Constraining neutrino mass from galaxy clustering measurements

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Cosmological neutrinos

- Oscillation experiments (95%): $M_\nu = \Sigma m_\nu > 0.06$ eV

  Gonzales-Garcia et al (2014), Forero et al (2014), Esteban et al (2017)

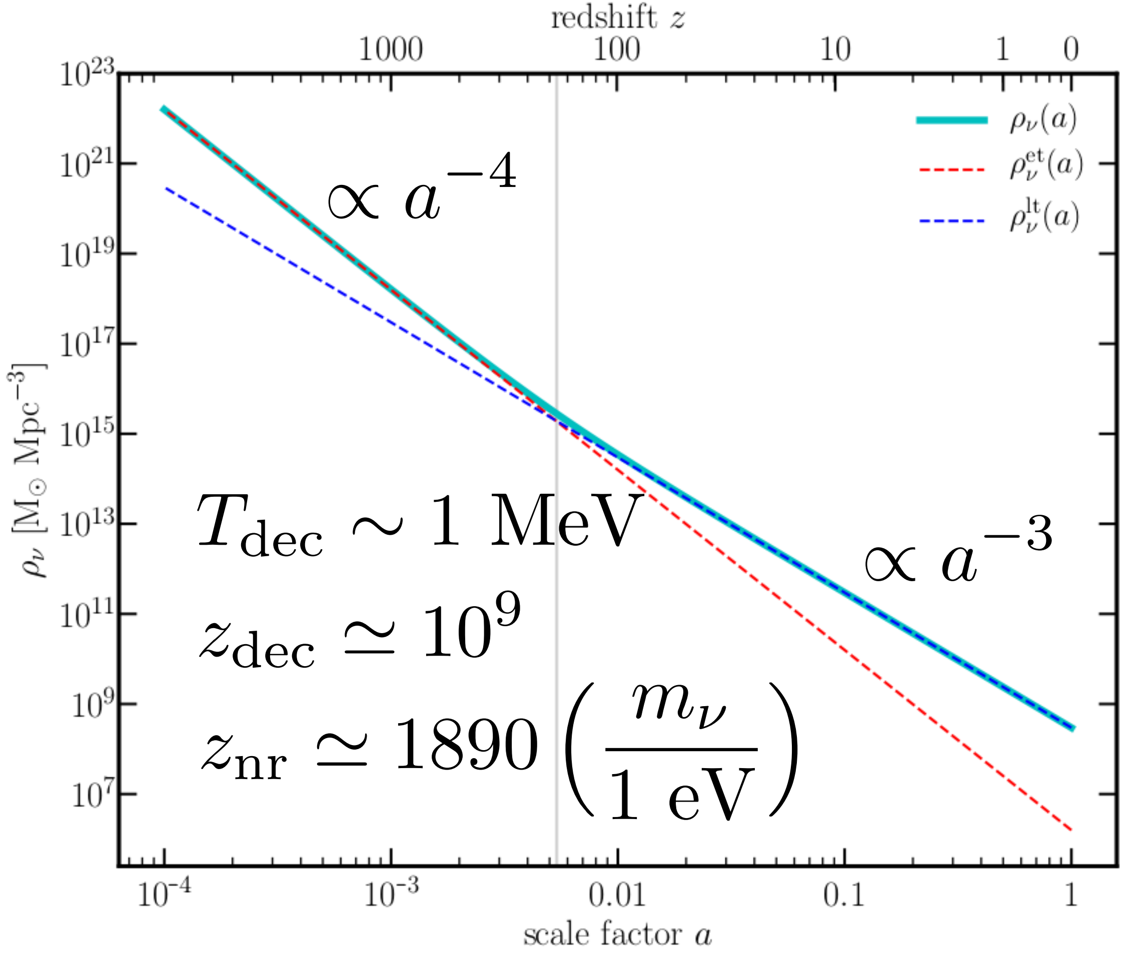
- β-decay experiments (95%): $m(\nu_e) < 2.2$ eV

  Kraus et al (2005)

- In cosmology: hot dark matter accounting for a fraction of total dark matter

  $M_\nu < 0.49$ eV (Planck collaboration, 2015), $M_\nu < 0.22$ eV (Pellejero-Ibanez et al, 2016), $M_\nu < 0.12$ eV (Palanque-Delabrouille et al, 2015) and many many more…

Cosmological neutrinos



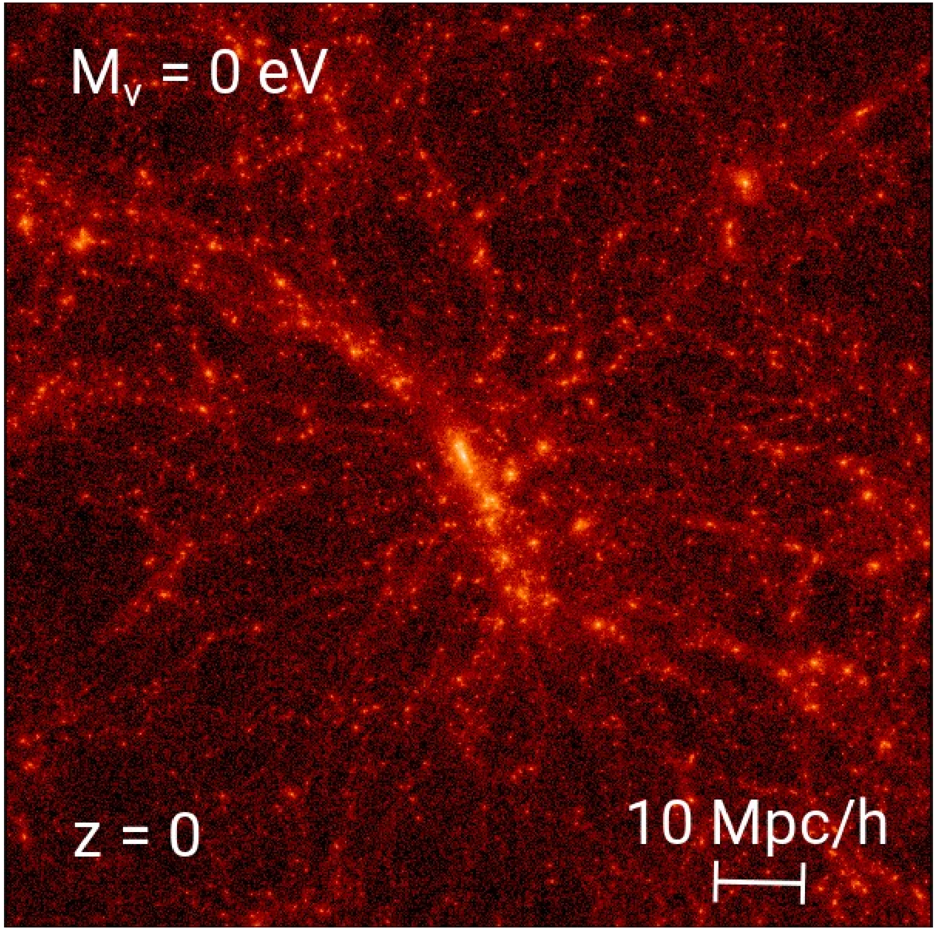
- Light (< 1 eV)
- Weakly interacting
- Fermi-Dirac distribution
- Let's consider:
  - Total mass M_ν
  - Degenerate case $M_\nu = 3\ m_\nu$

Growth of matter overdensities

$$\frac{\partial^2 \delta_i}{\partial t^2} + 2H\frac{\partial \delta_i}{\partial t} = \frac{c_s^2 \nabla^2 \delta_i}{a^2} + 4\pi G\bar{\rho}\delta_{\rm tot}$$

$$k_{\rm FS} = \sqrt{\frac{4\pi G\bar{\rho}a^2}{c_s^2}} \simeq 0.91\frac{\sqrt{\Omega_m(1+z)+\Omega_\Lambda}}{(1+z)^2}\left(\frac{m_\nu}{1\,{\rm eV}}\right)\,h\,{\rm Mpc}^{-1}$$

