Relaxing Limits from Big Bang Nucleosynthesis on Heavy Neutral Leptons with Axion-like Particles

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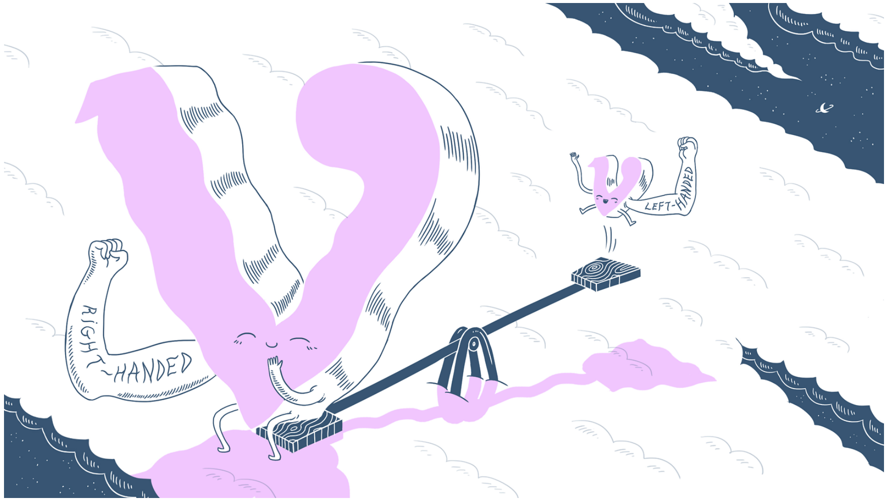
Arxiv: 2410.06970

Outlines

Heavy Neutral Lepton & Seesaw Mechanism

Motivation:Massless SM neutrinos
HNLs give mass to light active neutrinos



Dirac mass by **Right-Handed Neutrinos**:

$$\mathscr{L}_{Dirac} = -Y_\nu \bar{L} \cdot H \nu_R + \text{h.c.}$$

Majorana Right-Handed Neutrinos:

$$\mathscr{L}_{Majorana} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N + \text{ h.c.}$$

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

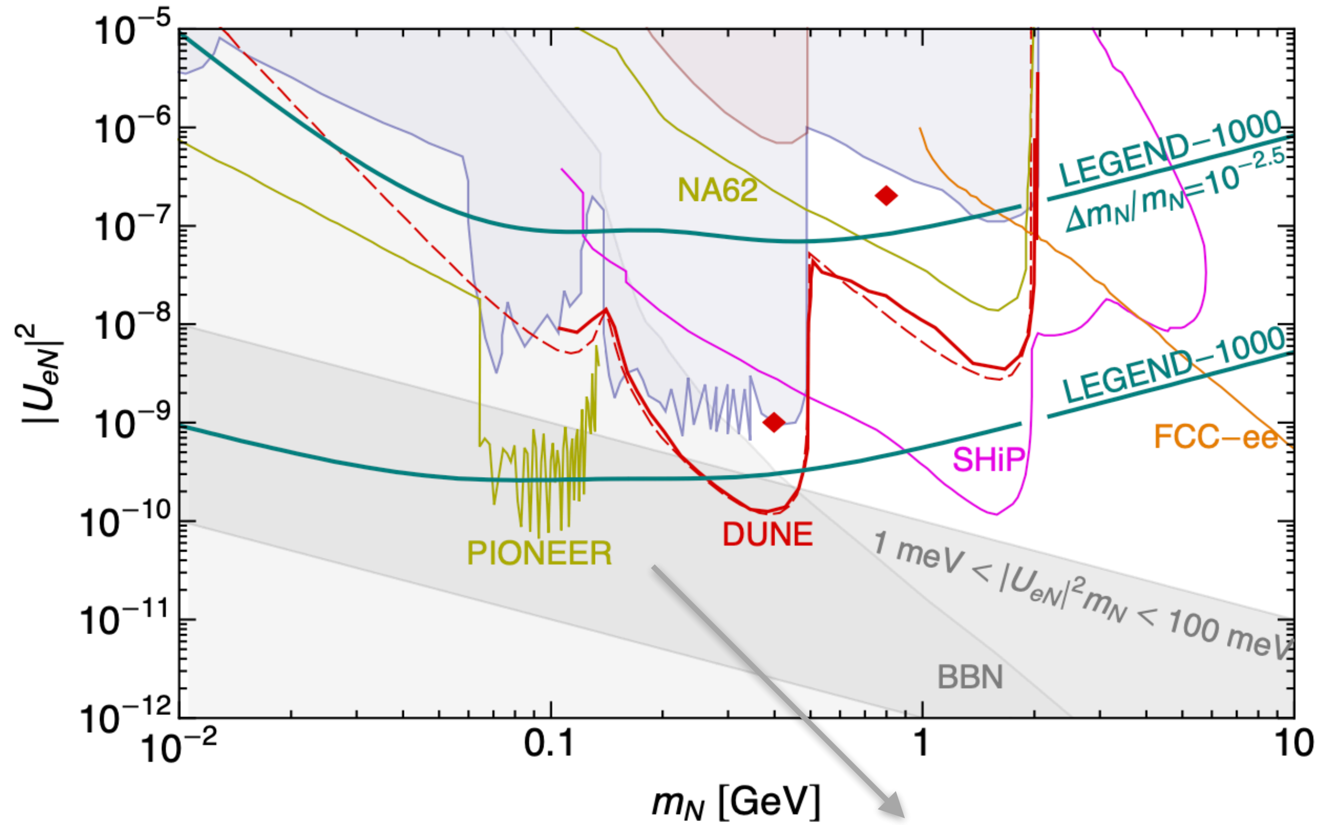
Light Neutrino Mass:

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

$$|V_{eN}|^2 \simeq \frac{m_\nu}{M_R}$$ Active-Sterile mixing

Current Status of HNL Searches

$f_a = 10^3$ GeV
$m_a =$ eV - MeV

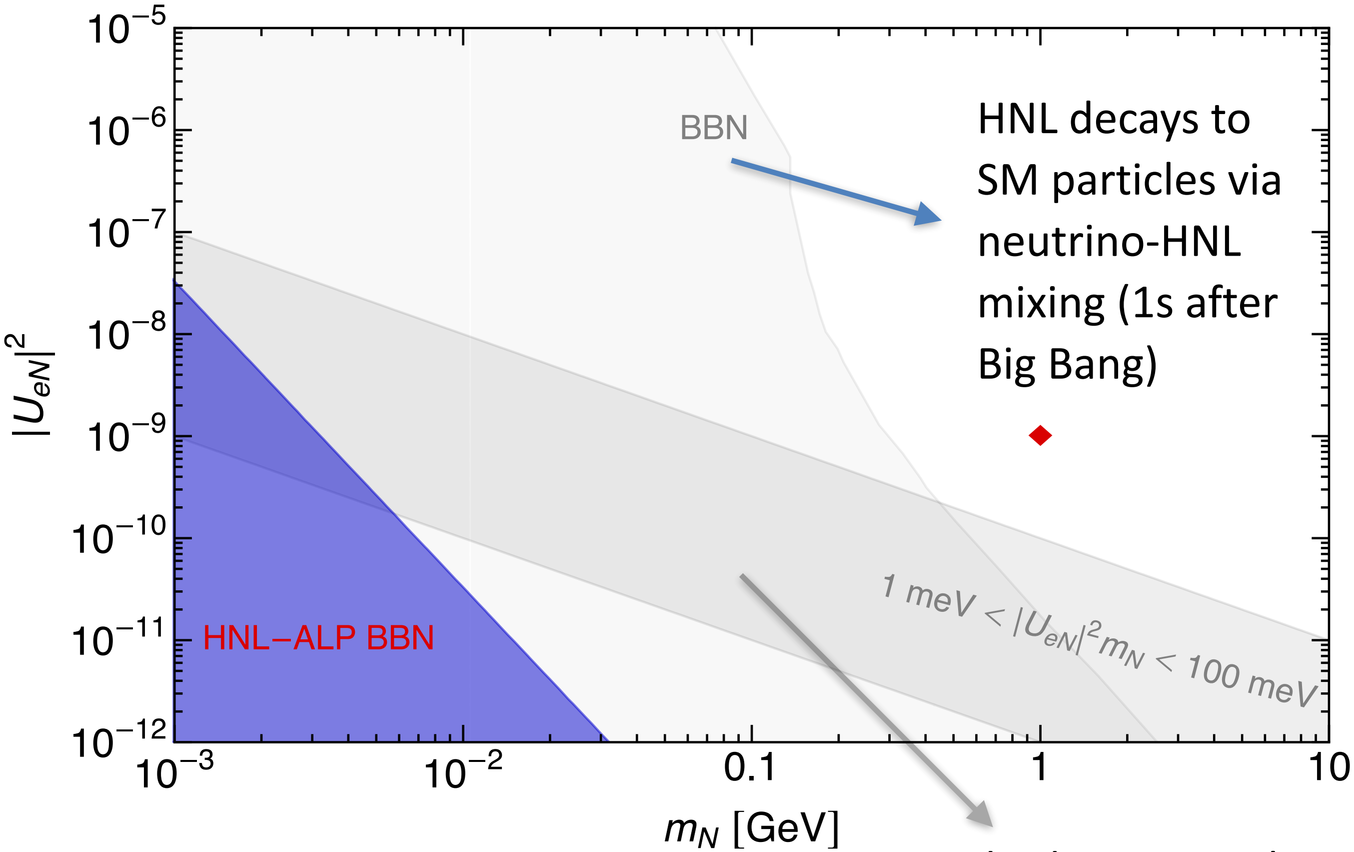


Standard Seesaw relation limit by $|V_{eN}|^2 = m_\nu / m_N$

Benchmarks: 1 GeV at $|V_{eN}|^2=10^{-9}$

Big Bang Nucleosynthesis (Primordial He)

$f_a = 10^3$ GeV
$m_a =$ eV - MeV



HNL decays to SM particles via neutrino-HNL mixing (1s after Big Bang)

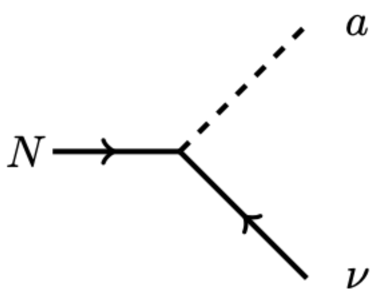
Standard Seesaw relation limit by $|V_{eN}|^2 = m_\nu / m_N$

Benchmarks: 1 GeV at $|V_{eN}|^2$=10^{-9}

HNL & ALP Interactions

$$\mathscr{L}_{aN} = \frac{C_{aN}}{f_a}\left(\partial_\mu a\right)\bar{N}\gamma^\mu\gamma_5 N = -\frac{2iC_{aN}}{f_a}m_N a\bar{N}\gamma_5 N = -\frac{2iC_{aN}U_{\nu N}}{f_a}m_N a\bar{N}\gamma_5\nu$$

