Advancing our understanding of how new physics affects cosmic neutrinos

Based on [2409.15129]+[2409.07378] and [2411.00892]+[2411.00931]

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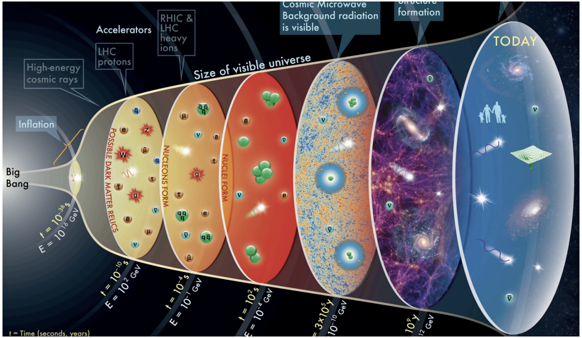
Introduction I

– BBN+CMB: currently, the earliest messengers from the Early Universe with $\boldsymbol{T \simeq}$ **few MeV**
– Observations may constrain/reveal the existence of non-standard physics at that epoch



Key point to derive constraints/sensitivities: how cosmic neutrinos evolve under non-standard scenarios?

Introduction II

- Neutrinos in the Early Universe were in thermal equilibrium:

$$\nu\bar{\nu} \leftrightarrow e^+e^-, \; \nu e^{\pm} \leftrightarrow \nu e^{\pm} \tag{1}$$

- Temperatures $T = 0.5 - 5$ MeV – neutrinos decouple:

$$\Gamma_{\text{int},\nu} \simeq H \tag{2}$$

- Standard cosmological scenario [2306.05460]:

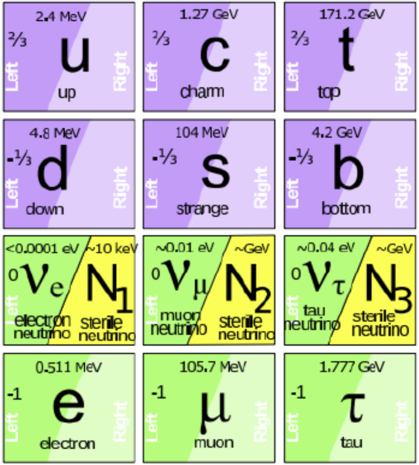
$$N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\text{UR}} - \rho_{\gamma}}{\rho_{\gamma}} \approx 3.043 \tag{3}$$

  agrees with CMB measurements $N_{\text{eff}} = 2.99 \pm 0.17$ at 68% CL
- Ongoing Simons Observatory observations: aim to determine N_{eff} with % level accuracy

Introduction III

Example of non-standard scenarios

- Late reheating scenarios
- Long-lived particles (LLPs) relics
- Lepton flavor asymmetries
- Evaporating black holes
- Decaying topological defects
- ...
- ***Combination of these***



Evolution of neutrinos around decoupling: key points I

Properties of neutrino equilibration

Feature	Consequence
νs interact with themselves and $e^{\pm}$ via weak interactions	Cross-section scaling: $\sigma \propto G_F s^2$. νs with various energies equilibrate differently
EM rates $\gg$ weak rates	EM plasma is always thermal at the scales of ν thermalization
$\Gamma_{\text{weak}}/H \propto T^3$	ν decoupling is not instantaneous

– Microscopics of thermalization is important both
  - Quantitatively (the value of $|\Delta N_{\text{eff}}|$)
  - Qualitatively ($\text{sign}(\Delta N_{\text{eff}})$)

– These features can be captured by solving the equation on the neutrino distribution

Evolution of neutrinos around decoupling: key points II

- Neutrino Boltzmann equation:

$$\partial_t f_{\nu_\alpha} - Hp\partial_p f_{\nu_\alpha} = \mathcal{I}_{\text{coll},\alpha}[f_{\nu_\alpha}, p] \tag{4}$$

- Collision integral:

$$\mathcal{I}_{\text{coll},\alpha} = \sum_k \int d\Phi_k |\mathcal{M}|^2 F[f], \tag{5}$$

where $F[f]$ is statistical factor and $d\Phi_k$ is the phase space:

$$d\Phi_k = \frac{1}{2E_{\nu_\alpha}} \prod_{i=2} \frac{d^3 p_i}{(2\pi)^3 2E_i} \prod_{f=1} \frac{d^3 p_f}{(2\pi)^3 2E_f} (2\pi)^4 \delta^{(4)} \left(\sum_{i=1} p_i - \sum_{f=1} p_f \right) \tag{6}$$

- Processes:

$$\nu\bar{\nu} \leftrightarrow e^+e^-,\ \nu e^\pm \leftrightarrow \nu e^\pm,\ X \to n\nu,\ X \to \text{jets},\ X \to l + \text{jets}, \dots \tag{7}$$

Evolution of neutrinos around decoupling: key points III

Additional equations

- Thermodynamics and expansion of the Universe
- Evolution of “mother particles” of non-standard physics
  Abundance evolution, BH evaporation, defects decay, etc.
- Evolution of secondary non-ν products injected by non-standard physics
  - EM particles $e^{\pm}, \gamma$: increase the EM temperature
  - Metastable particles $Y = \mu, \pi^{\pm}, K$: $\tau_Y \gtrsim \Gamma^{-1}_{\text{int},Y}$

Complexities in solving the ν Boltzmann equation

Solving the Boltzmann equation explicitly: momentum discretization

Feature	Consequence
Stiffness (expansion rate vs interaction rate)	Non-trivial to maintain performance and accuracy
Momenta population: thermal tail $y = \text{const}$ +non-standard part $F(p) = \text{const}$	Complicated to define efficient momentum binning other than linear
Non-trivial phase space: $2 \to 3$ scatterings, decays into jets, ...	$d\Phi_k$ cannot be introduced/reduced analytically

