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ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

What can we learn from averaging Cosmological Observables in different environments?

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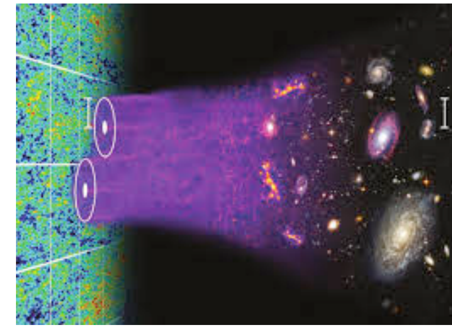
Motivations



- Additional information washed out by averaging over all environments?
- Improving systematic errors: BAO

- Screening mechanisms: suppress grav. forces in underdense regions

Upcoming surveys: high volume, so why not?

Outlines

- Improving the BAO scale measurement using environmental correlation function

- Testing the imprint of non-standard cosmologies using Monte Carlo random walks

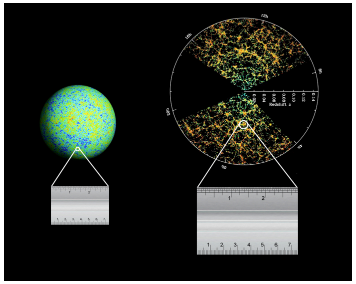
- Testing the consistency of the growth rate measurement in different environments with 6dFGS

Improving the BAO scale measurement using environmental weighting

BAO peak reconstruction

- **Baryon Acoustic Oscillations:**

Excess of matter on scale R~110 Mpc/h (peak in the matter correlation function)
Use as standard ruler



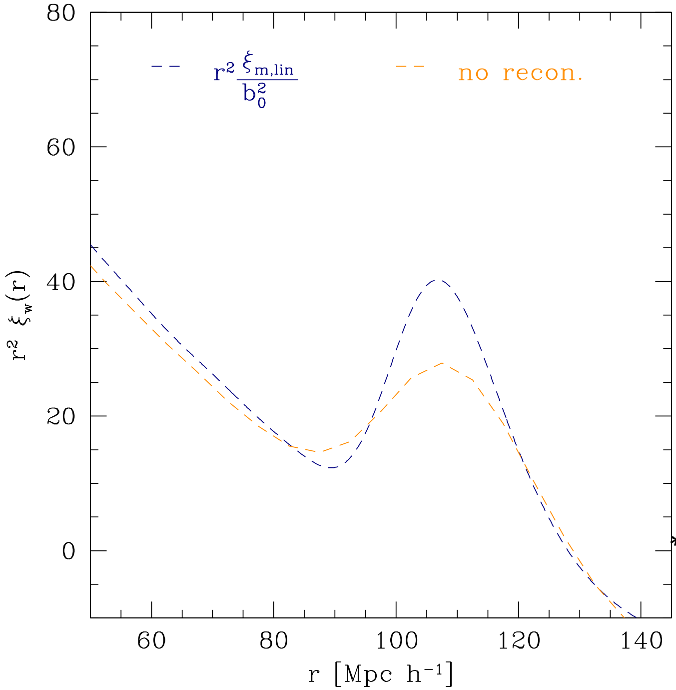
(Images courtesy NASA's Wilkinson Microwave Anisotropy Probe, left, and Sloan Digital Sky Survey, right)

- **Non-linear effects:**

Blur & Shift the BAO peak

- **Other effects:**

Redshift space distortions
Biased tracers



*Measured correlation functions in 1000 COLA^ simulations**
^COmoving Lagrangian Acceleration method
(Tassev et al. 2013 JCAP 0636)
** Simulations Run by J. Koda* (Kazin et al 2014 MNRAS Vol. 441 I4 *)*

Restoring the BAO peak

Standard reconstruction in simulations *(Eisenstein et al. 2006)*:

1- Measure local density around each galaxy

2- Compute the corresponding ``displacement field''

$$\mathrm{div}\,\boldsymbol{\Psi}=-\delta_m(Rs)$$

3- Move each galaxy position **x** by **x**-Ψ

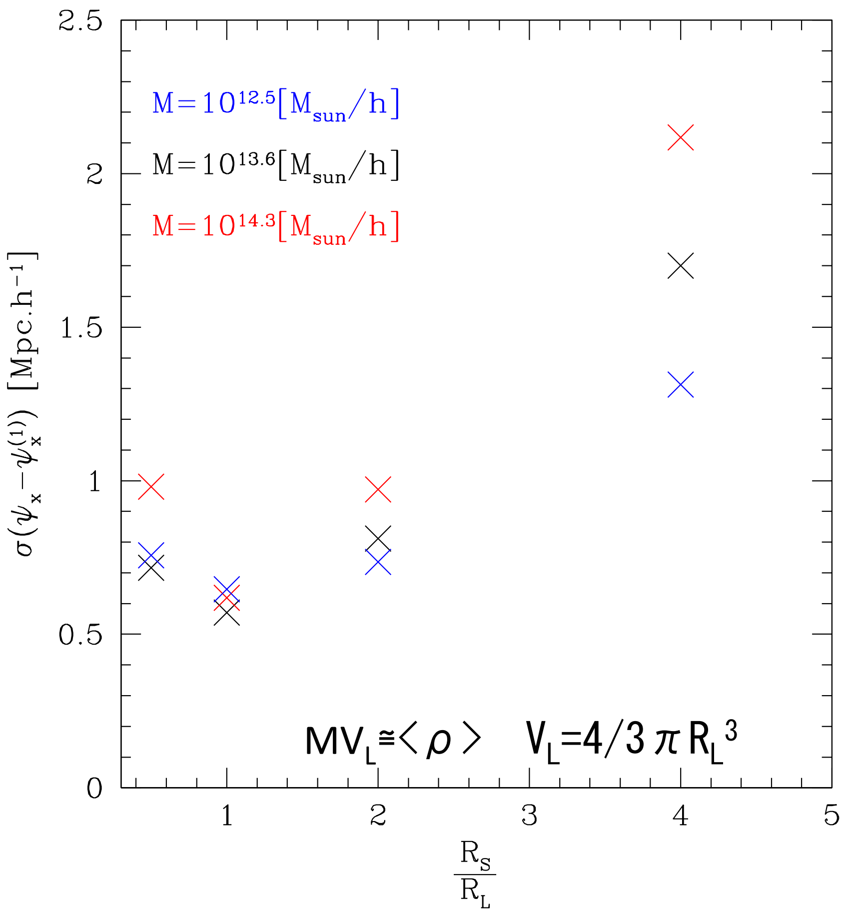
If no biased tracers & no NL **q**=**x**-Ψ

Displacement of halos:

Achitouv & C. Blake ArXiv: 1507.03584 M. Kopp,C. Ulman& I. Achitouv ArXiv: 1606.02301

