Hunting Modified Gravity and Neutrinos with Clusters of Galaxies

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Overview

- Modified Gravity. Why? And What?
- Neutrinos in Cosmology
- Constraining new physics with clusters of galaxies

Modified Gravity

General Relativity is not well tested on cosmological scales.

- Revisit Einstein-Hilbert action:

$$S = \int \mathrm{d}x^4 \sqrt{-g} \left(\frac{R - 2\Lambda}{16\pi G} + \mathcal{L}_m \right)$$

- Generalise

$$S = \int \mathrm{d}x^4 \sqrt{-g} \left(\frac{R + f(R)}{16\pi G} + \mathcal{L}_m \right)$$

Phenomenology I

Modified gravity wish list:

- should be free of ghosts
- should allow cosmological solutions
- shouldn't mess with the solar system

Phenomenology II

- Consistent and viable extensions of GR are hard!
- Modified gravity in general leads to fifth forces

  → Viable theories require screening mechanisms

- Growth will be scale dependant

Hu-Sawicki Gravity

$$f(R) \approx -2\Lambda - f_{R0}\frac{\bar{R}_0^2}{R}$$

cosmological constant

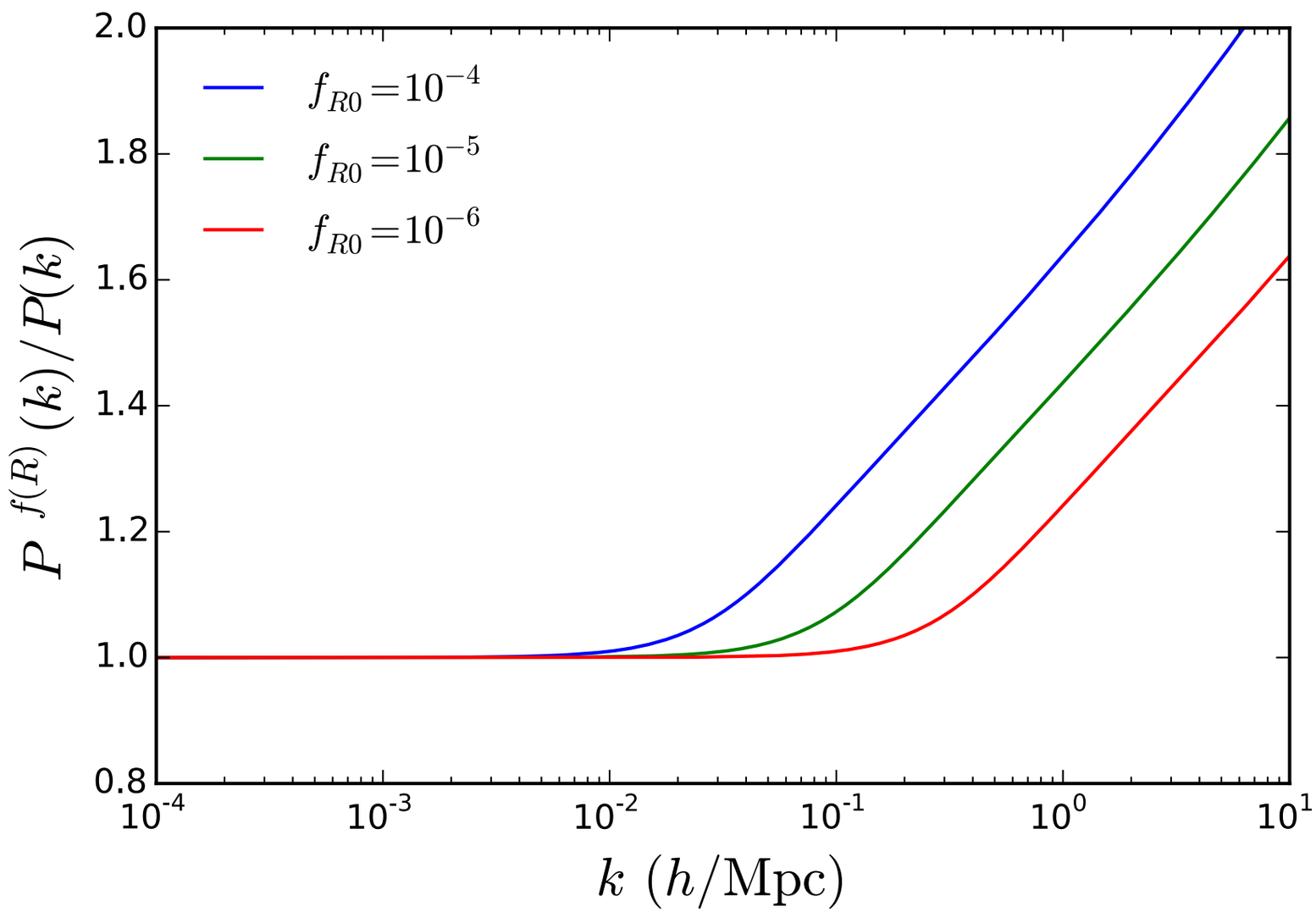
for $f_{R0} \ll 1$ background expansion unchanged

New degree of freedom: scalar field $f_R = \frac{\mathrm{d}f}{\mathrm{d}R}$

→ enhances gravity on perturbative level by 4/3

Where to look for f(R)?

