Probing Dark Energy with cosmic voids

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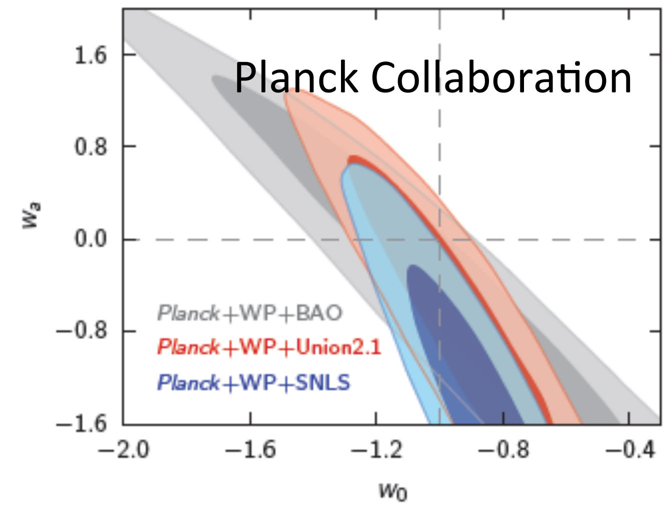
Motivation

- **How can we distinguish between different models of Dark Energy?**
  - ➢ Universe expansion probes the *quantity* of Dark Energy
  - ➢ Cosmic structures = more information to probe the *nature* of Dark Energy

e.g. clustering, RSD of galaxies,... What about cosmic voids?



Constraints from measurements of the initial density perturbations & background expansion of the Universe

- **Additional information washed out by averaging over all environments?**

e.g. underdense Vs. overdense regions of the Universe (see BAO, RSD…)

- **Screening mechanisms: suppress grav. forces in underdense regions**

e.g. f(R) gravity,…

Cosmic void properties = lots of potential but too few accurate predictions

Questions

How to predict the evolution of void density profiles for non-standard cosmologies?

Is the growth rate probed in underdense regions the same as the growth rate in average regions of the Universe?

Can we model accurately RSD around voids?

Outline

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

e.g. How to predict the evolution of void density profiles in non-standard cosmologies ?

2- Consistency of growth rate measurements in different environments, with 6dFGS

e.g. Is the growth rate in underdense environments the same as the growth rate in average regions of the Universe?

3- Probing Quintessence Dark Energy with RSD around voids

e.g. Can we model accurately RSD around voids?

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

I. Achitouv, Phys. Rev. D 94, 103524 (2016), arXiv:1609.01284

Predicting void density profiles with random walks

- Evolution of the smoothed linear density field:

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

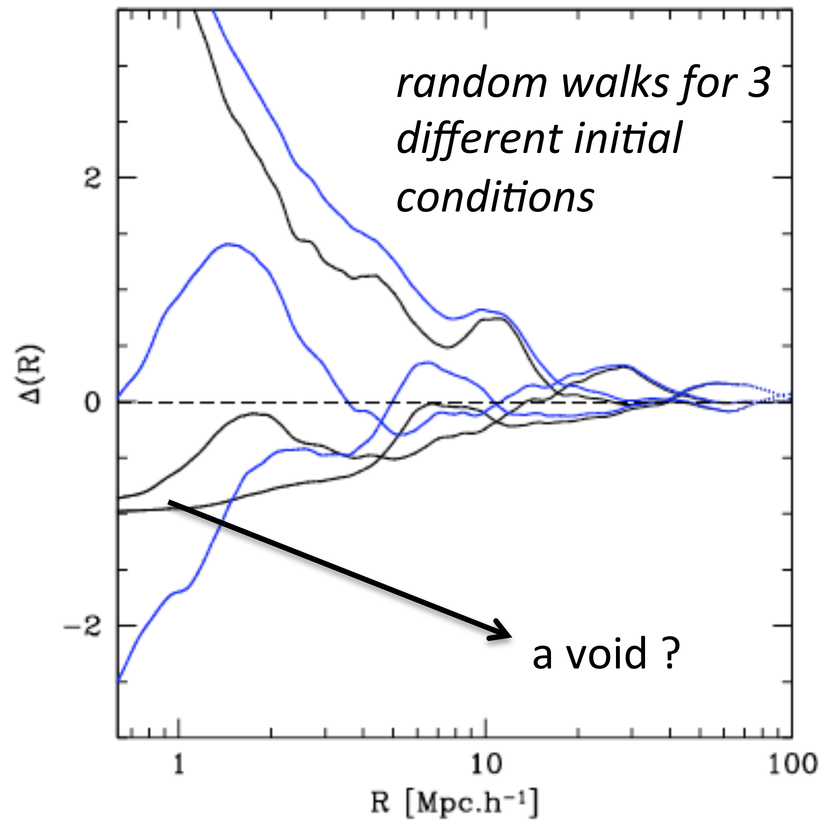
$\langle\delta(k')\delta(k)\rangle = P_{lin}(k)$

