Mixed Dark Matter and Galaxy Clustering: The Importance of Relative Perturbations

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with Fabian Schmidt

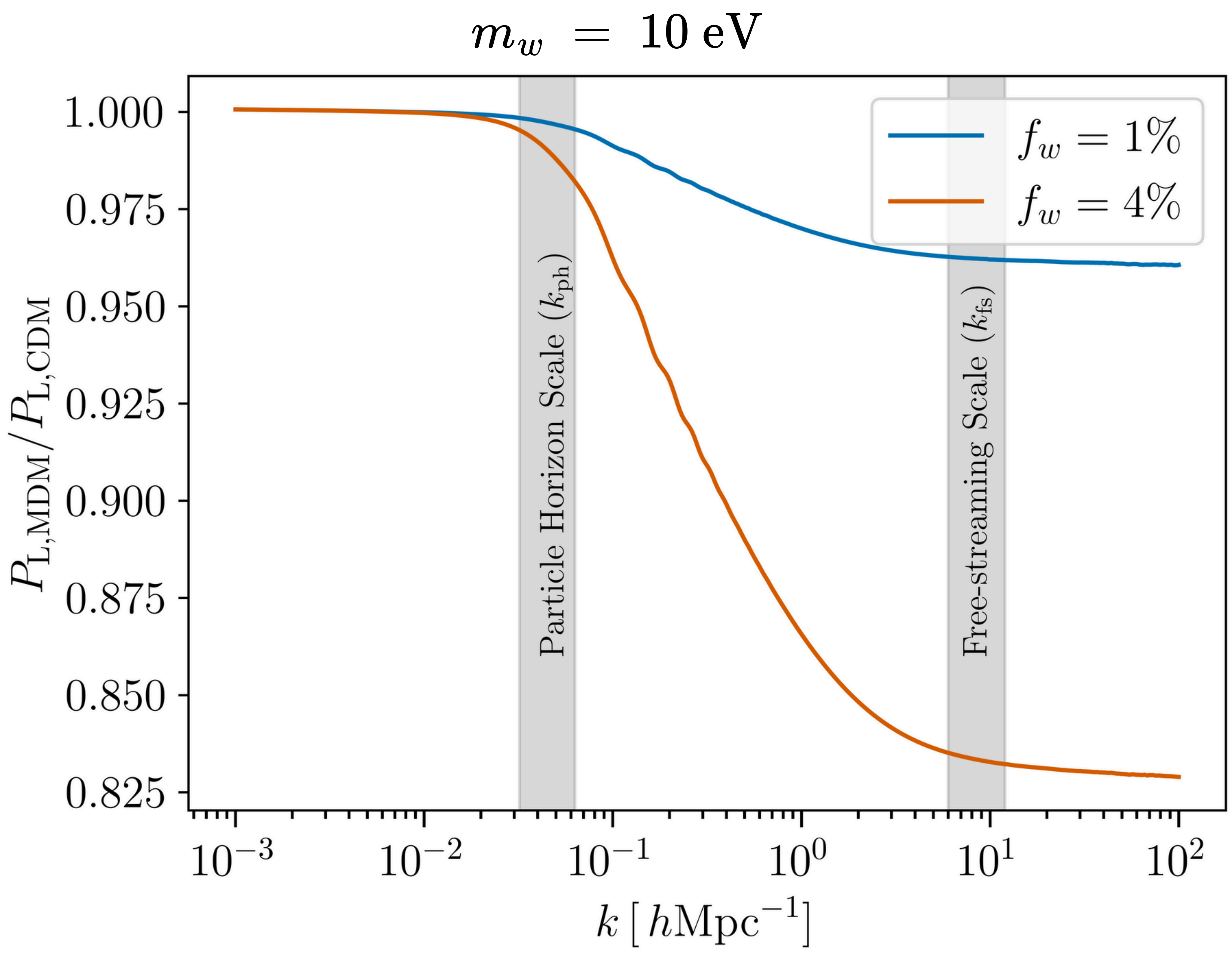
30.09.2025

New Physics from Galaxy Clustering, @GGI

Based on: 2508.21481

MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Warm Dark Matter and Structure Formation



$$f_w \equiv \frac{\Omega_w}{\Omega_c + \Omega_w} = \frac{\Omega_w}{\Omega_{\rm DM}}$$

