# How new physics at MeV temperatures affects cosmic neutrinos and BBN

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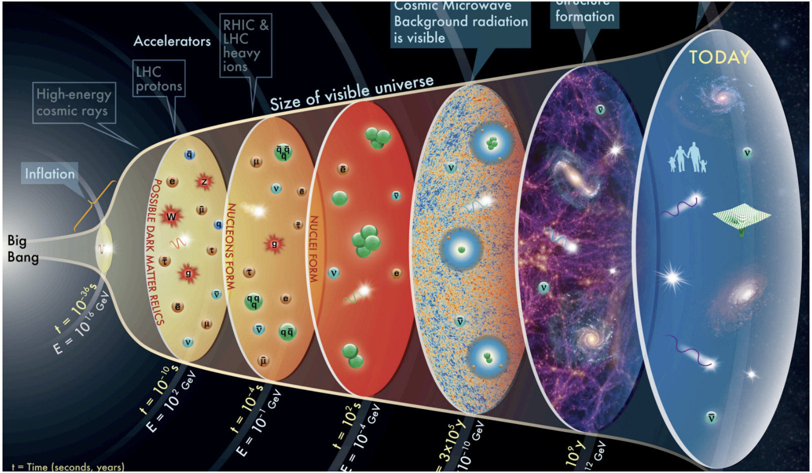
Cosmo coffee

November 27, 2024

# Outline



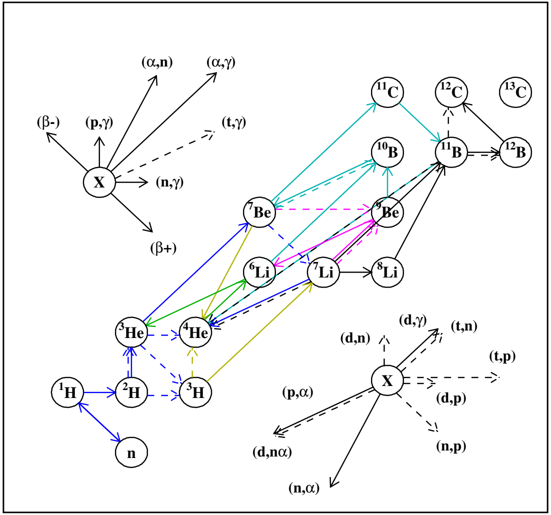

- Cosmological probes: BBN and CMB
- New physics at MeV temperatures
- Case of decaying Long-Lived Particles: challenges and advances

# BBN I

## BBN

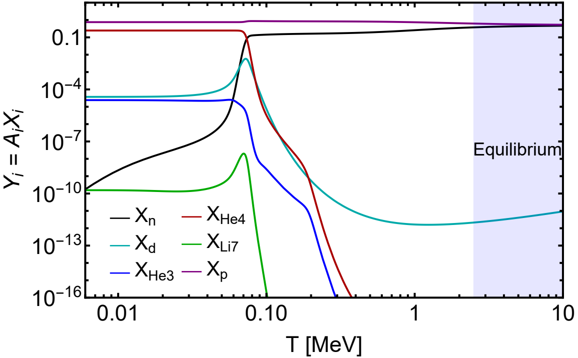
– Formation of light primordial nuclei
– Timescale: $t_{\text{BBN}} \simeq$ **few minutes**, or $T_{\text{BBN}} \simeq 20-80\ \text{keV}$
– Primordial abundances:

$$Y_i \equiv A_i \frac{n_i}{n_B} \qquad (1)$$




[1801.08023

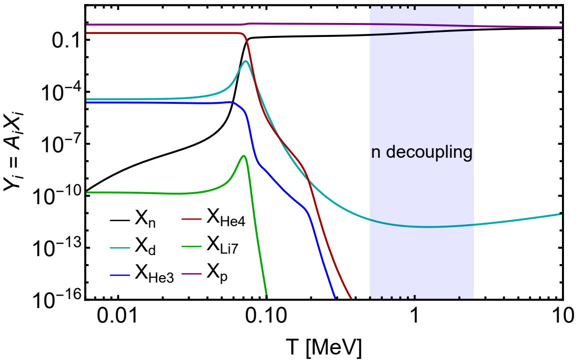
# BBN II




– $T \gtrsim 5$ **MeV**: all abundances are determined by nuclear statistical equilibrium

$$Y_i^{\mathrm{NSE}} = g_i \zeta(3)^{A_i-1} 2^{\frac{3A_i-5}{2}} \pi^{\frac{1-A_i}{2}} \left(\frac{m_i T^{A_i-1}}{m_p^{Z_i} m_n^{A_i-Z_i}}\right)^{3/2} \eta^{A_i-1} Y_p^{Z_i} Y_n^{A_i-Z_i} \mathrm{e}^{B_i/T} \tag{2}$$

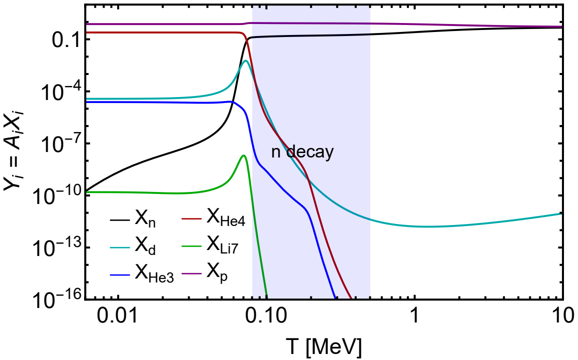
# BBN III




– **$\mathbf{0.5\ MeV} \lesssim T \lesssim \mathbf{5\ MeV}$**: neutrons start decoupling:

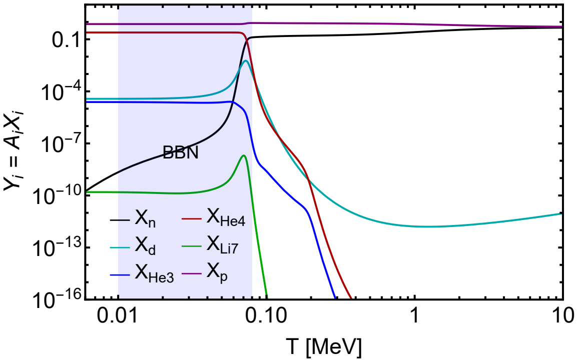
$$\left.\frac{n_n}{n_p}\right|_T \neq \exp[-\Delta m/T] \quad (3)$$

# BBN IV




– **80 keV $\lesssim T \lesssim$ 0.5 MeV**: free decays of neutrons

# BBN V



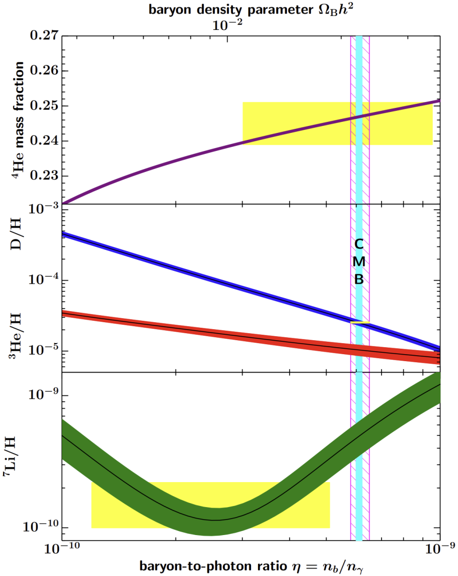

– **5 keV $\lesssim T \lesssim$ 80 keV**: passing deuterium bottleneck and start of nucleosynthesis