Suppression of clustering



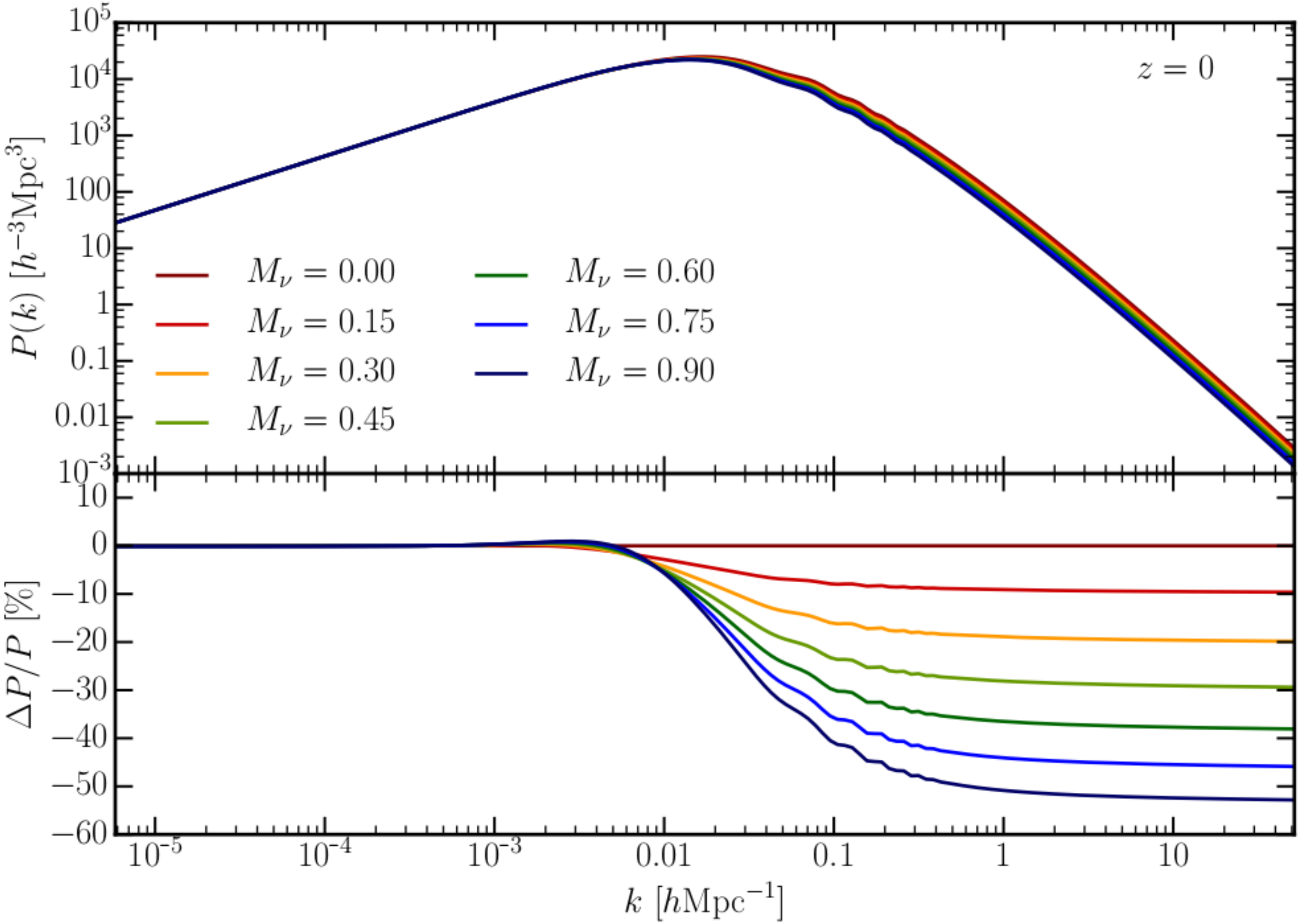
Poisson's equation

$$\nabla^2 \varphi = 4\pi G \bar{\rho} a^2 \left[(1 - \mathfrak{f}_\nu)\delta_{\text{cold}} + \underline{\mathfrak{f}_\nu \delta_\nu} \right]$$

Effectively → 0, for $k > k_{FS}$

DEMNUni simulations by C. Carbone

Suppression of clustering



Galaxy clustering ratio

Galaxy clustering

- Galaxies are a discrete, biased sampling of the underlying matter field
- If the bias function is local and deterministic

$$\delta_g(x) = F[\delta(x)]$$

- If it is also smooth enough

$$\delta_g(x) = \sum_{i=0}^{\infty} \frac{b_i}{i!} \delta^i(x)$$

Fry & Gaztañaga (1993)

Clustering ratio

Bel & Marinoni (2014)

- 2PCF: $$\xi_{g,R}(r) = b_1^2 \xi_R(r)$$

- Variance: $$\sigma^2_{g,R} = b_1^2 \sigma^2_R$$

- CR: $$\eta_{g,R}(r) \equiv \frac{\xi_{g,R}(r)}{\sigma^2_{g,R}} \equiv \frac{\xi_R(r)}{\sigma^2_R} \equiv \eta_R(r)$$

- z-space (Kaiser): $$\eta^z_{g,R}(r) \equiv \eta_R(r)$$

Clustering ratio: 2nd order

- Hierarchical growth of fluctuations

$$\langle \delta_R^n \rangle_c = S_n \; \sigma_R^{2(n-1)}$$

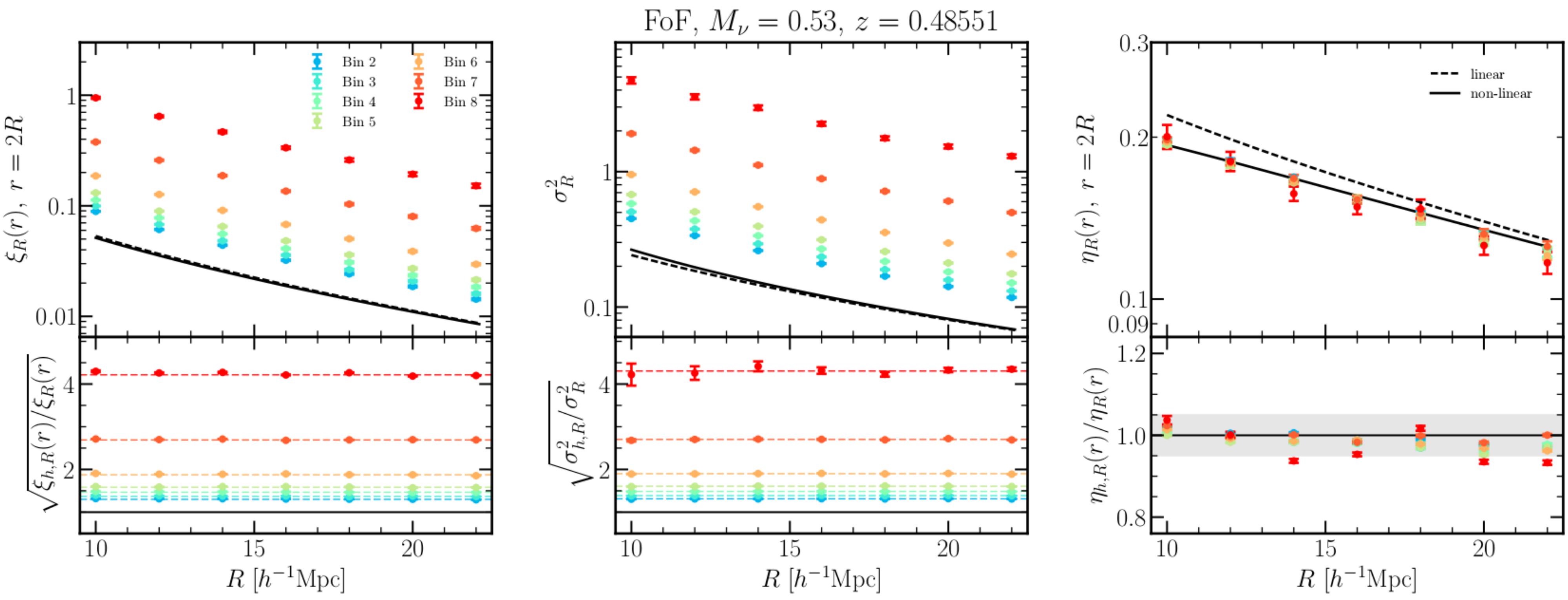
$$\left\langle \delta_{i,R}^n \delta_{j,R}^m \right\rangle_c = C_{nm} \; \xi_R(r) \; \sigma_R^{2(n+m-2)}$$

- With large enough *R*, CR is unbiased

$$\eta_{g,R}(r) \sim \eta_R(r) - \left\{ (S_{3,R} - C_{12,R}) \frac{b_2}{b_1} + \frac{1}{2} \left(\frac{b_2}{b_1} \right)^2 \right\} \xi_R(r) + \frac{1}{2} \left(\frac{b_2}{b_1} \right)^2 \; \eta_R(r) \; \xi_R(r)$$

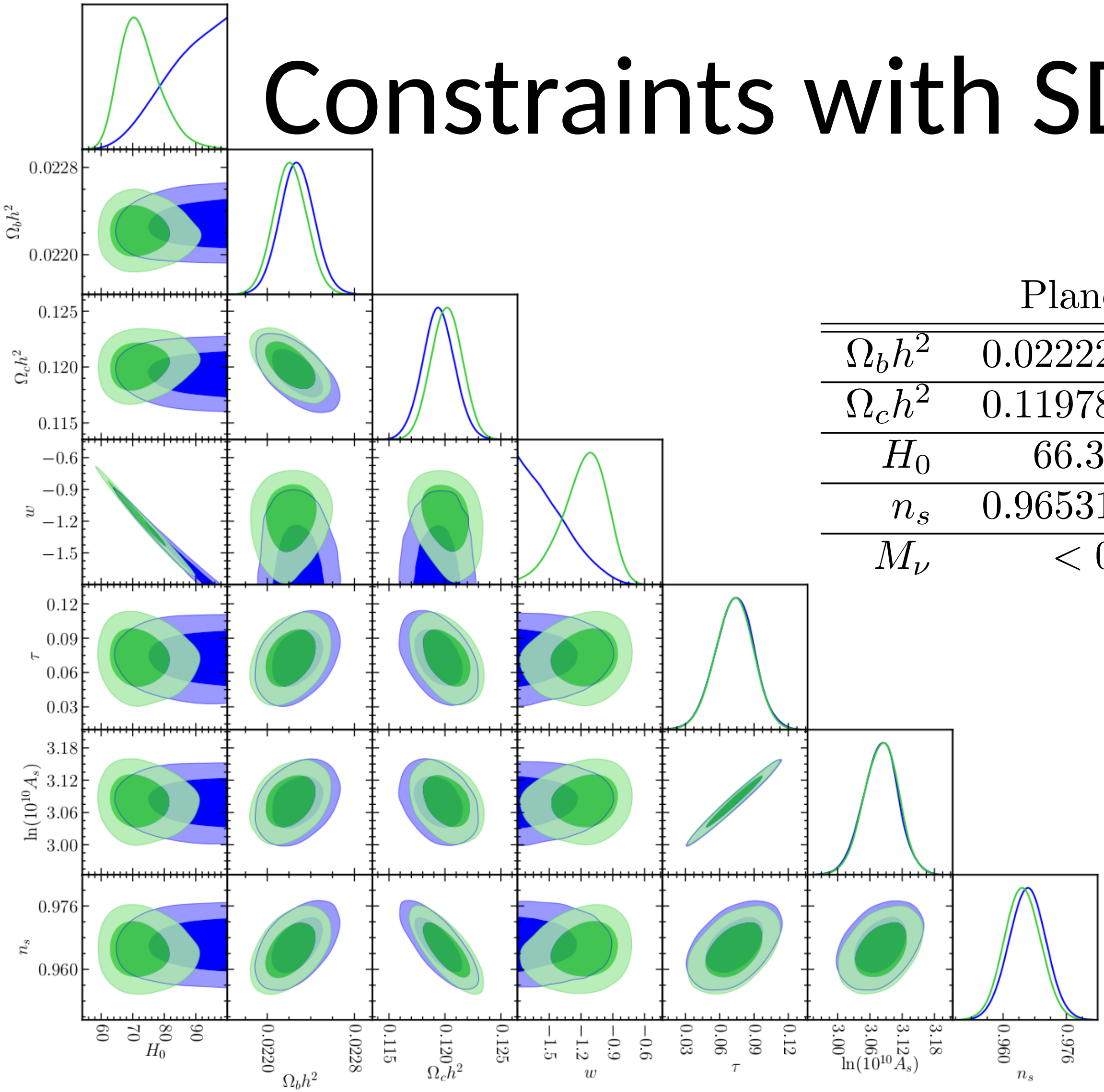
Possible nonlocal contributions only affect b_2 (Bel et al, 2015)