Boyarsky+ 2009
Xu+ 2022
Parimbelli+ 2022

- CDM paradigm has well known problems especially on small scales.
- MDM with sterile neutrinos produced by DW mechanism
- Two scales ($k_{\rm ph},\ k_{\rm fs}$) and two parameters ($m_w,\ f_w$)

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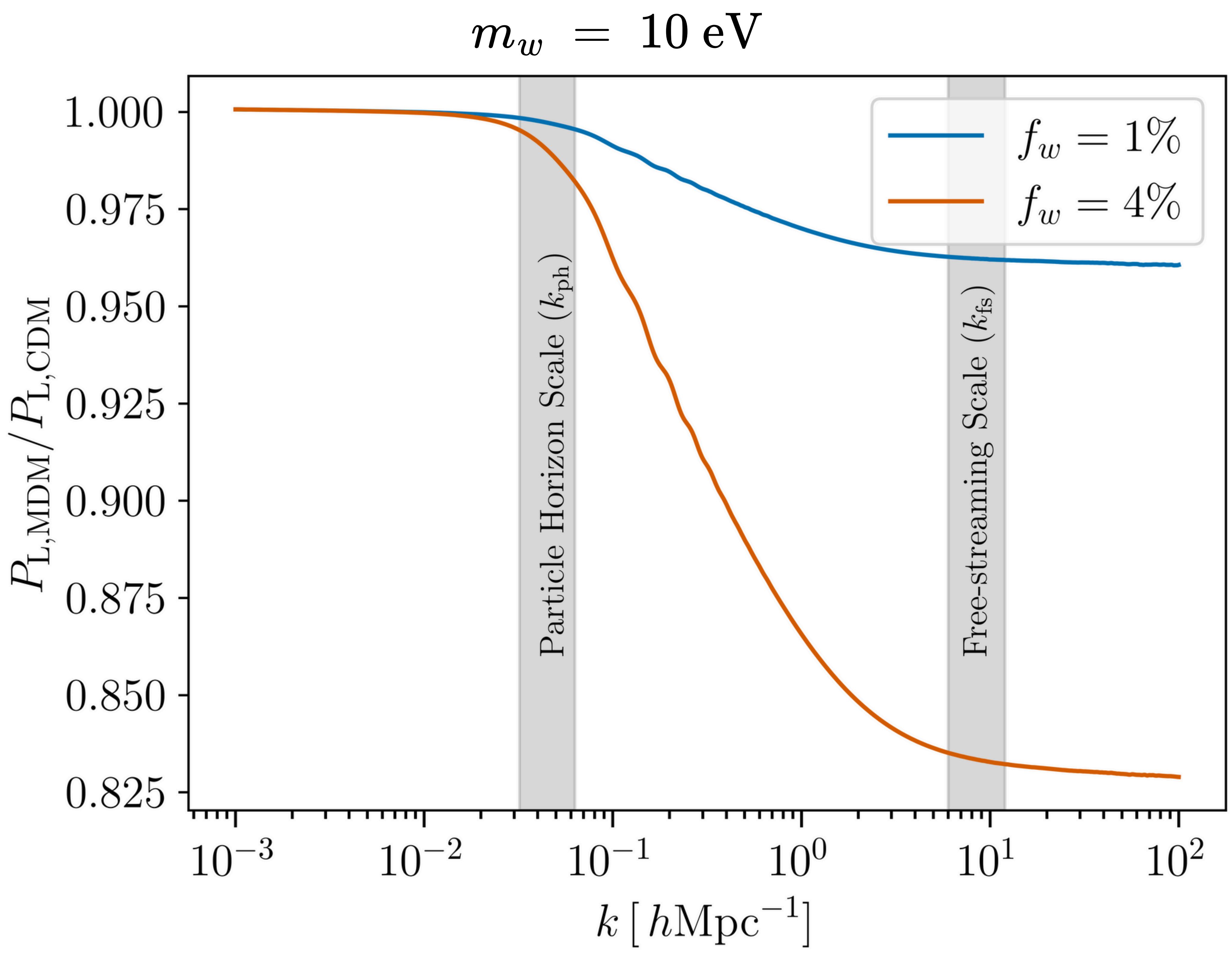

