Cosmology on Safari

Void properties in $f(R)$ gravity

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Cai, Padilla & Li, arXiv:1410.1510
Outline

- Modified Gravity (MoG) and f(R)
- Abundance and large scale DM profiles: MoG, tensions in LCDM
- MoG simulations
- MoG-void connection
- GR or MoG? void abundances and profiles: density and lensing. arXiv:1410.1510
MoG

new degrees of freedom

massive gravity
bimetric gravity

tensor
(spin-2)

modified source gravity

vector
(spin-1)

teleparallel and f(T) gravity
Einstein Aether gravity

scalar
(spin-0)

screened
unscreened

modified Gauss-Bonnet gravity
coupled quintessence models
extended quintessence models

derivative coupling type

DGP braneworld model
Galileon gravity
k-Mouflage gravity
kinetic braiding model

scalar tensor type

constant coupling

f(R) gravity

varying coupling

chameleon models
symmetron models
dilaton models

Courtesy Baojiu Li
Modified gravity (MoG) models can explain the accelerating expansion **without a cosmological constant**.

Scalar field coupled to matter (consistent with f(R) models) or extra term in Einstein-Hilbert action trigger extra **fifth force** that enhances gravity.

Screening mechanism that suppresses fifth force in high density regions is needed to make observationally viable theory.

Fifth force is screened in early universe (CMB is unchanged) and in high density regions (Solar system).
f(R) MOG

Replace cosmological constant by f(R) in the action, but ensure screening mechanism and GR where tested already:

\[
S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} M_{\text{Pl}}^2 (R + f(R)) + \mathcal{L}_m \right]
\]

Hu-Sawicky f(R) model:

\[
f(R) = - M^2 \frac{c_1 (-R/M^2)^n}{c_2 (-R/M^2)^n + 1}
\]

where

\[
\frac{c_1}{c_2} = - \frac{1}{n} \left[ 3 \left( 1 + 4 \frac{\Omega_\Lambda}{\Omega_m} \right) \right]^{1+n} f_{R0}
\]

and the characteristic mass \( M \) satisfies

\[
M^2 = \frac{8\pi G \rho_m}{3} = H_0^2 \Omega_m
\]

Cluster abundance data constrain: \( |f_{R0}| \lesssim 10^{-4} \) for \( n=1 \) (Schmidt et al. 2009).

This is the chameleon parameter.

Also with other observables: Jennings et al. (2012), Hellwing et al. (2013)
MoG and LCDM

Due to fifth force haloes grow faster in MoG and are more massive and abundant in these models (Li et al., 2012).

Some tension with LCDM on the masses of the more massive clusters (El Gordo, Jack’s talk).

However, analyses using extreme value statistics (e.g. Harrison & Coles 2012) seem to indicate this is actually not a problem.
MoG and LCDM

But high mass end could be overestimated because baryons are not included: increased tension for LCDM.

Illustris simulation:

Volkersberger et al. 2014
Too big to fail problem

- Strong tension in masses of satellites: influenced by inner density profile of DM haloes. Unresolved issue.

- Another possible solution: WDM but complicated to simulate due to numerical stabilities that produce spurious low mass objects.
LCDM and MoG-void connection

Further tension from Integrated Sachs-Wolfe effect (ISW).

Pápai et al. find a 2-sigma difference in measurement from SDSS superstructure (superclusters and voids) and LCDM.

Nadathur, Hodgkiss & Sarkar (2013) include systematics (using largest voids only) and find discrepancy of 3sigma.

Similar conclusions by Flender et al. 2012, Hernandez-Monteagudo & Smith 2012

Voids are emptier and there are more superclusters in SDSS.
Non-linear problem
Hu-Sawicky f(R) model: $f(R) = -M^2 \frac{c_1 (-R/M^2)^n}{c_2 (-R/M^2)^n + 1}$ where $\frac{c_1}{c_2} = \frac{1}{n} \left[ 3 \left( 1 + 4 \frac{\Omega_\Lambda}{\Omega_m} \right) \right]^{1+n} f_{R0}$

and the characteristic mass $M$ satisfies

$$M^2 = 8\pi G \bar{\rho}_{m0} / 3 = H_0^2 \Omega_m$$

Cluster abundance data constrain: $|f_{R0}| \lesssim 10^{-4}$ for $n=1$ (Schmidt et al. 2009). This is the chameleon parameter.