– Model dependence
– Performance issues: timing scales as

$$t_{\text{solve}} \sim E_{\nu,\max}^{k+2}, k \geq 2, \quad (8)$$

where k is the dimensionality of the reduced $d\Phi_k$, $E_{\nu,\max}$ is the maximal comoving neutrino energy

Solving neutrino Boltzmann equation with νDSMC I

Idea: instead of solving explicitly, use Monte-Carlo simulations

- Start with a system of $\nu_s, e^{\pm}, X$
- Simulate their interactions throughout the evolution of the Universe
- Analog in physics of rarefied gases: **Direct Simulation Monte-Carlo (DSMC)**

Advantages:

- No need to discretize momentum
  Interactions will decide on the momentum flow
- Universal description of interactions
- No constraints from analytic reducibility of phase space
  May use phase space simulated in MC tools
- Strong performance
  DSMC handles billions of particles

Solving neutrino Boltzmann equation with νDSMC II

Vanilla DSMC (utilizing so-called No-Time-Counter method)

1. Beginning of timestep Δt: update particles' $\{\mathbf{r}_i, \mathbf{v}_i\}$ due to external forces
2. Split the system of volume V into cells containing N_{cell} particles
3. For each cell, sample N_{sample} pairs of particles to interact:

$$N_{\text{sample}} = \frac{1}{2} N_{\text{cell}}(N_{\text{cell}} - 1) \overbrace{\frac{(\sigma v)_{\text{max}}}{V_{\text{cell}}} \Delta t}^{\omega^{\text{max}}_{\text{cell}} \cdot \Delta t} \tag{9}$$

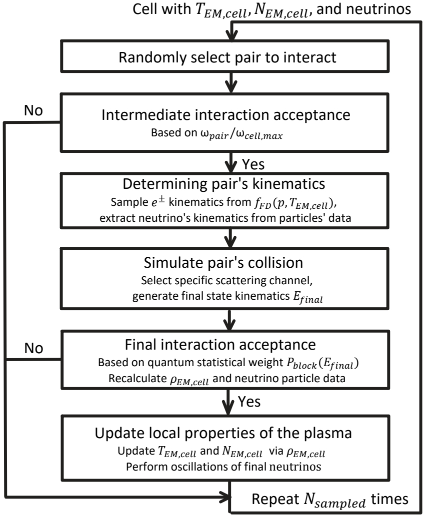
3. Iteratively: for each sampled pair, accept the interaction with the probability $P_{\text{acc}} = (\sigma v)_{\text{pair}}/(\sigma v)_{\text{max}}$. If accepted, generate the kinematics and final state

[Prog.Astron.Aeron. 117, 211–226 (1989)])

Solving neutrino Boltzmann equation with $\boldsymbol{\nu}$DSMC III

To apply it to neutrinos, DSMC requires fundamental modifications (**$\boldsymbol{\nu}$DSMC**):

1. **Expansion of the Universe**: redshift particles' momenta and system volume
2. **EM plasma properties**: represent the EM particles globally by $\boldsymbol{T_{\mathrm{EM}}}$ and at cell level by $\boldsymbol{T_{\mathrm{EM,cell}}}$; update it after any interaction involving EM particles
3. **Quantum statistics**: final interaction approval decision based on the blocking factors $\boldsymbol{1 - f_{\mathrm{final}}(E_{\mathrm{final}})}$ for the final states
4. **Decaying particles**: introduce $\boldsymbol{N_{\mathrm{LLP}}}$ LLPs, distribute their decay times throughout the evolution, simulate decays (e.g., in `SensCalc/Pythia8`)



Solving neutrino Boltzmann equation with νDSMC IV

Neutrino DSMC prototype written in `Mathematica` [:)]

- Already performs much faster than the discretization approach for setups with $E_{\nu,\max} \gtrsim 20$ MeV
- **Cross-checks:** comparing with the state-of-the-art approaches in the case of a few well-defined setups
  See backup
- Fully public version and the study of late reheating scenario as an example: in preparation

Code may be provided upon request

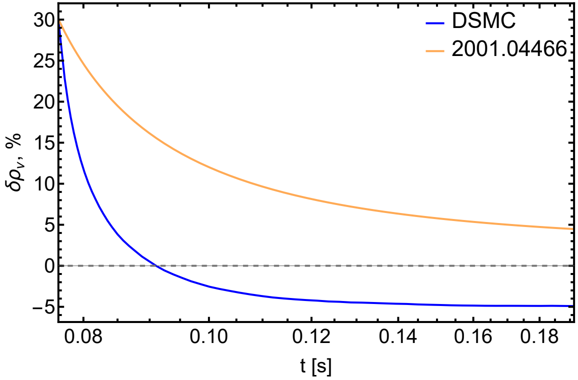
Solving neutrino Boltzmann equation with $\boldsymbol{\nu}$DSMC V

– Definition of N_{eff}:

$$N_{\text{eff}} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{8}{7} \frac{\rho_{\text{UR}} - \rho_\gamma}{\rho_\gamma}\Bigg|_{T_{\text{CMB}}} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{8}{7} \frac{\rho_\nu}{\rho_\gamma}\Bigg|_{T_{\text{CMB}}} \quad (10)$$

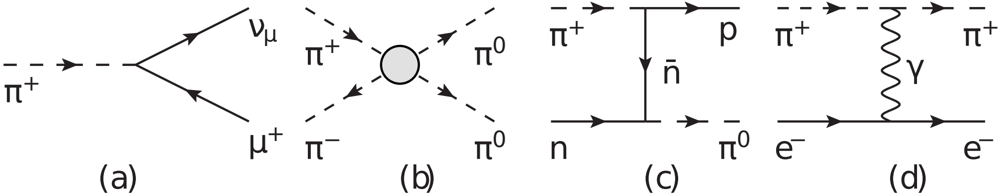
– Dynamical analog:

$$\delta\rho_\nu = \left(\frac{\rho_{\text{EM}}}{\rho_\nu}\right)_{\Lambda\text{CDM}} \frac{\rho_\nu}{\rho_{\text{EM}}} - 1 \quad (11)$$



