Testing gravity with cosmology: efficient simulations, novel statistics and analytical approaches

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Origins of cosmic acceleration

- Recent accelerative epoch poses great theoretical challenge

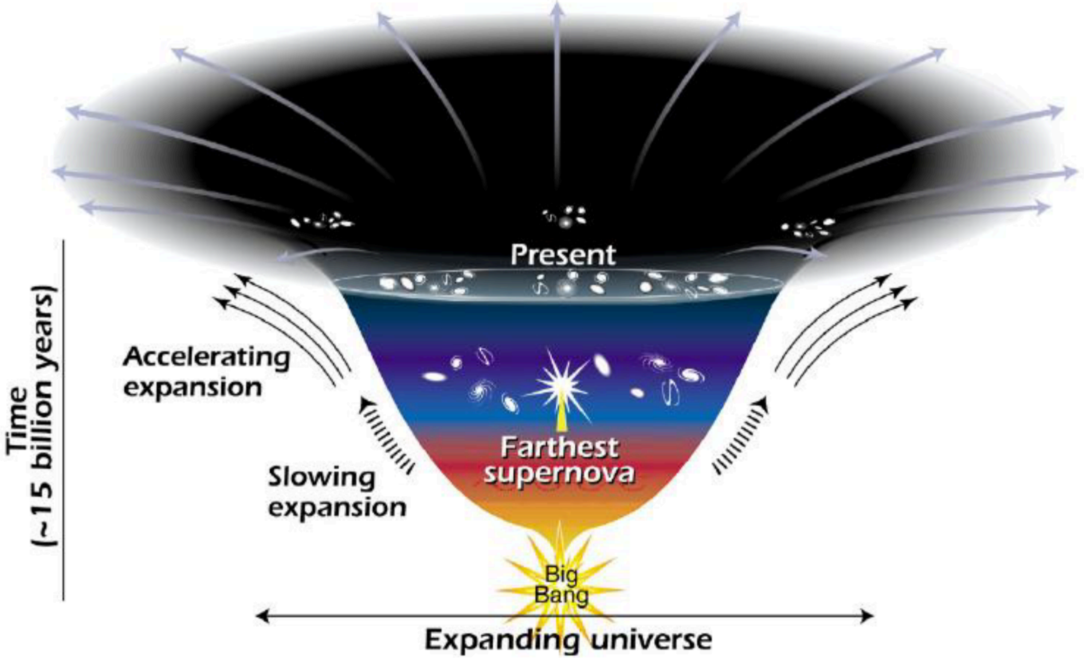
Modify Gravity?

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

Dark energy?

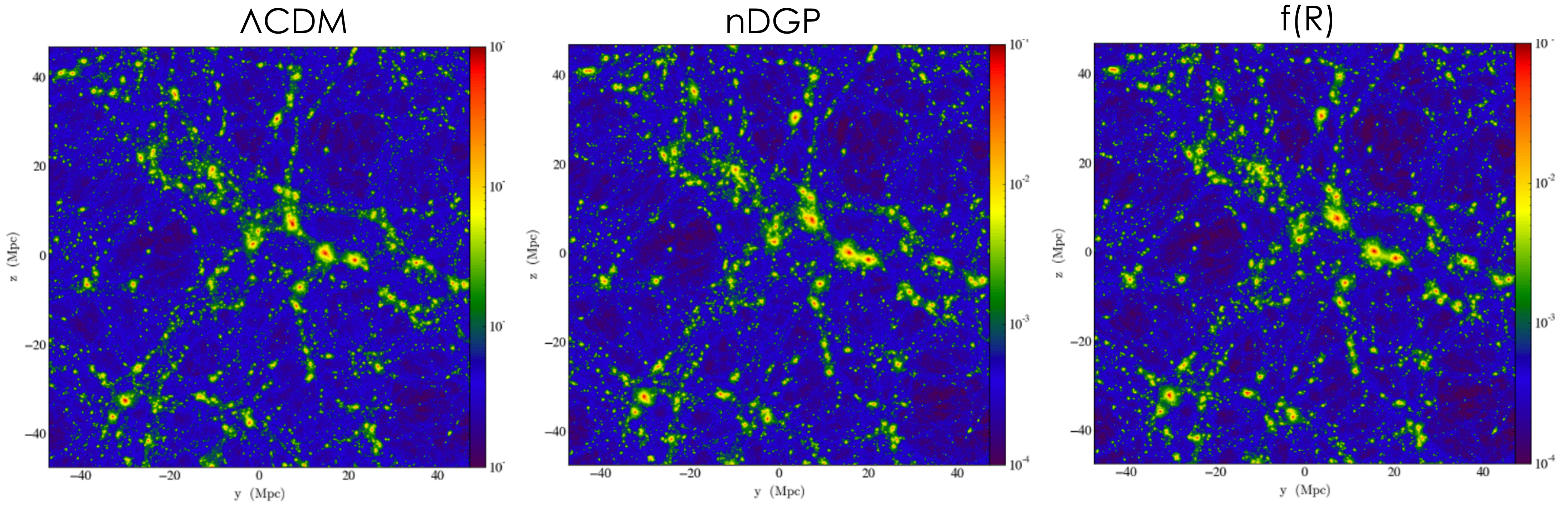
Λ?

- Within GR framework
- Cosmological constant Λ + CDM
- Dark energy
- Challenges to ΛCDM
    - Cosmological constant problem



Cosmological scales as probes of viable MG models

- Alternative proposal → **modified gravity** + screening
- MG-ΛCDM degeneracy *broken* at cosmological scales
- Upcoming LSS surveys can *constrain* MG models



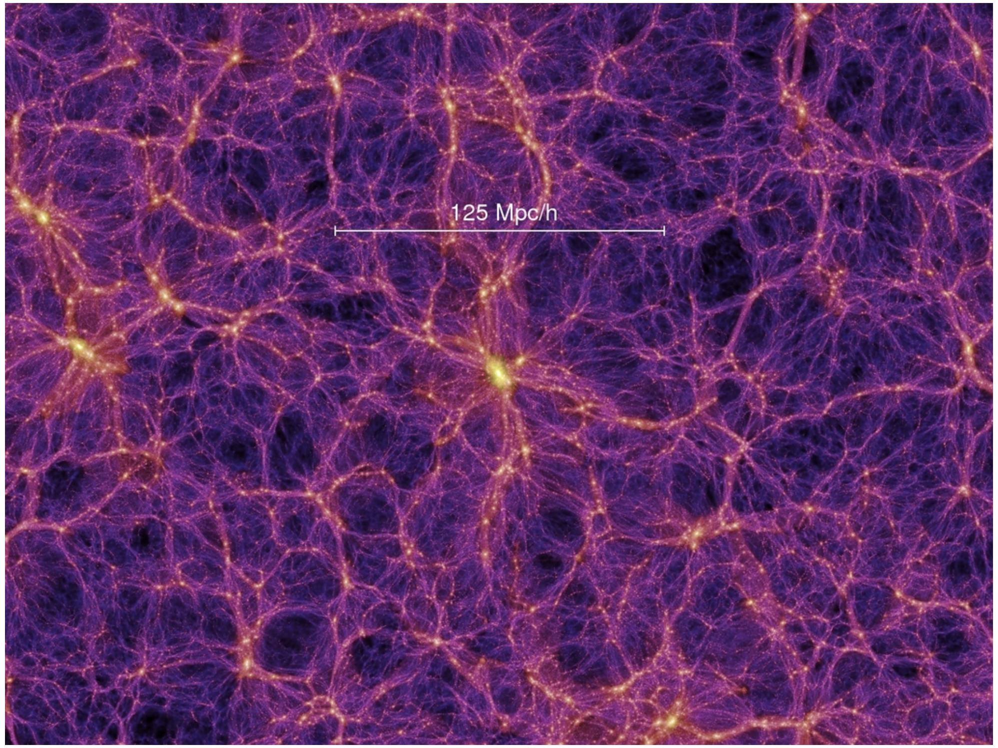
K. Koyama, 2015

Theoretical modeling of LSS in MG necessary

- Model-dependent cosmological tests of gravity from upcoming data
- Theoretically model structure formation in MG

However:

- N-body simulations computationally expensive
  - Efficient simulation schemes
- Detection challenging
  - Novel statistics
- Surveys observe *galaxies*
  - Biased tracers
  - Redshift space distortions



Millennium Simulation, 2005

Efficient COLA hybrid scheme

Efficient simulation schemes

- Accurate but *expensive* N-body simulations vs Fast but *approximate* perturbation theory

Why not combine?

- Hybrid "COmoving Lagrangian Acceleration" COLA scheme

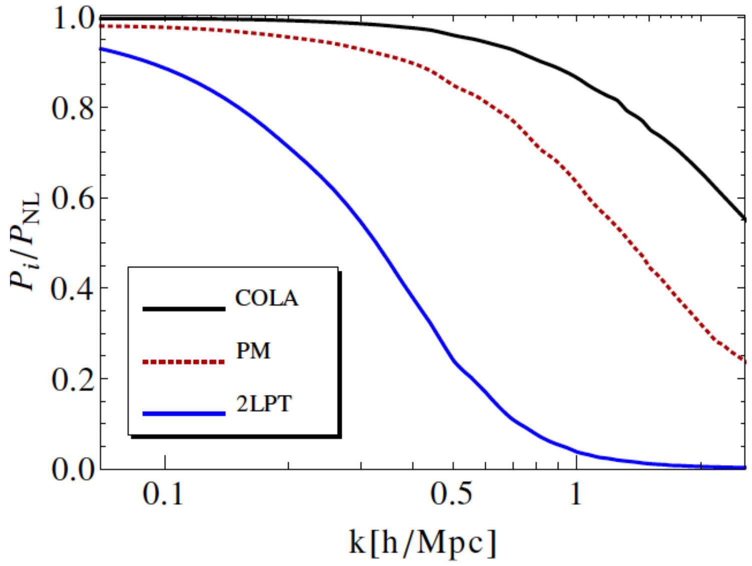
S. Tassev et al. 2013

$$\boldsymbol{x}_{\text{res}} \equiv \boldsymbol{x} - \boldsymbol{x}_{\text{LPT}}$$

$$\partial_t^2 \boldsymbol{x}_{\text{res}} = -\nabla\Phi - \partial_t^2 \boldsymbol{x}_{\text{LPT}}$$

N-body 2LPT solution

S. Tassev et al. 2013



COLA simulations for MG: chameleons

In MG: *non-minimally* coupled scalar φ

N body component

$$\ddot{\mathbf{x}} + 2H\dot{\mathbf{x}} = -\frac{1}{a^2}\left(\nabla_{\mathbf{x}}\Phi_N + \frac{\beta}{M_{Pl}}\nabla_{\mathbf{x}}\phi\right)$$

Fifth force

LPT component

$$\ddot{D}_1(\mathbf{k},a) + 2H\dot{D}_1(\mathbf{k},a) = \frac{3}{2}\Omega_m(a)H^2 D_1(\mathbf{k},a)\frac{G_{eff}}{G}$$

MG linear growth factor

Scale-dependent modification

- MG introduces new fifth force
- Need to solve highly nonlinear Klein-Gordon equation
- Computationally expensive!

- LPT growth factor becomes scale-dependent
- Also computationally expensive!
- More about this part later

Solutions: Effective screening implementation

Speed-up by 2 order of magnitude!

N body component

- Solve linearized KG
- Attach thin shell factor to KG fifth force

$$\ddot{\mathbf{x}} + 2H\dot{\mathbf{x}} = -\frac{1}{a^2}\left(\nabla_{\mathbf{x}}\Phi_N + \frac{\Delta\mathcal{R}_c}{\mathcal{R}_c}\frac{\beta}{M_{Pl}}\nabla_{\mathbf{x}}\phi\right)$$

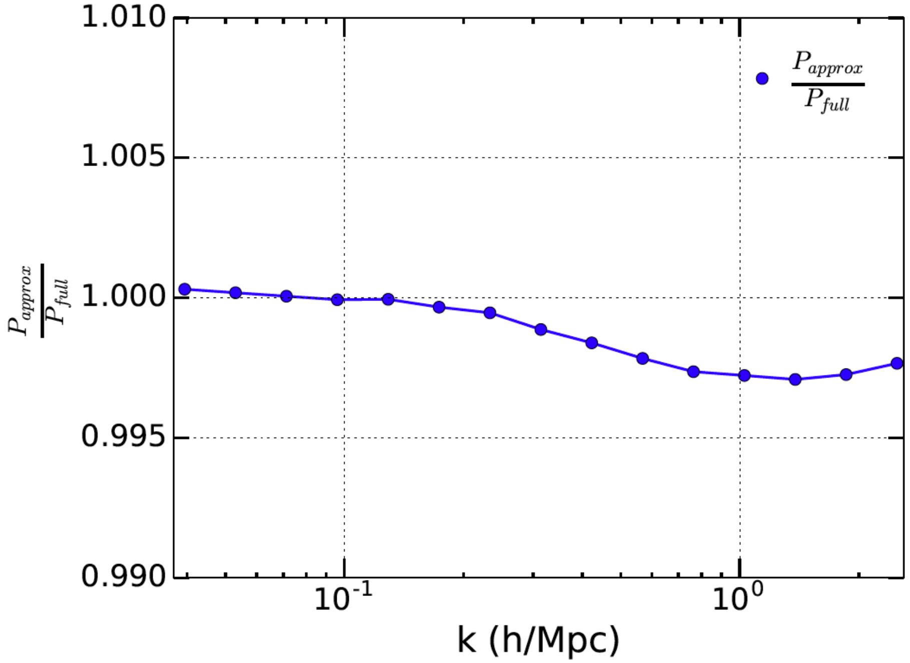
- Phenomenological factor

$$\frac{\Delta\mathcal{R}_c}{\mathcal{R}_c} = \begin{cases} \frac{\phi(a)}{2\beta(a)M_{Pl}|\Phi_N|} & \text{if } \frac{\phi(a)}{2\beta(a)M_{Pl}|\Phi_N|} < 1 \\ 1 & \text{if } \frac{\phi(a)}{2\beta(a)M_{Pl}|\Phi_N|} > 1 \end{cases}$$

H. Winther & P. Ferreira, 2014

LPT component

- Scale-dependent growth negligible!

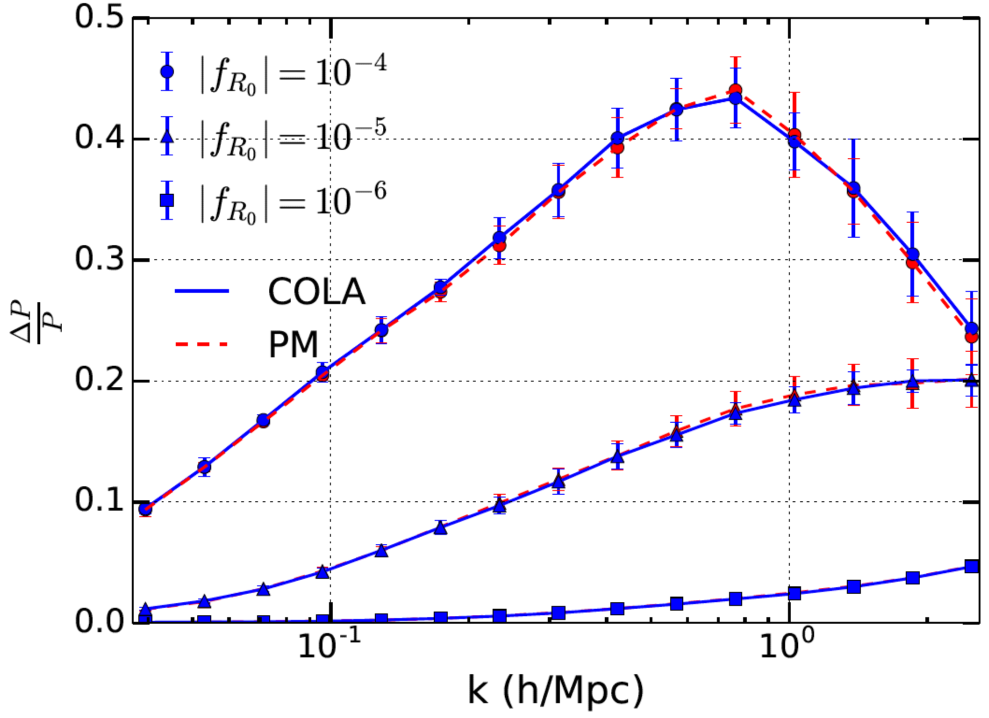


Valogiannis and Bean, (2017)

