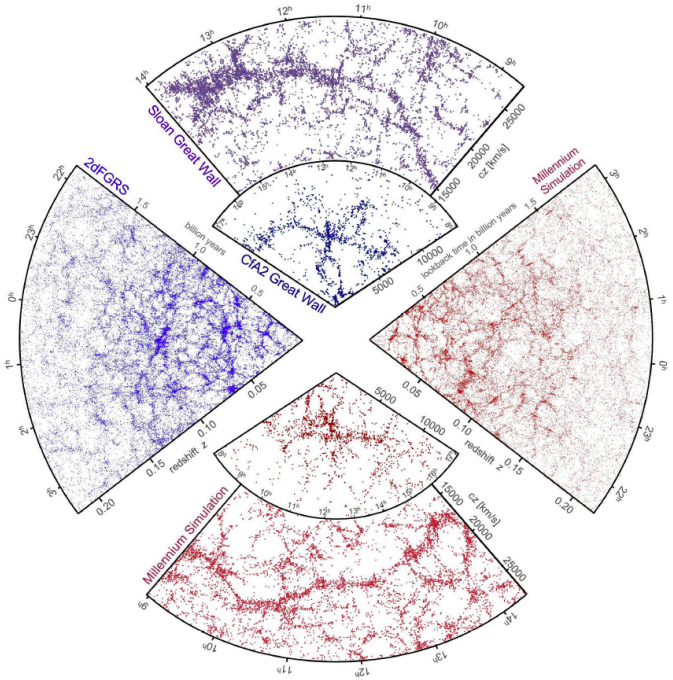
An accurate model for redshift space clustering of biased tracers in modified gravity

Georgios Valogiannis[1]; Rachel Bean[1] ; Alejandro Aviles[2]
[1]Department of Astronomy, Cornell University, Ithaca, NY, USA
[2]National Institute for Nuclear Research, Ciudad de Mexico, 11801, Mexico

In collboration with: Rachel Bean, Alejandro Aviles

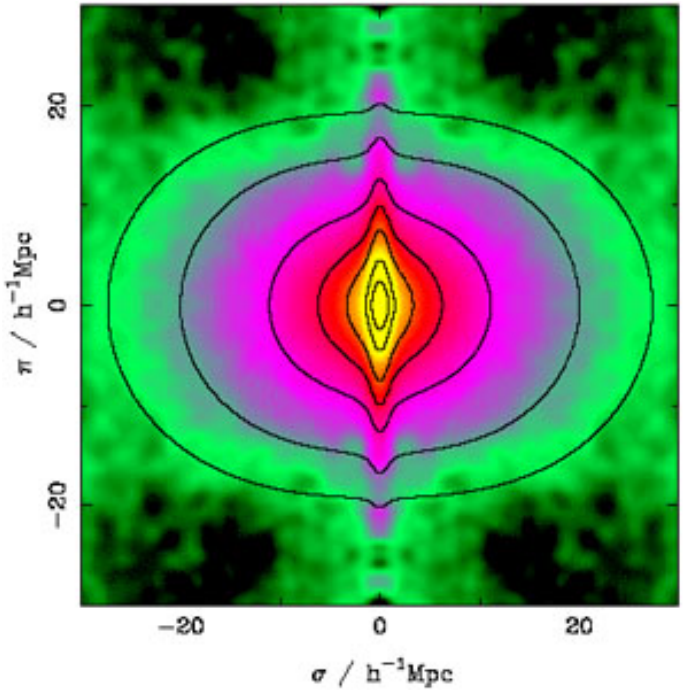
G.Valogiannis & R. Bean, Phys. Rev. D 99, 063526 (2019), arXiv: 1901.03763
G.Valogiannis, R. Bean & A. Aviles, submitted to JCAP (2019), arXiv: 1909.05261



V. Springel et al. (2006)

Georgios Valogiannis
Cornell University

Cosmic Controversies
Chicago
October 8th, 2019



Peacock et al. 2001

Cosmological tests of modified gravity theories

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

Modified Gravity?

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

Dark energy?

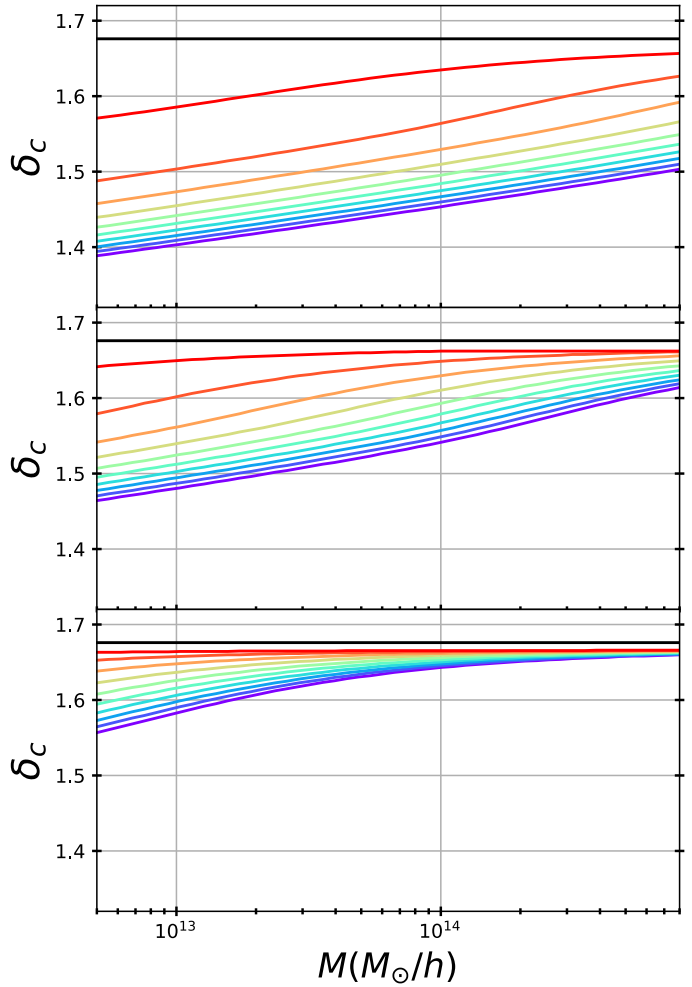
Λ?

