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References: This code of conduct is based heavily on that of the INT and the APS. We are also grateful to Roxanne Springer for valuable discussion and guidance.

THE ROYAL SOCIETY

UCL

Relaxing Big Bang Nucleosynthesis constraints on HNLs with ALPs

Rising Researchers Seminar Series
2nd December, 2025

Collaborators : Frank F. Deppisch, Tomás E. Gonzalo, Zhong Zhang
JCAP02(2025)054 [arXiv : 2410.06970]

Chayan Majumdar

IMP, CAS

Plan of the talk

- Introduction to ALP and HNL
- Framework
- Cosmological evolution of HNL and ALP
- Constraints from Cosmology and Astrophysics
- Prospects in future HNL direct search experiments
- Summary

Axion-like particles (ALPs)

Strong CP Problem $\Rightarrow$ $\Theta_{QCD} < 10^{-11}$?

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$\Downarrow$

Solution : QCD Axions

[Peccei,Quinn ’77; Weinberg ’78; Wilczek ’78]

Axion-like particles (ALPs)

Strong CP Problem $\Rightarrow$ $\Theta_{QCD} < 10^{-11}$?

$\Downarrow$

Solution : QCD Axions

[Peccei,Quinn '77; Weinberg '78; Wilczek '78]

- However, more fundamental theories such as the string theory can suggest the presence of particles similar to axions. [Svrcek & Witten '04, Arvanitaki et al. '10]
- Hypothetical particles which are similar to QCD axions are called axion-like particles (ALPs).
- ALPs don't obey the mass-coupling relation [Weinberg '78, ... Borsanyi et al. '16].
- Possible dark matter candidates [Ringwald '16].

Heavy Neutral Leptons (HNLs)

- Couple with the SM via active-sterile mixing ($U_{\alpha N}$).

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Spectrum of Phenomenon

1. Origin of small neutrino masses
2. Dark Matter (DM)
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Experimental Observations

1. Reactor Anti-neutrino anomaly [Phys. Rev. D 83, 07300].
2. Gallium Anomaly [Phys. Rev. C 80 015807].
3. Accelerator anomaly [Phys. Rev. Lett. 110, 161801].

Framework

SM + HNLs (N) + ALPs (a) :

$$\mathscr{L} = \mathscr{L}_{\rm SM} + i\bar{N}_{iR}\gamma_\mu\partial^\mu N_{iR} - (Y_\nu)_{\alpha i}\bar{L}_\alpha\tilde{H}N_{iR} - \frac{1}{2}(\mathscr{M}_R)_{ij}\bar{N}^c_{iR}N_{jR} + \mathscr{L}_a + \mathscr{L}_{aNN} + h.c.$$

where $$\mathscr{L}_{aNN} = \sum_{\kappa=1}^{\mathscr{N}} \frac{1}{f_a}(\partial_\mu a)\bar{N}_\kappa\gamma^\mu\gamma_5 N_\kappa = -\sum_{\kappa=1}^{\mathscr{N}} \frac{2i}{f_a} m_{N_\kappa} a\bar{N}_\kappa\gamma_5 N_\kappa$$ [S. Gola et al., '22]

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Considering HNL couples only to ν_e :

$$\mathscr{L}_{aN\nu} = -\frac{2i}{f_a} m_N U_{eN} a \bar{N} \gamma_5 \nu_e$$

$$\mathscr{L}_{a\nu\nu} = -\frac{2i}{f_a} m_N |U_{eN}|^2 a \bar{\nu}_e \gamma_5 \nu_e = -\frac{2i}{f_a} m_\nu a \bar{\nu}_e \gamma_5 \nu_e$$

HNL decays

Majorana HNL with mass around MeV-GeV scale decays leptonically or semi-leptonically :

[A. Atre et al., '09; P. Coloma et al., '21]

$$\Gamma^{N\to \mathrm{SM}} = \sum_{l} \Gamma^{\nu_e l^+ l^-} + \sum_{l=\mu,\tau} 2\Gamma^{e^- l^+ \nu_l} + \sum_{l} \Gamma^{\nu_e \nu_l \bar{\nu}_l} + \sum_{P} \Gamma^{P\nu_e} + \sum_{P} 2\Gamma^{P^+ e^-} + \sum_{V} \Gamma^{V\nu_e} + \sum_{V} 2\Gamma^{V^+ e^-}$$

$$\approx \left(\frac{6 f_M^2}{\pi} + \frac{m_N^2}{20\pi^3} \right) m_N^3 |U_{eN}|^2 G_F^2$$

[P. D. Bolton et al., '20]

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New decay channel for HNL $N \to a\nu$:

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

$$\Downarrow$$

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

Axionic decay channel will be dominant for

$$m_N < \frac{\sqrt{5\,|\,1 - 24G_F^2 f_M^2 f_a^2\,|\,\pi}}{f_a G_F}\,.$$

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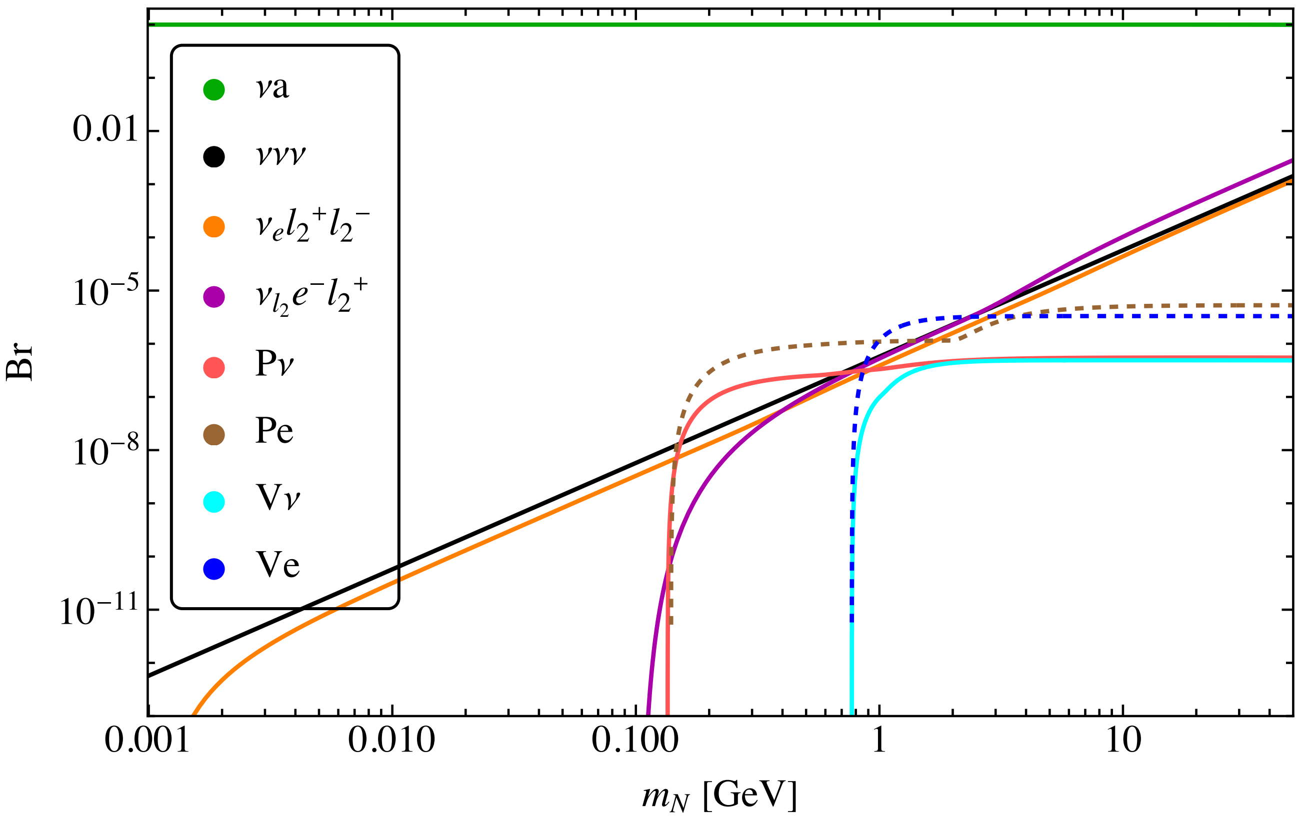
$$f_a = 1\ \mathrm{TeV}, \mathrm{m_a} = 1\ \mathrm{keV}$$



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$$m_N < \frac{\sqrt{5\,|\,1 - 24 G_F^2 f_M^2 f_a^2\,|\,\pi}}{f_a G_F}.$$

