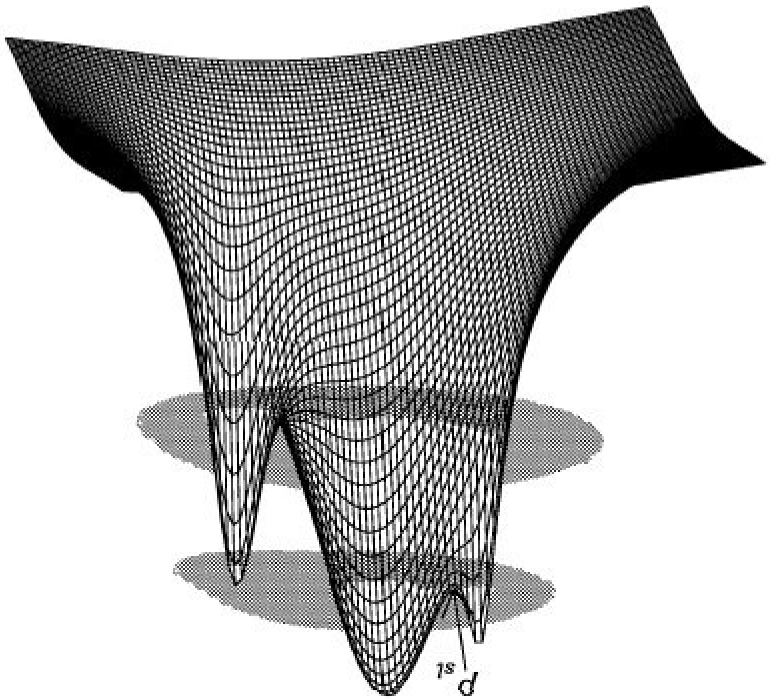


figure inverted from
Neyrinck et al, 2005!

Growth of voids through watershed transform

Applying ZOBOV to SDSS data

- DR7 Main Galaxy sample (NYU VAGC) Blanton et al. (2005)
  - spectroscopic samples *dim1*, *dim2*, *bright1*, *bright2*
  - redshift ranges $z < 0.05$, $z < 0.1$, $z < 0.15$, $z < 0.2$
- DR7 Luminous Red Galaxy sample Kazin et al. (2010)
  - *lrgdim and lrgbright*
  - redshift ranges $0.16 < z < 0.36$, $0.16 < z < 0.44$
  - *lrgdim* only quasi-volume limited
- Tracer galaxy number density varies by 3 orders of magnitude from *dim1* to *lrgbright* !

The Jubilee simulation

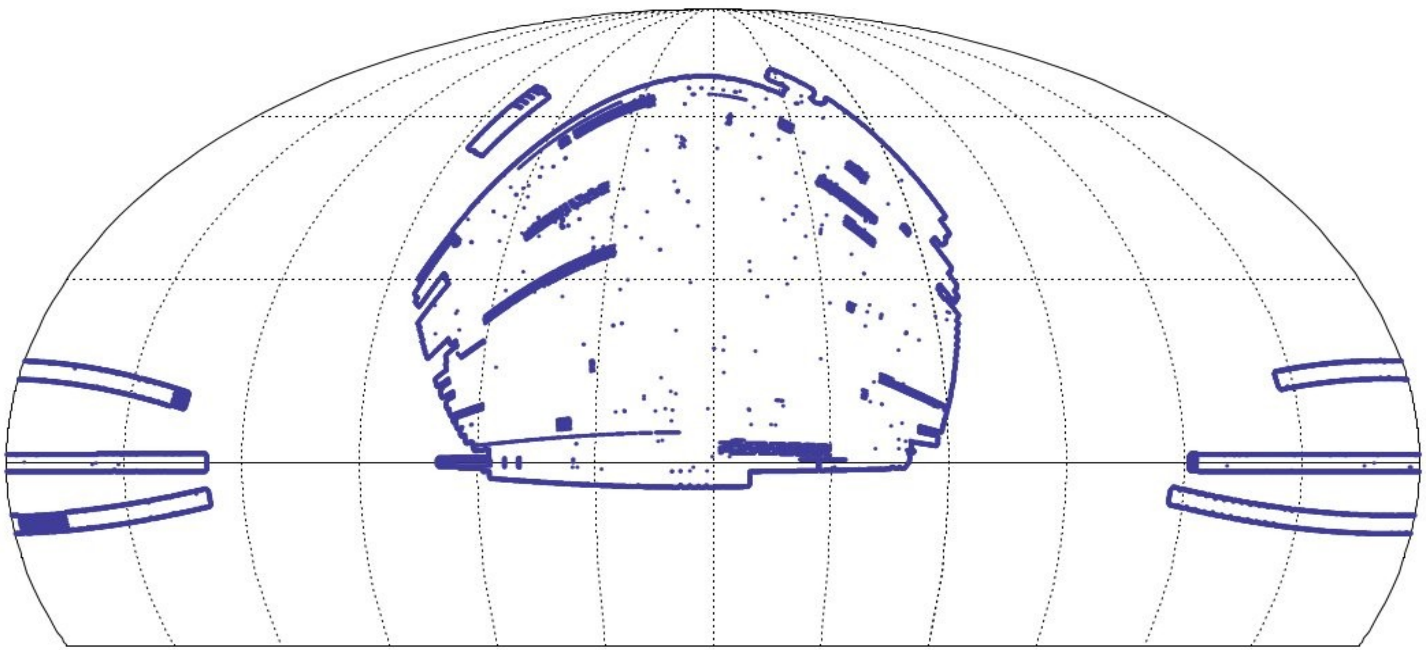
- Very large N-body simulation Watson et al. (2014a) (arXiv:1305.1976)
  - $(6\,h^{-1}\mathrm{Gpc})^3$ box
  - 6000^3 particles
  - particle mass $\sim 7.5 \times 10^{10}\,\mathrm{M}_\odot$
  - halo mass resolution $\sim 1.5 \times 10^{12}\,\mathrm{M}_\odot$
  - WMAP5 cosmology
- HOD modelling of LRGs on the light cone

  details in Watson, … , SN et al. (2014b)

- Two mock LRG catalogues - “JDim” and “JBright”
  - match the properties of real SDSS LRG samples

