Probing Dark Energy with RSD around voids

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erc
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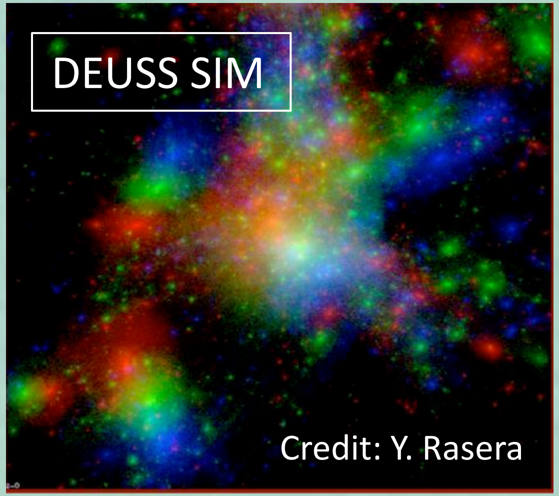
Exploring Dark Energy Cosmic Structures

How to distinguish between Dynamical *vs.* Λ *vs.* MG theories ?



- Besides global expansion of the Universe, DE impacts the formation of the cosmic web
- Cosmic Structures formation can help us break the degeneracies between different DE interpretations
- Growth rate of cosmic structures:

$$f(\Omega_m) \equiv \frac{1}{H}\frac{\dot{D}}{D} = \frac{d\ln D}{d\ln a} \approx \Omega_m^{0.6}.$$

Sensitive to the background expansion

Depends on gravitational forces

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho_b \delta.$$

Linear regime + GR:

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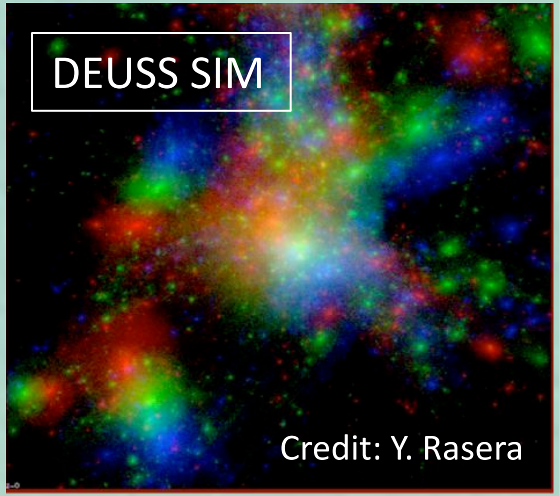

- NL scales can help us break the degeneracies between different DE interpretations

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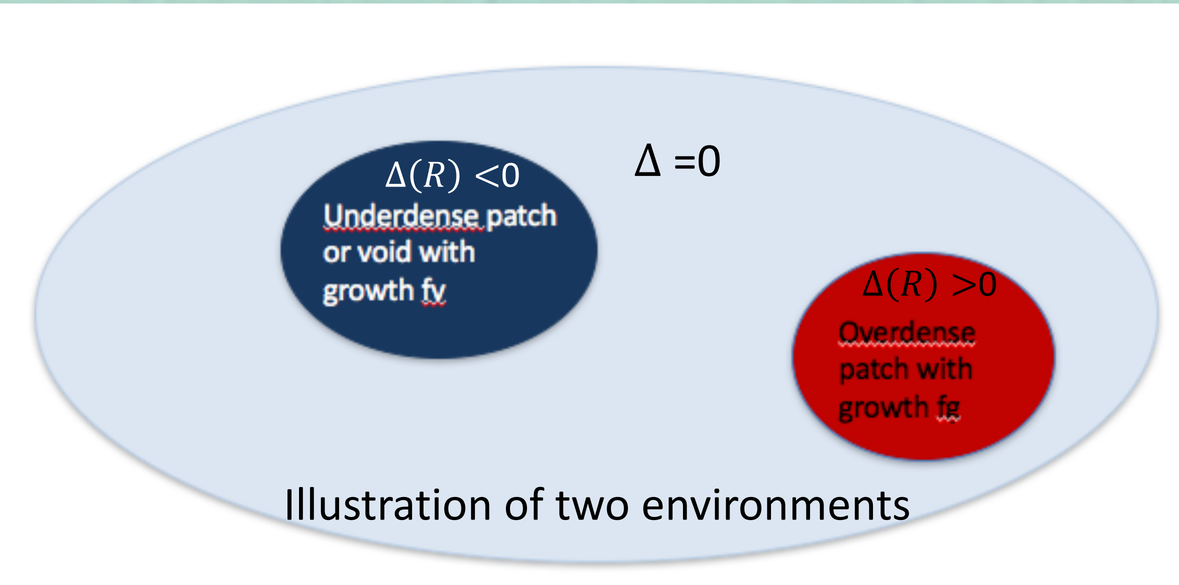
- Growth rate of cosmic structures: $$f(\Omega_m) \equiv \frac{1}{H}\frac{\dot{D}}{D} = \frac{d\ln D}{d\ln a} \approx \Omega_m^{0.6}.$$

The growth rate as a function of time/scale is very sensitive to the nature of DE

Why probing RSD around voids?



Why probing RSD around voids?

- Environmental effects →test f in Non-linear regime → more information
- Pertinent test of MG theories (screening mechanism)
- Different systematic errors (void evolution is less NL than halo evolution)