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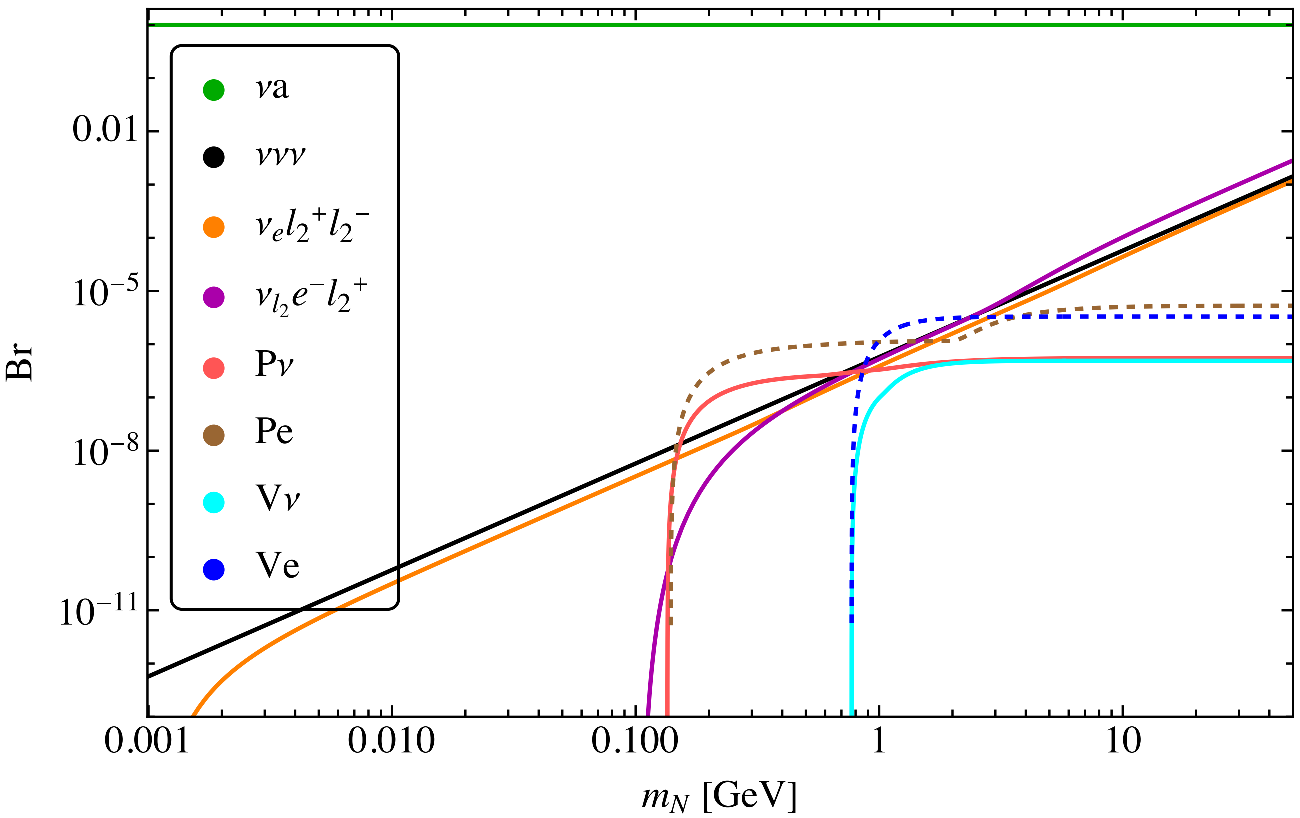
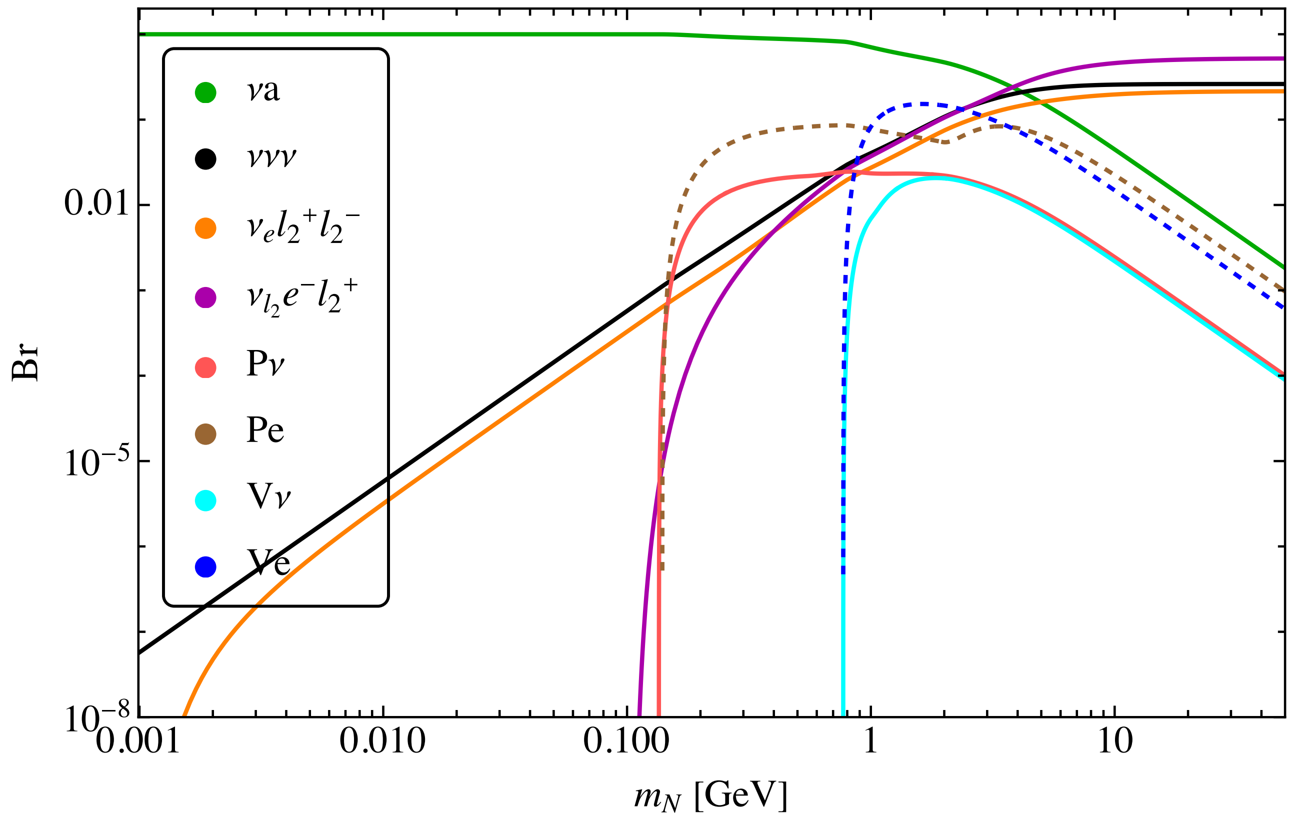
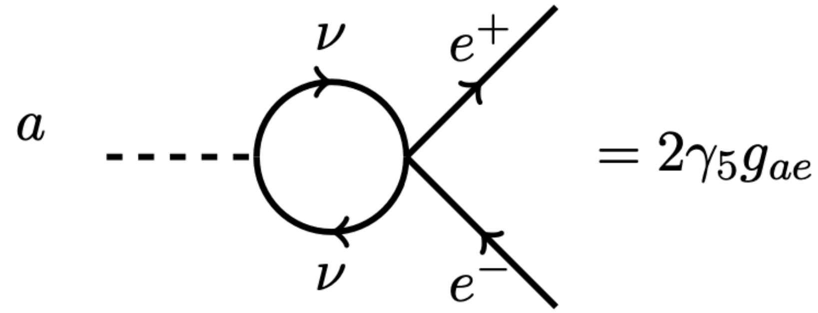
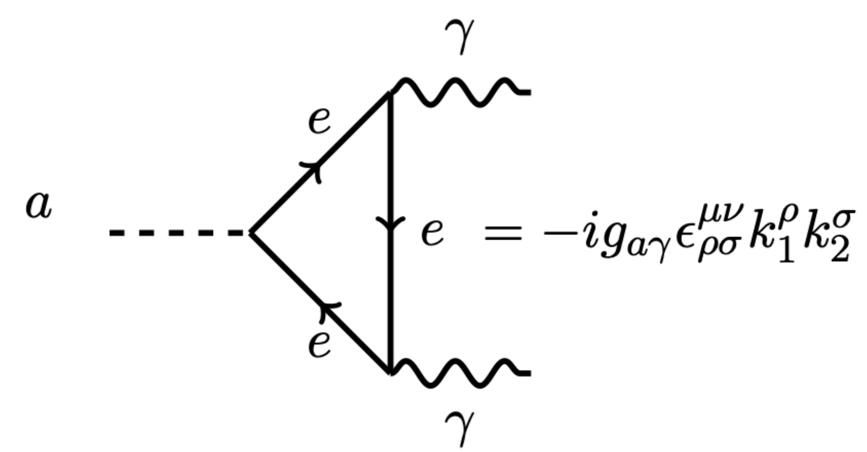


