Relaxing limits from Big Bang Nucleosynthesis on Heavy Neutral Leptons with Axion-like Particle

21/08/2025@TDLI,

Based on JCAP 02 (2025) 054,

In collaboration with

Frank F. Deppisch, Tomas E. Gonzalo and Chayan Majumdar

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Southeast University

Outlines

1. Introductions
2. Model
3. Big Bang Nucleosynthesis
4. Cosmic Microwave Background
5. Cosmological history
6. Results
7. Direct searches
8. Conclusion

Introductions

Theoretical issues:

- Neutrino mass
- Dark matter
- Matter-antimatter asymmetry

Observations:

- Accelerator
- Atomic & Nuclear processes
- Astrophysics & Cosmology

Dark New Physics

New Physics:

Heavy Neutral Leptons (Right-Handed Neutrinos), $yLHN$

Axion-like Particles, $F(\partial_\mu a/f_a)$

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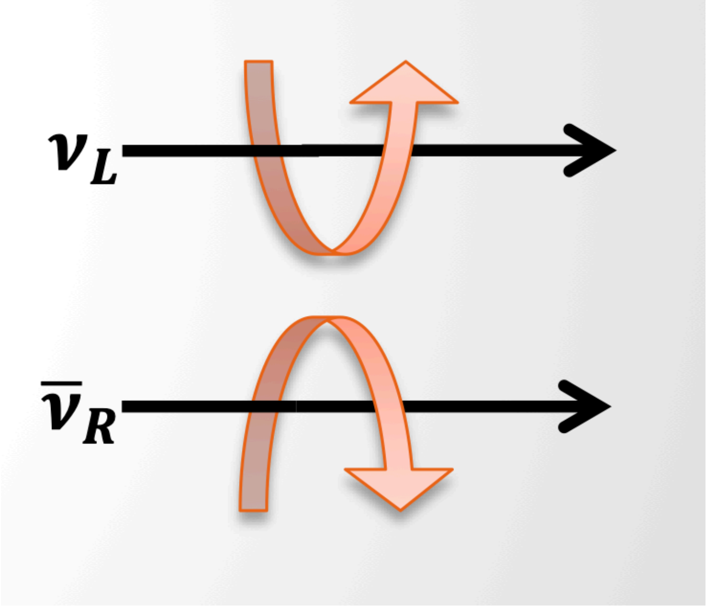
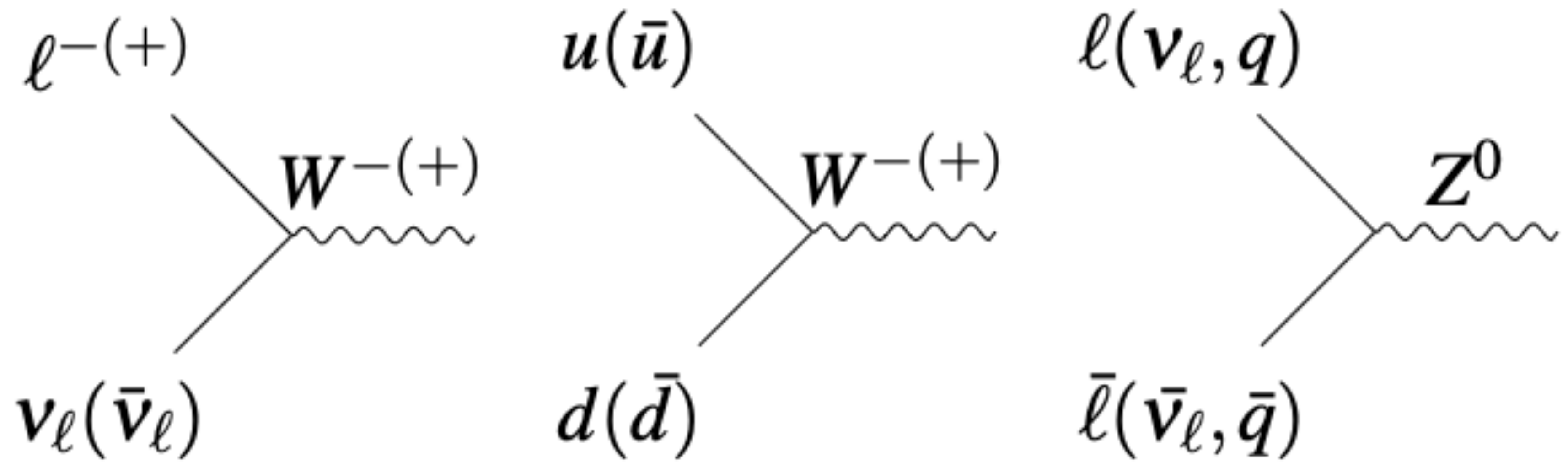


SM Neutrinos

- Three active flavours of SM neutrinos: ν_e, ν_μ, ν_τ
- SM $SU(2)_L$ doublet and left-handed current (Parity Violation)
- Massless due to the absence of right-handed partner (No Dirac mass, $y\bar{L}H\ell_R$)
- Majorana nature: $\bar{\nu}^c = \nu$? (Majorana mass $m\bar{\nu}^c\nu$?)

$SU(2)_L$ doublet: $(\nu_e, e), (\nu_\mu, \mu), (\nu_\tau, \tau)$



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Beyond SM Neutrino

Neutrino oscillation: Neutrinos change their flavours during propagation.

$$\left|\nu_\ell(t)\right\rangle = \sum_{i=1}^{3} U_{\ell i}^{*} e^{-iE_i t}\left|\nu_i(0)\right\rangle,$$ $U_{\ell i}$ is the mixing between two flavours.

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{i,j} U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*} \exp\left(-i\frac{\Delta m_{ij}^2 L}{2E}\right) \rightarrow \boxed{\text{Mass difference !}}$$

Neutrino mixing: Misalignment between the neutrino mass states and flavour states.

$$\nu_\ell(x) = \sum_{i=1}^{3} U_{\ell i}^{*} \nu_i(x), \ell = e, \mu, \tau\,.$$

$$U_{\mathrm{PMNS}} = U_{23}(\theta_{23}) U_{13}(\theta_{13}, \delta) U_{12}(\theta_{12})$$
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Beyond SM Neutrinos

A possible solution to massive neutrinos: Right-handed neutrino singlet (HNL), N_R

$$\mathscr{L}_{Yukawa} = -Y_\nu \bar{L} \cdot HN + \text{h.c.}$$

$$\mathscr{L}_{Seesaw} = -m_D \bar{\nu}_L N - 1/2 \bar{N}^c M_R N + \text{ h.c.}$$

Dirac Majorana

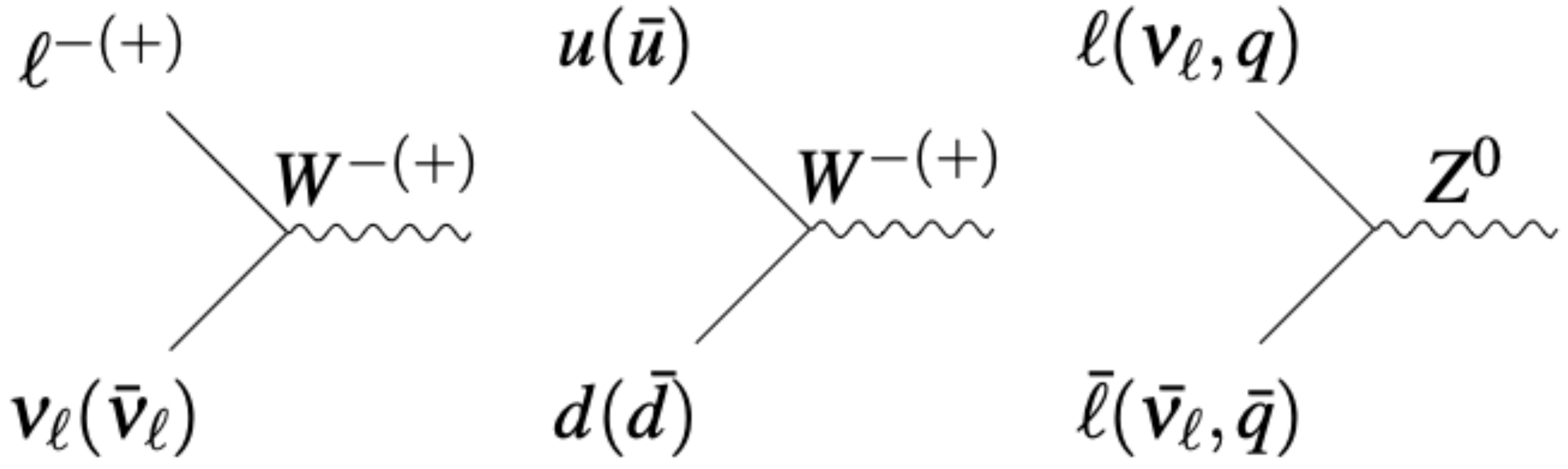
Active-sterile mixing

$$\mathscr{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} = U_{\nu N} \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} U_{\nu N}^T$$

$$|U_{\nu N}|^2 \simeq \frac{m_\nu}{M_R}$$

$$m_\nu \simeq \frac{m_D^2}{M_R} \simeq \frac{(1)^2}{10^{10}} \text{GeV} = 0.1\text{eV}$$

Upper bound for neutrino mass



Beyond SM Neutrino

- HNLs can interact with SM particles via active-sterile mixing
- HNLs can be produced by hadron (or lepton) collisions or decays
- HNLs can decay to leptons, quarks and hadrons
- HNLs can generate matter-antimatter asymmetry via leptogenesis

Decay channels:

$N \to 3\nu$ $\quad N \to P^+e^-$

$N \to \ell^+\ell^-\nu$ $\quad N \to V\nu_e$ $\quad N \to \bar{q}q\nu$

$N \to P\nu_e$ $\quad N \to V^+e^-$

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Axion-like Particles (ALPs)

Axions:

- Proposed for Strong CP problem in QCD
- Pseudo-scalar boson and interact with the quark sector
- Potential candidate for dark matter

ALPs:

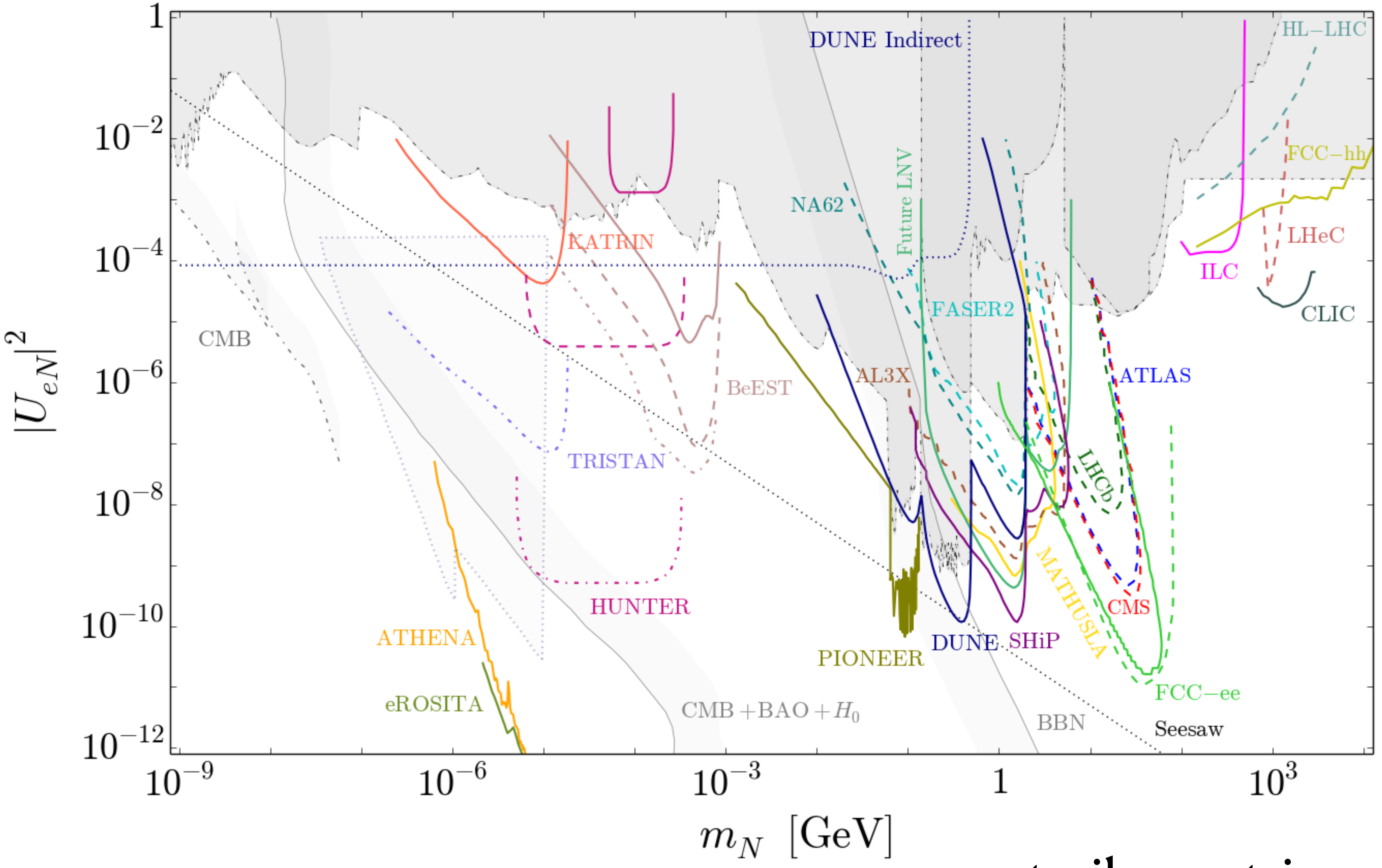
- Not necessarily interact with the quark sector
- Pseudo-Nambu-Goldstone boson (massive)
- Potential candidate for dark matter

Current Status & Model

Current Status for HNL Searches

P. Bolton, F. Deppisch, B. Dev

Moriond 2022



1. HNLs interact via mixing with neutrinos
2. Seesaw relation $|U_{eN}|^2 = m_\nu/m_N$
3. More than one HNLs
4. BBN & CMB excluded HNL masses below GeV ($\tau_N < 1$s)

sterile-neutrino.org

Model

- HNL-ALP coupling is introduced

$$\mathscr{L}_{aNN} = -\sum_{\kappa=1}^{\mathcal{N}} \frac{1}{f_a}\left(\partial_\mu a\right)\bar{N}_\kappa \gamma^\mu \gamma_5 N_\kappa$$

- ALPs can interact with SM via active-sterile mixing
- 1+1 simplified neutrino model
- $1\mathrm{MeV} < m_N \lesssim 1\mathrm{GeV}$ and $m_a \lesssim 1\mathrm{keV}$
- A new tree level decay mode of HNLs is added $N \to a\nu$
- Life time of HNLs can be changed by the new mode
- Low mass HNLs can be possible

Collider: Giorgi, Merlo, Tastet, *Fortsch.Phys.* 71 (2023) 4-5, 2300027

Marcos, Giorgi, Merlo, Tastet, *SciPost Phys.* 18 (2025) 084

Beam dump: Wang, Zhang, Liu, PR*D* 111 (2025) 3, 035010, *JHEP* 01 (2025) 070, *PRD* 110 (2024) 7

Abdullahi, Gouvea, Dutta, Shoemaker, Tabrizi, PRL 133, 261802 (2024)

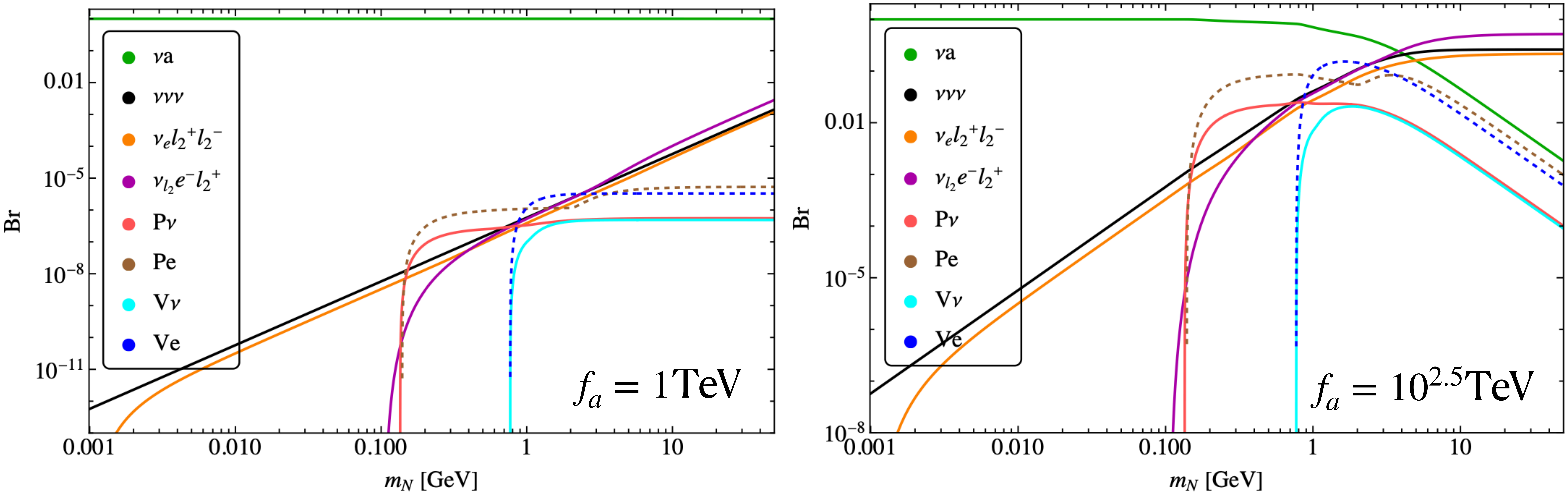
Astrophysics: Gola, Mandal, Sinha, *Int.J.Mod.Phys.A* 37 (2022) 22, 2250131

HNL decay

$$\boxed{\Gamma^{N\to a\nu} = \frac{\left|U_{eN}\right|^2 m_N^3}{4\pi f_a^2}\sqrt{1+\left(\frac{m_a}{m_N}\right)^2}\left[1-\left(\frac{m_a}{m_N}\right)^2\right]^{3/2} \approx \frac{\left|U_{eN}\right|^2 m_N^3}{4\pi f_a^2}}$$

$$\tau_{N\to a\nu} \approx 8.6\times 10^{-4}\ \mathrm{s}\times\left(\frac{f_a}{1\mathrm{TeV}}\right)^2\times\left(\frac{10^{-14}}{\left|U_{eN}\right|^2}\right)\times\left(\frac{1\mathrm{GeV}}{m_N}\right)^3$$

