The νMSM, Dark Matter and Neutrino Masses

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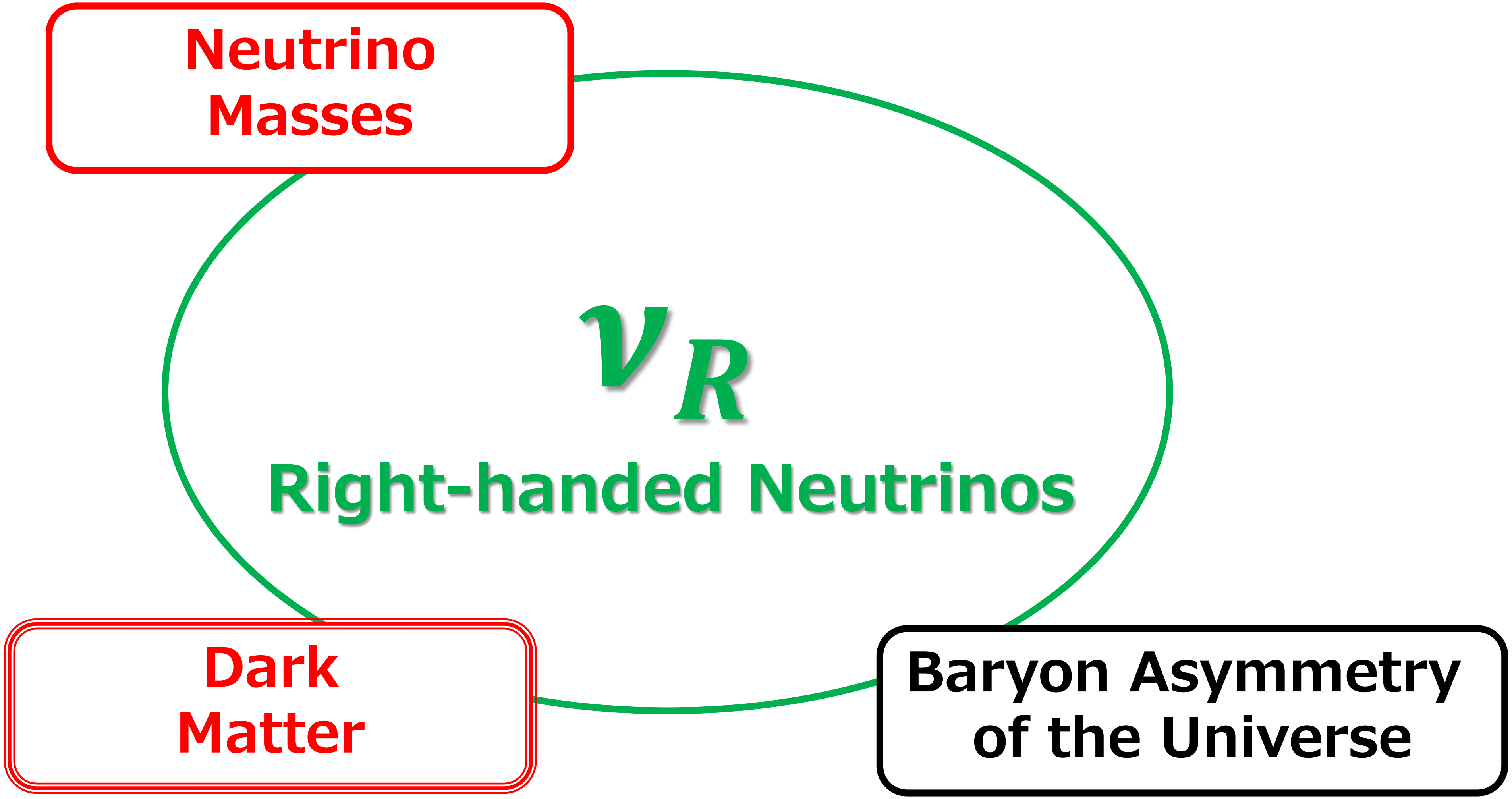
Contents

- **Introduction**
  - Motivation
  - The νMSM
- **Sterile Neutrino as Dark Matter**
  - Production
  - Constraints
  - Current status of sterile neutrino dark matter
  - Search for sterile neutrino dark matter
- **Summary**

Overview


Neutrino Masses
ν_R
Right-handed Neutrinos
Dark Matter
Baryon Asymmetry of the Universe

Introduction

Origin of neutrino masses

- Neutrino mass scales
  - Atmospheric: $\Delta m^2_{\rm atm} \simeq 2.4\times 10^{-3}\,{\rm eV}^2$
  - Solar : $\Delta m^2_{\rm sol} \simeq 7.5\times 10^{-5}\,{\rm eV}^2$

  $\Rightarrow$ **Clear signal for new physics beyond the SM !**

- Important questions:
  - **What is the origin of neutrino masses?**
  - **What are the implications to other physics?**
  - **How do we test it experimentally?**

Neutrino masses by
the seesaw mechanism

Standard Model

Higgs Boson	Quarks and Leptons (left-handed)	(right-handed)	Gauge Bosons
h	$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$	$\begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix}$	g, Z^0
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$e_R \quad \mu_R \quad \tau_R$	$W^\pm$, γ

Three right-handed neutrinos

Higgs Boson	Quarks and Leptons (left-handed)	Quarks and Leptons (right-handed)	Gauge Bosons
h	$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$	$u_R \; c_R \; t_R$ $d_R \; s_R \; b_R$	g Z^0
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$e_R \; \mu_R \; \tau_R$ $\nu_{R1} \; \nu_{R2} \; \nu_{R3}$	$W^\pm$ γ

Extension by RH neutrinos ν_R

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

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

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

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

- **Light active neutrinos ν**
  - → explain neutrino oscillations

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

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

- **Heavy Neutral Leptons (Sterile Neutrinos) N**
  - $N \simeq \nu_R$
  - Mass M_M
  - Mixing $\Theta = M_D/M_M$

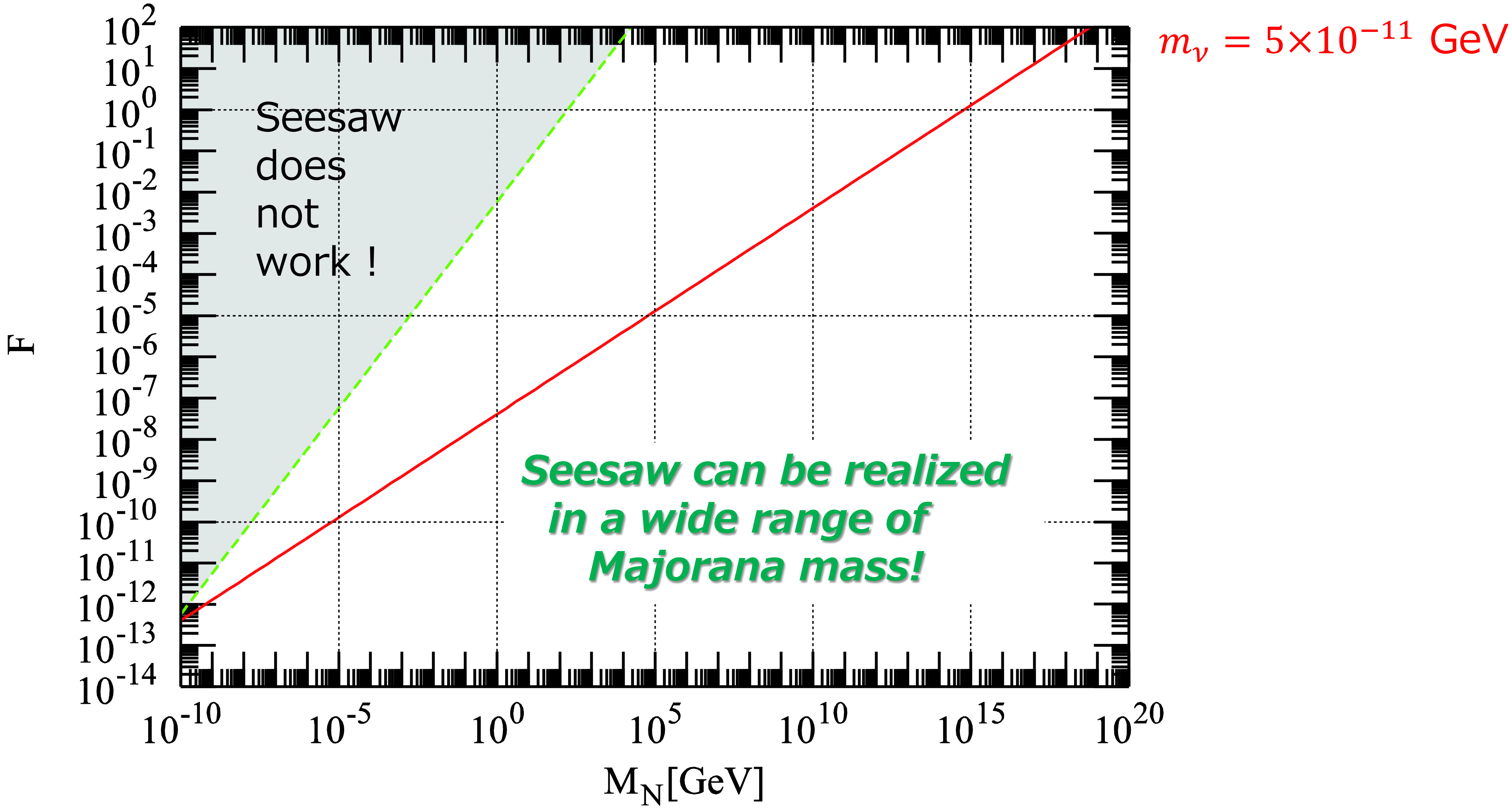
$$\nu_L = U\,\nu + \Theta\,N^c$$

Yukawa Coupling of HNL (Sterile ν)