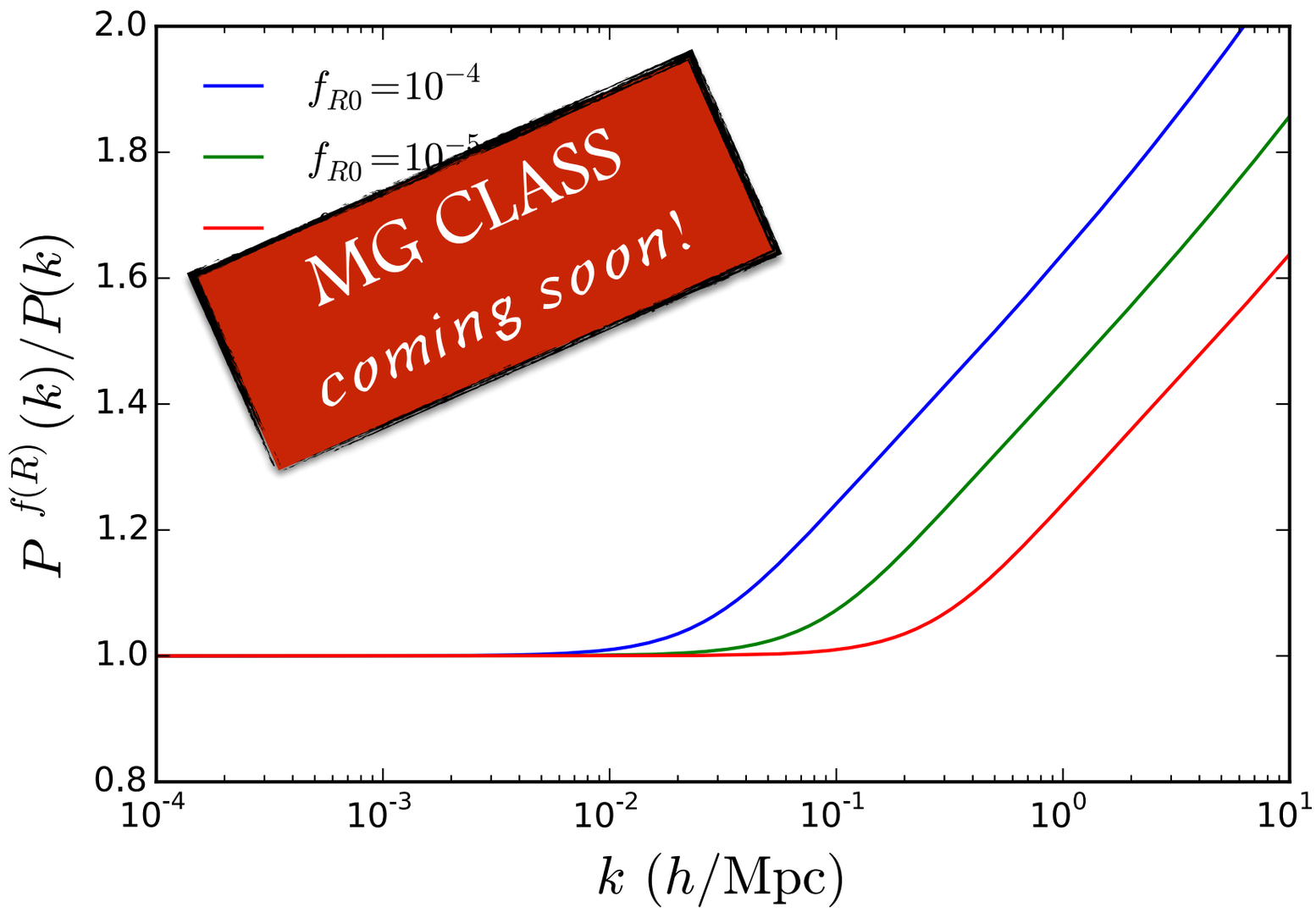
Boost of linear structure growth above screening scale



Cluster scales!

Where to look for f(R)?

Boost of linear structure growth above screening scale



Cluster scales!