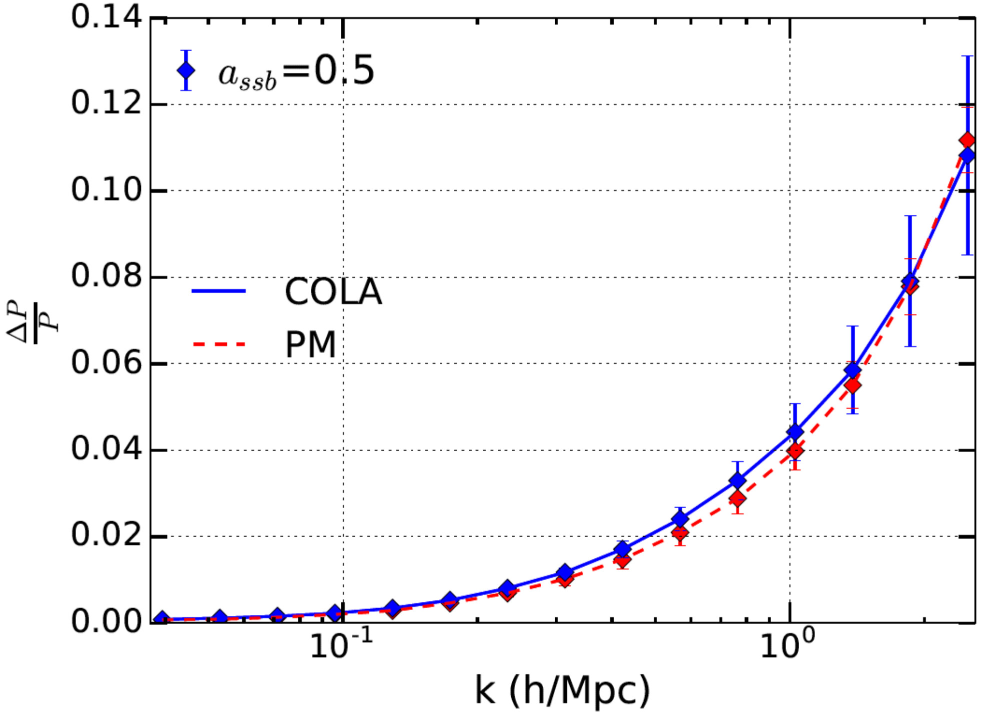
Comparison of N-Body and COLA power spectra

- MG COLA hybrid agrees well with N–body results!
- ~100x faster!
- Emulators

f(R) (W. Hu & I .Sawicki, 2007)



Symmetron (K, Olive & M.Pospelov, 2008)

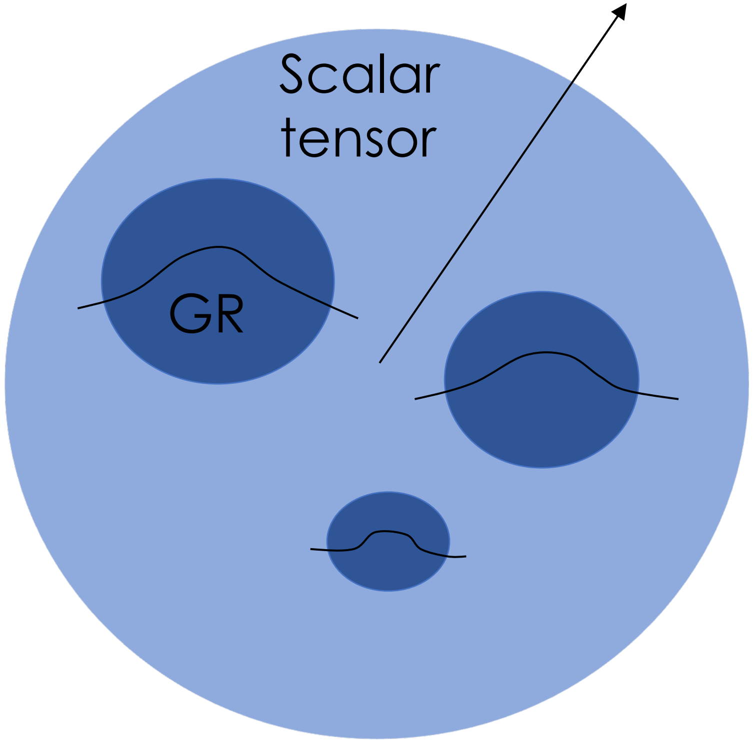


Valogiannis and Bean, Phys. Rev. D 95, 103515 (2017)

Detection challenging - need for a new statistic

Novel statistics

- "Screening" suppresses deviations in high densities
- Signals strongly suppressed by screening – detection challenging
- Need for new statistic!



K. Koyama 2017

Marked density transformation

- **Up-weighting low density, unscreened regions** and down-weight highly screened regime can **highlight** MG signals in density fields
- Fundamental quantity of interest

$$\delta(\mathbf{x}, a) = \frac{\rho_m(\mathbf{x}, a)}{\bar{\rho}_m} - 1$$

- Variety of density transformations in literature
  - Logarithmic re-mapping (M. Neyrinck et al. 2009)

$$\delta' = \ln(\delta + 1)$$

  - Clipping density field (F. Simpson et al. 2011)

$$\delta' = \delta_c = \begin{cases} \delta & \text{if } \delta < \delta_0 \\ \delta_0 & \text{if } \delta > \delta_0 \end{cases}$$

  - **«Marked»** transformation (M. White, 2016)

$$\delta' = m(\delta) = \left(\frac{\rho_* + 1}{\rho_* + \rho_m}\right)^p = \left(\frac{\rho_* + 1}{\rho_* + \bar{\rho}_m(\delta + 1)}\right)^p$$

Quantifying enhancement

- Dark matter N-body simulations using Particle-Mesh (PM) code (Valogiannis & Bean 2017)
- Simulation box side L=200 Mpc/h, 256^3 particles, resolved on 512^3 grid
- 40 density snapshots at z=0 for ΛCDM, f(R) and symmetron cosmologies
- 2D projection → 3x40=120 power spectra
- Covariance matrix

$$C_{ij} = \frac{1}{N_{seed} - 1} \sum_{r}^{N_{seed}} \left(P_r(k_i) - \bar{P}(k_i)\right)\left(P_r(k_j) - \bar{P}(k_j)\right)$$

- Fisher information in the parameter

$$I_\alpha = \sum_{i,j}^{N_{bins}} \frac{\partial P(k_i)}{\partial \alpha} C_{ij}^{-1} \frac{\partial P(k_j)}{\partial \alpha}$$

- Signal-to-Noise Ratio (SNR)

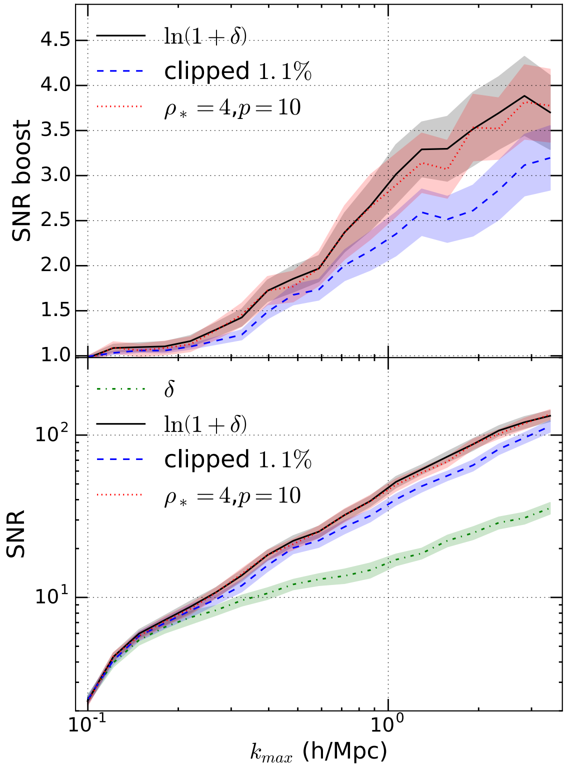
$$SNR = \sqrt{\sum_{i,j}^{N_{bins}} \bar{P}(k_i) C_{ij}^{-1} \bar{P}(k_j)}$$

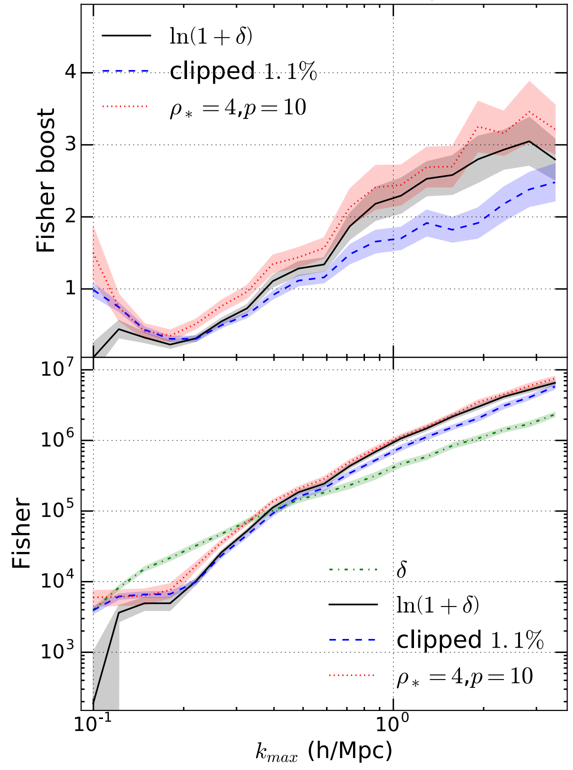
Information boost

- Assess level of additional information encoded, in terms of "boost"
- Marked transformation **increases** information relative to standard δ

$$\text{SNR boost} = \frac{\text{SNR}(\delta')}{\text{SNR}(\delta)}$$

$$\text{Fisher boost} = \sqrt{\frac{I_\alpha(\delta')}{I_\alpha(\delta)}}$$





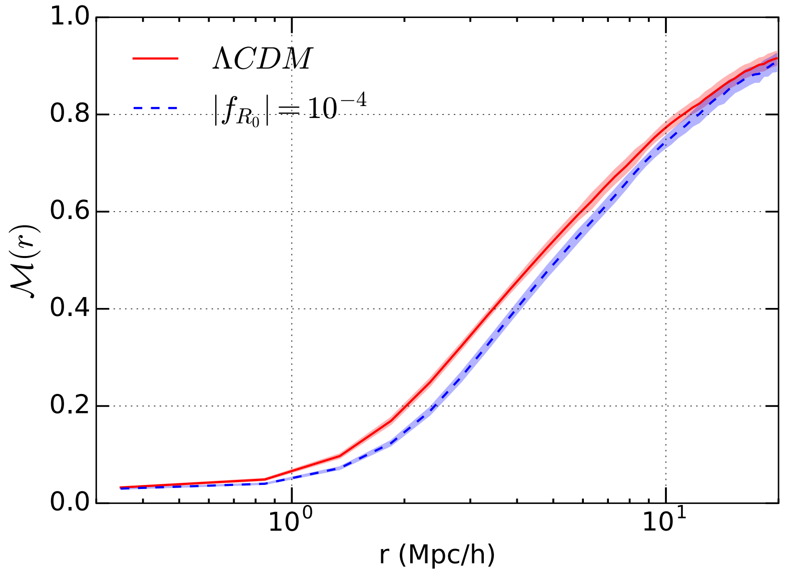
Valogiannis & Bean, 2018

Marked correlation function in MG

- Screening mechanism produces unique density dependent signature
- What other density-dependent statistics?
- Marked correlation function (Sheth, R.K., Connolly, A.J., & Skibba, R. 2005)
- Real space statistic to test MG (M. White, 2016)

$$\mathcal{M}(r) \equiv \frac{1}{n(r)\bar{m}^2} \sum_{ij} m_i m_j = \frac{1+W}{1+\xi}$$

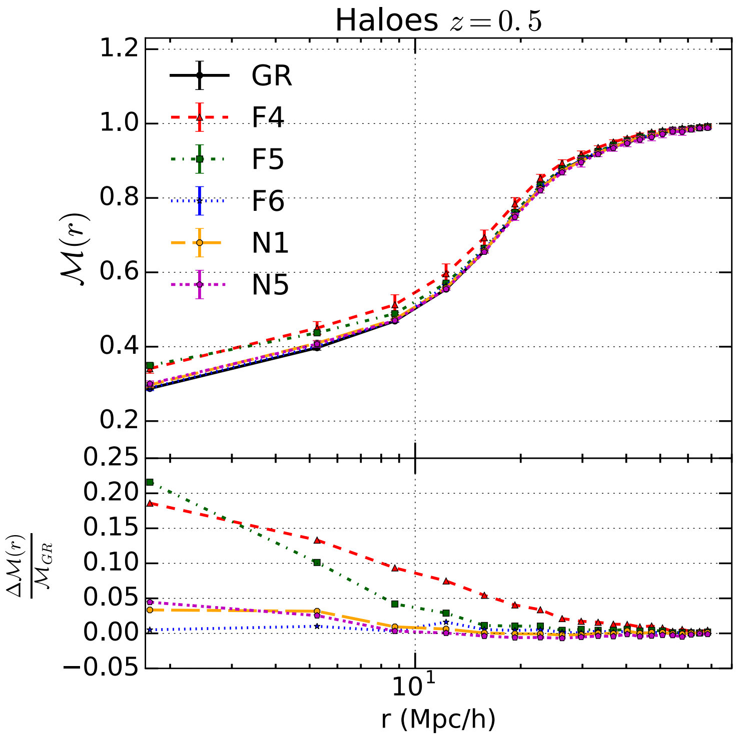
Result for dark matter

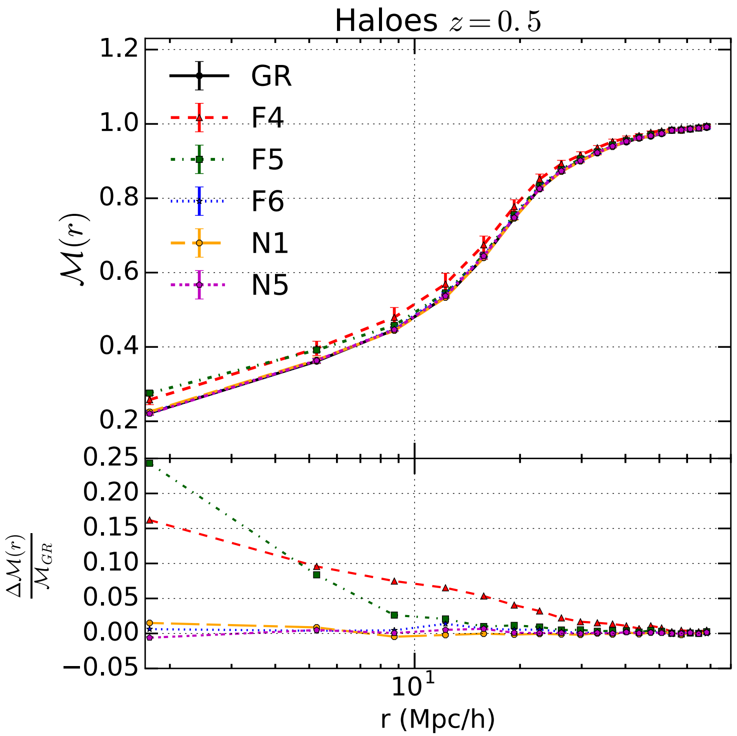


Valogiannis & Bean, 2018

Halo-marked correlation function

- Marked correlation functions for dark matter halos at z=0.5

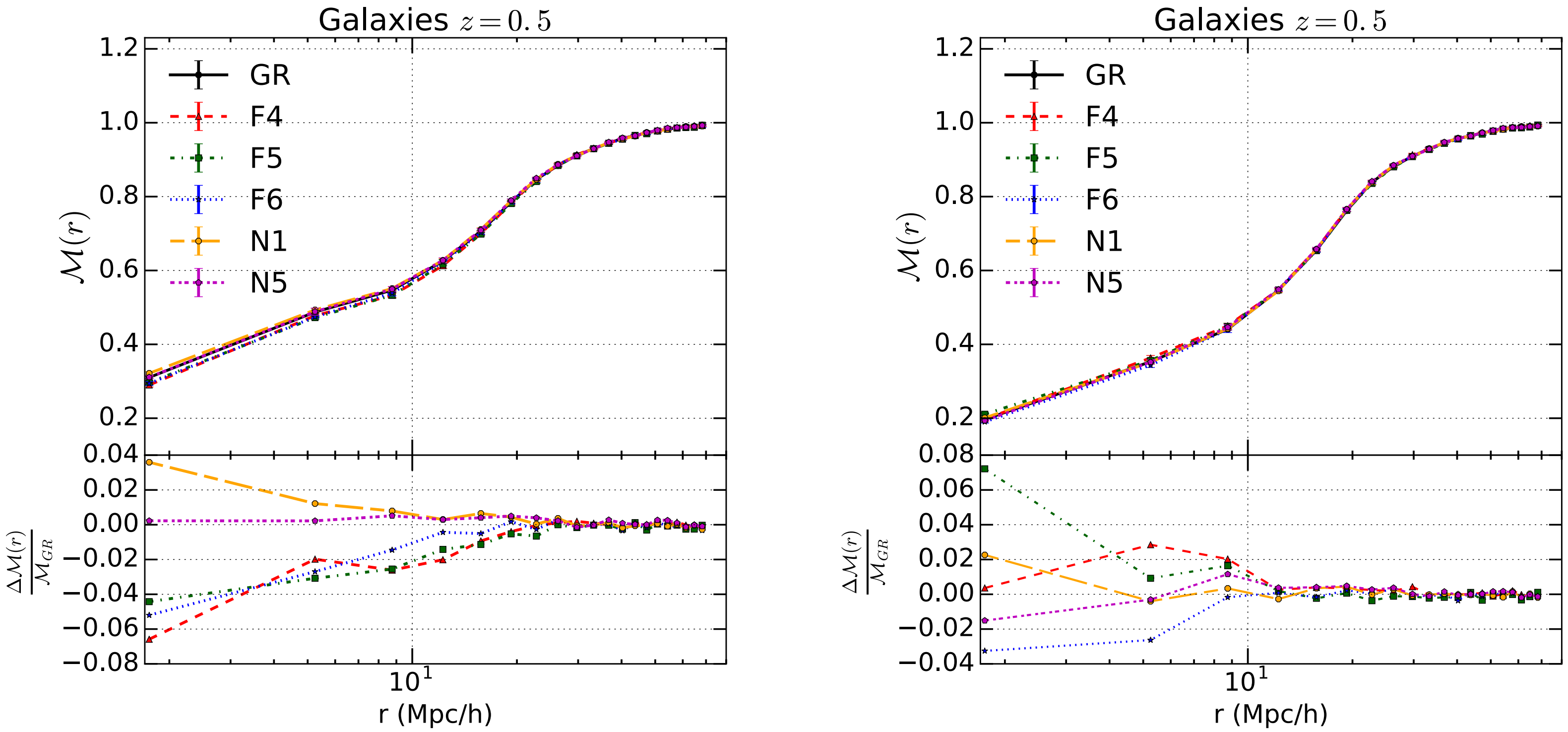




DESI MG white paper, in prep.