Clustering ratio: unbiased



MZ et al (2018)

Constraints with SDSS DR7 + 12



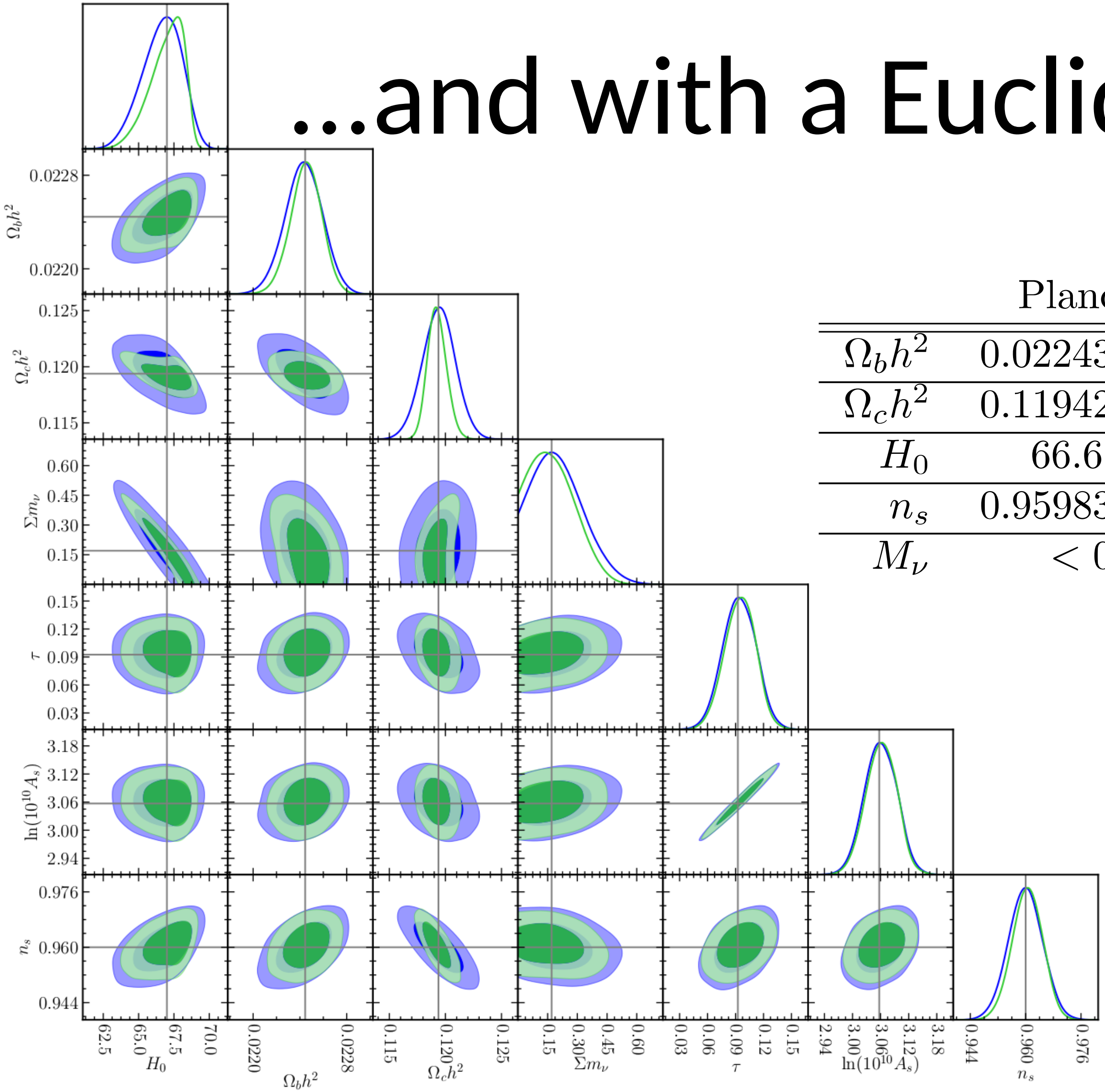
	Planck (95%)	Planck+CR (95%)	
$\Omega_b h^2$	0.02222 ± 0.00033	0.02222 ± 0.00031	$\sim 6\%$
$\Omega_c h^2$	0.11978 ± 0.00291	0.11972 ± 0.00255	$\sim 12\%$
H_0	66.36 ± 3.15	66.47 ± 2.93	$\sim 7\%$
n_s	0.96531 ± 0.00951	0.96550 ± 0.00906	$\sim 5\%$
M_ν	< 0.49402	< 0.47835	$\sim 3\%$

MZ et al (2018)

Planck

Planck + CR

...and with a Euclid-like survey



	Planck (95%)	Planck+CR (95%)	
$\Omega_b h^2$	0.02243 ± 0.00031	0.02245 ± 0.00026	$\sim 15\%$
$\Omega_c h^2$	0.11942 ± 0.00290	0.11926 ± 0.00167	$\sim 40\%$
H_0	66.67 ± 2.63	66.98 ± 2.18	$\sim 20\%$
n_s	0.95983 ± 0.00964	0.96046 ± 0.00854	$\sim 10\%$
M_ν	< 0.43157	< 0.37693	$\sim 14\%$

MZ et al (2018)

Planck

Planck + CR

Galaxy power spectrum

Galaxy bias: subhalo abundance matching (SHAM)

- Matching according to $v_{\rm max} = \max(\sqrt{GM(<r)/r})$

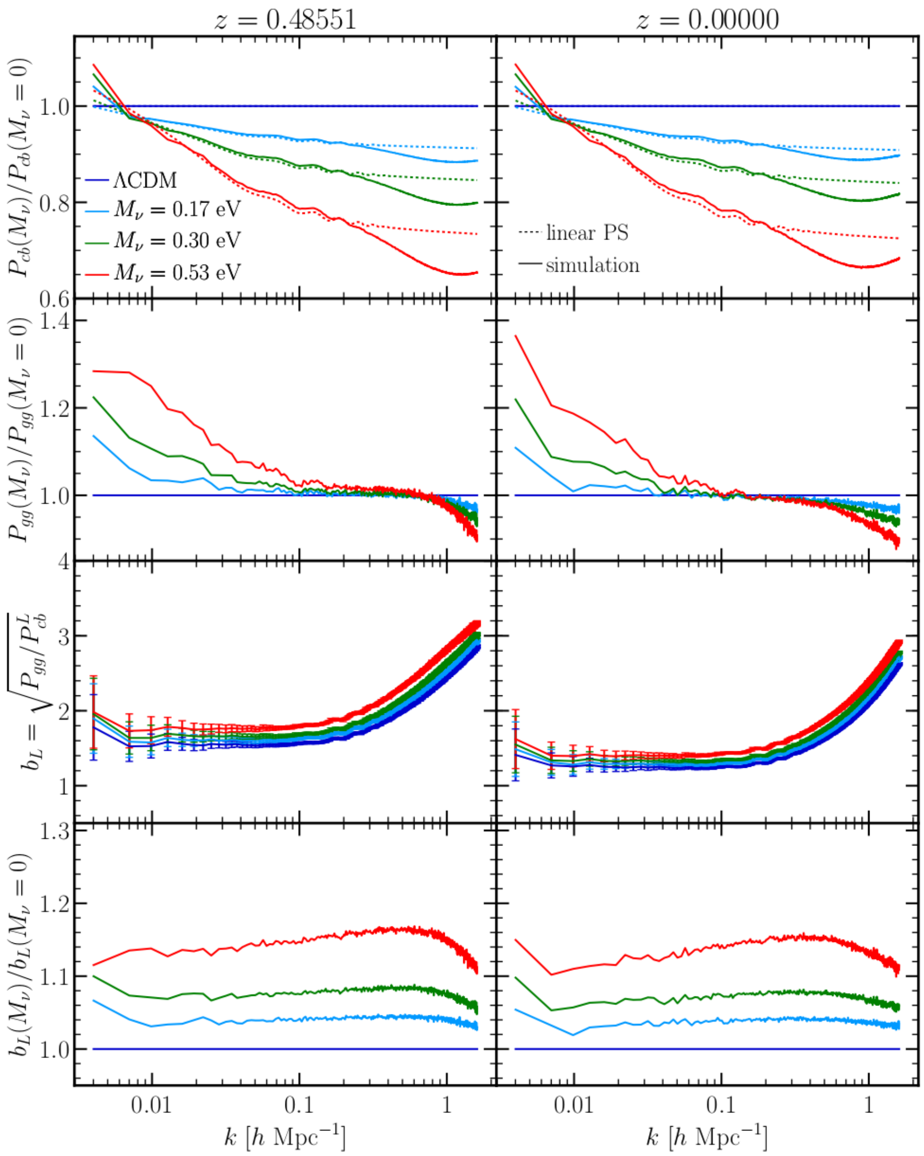
- DEMNUni sims (C. Carbone) $z \simeq \{0.0, 0.5, 1.0, 1.5, 2.0\}$

  Carbone et al (2016), Castorina et al (2015), **presented today by Andrea Pezzotta**

