“scale-dependence and neutrinos”

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Galaxies meets QCD 22.2.2024

2008.00013 (JCAP), 2110.13930 (PRD),
2205.11533 (JCAP), 2308.07379 (JCAP), ...
with
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Henrique Rubira, Marco Marinucci, ...

Outline

- What I mean by scale-dependent models
- Why are they challenging?
- Example: *Freestreaming neutrinos in LSS*
- EFT and comparison to N-body
- Outlook

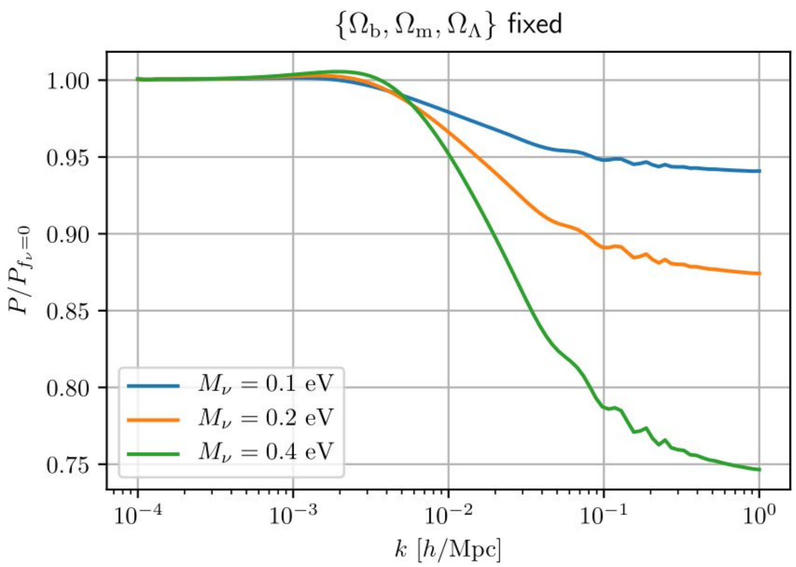
Scale-dependent models

- "New" physics on scales relevant for LSS
- New scale(s) varying in time
- This talk: *massive neutrinos*

$$\nabla^2\Phi = \frac{3}{2}\mathcal{H}^2\Omega_m\left[f_{\rm cb}\delta_{\rm cb} + f_\nu\delta_\nu\right]$$

$$\delta_\nu \sim \begin{cases} \delta_{\rm cb}\,, & k \ll k_{\rm FS} \\ 0\,, & k \gg k_{\rm FS} \end{cases}$$

$$k_{\rm FS} \propto m_\nu (1+z)^{-1/2}$$



- Euclid galaxy clustering forecast: $\sigma\left(\sum m_\nu\right) \simeq 0.03$ eV [Ivanov et.al. 2019] (neutrinos treated linearly)

Scale-dependent models

- Other BSM models:
  - f(R) gravity

scale-dep. lin. term

scale-dep. nonlin. terms

$$k^2\Phi = \frac{3}{2}\mathcal{H}^2\Omega_{\rm m}\mu(k,\tau)\delta + \int_{\mathbf{q}_1,\mathbf{q}_2}\gamma_2(\mathbf{q}_1,\mathbf{q}_2)\delta_{\mathbf{q}_2}\delta_{\mathbf{q}_2} + \int_{\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3}\gamma_3(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3)\delta_{\mathbf{q}_2}\delta_{\mathbf{q}_2}\delta_{\mathbf{q}_3}$$

  - New light relics ⟶ see massive neutrinos
  - Warm DM/decaying DM ⟶ see massive neutrinos
  - DM interactions with baryons, DE, ...
- Vlasov-PT: modeling stress tensor dynamically [Garny et.al. 2022]

Technical challenges

- Fast integral computation with FFTlog: $P(k) = \sum_m c_m k^{\nu + \mathrm{i}\eta_m}$

$$\int \mathrm{d}^3q \; F_2(\mathbf{k}-\mathbf{q},\mathbf{q}) P(|\mathbf{k}-\mathbf{q}|) P(q) \longrightarrow \sum_{n,m} \int \frac{\mathrm{d}^3q \; c_n c_m}{q^{2\nu_1} \, |\mathbf{k}-\mathbf{q}|^{2\nu_2}} = \sum_{n,m} \underbrace{c_n c_m}_{\text{cosmology}} k^{3-2\nu_{12}} \underbrace{f(\nu_1,\nu_2)}_{\text{precompute}}$$

\+ New scale:

cosmology dep.

$$\int \mathrm{d}^3q \; \frac{c_n c_m}{q^{2\nu_1} \, |\mathbf{k}-\mathbf{q}|^{2\nu_2}} \, h\left(\frac{k_{\mathrm{FS}}}{q}, \frac{k_{\mathrm{FS}}}{|\mathbf{k}-\mathbf{q}|} \right)$$

\+ Time-dependent scale:

$$\delta \sim \int \mathrm{d}\tau' \; \mathcal{G}(k,\tau') \int \mathrm{d}^3q \; F_2(|\mathbf{k}-\mathbf{q}|, q, k_{\mathrm{FS}}; \tau')$$

Green's function scale-dep.