ZOBOV: example complications

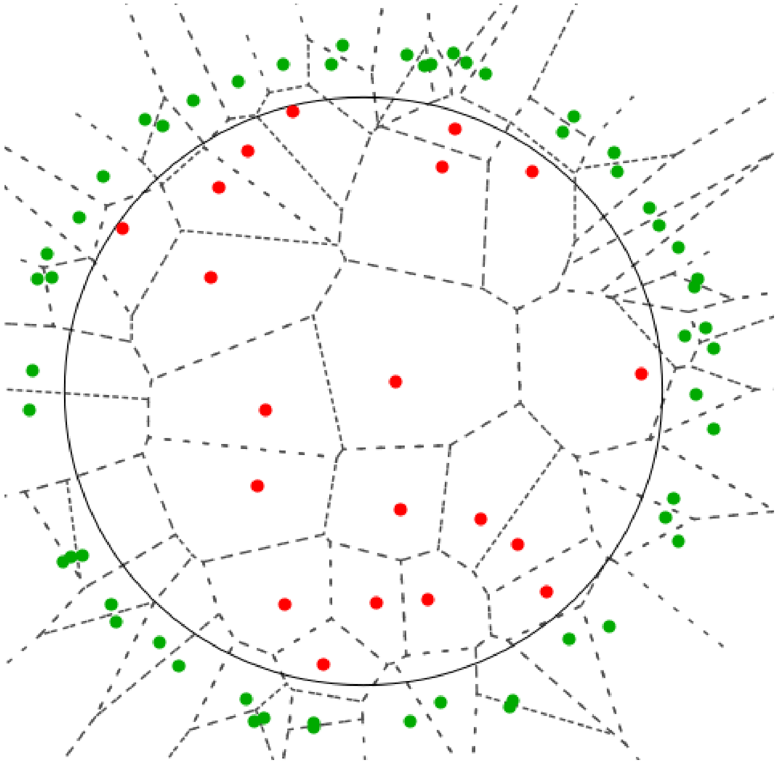
- Survey boundaries



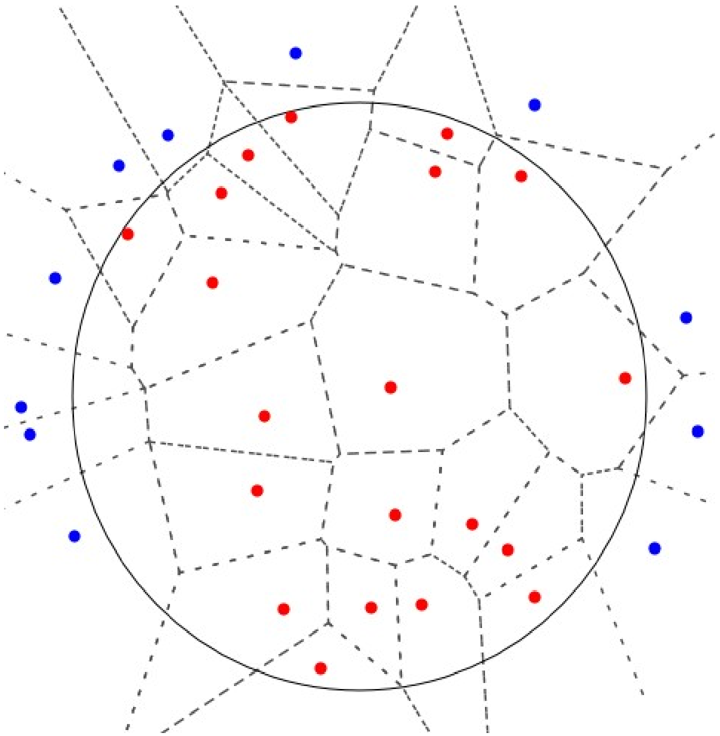
ZOBOV: example complications

- Survey boundaries
  - complicated shape (not periodic cubic box!)
  - many holes
- Use buffer/boundary particles to limit growth of Voronoi cells
  - buffer must be dense enough!

ZOBOV: example complications



vs.



ZOBOV: summary

- There are various complications to using ZOBOV on galaxy data
- Accounting for these is necessary if the voids found are to be useful for science
- We provide a public catalogue of voids where these complications have been correctly accounted for:

SN & Hotchkiss, 2014, MNRAS

(arXiv:1310.2791)

http://research.hip.fi/user/nadathur/download/dr7catalogue/

Defining void types

- Type1 voids:
  - $\rho_{\rm min} < 0.3$
  - statistically distinct from Poisson noise at 99.5% C.L.
  - $\rho_{\rm link} < 1\,, r < 2$ to control merging
- Type2 voids:
  - more traditional, conservative, definition
  - $\rho_{\rm min} < 0.2\,,\ \rho_{\rm link} < 0.2\,,\ r < 2$
- Type3 voids
  - $\rho_{\rm min} < 0.3\,,\ \rho_{\rm link} < 0.3\,,\ r < 2$
  - “cleaner” than Type1, more numerous than either
  - *(not included in public release, can be easily obtained)*

Self-similarity and universality

- What do these terms mean?

- **Self-similar:** voids can be *rescaled* by single parameter related to void size
  - after rescaling, density profile independent of void size

- **Universal:** density profile independent of tracer population used for detection

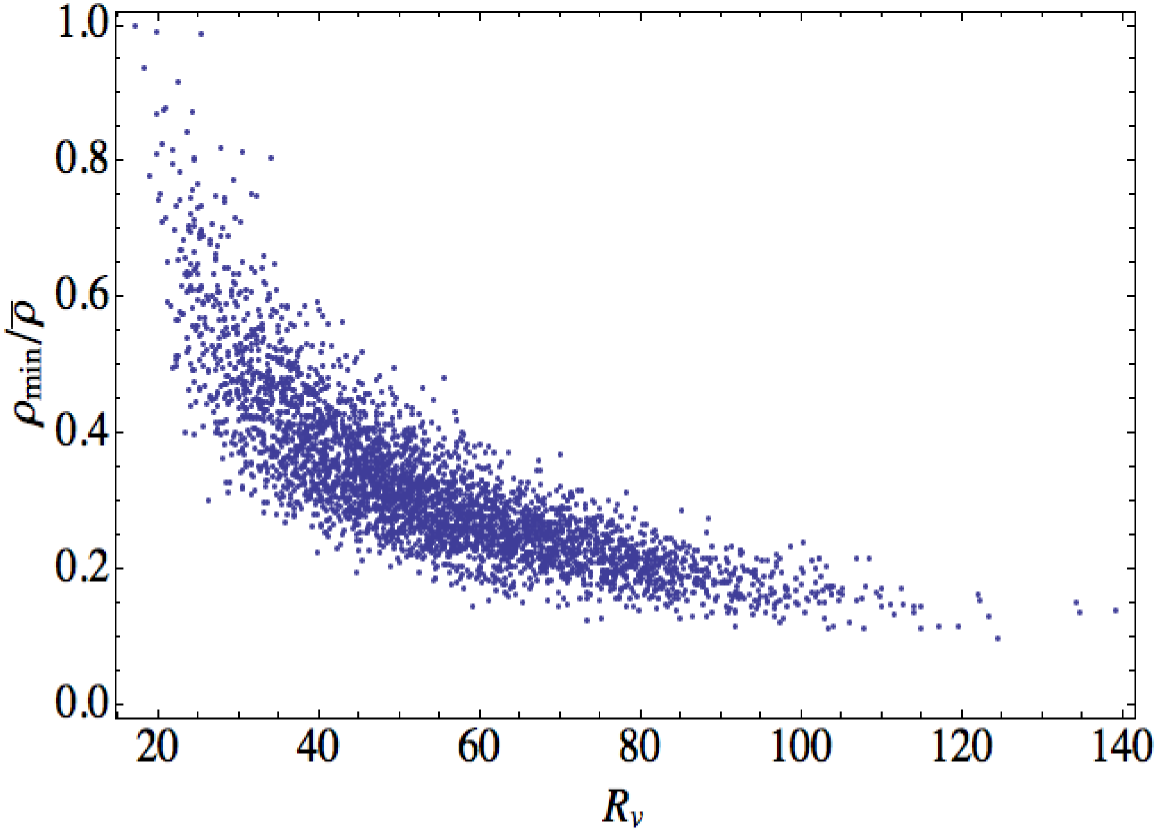
- A universal void profile would be a very important tool
- Already important *assumptions* in many analyses!