# BBN VI

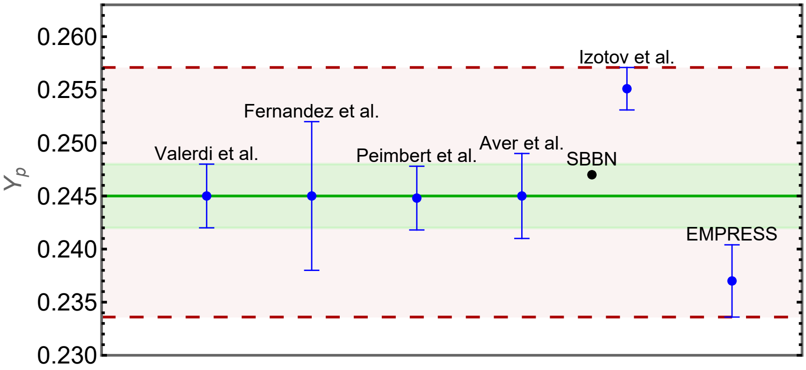
- **Observables**: primordial abundances
  - $^4$**He**
  - $^3$**He**
  - **D**
  - $^7$**Li**

  estimated by spectral measurements of low-metallicity regions
- **Theory**: SBBN – thermal SM plasma + $\boldsymbol{\eta_B}$ [1801.08023]
- **Cosmological lithium problem**:

$$Y_{^7\mathrm{Li}} = \begin{cases} (1.6 \pm 0.3) \cdot 10^{-10}, & \text{observations} \\ (4.7 \pm 0.7) \cdot 10^{-10}, & \text{theory} \end{cases}$$



# BBN VII



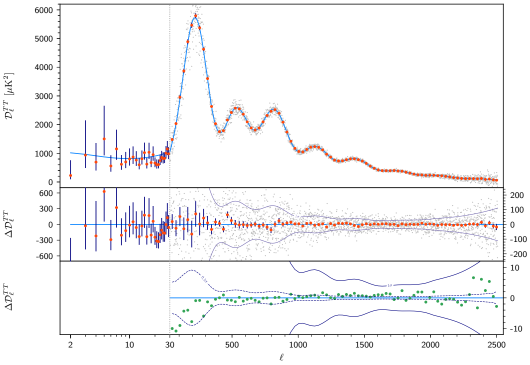

Measurement of primordial helium abundance $Y_p \equiv 4n_{\mathrm{He}}/n_p$:

- Extrapolation from poor-metallicity regions to the region of zero metallicity [2010.04180], [2203.09617], [1408.6953]
- Suffers from systematic uncertainties
- $\Lambda$CDM prediction [1801.08023] agrees with the measurements

# CMB I

## CMB

- Photon bath snapshot from recombination
- Timescale: $t_{\mathbf{CMB}} \simeq$ **300000 years**, or $T_{\mathbf{CMB}} \simeq \mathbf{1\ eV}$



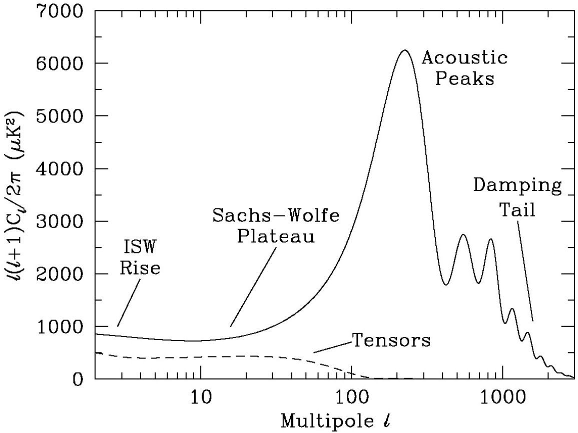
# CMB II

- **Observables**: relic radiation with $T \approx 2.7$ K
- Small inhomogeneities:

$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{l,m} \Theta_l^m Y_l^m(\theta,\phi), \quad (4)$$

$$\langle \Theta_l^m \Theta_{l'}^{m'} \rangle = C_l^{TT} \delta_{mm'} \delta_{ll'} \quad (5)$$

- Characteristic picture of the standing waves with dampening at high multipoles

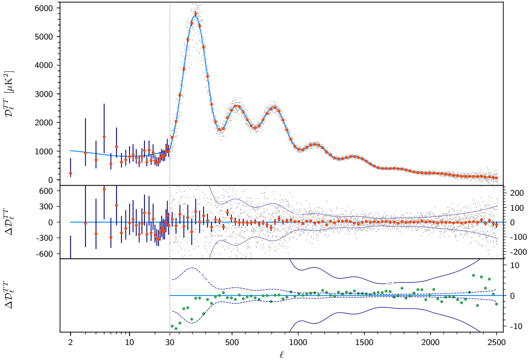


# CMB III

– **Planck measurements** [1807.06209] agree with ΛCDM, but there is large window for uncertainty. E.g.,

$$\boldsymbol{N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\text{UR}} - \rho_\gamma}{\rho_\gamma}} \qquad (6)$$

is $\boldsymbol{N_{\text{eff}}^{\text{Planck}} = 2.99^{+0.33}_{-0.34}}$ at 95%CL ($\boldsymbol{N_{\text{eff}}^{\Lambda\text{CDM}} \approx 3.043 - 3.044}$)




– Ongoing measurements by **Simons Observatory** will significantly improve the accuracy

*Percent-level precision in* $\boldsymbol{N_{\textit{eff}}}$

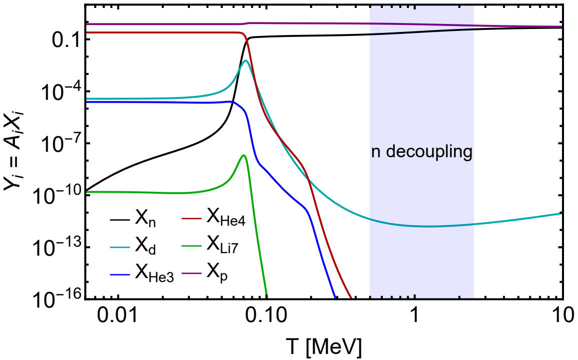
# New physics at MeV temperatures

# BBN, CMB, and new physics at MeV temperatures

- Both BBN and CMB are sensitive to the physics at temperatures

$$\boldsymbol{T \sim 5\ \mathrm{MeV} \gg T_{\mathrm{BBN/CMB}}} \quad (7)$$

- Equivalently, cosmic times $\boldsymbol{t \sim 10^{-2}}$ **s**




**Reason: neutrons and neutrinos start decoupling at $T \simeq$ few MeV**

Any deviation from the standard scenario may leave imprints

# Affecting BBN I

- Ratio $X_n \approx n_n/(n_n + n_p)$ defines the helium abundance:

$$Y_{^4\text{He}} \approx 4\frac{n_{\text{He}}}{n_B} = 2X_n(T_{\text{BBN}}) \tag{8}$$