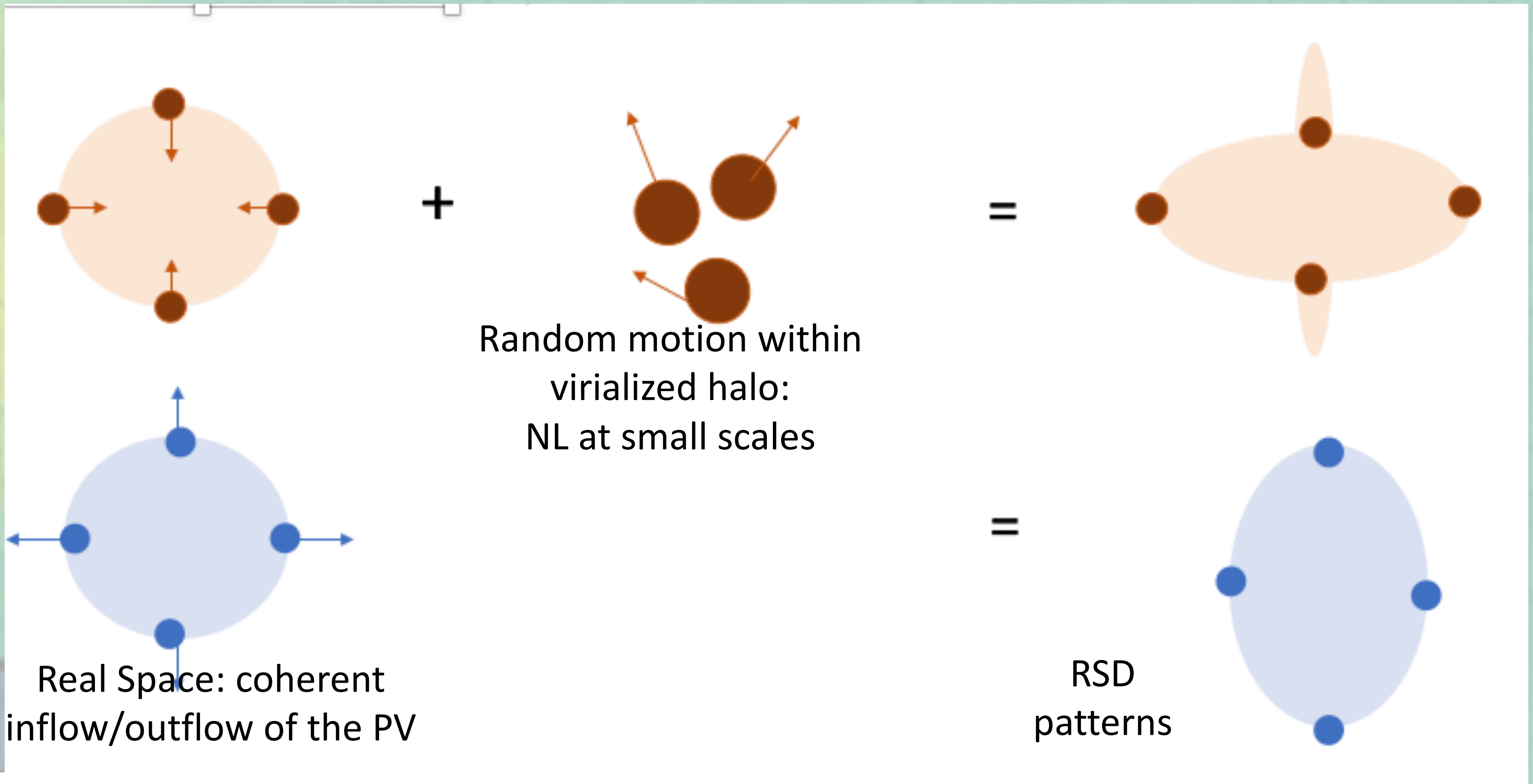
Outline

I. Overview of Growth rate measurement in underdense regions

II. Do we expect the growth rate in underdense regions to be the same as the growth rate in overdense regions or in averaged regions of the Universe?

III. How to probe the growth rate in the highly non-linear regime?

Why are RSD sensitive to the linear growth rate ?



$$\vec{\nabla} \cdot \mathbf{v} = -a\frac{\partial \delta}{\partial t} = -a\delta\frac{\dot{D}}{D} = -a\delta H f(\Omega_m)$$

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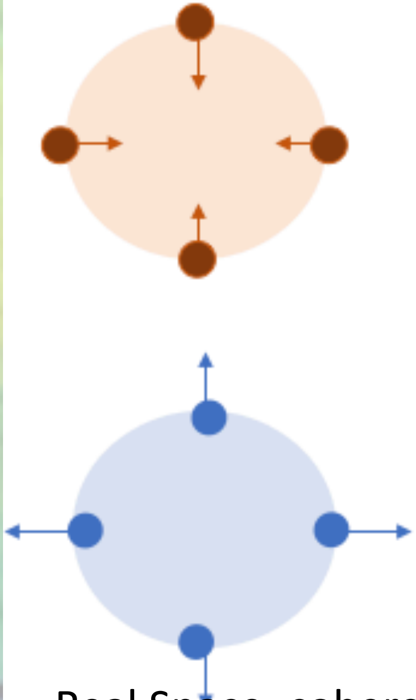
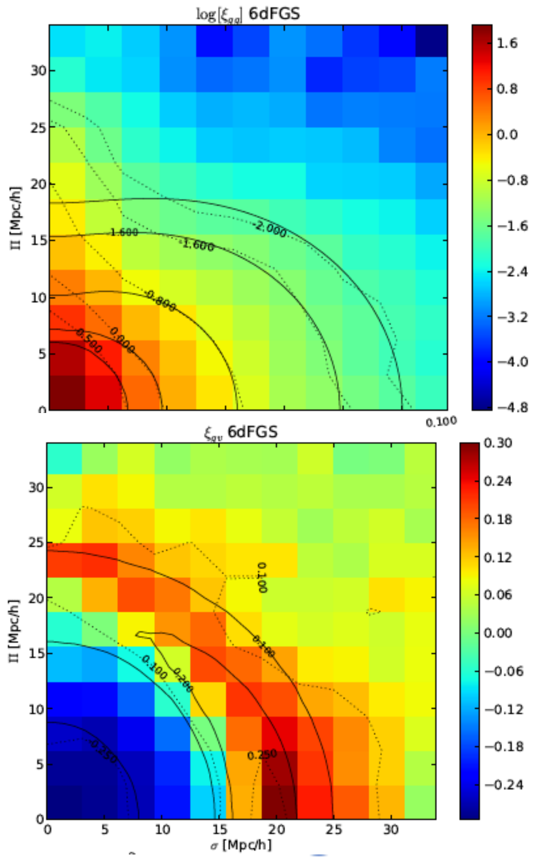


Real Space: coherent inflow/outflow of the PV

+

Random motion within virialized halo:
NL at small scales

=



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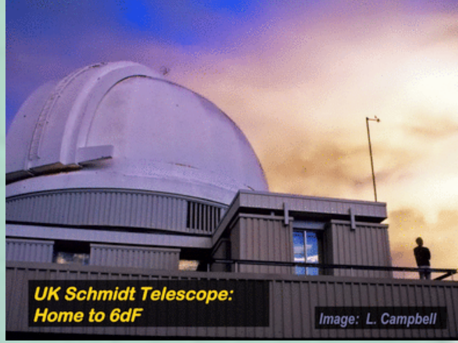
I. Achitouv, C. Blake, P. Carter, J. Koda & F. Beutler, Phys. Rev. D , (2017)



Low z survey parent of TAIPAN, ~ 100K galaxies

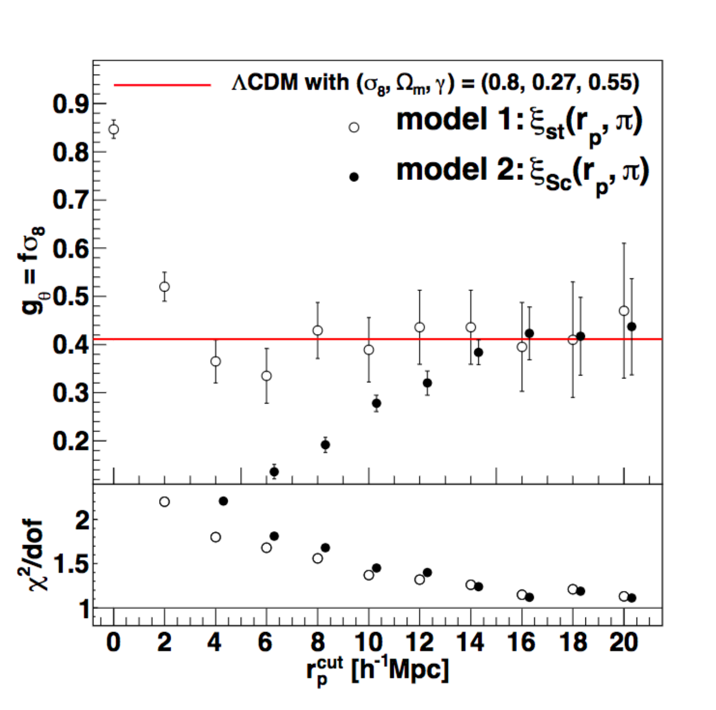
NL also impact RSD around Voids…

Assumptions & Model:

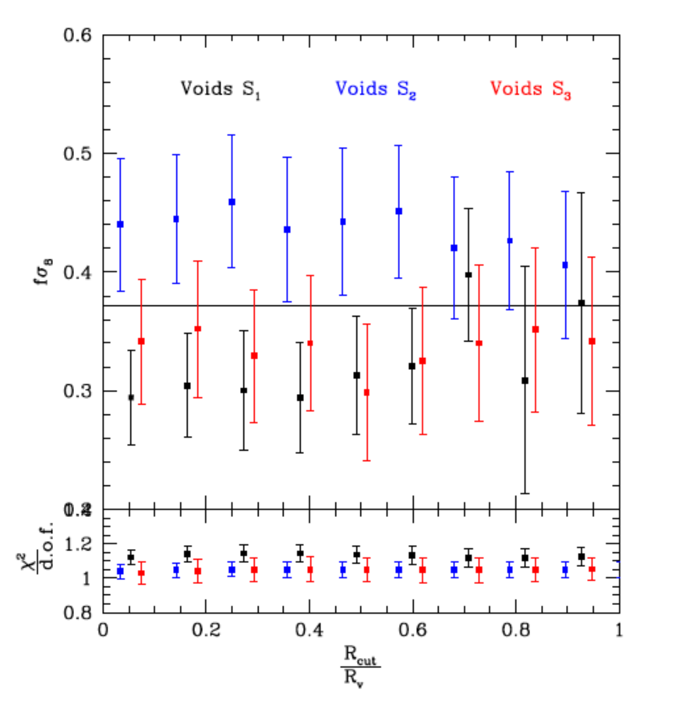
- Gausian Streaming Model (e.g. Peebles 93; Fisher 94)

$$\chi^2(R_{cut}) = \sum_{R_i=0}^{R_i=R_{cut}} \frac{(\xi_{data}(R_i) - \xi_{theo}(R_i))^2}{\sigma_i^2}$$

Keep in mind that standard procedures throw away data at small scales



F. Beutler et al., MNRAS (2012)



I. Achitouv, Phys. Rev. D (2017)

$$1 + \xi^s_{\rm vm}(r_\sigma, r_\pi) = \int_{-\infty}^{\infty} \left[1 + \delta\left(r_\sigma, r_\pi - \frac{v_\pi}{aH}\right)\right] \times p(v_\pi) dv_\pi$$

Results with 6dFGS

Assumptions & Model:
- Gausian Streaming Model
- ΛCDM cosmology
- Linear bias
- Constant velocity dispersion (nuisance parameter)
- We consider voids of size ~20Mpc.h^{-1}

We found for 6dFGS a consistency between the linear growth rates in the two environments:

$f\sigma_8$ = 0.36±0.06 for gal-gal RSD

$f\sigma_8$ = 0.39±0.11 for the gal-void RSD

I. Achitouv, C. Blake, P. Carter, J. Koda & F. Beutler, Phys. Rev. D , (2017)

Results with 6dFGS

3 independant analysis for the gal-void RSD, using GSM but covering 3 different redshifts & having different void selection.

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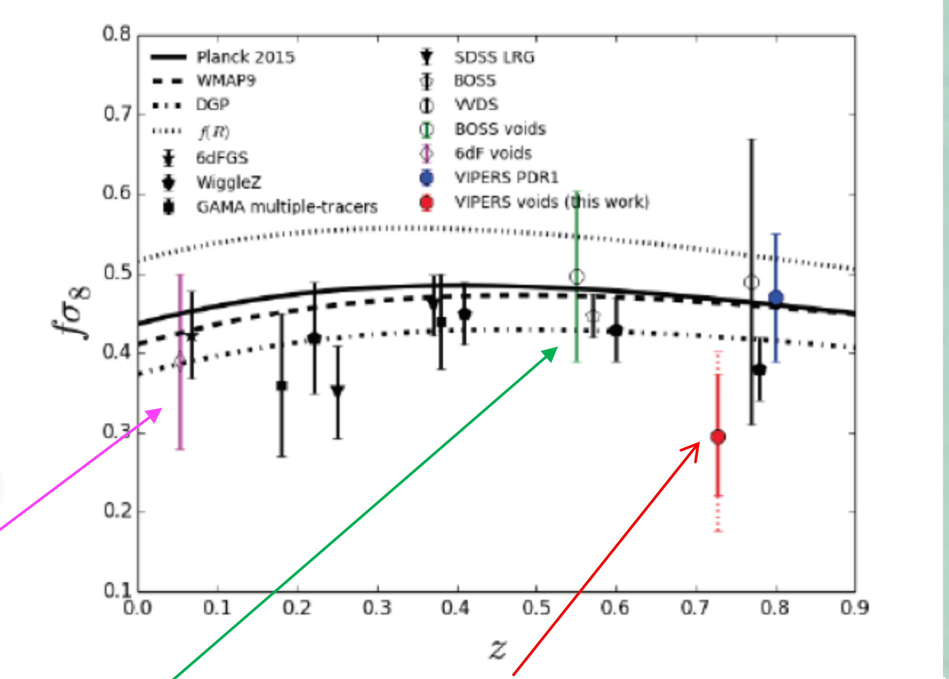

Hawken et al., A&A (2017)

Hamaus et al., PRL (2016)

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Why perform multipole analysis of the RSD around voids ?

- Different treatment of the data

$$\xi_\ell(r) = \int_0^1 \xi^s(r,\mu)(1+2\ell)P_\ell(\mu)\mathrm{d}\mu$$

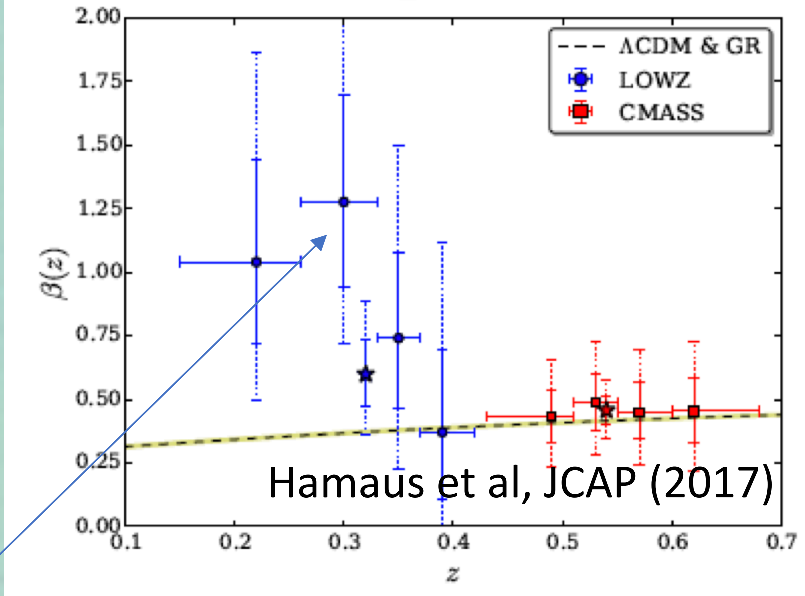
- Easier to test for systematic errors

- In principle we can infer the growth rate simply from the data (no modeling of the real space correlation function)