Neutrinos in cosmology

Neutrinos are massive: $$0.06\,\mathrm{eV} < \sum m_\nu < 6\,\mathrm{eV}$$

from oscillations — from direct measurements

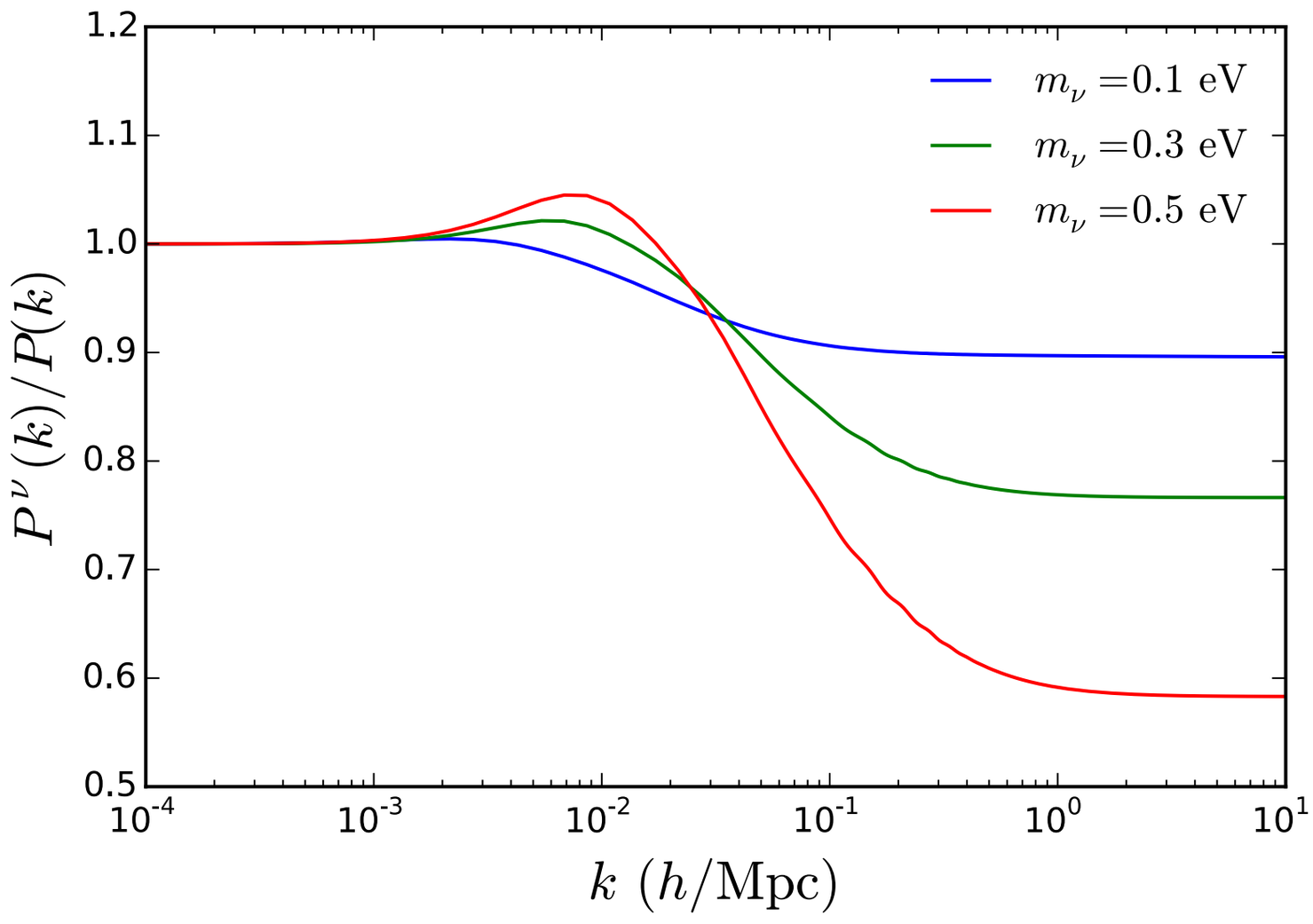
- At least one additional cosmological fluid:

$$\Omega_\nu = \frac{\sum m_i}{93.14\,h^2\,\mathrm{eV}}$$

- Background evolution almost identical, but growth of structures changed

Where to look for neutrinos?

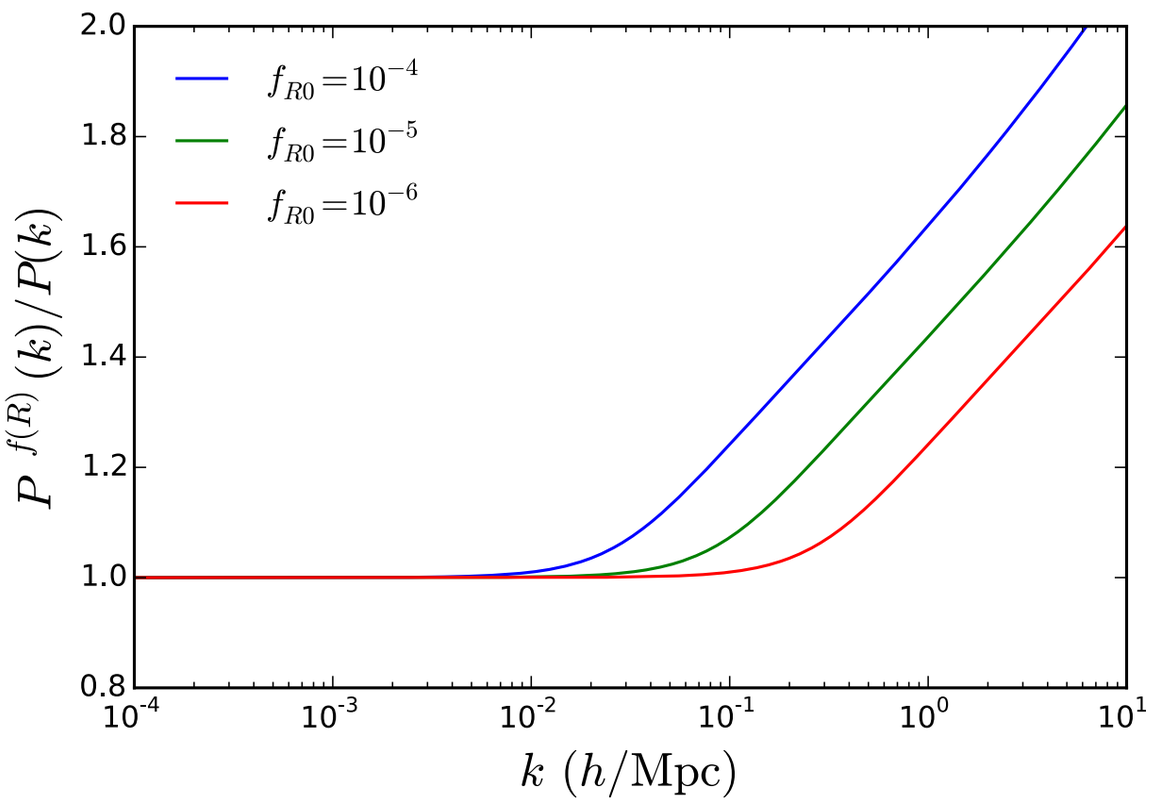
Suppression of linear structure growth below $k_{\rm nr}$ where neutrinos become non-relativistic