M. Schmittfull et.al. 2016
J. E. McEwen et.al. 2016
X. Fang et.al. 2017
M. Simonović et.al. 2018
G. D'Amico et.al. 2021

Alternative: “brute force” Monte Carlo integration

- Integrate loops with Monte Carlo
- Each sample: solve kernel ODE hierarchy

$$\partial_\tau F_a^{(n)}(\tau) + \Omega_{ab}(\mathbf{k},\tau) F_a^{(n)}(\tau) = \sum_{m=1}^{n-1} \gamma_{abc}(\tau) F_b^{(n)}(\tau) F_c^{(n-m)}(\tau)$$

+ Scale-dependence, additional components, additional vertices …

− Computational cost ~ 10^3 - 10^4 times FFTlog
  - Unfeasible for traditional MCMC

M. Garny and **PT** 2020
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Neutrinos beyond linear theory

- Model CDM+baryons and neutrinos as a two-component fluid

$$\partial_\tau \begin{pmatrix} \delta_{\rm cb} \\ \theta_{\rm cb} \\ \delta_\nu \\ \theta_\nu \end{pmatrix}_{\mathbf{k},a} + \Omega(\mathbf{k},\tau) \begin{pmatrix} \delta_{\rm cb} \\ \theta_{\rm cb} \\ \delta_\nu \\ \theta_\nu \end{pmatrix}_{\mathbf{k},b} = \int_{\mathbf{p},\mathbf{q}} \gamma_{abc}(\mathbf{p},\mathbf{q}) \begin{pmatrix} \delta_{\rm cb} \\ \theta_{\rm cb} \\ \delta_\nu \\ \theta_\nu \end{pmatrix}_{\mathbf{p},b} \begin{pmatrix} \delta_{\rm cb} \\ \theta_{\rm cb} \\ \delta_\nu \\ \theta_\nu \end{pmatrix}_{\mathbf{q},c}$$

neutrino freestreaming scale

- Fluid approximation for neutrinos when $z \ll z_{\rm NR} = 189 \frac{m_\nu}{0.1\ {\rm eV}}$
- Non-linear corrections: $z \lesssim 10$
- Relax EdS approximation ($f^2 \neq \Omega_{\rm M}$)

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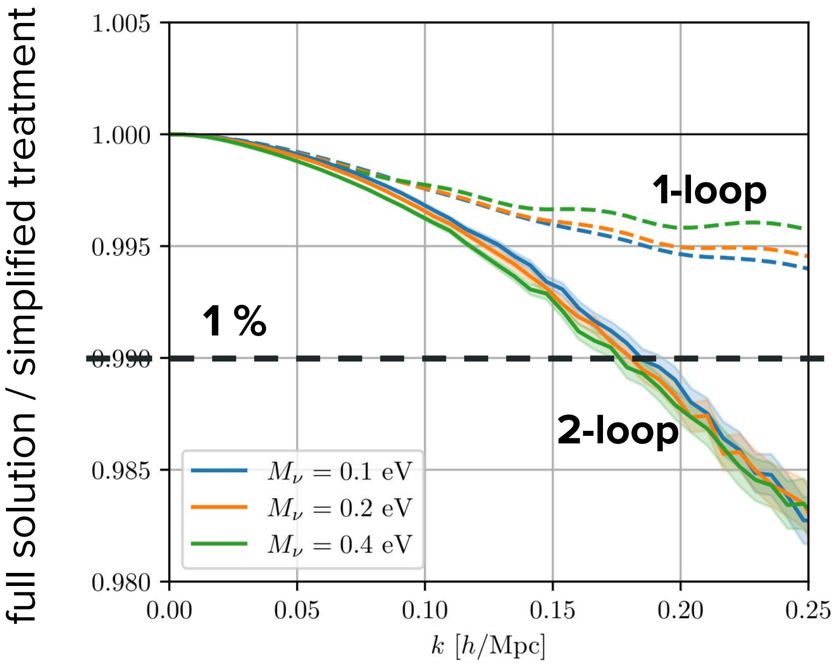
Comparison to simplified treatment