$$\xi_0(r) - \bar{\xi}_0(r) = \xi_2(r)\frac{3+\beta}{2\beta}$$

- Easier to compute Covariance matrices…

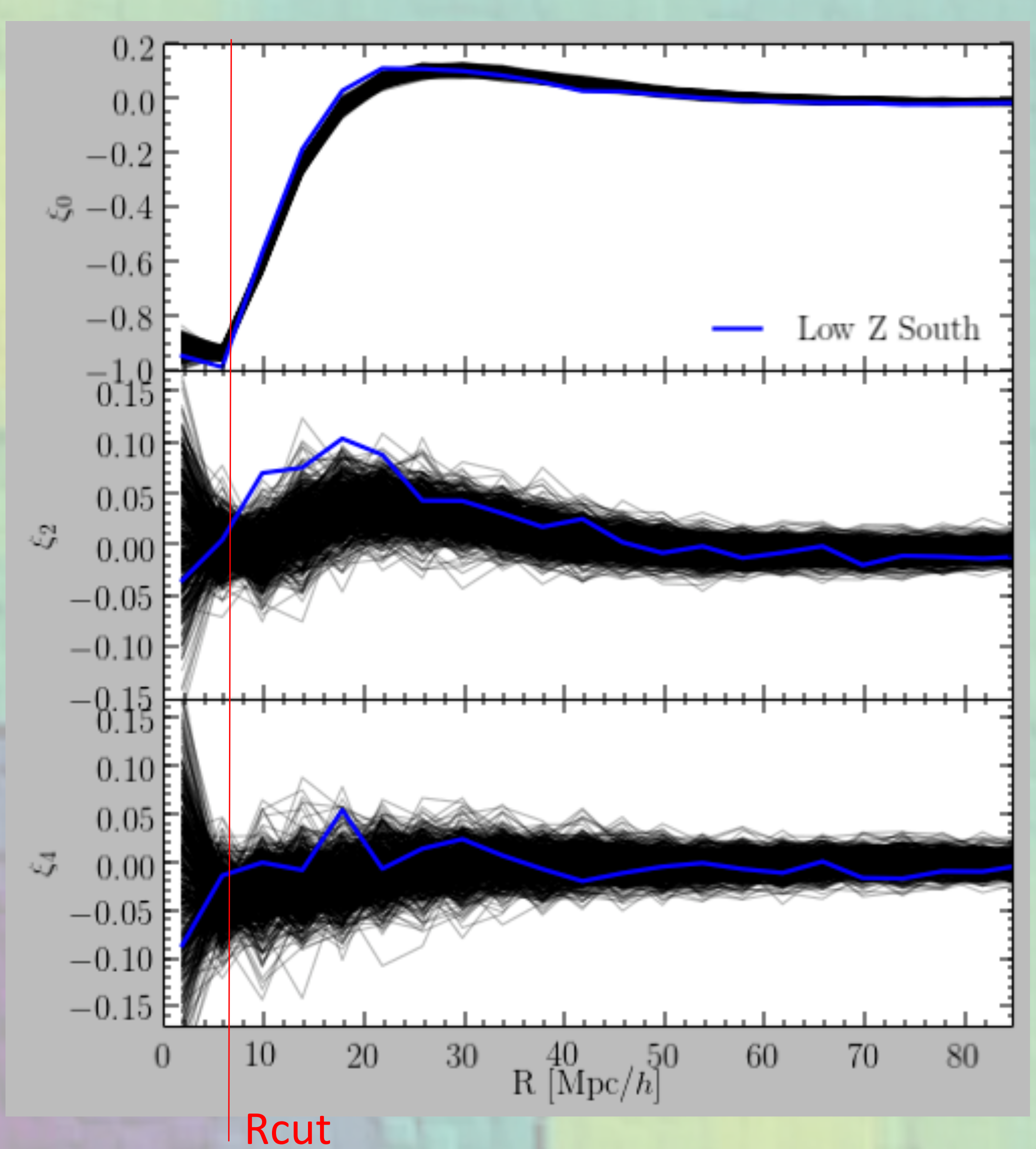
$$\varepsilon_i = \xi_2(r_i) - \frac{2\beta}{3+\beta}\left[\xi_0(r_i) - \bar{\xi}_0(r_i)\right]$$

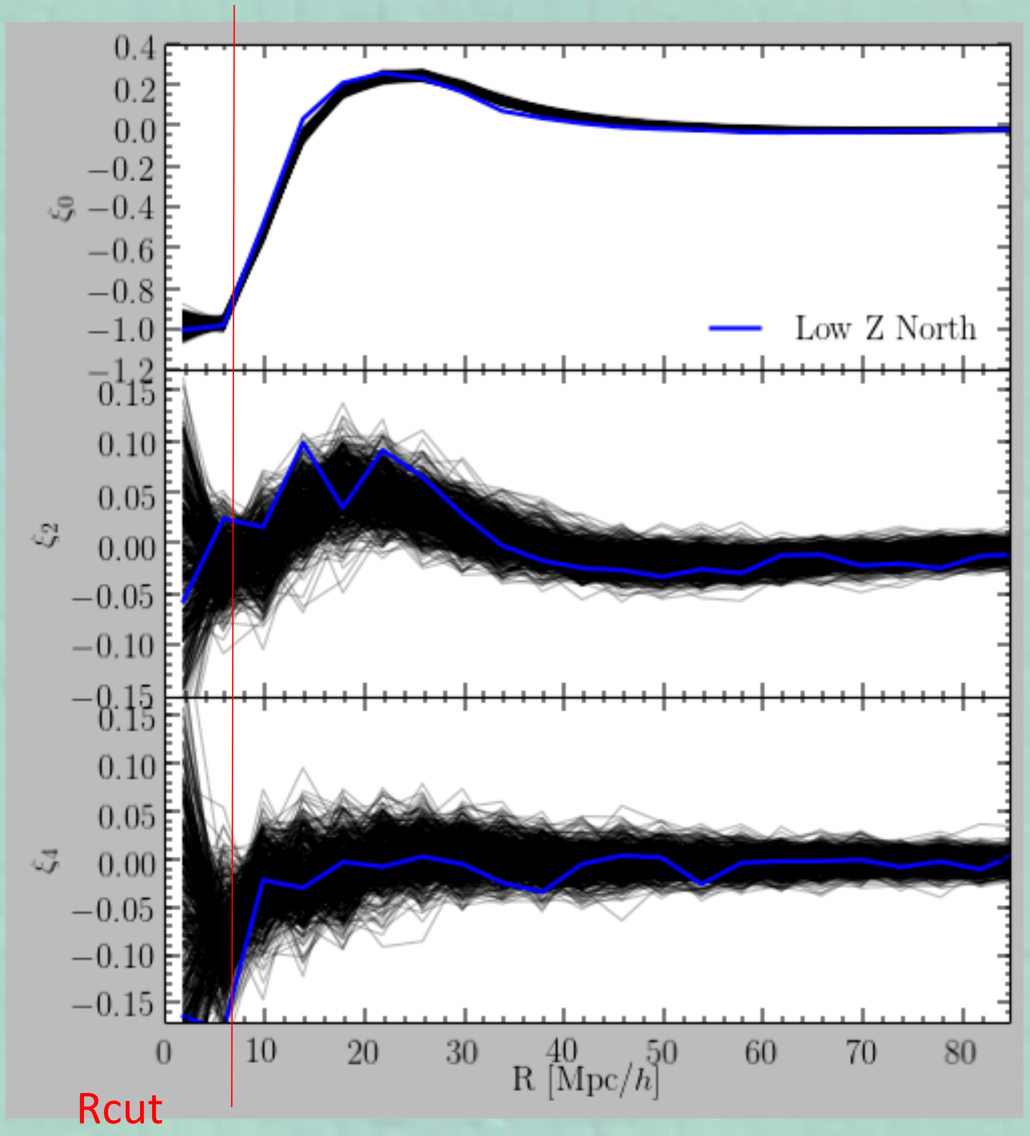


Questions:
- Is it new physic?
- Is it a bad estimation of the quadrupole – bad approximation of the error bars?
- Failure of the model at small scales?