- 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)
  - **Redshift Space Distortions (RSD)** in galaxy clustering (N. Kaiser, 1987, G. Efstathiou et al., 1988)

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

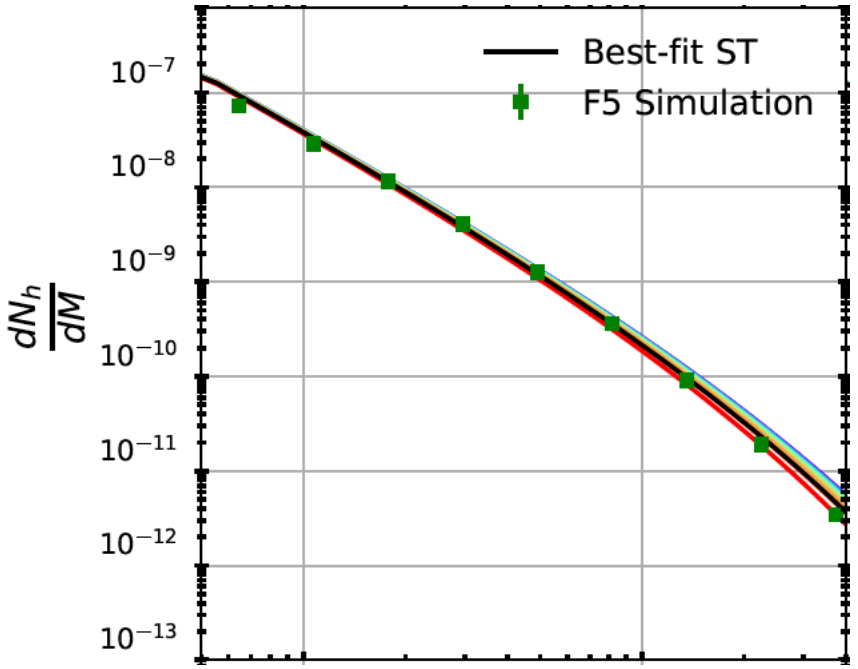
f(R) Hu-Sawicki, 2007



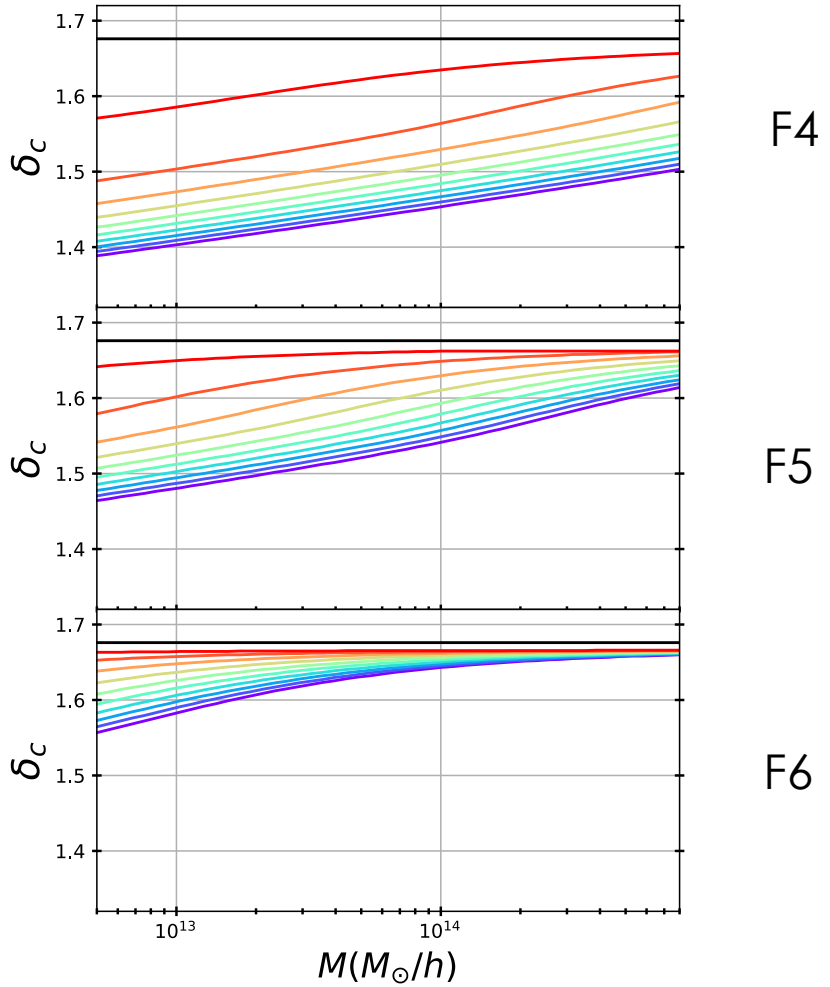
Valogiannis & Bean (2019), arXiv: 1901.03763

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



f(R) Hu-Sawicki, 2007

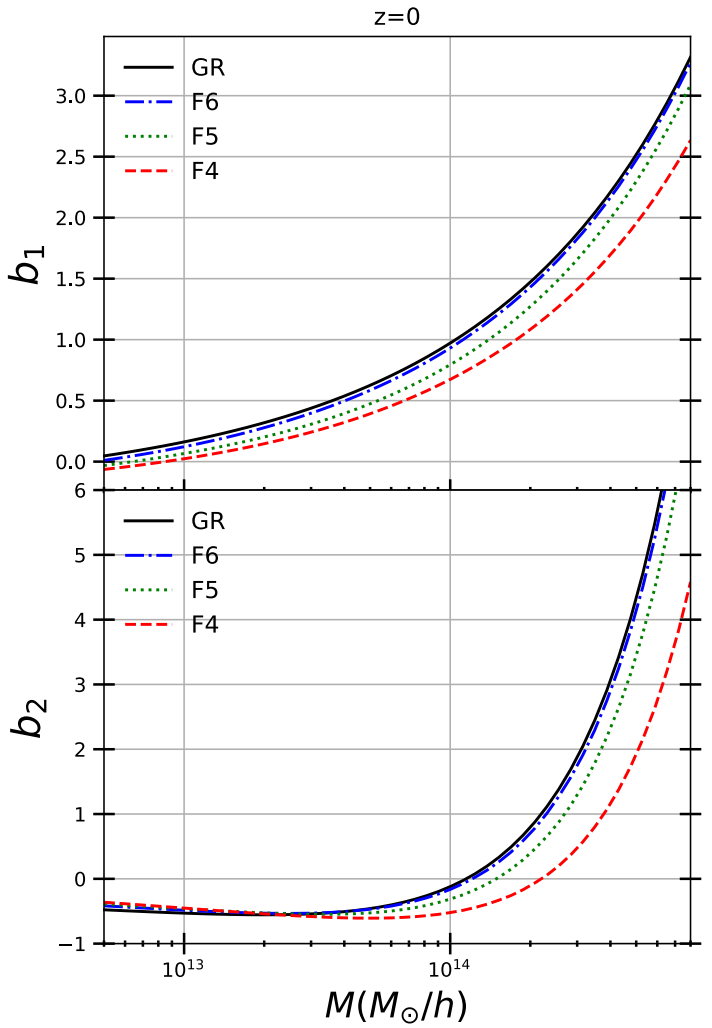


Valogiannis & Bean (2019), arXiv: 1901.03763

Peak-Background Split Lagrangian biases in MG

- Peak-Background Split (PBS) formalism for bias
  - N. Kaiser (1984), J. Bardeen et al. (1986), H. J. Mo et al. (1997), F. Schmidt et al. (2013)
  - 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)

f(R) Hu-Sawicki, (2007)



