Voids as a probe of Modified Gravity

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Introduction and Motivation

•Light scalar fields coupled to matter (baryons) are predicted by many theories of HEP beyond the standard model.

•Coupled means we have a fifth-force in nature. If it exists, is there any room for cosmological signatures (of the fifth-force)?

•A fifth-force is strongly constrained from local gravity experiments (inverse square law, solar-system tests, EP).

•Naive conclusion: Either very short range or very weakly coupled, in other words: no cosmological effects of the fifth-force!

•Not the case if the field has a screening mechanism. The fifth-force can remain 'hidden' to local experiments!

•There are two general classes of models has this property: Those who have non-linearities in the interaction potential/coupling (Chameleon / Symmetron (1,3)) and those who have it in the kinetic terms (Vainshtein mechanism (2), p(X)).

(1) Khoury & Weltman **0309300**, (2) Vainshtein Phys. Lett. **B39** (1972) (3) Khoury & Hinterbichler **1001.4525.**

Introduction and Motivation

•In this talk, the focus is on modified theories of gravity which include a new scalar degree of freedom coupled to (all) matter.

Action

$$S = \int dx^4 \sqrt{-g} \left[\frac{R}{2} M_{\rm pl}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi) \right] + S_m(A^2(\phi) g_{\mu\nu}, \psi_i)$$

•We have used the symmetron (beta=1, range = 2 Mpc/h) as our working example, but the signatures discussed here holds qualitative for many models in this class.

Potential

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Coupling

$$A(\phi) = 1 + \frac{1}{2}\left(\frac{\phi}{M}\right)^2 + \mathcal{O}\left[(\phi/M)^4\right]$$

Screened Modified Gravity

- For the symmetron the mirror symmetry of the model is restored in high density regions and the field is pushed towards $\phi=0$ where the coupling to matter vanishes.
- In low density regions the field settles at one of the two minimums where ϕ != 0.
- Since screening depends on the ambient density, the largest signatures are found in regions of low density.
- In particular, we expect the fifth-force to be in full play in voids. This is investigated using N-body simulations.
- Previous studies has shown we get more large voids with MG (see e.g. Li,Zhao,Koyama **1111.2602** for the Hu-Sawicki f(R)-model).

N-body simulations of Screened Modified Gravity

Due to the high non-linear form of MG models a full non-linear analysis is often required to gain quantitative insight into structure formation.

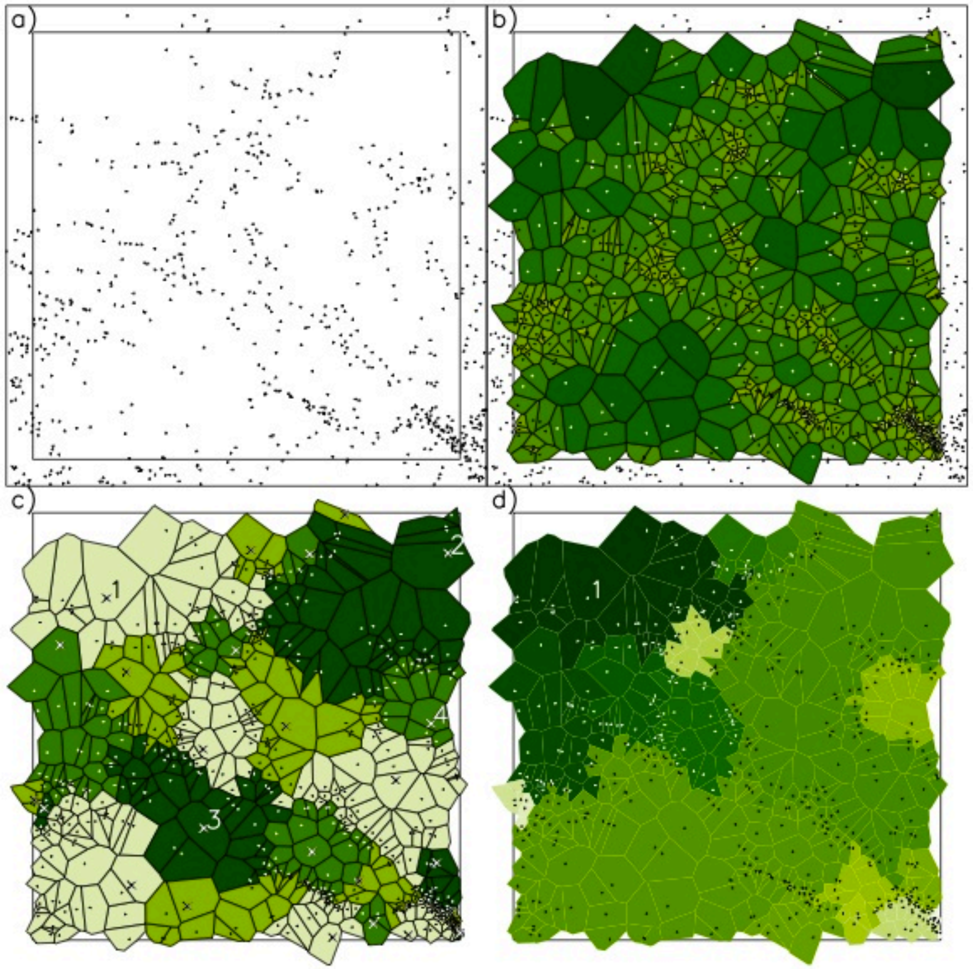
The KG equation for the scalar field is solved at each time-step and used to propagate the N-body particles:

$$\frac{1}{a^2}\nabla^2\phi \simeq \frac{dV}{d\phi} + \frac{dA}{d\phi}\rho_m \qquad \ddot{\vec{x}} + 2H\dot{\vec{x}} = -\frac{1}{a^2}\vec{\nabla}\Phi - \frac{1}{a^2}\frac{dA}{d\phi}\vec{\nabla}\phi$$

We have used N-body simulations of the Symmetron model (Davis.et.al **1108.3081**)

See Baojiu Li's talk later this week for code details.

Voids from N-body simulations



Several ways to define and locate voids (Colberg et.al. **0803.0918**)

We have used the ZOBOV void finder (Neyrinck **0712.3049**)

Parameter free void finder, based on a Voronoi tesselation and the watershed technique.

Void stacking

Voids have many complicated shapes mainly produced by the gravitational shear field.

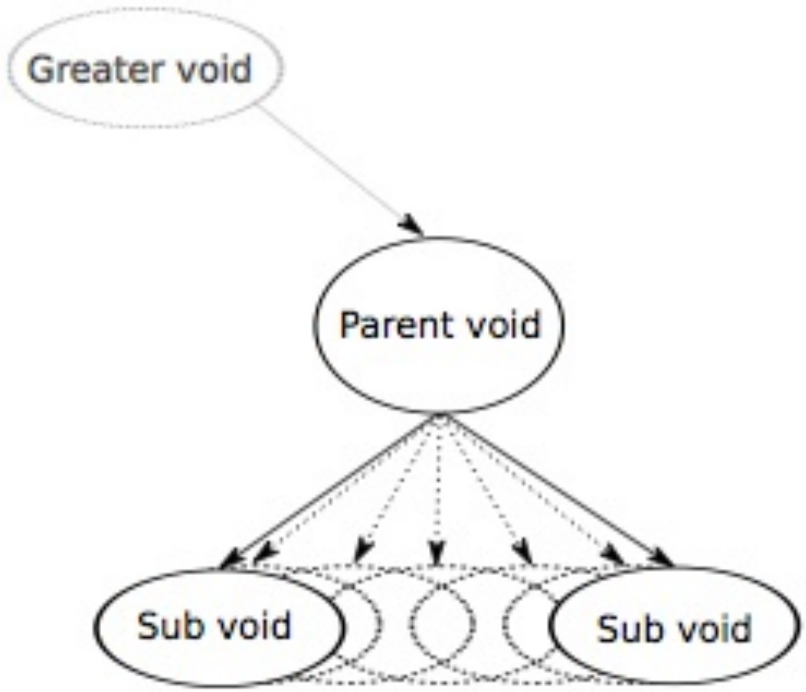
The average void shape is spherical in physical coordinates under the assumption of isotropy of density fluctuations.