CDM+baryons density power spectrum

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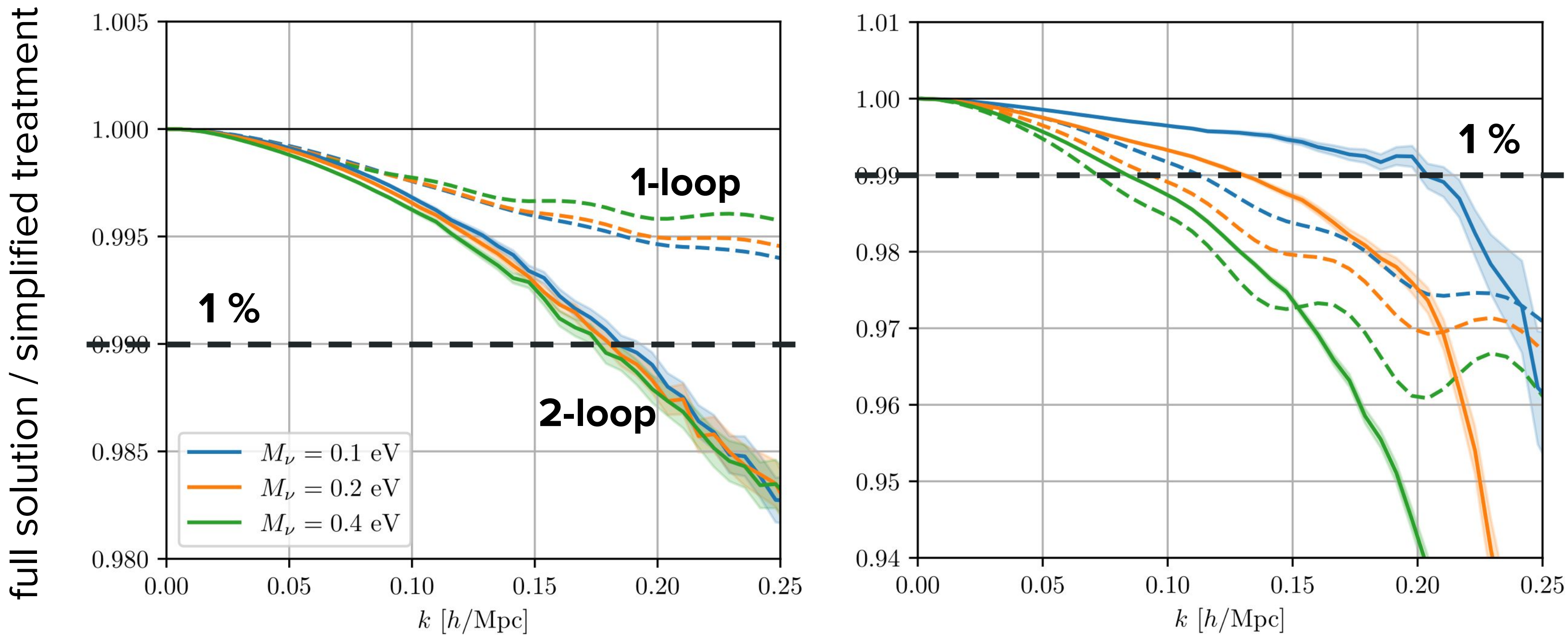
Comparison to simplified treatment



CDM+baryons density power spectrum

CDM+baryons velocity power spectrum

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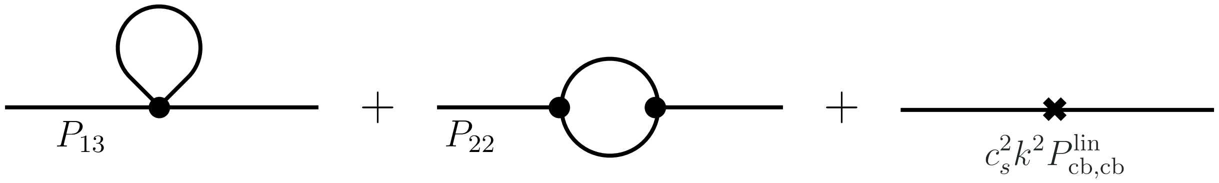
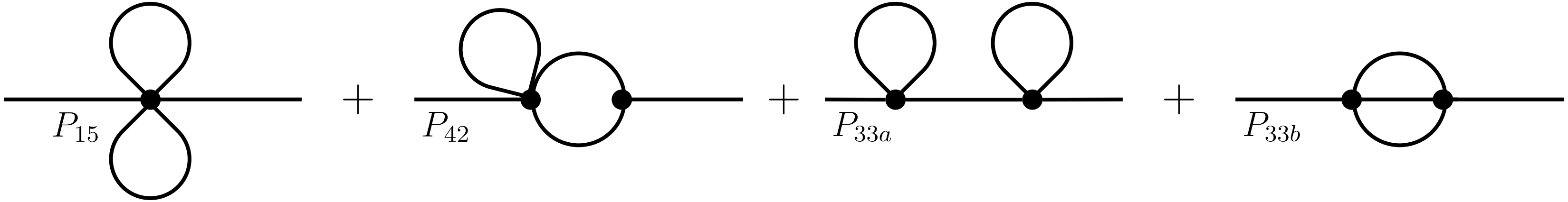
EFT at 1-loop

