Modeling and Constraining the Cluster Mass Function to Test Gravity at Large Scales

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Work presented here in collaboration with:

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Constraining alternative theories of gravity

1. Strength from cluster observations: constraining gravity at large scales, either using concrete models or general parameterizations.

2. Worked example: viable f(R) gravity models with the chameleon screening mechanism.

3. For f(R), current prospects for improvement are primarily based on analyses including less massive and low-z objects.

Hu-Sawicki f(R) gravity model (departing from GR)

$$f(R) = -2\Lambda - \frac{f_{R0}}{n}\frac{\bar{R}_0^{n+1}}{R^n}$$

Approximated Hu-Sawicki model in the high curvature regime. In the limit $|f_{R0}| << 10^{-2}$ closely mimics the LCDM expansion history

$$\lambda_{C0} \approx 29.9\sqrt{\frac{|f_{R0}|}{10^{-4}}\frac{n+1}{4-3\Omega_m}}\ h^{-1}\mathrm{Mpc}$$

Compton wavelength; scales below this present modified gravity until GR is recovered when the fifth force is screened by non-linear effects

$$g(a,k) \equiv -\frac{1}{3}\frac{k^2}{k^2 + m_{f_R}^2 a^2}$$

$$m_{f_R}^{-2} = \lambda_C^2 = 3 f_{RR} \qquad f_R \equiv \frac{\partial f}{\partial R}$$

Linear growth is different than GR+LCDM

Halo mass function modeling

$$n_{\Delta_v} \equiv \frac{dn}{d\ln M_v} = \frac{\bar{\rho}_m}{M_v}\frac{d\ln\nu}{d\ln M_v}\nu f(\nu)$$

Sheth-Tormen mass function

$$\nu f(\nu) = A\sqrt{\frac{2}{\pi}a\nu^2}\left[1+(a\nu^2)^{-p}\right]\exp\left[-a\nu^2/2\right]$$

$\nu = \delta_c/\sigma(M_v)$ Peak height

$$\delta_c(\Omega_m, z) = \mathcal{A}\left(1-\mathcal{B}\log_{10}\left[1+\frac{\Omega_m^{-1}-1}{(1+z)^3}\right]\right)$$

Density threshold fitting formula

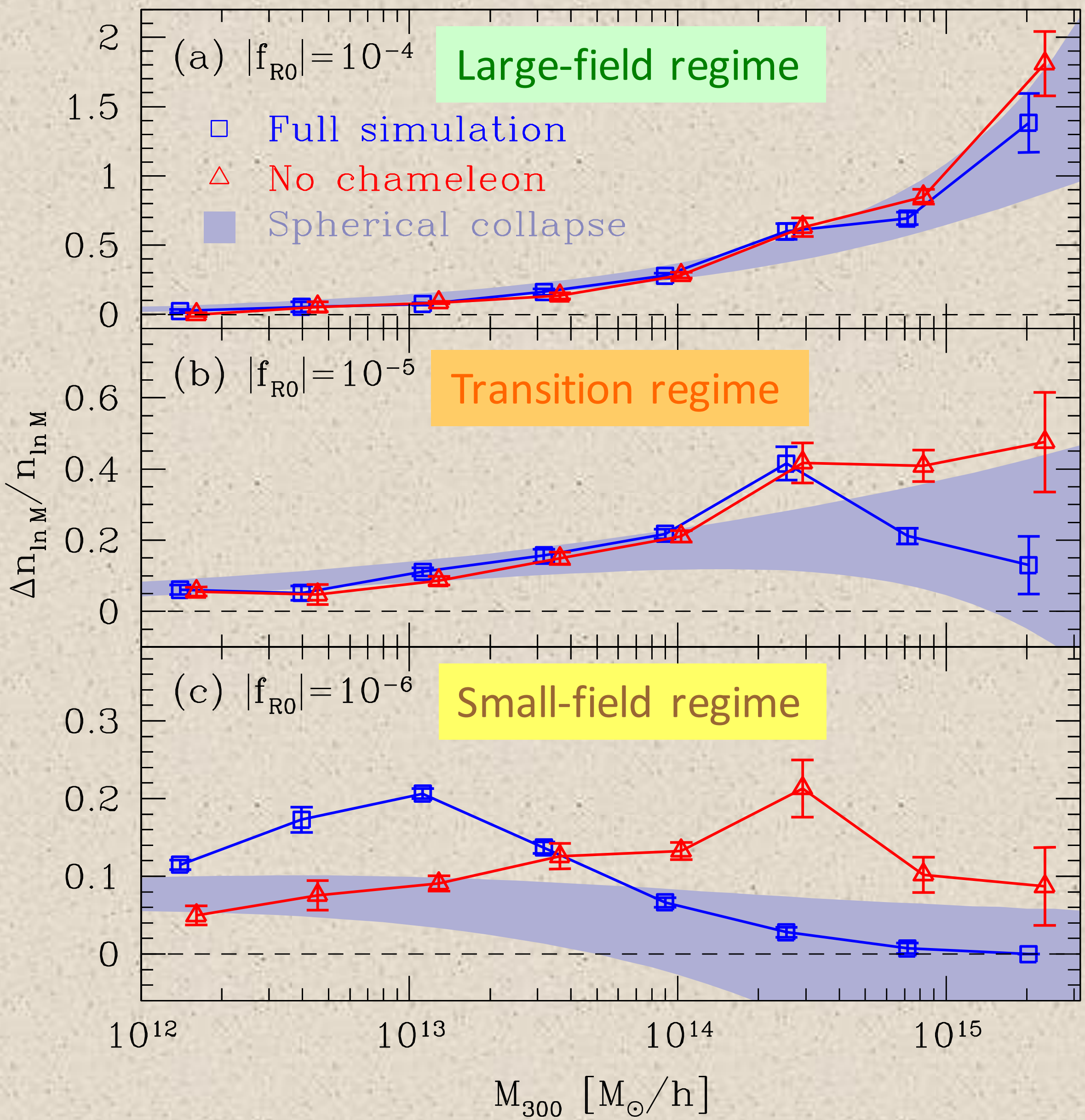
$$n_\Delta = \left(\left.\frac{n_\Delta^{f(R)}}{n_\Delta^{\mathrm{GR}}}\right|_{\mathrm{ST}}\right) n_\Delta\big|_{\mathrm{Tinker}}$$