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- CDM paradigm has well known problems especially on small scales.
- MDM with sterile neutrinos produced by DW mechanism
- Two scales ($k_{\mathrm{ph}},\ k_{\mathrm{fs}}$) and two parameters ($m_w,\ f_w$)
- The question: **How accurate the single fluid treatment is?**

Equations for the Two Fluid Picture

Shoji+ 2010
Verdiani+ 2025

$$\delta_c' + \theta_c = 0$$

$$\theta_c' + \mathcal{H}\theta_c + \frac{3}{2}\Omega_m(a)\mathcal{H}^2\delta_m = 0$$

$$\delta_w' + \theta_w = 0$$

$$\theta_w' + \mathcal{H}\theta_w + \frac{3}{2}\Omega_m(a)\mathcal{H}^2\delta_m - c_s^2(a)k^2\delta_w = 0$$

$$\delta_m := f_w\delta_w + f_c\delta_c$$

$$\delta_r := \delta_c - \delta_w$$

$$\delta_m' + \theta_m = 0$$

$$\theta_m' + \mathcal{H}\theta_m + \frac{3}{2}\Omega_m\mathcal{H}^2\delta_m - \frac{c_{s_i}^2 k^2}{a^2}\left(f_w\delta_m - \cancel{f_w f_c\delta_r}\right) = 0$$

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Solutions:

$$\delta_m^{(1)}(\mathbf{k},a) = a\delta_m^{(0)}(\mathbf{k}) - \frac{R_p(\mathbf{k})f_w}{3H_0} + \mathcal{O}\left(\frac{k}{k_{\rm fs}}\right)^4$$

$$\theta_m^{(1)}(\mathbf{k},a) = -a^{\frac{1}{2}}H_0\delta_m^{(0)}(\mathbf{k}) + \mathcal{O}\left(\frac{k}{k_{\rm fs}}\right)^4$$

with $\quad R_p(\mathbf{k}) = -\frac{2c_{s_i}^2 k^2}{H_0}\delta_m^{(0)}(\mathbf{k})$

$$\delta_r^{(1)}(\mathbf{k},a) = R_0(\mathbf{k}) - \ln(a)\frac{R_p(\mathbf{k})}{H_0} + \frac{R_-(\mathbf{k})}{\sqrt{a}H_0}$$

