

CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

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

SWIN
BUR
NE *

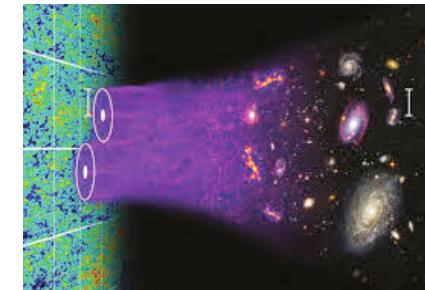
SWINBURNE
UNIVERSITY OF
TECHNOLOGY

Ixandra Achitouv

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?



Ixandra Achitouv

Outliness

- 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

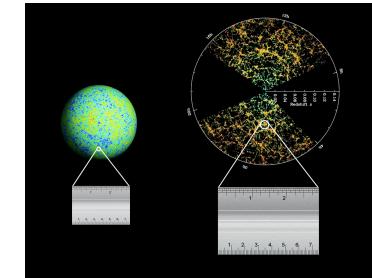
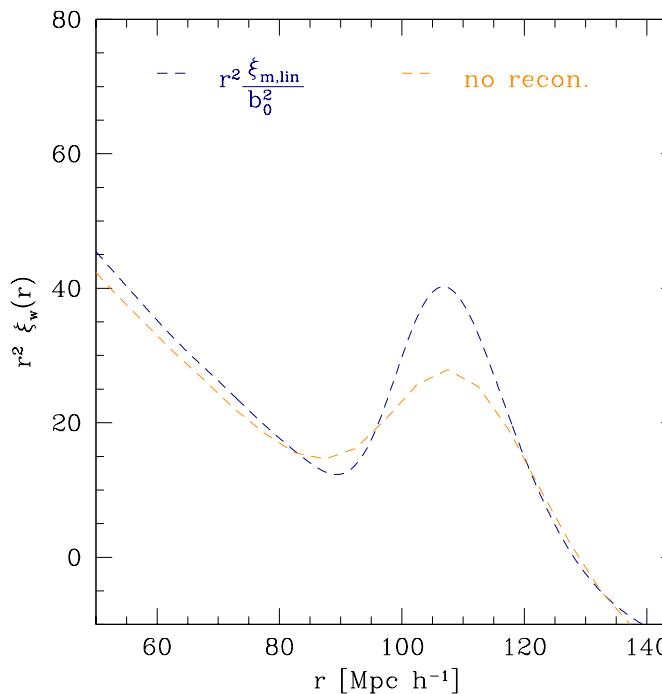
Ixandra Achitouv

Improving the BAO scale measurement using environmental weighting

BAO peak reconstruction

- **Baryon Acoustic Oscillations:**
 Excess of matter on scale $R \sim 110 \text{ Mpc}/h$
 (peak in the matter correlation function)
 Use as standard ruler

- **Non-linear effects:**
 Blur & Shift the BAO peak
- **Other effects:**
 Redshift space distortions
 Biased tracers



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

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 L4)

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''

$$\text{div } \Psi = -\delta_m(R_s)$$

3- Move each galaxy position \mathbf{x} by $\mathbf{x} - \Psi$

If no biased tracers & no NL $\mathbf{q} = \mathbf{x} - \Psi$

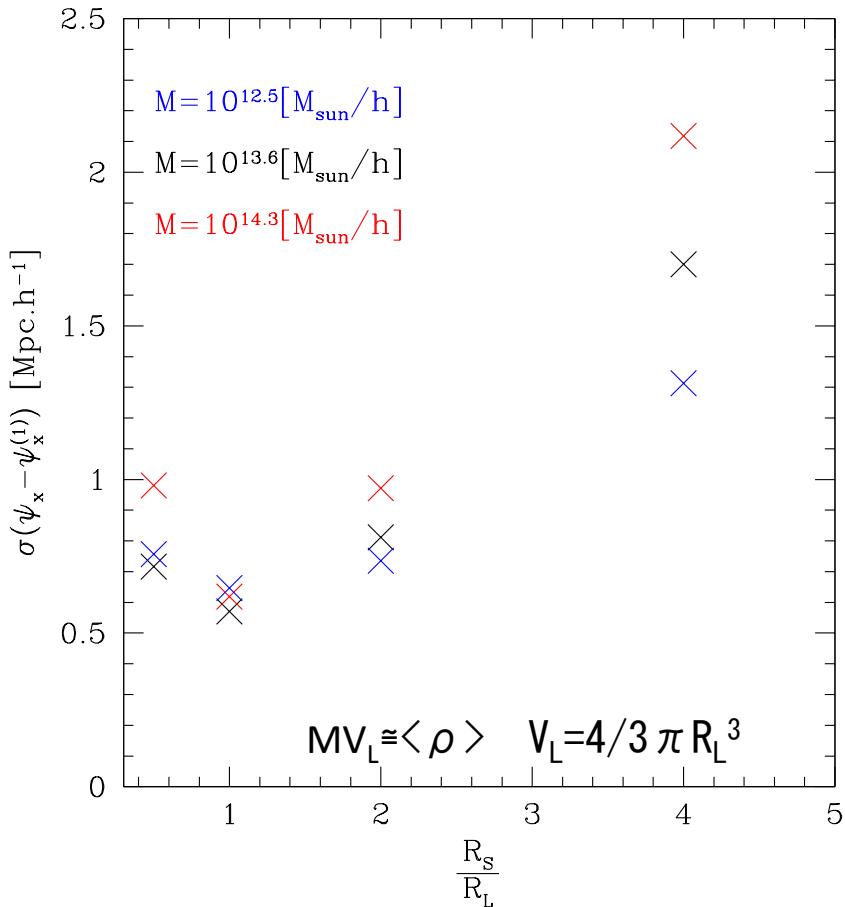
Displacement of halos:

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

- 1st order LPT approx:

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

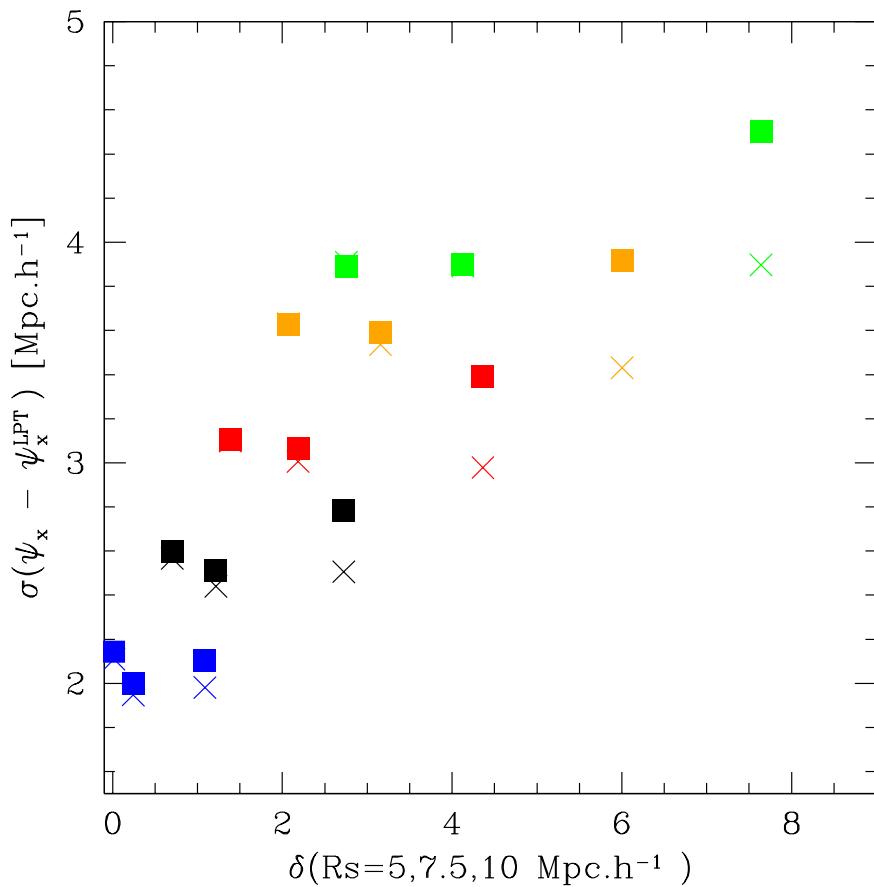
Optimal smoothing scale = initial size of the proto-halo



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

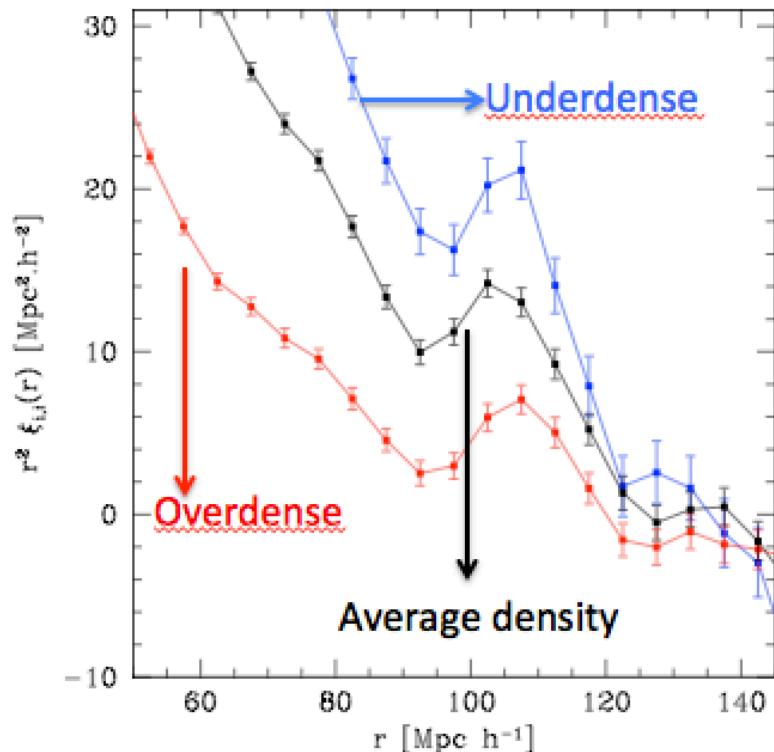
Reconstructed correlation function in different environments:

- **Landy-Szalay estimator:**

$$\xi_{E_i E_j} = \frac{DD_{ij}}{RR_{ij}} \frac{nR_i nR_j}{nD_i nD_j} - \frac{DR_{ij}}{RR_{ij}} \frac{nR_i}{nD_i} - \frac{DR_{ji}}{RR_{ij}} \frac{nR_j}{nD_j} + 1$$

- **Sharper peak in underdense environment**
less NL effects
reconstruction more accurate
- **The total correlation function can be expressed as**

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



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:

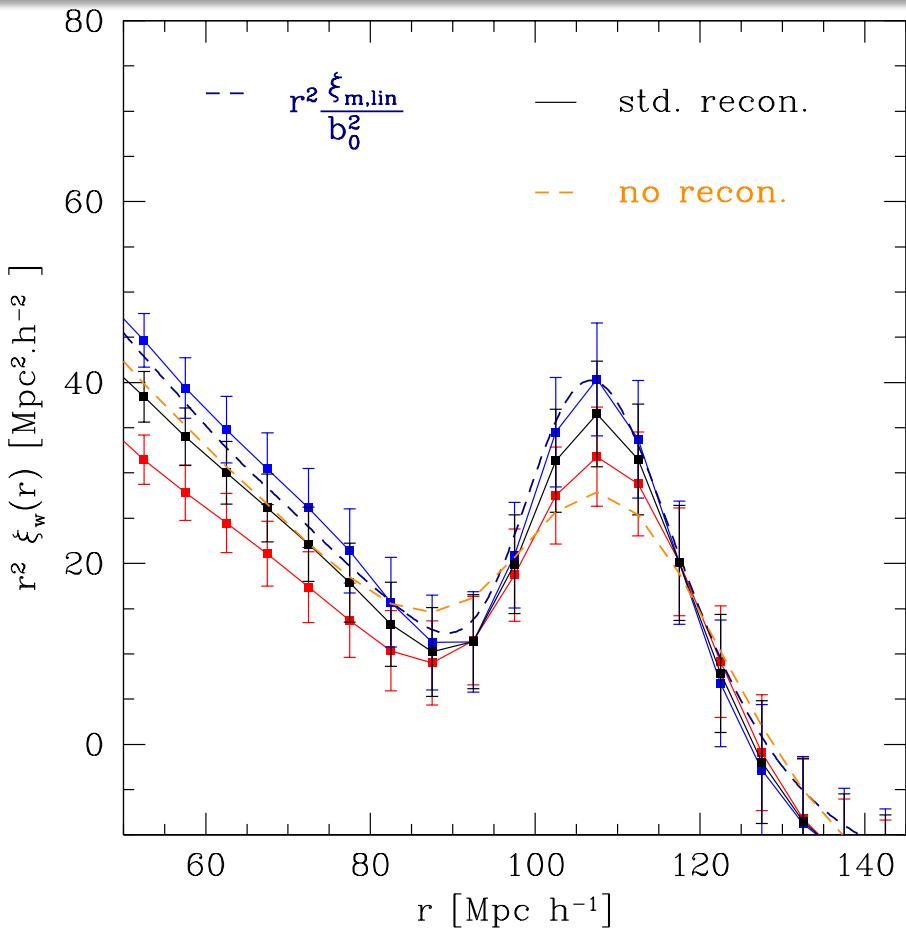
- Simple idea:

$$\xi_{ij} \rightarrow w_{ij} \xi_{ij} \quad \& \quad w_{ij} = (w_i w_j)^{1/2}$$

reproduce linear correlation
function shape at the BAO scale

$$\xi_{\text{weighted}} = \frac{\sum_{ij} w_{ij} (\alpha_{ij} R R_{ij} \xi_{ij} + \beta_{ij})}{\sum_{ij} w_{ij} R R_{ij}}$$

Weighting+ 2LPT + $R_s \rightarrow R_L$
 ~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 depends on the scalar curvature perturbation

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

- We can specify the model by choosing:

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

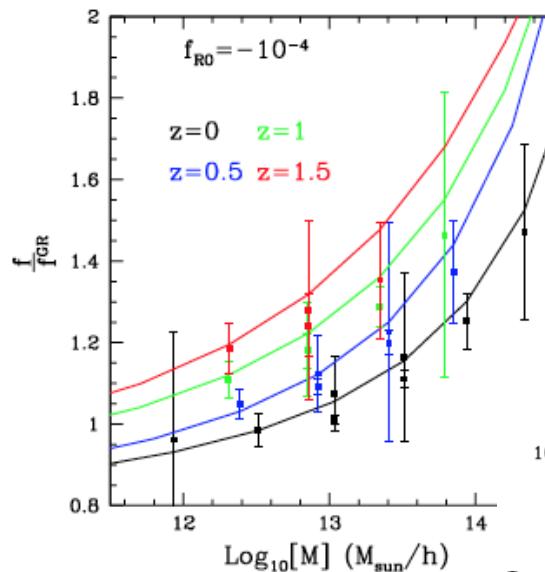
The imprint of $f(R)$ in the LSS

- Multiplicity function:

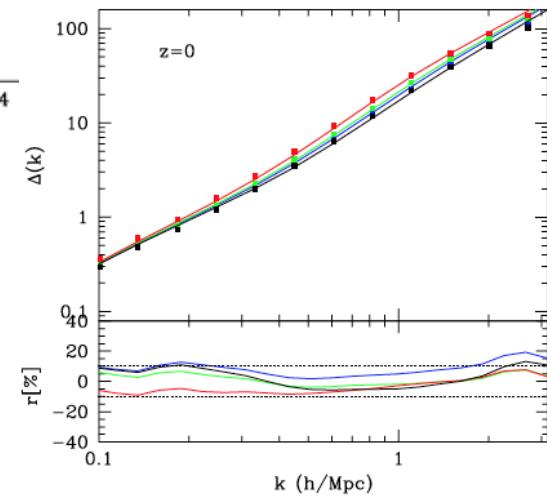
$$\frac{dn}{dM} = f(\sigma) \frac{\rho_m}{M^2} \frac{d \log \sigma^{-1}}{d \log M}$$

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

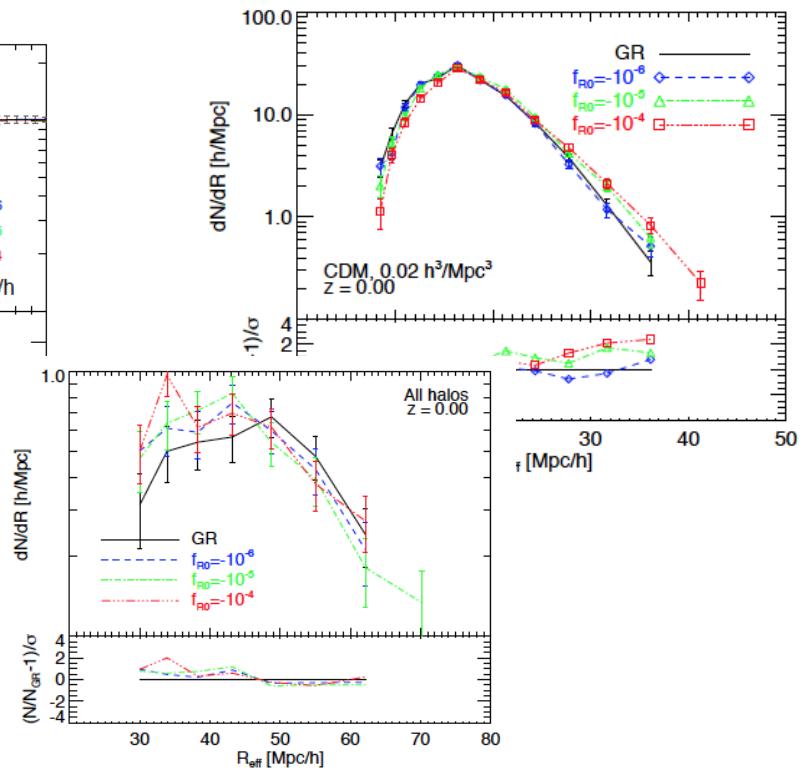
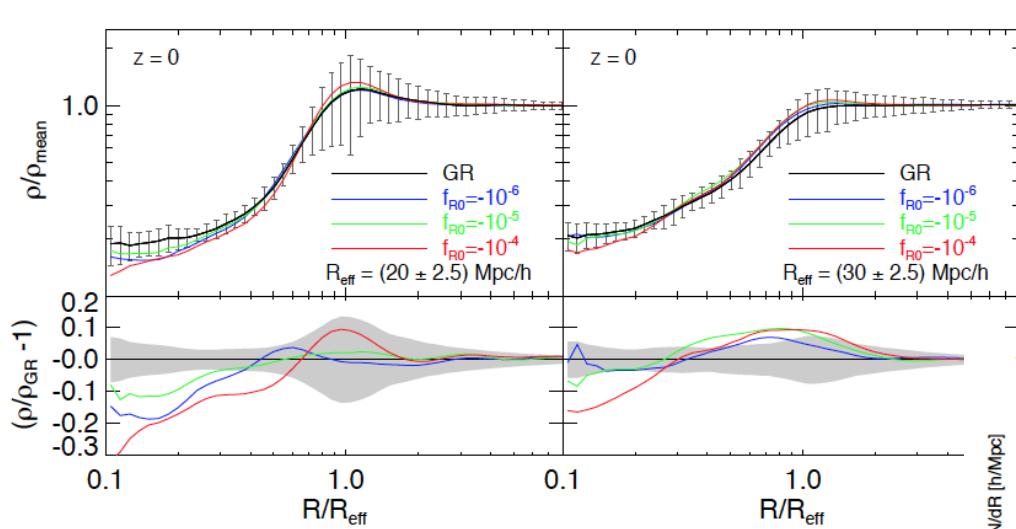
We can model ‘most’ of these effects with the EST and the halo model



