RAMSES With Massive Neutrinos and f(R) Gravity

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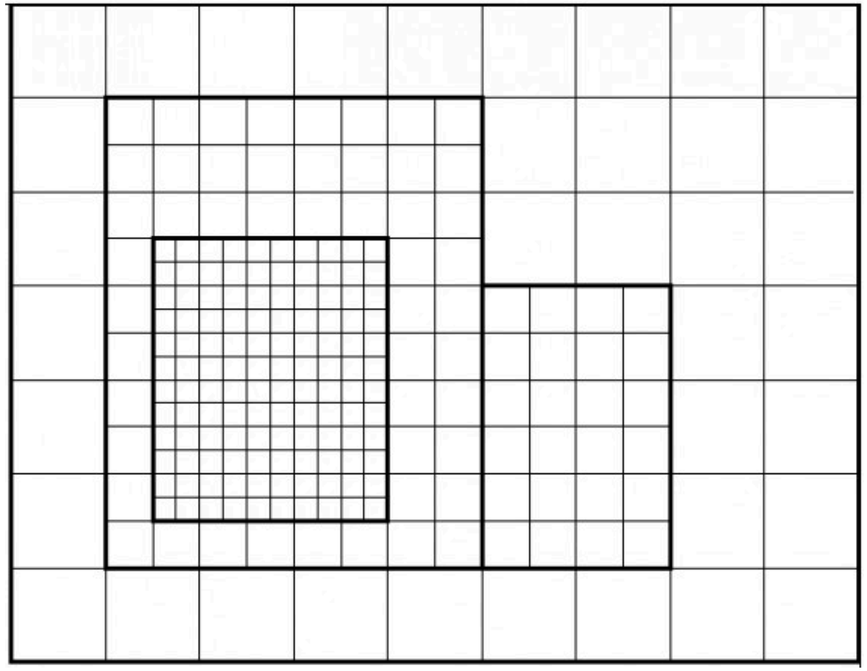
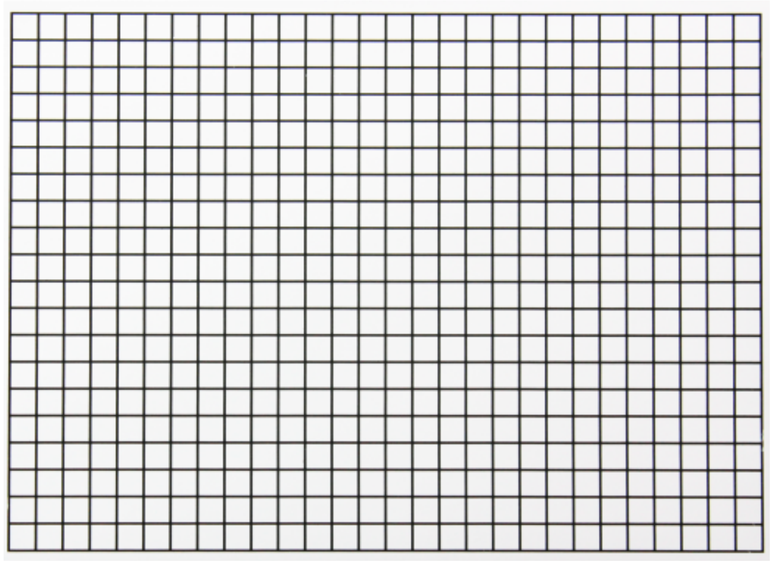
Adaptive Mesh Refinement (AMR)