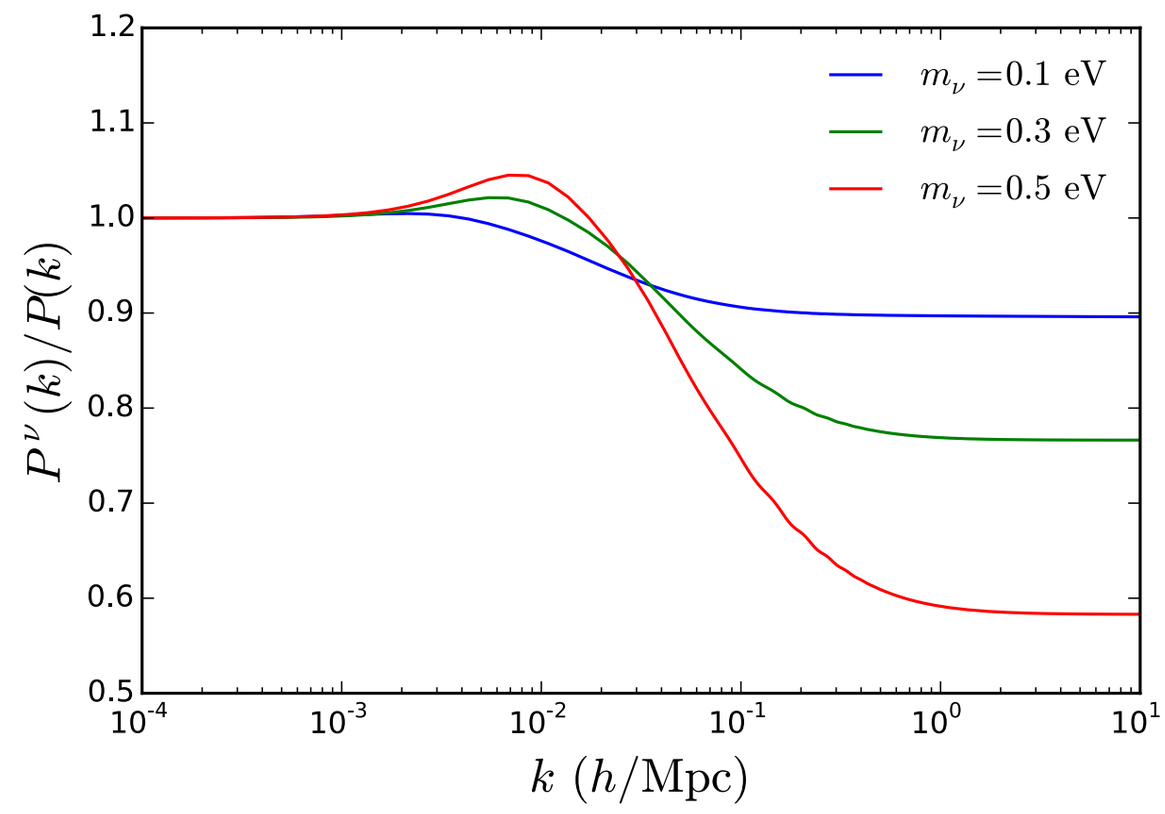


Cluster scales!

Neutrinos vs. f(R)

Tug of war with the power spectrum:





Nonlinear dynamics and combination of probes breaks degeneracy, but requires careful modelling

Cosmology with Clusters

Prediction of cluster counts:

$$N = \int \mathrm{d}z \, \frac{\mathrm{d}V}{\mathrm{d}z} \int \mathrm{d}M \, n(M,z) \int \mathrm{d}\eta P(\eta|M)$$

geometry growth astrophysics

with halo mass function

$$n(M,z) = \bar{\rho}_m \frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}\ln M} f(\sigma)$$