- Evolution of $X_n$: conversion $n \leftrightarrow p$ driven by weak interactions+neutron decays

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{9}$$

# Affecting BBN II

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1-X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{10}$$

## 1. Modifying time-temperature relation

- Dark radiation
- Decaying massive relic

# Affecting BBN III

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{11}$$

## 2. Disturbing properties of neutrinos

– Changing the neutrino-to-EM ratio:

$$\left.\frac{\rho_{\nu_e}}{\rho_{\text{EM}}}\right|_{T\gg m_e} \neq \frac{g_{*,\nu_e}}{g_{*,\gamma} + g_{*,\text{EM}}} = \frac{7}{22} \tag{12}$$

– Neutrino spectral distortions:

$$f_{\nu_e}(p, T) \neq \frac{1}{\exp[p/T_{\nu_e}] + 1} \tag{13}$$

– Neutrino-antineutrino asymmetry:

$$f_{\nu_e}(p, T) \approx \frac{1}{\exp[(p + \mu_{\nu_e})/T_\nu] + 1} \tag{14}$$

# Affecting BBN IV

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{15}$$

**3. Modifying "constants" at MeV temperatures**

- Varying the weak scale [2402.08626]
- Changing the neutron-proton mass difference [1401.6460]
- Variations of the gravitational constant [1910.10730]

# Affecting BBN V

$$\frac{dX_n}{dt} = (\Gamma^{\text{weak}}_{p\to n} + \Gamma^{\text{new}}_{p\to n})(T(t))(1 - X_n) - (\Gamma^{\text{weak}}_{n\to p} + \Gamma^{\text{new}}_{n\to p})(T(t))X_n \qquad (16)$$

## 4. Add new $p \leftrightarrow n$ processes

– Decays into metastable particles such as muons and mesons [1812.07585] [2008.00749]

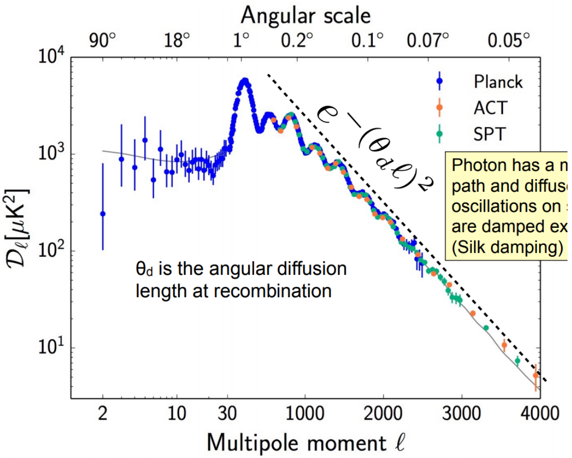
# Affecting CMB I

– The effect of new physics at MeV scales on CMB is mainly encapsulated in the scaling of the diffusion damping:

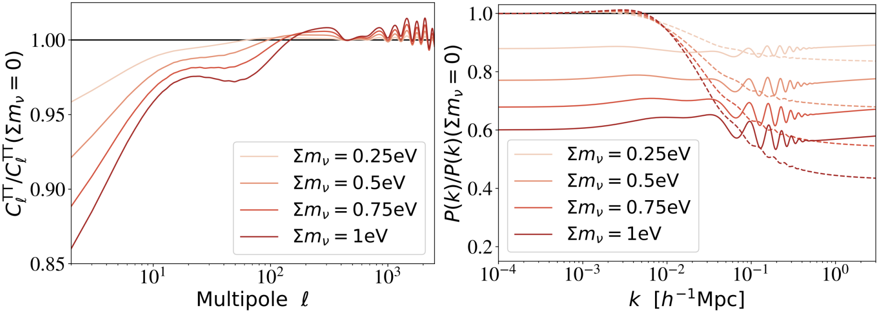
$$\theta_d \propto \frac{(1+0.22N_{\text{eff}})^{1/4}}{\sqrt{1-Y_p}}, \tag{17}$$

where

$$N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\text{UR}}-\rho_\gamma}{\rho_\gamma} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_\nu + \rho_{\text{dark radiation}}}{\rho_\gamma} \tag{18}$$



# Affecting CMB II




*pdg*

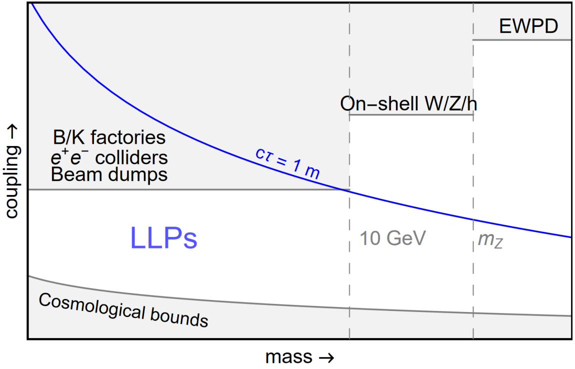
– Neutrino spectral shape is crucial in determining the impact of neutrino masses [2111.12726]

# Long-lived particles

## Opportunities, challenges, and advances

# Long-lived particles I

- Consider a new unstable particle with mass $m$ and coupling $g$
- Masses $m \ll \Lambda_{\rm EW}$: past experiments excluded large $g$
- $c\tau \propto m^{-\alpha} g^{-2} \Rightarrow$ unexplored parameter space corresponds to **Long-Lived Particles** (LLPs)



# Long-lived particles II

"Portals" – lowest-dimensional gauge-invariant operators with LLPs:
*(potentially connecting to dark sectors)*

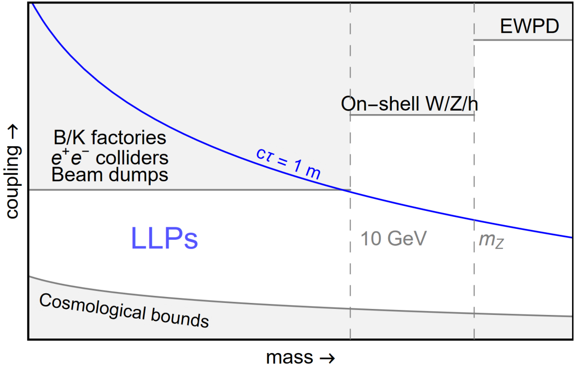
| Model | (Effective) Lagrangian | What it looks like |
|---|---|---|
| HNL $\boldsymbol{N}$ | $\boldsymbol{Y\bar{L}\tilde{H}N + \text{h.c.}}$ | Heavy neutrino with interaction suppressed by $\boldsymbol{U \sim Y v_h/m_N \ll 1}$ |
| Higgs-like scalar $\boldsymbol{S}$ | $\boldsymbol{c_1 H^\dagger H S^2 + c_2 H^\dagger H S}$ | A light Higgs boson with interaction suppressed by $\boldsymbol{\theta \sim c_2 v_h/m_h}$ |
| Dark photon $\boldsymbol{V}$ | $\boldsymbol{-\frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu}}$ | A massive photon with interaction suppressed by $\boldsymbol{\epsilon}$ |
| ALP $\boldsymbol{a}$ | $\boldsymbol{a g_a G^{\mu\nu}\tilde{G}_{\mu\nu} + \dots}$ | A $\boldsymbol{\pi^0/\eta/\eta'}$-like particle with the interaction suppressed by $\boldsymbol{f_\pi g_a}$ |