Fixed grid



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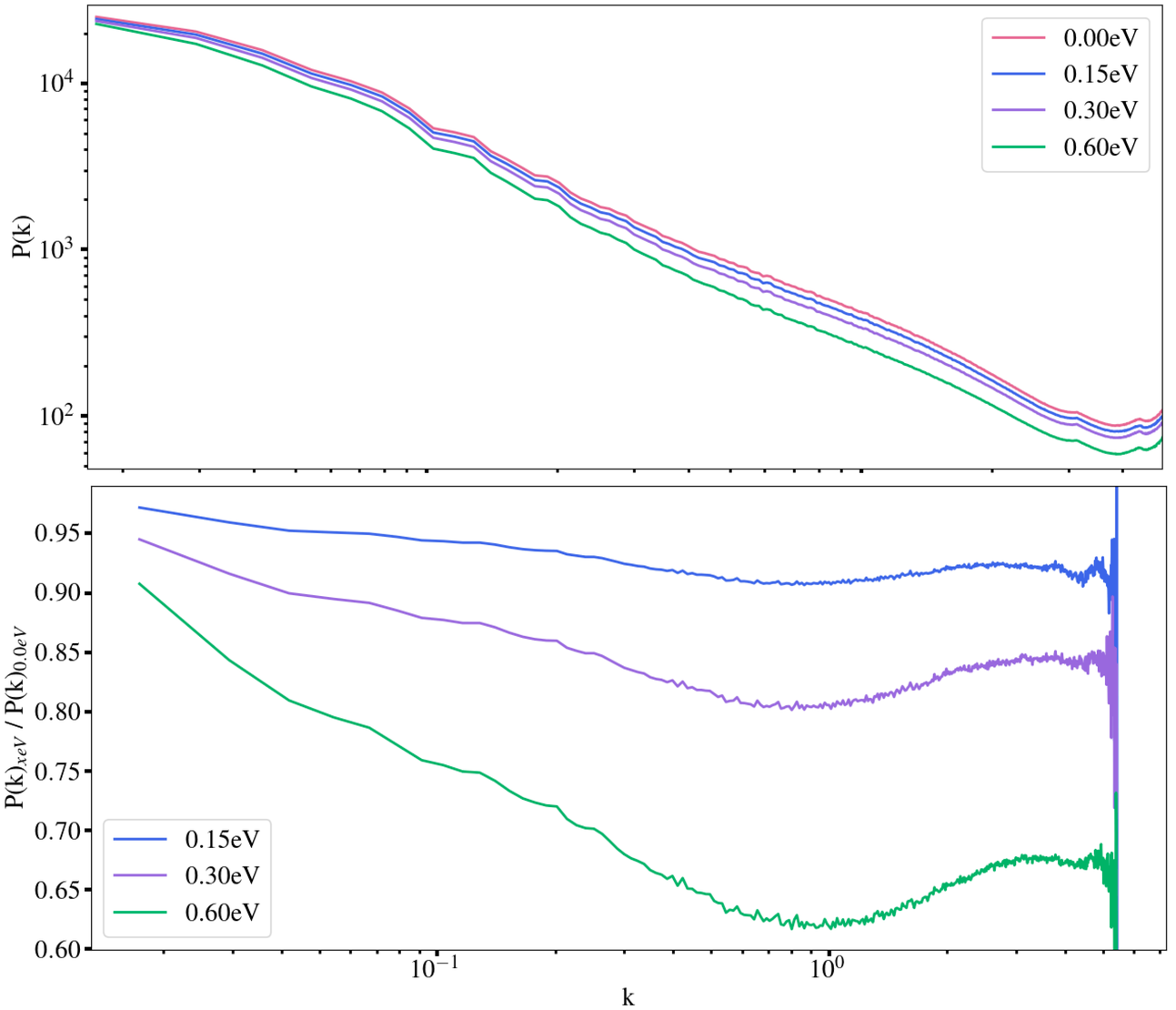
RAMSES with **Massive Neutrinos** and f(R) Gravity

- Experiments: $0.06\,\mathrm{eV} \leq \sum \mathrm{m}_\nu \leq 1.1\,\mathrm{eV}$
- Cosmology: $\sum m_\nu < 0.12\,\mathrm{eV}$
- 0.5 - 1.1 % of CDM
- Free-streaming $\rightarrow$ suppression of growth



