NONLOCAL HALO BIAS WITH AND WITHOUT MASSIVE NEUTRINOS

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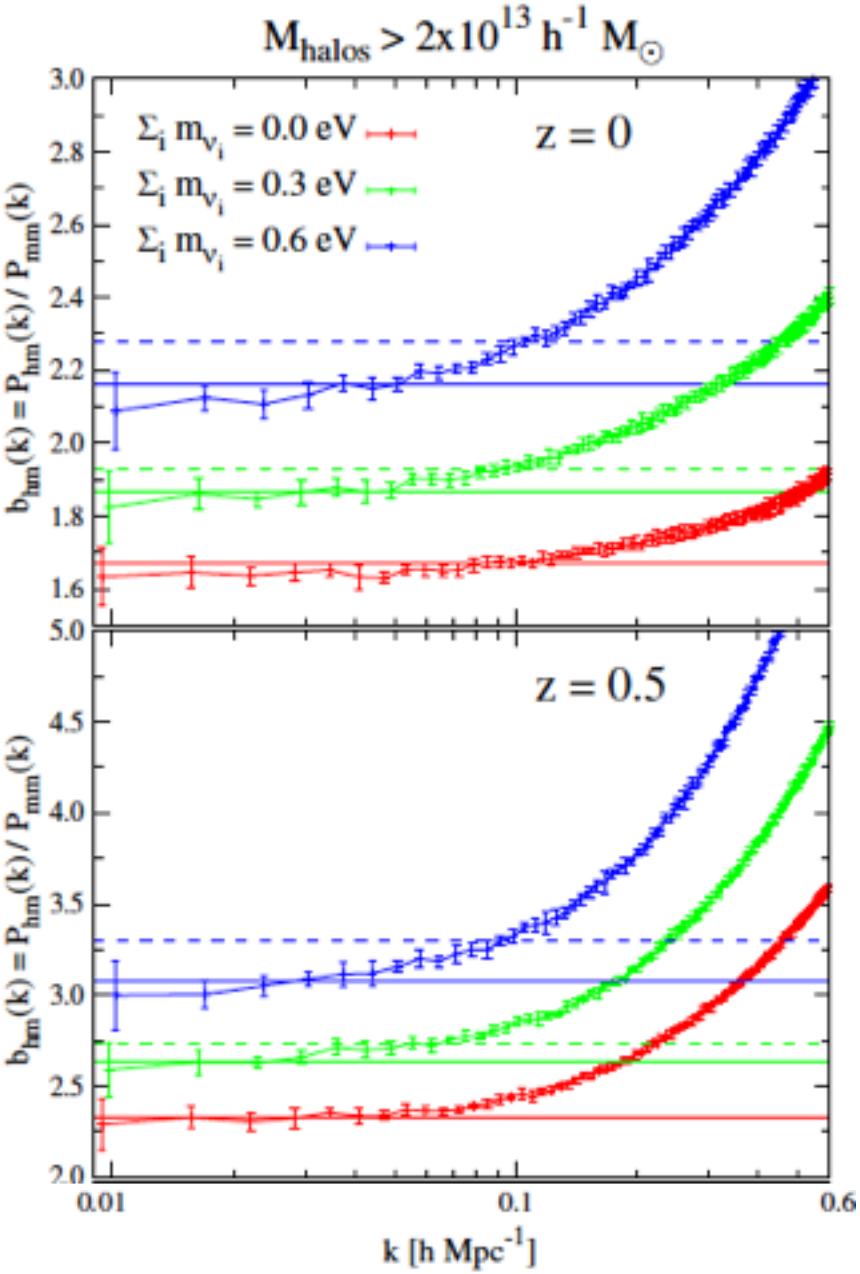
ArXiv: 1405.1435
with V. Desjacques, A. Kehagias and A. Riotto

MOTIVATION



Cosmology with massive neutrinos

Villaescusa-Navarro et al. JCAP 1403 (2014) 011

Castorina et al. JCAP 1402 (2014) 049

Costanzi et al. JCAP 1312 (2013) 012

MOTIVATION

WHAT DO WE NEED?

$$b_{\mathrm{hm}} = \frac{P_{\mathrm{hm}}}{P_{\mathrm{mm}}} = \frac{\langle \delta_h \delta_m \rangle}{\langle \delta_m \delta_m \rangle}$$

δ_m

- Analytic methods (PT, EFToLSS, …)
- Numerical methods (CAMB, CLASS, …)

$$\delta_h = \sum_i b_i \cdot invariants(\delta, \delta^2, \ldots)$$

MOTIVATION

WHAT DO WE NEED?