- 1st order LPT approx:

$$\Psi^{(1)}(q,z,R_S) = \frac{\mathbf{v}_i(R_S)D(z)}{a_i H(a_i) f(a_i) D(z_i)}$$

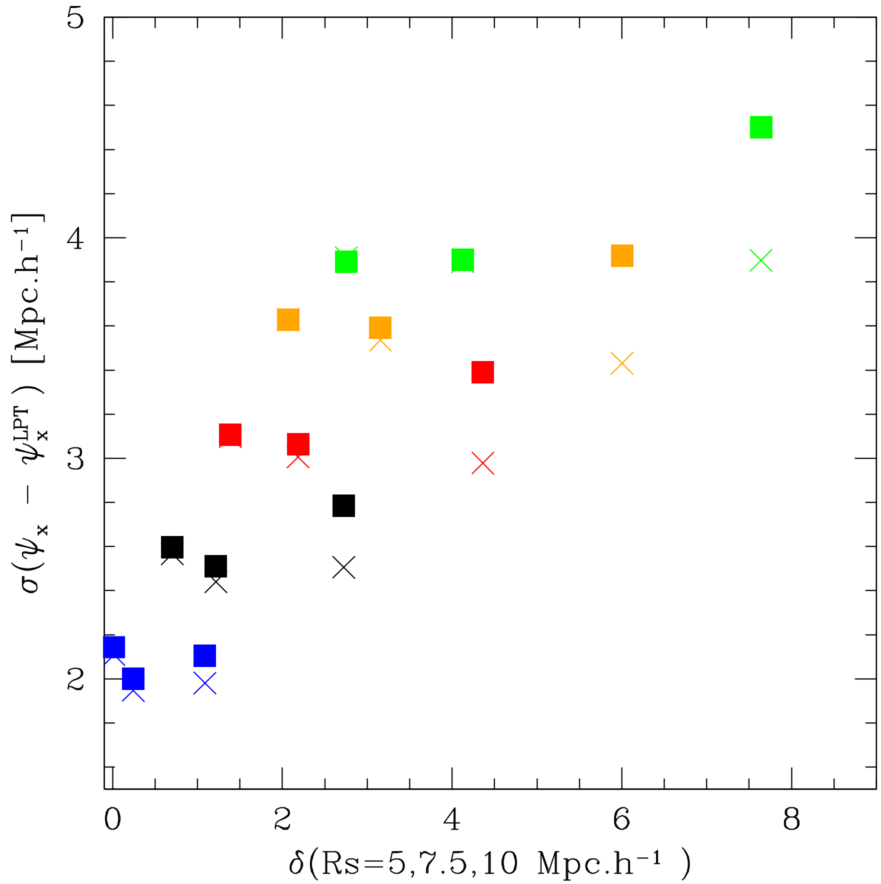


Optimal smoothing scale = initial size of the proto-halo

Performance of the reconstruction for different environments:

- Low sensitivity to the smoothing scale
- High sensitivity to the environment, independent of the LPT orders

The reconstruction efficiency decreases in dense environments where NL effects become important.



I. Achitouv & C. Blake ArXiv: 1507.03584

Reconstructed correlation function in different environments:

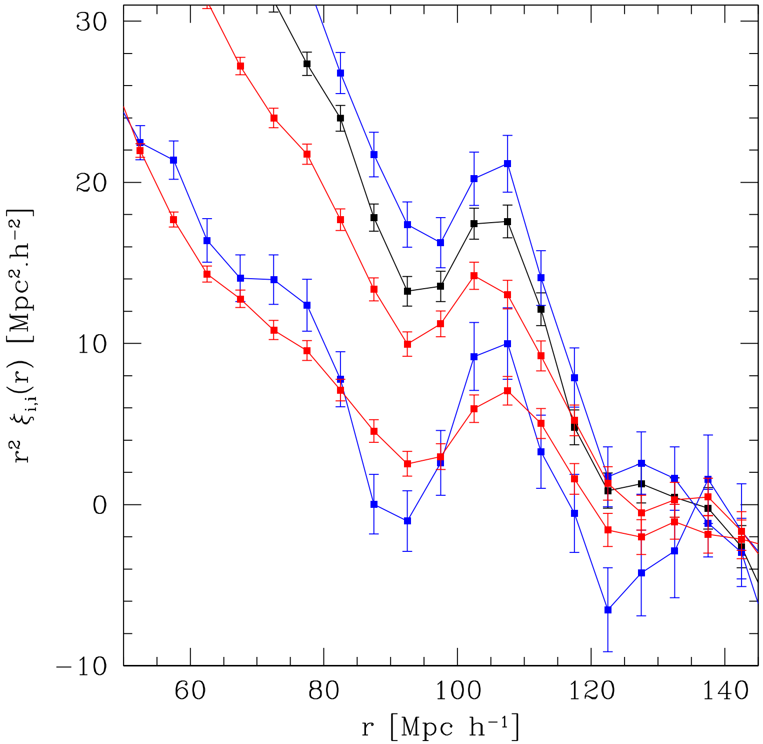
- **Landy-Szalay estimator:**

$$\xi_{E_iE_j} = \frac{DD_{ij}}{RR_{ij}}\frac{nR_inR_j}{nD_inD_j} - \frac{DR_{ij}}{RR_{ij}}\frac{nR_i}{nD_i} - \frac{DR_{ji}}{RR_{ij}}\frac{nR_j}{nD_j} + 1$$

- **Sharper peak in underdense environment**
  less NL effects
  reconstruction more accurate

- **The total correlation function can be expressed as**

$$\xi_{\rm tot} = \frac{\sum_{ij}(\alpha_{ij}\,RR_{ij}\,\xi_{ij} + \beta_{ij})}{\sum_{ij} RR_{ij}}$$



I. Achitouv & C. Blake ArXiv: 1507.03584

Can we build a new estimator of ξ_{tot} which improves the reconstruction of the BAO peak?

Weighting the reconstructed correlation function:

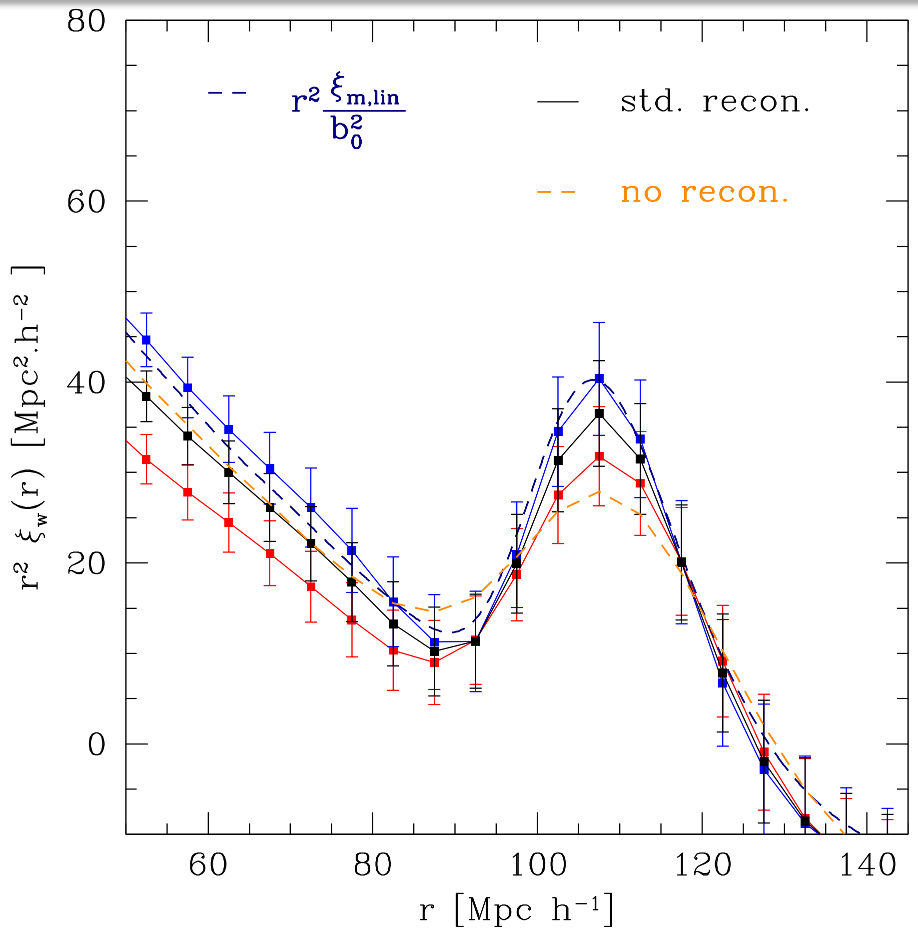
- **Simple idea:**

ξ_{ij} → wij ξ_{ij} & wij=(wi wj)$^{1/2}$

reproduce linear correlation function shape at the BAO scale

$$\xi_{\rm weighted} = \frac{\sum_{ij} w_{ij} \left(\alpha_{ij} RR_{ij}\, \xi_{ij} + \beta_{ij}\right)}{\sum_{ij} w_{ij} RR_{ij}}$$

Weighting+ 2LPT + R_s → R_L
~8% improvement on the measurement of the BAO scale



I. Achitouv & C. Blake ArXiv: 1507.03584

Testing the imprint of non-standard cosmologies using Monte Carlo random walks

The imprint of modified gravity

- Adding a function of the Ricci scalar to the E-H Action: f(R) gravity (Hu & Sawicki 2007)

$$S = \int d^4x \sqrt{-g} \left(\frac{R + f(R)}{16\pi G} + \mathcal{L}_m \right)$$

The f(R) can be tuned to be close to the background expansion of LCDM

- Poisson equation is depends on the scalar curvature perturbation

$$\nabla^2 \phi = \frac{16\pi G}{3} \delta\rho - \frac{1}{6} \delta R \qquad \delta R = R_0 \left(\sqrt{\frac{f_{R0}}{f_R}} - 1 \right)$$

  - We can specify the model by choosing:

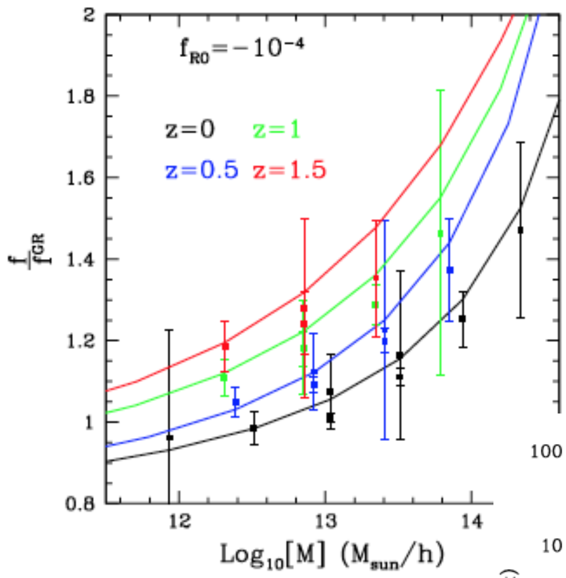
$f_R \propto R$ and background amplitude at z=0: f_{R0} e.g. $f_{R0}=-10^{-4}$

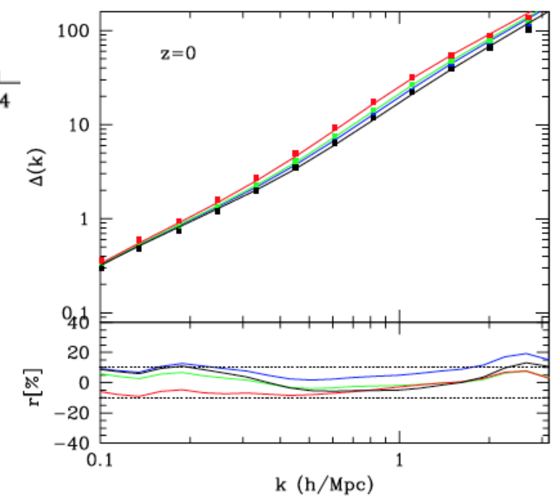
The imprint of f(R) in the LSS

- Multiplicity function:

$$\frac{dn}{dM} = f(\sigma)\frac{\rho_m}{M^2}\frac{d\log\sigma^{-1}}{d\log M}$$

- Halo profile, bias, non-linear P(k)...