Seesaw relation of neutrino masses

$$M_\nu = -M_D^T\, M_N^{-1} M_D$$

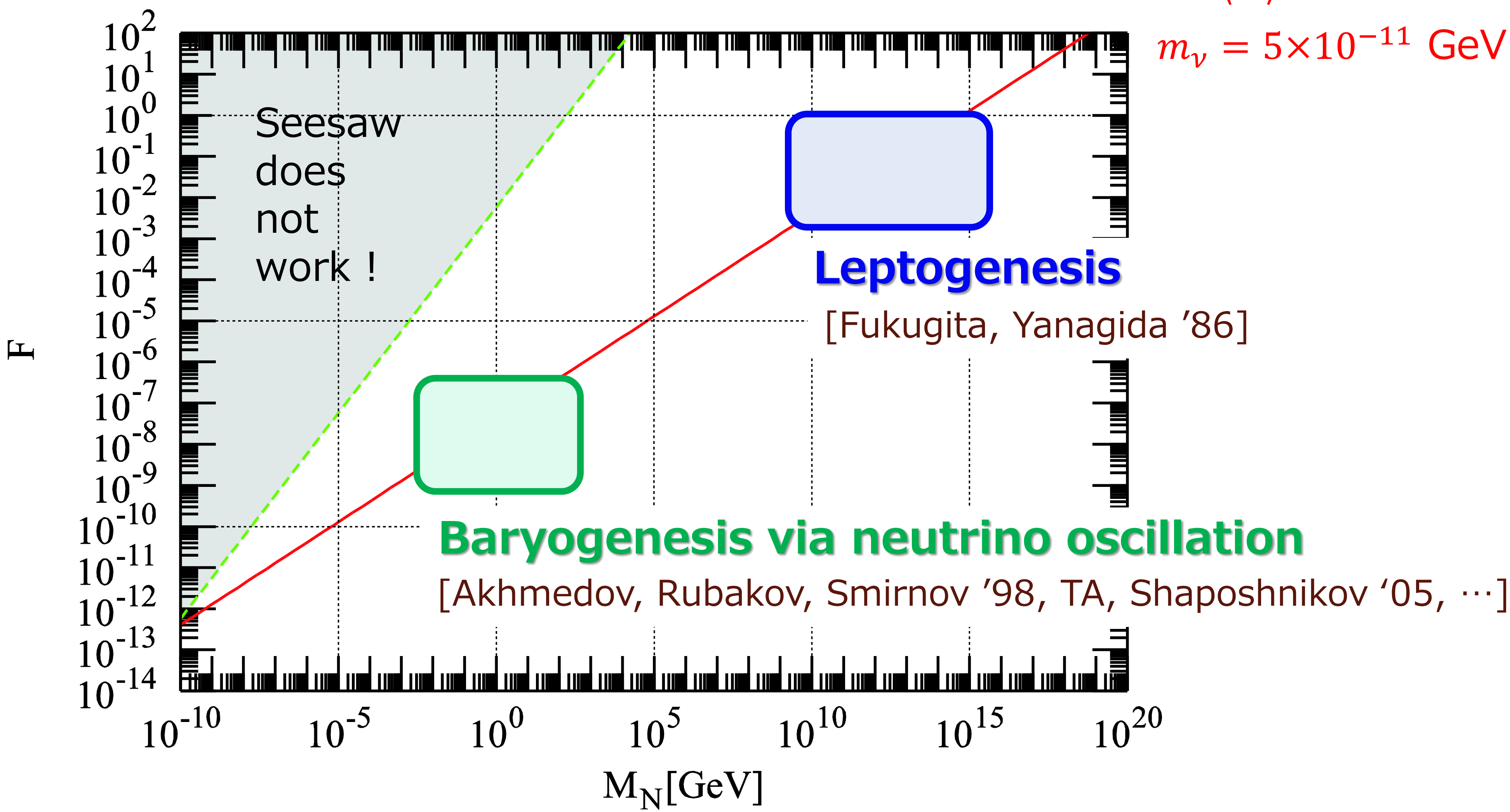
$$F = \frac{\sqrt{m_\nu M_N}}{\langle\Phi\rangle}$$



Yukawa Coupling of HNL (Sterile ν)

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

$m_\nu = 5\times10^{-11}$ GeV



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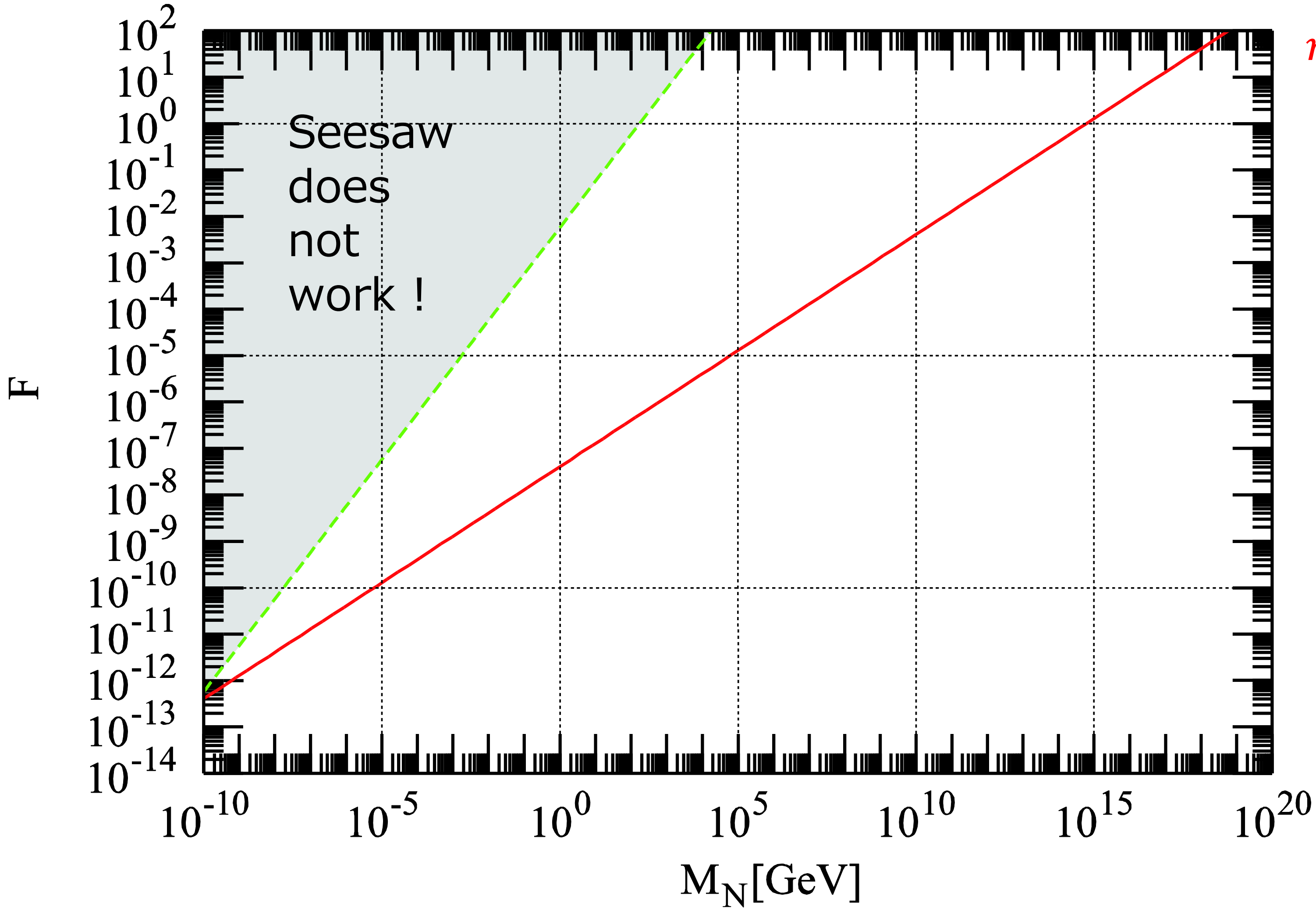
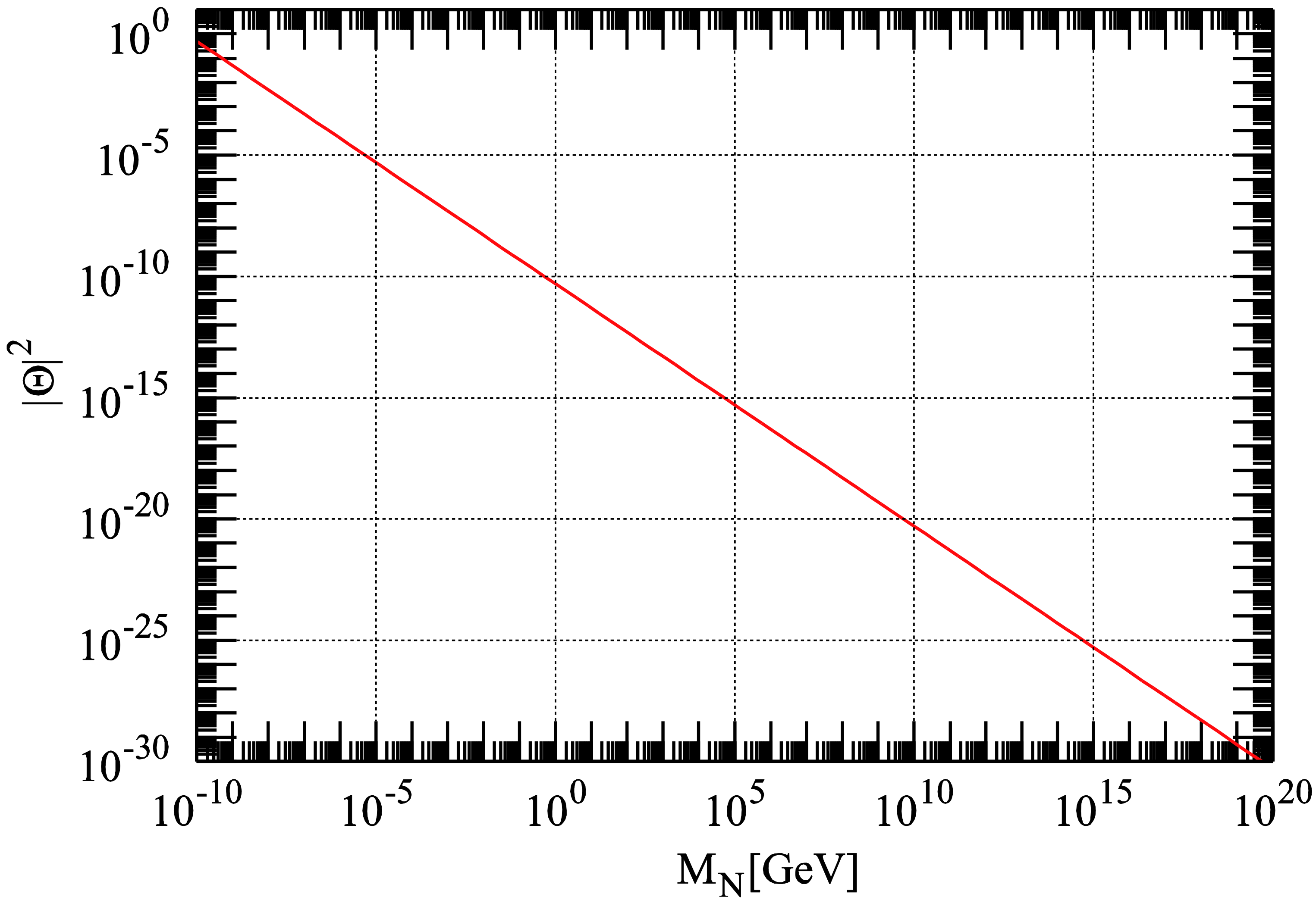
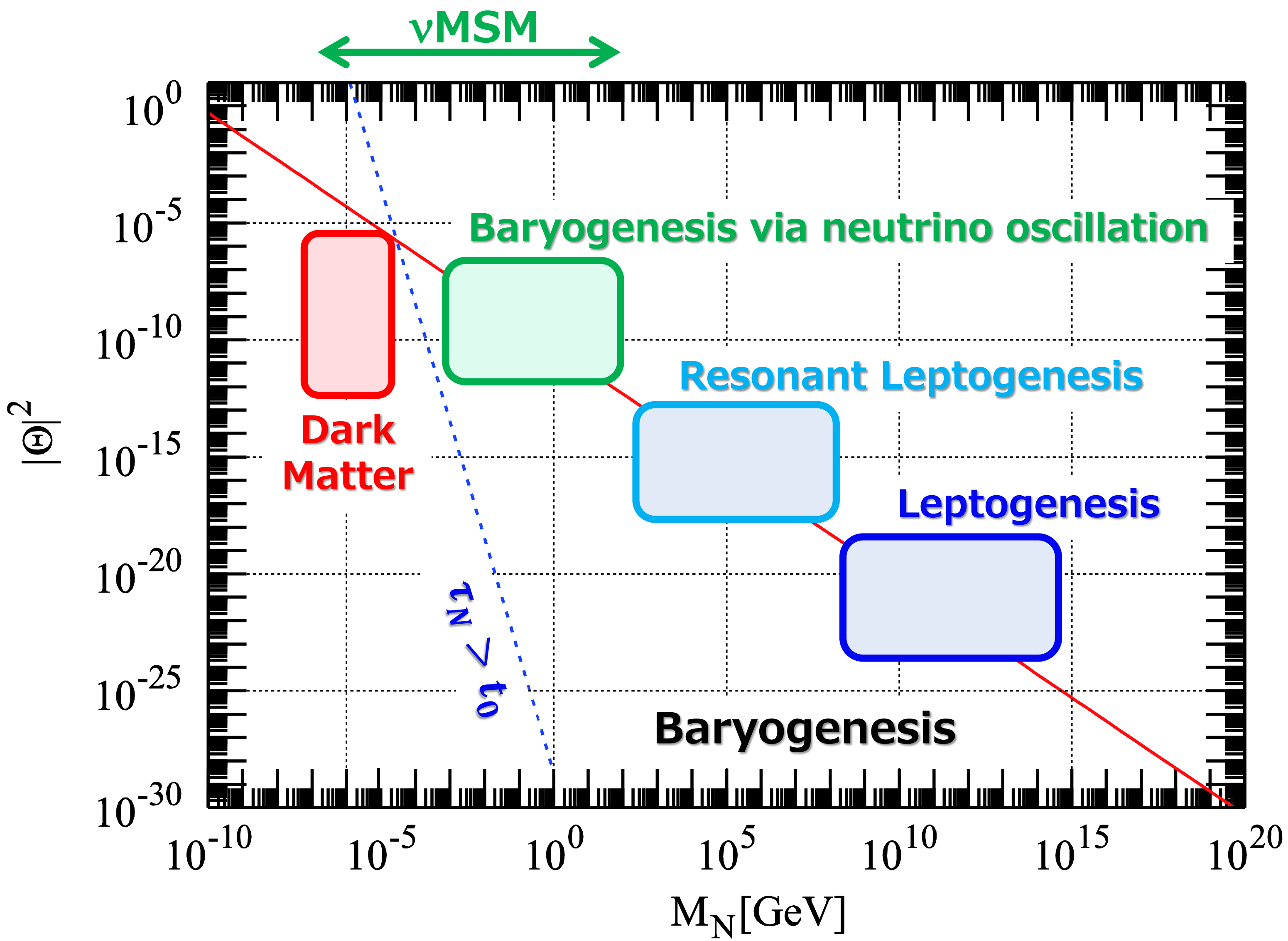