Self-similarity and universality

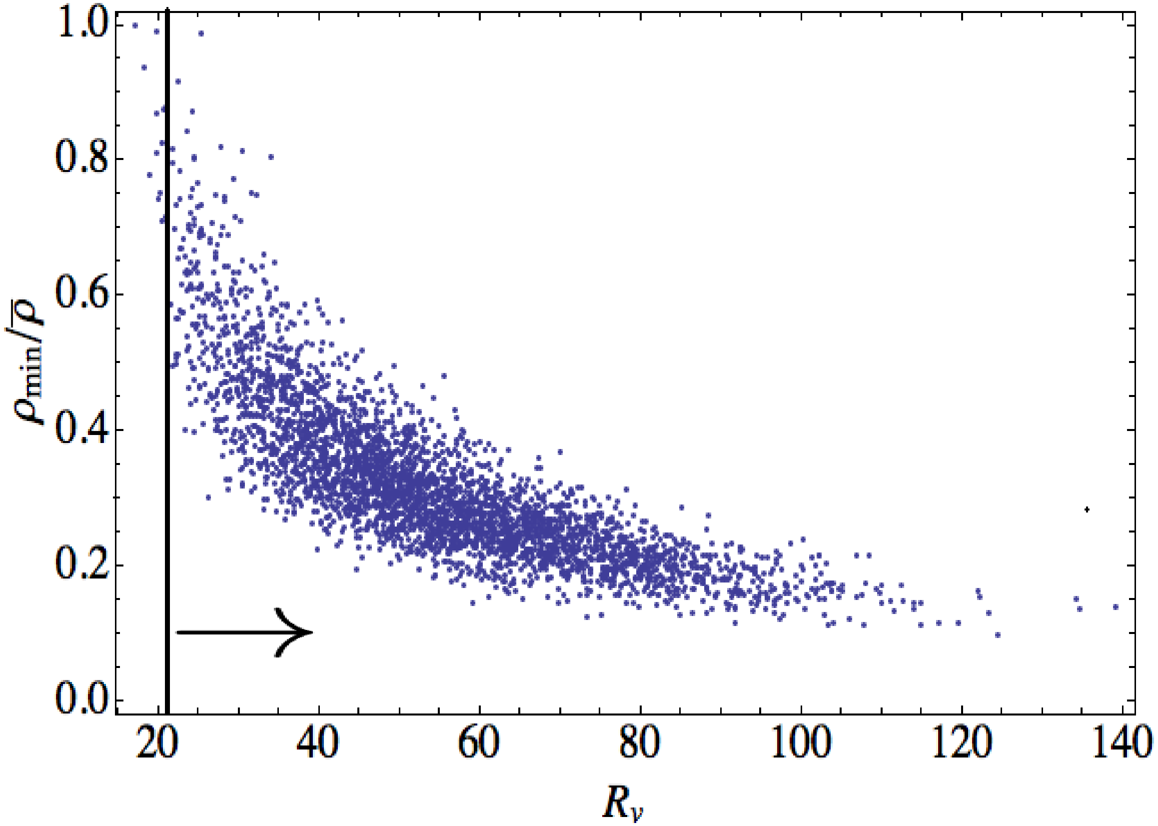
- Recent conflicting results in the literature …

- Ricciardelli et al. (1402.2976):
  - voids are self-similar
  - but profiles depend somewhat on tracer galaxy luminosity
- Hamaus et al. (1403.5499):
  - voids *not* self-similar
  - rescaled profile depends on void size
  - but dependence consistent across tracer populations