Galaxy-marked correlation function

- Marked correlation functions for galaxies at z=0.5

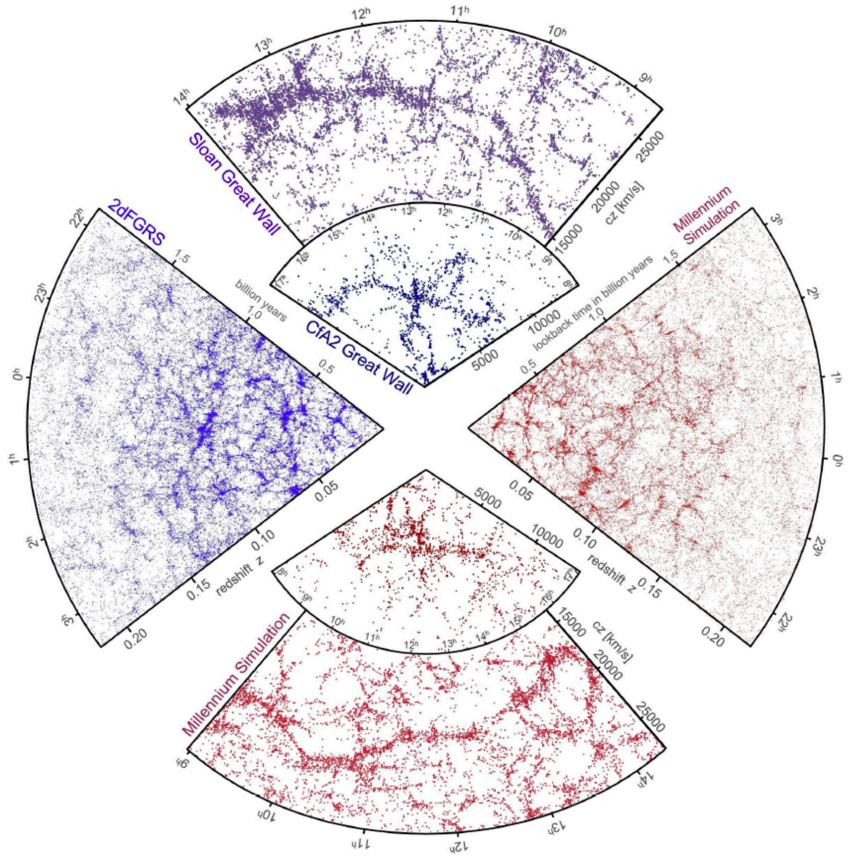


DESI MG white paper, in prep

Signatures of viable MG models using biased tracers

Biased tracers

- Spectroscopic surveys observe galaxies that do *not* trace dark matter field perfectly
  - **Biased** tracers (N. Kaiser 1987, G. Efstathiou 1988)
- Analytical predictions for 2-point statistics of biased tracers in gravity models (GR, MG) necessary



V. Springel et al. (2006)

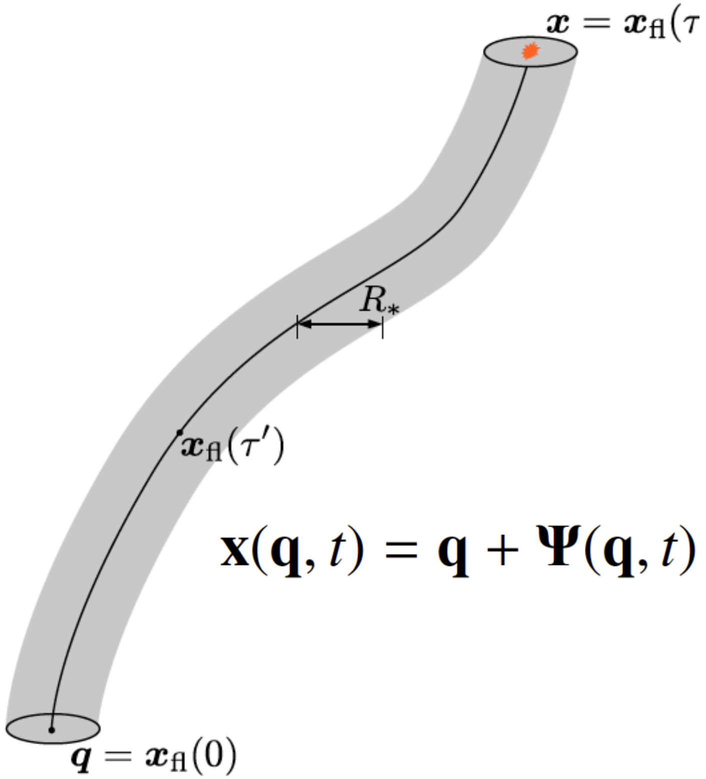
Nonlinear predictions for biased tracers

- Modeling two-point statistics for biased tracers – 3 regimes

Linear regime - Quasi-linear regime - Nonlinear regime

Linear regime	Quasi-linear regime	Nonlinear regime
Linear bias $P_{hh}(k) = b^2 P_{dm}(k)$	Nonlinear PT Eulerian, Lagrangian PT approaches	Simulations +empirical modeling

- Dark matter field evolution ✓
  - 3rd order LPT in MG *(A. Aviles & J. L. Cervantes-Cota, 2017)*
- Convolution Lagrangian PT for biased tracers (CLPT) ✓
  - In GR *(Carlson et al. 2013)*
  - **In MG** *(A. Aviles et al. 2018, Valogiannis & Bean 2019)*
- **Lagrangian bias in MG**



$$\mathbf{x}(\mathbf{q}, t) = \mathbf{q} + \mathbf{\Psi}(\mathbf{q}, t)$$

V. Desjacques et al. (2017)

$$\delta_X(\mathbf{x}, t) = \int d^3q F\left[\delta_R(\mathbf{q})\right] \delta_D\left[\mathbf{x} - \mathbf{q} - \mathbf{\Psi}(\mathbf{q}, t)\right] - 1$$

Biased tracers — LPT displacement

Peak-Background Split Lagrangian biases in GR

- Lagrangian bias factors - rigorous definition
  - Response to a large wavelength density perturbation Δ
- Unconditional/universal halo mass function

$$\bar{n}_h(M) = \frac{\partial^2 \bar{N}_h}{\partial V \partial \ln M} = \frac{\bar{\rho}_m}{M}\nu_c(M) f\left[\nu_c(M)\right] \frac{d \ln \nu_c(M)}{dM}$$

F. Schmidt et al. (2013)

$$b_n^L(M) = \frac{1}{\bar{n}_h(M,0)} \frac{d^n \bar{n}_h(M,\Delta)}{d\Delta^n}\bigg|_{\Delta=0}$$

Conditional halo mass function

Unconditional halo mass function

$$\nu_c(M) = \frac{\delta_{cr}}{\sigma(M,z)} = \frac{\delta_{cr}}{D(z)\sigma(M)}$$

- Sheth-Tormen (ST) mass function

$$\nu_c f\left[\nu_c\right] = \sqrt{\frac{2}{\pi}} A(p)\left[1 + \frac{1}{(q\nu_c^2)^p}\right] \sqrt{q}\nu_c e^{\frac{-q\nu_c^2}{2}}$$

- Peak-Background Split (PBS) formalism biases

$$b_1^L(M) = \frac{-1}{\delta_{cr}}\left[q\nu_c^2 - 1 + \frac{2p}{1 + \left(q\nu_c^2\right)^p}\right],$$

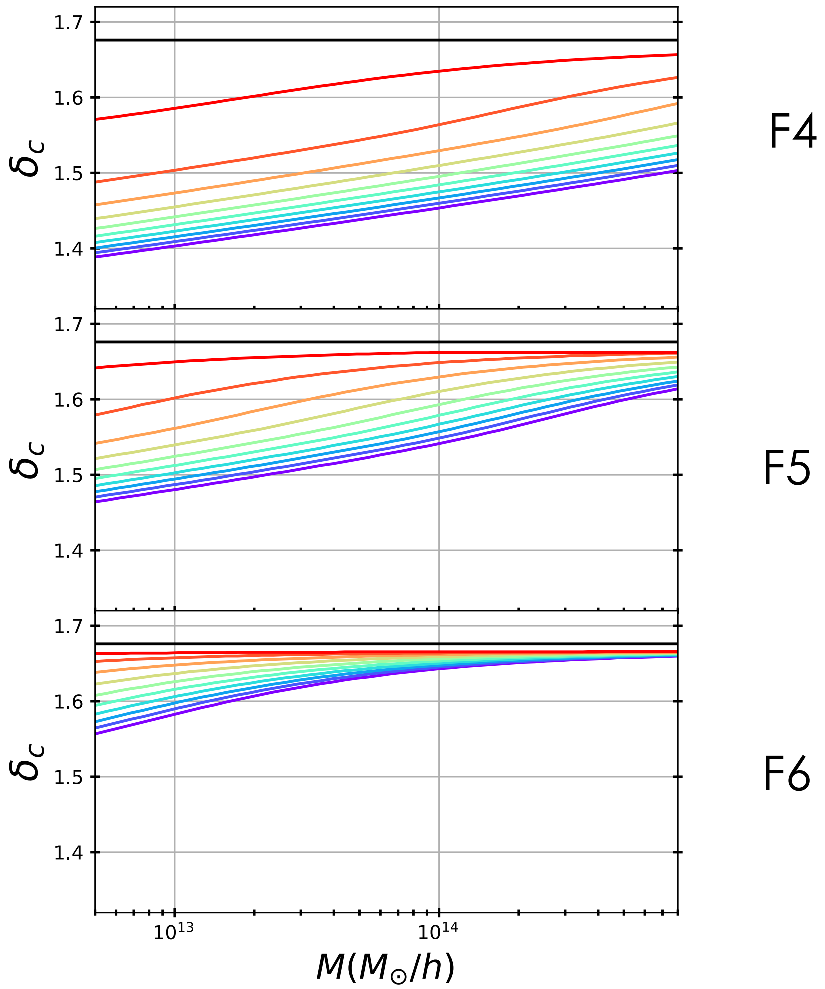
$$b_2^L(M) = \frac{1}{\delta_{cr}^2}\left[q^2\nu_c^4 - 3q\nu_c^2 + \frac{2p\left(2q\nu_c^2 + 2p - 1\right)}{1 + \left(q\nu_c^2\right)^p}\right]$$

- Calculation *not* valid in MG!

Gravitational collapse in MG

- Density 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

[−1(purple), −0.72, −0.43, −0.15, 0.13, 0.42, 0.7, 0.98, 1.27, 1.55(red)]



f(R), Valogiannis & Bean (2019)

Peak-Background Split Lagrangian biases in MG

- PBS formalism should be *modified* in MG

- Mass function model in MG

$$\nu_{cMG}(z, M, \delta_{env}) = \frac{\delta_{cr}(z, M, \delta_{env})}{D^{(1)}(z)\sigma(M)}$$

- PBS Lagrangian biases in MG

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

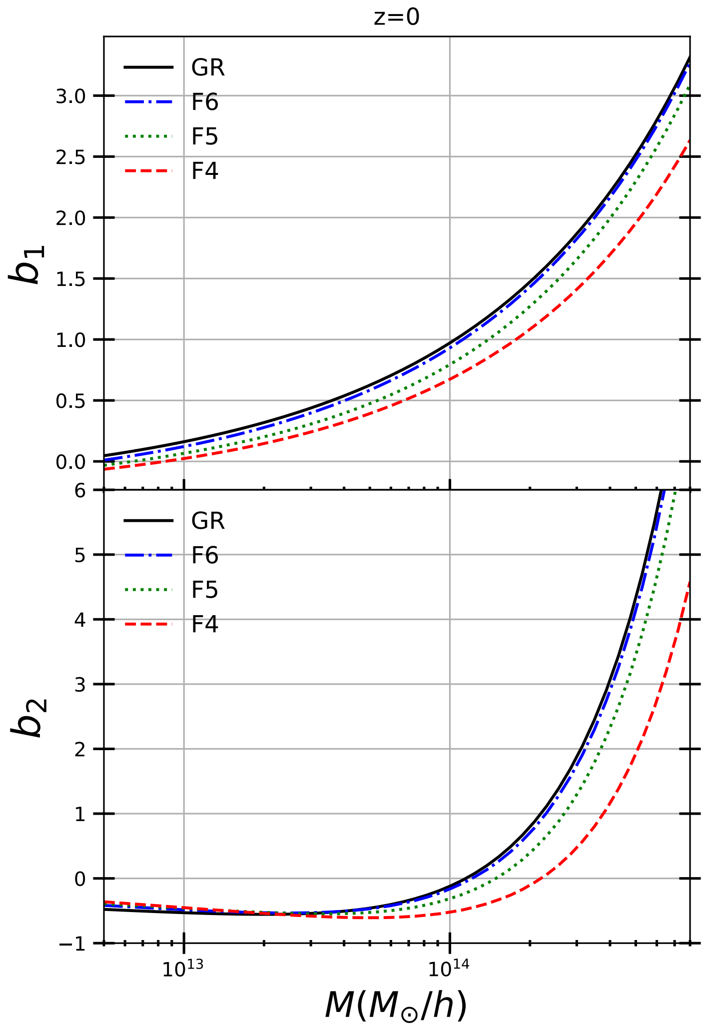
$$b^1_{MG}(M, \delta_{env}) = \frac{\frac{d\delta_{cr}(M,\delta_{env})}{d\delta_{env}} - 1}{\delta_{cr}(M, \delta_{env})}\left[q\nu^2_{cMG} - 1 + \frac{2p}{1 + \left(q\nu^2_{cMG}\right)^p}\right],$$

$$b^2_{MG}(M, \delta_{env}) =$$

$$\frac{\left(\frac{d\delta_{cr}(M,\delta_{env})}{d\delta_{env}} - 1\right)^2}{\delta^2_{cr}(M, \delta_{env})}\left[q^2\nu^4_{cMG} - 3q\nu^2_{cMG} + \frac{2p\left(2q\nu^2_{cMG} + 2p - 1\right)}{1 + \left(q\nu^2_{cMG}\right)^p}\right]$$

$$+ \frac{d^2\delta_{cr}(M, \delta_{env})}{d\delta^2_{env}}\frac{1}{\delta_{cr}(M, \delta_{env})}\left[q\nu^2_{cMG} - 1 + \frac{2p}{1 + \left(q\nu^2_{cMG}\right)^p}\right].$$

Valogiannis & Bean (2019)



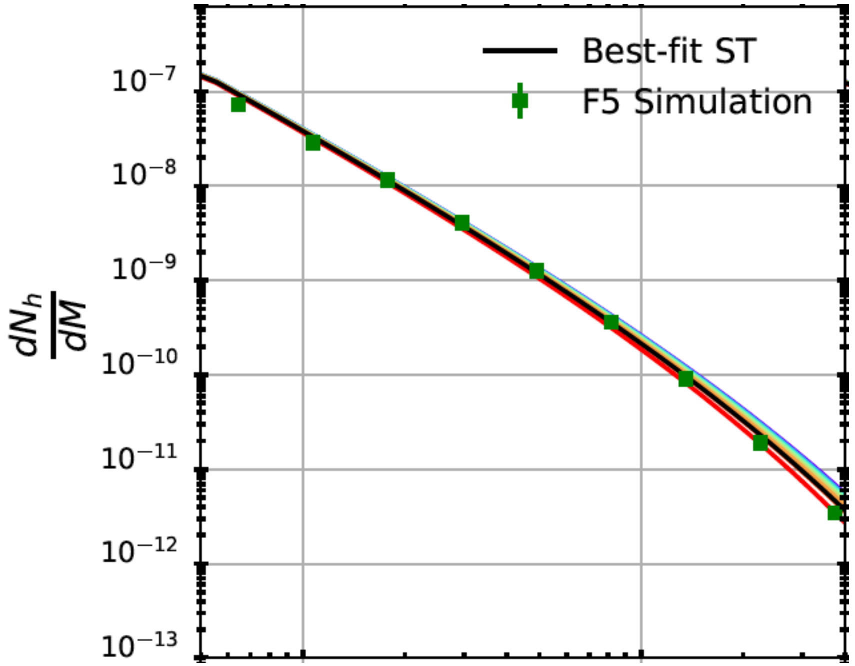
f(R), Valogiannis & Bean (2019)