$f_a = 10^{2.5}$ TeV, $\mathrm{m_a} = 1$ keV



ALP decays





Effective ALP-electron and ALP-photon couplings :

$$g_{aee} \approx \frac{\sqrt{2} G_F |U_{eN}|^4 m_e m_N^2}{16\pi^2 f_a}, \qquad g_{a\gamma\gamma} \approx \frac{\sqrt{2} e^2 G_F |U_{eN}|^4 m_N^2}{32\pi^4 f_a} \left(1 + \frac{1}{12}\frac{m_a^2}{m_e^2}\right)$$

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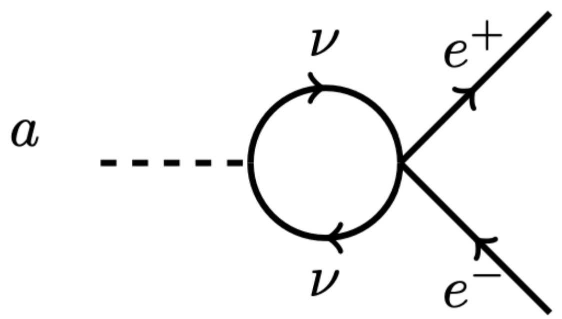
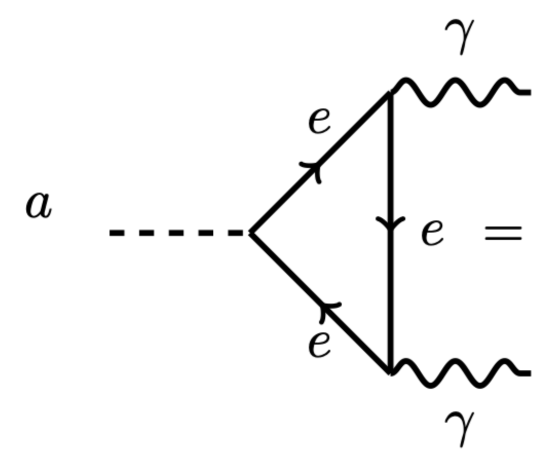


$= 2\gamma_5 g_{ae}$



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

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New decay channel for ALP $a \rightarrow \nu\nu$:

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

$$\Downarrow$$

$$\tau_a \approx 1\ \text{sec}\left(\frac{1\ \text{GeV}}{\text{m}_\text{N}}\right)^2\left(\frac{1\ \text{keV}}{\text{m}_\text{a}}\right)\left(\frac{2.03\times10^{-6}}{|\text{U}_\text{eN}|}\right)^2\left(\frac{\text{f}_\text{a}}{1\ \text{TeV}}\right)^2$$

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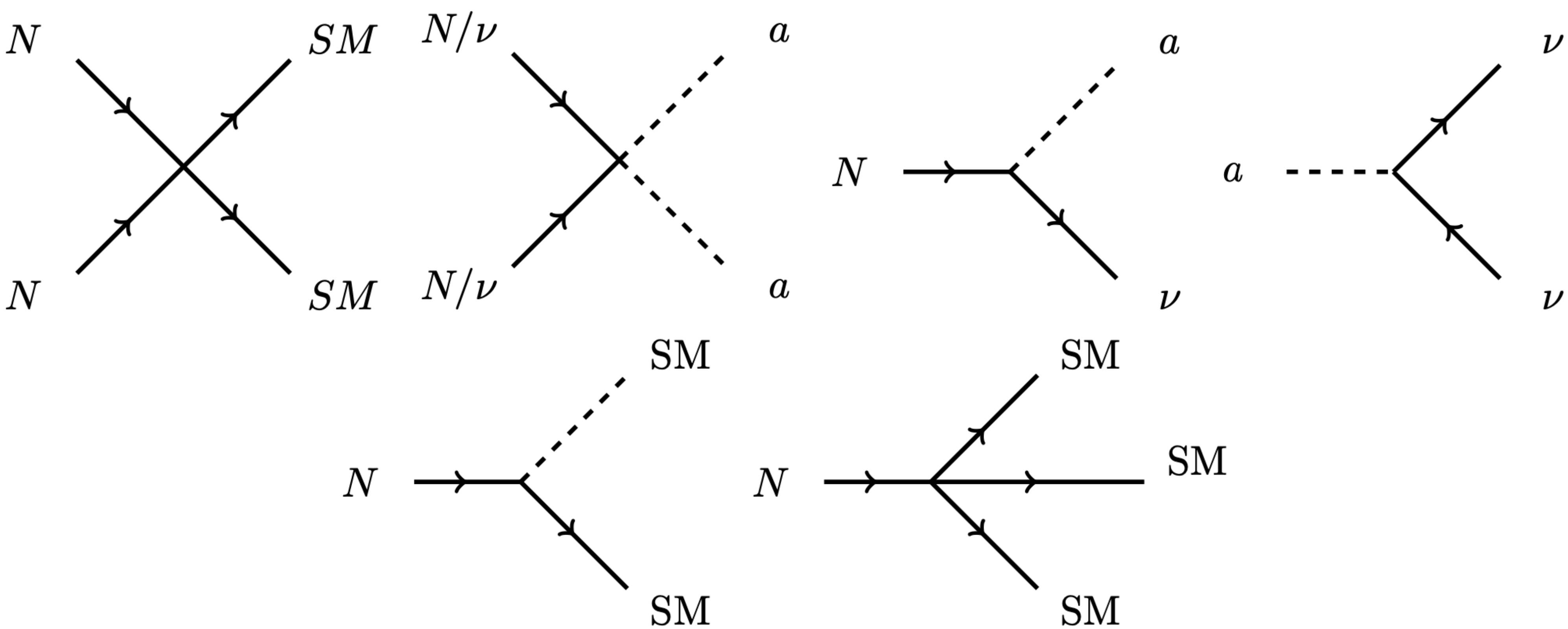
Cosmological evolution of HNLs and ALPs

Boltzmann Equations :

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

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

[P. Gondolo et al., ’91; M. Escudero et al., ’19]



Abundances before BBN

Boltzmann Equations for HNL evolution :

$$\frac{dn_N}{dt} + 3Hn_N = -\langle\sigma_{NN\to \mathrm{SM}}v\rangle(n_N^2 - n_N^{\mathrm{eq},2}) - \langle\sigma_{NN\to aa}v\rangle\left(n_N^2 - n_N^{\mathrm{eq},2}\frac{n_a^2}{n_a^{\mathrm{eq},2}}\right)$$
$$-\langle\Gamma_{N\to \mathrm{SM}}\rangle(n_N - n_N^{\mathrm{eq}}) - \langle\Gamma_{N\to a\nu}\rangle\left(n_N - n_N^{\mathrm{eq}}\frac{n_a}{n_a^{\mathrm{eq}}}\right)$$

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Boltzmann Equations for ALP evolution :

$$\frac{dn_a}{dt} + 3Hn_a = -\langle\sigma_{aa\to \nu\nu}v\rangle(n_a^2 - n_a^{\mathrm{eq},2}) - \langle\sigma_{aa\to NN}v\rangle\left(n_a^2 - n_a^{\mathrm{eq},2}\frac{n_N^2}{n_N^{\mathrm{eq},2}}\right)$$
$$-\langle\Gamma_{a\to \nu\nu}\rangle(n_a - n_a^{\mathrm{eq}}) + \langle\Gamma_{N\to a\nu}\rangle\left(n_N - n_N^{\mathrm{eq}}\frac{n_a}{n_a^{\mathrm{eq}}}\right)$$

These equations can also be expressed in terms of $Y_X \equiv \dfrac{n_X}{s}$ and $z \equiv \dfrac{m_X}{T}$.

Abundances after BBN : temperature evolution

- HNL depletes very fast before BBN ⇒ ALP abundance only decreases with time at late times.

- ALP abundance after BBN will solely be determined by their decays $a \to \nu\nu$:

$$zHs\frac{dY_a}{dz} = -\gamma_{a\to\nu\nu}\left(\frac{Y_a}{Y_a^{\rm eq}} - 1\right) \qquad \text{with} \qquad \gamma_{X\to Y} = \langle\Gamma_{X\to Y}\rangle n_X^{\rm eq}$$

[A. Boyarsky et al., '21]

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[A. Boyarsky et al., '21]

Short-lived ALPs

Decay shortly after the BBN

⇓

Number density completely disappears

Long-lived ALPs

Abundance freezes out after BBN

⇓

Only deplete slowly

Abundances after BBN : temperature evolution

- Before neutrino decoupling, ALP decay rate is negligible $\Rightarrow$ photon and neutrino temperature change via adiabatic cooling. [M. Hufnagel et al., '18]
- After BBN, $a \to \nu\nu$ becomes important $\Rightarrow$ neutrino temperature increases $\Rightarrow$ effect on N_{eff}.