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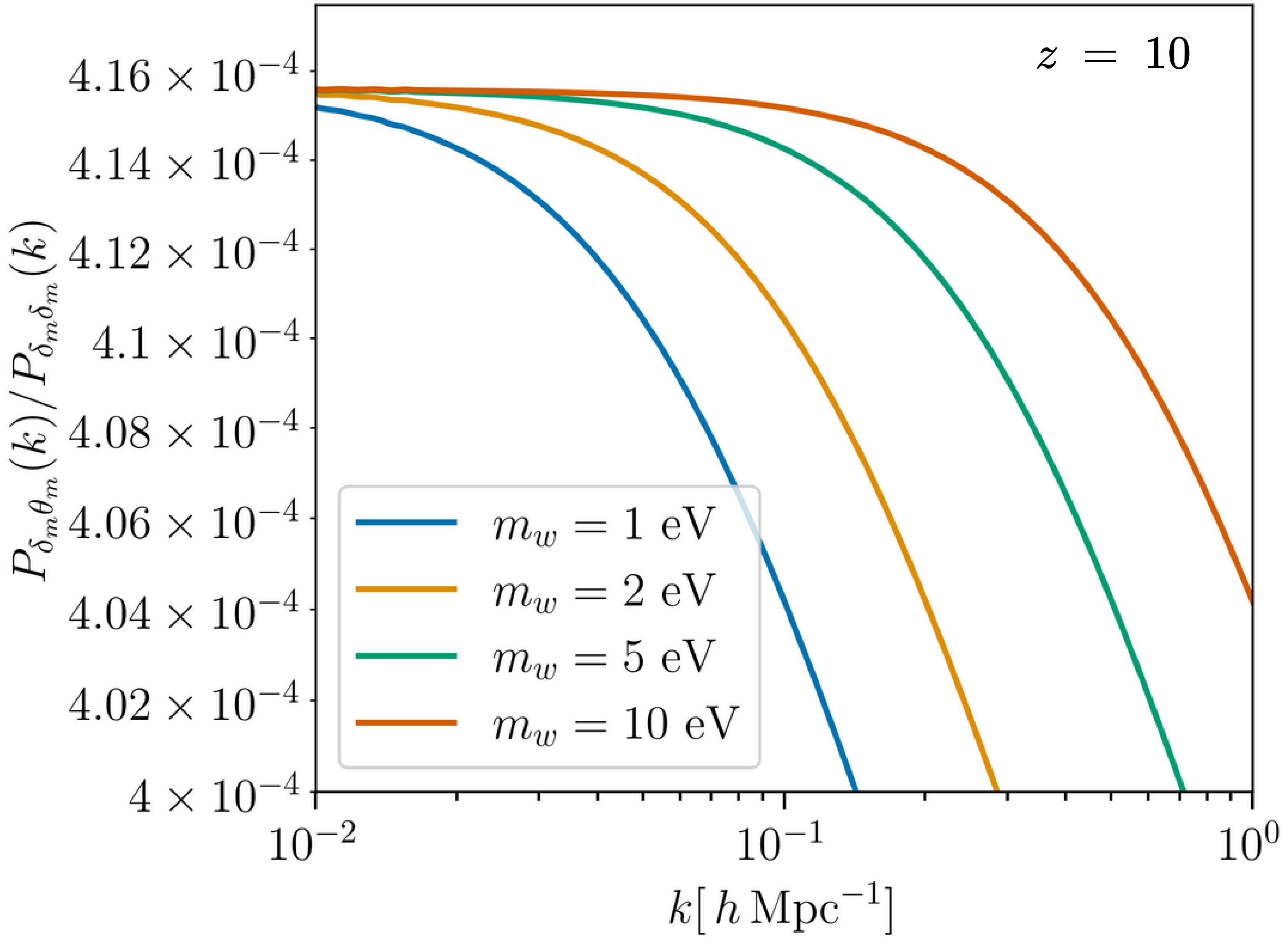
$$\theta_r^{(1)}(\mathbf{k},a) = \frac{R_p(\mathbf{k})}{\sqrt{a}} + \frac{R_-(\mathbf{k})}{a}$$

WHAT ABOUT SCALE DEPENDENT GROWTH (&BIAS) ???