Halo mass function fitting in MG

- In GR, standard fit (q,p)=(0.75,0.3)
  - *(R. Sheth et al. 2001)*
- In MG, ST values *different* - absorb novel physics of gravitational collapse
- Best-fit (q,p) against MG simulations

	Best-fit ST		Predicted Biases	
Models	q	p	b_1	b_2
Group I : GR	0.726	0.345	0.301	-0.501
Group I : F4	0.671	0.361	0.120	-0.435
Group I : F5	0.765	0.321	0.211	-0.470
Group I : F6	0.670	0.362	0.230	-0.449
Group I : N1	0.701	0.369	0.224	-0.661
Group I : N5	0.702	0.357	0.268	-0.503
Group II : GR Low	0.674	0.362	0.345	-0.183
Group II : GR Mid.	0.728	0.342	0.925	-0.05
Group II : GR High	0.806	0.594	1.720	1.900
Group II : F5 Low	0.733	0.314	0.295	-0.170
Group II : F5 Mid.	0.788	0.282	0.909	-0.033
Group II : F5 High	0.746	0.305	1.491	0.416

Environmental averaging



Valogiannis & Bean (2019)

2-point correlation function results

Theory:

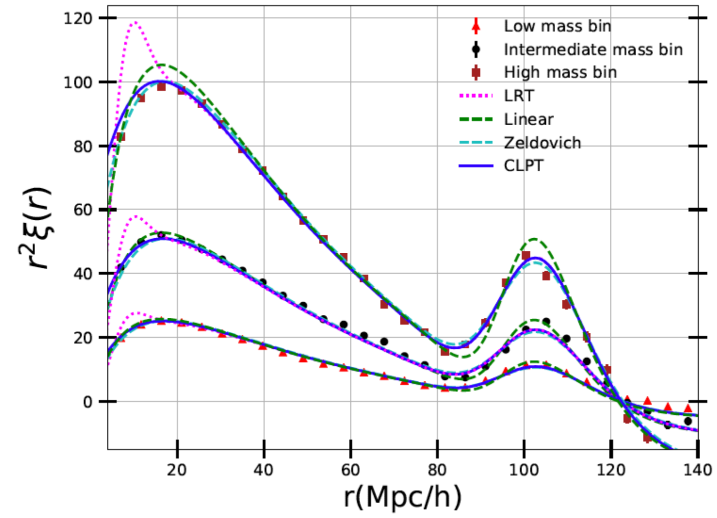
- f(R) (chameleon)
  Hu-Sawicki, 2007

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

N-body simulations:

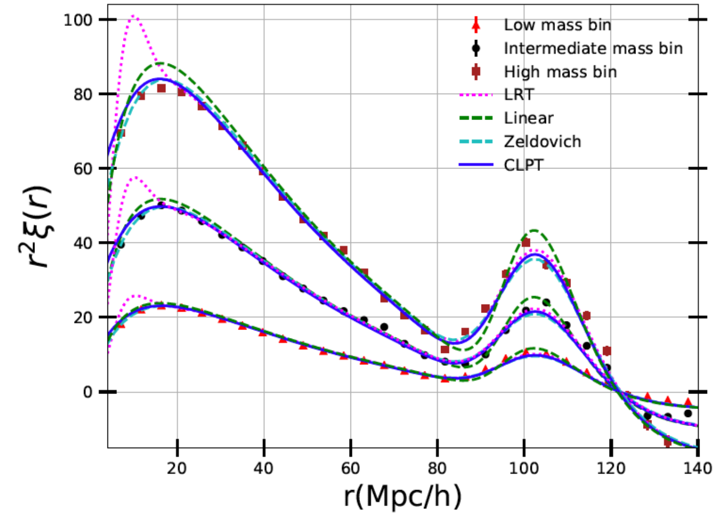
- f(R) Lightcone project:
  - z=1, L=1536 Mpc/h
  - 3 mass bins
  - C. Arnold et al. (2018)

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



GR

CLPT matches N-body data across mass bins

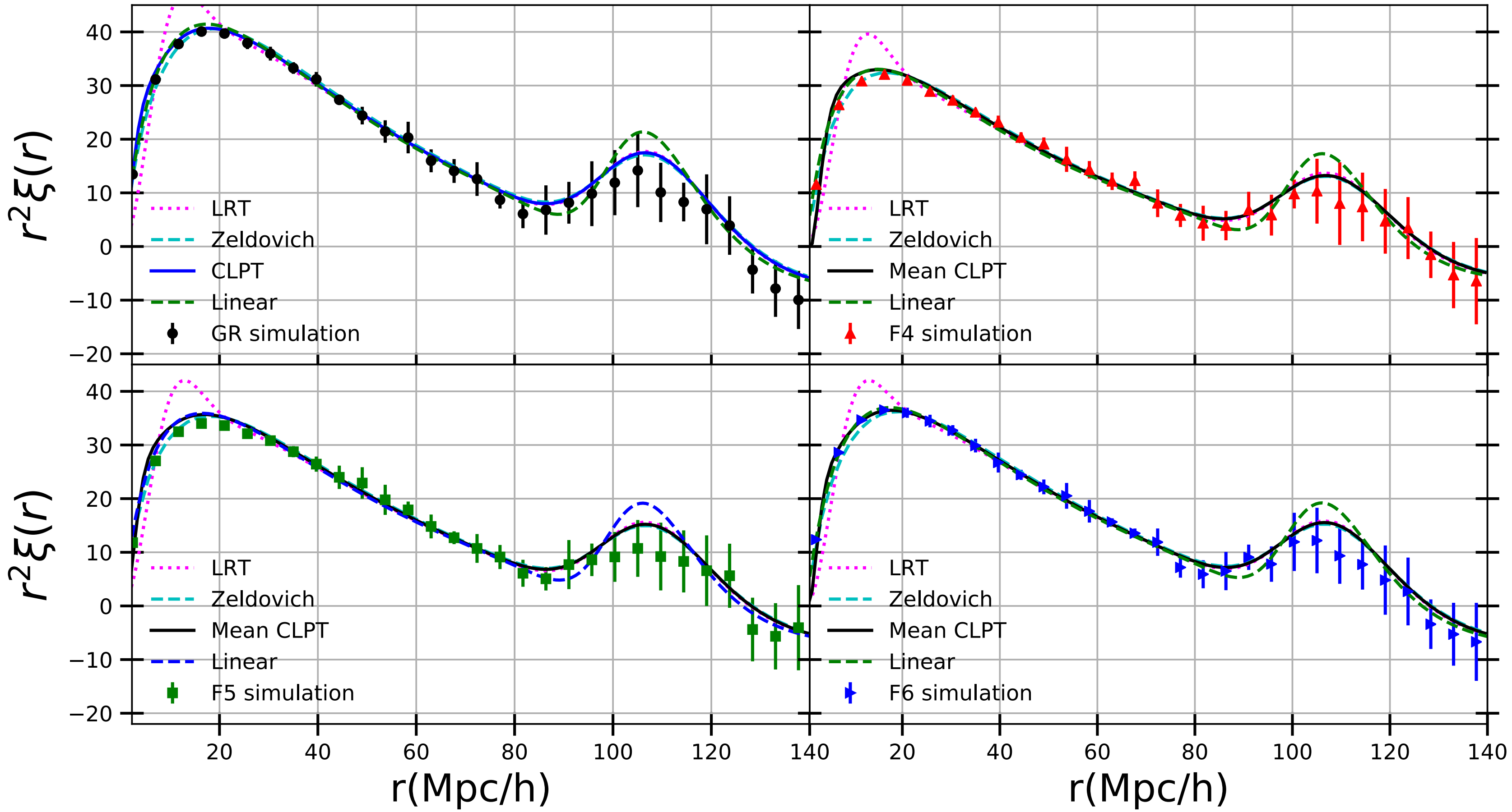


F5

Valogiannis & Bean (2019)

2-point correlation function results

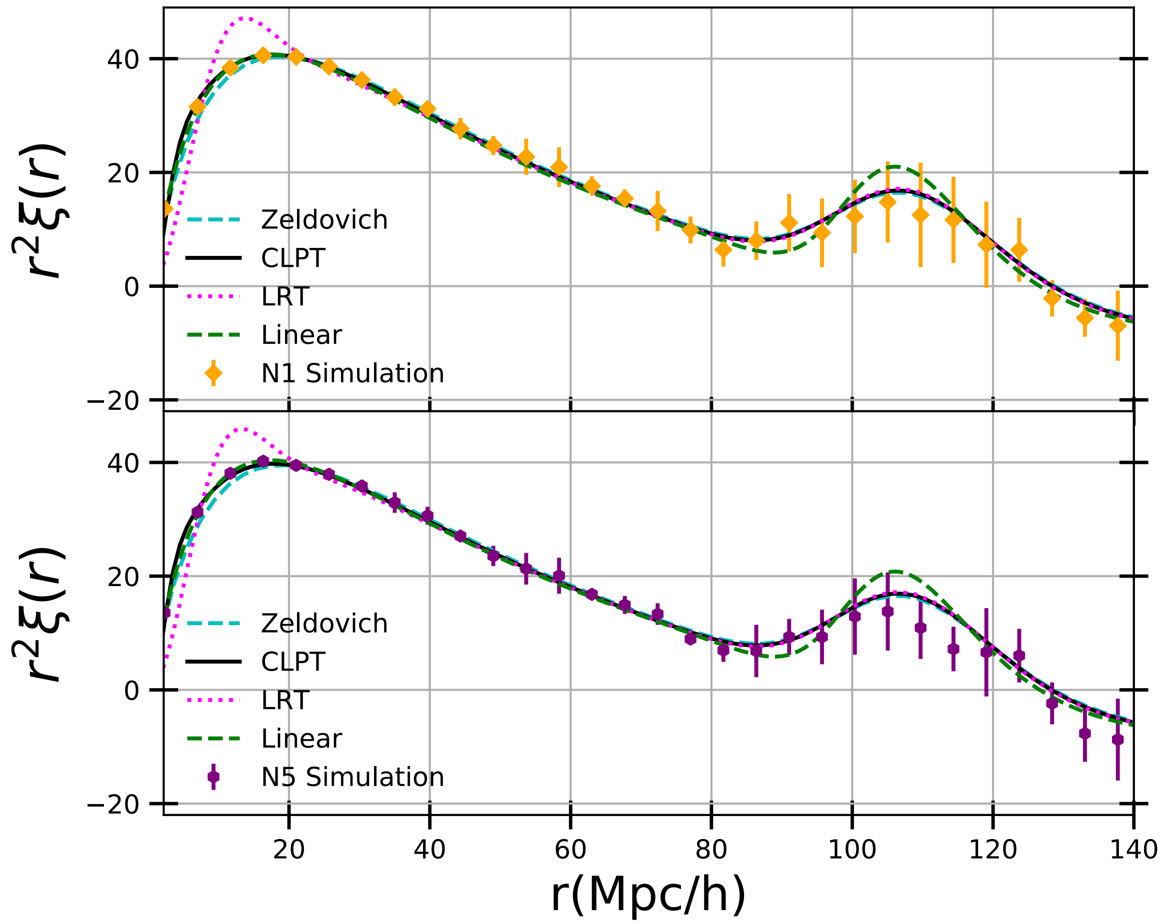
- Consistency for varying degrees of f(R) screening z=0.5 !



Valogiannis & Bean (2019)

2-point correlation function results

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

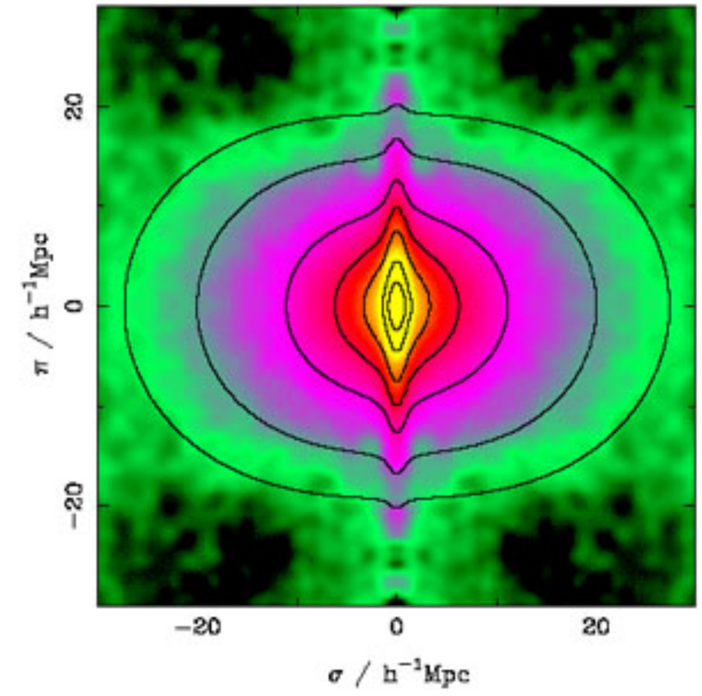


Valogiannis & Bean (2019)

Testing MG models in redshift-space

Redshift space distortions

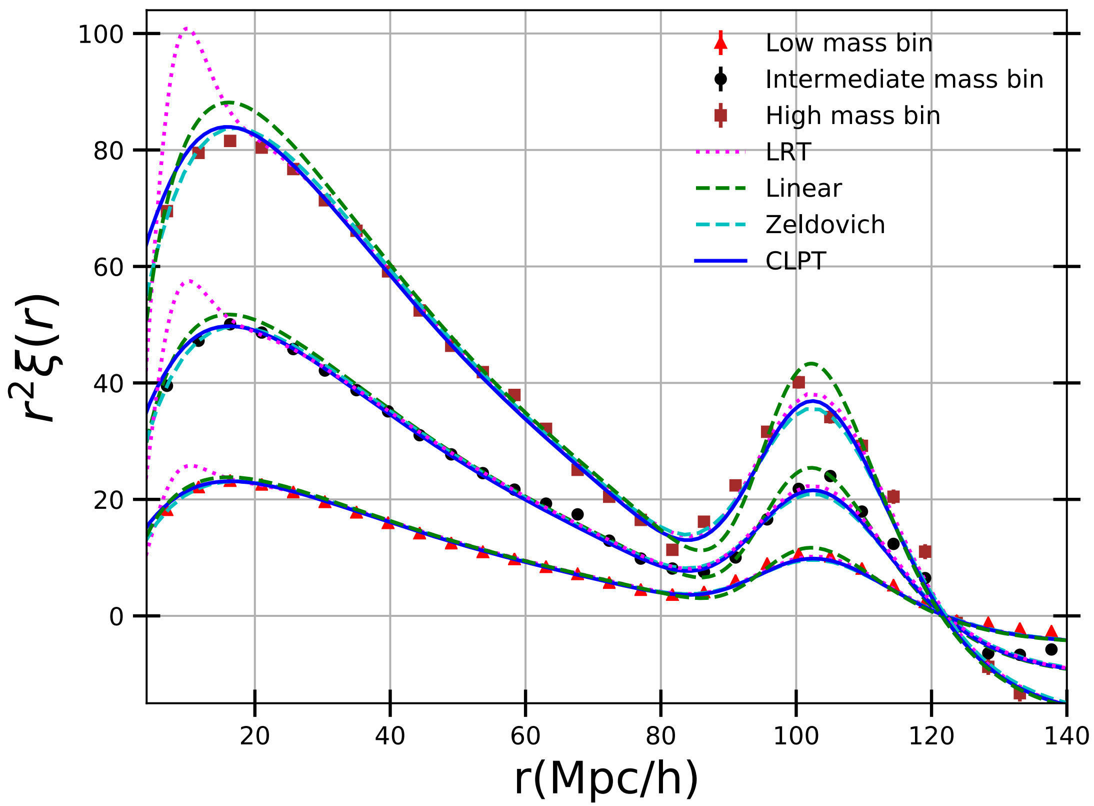
- Spectroscopic surveys observe *galaxies*:
  - **biased tracers** (galaxy clustering in different environments) = Lagrangian bias in MG (1901.03763)
  - **Redshift Space Distortions =** Gaussian streaming model (GSM) (paper in prep)



Peacock et al. 2001

Necessary ingredients to model RSD in MG

- Nonlinear evolution of DM field in MG
  - Lagrangian perturbation theory (LPT) ✓
    (*A. Aviles & J. L. Cervantes-Cota, 2017*)
- Halo bias in MG
  - Convolution LPT for biased tracers in MG ✓
    (*A. Aviles et al. 2018, Valogiannis & Bean 2019*)
  - Sheth–Tormen (ST) halo bias in MG ✓
    (*G. Valogiannis & R. Bean 2019*)