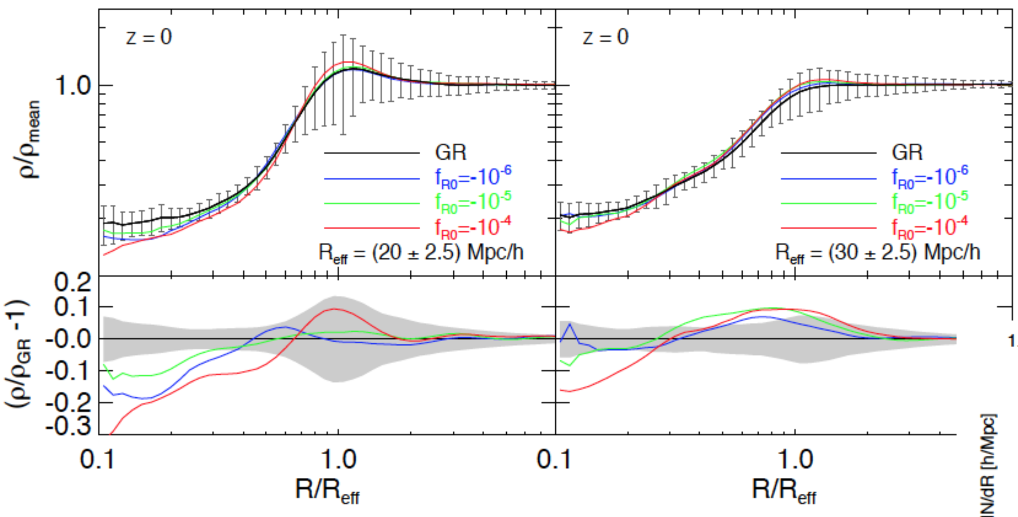


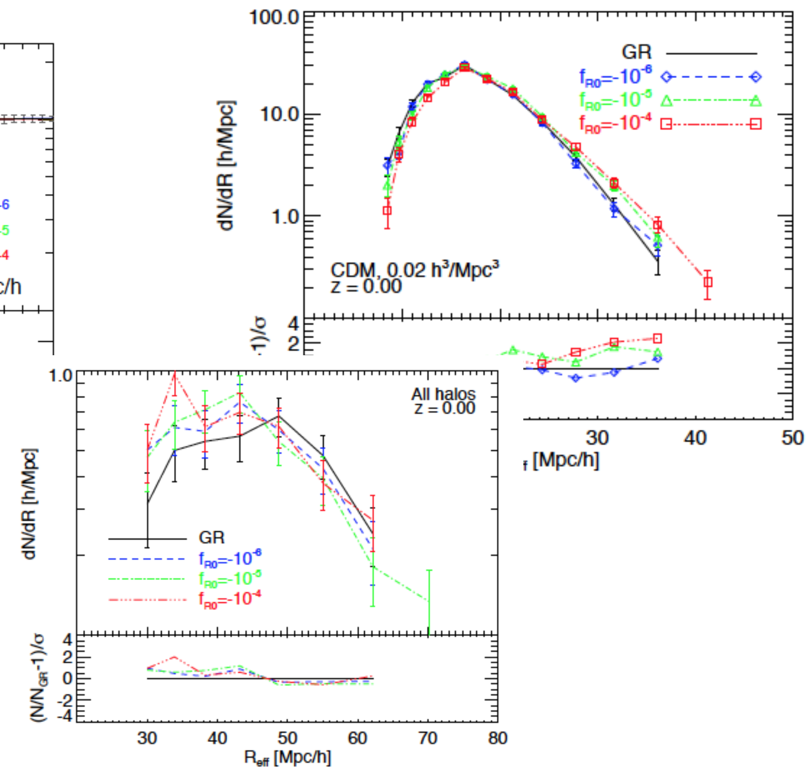


I.Achitouv, M. Baldi, E. Puchwein & J. Weller arXiv: **1511.01494**

We can model `most' of these effects with the EST and the halo model

Void Profiles & void abundance:





The theory is still missing…

I.Achitouv, M. Baldi, E. Puchwein & J. Weller arXiv: **1511.01494**

Monte Carlo Random Walks

- Evolution of the smoothed linear density field:

$$\frac{\partial \Delta(\mathbf{x}, R, \ln k)}{\partial \ln k} = \eta(\mathbf{x}, \ln k)\tilde{W}(k, R),$$

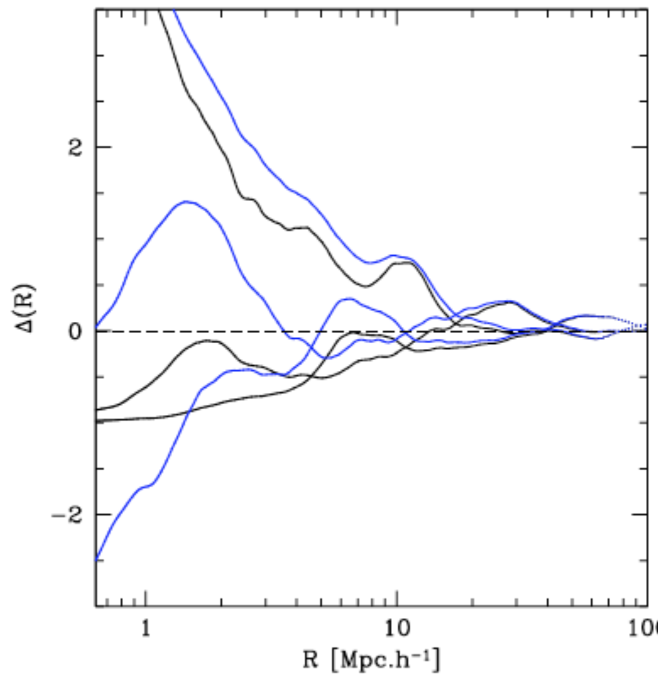
$$\langle \eta(\mathbf{x}_1, \ln k_1)\eta(\mathbf{x}_2, \ln k_2)\rangle = \delta_D(\ln k_2 - \ln k_1) P_{\rm Lin}(k_1)\frac{\sin k_1 R}{k_1 R}.$$

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

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

Smoothed non-linear Pk

Smoothed linear Pk



I.Achitouv, arXiv 1609.01284

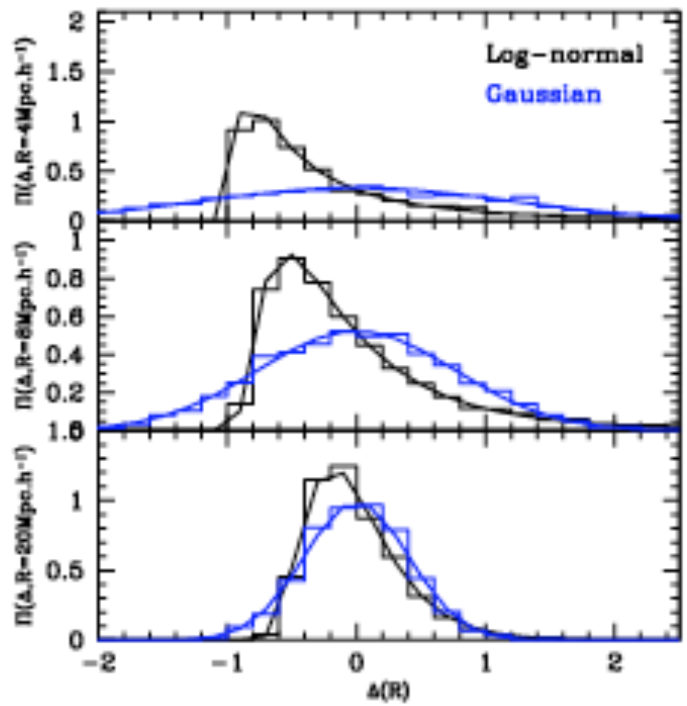
Monte Carlo Random Walks

- Initial density fluctuation PDF

$$P(\Delta,\sigma_{\rm Lin}) = \frac{1}{\sqrt{2\pi\sigma^2_{\rm Lin}(R)}}\exp\left(-\frac{\Delta^2}{2\sigma^2_{\rm Lin}(R)}\right)$$

- Non-linear density fluctuation PDF

$$P(\Delta_{\rm LN},\sigma^2_{\rm NL}(R)) = \frac{1}{\sqrt{2\pi\sigma^2_{\rm eff}}}\times$$
$$\exp\left[-\frac{(\ln(1+\Delta_{\rm LN})+\sigma^2_{\rm eff}/2)^2}{2\sigma^2_{\rm eff}}\right]\frac{1}{1+\Delta_{\rm LN}}$$



I.Achitouv arXiv 1609.01284

What do we do now?