Any heavy ($m \gtrsim 50 - 100$ MeV) relic decaying at neutrino decoupling would decrease N_{eff}

Evolution of metastable decay products I



- Consider injection of **metastable particles**: $\boldsymbol{Y = \mu, \pi^{\pm}/K}$
- Before decaying (a), $\boldsymbol{Y}$s may participate in
  - Elastic scattering off EM particles (d)
  - Interactions with nucleons (c)
  - Self-annihilations (b)

Reactions (b), (c): dropped in the literature when studying the impact of LLPs on neutrinos

Evolution of metastable decay products II

– To trace the dynamics of metastables $\boldsymbol{Y = \{\mu, \pi, K\}}$, solve the system of integrated Boltzmann equations:

$$\begin{cases} \frac{dn_Y}{dt} + 3Hn_Y = \frac{n_X}{\tau_X} N_Y^X - \frac{n_Y}{\tau_Y} - n_Y n_{\bar{Y}} \langle \sigma_{\text{ann}}^Y v \rangle - \left(\frac{dn_Y}{dt}\right)_{\mathcal{N}} + \sum_{Y' \neq Y} n_{Y'} \Gamma_{Y' \to Y}, \\ \frac{dn_{\bar{Y}}}{dt} + 3Hn_{\bar{Y}} = \frac{n_X}{\tau_X} N_{\bar{Y}}^X - \frac{n_{\bar{Y}}}{\tau_Y} - n_{\bar{Y}} n_Y \langle \sigma_{\text{ann}}^Y v \rangle - \left(\frac{dn_{\bar{Y}}}{dt}\right)_{\mathcal{N}} + \sum_{Y' \neq Y} n_{Y'} \Gamma_{Y' \to \bar{Y}}, \end{cases} \tag{12}$$

Here:

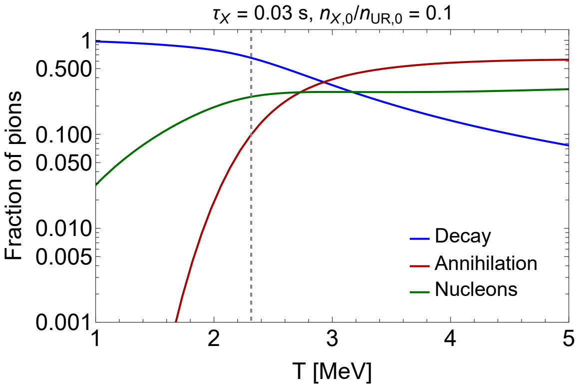
- **Direct decays of LLPs**
- **Decays**
- **Self-annihilations**
- **Interactions with nucleons**
- **Produced secondarily from heavier $\boldsymbol{Y}$s**

– When solving the neutrino Boltzmann equation with meson sources, account for secondary production and reduced decay probability of $\boldsymbol{Y}$s

Evolution of metastable decay products III

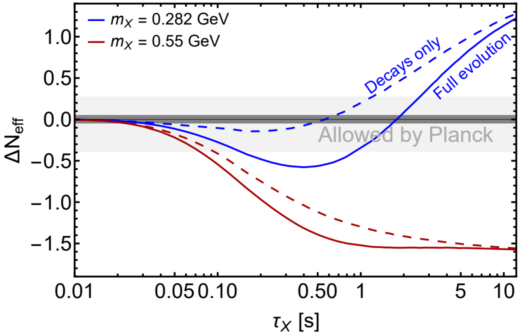
At MeV temperatures, Ys prefer to annihilate or interact with nucleons

- Decays into neutrinos are suppressed
- In terms of the energy deposition, Ys behave like EM plasma particles
- Interactions with nucleons are very important for BBN [1006.4172], [2008.00749]

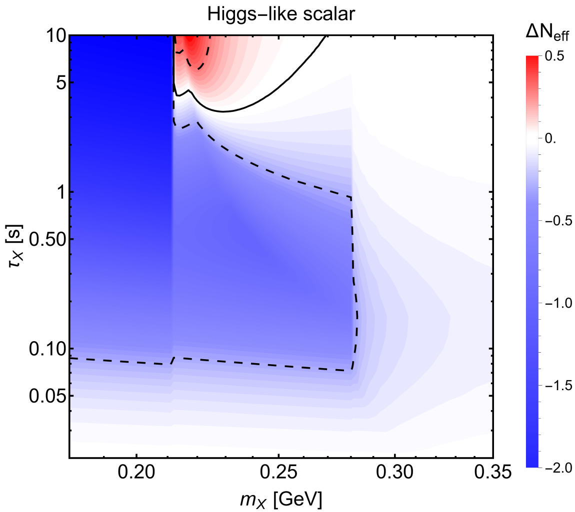


- $K^{\pm}$ particles: induce energy asymmetry between νs and $\bar{\nu}$s

Bringing together



- Combined impact of metastable dynamics and non-thermal neutrinos: $\Delta N_{\text{eff}}(\tau_{\text{LLP}})$ may change sign
- Right panel: parameter space of Higgs-like scalar



Conclusions

- BBN and CMB observations are a powerful new physics exclusion/potential discovery playground
- To derive constraints/sensitivities, one needs to accurately solve the neutrino Boltzmann equation in a model-agnostic fashion
- $\boldsymbol{\nu}$DSMC: solving neutrino Boltzmann equation by methods from particle physics
- To be released soon: a $\boldsymbol{\nu}$DSMC versatile framework tracing the impact of new physics on BBN and CMB

Backup slides

Neutrinophilic decays: does N_{eff} decrease? I

- Definition of N_{eff}:

$$N_{\text{eff}} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{8}{7} \frac{\rho_{\text{UR}} - \rho_\gamma}{\rho_\gamma}\bigg|_{T_{\text{CMB}}} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{8}{7} \frac{\rho_\nu}{\rho_\gamma}\bigg|_{T_{\text{CMB}}} \tag{13}$$

What happens if we add new physics particles decaying solely into neutrinos?