Ingredients	*LARGE SCALES*	*SMALL SCALES*
MASSIVE NEUTRINOS		
HALO BIAS		

MASSIVE NEUTRINOS

Neutrino perturbations

$$\delta_m = (1 - f_\nu)\delta_{cb} + f_\nu \delta_\nu$$

$$f_\nu = \frac{\Omega_\nu}{\Omega_m}$$

cb = CDM + baryons

Some numbers

$$\sum m_\nu = 0.1 - 0.6 eV$$

$$f_\nu \simeq 0.01 - 0.05$$

$$\Omega_m = 0.2708$$

MASSIVE NEUTRINOS

Considerations

1. Massive neutrinos contribute to gravitational clustering through the Poisson equation

$$\nabla^2 \phi = 4\pi G a^2 \rho_m \delta_m$$

so even if $\delta_{cb} \simeq \delta_\nu$ the contribution is suppressed as $f_\nu \simeq 0.05$

2. Neutrino perturbations stay linear up to higher k than CDM because of large velocity dispersion (Hot DM) so they free-stream with a characteristic scale

$$k_{\mathrm{FS}} \simeq 1.5 \sqrt{\frac{\Omega_m(z)}{1+z}} \left(\frac{\sum m_\nu}{\mathrm{eV}}\right) \mathrm{h}^{-1}\mathrm{Mpc} \simeq 0.08 - 0.47\,\mathrm{h}^{-1}\mathrm{Mpc} \qquad z = 0$$

$k >> k_{\mathrm{FS}}$ no clustering (suppression of the growth)

$k << k_{\mathrm{FS}}$ clustering (behave like CDM)

MASSIVE NEUTRINOS

Ingredients	*LARGE SCALES*	*SMALL SCALES*
MASSIVE NEUTRINOS	***Behave like CDM***	***Free-streaming (growth suppression)***
HALO BIAS		

Cold Dark Matter prescription

Assume that dark matter halos trace CDM plus baryons, with a linear growth rate suppressed in a scale dependent way by the massive neutrinos

$$\delta_h = \sum_i b_i \cdot invariants(\delta_c, \delta_c^2, ...)$$

HALO BIAS

A model for the halo bias :

$$\delta_{\mathrm{h}} = b_{10}\delta - b_{01}\nabla^2\delta + \frac{1}{2!}b_{20}\delta^2 + \frac{1}{2}b_{s^2}s^2 + b_{\psi}\psi + b_{st}s\cdot t + \cdots$$

where

$$b_{10} = 1 + b_{10}^{\mathrm{L}}, \quad b_{01} = -R_v^2 + b_{01}^{\mathrm{L}}, \quad b_{20} = b_{20}^{\mathrm{L}} + \frac{8}{21}b_{10}^{\mathrm{L}},$$

$$b_{s^2} = -\frac{4}{7}b_{10}^{\mathrm{L}}, \quad b_{\psi} = -\frac{1}{2}b_{10}^{\mathrm{L}}, \quad b_{st} = -\frac{5}{7}b_{10}^{\mathrm{L}}.$$

HALO BIAS

- NONLOCALITY BY GRAVITATIONAL MODE-COUPLING

On sufficiently large scales, the number density of proto-halos through cosmic time is conserved $\dot{\delta}_h + \nabla \cdot [(1+\delta_h)\vec{v}] = 0$

We can thus solve $\dot{\delta}_h - \dot{\delta} + \nabla \cdot [(\delta_h - \delta)\vec{v}] = 0$ order by order in perturbation theory

Elia, Kulkarni, Porciani, Pietroni and Matarese (2011)
Chan, Scoccimarro and Sheth (2012)

- NONLOCALITY AT EARLY TIMES

We assumed $\delta_h(\tau_i) = \sum_l \frac{b_l^L(\tau_i)}{l!}\delta^l(\tau_i)$ but the peak model allows for scale dependence at early times $\delta_h(\vec{x},\tau_i) = b_{10}^{\mathrm{L}}(\tau_i)\delta(\vec{x},\tau_i) - b_{01}^{\mathrm{L}}(\tau_i)\nabla^2\delta(\vec{x},\tau_i) + \ldots$

Desjacques (2013)

- VELOCITY BIAS

Baldauf, Desjacques and Seljiak (2014)
Biagetti, Desjacques, Kehagias and Riotto (2014)

Peak velocities are statistically biased at linear order

$$\vec{v}_h(\vec{x},\tau_i) = \vec{v}(\vec{x},\tau_i) - R_v^2 \nabla\delta(\vec{x},\tau_i)$$