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Temperature evolution of photon

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

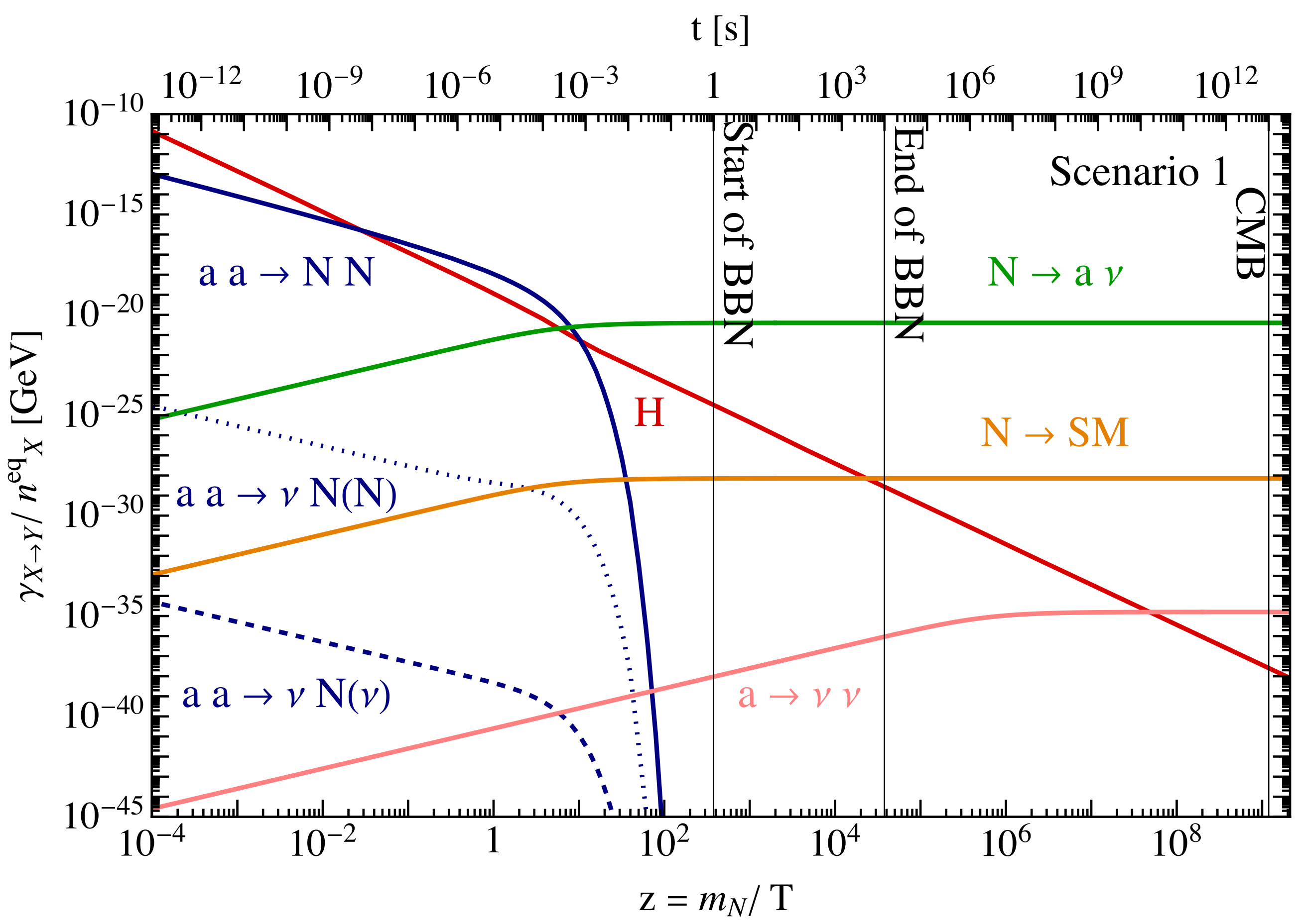
Temperature evolution of neutrino

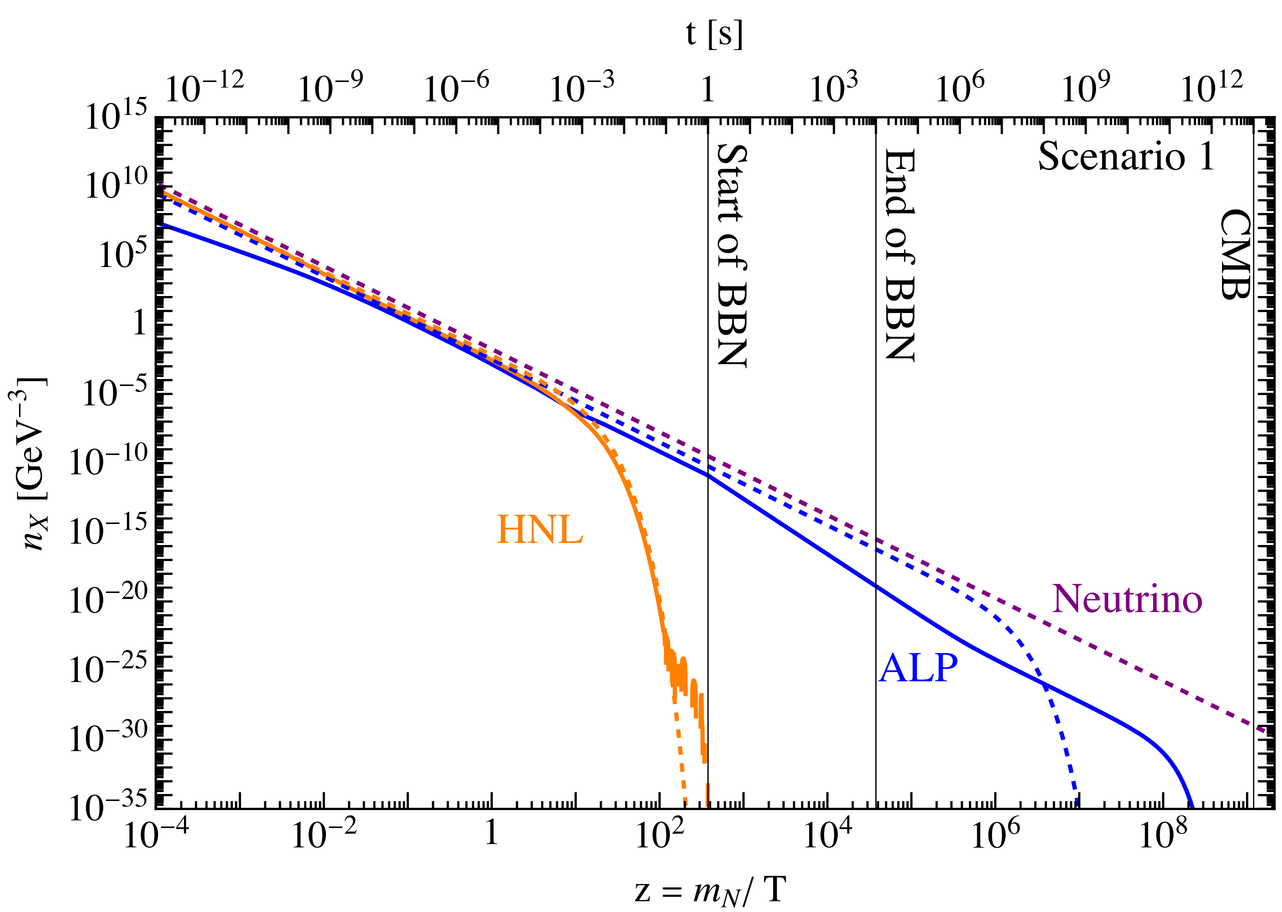
$$\frac{dT_\nu}{dt} = -\frac{12H\rho_\nu + 3H(\rho_a + p_a) + \frac{\delta \rho_a}{\delta t}}{3\frac{\partial \rho_\nu}{\partial T_\nu} + \frac{\partial \rho_a}{\partial T_\nu}}$$

[M. Escudero et al., '18; '20]