By stacking voids we can extract the effects modified gravity have on the average void.

The individual shapes of voids (and halos) can also be used as a probe of MG (See C. Llinares talk later this week).

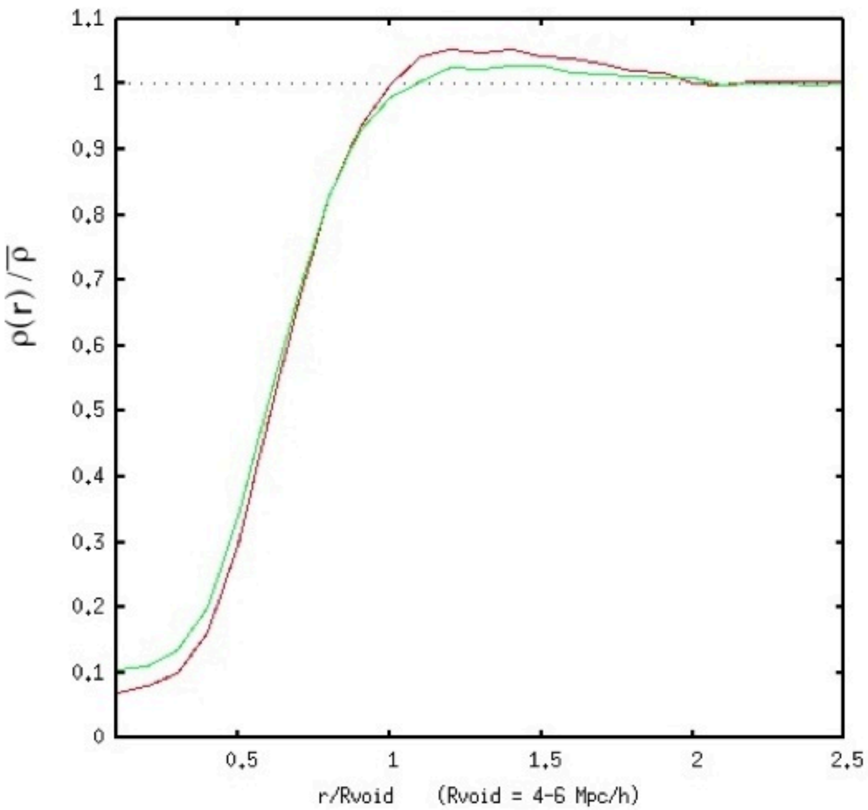
We have implemented the void stacking method suggested by Lavaux, Wandelt **1110.0345.** Originally proposed as a test of dark energy using the AP test.