- We can quickly generated an estimate of non-standard gravity on density fluctuation statistics

- Application: how void profiles changes for f(R) modify gravity

- Other application: overdense patches of matter, void abundance, rare statistics…?

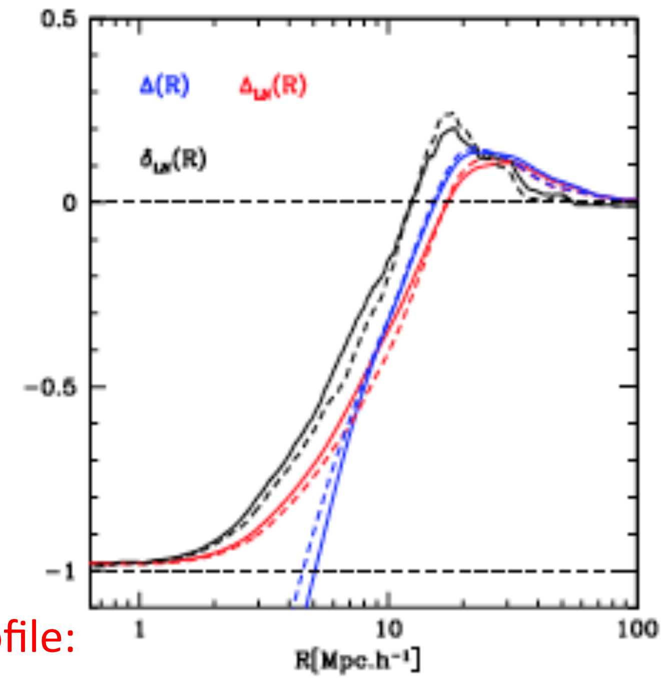
The Imprints of f(R) gravity on void profiles using MCRW

- I used MGHalofit *(Zhao, ApJS, 2014)* for the f(R) $P_{NL}(k)$
- Selecting Random Walks that satisfy 2+1 criteria:

$$\delta_{\rm LN}(R_v \pm \varepsilon) > 0 \qquad R_v = 17.25 \mathrm{Mpc.h}^{-1}$$

$$\Delta_{\rm LN}(R < R_m) < -0.9 \qquad R_m = 2 \mathrm{Mpc.h}^{-1}$$

$$\Delta_{\rm LN}(R < R_v) < \Delta_{\rm LN}(R_v)$$



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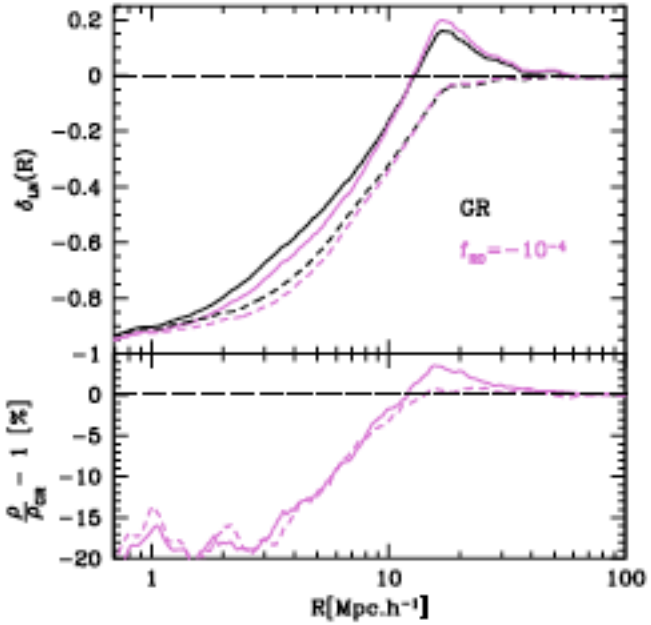
We recover the N-body simulations trend for the f(R) profile: voids are more empty and the ridge amplitude is higher than the GR profile

Imprint of f(R) for different type of voids

- Selection of voids can enhance the imprint of f(R)
- Flexible void finder can be tuned to study specific cosmology.



I.Achitouv arXiv 1609.01284

Testing the consistency of the growth rate in different environments with the 6dF galaxy survey

Linear Perturbation theory :

- Evolution of the linear density fluctuations:

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

- Linear growth rate for a ΛCDM universe:

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

Sensitive to the background expansion

Depends on gravitational forces

- Peculiar velocities of galaxies are sourced by the gravitational potential

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

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Probing the linear growth rate in different environments:

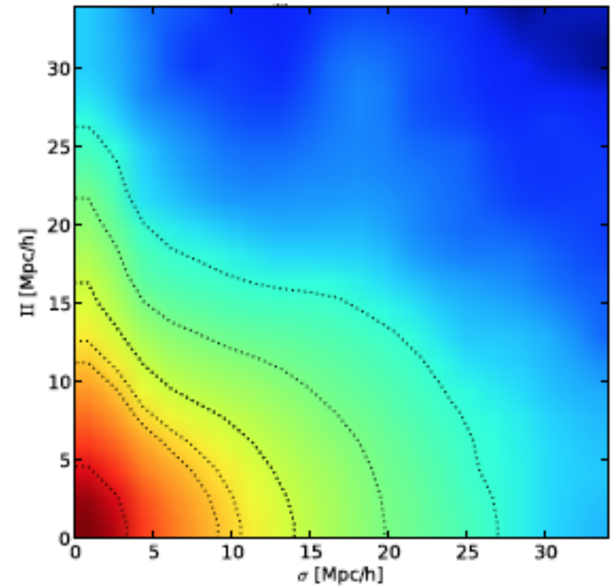
- Redshift space distortions:

Asymmetry of the correlation function due to peculiar velocities of galaxies.

$$\xi_{gg}(\sigma,\pi) = \int \xi^l(\sigma, \pi - \frac{v}{H_0})P(v)dv$$

Large scales: coherent infall/ outflow due to density fluctuation (Kaiser effect) sensitive to the growth rate

Small scales: random motion of galaxies within group (FoG)



I. Achitouv & C. Blake Arxiv: 1606.03092

Probing the linear growth rate in different environments:

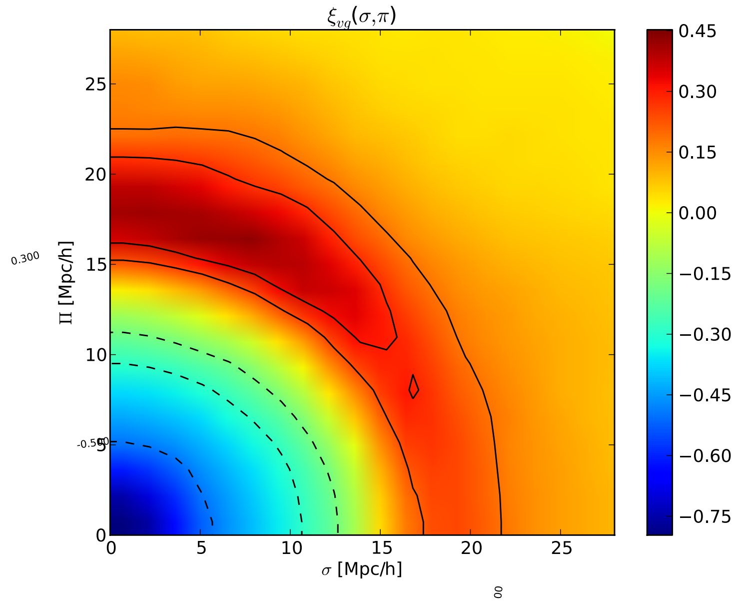
- The galaxy-void correlation function in RS: outflow motion of the galaxies sensitive to the growth rate

$$v_p(r) = -\frac{1}{3} H_0 r \Delta(r) f$$

$$\Delta(r) = \frac{3}{r^3} \int_0^r \xi_{v-\mathrm{DM}}(y) y^2 dy.$$

Small scales Virial motion of the galaxies P(v)dv

$$P(v)dv = \frac{1}{\sqrt{2\pi\sigma_v}} \exp\left[-\frac{v^2}{2\sigma_v}\right] dv,$$



Voids identified in *DEUSS N-body*

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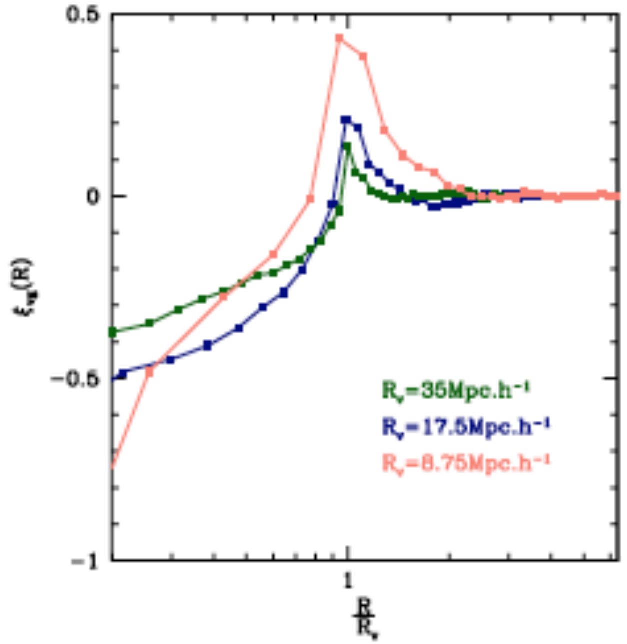
An alternative void finder

- Probing a few measurement of the density fluctuation around random positions.

$$\delta^{j}_{\mathrm{T,G}} = \frac{\mathrm{DT(j,R_i)}}{\mathrm{RT(j,R_i)}}\frac{N_{\mathrm{Ran}}}{N_{\mathrm{Gal}}} - 1.$$

$$\begin{aligned}
\delta^{j}_{\mathrm{T,G}}(j, R = 1 \pm 1\mathrm{Mpc.h^{-1}}) &< -0.9 \\
\delta^{j}_{\mathrm{T,G}}(j, R = 2 \pm 1\mathrm{Mpc.h^{-1}}) &< -0.7, \\
\delta^{j}_{\mathrm{T,G}}(j, R = R_v + \Delta R) &> \delta^{j}_{\mathrm{T,G}}(j, R_v) \text{ and} \\
\delta^{j}_{\mathrm{T,G}}(j, R = R_v \pm 1\mathrm{Mpc.h^{-1}}) &\geq 0
\end{aligned}$$



I.Achitouv arXiv 1609.01284

Systematics errors for the growth rate

- Testing the effect of the ridge in the DM- voids RS correlation function:

- At fixed void radius the amplitude of the void ridge impact the systematic error in the GSM

- Other systematics effect need to be adress for precise measurement of the growth rate

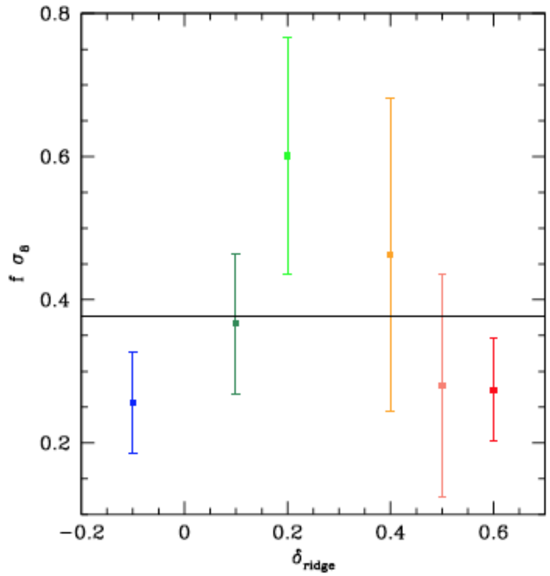


FIG. 10: Best fitting values for $f\sigma_8$ as function of the ridge amplitude. The different colors correspond to voids with the same radius but a density fluctuation at the ridge $\delta_{\rm ridge} = -0.1, 0.1, 0.2, 0.4, 0.5, 0.6$ for the blue, dark green, green, orange, pink and red squares respectively.

Selection of the void is important

I.Achitouv arXiv 1609.01284

6dF Galaxy Survey:

http://www.6dfgs.net/

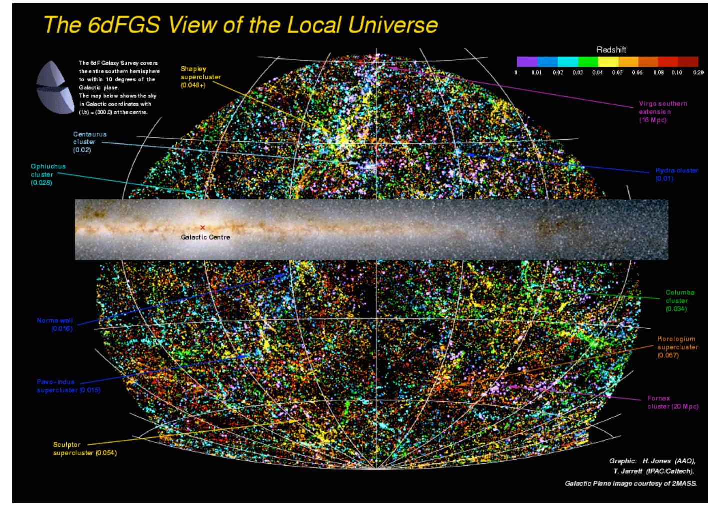
- Low redshift survey z~0.1

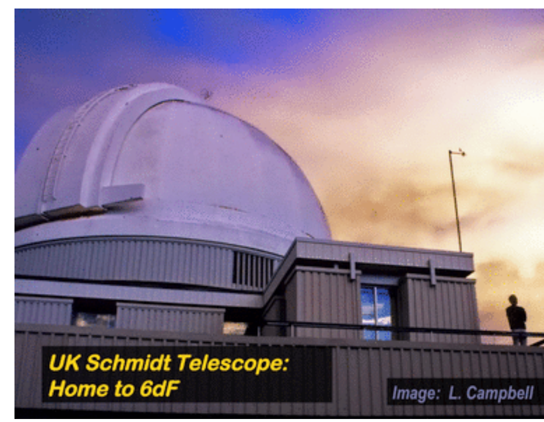
- Sensitive to the late-time accelerated expansion of the universe (DE)

- Mapped nearly half the sky (southern hemisphere)

- Large volume that can probe large voids

- Catalogue of ~ 100,000 galaxies and measurement of ~8,000 peculiar velocities.