Mixing of HNL (Sterile ν)

$$|\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \qquad m_\nu = 5\times10^{-11}\ \text{GeV}$$



Various Physics of RH neutrinos



Roles of three HNLs in the νMSM

N_1 ("Dark" HNL with 10 keV mass)

- **Dark Matter Candidate**
- To avoid constraints, Yukawa coupling constants (mixing angles) should be very suppressed.

N_2 and N_3 ("Bright" and "Clear" HNLs with 0.1-10^2 GeV masses)

- **Neutrino Oscillation data**
  - Masses and mixings of active neutrinos
- **Baryon Asymmetry of the Universe (BAU)**
  - Mechanism via neutrino oscillation
    [Akhmedov, Rubakov, Smirnov '98, TA, Shaposhnikov '05, ⋯]

Sterile Neutrino as Dark Matter

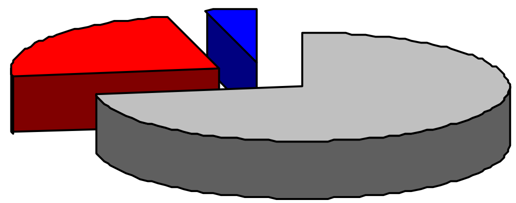
Dark matter

- Cosmological parameters are well determined now !
  - From CMBR anisotropy [Planck 2015]

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

$\Omega_{\rm dm} = \rho^0_{\rm dm}/\rho_{\rm cr}$

h : H_0 in units of 100km/sec/Mpc



- Particle physics candidate
  - "dark" (charge neutral)
  - stable within the age of the universe ($\tau > t_U \sim 10^{17}$sec)
  - its abundance should be $\Omega_{\rm dm} h^2$
  - avoids cosmological constraints

→ No candidate in the SM

Active Neutrino as Dark Matter?

Active Neutrinos as Dark Matter

- **Massive active neutrino was a candidate for dark matter, but it cannot be the dominant component of dark matter !**

- **Cosmological upper bound on sum of active neutrino masses**

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

PLANCK 2015[arXiv:1502.01589]

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

$\rho_{cr} = 10.5\, h^2\ \mathrm{GeV\ m^{-3}}$

$H_0 = 100\, h\ \mathrm{km}\ s^{-1}\mathrm{Mpc}^{-1}$

$h = 0.6774 \pm 0.0046$

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

- **Too small to explain the Dark Matter density**

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

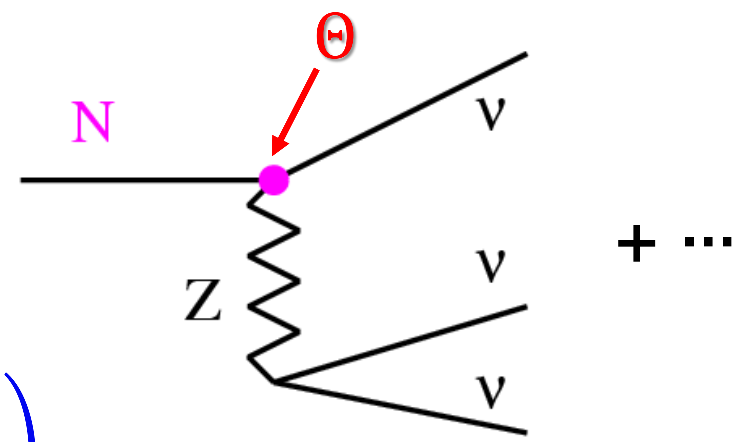
Sterile Neutrino
as Dark Matter?

Sterile Neutrino as Dark Matter

- **Sterile neutrino N_1 with $M_1 = O(10)$ keV is a good candidate for (warm) dark matter**

- **Sterile neutrino N_1 is not completely stable**
  (without introducing symmetry)
  - Dominant decay: $N_1 \to 3\,\nu$
  - 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 Sterile Neutrino

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

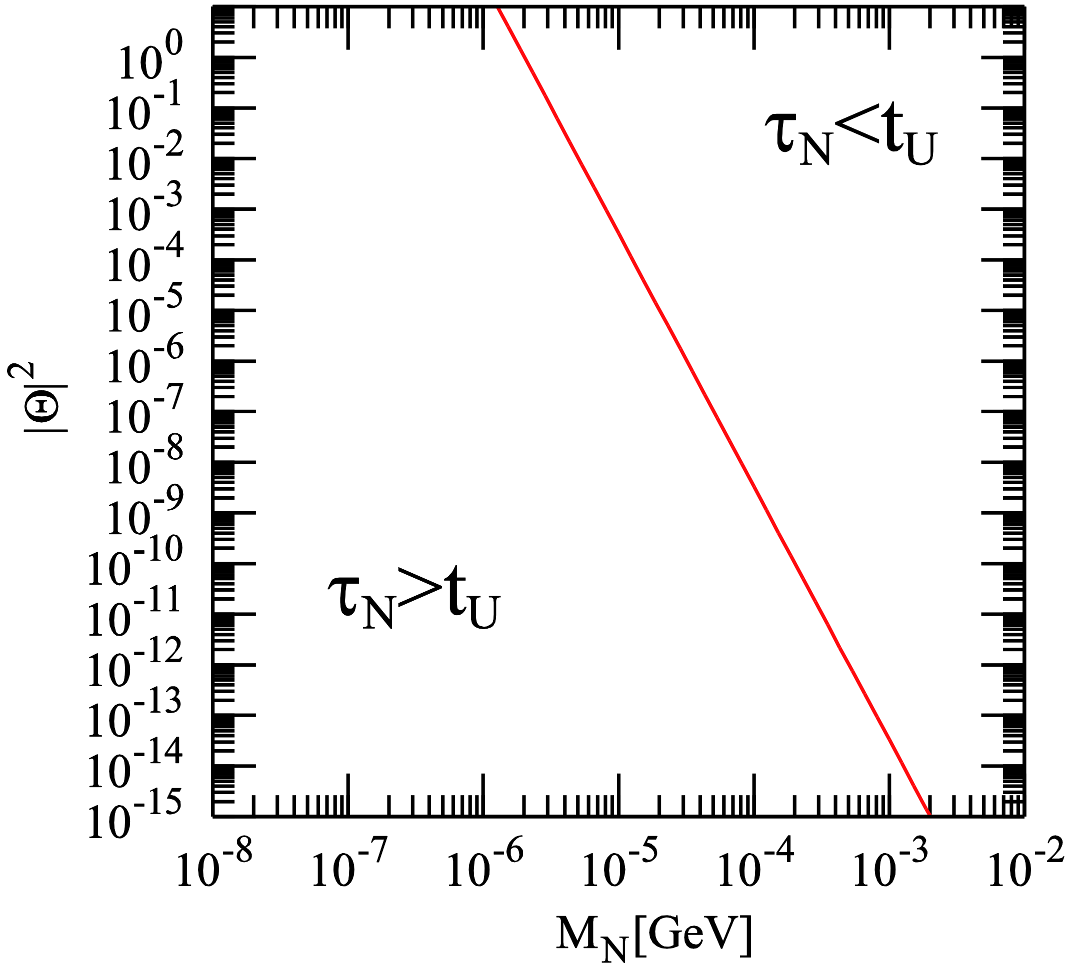
$t_U = (13.81 \pm 0.05)$ Gyr [PDG '15]

When M_N=10 keV,

$\tau_N > t_U$ if $|\Theta|^2 < 3.3\times10^{-4}$

When $M_N \lesssim$1 keV,

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



Sterile neutrino 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 Dark Matter Sterile Neutrino -- Simplest Case --

Production of DM

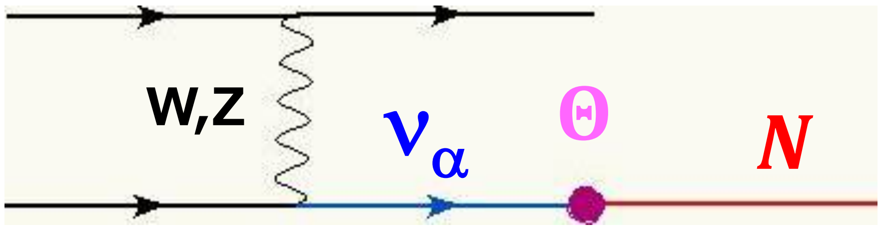
- **When the active-sterile mixing is small, dark matter N_1 is not thermalized in the early universe**
  - Present abundance is sensitive to the initial condition
    →
    Usually, the abundance is taken to be zero initially,
    i.e., after the reheating of the inflation

- **Production scenarios:**
  - **Dodelson-Widrow scenario**
    - (Non-resonant) production via active-sterile neutrino mixing
  - **Shi-Fuller scenario**
    - Resonant production due to lepton asymmetry
  - **Other scenarios**
    - Production by interaction which is absent in the seesaw mechanism