- $\bar{n} = \{10^{-3}, 3 \times 10^{-4}, 10^{-4}\}\ h^3\ \mathrm{Mpc}^{-3}$

Linear bias model

$$P_g(k) = b_1^2 P(k)$$

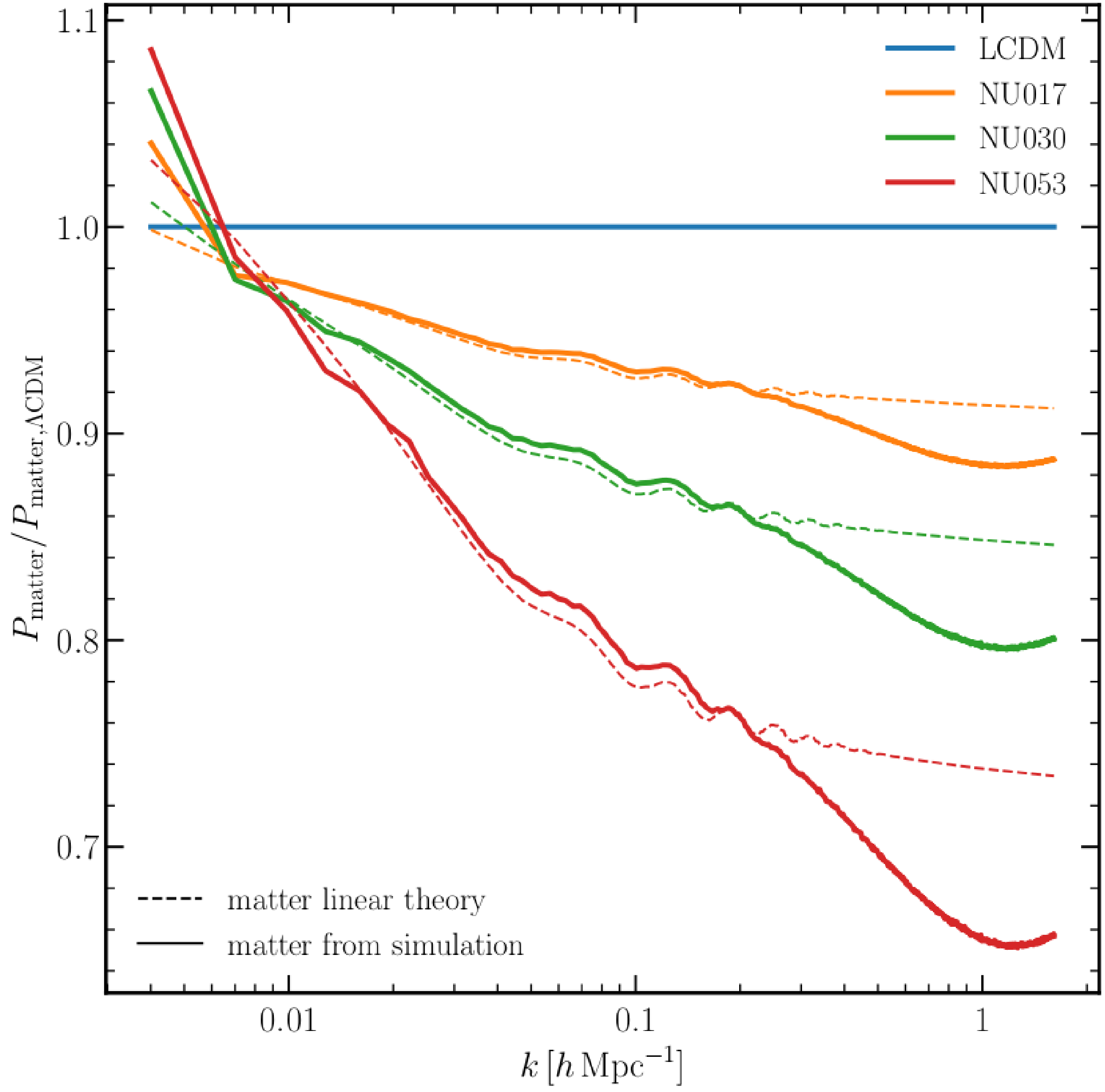


Massive / massless case for **cold matter**

Massive / massless case for **galaxies**

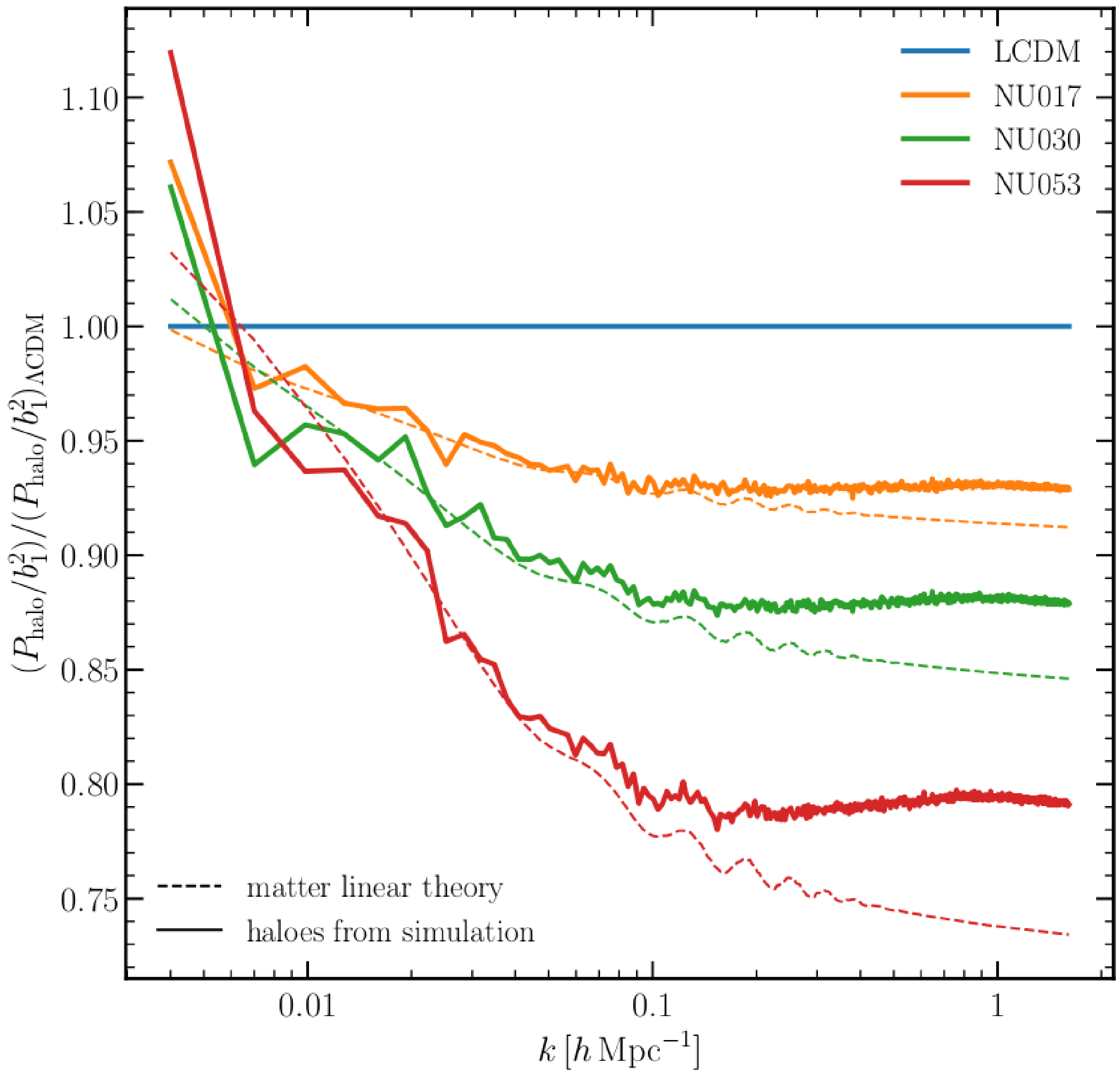
Linear bias (gaussian errors)

Massive / massless case for the **linear bias**



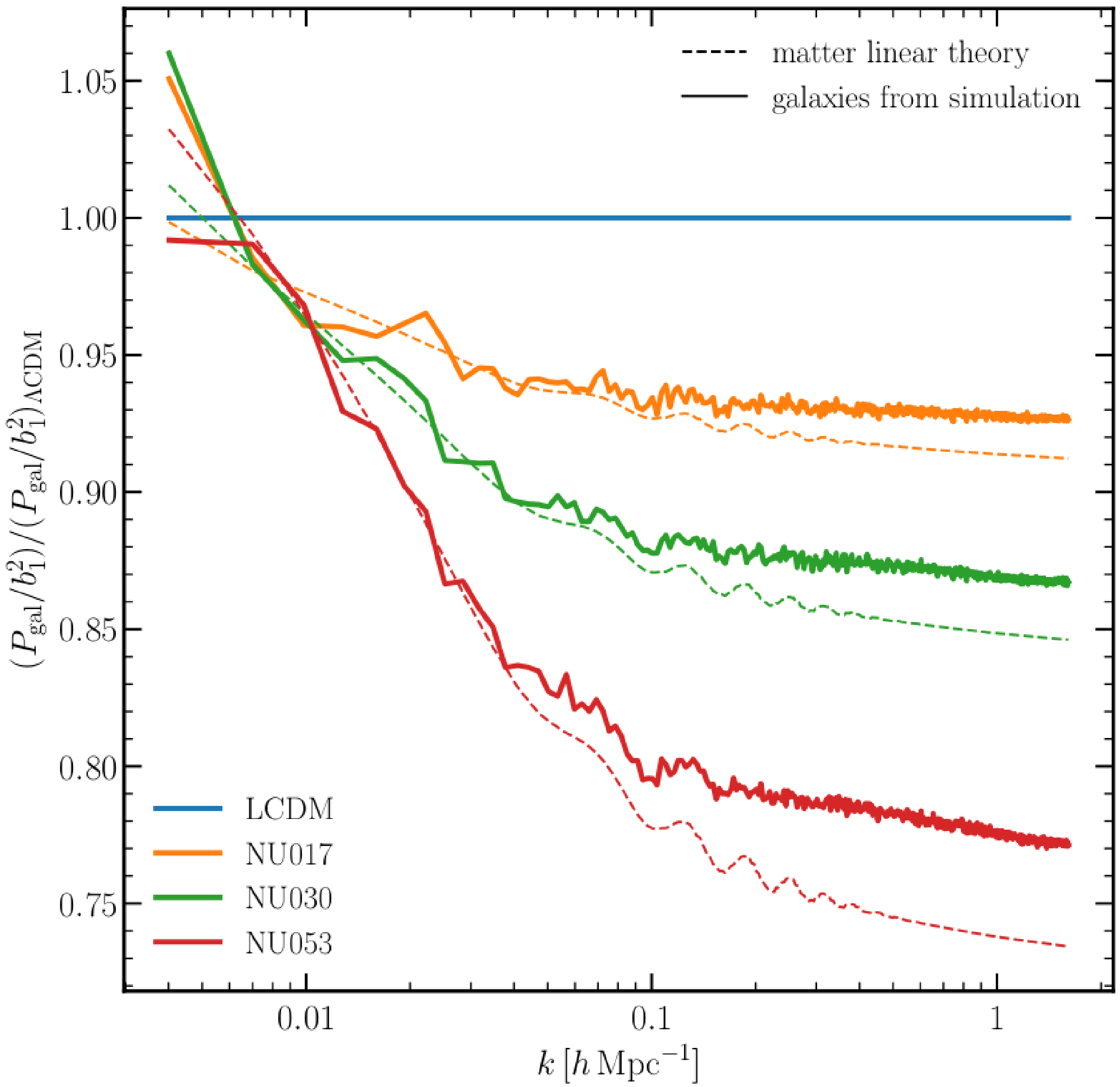
LCDM
NU017
NU030
NU053
1.1
1.0
0.9
0.8
0.7
$P_{\mathrm{matter}}/P_{\mathrm{matter},\Lambda\mathrm{CDM}}$
0.01
0.1
1
$k\,[h\,\mathrm{Mpc}^{-1}]$
matter linear theory
matter from simulation