Abundances and interaction rates evolution

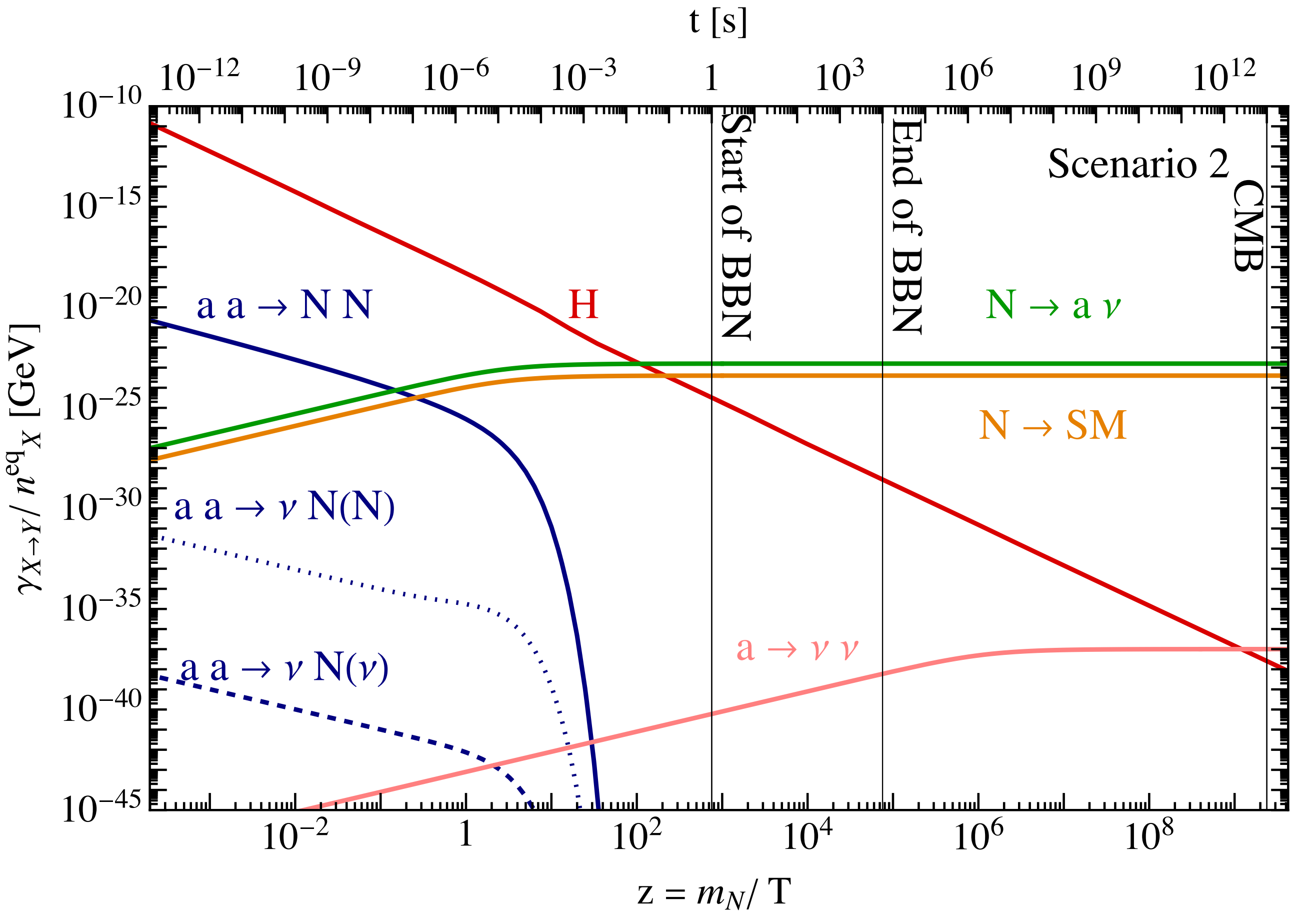
$f_a = 1\ \mathrm{TeV}, \mathrm{m_a} = 1\ \mathrm{keV}$

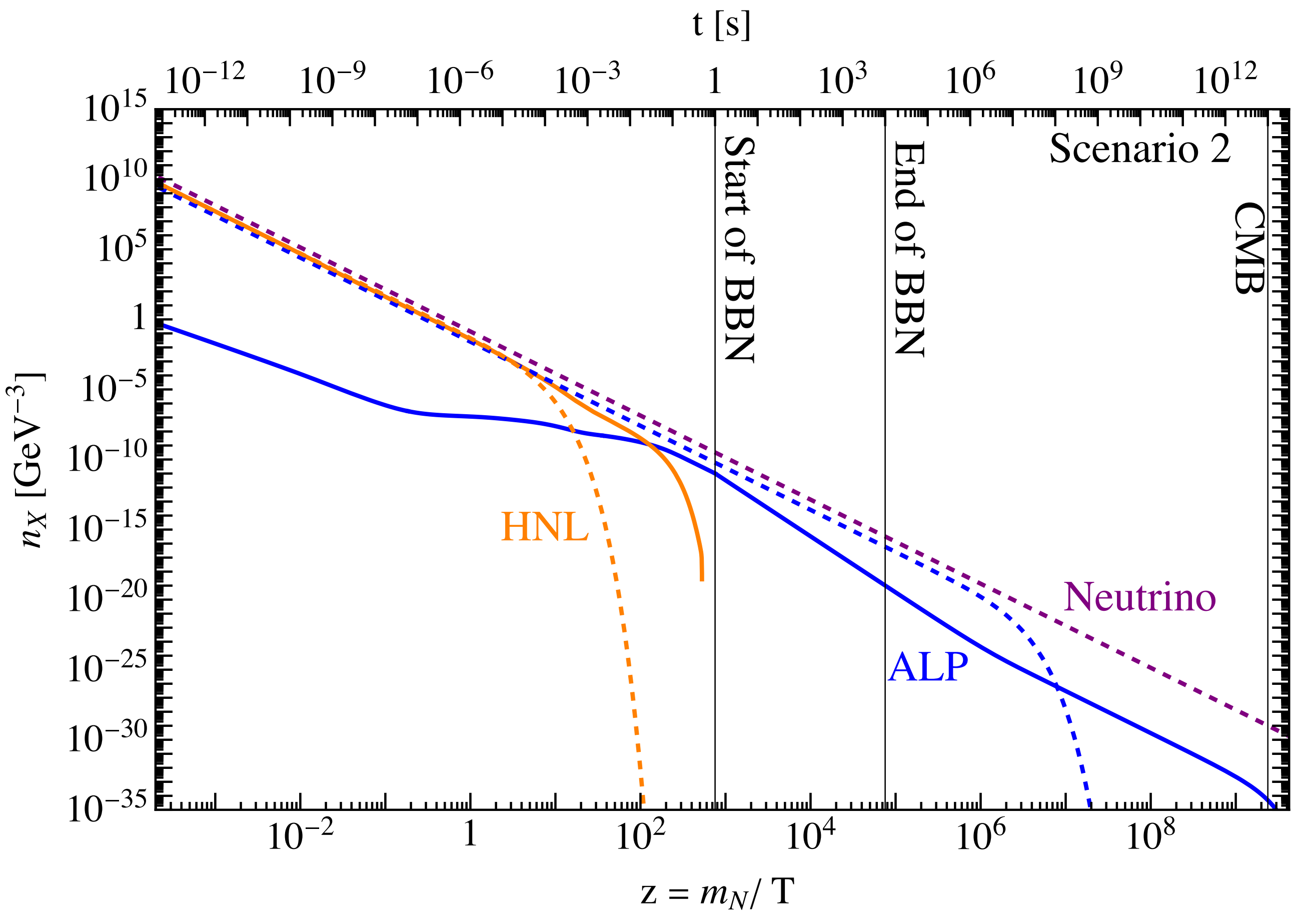




Abundances and interaction rates evolution

$$f_a = 10^{2.5}\ \text{TeV}, m_a = 1\ \text{keV}$$





Constraints from Cosmology, Astrophysics and Direct searches

Big Bang Nucleosynthesis : HNL

- Predictions of formation of primordial element abundances ⇒ very sensitive to the cosmological state of universe between neutrino decoupling and CMB. [F. Iocco et al., '09]

- Modification in neutrino bath temperature ⇒ catastrophic change in primordial element abundances. [A. Boyarsky et al., '21]

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Our scenario :

HNL decaying to mesons disturb initial abundances for proton and neutrons for BBN.

$\Downarrow$

Short-lived HNLs

$\Downarrow$

Abundances of protons and neutrons got enough time to restore their values from ΛCDM

$\Downarrow$

No effect on BBN, we set a conservative limit on τ_N. [A. Boyarsky et al., '21, A. D. Dolgov et al., '2000, O. Ruchayskiy et al, '12]

Big Bang Nucleosynthesis : ALPs

- ALP decays before neutrino decoupling via $a \to \nu\nu \Rightarrow$ change in neutrino bath temperature $\Rightarrow$ delaying neutrino decoupling and formation of primordial abundances.

Our scenario : ALP decays after the end of BBN i.e., $\tau_a > 10^4$ sec

- Subsequent decays of ALPs mostly via $a \to \gamma\gamma$ can affect the primordial abundances $\to$ negligible in our scenario.

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- Even if ALPs do not decay before BBN, they still affect the abundances if they are too abundant $\Rightarrow$ would act as dark radiation and modify the Hubble rate during radiation domination era $\Rightarrow$ modification in $N_{\rm eff}(z_{\rm BBN})$.

$$\Delta N_{\rm eff}^{\rm BBN} \approx \frac{\rho_a}{\rho_\gamma}$$

- $N_{\rm eff}^{\rm BBN} = 2.86 \pm 0.15 \Rightarrow$ we set upper bound on ALP abundance at BBN by considering $\Delta N_{\rm eff}^{\rm BBN} \leq 0.2$

  [B. D. Fields et al., '20]

Cosmic Microwave Background

- End of BBN, any particle that injects energy in primordial plasma $\Rightarrow$ modify the observations of CMB.

- Major source of energy injection is via $a \to \nu\nu$: do not expect the constraints arising from CMB anisotropies due to negligible $a \to \gamma\gamma$ decay rate. [C. Balázs et al., '20]

- $a \to \nu\nu$ increases the neutrino bath temperature $\Rightarrow$ effect on $N_{\rm eff}$.

$$N_{\rm eff}^{\rm CMB} = N_{\rm eff}^{\rm BBN} \left(\frac{11}{4}\right)^{4/3} \left(\frac{T_\nu}{T_\gamma}\right)^4 = 3.044 \pm 0.384.$$

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- Furthermore, if ALPs become non-relativistic at recombination and $\tau_a > 10^{13}$ sec ⇒ they would contribute as dark matter.