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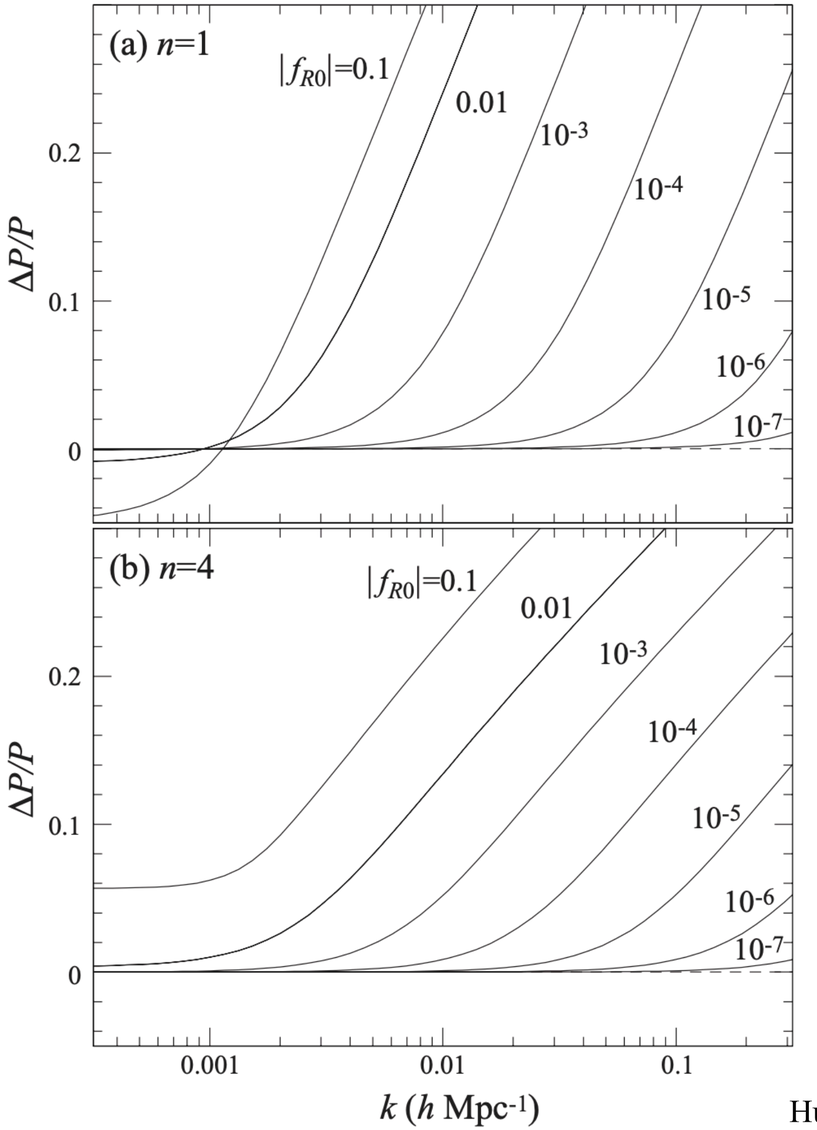
- $S = \int \frac{R}{16\pi G}\sqrt{-g}d^4x$
- $S = \int (\frac{R}{16\pi G} + L_m)\sqrt{-g}d^4x$
- $S = \int (\frac{R+f(R)}{16\pi G} + L_m)\sqrt{-g}d^4x$
- $f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1}, \ m^2 = H_0^2 \Omega_m$
- Two parameters: n and f_{R0}
- $f_{R0} = -n \frac{c_1}{c_2^2} (\frac{\Omega_m}{3(\Omega_m + 4\Omega_\Lambda)})^{n+1}$
- Screened fifth force
- Enhance structure growth



Hu & Sawicki 2007

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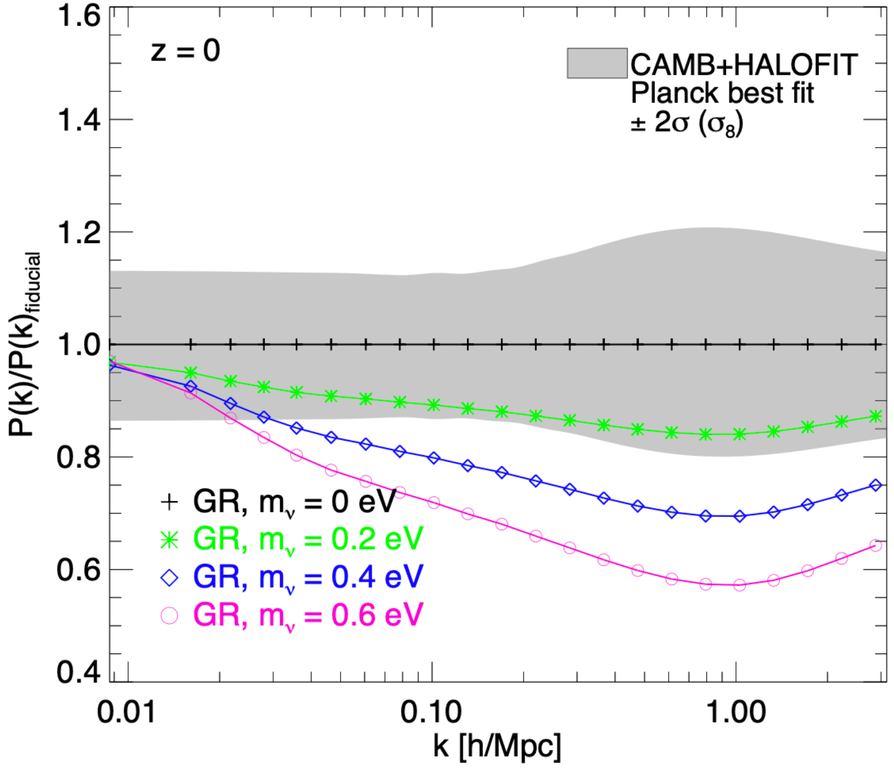