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

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

Smoothed, non-linear Pk

Smoothed, linear Pk

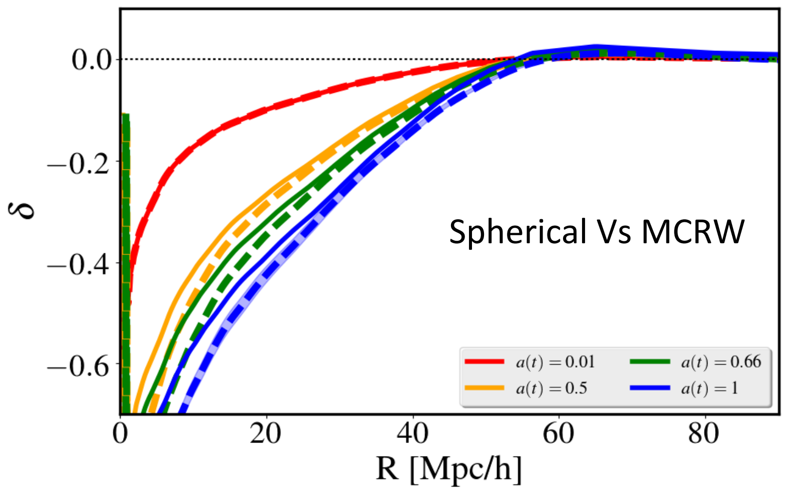


What can we do now?

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

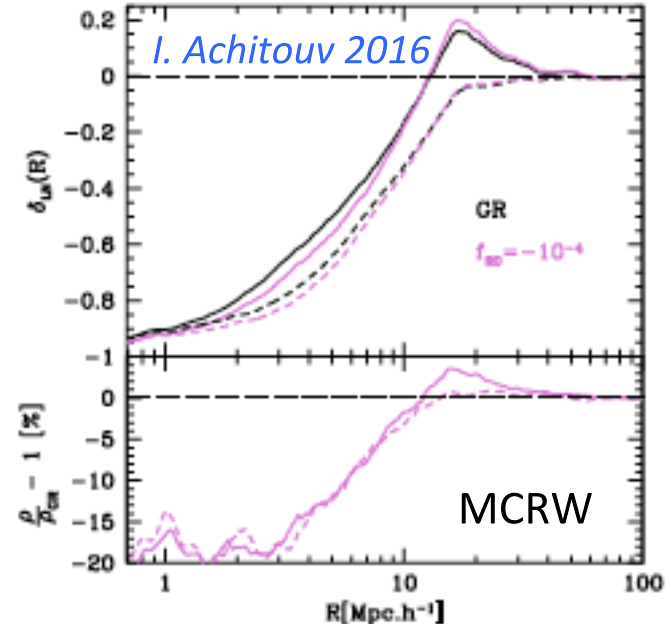
e.g. quick estimate of how void profiles change for MG theories

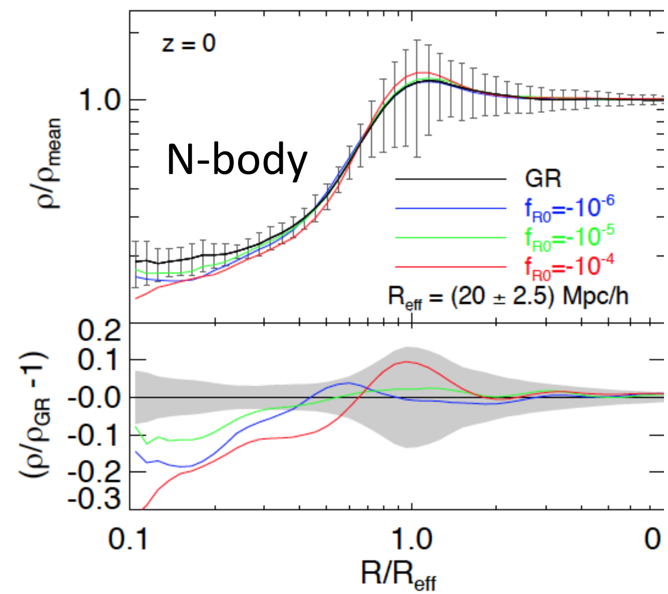
- Follow evolution of the profile as function of z