Valogiannis & Bean (2019), arXiv: 1901.03763

2-point correlation function for halos in MG

Theory:

- f(R) (chameleon)
  Hu-Sawicki, 2007

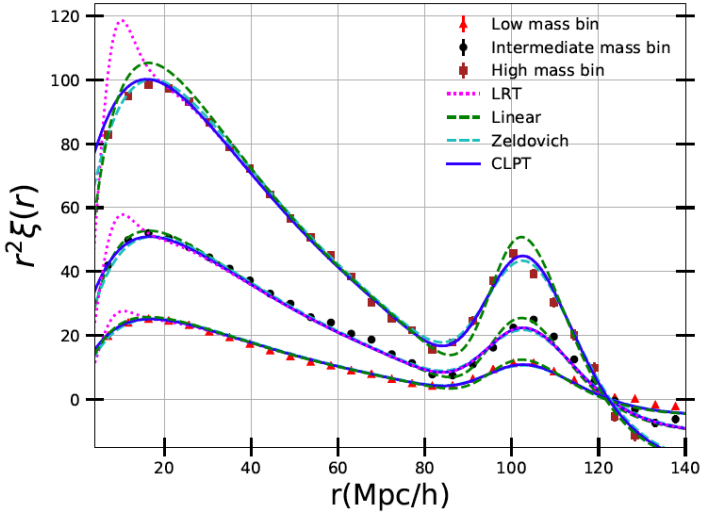
- nDGP (Vainshtein)
  G. Dvali et al. 2000

N-body simulations:

- f(R) Lightcone project:
  - z=1, L=1536 Mpc/h
  - 3 mass bins
  - C. Arnold et al. (2018)

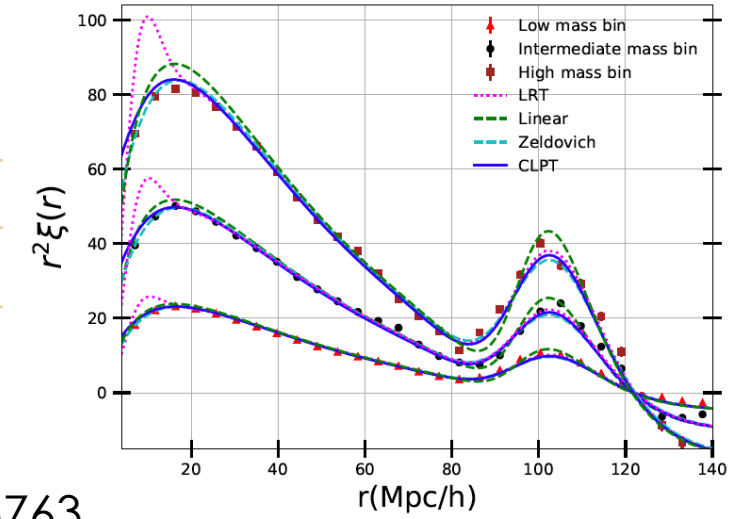
- f(R) & nDGP ELEPHANT sims:
  - z=0.5, L=1024 Mpc/h
  - 1 mass bin
  - M. Cautun et al. (2017)

z=1



GR

Theory matches N-body data across mass bins



MG

Valogiannis & Bean (2019), arXiv: 1901.03763

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)

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

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)

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

- GSM ingredients
  - Real-space ξ(r) for biased tracers in MG ✓
  - **Pairwise velocity $v_{12}(r)$ for biased tracers in MG**

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

  - **Dispersion $\sigma_{12}^2(r)$ for biased tracers in MG**
    - Model $v_{12}(r)$ & $\sigma_{12}^2(r)$ using LPT
    - $\dot{\Psi} \neq f\, H\, \Psi$ in MG – scale-dependence!!

$$\sigma_{12}^2(r,\mu) = \frac{\langle [1+\delta(\mathbf{x})][1+\delta(\mathbf{x}+\mathbf{r})][v_z(\mathbf{x}+\mathbf{r}) - v_z(\mathbf{x})]^2 \rangle}{\langle [1+\delta(\mathbf{x})][1+\delta(\mathbf{x}+\mathbf{r})] \rangle}$$

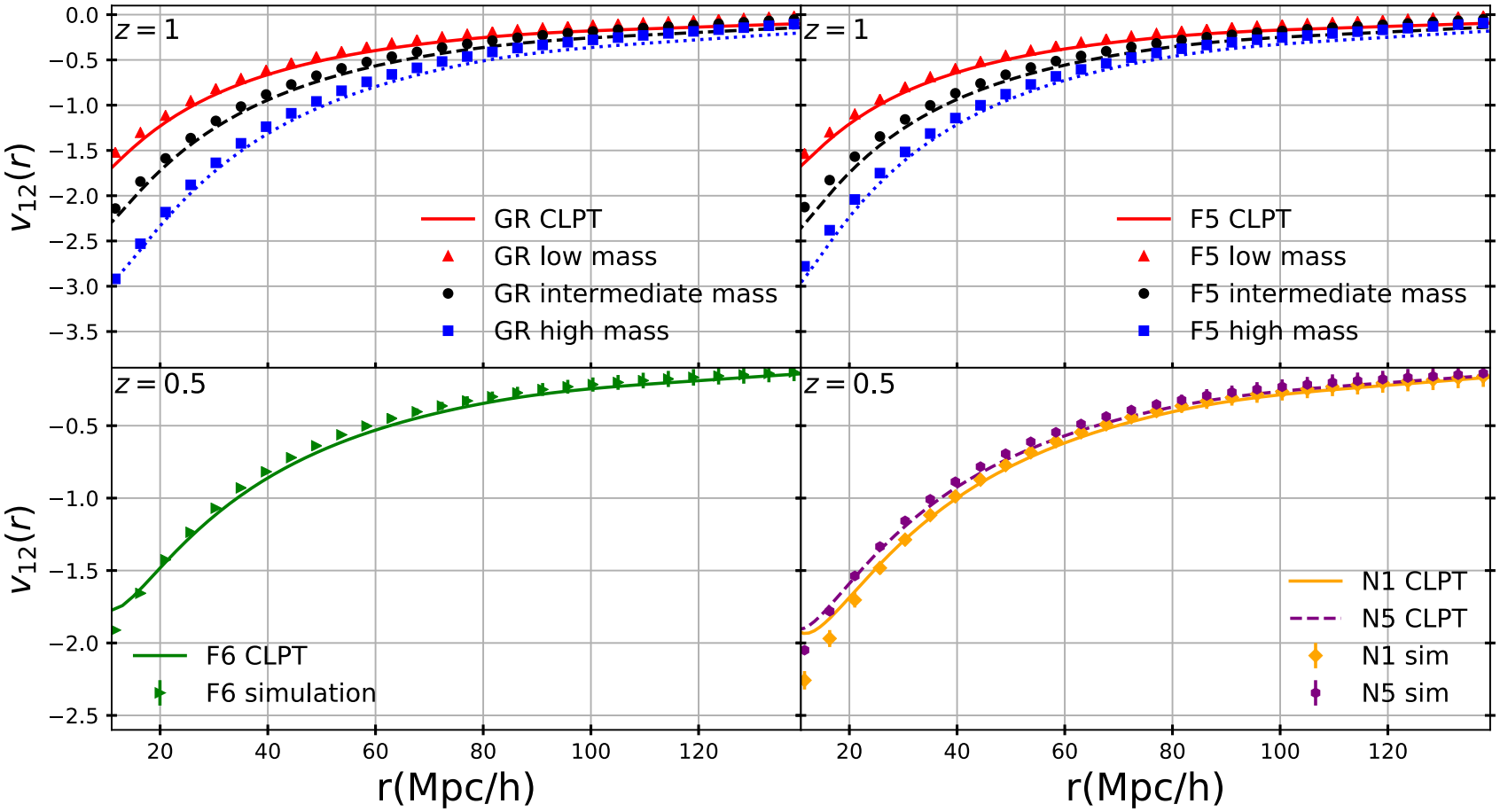
Pairwise velocity (v) model matches sims well