Matter



LCDM
NU017
NU030
NU053
matter linear theory
haloes from simulation
$(P_{\rm halo}/b_1^2)/(P_{\rm halo}/b_1^2)_{\Lambda\rm CDM}$
$k\ [h\,\rm Mpc^{-1}]$
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.01
0.1
1

Haloes

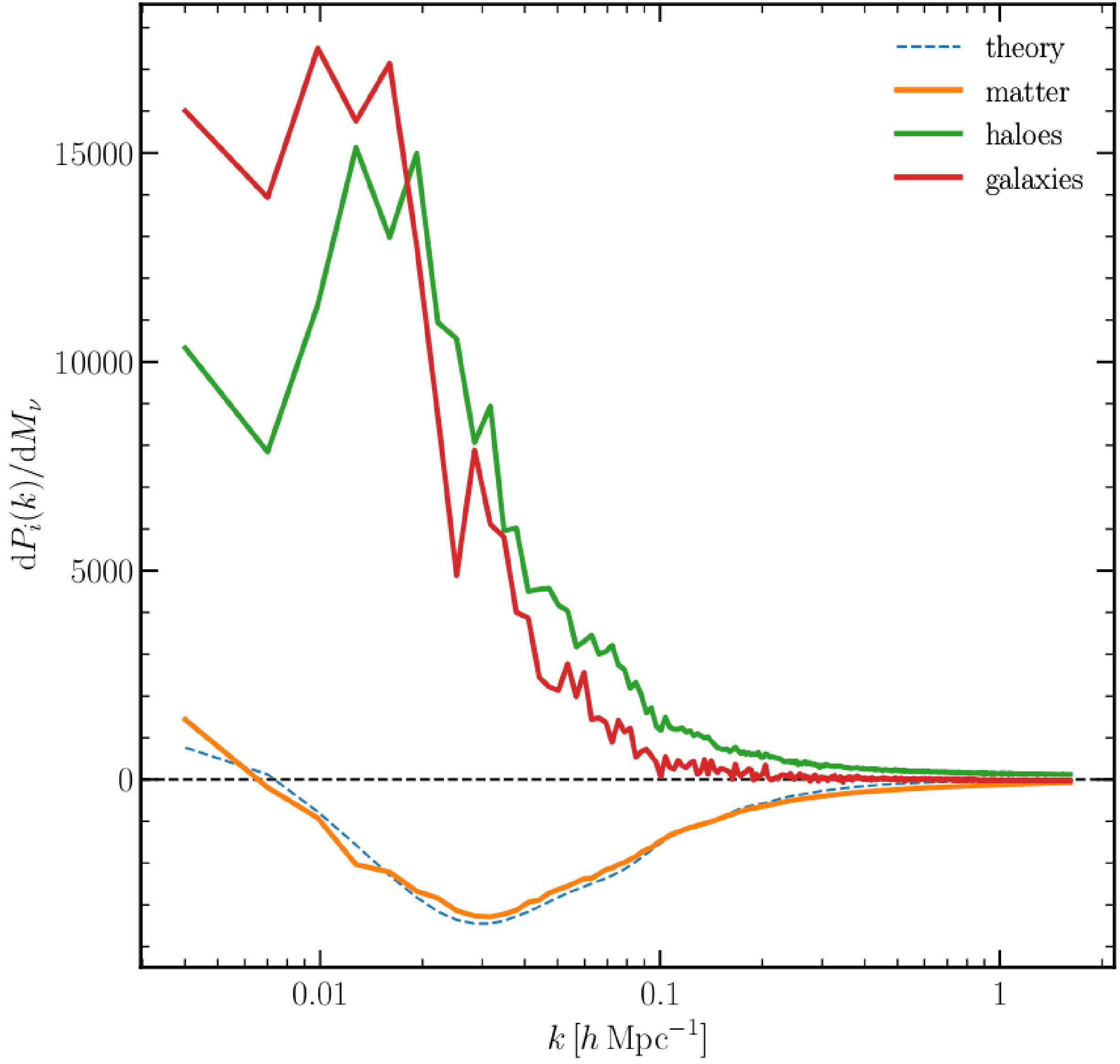


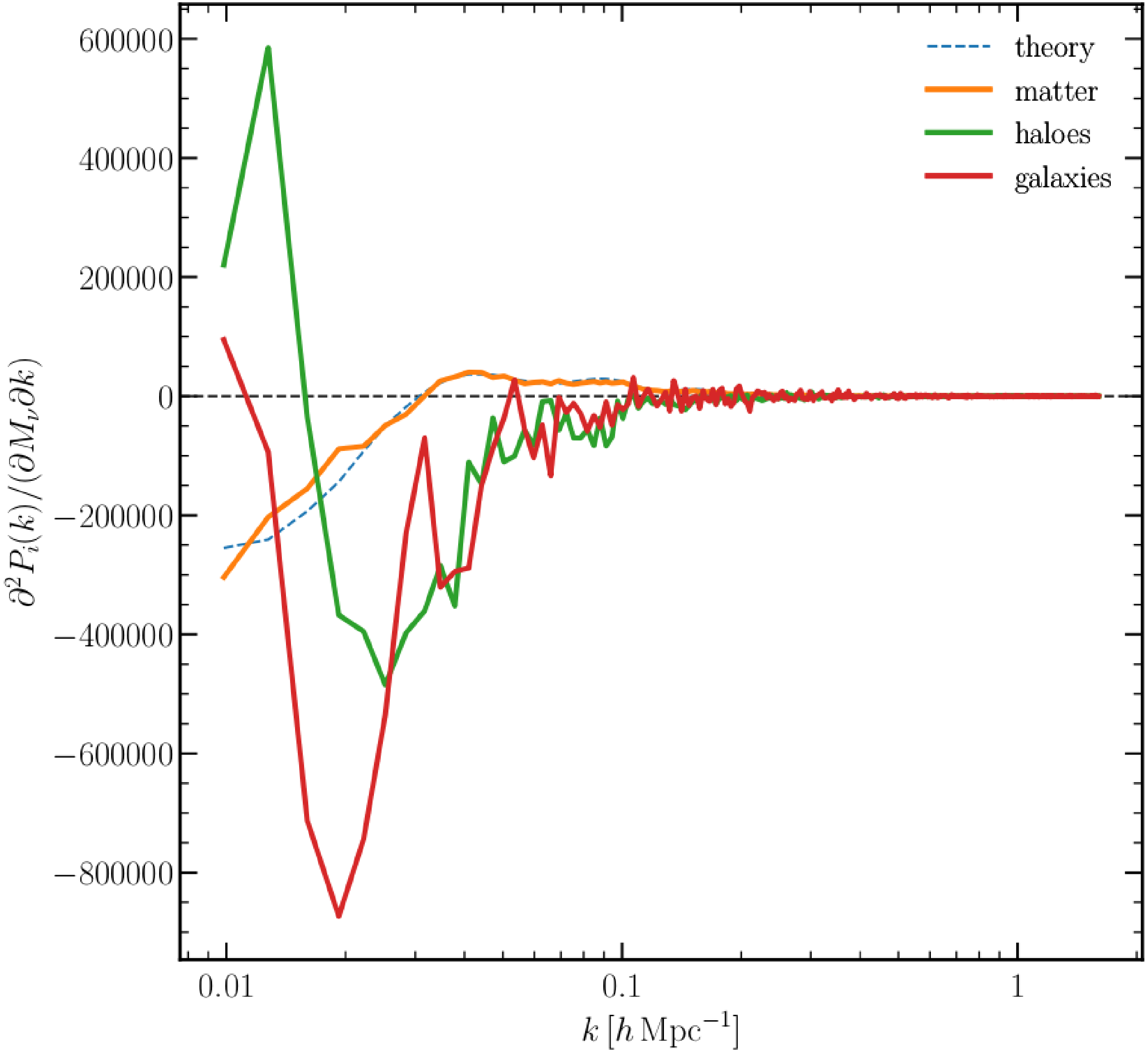
matter linear theory
galaxies from simulation
LCDM
NU017
NU030
NU053
$(P_{\rm gal}/b_1^2)/(P_{\rm gal}/b_1^2)_{\Lambda\rm CDM}$
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.01
0.1
1
$k\ [h\,\rm Mpc^{-1}]$