V. Demchenko, Y. Cai, I, Achitouv in prep

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





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

2- Consistency of growth rate measurements in different environments with 6dFGS

I. Achitouv, C. Blake, P. Carter, J. Koda & F. Beutler, Phys. Rev. D 95, 083502 (2017) , arXiv: 1606.03092

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

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

Probing the linear growth rate with RSD:

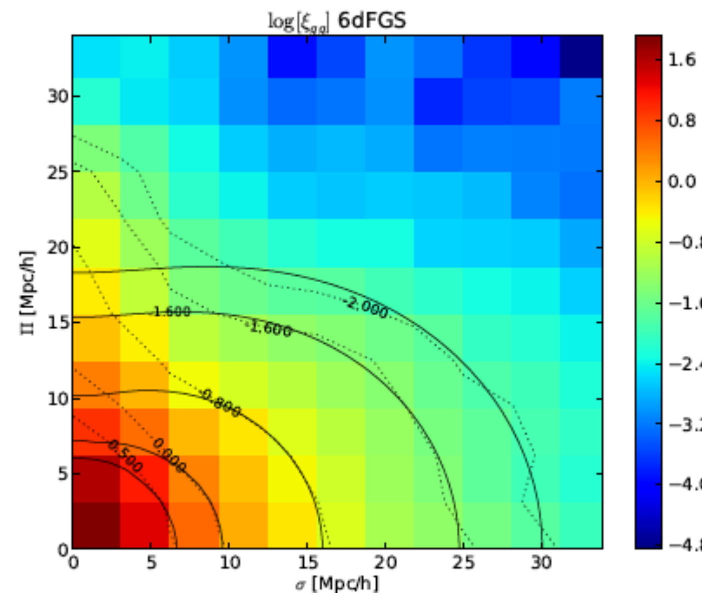
- Redshift space distortions:

Asymmetry in 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)



Galaxy autocorrelation function in 6dFGS

Probing the linear growth rate with cosmic voids:

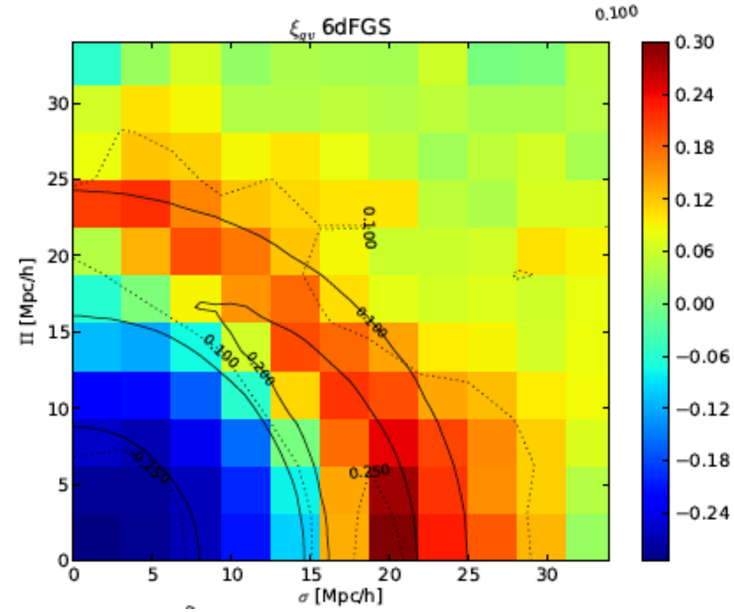
- The galaxy-void correlation function in RS: outflow motion of the galaxies **sensitive to the growth rate**