Multipole analysis of the RSD around voids in Low Z sample

My Preliminary results





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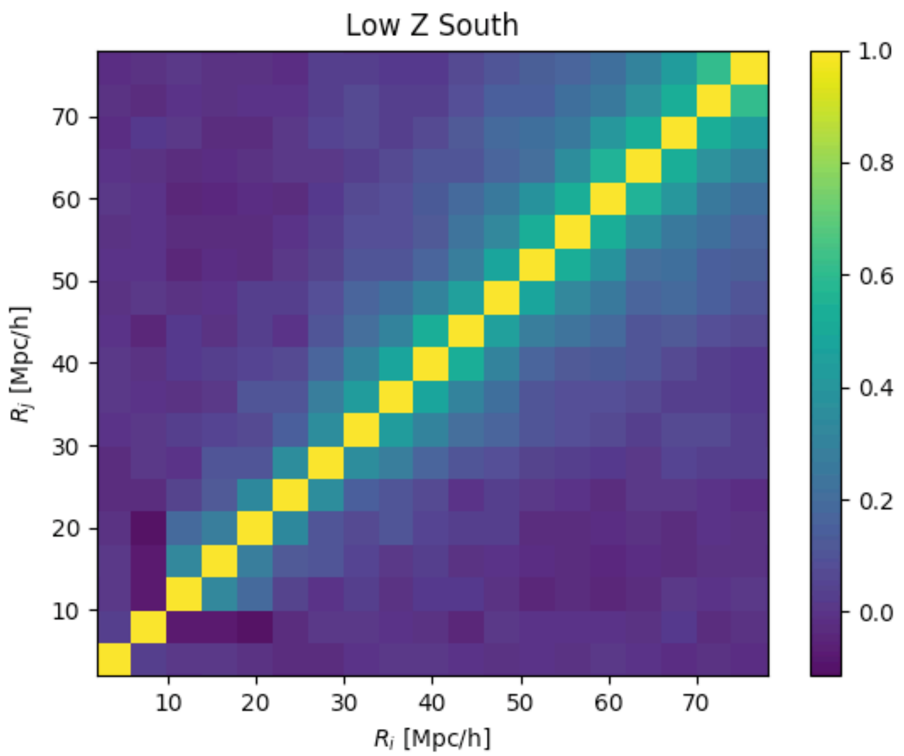
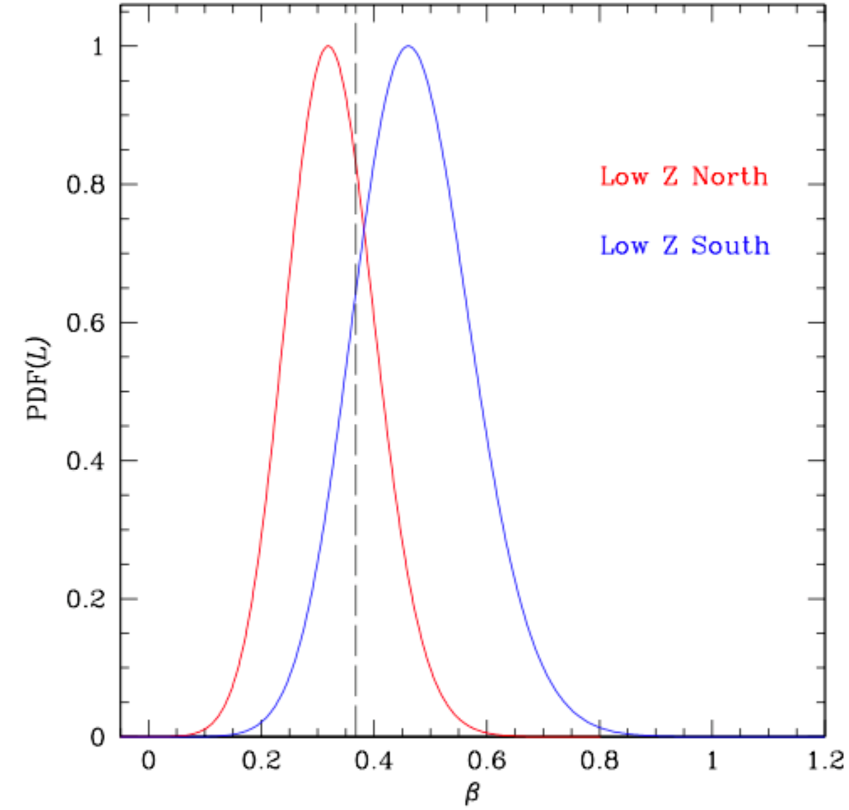


Correlation Matrix for the residual using 500 mocks

$$L(\xi_\ell|\beta) = \frac{1}{(2\pi)^{N/2}\sqrt{\det \mathbf{C}}} \exp\left(-\frac{1}{2}\sum_{i,j}^{N} \varepsilon_i \mathbf{C}_{ij}^{-1} \varepsilon_j\right)$$



Consistency with expected LCDM cosmology $\boldsymbol{\beta}$= 0.37
LZ South BF 0.47+- 0.1
LZ North BF 0.32+-0.08

Going one step further:
The analysis of the growth rate in the non-linear regime

Can we use the environmental growth rate to test cosmology on highly NL scales ?

- Standard 2-pt RSD analyses do not generally recover the linear growth rate expectation below a certain scale.
- Can we use the data below that scale: is there more information to gain?

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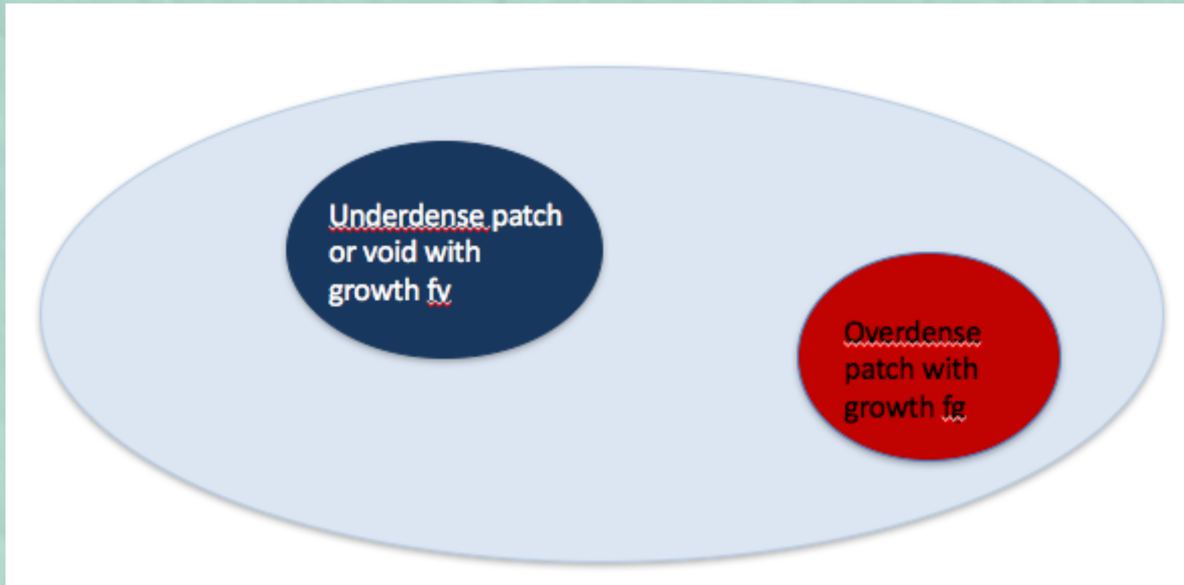
Naive ''island Universe'' picture can be helpful

