Neutrino theory of everything?
dark matter, baryogenesis and neutrino masses

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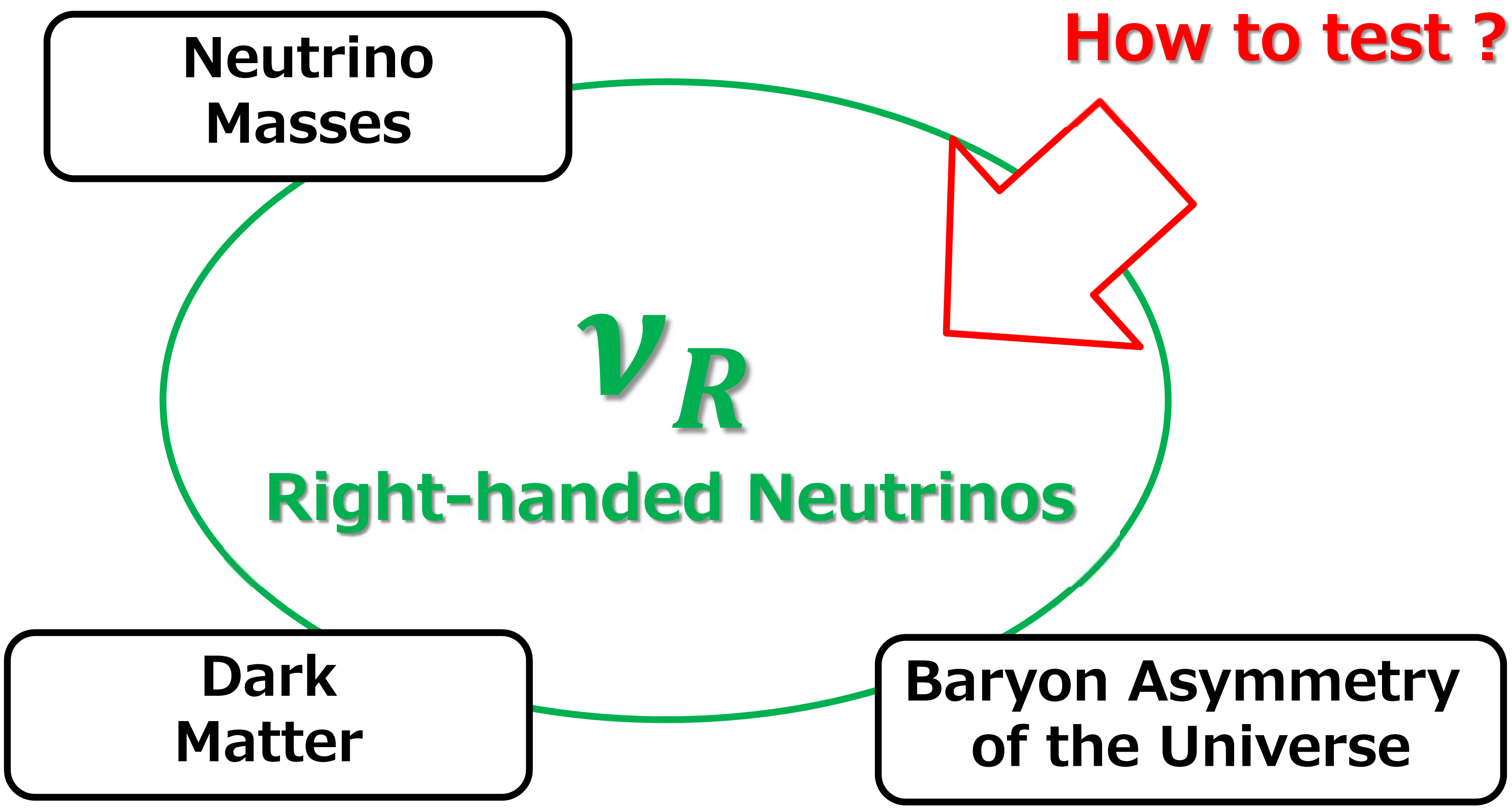
Overview


How to test ?
Neutrino Masses
ν_R
Right-handed Neutrinos
Dark Matter
Baryon Asymmetry of the Universe

Neutrino Masses

—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 ($M_D = F\langle\Phi\rangle \ll M_M$)

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

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

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

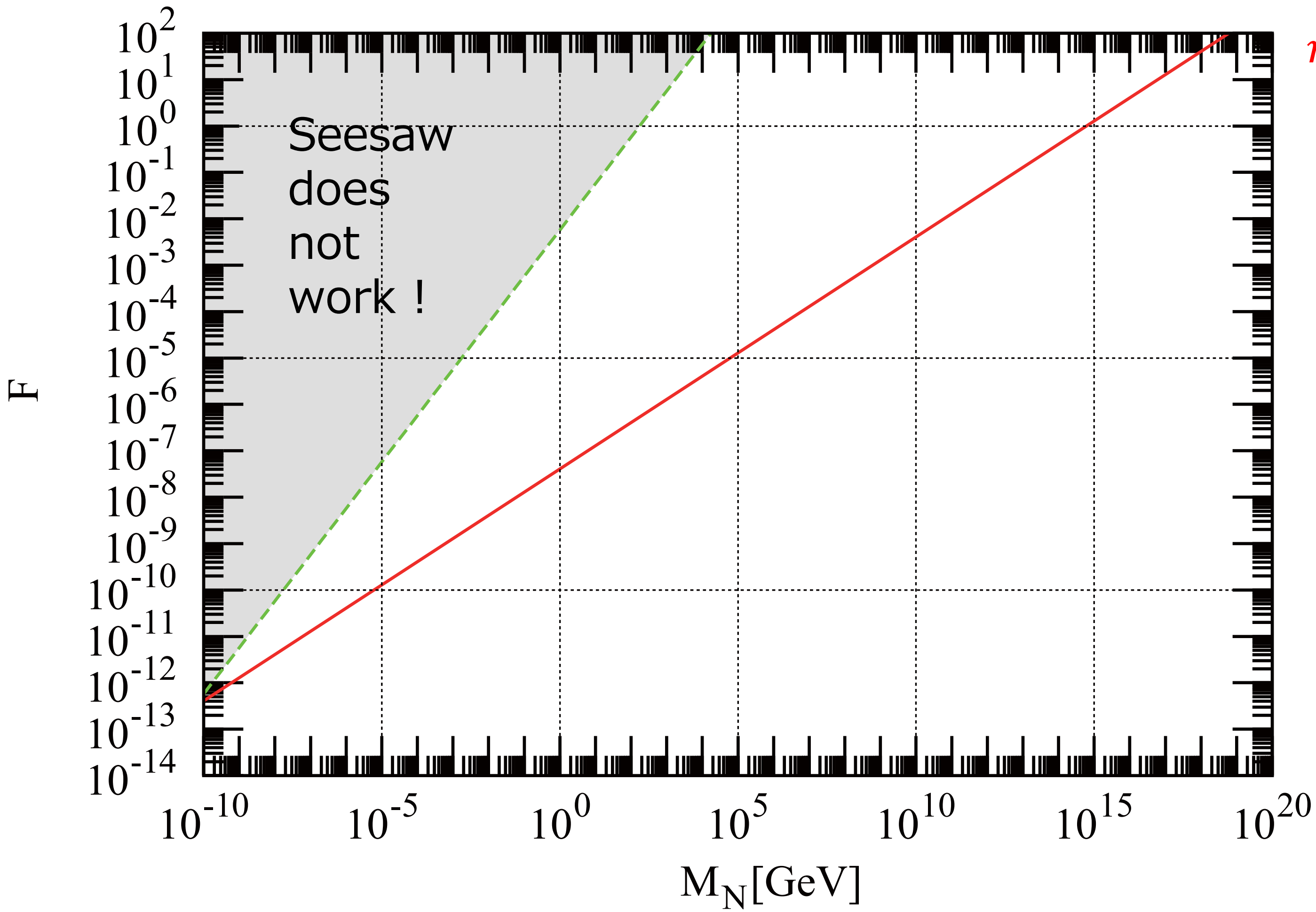
- **Light active neutrinos ν**
  - → explain neutrino oscillations
- **Heavy neutral leptons N** ($N \simeq \nu_R$)
  - Mass M_M
  - Mixing $\Theta = M_D/M_M$