*Other portals with LLPs exist, but models above are attractive given their renormalizability/simplicity of UV completion*

*See also 1504.04855, 1901.09966*

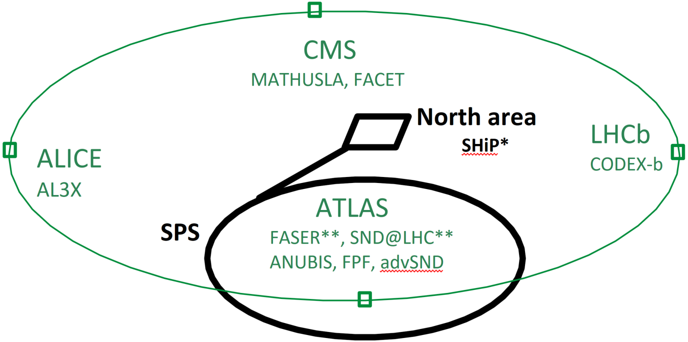
# Long-lived particles III

- Small couplings $\boldsymbol{g}$: may be probed by cosmology
- Large couplings $\boldsymbol{g}$: target for laboratory experiments




**Cosmological and lab probes work in synergy**

# Long-lived particles IV




- **Next 10 years**: various laboratory experiments and cosmological probes will be able to explore LLP's parameter space
- Comprehensive understanding of how to translate theoretical input (LLP) to observables is required

# Classification of LLPs' decays

## Effects of LLPs significantly depend on their decay modes

- Purely EM decays:

$$\mathbf{LLP} \to \boldsymbol{e^+e^-/\gamma\gamma/\pi^0\gamma, \ldots} \tag{19}$$

- Decays into neutrinos:

$$\mathbf{LLP} \to \boldsymbol{2\nu/3\nu/\pi^0\nu, \ldots} \tag{20}$$

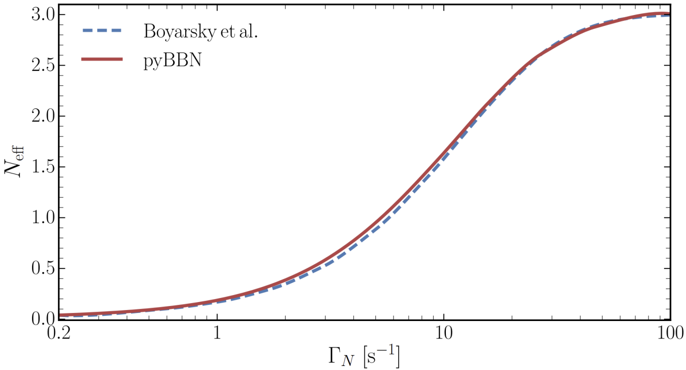
- Hadronic/semileptonic decays:

$$\mathbf{LLP} \to \boldsymbol{\pi^+\pi^-\pi^0/\pi^+l^-/4\pi/q\bar{q}, \ldots} \tag{21}$$

# LLPs decaying into EM particles

**EM decays:**

- Decrease $\boldsymbol{N_{\text{eff}}}$
- May induce slight distortions in $\boldsymbol{f_\nu}$
- Decrease $\Gamma_{p\leftrightarrow n}$, decrease $H$



# Decays into neutrinos I

## Special properties of neutrinos and EM particles

– Neutrino interaction cross-sections grow with energy:

$$\sigma_{\nu X}(s_{\nu X}) \sim G_F^2 s_{\nu X} \cdot v, \quad X = \nu, \bar{\nu}, e^{\pm} \tag{22}$$

– Neutrino thermalization rates are much smaller than the EM:

$$\frac{\Gamma_{\nu,\text{th}}}{\Gamma_{\text{EM,th}}} \sim \frac{n_\nu G_{\text{F}}^2 \langle s\rangle}{n_e \alpha_{\text{EM}}/T^2} \sim \frac{G_{\text{F}}^2}{\alpha_{\text{EM}}} T^4 \sim 10^{-20}\left(\frac{T}{1\text{ MeV}}\right)^4 \tag{23}$$

EM plasma is always in equilibrium while neutrinos thermalize slowly

**What happens if heavy LLPs decay into neutrinos (so $E_\nu \gg 3.15T$)?**

# Decays into neutrinos II

Answer is in solving the unintegrated neutrino Boltzmann equation:

$$\partial_t f_{\nu_\alpha} - Hp\partial_p f_{\nu_\alpha} = \mathcal{I}_{\text{coll}} \tag{24}$$

State-of-the-art approach discretizes the comoving momentum space $y(t) = p \cdot a(t) \to \{y_i\}$, where $i = \overline{1, n}$ [9506015]:

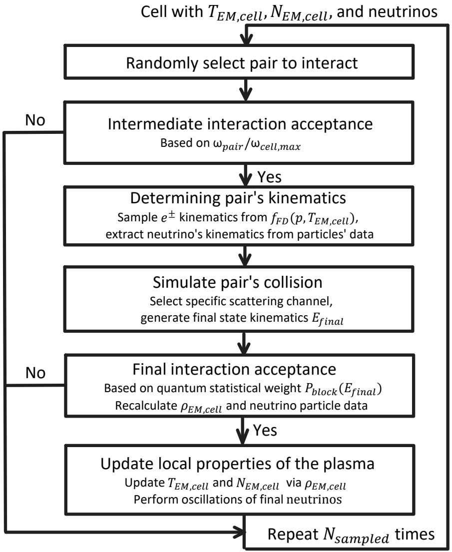
$$\mathcal{I}_{\text{coll}} = \int G(\vec{x}) d^l \vec{x} = \prod_{k=1}^{l} \sum_{i_k=1}^{n} \tilde{G}, \quad l \geq 2 \tag{25}$$

## Past studies are contradictory

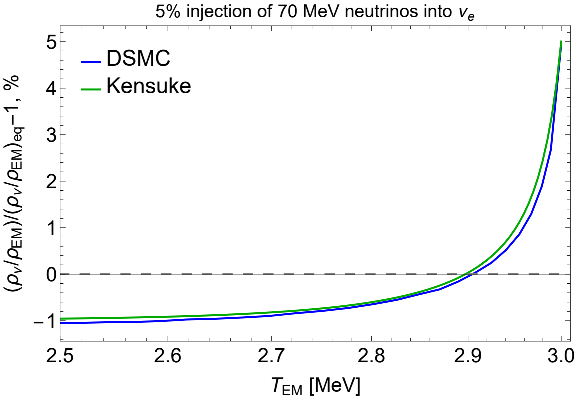
- Some predict an increase of $N_{\text{eff}}$ [0008138], [2104.11752]
- The others show a (mass- and lifetime-dependent) decrease [2103.09831] [2109.11176]