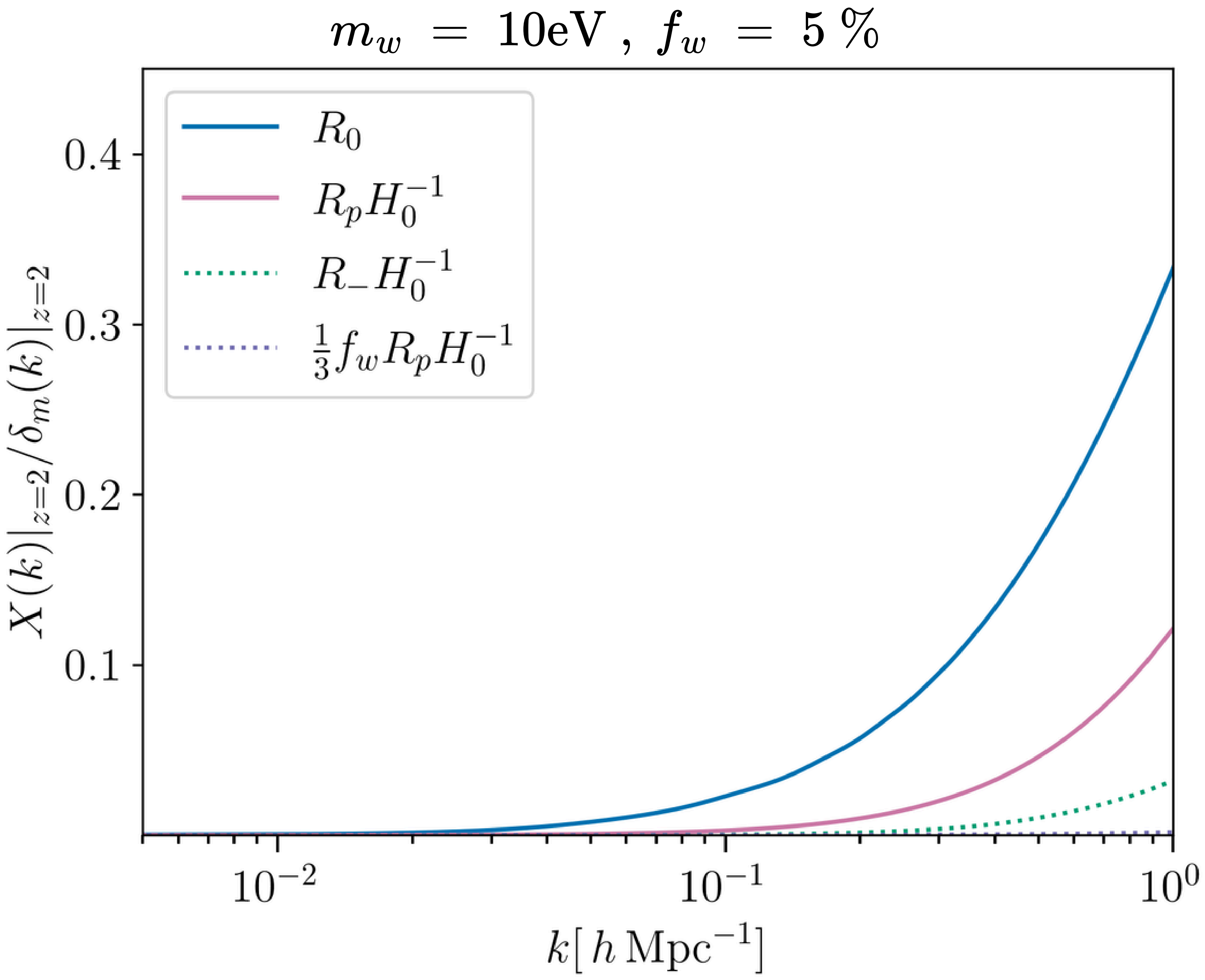
Numerical Results from CLASS

Lesgourgues+ 2015

Scale Dependence



Hierarchy in Between the Modes



Galaxy bias Expansion

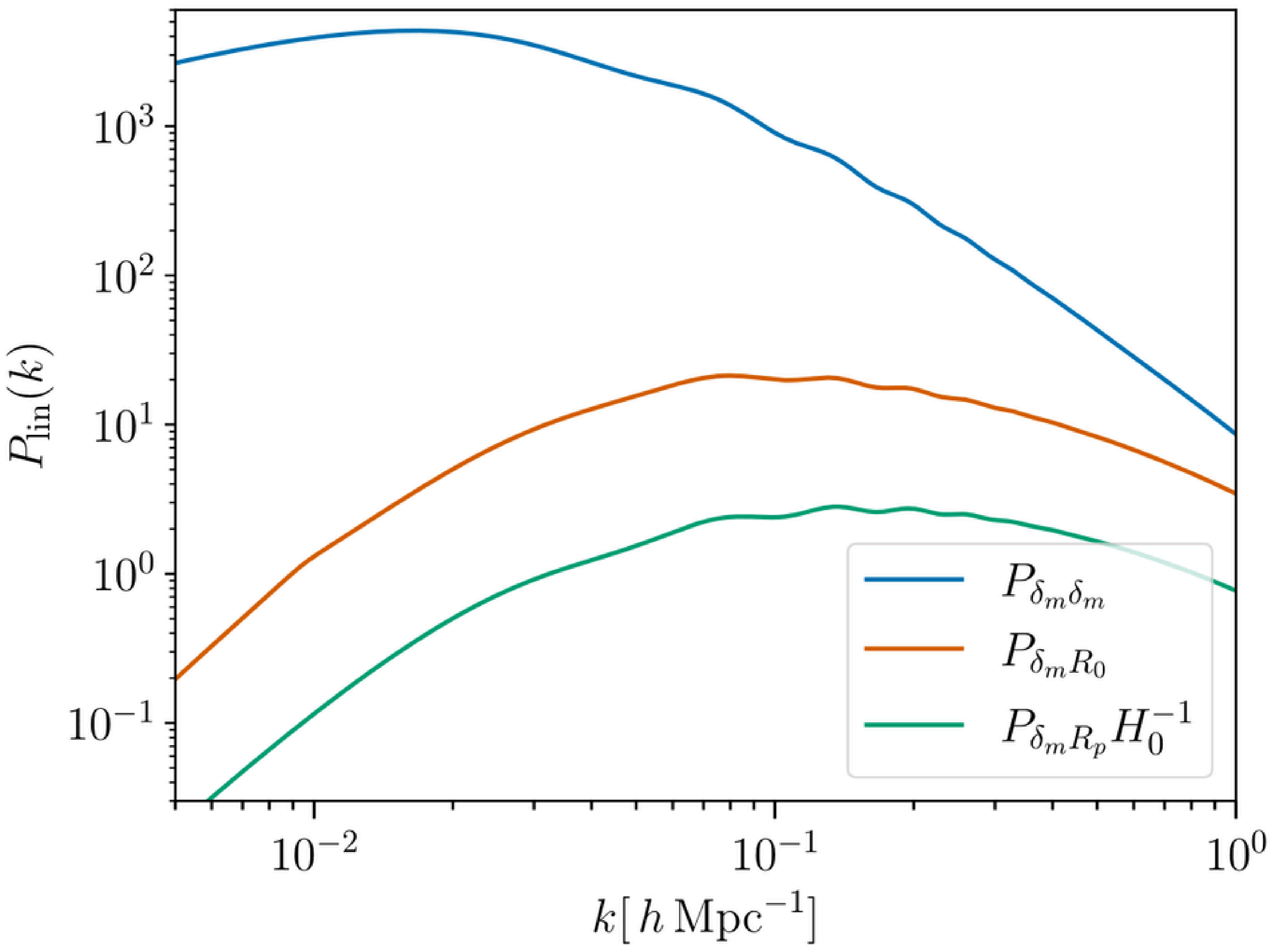