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



Void Profiles & void abundance:



The theory is still missing...

I.Achitouv, M. Baldi, E. Puchwein & J. Weller arXiv: [1511.01494](https://arxiv.org/abs/1511.01494)

Ixandra Achitouv

Monte Carlo Random Walks

- Evolution of the smoothed linear density field:

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

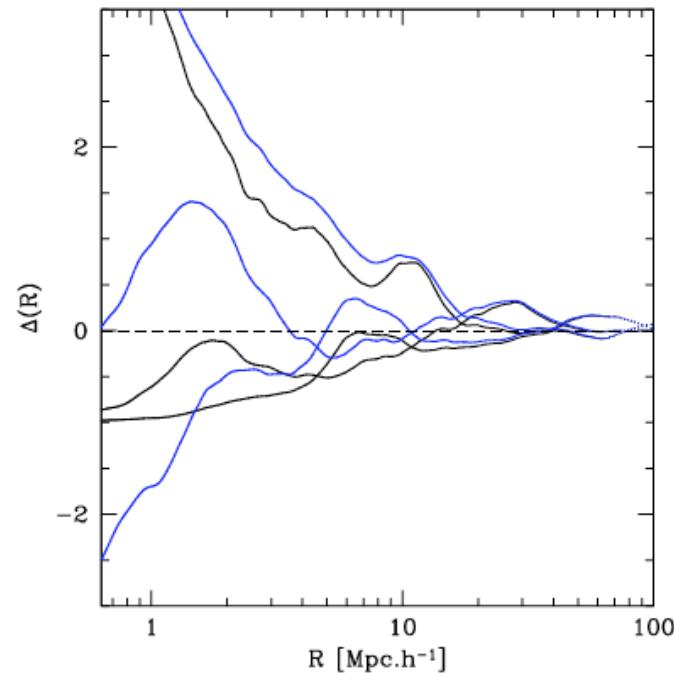
$$\langle \eta(\mathbf{x}_1, \ln k_1) \eta(\mathbf{x}_2, \ln k_2) \rangle = \delta_D(\ln k_2 - \ln k_1) P_{\text{Lin}}(k_1) \frac{\sin k_1 R}{k_1 R}.$$

