宇宙論におけるステライルニュートリノ

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第28回ニュートリノ研究会@宇宙線研究所

Introduction

Introduction

- Today,
  I discuss cosmology of a gauge-singlet fermion $\boldsymbol{N}$,
  which mixes with LH neutrinos as

$$\nu_{L\alpha} = U_{\alpha i}\, \nu_i + \Theta_\alpha\, \boldsymbol{N}$$

ν_i : active neutrinos with m_i

$\boldsymbol{N}$: heavy neutral lepton (HNL) with M_N

(sterile neutrino, heavy neutrino, right-handed neutrino⋯)

HNL is well-motivated particle beyond the Standard Model in various respects of particle physics and cosmology

Motivations for HNL

- One of the most important motivations is neutrino masses !
  - HNLs are key players of the seesaw mechanism
  - LSND, MiniBooNE, Reactor anomalies (?)
  - …
- HNLs are important for cosmology
  - Dark Matter
  - Baryon Asymmetry of the Universe
    - "Standard Leptogenesis" ,…
  - Dark Radiation
  - Astrophysical phenomena
    - Pulsar kick, SN explosion…
  - …

Heavy Neutral Leptons and Seesaw Mechanism

RH Neutrinos ν_R and Seesaw Mechanism

$$\delta L = i\overline{\nu_R}\partial_\mu \gamma^\mu \nu_R - F\,\overline{L}\,\nu_R \Phi - \frac{M_M}{2}\overline{\nu_R}\nu_R^c + \text{h.c.}$$

Minkowski '77
Yanagida '79
Gell-Mann, Ramond, Slansky '79
Glashow '79

- Seesaw mechanism ($M_D = F\langle\Phi\rangle \ll M_M$)

$$-L = \frac{1}{2}(\overline{\nu_L}, \overline{\nu_R^c})\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c = \frac{1}{2}(\overline{\nu}, \overline{N^c})\begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix} + h.c.$$

$$M_\nu = -M_D^T \frac{1}{M_M} M_D$$

$$U^T M_\nu U = diag(m_1, m_2, m_3)$$

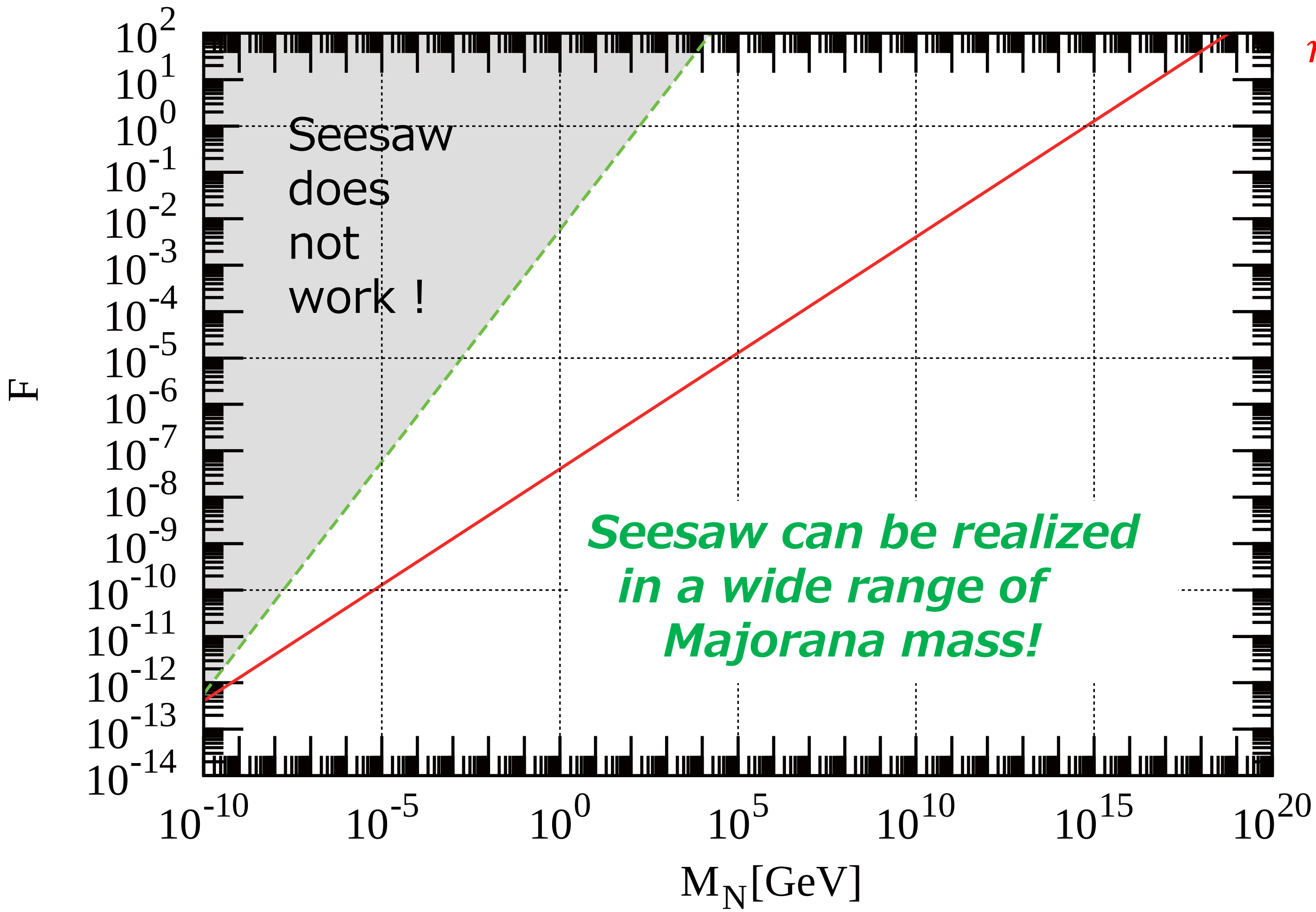
- **Light active neutrinos ν**
  - → explain neutrino oscillations
- **Heavy neutral leptons N** ($N \simeq \nu_R$)
  - Mass M_M
  - Mixing $\Theta = M_D / M_M$

mixing in CC current $\nu_L = U\,\nu + \Theta\, N^c$

Yukawa Coupling of HNL

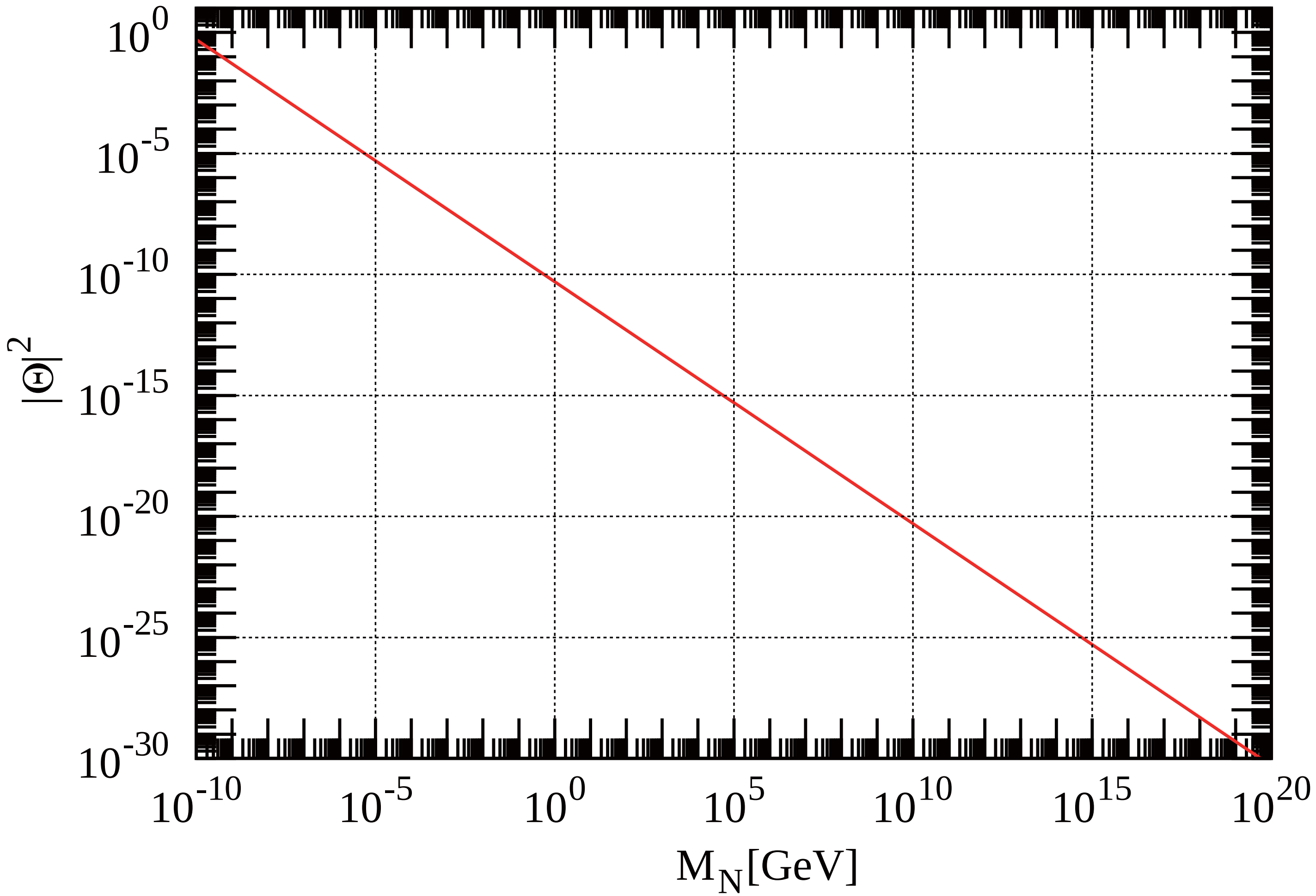
$$F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

$m_\nu = 5 \times 10^{-11}$ GeV

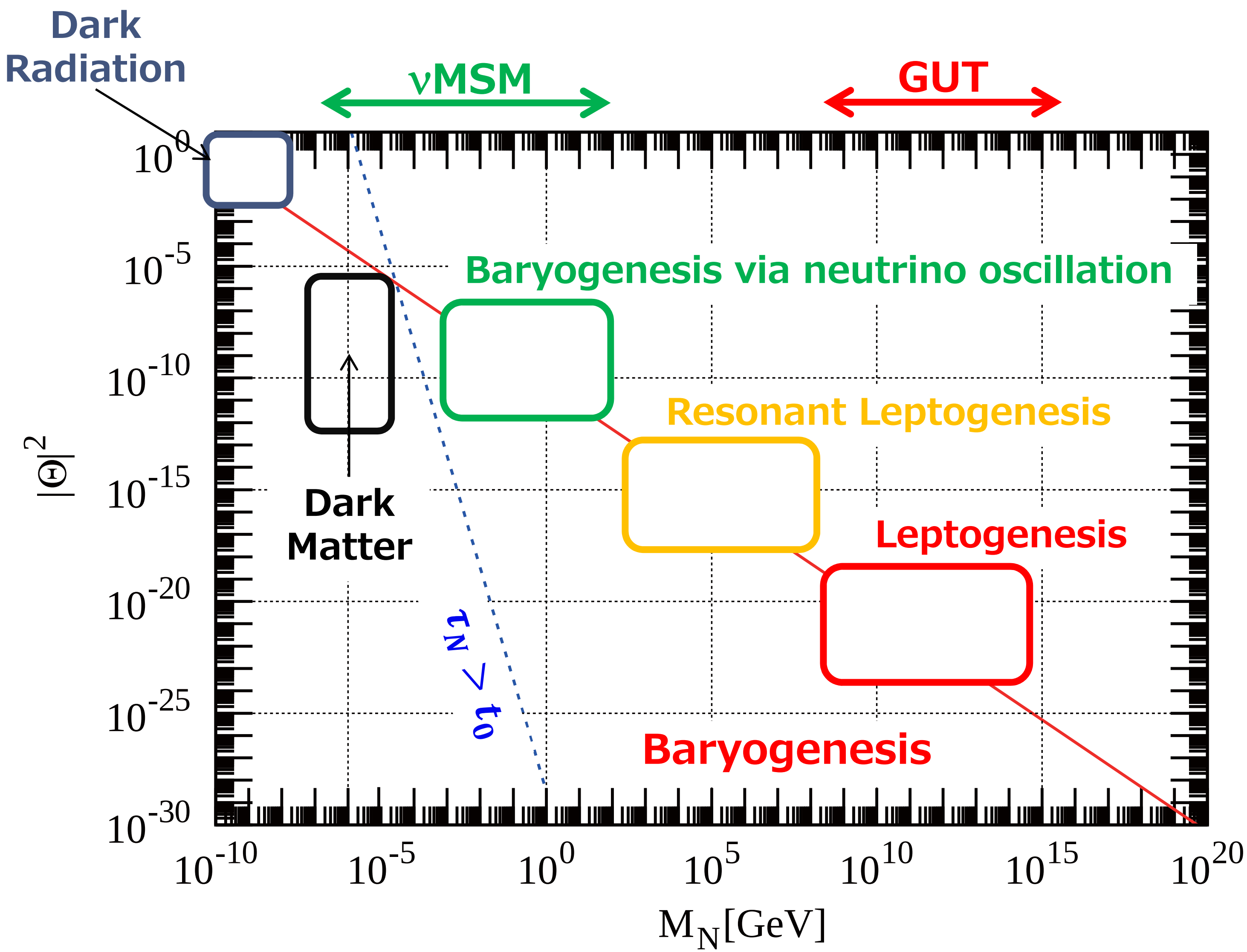


Mixing of HNL

$$|\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \qquad m_\nu = 5 \times 10^{-11}\ \text{GeV}$$



Various Physics of HNL



Review of Particle Physics

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Heavy Neutral Leptons, Searches for

(A) Heavy Neutral Leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 >$ 6.2×10^{-8} at m_{L^0} = 20 GeV and $>$ 5.1×10^{-10}

Motivations for HNL

- One of the most important motivations is neutrino masses !
  - HNLs are key players of the seesaw mechanism
  - LSND, MiniBooNE, Reactor anomalies (?)
  - ⋯

- HNLs are important for cosmology
  - Dark Matter
  - Baryon Asymmetry of the Universe
    - "Standard Leptogenesis" , ⋯
  - Dark Radiation
  - Astrophysical phenomena
    - Pulsar kick, SN explosion⋯
  - ⋯

$\Delta N_{eff} = 1$ is excluded @>99% CL

See, e.g., a review by
A. Kusenko Phys.Rept. 481 (2009) 1

Sterile Neutrino and Dark Matter

Active Neutrino as Dark Matter

- Massive active neutrinos were classical candidate for dark matter, but they cannot be dark matter !

