Precision modeling of neutrino impact on LSS

Based on works in collaboration with M. Garny, M. Escudero:

JCAP **01** (2021) 020 [2008.00013], JCAP **09** (2022) 054 [2205.11533],
Phys. Rev. D **106** (2022) 063539 [2207.04062]

Petter Taule

Euclid-France Theory and Likelihood Workshop

28.11.2022

Outline

1. Introduction

2. Framework to compute loop corrections with general time- and scale-dependence

3. Application: massive neutrinos in LSS

4. Non-standard neutrino interactions: CMB constraints and impacts on LSS

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Baumann et.al. '10, Carrasco et.al. '12, Desjacques et.al. '16

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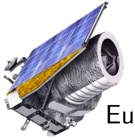
- The future is bright


Euclid

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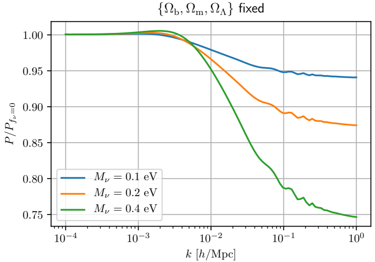
- Application: **massive neutrinos in structure formation**
- Scale-dependent suppression of power spectrum from neutrino freestreaming

$$k_{\mathrm{FS}} \simeq \frac{0.05\ h/\mathrm{Mpc}}{\sqrt{1+z}} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{\Omega_m}{0.3}\right)^{1/2}$$



Eulerian perturbation theory

- Equations of motion for cold DM (+baryons)

$$\partial_\tau \delta + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$
$$\partial_\tau \mathbf{v} + \mathcal{H}\mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\phi$$

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Rewritten in compact form ($\theta = \nabla \cdot \mathbf{v}$)

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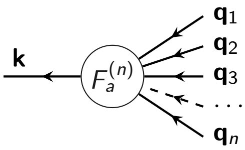
- Perturbation theory on mildly non-linear scales $k \sim 0.1\ h/\mathrm{Mpc}$

$$\begin{pmatrix}\delta\\ \theta\end{pmatrix}_a = \sum_{n=1}^{\infty}\int_{\mathbf{q}_1,\ldots,\mathbf{q}_n} \delta_D(\mathbf{k} - \sum_j \mathbf{q}_j)\ F_a^{(n)}(\mathbf{q}_1,\ldots,\mathbf{q}_n) \prod_{j=1}^{n}\delta_0(\mathbf{q}_j,\tau_{\mathrm{ini}})$$

EdS: analytic solutions for $F_a^{(n)}$



Bernardeau et.al. 2001

Eulerian perturbation theory, extended

- **Extension**: Generic time- and scale-dependence and multiple components

$$\partial_\tau \begin{pmatrix} \delta \\ \theta \\ \cdots \end{pmatrix}_a + \Omega_{ab}\left(\mathbf{k}, \tau\right) \begin{pmatrix} \delta \\ \theta \\ \cdots \end{pmatrix}_b = \int \mathrm{d}^3\mathbf{q}\, \gamma_{abc} \begin{pmatrix} \delta \\ \theta \\ \cdots \end{pmatrix}_b \begin{pmatrix} \delta \\ \theta \\ \cdots \end{pmatrix}_c$$

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Pros:

- Exact time-dependence in ΛCDM and wCDM
- **Neutrino freestreaming**
- Viscous DM, warm DM
- Additional light relics
- …

Cons:

- No analytic solution (in general)
- Slow: numerical loop integration solving ODE for $F_a^{(n)}$ at every integration point

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Two-component fluid

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- CDM+baryons (cb): one joint component
- Neutrinos: $z_{\mathrm{nr}} \simeq 189 \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)$
  - $z > 25$: Full Boltzmann hierarchy (linear)
  - $z < 25$: Fluid description (non-linear)

D. Blas et.al. 1408.2995
M. Garny, PT 2008.00013, 2205.11533

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- Fluid perturbations: $(\delta_{\rm cb}\,, \theta_{\rm cb}\,, \delta_\nu\,, \theta_\nu)$
- cb and ν coupled via gravity, equation for neutrino velocity

$$\partial_\tau \theta_\nu + \mathcal{H}\theta_\nu + \frac{3}{2}\mathcal{H}^2\Omega_m[f_\nu\delta_\nu + (1-f_\nu)\delta_{\rm cb}] - k^2 c_s^2 \delta_\nu + k^2\sigma = ...$$