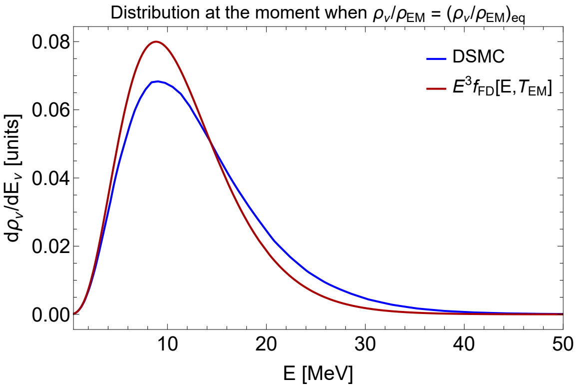
# DSMC approach I

- To address this problem and other issues (performance, limited applicability), we developed new approach [2409.07378], [2409.15129]
- Idea: replace the collision integral with the system of $\nu$s, $e^{\pm}$, LLPs, and simulate their interactions
- Account for the instant thermalization of the EM plasma, $\nu$ oscillations, Pauli principle
- Cross-checked against existing methods in the case of well-defined setups



# Back to neutrinophilic LLPs I

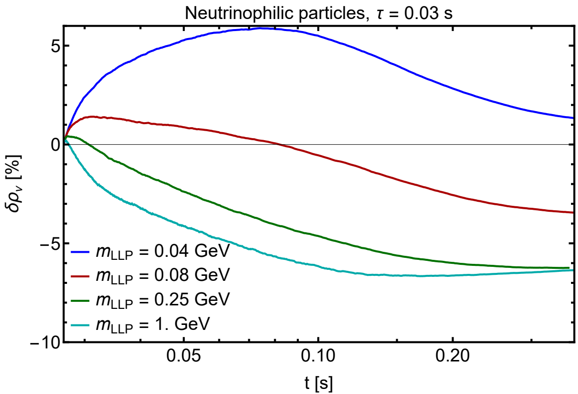



– Instant injection scenario: the ratio $\rho_\nu/\rho_{\mathbf{EM}}$ is first larger than $(\rho_\nu/\rho_{\mathbf{EM}})_{\mathbf{\Lambda CDM}}$, but then quickly drops below

– Reason: high-energy neutrinos distort the neutrino spectrum and shift the balance of the energy exchange to the EM sector

# Back to neutrinophilic LLPs II

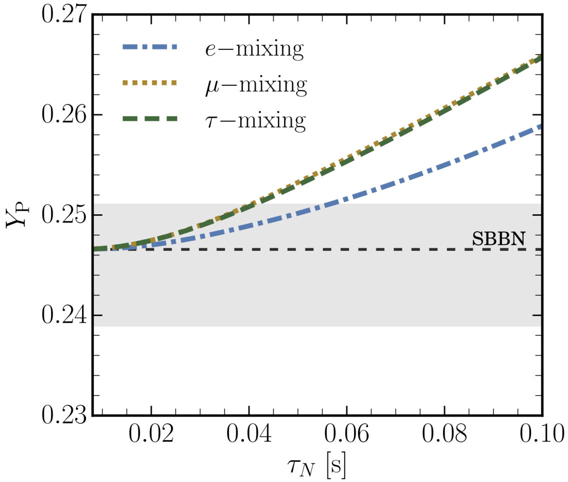



– Conclusion: **generic LLPs with mass $m \gg 3T$ decaying into SM species at MeV temperatures always decrease $N_{\text{eff}}$**

*[2409.15129]*

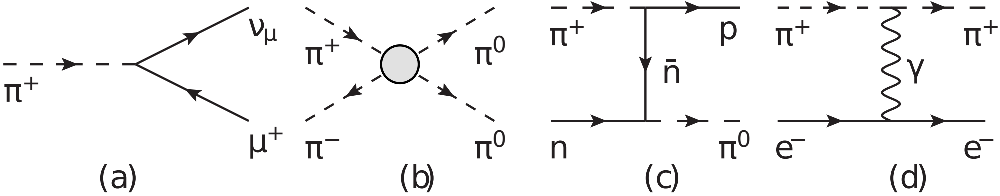
# Back to neutrinophilic LLPs III

- $p \to n$ process has threshold $\Delta = m_n - m_p$
- High-energy neutrinos enhance the $p \to n$ rate and increase the $n/p$ ratio
- Overall, they increase the $^4$He abundance




[2006.07387]

# Decays into metastable species I




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

*[2411.00931], [2411.00892]*

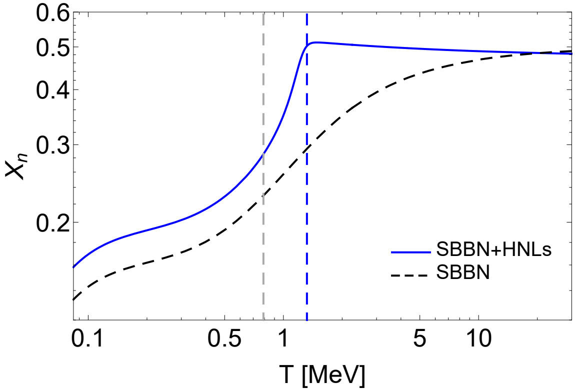
# Decays into metastable species II

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

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

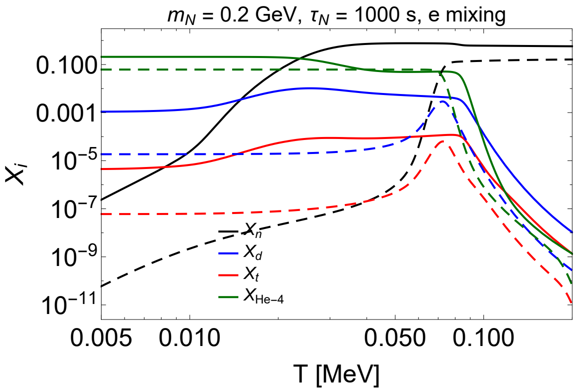
$$\frac{\sigma^{\text{meson}}_{p\leftrightarrow n}}{\sigma^{\text{weak}}_{p\leftrightarrow n}} \sim \frac{m_p^{-2}}{G_F^2 T^2} \simeq 10^{16}\left(\frac{1\text{ MeV}}{T}\right)^2$$

- If present, meson-driven effect dominates over all other effects of LLPs on BBN
- It leads to an increase in the helium abundance




[1006.4172], [2008.00749]

# Decays into metastable species III



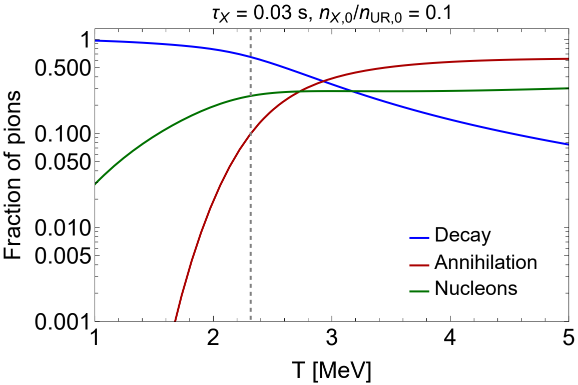

– Meson-driven processes (incl. nuclear dissociation) dominate the other effects until $T \simeq 5$ keV, where photodisintegration becomes important