Existing approaches are contradictory

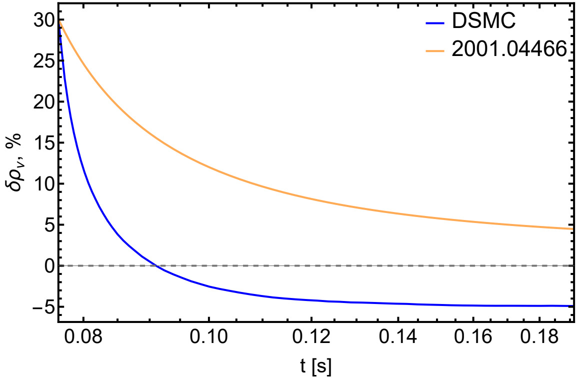
- **Integrated** approach [2001.04466]: N_{eff} increases
- **Discretization** approach:
  - Refs. [0008138], [2104.11752]: N_{eff} increases
  - Refs. [2103.09831] [2109.11176]: N_{eff} may **decrease** *(for injected neutrino energies $E_\nu \gg T$)*

Neutrinophilic decays: does N_{eff} decrease? II

- Setup: instantly injected **70 MeV** neutrinos at $\boldsymbol{T = 3}$ **MeV**
- Introduce dynamical analog of $\boldsymbol{\Delta N_{\text{eff}}}$:

$$\boldsymbol{\delta\rho_\nu = \left(\frac{\rho_{\text{EM}}}{\rho_\nu}\right)_{\Lambda\text{CDM}} \frac{\rho_\nu}{\rho_{\text{EM}}} - 1} \quad (14)$$

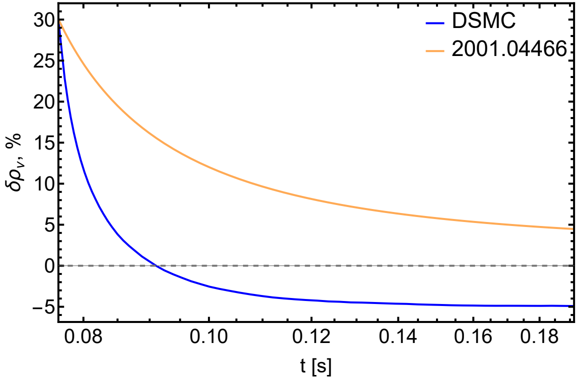
- Study how it evolves



$\boldsymbol{\delta\rho_\nu}$ drops from positive to negative $\boldsymbol{\Rightarrow \Delta N_{\text{eff}} < 0}$. Why?

Neutrinophilic decays: does N_{eff} decrease? III

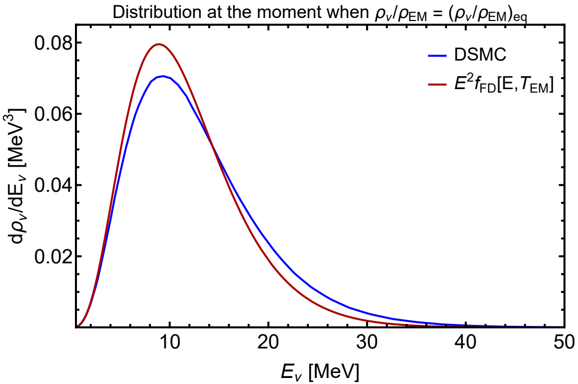
- High-energy $\boldsymbol{\nu}$s interact much faster than thermal interactions ($\boldsymbol{\sigma}_{\text{int}} \sim \boldsymbol{s}$)
- They will either redistribute the energy in the neutrino sector or pump the energy to the EM plasma
- The EM plasma thermalizes instantly $\Rightarrow$ no fast inverse reactions



$\delta\rho_\nu$ quickly drops to zero

Neutrinophilic decays: does N_{eff} decrease? IV

- Let us look closer at the moment $\delta\rho_\nu = 0$
- Thermalization causes characteristic change in actual $p^2 f_\nu(p)$ (compared to $p^2 f_{\text{FD}}$):
  - **Overrepresented** at high p
  - **Underrepresented** at low p
- This change shift the balance in the energy transfer $\nu \leftrightarrow$ **EM** to the right



Any heavy ($m \gtrsim 50 - 100$ MeV) relic decaying at neutrino decoupling would decrease N_{eff}

DSMC: cross-checks I

- DSMC has been cross-checked against the integrated Boltzmann approach from Ref. [2001.04466] and the unintegrated approach from Ref. [2005.07047]
- For cross-checks, we have considered toy setups of the instant neutrino injections:
  - At some temperature T_{inj}, we inject neutrinos with various properties
  - They start equilibrating with the EM particles. We trace both the integrated evolution

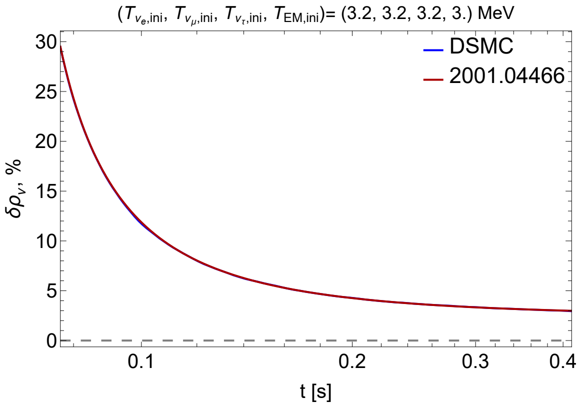
$$\delta\rho_{\nu} = \left(\frac{\rho_{\text{EM}}}{\rho_{\nu}}\right)_{\Lambda\text{CDM}} \frac{\rho_{\nu}}{\rho_{\text{EM}}} - 1 \quad (15)$$

    and the energy distribution

DSMC: cross-checks II

Setup 1:

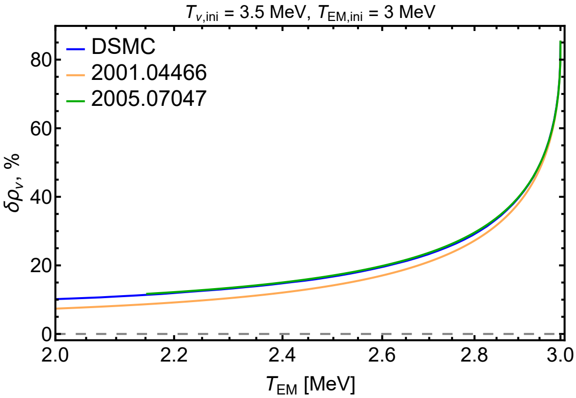
- Start with the equilibrium shape of the neutrino distribution but with $\boldsymbol{T_\nu = 3.2}$ **MeV**, $\boldsymbol{T_{\mathrm{EM}} = 3}$ **MeV**
- At each step, assume that the neutrino spectrum gets rebuilt to acquire an equilibrium shape
- Under this simplification, the results fully agree with the integrated approach [2001.04466]



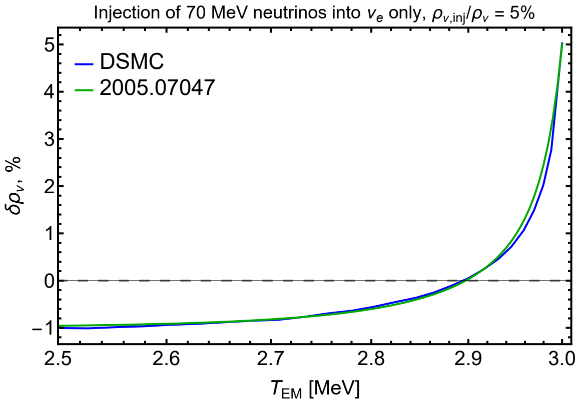
DSMC: cross-checks III

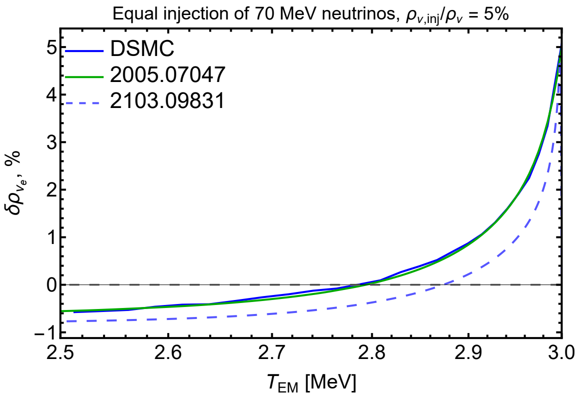
Setup 2:

- Start with the same setup, but allow distortions of the neutrino distribution
- The results disagree with [2001.04466], but agree with the unintegrated approach [2005.07047]
- They signal that the neutrino spectral distortions develop even if one starts with the equilibrium distributions – due to the energy dependence of $\boldsymbol{\sigma_\nu}$



DSMC: cross-checks IV

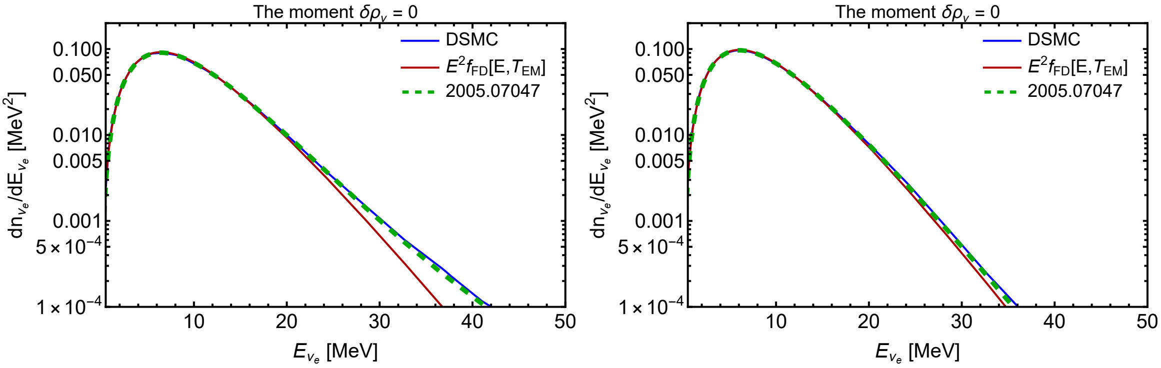




Setup 3:

- Instant injection of $\boldsymbol{\rho_{\nu,\text{inj}}/\rho_\nu = 5\%}$ at $\boldsymbol{T = 3}$ **MeV**
- Results fully agree with [2005.07047]

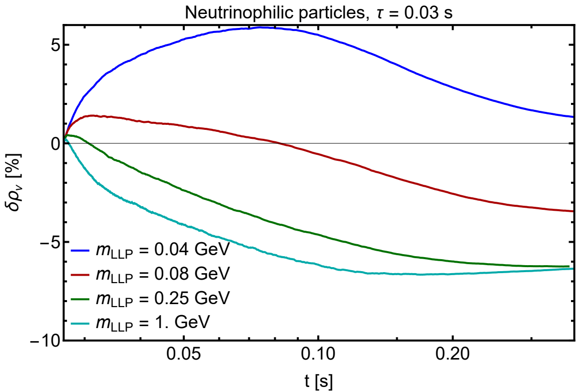
DSMC: cross-checks V



Setup 3:

- Instant injection of $\boldsymbol{\rho_{\nu,\mathrm{inj}}/\rho_\nu = 5\%}$ at $\boldsymbol{T = 3}$ **MeV**
- Results fully agree with [2005.07047]