$$\sigma^2(M,z) = \frac{1}{2\pi^2} \int \mathrm{d}k \, k^2 P(k,z) \, W^2(kR)$$

Chameleon Screening

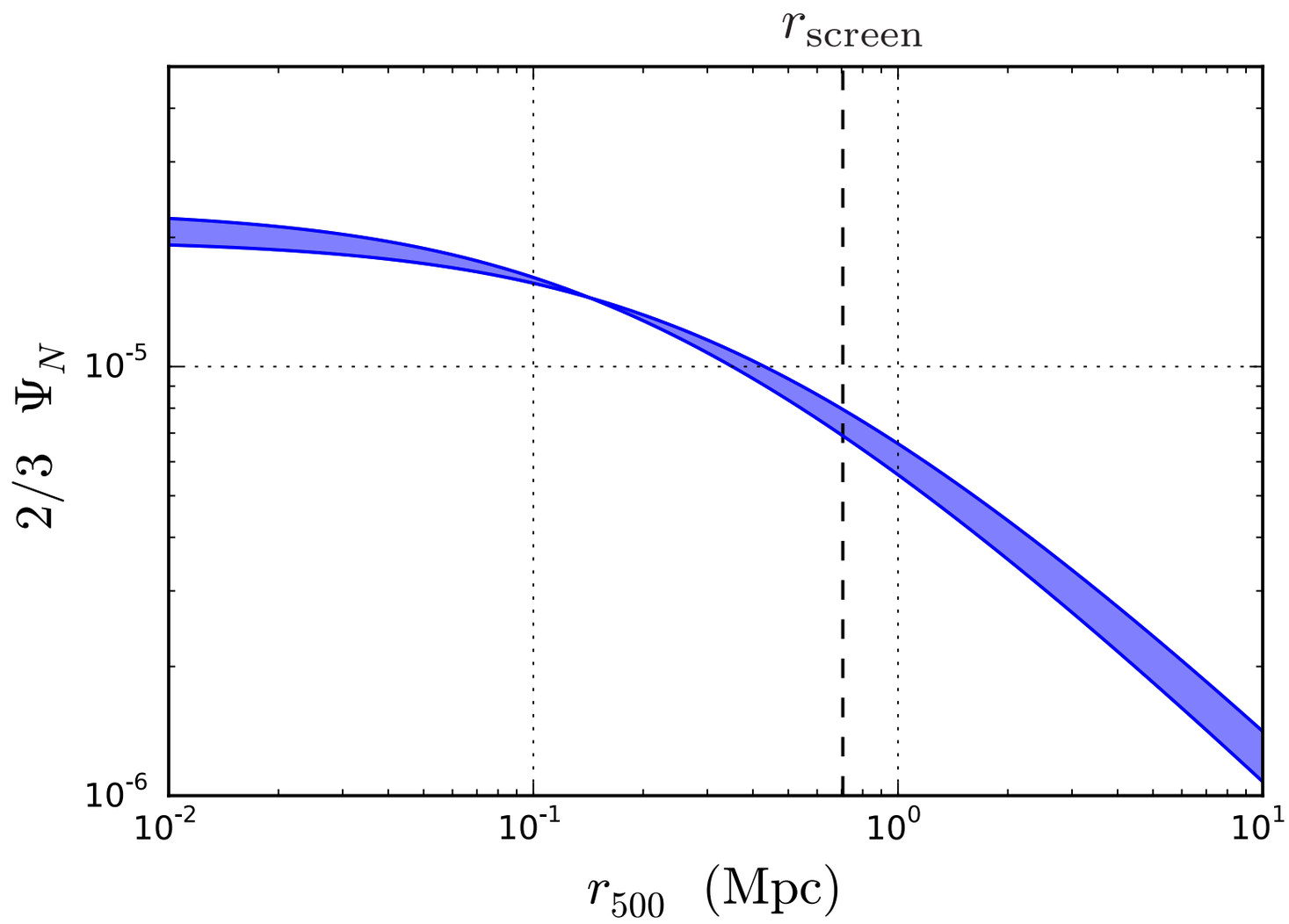
Recover GR limit for

$$f_{R0} \leq \frac{2}{3}\Psi_N$$

Infer mass via hydrostatic equilibrium:

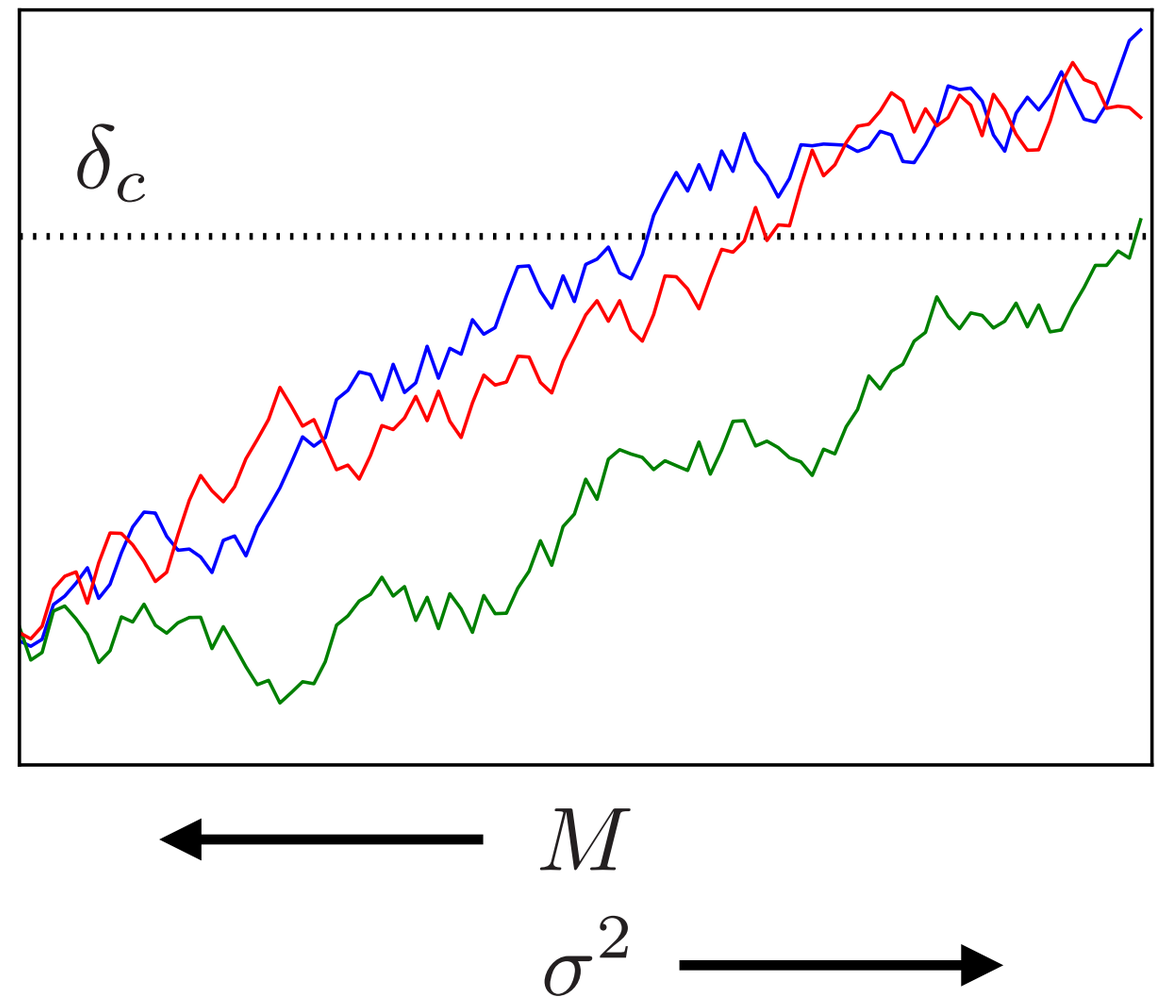
$$\frac{dP}{dr} = \rho_{\rm gas}\frac{d\Psi}{dr}$$