Matter

Derivatives

wrt neutrino mass





Derivatives

wrt neutrino mass and scale

Nonlocal, nonlinear model

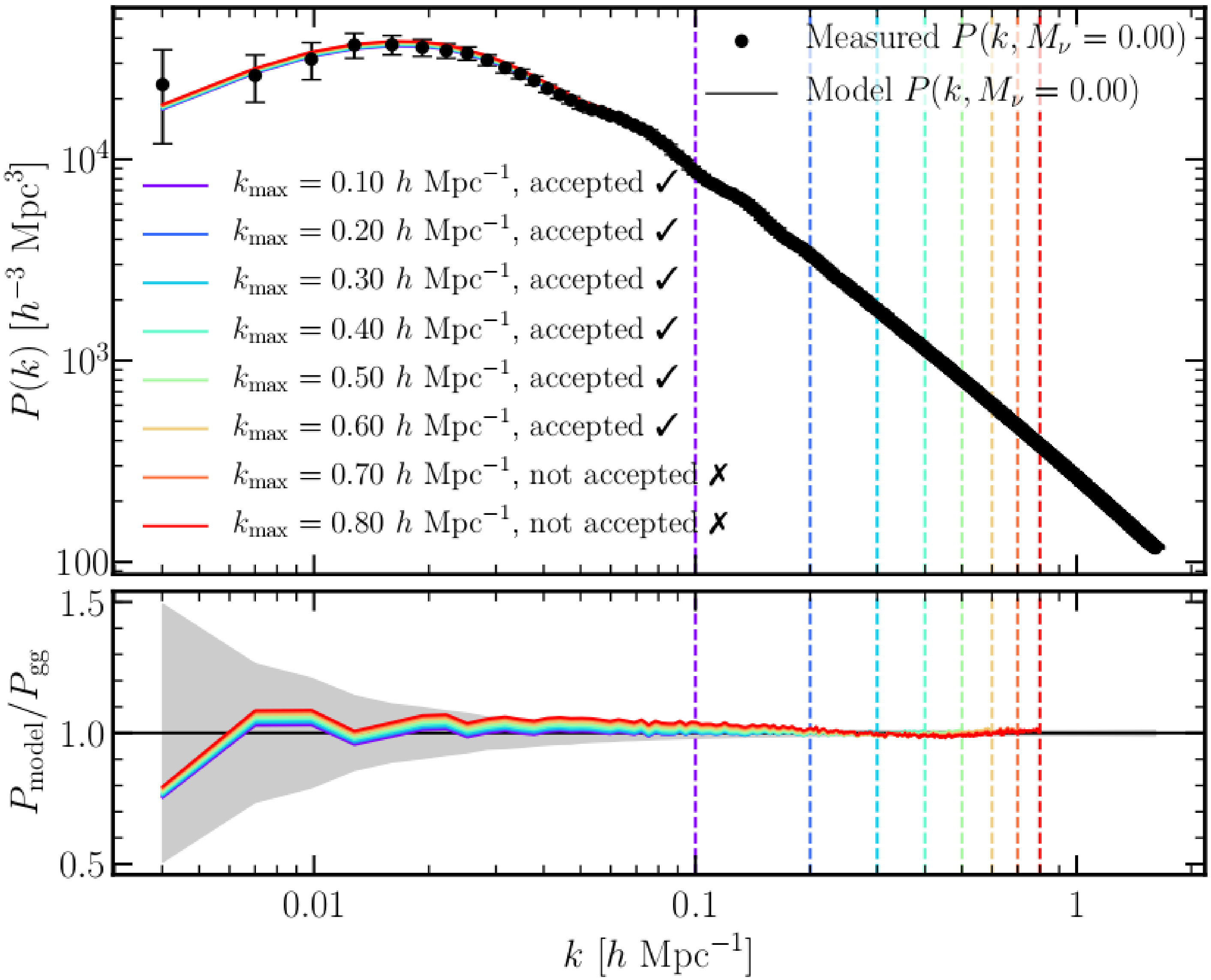
$$P_{\mathrm{g},\delta\delta}(k) = b_1^2 P_{\delta\delta}(k) + 2b_1 b_2 P_{b_2,\delta}(k) + 2b_1 b_{s^2} P_{b_{s^2},\delta}(k)$$
$$+ 2b_1 b_{3\mathrm{nl}} \sigma_3^2(k) P^{\mathrm{lin}}(k) + b_2^2 P_{b_2^2}(k)$$
$$+ 2b_2 b_{s^2} P_{b_2 s^2}(k) + b_{s^2}^2 P_{b_{s^2}^2}(k)$$

McDonald & Roy (2009)

Nonlocal, nonlinear: free parameters

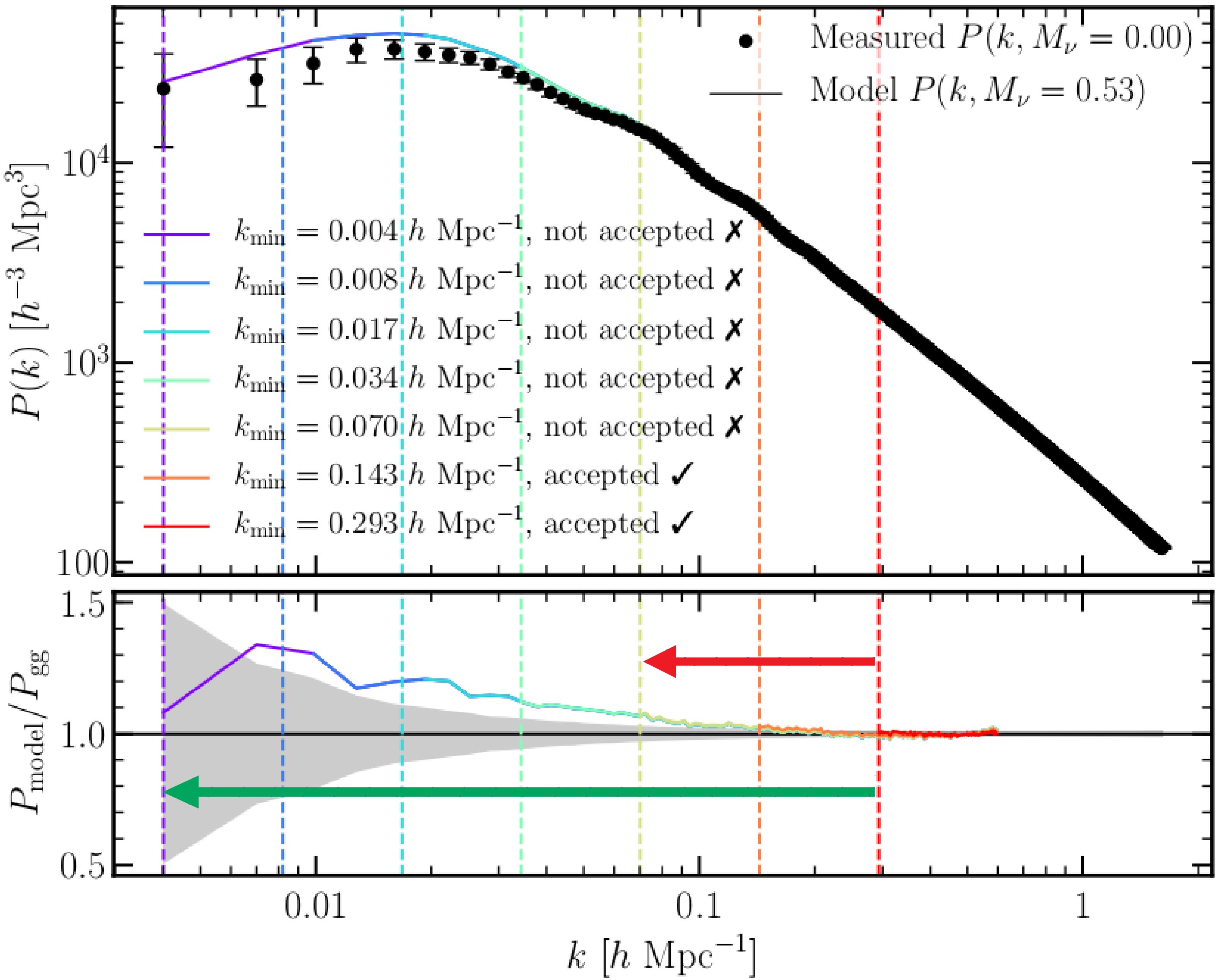
- In principle, 4 free parameters $b_1,\ b_2,\ b_{s^2},\ b_{3nl}$
- If bias is local in lagrangian coordinates
  - Chan et al, 2012: $b_{s^2} = -\frac{4}{7}(b_1 - 1)$
  - Beutler et al, 2014; Saito et al, 2014: $b_{3nl} = -\frac{32}{315}(b_1 - 1)$
- Or even relaxing this assumption
  - Chan et al, 2012: $b_{s^2} = -\frac{4}{7}(b_1 - 1.43)$
  - Bel at al, 2015: $b_{s^2} = -\frac{4}{7}(b_1 - 0.8)$