- Planck 2015: [arXiv:1502.01589]
  - Upper bound on sum of active neutrino masses

$\Sigma m_i < 0.23$ eV (95%CL)

$$\Omega_\nu h^2 = \frac{\Sigma m_i}{93.14\ \mathrm{eV}} < 0.0025$$

cf. $\Omega_X = \frac{\rho_X}{\rho_{cr}}$

$$\rho_{cr} = 10.5\ h^2\ \mathrm{GeV\ m^{-3}}$$
$$H_0 = 100\ h\ \mathrm{km}\ s^{-1}\mathrm{Mpc}^{-1}$$
$$h = 0.6774 \pm 0.0046$$

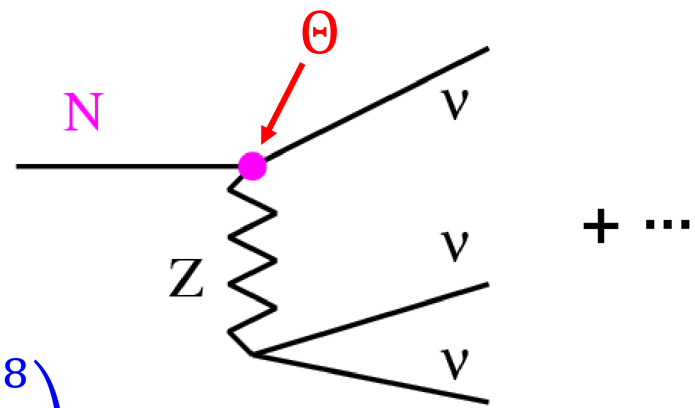
  - Too small to explain the Dark Matter density

$$\Omega_{dm} h^2 = 0.1188 \pm 0.0010$$

Sterile Neutrino as Dark Matter

- Sterile neutrino N with $M_N = O(10)$ keV is a good candidate for (warm) dark matter.
  [Peebles '82, Olive, Turner '82, ⋯

- Such a particle N is not completely stable (without introducing symmetry)
  - Dominant decay: $N \to 3\,\nu$
  - Lifetime can be very long !



$$\tau_{N_1} = 5 \times 10^{26} \mathrm{sec} \left(\frac{\mathrm{keV}}{M_1}\right)^5 \left(\frac{10^{-8}}{\Theta^2}\right)$$

Stability of HNL

- $\tau_N > t_U$ (age of the univ.)

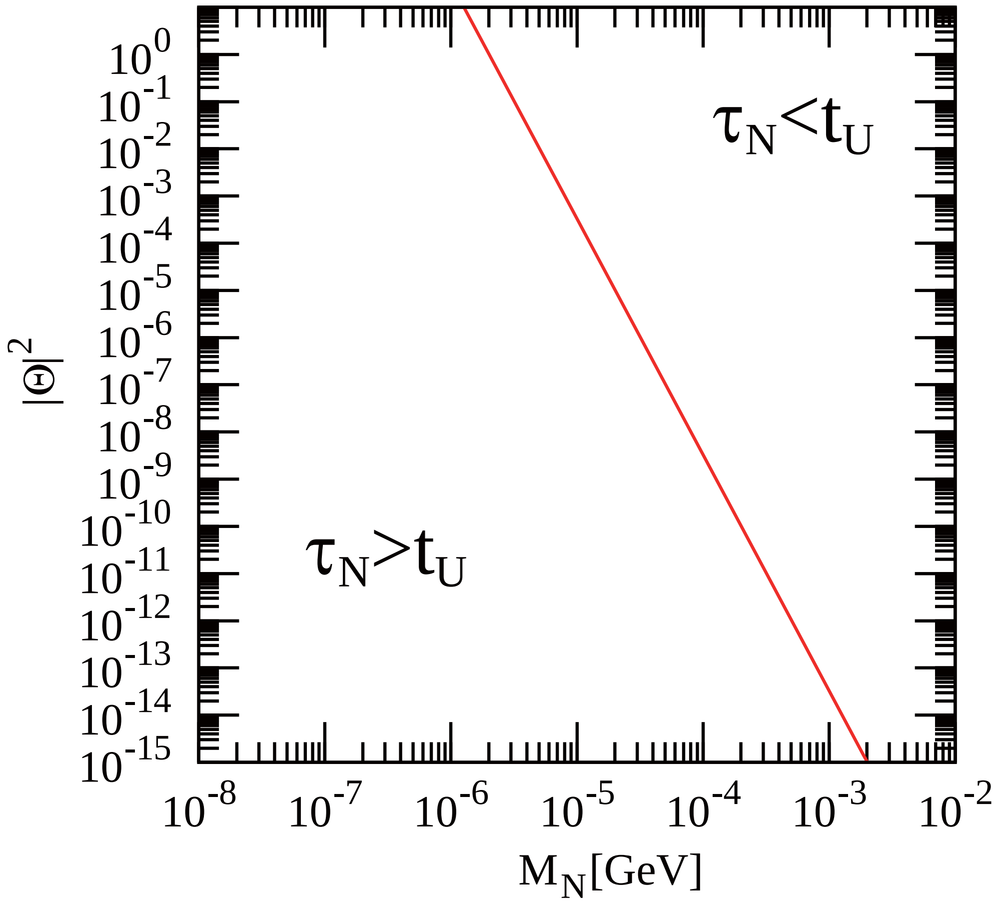
$t_U = (13.81 \pm 0.05)$ Gyr [PDG '15]

When M_N=10 keV,

$|\Theta|^2 < 3.3 \times 10^{-4}$ for $\tau_N > t_U$

When $M_N \lesssim$1 keV,

$\tau_N > t_U$ even if $|\Theta|^2 \simeq 1$



HNL with keV mass can be stable within the age of the universe for small mixings.

However, this is not enough for realistic dark matter (see the discussion of X-ray constraint later.)

Production of DM

- Dark Matter Abundance in the present universe

$$\Omega_{dm} h^2 = 0.1188 \pm 0.0010$$

[Planck 2015: arXiv:1502.01589]

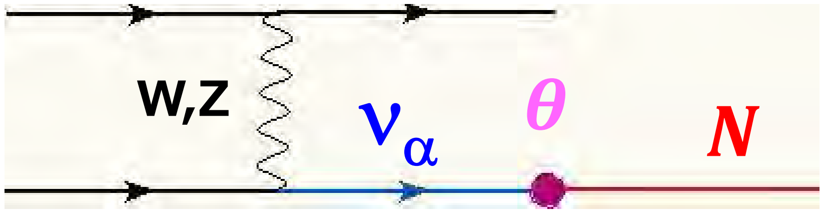
How N's are produced ?

- Due to the smallness of mixing, dark matter N is not thermalized in the early universe

- Production scenarios:
  - Dodelson-Widrow scenario
    - (Non-resonant) production via active-sterile neutrino mixing
  - Shi-Fuller scenario
    - Resonant production due to lepton asymmetry
  - Production by other interactions
  - ⋯

Dodelson-Widrow Scenario '94 [hep-ph/9303287]

- Production by thermal scatterings induced via active-sterile neutrino mixing Dodelson, Widrow '94 [hep-ph/9303287]



$+ \cdots$

- Evolution of number density n_N is roughly described by

$$\frac{d}{dt} n_N + 3H n_N = P(\nu \to N) \Gamma_\nu \, n_\nu$$

Γ_ν: interaction rate of ν
n_ν: number density of ν

$$P(\nu \to N) = \sin^2(2\theta_m) \sin^2(\omega_m t)$$

Mixing angle θ_m in the early universe can be different from the vacuum mixing angle θ !

Active-Sterile Mixing in the early universe

- Effective Hamiltonian: $H_{eff} = H_0 + V_T$

Free part: $H_0 = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos 2\theta & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta \end{pmatrix} = \frac{1}{4T}\begin{pmatrix} -M_N^2 & 2\theta M_N^2 \\ 2\theta M_N^2 & M_N^2 \end{pmatrix}$

Thermal corr.: $V_T = \begin{pmatrix} -bG_F^2 T^5 & 0 \\ 0 & 0 \end{pmatrix}$ $\quad b = 20 \sim 80$

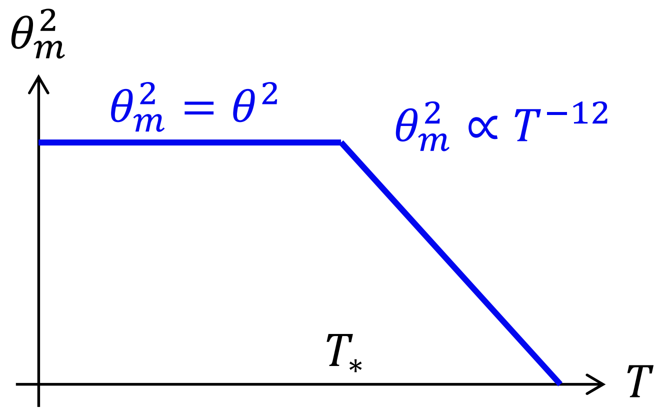
$$H_{eff} = \frac{1}{4T}\begin{pmatrix} -M_N^2 - 4bG_F^2 T^6 & 2\theta M_N^2 \\ 2\theta M_N^2 & M_N^2 \end{pmatrix}$$

- Mixing angle in the early universe

$$\tan 2\theta_m = \frac{4\theta M_N^2}{2M_N^2 + 4bG_F^2 T^5}$$

Mixing is very suppressed for $T \gg T_*$

$$T_* = \left(\frac{1}{2b}\right)^{\frac{1}{6}} \left(\frac{M_N}{G_F}\right)^{\frac{1}{3}} \simeq 100\text{MeV}\left(\frac{M_N}{1\text{keV}}\right)^{\frac{1}{3}}$$



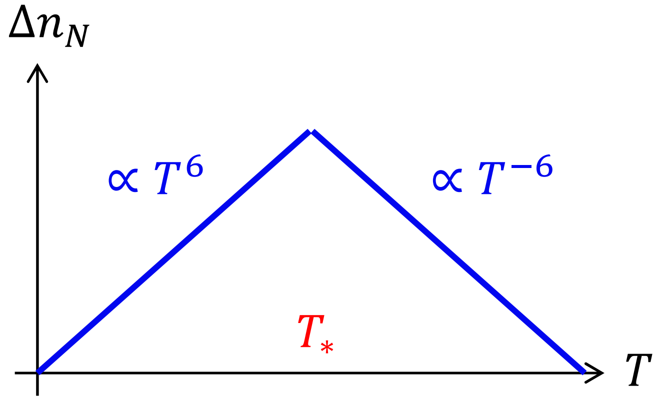
Abundance of DM N

- Dominant production occurs at $T = T_*$

$$\dot{n}_N + 3Hn_N = \sin^2(2\theta_m)\,\sin^2(\omega_m t)\,\Gamma_\nu\, n_\nu$$

$$\Delta n_N = \frac{1}{2}\sin^2 2\theta_m\,\Gamma_\nu\, n_\nu\,\frac{M_p}{T^2} \propto \begin{cases} T^{-6} & (T > T_*) \\ T^{6} & (T < T_*) \end{cases}$$

$\Gamma_\nu \sim G_F^2 T^5$ $\qquad n_\nu \sim T^3$



$$Y_N = \frac{n_N}{s} = \frac{\Delta n_N(T_*)}{s(T_*)} \sim \frac{\theta^2\, G_F^2 T_*^5\, T_*^3\, \frac{M_p}{T_*^2}}{T_*^3} = \theta^2 G_F^2 M_p T_*^3 \simeq \theta^2 G_F M_p M_N$$