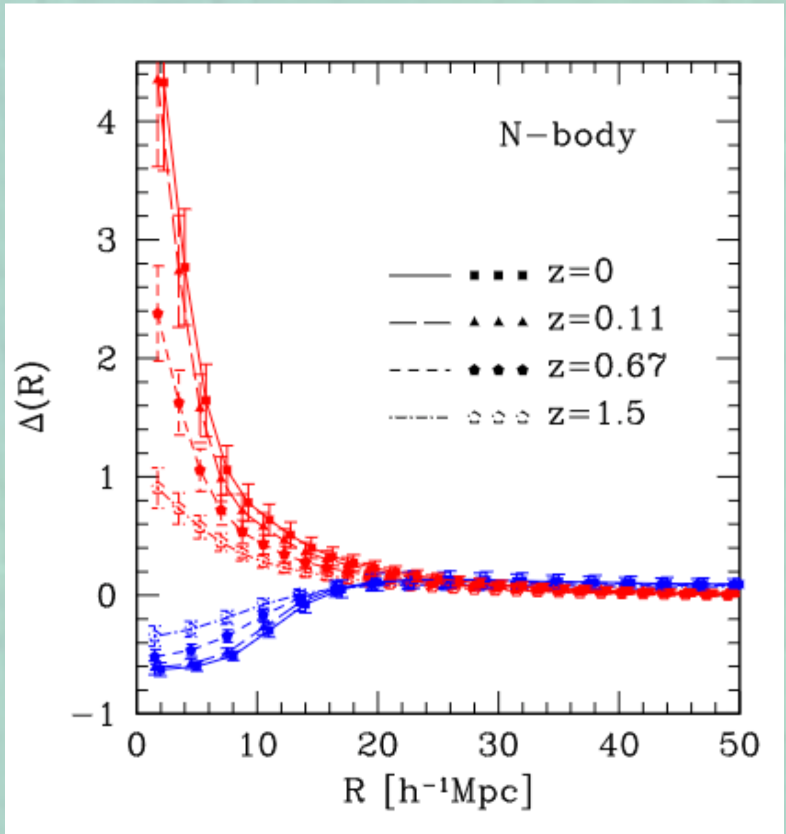


Separate Universe prediction may not work for island radius R~10Mpc/h
e.g. non-linear coupling of large perturbations on small scales modes, although see Chiang et al. PRD 2017

Can we use the environmental growth rate to test cosmology on highly NL scales ?

What is the value of the growth rate in small under/overdense regions of density contrast $\Delta(R)$?

$$f = \frac{dln\,\Delta(R)}{dln\,a}$$



Achitouv & Cai 2018, arXiv 1806.04684

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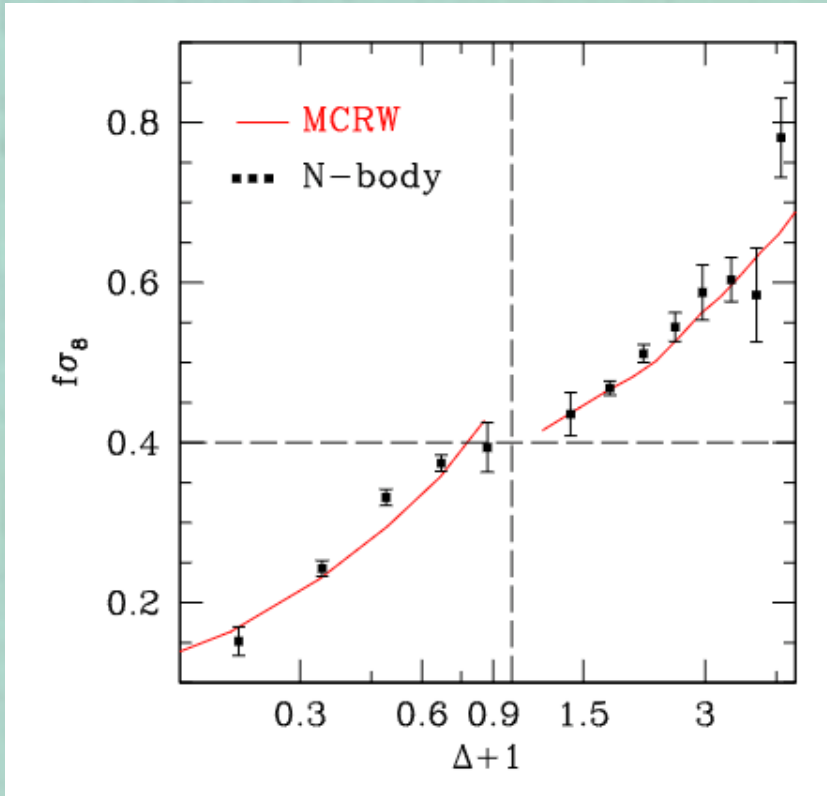

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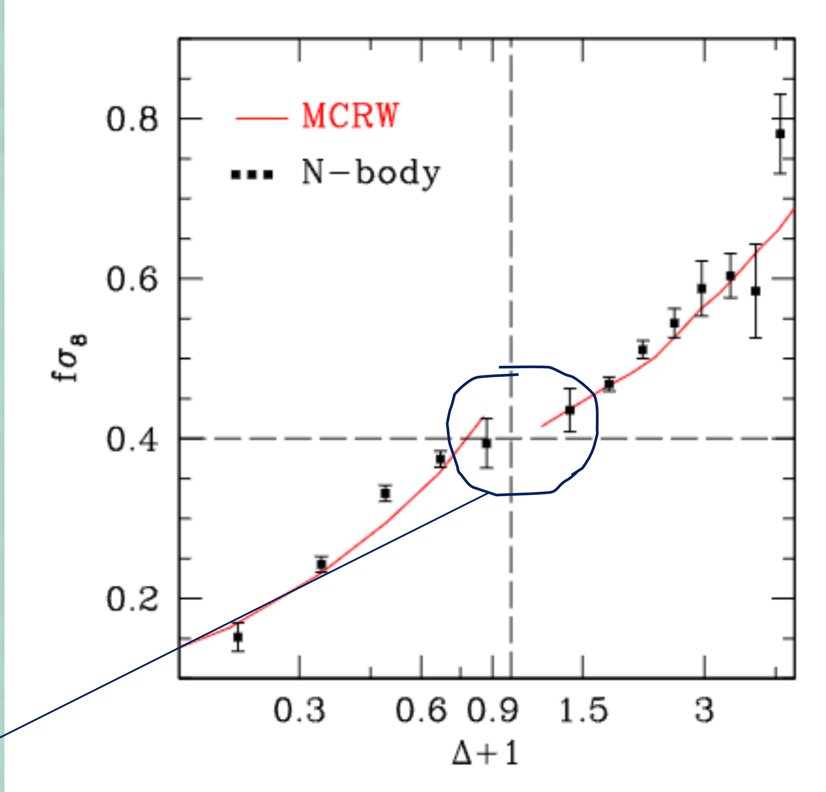
Why do we want to measure f(Δ) instead of f(<R)?

- f(Δ) : different scales can contribute to Δ → access the NL scales
- Probing f(Δ) should contain more information than 2-pt RSD →Does the slope f(Δ) changes for MG ?



Linear information

Achitouv & Cai 2018, arXiv 1806.04684

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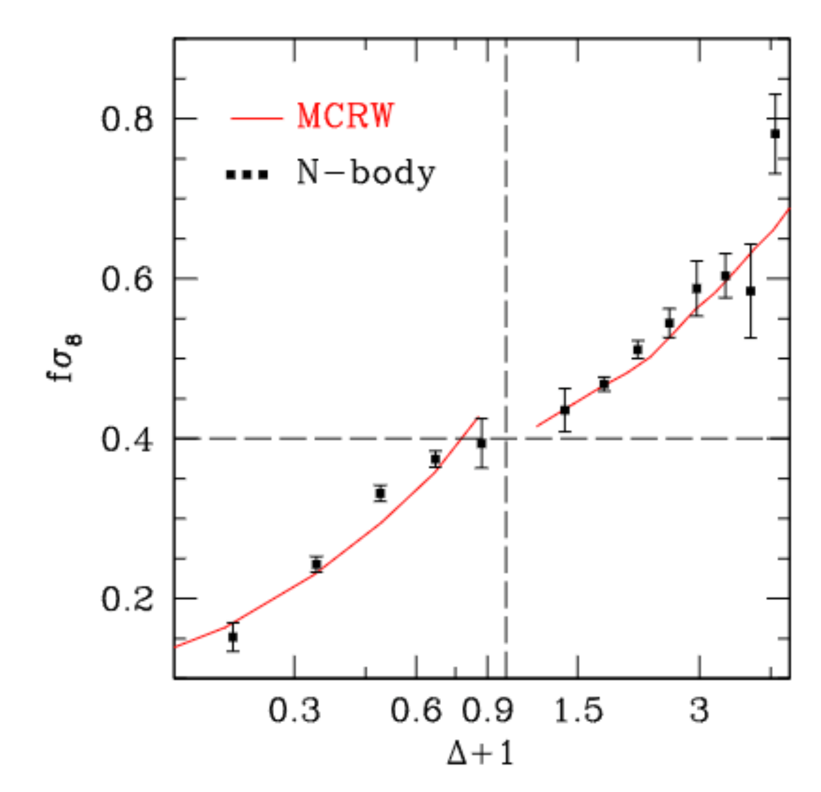

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Link with observation?