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

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

Smoothed non-linear
Pk

Smoothed linear Pk



I.Achitouv, arXiv 1609.01284

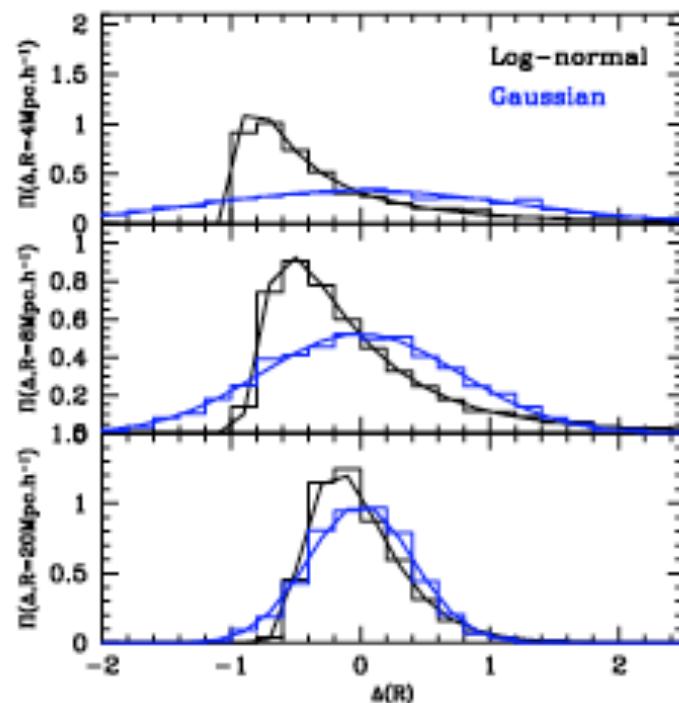
Monte Carlo Random Walks

- Initial density fluctuation PDF

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

- Non-linear density fluctuation PDF

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



I.Achitouv arXiv 1609.01284

Ixandra Achitouv

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 $f(R)$ $P_{NL}(k)$

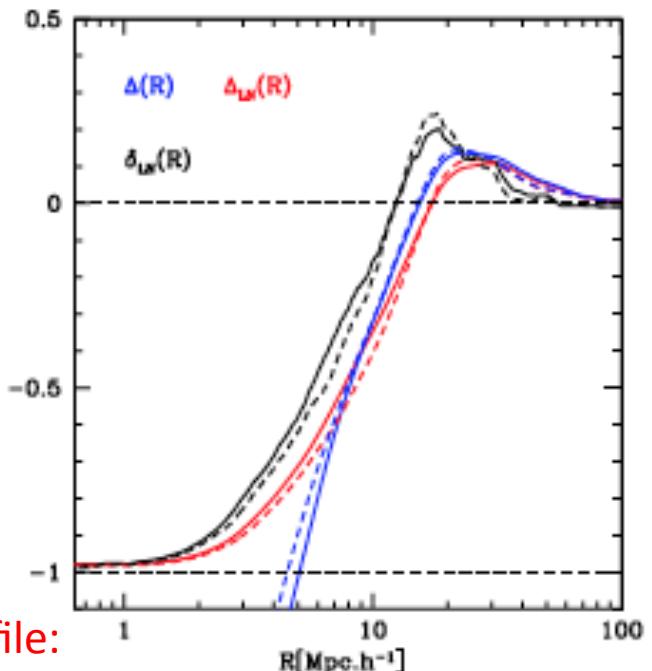
- Selecting Random Walks that satisfy 2+1 criteria:

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

$$\Delta_{LN}(R < R_m) < -0.9, \quad R_m = 2 \text{Mpc.h}^{-1}$$

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

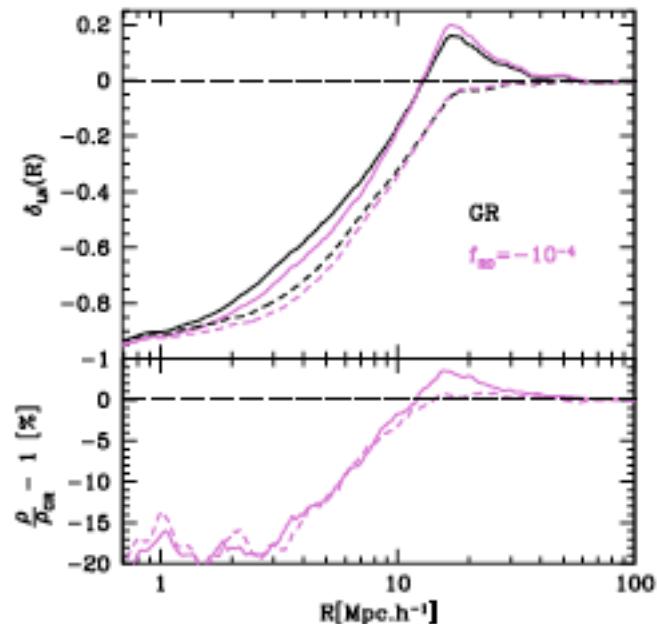
We recover the N-body simulations trend for the $f(R)$ profile:
 voids are more empty and the ridge amplitude is
 higher than the GR profile



I.Achitouv arXiv 1609.01284

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

Ixandra Achitouv

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 Λ CDM 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

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

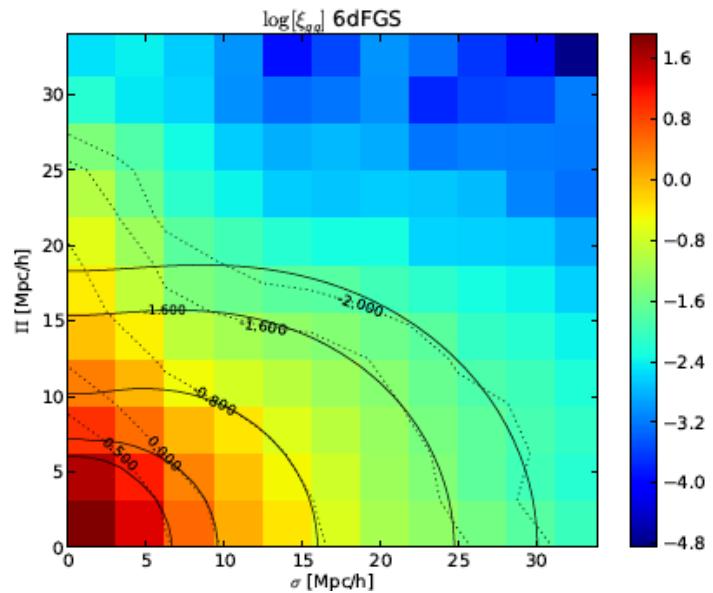
Probing the linear growth rate in different environments:

- 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 et al. Arxiv:
1606.03092

Probing the linear growth rate in different environments:

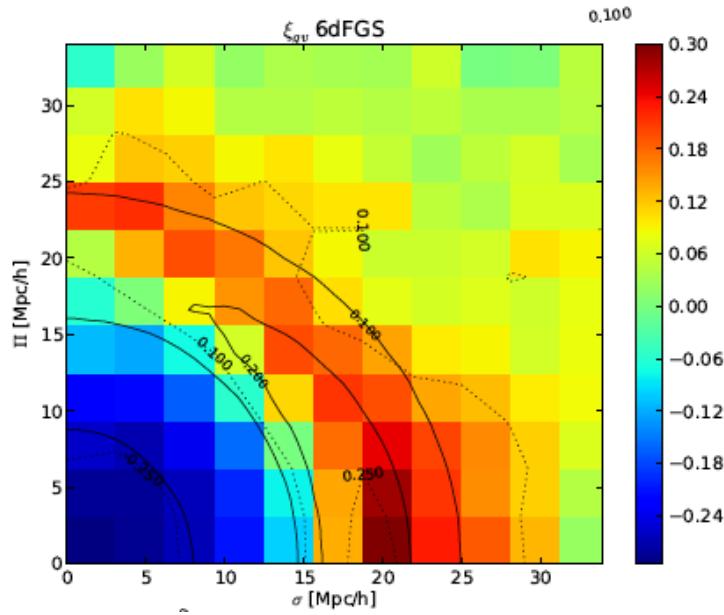
- The galaxy-void correlation function in RS: outflow motion of the galaxies **sensitive to the growth rate**

$$v_p(r) = -\frac{1}{3}H_0r\Delta(r)f,$$

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

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

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



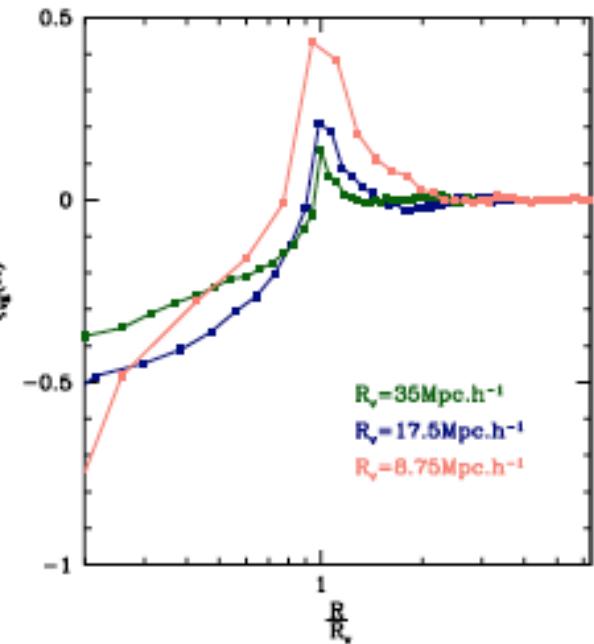
Voids identified in 6dFGS:
I. Achitouv et al. arxiv: 1606.03092

An alternative void finder

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

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

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



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 address for precise measurement of the growth rate

Selection of the void is important

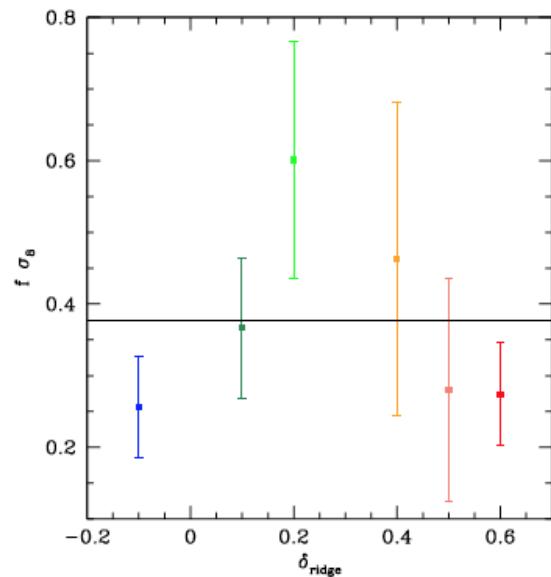


FIG. 10: Best fitting values for $f\sigma_8$ as function of the ridge amplitude. The different colors correspond to voids with the same radius but a density fluctuation at the ridge $\delta_{\text{ridge}} = -0.1, 0.1, 0.2, 0.4, 0.5, 0.6$ for the blue, dark green, green, orange, pink and red squares respectively.