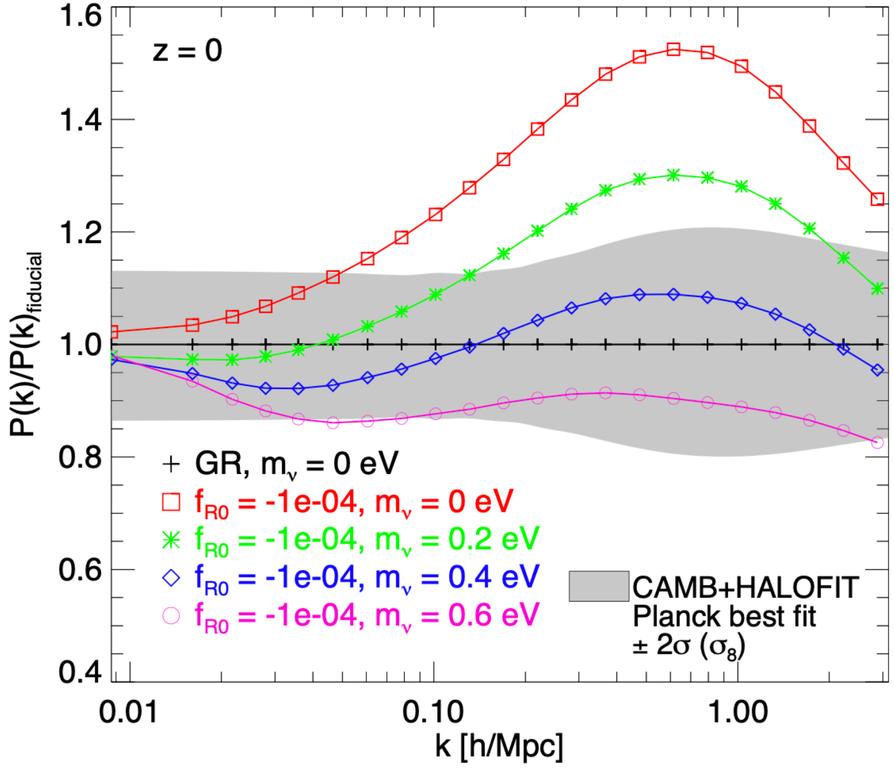

Baldi et al. 2014

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RAMSES with Massive Neutrinos and f(R) Gravity

- Neutrino family
- $\frac{d\mathbf{x_P}}{dt} = \mathbf{v_P}$ and $\frac{d\mathbf{v_P}}{dt} = -\nabla_x \phi$
- *gevolution,* Adamek et al. 2017: geodesic equation

$$q_i' = -\frac{2q^2+m^2a^2}{\sqrt{q^2+m^2a^2}}\phi_{,i} + \sqrt{q^2+m^2a^2}\chi_{,i} - q^j B_{j,i} + \frac{1}{2}\frac{q^j q^k h_{jk,i}}{\sqrt{q^2+m^2a^2}}$$

- $\delta_{ij}\frac{\partial x^j}{\partial \tau} = \frac{q_i}{\sqrt{q^2+m^2a^2}}$
- Super-comoving coordinates: $\tilde{q}_i' = -\frac{2D+1}{\sqrt{D+1}}\tilde{\nabla}\tilde{\phi}, \quad x_i' = \frac{\tilde{q}_i}{\sqrt{D+1}}$

q - momentum
a - scale factor
m - particle mass
$\chi = \phi - \psi$
ϕ, ψ - grav. scalar potentials
B_i - vector field
h_{ij} - tensor field
$,i = \partial/\partial x^i$
$' = \partial/\partial\tau$
τ - conformal time

