Imprints of Modified Gravity Scenarios on the Inner Structure of Massive Dark Matter Halos

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Modified Gravity

Modified Einstein-Hilbert Action

$$S = \int d^4x\sqrt{-g}\,\frac{R + f(R)}{16\pi G}$$

- Departure from GR as source of cosmic acceleration
  - Reproduces observed cosmic expansion
  - Observationally viable

- Screening mechanism recovers GR at small scales

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- **Chameleon** Khoury & Weltman (2004)
- **Symmetron** Hinterbichler & Khoury (2010)
- **Vainshtein** Vainshtein (1972)

- Imprints on Cosmic Structures
  - Growth linear scales
  - Screening effects & non-linear regime

Screening Mechanism

Einstein Frame

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\nabla_\mu\varphi\nabla^\mu\varphi - V(\varphi)\right] + S_m(\psi^{(i)}, \tilde{g}_{\mu\nu}) \qquad \tilde{g}_{\mu\nu} = A^2(\varphi)g_{\mu\nu}$$

Scalar Fifth Force

$$\ddot{\boldsymbol{x}} + 2H\dot{\boldsymbol{x}} + \frac{1}{a^2}\nabla(\Phi + \log A) = 0 \longrightarrow$$

$$\mathbf{F}_{\text{Fifth}} = -\frac{m}{a^2}\nabla \log \mathrm{A}$$

$$\lambda_{\text{Fifth}} = \left(\frac{d^2V_{\text{eff}}}{d\varphi^2}\right)^{-1/2}$$

$$V_{\text{eff}}(\varphi) = V(\varphi) + \rho_m[A(\varphi) - 1]$$

Hu-Sawicki Gravity

Hu & Sawicki (2007)

$$f(R) = -m^2\frac{c_1\left(\frac{R}{m^2}\right)^n}{c_2\left(\frac{R}{m^2}\right)^n + 1} \longrightarrow$$

$$V(\varphi) = \frac{m_{Pl}^2}{2}\frac{f_R R - f}{(1 + f_R)^2}$$

$$A(\varphi) = e^{\beta\varphi/m_{Pl}}$$

$$\lambda_{\text{Fifth}} = \frac{\sqrt{|f_{R0}|(n+1)}}{H_0}\left(\frac{\Omega_m + 4\Omega_\Lambda}{\Delta_m + 4\Omega_\Lambda}\right)^{1+\frac{n}{2}}$$

- Depends on f(R) parameters (f_{R0}, n) and local density of matter
- Screened in high density regions

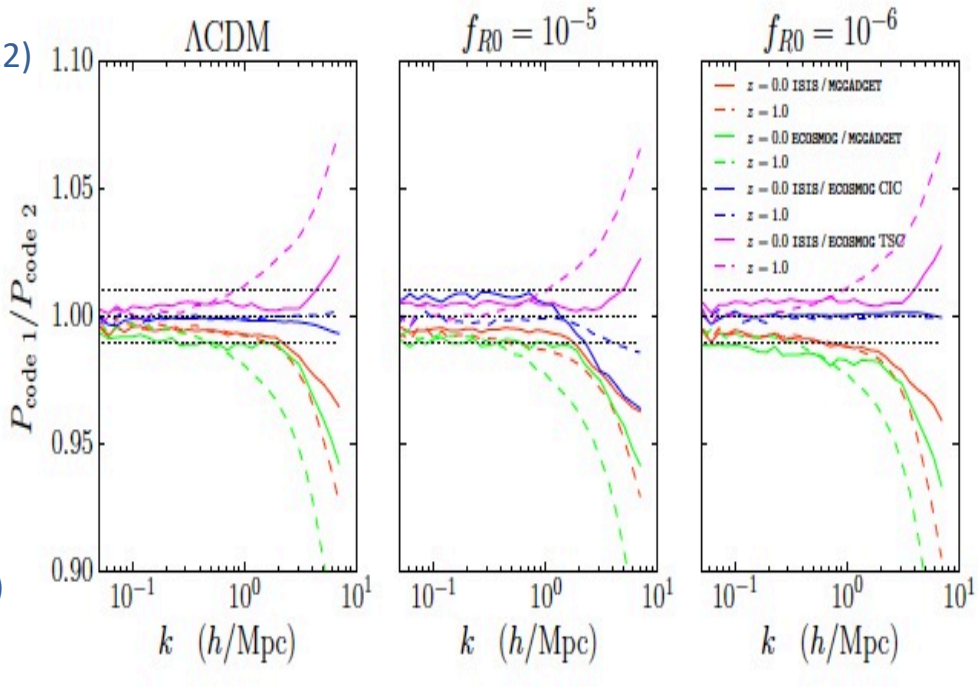
N-body Simulations

Modified Poisson Equation (Jordan Frame)

$$\nabla^2\Phi = \frac{16\pi G}{3}a^2\delta\rho_m + \frac{a^2}{6}\delta R \qquad \nabla^2\delta f_R = -\frac{a^2}{3}[\delta R + 8\pi G\delta\rho_m]$$