Valogiannis & Bean (2019)

Necessary ingredients to model RSD in MG

- Real-to-redshift space mapping ?
  - "Direct" Lagrangian mapping to redshift space ✗
- Plane-parallel approximation

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

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

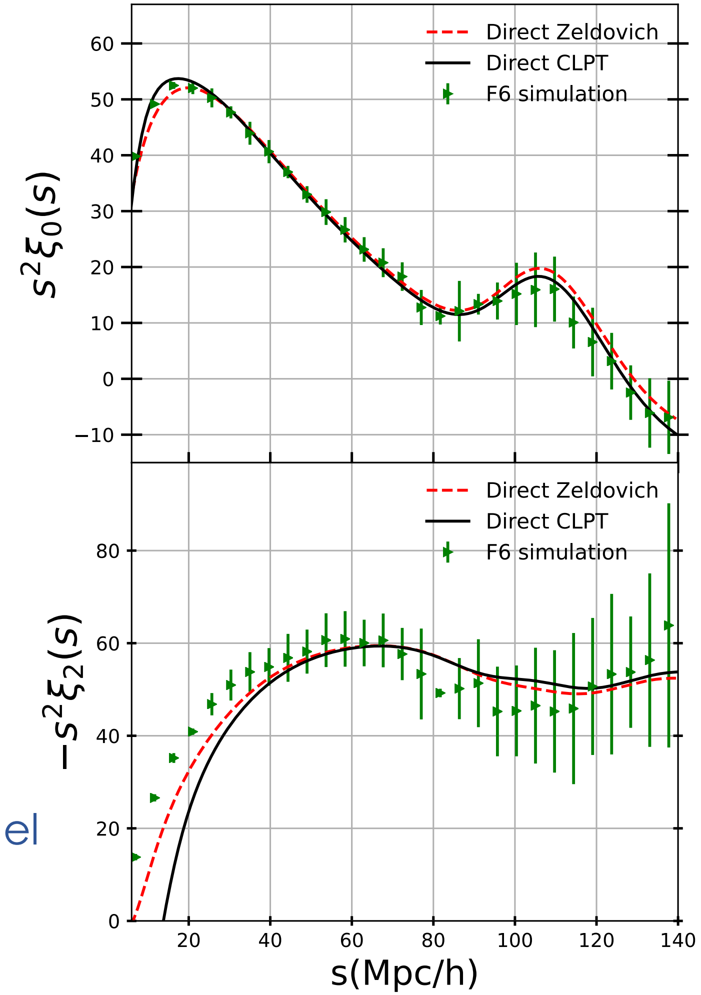
redshift real mapping

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

$l = 0$

$l = 2$

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



Valogiannis et al. (in prep.)

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

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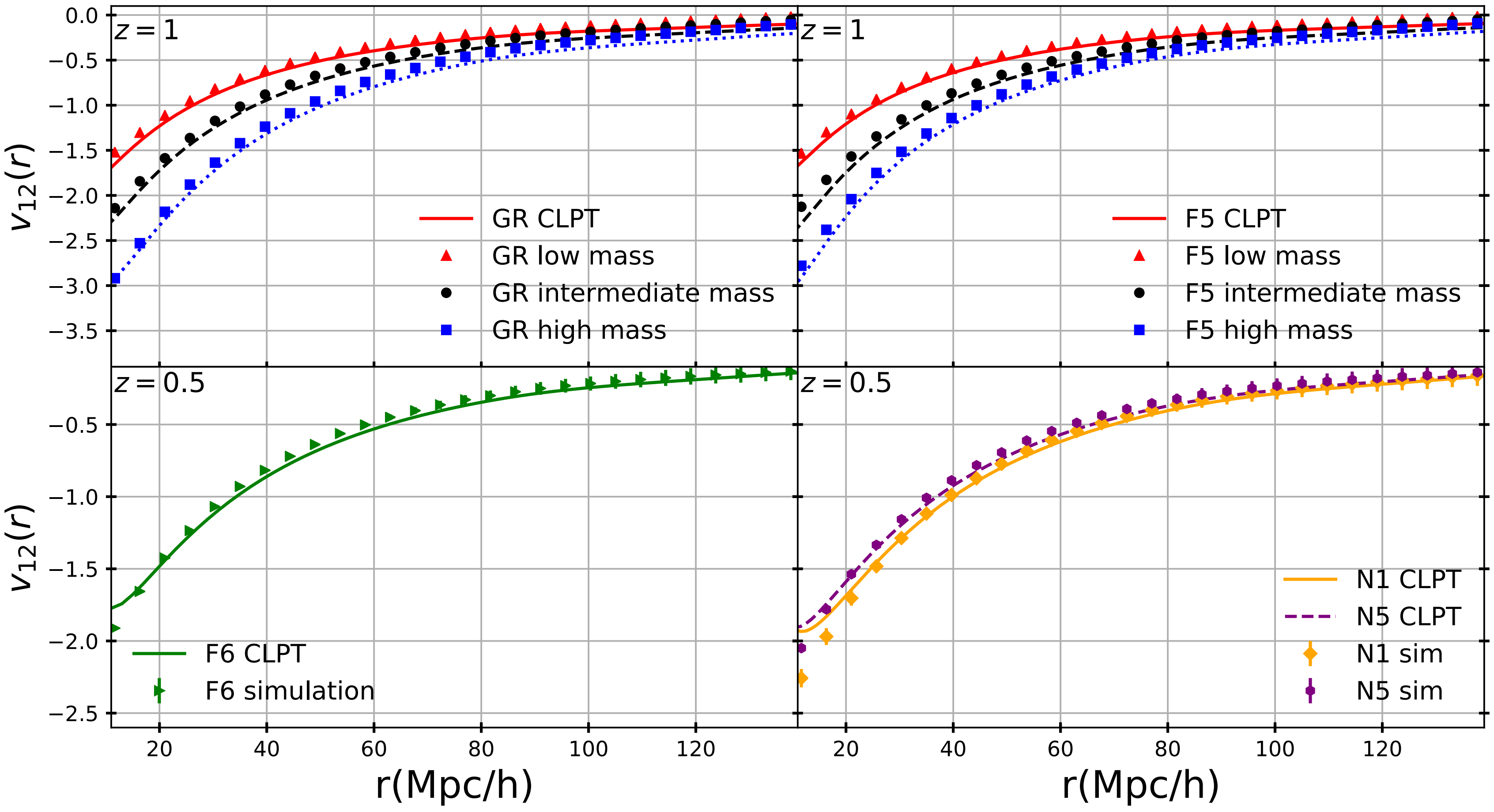
  - 1 mass bin
  - M. Cautun et al. (2017)

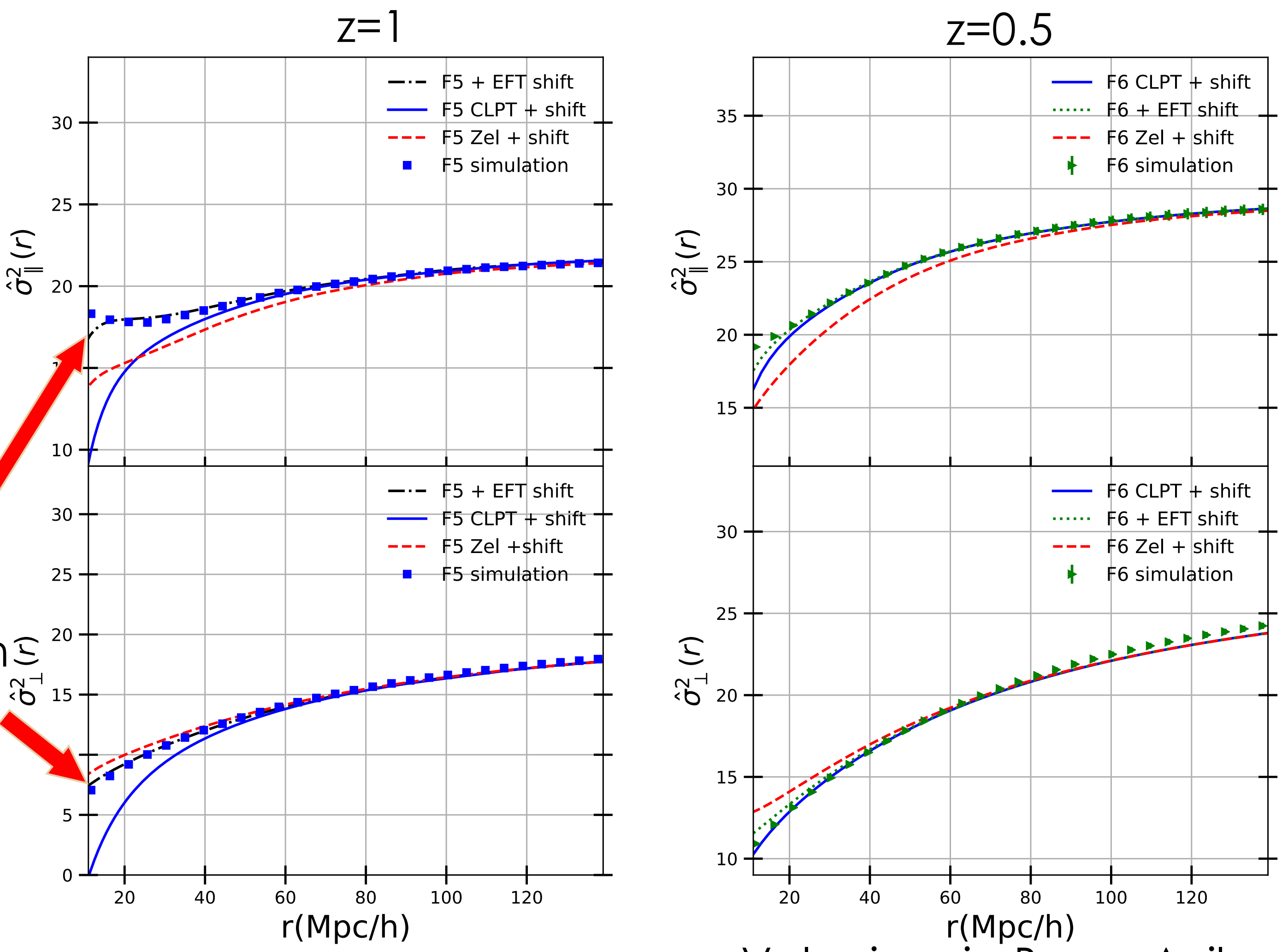


Valogiannis. Bean, Aviles
(in prep.)

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

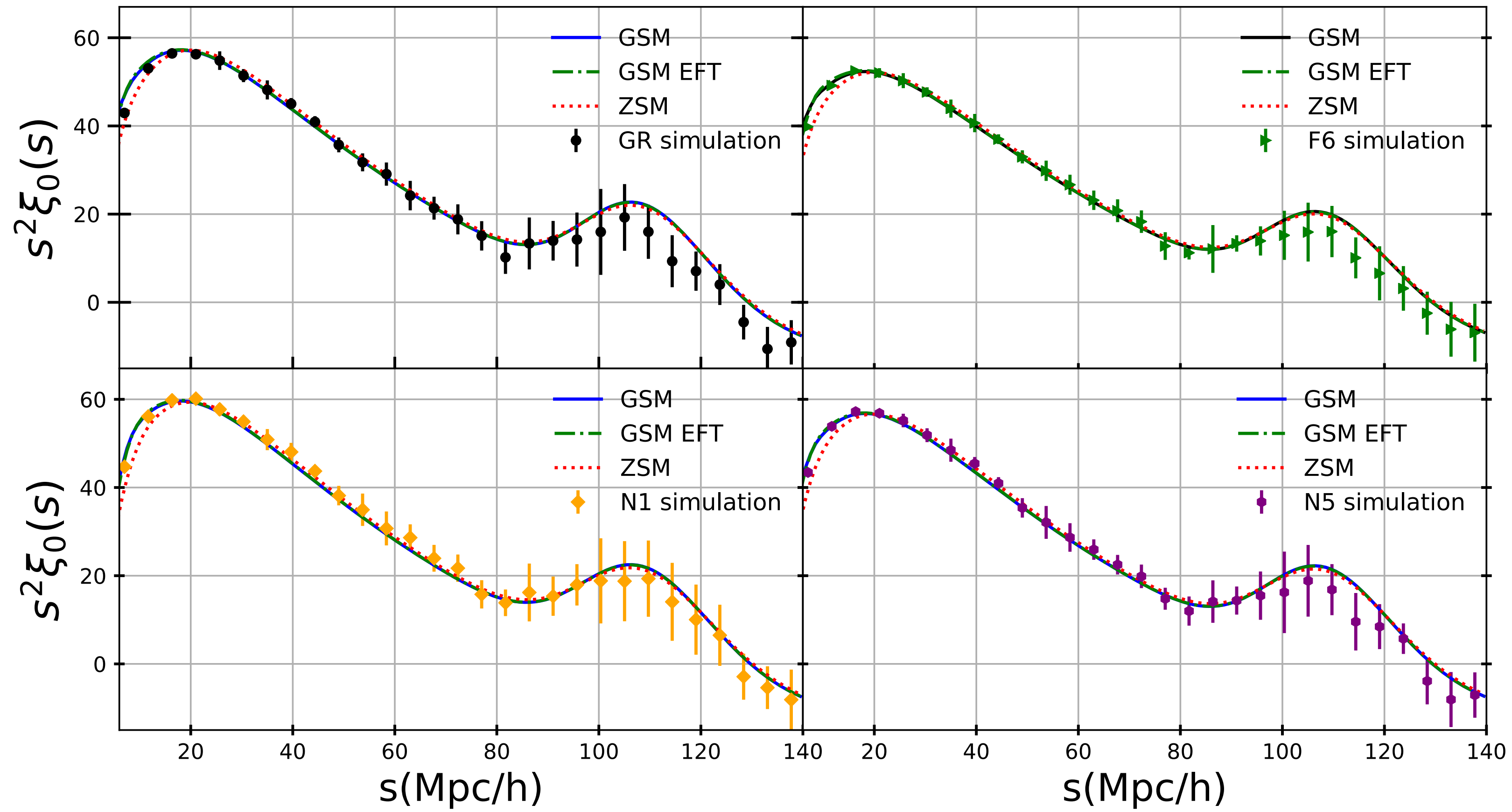


Valogiannis. Bean, Aviles (in prep.)

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

Accurate monopole predictions across MG models

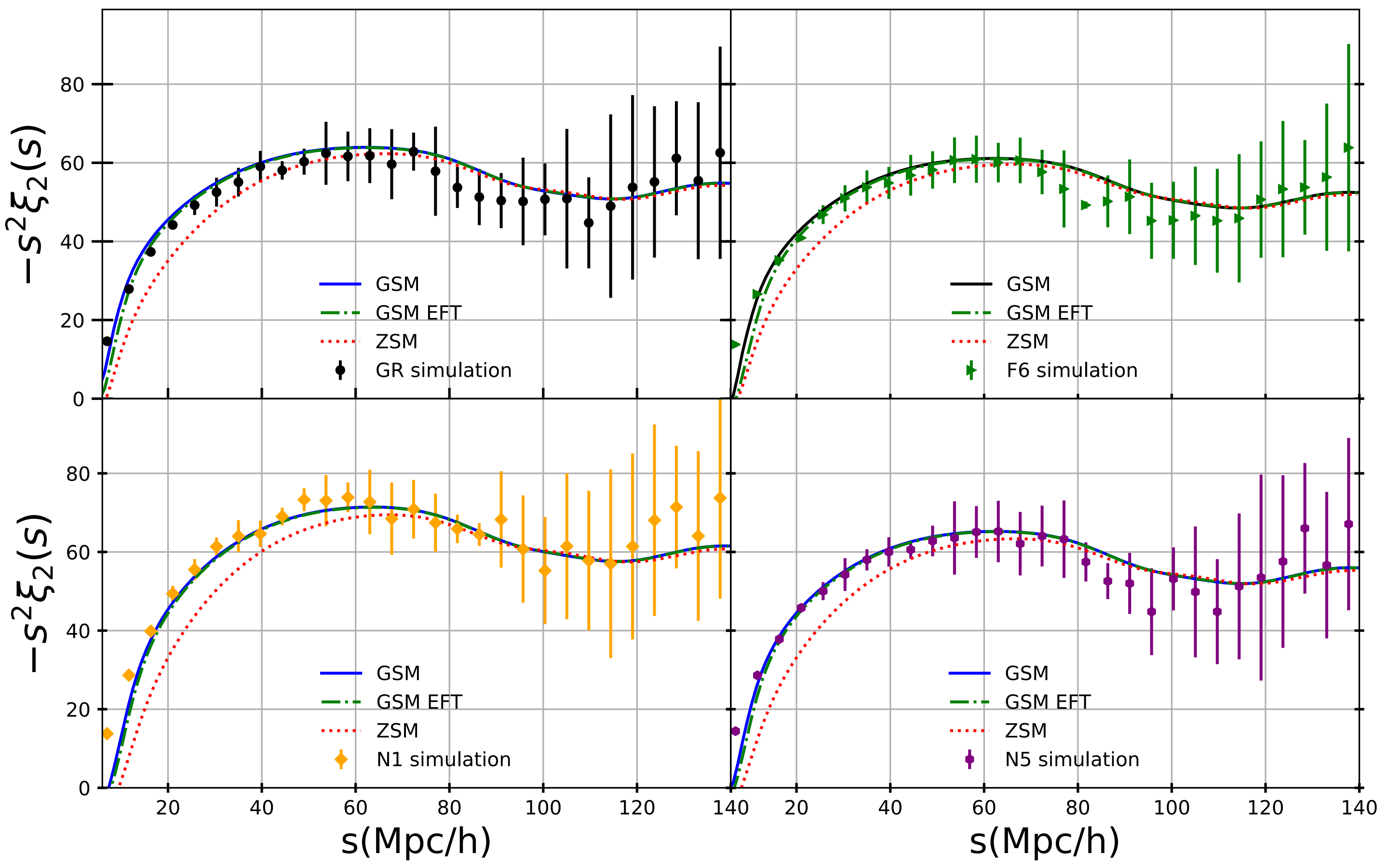
z=0.5



Valogiannis. Bean, Aviles
(in prep.)