Dodelson-Widrow Scenario

- 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

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

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

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

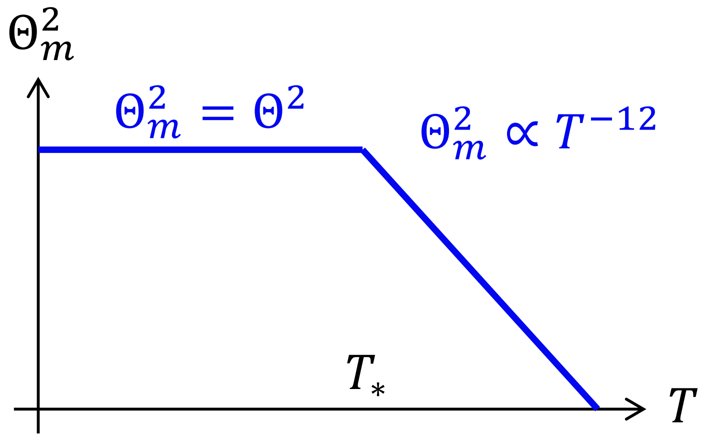
$$H_{eff} = \frac{1}{4T}\begin{pmatrix} -M_N^2 - 4bG_F^2 T^6 & 2\Theta M_N^2 \\ 2\Theta M_N^2 & M_N^2 \end{pmatrix}$$

- Mixing angle in the early universe

$$\tan 2\Theta_m = \frac{4\Theta M_N^2}{2M_N^2 + 4bG_F^2 T^6}$$

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

$$T_* = \left(\frac{1}{2b}\right)^{\frac{1}{6}} \left(\frac{M_N}{G_F}\right)^{\frac{1}{3}} \simeq 130\mathrm{MeV}\left(\frac{M_N}{1\mathrm{keV}}\right)^{\frac{1}{3}}$$



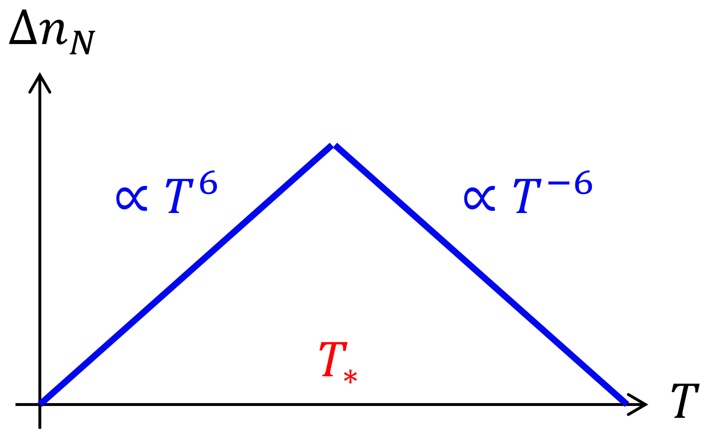
Abundance of DM *N*

- Dominant production occurs at $T = T_*$

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

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

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



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

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

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

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

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

For the precise estimation of $\Omega_{N_1} h^2$

- We have to
  - **Solve kinetic equation for density matrix**
    - Including the oscillation effects in addition to the rapid interaction of active neutrinos and the production and destruction of sterile neutrinos
  - **Take into account hadronic uncertainties,**
    since dominant production occurs near the quark-hadron transition

$$T_* = \left(\frac{1}{2b}\right)^{\frac{1}{6}} \left(\frac{M_N}{G_F}\right)^{\frac{1}{3}} \simeq 130\mathrm{MeV}\left(\frac{M_N}{1\mathrm{keV}}\right)^{\frac{1}{3}}$$

    - Hadronic contributions to production rates
    - QCD equation of state
      (how the effective degrees of freedom evolve at the transition)

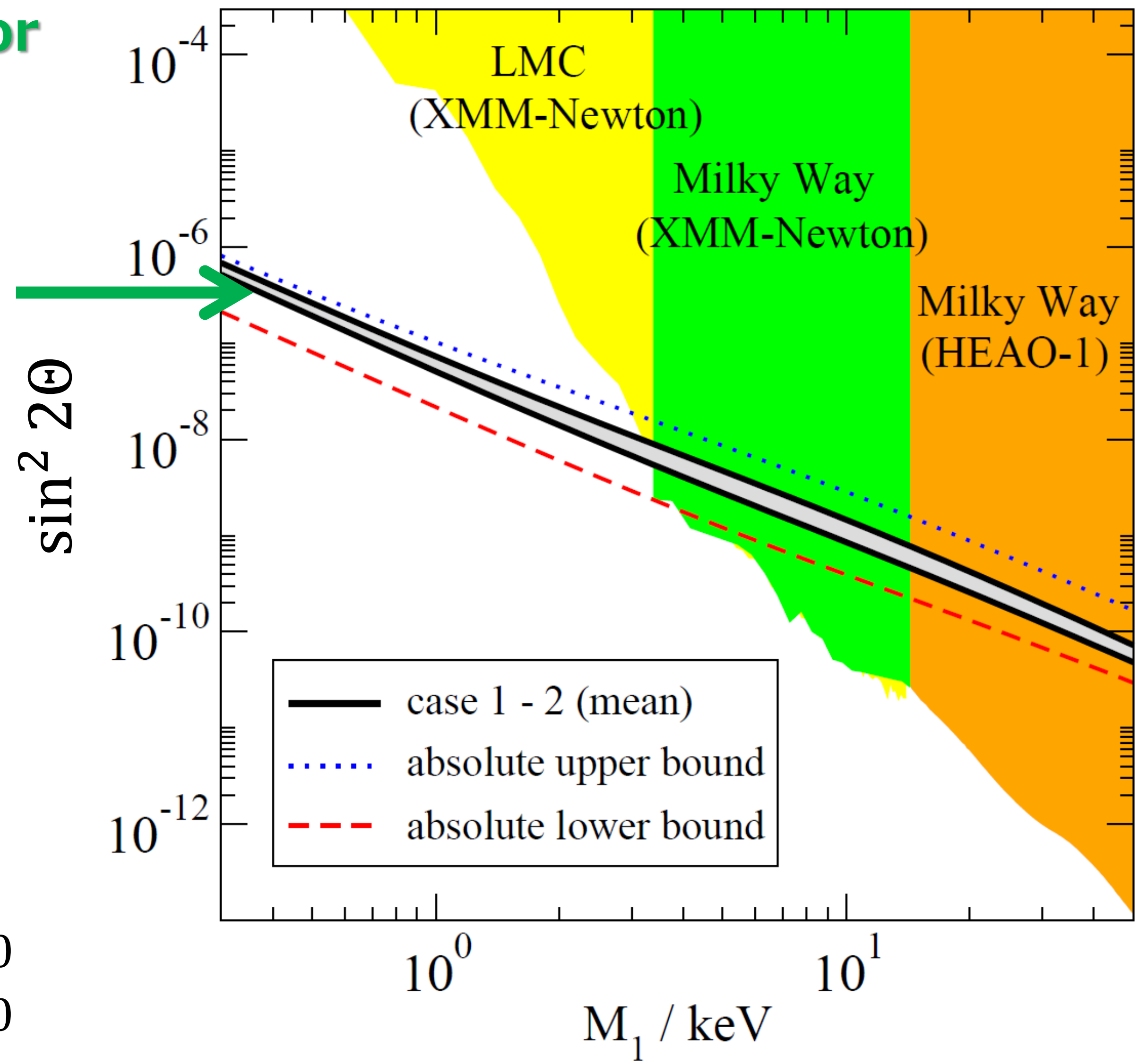
TA, Laine, Shaposhnikov '07 [hep-ph/0612182]

Mixing angle required for DM abundance

TA, Laine, Shaposhnikov '07

Mixing angle required for
$\Omega_{N_1} = \Omega_{dm}$

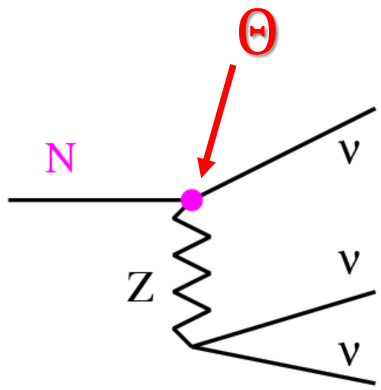
$$\sin^2 2\Theta \simeq 8\times10^{-8}\left(\frac{M_N}{1\mathrm{keV}}\right)^2$$



case 1: $\Theta_{e1} \neq 0, \Theta_{\mu1} = \Theta_{\tau1} = 0$
case 2: $\Theta_{\tau1} \neq 0, \Theta_{\mu1} = \Theta_{e1} = 0$

Constraint on radiative decay of DM N

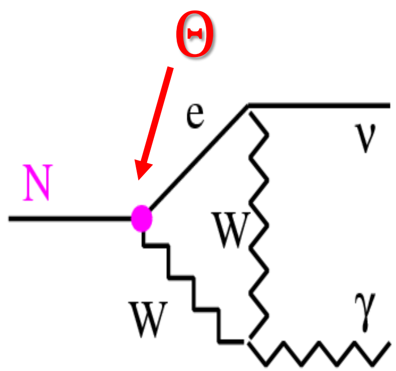
- **N is not completely stable particle !**
  - Dominant decay: $N_1 \to 3\nu$ for $M_1 \sim$keV
  - Lifetime can be very long



\+ …

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

- **N is not completely “dark” !**
  - Subdominant decay: $N_1 \to \nu + \gamma$
  - Branching ratio is very small