Numerical Simulation Codes

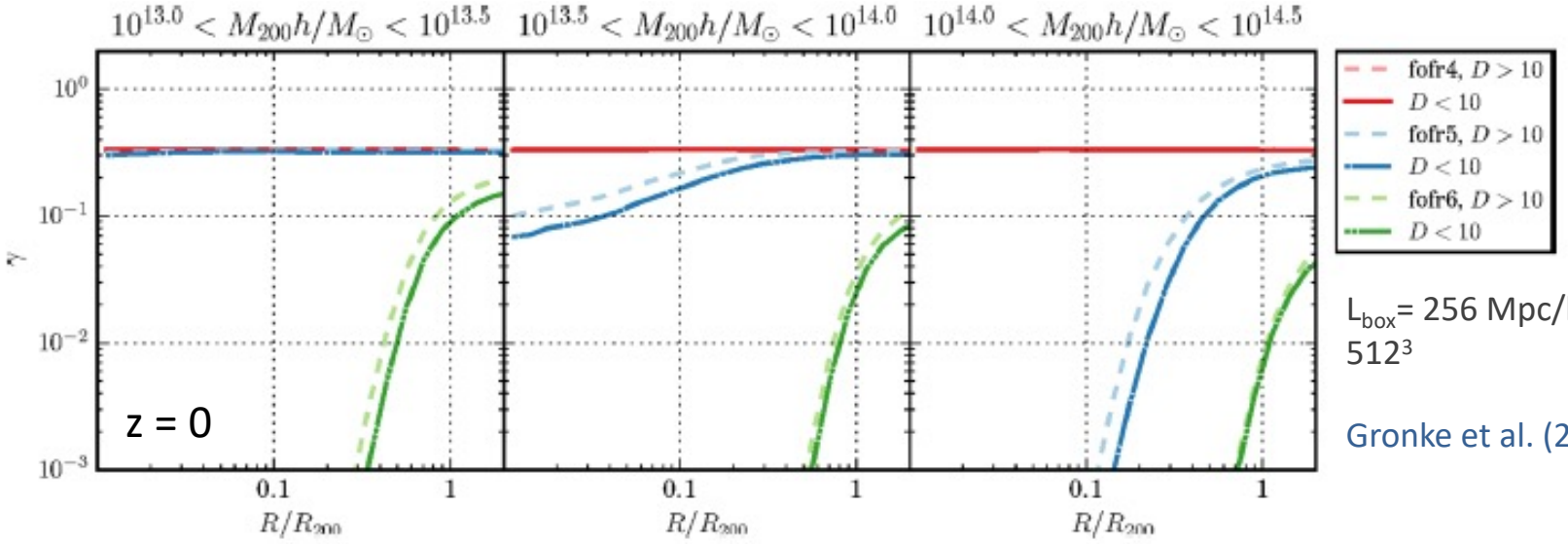
- ECOSMOG Li, Zhao, Teyssier & Koyama (2012)
  - Gravity Solver with AMR
  - Based on RAMSES modification
- ISIS Llinares, Mota & Winther (2013)
  - Einstein Frame
  - Poisson and φ Solver with AMR
  - Based on RAMSES modification
- MG-Gadget Puchwein, Baldi, Springel (2013)
  - Gravity Solver with TreePM
  - Based on Gadget modification



Winther et al. (2015)

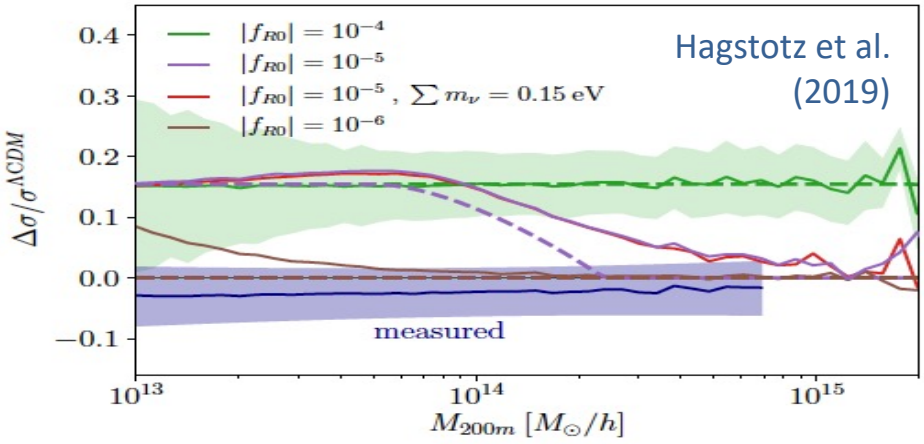
Unscreened Effects in Massive Halos

Scalar Fifth Force vs Newtonian Force



L_{box}= 256 Mpc/h, N_p= 512^3

Gronke et al. (2015)



Hagstotz et al. (2019)