Application of DSMC to realistic models I



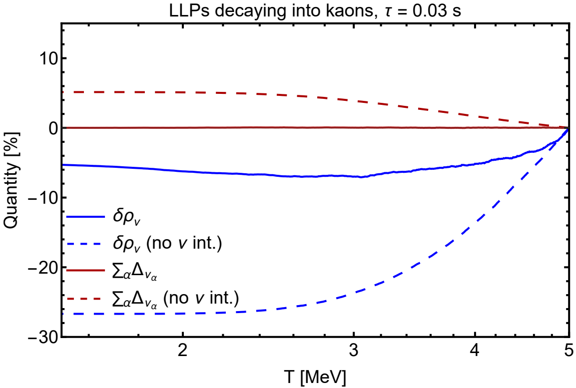
– Example: short-lived neutrinophilic particle with mass $\boldsymbol{m}$

– Cumulative $\boldsymbol{\delta\rho_\nu}$ crosses zero if $\boldsymbol{E_{\nu,\mathrm{inj}} = m/2}$ becomes $\boldsymbol{\gg \langle E_{\nu,\mathrm{thermal}}\rangle = 3T}$

Application of DSMC to realistic models II

- Kaonphilic particle – incorporated into $\boldsymbol{\nu}$DSMC
- Decays into kaons would inequally inject energy into neutrinos and antineutrinos
- Introduce neutrino-antineutrino energy asymmetry:

$$\boldsymbol{\Delta_\alpha = \frac{\rho_{\nu_\alpha} - \rho_{\bar{\nu}_\alpha}}{\rho_{\nu_\alpha} + \rho_{\bar{\nu}_\alpha}}} \quad (16)$$



If LLPs have small lifetimes, Δ_α would be erased by efficient energy redistribution

Qualitative understanding of neutrino thermalization I

– The amount of energy that ends up in the EM plasma right after the injection of high-energy neutrinos is

$$\xi_{\mathrm{EM,eff}}(E_{\nu}^{\mathrm{inj}}, T) = \xi_{\mathrm{EM}} + \xi_{\nu} \times \epsilon(E_{\nu}^{\mathrm{inj}}, T), \tag{17}$$

where $\xi_{\nu} = 1 - \xi_{\mathrm{EM}}$ is the energy fraction that LLPs directly inject into the neutrino sector and ϵ is the effective fraction of ξ_{ν} that went to the EM plasma during the thermalization

*The latter quantity can be split in a contribution from non-equilibrium neutrinos ($\epsilon_{non\text{-}eq} = E_{\nu}^{non\text{-}eq \to EM}/E_{\nu}^{inj}$) and an **EM**pheffective contribution from thermal neutrinos ($\epsilon_{thermal} = E_{\nu}^{thermal \to EM}/E_{\nu}^{inj}$)*

– If $\epsilon > 0.5$, then $\xi_{\mathrm{EM,eff}} > 0.5$, and N_{eff} may become negative

Qualitative understanding of neutrino thermalization II

- A simple estimate of ϵ as a function of the injected neutrino energy E_{ν}^{inj} and temperature T. We start with describing the thermalization process of a **EM**phsingle injected neutrino, which causes a cascade of non-equilibrium neutrinos. Such a cascade can result after the injected neutrino participates in the processes

$$\nu_{\text{non-eq}} + \nu_{\text{therm}} \to \nu_{\text{non-eq}} + \nu_{\text{non-eq}} \tag{18}$$

$$\nu_{\text{non-eq}} + \overline{\nu}_{\text{therm}} \to e^{+} + e^{-} \tag{19}$$

$$\nu_{\text{non-eq}} + e^{\pm} \to \nu_{\text{non-eq}} + e^{\pm}, \tag{20}$$

- Assume that in the processes (18) and (20) each non-equilibrium neutrino in the final state carries half of the energy of the non-equilibrium neutrino in the initial state.
- Thus, roughly speaking, the thermalization occurs during $N_{\text{therm}} \simeq \log_2(E_{\nu}^{\text{inj}}/3.15T)$ interactions
- In addition, the process (18) doubles the number of non-equilibrium neutrinos, while (19) makes neutrinos disappear and (20) leaves the number unchanged

Qualitative understanding of neutrino thermalization III

- Therefore, after the k-th step in the cascade, the average number of non-equilibrium neutrinos is given by:

$$N_\nu^{(k)} = N_\nu^{(k-1)}\left(2P_{\nu\nu\to\nu\nu} + P_{\nu e\to\nu e}\right) = N_\nu^{(0)}\left(2P_{\nu\nu\to\nu\nu} + P_{\nu e\to\nu e}\right)^k, \quad (21)$$

  with $N_\nu^{(0)} = 1$, and the total non-equilibrium energy is:

$$E_\nu^{(k)} = E_\nu^{(k-1)}\left(P_{\nu\nu\to\nu\nu} + \frac{1}{2}P_{\nu e\to\nu e}\right) = E_\nu^{\text{inj}}\left(P_{\nu\nu\to\nu\nu} + \frac{1}{2}P_{\nu e\to\nu e}\right)^k, \quad (22)$$

  where $P_{\nu\nu\to\nu\nu}$, $P_{\nu\nu\to ee}$, and $P_{\nu e\to\nu e}$ are the average probabilities of the processes (18)–(20), respectively, and their sum equals unity
- We define these probabilities as $P_i = \Gamma_i/\Gamma_\nu^{\text{tot}}$, where Γ_i is the interaction rate of each process and Γ_ν^{tot} is the total neutrino interaction rate.