- Present abundance

$$\Omega_N h^2 = \frac{\rho_N}{\rho_{cr}/h^2} = \frac{M_N n_N}{\rho_{cr}/h^2} = \frac{M_N Y_N}{\frac{\rho_{cr}}{s\, h^2}} = \frac{M_N Y_N}{3.6 * 10^{-9}\mathrm{GeV}}$$

$$\Omega_N h^2 \sim 0.1 \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{M_N}{1\ \mathrm{keV}}\right)^2$$

For the seesaw case $\theta = \frac{M_D}{M_N}$

⇨ *Ω_N is determined only by M_D and independent on M_M !*

For the precise estimation of $\Omega_N h^2$

- We have to
  - Solve kinetic equation for density matrix
    - Including the oscillation effects, the rapid interaction of active neutrinos and the production/destruction of sterile neutrinos
  - Take care of hadronic uncertainties since the dominant production occurs near the hadron-quark transition
    - Hadronic contributions to production rates
    - QCD equation of state
      (how the effective degrees of freedom evolve at the transition)

See the analysis in

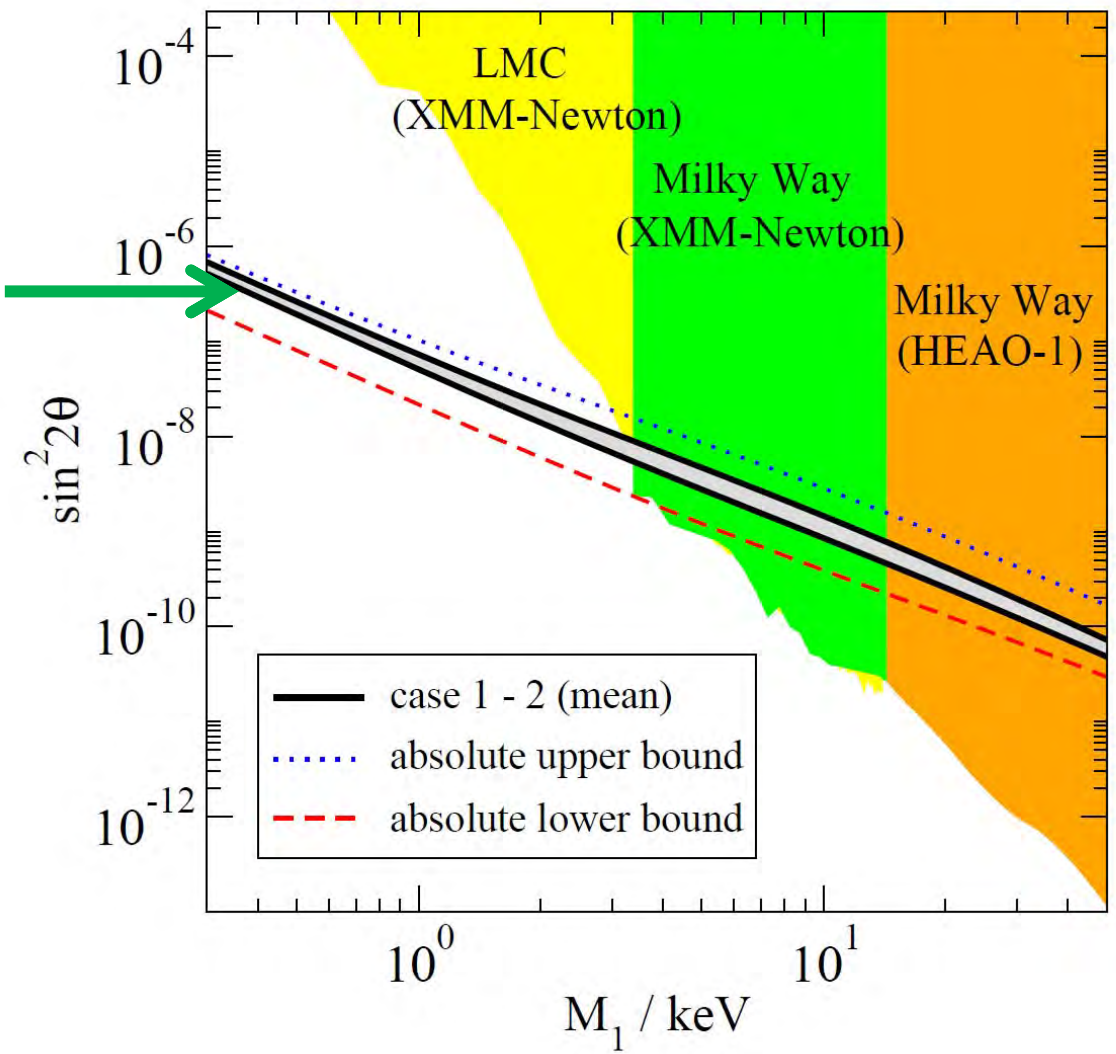
TA, Laine, Shaposhnikov '07 [hep-ph/0612182]

Mixing angle required for DM abundance

TA, Laine, Shaposhnikov '07

Mixing angle required for
$\Omega_N = \Omega_{dm}$

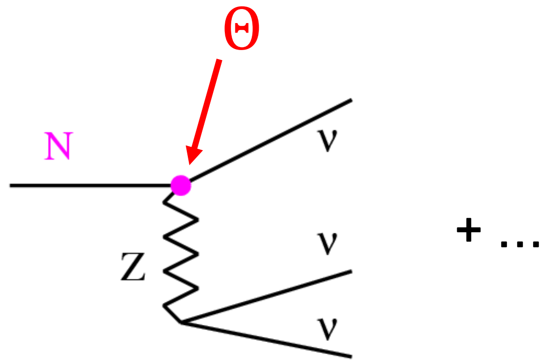
$$\sin^2 2\theta \simeq 8 \times 10^{-8} \left(\frac{M_N}{1\text{keV}}\right)^2$$



Constraint on radiative decay of DM N

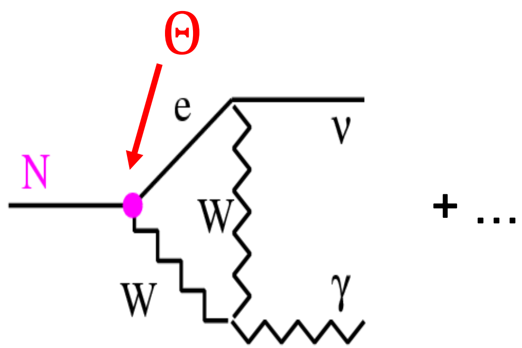
- N is not completely stable particle !
  - Dominant decay: $N_1 \to 3\nu$ for $M_1 \sim$keV
  - Lifetime can be very long

$$\tau_{N_1} = 5 \times 10^{26} \mathrm{sec} \left(\frac{\mathrm{keV}}{M_1}\right)^5 \left(\frac{10^{-8}}{\Theta^2}\right)$$



- **N is not completely "dark" !**
  - Subdominant decay: $N \to \nu + \gamma$
  - Branching ratio is very small

$$Br = 27\alpha_{em}/8\pi$$



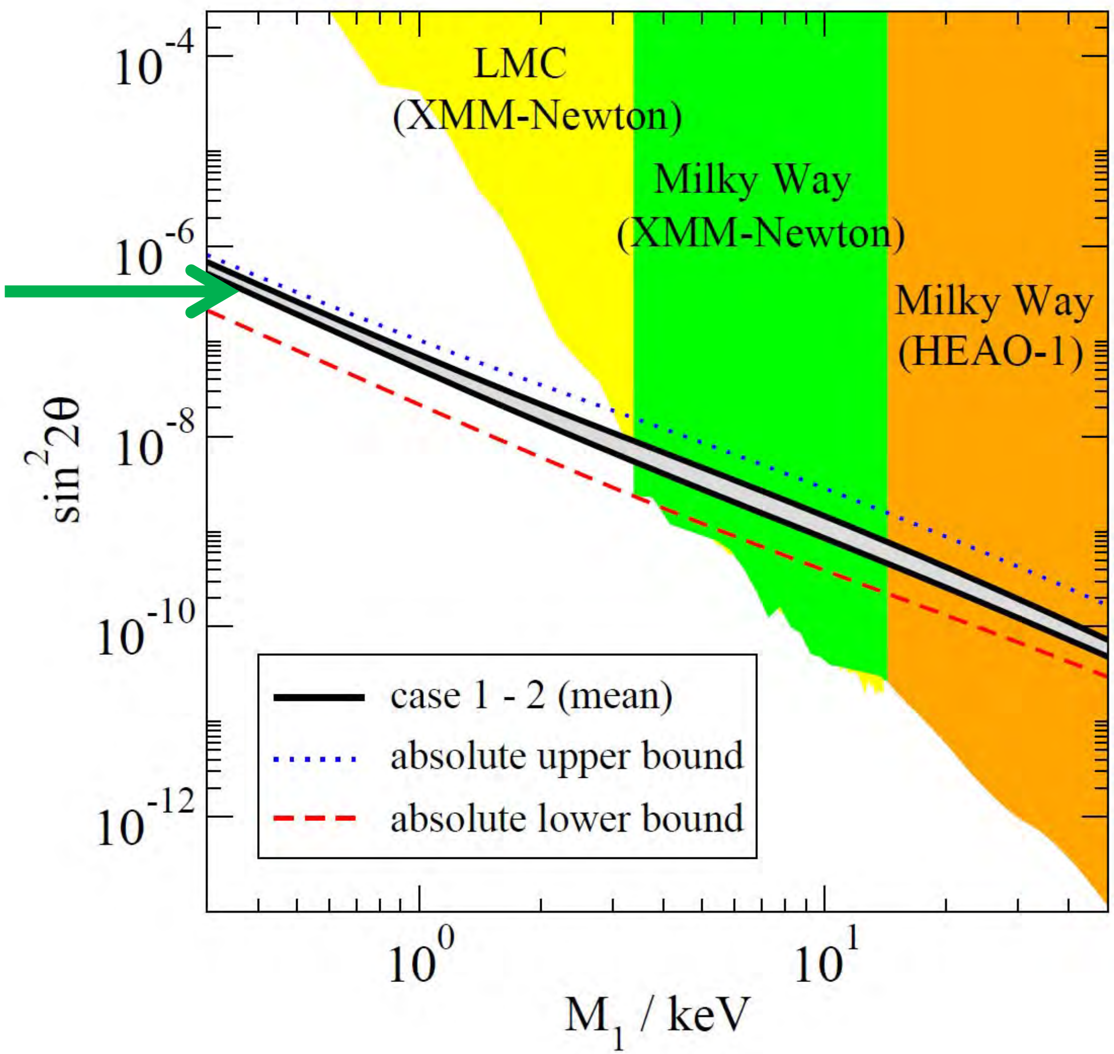
  - Severely restricted from x-ray observations
    * Recently, detection of x-ray line is reported !

Mixing angle required for DM abundance

TA, Laine, Shaposhnikov '07

Mixing angle required for
$\Omega_N = \Omega_{dm}$

$\sin^2 2\theta \simeq 8 \times 10^{-8} \left(\frac{M_N}{1\mathrm{keV}} \right)^2$



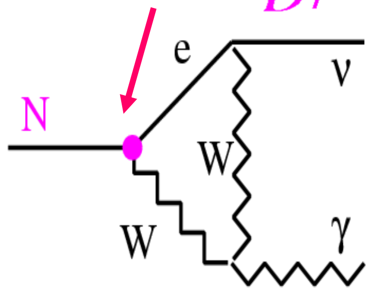
$M_N < 3$ keV
is possible !

Cosmological Constraints

- **Radiative decays of DM**
  - Subdominant decay: $N_1 \to \nu + \gamma$
  - Severely restricted from X-ray observations

  $\Rightarrow$ **Upper bound on mixing angle !**

$\theta = M_D/M_1$



- **Structure formation** $\lambda_{FS} \sim \text{Mpc}\left(\frac{\text{keV}}{M_1}\right)\frac{\langle|q_N|\rangle}{\langle|q_\nu|\rangle}$
  - DM N_1 plays as WDM and may erase structures on small scales!