New decay channel of HNLs



$$\tau_N = \frac{1}{\Gamma_{Na\nu}} \simeq \frac{8\pi f_a^2}{U_{\nu N}^2 m_N^3} = 1\text{sec} \times 8\pi \times \left(\frac{\mathrm{f_a}}{1\mathrm{TeV}}\right)^2 \times \left(\frac{10^{-7}}{\mathrm{U}_{\nu\mathrm{N}}}\right)^2 \times \left(\frac{100\mathrm{MeV}}{\mathrm{m_N}}\right)^3$$

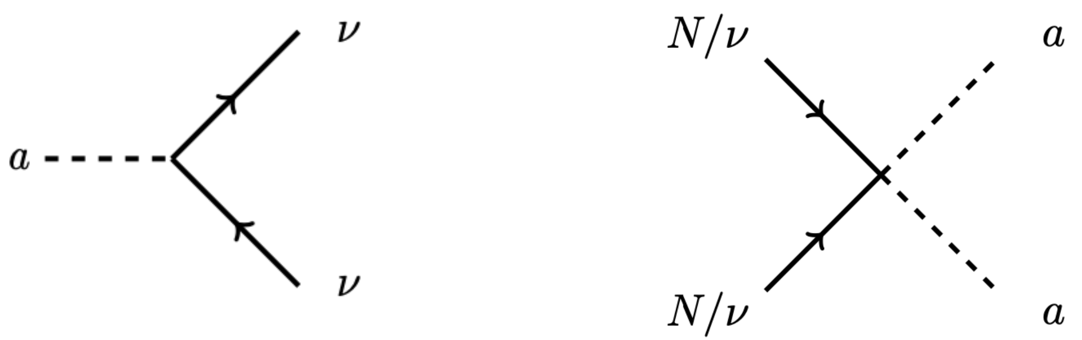
GeV HNL can survive for 0.1s

$$f_a = 10^3\ \text{GeV},\ |V_{eN}|^2 = 10^{-9}$$

HNL & ALP Interactions

$$\mathscr{L}_{aN} = \frac{C_{aN}}{f_a}\left(\partial_\mu a\right)\bar{N}\gamma^\mu\gamma_5 N = -\frac{2iC_{aN}}{f_a}m_N a\bar{N}\gamma_5 N = -\frac{2iC_{aN}U_{\nu N}}{f_a}m_N a\bar{N}\gamma_5\nu$$