$\mathcal{A} = 1.6865$ and $\mathcal{B} = 0.0123$ for GR

$\mathcal{A} = 1.7063$ and $\mathcal{B} = 0.0136$ for $f(R)$

$n_{\mathrm{ST}}^{f(R)}/n_{\mathrm{ST}}^{\mathrm{GR}}$ We set this equal to 1 when becomes <1

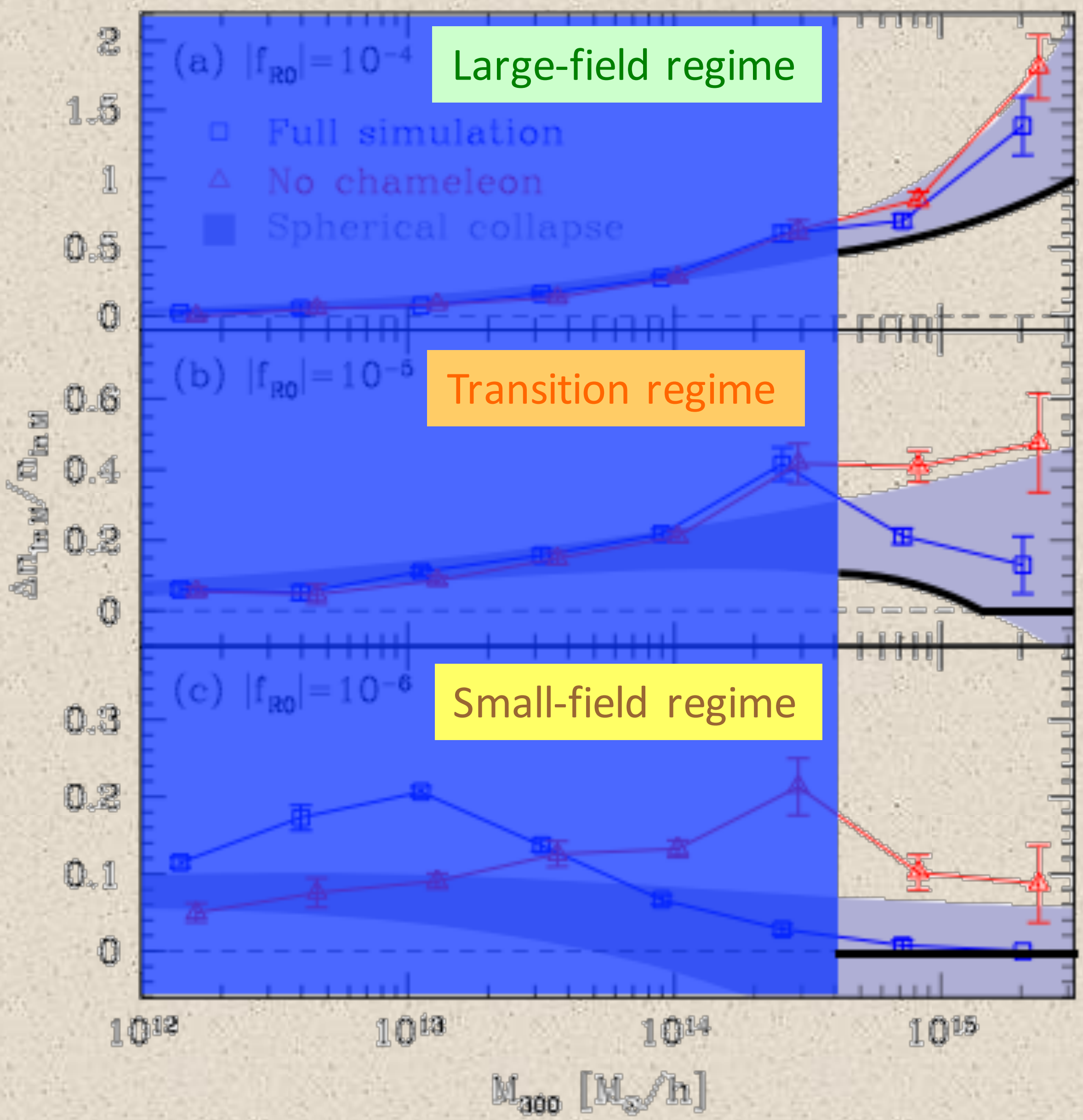
Halo mass function modeling



- Using N-body simulations including the Chameleon screening mechanism (Schmidt et al 2009).

- Our modeling is based on the bottom line of the blue shaded area, which as shown here is conservative.

Halo mass function modeling



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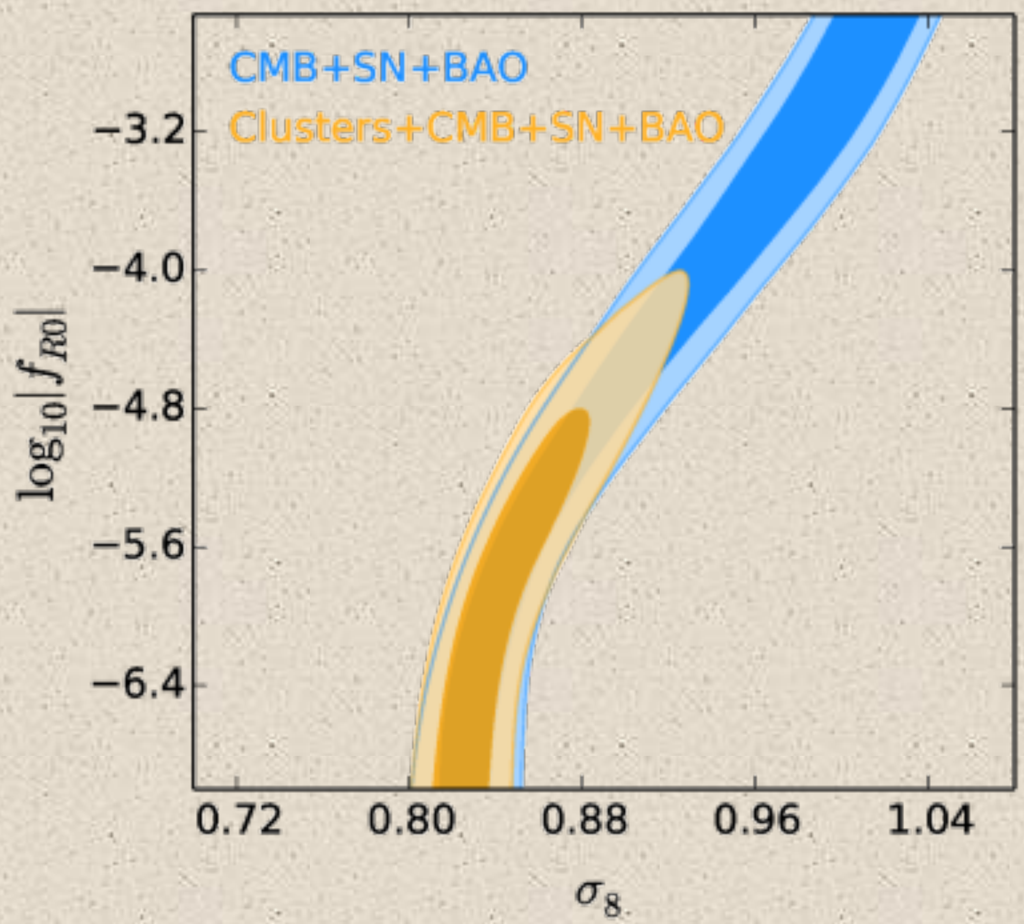
HS n=1 f(R) growth + flat ΛCDM