  $\Rightarrow$ **Lower bound on mass** (Ly-α forest observations)
  - $M_1 \gtrsim 8\ \text{keV}$ (DW scenario)

  Boyarsky, Lesgourgues, Ruchayskiy, Viel '09,'09

- **Phase-space analysis** (Tremaine-Gunn bound)
  - $M_1 \gtrsim 1-2\ \text{keV}$

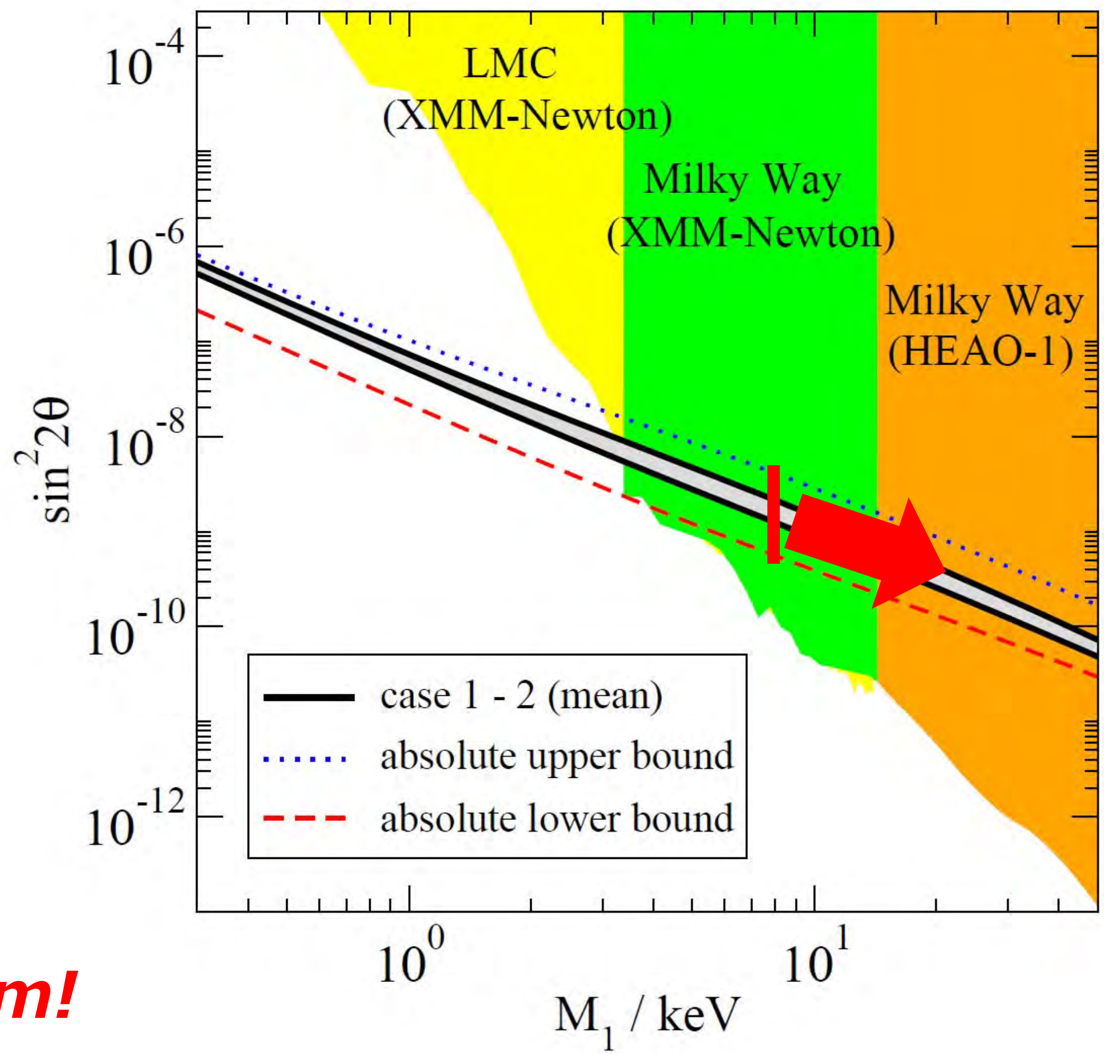
  Tremaine, Gunn '79
  Boyarsky, Ruchayskiy, Iakubovskyi '08
  Gorbunov, Khmelnitsky, Ruvakov '08

Mixing angle required for DM abundance

TA, Laine, Shaposhnikov '07

Mixing angle required for
$\Omega_N = \Omega_{dm}$

$$\sin^2 2\theta \simeq 8 \times 10^{-8} \left(\frac{M_N}{1\text{keV}} \right)^2$$



$M_N < 3$ keV is possible !

Not allowed since it is too warm!

Shi-Fuller Scenario

[Shi, Fuller '99, astro-ph/9810076]

- Due to the lepton asymmetry at $T \sim 100$ MeV, the resonant production of DM particle is possible !

$$H_0 = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos 2\theta & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta \end{pmatrix} = \frac{1}{4T}\begin{pmatrix} -M_N^2 & 2\theta M_N^2 \\ 2\theta M_N^2 & M_N^2 \end{pmatrix}$$

$$V_T = \begin{pmatrix} -bG_F^2 T^5 & 0 \\ 0 & 0 \end{pmatrix} \qquad b = 20 \sim 80$$

  - Lepton asymmetry $\mathcal{L}$ induces the additional contribution

$$V_L \simeq \begin{pmatrix} 0.35\, G_F T^3\, \mathcal{L} & 0 \\ 0 & 0 \end{pmatrix}$$

$$H_{eff} = H_0 + V_T + V_L = \frac{1}{4T}\begin{pmatrix} -M_N^2 - 4bG_F^2 T^6 + 1.4 G_F T^4 \mathcal{L} & 2\theta M_N^2 \\ 2\theta M_N^2 & M_N^2 \end{pmatrix}$$

$$\tan 2\theta_m = \frac{4\theta M_N^2}{2M_N^2 + 4bG_F^2 T^5 - 1.4 G_F T^4 \mathcal{L}}$$

Production is enhanced due to the MSW effect

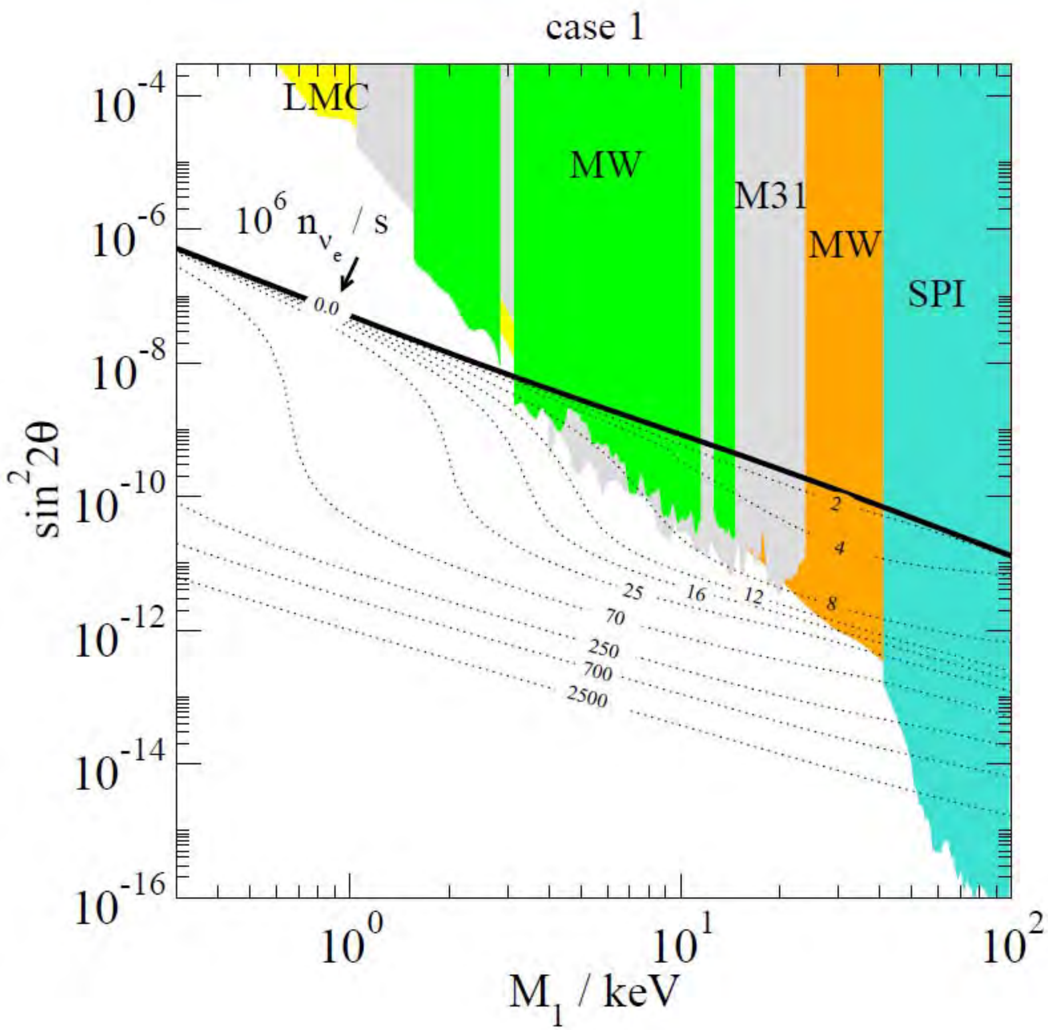
Mixing angle required for DM abundance

Laine, Shaposhnikov '08

- Resonant production

  Smaller mixing can account for the correct dark matter abundance

$M_N < 50$ keV is possible !

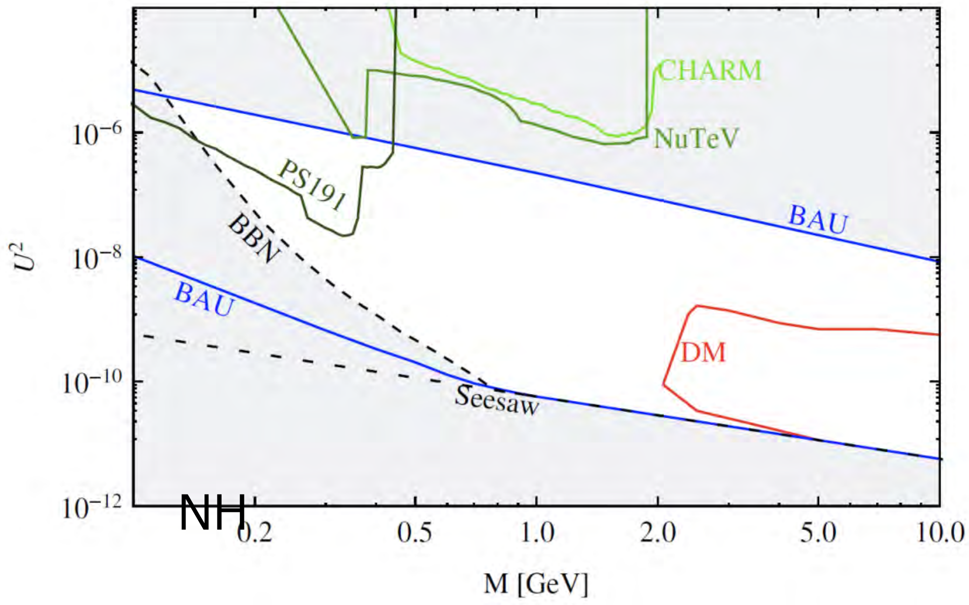


Sterile Neutrino as Dark Matter

- Dodelson-Widrow scenario conflicts with cosmological constraints
  ⇒ Other production mechanism is needed
  - Shi-Fuller mechanism with large lepton asymmetry
  - Addition of new d.o.f (scalar, Z', ⋯)

  Shaposhnikov, Tkachev '06, Kusenko '06, Petraki, Kusenko '06
  Bezrukov, Gorbunov '10, Bezrukov, Kartavtsev, Lindner '12, Tsuyuki '14, ⋯

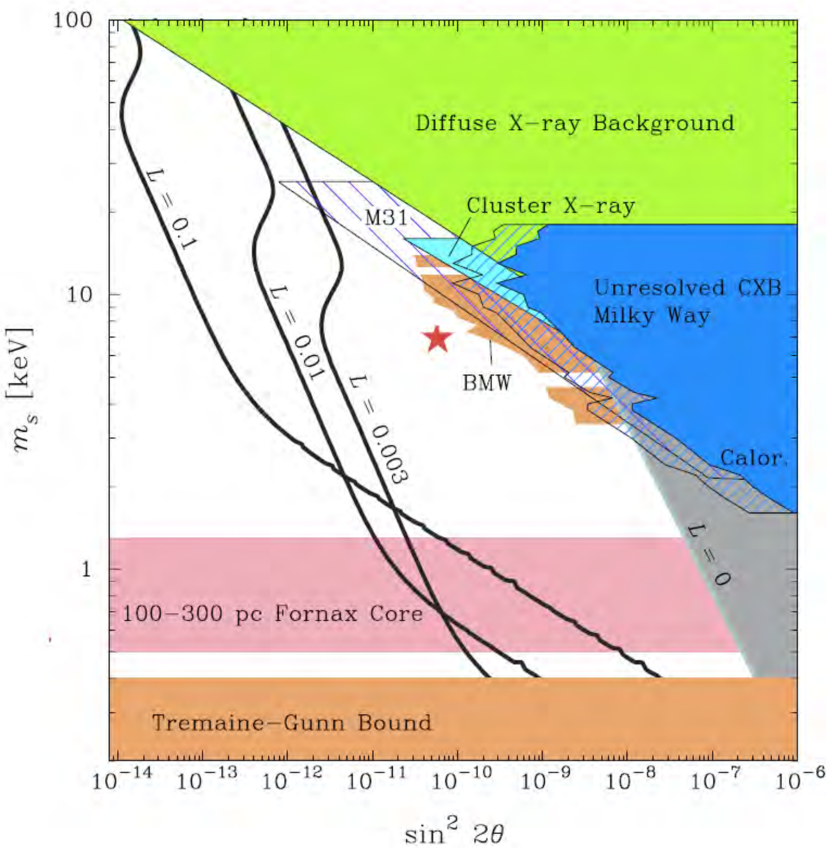
- Large lepton asymmetry for Shi-Fuller mechanism can be generated by HNLs
  - Baryogenesis at $T \gtrsim M_W$
  - Leptogenesis before DM production

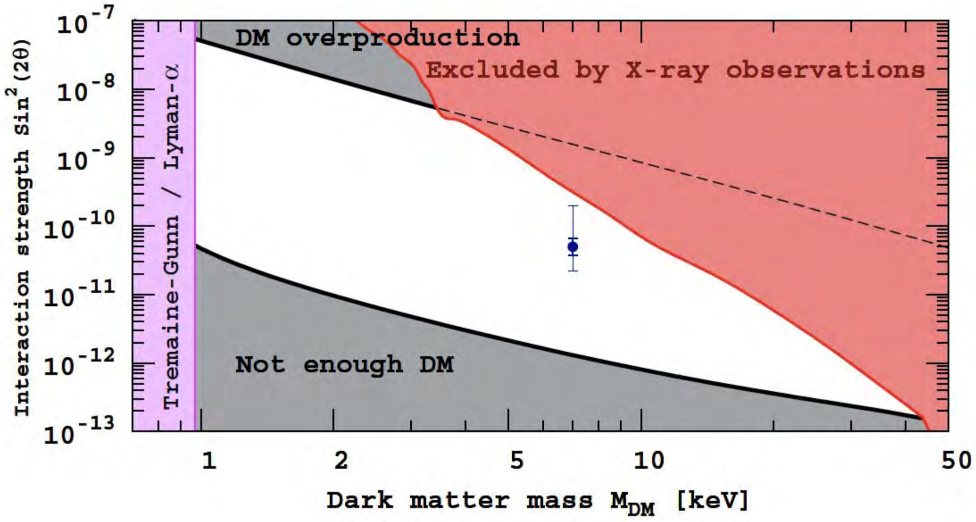


Canetti, Drewes, Shaposhnikov '13
Canetti, Drewes, Frossard, Shaposhnikov '13

X-rays from DM N decays?