Minimum scale



χ^2 test with 0.05 significance

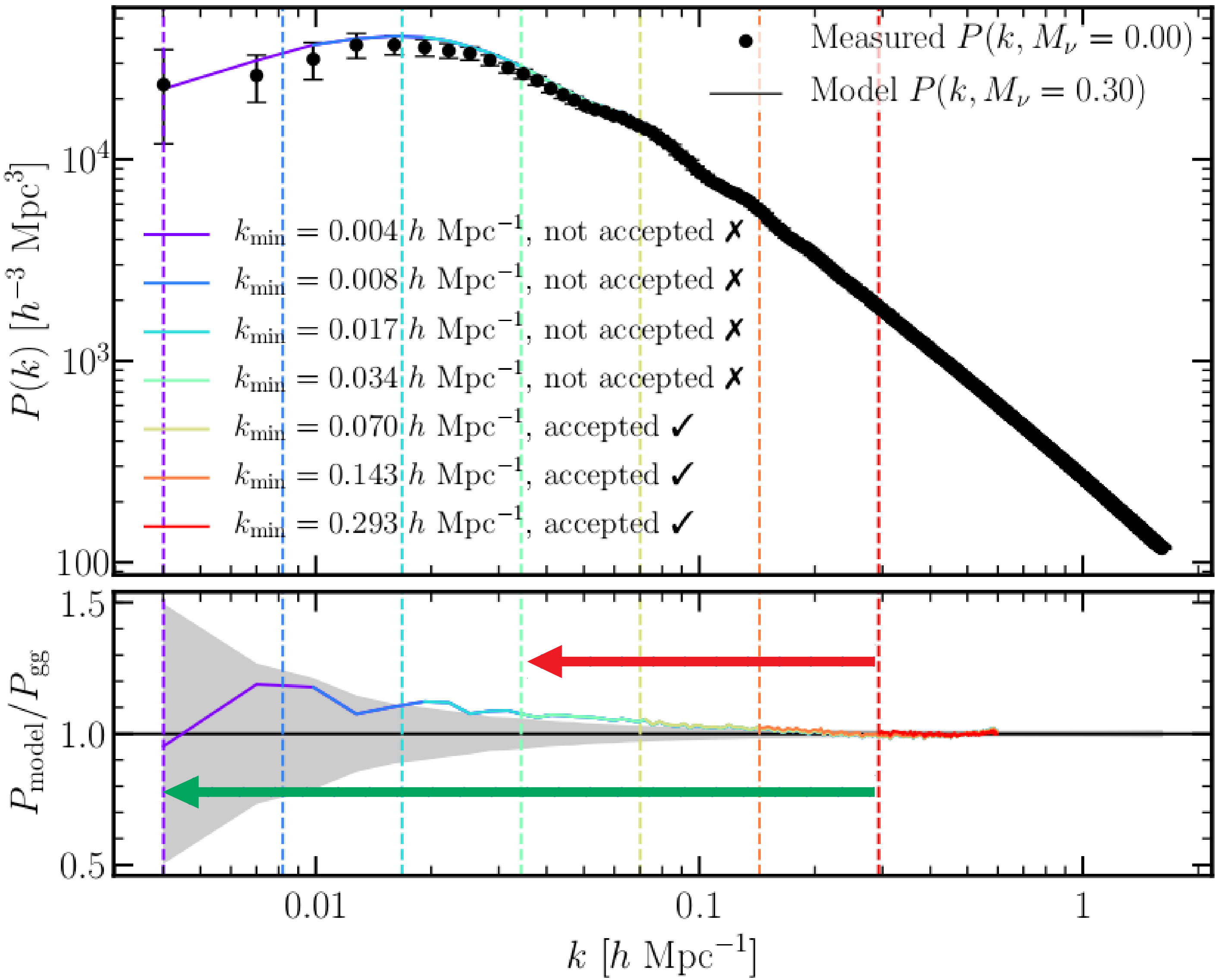
Maximum scale



test cannot reject wrong hypothesis

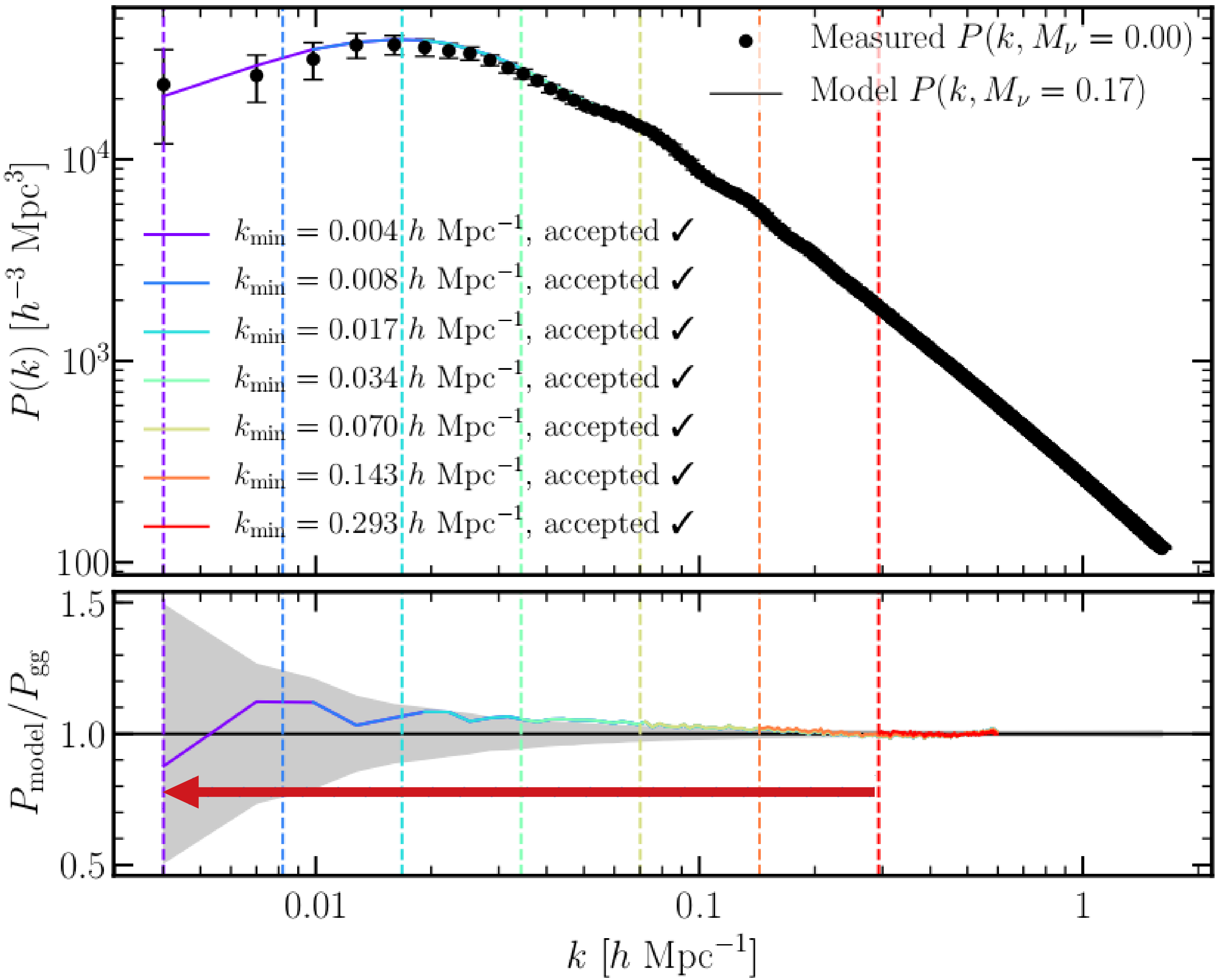
model can distinguish different neutrino mass

Maximum scale



test cannot reject wrong hypothesis

model can distinguish different neutrino mass



Maximum scale

test cannot reject wrong hypothesis

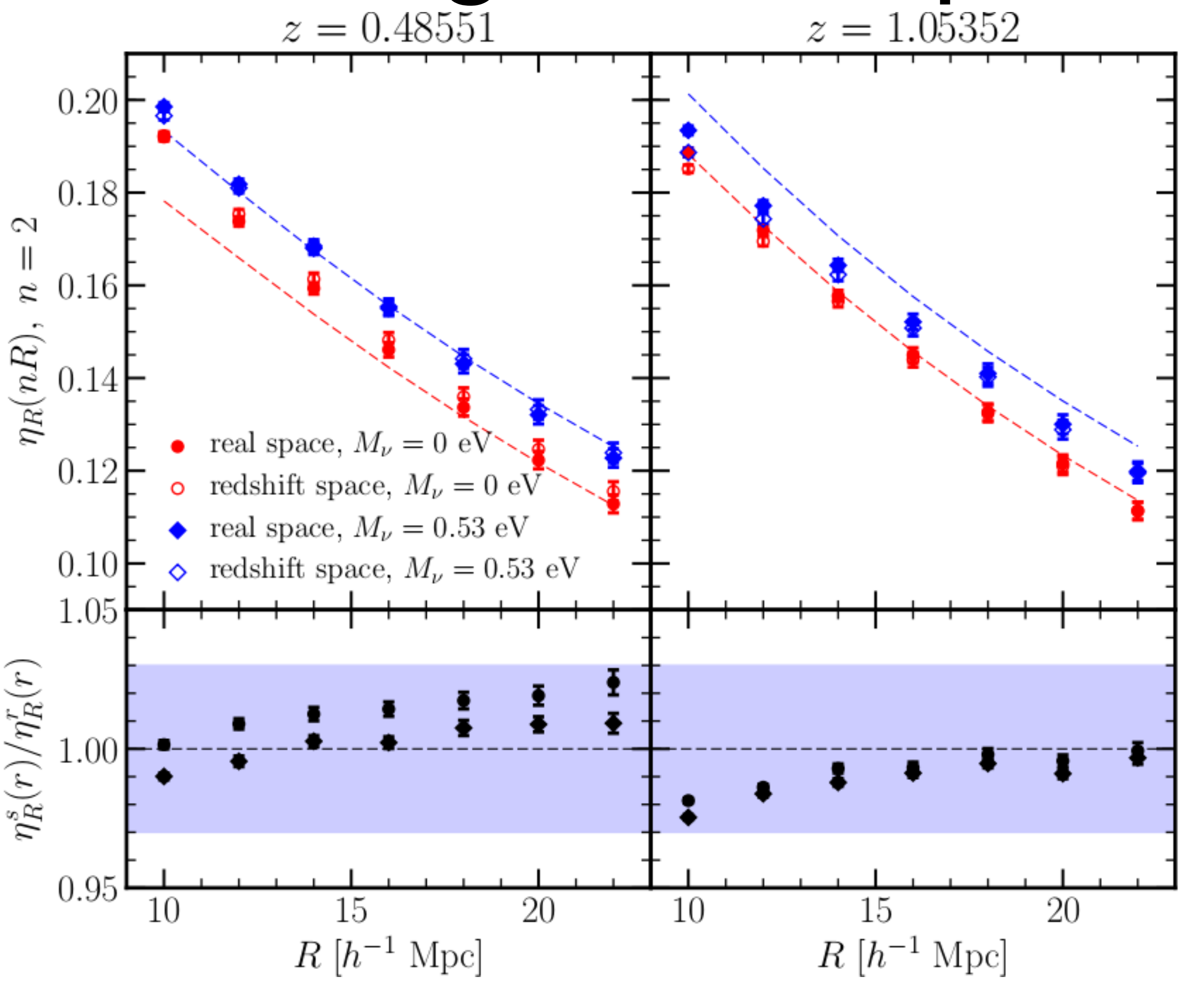
~~model can distinguish different neutrino mass~~