*PhD thesis*

# Decays into metastable species IV

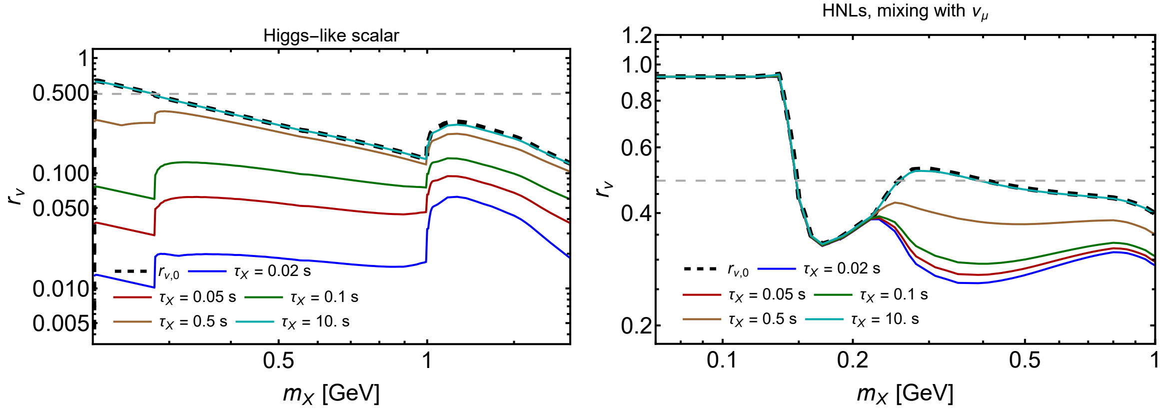
## Back to neutrinos

- At MeV temperatures, metastable particles prefer to annihilate or interact with nucleons
- Decays into neutrinos are suppressed




[2411.00931], [2411.00892]

# Decays into metastable species V




– Relevant until LLP lifetimes $\boldsymbol{\tau \simeq 10}$ **s**:

$$\boldsymbol{\Gamma_{\text{ann/nucl}} \propto T^3} \tag{26}$$

# Decays into metastable species VI

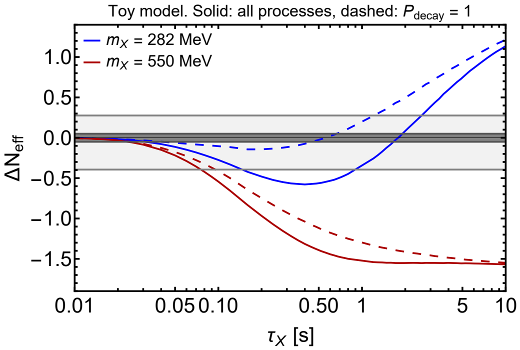
**Special case: charged kaons**

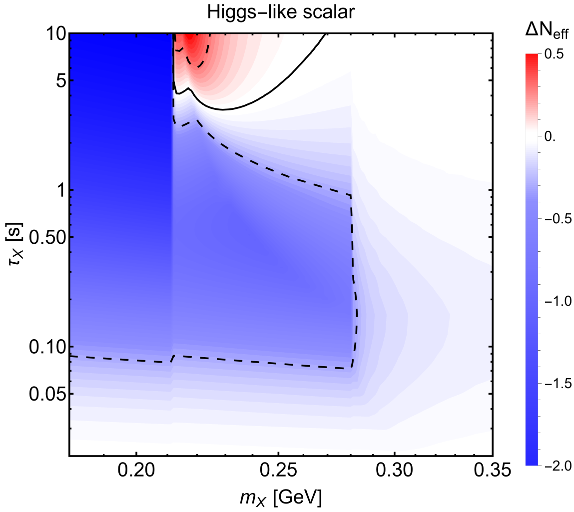
- **Threshold-less** interactions with nucleons:

$$K^- + N \to \Omega/\Sigma + \pi \to N' + 2\pi \tag{27}$$

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

# Decays into metastable species VII



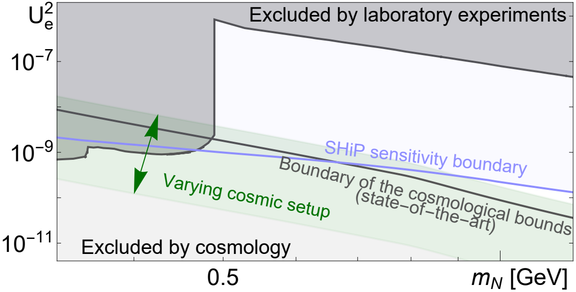




- Combined impact of metastable dynamics and non-thermal neutrinos: $\Delta N_{\text{eff}}$ changes sign
- Effects of mesons disappearance: severe quantitative impact

*[2411.00931],[2411.00892]*

# Concluding remarks I

- BBN and CMB: important messengers in constraining (present) and discovering new physics
- Complementarity between cosmo and lab probes is essential



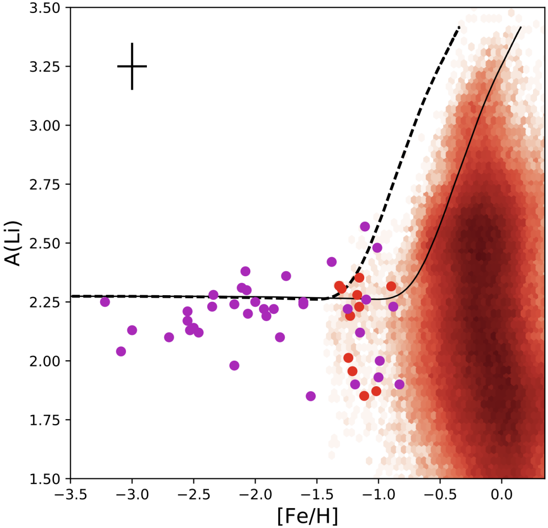

- Necessary efforts from theory to prepare for future CMB observations:
  - Defining the uncertainty in the cosmological constraints *(varying lepton asymmetry, adding dark radiation, etc.)*
  - Developing versatile framework for studying the effects of new physics

# Backup slides

# Cosmological lithium problem

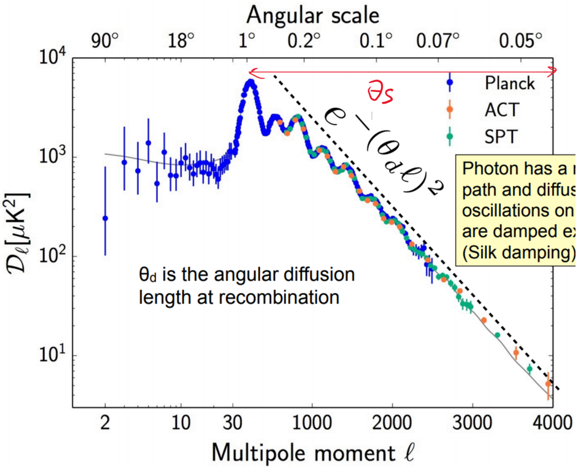
**Cosmological lithium problem:**

- Explanation by SM-driven nuclear destruction is unlikely [1312.0894]
- Stellar depletion of $^7$**Li** [2204.03167]?
- New physics (e.g., [1006.4172])?