- Unidentified x-ray line with E=3.5keV
  Bulbul et al (arXiv:1402.2301)
  Boyarsky, Ruchayskiy, Iakubovskyi, Franse (arXiv:1402.4119)





Can be explained by DM N_1

- $M_1 \simeq 7$ keV
- $\sin^2 2\Theta_1 = O(10^{-10})$

Sterile Neutrino and Baryon Asymmetry of the universe

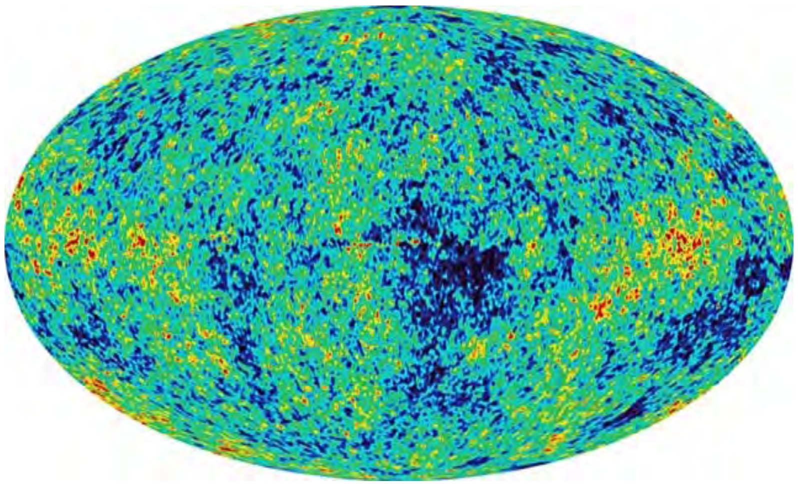
Baryon asymmetry of the universe (BAU)

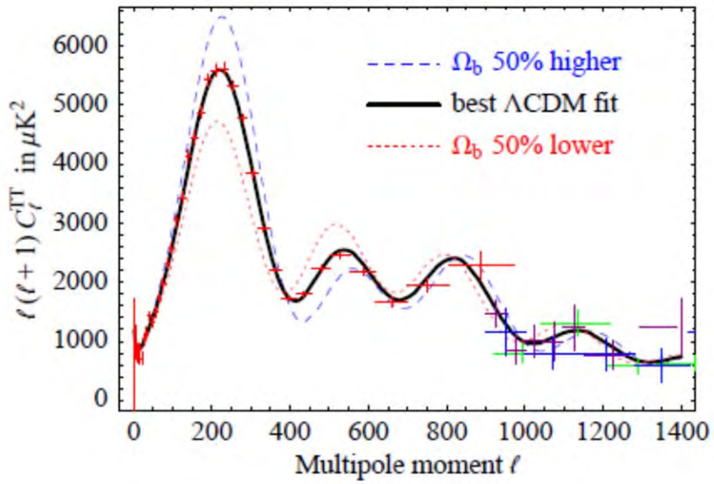
Baryon Number B = (# of baryons) − (# of antibaryons)

$$\frac{n_B}{s} = (8.676 \pm 0.054) \times 10^{-11}$$

Planck 2015
[arXiv:1502.01589]

n_B : Baryon number density
s : Entropy density





[Strumia 06]

Conditions for baryogenesis

- **Sakharov (1967)**

(1) Baryon number B is violated

(2) C and CP symmetries are violated

(3) Out of thermal equilibrium

"According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

Baryogenesis Conditions in the SM

- B+L violations
  - Sphaleron for T>100GeV

- C and CP violations
  - 1 CP phase in the quark-mixing (CKM) matrix

$$\mathrm{CPV} \propto J_{CP}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) / T_{EW}^{12} \sim 10^{-19}$$

→ too small

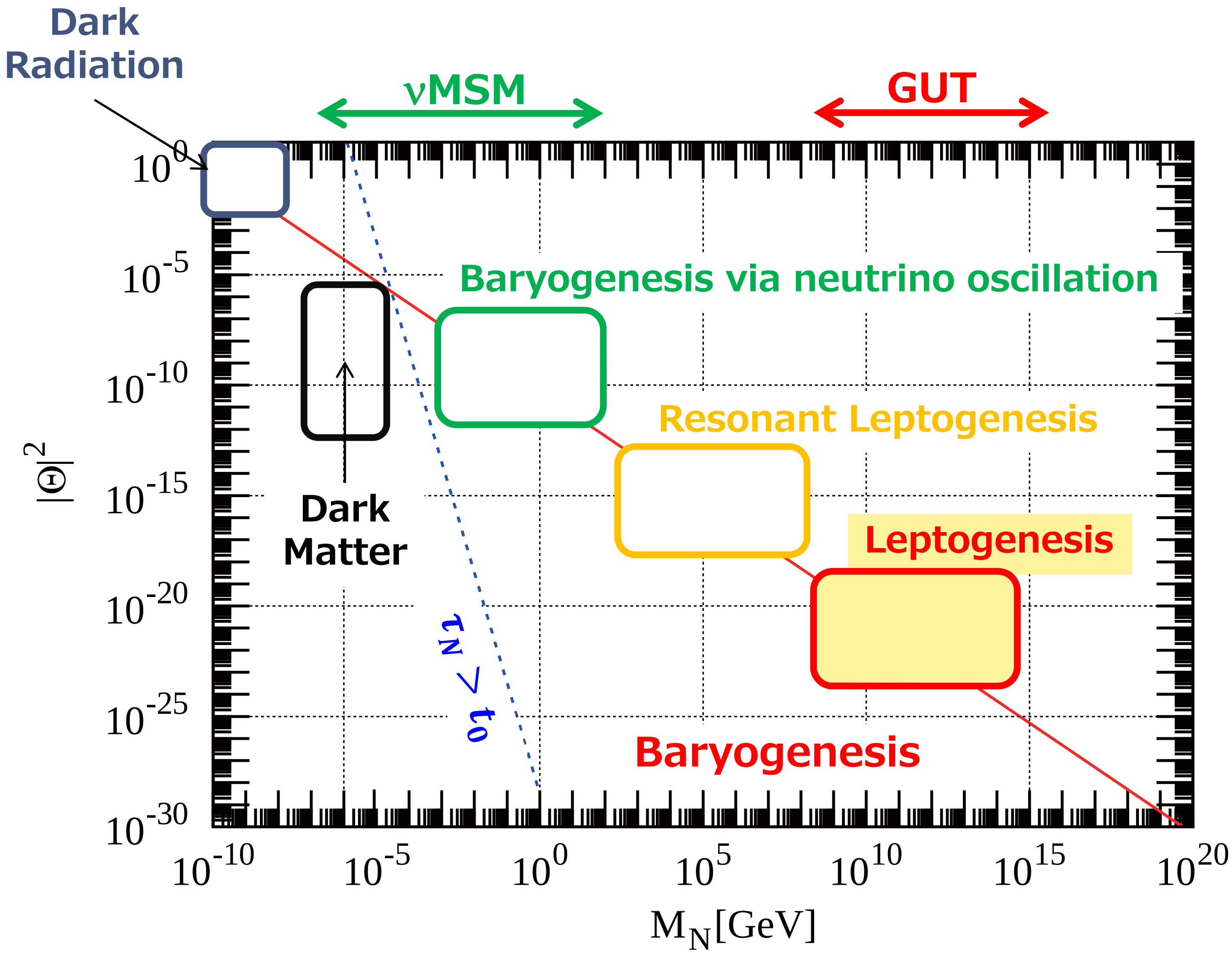
- Out of equilibrium
  - Strong 1st order phase transition if $m_H < 72$ GeV, but $m_H \simeq 126$ GeV

→ not satisfied

[Kajantie, Laine, Rummukainen, Shaposhnikov]

New physics is needed !

Various Physics of HNL



Leptogenesis

[Fukugita, Yanagida '86]

- Majorana masses break L

$$\mathcal{L} = -F\,\overline{L}\,\Phi\,N - \frac{M}{2}\overline{N^c}\,N + h.c.$$

lepton number

$\Phi : 0$

$L : +1$

$N : +1$

- RH neutrino decay can produce L

$$\begin{cases} N \to L + \overline{\Phi} \\ N \to \overline{L} + \Phi \end{cases}$$

$$\Gamma(N \to L + \overline{\Phi}) \neq \Gamma(N \to \overline{L} + \Phi) \text{ if CPV}$$

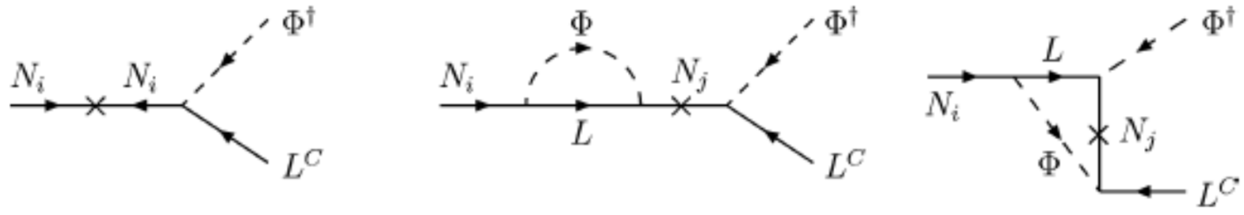
- Produced L is partially converted into B by sphaleron

$$B_f = \frac{8N_F + 4}{22N_F + 13}(B - L)_i = 0.35(B - L)_i$$

CP Violation

- CP violation in neutrino Yukawa couplings

$$\Gamma(N_1 \to L + \overline{\Phi}) \neq \Gamma(N_1 \to \overline{L} + \Phi)$$



$$\begin{aligned}\epsilon_1 &= \frac{\Gamma(N_1 \to L + \overline{\Phi}) - \Gamma(N_1 \to \overline{L} + \Phi)}{\Gamma(N_1 \to L + \overline{\Phi}) + \Gamma(N_1 \to \overline{L} + \Phi)} \\ &= \frac{3}{16\pi}\frac{1}{(F^\dagger F)_{11}}\left[\mathrm{Im}(F^\dagger F)^2_{13}\frac{M_1}{M_3} + \mathrm{Im}(F^\dagger F)^2_{12}\frac{M_1}{M_2}\right] \\ &\simeq 10^{-6}\,\delta_{\rm eff}\left(\frac{M_1}{10^{10}\mathrm{GeV}}\right)\left(\frac{m_3}{0.05\mathrm{eV}}\right)\end{aligned}$$

$M_1 \ll M_{2,3}$

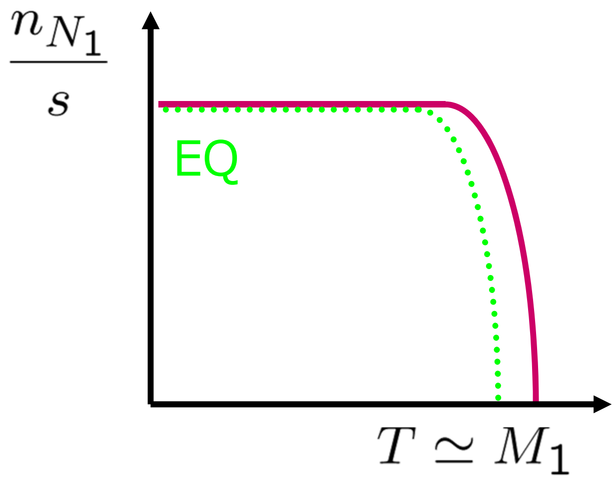
$|F_{33}| \gg$ others

$\delta_{\rm eff}$: effective CP viol. param.