Cataneo et al 15 (PRD 2015, 92, 044009)



$$|f_{R0}| < 1.62 \times 10^{-5} \, (All)$$

Clusters: XLF: BCS+REFLEX+MACS (z<0.5) 224 survey with 94 X-ray follow-up (Mantz et al 2015) + cluster f_{gas} (Mantz et al 2014)

CMB (Planck collaboration 2014; SPT, Story et al 2013; ACT, Das et al 2014) + SNIa (Union 2.1, Suzuki et al 2012) + BAO (6dF, Beutler et al 2011; SDSS, Padmanabhan et al 2012, Anderson et al 2014; WiggleZ, Blake et al 2011)

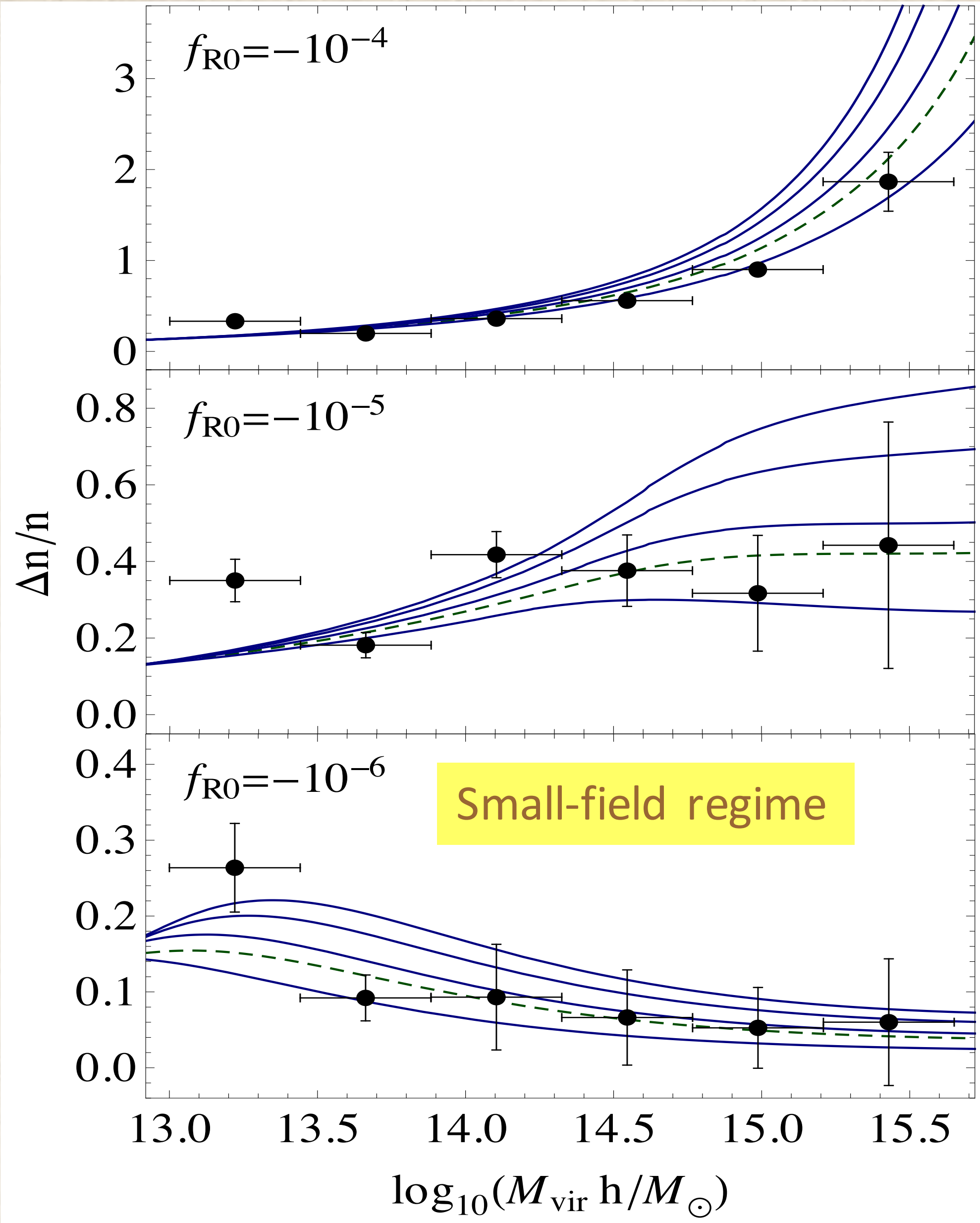
Gold: all data sets combined

For General Relativity $|f_{R0}|=0$

Correlation between σ_8 and $|f_{R0}|$

$$\rho = 0.73 \, (All) \quad \rho = 0.90 \, (CMB)$$

Halo mass function modeling



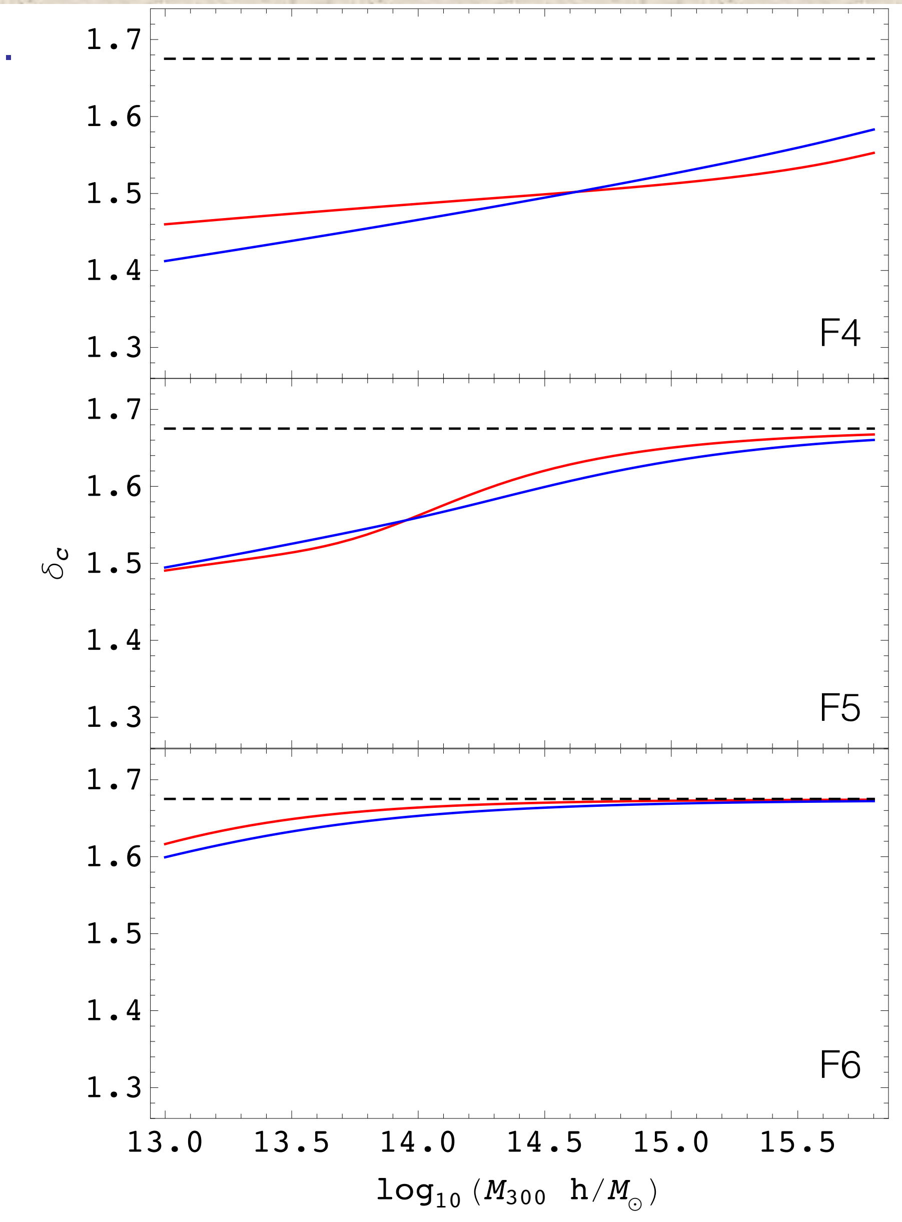
- For Chameleon gravity models using medium-resolution N-body simulations for f(R) as limiting case (Lombriser et al 2014).