- In principle include 1-loop ctr. terms $\propto \delta_{\rm cb}^{(1)}, \theta_{\rm cb}^{(1)}, \delta_{\nu}^{(1)}, \theta_{\nu}^{(1)}$
- Assume $k_{\rm FS} \ll k \ll k_{\rm NL}$ (breaks down for $m_\nu \gtrsim 0.15$ eV)
  - Have $\delta_{\rm cb}^{(1)} \propto \theta_{\rm cb}$, $\delta_{\nu}^{(1)} = \theta_{\nu}^{(1)} = 0$
  - Standard ctr. term $c_s^2 k^2 P_{\rm cb,cb}^{\rm lin}$



Renormalizing the two-loop correction

- EFT stress tensor: ~ 10 counterterm operators (DM only)
- In practice: degeneracies, risk of overfitting



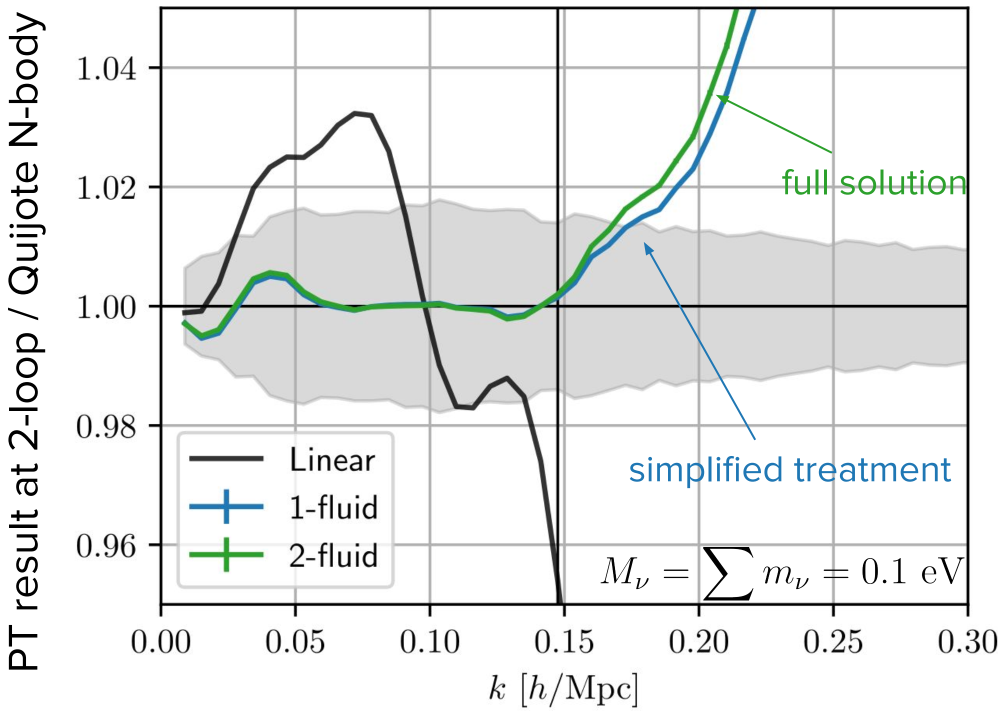
- Two-parameter ansatz

Baldauf et.al. 2015

  - Double-hard limit renormalized by one-loop ctr.term. $c_{\rm s}^2 k^2 P_{\rm lin}$
  - Single-hard limit: *free parameter* $\times$ *factorized single-hard shape*

- Sufficent to renormalize the UV, but does not necessarily capture complete UV physics

Comparison to N-body



CDM+baryons density spectrum

- 2-parameter EFT setup for 2-loop, extended to neutrino-case
- Impact of taking exact scale- and time-dependence into account is largely degenerate with one-loop counterterm
- Models cannot be distinguished at this level of precision

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Summary

- Challenging to incorporate (additional) scale-dependence
- Example: two-component fluid of *CDM+baryons and neutrinos*
  - Small effect on density spectrum
  - Larger on velocity spectrum
  - Degeneracy with counterterms

Outlook

- Safe to treat neutrinos linearly; neglect scale-dep.
  - See also Senatore et.al 2017 and H. Noriega et.al. 2022
- Similar conclusion for f(R) [Rodriguez-Meza et.al 2023, B. Bose et.al. (EUCLID) 2023]
- Ideally: fast evaluation of integrals including scale-dependence

$$\delta \sim \int \mathrm{d}\tau' \; \mathcal{G}(k,\tau') \int \mathrm{d}^3 q \; F_2(|\mathbf{k}-\mathbf{q}|, q, k_{\mathrm{FS}}; \tau')$$

Thank you!