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

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

- Small scales virial motion of galaxies P(v)dv

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



Galaxy- Void correlation function in 6dFGS

6dF Galaxy Survey:

http://www.6dfgs.net/

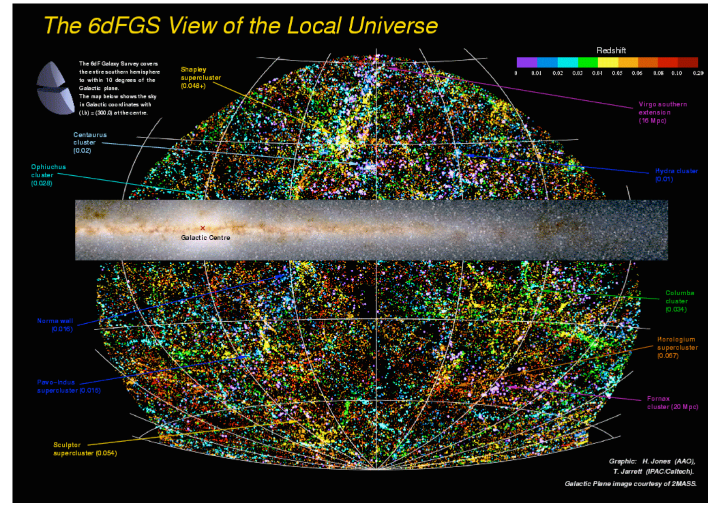
- Low redshift survey (z~0.1).

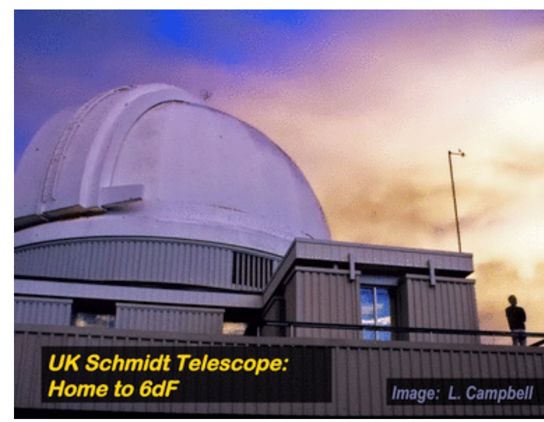
- Sensitive to the late-time accelerated expansion of the universe (DE)

- 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.





Consistency of the growth rate

Assumptions:

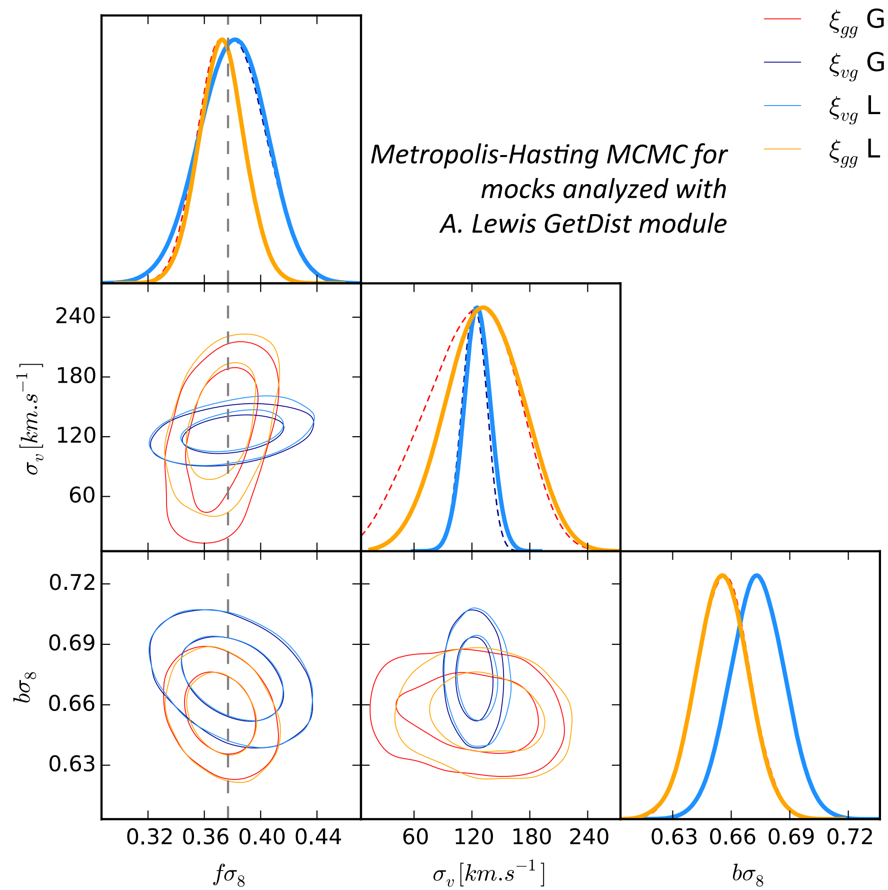
- ΛCDM cosmology
- Linear bias
- Constant velocity dispersion (nuisance parameter)
- We consider voids of size 17.5Mpc.h^{-1}