- Modeling the effect of the Chameleon screening mechanism to the mass function to obtain a more accurate mass function and stronger constraints (Cataneo et al 2017, in prep.).

- The small-field regime is potentially constrainable by lower-mass cluster data (with a ~5% mass calibration precision). The curves depend on the environmental density.

Chameleon screening refinement

Cataneo et al 16, (JCAP 2016, 12, 024)



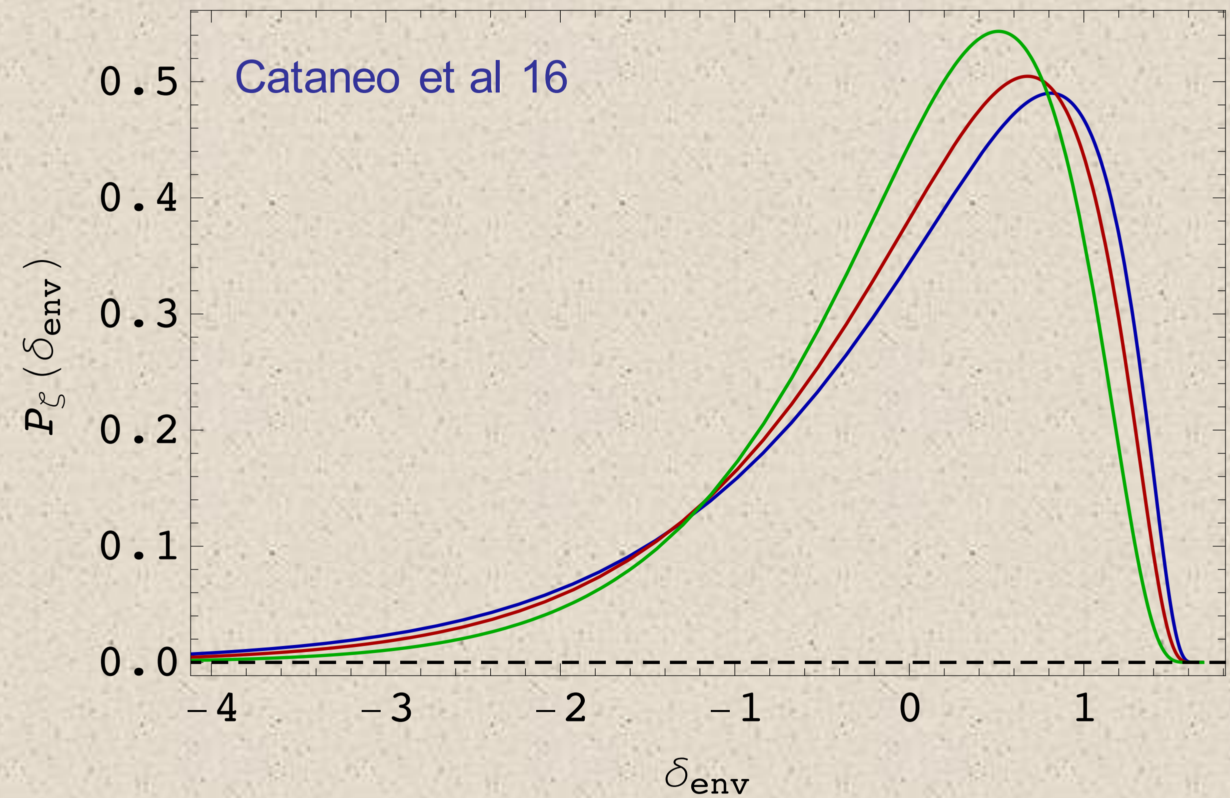
- Modeling the effect of the Chameleon screening mechanism on the mass function using high-resolution N-body simulations to obtain a more accurate mass function (Cataneo, Rapetti, Lombriser, Li, 2016)

- Spherical collapse thresholds at z=0 (Omega_m=0.281). Lombriser et al 2014 calculations at the peak of the environmental density distribution in blue and our corrected/calibrated delta_c in red to account for self-screening and environmental screening mechanisms.