- We can also constraint the parameter space considering $\Omega_{\rm DM} h^2 \sim 0.12$.

Supernovae : SN1987A

- Core of Supernovae (SN) is very hot and dense with $T \sim 30$ MeV.
- Weakly interacting particles can free-stream and escape the core $\Rightarrow$ contributing to SN cooling.
- Primary source of such cooling is neutrinos (with $E_\nu \leq 30$ MeV) : Neutrino burst observed for SN1987A by various water Cherenkov detectors. [KAMIOKANDE-II collaboration, '87; Y. Totsuka et al., '88]

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- HNLs and ALPs can also contribute to SN cooling $\Rightarrow$ very constrained from SN1987A luminosity measurements. [A. D. Dolgov et al., '00; G. M. Fuller et al., '09; L. Mastrototaro et al., '20 …]
- Secondary decays of HNL and ALP into neutrinos $\Rightarrow$ additional flux of neutrinos over the normal burst $\Rightarrow$ more constrained as compared to SN cooling. [D. F. G. Fiorillo et al., '23; V. Syvolap '23]

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- $N \to a\nu \to 3\nu$: SN limits from Cherenkov detectors on traditional HNLs can be directly applied $\Rightarrow$ applied for larger mixing angles.

Supernovae : SN1987A

- Secondary neutrino flux from keV-scale ALP decay is smaller as compared to HNL decays which can escape the SN core.

- Heavy HNLs cannot escape $\Rightarrow$ SN constraints from the production of ALPs are stronger for $m_N \geq 400$ MeV. [K. Akita et al., '24]

- $g_{aee} \leq 10^{-7}$ $\Rightarrow$ weak limits for heavier HNLs and larger mixing.

- Additional constraints from secondary decays of HNLs and/or ALPs to photons $\Rightarrow$ very weak in our scenario for the considered mass range.

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- ALP production at core of white dwarfs and RGB stars can lead to strong cooling with $g_{aee} \sim 10^{-13}$ $\Rightarrow$ negligible constraint in the parameter space considered. [L. D. Luzio et al., '20]

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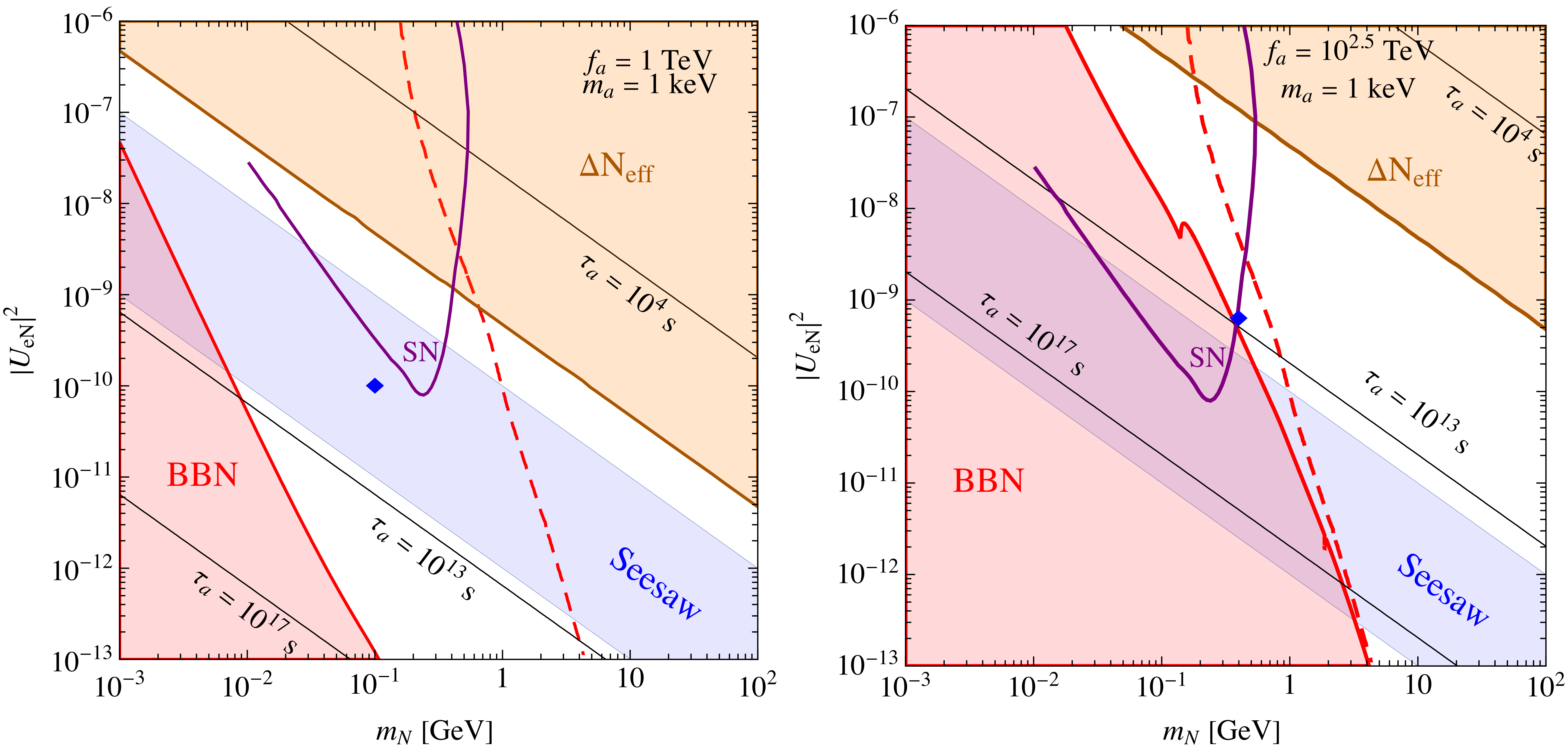
- $g_{aee} \leq 10^{-7}$ $\Rightarrow$ weak limits for heavier HNLs and larger mixing.

- Additional constraints from secondary decays of HNLs and/or ALPs to photons $\Rightarrow$ very weak in our scenario for the considered mass range.

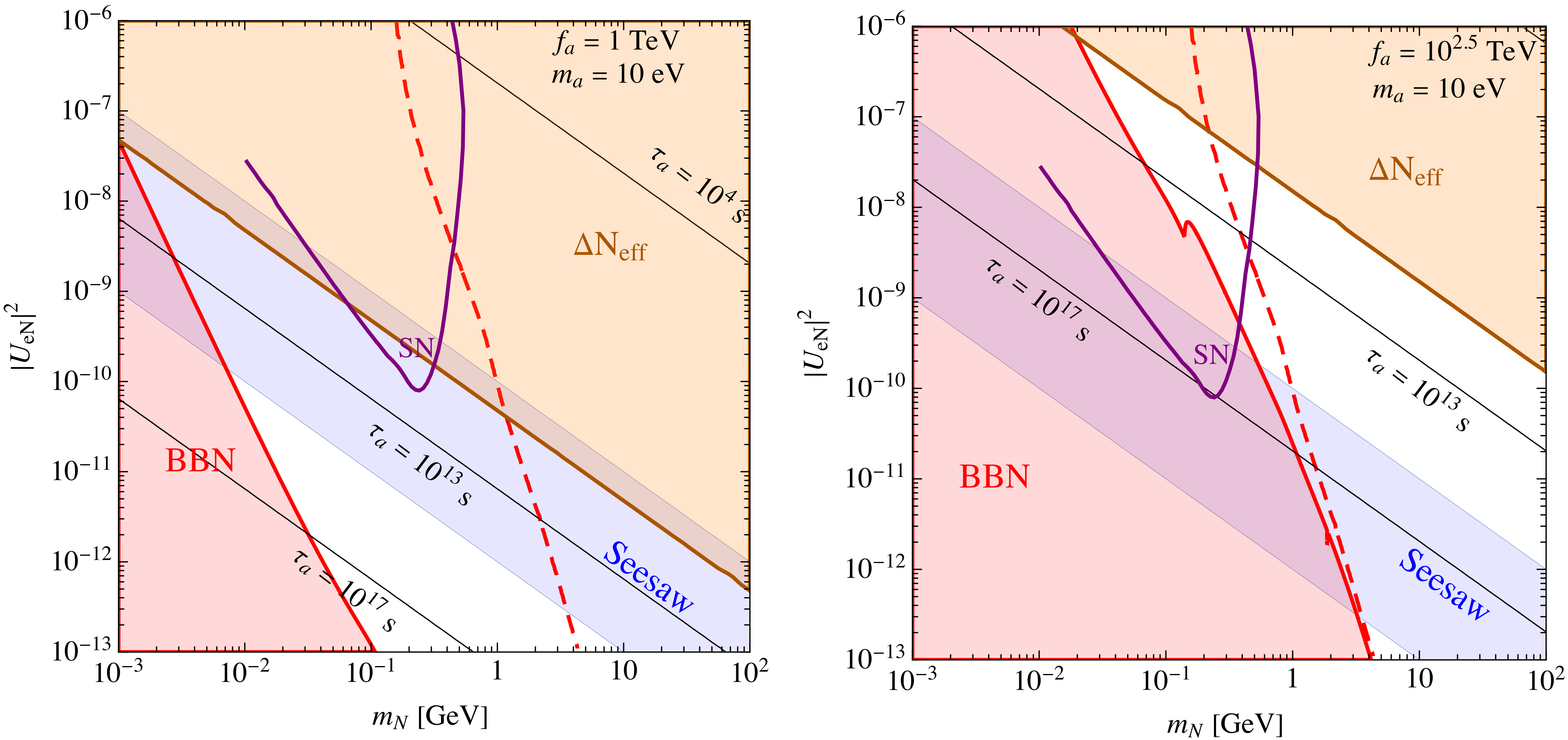
- ALP production at core of white dwarfs and RGB stars can lead to strong cooling with $g_{aee} \sim 10^{-13}$ $\Rightarrow$ negligible constraint in the parameter space considered. [L. D. Luzio et al., '20]