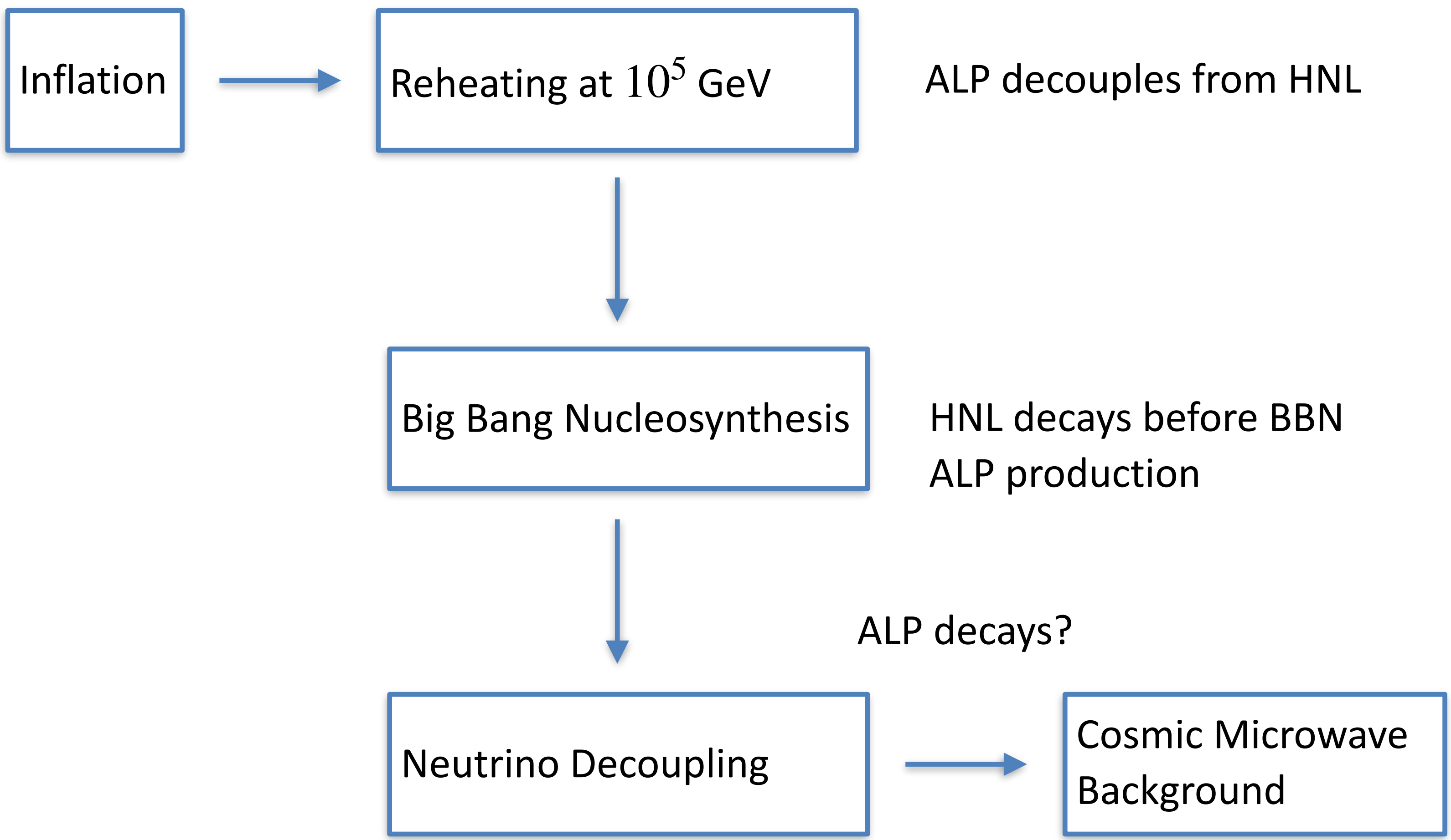
Decay channel of ALPs



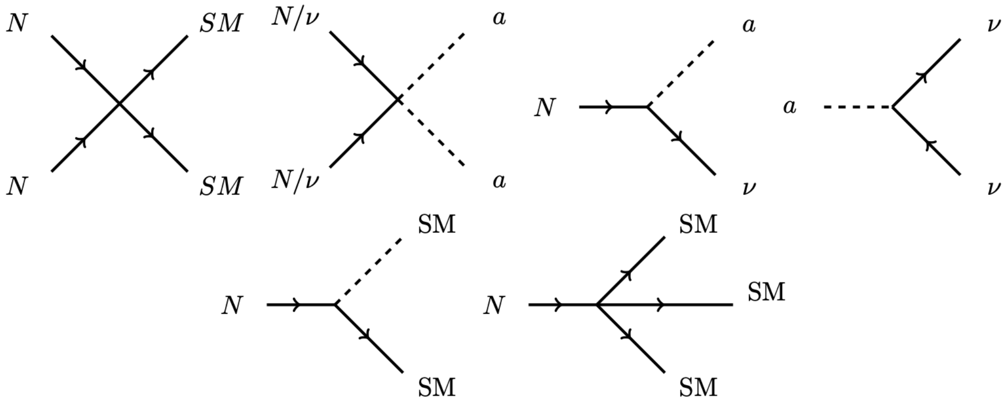
$$\tau_a = 1\ \mathrm{sec} \times \left(\frac{1\ \mathrm{GeV}}{\mathrm{m_N}}\right)^2 \times \left(\frac{1\ \mathrm{keV}}{\mathrm{m_a}}\right) \times \left(\frac{2.03\times10^{-6}}{|\mathrm{U_{eN}}|^2}\right)^2 \times \left(\frac{\mathrm{f_a}}{1\ \mathrm{TeV}}\right)^2$$