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

Yukawa Coupling and Mass of HNL

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

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



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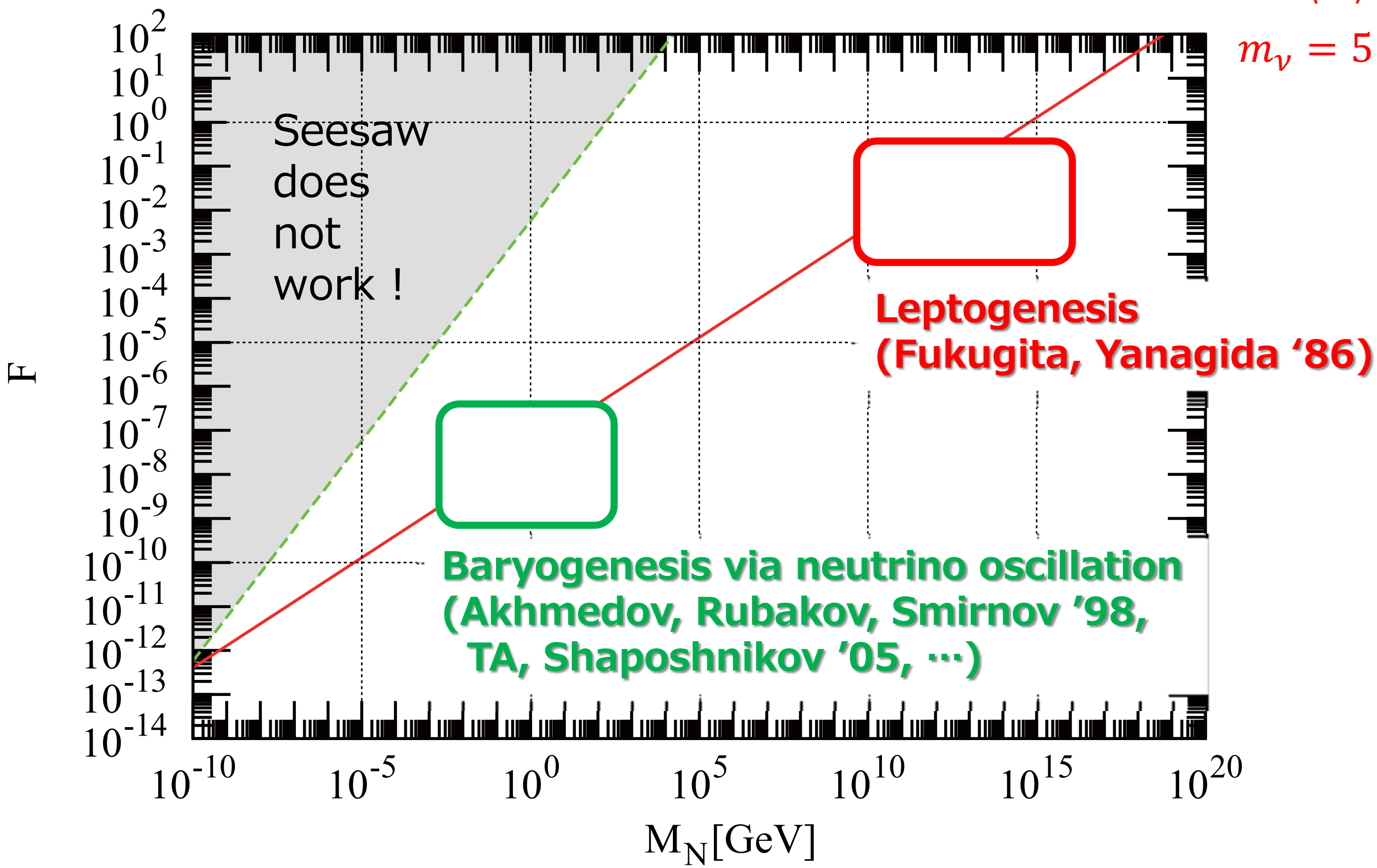
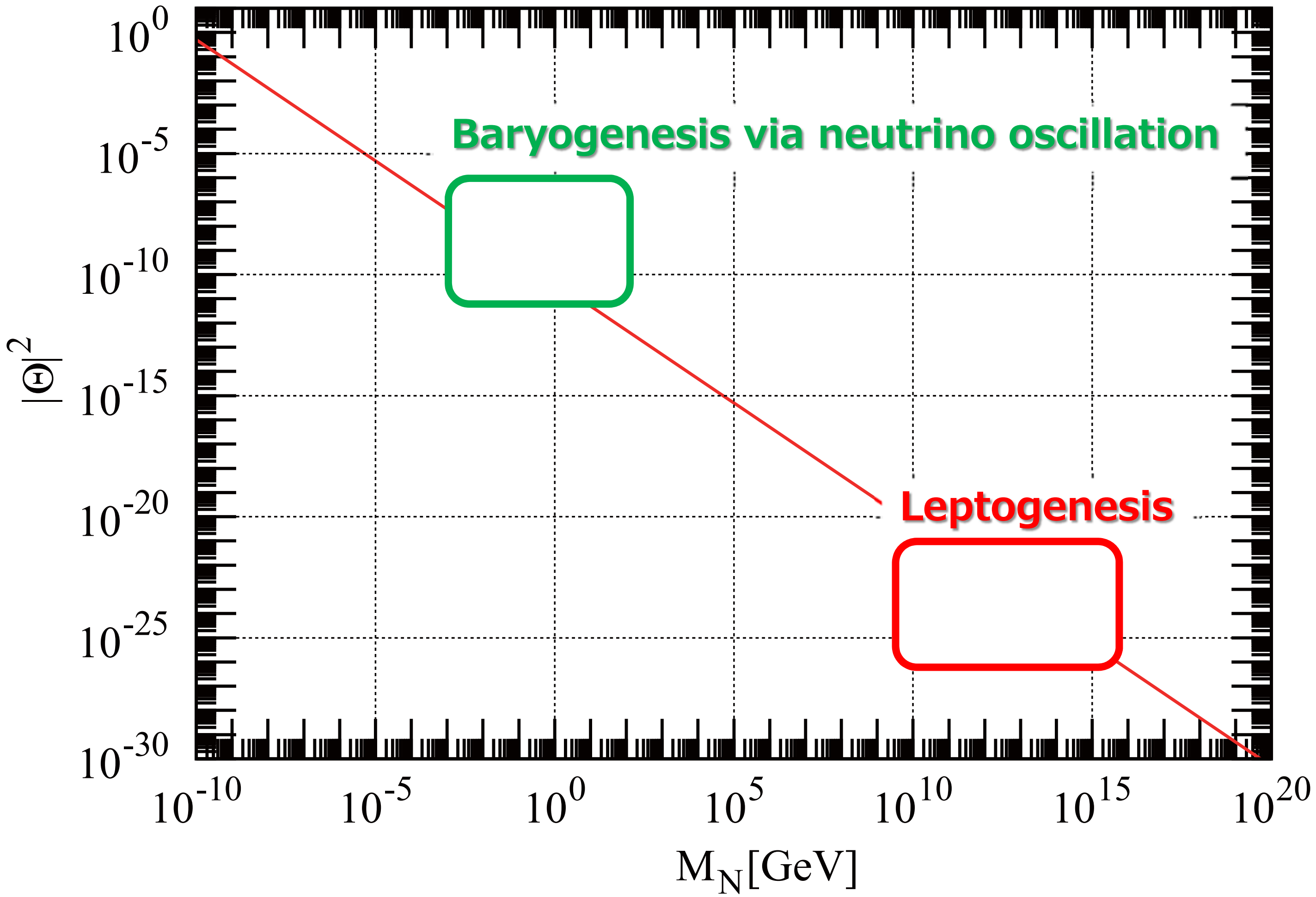
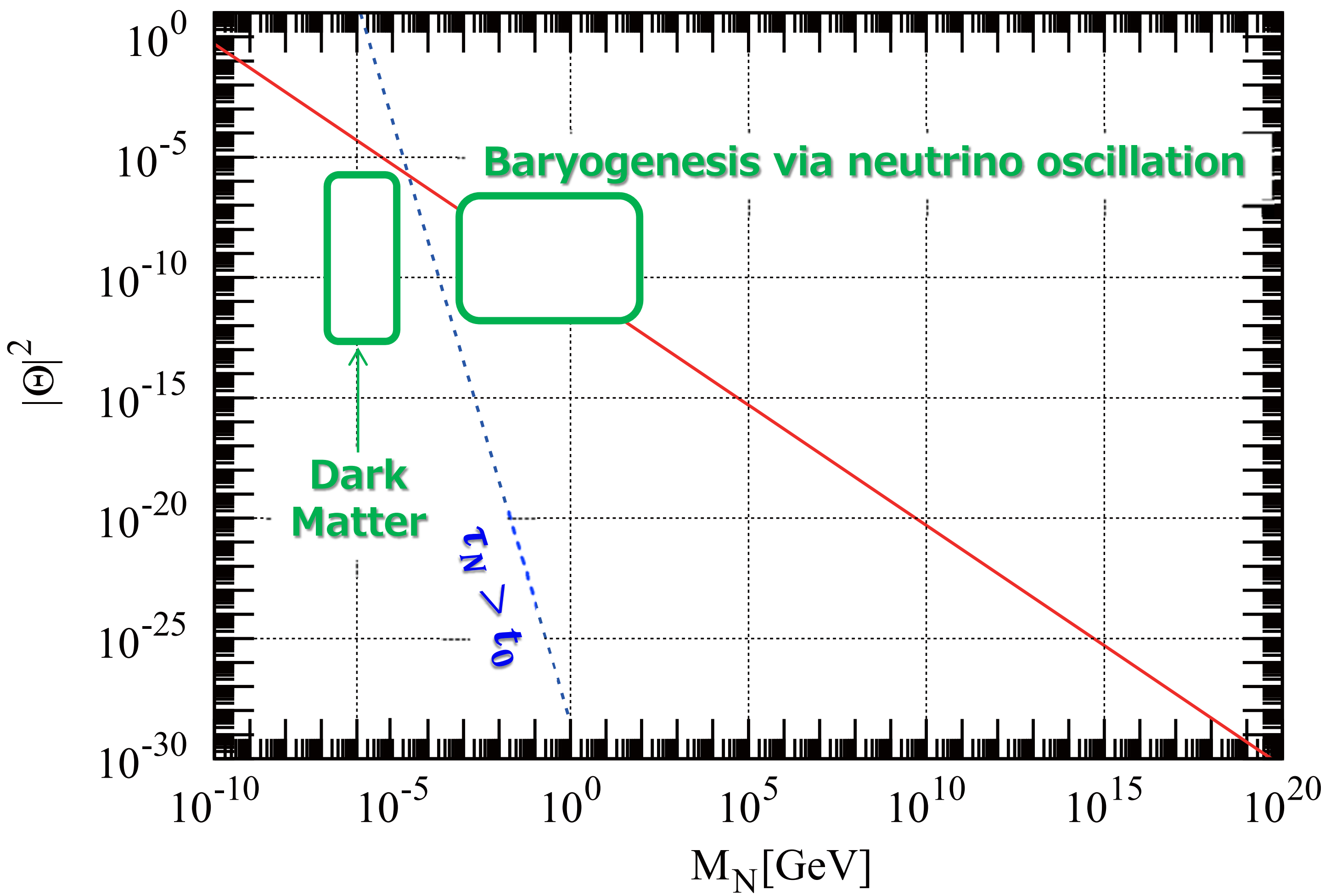