$m_a = 1\mathrm{keV}$



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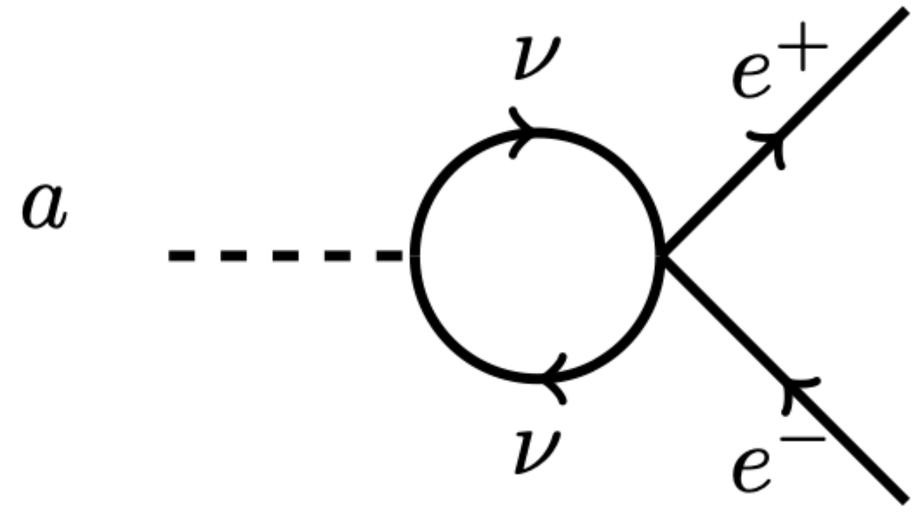
ALP decay

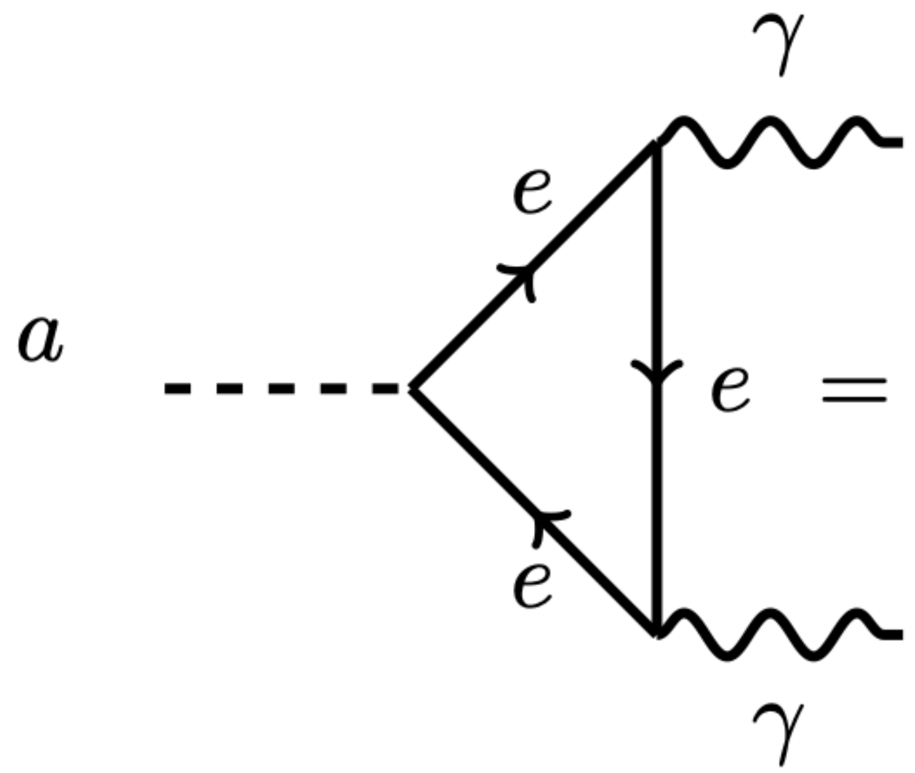
$$\boxed{\Gamma^{a\to\nu\nu} = \frac{1}{f_a^2}\frac{m_N^2 m_a U_{eN}^4}{2\pi}\sqrt{1-\frac{4m_\nu^2}{m_a^2}}\left(1-\frac{2m_\nu^2}{m_a^2}\right) \simeq \frac{m_N^2 m_a U_{eN}^4}{2\pi f_a^2}}$$

$$\tau_a = 1\mathrm{sec}\times\left(\frac{1\mathrm{GeV}}{\mathrm{m_N}}\right)^2\times\left(\frac{1\mathrm{keV}}{\mathrm{m_a}}\right)\times\left(\frac{2.03\times10^{-6}}{\left|\mathrm{U_{eN}}\right|^2}\right)^2\times\left(\frac{\mathrm{f_a}}{1\mathrm{TeV}}\right)^2$$

Other decay modes via loop:



$$= 2\gamma_5 g_{ae}$$



$$= -i g_{a\gamma}\epsilon^{\mu\nu}_{\rho\sigma}k_1^\rho k_2^\sigma$$

$$g_{ae} \approx \frac{\sqrt{2}G_F\left|U_{eN}\right|^4 m_e m_N^2}{16\pi^2 f_a} = \frac{\sqrt{2}G_F\left|U_{eN}\right|^4 m_e m_N^2}{16\pi^2 f_a}$$

$$g_{a\gamma} \approx \frac{e^2 g_{ae}}{2\pi^2 m_e}\left(1+\frac{1}{12}\frac{m_a^2}{m_e^2}\right) = \frac{\sqrt{2}e^2 G_F\left|U_{eN}\right|^4 m_N^2}{32\pi^4 f_a}\left(1+\frac{1}{12}\frac{m_a^2}{m_e^2}\right)$$

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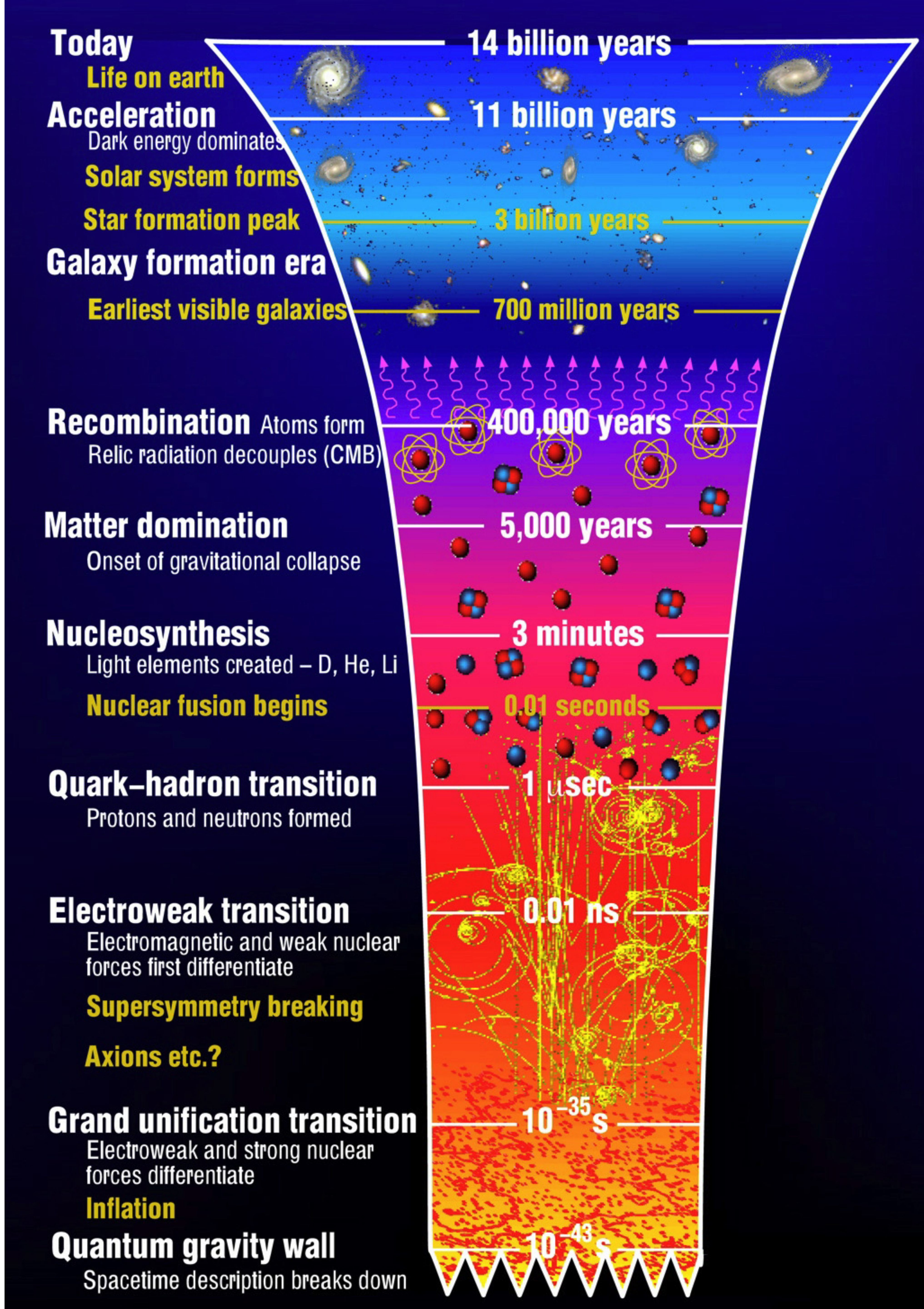
Cosmological History

- particles are initial in the plasma
- Neutrinos decouple from the plasma due to expansion
- Light primordial elements are formed during BBN
- Electrons combine with protons to form CMB