Neutrino sound velocity c_s^2 and σ from linear theory

$\rightarrow$ scale-dependent dynamics

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Comparison

- *Full solution*: two-component fluid embedded in extended Eulerian perturbation theory
- Commonly used *simplified treatment*: EdS approximation and neutrino perturbations included only linearly
- Dashed lines: linear+1-loop. Solid lines: linear+1-loop+2-loop

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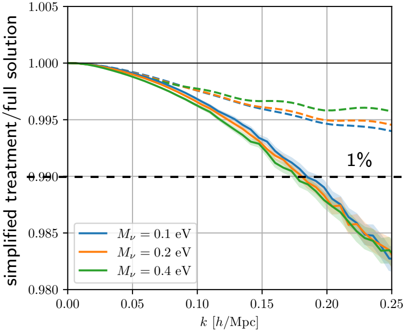

CDM+baryons density spectrum $\langle\delta\delta\rangle$

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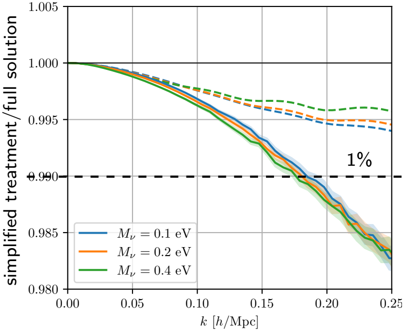

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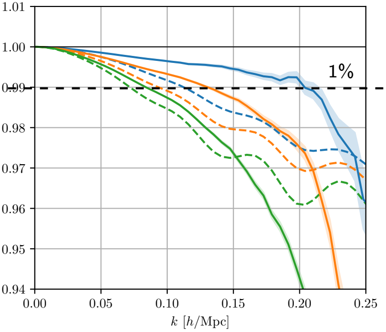


CDM+baryons velocity spectrum $\langle\theta\theta\rangle$

M. Garny, PT 2205.11533

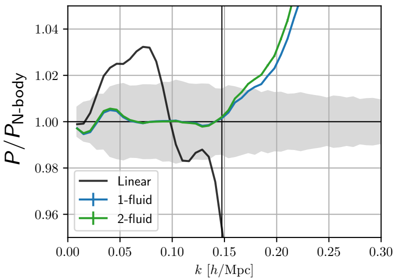
EFTofLSS

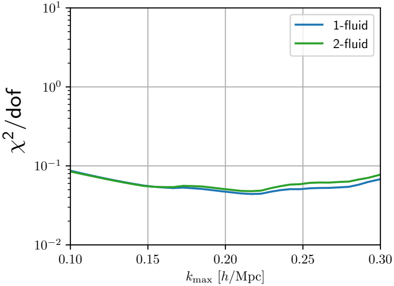
- “Standard” cosmological PT sensitive to unknown UV physics ($k > k_{\mathrm{NL}}$)
- **Effective theory**: [1]
  - Do not need to know small-scale to do long-distance physics
  - Correct for UV-dependence by effective operators with free coefficients
  - Symmetries: equivalence principle, Galilean invariance
- Two-component fluid with neutrinos: EFT for $k_{\mathrm{FS}} \ll k \ll k_{\mathrm{NL}}$ [2]

[1] Baumann et.al. 1004.2488
Carrasco et.al. 1206.2926
[2] M. Garny, PT 2205.11533

Comparison to N-body

- Including EFT counterterms, fitted to Quijote[1] N-body results, for $\sum m_\nu = 0.1$ eV
- 1-fluid: simplified treatment
  2-fluid: full solution





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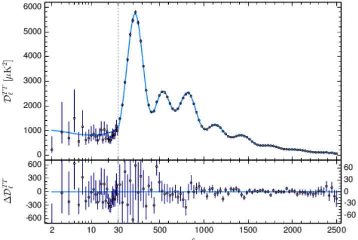
[1] F. Villaescusa-Navarro et.al. 1909.0573

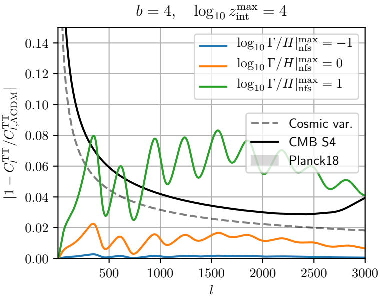
II. Non-standard neutrino interactions

Non-standard neutrino interactions

- Freestreaming neutrinos imprint signals in the CMB
- Non-standard neutrino interactions that prevents freestreaming can be tested with the CMB