Bias in X-ray mass estimates by ~10%



Excursion Set Theory

- The smoothed density field performs random walks as function of the smoothing scale
- Collapsed objects form as soon as a critical threshold is crossed



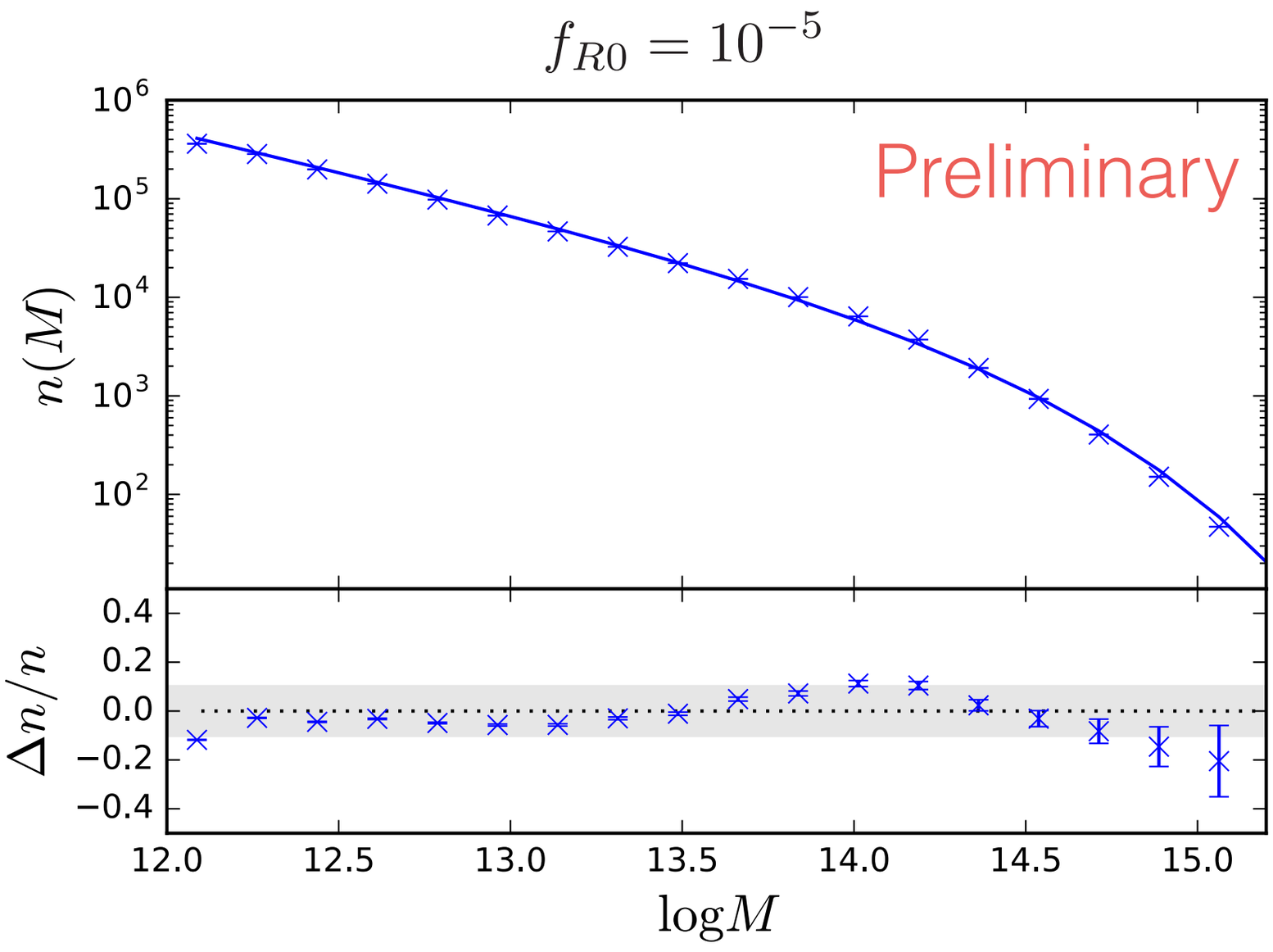
Cluster abundance in f(R)

- Kopp et al (1306.3233): obtain numerical solutions for $\delta_c(M, f_{R0}, z)$
- Collaps is ellipsoidal: stochastic, drifting barrier:

$$\delta_c(M, f_{R0}, z) + \beta\sigma^2$$

- Mass function involves two free parameters

Cluster abundance in f(R)