Qualitative understanding of neutrino thermalization IV

– Assuming a Fermi-Dirac distribution for neutrinos and averaging over neutrino flavours, we find:

$$P_{\nu\nu\to\nu\nu} \approx 0.76, \quad P_{\nu\nu\to ee} \approx 0.05, \quad P_{\nu e\to\nu e} \approx 0.19 \tag{23}$$

– Finally, the value of $\epsilon_{\text{non-eq}}$ that accounts for the energy transfer from non-equilibrium neutrinos to the EM plasma is given by:

$$\epsilon_{\text{non-eq}} = \frac{1}{E_\nu^{\text{inj}}} \sum_{k=0}^{N_{\text{therm}}} \left(\frac{P_{\nu e\to\nu e}}{2} + P_{\nu\nu\to ee} \right) E_\nu^{(k)} \tag{24}$$

– In addition to the transferred non-equilibrium energy, the non-equilibrium neutrinos catalyze the energy transfer from thermal neutrinos to the EM plasma via the processes (18) and (19).

Qualitative understanding of neutrino thermalization V

- We assume that each reaction (18) transfers an energy amount of $3.15T$ from the thermal neutrino sector to non-equilibrium neutrinos, which then via (19) ends up in the EM plasma
- Moreover, each reaction (19) contributes to another energy transfer of $3.15T$ from thermal neutrinos to the EM plasma
- The effective contribution coming from this transfer is therefore:

$$\boldsymbol{\epsilon_{\text{thermal}} = \frac{3.15T}{E_{\nu}^{\text{inj}}} N_{\nu}^{\text{therm}\to\text{EM}} = \\ = \frac{3.15T}{E_{\nu}^{\text{inj}}} P_{\nu\nu\to ee}\left(\sum_{k=0}^{N_{\text{therm}}} N_{\nu}^{(k)} + \left[P_{\nu\nu\to\nu\nu} + \sum_{k=1}^{N_{\text{therm}}} (2P_{\nu\nu\to\nu\nu})^{(k)}\right]\right),} \quad (25)$$

where the first term in the round brackets is the contribution from the process (19) and the terms in the square brackets are the contribution from the process (18)
Note that the factor of 2 in the second sum accounts for the doubling of non-equilibrium neutrinos in the process (18).

Processes with mesons and muons I

- Consider first the case of muons μ. They do not efficiently interact with nucleons, but may annihilate instead:
$$\mu^+ + \mu^- \to e^+ + e^- \tag{26}$$
- Annihilation cross-section:
$$\sigma^{\mu}_{\text{ann}} = \frac{4\pi\alpha_{\text{EM}}^2}{m_\mu^2} \tag{27}$$
- Assume first that annihilation is irrelevant and decays dominate. Then, the muon number density available for annihilations may accumulate during the muon lifetimes τ_μ:
$$n_\mu^{\text{acc}} v \approx n_{\text{LLP}}(t)\frac{\tau_\mu}{\tau_X} \tag{28}$$

Processes with mesons and muons II

– Compare the annihilation and decay rates:

$$\frac{\Gamma_{\mu}^{\text{decay}}}{\Gamma_{\mu}^{\text{ann}}} = \frac{\tau_X}{n_X \tau_{\mu}^{-2} \sigma_{\text{ann}}^{\mu} v} \tag{29}$$

– Plugging in the numbers, we get

$$\frac{\Gamma_{\mu}^{\text{decay}}}{\Gamma_{\mu}^{\text{ann}}} = 3.4 \cdot 10^{-4} \cdot \frac{\tau_X}{0.05\ \text{s}} \cdot \frac{0.1 n_{\text{UR}}}{n_X} \left(\frac{3\ \text{MeV}}{T}\right)^3 \tag{30}$$

– This means that annihilation is actually highly competitive to decay and dominate until n_X gets enormously suppressed

Processes with mesons and muons III

- Now, consider pions. Their lifetime is two orders of magnitude smaller, but the annihilation cross-section is larger in a comparable way (proceeds via strong interactions)
- In addition, there is the (thresholdless) interaction with nucleons:

$$\pi^+ + n \to p + \pi^0\gamma, \quad \pi^- + p \to n + \pi^0/\gamma \tag{31}$$

- Cross-section is [Phys. Rev. D 37, 3441]

$$\langle \sigma_{\text{nucl}}\beta\rangle \simeq 1.5 \text{ mb} \simeq 4 \text{ GeV}^{-2} \tag{32}$$

- Compare the decay rate with the rate of the interaction with nucleons:

$$\frac{\Gamma_\pi^{\text{decay}}}{\Gamma_\pi^{\text{nucl}}} = \frac{1}{\tau_\pi n_B X_n \sigma_{\text{nucl}} v} \simeq \left(\frac{3 \text{ MeV}}{T}\right)^3 \cdot \frac{10^{-9}}{\eta_B} \tag{33}$$

Meson-driven conversion and BBN I

- $\boldsymbol{\sigma^{\text{meson}}_{p\leftrightarrow n}}$ exceeds $\boldsymbol{\sigma^{\text{weak}}_{p\leftrightarrow n}}$ by many orders of magnitude
- As far as even tiny amounts of LLPs are present in the plasma, we may drop the weak conversion rates
- Evolution for $\boldsymbol{X_n \equiv n_n/n_B}$:

$$\boldsymbol{dX_n/dt = (1 - X_n)\Gamma^{\text{meson}}_{p\to n} - X_n\Gamma^{\text{meson}}_{n\to p}} \tag{34}$$

- Dynamical equilibrium solution (valid until the amount of LLPs is hugely exponentially suppressed):

$$\boldsymbol{X_n(t) = \frac{\Gamma^{\text{meson}}_{p\to n}}{\Gamma^{\text{meson}}_{p\to n} + \Gamma^{\text{meson}}_{n\to p}}} \tag{35}$$

Meson-driven conversion and BBN II

– Meson-driven rates:

$$\Gamma^{\text{meson}}_{N\to N'} = n_{\text{meson}} \cdot \langle \sigma^{\text{meson}}_{N\to N'} v\rangle \quad (36)$$