$D = L^2 H_0^2 \tilde{q}^2/a^2$

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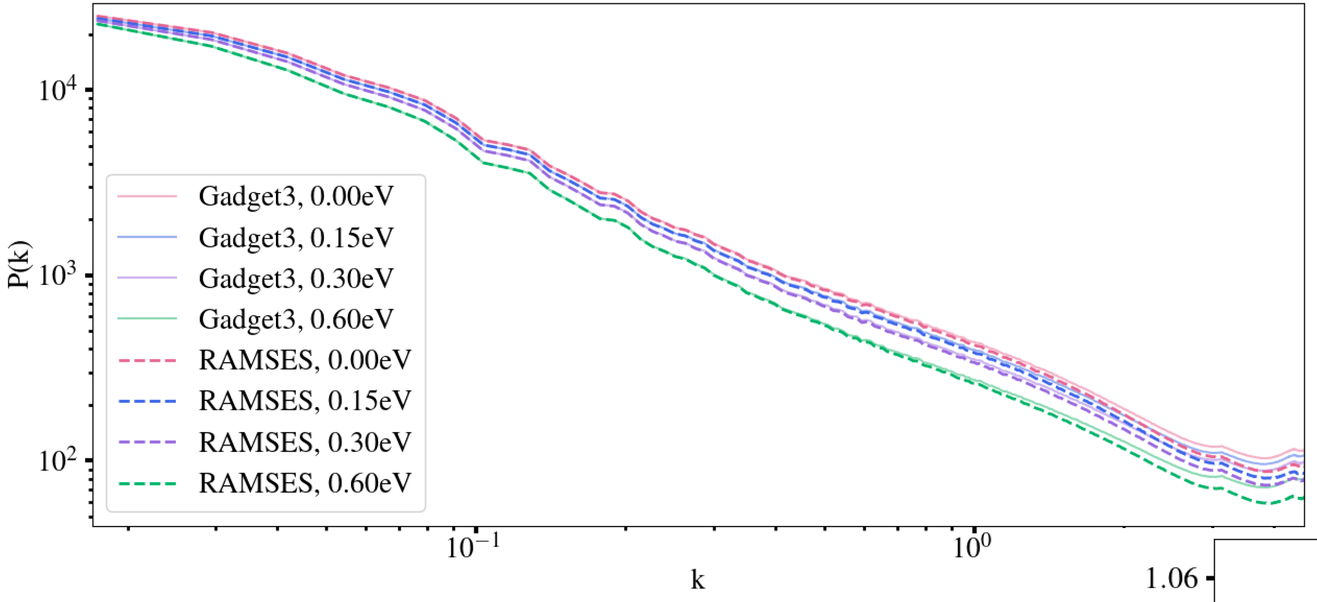
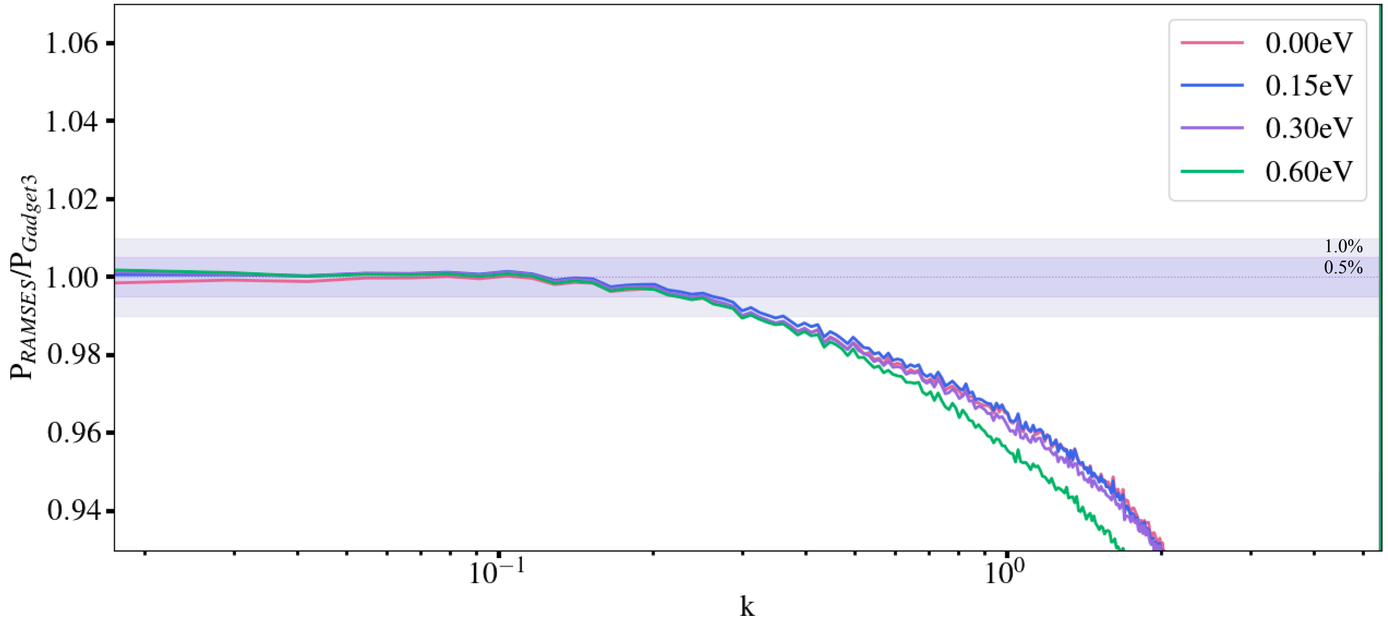