Accurate quadrupole predictions across MG models

z=0.5

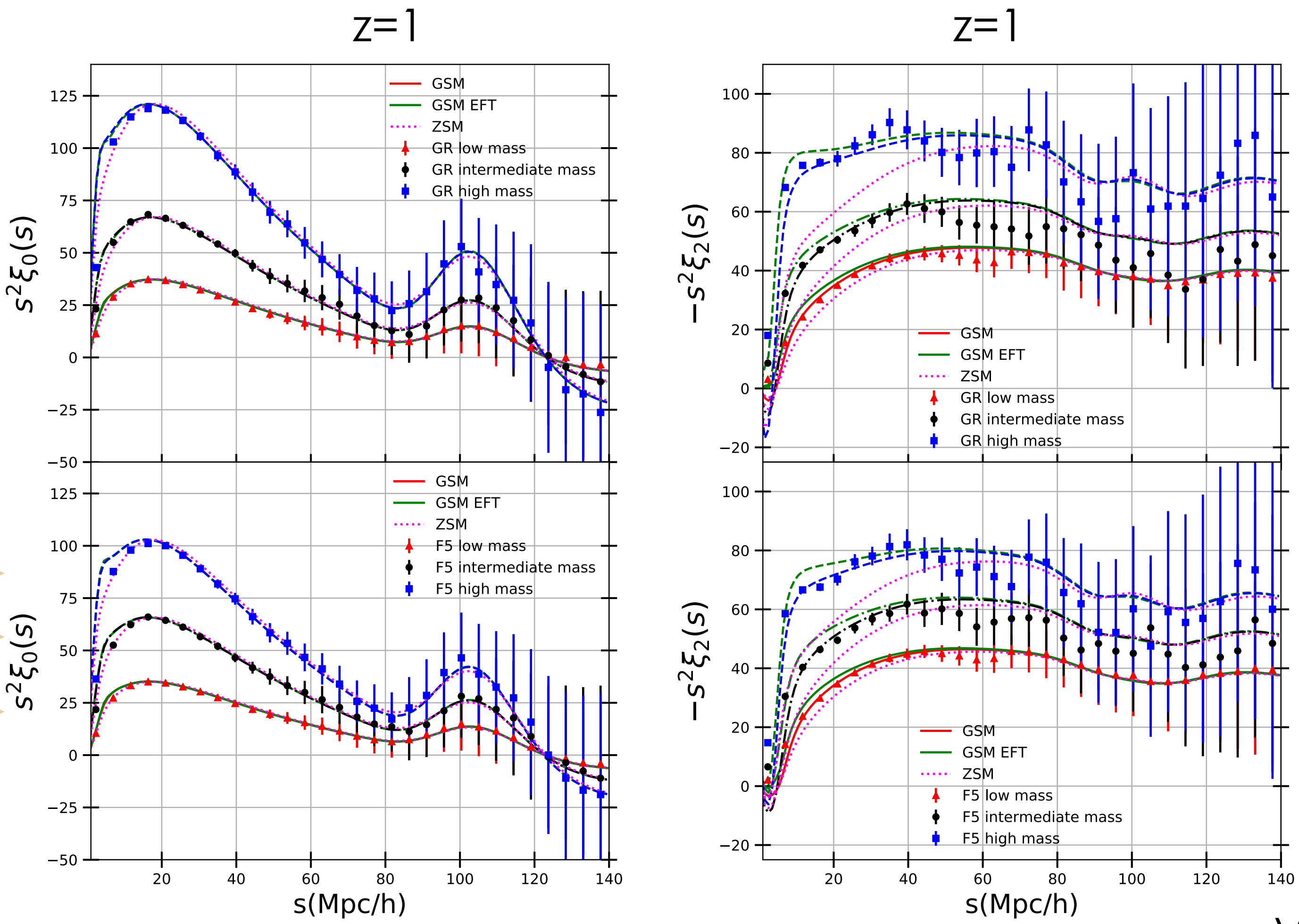


Valogiannis. Bean, Aviles
(in prep.)

Accurate predictions across different mass bins

Accurate bias predictions!

3 halo-mass bins

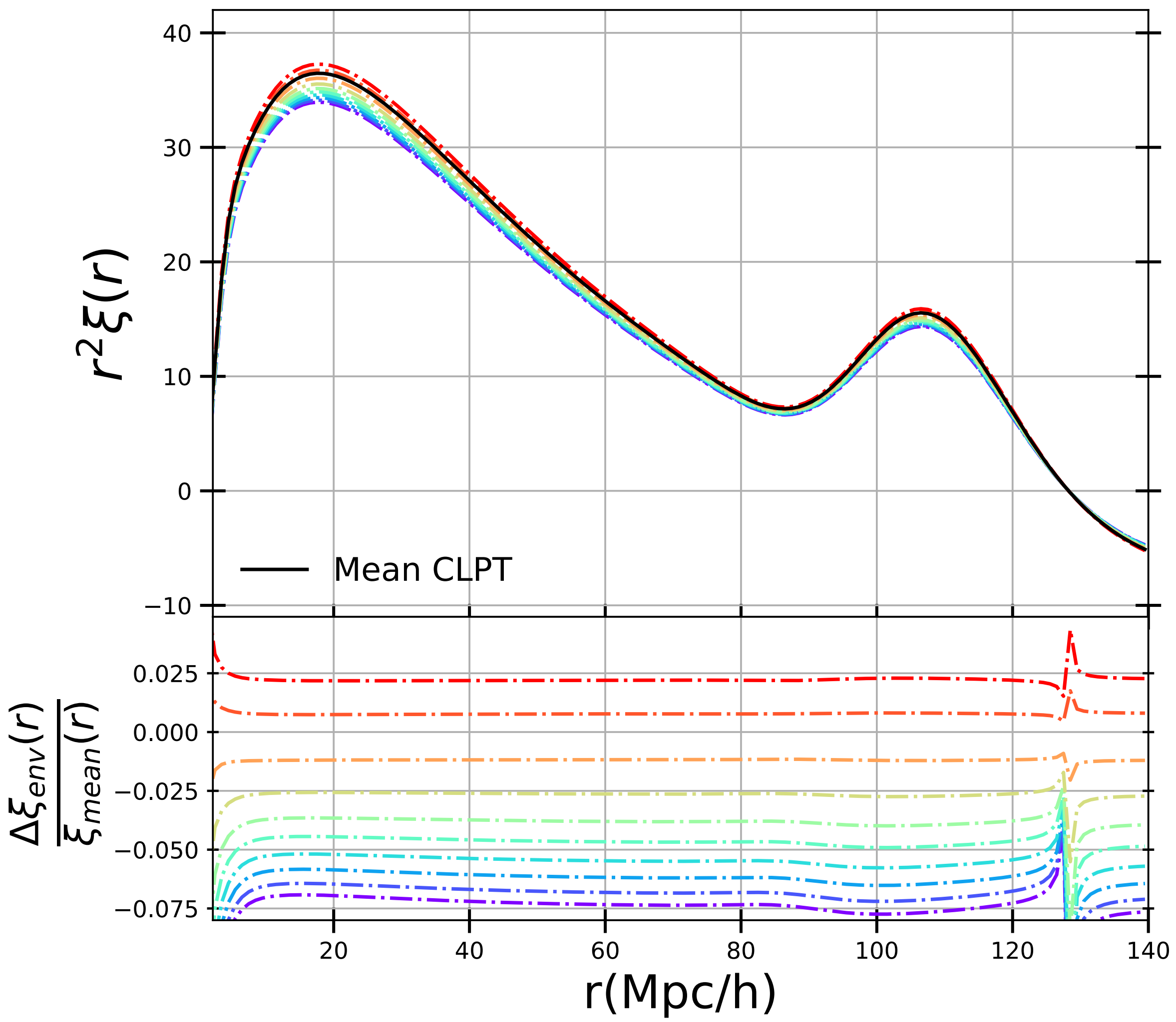


Valogiannis. Bean, Aviles (in prep.)

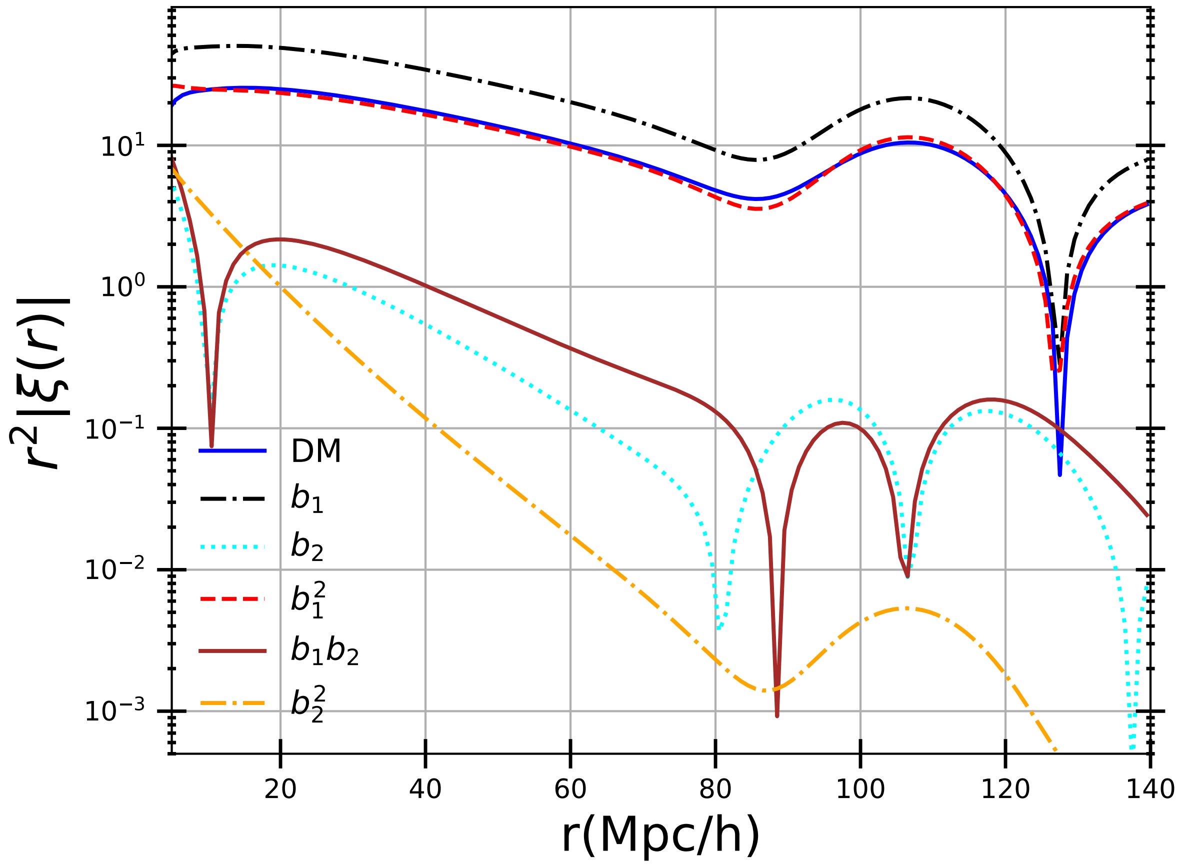
Summary

- Hybrid COLA scheme for efficient MG simulations
  - Valogiannis & Bean, 2017 , arXiv:1612.06469, Phys. Rev. D 95, 103515
  - Ideal for emulators (in progress)
- Novel statistics to detect MG signals
  - Valogiannis & Bean, 2018 , arXiv:1708.05652, Phys. Rev. D 97, 023535
  - Testing the theory of gravity with DESI: estimators, predictions and simulation requirements (in progress)
- Modeling 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
  - Prepared for submission
  - Bias & RSD **simultaneously** modeled in MG for the first time!

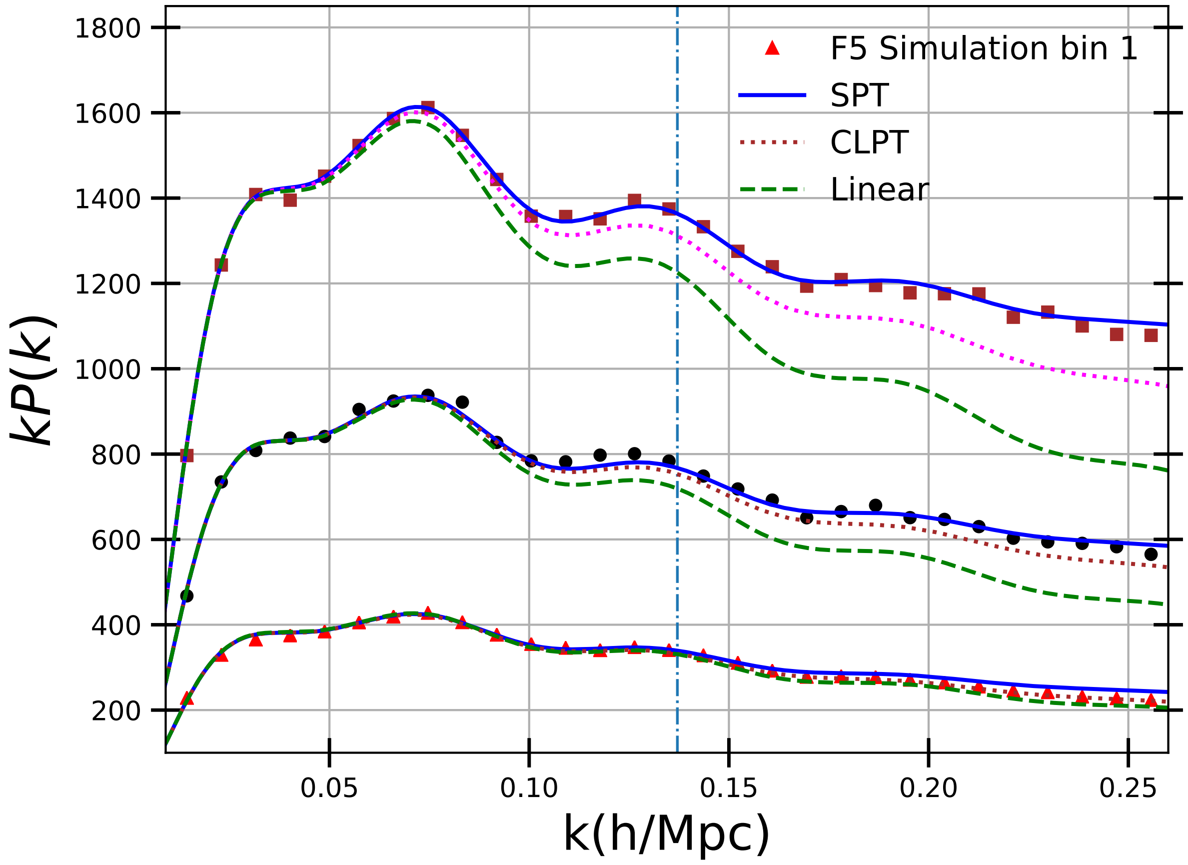
Thank you!