Theory:

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

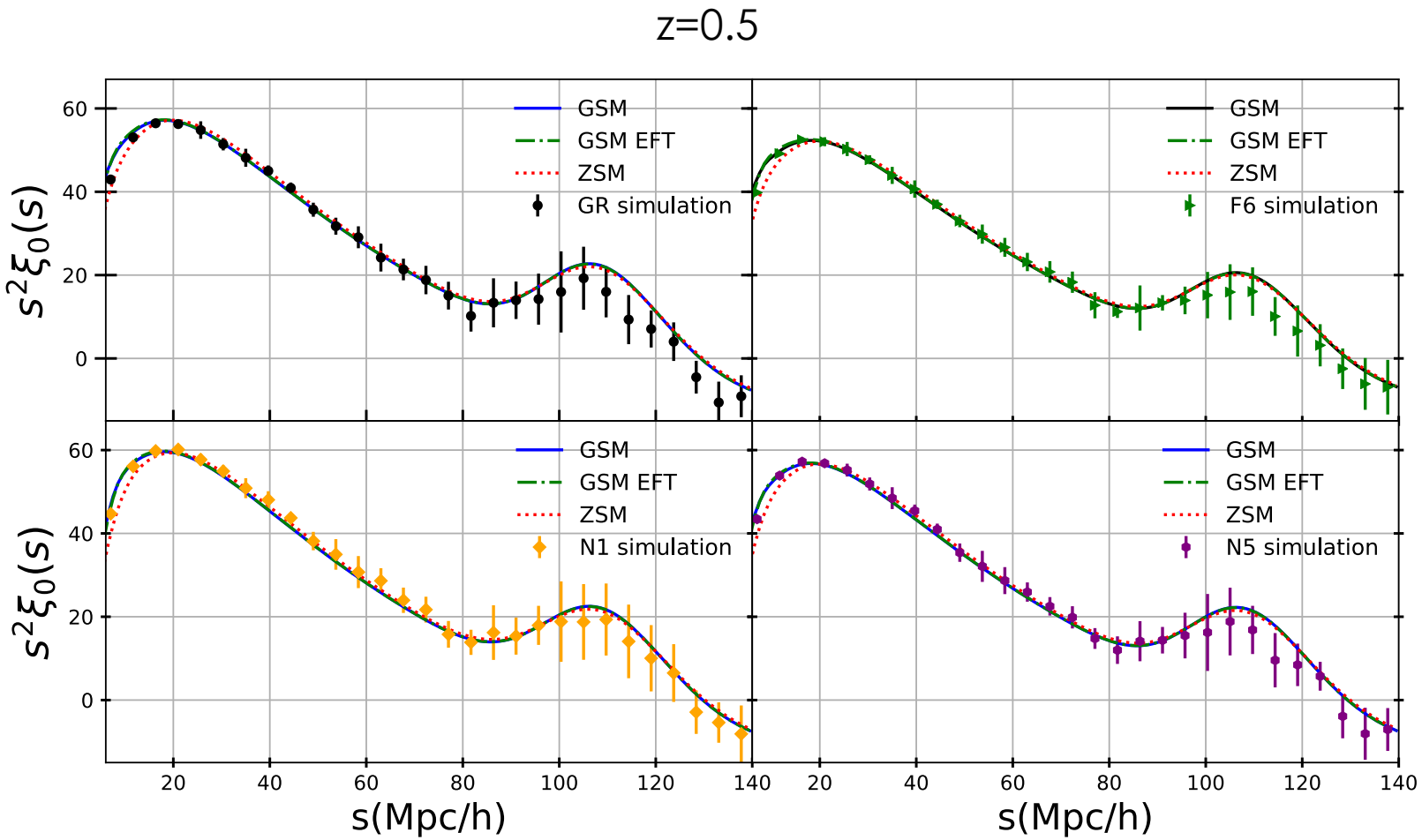
N-body simulations:

- 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)