L = 512 Mpc/h

$N_\nu = 512^3$

$N_{\rm CDM} = 512^3$



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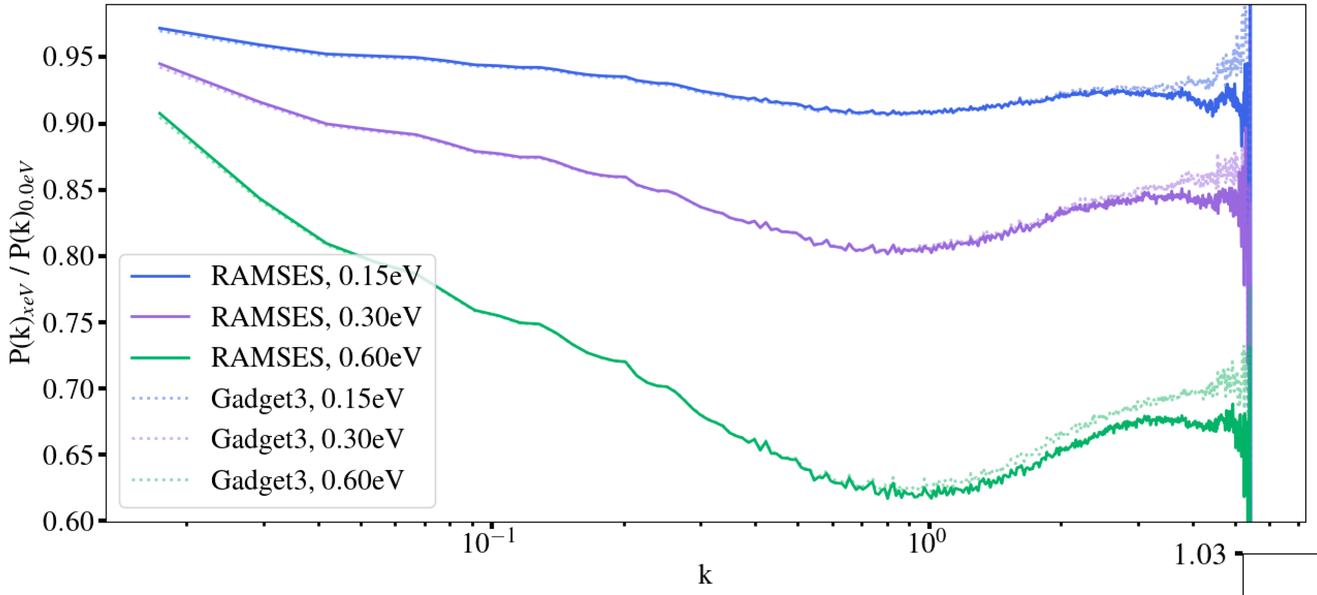