- We need density profile in different z bins

e.g. Lensing, counting galaxies

- We could use linear RSD model to infer NL growth

A new approach to predicts evolution of density profiles & Link with observational properties

Lognormal Monte Carlo Random Walks

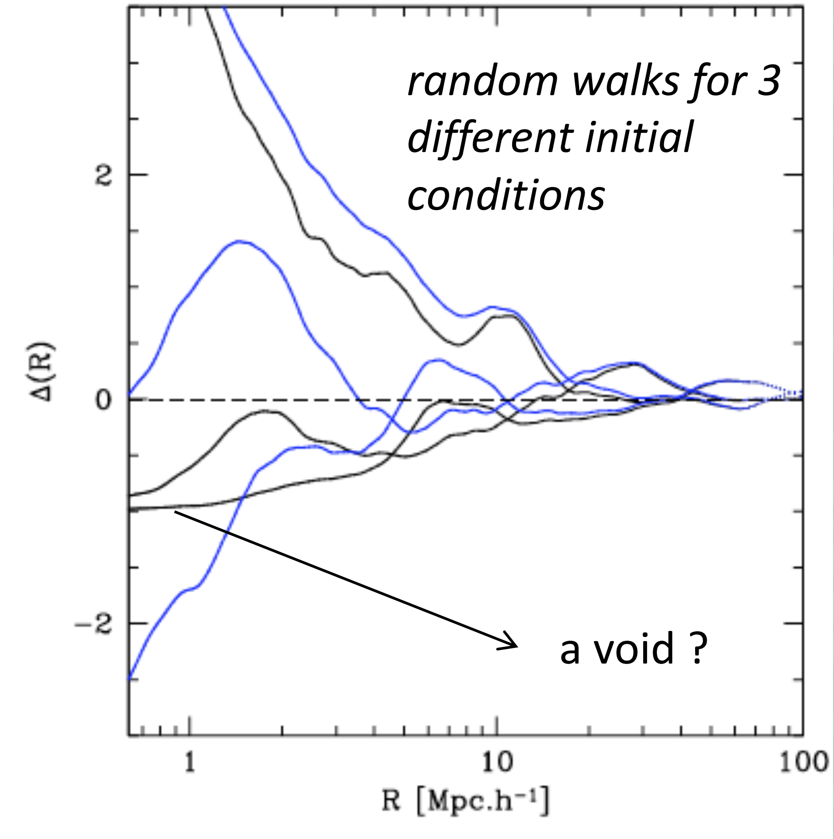
- Evolution of the smoothed linear density field:

$$\frac{\partial \Delta(R, \mathrm{x}=0)}{\partial R} = \int \frac{d^3k}{2\pi^3}\, \tilde{\delta}_k\, \frac{\partial \tilde{W}(k,R)}{\partial R}$$

$\langle \delta(k')\delta(k) \rangle = P_{lin}(k)$

- Today, the 1-point distribution of matter is well-described by a log-normal PDF:

$$\Delta_{\rm LN}+1 = \frac{1}{\sqrt{1+\sigma^2_{\rm NL}(R)}} \exp\left(\frac{\Delta}{\sigma_{\rm Lin}(R)}\sqrt{\ln(1+\sigma^2_{\rm NL}(R))}\right)$$



I. Achitouv, Phys. Rev. D 94, (2016)

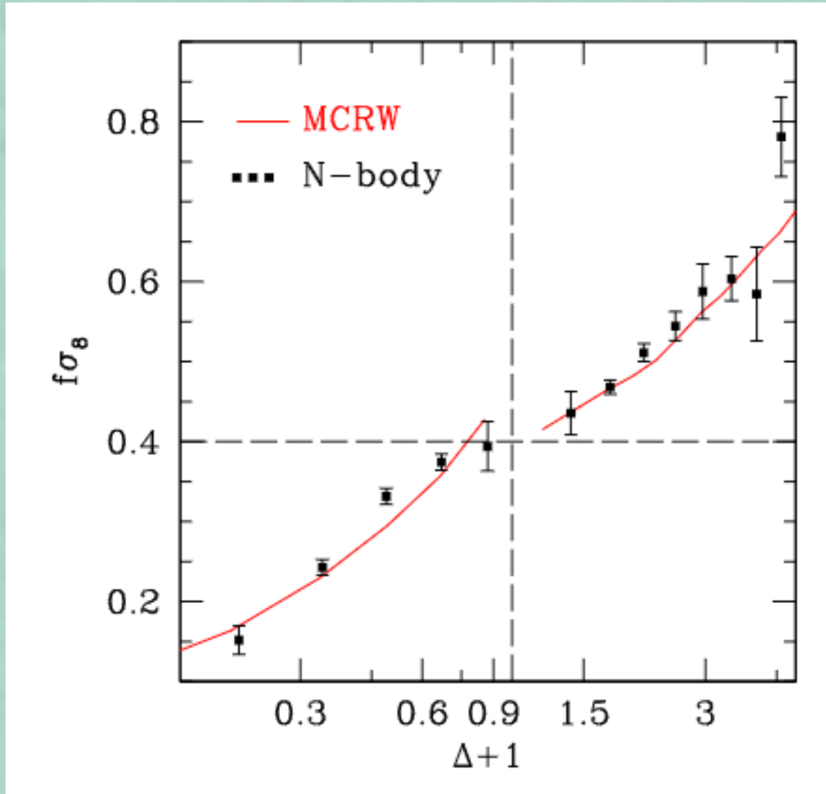
What can we do now?