Self-similarity and universality

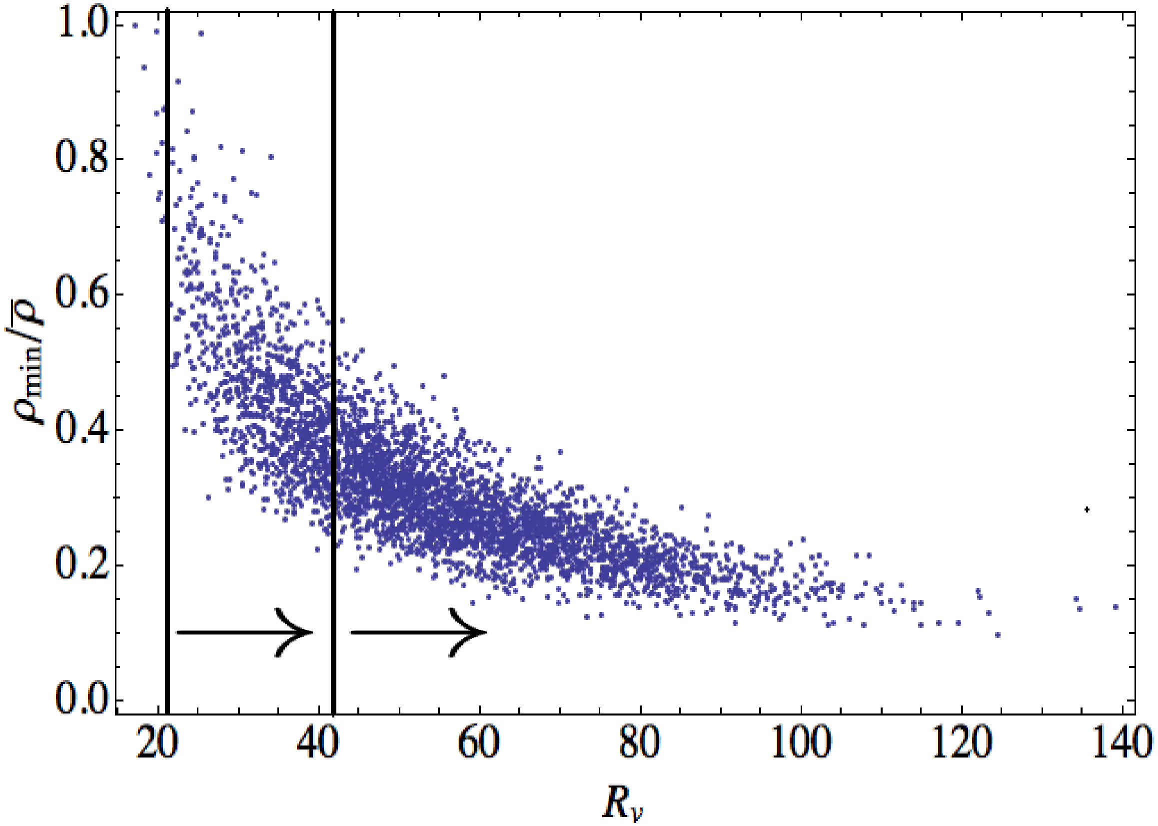


Self-similarity and universality



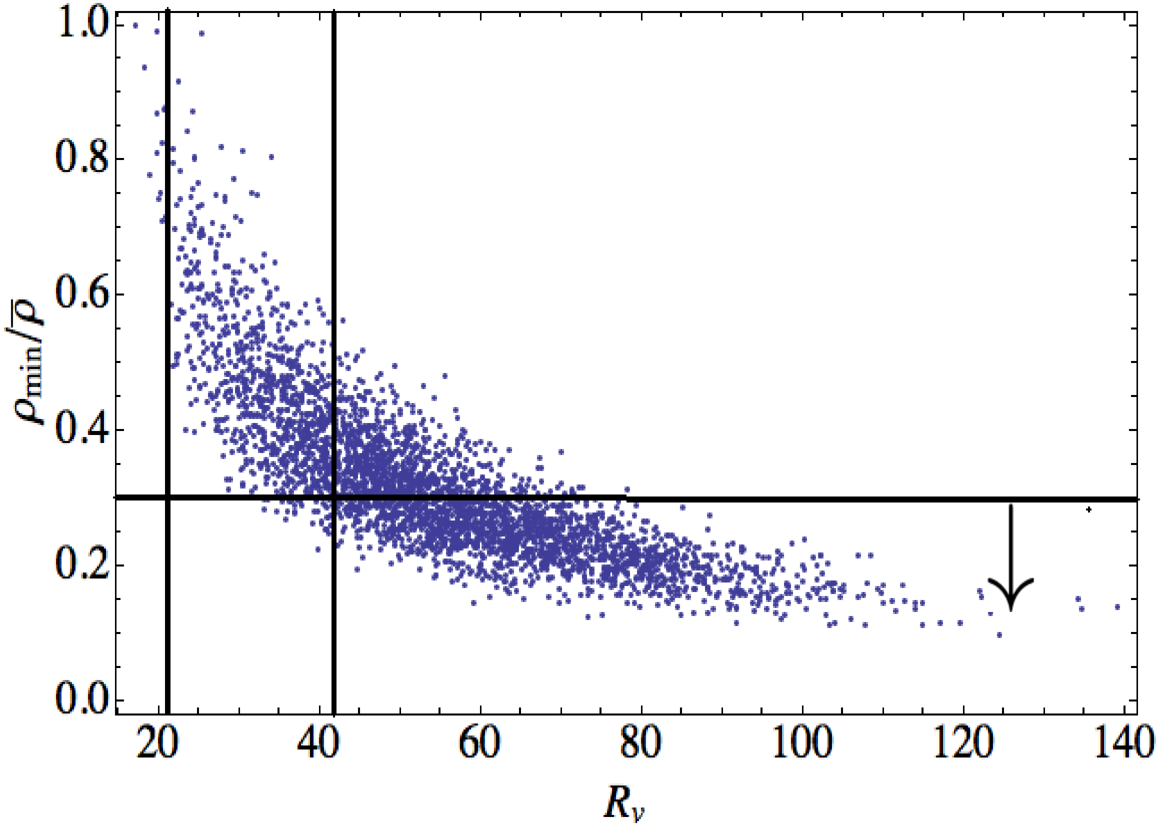
Not all selection cuts are equal …

Self-similarity and universality



Not all selection cuts are equal ...

Self-similarity and universality



Not all selection cuts are equal ...

How do we measure density profiles?

- Naive method: count particles in spherical shells
  - *j* radial bins for each void *i*, each of volume V_i^j

$$\rho_i^j = \frac{N_i^j}{V_i^j}$$

  - simple average

$$\overline{\rho^j} = \frac{1}{N_{\rm v}} \sum_{i=1}^{N_{\rm v}} \rho_i^j$$

  - error from standard deviation as usual

How do we measure density profiles?

- Reconstructing density from single number count measurement:

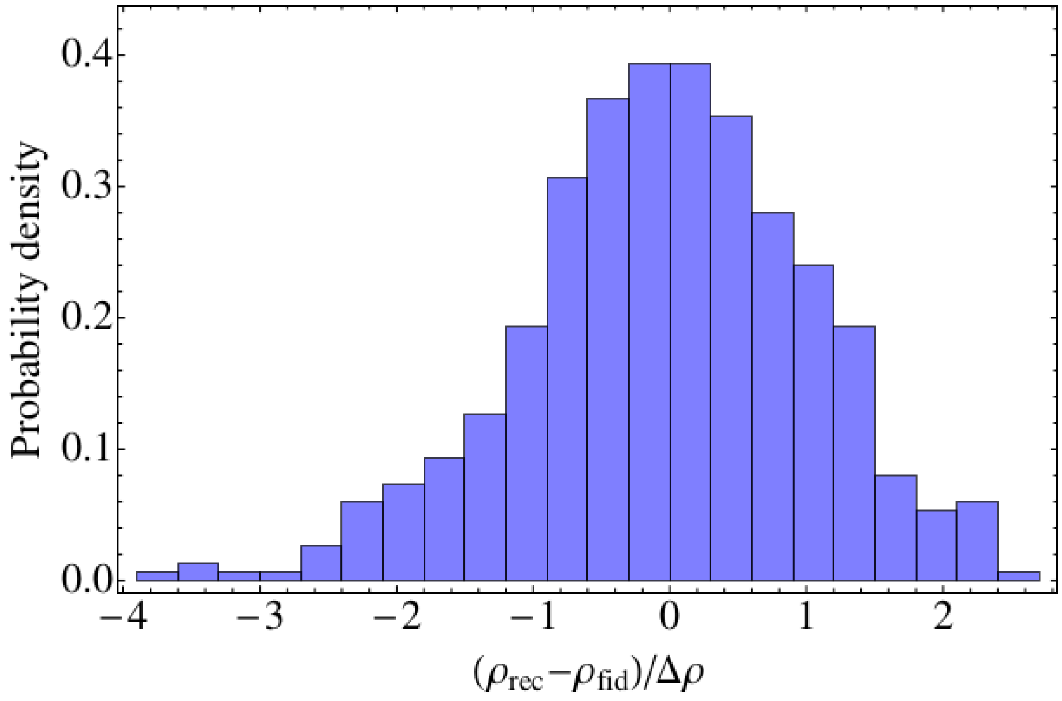
$$P(\lambda|N) = P(N|\lambda) = \frac{\lambda^N \exp(-\lambda)}{N!}$$

$$E[\lambda|N] = \int \lambda P(\lambda|N)\, d\lambda = N + 1 > N$$

- Using *N* instead of *N*+1 systematically underestimates, worse for small *N*

How do we measure density profiles?

- Naive method disadvantages:
  - systematically **biased low**, worse for small voids (!)
  - **noisy**, worse for small voids



How do we measure density profiles?

- “Poisson” method is better:
  - similar counts in shells, but

$$\overline{\rho^j} = \frac{\sum_{i=1}^{N_\mathrm{v}} N_i^j + 1}{\sum_{i=1}^{N_\mathrm{v}} V_i^j}$$

  - errors from Poisson distribution (asymmetric!)
  - equivalent to volume-weighting
  - unbiased, and less noisy

SN, Hotchkiss et al. (arXiv:1407.xxxx)

How do we measure density profiles?

- Using Voronoi tessellation is even better!