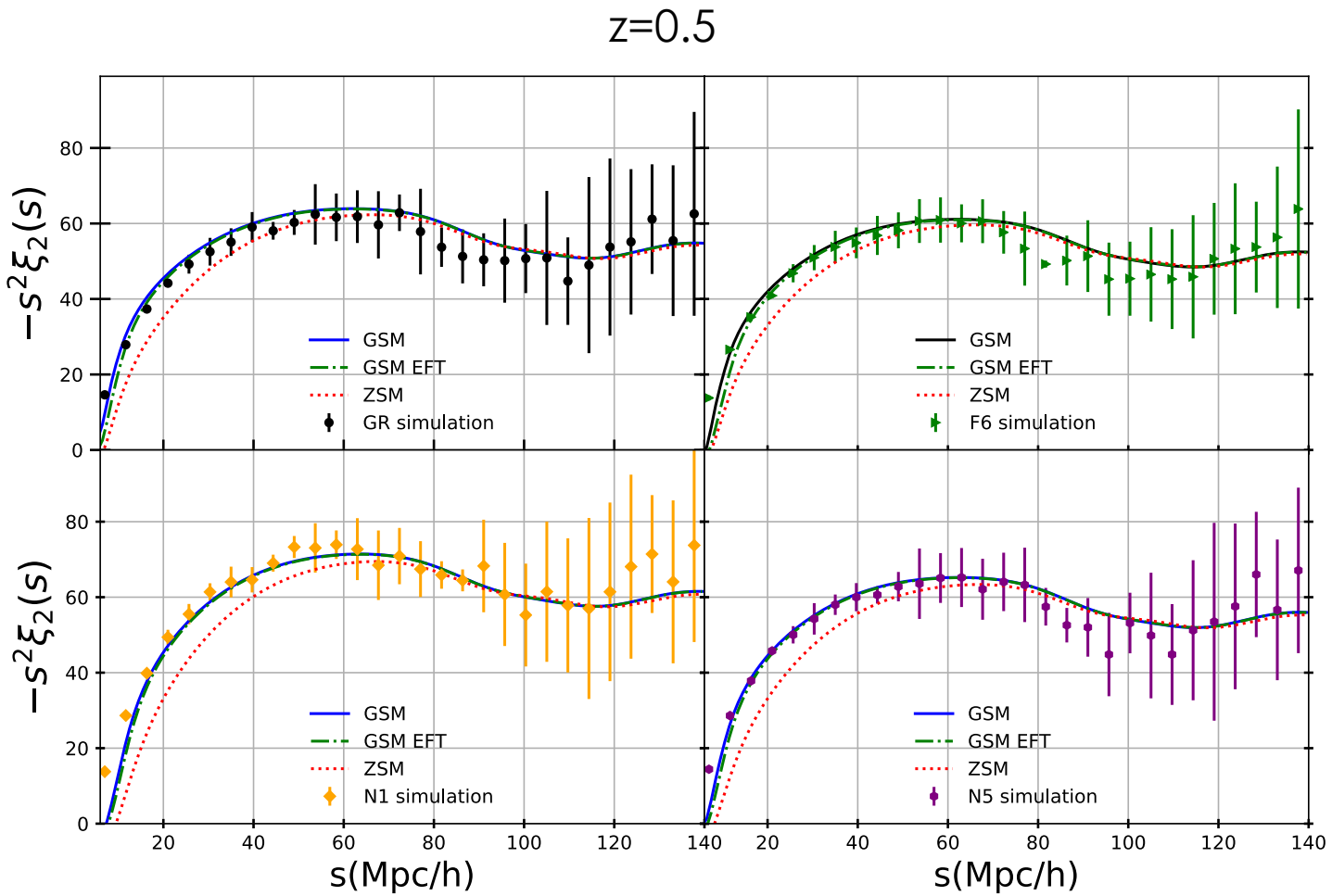
Valogiannis, Bean, Aviles (2019)
arXiv:1909.05261

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
  - Valogiannis & Bean, 2019 , arXiv:1901.03763, Phys. Rev. D 99, 063526
- In redshift space: Gaussian Streaming Model in MG
  - Valogiannis, Bean & Aviles (2019), arXiv:1909.05261, submitted to JCAP
  - 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

Georgios Valogiannis[1]; Rachel Bean[1] ; Alejandro Aviles[2]
[1]Department of Astronomy, Cornell University, Ithaca, NY, USA
[2]National Institute for Nuclear Research, Ciudad de Mexico, 11801, Mexico

In collboration with: Rachel Bean, Alejandro Aviles

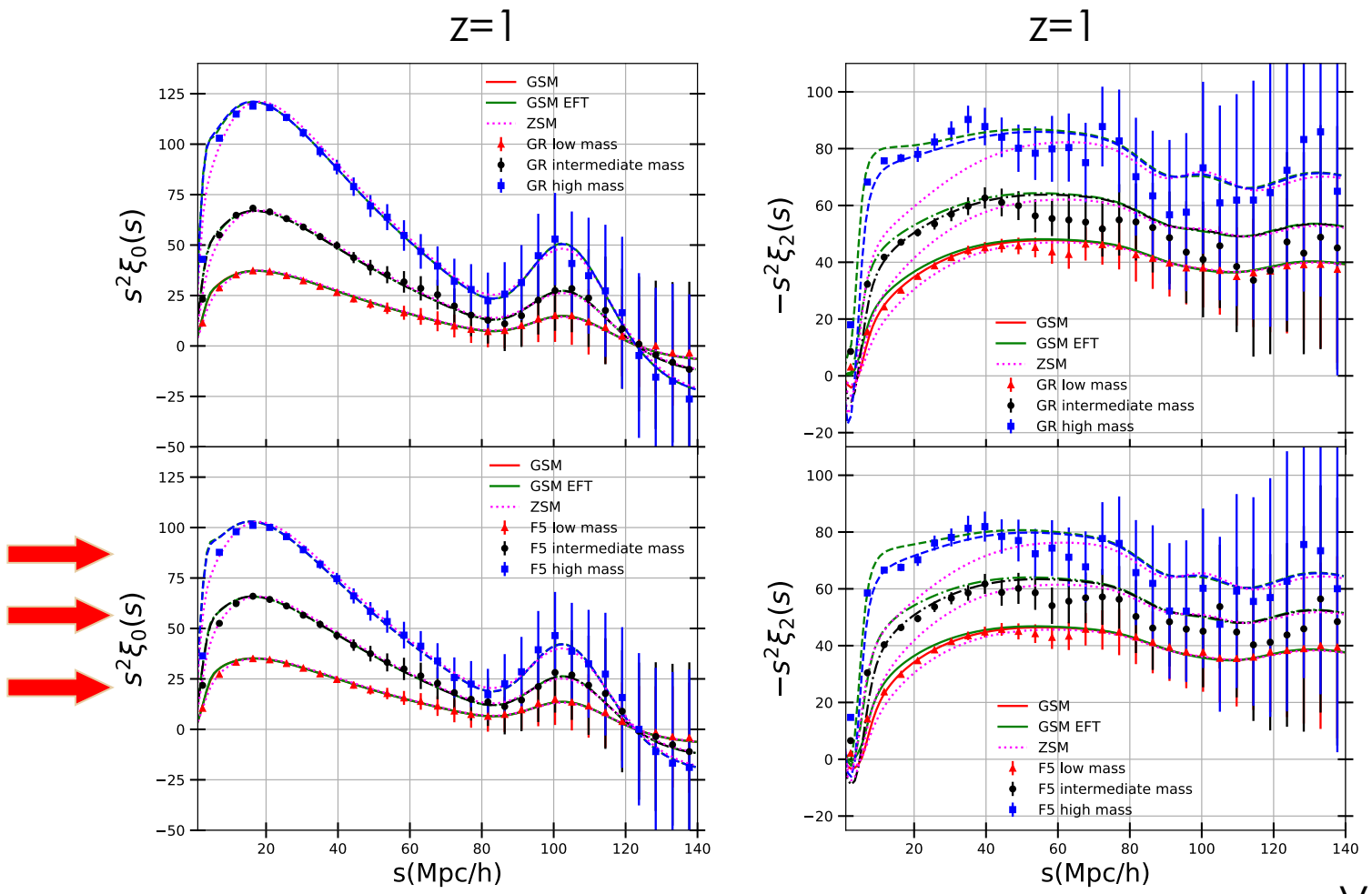
G.Valogiannis & R. Bean, Phys. Rev. D 99, 063526 (2019), arXiv: 1901.03763
G.Valogiannis, R. Bean & A. Aviles, submitted to JCAP (2019), arXiv: 1909.05261

Thank you!