Mixing and Mass of HNL

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

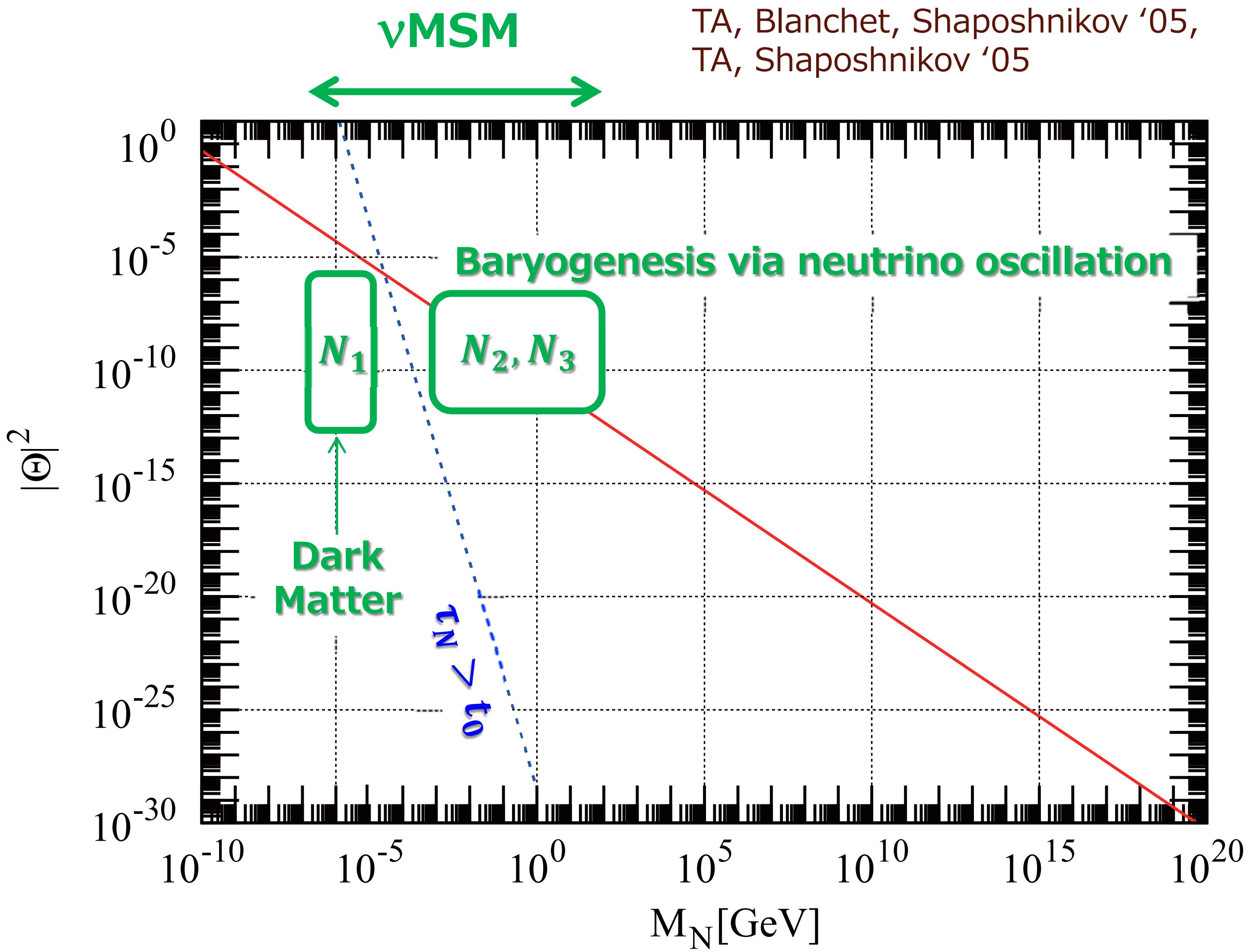


Various Physics of HNLs



Various Physics of HNLs

TA, Blanchet, Shaposhnikov '05,
TA, Shaposhnikov '05

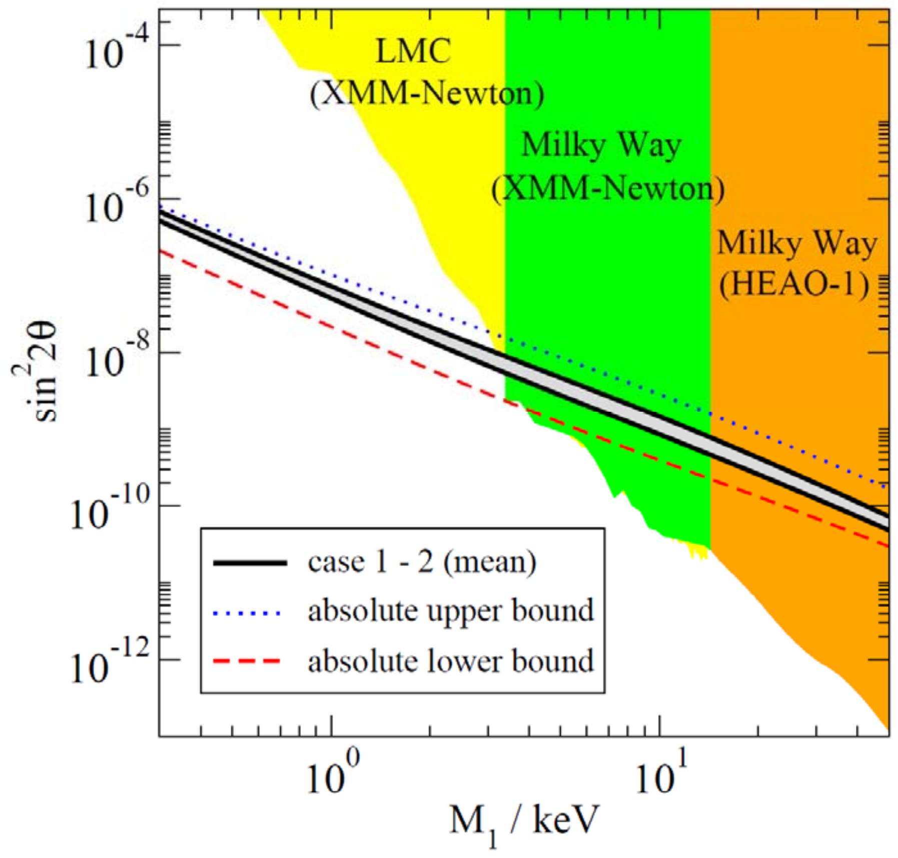


Dark Matter

— HNL N_1 with M_1~keV

Properties of DM N1

TA, Laine, Shaposhnikov '07



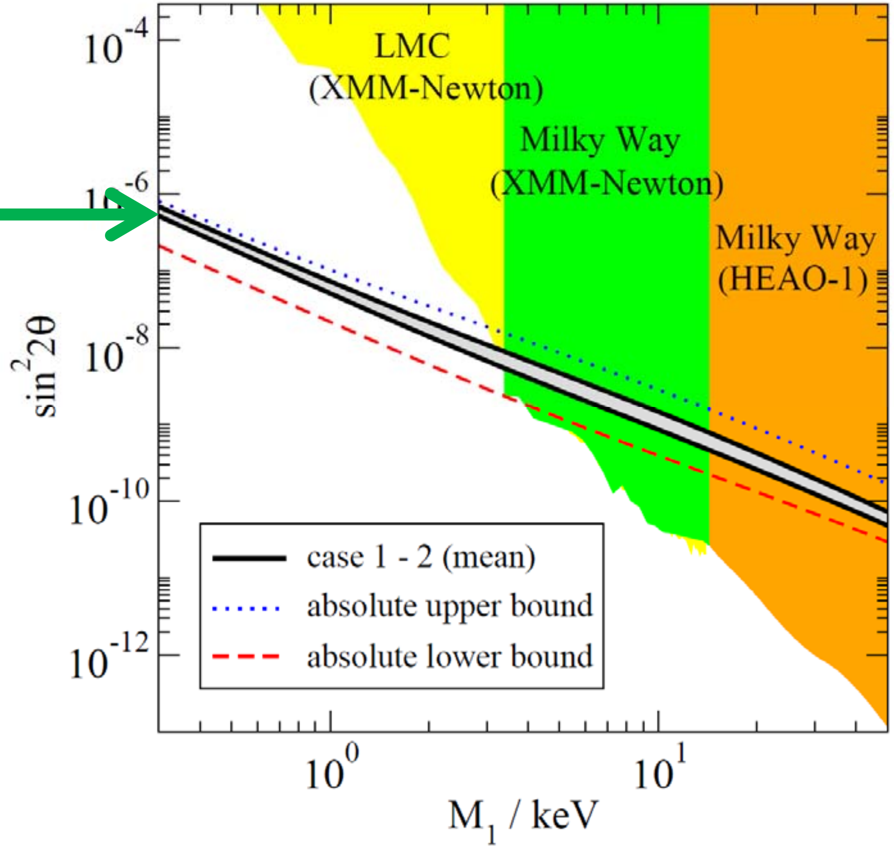
Mixing for DM abundance

- DM abundance

$$\Omega_{N_1} h^2 = \Omega_{dm} h^2 \simeq 0.1$$

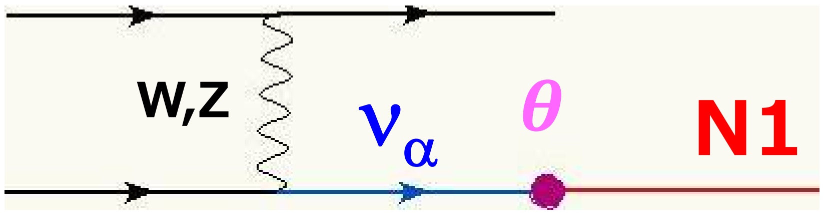
$$\sin^2 2\theta \simeq 8 \times 10^{-8} \left(\frac{M_N}{1\text{keV}}\right)^2$$