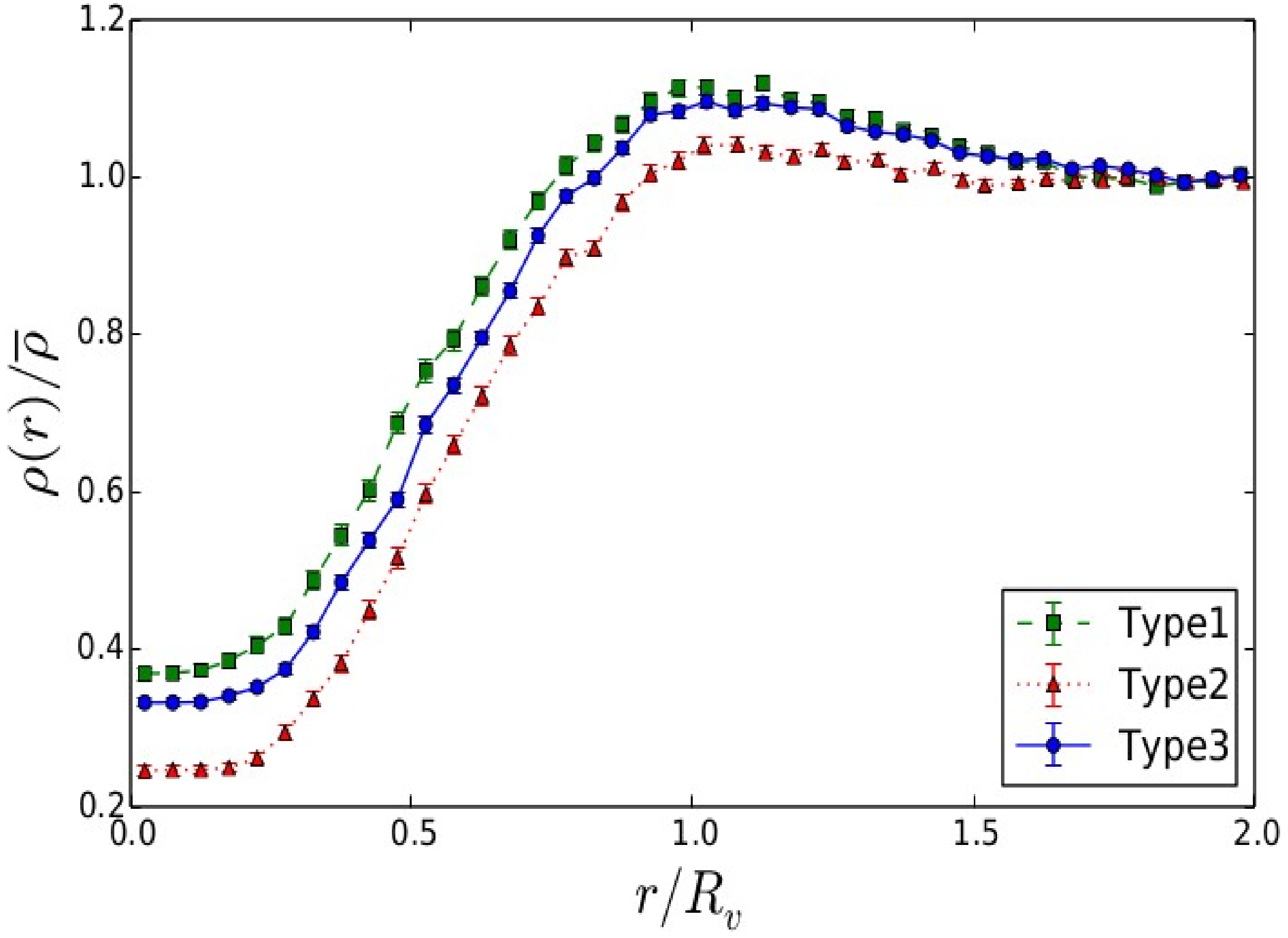
$$\overline{\rho^j} = \frac{\sum_{i=1}^{N_\mathrm{v}} \sum_{k=1}^{N_i^j} \rho_k V_k}{\sum_{i=1}^{N_\mathrm{v}} \sum_{k=1}^{N_i^j} V_k}$$

  - also volume-weighted
  - errors from jackknife
  - allows for selection function correction
  - allows for survey boundary effects
  - somewhat smoothes density

SN, Hotchkiss et al. (arXiv:1407.xxxx)

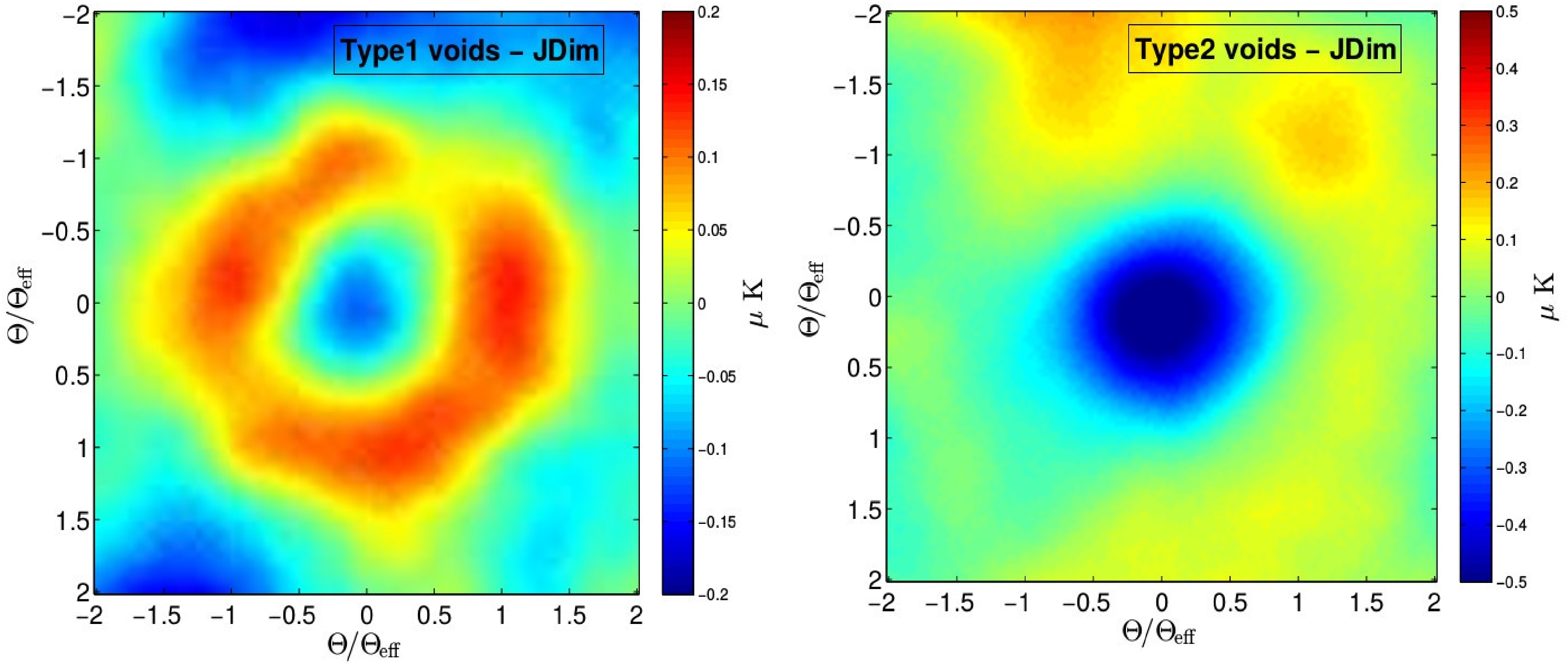
Dependence on ρ_{min}

Void stacks with different selection criteria:



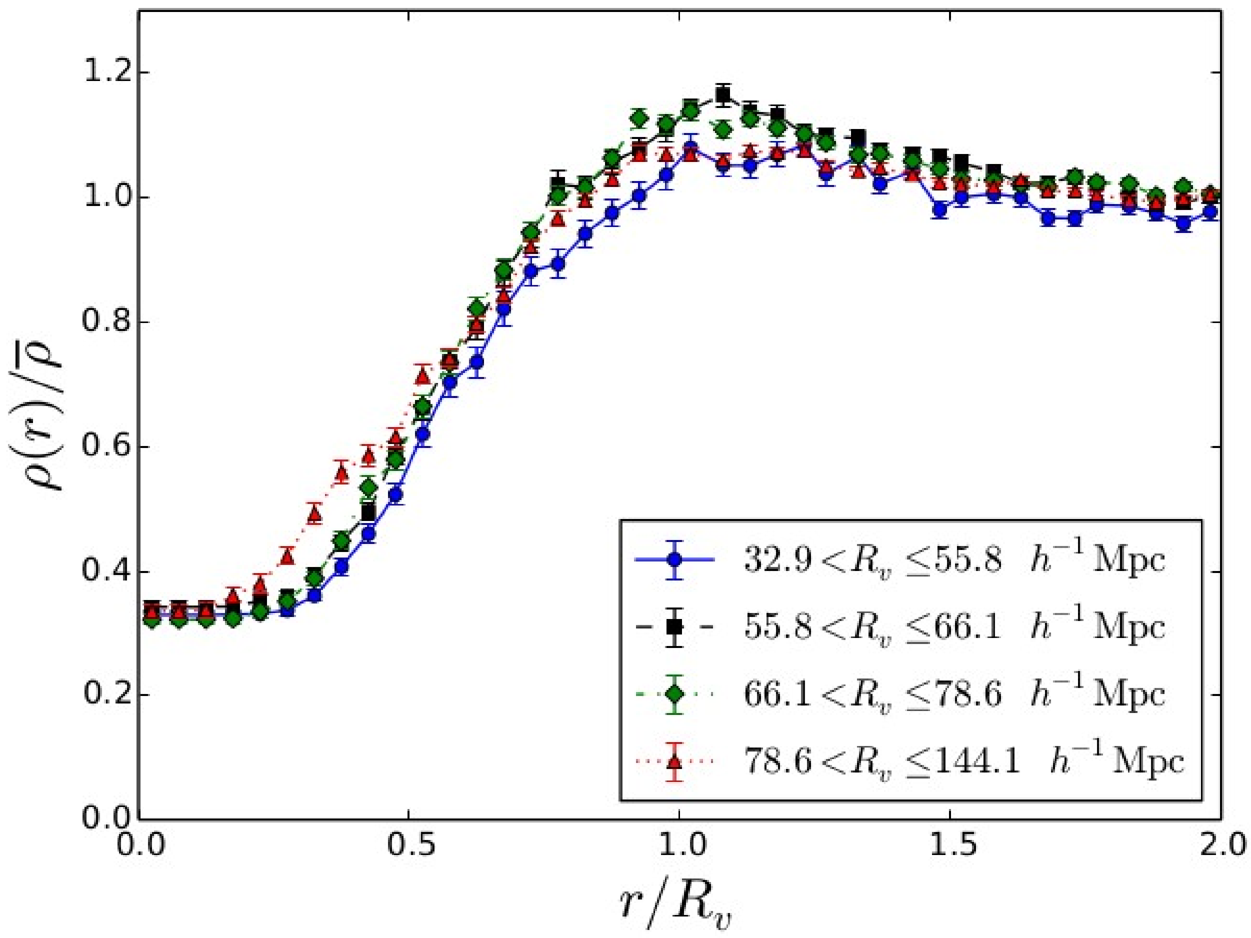
Dependence on ρ_{min}

Also, remember from Shaun's talk:



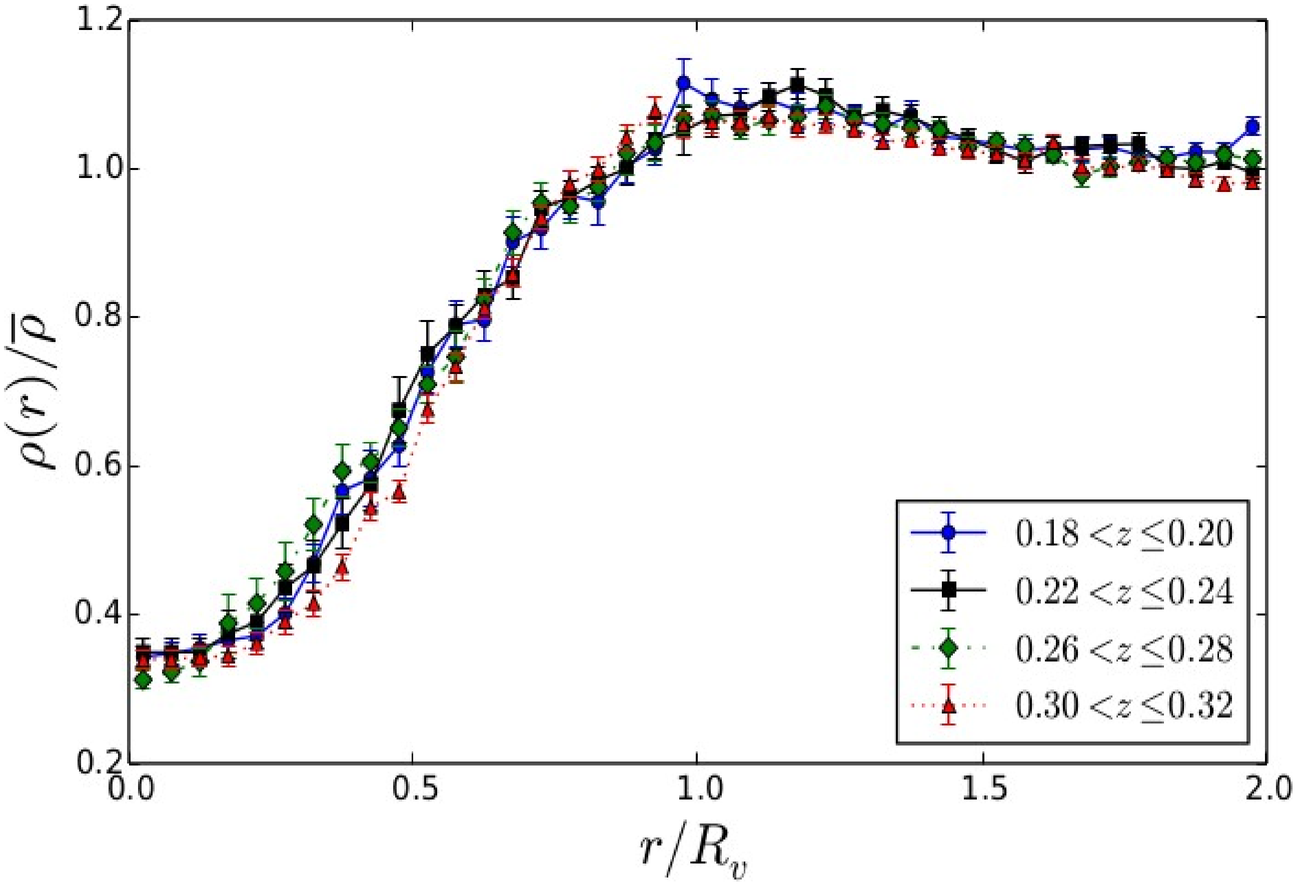
Voids are exactly self-similar

Stacks of simulated voids of different sizes:



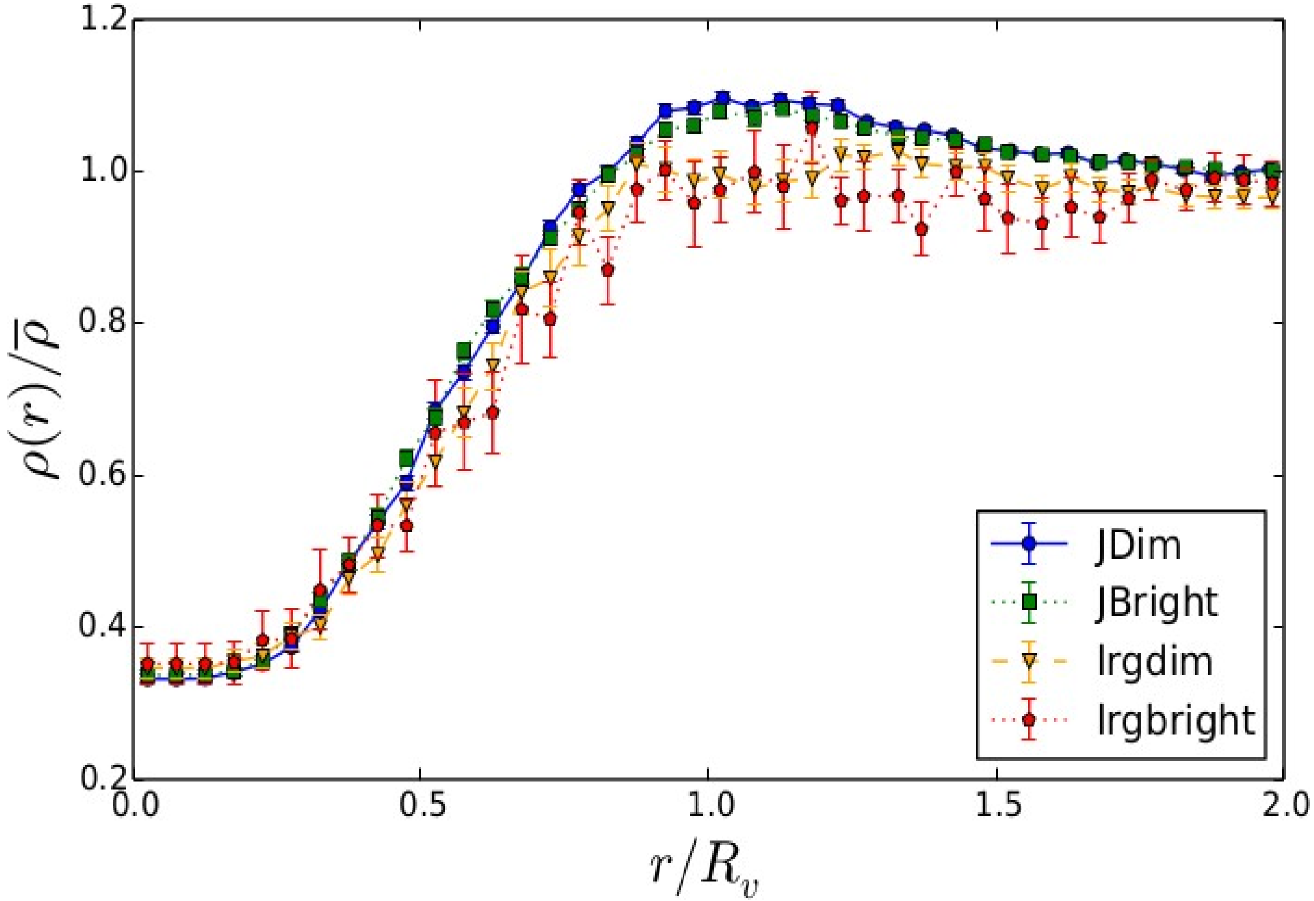
Profiles do not depend on redshift

Stacks of simulated voids in different redshift bins:



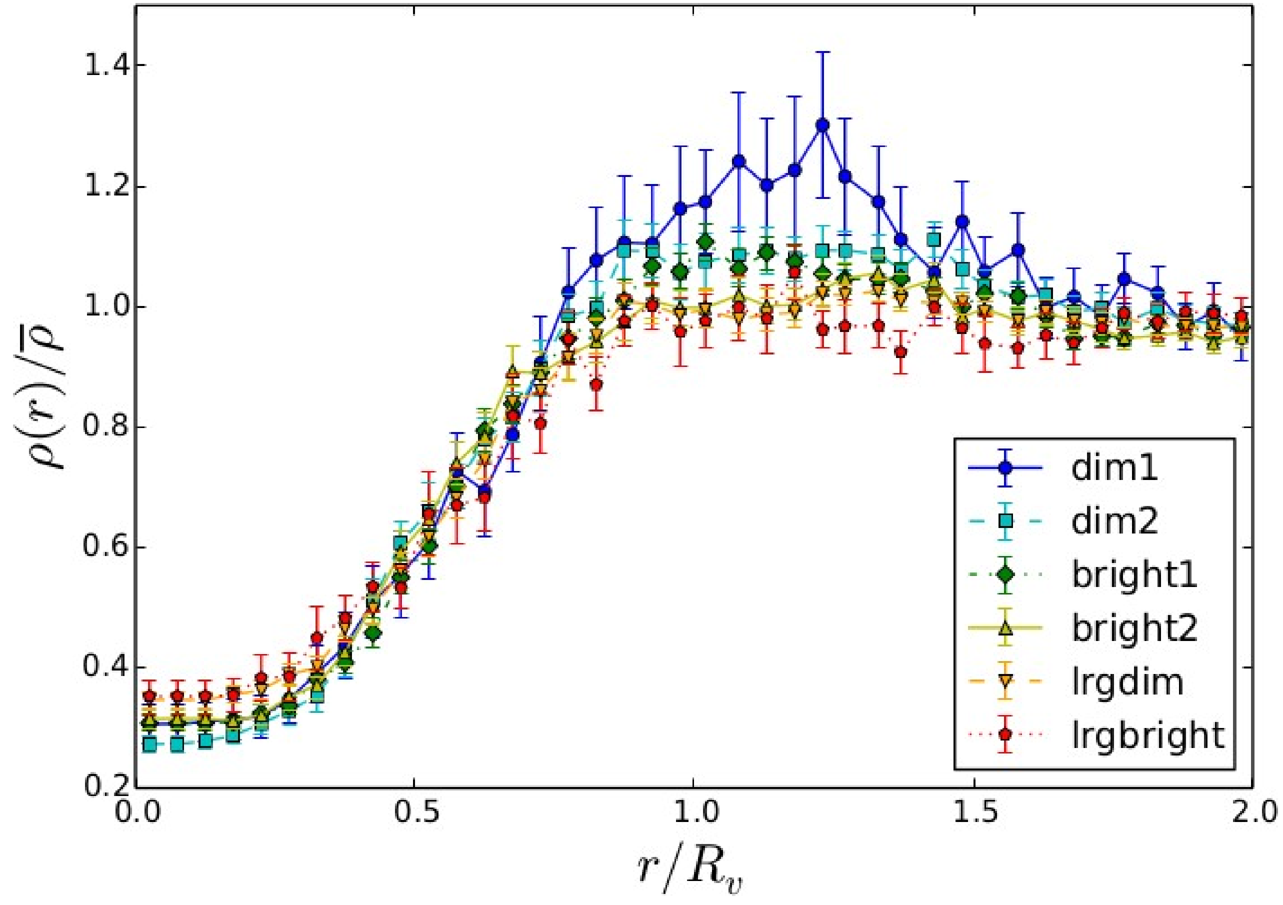
Simulation matches SDSS

Voids from real and mock LRG catalogues show very good agreement!