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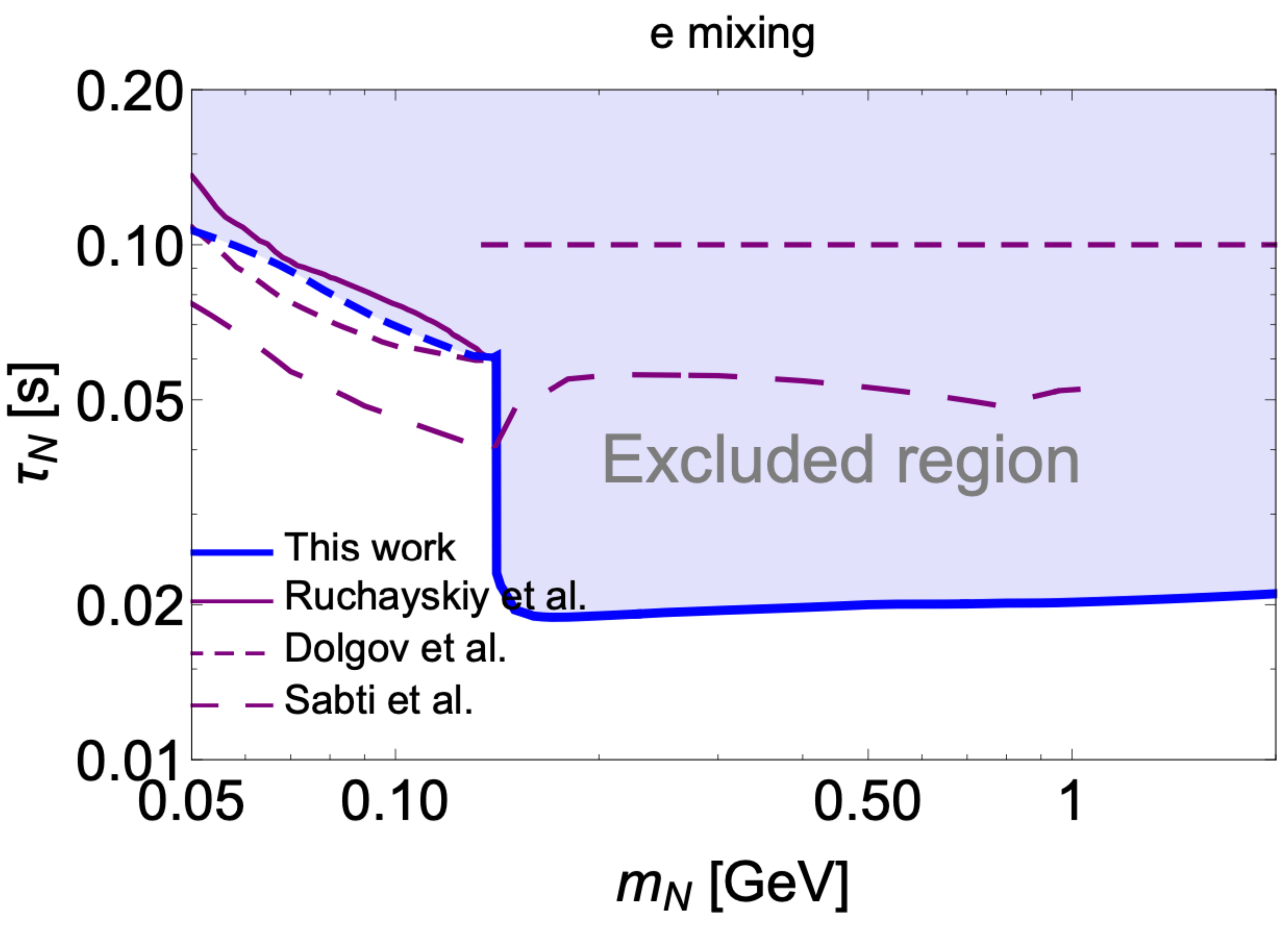
Big Bang Nucleosynthesis (BBN)

- Particles are kept in thermal equilibrium if interaction rates are fast enough
- Particles fall out of equilibrium as the Universe expands
- Weak interactions such as $n + \nu_e \rightarrow p + e^-$ is not in equilibrium and proton to neutron ratio falls out
- Strong interactions bind the nucleons together (eg. $n + p \rightarrow D$)
- Other primordial elements such as ^{3}He and ^{4}He formed shortly after D
- Extra energy injections to the plasma will impact the abundance of primordial elements

Big Bang Nucleosynthesis (BBN)

- Light and stable HNLs contribute to $N_{\mathrm{eff}} = 3 + g_s$
- HNL decay products increase the temperature for particles in equilibrium such as electron and photon
- HNL decay products modify the out of equilibrium particle spectra such as neutrino
- HNLs typically increase the primordial abundance of ^{4}He
- $\tau_N < 0.02$s for $m_N > m_\pi$



Boryarsky, Ovchynnikov, Ruchayskiy, Syvolap, PRD 104 (2021) 2, 023517

P.S.B.Dev, Q. Wu, X.Xu, 2507.12270 (HNL&BBN)

Cosmic Microwave Background (CMB)

- Occur after BBN and neutrino decoupling, neutrino and photon temperatures evolve differently
- Electrons combine with protons and release photons
- Occur after the last Compton scattering ($\Gamma_C < H$)
- Observed photon temperature nowadays $T_\gamma = 2.73\mathrm{K}$
- Total radiation density is calculated by $\rho_\mathrm{R} = \rho_\gamma \left(1 + 3\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\mathrm{eff} \right)$, $N_\mathrm{eff,SM} = 2.99^{+0.34}_{-0.33}$

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Cosmic Microwave Background (CMB)

- HNLs already decay before BBN
- ALPs may impact the CMB spectrum via electromagnetic injection
- N_{eff} can be affected by photon to neutrino ratio,

$$N_{\text{eff}}(t) = N_{\text{eff,BBN}} \left(\frac{T_\nu(t)}{T_\gamma(t)} \right)^4 \left(\frac{11}{4} \right)^{4/3}$$

- In our scenario, the main impact on CMB is from $a \to \nu\nu$
- ALPs decay after BBN and before CMB

Balaz, et al, JCAP 12(2022) 027

Cosmological History

- Boltzmann equations are used to compute the evolutions,

$$\frac{d\rho_X}{dt} + 3H\left(\rho_X + p_X\right) = \frac{\delta\rho_X}{\delta t} = \int g_X E \frac{d^3p}{(2\pi)^3}\mathscr{C}[f],$$

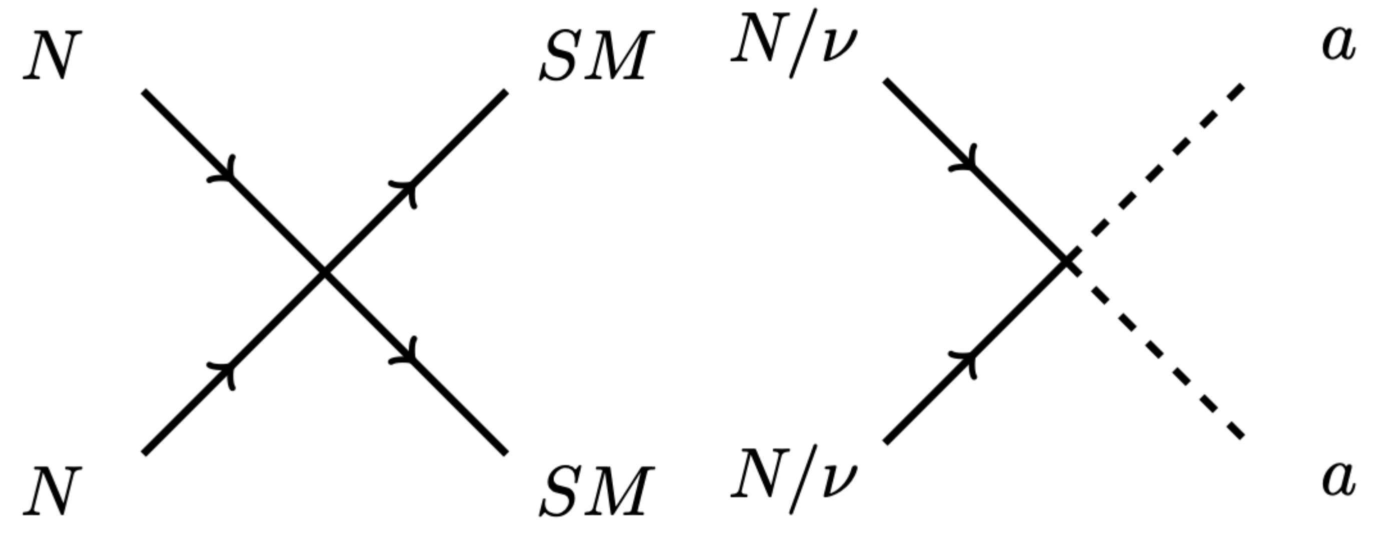
$$\frac{dn_X}{dt} + 3Hn_X = \frac{\delta n_X}{\delta t} = \int g_X \frac{d^3p}{(2\pi)^3}\mathscr{C}[f]$$

- Rates of processes are computed as flowing, $\gamma_{X\to Y} = \left\langle \sigma_{X\to Y} v \right\rangle n_X^{eq,2} = \left\langle \Gamma_{X\to Y} \right\rangle n_X^{eq}$,

$$\gamma_{X\to Y_1\ldots} = n_X^{eq}(z)\frac{K_1(z)}{K_2(z)}\Gamma_X$$

- The Boltzmann equations are separated into time before and after BBN for HNLs and ALPs

