In collaboration with: Rachel Bean, Alejandro Aviles


Georgios Valogiannis
Cornell University

Cosmic Controversies
Chicago
October 8th, 2019

V. Springel et al. (2006)

Peacock et al. 2001
Cosmological tests of modified gravity theories

- Modified gravity (MG) could be responsible for cosmic acceleration

\[ G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \]

- MG-ΛCDM degeneracy broken in large scales
- Modeling structure formation in MG necessary
- Full MG N-body sims are computationally expensive, due to non-linear screening
- Motivates analytical predictions for statistics of:
  - Biased tracers of underlying dark matter density field (N. Kaiser, 1984)
Halo formation in chameleon MG

- Density spherical collapse threshold now depends on mass & environment \( \delta_{cr} = \delta_{cr}(M, \delta_{env}, z) \)
  - B. Li & G. Efstathiou (2012), L. Lombriser et al. (2013)
  - Birkhoff’s theorem violated in MG

Halo formation in chameleon MG

- Density spherical collapse threshold now depends on mass & environment $\delta_{cr} = \delta_{cr}(M, \delta_{env}, z)$
  - B. Li & G. Efstathiou (2012), L. Lombriser et al. (2013)
  - Birkhoff’s theorem violated in MG
- Halo mass function not universal for all MG models

Peak-Background Split (PBS) formalism for bias
- Needs to be adapted in MG

PBS Lagrangian biases in MG

$b_1^{MG} < b_1^{GR}$, in agreement with simulations by C. Arnold et al., (2018)

2-point correlation function for halos in MG

Theory:
- $f(R)$ (chameleon)
  Hu-Sawicki, 2007
- nDGP (Vainshtein)
  G. Dvali et al. 2000

N-body simulations:
- $f(R)$ Lightcone project:
  - $z=1$, $L=1536$ Mpc/h
  - 3 mass bins
  - C. Arnold et al. (2018)
- $f(R)$ & nDGP ELEPHANT sims:
  - $z=0.5$, $L=1024$ Mpc/h
  - 1 mass bin
  - M. Cautun et al. (2017)

Necessary ingredients to model RSD in MG

- Real-to-redshift space mapping
  - Scale-dependent Gaussian Streaming model (GSM) ✓
    (B. Reid & M. White, 2011, L. Wang et al. 2013)

\[
1 + \xi^y(s_\perp, s_\parallel) = \int \frac{dy}{(2\pi)^{1/2}\sigma_{12}} [1 + \xi(r)] \exp \left\{ -\frac{[s_\parallel - y - \mu v_{12}]^2}{2\sigma_{12}^2} \right\}
\]

Redshift space

Real space
GSM ingredients in MG

• Real-to-redshift space mapping
  • Scale-dependent Gaussian Streaming model (GSM) ✓
    (B. Reid & M. White, 2011, L. Wang et al. 2013)

\[
1 + \xi^v(s_\perp, s_\parallel) = \int \frac{dy}{[2\pi]^{1/2}\sigma_{12}} \left[1 + \xi(r)\right] \exp\left\{ -\frac{[s_\parallel - y - uv_{12}]^2}{2\sigma_{12}^2}\right\}
\]

• GSM ingredients
  • Real-space $\xi(r)$ for biased tracers in MG ✓

• Pairwise velocity $v_{12}(r)$ for biased tracers in MG

\[
v_{12}(r) = \frac{\langle [1 + \delta(x)][1 + \delta(x+r)][v(x+r) - v(x)]\rangle}{\langle [1 + \delta(x)][1 + \delta(x+r)]\rangle}
\]

• Dispersion $\sigma_{12}^2(r)$ for biased tracers in MG
  • Model $v_{12}(r)$ & $\sigma_{12}^2(r)$ using LPT
  • $\Psi \neq f H \Psi$ in MG – scale-dependence!!
Pairwise velocity ($v$) model matches sims well

Theory:
- $f(R)$ (chameleon)
  Hu-Sawicki, 2007
- nDGP (Vainshtein)
  G. Dvali et al. 2000

N-body simulations:
- $f(R)$ Lightcone project:
  - $z=1$, $L=1536$ Mpc/h
  - 3 mass bins
  - C. Arnold et al. (2018)
- $f(R)$ & nDGP ELEPHANT sims:
  - $z=0.5$, $L=1024$ Mpc/h
  - 1 mass bin
  - M. Cautun et al. (2017)

Valogiannis, Bean, Aviles (2019)
arXiv:1909.05261
Accurate monopole predictions across MG models

Valogiannis, Bean, Aviles (2019)
arXiv:1909.05261
Accurate quadrupole predictions across MG models

Valogiannis, Bean, Aviles (2019)
arXiv:1909.05261
Summary

• Accurate modeling of 2-point statistics for biased tracers in MG

• In redshift space: Gaussian Streaming Model in MG
  • Bias & RSD simultaneously modeled in MG for the first time!

• Great agreement (monopole & quadrupole) for variety of MG models with different amounts of screening, screening mechanisms, and mass ranges.
  • Flexible analytical model
  • Can be applied to any scalar-tensor theory
In collaboration with: Rachel Bean, Alejandro Aviles

Thank you!
Accurate predictions across different mass bins

3 halo-mass bins

Accurate bias predictions!

Valogiannis, Bean, Aviles (in prep.)
Non-linear contributions to $\sigma^2$ not fully captured by LPT.

Usually well-modeled by a constant offset for all $r$

(B. Reid & M. White, 2011, L. Wang et al. 2013)

Alternative uses EFT term based term in $\xi$

(Z. Vlah et al. 2016)

Constant calibrated off a single large scale measurement then models smaller scale effects.

Valogiannis, Bean, Aviles (in prep.)
Necessary ingredients to model RSD in MG

- Real-to-redshift space mapping?
  - "Direct" Lagrangian mapping to redshift space \( X \)

- Plane-parallel approximation

\[
\mathbf{s} = \mathbf{x} + \frac{\hat{\boldsymbol{z}} \cdot \mathbf{v}(\mathbf{x})}{aH} \hat{\boldsymbol{z}}
\]

\[
\Psi^s = \Psi + \frac{\hat{\boldsymbol{z}} \cdot \dot{\Psi}}{H} \hat{\boldsymbol{z}}
\]

\[
\xi^s_l(s) = \frac{2l+1}{2} \int_{-1}^{1} d\mu_s \, L_l(\mu_s) \xi^i(s, \mu)
\]

\[|f_{R0}| = 10^{-6} \text{ (F6) Hu-Sawicki model}\]

Valogiannis et al. (in prep.)
2-point correlation function results

- Consistency for varying degrees of f(R) screening $z=0.5$ !

Valogiannis & Bean (2019)
2-point correlation function results

- Consistency for varying degrees of Vainshtein screening at z=0.5!
Power spectrum results

Valogiannis & Bean (2019)