R_v characteristic scale proportional to the Lagrangian radius of the halo

HALO BIAS + MASSIVE NEUTRINOS

Ingredients	*LARGE SCALES*	*SMALL SCALES*
MASSIVE NEUTRINOS	***Behave like CDM***	***Free-streaming (growth suppression)***
HALO BIAS	***Linear***	***Non-local***

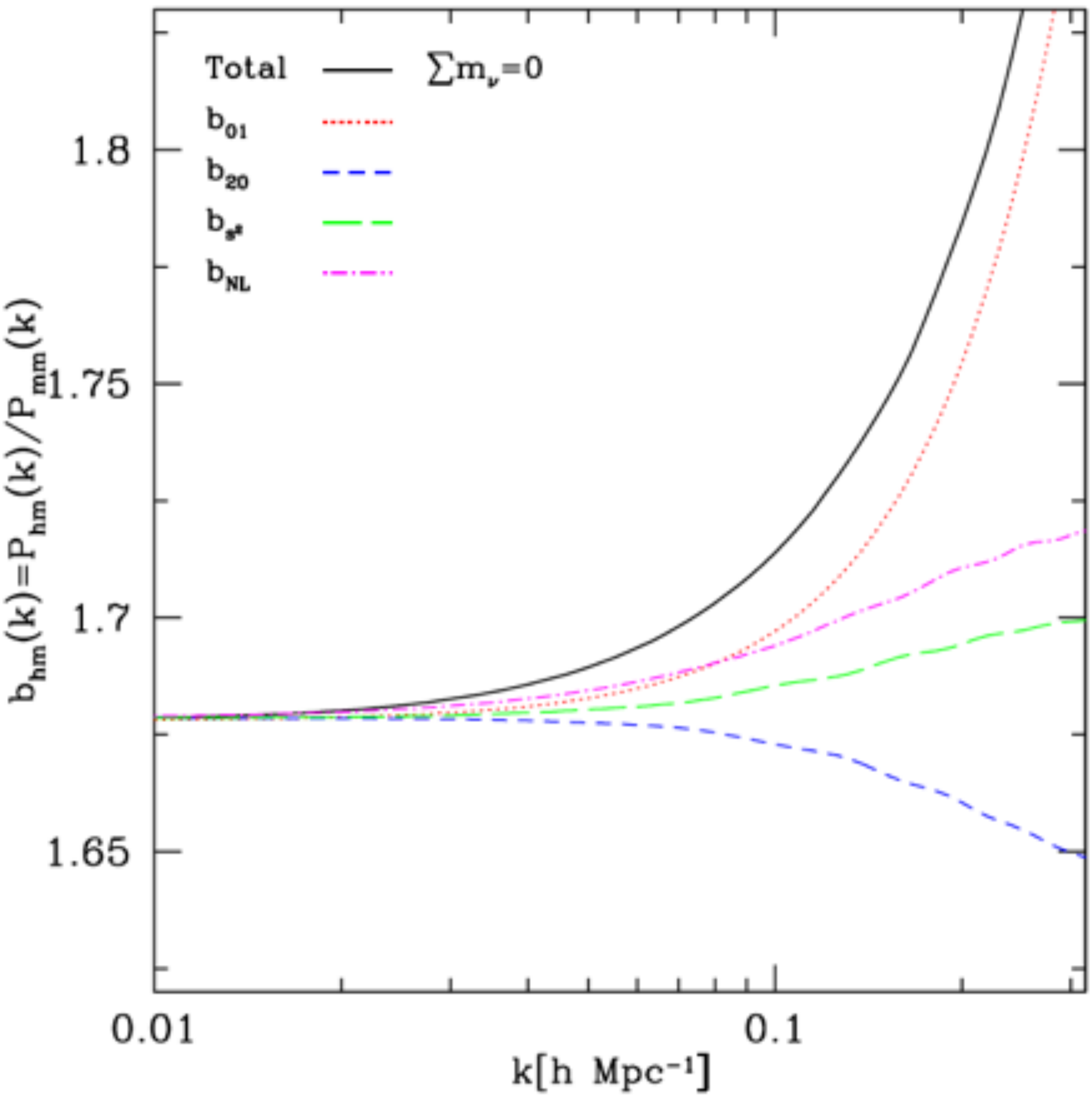
$$b_{\rm hm} = \frac{P_{\rm hm}}{P^{\rm NL}_{\rm mm}} = \frac{\left(b_{10} + b_{01} k^2\right) P^{\rm NL}_{\rm cm}(k) + \Delta P_{\rm hm}(k) + P_{\rm cc}(k) I_3(k)}{P^{\rm NL}_{\rm mm}(k)}$$