Cosmological History



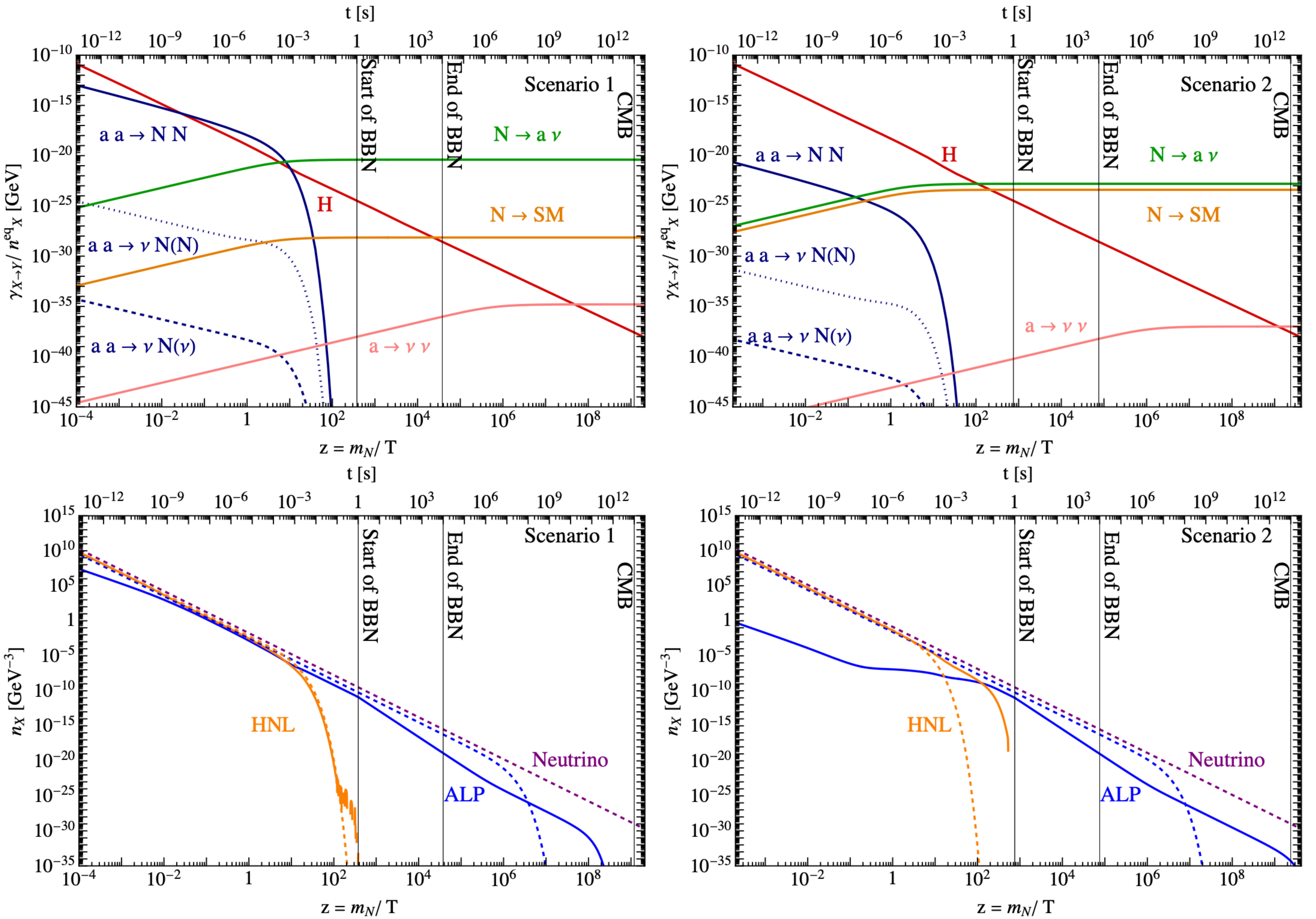
Before BBN:
$$zHs\frac{dY_N}{dz} = -\gamma^{\rm eq}_{NN\to SM}\left(\frac{Y_N^2}{Y_N^{\rm eq,2}}-1\right) + \gamma^{\rm eq}_{aa\to NN}\left(\frac{Y_a^2}{Y_a^{\rm eq,2}}-\frac{Y_N^2}{Y_N^{\rm eq,2}}\right)$$
$$-\gamma_{N\to SM}\left(\frac{Y_N}{Y_N^{\rm eq}}-1\right) - \gamma_{N\to a\nu}\left(\frac{Y_N}{Y_N^{\rm eq}}-\frac{Y_a}{Y_a^{\rm eq}}\right),$$
$$zHs\frac{dY_a}{dz} = -\gamma^{\rm eq}_{aa\to\nu\nu}\left(\frac{Y_a^2}{Y_a^{\rm eq,2}}-1\right) - \gamma^{\rm eq}_{aa\to NN}\left(\frac{Y_a^2}{Y_a^{\rm eq,2}}-\frac{Y_N^2}{Y_N^{\rm eq,2}}\right)$$
$$-\gamma_{a\to\nu\nu}\left(\frac{Y_a}{Y_a^{\rm eq}}-1\right) + \gamma_{N\to a\nu}\left(\frac{Y_N}{Y_N^{\rm eq}}-\frac{Y_a}{Y_a^{\rm eq}}\right),$$

$$Y_X = n_X/s$$
$$s = \frac{2\pi^2}{45}g_* T^3$$
$$z = m_N/T$$

After BBN:
$$zHs\frac{dY_a}{dz} = -\gamma_{a\to\nu\nu}\left(\frac{Y_a}{Y_a^{\rm eq}}-1\right), \quad \text{with} \quad z > z_{\rm BBN}$$

Scenario	m_N [GeV]	$\lvert U_{eN}\rvert^2$	f_a [TeV]	m_a [keV]
1	10^{-1}	10^{-10}	1	1
2	$10^{-0.4}$	$10^{-9.2}$	$10^{2.5}$	1
3	-	-	1	10^{-2}
4	-	-	$10^{2.5}$	10^{-2}

- $N \to a\nu$ dominant
- HNLs decay before BBN
- ALPs decay between BBN and CMB
- Scattering only dominant in the early time
- ALPs decay dominantly in later time



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Results

Scenario	m_N [GeV]	$\lvert U_{eN}\rvert^2$	f_a [TeV]	m_a [keV]
1	10^{-1}	10^{-10}	1	1
2	$10^{-0.4}$	$10^{-9.2}$	$10^{2.5}$	1
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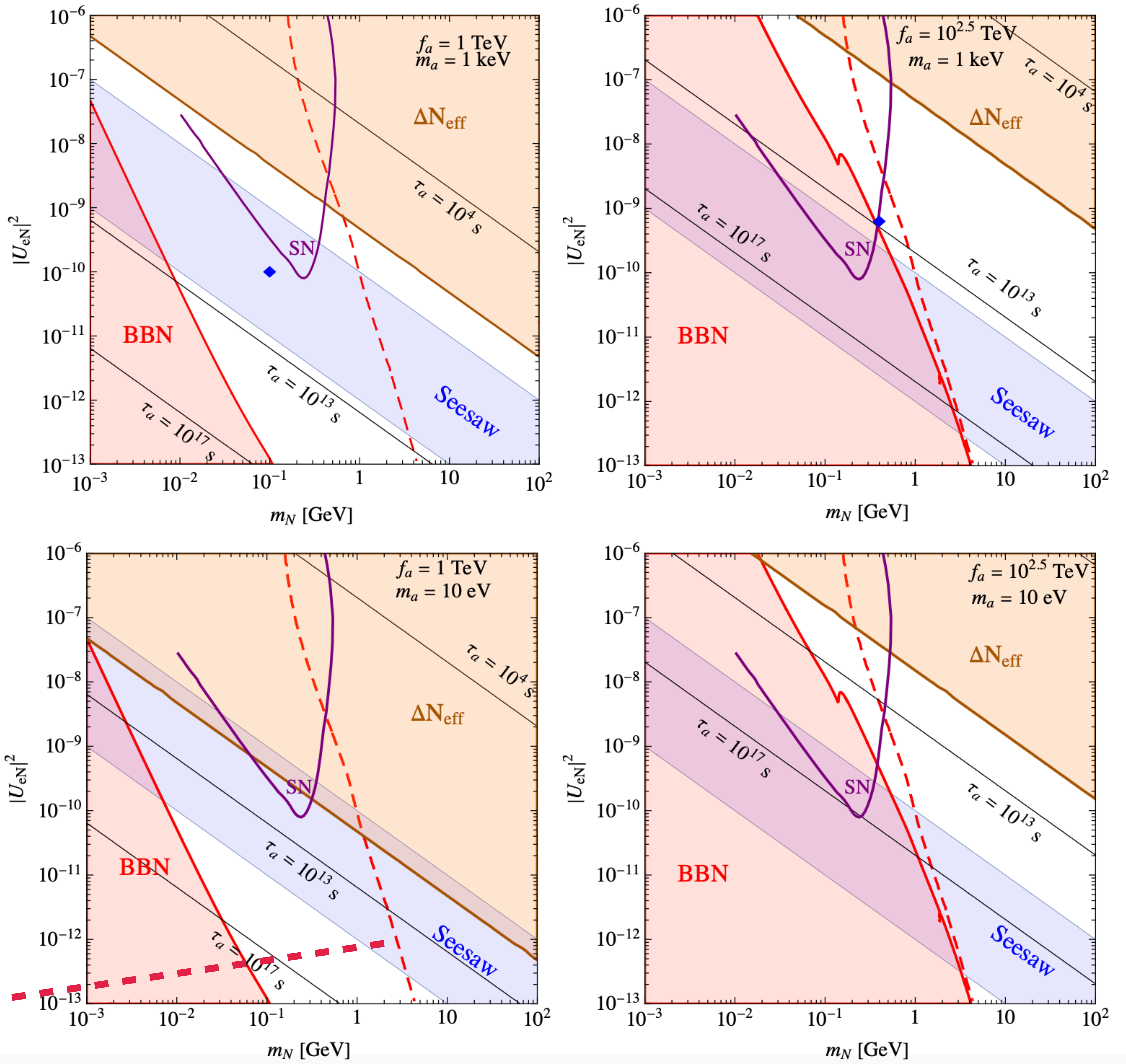
4	-	-	$10^{2.5}$	10^{-2}