GeV HNL can survive for 0.1s $f_a = 10^3$ GeV, $|V_{eN}|^2 = 10^{-9}$

Evolutions of HNLs & ALPs



Evolutions of HNLs & ALPs



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

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

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

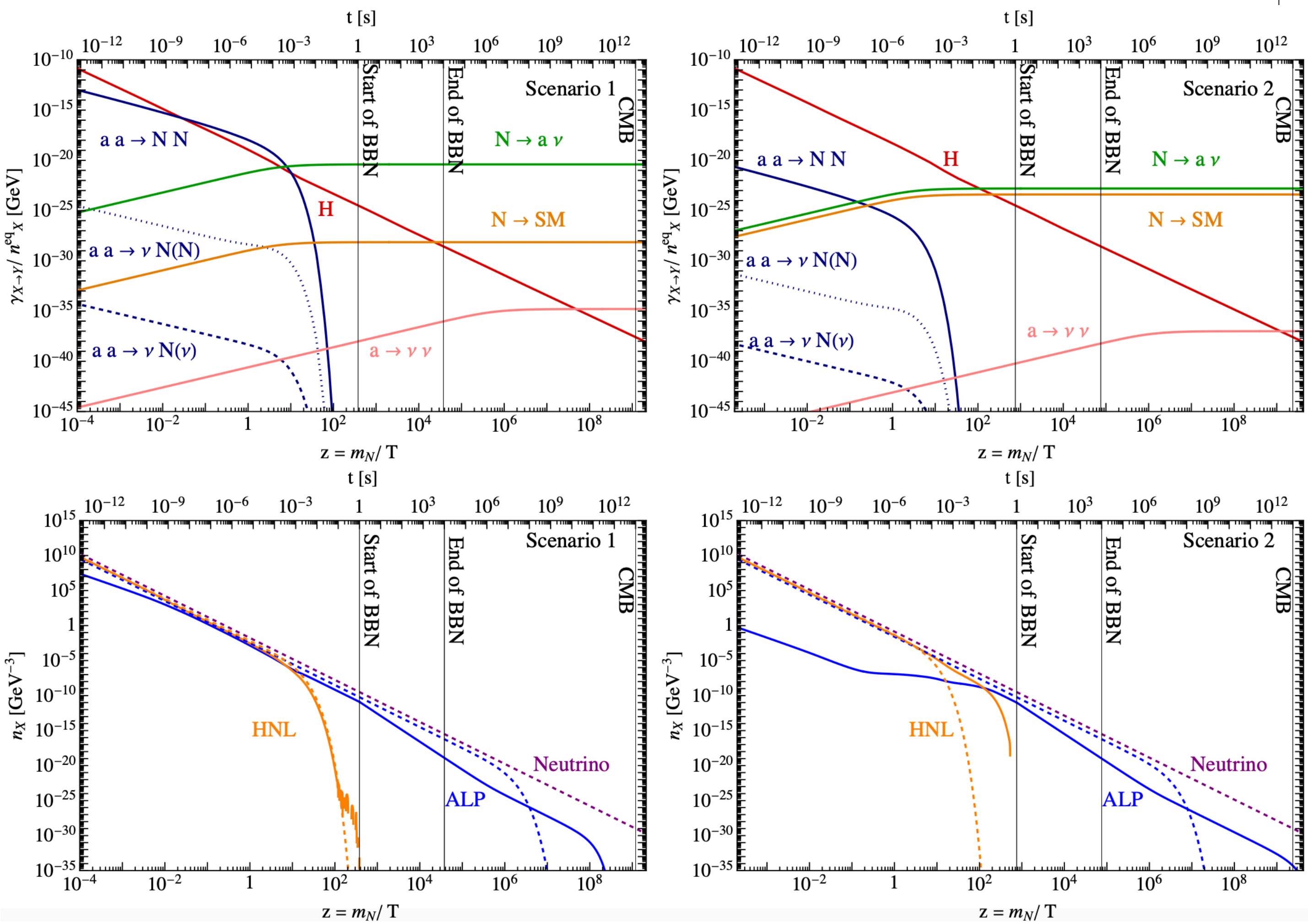
$$zHs\frac{dY_a}{dz} = -\gamma^{\rm eq}_{aa\to \nu\nu}\left(\frac{Y_a^2}{Y_a^{\rm eq,2}} - 1\right) - \gamma^{\rm eq}_{aa\to NN}\left(\frac{Y_a^2}{Y_a^{\rm eq,2}} - \frac{Y_N^2}{Y_N^{\rm eq,2}}\right)$$