– Number density of mesons given by dynamic equilibrium:

$$n_{\text{meson}} \approx \frac{n_{\text{LLP}}}{\tau_{\text{LLP}}} \cdot \text{Br}_{\text{LLP}\to\text{meson}} \cdot P_{\text{conv}}, \quad P_{\text{conv}} \simeq \frac{n_B \langle \sigma^{\text{meson}}_{N\to N'} v\rangle}{n_B \langle \sigma^{\text{meson}}_{N\to N'} v\rangle + \tau^{-1}_{\text{meson}}} \quad (37)$$

– Depending on the meson, $P_{\text{conv}} = \mathcal{O}(0.1-1)$ at MeV temperatures

– Cross-sections $\langle \sigma^{\text{meson}}_{N\to N'} v\rangle$:

$$\langle \sigma^{\text{meson}}_{n\to p} v\rangle \simeq \sigma^{\text{meson}}_{p\to n} v\rangle \quad (38)$$

due to isospin symmetry

– As result, $X_n \simeq 1$ – much higher than in ΛCDM

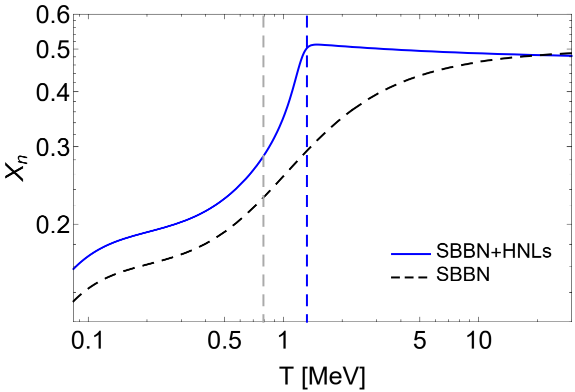
Meson-driven conversion and BBN III

Meson-driven $p \leftrightarrow n$ conversion and impact on BBN

- Strong hierarchy between meson- and weak-driven $\boldsymbol{p \leftrightarrow n}$ conversion:

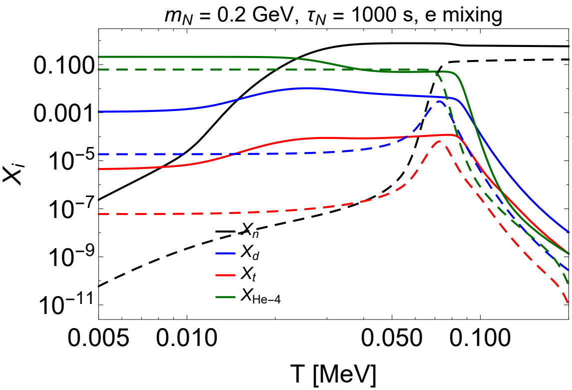
$$\frac{\sigma^{\text{meson}}_{p\leftrightarrow n}}{\sigma^{\text{weak}}_{p\leftrightarrow n}} \sim \frac{m_p^{-2}}{G_F^2 T^2} \simeq 10^{16}\left(\frac{1\text{ MeV}}{T}\right)^2$$

- If present, meson-driven effect dominates over all other effects of LLPs on BBN
- Once mesons disappear, weak processes try to tend $\boldsymbol{X_n}$ to its ΛCDM value. Unsuccessful if they start decoupling
- It leads to an increase in the helium abundance



[1006.4172], [2008.00749]

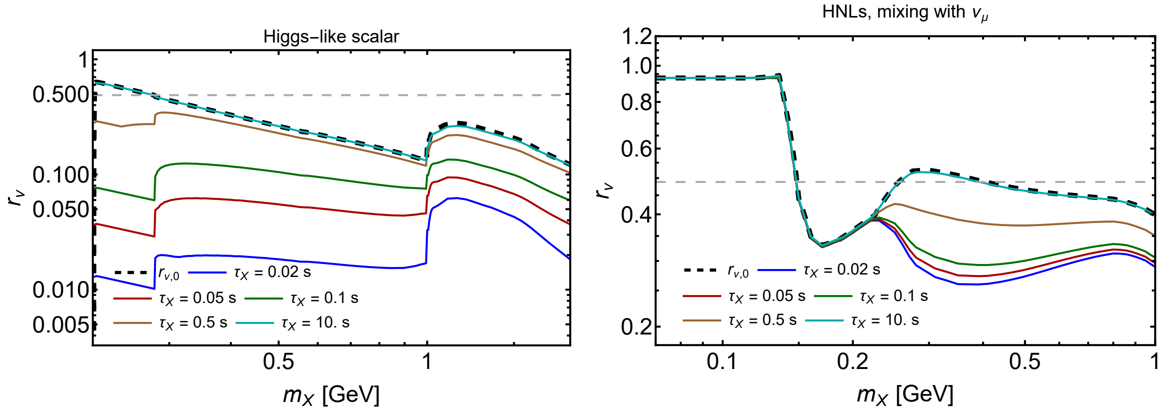
Meson-driven conversion and BBN IV



– Meson-driven processes (incl. nuclear dissociation) dominate the other effects until $T \simeq 5$ keV, where photodisintegration becomes important

PhD thesis

Dynamics of metastables and neutrinos I



– Introduce fraction $r_\nu = E_{\text{LLP}\to\nu}/m_{\text{LLP}}$

– Relevant until LLP lifetimes $\tau \simeq 10$ s: $\Gamma_{\text{ann/nucl}} \propto T^3$

Dynamics of metastables and neutrinos II

Special case: charged kaons

- **Threshold-less** interactions of $\boldsymbol{K^-}$ with nucleons:

$$\boldsymbol{K^- + N \to \Omega/\Sigma + \pi \to N^{(\prime)} + 2\pi} \tag{39}$$

- Does not exist for $\boldsymbol{K^+}$ [Phys. Rev. D 37, 3441]
- Much less $\boldsymbol{K^-}$ decays $\Rightarrow$ **asymmetry in the neutrino-antineutrino energy distribution**