Accurate predictions across different mass bins

Accurate bias predictions!

3 halo-mass bins



Valogiannis. Bean, Aviles (in prep.)

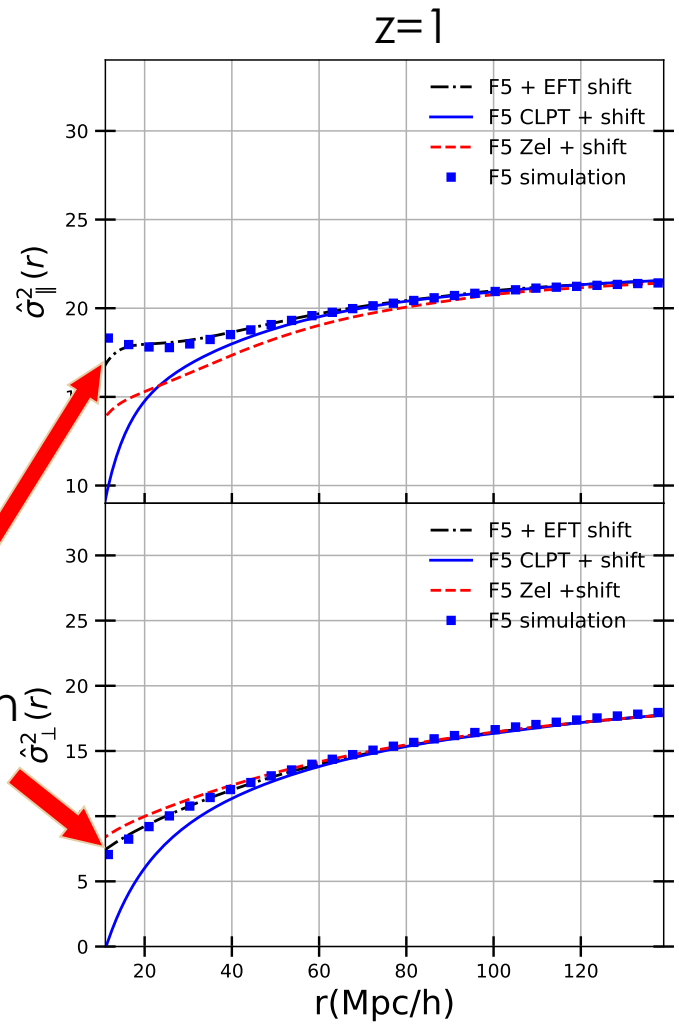
Modeling velocity dispersion (σ^2)+ shift

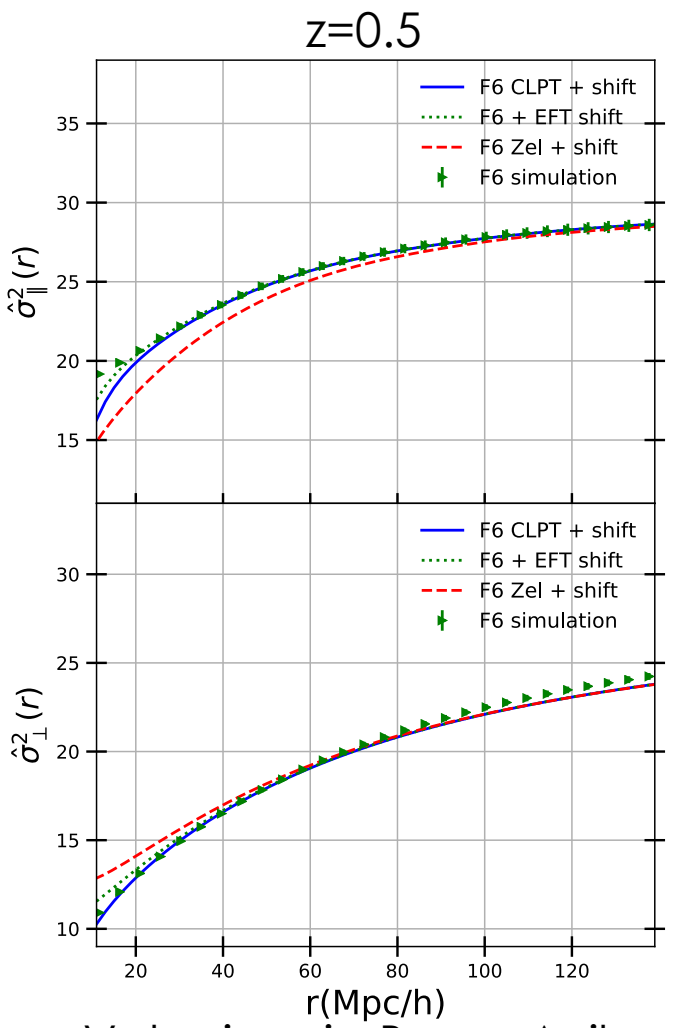
- Non-linear contributions to σ^2 not fully captured by LPT.
- Usually well-modeled by a constant offset for all r

  (B. Reid & M. White, 2011, L. Wang et al. 2013)
- Alternative uses EFT term based term in ξ

  (Z. Vlah et al. 2016)

Constant shift added to match large-scales





- 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 ✗

- Plane-parallel approximation

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

$$\xi_l^s(s) = \frac{2l+1}{2}\int_{-1}^{1} \mathrm{d}\mu_s \; L_l(\mu_s)\xi_l^s(s,\mu)$$