Enhanced Velocity Dispersion

- Dustgrain-Pathfinder Sims (L_{box}= 750 Mpc/h, N_p= 768^3)
- Deeper Potential Well (unscreened regions)
- Virial Condition -> Higher Velocity Dispersion

Halo Density Profiles

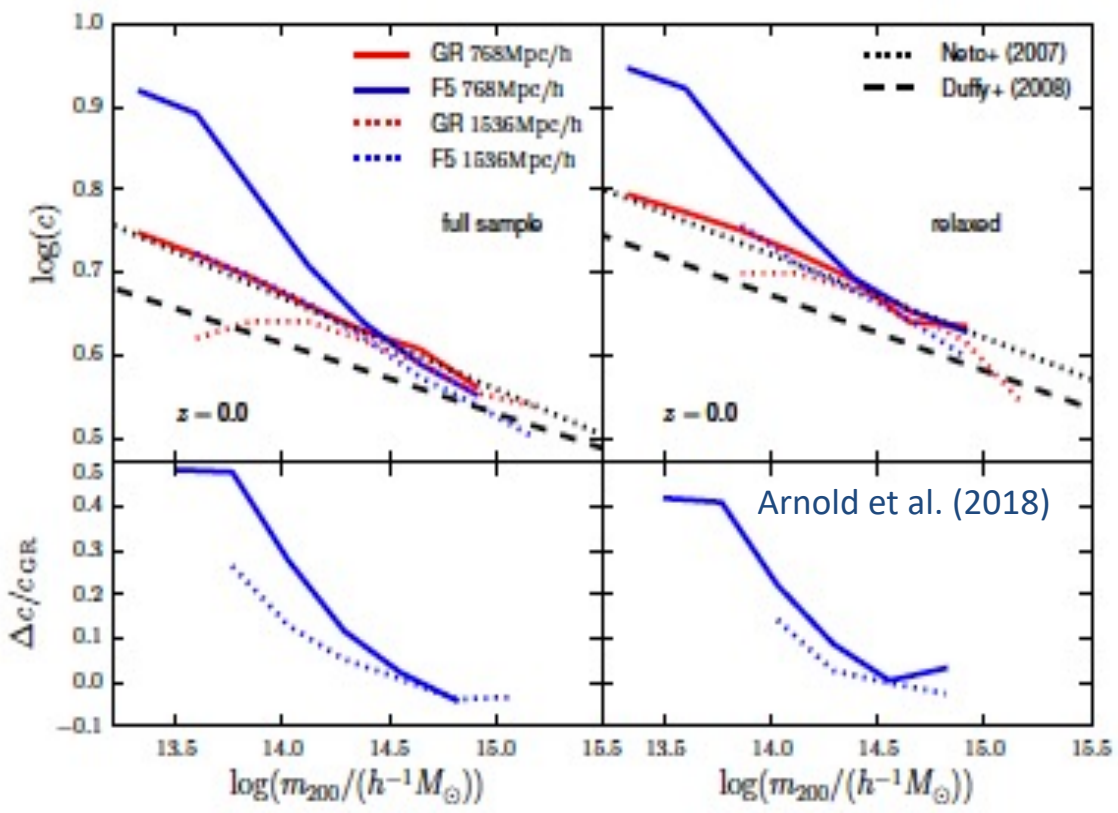
NFW Profile

$$\rho_{\rm NFW}(r) = \frac{M_{200}}{4\pi[\ln(1+c) - c/(1+c)]} \times \frac{1}{r\left(\frac{r_{200}}{c} + r\right)^2}$$

$$c = \frac{r_{200}}{r_s}$$

halo concentration

Concentration-Mass Relation



Arnold et al. (2018)