I.Achitouv arXiv 1609.01284

Ixandra Achitouv

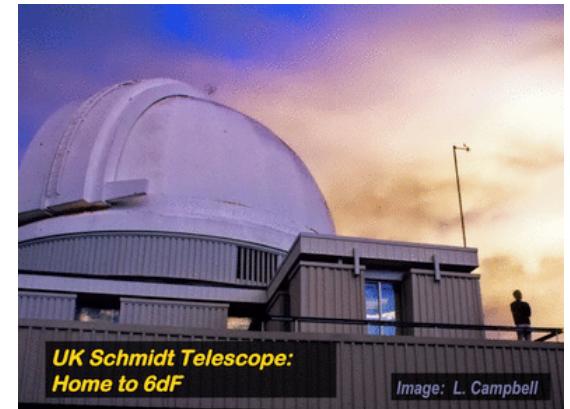
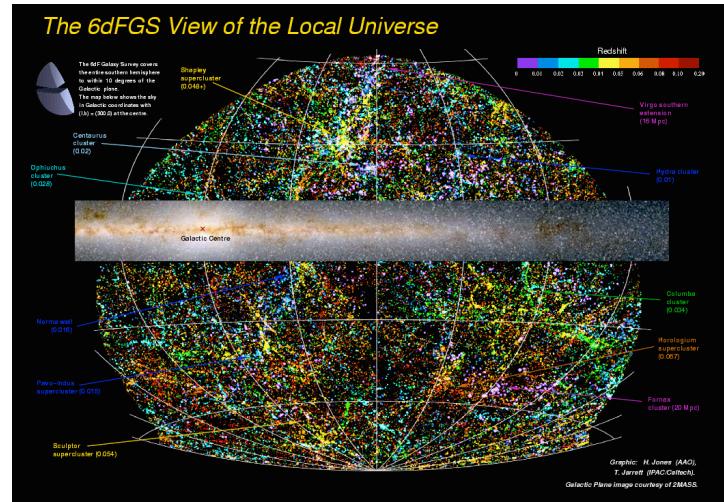
6dF Galaxy Survey:

<http://www.6dfgs.net/>

- Low redshift survey $z \sim 0.1$
- 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 $\sim 100,000$ galaxies and measurement of $\sim 8,000$ peculiar velocities.



Ixandra Achitouv

Consistency of the growth rate

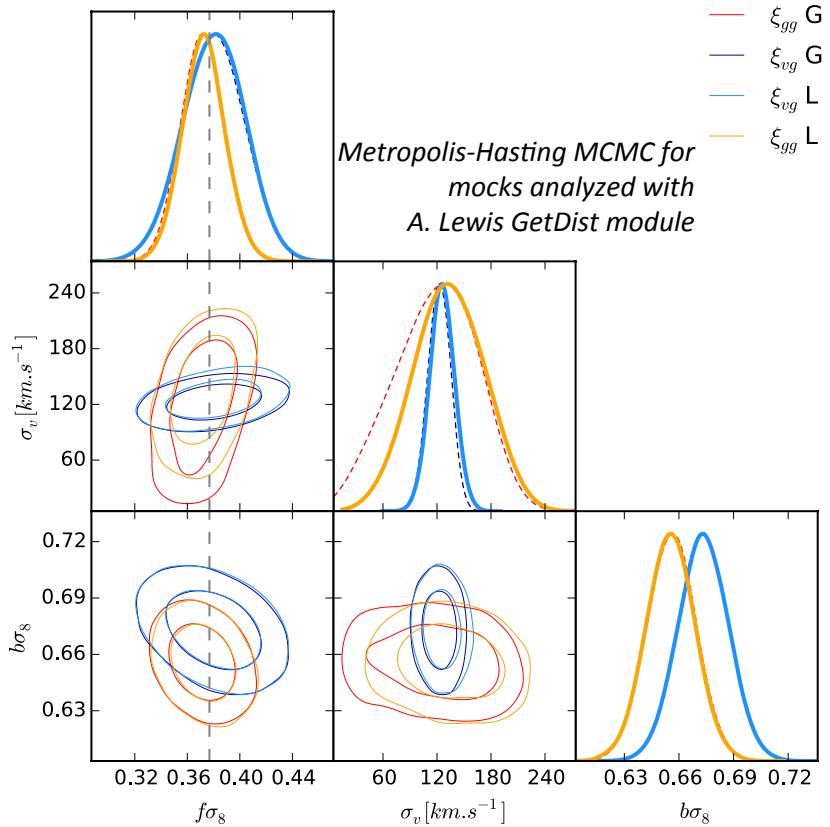
Assumptions:

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

We found for 6dFGS a consistency with Λ CDM:

$f\sigma_8 = 0.36 \pm 0.06$ for gal-gal RSD
 and $f\sigma_8 = 0.39 \pm 0.11$ for the gal-void RSD

Test on mocks:



I. Achitouv et al. Arxiv:1606.03092

Conclusion

- Looking at different environments can be helpful to:
 - Improve current cosmological probes ~ 8% for BAO
 - Challenge the Λ CDM 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 alpha fit

The distortion factor:

- χ^2 (α) estimate

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

- $\alpha=1$ no shift in BAO peak
- σ_α over 1000 boxes = error in BAO scale measurement

Standard reconstruction:

- $R_s=10 \text{ Mpc/h}$ and $x=0$
- Zel'dovitch approximation

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