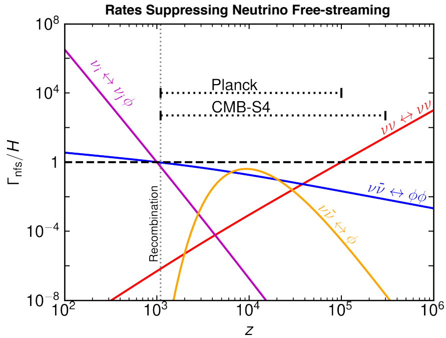


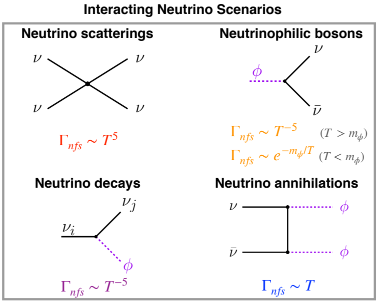
Planck collaboration 1807.06209



Non-standard neutrino interactions

- Power-law rates: $\Gamma_{\rm nfs} \propto T^{n_{\rm int}}$ with $n_{\rm int} = [-5, -3, -1, 1, 3, 4, 5]$
- Transient rates in redshift

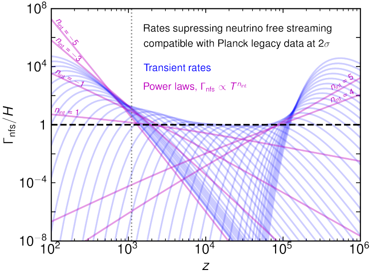




e.g. Chacko et.al. '03, Beacom et.al '04, Hannestad et.al. '05, Archidiacono et.al. '13, Cyr-Racine et.al. '13, Escudero et.al. '19, Forastieri et.al. '19, Choudhury et.al. '20, Brinckmann et.al. '20, Escudero et.al. '21 Abellán et.al. '21, Chen et.al. '22,

CMB constraints and LSS impacts

Full Planck legacy analysis with CLASS and MontePython



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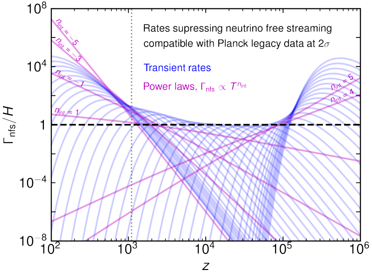
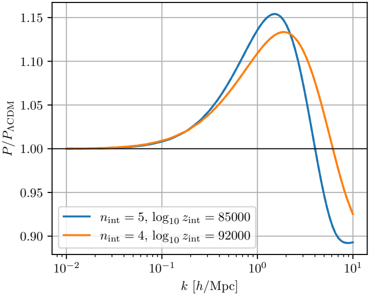


Impact on power spectrum from high-z interactions ($\propto T^4$ and $\propto T^5$)



→ *Redshift-window* $2000 < z < 10^5$ where neutrino freestreaming cannot be dampened

→ LSS probes can constrain non-standard neutrino interactions

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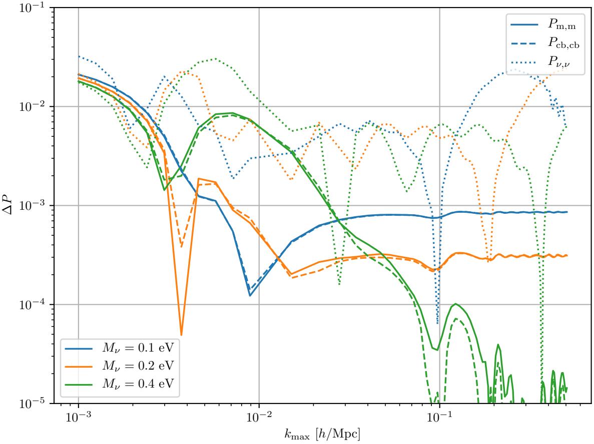
Summary