$$\Delta P_{\rm hm} \propto \; b_{s^2}, b_{20}$$

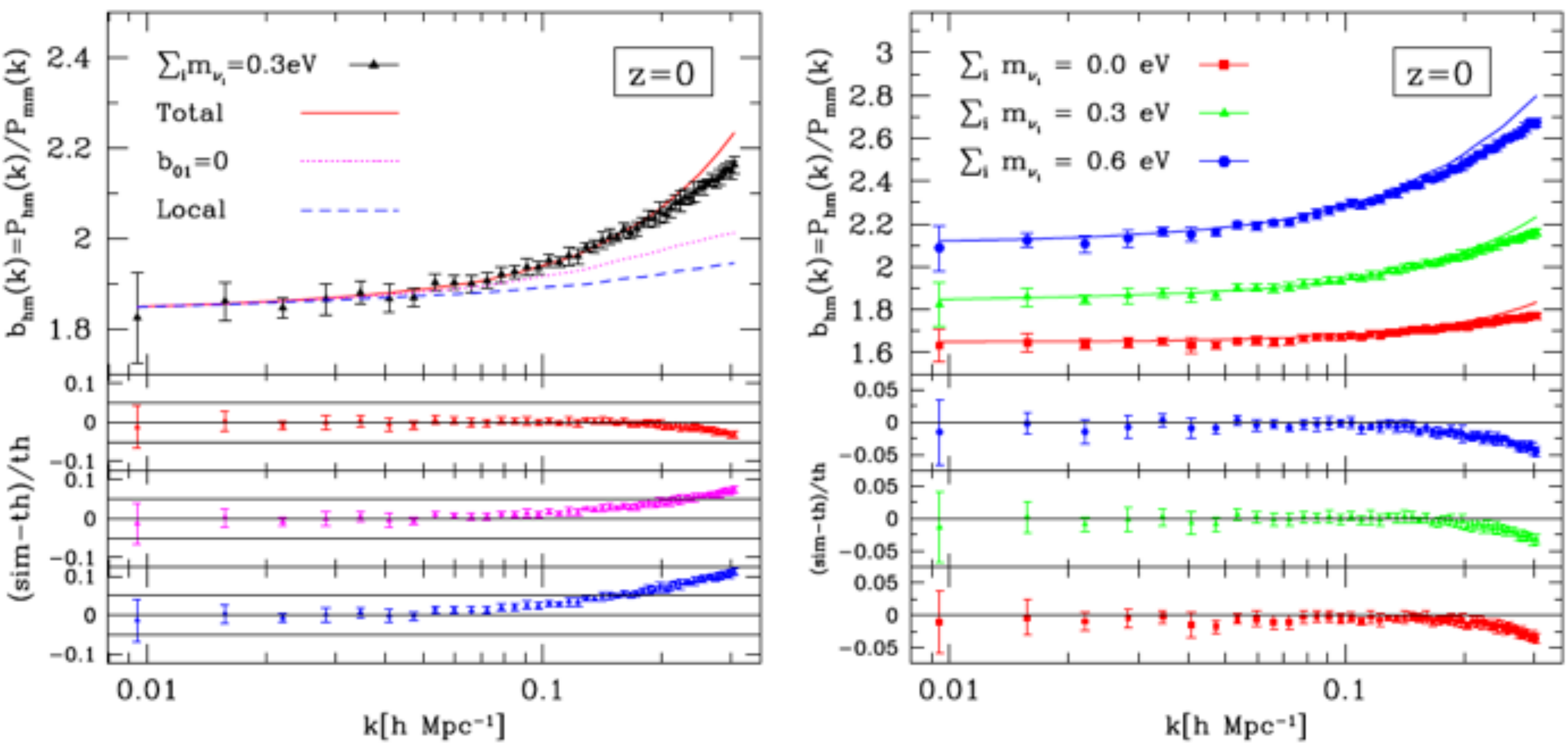
where

$$P_c c(k) I_3(k) \propto \; \frac{32}{105}\left(b_{st} - \frac{5}{2} b_{s^2} + \frac{16}{21} b_\psi\right) = \frac{32}{315} b^{\rm L}_{10} \equiv b_{\rm NL}$$

HALO BIAS WITHOUT NEUTRINOS



HALO BIAS WITH NEUTRINOS



TAKE HOME MESSAGE

In cosmologies with massive neutrinos, scale dependences arise at mildly non-linear scales, partly due to linear suppression growth and partly to non locality of bias: neither can be neglected to predict N-body simulations.