- $0.1\Delta N_{\rm eff} = 0.0384$ at CMB
- Seesaw band $1\text{meV} \le m_\nu \le 100\text{meV}$
- Stronger couplings give less constraints on the parameter space
- $f_a > 10^3$TeV, SBBN dominant
- Lighter ALPs contribute more to $N_{\rm eff}$



SBBN for HNLs

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Results

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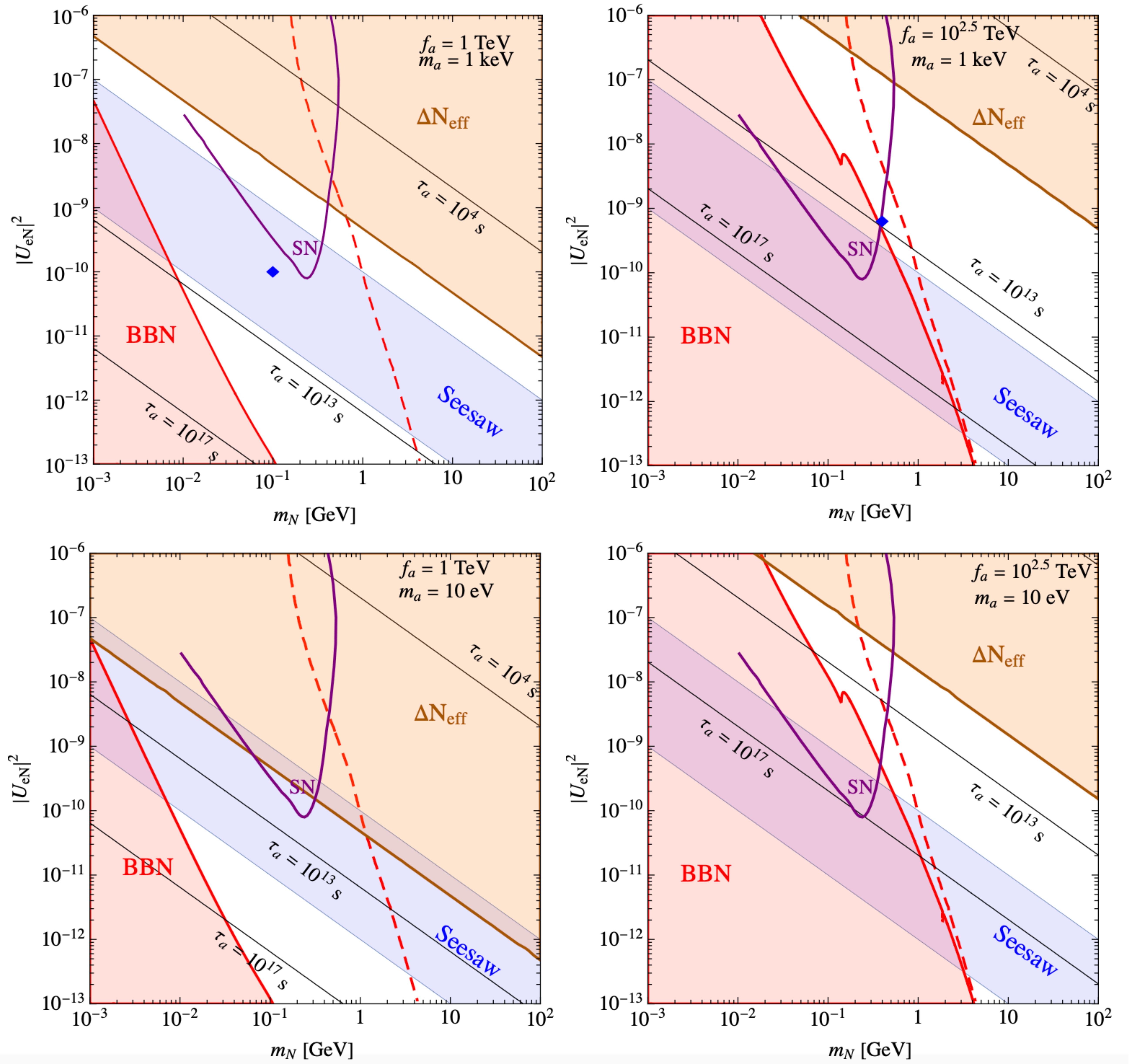
- SN1987 excludes relatively high mixing for 10MeV ~ 1GeV masses
- HNLs and ALPs contribute to SN cooling
- Neutrinos emissions by HNL or ALP decay
- g_{ae} and $g_{a\gamma}$ are negligible compared to current constraints



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Direct Searches for HNLs

- The number of events for Beam Dump experiment (DUNE),

$$N_{\text{sig}} = N_P \times \text{Br}(\text{P} \to \text{N}) \times \text{Br}(\text{N} \to \text{charged}) \times \epsilon_{\text{geo}}$$

- The geometric factor of the cylindrical detector is parameterised by

$$\epsilon_{\text{geo}} = e^{-\frac{m_N \Gamma_N}{p_N} L} \left(1 - e^{-\frac{m_N \Gamma_N}{p_N} \Delta L}\right)$$

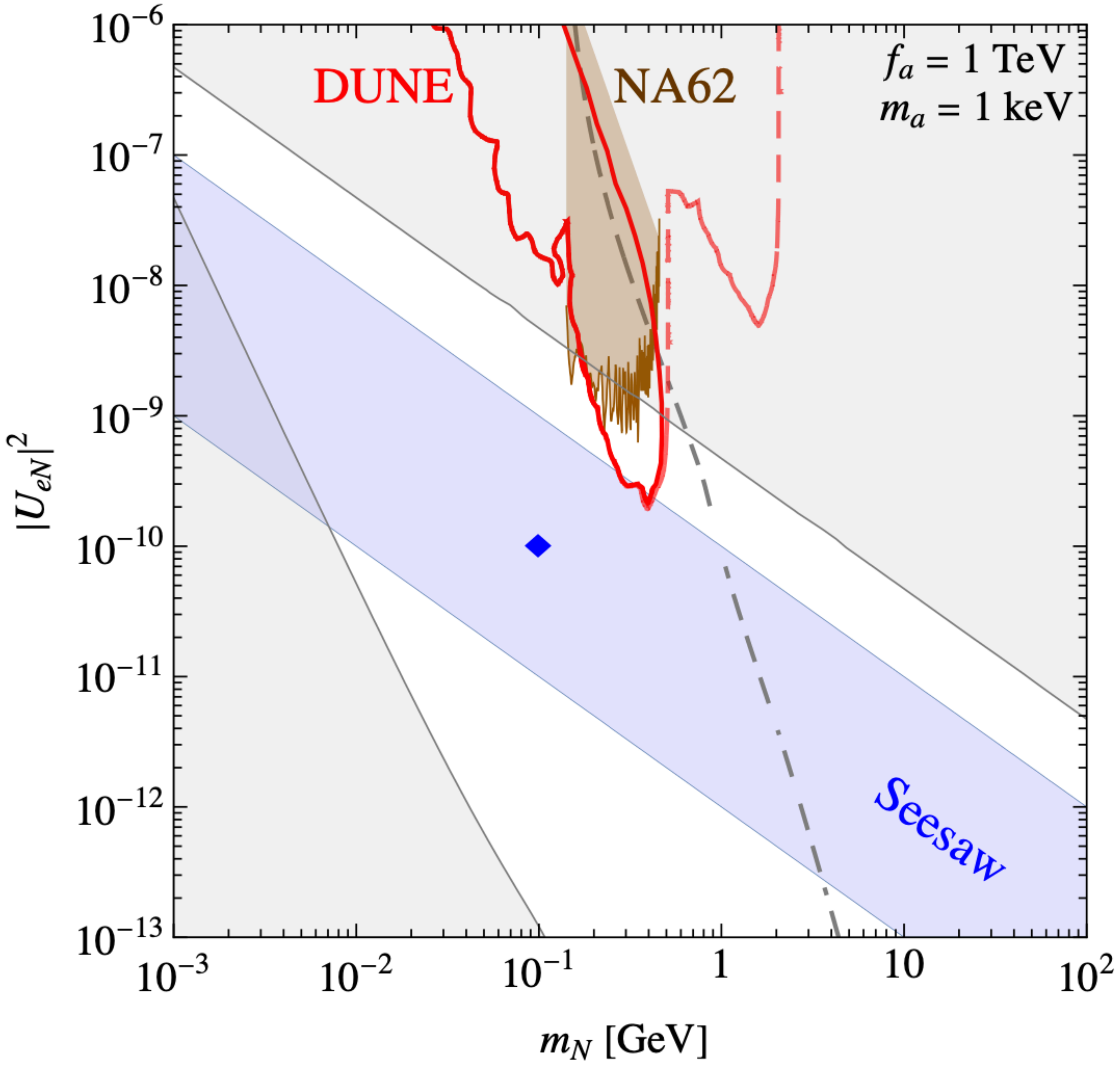
- There is only a new invisible ALP decay channel in the model
- The event ratios between the standard and HNL-ALP scenarios is