- Long-lived ALPs that survive after recombination may still be observable today through their decay products $\Rightarrow$ can be probed in observations of extra-galactic background light (EBL) or via X-rays with $g_{a\gamma\gamma} \sim 10^{-15}$ GeV^{-1} $\Rightarrow$ negligible. [D. Cadamuro et al., '12; C. Balázs et al., '20]

Parameter space with $m_a = 1$ keV

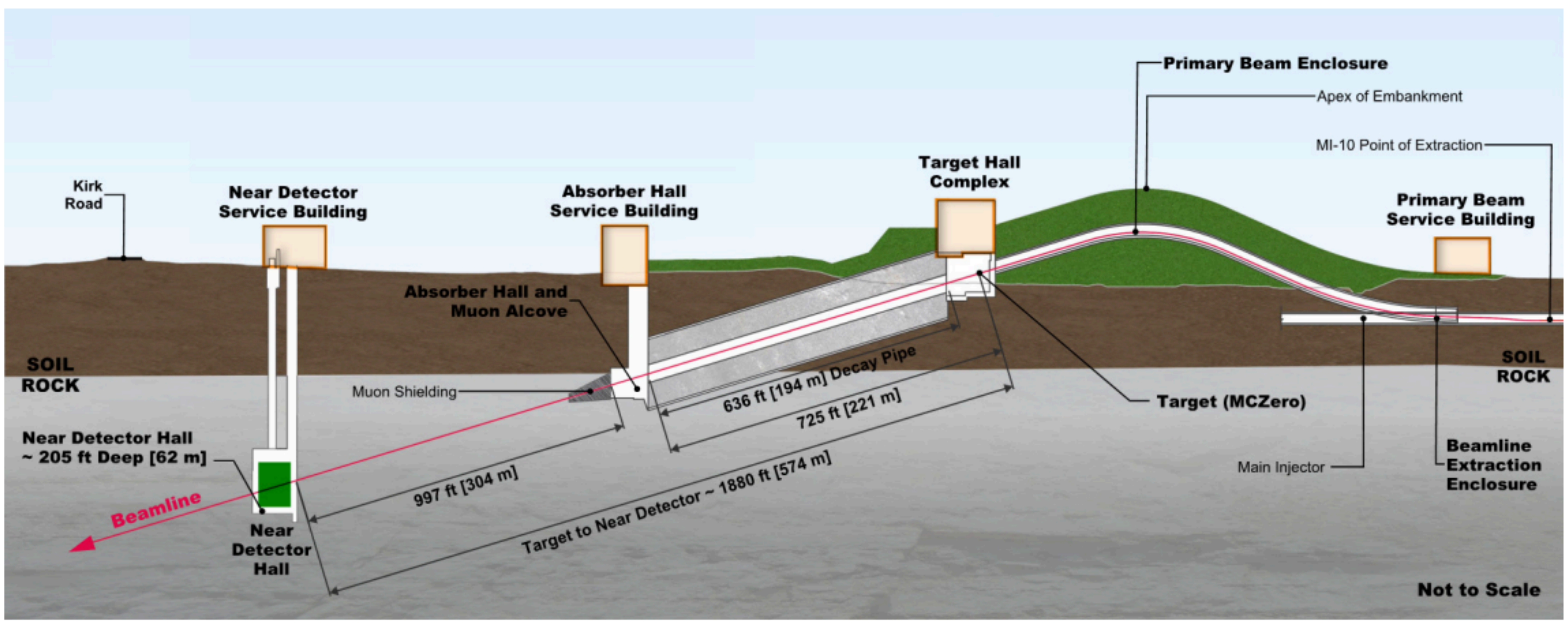


Parameter space with $m_a = 10$ eV



Impact on direct HNL searches

- Future HNL searches, based on long-lived particle searches, will probe small U_{eN} approaching the seesaw expectation.
- Prominent examples : PIONEER, NA62, DUNE, SHiP, FCC-ee …
- Near detector (ND) of DUNE is located at a distance of L = 574 m from HNL production point and a depth of ΔL = 5 m along the beam axis.



DUNE collaboration

Prospects in DUNE

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

[P. D. Bolton et al., ’22]

Geometrical efficiency factor :

$$\epsilon_{\rm geo} \equiv {\rm Exp}\left[-\frac{{\rm m_N}\Gamma_{\rm N}{\rm L}}{{\rm p_{N_z}}}\right]\left(1 - {\rm Exp}\left[-\frac{{\rm m_N}\Gamma_{\rm N}\Delta{\rm L}}{{\rm p_{N_z}}}\right]\right)$$

$$\frac{N'_{\rm sig}}{N_{\rm sig}} = \frac{{\rm Br'}({\rm N} \to {\rm charged})}{{\rm Br}({\rm N} \to {\rm charged})} \cdot \frac{\epsilon'_{\rm geo}}{\epsilon_{\rm geo}}$$

Prospects in DUNE

$$N_{\rm sig} = N_P \times {\rm Br(P \to N)} \times {\rm Br(N \to charged)} \times \epsilon_{\rm geo}$$ [P. D. Bolton et al., ’22]

Geometrical efficiency factor :

$$\epsilon_{\rm geo} \equiv {\rm Exp}\left[-\frac{\rm m_N \Gamma_N L}{\rm p_{N_z}}\right]\left(1 - {\rm Exp}\left[-\frac{\rm m_N \Gamma_N \Delta L}{\rm p_{N_z}}\right]\right)$$

$$\frac{N'_{\rm sig}}{N_{\rm sig}} = \frac{\rm Br'(N \to charged)}{\rm Br(N \to charged)} \cdot \frac{\epsilon'_{\rm geo}}{\epsilon_{\rm geo}}$$

$$\frac{\epsilon'_{\rm geo}}{\epsilon_{\rm geo}} = {\rm Exp}\left[-\frac{\rm m_N}{\rm p_{N_z}}\Gamma({\rm N \to a\nu}){\rm L}\right]\frac{\Gamma'_{\rm N}}{\Gamma_{\rm N}}$$ for shallow detector depth $$\frac{m_N \Gamma_N \Delta L}{p_{N_z}} \ll 1$$

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

Prospects in DUNE

$$N_{\rm sig} = N_P \times {\rm Br(P \to N)} \times {\rm Br(N \to charged)} \times \epsilon_{\rm geo}$$ [P. D. Bolton et al., '22]

Geometrical efficiency factor :

$$\epsilon_{\rm geo} \equiv {\rm Exp}\left[-\frac{\rm m_N \Gamma_N L}{\rm p_{N_z}}\right]\left(1 - {\rm Exp}\left[-\frac{\rm m_N \Gamma_N \Delta L}{\rm p_{N_z}}\right]\right)$$