Conclusions

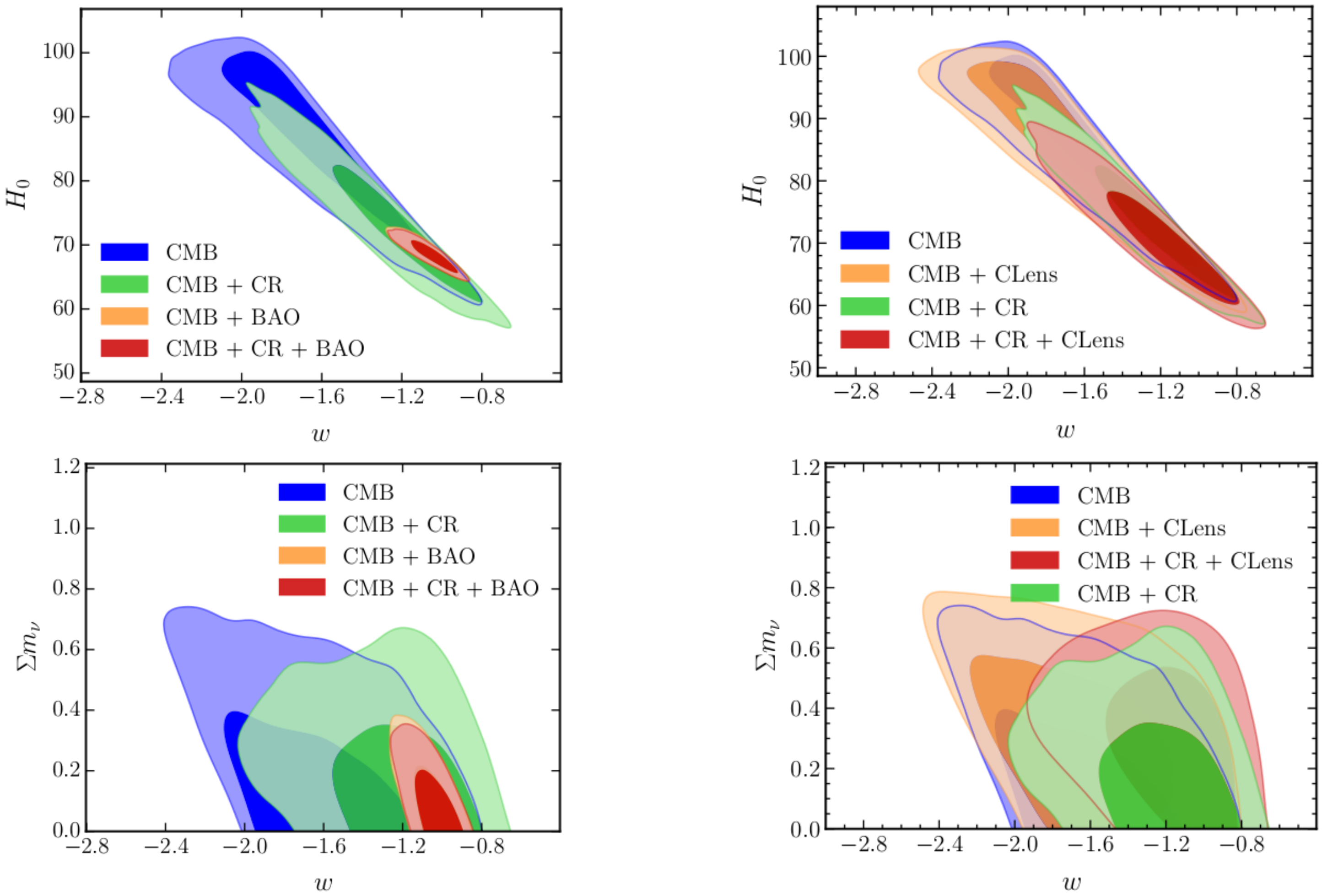
- **Extended** clustering ratio to cosmologies that include massive neutrinos
- Using SDSS data, **12% improvement** on Ω_{cdm} constraints, but **not yet competitive** for M_ν
- Forecasts for Euclid show **40% improvement** for Ω_{cdm} and **14% improvement** for M_ν
- **Galaxy power spectrum** in the presence of neutrinos with SHAM technique
- Neutrino mass parameter **completely degenerate** if only small scales are included in the fit
- **Window of scales** where this degeneracy is broken
- MCMC approach to assess the effect on **cosmological parameter constraints**
- **Realistic** galaxies (impact of SHAM flavour, different galaxy populations…)

Backup slides

Clustering ratio: z-space



Clustering ratio: CR + BOSS/CLens



Nonlocal, nonlinear: convolution terms

$$P_{b_2\delta}(k) = \int \frac{\mathrm{d}^3q}{(2\pi)^3} P^l(q) P^l(|\boldsymbol{k}-\boldsymbol{q}|)\mathcal{F}_2^{\mathrm{SPT}}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}),$$

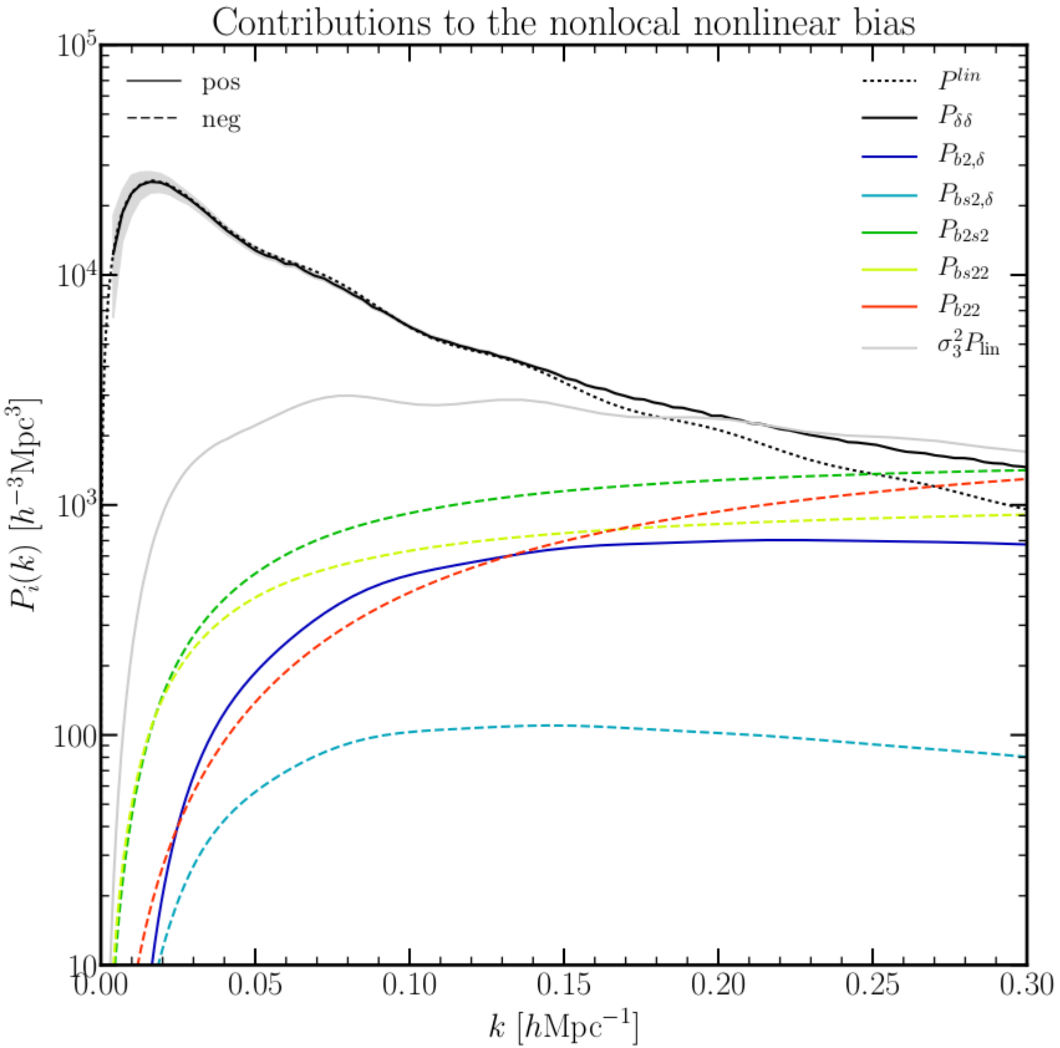
$$P_{b_{s^2}\delta}(k) = \int \frac{\mathrm{d}^3q}{(2\pi)^3} P^l(q) P^l(|\boldsymbol{k}-\boldsymbol{q}|)\mathcal{F}_2^{\mathrm{SPT}}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}) S_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}),$$

$$P_{b_2 s^2}(k) = -\frac{1}{2}\int \frac{\mathrm{d}^3q}{(2\pi)^3} P^l(q)\left[\frac{2}{3}P^l(q) - P^l(|\boldsymbol{k}-\boldsymbol{q}|) S_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right],$$

$$P_{b^2_{s^2}}(k) = -\frac{1}{2}\int \frac{\mathrm{d}^3q}{(2\pi)^3} P^l(q)\left[\frac{4}{9}P^l(q) - P^l(|\boldsymbol{k}-\boldsymbol{q}|) S_2^2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right],$$

$$P_{b_2^2}(k) = -\frac{1}{2}\int \frac{\mathrm{d}^3q}{(2\pi)^3} P^l(q)\left[P^l(q) - P^l(|\boldsymbol{k}-\boldsymbol{q}|)\right],$$

$$\sigma_3^2(k) = \int \frac{\mathrm{d}^3q}{(2\pi)^3} P^l(q)\left[\frac{5}{6} + \frac{15}{8} S_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}) S_2(-\boldsymbol{q},\boldsymbol{k}) - \frac{5}{4} S_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right]$$


Contributions to the nonlocal nonlinear bias
pos
neg
P^{lin}
$P_{\delta\delta}$
$P_{b2,\delta}$
$P_{bs2,\delta}$
P_{b2s2}
P_{bs22}
P_{b22}
$\sigma_3^2 P_{\rm lin}$
$P_i(k)\ [h^{-3}\mathrm{Mpc}^3]$
$k\ [h\mathrm{Mpc}^{-1}]$
10^5
10^4
10^3
100
10
0.00
0.05
0.10
0.15
0.20
0.25
0.30