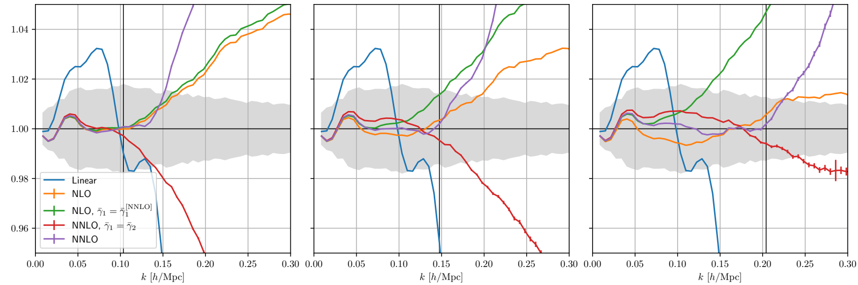
- Eulerian PT extension that can capture general time- and scale-dependence
  - Allows to consider extended models, but not efficient enough for MCMC
- Application: Effect of neutrino perturbations beyond linear theory
  - Discrepancy on density spectrum largely degenerate with counterterms
  - Larger impact of scale-dependence due to neutrinos on velocity spectrum $\rightarrow$ RSD
- Non-standard neutrino interactions
  - *Freestreaming window* $2000 < z < 10^5$ in which neutrinos cannot interact significantly
  - Interactions dampening freestreaming at high redshift can be probed by LSS