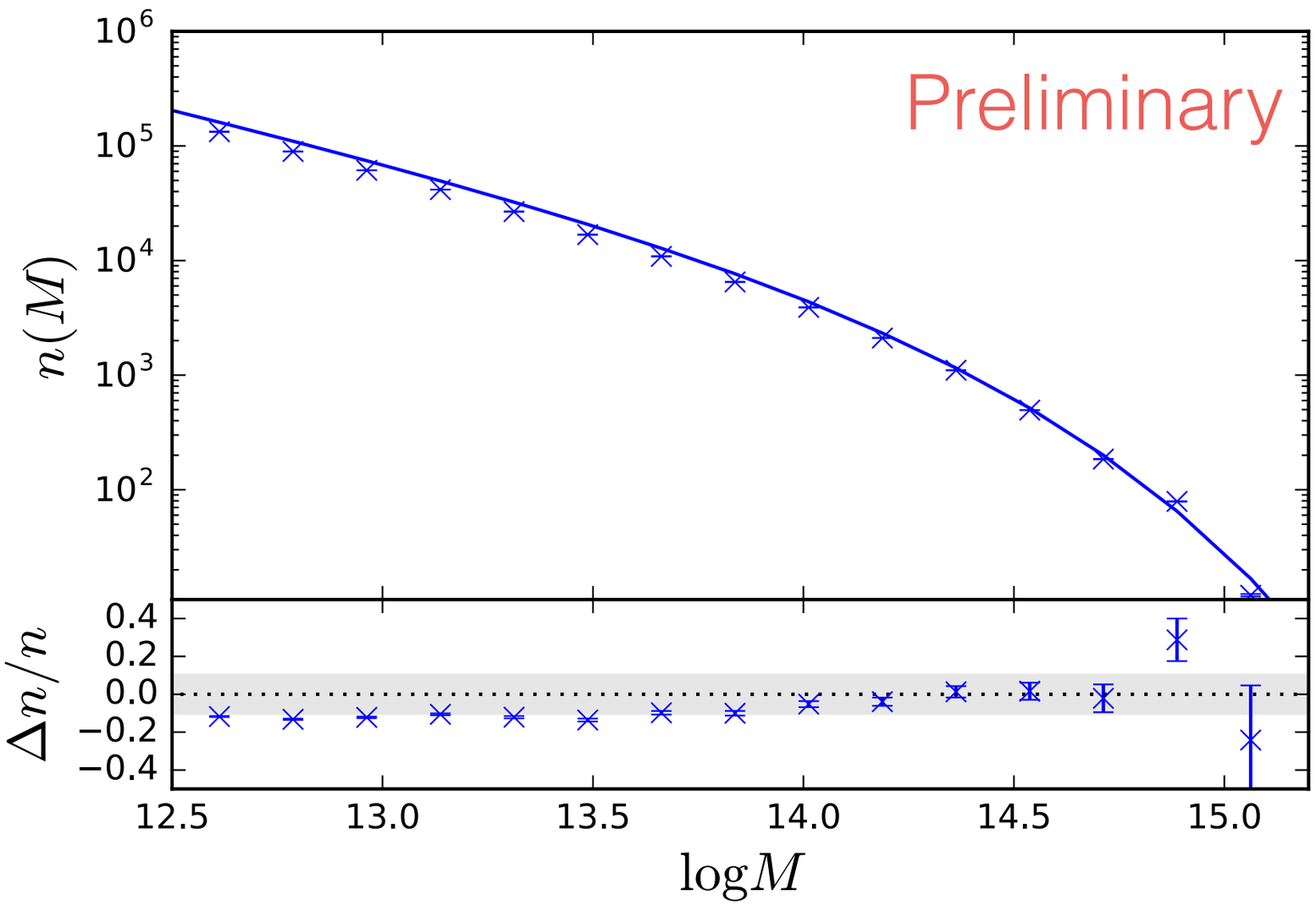


fit barrier parameters once to N-body simulations

~10% agreement possible

Joint cluster abundance

$$f_{R0} = 10^{-5} + \sum m_\nu = 0.3\,\mathrm{eV}$$



Theory captures neutrino effects without refitting

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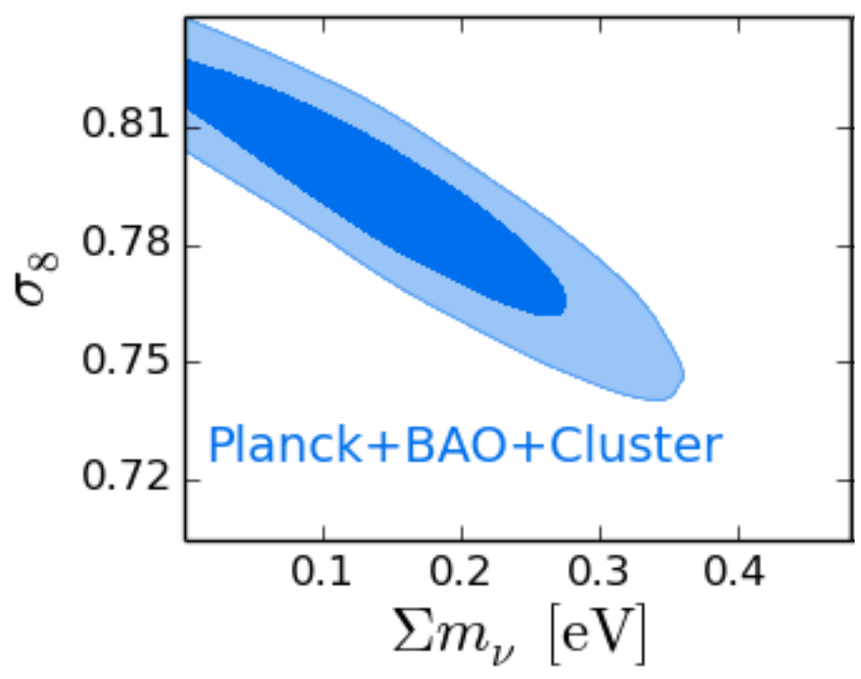
Current constraints