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The equations needed for the N-body simulation are (Jennings et al., 2012):

$$\nabla^2 f_R = -\frac{1}{3} a^2 \left[ R(f_R) - \ddot{R} + 8\pi G (\rho_m - \bar{\rho}_m) \right]$$

$$\nabla^2 \Phi = \frac{16\pi G}{3} a^2 (\rho_m - \bar{\rho}_m) + \frac{1}{6} a^2 \left[ R(f_R) - \ddot{R} \right]$$

Simulations from Zhao, Li & Koyama, 2012: ECOSMOG code (Li et al. 2012) based on RAMSES (Teyssier 2002)

GR and f(R) models start from the same initial conditions.
MoG simulations: $f(R)$

WMAP7 cosmology:
\[
\{ \Omega_m, \Omega_\Lambda, n_s, h \equiv H_0/(100\text{km/s/Mpc}), \sigma_8 \} = \{0.24, 0.76, 0.961, 0.73, 0.80\}
\]

<table>
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<tr>
<th>Models</th>
<th>$L_{box}$ ($h^{-1}$ Gpc)</th>
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<td>1.0</td>
<td>1024$^3$</td>
<td>1024$^3$</td>
<td>65536$^3$</td>
<td>$</td>
<td>\epsilon</td>
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<tr>
<td>$\Lambda$CDM, F6, F5, F4</td>
<td>1.5</td>
<td>1024$^3$</td>
<td>1024$^3$</td>
<td>65536$^3$</td>
<td>$</td>
<td>\epsilon</td>
</tr>
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Analysis centred on 1 $\text{Gpc}^3$ volume (SDSS LRG size)

$F4$: $|f_{R0}| = 10^{-4}$ No-Ch

$F5$: $|f_{R0}| = 10^{-5}$

$F6$: $|f_{R0}| = 10^{-6}$ Full-Ch
$f(R)$

Gong-Bo Zhao
Haloes and the fifth force

Positive fifth force outside haloes acting in addition to newtonian.

Effect present at low masses.

At high masses effect increases for high fifth force strength parameter.

Could reconcile El Gordo more easily
Could help with the too big to fail problem
MoG simulations: $f(R)$

Power spectra:
Zhao, Li & Koyama, 2012

Non linear power increased ($\sim1$-halo term)
MoG simulations: $f(R)$

Mass functions:
Zhao, Li & Koyama, 2012

$z=1$  
$z=0$

No screening
Intermediate screening
Full Chameleon

Enhancement at low masses
Enhancement at high masses
Clampitt et al. 2013 calculate the fifth and newtonian forces for a top-hat void. Negative fifth force inside voids acting in opposite direction to newtonian. Stronger for lower internal density, and for small voids.
Identifying voids

mP05 (modified Padilla et al. 2005, MNRAS 363, 977): largest spheres with integrated density

$\rho_{\text{min}} / \bar{\rho} < 0.2$.

Fast transition to average density.

Zivick+15

$z=0.43$, $R_{\text{eff}} = 15-20 \ h^{-1} \text{Mpc}$
Void abundances

mP05 void abundances in f(R) simulations and GR.

25% difference between F6 and GR (highly significant), and up to x3 factor for F4 is promising!

CPL, arXiv:1410.1510
Zivick, Sutter et al. (arXiv:1411.5694) predict consistent differences for EUCLID voids, matching space density of future samples.

However, they randomly sample a fraction of dark matter particles in the simulation instead of using biased tracers of the density field.
Void abundances for biased tracers

mP05 void abundances in f(R) simulations and GR.

Behaviour is reversed.

Differences are smaller and depend on radius of void when tracers are used.

CPL, arXiv:1410.1510
Profile around GR centre of the largest void:

There are more haloes in F4 inside the void.

CPL, arXiv:1410.1510
Because of the way halos form in f(R) models, the stacked profiles only show mild differences: less pronounced ridges in f(R).

CPL, arXiv:1410.1510
DM profiles confirm emptier voids in \( f(R) \) models even if halo density is the same.

But how to measure DM profiles around halo defined voids?

CPL, arXiv:1410.1510
Lensing profiles

Derivative of the 3D density profile around mP05 voids as analog of the tangential shear profile.

\[ \Delta \Sigma(R) = \gamma_t \Sigma_c = \Sigma(< R) - \Sigma(R), \]

\[ \Sigma_c = \frac{c}{4\pi G} \frac{D_A(z_s)}{D_A(z_l) D_A(z_l, z_s)(1+z_l)}. \]

3-sigma detection expected for F5.

errors for LRG volume

CPL, arXiv:1410.1510

See Amendola et al. 1999; Krause et al. 2013; Higuchi et al. 2013
Conclusions

- The LCDM model is extremely successful yet there are tensions: larger small haloes (TBTF), emptier voids (ISW), more massive superclusters (ISW), massive clusters at high-z. Voids can provide high signal to noise to detect f(R) gravity.

- Strong variation in significance of comparison between GR and f(R) depending on whether the mass or a tracer is used to detect/analyse voids.

- Voids provide many plausible tests involving:
  - abundance of tracer voids for large void sizes,
  - density profiles of voids if mass is used,
  - lensing by voids is a good way to trace profiles using the mass.
  - Combination of abundance+lensing profiles

\[ f(R) \text{ simulations of } 1\text{Gpc}^3 \]
\[ 1/6\text{th that of BOSS DR11} \]

CPL, arXiv:1410.1510
Thank you