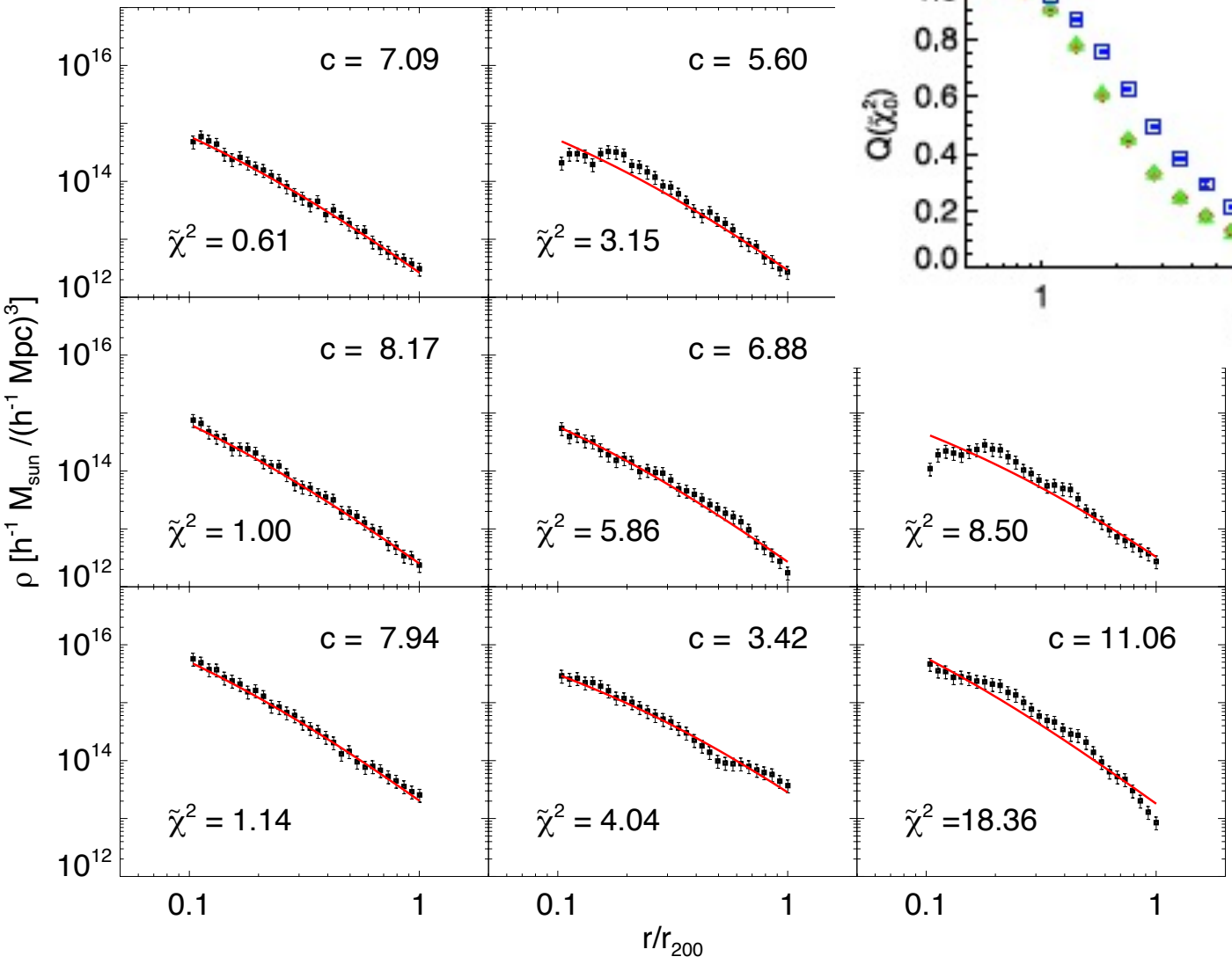
- f(R) vs GR sims (L_{box}= 768, 1536 Mpc/h, $N_p=2048^3$)
- Unscreened halos are more concentrated

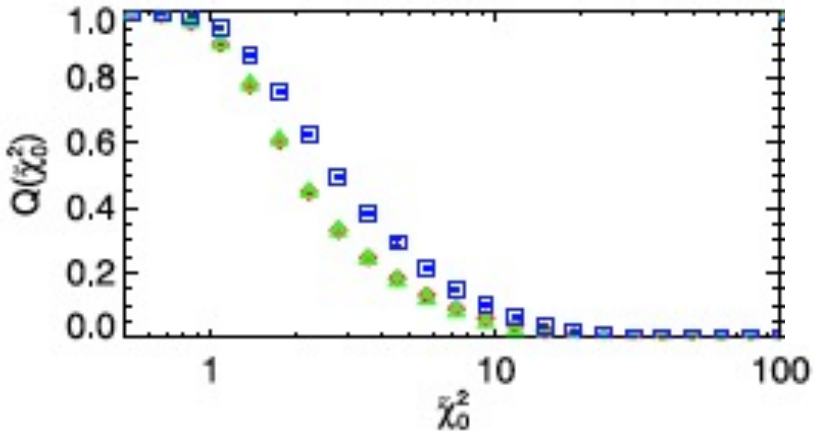
Pitfalls & Challenges

- Baryonic processes in the inner halo region e.g. Gnedin et al. (2004); Duffy et al. (2010); De Boni et al. (2013)
- Selection Effects and Observational Model Assumptions
  e.g. Oguri et al. (2005); Corless, King & Clowe (2009), Sereno et al. (2013)
- Goodness-of-fit of NFW to MG halos?
- Perturbed profiles

The Core of the Problem

Balmes, Rasera, Corasaniti, Alimi (2014)

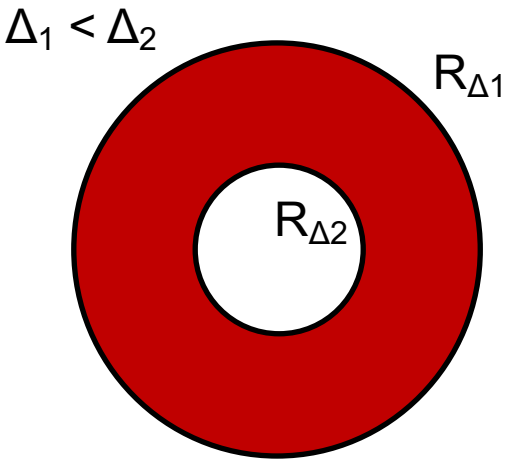




- distribution of c correlates with goodness-of-fit

See also Ragagnin et al. (2020)