Schmidt 2016
Verdiani+ 2025

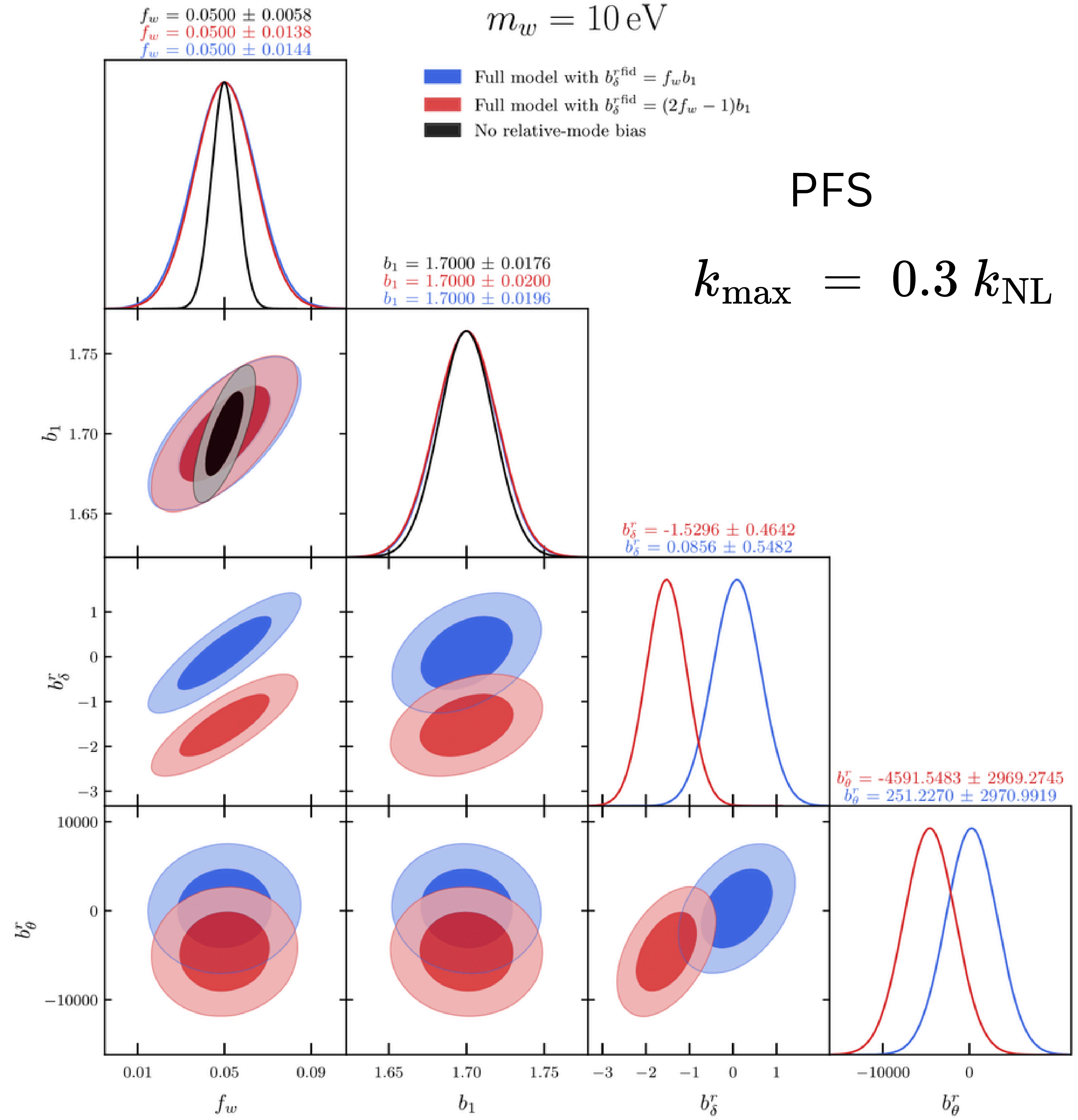
$$\delta_g(\mathbf{k},\eta) = \sum_{\mathcal{O}} b_{\mathcal{O}}(\eta)\mathcal{O}(\mathbf{k},\eta)$$

Two fluid system →

$$\delta_g^{(1)}(\mathbf{x},\eta) = b_1(\eta)\delta_m^{(1)}(\mathbf{x},\eta) + b_\delta^r(\eta)R_0(\mathbf{x},\eta) + b_\theta^r(\eta)R_p(\mathbf{x},\eta) + \epsilon(\mathbf{x},\eta)$$