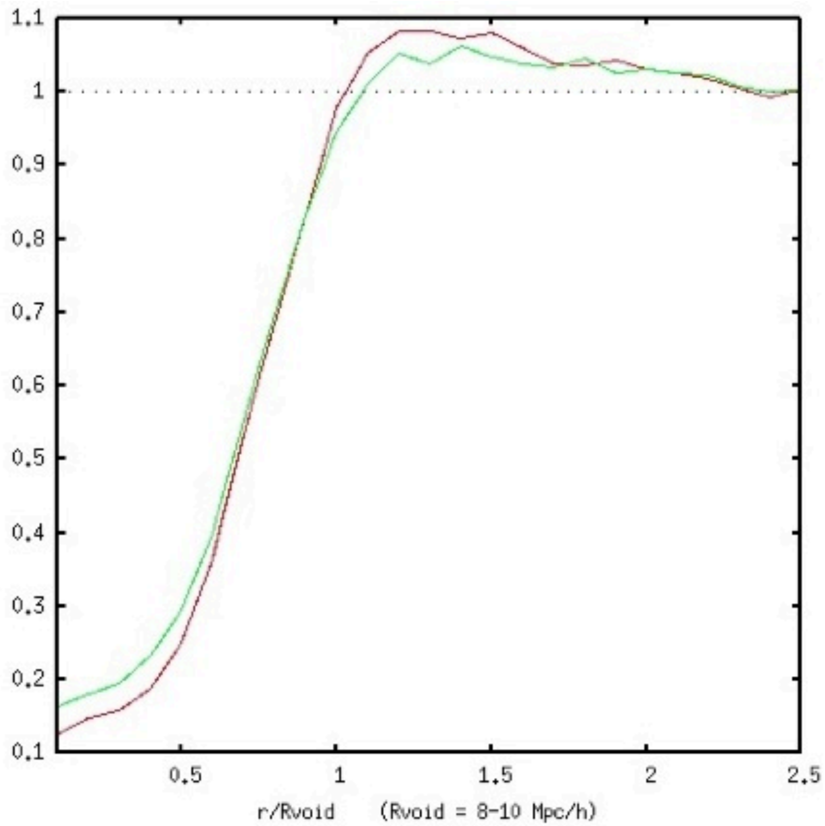
Void stacking



1) We apply the ZOBOV void finder algorithm.
2) We store the found voids in a tree.
3) We walk the tree, and stop whenever the effective radii, reff , is within a given range, between Rmin and Rmax.
4) reff is obtained by computing the radius of the sphere which has the same volume as the void.
5) We compute the position of the particles according to the volume-weighed barycenter for each void.
6) We compute the density of the void within a sphere of radius reff/4. We only accept voids that have a core density less than 20% of the mean matter density of the universe.
7) Around each volume-weighed barycenter, we extract a spherical volume, of radius Rcut = 3 × Rmax. The center of the extracted volume is put at the origin. We do this for all selected voids.