\+ …

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

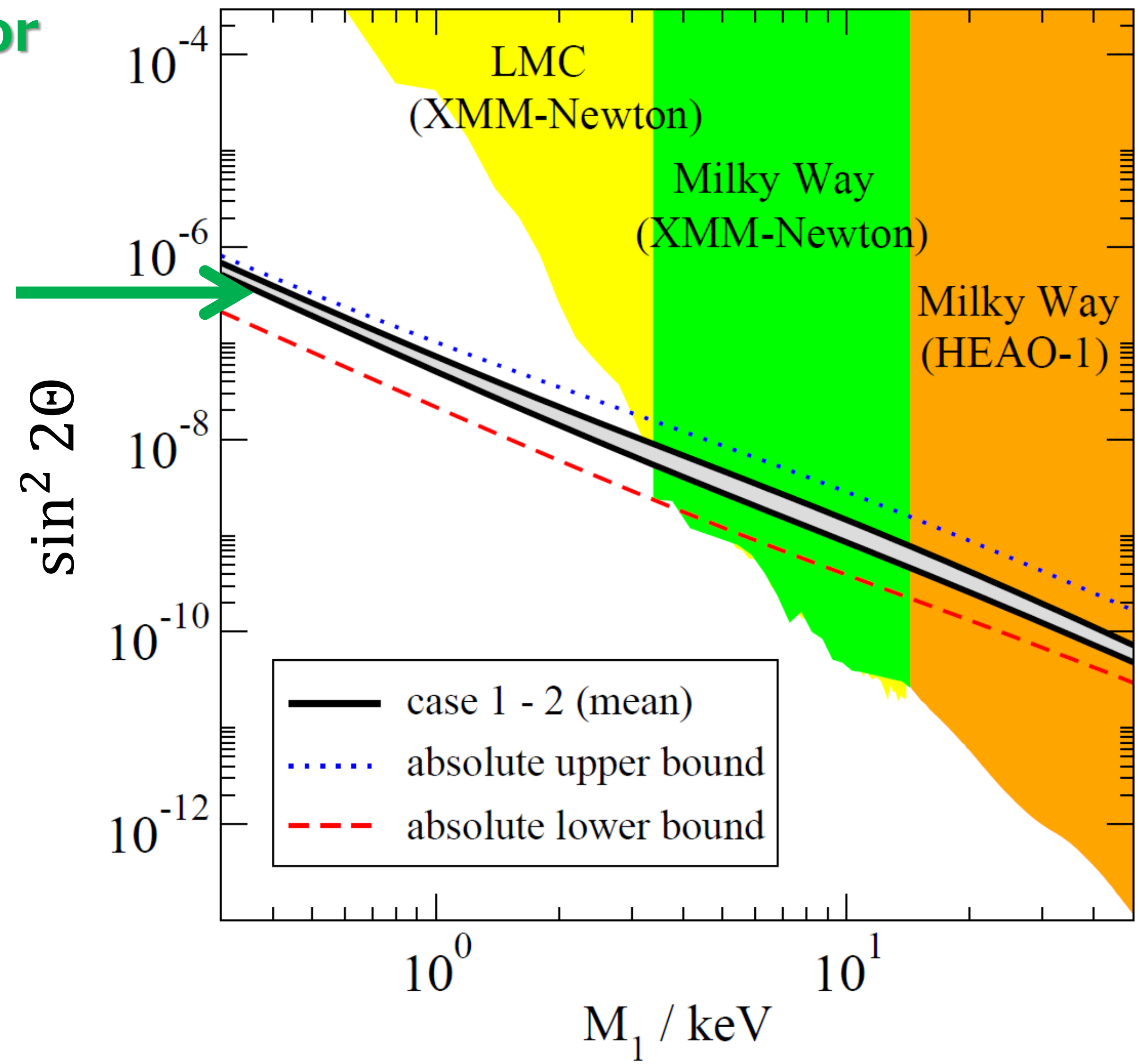
  - Severely restricted from x-ray observations

Mixing angle required for DM abundance

TA, Laine, Shaposhnikov '07

Mixing angle required for
$$\Omega_{N_1} = \Omega_{dm}$$

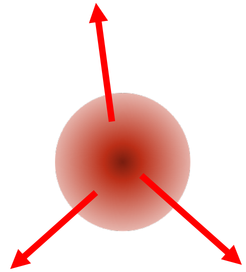
$$\sin^2 2\theta \simeq 8\times10^{-8} \left(\frac{M_N}{1\text{keV}}\right)^2$$



M_N < 3 keV is possible !

Warm Dark Matter

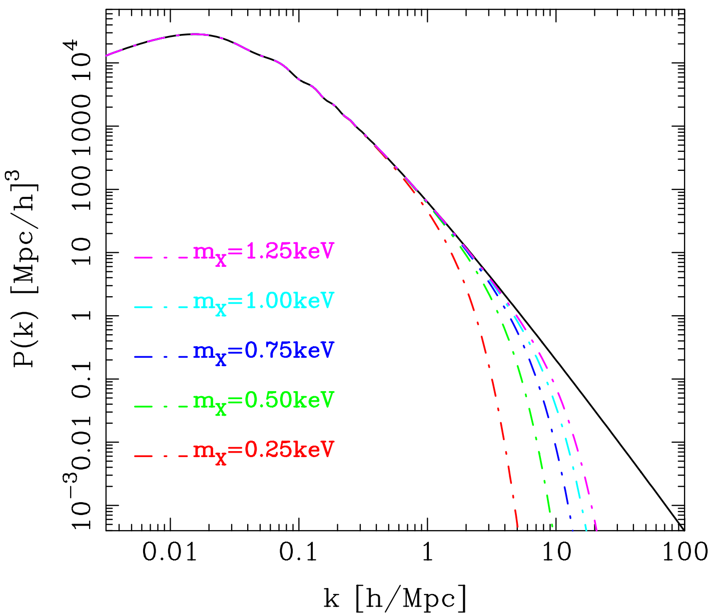
- **Sterile neutrino DM is WDM**
  - Free streaming length: $\lambda_{FS} \sim \mathrm{Mpc}\left(\frac{\mathrm{keV}}{M_1}\right)\frac{\langle q_{N_1}\rangle}{\langle q_\nu\rangle}$



- **WDM's stream out of over-dense regions, which suppresses the growth of density fluctuations on scales smaller than λ_{FS}**

→ may solve difficulties in small scale structures of CDM

Smith, Markovic '11



- **Constraints from Ly-α forests**
  - Lower bound on DM mass

$$M_1 > (10 - 34)\ \mathrm{keV}$$ @95% CL

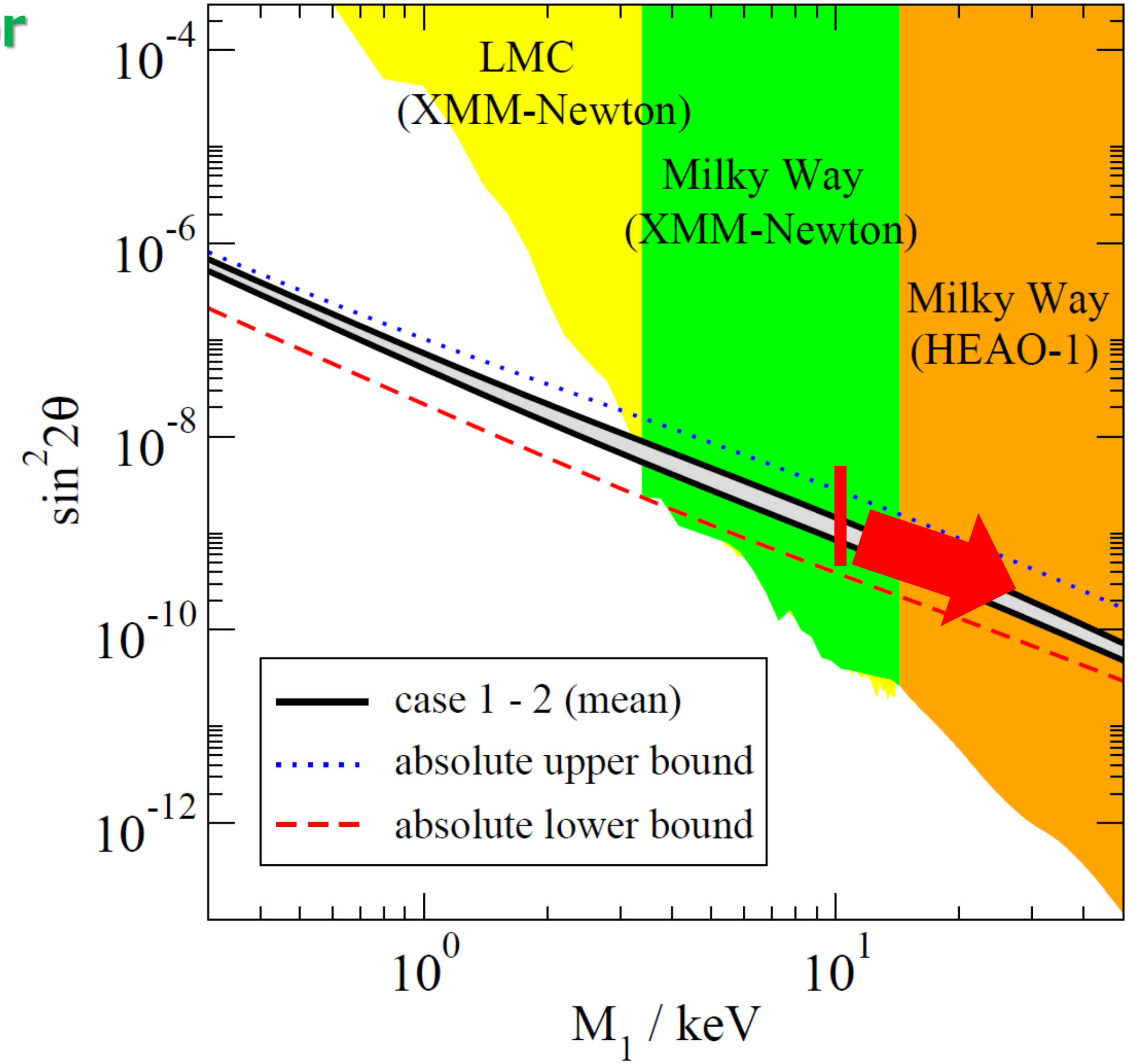
Baur et al [1706.03118]

Mixing angle required for DM abundance

TA, Laine, Shaposhnikov '07

Mixing angle required for
$$\Omega_{N_1} = \Omega_{dm}$$

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



- **X-ray const. gives** $M_N < 3$ **keV**
- **Ly-α const. gives** $M_N > (10-34)$ **keV**

DW scenario is excluded !

Production of Dark Matter Sterile Neutrino -- Possible Scenarios --

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 !**
  - **Lepton asymmetry $\mathcal{L}$ induces the additional potential**

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

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

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

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

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

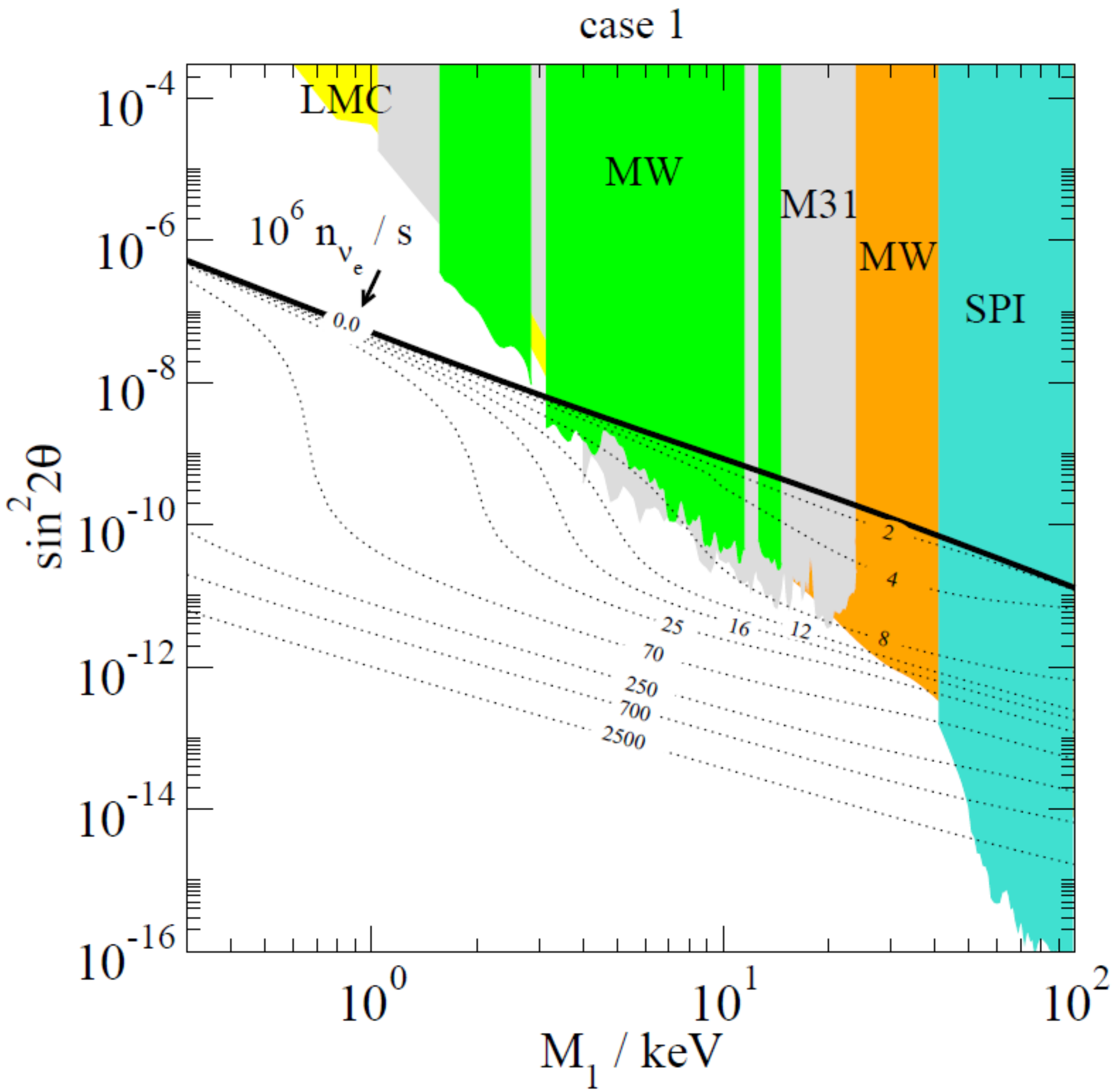
Production is enhanced due to the MSW effect