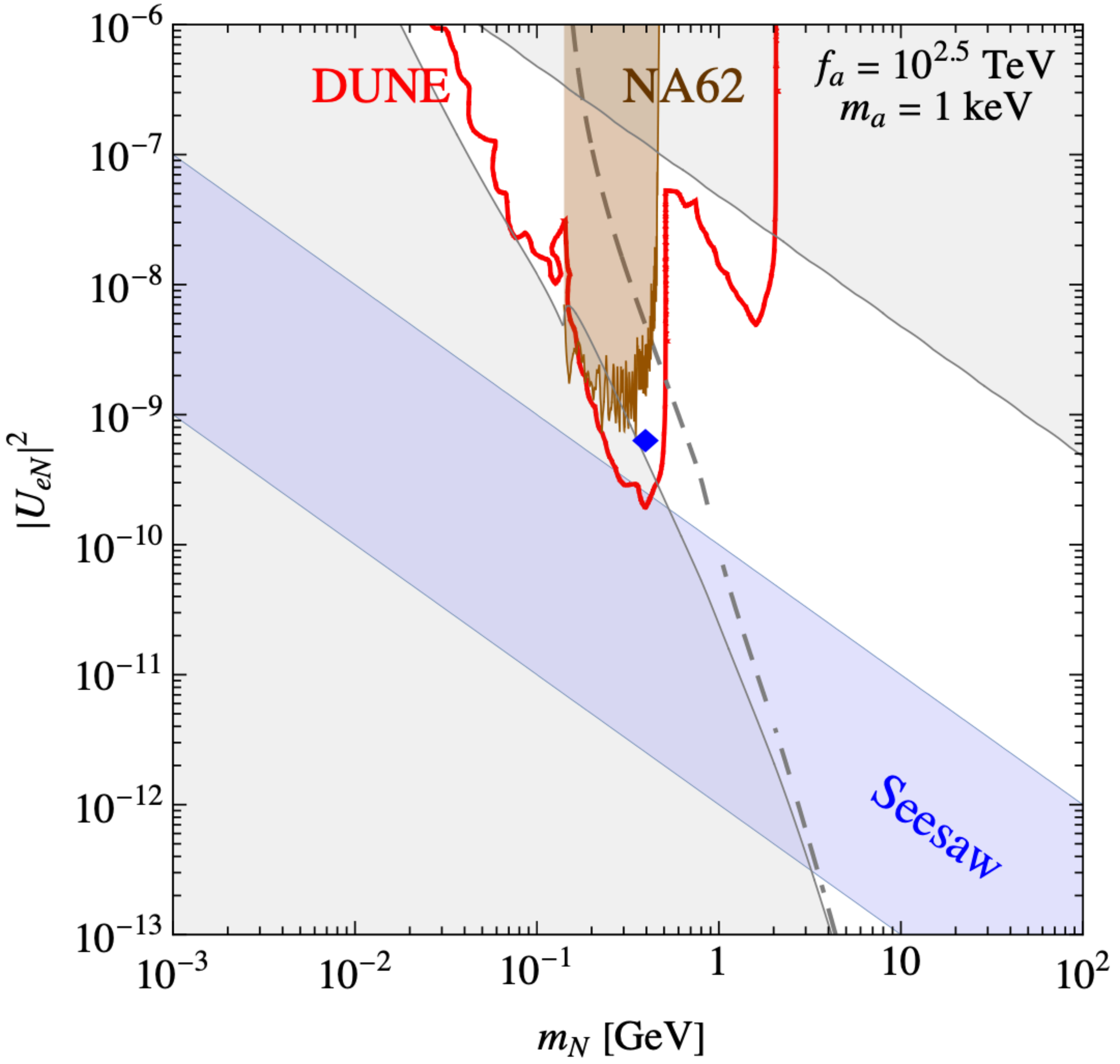
$$\frac{N'_{\text{sig}}}{N_{\text{sig}}} = \exp\left[-\frac{m_N}{p_{N_z}} \Gamma(N \to a\nu) L\right]$$

Direct Searches for HNLs

Scenario	m_N [GeV]	$\lvert U_{eN}\rvert^2$	f_a [TeV]	m_a [keV]
1	10^{-1}	10^{-10}	1	1
2	$10^{-0.4}$	$10^{-9.2}$	$10^{2.5}$	1
3	-	-	1	10^{-2}
4	-	-	$10^{2.5}$	10^{-2}

- Weaker coupling gives the same sensitivity
- Stronger coupling coincides in the low mass region
- The decay length compensates the invisible branching ratio





Conclusion

- A simplified model of HNL-ALP is studied to relax the BBN constraint on HNLs
- MeV mass HNLs are possible by adding new invisible decay modes.
- Stronger HNL-ALP couplings give distinct Beam Dump signatures at high HNL masses.
- More precise simulation of beam dump experiments (in progress)

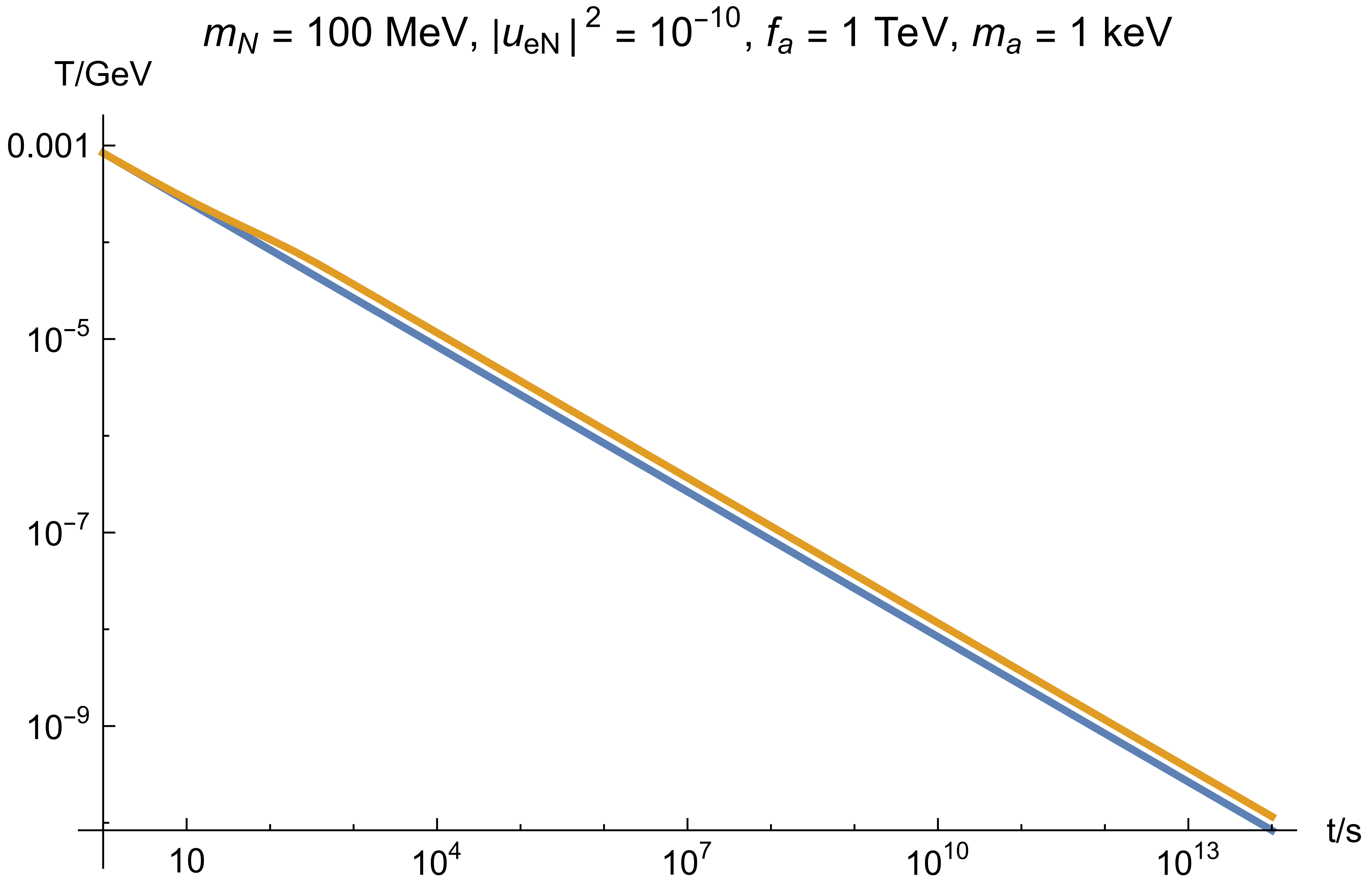
Thank you very much for your attention!