$$- \gamma_{a\to \nu\nu}\left(\frac{Y_a}{Y_a^{\rm eq}} - 1\right) + \gamma_{N\to a\nu}\left(\frac{Y_N}{Y_N^{\rm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

$$Y = n/s$$

$$z = m_N/T$$

Evolutions of HNLs & ALPs

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



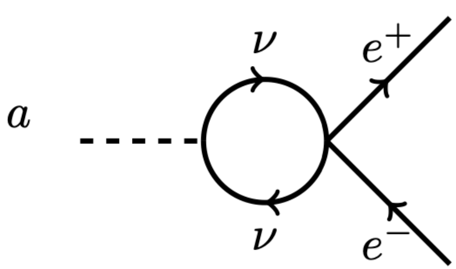
HNLs decay before BBN

ALPs decay after BBN

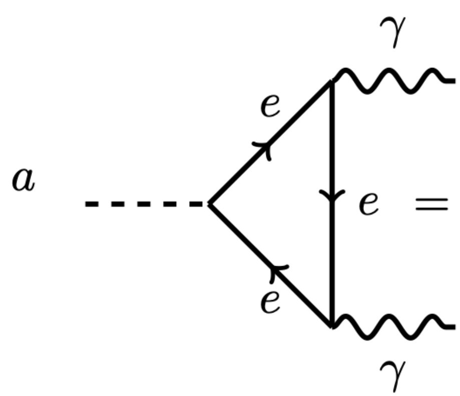
Astrophysical Constraints

1. SN 1987A (cooling of the core)
2. ELB (X-ray emissions from ALP)
3. Cooling of White Dwarfs or RGB
4. Neff at CMB

$$N_{\mathrm{eff}}^{\mathrm{CMB}} = N_{\mathrm{eff}}^{\mathrm{BBN}} \left(\frac{11}{4}\right)^{\frac{4}{3}} \left(\frac{T_\nu}{T_\gamma}\right)^4$$