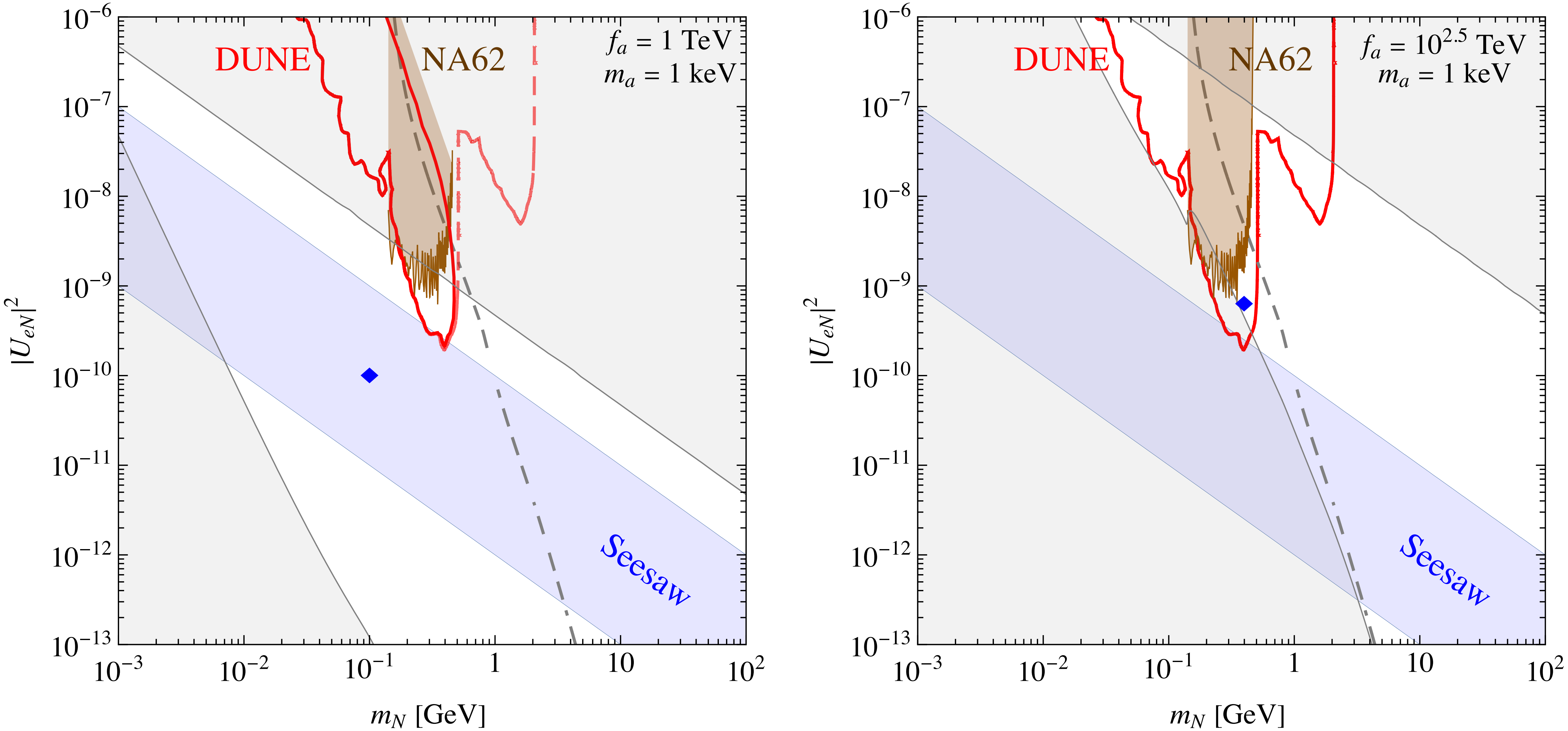
$$\frac{N'_{\rm sig}}{N_{\rm sig}} = \frac{\rm Br'(N \to charged)}{\rm Br(N \to charged)} \cdot \frac{\epsilon'_{\rm geo}}{\epsilon_{\rm geo}}$$

$$\frac{\epsilon'_{\rm geo}}{\epsilon_{\rm geo}} = {\rm Exp}\left[-\frac{\rm m_N}{\rm p_{N_z}}\Gamma({\rm N \to a}\nu){\rm L}\right]\frac{\Gamma'_{\rm N}}{\Gamma_{\rm N}}$$ for shallow detector depth $$\frac{m_N \Gamma_N \Delta L}{p_{N_z}} \ll 1$$

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

For longer decay lengths as long as $\frac{m_N}{p_{N_z}}\Gamma(N \to a\nu)L \ll 1 \Rightarrow$ we expect same sensitivity for DUNE as in the standard SM+HNL scenario.

Prospects in DUNE and NA62



- NA62 experiment used secondary 75 GeV hadron beam containing a fraction of Kaons and has been able to probe the decays $K^+ \to l^+ N \Rightarrow$ single detected track of the charged lepton and a peak in its missing mass distribution. [K. Dias, '22]
- This experiment is currently insensitive to the HNL decays $\Rightarrow$ presence of $N \to a\nu$ will not affect the sensitivity, but future beam-dump configuration will have same prospect as of DUNE.

Summary

- We explore a framework with MeV–GeV scale HNLs and keV scale ALPs, introducing additional decay channels for both.
- The axionic decay channel of HNL dominates over its Standard Model modes and plays a key role in shaping its cosmological evolution.
- We focus on scenarios where HNL decays before BBN and ALP decays after BBN, ensuring minimal impact on primordial element abundances.
- Cosmological and astrophysical constraints bound the parameter space, but viable regions remain testable in future experiments like DUNE and NA62.

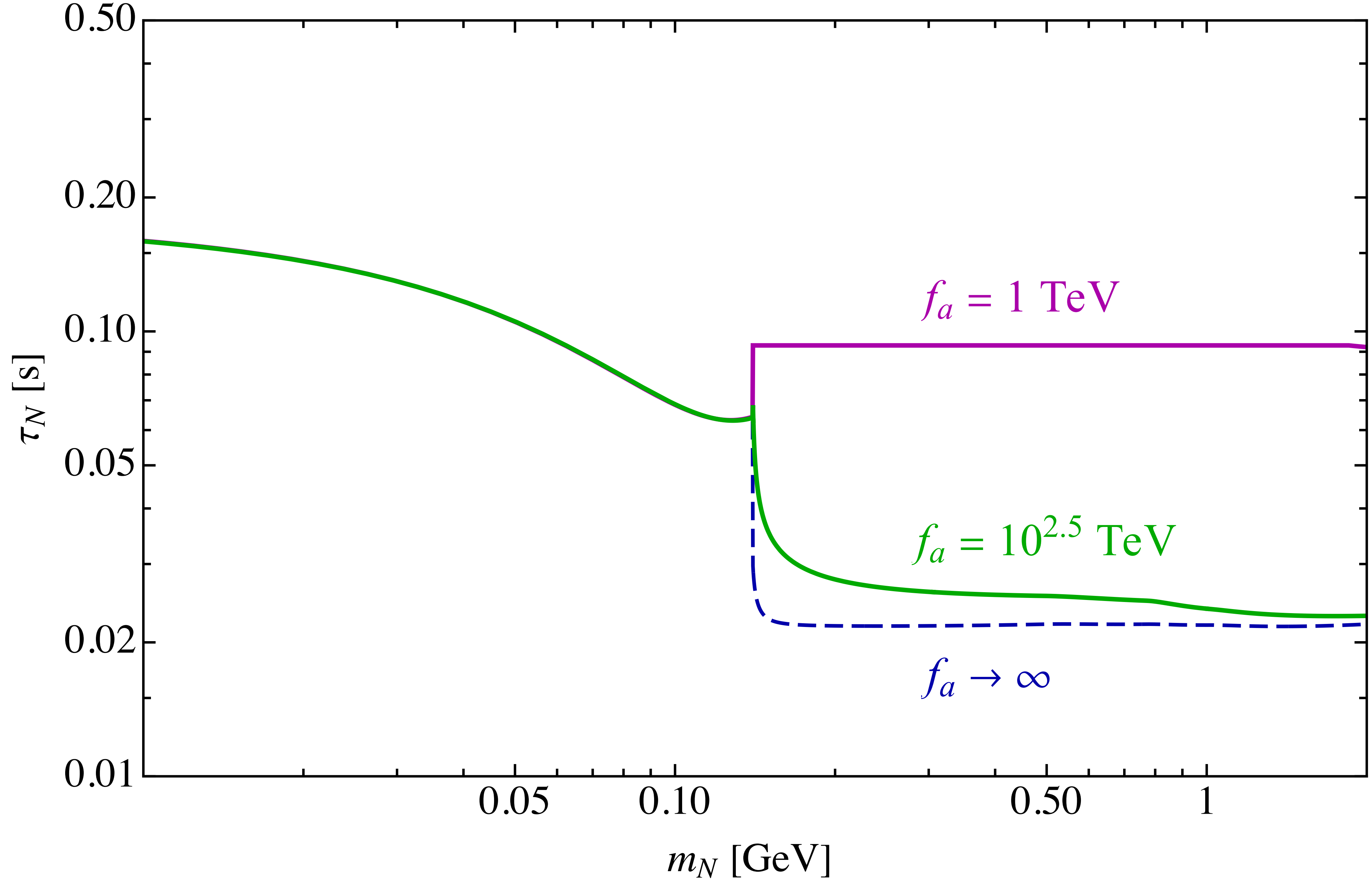
Thank you!

Comments, Questions, Suggestions!!!

Benchmark values

Scenario	m_N [GeV]	$\|U_{eN}\|^2$	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}

HNL lifetime



Thermally averaged interaction density

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

$$\gamma_{X_1X_2\to Y_1Y_2} = \frac{T}{64\pi^4}\int_{s_{min}}^{\infty}\sqrt{s}\hat{\sigma}(s)K_1\left(\frac{\sqrt{s}}{T}\right)ds, \quad \hat{\sigma}(s) = 2s\sigma(s)\ \lambda(1, m_{X_1}^2/s, m_{X_2}^2/s)$$