$m_w = 10\text{eV}$, $f_w = 5\ \%$

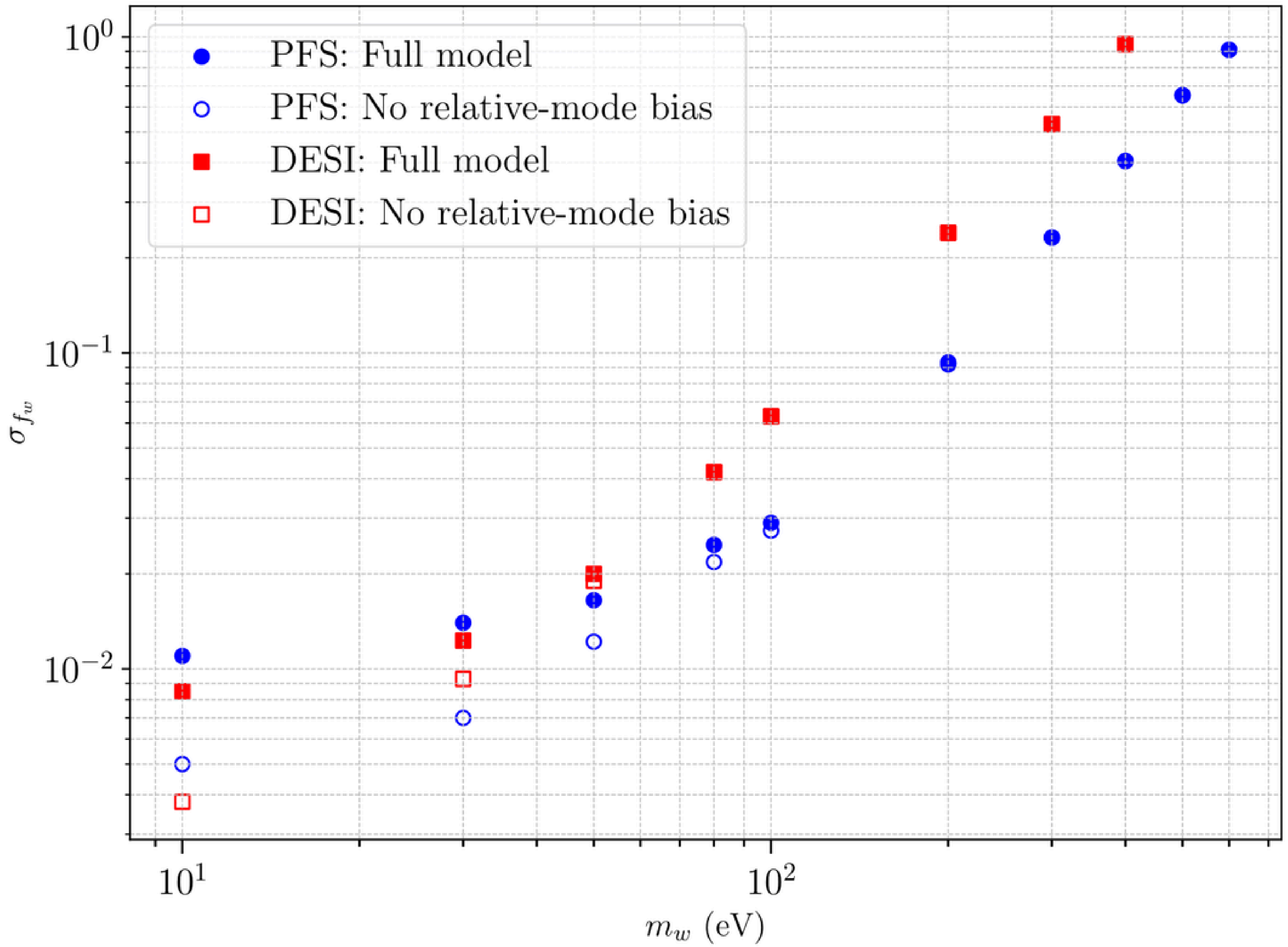




PFS

$k_{\rm max} = 0.3\ k_{\rm NL}$

Fisher Results for PFS&DESI



Some Remarks:

- The relative perturbations are significant especially for low mass warm components.
- DESI best constrains low mass; PFS pushes sensitivity to higher mass.
- Fisher bias for the lightest particle up to 5.7σ for PFS and 3.6σ DESI.

Future Prospects:

- Going beyond linear order, and look at the ranking of the additional modes.
- Extending the literature in Lyman-alpha forest and galaxy shape analysis.
- Measuring the relative mode biases with the help of simulations.