We found for 6dFGS a consistency with ΛCDM:

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

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

Test on mocks:



Derivation of the growth rate using RSD around voids

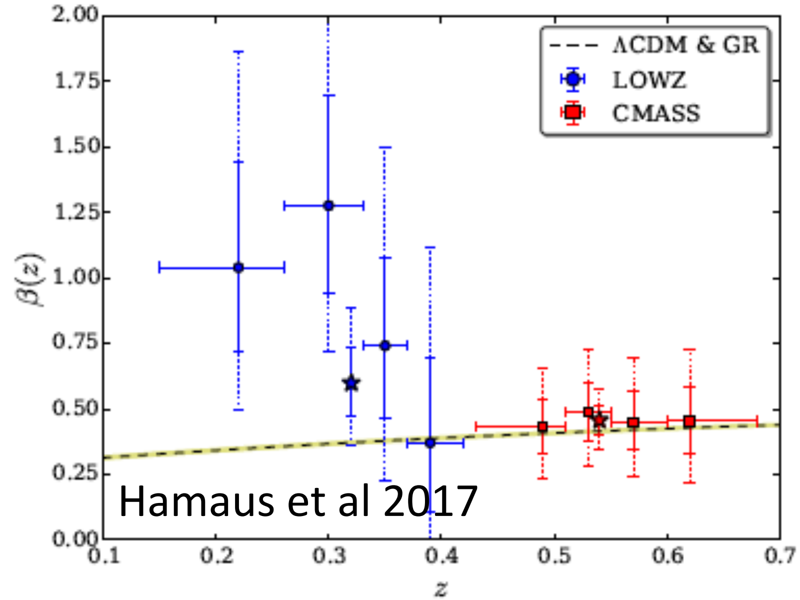


Figure 9. Growth rate constraints as a function of redshift from LOWZ (blue circles) and CMASS (red squares). Stars represent the joint constraint from voids of all redshifts in each sample. Vertical solid lines indicate 1σ, dotted lines 2σ confidence intervals. Horizontal lines delineate redshift bins. The dashed line with yellow shading shows $\beta = \Omega_m^\gamma(z)/b$, with $\Omega_m(z=0) = 0.308 \pm 0.012$ [70], $\gamma = 0.55$ [45], and $b = 1.85$ [52], assuming a flat ΛCDM cosmology and GR.

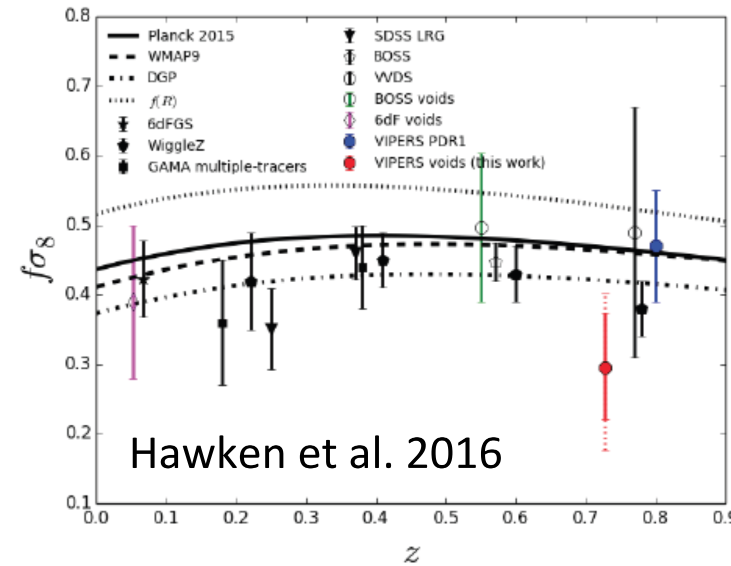


Fig. 12: Comparison to other estimates of the growth rate (Beutler et al. 2012; Blake et al. 2011, 2013; Samushia et al. 2012, 2014; Guzzo et al. 2008). Of particular interest are the measurement using conventional galaxy clustering techniques on VIPERS PDR1 (blue filled circle: de la Torre et al. 2013); the measurement using voids in BOSS (green open circle: Hamaus et al. 2016); and the measurement using voids in 6dF (magenta diamond: Achitouv & Blake 2016).