Mixing angle required for DM abundance

Laine, Shaposhnikov '08

- **Resonant production**

  Smaller mixing can account for the correct dark matter abundance

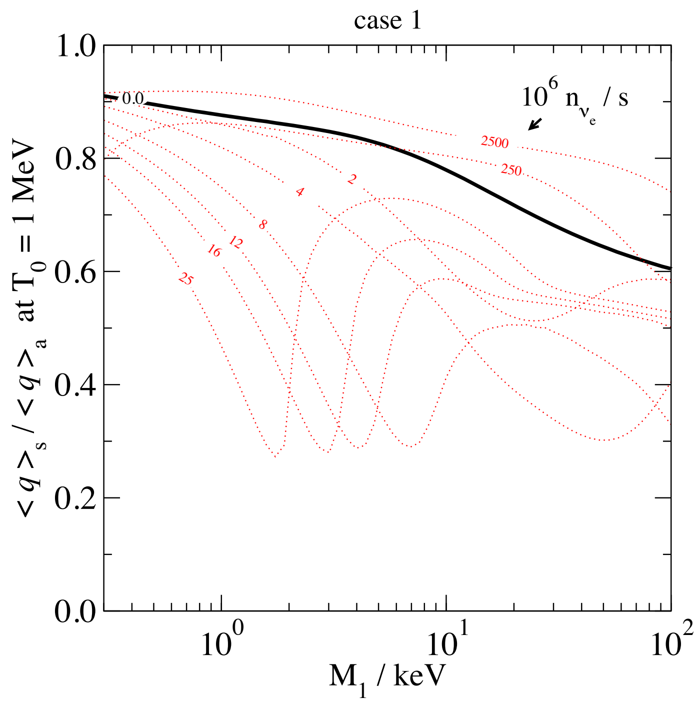


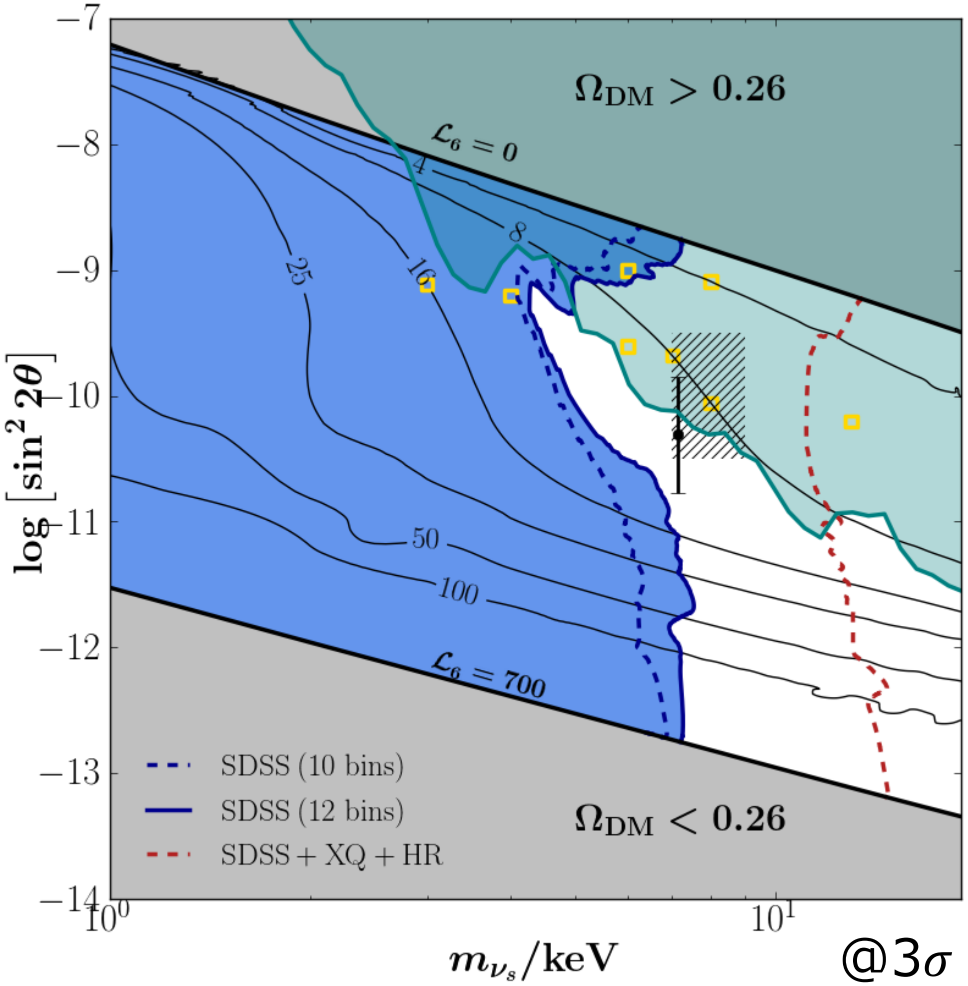
$M_N < 50$ keV is possible !

Constraints from Ly-α forests

- Constraints from Ly-α forests for Shi-Fuller scenario is shown by blue region

- Viable region exists!





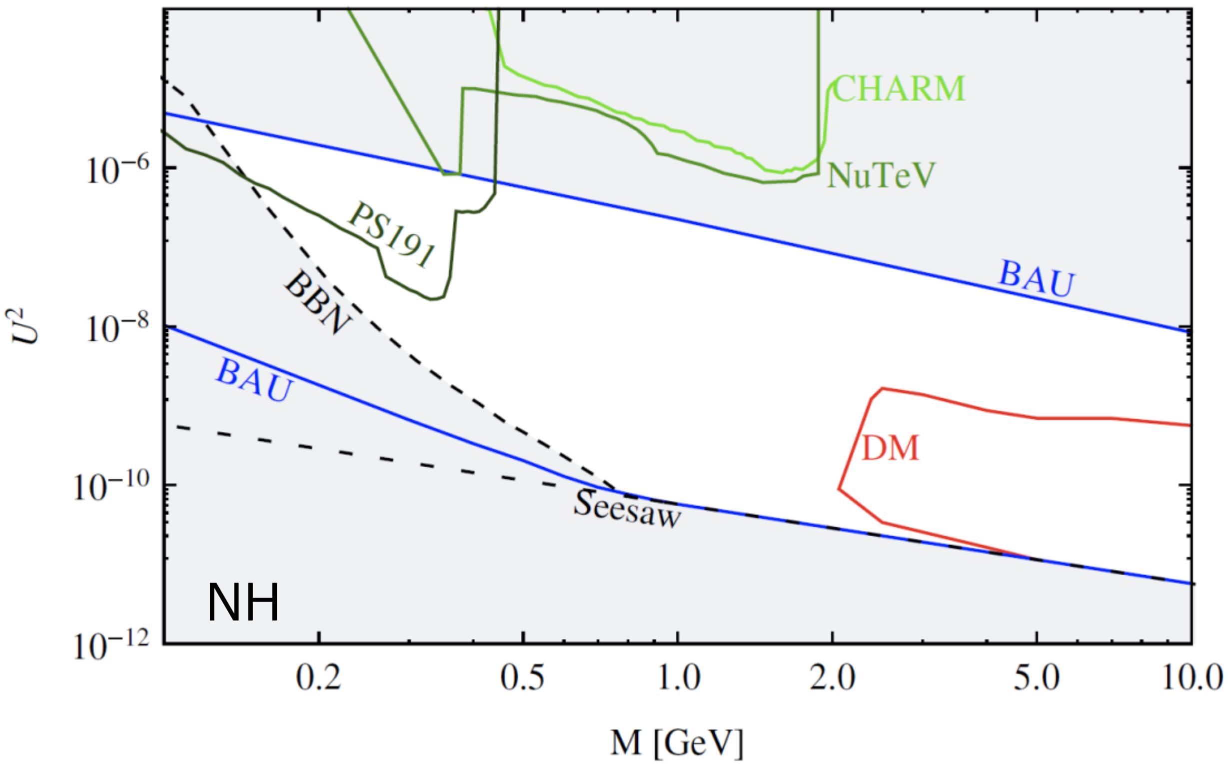
@3σ

Baur et al [1706.03118]

Origin of lepton asymmetry

- Large lepton asymmetry for Shi-Fuller mechanism can be generated by heavier HNLs N_2 and N_3
  - Baryogenesis via oscillation mechanism at $T \gtrsim M_W$
  - Leptogenesis around DM production at $T{\sim}100$ MeV

    Canetti, Drewes, Shaposhnikov ’13
    Canetti, Drewes, Frossard, Shaposhnikov ‘13



Sterile Neutrino as Dark Matter

- The simplest 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, ⋯

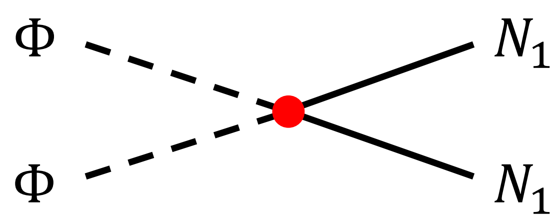
  incomplete list

  - ⋯

Production by higher-dimensional operator

- Higher-dimensional operator provides additional production of DM sterile neutrinos