Halo Sparsity



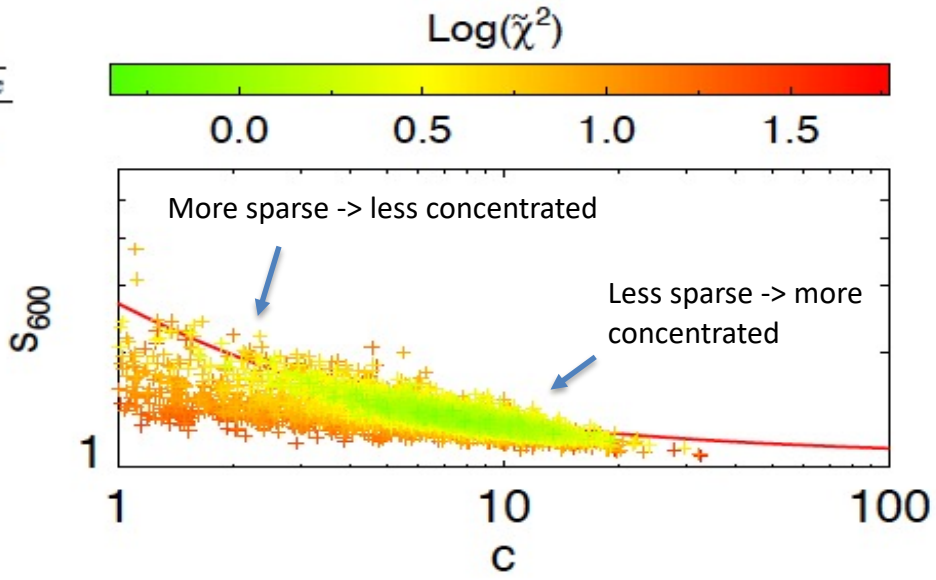
Mass Ratio $$s_{\Delta_1\Delta_2} = \frac{M_{\Delta_1}}{M_{\Delta_2}} \equiv 1 + \frac{\Delta M}{M_{\Delta_2}}$$

- $\Delta_1 \geq 100$ (preserve halo individuality)
- $\Delta_2 \leq 2000$ (avoid baryon dominated region)

Sparsity of NFW Halos

$$s_\Delta = \frac{200}{x^3\Delta} \quad \& \quad x^3\frac{\Delta}{200} = \frac{\ln(1+cx) - \frac{cx}{1+cx}}{\ln(1+c) - \frac{c}{1+c}}$$

- Halos with <1σ NFW along the expected relation
- Distributed nearly constant value with small scatter



Balmes, Rasera, Corasaniti, Alimi (2014)

Cosmological Proxy

Halo Sparsity Properties

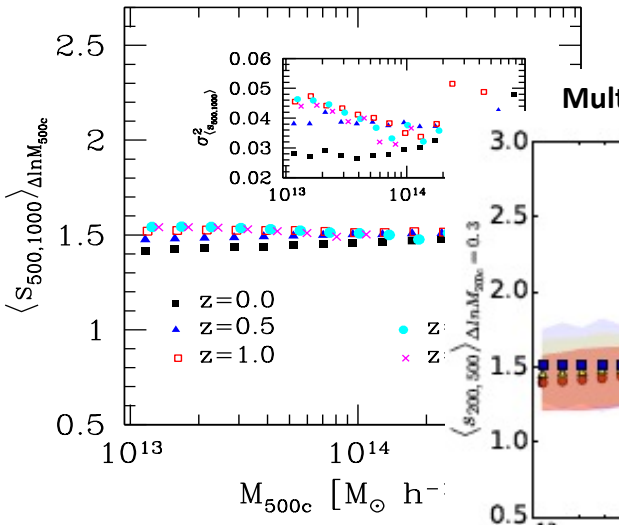
Balmes et al. (2014); Corasaniti et al. (2018); Corasaniti & Rasera (2019)

- Nearly constant with mass (<10% variation across 2 orders in mass)
- Intrinsic scatter bounded to ~20%
- Trend independent of Δ_1 and Δ_2
- Average Sparsity from Halo Mass Function Relation