3- Probing Quintessence Dark Energy with RSD around voids: an improved model

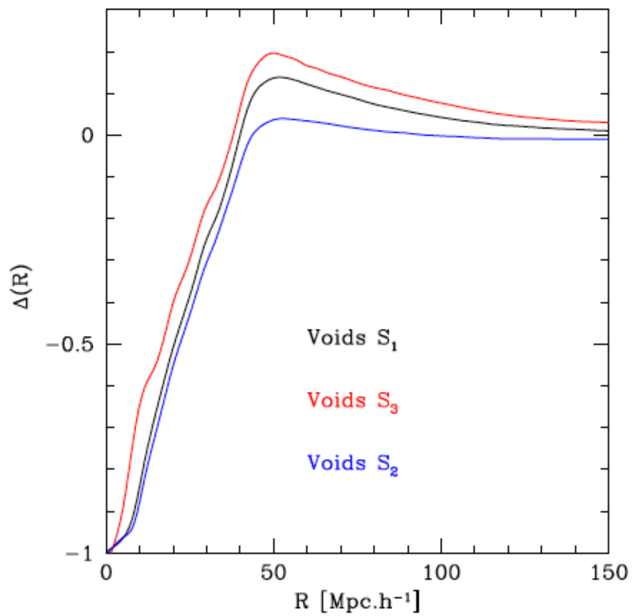
I. Achitouv, submitted to PRD, arXiv:1707.08121

Improving velocity profile model around voids

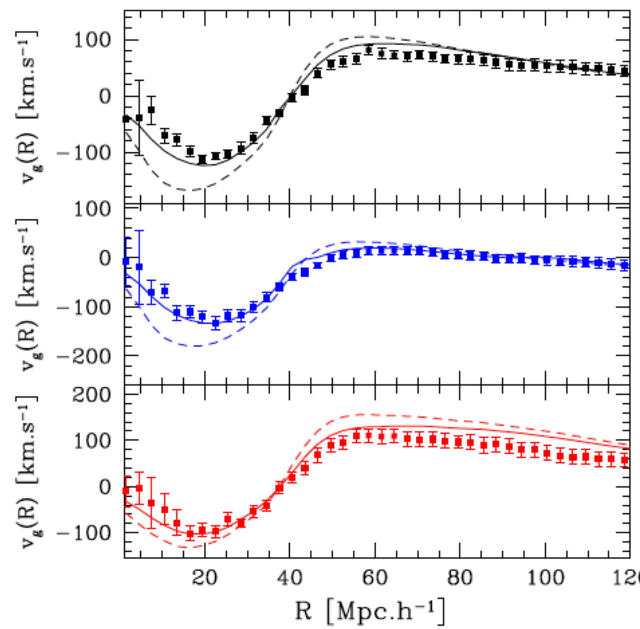
N-body simulations from *www.deus-consortium.org/*

- Previous works found systematic errors in the derivation of the growth rate using RSD around cosmic voids e.g. Hamaus et al. 2017

Void cumulative profiles in Dark Matter density field



Velocity profiles around voids measured in the mocks



Linear approximation:

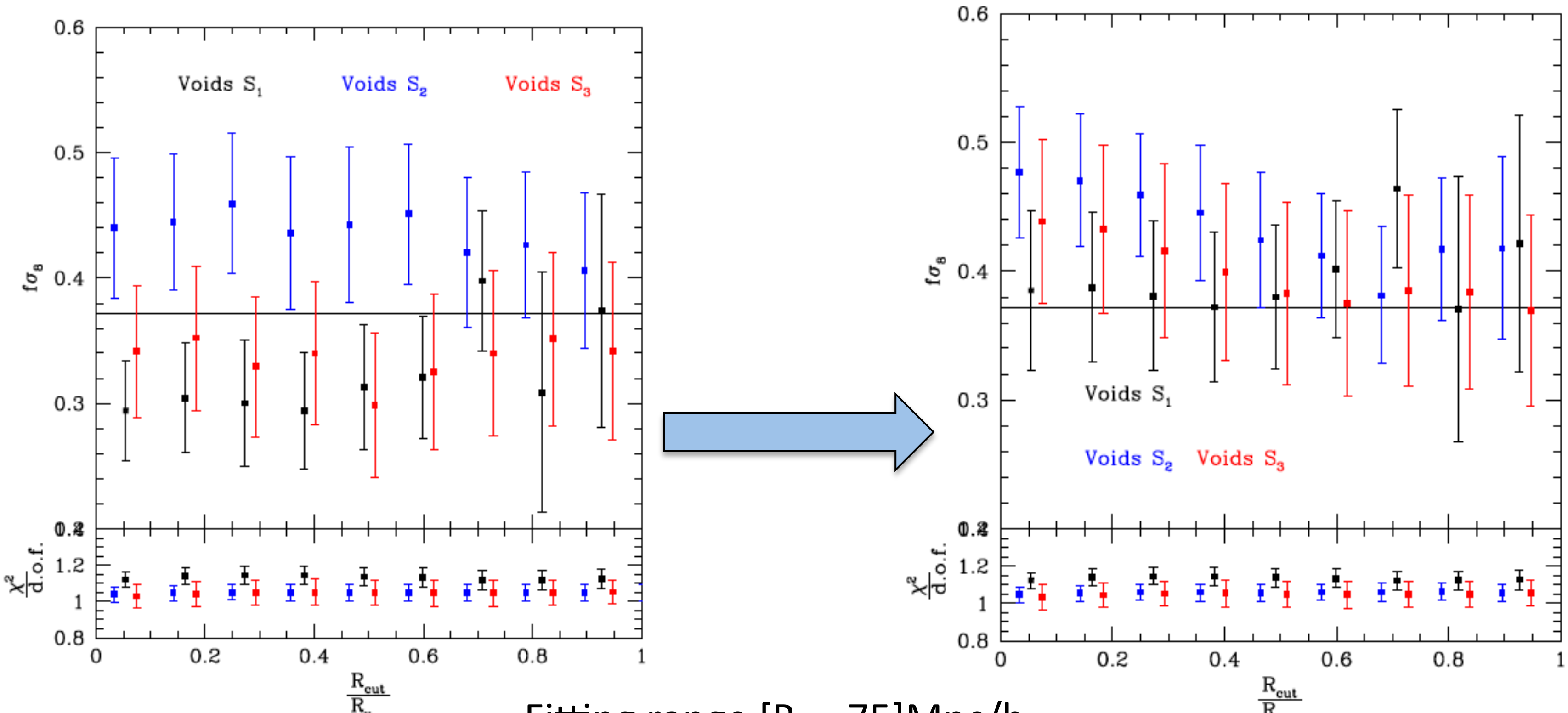
$$v_g(R) = -fH_0\frac{R}{3}\Delta(R)$$

Semi-empirical correction:

$$v_g(R) = -fH_0\frac{R}{3}\Delta(R) + \varepsilon\frac{3}{7}f_2H_0\frac{R}{6}\Delta^{(2)}$$

Reducing systematics in the growth rate derivation

- Theory breaks down for δ→-1 leading to a fitting range R_{cut}= sqrt[π^2+σ^2] Cai et al. 2016