Universality

Profile similarity over voids in all SDSS galaxy catalogues

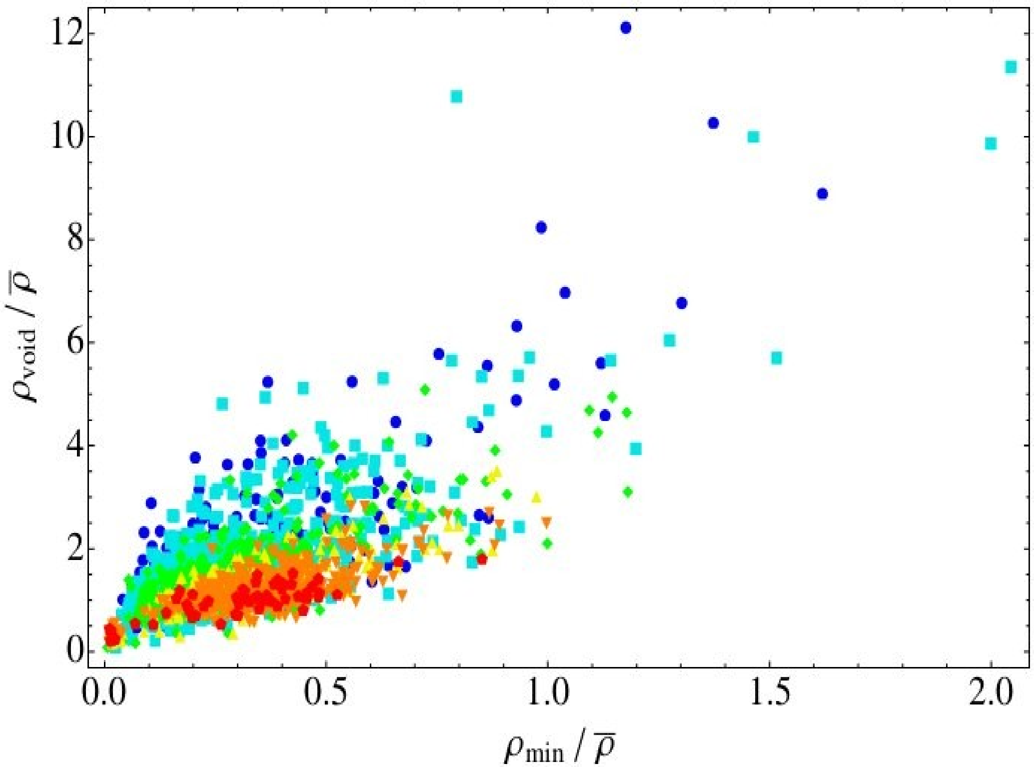


(Void sizes in this figure span an order of magnitude, ~9-90 Mpc/h)

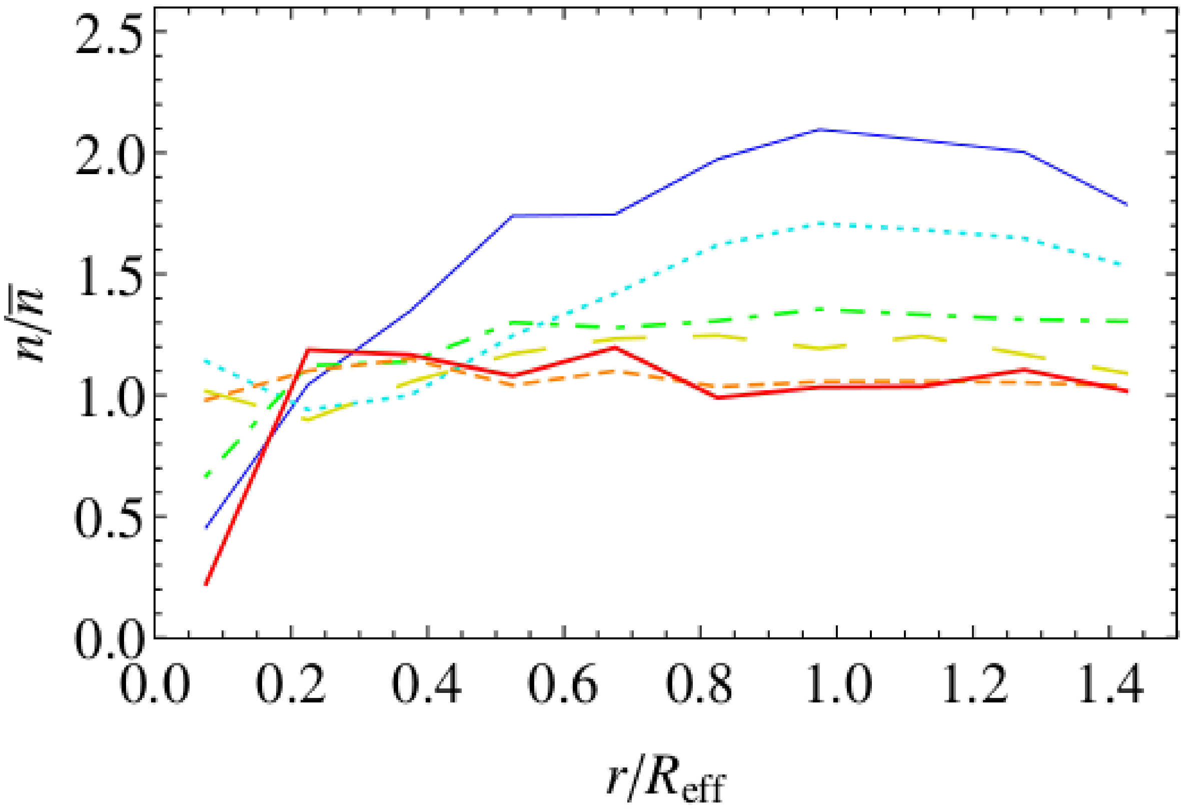
Summary

- How to build a void catalogue that meets minimal conditions
  - but you don't have to, you can use ours
- The density profile around our simulated voids is:
  - self-similar
  - independent of redshift (within simulation range)
- Profiles from simulation and SDSS data agree
- Profiles from SDSS are *universal*

spare slides



Voids from Sutter et al. (2012)



Voids from Sutter et al. (2012)