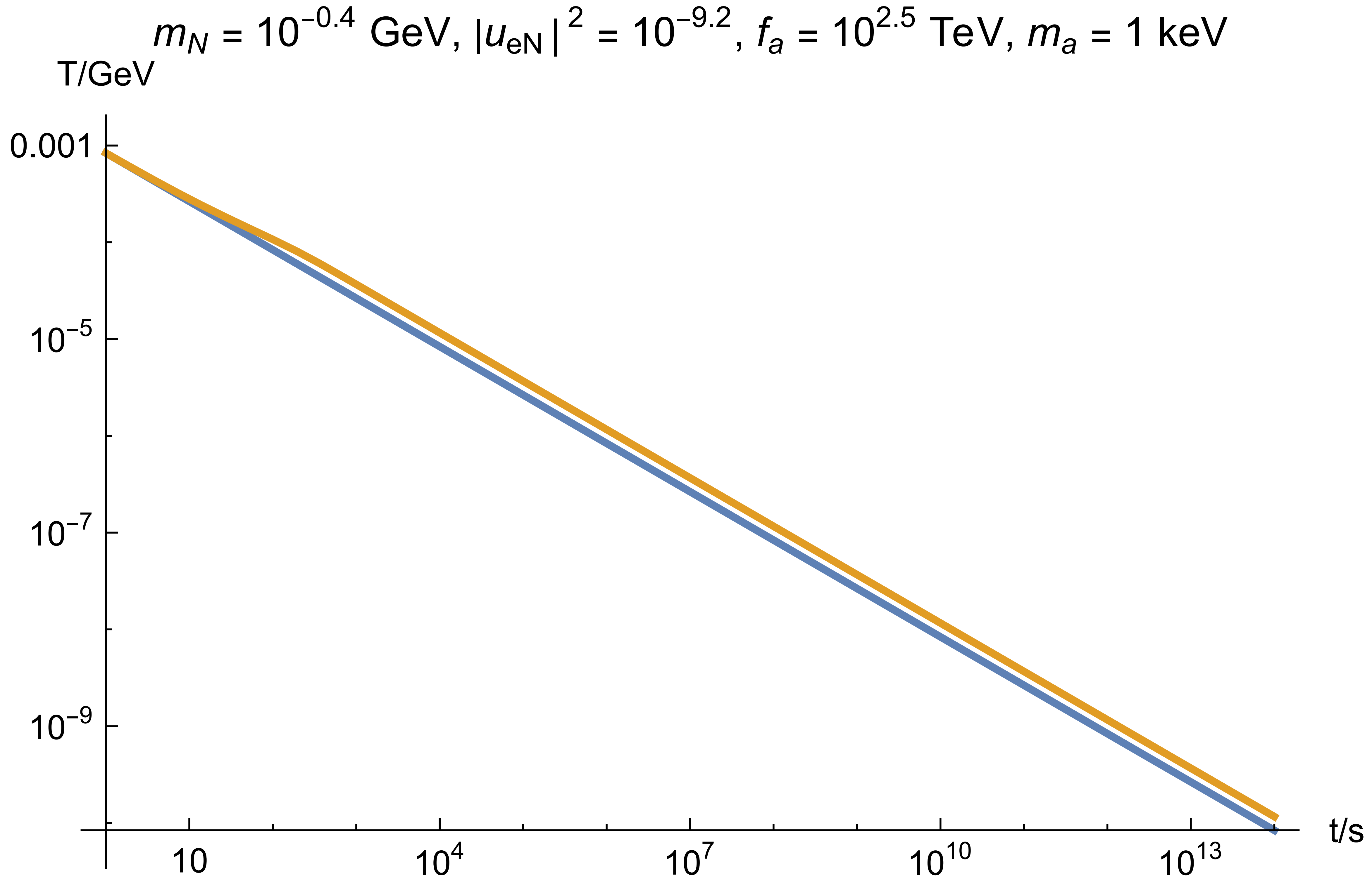
Any questions?

Temperature

$$\frac{dT_\gamma}{dt} = -\frac{4H\rho_\gamma + 3H(\rho_e + p_e)}{\frac{\partial \rho_\gamma}{\partial T_\gamma} + \frac{\partial \rho_e}{\partial T_\gamma}}$$

$$\frac{dT_\nu}{dt} = -\frac{12H\rho_\nu + 3H(\rho_a + p_a) + \delta\rho_a/\delta t}{3\frac{\partial \rho_\nu}{\partial T_\nu} + \frac{\partial \rho_a}{\partial T_\nu}}$$





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HNL life time

$$\boxed{m_N < \frac{\sqrt{5\left|1-24G_F^2 f_M^2 f_a^2\right|\pi}}{f_a G_F}}$$

$$\Gamma^{\nu_e \ell^- \ell^+} = \left|U_{eN}\right|^2 \frac{G_F^2 m_N^5}{96\pi^3}\left[\left(C_1 + 2\sin^2\theta_W \delta_{e,\ell}\right) f_1\left(x_\ell\right) + \left(C_2 + \sin^2\theta_W \delta_{e,\ell}\right) f_2\left(x_\ell\right)\right]$$

$$\Gamma^{e^-\ell^+\nu_\ell} = \left|U_{eN}\right|^2 \frac{G_F^2 m_N^5}{192\pi^3}\left[1 - 8x_\ell^2 + 8x_\ell^6 - x_\ell^8 - 12x_\ell^4 \ln\left(x_\ell^2\right)\right]$$

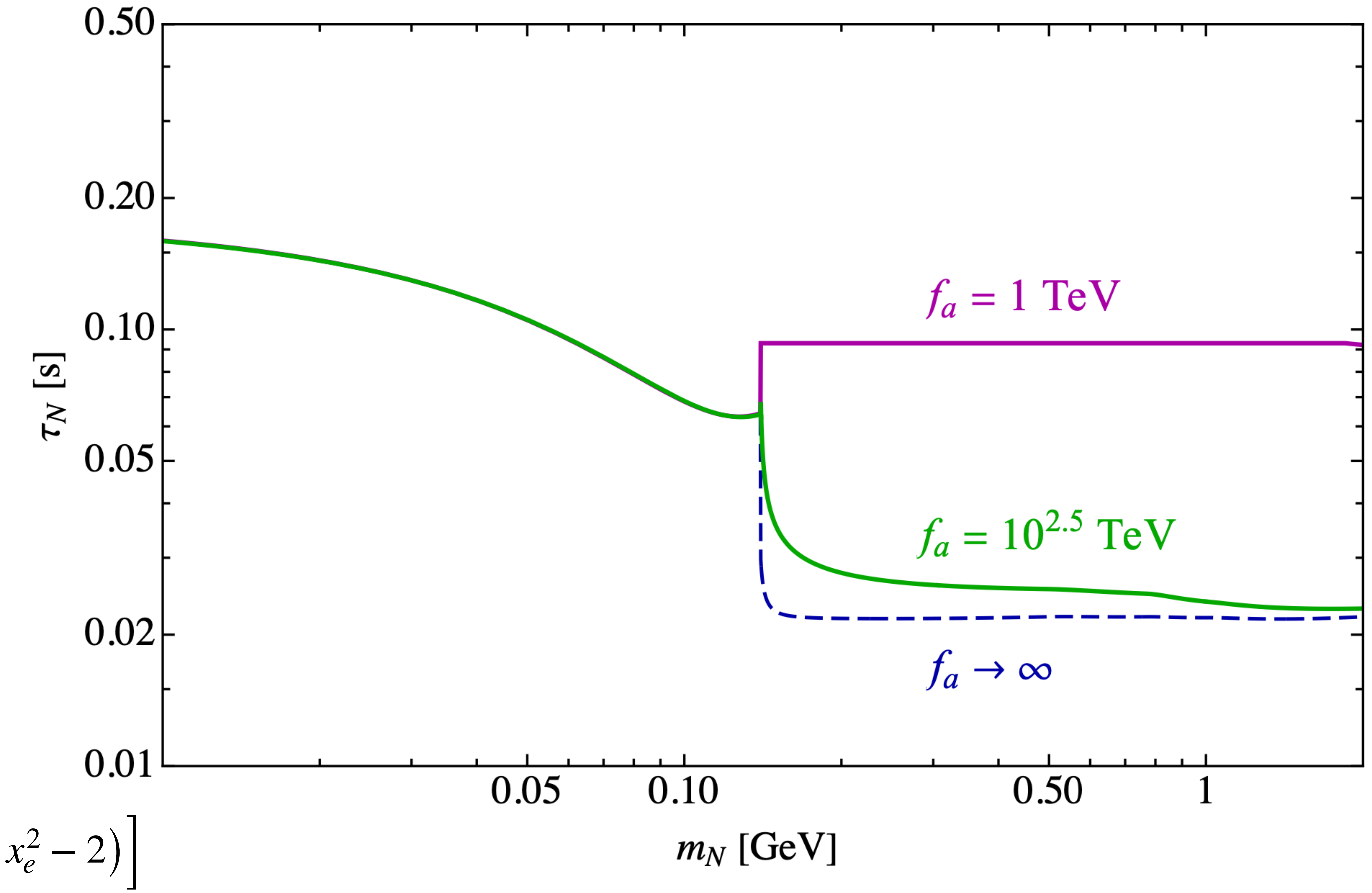
$$\Gamma^{\nu_e \nu_\ell \bar{\nu}_\ell} = \frac{G_F^2}{96\pi^3}\left|U_{eN}\right|^2 m_N^5$$

$$\Gamma^{P\nu_e} = \frac{G_F^2 m_N^3}{32\pi} f_P^2 \left|U_{eN}\right|^2 \left(1 - x_P^2\right)^2$$

$$\Gamma^{P^+e^-} = \frac{G_F^2 m_N^3}{16\pi} f_P^2 \left|U_{eN}\right|^2 \left|V_{qq'}\right|^2 \lambda^{1/2}\left(1, x_P^2, x_e^2\right)\left[1 - x_P^2 - x_e^2\left(2 + x_P^2 - x_e^2\right)\right]$$

$$\Gamma^{V\nu_e} = \frac{G_F^2 m_N^3}{32\pi m_V^2} f_V^2 \kappa_V^2 \left|U_{eN}\right|^2 \left(1 + 2x_V^2\right)\left(1 - x_V^2\right)^2$$

$$\Gamma^{V^+e^-} = \frac{G_F^2 m_N^S}{16\pi m_{V+\pm}^2} f_V^2 \left|U_{eN}\right|^2 \left|V_{qq'}\right|^2 \lambda^{1/2}\left(1, x_V^2, x_e^2\right)\left[\left(1 - x_V^2\right)\left(1 + 2x_V^2\right) + x_e^2\left(x_V^2 + x_e^2 - 2\right)\right]$$



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