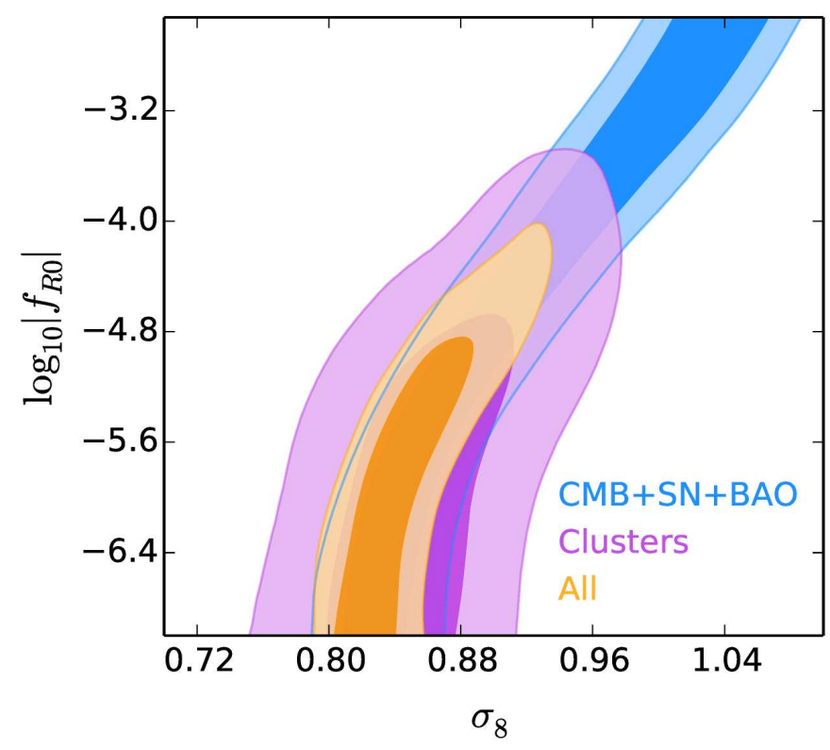
State of the art from Clusters (+ Planck + BAO):

$$\sum m_\nu = 0.2 - 0.3\mathrm{eV}$$



Costanzi et al 1407.8338

$$\log_{10} f_{R0} < 4.5$$



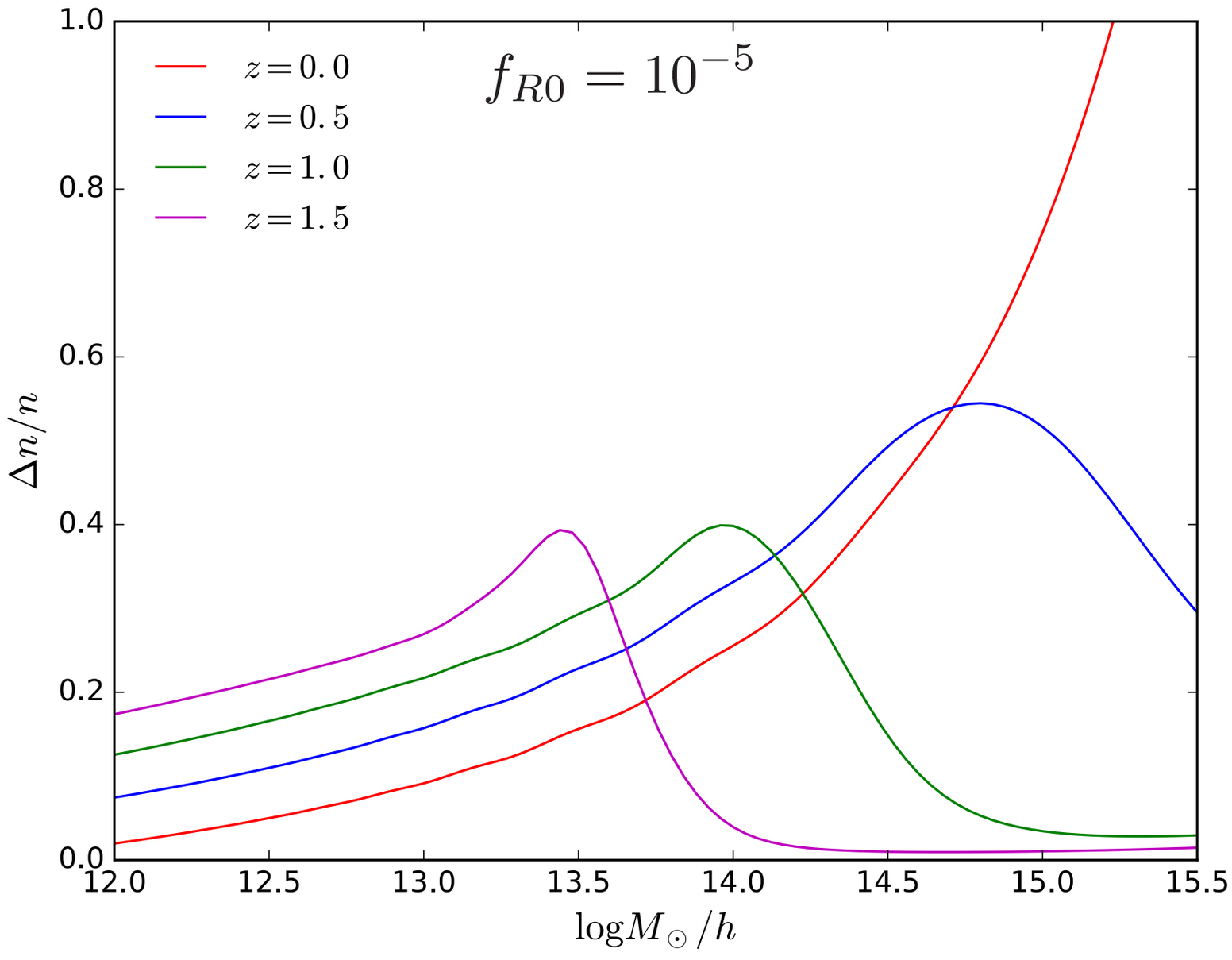
Cataneo et al 1412.0133

Summary

- Degeneracy of modified gravity and neutrino effects on LSS: Joint constraints necessary for realistic limits on new physics

- New tests combine astrophysics (to infer cluster masses) and cosmology

Cluster abundance in f(R)



Effect largest for massive, nearby clusters