Fitting range [R_{cut}-75]Mpc/h

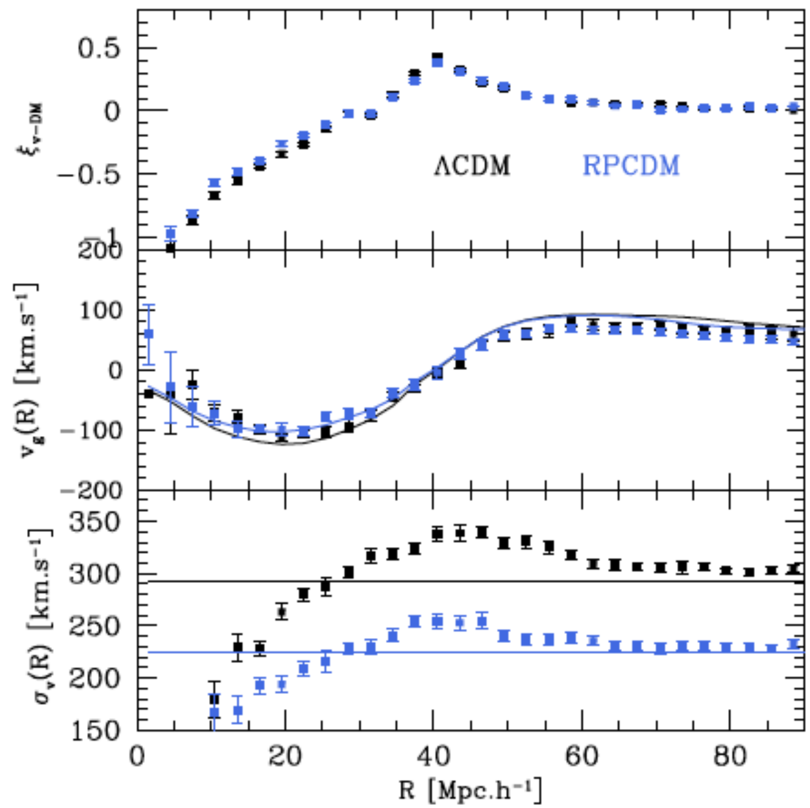
Linear approximation of vg(R)
+ constant velocity dispersion

Semi-empirical correction of vg(R)
+ *exact* velocity dispersion

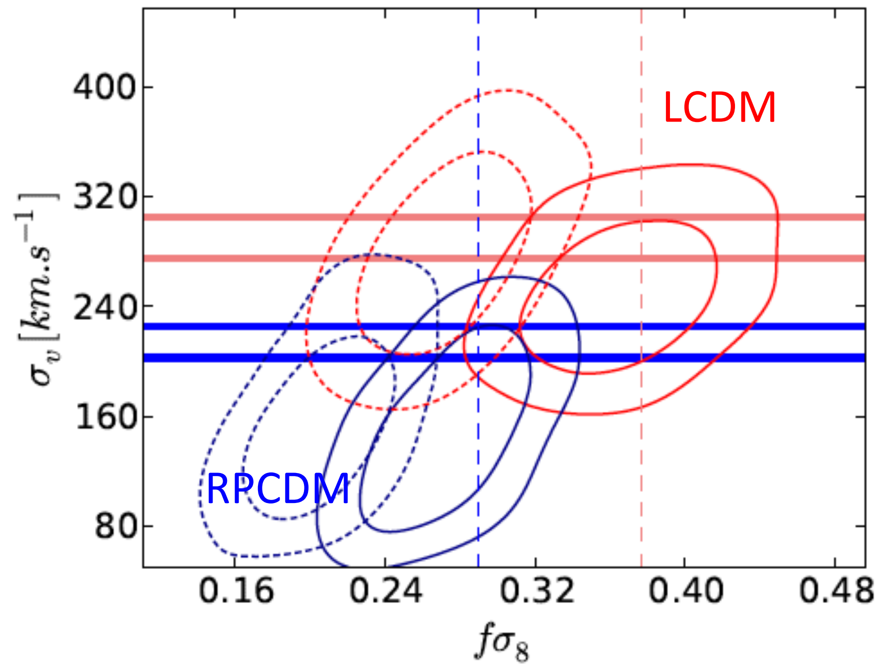
Probing Dark Energy with RSD around voids

N-body simulations from *www.deus-consortium.org/*

- Velocity dispersion carries DE imprint
- Linear approximation of vg(R) = systematic offset of the growth rate



Real-space characteristic of void profiles for quintessence DE Vs. ΛCDM



Inferred values from mocks in redshift space using linear Vs. correction for vg

Conclusions

Cosmological parameters inferred from statistical properties of cosmic voids are relatively new, but could potentially play a central role to reveal departures from GR.

- Accurate theoretical predictions of void properties

> Further work needed, e.g. dNv/dR,…

- Used 6dFGS to infer constraints on the growth rate that are currently still in good agreement with ΛCDM

> TAIPAN SURVEY see WP: da Cunha *et al.* (2017)

- Probing growth rate with RSD around voids is new, and systematic errors have to be addressed as statistical errors will shrink

> Still ongoing, see other surveys e.g. SDSS (Hamaus *et al.* 2016 & 2017), VIPERS (Hawken *et al.* 2016)

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

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