# $N_{\text{eff}}$ from CMB I

CMB measures angular scales:




1) **Sound horizon scale** $\theta_s$, given by the position of the first peak:

$$\theta_{\mathbf{s}} = \frac{r_{\mathbf{s}}}{D_A}, \quad r_{\mathbf{s}} = \int_{\infty}^{z_*} c_s \frac{dz}{H(z)}, \tag{28}$$

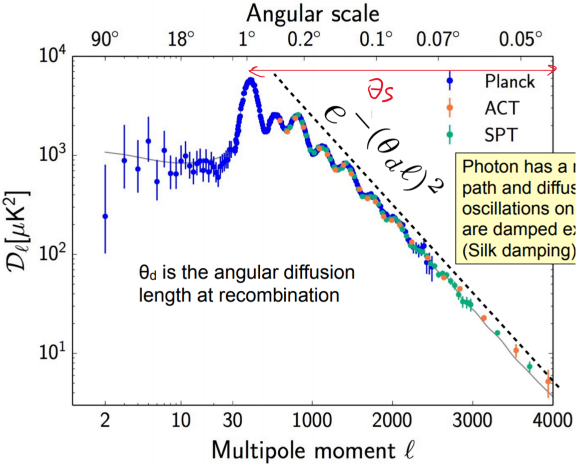
with $c_{\mathbf{s}} = [3\,(1+R)]^{-1/2}$

# $N_{\text{eff}}$ from CMB II

2) **Diffusion damping scale** $\theta_{\mathbf{d}} = r_{\mathbf{d}}/D_A$, given by damping of the further peaks:

$$r_{\mathbf{d}}^2 = \int_{z_*}^{\infty} \frac{\mathbf{d}z}{a(z)H(z)\sigma_{\mathbf{T}}n_e}\left(\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)}\right) \quad (29)$$

with $R = \frac{3\rho_{\mathbf{b}}}{4\rho_\gamma}$, $D_A$ being the **last scattering surface**, $D_A = \int_{z_*}^{0} dz/H(z)$



# $N_{\text{eff}}$ from CMB III

- What kind of quantities/observables are affected by $\boldsymbol{N_{\text{eff}}}$? $z_*$, $\theta_s$, $\theta_d$...
- However, not all of these effects truly characterizes the neutrino density, since they can be produced by varying several other $\Lambda$CDM parameters
- In particular,

$$\boldsymbol{z_* = \omega_m/(\omega_{\text{rad}}(1 + 0.22 N_{\text{eff}}))} \quad (30)$$

  may change both due to $\omega_m$ (its CDM part) and $\boldsymbol{N_{\text{eff}}}$
- By rescaling appropriate parameters we may eliminate as many degeneracies as possible to keep only irreducible effects of $\boldsymbol{N_{\text{eff}}}$
- In order to get rid of one of the most "degenerate" effects - $z_*$, let us rescale all energy densities by the same factor $\boldsymbol{x = (1 + 0.22 N_{\text{eff}})/(1 + 0.22 \cdot 3.043)}$. Simultaneously, such rescaling leads to $\boldsymbol{\theta_s = \text{const}}$
- The only effect is left – an increase $\boldsymbol{\theta_d \to x^{1/4}\theta_d}$ [pdg]

# $N_{\text{eff}}$ from CMB IV

– However, a redundant degeneracy is left – between $N_{\text{eff}}$ and $^4\text{He}$ fraction $Y_p$. It appears since the diffusion length scales as $r_d \sim n_e^{-1} \sim 1/\sqrt{1-Y_p}$, and as a result

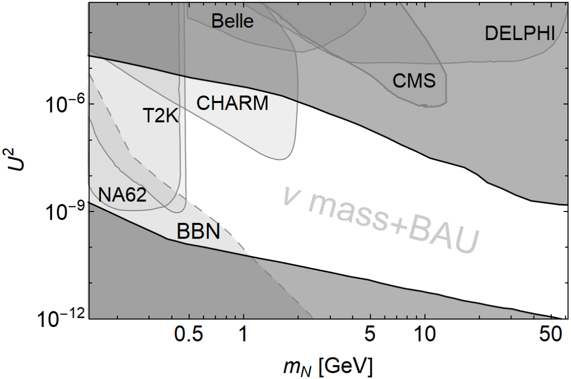
$$\theta_d \propto \frac{(1+0.22N_{\text{eff}})^{1/4}}{\sqrt{1-Y_p}} \tag{31}$$

In the result, CMB imposes constraints on $Y_p, N_{\text{eff}}$

# LLPs and BSM problems

– LLPs may have “hidden” parameters other than mass and coupling
– They may, in particular, be responsible for the resolution of the BSM problems
– Example: HNLs may exist in quasi-degenerate pairs:

$$\Delta m_N \ll m_N, \quad |\Delta U| \ll |U| \quad (32)$$




– By tuning $\Delta m, \Delta U$, one may explain the baryon asymmetry of the Universe and neutrino masses [0804.4542]

# 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

$$\xi_{\text{EM,eff}}(E_\nu^{\text{inj}}, T) = \xi_{\text{EM}} + \xi_\nu \times \epsilon(E_\nu^{\text{inj}}, T), \tag{33}$$

  where $\xi_\nu = 1 - \xi_{\text{EM}}$ is the energy fraction that LLPs directly inject into the neutrino sector and $\epsilon$ is the effective fraction of $\xi_\nu$ 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 $\xi_{\text{EM,eff}} > 0.5$, and $N_{\text{eff}}$ may become negative

# Qualitative understanding of neutrino thermalization II

– A simple estimate of $\epsilon$ as a function of the injected neutrino energy $E_{\nu}^{\mathbf{inj}}$ 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

$$\nu_{\mathbf{non\text{-}eq}} + \nu_{\mathbf{therm}} \to \nu_{\mathbf{non\text{-}eq}} + \nu_{\mathbf{non\text{-}eq}} \tag{34}$$

$$\nu_{\mathbf{non\text{-}eq}} + \overline{\nu}_{\mathbf{therm}} \to e^{+} + e^{-} \tag{35}$$

$$\nu_{\mathbf{non\text{-}eq}} + e^{\pm} \to \nu_{\mathbf{non\text{-}eq}} + e^{\pm}, \tag{36}$$

– Assume that in the processes (34) and (36) 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 $N_{\mathbf{therm}} \simeq \log_2(E_{\nu}^{\mathbf{inj}}/3.15T)$ interactions

– In addition, the process (34) doubles the number of non-equilibrium neutrinos, while (35) makes neutrinos disappear and (36) 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:

$$\boldsymbol{N_{\nu}^{(k)} = N_{\nu}^{(k-1)}\left(2P_{\nu\nu\to\nu\nu} + P_{\nu e\to\nu e}\right) = N_{\nu}^{(0)}\left(2P_{\nu\nu\to\nu\nu} + P_{\nu e\to\nu e}\right)^{k}}, \tag{37}$$

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

$$\boldsymbol{E_{\nu}^{(k)} = E_{\nu}^{(k-1)}\left(P_{\nu\nu\to\nu\nu} + \frac{1}{2}P_{\nu e\to\nu e}\right) = E_{\nu}^{\text{inj}}\left(P_{\nu\nu\to\nu\nu} + \frac{1}{2}P_{\nu e\to\nu e}\right)^{k}}, \tag{38}$$

where $\boldsymbol{P_{\nu\nu\to\nu\nu}}$, $\boldsymbol{P_{\nu\nu\to ee}}$, **and** $\boldsymbol{P_{\nu e\to\nu e}}$ are the average probabilities of the processes (34)–(36), respectively, and their sum equals unity

– We define these probabilities as $\boldsymbol{P_i = \Gamma_i/\Gamma_{\nu}^{\text{tot}}}$, where $\Gamma_i$ is the interaction rate of each process and $\boldsymbol{\Gamma_{\nu}^{\text{tot}}}$ 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:

$$\boldsymbol{P_{\nu\nu\to\nu\nu} \approx 0.76, \quad P_{\nu\nu\to ee} \approx 0.05, \quad P_{\nu e\to\nu e} \approx 0.19} \tag{39}$$

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

$$\boldsymbol{\epsilon_{\text{non-eq}} = \frac{1}{E_\nu^{\text{inj}}}\sum_{k=0}^{N_{\text{therm}}}\left(\frac{P_{\nu e\to\nu e}}{2} + P_{\nu\nu\to ee}\right)E_\nu^{(k)}} \tag{40}$$

– 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 (34) and (35).