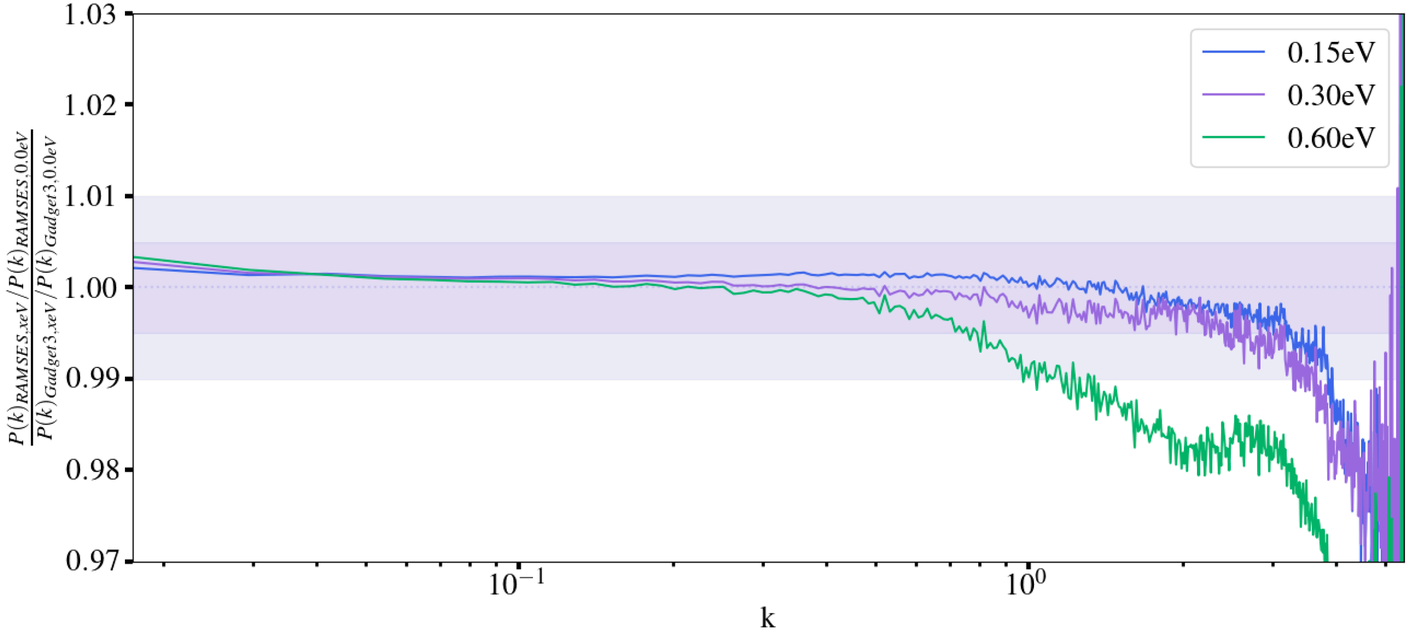

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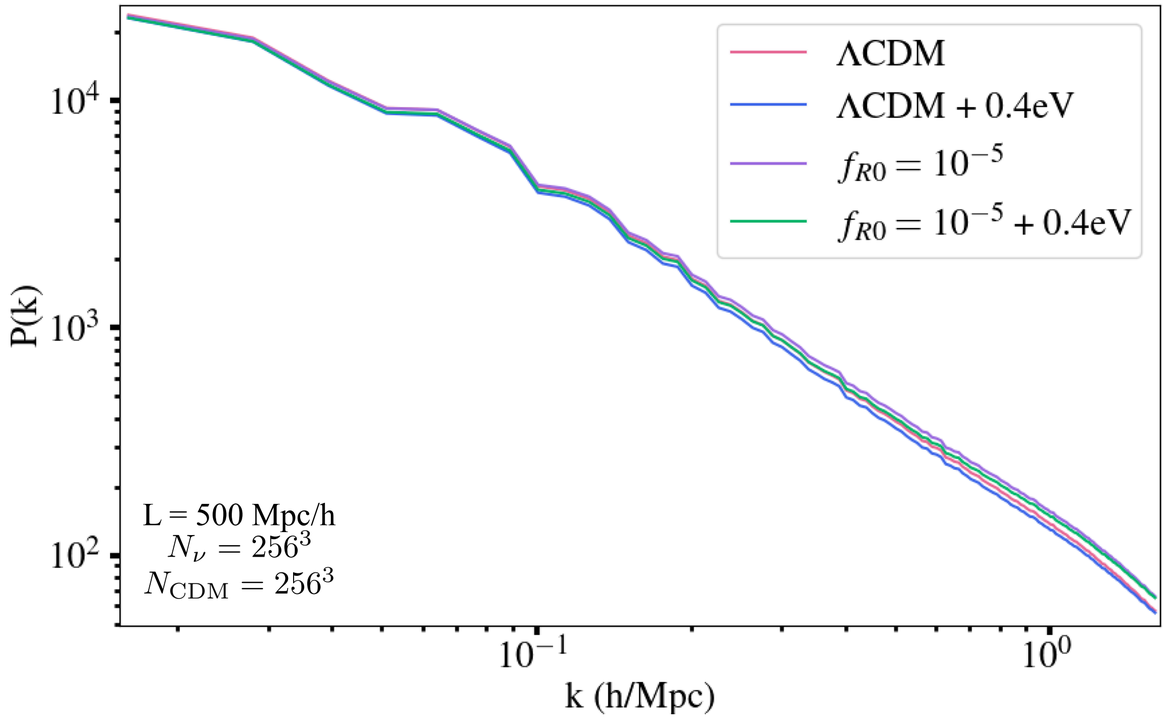