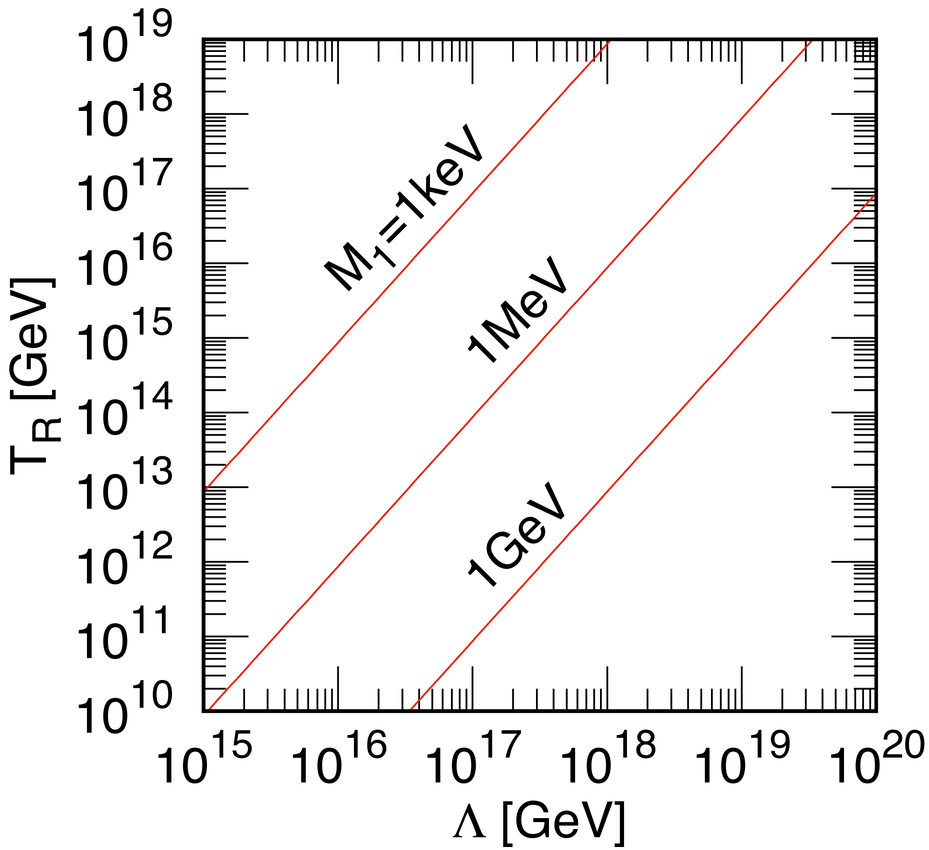
$$\mathcal{L} = \frac{1}{2\Lambda}\Phi^\dagger\Phi\,\overline{\nu_R^c}\nu_R + \text{h.c.}$$



- Dominant production occurs at reheating epoch

$$\Omega_{N_1}h^2 \simeq 0.1\left(\frac{M_p}{\Lambda}\right)^2\left(\frac{T_R}{10^{13}\ \text{GeV}}\right)\left(\frac{M_1}{5\ \text{GeV}}\right)$$

Bezrukov, Gorbunov, Shaposhnikov '09



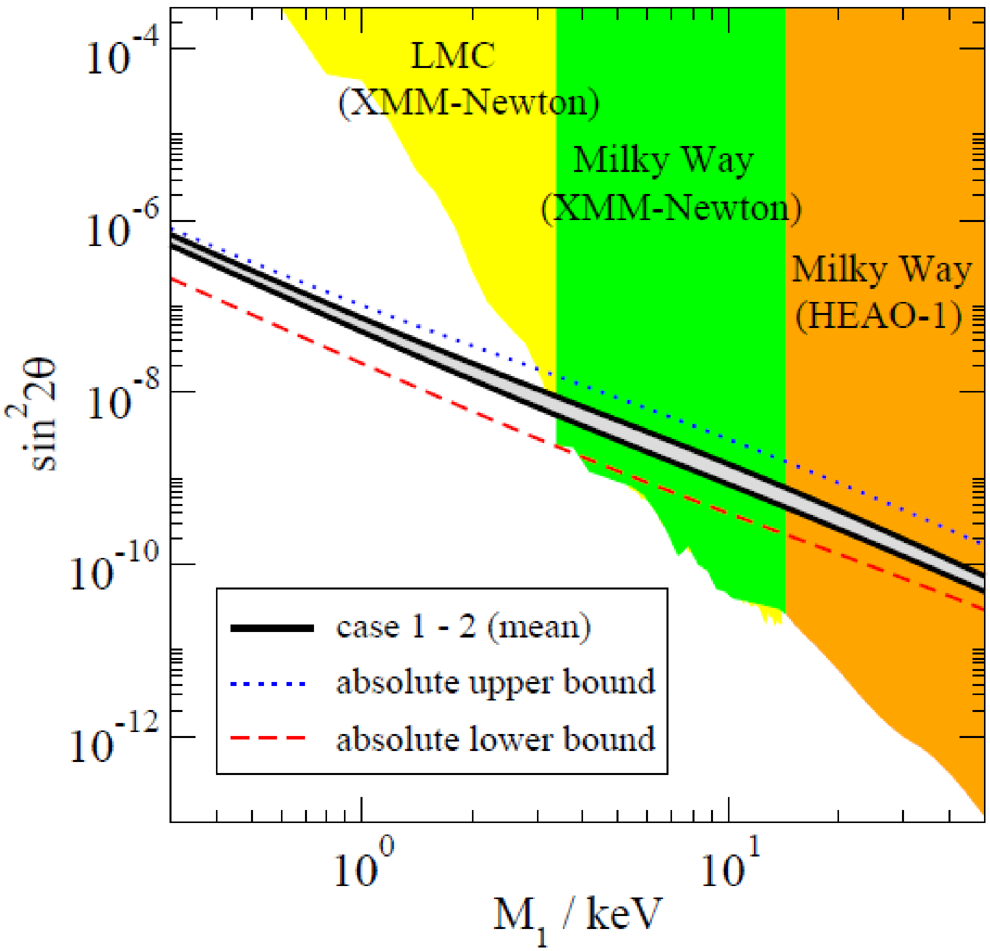
TA, Eijima, Ishida, Minogawa, Yoshii '17

Implications

- DM sterile neutrino N1 must have suppressed Yukawa interaction !

$$|F_{\alpha I}| \lesssim 10^{-12}$$

What this implies???



How many RH neutrinos are needed?

- We need at least "two" sterile (RH) neutrinos to explain $\Delta m^2_{\rm atm} \simeq 2.5 \times 10^{-3}\,\text{eV}^2\,, \quad \Delta m^2_{\rm sol} \simeq 8.0 \times 10^{-5}\,\text{eV}^2$
  - In this case, the lightest active neutrino is massless

- DM sterile neutrino:

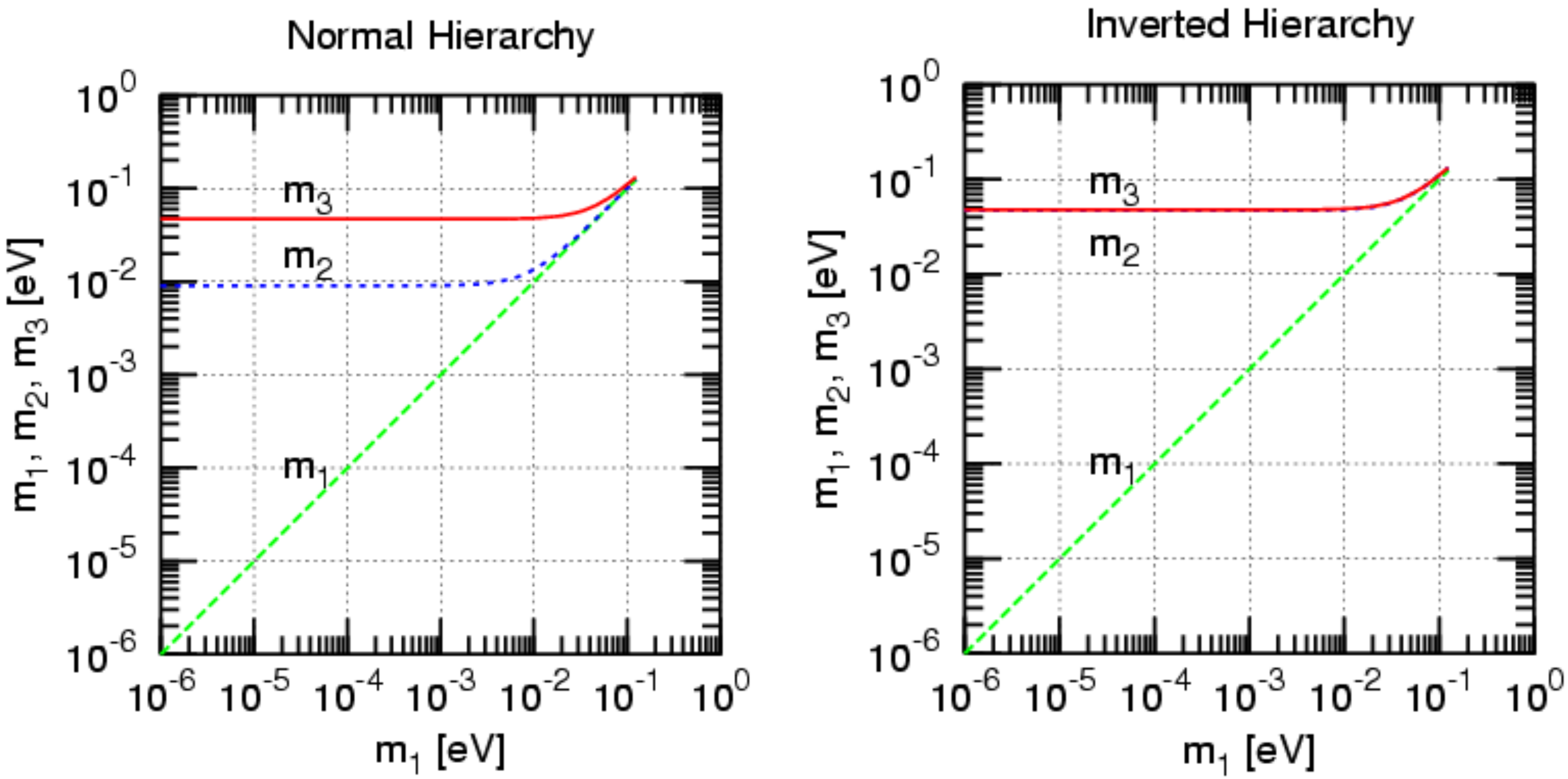
$$m_{\rm dm} = \sum_{\alpha=e,\mu,\tau} \frac{|M_D|^2_{\alpha 1}}{M_1} \simeq 2 \cdot 10^{-5}\text{eV}\left(\frac{\text{keV}}{M_1}\right) \ll \sqrt{\Delta m^2_{\rm sol}} \simeq 9 \times 10^{-3}\text{eV}$$

  - DM sterile neutrino is irrelevant for explaining neutrino mass scales in oscillation experiments (as well as baryogenesis and $0\nu\beta\beta$ decay)

- We need at least "three" sterile neutrinos !
  - In this case,

$$m_{\nu_1} \lesssim m_{\rm dm} \simeq 2 \cdot 10^{-5}\text{eV}\left(\frac{\text{keV}}{M_1}\right)$$