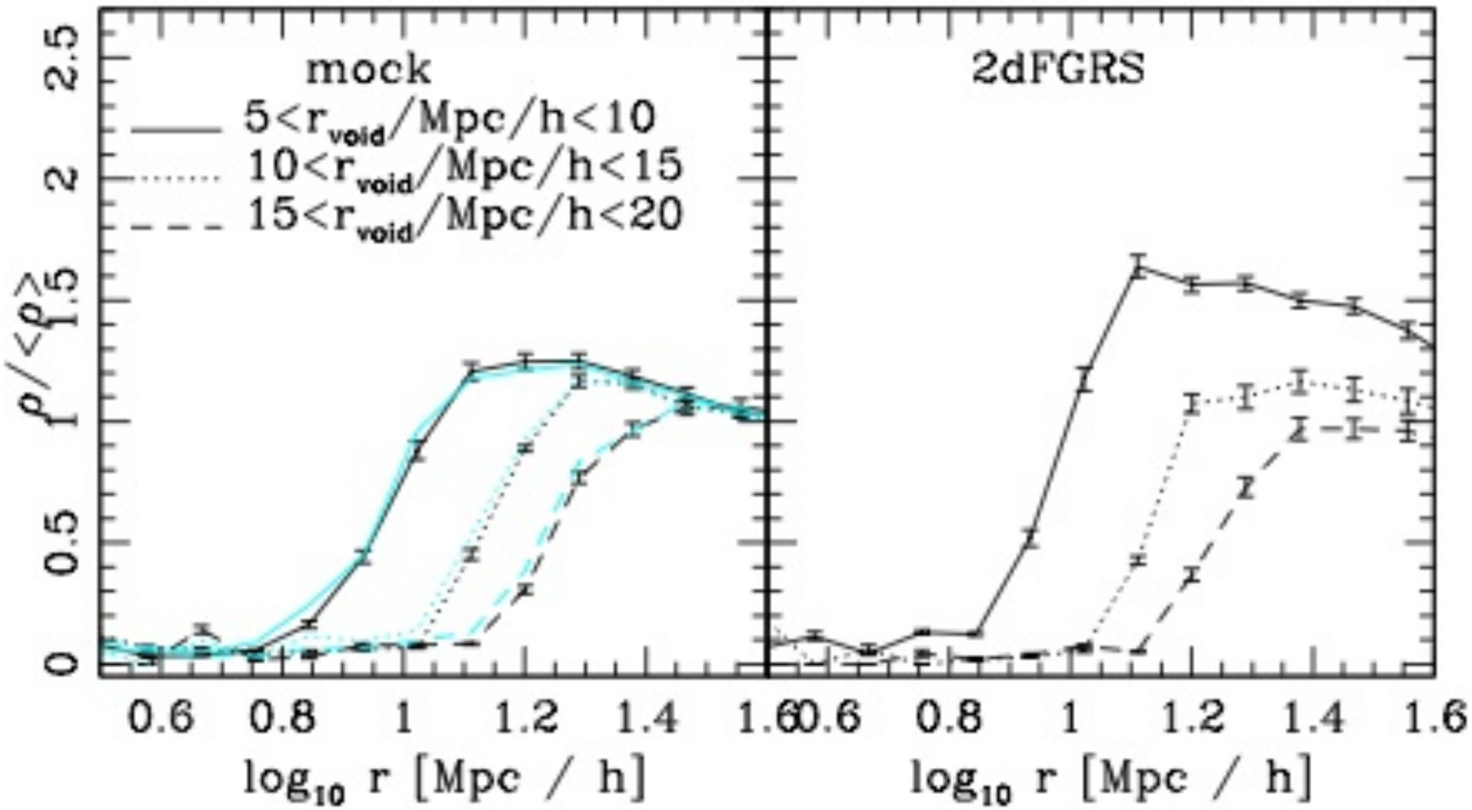
Stacked void profiles





The presence of a fifth-force pushes more matter out of the voids making them deeper compared to LCDM. Small O(%) effects in our fiducial model.

Stacked void profiles

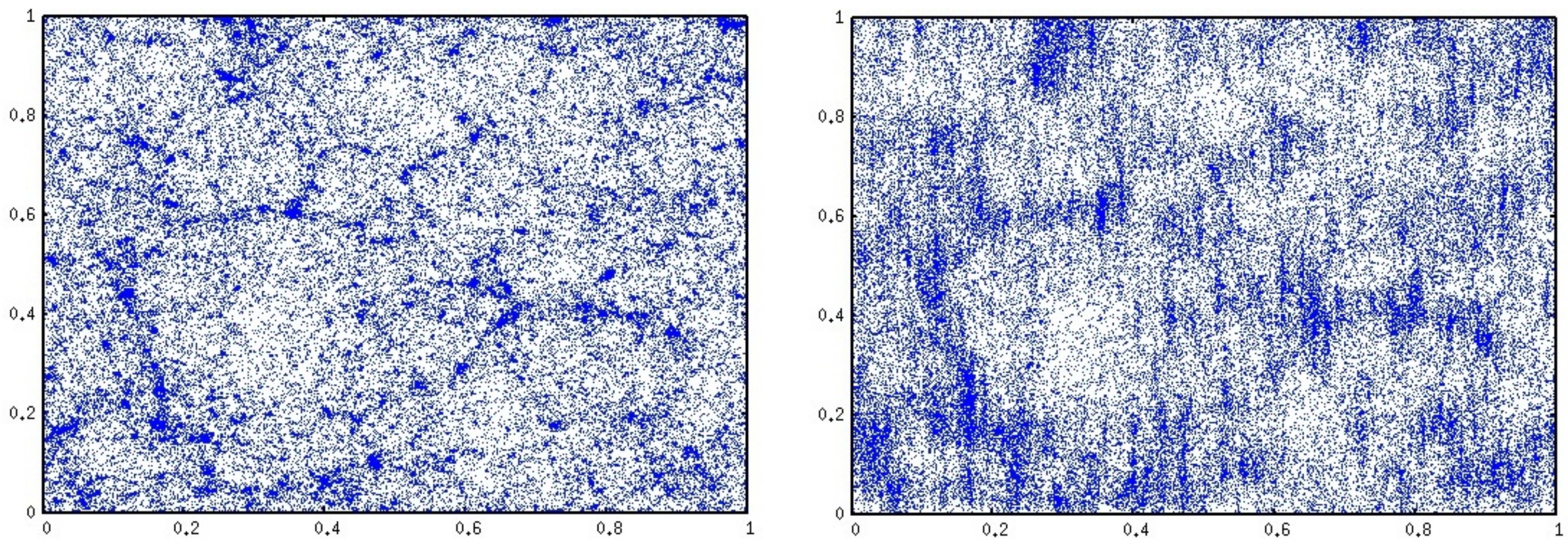


Void profiles from the 2dF survey and mock galaxy simulations (Ceccarelli et.al. **0805.0797**).
Note: Observations are in terms of galaxies, simulations are dark matter only.