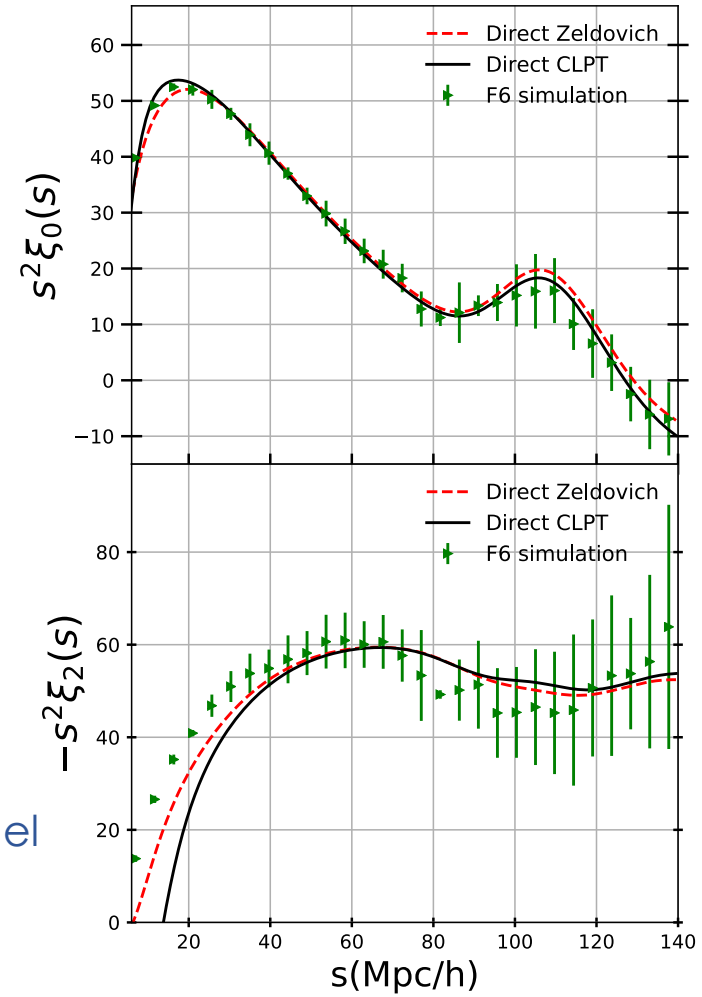
$l = 0$

$l = 2$

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

redshift real mapping

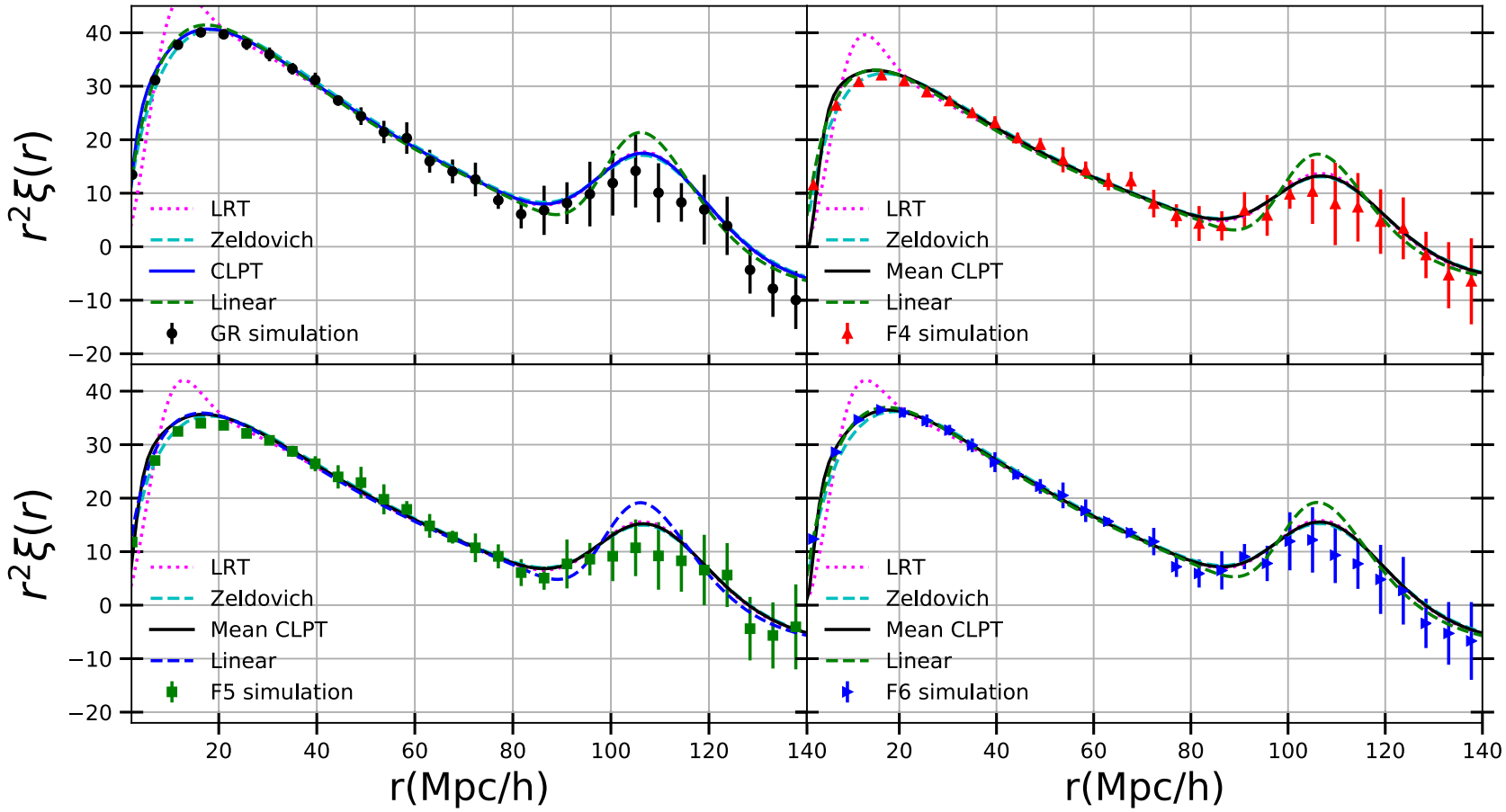
$|f_{R0}| = 10^{-6}$ (F6) Hu-Sawicki model



Valogiannis et al. (in prep.)