Out of Equilibrium Decay

- For $T \gg M_1$, N_1 is in thermal equilibrium

$$N_1 \to L + \overline{\Phi}$$
$$N_1 \leftarrow L + \overline{\Phi}$$



- For $T < M_1$

$$n_{N_1}^{\text{EQ}} \propto \exp(-M_1/T)$$

If $\Gamma_{N_1} < H(T \sim M_1)$

n_{N_1} cannot catch up with $n_{N_1}^{\text{EQ}}$

→ Out of equilibrium decay of N_1

BAU via Leptogenesis

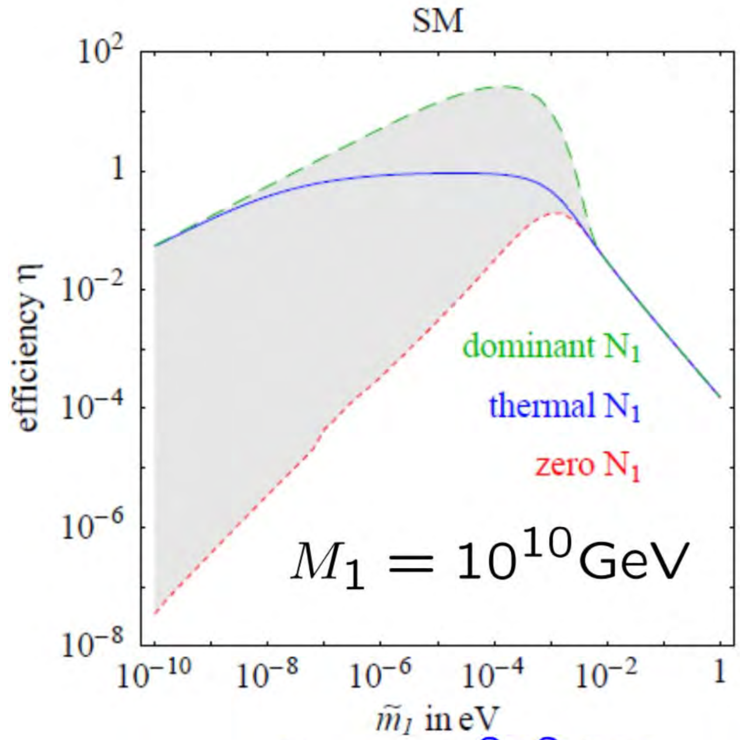
$$\frac{n_B}{s} = \frac{n_{N_1}}{s} \times \epsilon_1 \times 0.35 \times \eta$$

Efficiency factor

Number of $N_1 \sim 10^{-2}$

CP asymmetry $\propto M_1$

Sphaleron conv.



$$\tilde{m}_1 = F_1^2 v^2 / M_1$$

[Giudice et al 03]

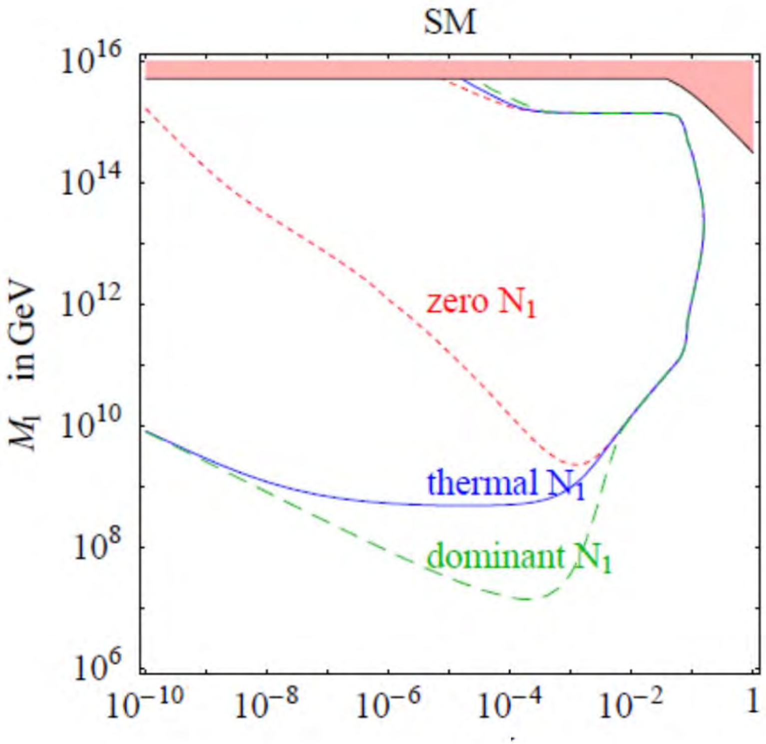
Lower Bound on Mass M_1

[Giudice et al '03]

$$\frac{n_B}{s} \propto \epsilon_1 \propto M_1$$

⇩

Lower bound on mass

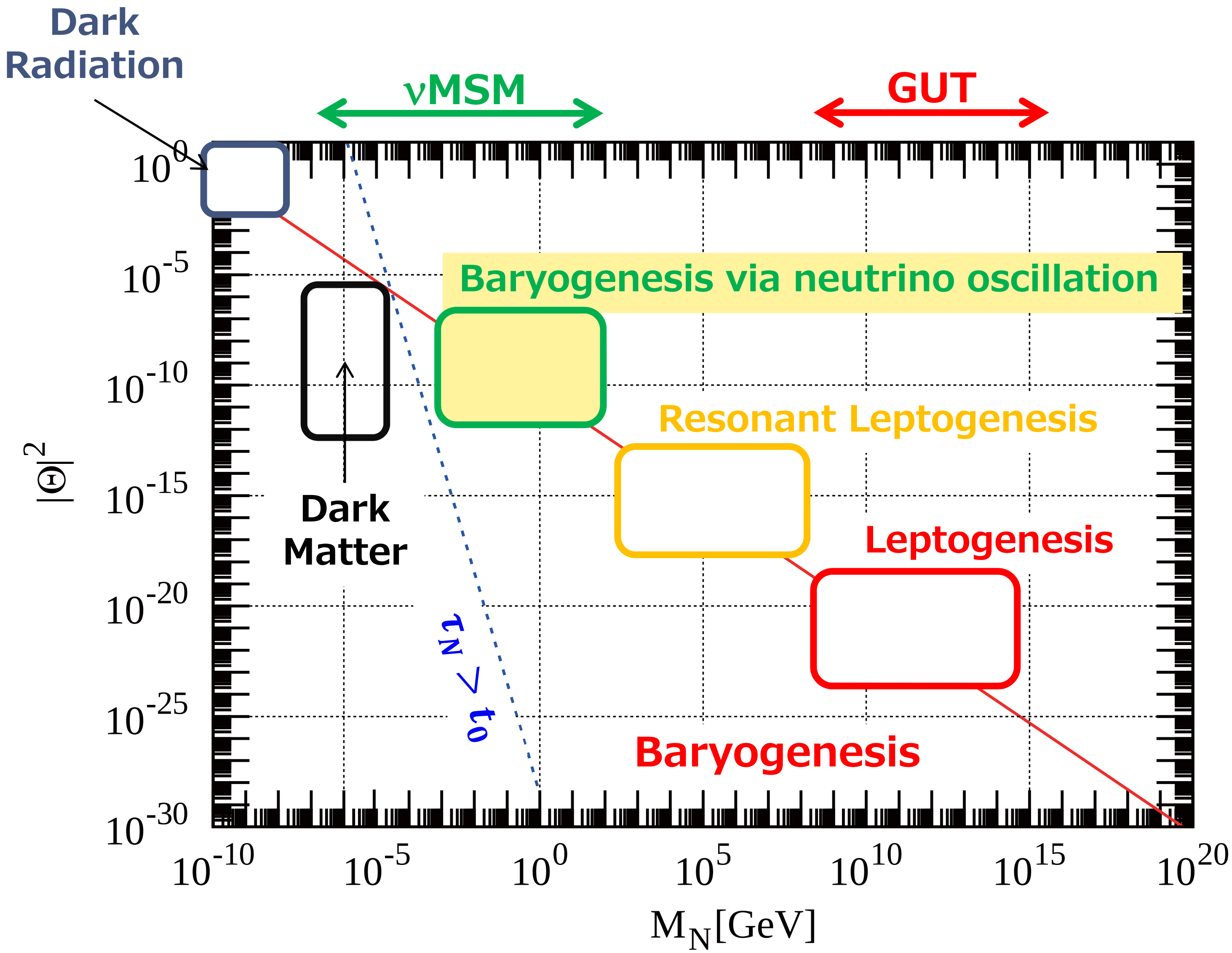


$$M_1 > \begin{cases} 2.4 \times 10^9\ \text{GeV} & \text{if } N_1 \text{ has zero} \\ 4.9 \times 10^8\ \text{GeV} & \text{if } N_1 \text{ has thermal} \quad \text{initial abundancy} \\ 1.7 \times 10^7\ \text{GeV} & \text{if } N_1 \text{ has dominant} \end{cases}$$

Baryogenesis via neutrino oscillation

[Akhmedov, Rubakov, Smirnov '98]
[TA, Shaposhnikov '05]

Various Physics of HNL



Baryogenesis conditions

- **B and L violations**
  - (B+L) violation due to sphaleron
  - L violation due to Majorana masses

    Majorana masses < 100 GeV

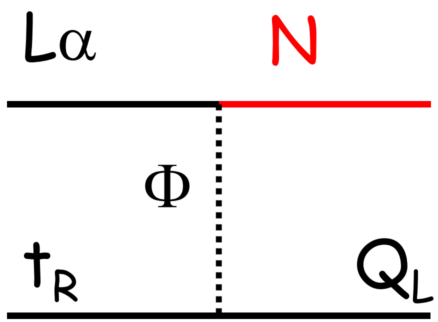
    → negligible for T>100 GeV

- **C and CP violations**
  - 1 CP phase in quark sector
  - 6 CP phases in lepton sector

Baryogenesis conditions

- **Out of equilibrium**
  - No 1st order EW phase transition as in the MSM
  - Heavy neutral leptons can be out of equilibrium, if Yukawa couplings are small enough
    - To ensure this condition up to T～100GeV

$$\Rightarrow \quad f_{1,2,3} < 2\times10^{-7}$$



The model with HNLs with MN<100 GeV can realize all three conditions for baryogenesis

Baryogenesis via Neutrino Oscillation

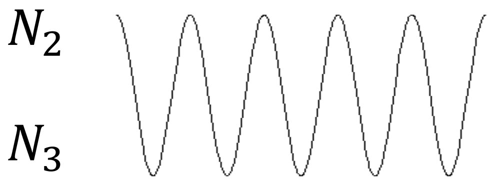
- Oscillation of HNLs can be a source of BAU

  Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)

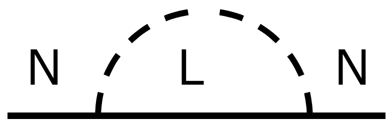
  Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
  TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
  Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)

  - Oscillation starts at $T_{osc} \sim (M_0\, M_N\, \Delta M)^{1/3}$

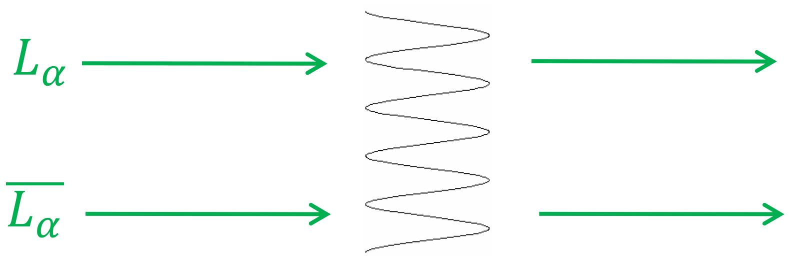
Medium effects

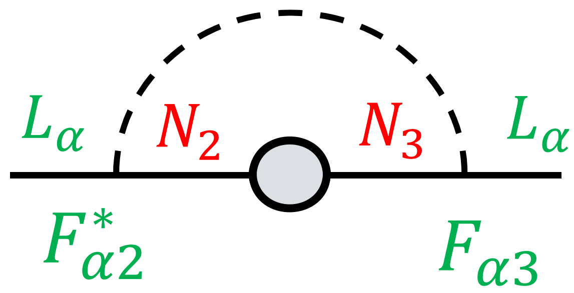


$$V_N = \frac{T^2}{8\,k} F^\dagger F$$



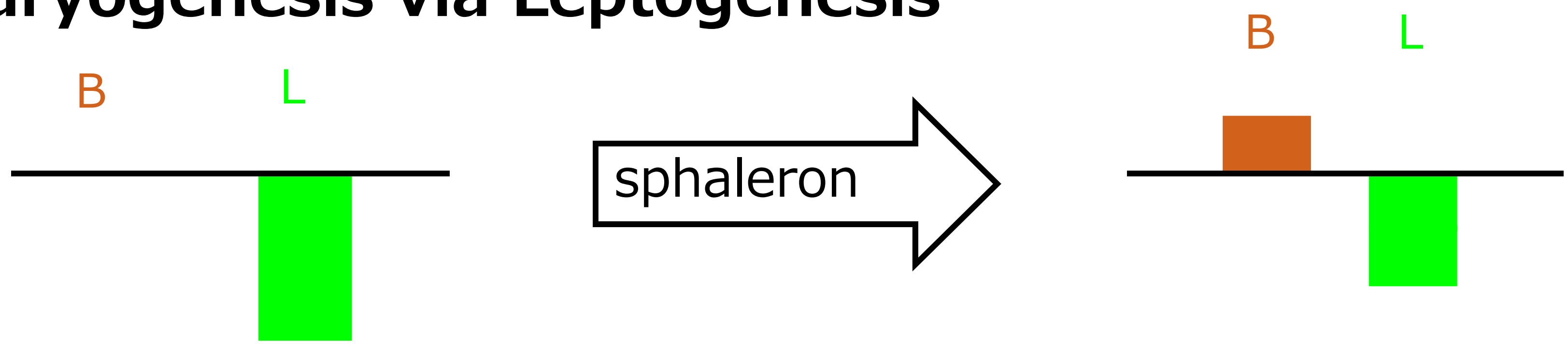
  - Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV



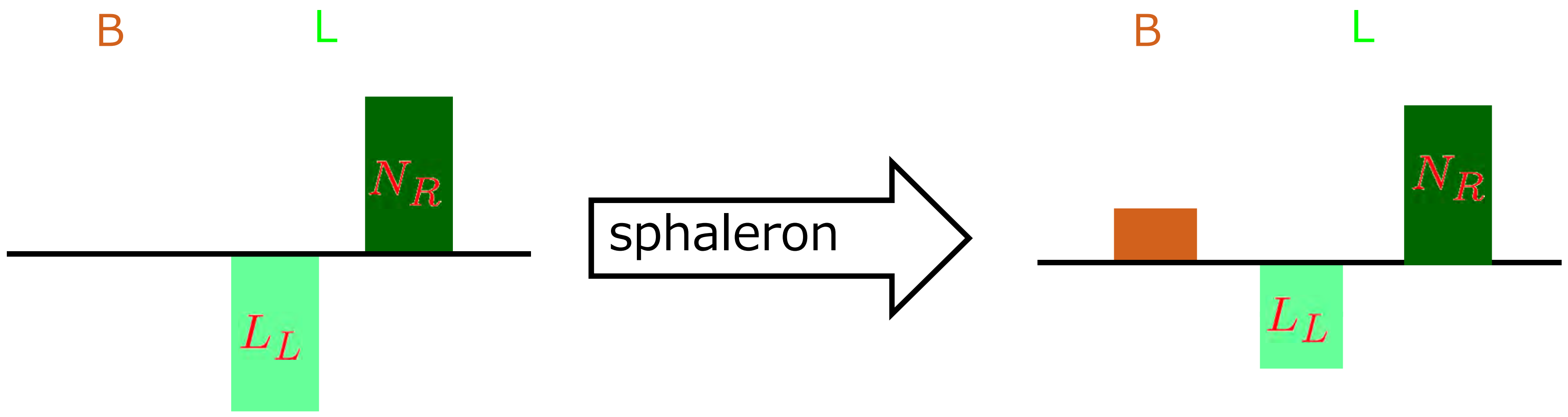


Key Point

Baryogenesis via Leptogenesis



Baryogenesis via Neutrino Oscillation



Evolution of Each Asymmetry

Active Sector

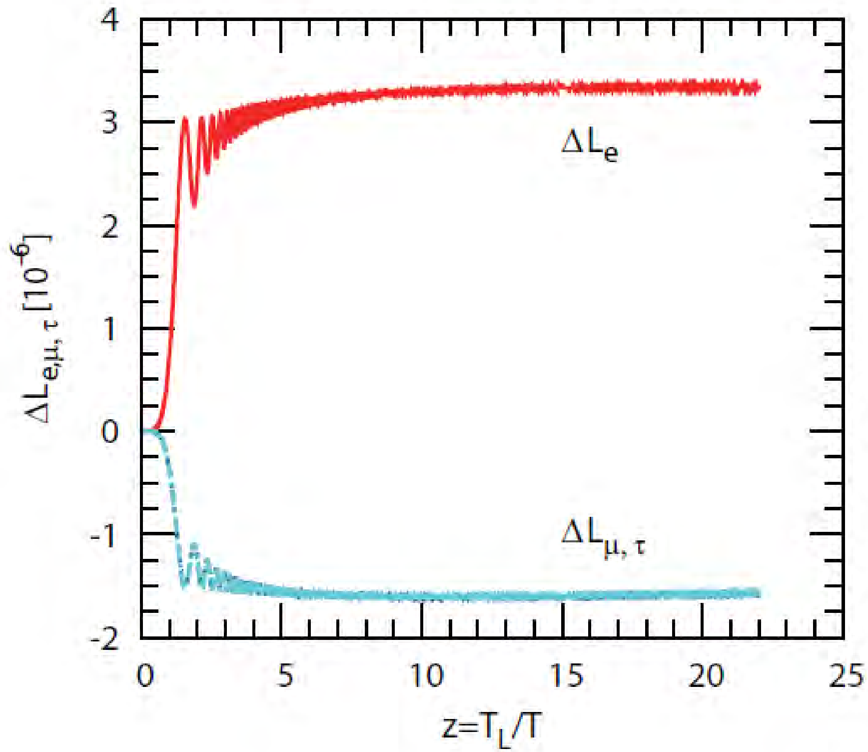


Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Sterile Sector

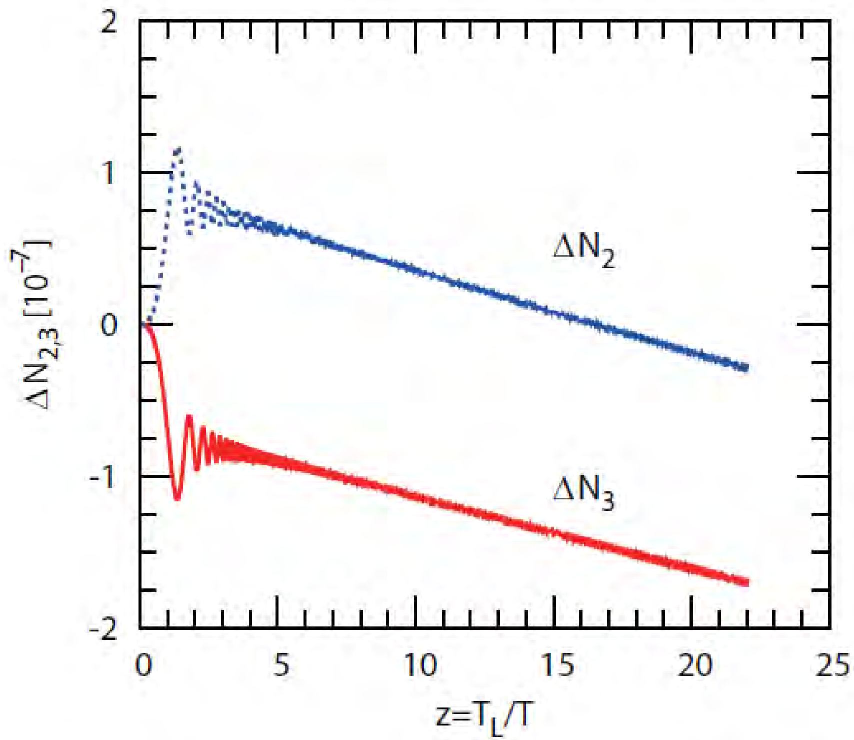
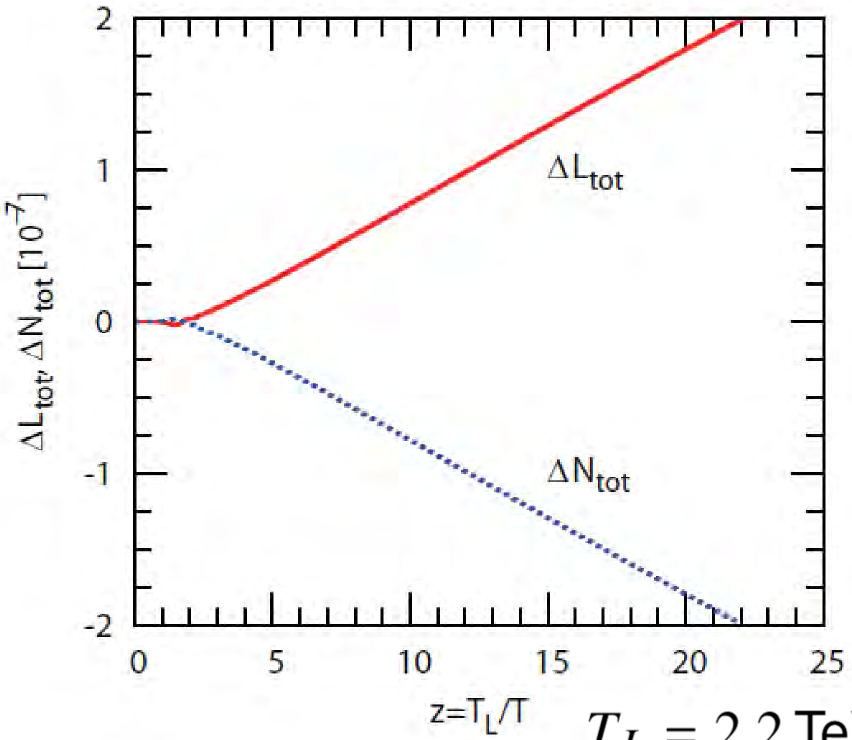


Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

$$T_{osc} = 2.2 \text{ TeV}$$

Evolution of Asymmetries



$T_L = 2.2$ TeV

Figure 7: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Shaleron converts ΔL partially into baryon asymmetry

[Kuzmin, Rubakov, Shaposhnikov]

$$B = -\frac{28}{79}\Delta L_{tot} \neq 0$$

$$\frac{n_B}{s} = -2.5\times 10^{-4}\Delta L_{tot}(T_W)$$

⬍

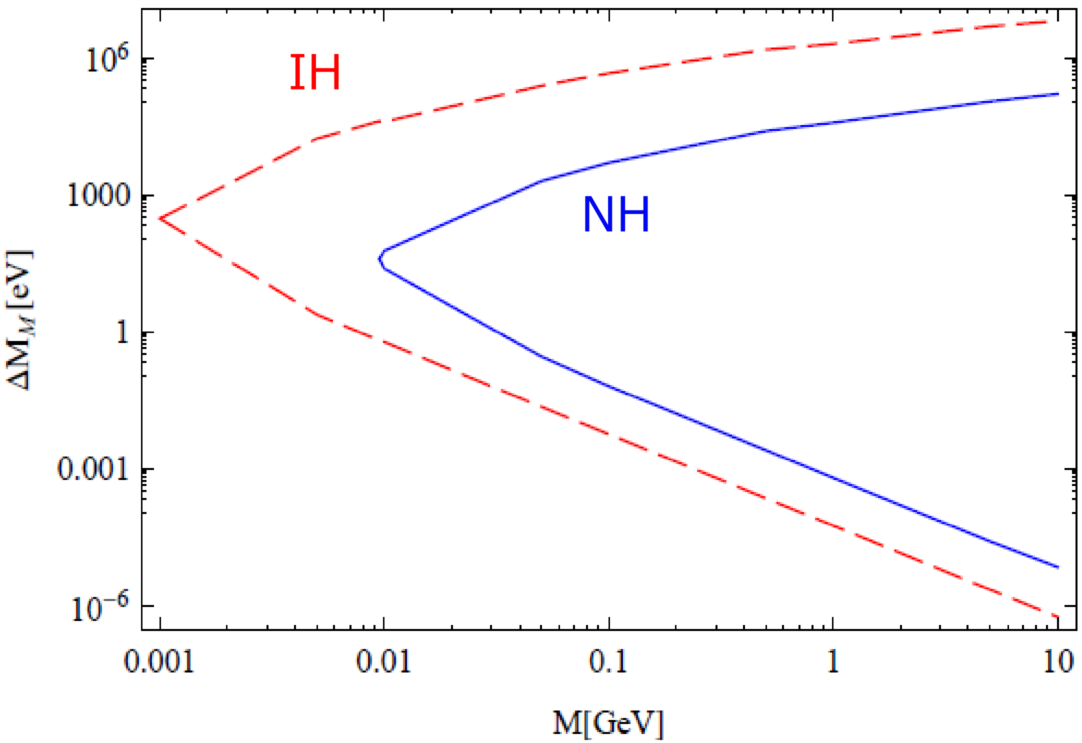
$$\frac{n_B}{s} = (8.579 \pm 0.109)\times 10^{-11}$$

[Planck 2013]