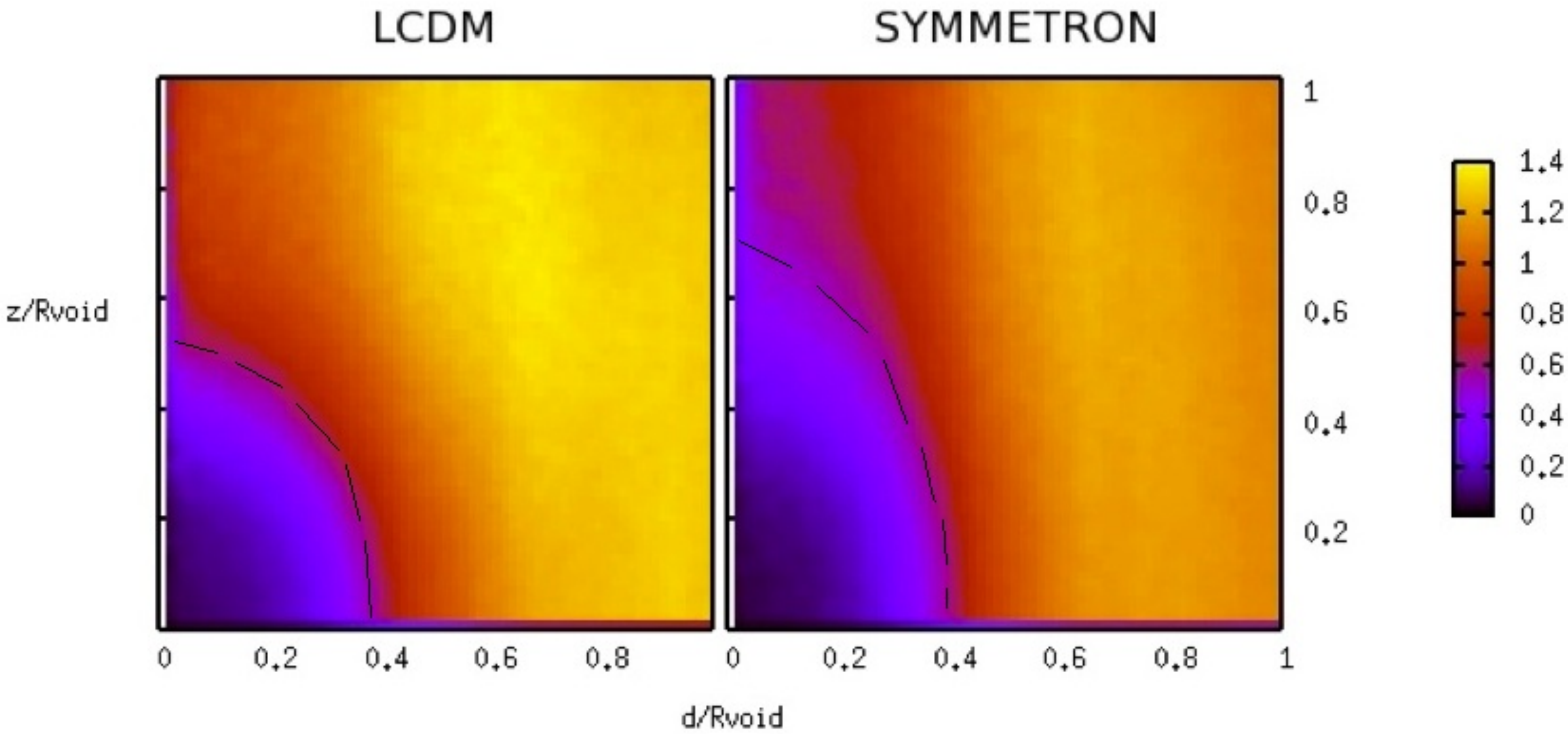
Redshift-space distortions

Observations of galaxies are in terms of redshifts which are contaminated by peculiar velocities.