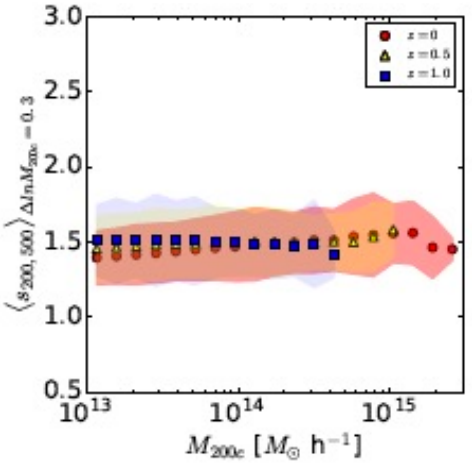
$$\int_{M_{\Delta_2}^{min}}^{M_{\Delta_2}^{max}} \frac{dn}{dM_{\Delta_2}} d\ln M_{\Delta_2} = \langle s_{\Delta_1,\Delta_2} \rangle \int_{\langle s_{\Delta_1,\Delta_2} \rangle M_{\Delta_2}^{min}}^{\langle s_{\Delta_1,\Delta_2} \rangle M_{\Delta_2}^{max}} \frac{dn}{dM_{\Delta_1}} d\ln M_{\Delta_1}$$

- Accurate to sub-percent level

RayGalGroupSims/LCDM-WMAP7



MultiDark/LCDM-Planck



	z	$\left\langle \frac{M_{200c}}{M_{500c}} \right\rangle$	$\frac{\langle 1/M_{500c} \rangle}{\langle 1/M_{200c} \rangle}$	$\frac{\langle M_{200c} \rangle}{\langle M_{500c} \rangle}$	$\langle s^{MF}_{200,500} \rangle \pm \sigma^{MF}_{\langle s_{200,500} \rangle}$
MDPL2	0.0	1.42	1.41	1.42	1.40 ± 0.01
	0.5	1.47	1.46	1.46	1.48 ± 0.02
	1.0	1.51	1.51	1.48	1.52 ± 0.03
Raygal	0.0	1.50	1.48	1.49	1.49 ± 0.03
	0.5	1.54	1.53	1.53	1.54 ± 0.05
	1.0	1.55	1.54	1.52	1.54 ± 0.05

Corasaniti, & Rasera (2019); Corasaniti, Sereno, Ettori (2021)

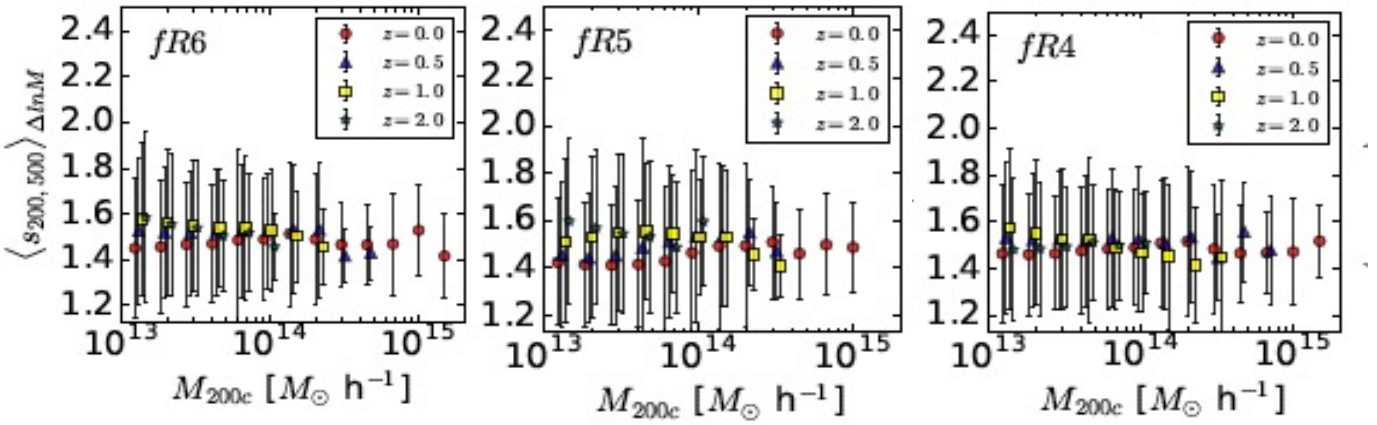
Consistency Relations

$$\langle s_{\Delta_1,\Delta_2} \rangle \equiv \left\langle \frac{M_{\Delta_1}}{M_{\Delta_2}} \right\rangle \cong \frac{\left\langle \frac{1}{M_{\Delta_2}} \right\rangle}{\left\langle \frac{1}{M_{\Delta_1}} \right\rangle} \cong \langle s^{MF}_{\Delta_1\Delta_2} \rangle$$