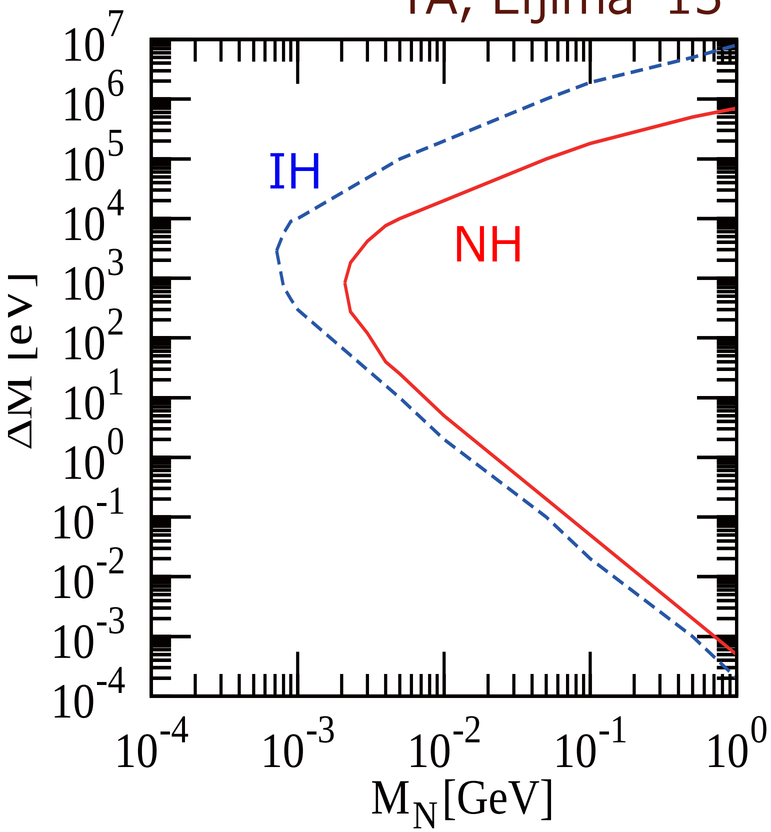
Baryogenesis Region

Region accounting for $\frac{n_B}{s} = (8.55\text{-}9.00)\times 10^{-11}$

Canetti, Shaposhnikov '10



TA, Eijima '13



$M_N > 2.1$ MeV (NH) $\quad$ $M_N > 0.7$ MeV (IH)

BBN Constraint on Lifetime

- Long-lived $N_{2,3}$ may spoil the success of BBN
  - Speed up the expansion of the universe
    - $\rho_{\rm tot} = \rho_{\rm MSM} + \rho_{N_{2,3}} \Rightarrow \; H^2 = \frac{\rho_{\rm tot}}{3\,M_P^2}$
    - p-n conv. decouples earlier $\Longrightarrow$ overproduction of $^4\mathrm{He}$

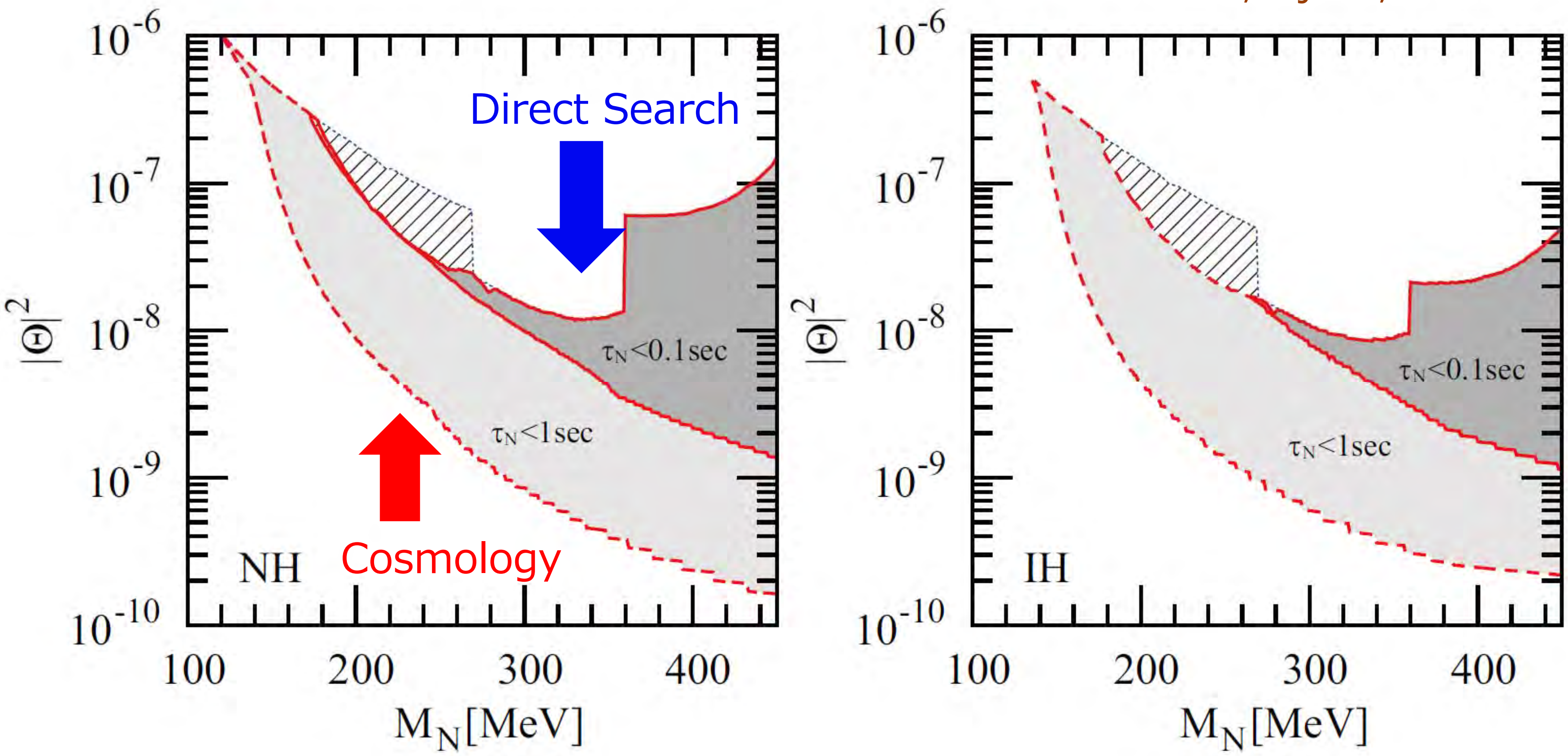
      $n + \nu \; \leftrightarrow \; p + e^-, \ldots$
  - Distortion of spectrum of active neutrinos
    - $N_{2,3} \; \rightarrow \nu\,\bar{\nu}\,\nu, \; e^+\,e^-\,\nu, \ldots$
    - Additional neutrinos may not be thermalized

  $\Rightarrow$ Upper bound on lifetime

- Dolgov, Hansen, Rafflet, Semikoz ('00)
  - One family case: $\tau_N < 0.1\,\mathrm{sec} \;\; \mathrm{for}\; M_N > m_\pi$

Constraints on HNLs

TA, Eijima, Takeda '14



Good target for search experiments !

Yukawa Couplings of N2 and N3

$$F = U_{\rm PMNS}\, D_\nu^{1/2}\, \Omega\, D_N^{1/2} / \langle \Phi \rangle$$ **(in NH)**

Casas, Ibarra (01)

- Parameters of light (active) neutrinos

$D_\nu^{1/2} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3} = 0)$: ν masses

Dirac phase δ

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$$

Majorana phase η

- Parameters of heavy neutrinos

$D_N^{1/2} = \mathrm{diag}(\sqrt{M_2}, \sqrt{M_3})$: N masses

$$\Omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$$

Complex number $\boldsymbol{\omega}$

Sign parameter $\boldsymbol{\xi = \pm 1}$

Kinetic Equation in ARS

- Sterile neutrinos: [Akhmedov, Rubakov, Smirnov '98]

$$i\frac{d\rho_{NN}}{dt} = \left[H^0_{NN} + V_N , \rho_{NN} \right] - \frac{i}{2}\left\{ \Gamma^d_{NN} , \rho_{NN} - \rho^{eq}_{NN} \right\}$$

  - Effective potential and destruction rate

$$V_N = \frac{T}{8} F^\dagger F \qquad \Gamma^d_N = 0.04\, V_N$$

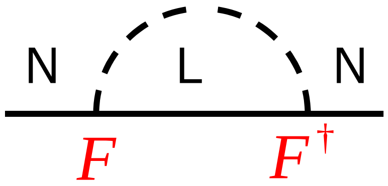
$$F^\dagger F = D_N^{1/2} \Omega^\dagger D_\nu \Omega D_N^{1/2}$$

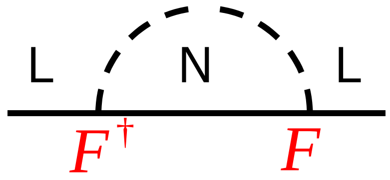
Independent on PMNS matrix
→ insensitive to neutrino parameters !

Kinetic Equations in AS

[TA, Shaposhnikov '05]

- Include the new effect
  - **Exchange of asymmetries between sterile (RH) neutrinos and active (LH) leptons**





Kinetic Equations in AS

- Sterile (RH) neutrinos: [TA, Shaposhnikov '05]

$$i\frac{d\rho_{NN}}{dt} = \left[H^0_{NN} + V_N, \rho_{NN} \right] - \frac{i}{2}\left\{ \Gamma^d_{NN}, \rho_{NN} - \rho^{eq}_{NN} \right\} + \frac{i\sin\phi}{4} T \cdot F^\dagger (\rho_{LL} - \rho^{eq}_{LL}) F$$

- Active (LH) leptons:

$$i\frac{d\rho^{diag}_{LL}}{dt} = [H^0_{LL} + V_L, \rho^{diag}_{LL}] - \frac{i}{2}\left\{ \Gamma^d_{LL}, \rho^{diag}_{LL} - \rho^{eq}_{LL} \right\} + \frac{i\sin\phi}{4} T \cdot F(\rho_{NN} - \rho^{eq}_{NN}) F^\dagger$$

Does depend on MNS matrix
→ sensitive to neutrino parameters !

Dirac phase δ and Majorana phase η !

NH Case

[TA, Ishida '10]

$$\delta_\nu = \frac{1}{2}\sin\theta_{12}\sin 2\theta_{13}[\cos^2\theta_{13}(3+\cos 4\theta_{23}) - 4\sin^2\theta_{13}]\,\sin(\delta+\eta) + \cos\theta_{12}\sin 4\theta_{23}\cos^3\theta_{13}\sin\eta + \mathcal{O}(r_m)\,.$$

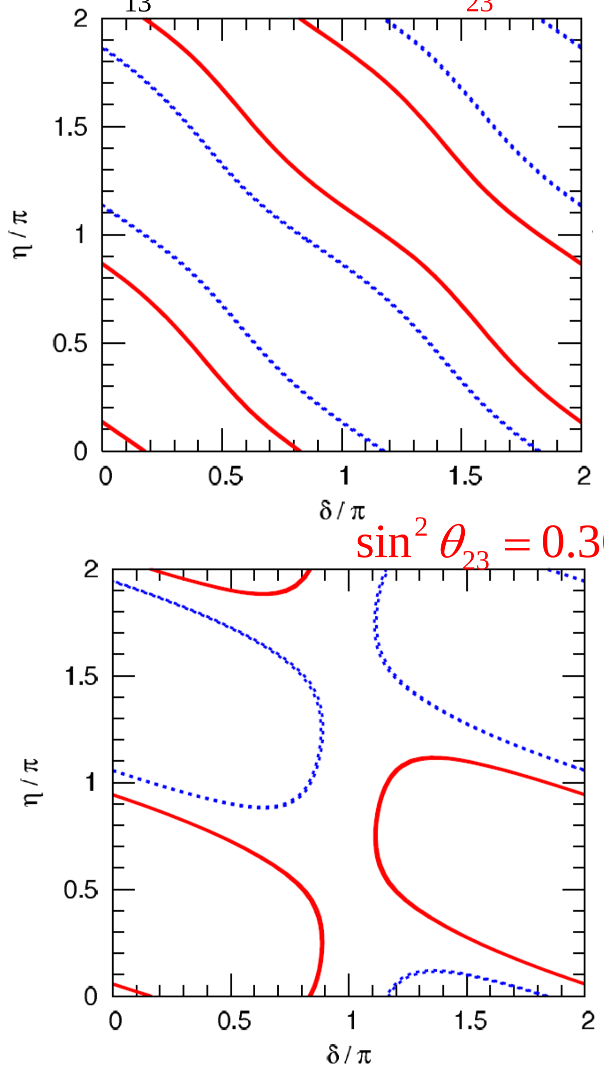
$$r_m = m_{sol} / m_{atm} = 0.18$$

- When θ23 = π/4 (maximal)
  - $\mathrm{BAU} \propto \sin(\delta+\eta)$
- When θ13 = 0
  - $\mathrm{BAU} \propto \sin\eta$
- When θ23 = π/4 and θ13 = 0
  - $\delta_\nu = 0$

No BAU is generated !

$M_3 = 5\mathrm{GeV}, \Delta M_{32}^2 / M_3^2 = 10^{-8}$

$\sin^2\theta_{13} = 0.053$ $\sin^2\theta_{23} = 0.5$



Summary

- Heavy neutral leptons (or sterile neutrinos, heavy neutrinos, right-handed neutrinos⋯) are well-motivated particles physics beyond the standard Model.
- One of the most important motivations is the seesaw mechanism for neutrino masses.
- Cosmology of heavy neutral leptons are very interesting !
  - Dark Matter ($M_N \sim 10$ keV)
  - Baryogenesis
    - Leptogenesis ($M_N > 10^9$ GeV)
    - Baryogenesis via neutrino oscillation (M_N~0.1-100GeV)
    - ⋯

Search for heavy neutral leptons is very important for understanding the origin of neutrino masses as well as the mysteries of our universe!