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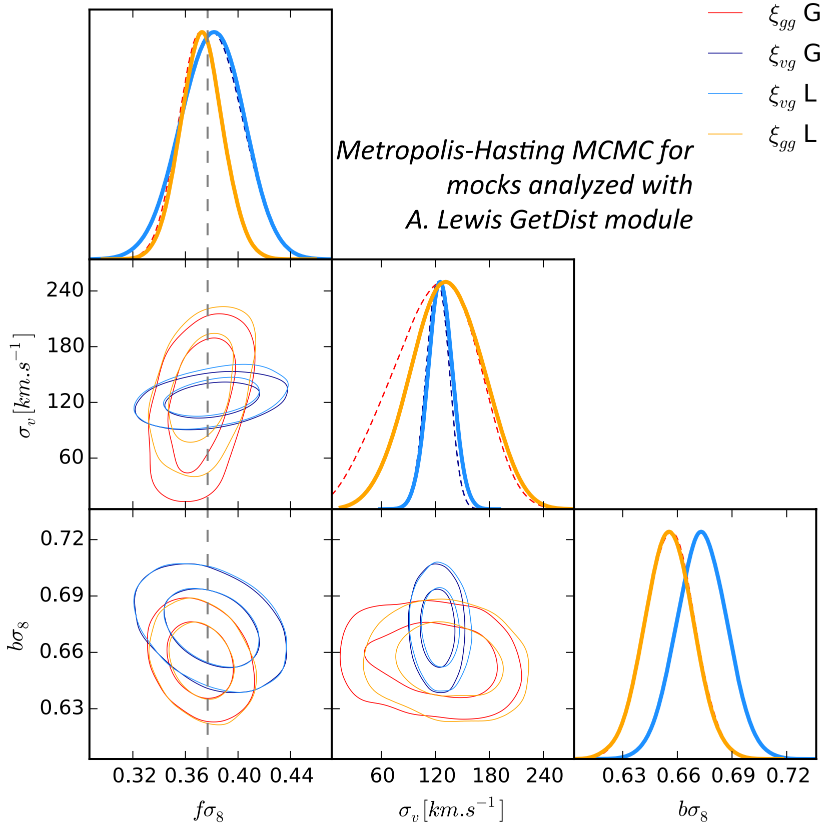
Consistency of the growth rate

Assumptions:

- ΛCDM cosmology
- Linear bias
- Constant velocity dispersion (nuisance parameter)
- We consider voids of size 17.5Mpc.h^{-1}

We found for 6dFGS a consistency with ΛCDM:
$f\sigma_8$ =0.36±0.06 for gal-gal RSD
and $f\sigma_8$ =0.39±0.11 for the gal-void RSD

Test on mocks:



I. Achitouv & C. Blake Arxiv:1606.03092

Conclusion

- Looking at different environments can be helpful to:

-Improve current cosmological probes ~ 8% for BAO
-Challenge the ΛCDM picture of our universe / GR model

- We can use MCRW to test departure from the LCDM universe
- Good approximation to study void profiles
- Can be extended to study void abundance…

- With 6dFGS we find consistency with LCDM but:

-Large statistical errors that will become lower with upcoming surveys giving a good opportunity to perform such analyses.
- Interesting to test for different models of gravity and DE

The distortion factor:

- X^2 (α) estimate

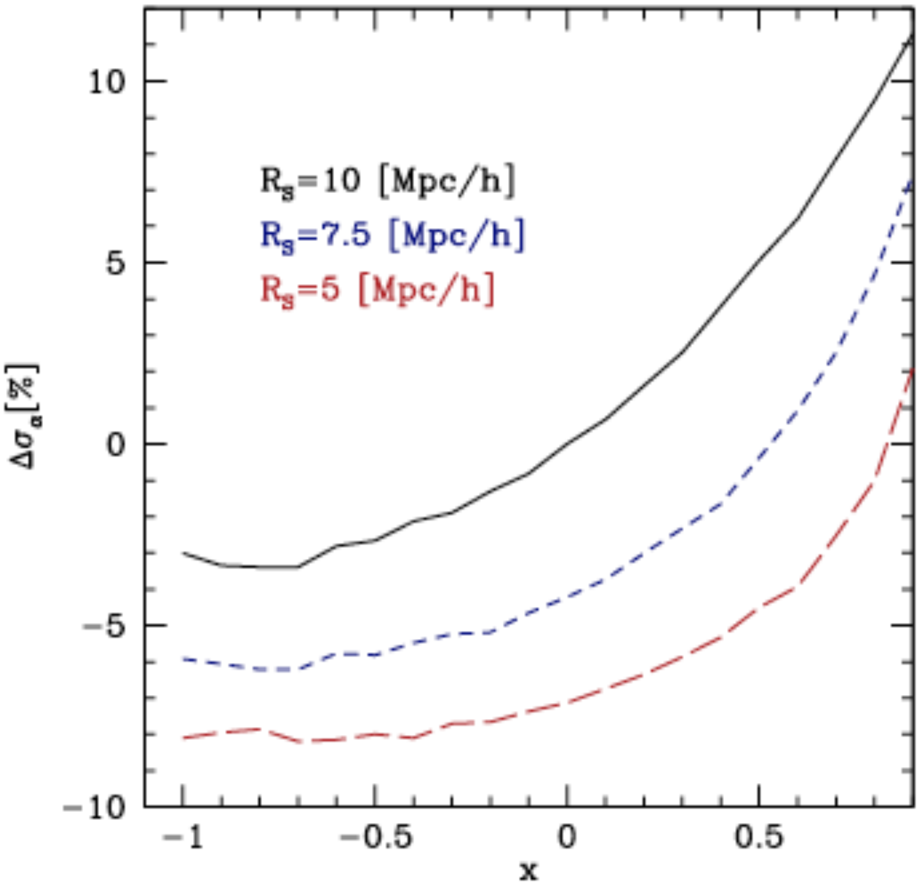
$$\xi^{\rm flt}(r) = B^2 \xi_m(\alpha r) + A(r)$$

- α=1 no shift in BAO peak
- σ_α over 1000 boxes = error in BAO scale measurement

Standard reconstruction:

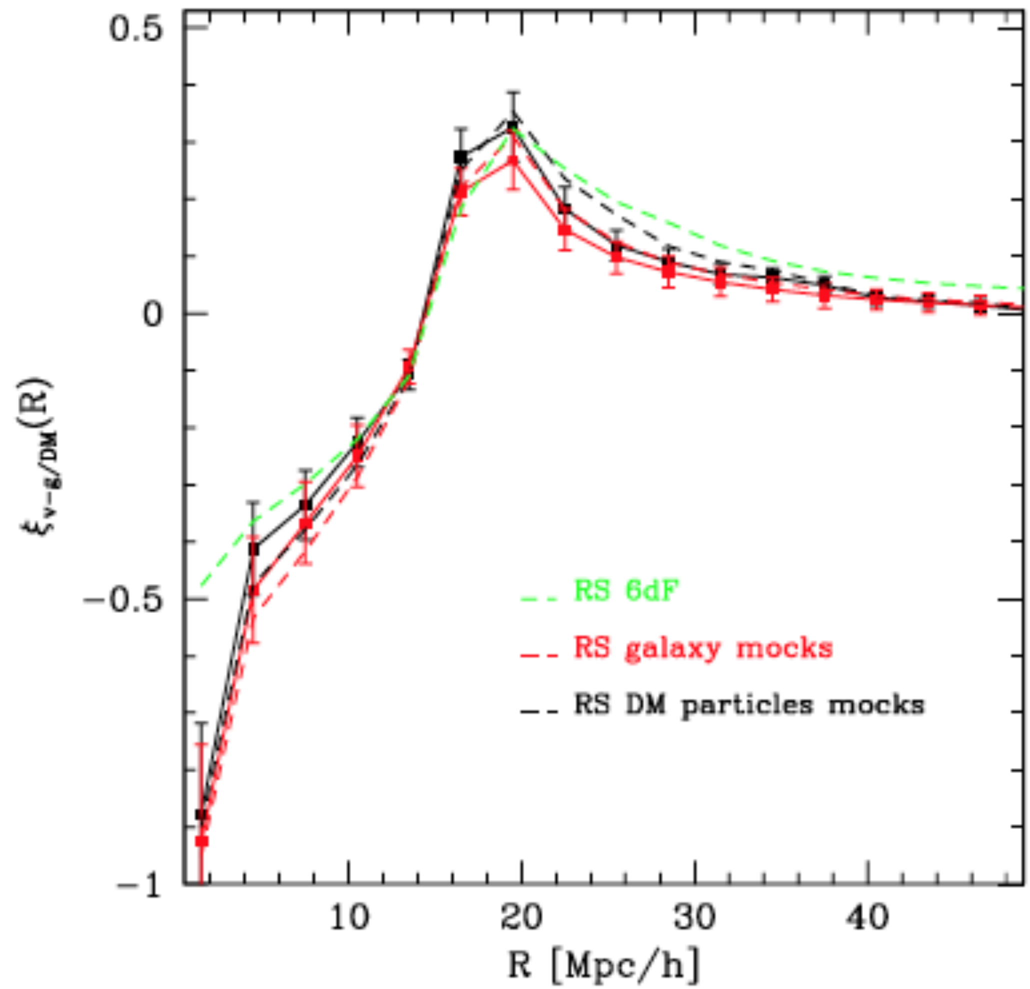
- R_S=10Mpc/h and x=0
- Zel'dovitch approximation

Weighting+ 2LPT + $R_s \rightarrow R_L$
~8% improvement



Identifying voids:
I. Achitouv, in prep

Density criteria to identify voids of size Rv=20Mpc/h



Motivations

- **Simple idea:**

$\xi_{ij} \rightarrow wij\ \xi_{ij}$ & $wij=(wi\ wj)^{1/2}$

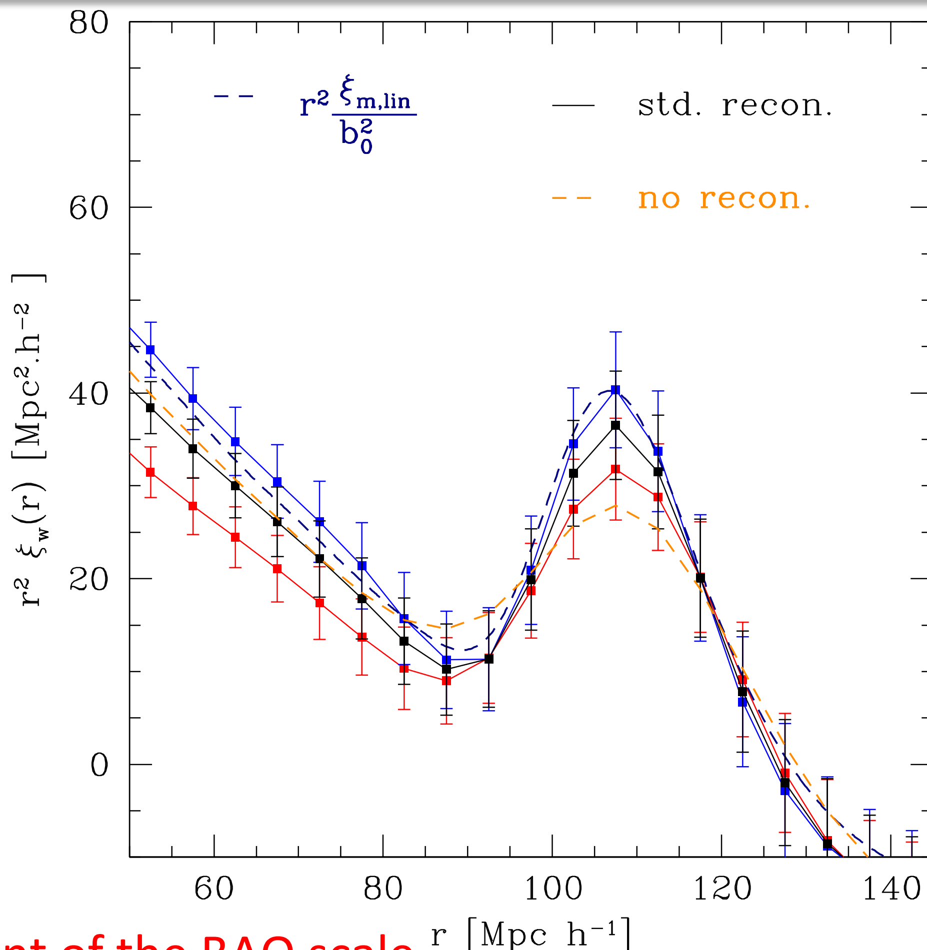
reproduce linear correlation function shape at the BAO scale

broad choices of parameters

- **Elaborated idea:**

$$\xi_{\mathrm{weighted}} = \frac{\sum_{ij} w_{ij} \left(\alpha_{ij} RR_{ij}\, \xi_{ij} + \beta_{ij}\right)}{\sum_{ij} w_{ij} RR_{ij}}$$

$wi=1+(i-i_{av})\ x/(i_{max}-i_{av})$ $x=[-1,1]$



Weighting+ 2LPT + $R_s \rightarrow R_L$
~8% improvement on the measurement of the BAO scale