Chameleon screening refinement

$$\delta_c^{\rm eff} = \epsilon(M \mid M_{\rm th}^{(1)}, \mu, M_{\rm th}^{(2)}, \nu, \alpha) \times \delta_c(\delta_{\rm env}^{\rm peak})$$

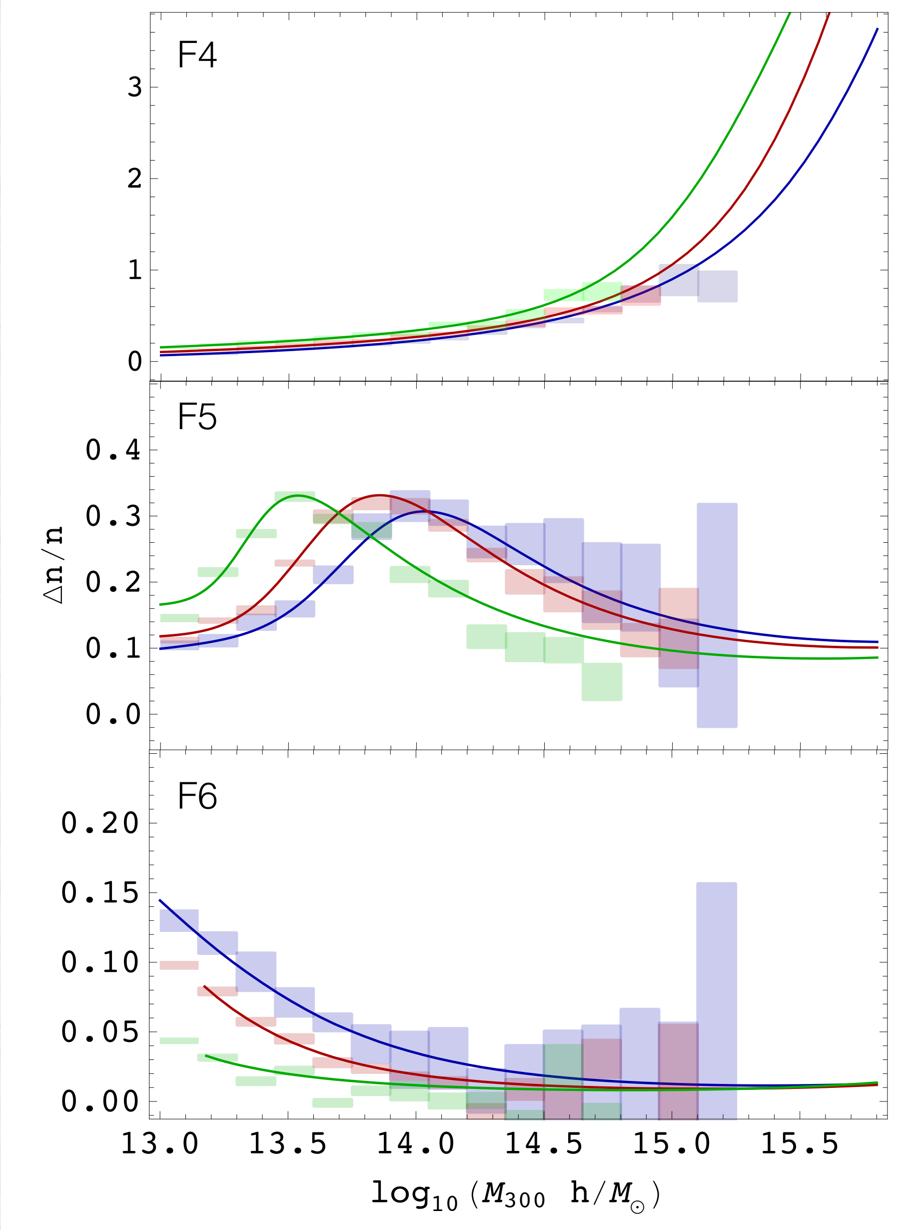
$$\epsilon = \frac{1 + (M/M_{\rm th}^{(1)})^{\eta}(\delta_{\rm c}^{\Lambda}/\delta_{\rm c}^{f(R)})^{\chi} + (M/M_{\rm th}^{(2)})^{\vartheta}(\delta_{\rm c}^{f(R)}/\delta_{\rm c}^{\Lambda})}{1 + (M/M_{\rm th}^{(1)})^{\eta} + (M/M_{\rm th}^{(2)})^{\vartheta}}$$



GR/LCDM environmental density probability distribution (Lam & Sheth 08); z=0, 0.2, 0.5; Omega_m=0.281

New halo mass function

Cataneo et al 16



- High-resolution: L_box=1024 Mpc/h; N_particles=1024; force resolution = 15.3 kpc/h; N_realizations = 1; z = 0 (blue), 0.1, 0.2 (red), 0.3, 0.4, 0.5 (green); n_s=0.971, Omega_m=0.281, H0=69.7, T_CMB=2.7255, Y_He=0.24, N_nu=3, sigma_8=0.82 (flat LCDM background). Current fits:

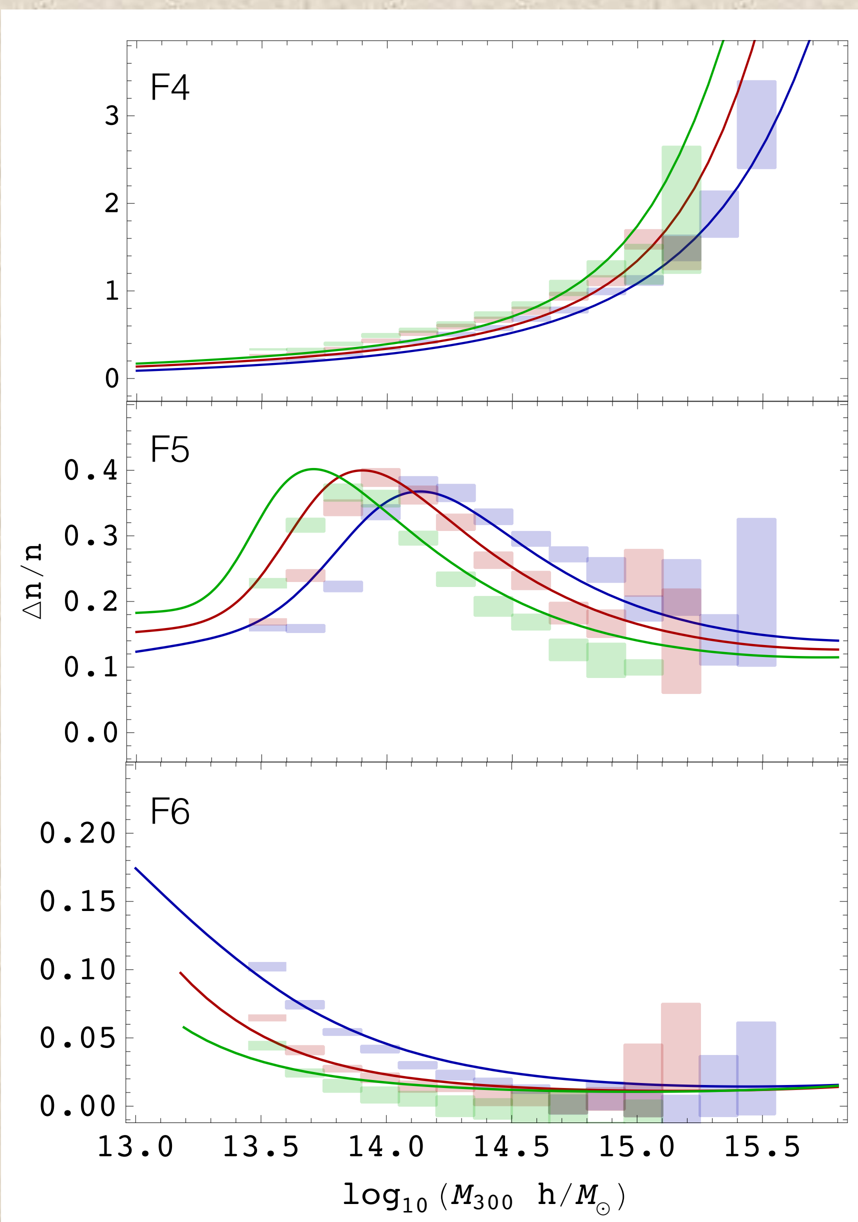
5% for $10^{13.5} \leqslant M_{300\mathrm{m}}(M_\odot/h)^{-1} \leqslant 10^{15.5}$

$10^{-6} \leqslant |f_{R0}| \leqslant 10^{-4}$ and $0 \leqslant z \leqslant 0.5$

- Rockstar halo finder with spherical overdensity masses with average density equals 300ρ_m; simulations divided in octants; uncertainties on the HMF f(R)/GR ratios propagated with the jackknife method with halos in mass bins of Δlog10(M)=0.15. (We only keep mass bins with N_halos>20.)

New halo mass function

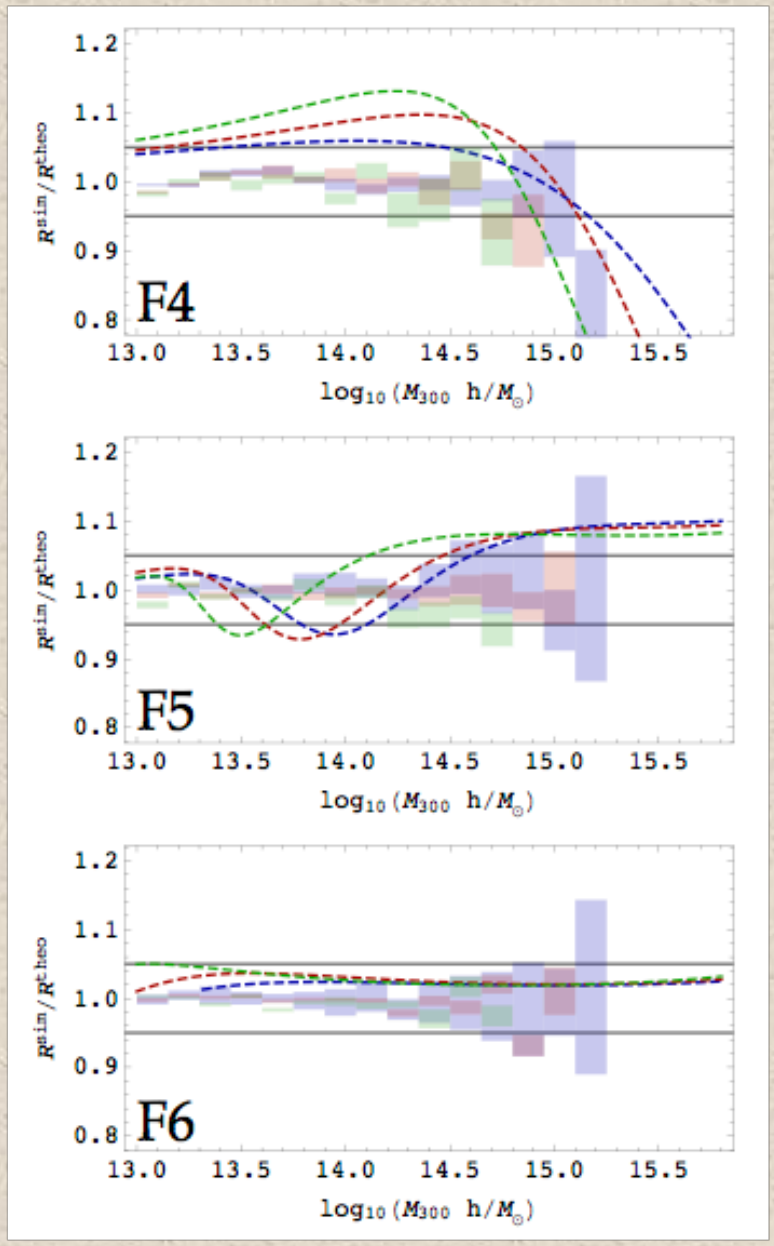
Cataneo et al 16



- Low-resolution: L_box=1.5 Gpc/h; N_particles=1024; force resolution = 22.9 kpc/h; N_realizations = 6; z = 0 (blue), 0.11, 0.25 (red), 0.43 (green); n_s=0.958, Omega_m=0.24, H0=73, T_CMB=2.7255, Y_He=0.24, N_nu=3, sigma_8=0.796 (flat LCDM background).