1/Generate 1M log-normal MCRW at z=0: a couple of hours…

2/ Compute these walks at higher z: 2mins on my laptop

3/ Compute the growth rate as we do in N-body simulation as f(Δ): 2mins

$$f = \frac{dln\,\Delta(R)}{dln\,a}$$

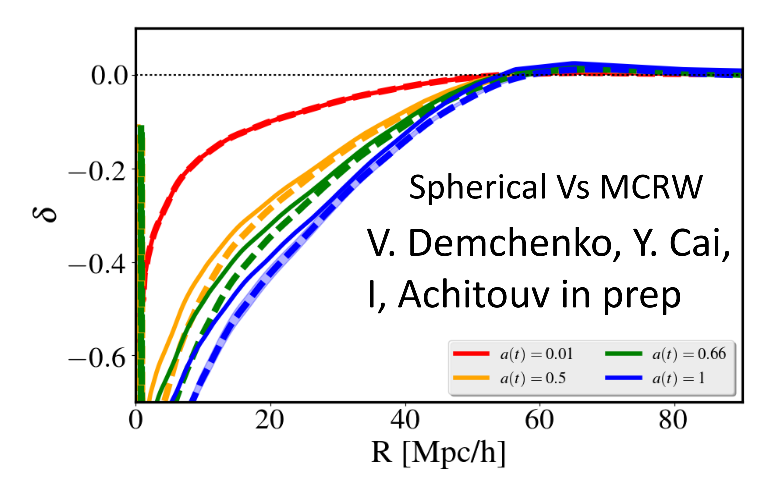


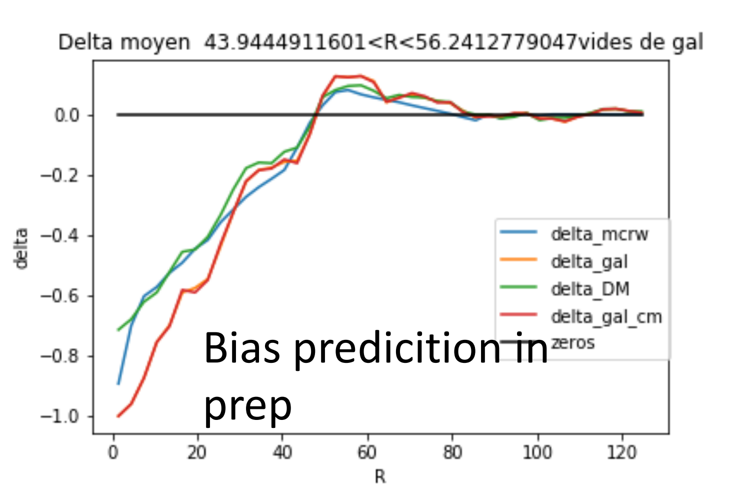
What can we do now?

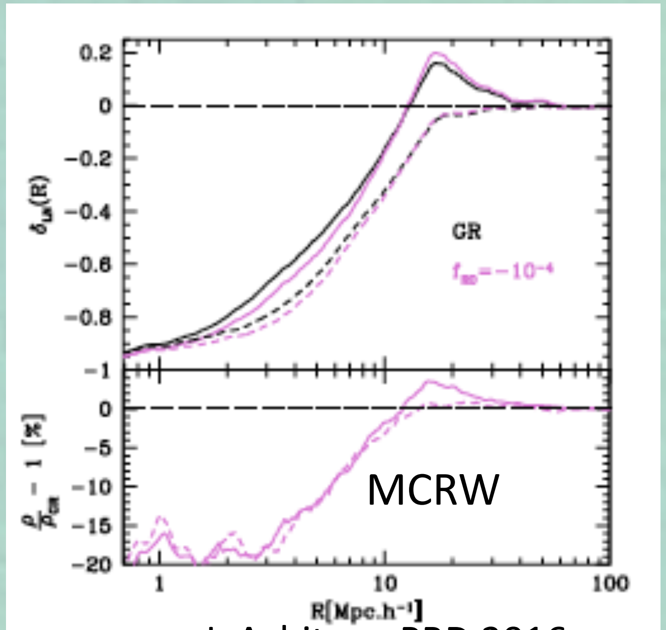
- Generate an estimate of non-standard gravity impact on density fluctuation statistics

e.g. quick estimate of how void profiles change for MG theories

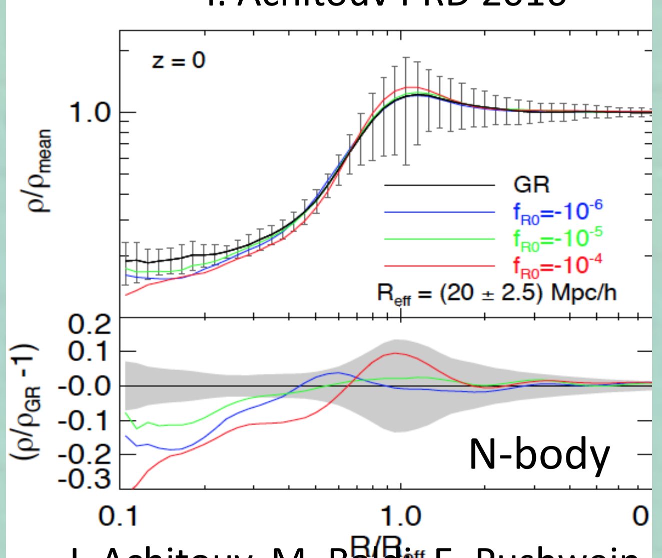
- Follow evolution of the profiles as a function of z with no need to start from z_{ini} (as we need for observations).







I. Achitouv PRD 2016



I. Achitouv, M. Baldi, E. Pushwein & J. Weller 2015

- Other applications: void abundance, Nonlinear growth rate as a function of the environment

Conclusion:

- Cosmic voids could play a central role in testing MG theories BUT still some effort required to adress systematic errors….
- Growth rate measurement: Potentially new information beyond the linear regime that require new approaches e.g. f(Δ)

Prospects & ongoing work:

- Testing mutlipole analysis with:
  - SDSS
  - TAIPAN
  - EUCLID
- Applyting the f(Δ) approach to MG simulations and observations

Other slides

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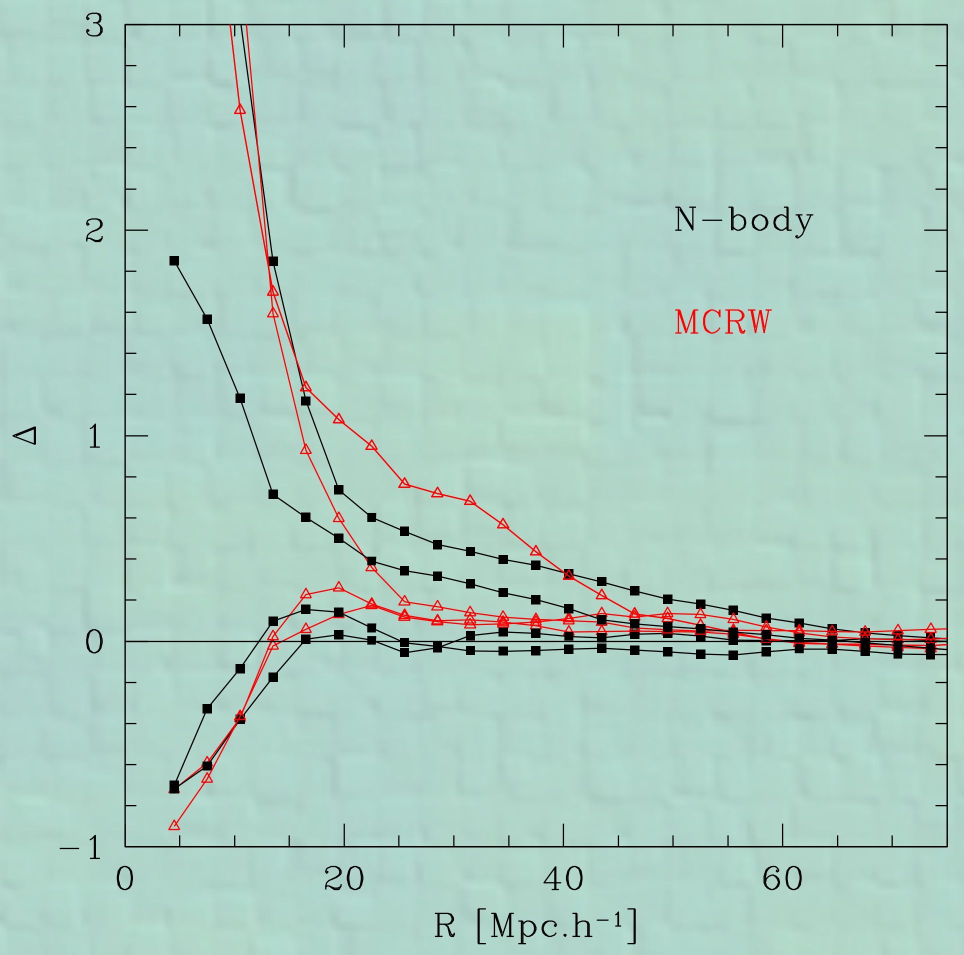

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