TA, Laine, Shaposhnikov '07



DM N_1 is produced by scatterings

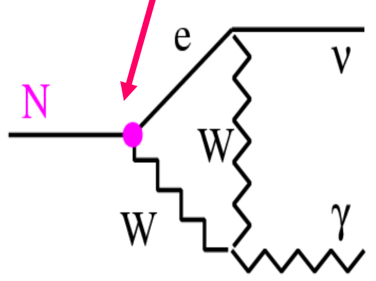
Dodelson, Widrow '94



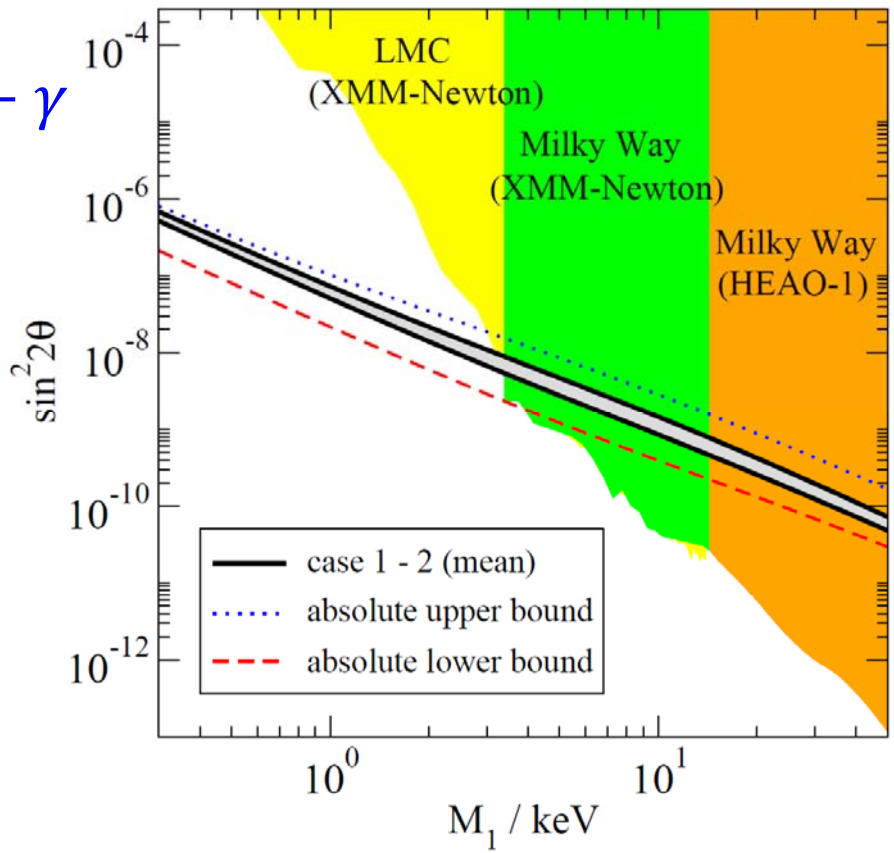
Cosmological constraint (1)

- **Radiative decays of DM**
  - Dominant decay: $N_1 \to 3\nu$
  - Subdominant decay $N_1 \to \nu + \gamma$

$\theta = M_D/M_1$



TA, Laine, Shaposhnikov '07



Severely restricted from X-ray observations

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

Cosmological constraint (2)

- DM N_1 plays as WDM and may erase structures on small scales!

$$\lambda_{FS} \sim \mathrm{Mpc}\left(\frac{\mathrm{keV}}{M_1}\right)\frac{\langle|q_N|\rangle}{\langle|q_\nu|\rangle}$$

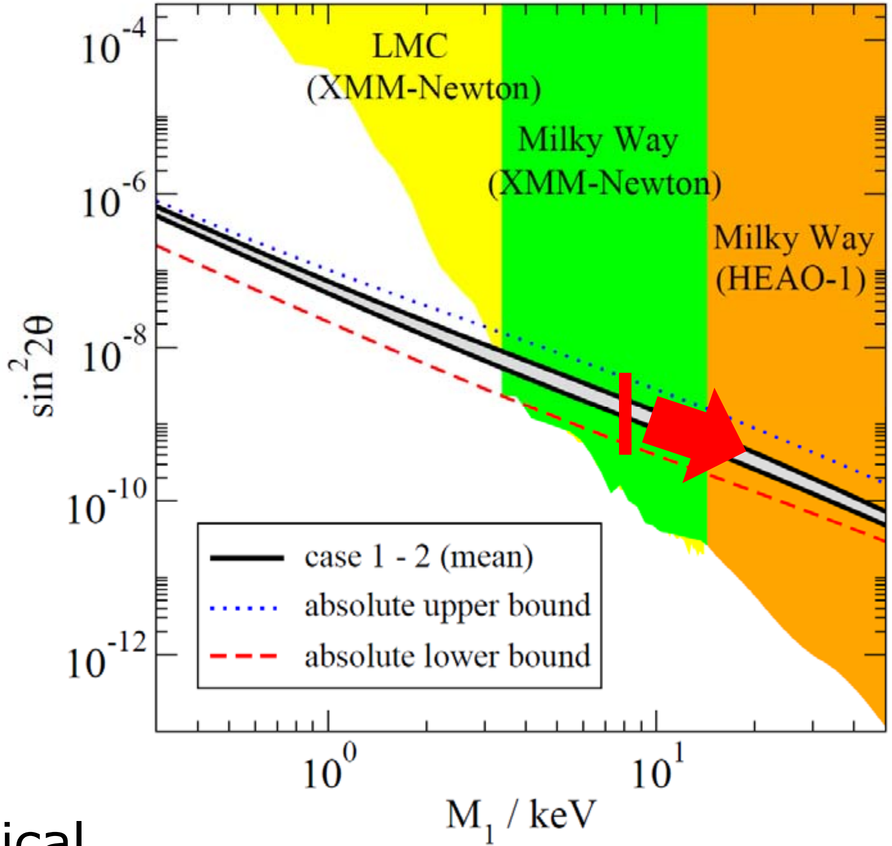
⇒ **Lower bound on mass**

- Ly-α forest observations

$M_1 \gtrsim 8\ \mathrm{keV}$ (DW scenario)

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

TA, Laine, Shaposhnikov '07

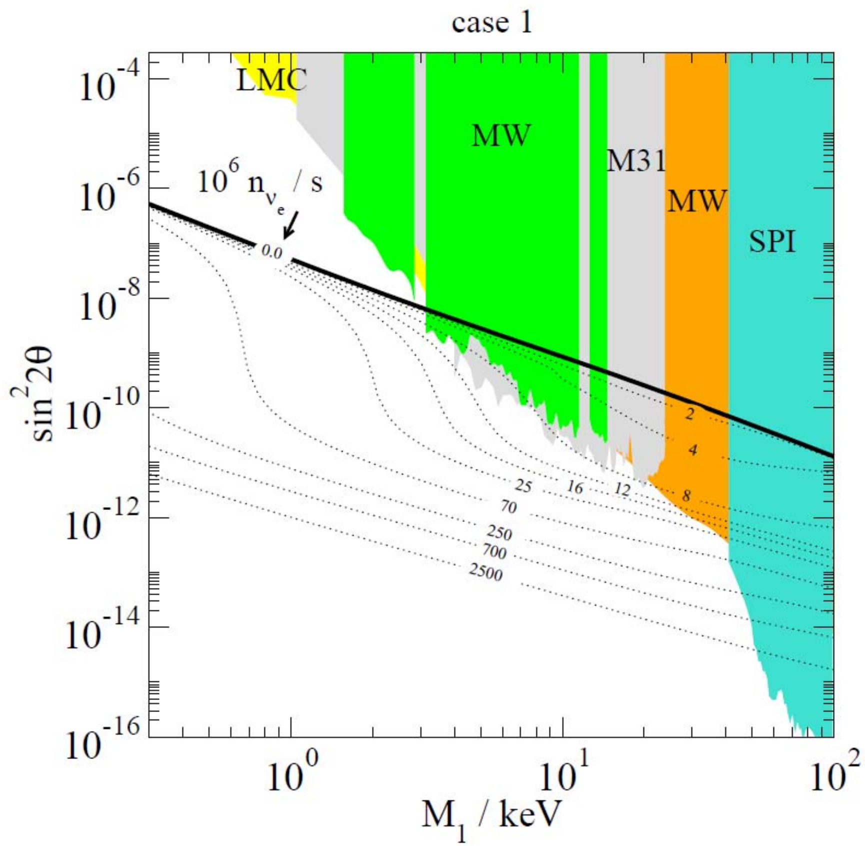


- The simplest Dodelson-Widrow scenario conflicts with cosmological constraints

Current status

Other production mechanism is needed !!