# Qualitative understanding of neutrino thermalization V

- We assume that each reaction (34) transfers an energy amount of $3.15T$ from the thermal neutrino sector to non-equilibrium neutrinos, which then via (35) ends up in the EM plasma
- Moreover, each reaction (35) contributes to another energy transfer of $3.15T$ from thermal neutrinos to the EM plasma
- The effective contribution coming from this transfer is therefore:

$$\epsilon_{\text{thermal}} = \frac{3.15T}{E_{\nu}^{\text{inj}}} N_{\nu}^{\text{therm}\to\text{EM}} = $$
$$= \frac{3.15T}{E_{\nu}^{\text{inj}}} P_{\nu\nu\to ee}\left(\sum_{k=0}^{N_{\text{therm}}} N_{\nu}^{(k)} + \left[P_{\nu\nu\to\nu\nu} + \sum_{k=1}^{N_{\text{therm}}} (2P_{\nu\nu\to\nu\nu})^{(k)}\right]\right), \quad (41)$$

where the first term in the round brackets is the contribution from the process (35) and the terms in the square brackets are the contribution from the process (34) *Note that the factor of 2 in the second sum accounts for the doubling of non-equilibrium neutrinos in the process* (34).

# Processes with mesons and muons I

- Consider first the case of muons $\mu$. They do not efficiently interact with nucleons, but may annihilate instead:

$$\mu^{+} + \mu^{-} \to e^{+} + e^{-} \tag{42}$$

- Annihilation cross-section:

$$\sigma^{\mu}_{\text{ann}} = \frac{4\pi\alpha^{2}_{\text{EM}}}{m^{2}_{\mu}} \tag{43}$$

- Assume first that annihilation is irrelevant and decays dominate. Then, the muon number density available for annihilations may accumulate during the muon lifetimes $\tau_{\mu}$:

$$n^{\text{acc}}_{\mu} v \approx n_{\text{LLP}}(t)\frac{\tau_{\mu}}{\tau_{X}} \tag{44}$$

# Processes with mesons and muons II

– Compare the annihilation and decay rates:

$$\frac{\Gamma_{\mu}^{\text{decay}}}{\Gamma_{\mu}^{\text{ann}}} = \frac{\tau_X}{n_X \tau_{\mu}^{-2} \sigma_{\text{ann}}^{\mu} v} \tag{45}$$

– Plugging in the numbers, we get

$$\frac{\Gamma_{\mu}^{\text{decay}}}{\Gamma_{\mu}^{\text{ann}}} = 3.4 \cdot 10^{-4} \cdot \frac{\tau_X}{0.05\text{ s}} \cdot \frac{0.1 n_{\text{UR}}}{n_X} \left(\frac{3\text{ MeV}}{T}\right)^3 \tag{46}$$

– 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:

$$\pi^+ + n \to p + \pi^0\gamma, \quad \pi^- + p \to n + \pi^0/\gamma \tag{47}$$

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

$$\langle \sigma_{\text{nucl}}\beta\rangle \simeq 1.5\ \text{mb} \simeq 4\ \text{GeV}^{-2} \tag{48}$$

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

$$\frac{\Gamma_\pi^{\text{decay}}}{\Gamma_\pi^{\text{nucl}}} = \frac{1}{\tau_\pi n_B X_n \sigma_{\text{nucl}} v} \simeq \left(\frac{3\ \text{MeV}}{T}\right)^3 \cdot \frac{10^{-9}}{\eta_B} \tag{49}$$

# 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 $\boldsymbol{X_n \equiv n_n/n_B}$:

$$\boldsymbol{dX_n/dt = (1 - X_n)\Gamma^{\text{meson}}_{p\to n} - X_n\Gamma^{\text{meson}}_{n\to p}} \tag{50}$$

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

$$\boldsymbol{X_n(t) = \frac{\Gamma^{\text{meson}}_{p\to n}}{\Gamma^{\text{meson}}_{p\to n} + \Gamma^{\text{meson}}_{n\to p}}} \tag{51}$$

# Meson-driven conversion and BBN II

- Meson-driven rates:

$$\Gamma^{\text{meson}}_{N\to N'} = n_{\text{meson}} \cdot \langle \sigma^{\text{meson}}_{N\to N'} v\rangle \tag{52}$$

- Number density of mesons given by dynamic equilibrium:

$$n_{\text{meson}} \approx \frac{n_{\text{LLP}}}{\tau_{\text{LLP}}} \cdot \text{Br}_{\text{LLP}\to\text{meson}} \cdot P_{\text{conv}}, \quad P_{\text{conv}} \simeq \frac{n_B\langle \sigma^{\text{meson}}_{N\to N'} v\rangle}{n_B\langle \sigma^{\text{meson}}_{N\to N'} v\rangle + \tau^{-1}_{\text{meson}}} \tag{53}$$

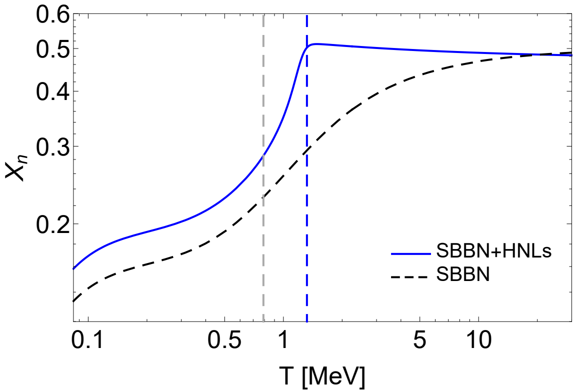
- Depending on the meson, $P_{\text{conv}} = \mathcal{O}(0.1 - 1)$ at MeV temperatures
- Cross-sections $\langle \sigma^{\text{meson}}_{N\to N'} v\rangle$:

$$\langle \sigma^{\text{meson}}_{n\to p} v\rangle \simeq \sigma^{\text{meson}}_{p\to n} v\rangle \tag{54}$$

  due to isospin symmetry
- As result, $X_n \simeq 1$ – much higher than in ΛCDM

# Meson-driven conversion and BBN III

– Once mesons disappear, weak processes try to tend $X_n$ to its ΛCDM value
– If weak reactions start decoupling, it is unsuccessful

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