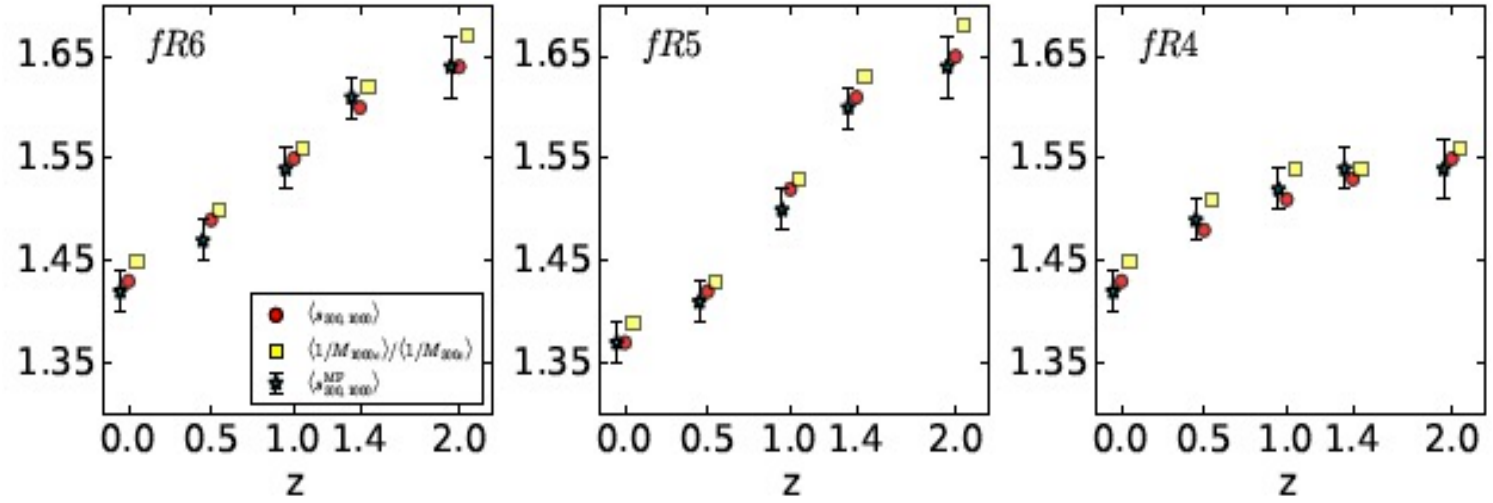
Halo Sparsity of f(R) models

Dustgrain-Pathfinder Halo Catalogs

- SOD halos with $M_{200c} > 10^{13}\ M_{sun}/h$
- Independence with halo mass



- Consistency Relations



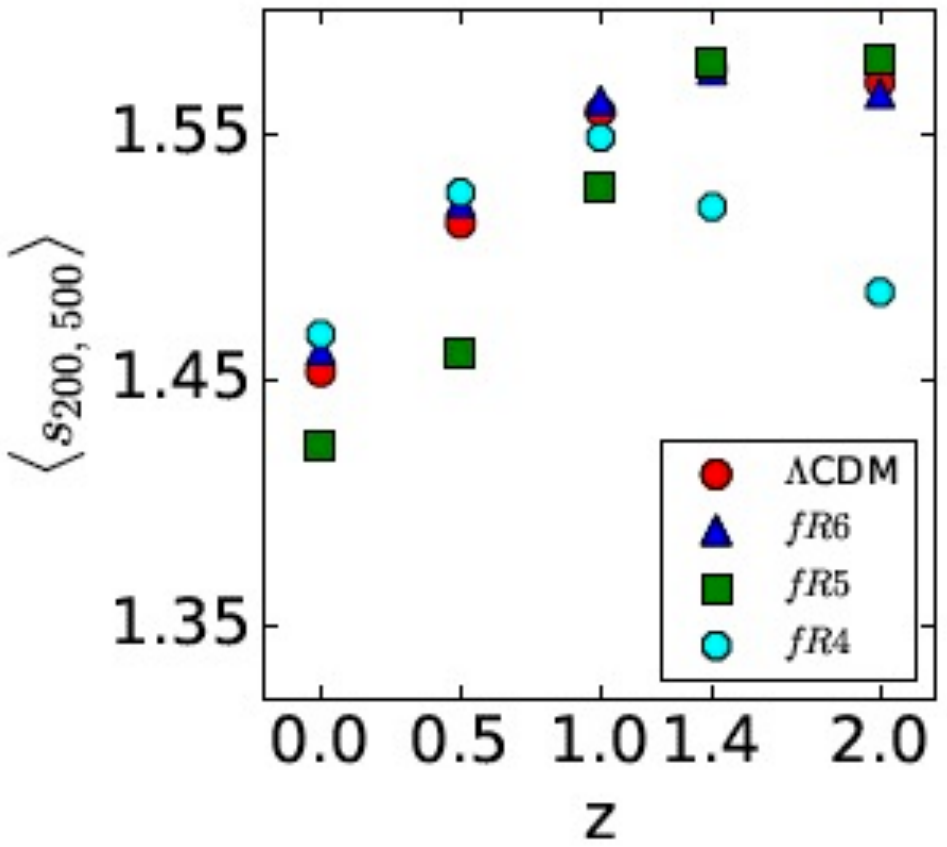
Corasaniti, Giocoli & Baldi (2020)