Active neutrino masses



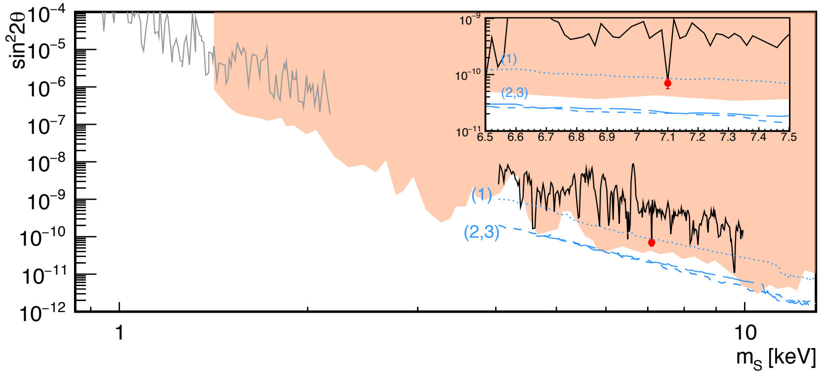
➡ **exclude the degenerate masses of active neutrinos**

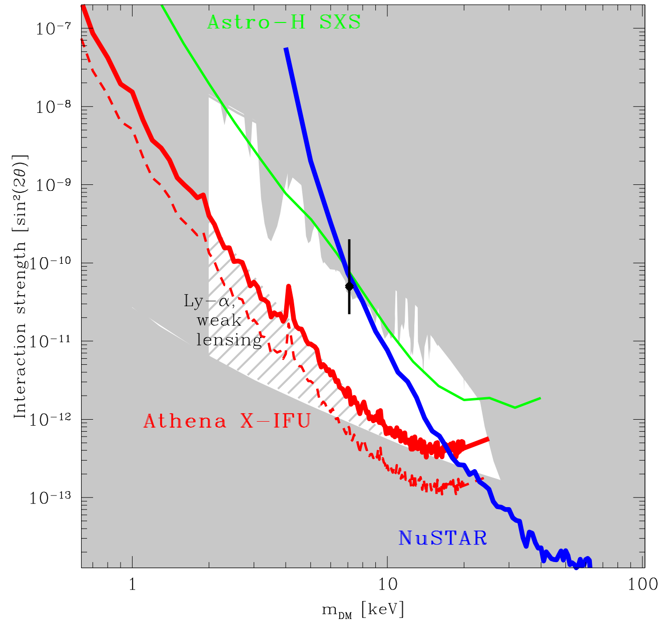
Search for Dark Matter
Sterile Neutrino

Search for sterile neutrino dark matter

- **Astrophysical search for radiative decay $N_1 \to \nu + \gamma$**
  - Astro-H/Hitomi + ⋯
  - Microcalorimeter sounding rockets
  - Athena X-ray telescope
  - ⋯

Figueroa-Feliciano et al [1506.05519]





Neronov, Malyshev[1509.02758]

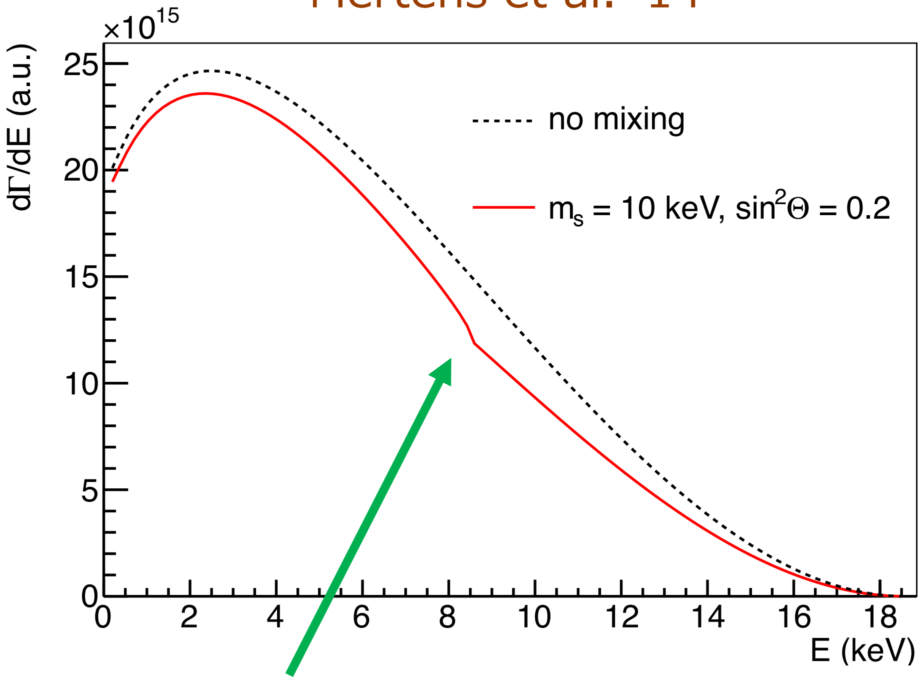
- **Crucial test for sterile neutrino dark matter**
  - **Mass + decay rate (mixing) → production scenario**

Search for sterile neutrino dark matter

- **Laboratory searches**
  - **Tritium beta decay** $^3\mathrm{H} \rightarrow\ ^3\mathrm{He}^+ + e^- + N_1$

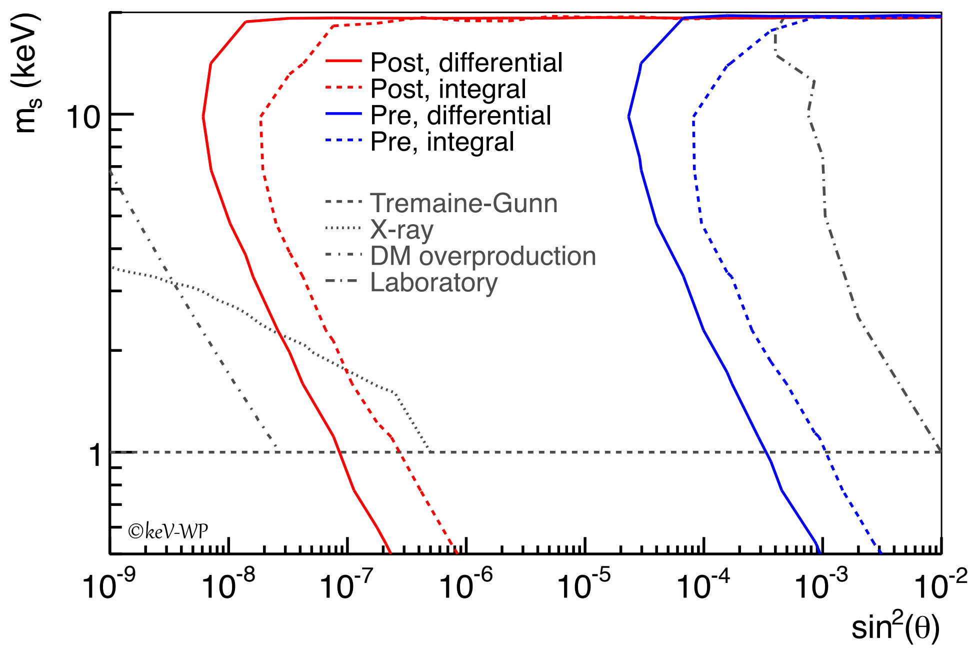
KATRIN experiment

Mertens et al. '14



Characteristic kink-like signature

Adhikari et al [1602.04816]

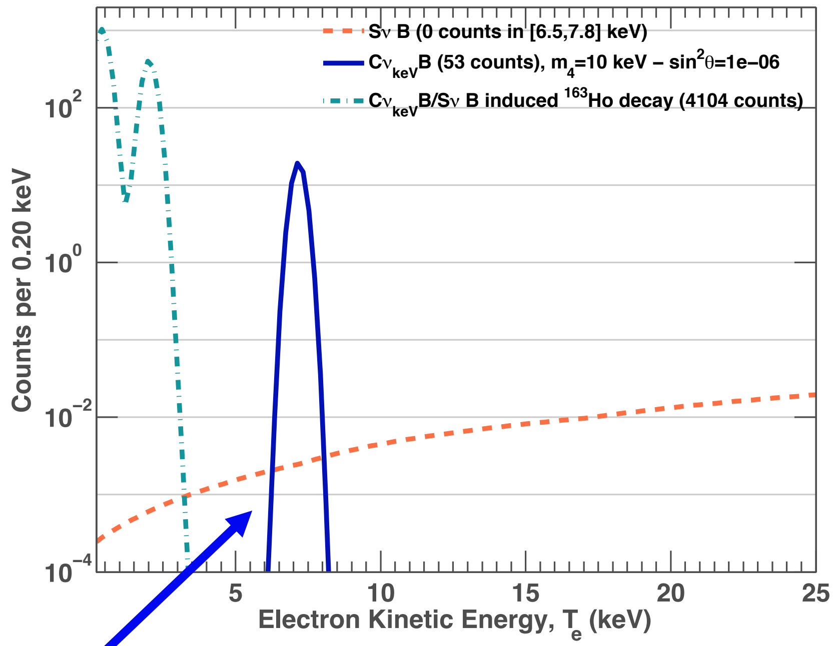


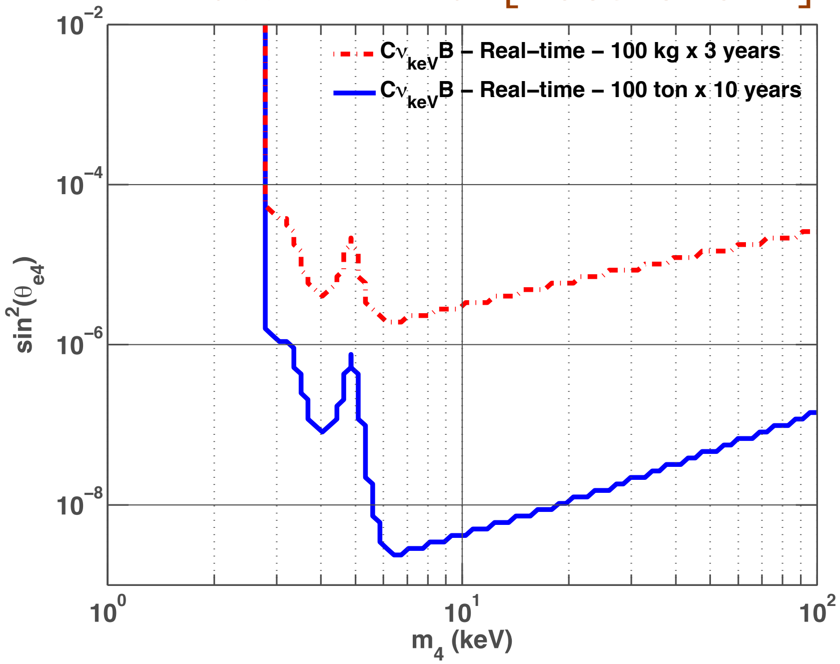
See also
PTOLEMY [1307.4738]

Search for sterile neutrino dark matter

- **Laboratory searches**
  - **Beta capture: EX)** $^{163}_{66}\mathrm{Dy} + N_1 \to {}^{163}_{67}\mathrm{Ho}^+ + e^-$

Lasserre et al [1609.04671]





signal

See also
Li, Xing [1009.5870], Li, Xing [1104.4000]
Long et al [1405.7654]

Summary

Summary

- **Sterile neutrino is a well-motivated candidate of dark matter in light of origin of neutrino masses**
  - Simple Dodelson-Widrow (non resonant production) scenario conflicts with cosmological constraints
  - Shi-Fuller (resonant production) scenario due to lepton asymmetry is possible
  - Other production scenarios have been discussed

- **Searches for sterile neutrino dark matter**
  - **Astrophysical searches for radiative decays, ⋯**
  - **Laboratory searches for tritium beta decay/beta capture**

Both approaches are essential !