Laine, Shaposhnikov '08



- Shi-Fuller mechanism with large lepton asymmetry

  Shi, Fuller '99

  - Scenario in the nuMSM

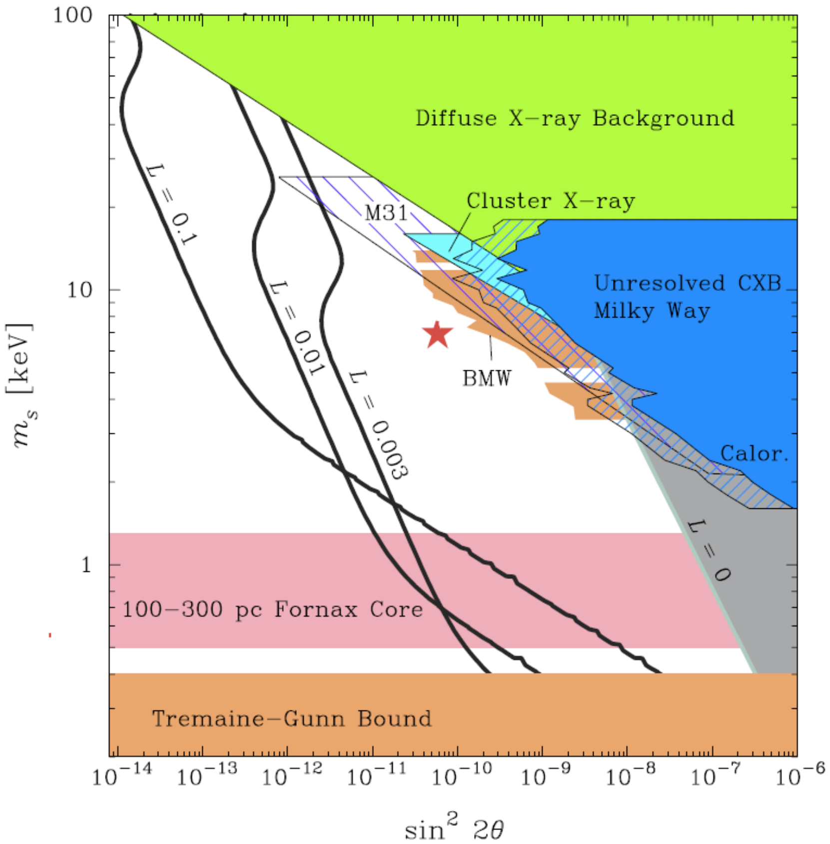
    Canetti, Drewes, Shaposhnikov '13
    Canetti, Drewes, Frossard, Shaposhnikov '13

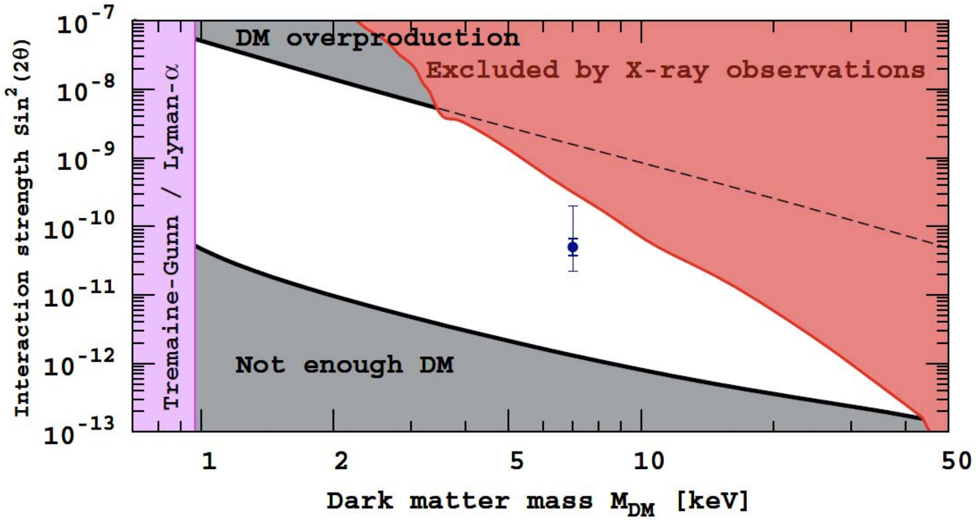
- Additional interactions of DM (scalar, Z', ⋯)

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

X-rays from DM N_1 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
- $\sin^2 2\Theta_1 = O(10^{-10})$

Baryon Asymmetry

—Baryogenesis via Neutrino Oscillation

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

Condiations for baryogenesis: Sakharov (1967)

(1) Baryon number B is violated

(2) C and CP symmetries are violated

(3) Out of thermal equilibrium

Baryogenesis in the νMSM

- ***B* and *L* violations**
  - *B* violation due to EW sphaleron for $T \gtrsim M_W$
  - *L* violation due to Majorana masses
    - Since $M_{2,3} \lesssim M_W$, this violating effect is negligible for baryogenesis temperature $T \gtrsim M_W$

- **C and CP violations**
  - 1 CP phase in quark sector
  - 6 CP phases in lepton sector
    - Among them 3 CP phases associated with $N_{2,3}$ are relevant

- **Out of equilibrium**
  - No 1st order EW phase transition as in the SM
  - $N_{2,3}$ can be out of equilibrium for $T \gtrsim M_W$, if Yukawa couplings are small enough

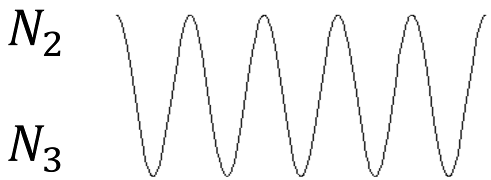
Baryogenesis via Neutrino Oscillation

- Oscillation of HNLs can be a source of BAU

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

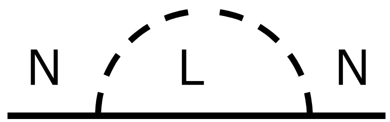
  Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
  TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
  Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)

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

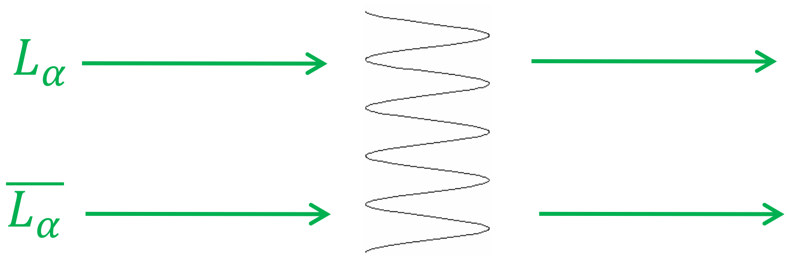


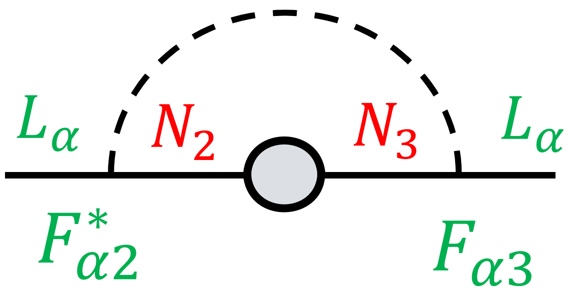
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



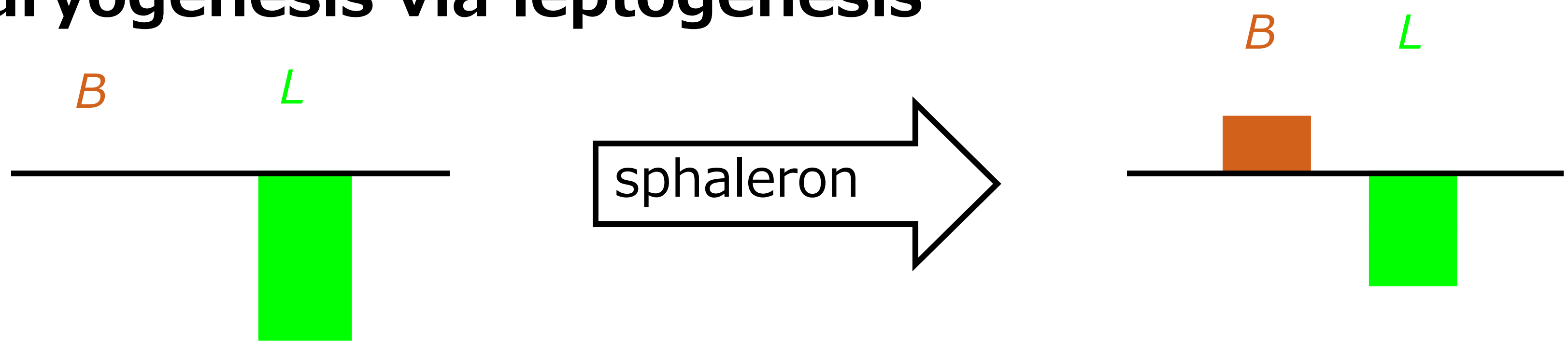
  - Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV



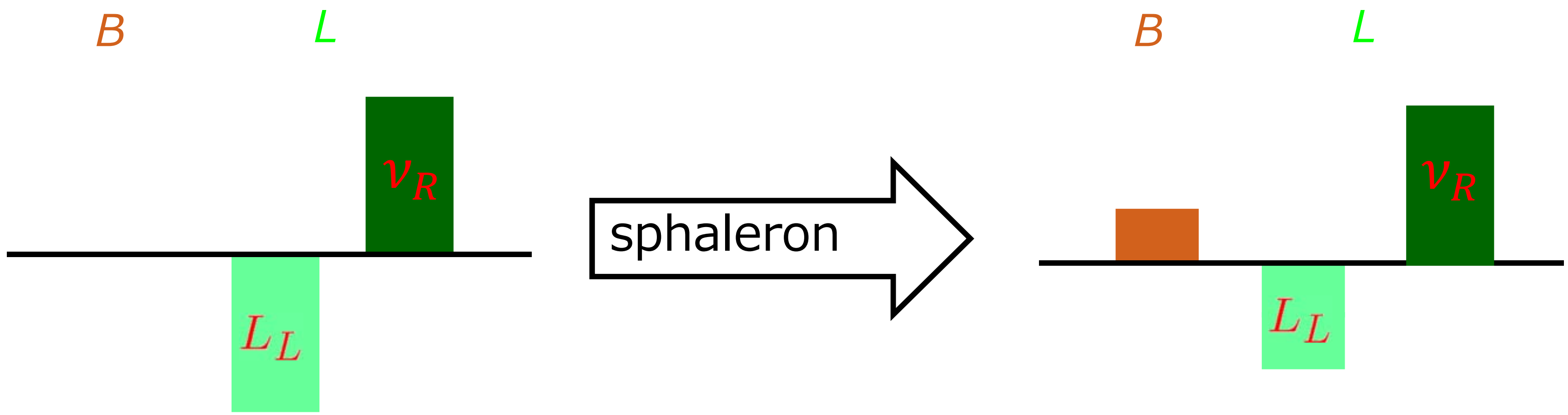


Key points

Baryogenesis via leptogenesis

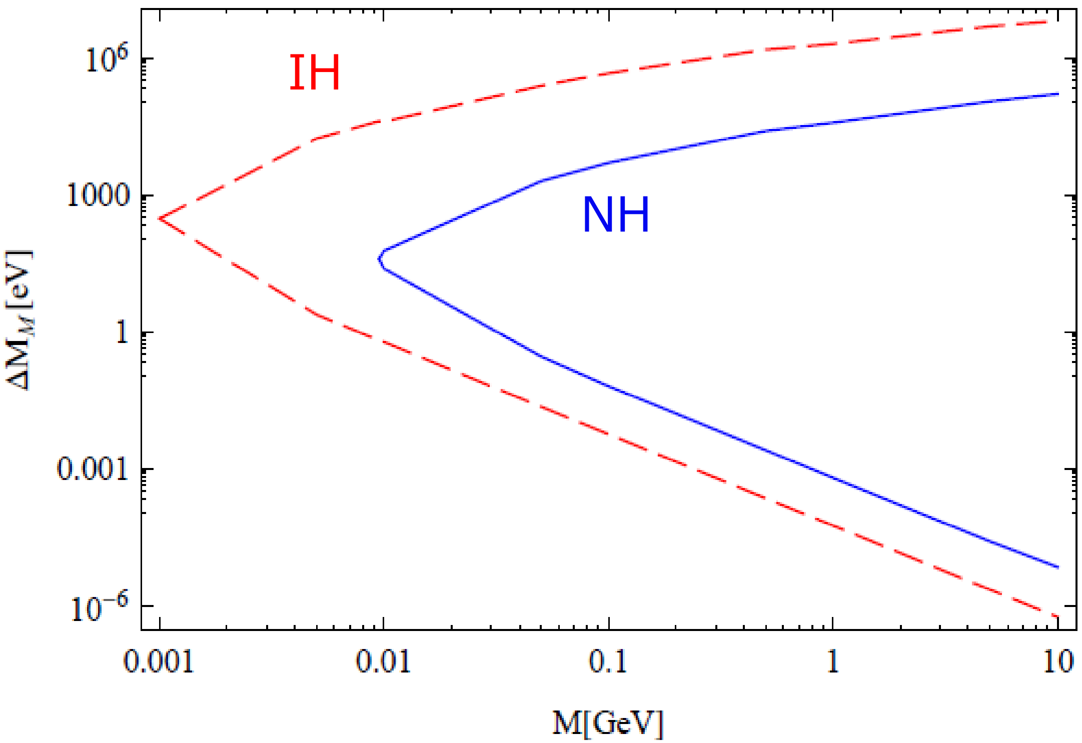


Baryogenesis via neutrino osc.