Screening Effects on Sparsity Evolution

Ensemble Average Sparsity

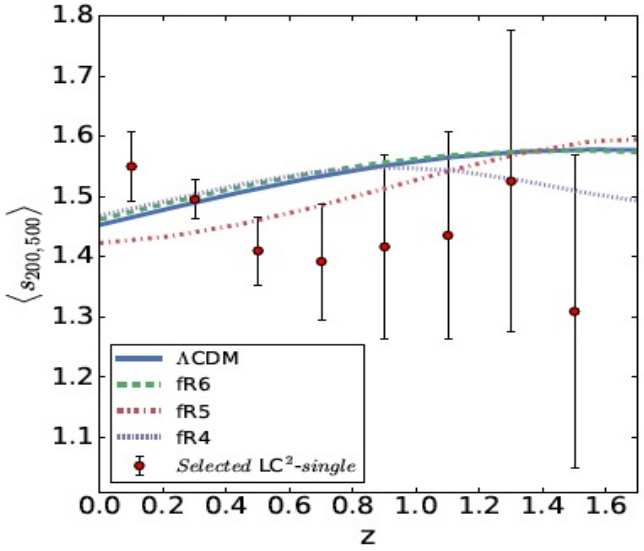
- $|f_0| = 10^{-4}$: halos > 10^{13} M_{sun}/h unscreened at z = 0
  - Linear Growth Enhanced than LCDM
  - Earlier Halo Formation -> More concentrated -> Less sparse
  - At z< 1, fifth force equally enhance radial profile of halos (<s> ~ LCDM)

- $|f_0| = 10^{-5}$: halos ~ $10^{13} – 10^{14}$ M_{sun} unscreened
  - Linear Growth ~ LCDM (<s> ~ LCDM)
  - Bulk of halos forming at z<1 are unscreened in the inner region with enhanced halo profile (more concentrated -> less sparse)



- $|f_0| = 10^{-6}$: halos ~ $10^{13} – 10^{15}$ M_{sun} screened
  - Sparsity evolution similar to LCDM

Observational Constraints



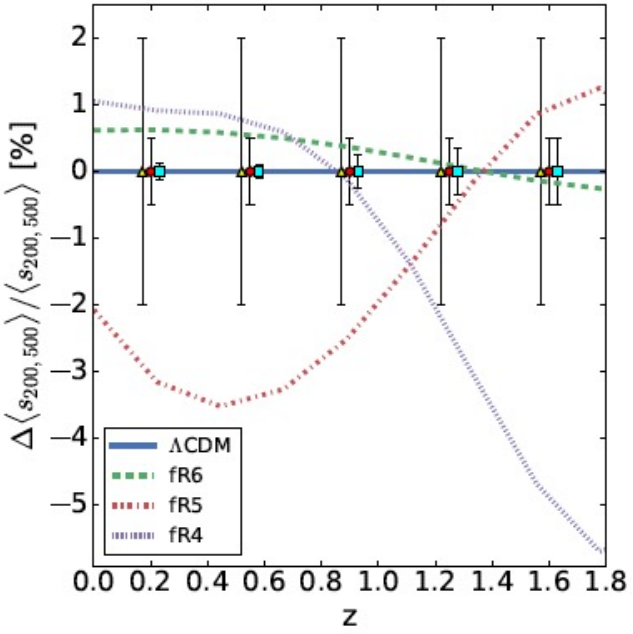
Cluster Lensing Masses

- Selected LC²-single cluster masses: 187 clusters
- No propagation of cosmological parameter degeneracies
- $\chi^2_{\Lambda CDM}$=10.1; χ^2_{fR6}=10.6; χ^2_{fR5}=11.1; χ^2_{fR4}=9.9

Cluster Survey Forecast

- Uncertainty dominated by cluster mass errors
- Assuming N~1000 clusters with e_M = *30%, 5%, ~1% (Euclid-like)*
- Systematics ~2% from radial dependent mass bias due to baryonic process (in LCDM)
- Dynamical Masses vs Lensing Masses

$\Delta_M = \frac{d}{dr}(\Phi - \Psi) / \frac{d}{dr}(\Phi + \Psi)$



Conclusions

- Unscreened scalar fifth force alters halo dynamical properties and mass distribution
- Depending on MG models enhanced velocity dispersion profile in group and cluster-like halos
- Modification in the halo mass distribution leads to testable predictions on the average halo sparsity evolution
- Needs of accurate cluster masses

Systematic Effects

Radial Dependent Mass Bias

- Baryonic Processes Altering Halo Mass Distribution (AGN feedback)
  Velliscig et al. (2014)
- Hydrostatic Mass Bias
  Biffi et al. (2016)
- Tangential Shear Profile
  Becker & Kravtsov (2011)

Cluster State	$r_{500,1000}$ [%]
CC	–3.7
NCC	0.1
Regular	0.3
Disturbed	–2.0

$$\frac{\Delta s_{\Delta_1,\Delta_2}}{s_{\Delta_1,\Delta_2}} = \frac{1+y_{\Delta_1}}{1+y_{\Delta_2}} - 1$$