Backup slides

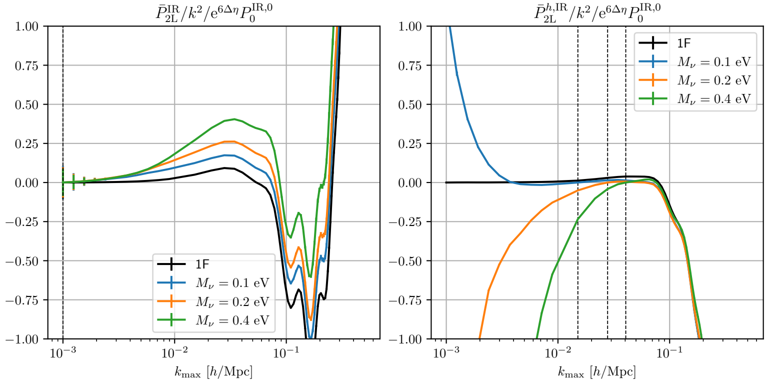
Linear two-fluid evolution



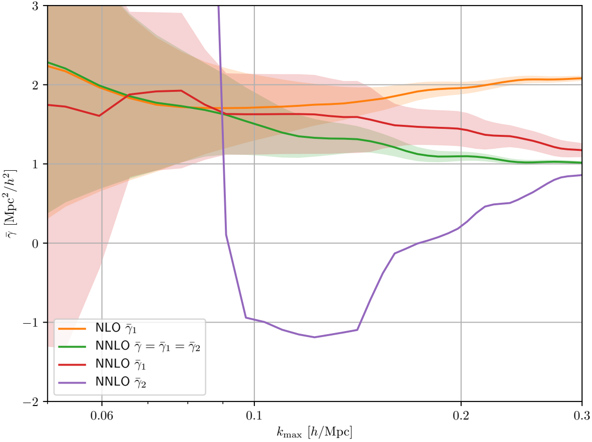
Order/parameter comparison



Two-loop subtraction



EFT parameters



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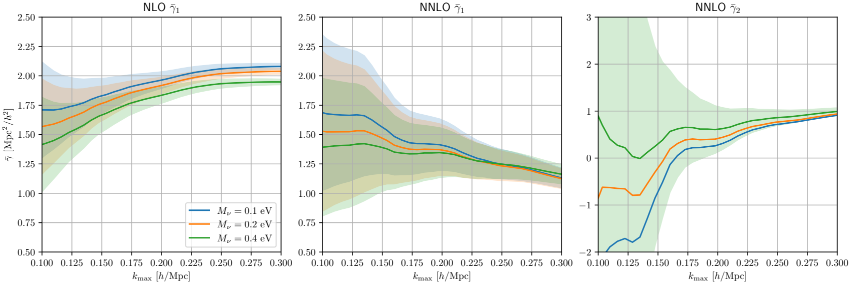
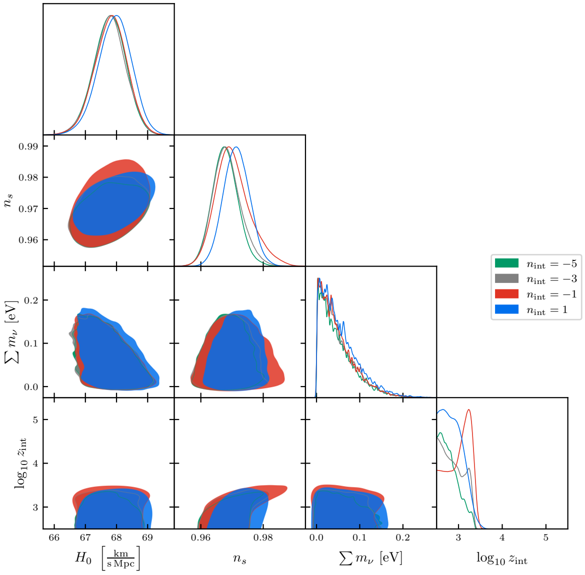
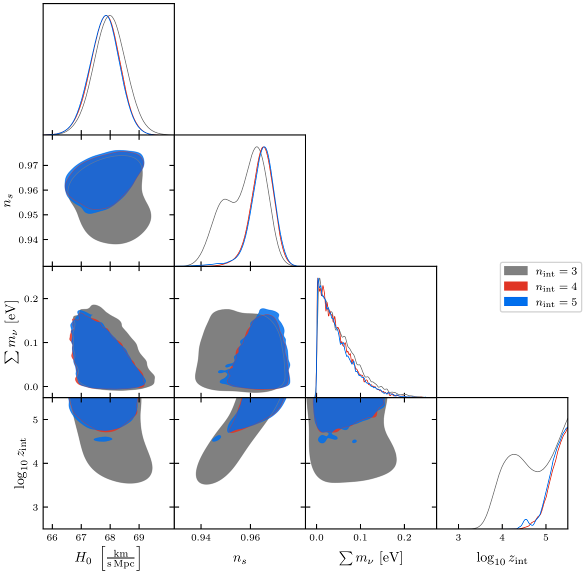



0.99
0.98
0.97
0.96
n_s
0.2
0.1
0.0
$\sum m_\nu$ [eV]
5
4
3
$\log_{10} z_{\rm int}$
66
67
68
69
0.96
0.98
0.0
0.1
0.2
3
4
5
H_0 $\left[\frac{\rm km}{\rm s\,Mpc}\right]$
n_s
$\sum m_\nu$ [eV]
$\log_{10} z_{\rm int}$
$n_{\rm int} = -5$
$n_{\rm int} = -3$
$n_{\rm int} = -1$
$n_{\rm int} = 1$



0.97
0.96
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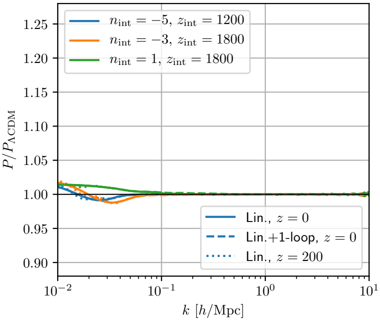
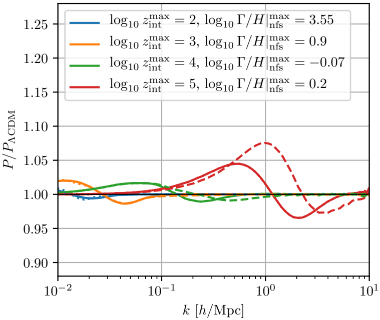
5
$\log_{10} z_{\rm int}$
$n_{\rm int} = 3$
$n_{\rm int} = 4$
$n_{\rm int} = 5$



$n_{\rm int} = -5$, $z_{\rm int} = 1200$
$n_{\rm int} = -3$, $z_{\rm int} = 1800$
$n_{\rm int} = 1$, $z_{\rm int} = 1800$
Lin., $z = 0$
Lin.+1-loop, $z = 0$
Lin., $z = 200$
$P/P_{\Lambda\rm CDM}$
k [h/Mpc]



$\log_{10} z_{\rm int}^{\rm max} = 2$, $\log_{10} \Gamma/H|_{\rm nfs}^{\rm max} = 3.55$
$\log_{10} z_{\rm int}^{\rm max} = 3$, $\log_{10} \Gamma/H|_{\rm nfs}^{\rm max} = 0.9$
$\log_{10} z_{\rm int}^{\rm max} = 4$, $\log_{10} \Gamma/H|_{\rm nfs}^{\rm max} = -0.07$
$\log_{10} z_{\rm int}^{\rm max} = 5$, $\log_{10} \Gamma/H|_{\rm nfs}^{\rm max} = 0.2$
$P/P_{\Lambda\rm CDM}$
k [h/Mpc]