- Rockstar halo finder with spherical overdensity masses with average density equals 300ρ_m; uncertainties on the HMF f(R)/GR ratios propagated with the jackknife method using the six realizations with halos in mass bins of Δlog10(M)=0.15. (We only keep mass bins with N_halos>20.)

New halo mass function

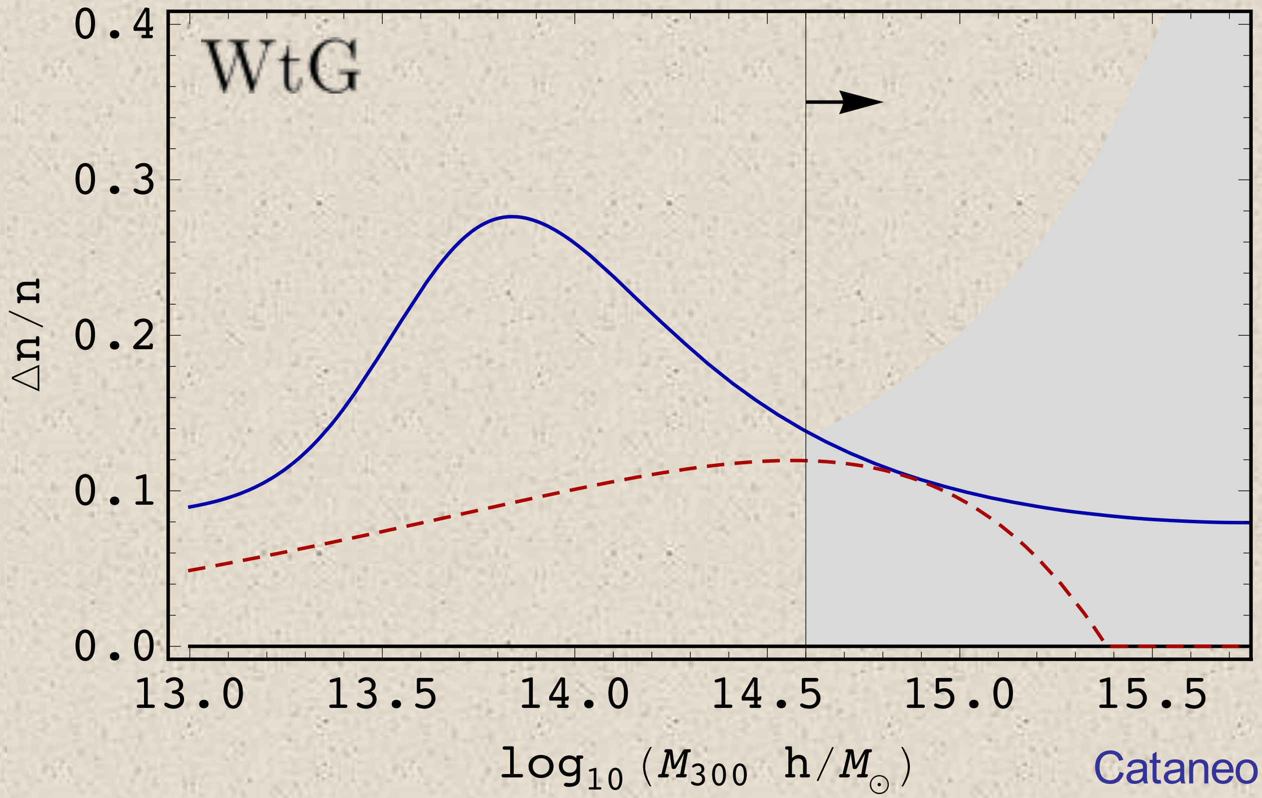


CATANEO ET AL 2016

$$\mathcal{R}(M, z, \bar{f}_{R0}, \boldsymbol{\theta}) = \frac{n^{f(R)}_{\ln M}}{n^{\rm GR}_{\ln M}}$$

- Dashed lines show the effect of neglecting the correction,
- which is only weakly dependent on standard cosmological parameters
- and potentially insensitive to baryonic physics and massive neutrinos