40
30
20
10
0
−10
$r^2\xi(r)$
Mean CLPT
0.025
0.000
−0.025
−0.050
−0.075
$\frac{\Delta\xi_{env}(r)}{\xi_{mean}(r)}$
20
40
60
80
100
120
140
r(Mpc/h)



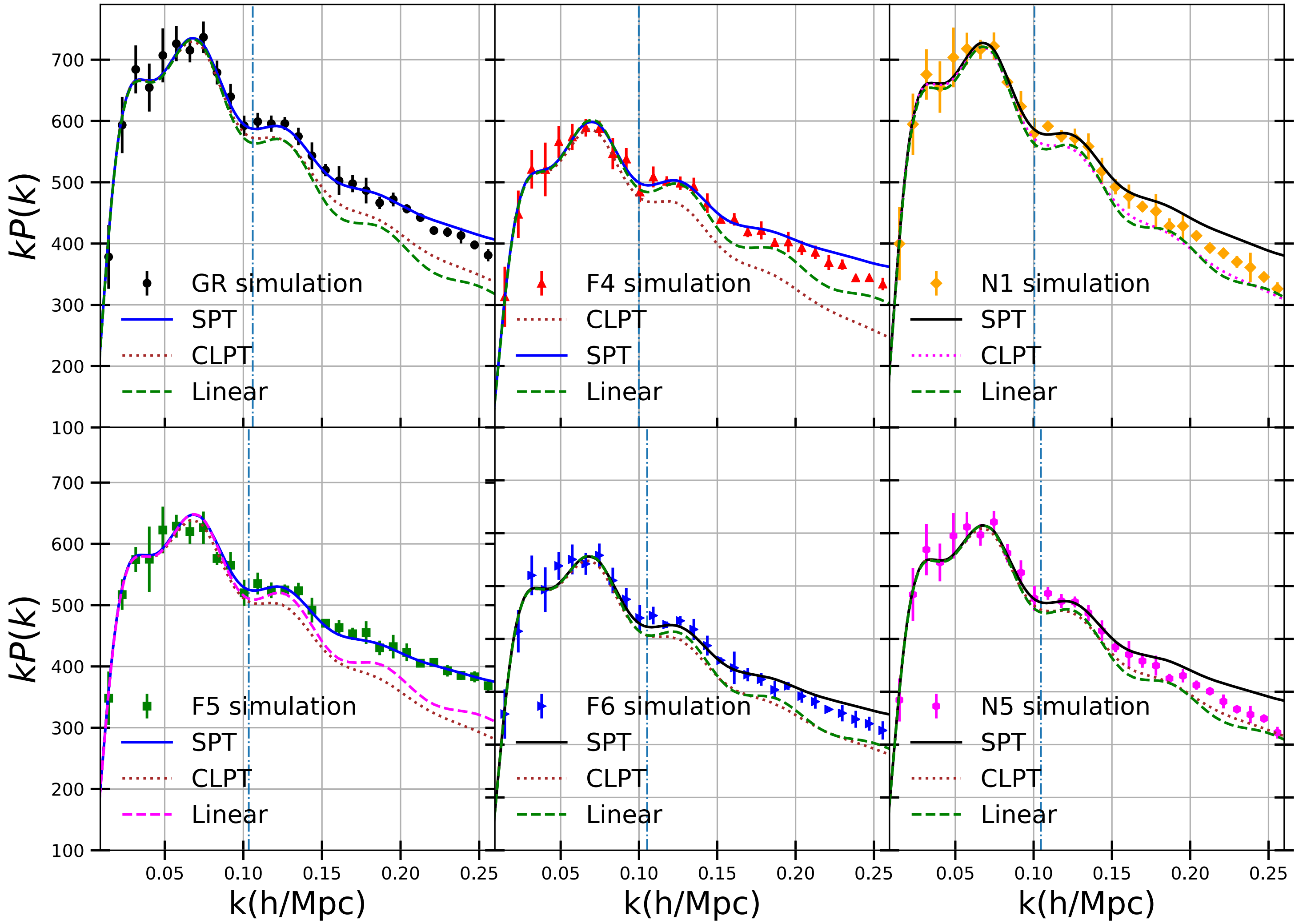
$r^2|\xi(r)|$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
40
60
80
100
120
140
r(Mpc/h)
DM
b_1
b_2
b_1^2
$b_1 b_2$
b_2^2



F5 Simulation bin 1
SPT
CLPT
Linear
1800
1600
1400
1200
1000
800
600
400
200
0.05
0.10
0.15
0.20
0.25
kP(k)
k(h/Mpc)

Power spectrum results

- Eulerian SPT expansion accurate



Valogiannis & Bean (2019)

Gravitational collapse in MG

$[-1(\text{purple}), -0.72, -0.43, -0.15, 0.13, 0.42, 0.7, 0.98, 1.27, 1.55(\text{red})]$

- Density 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
- Collapsing halo-overdensity $1 + \delta_h = y_h^{-3}$
- In MG

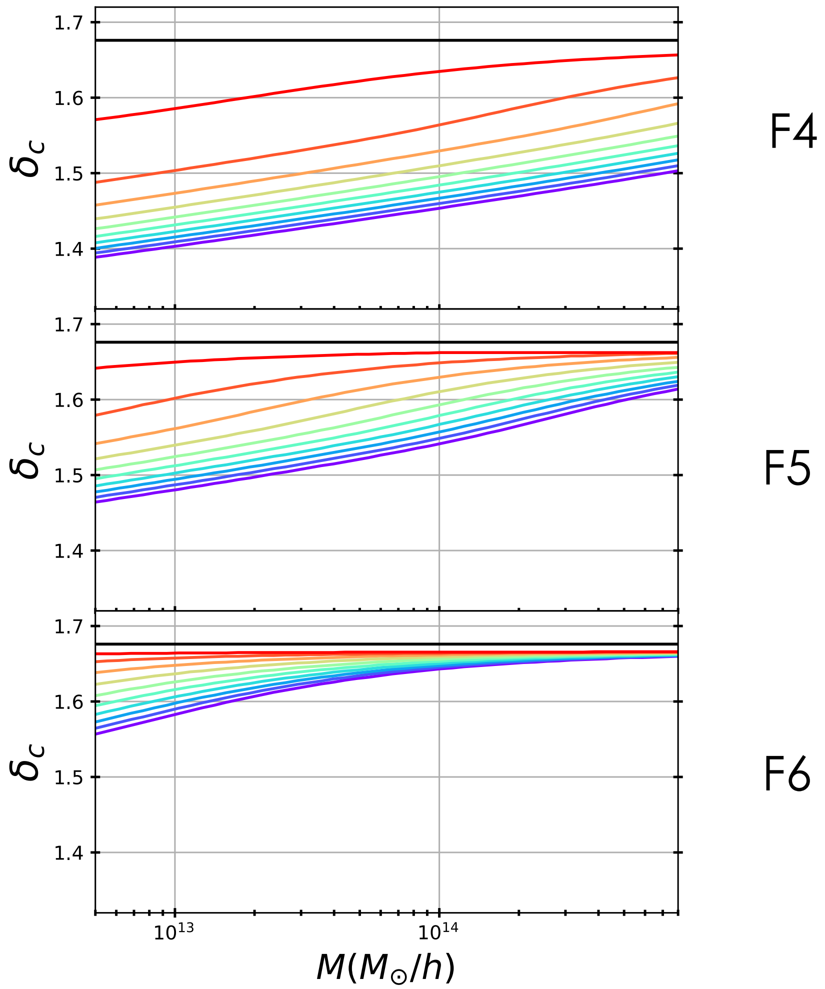
$$y_h'' - \left(2 - \frac{3}{2}\Omega(a)\right) y_h' + \frac{1}{2}\Omega(a)\frac{G_{eff}}{G}\left(y_h^{-3} - 1\right) y_h = 0$$

$$G_{eff} = (1 + E)\, G$$

- Chameleons

$$E = 2\beta^2 \left[3\frac{\Delta R}{R_{th}} - 3\left(\frac{\Delta R}{R_{th}}\right)^2 + \left(\frac{\Delta R}{R_{th}}\right)^3\right]$$

"Thin shell"



f(R), Valogiannis & Bean (2019)

$$\frac{\Delta R}{R_{th}} = \frac{|f_{R0}|a^3}{\Omega_m y_h^{-3} H_0^2 R_{th}^2}$$
$$\times \left[\left(\frac{1 + 4\frac{\Omega_\Lambda}{\Omega_m}}{(y_{env}a)^{-3} + 4\frac{\Omega_\Lambda}{\Omega_m}} \right)^{n+1} - \left(\frac{1 + 4\frac{\Omega_\Lambda}{\Omega_m}}{(y_h a)^{-3} + 4\frac{\Omega_\Lambda}{\Omega_m}} \right)^{n+1} \right]$$

$$E = \frac{2}{3\beta(a)} \frac{\sqrt{1 + \chi^3} - 1}{\chi^{-3}}$$

$$\chi^{-3} = \frac{\Omega_m n^2}{1.10894 a^3 \beta^2(a)} \frac{y_h^3 - 1}{y_h^3}$$

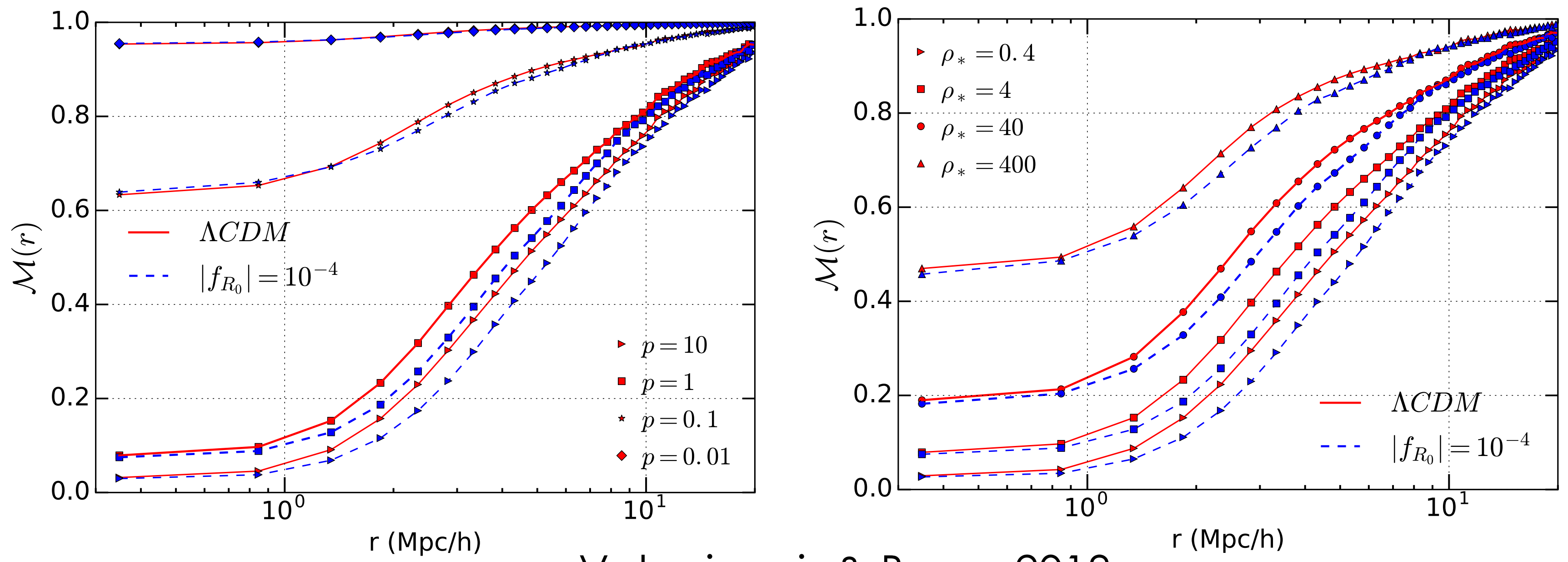
DESI-related work

- Dark matter-only simulations shed light on underlying gravitational physics
- Realistic surveys do **not** trace dark matter
    - Dark matter halos
    - Biased tracers
- Test marked statistics on realistic applications – DESI MG white paper (in prep)
- ELEPHANT simulations (M. Cautun et al., 2017): Simulation box side L=1024 Mpc/h, 1024^3 particles
- ΛCDM, f(R) and nDGP MG models
- Vainshtein Mechanism in nDGP (G. Dvali et al., 2000)
- Dark matter halo-finding
- Biased tracers (galaxies) – Halo Occupation Distribution (HOD)

Marked correlation function

- Screening mechanism produces unique density dependent signature
- What other density-dependent statistics?
- Marked correlation function (Sheth, R.K., Connolly, A.J., & Skibba, R. 2005)
- Real space statistic

$$\mathcal{M}(r) \equiv \frac{1}{n(r)\bar{m}^2} \sum_{ij} m_i m_j = \frac{1+W}{1+\xi}$$



Valogiannis & Bean, 2018

Summary and future work

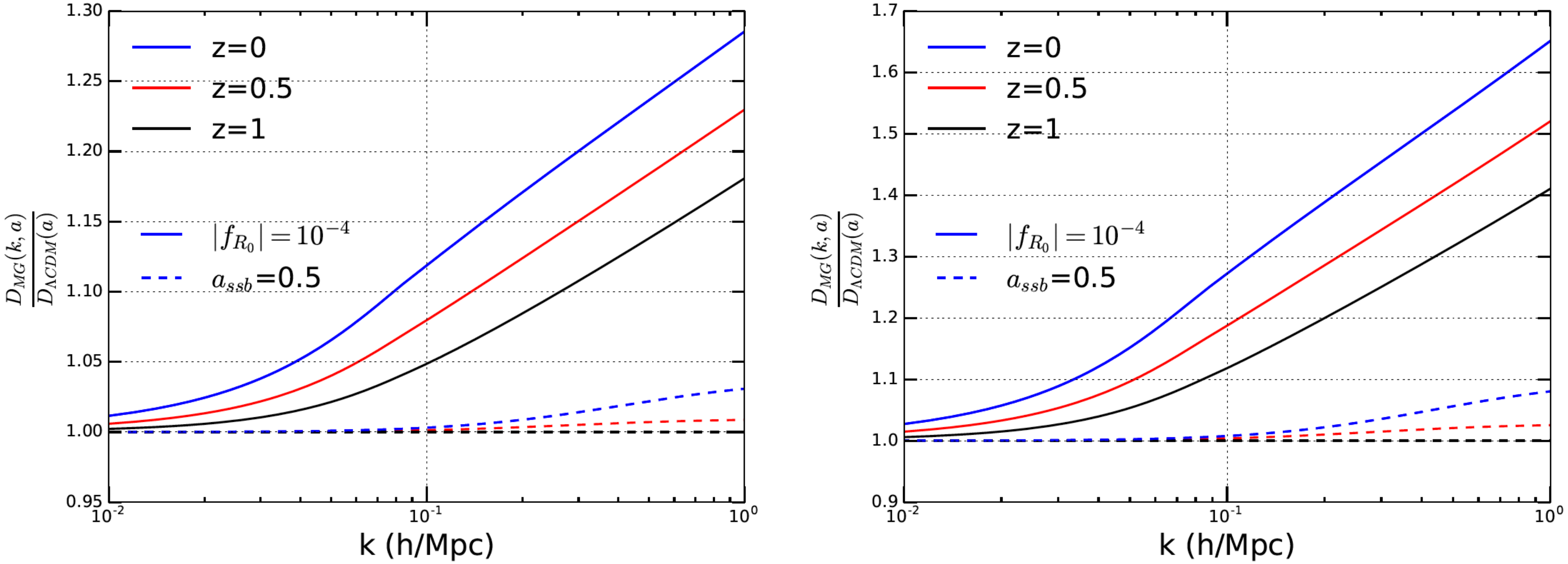
- Hybrid COLA scheme for efficient MG chameleon simulations
  - Phys. Rev. D 95, 103515 (2017)
- Simple, ”marked” density transformations serve as powerful tools for testing gravity
- Up-weight unscreened regions and down-weight high densities
  - Phys. Rev. D 97, 023535 (2018)
- “Testing the theory of gravity with DESI: estimators, predictions and simulation requirements” white paper in preparation
- C. H. Aguayo et al. (2018) & J. Armijo et al. (2018) on marks
- Further explore use of mark in the context of realistic observations
- Perturbation theory predictions for marked statistics

Conclusions and future work

- Simple, ”marked” density transformations serve as powerful tools for testing gravity
- Up-weight unscreened regions and down-weight high densities
- Enhance information encoded in 2-point statistics
- Marked correlation function for differentiating between MG and GR
- Phys. Rev. D 97, 023535 (2018)
- “Testing the theory of gravity with DESI: estimators, predictions and simulation requirements” white paper in preparation
- C. Hernandez Aguayo et al. (2018) & J. Armijo et al. (2018) on marks
- Further explore use of mark in the context of realistic observations
- Perturbation theory predictions for marked statistics

COLA simulations for MG: LPT component

- LPT growth factor becomes scale dependent



Valogiannis and Bean, Phys. Rev. D 95, 103515 (2017)

Features of marked correlation function

- In lower-density, unscreened regions, modifications significant
- In MG, *dark matter* particles in voids get pulled outwards faster
- Voids emptier in MG for **dark matter** $\rightarrow M_{GR} > M_{MG}$
- However, due to stronger gravity, **more** halos/galaxies form in voids
- As a result, for **halo/galaxy** marks $\rightarrow M_{GR} < M_{MG}$
- HOD parameters tuned to match observations – deviations vanish
- Marks encoding additional information e.g. gravitational potential