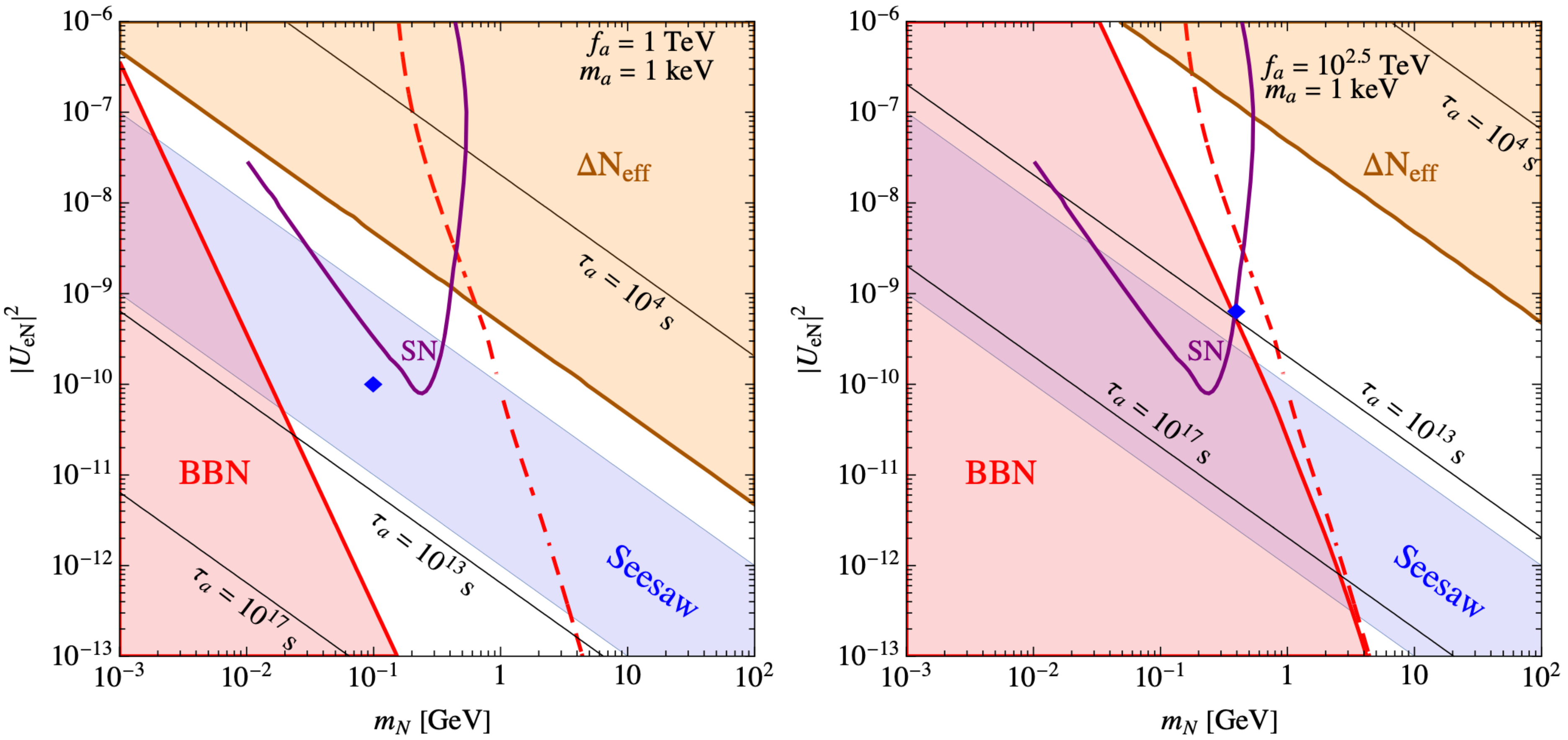


$$= 2\gamma_5 g_{ae}$$



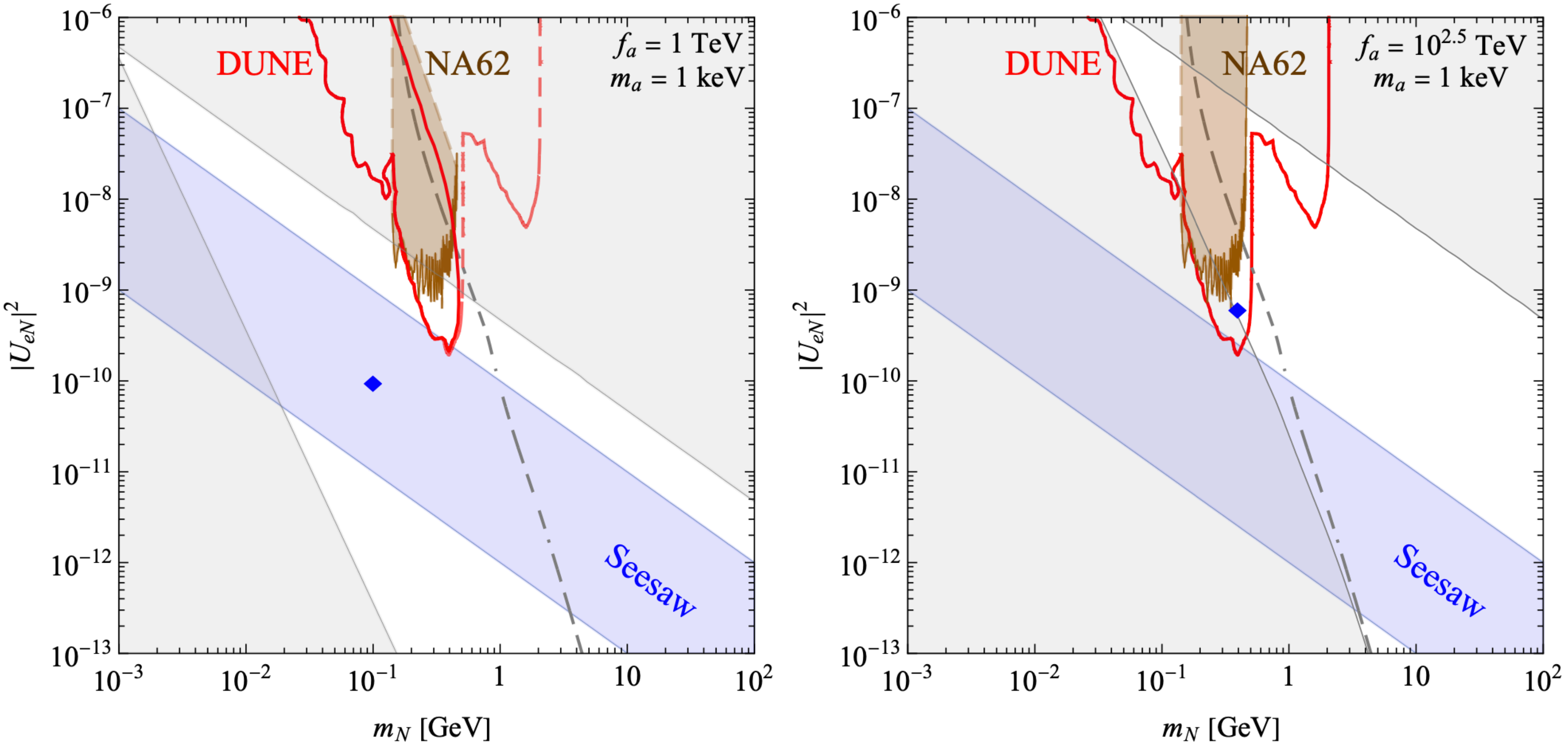
$$= -i g_{a\gamma} \epsilon^{\mu\nu}_{\rho\sigma} k_1^\rho k_2^\sigma$$

Results



$f_a = 1$ TeV
$m_a = 1$ keV
ΔN_{eff}
$\tau_a = 10^4$ s
SN
BBN
$\tau_a = 10^{13}$ s
$\tau_a = 10^{17}$ s
Seesaw
$|U_{eN}|^2$
m_N [GeV]
$f_a = 10^{2.5}$ TeV
$m_a = 1$ keV
$\tau_a = 10^4$ s
ΔN_{eff}
SN
$\tau_a = 10^{17}$ s
$\tau_a = 10^{13}$ s
BBN
Seesaw
$|U_{eN}|^2$
m_N [GeV]

Direct Search Results



Conclusion

1. BBN limits on HNLs can be evaded by the axionic channel.
2. ALPs and neutrinos produced will challenge current observations of Neff.
3. 1 MeV - 1 GeV HNLs are tightly constrained by SN.
4. Long-Lived HNL with axionic decay mode can be probed by beam dump experiments.
5. Precise modelling of beam dump experiments.
6. MeV HNLs can be studied in details.

Thanks for listening

Any Questions?