Comparison of current and prospective constraints

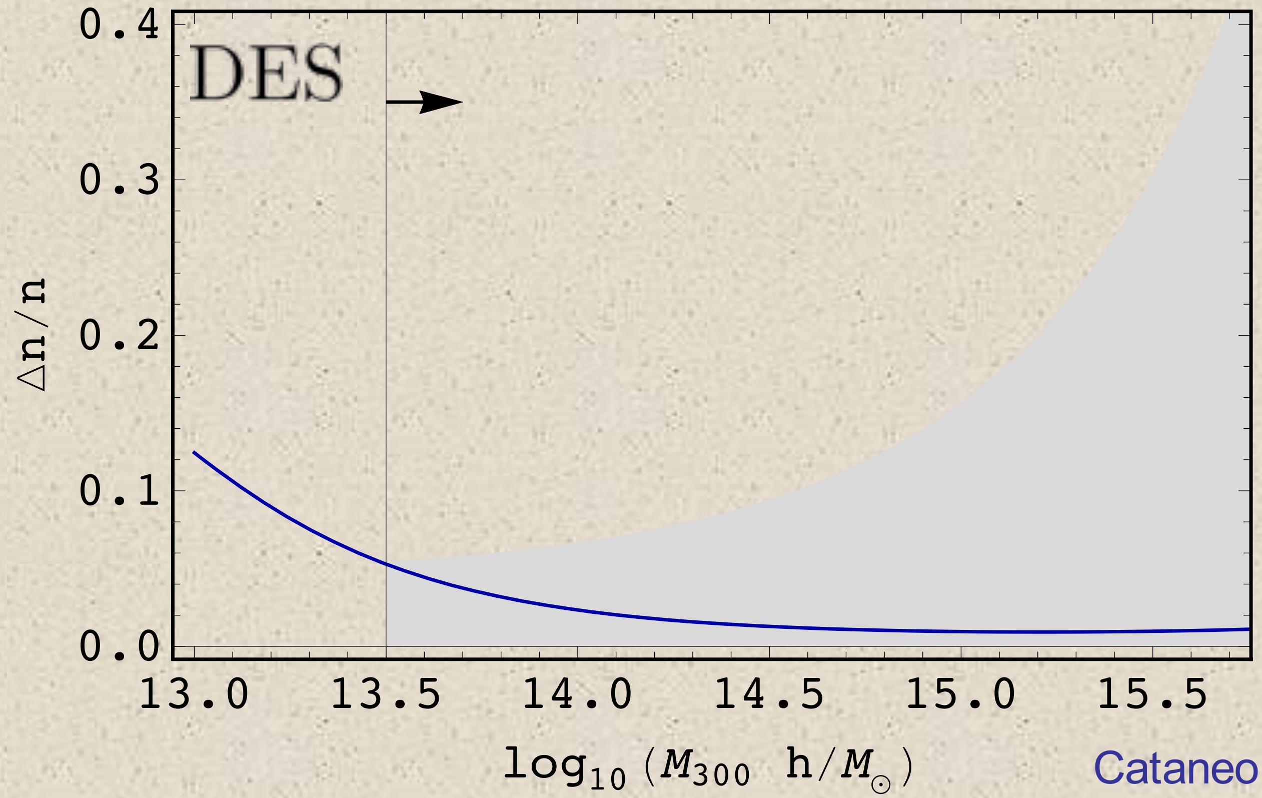


Cataneo et al 16

$$|\bar{f}_{R0}| \lesssim 5 \times 10^{-6}$$

Gray band, 7% mass calibration from WtG with the corresponding lower mass limit; red line, current 2-sigma level from the WtG constraints using the previous mass function; blue line, projected constraints for the next WtG constraints with the new f(R) HMF (~a factor of 2 improvement).

Prospective constraints for a lower mass/z survey

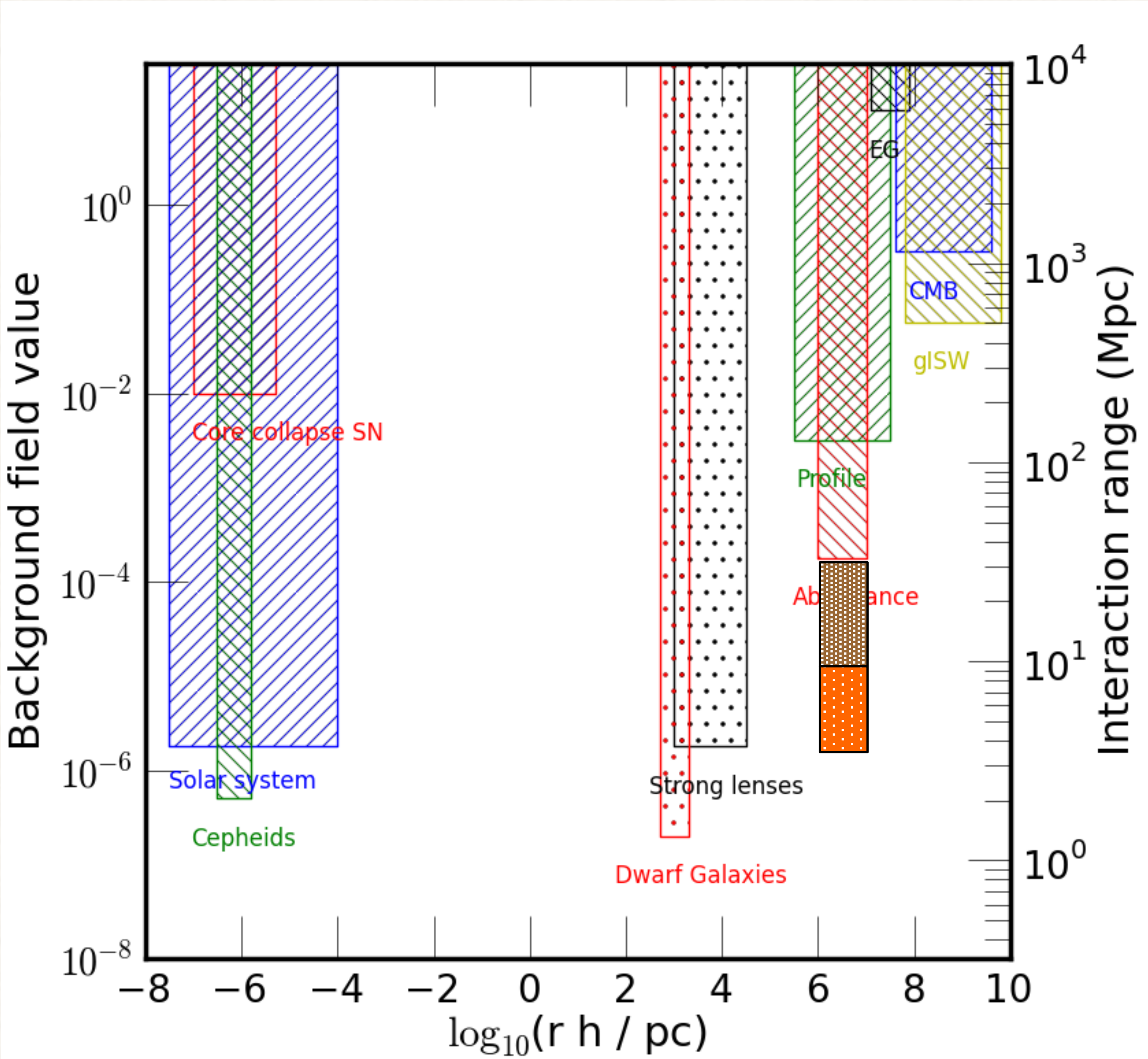


Cataneo et al 16

$$|\bar{f}_{R0}| \lesssim 10^{-6}$$

Gray band, 5% mass calibration from DES with the corresponding lower mass limit; blue line, projected constraints for DES constraints with the new f(R) HMF (~an order of magnitude improvement).

Comparison of current and prospective constraints



Adapted from Joyce, Jain, Khoury & Trodden 2014 (review)

Cataneo et al 15
λ_c<~10Mpc $|f_{R0}|$<~10^{-5}

Cataneo et al 17 (in pr.), a factor of ~2 better

DES forecast
λ_c<~3Mpc $|f_{R0}|$<~10^{-6}
(Cataneo et al 2016)