2-point correlation function results

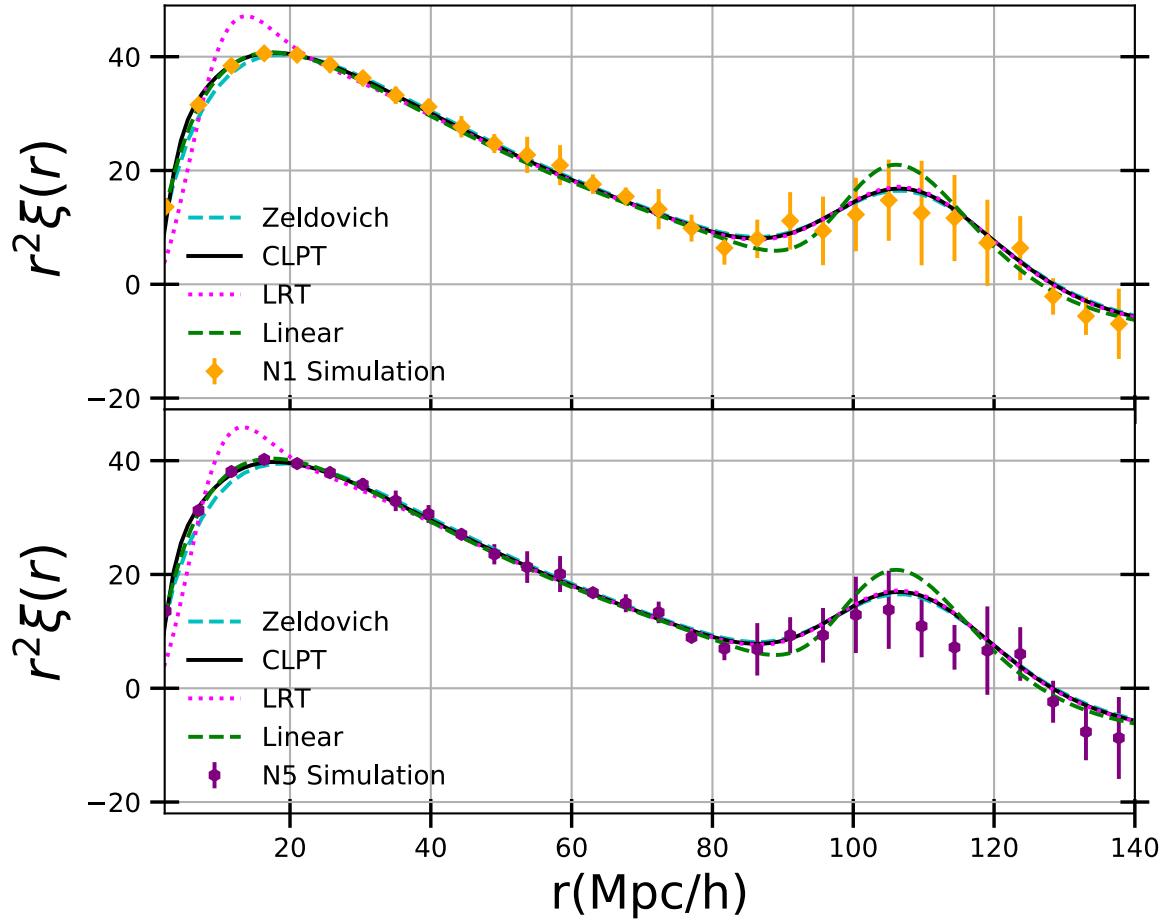
- Consistency for varying degrees of f(R) screening z=0.5 !



Valogiannis & Bean (2019)

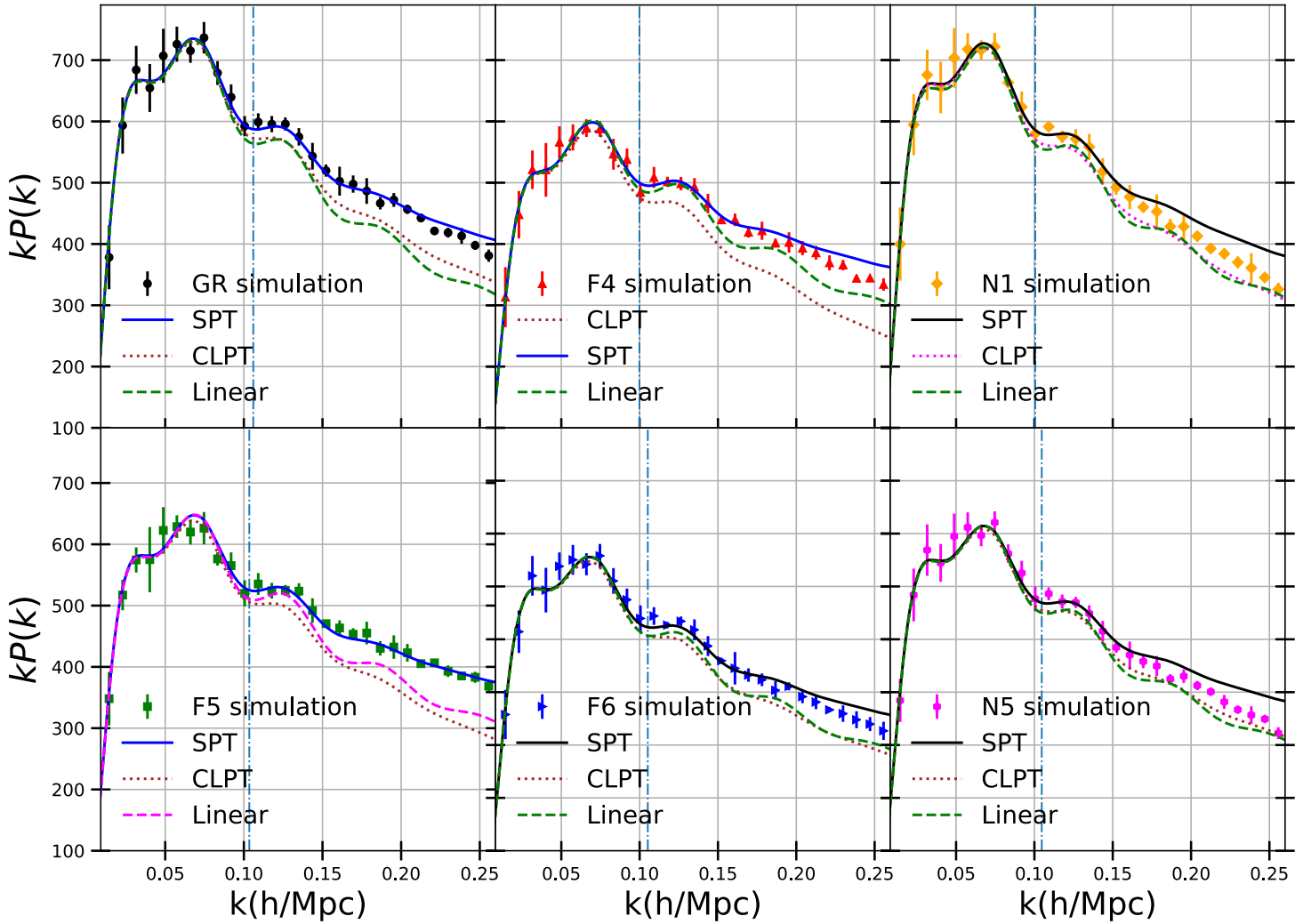
2-point correlation function results

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



Valogiannis & Bean (2019)

Power spectrum results



Valogiannis & Bean (2019)