Modeled by placing the observer at Z=0 in our simulation box and converting the position and velocity of the N-body particles to redshift-space.



Redshift-space distortions



The fifth-force amplifies velocities and therefore creates stronger redshift-space distortions. We now have a O(10%) effect. (See Jennings et.al. **1205.2698** for RSSD in f(R)**).**

Environment dependence

Modified gravity models predicts modifications of gravity within some critical length scale. In models with screening mechanisms one also generally have a critical mass/density which determines if screening occurs.

Observables can have a mass/scale dependence!

Screening can also occur for objects below this critical density given that they reside in a high-density region.

Observables can also have an environment dependence!

Environment dependence

Cosmological mass measurements generally separates into two classes:

Lensing mass measurements (probes the total energy): ML

Dynamical mass measurements (probes total force): MD

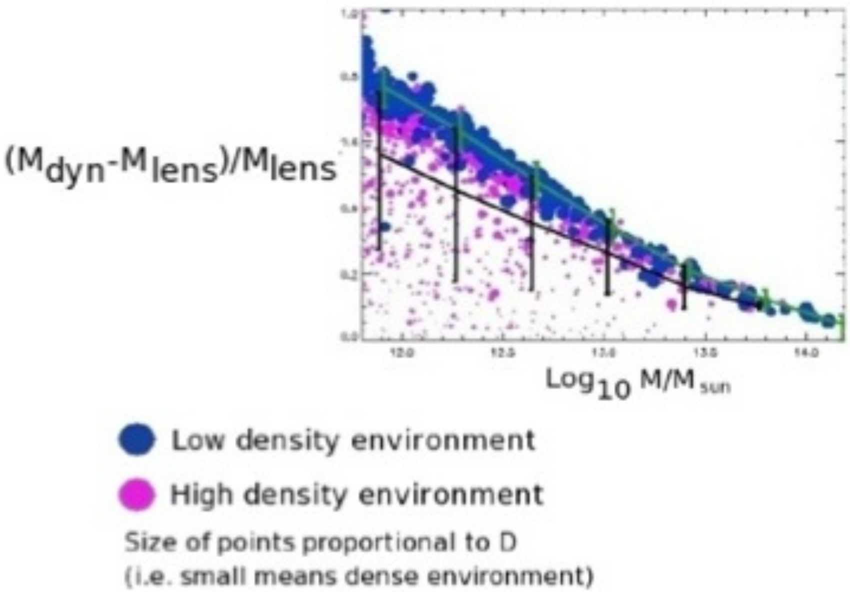
In GR ML = MD . In modified theories of gravity MD depends on how strong the fifth-force is.

The lensing mass ML is the same as predicted by GR ($\Phi + \Psi$ independent of ϕ).

This was first investigated from N-body simulations in DGP and f(R) (F. Schmidt **1003.0409** and Zhao,Li,Koyama **1105.0922**), see Zhao's talk later this week. We have done the same analysis for the symmetron (Winther,Mota,Li **1110.6438**).

Environment dependence

A strong dependence of ΔM = MD /ML − 1 with both mass and environment is found for viable parameters. Low-mass halos that reside in voids are not screened and the effect of MG can be strong.



$$D_{N,f} \equiv \frac{d_{N,M_{\rm NB}/M_L \geq f}}{r_{\rm NB}},$$

The environment (here quantified with D) can be defined using the location of halos in a void stack (work in progress).

This test also provides a way to distinguish between models with non-linear kinetic terms (Vainstein screening as in DGP) and non-linear potential terms (as in Chameleon / Symmetron).

Summary and Conclusions

- Modified Gravity with a screening mechanism are dominant in regions of low matter density.
- Voids are therefore a natural way of looking for signatures of modified gravity.
- We have looked at stacked voids. Deviations from LCDM in void profile are at O(%) level.
- Larger effects are found if the effects of RSS distortions are included (~10%).
- Work in progress to see how to relate this to observations. Can it be a new test of MG or are the effects too small?
- One of the most intriguing signatures of MG is the environment dependence of observables. Can use the void stack to define the environment in a more natural way.
- Future work will look into the possibility to constraint / distinguish MG from GR (and quintessence / coupled quintessence) using voids from near future observations.