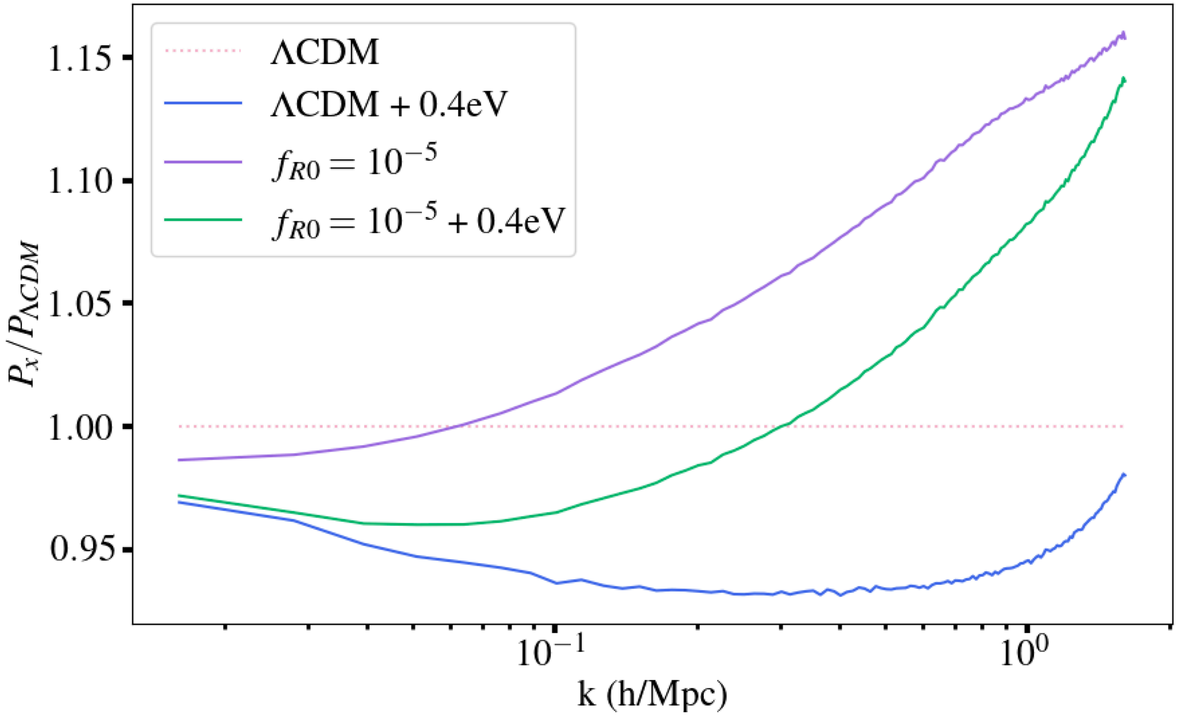

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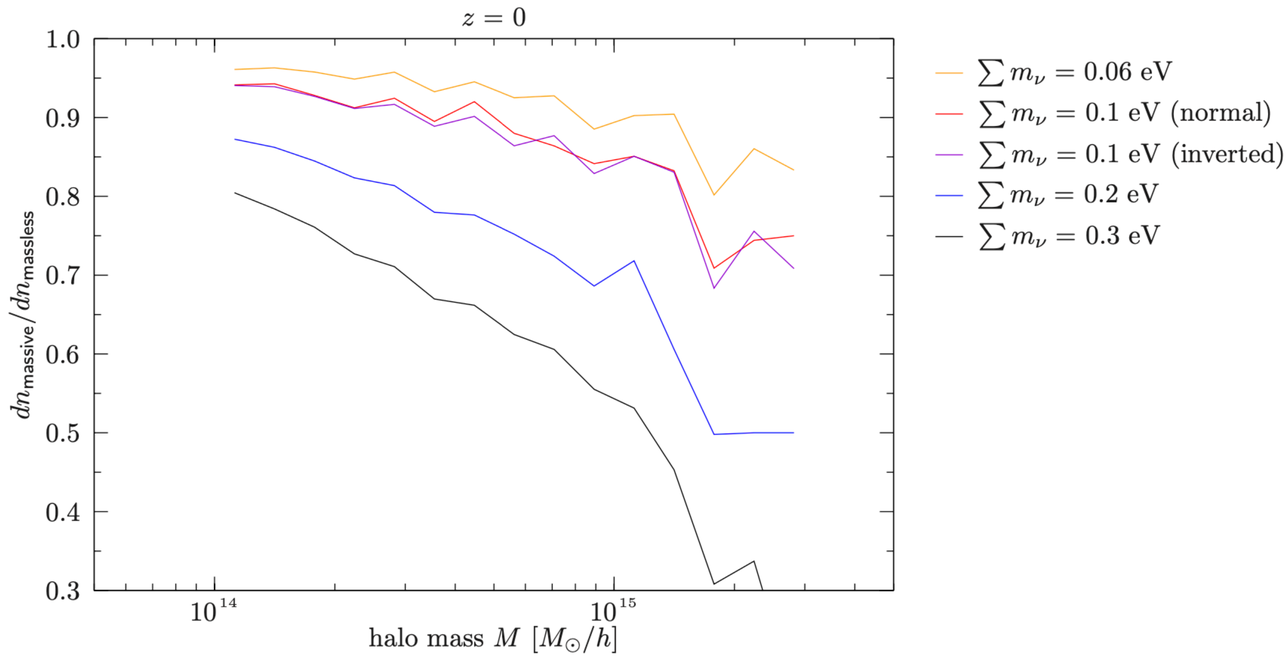
- Road ahead:
  - Power spectrum
  - Correlation function
  - Suppression/enhancement of structure growth
  - Halo Mass Function (HMF)
  - Cosmic voids:
    - Contarini et al. 2020: void size function
  - Euclid:
    - PL-KP-CL-3 Paper 4: HMF and HB
    - PL-KP-CL-3 Paper 5: halo profiles



Adamek et al. 2017

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Thank you!