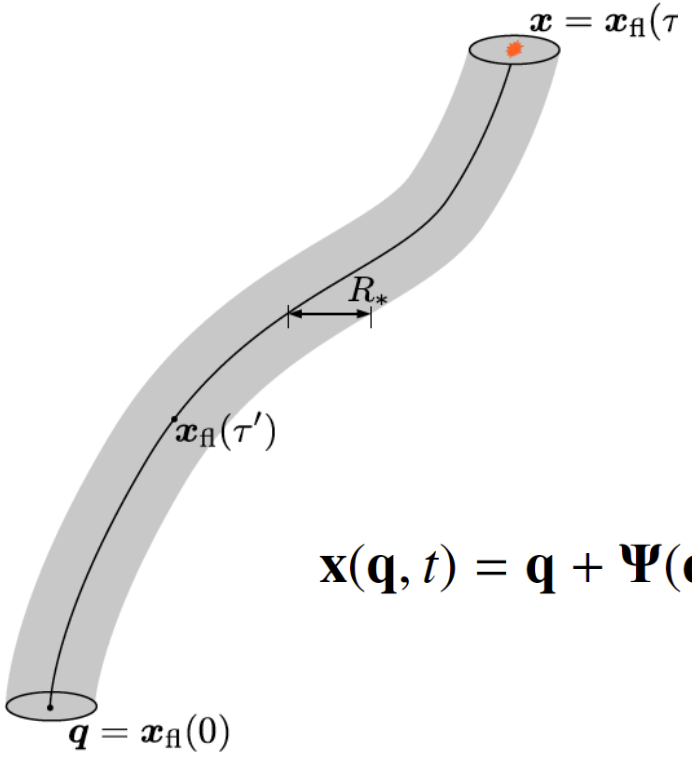
$$\mathcal{M}(r) \equiv \frac{1}{n(r)\bar{m}^2} \sum_{ij} m_i m_j = \frac{1+W}{1+\xi}$$

Necessary ingredients to model RSD in MG

- Nonlinear evolution of Dark Matter field in MG
- Halo bias modeling in MG
- Real-to-redshift space mapping in MG

Need to include
MG complications

- Modified, scale dependent growth rates
- Environment (density) dependent clustering
- Screening effects

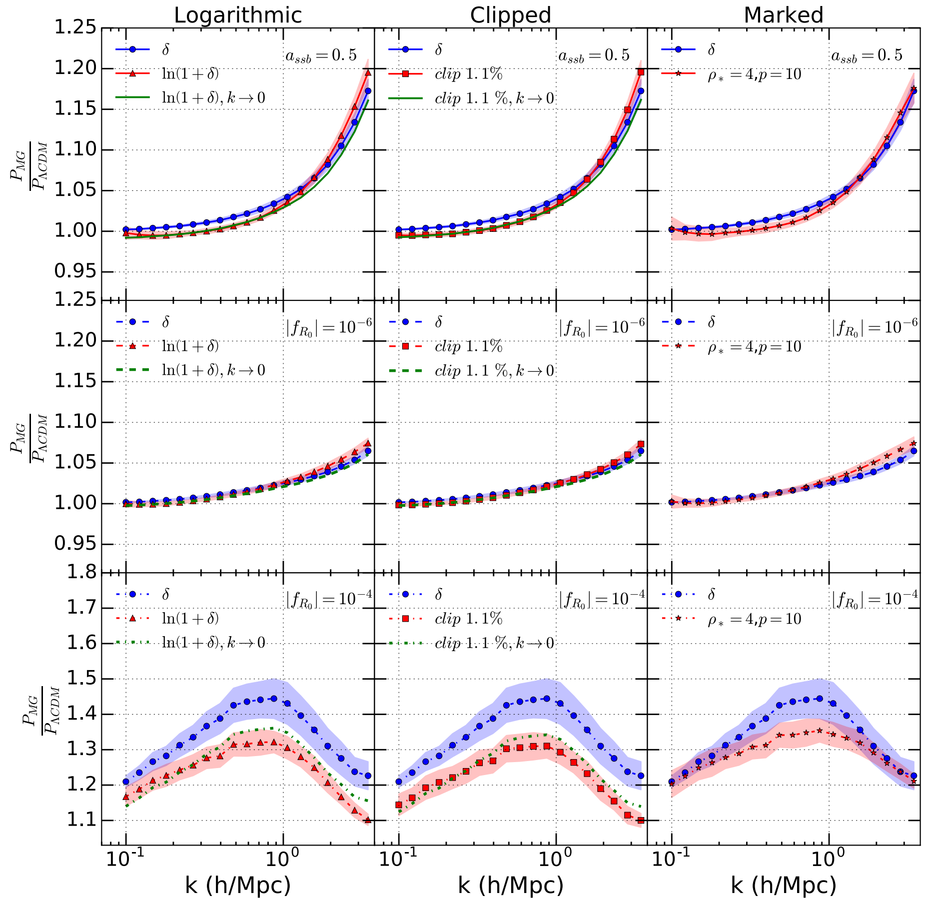


$$\mathbf{x}(\mathbf{q}, t) = \mathbf{q} + \boldsymbol{\Psi}(\mathbf{q}, t)$$

V. Desjacques et al. (2017)

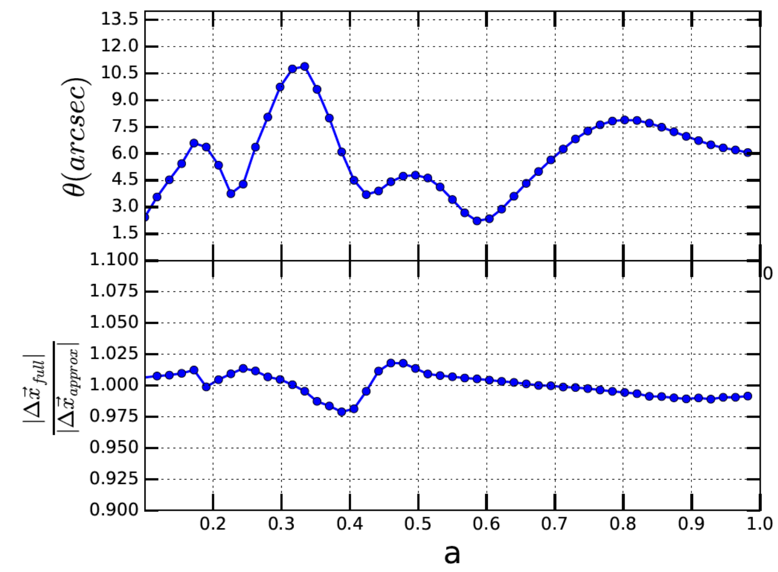
Power spectra

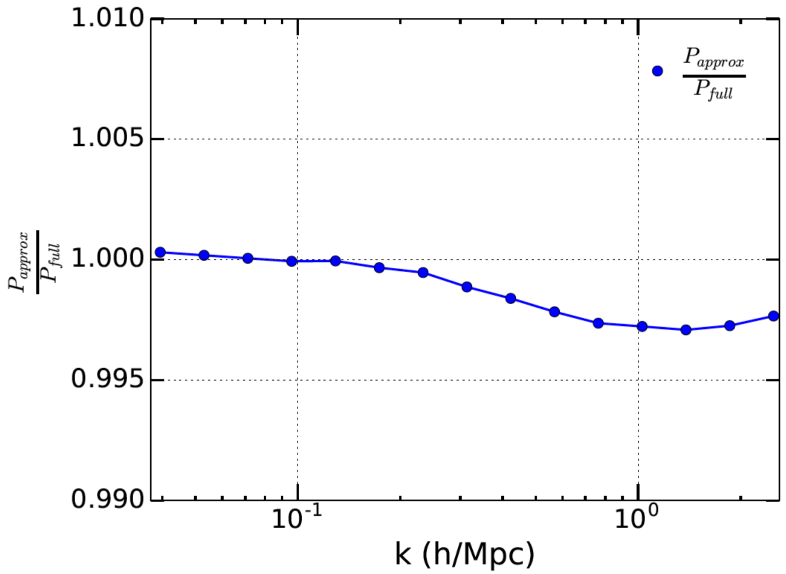
- MG deviations in power spectra enhanced in non-linear regime



Valogiannis & Bean, 2018

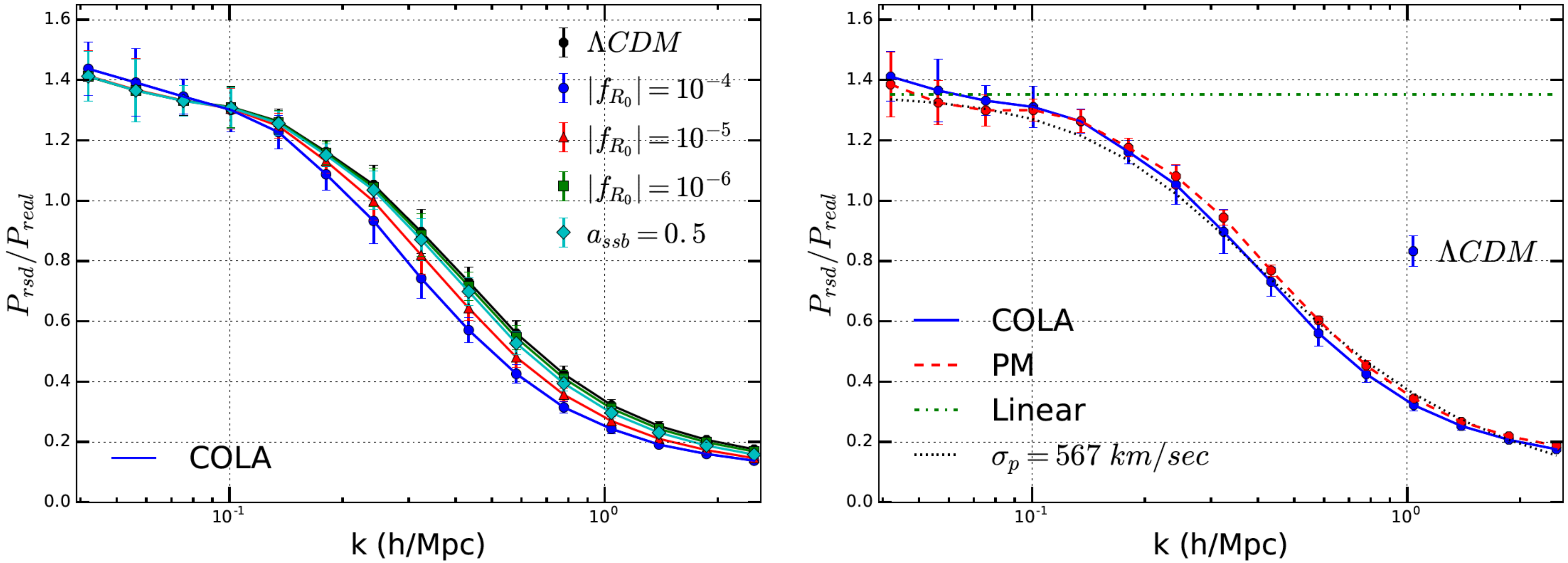
Solution: Scale dependent LPT growth negligible





Valogiannis and Bean, Phys. Rev. D 95, 103515 (2017)

Redshift Space Distortions



Valogiannis and Bean, Phys. Rev. D 95, 103515 (2017)

Chameleon mechanism generates density-dependent mass

- Scalar-tensor chameleon

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

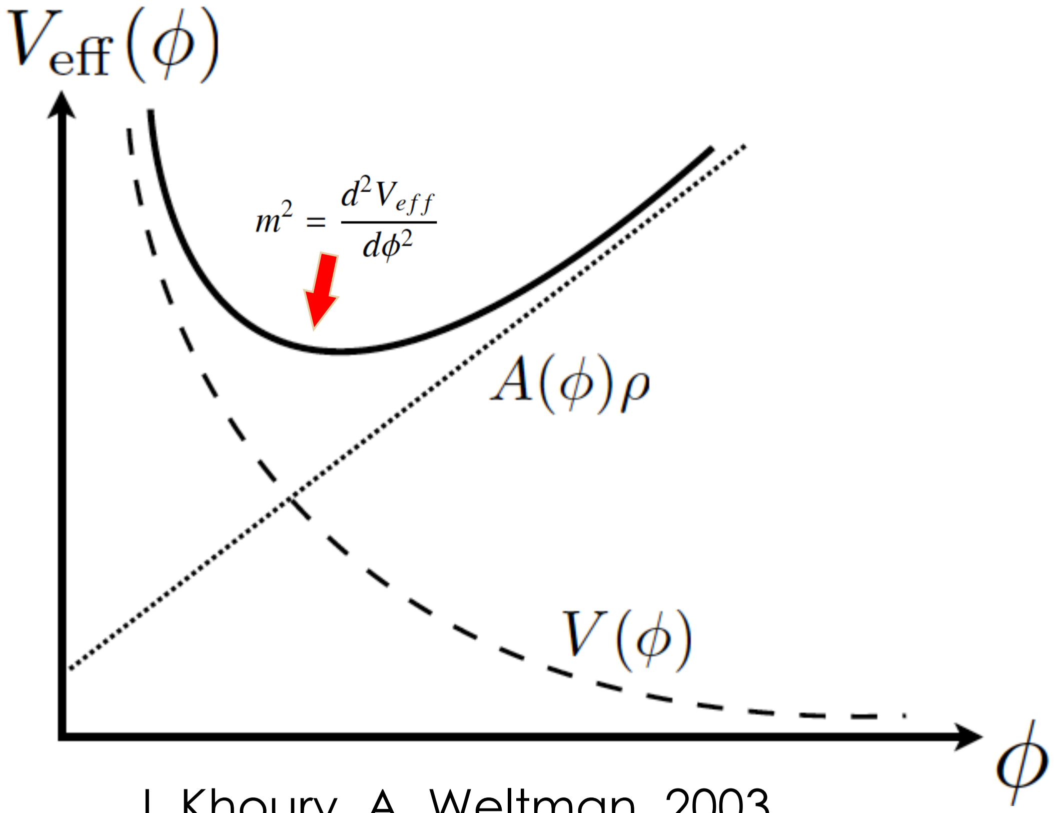
- Klein-Gordon equation for φ

$$\Box\phi = V_{eff,\phi}$$

- Effective potential

$$V_{eff} = V(\phi) + \frac{e^{\beta\phi/M_{pl}} \rho_m}{M_{Pl}}$$

runaway potential Coupling to matter



J. Khoury, A, Weltman, 2003

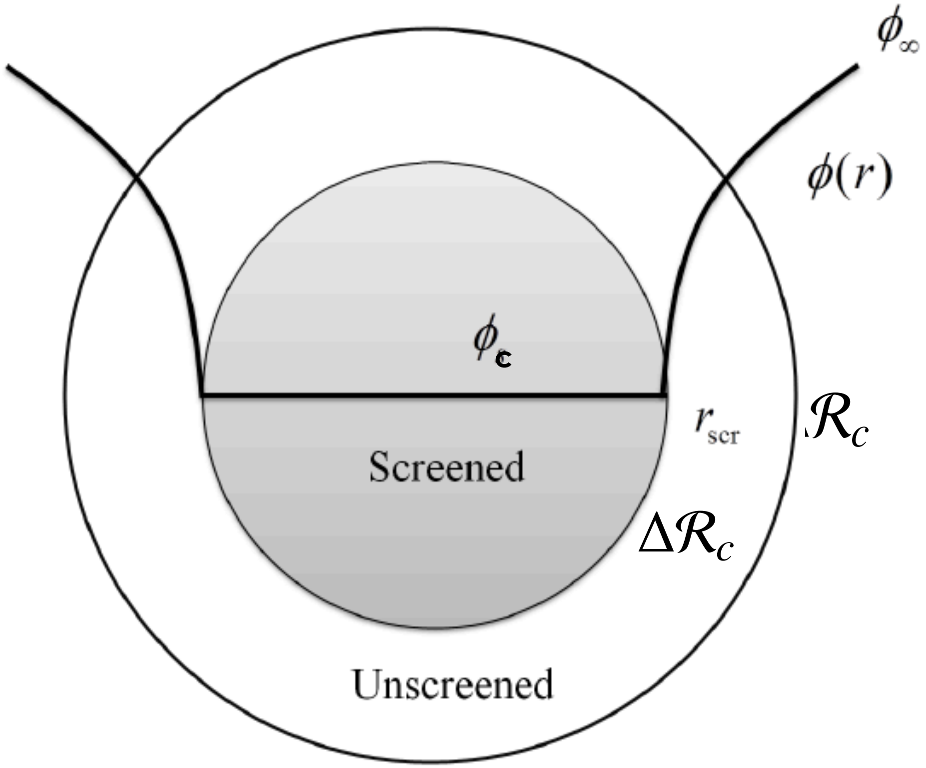
Fifth force phenomenology - thin shell effect

- In linear regime, no screening
- Fifth force in full effect

$$\frac{\Delta \mathcal{R}_c}{\mathcal{R}_c} > 1$$

$$F_\phi(r) \approx 2\beta_\infty^2 \frac{GM}{r^2}$$

J. Khoury, A, Weltman, 2003



- In dense regime interior mass decouples due to chameleon (Yukawa suppression)
- Effective coupled mass confined to a "thin shell"
- Fifth force screened $\frac{\Delta \mathcal{R}_c}{\mathcal{R}_c} = \frac{|\phi_\infty - \phi_c|}{2\beta_\infty M_{Pl}\Phi_N} \ll 1$

$$F_\phi(r) \approx 2\beta_\infty^2 \left(\frac{\Delta \mathcal{R}_c}{\mathcal{R}_c}\right) \frac{GM}{r^2}$$

Coupling "Thin Shell" Newton

Koyama 2015