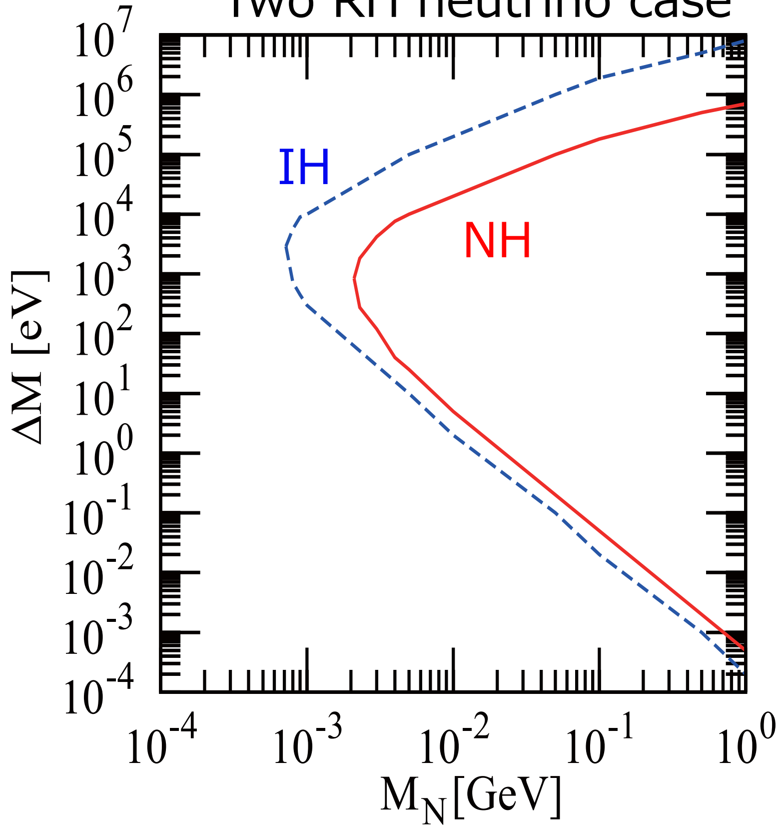
Baryogenesis Region

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



Canetti, Shaposhnikov '10

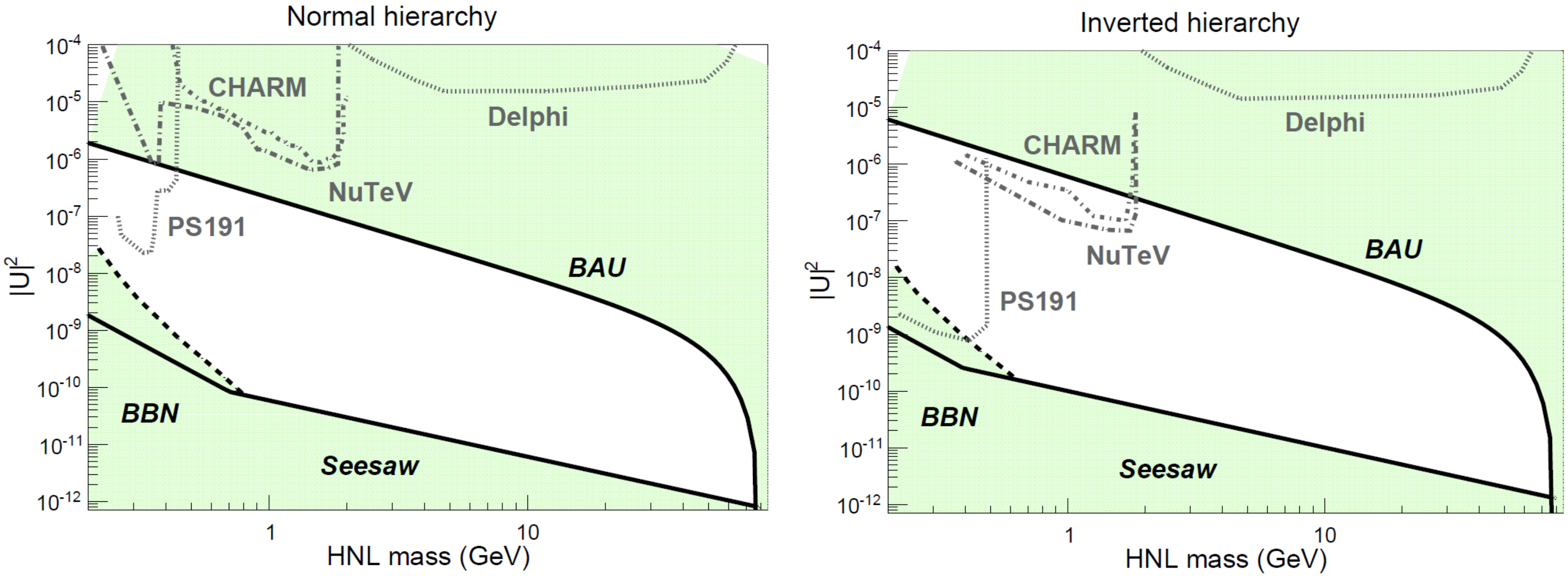
Two RH neutrino case



TA, Eijima '13

Allowed regions for HNLs N2 and N3

- Allowed region of HNLs N2 and N3 for the seesaw mechanism and baryogenesis via neutrino oscillation

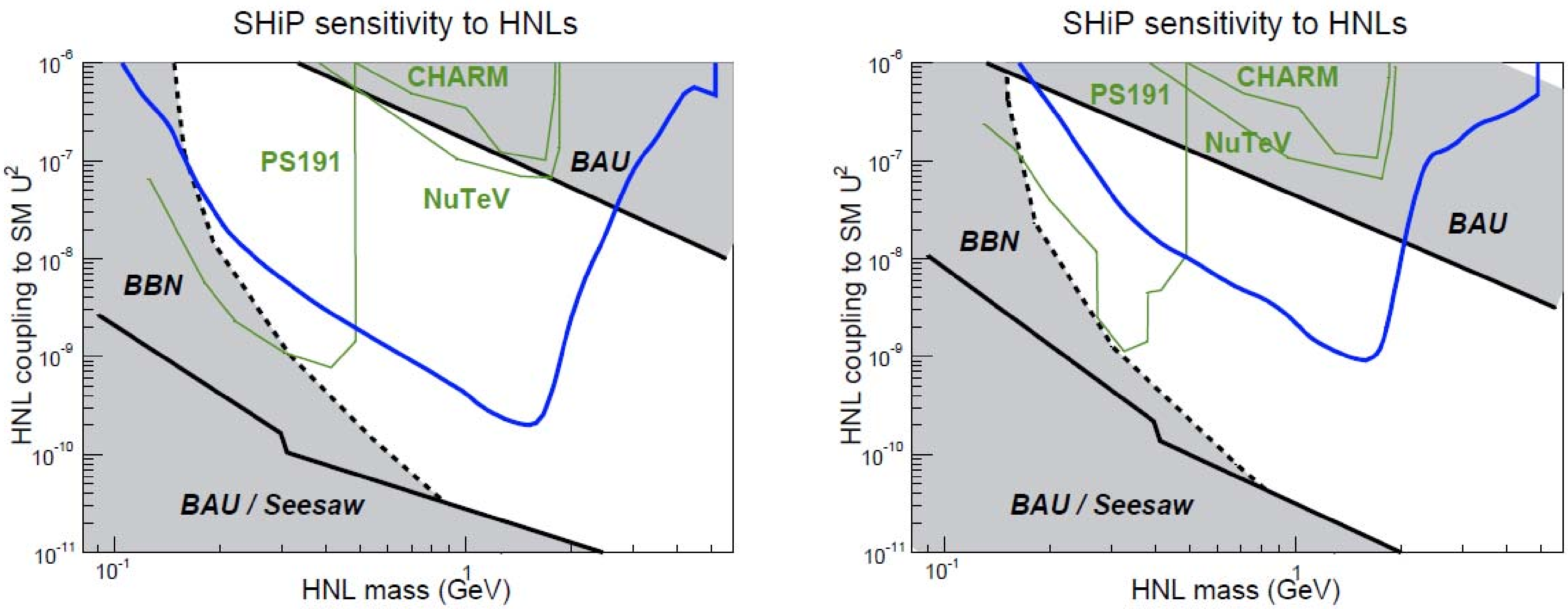


Blondel Graverini, Serra, Shaposhnikov (arXiv:1411.5230)

Experimental Tests for Heavy Neutral Leptons

Search at SHiP

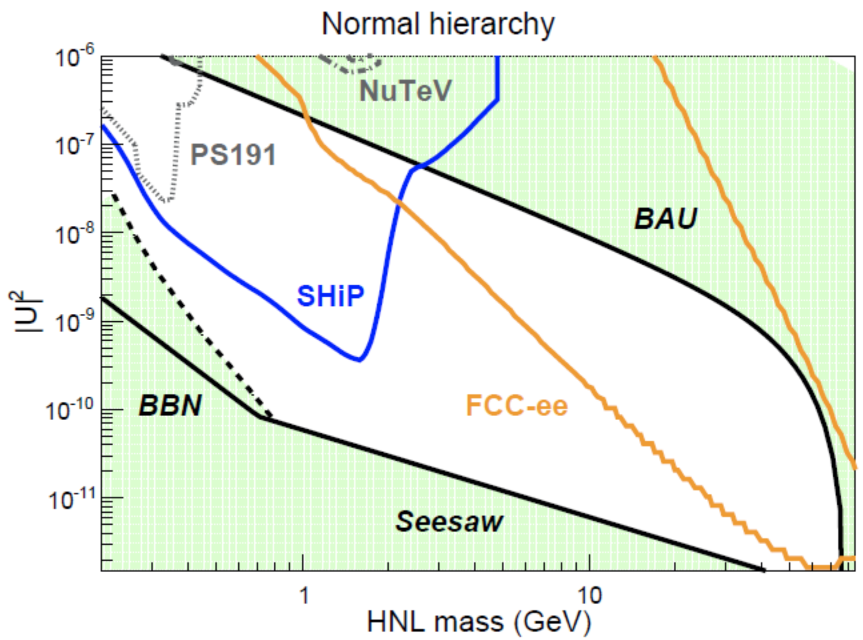
- SHiP is a fixed-target experiment at CERN SPS
- NHLs are produced in charmed meson decays
  → look for a visible decay of HNLs ($N \to \mu\pi,\ \mu e\nu, \dots$) inside detector



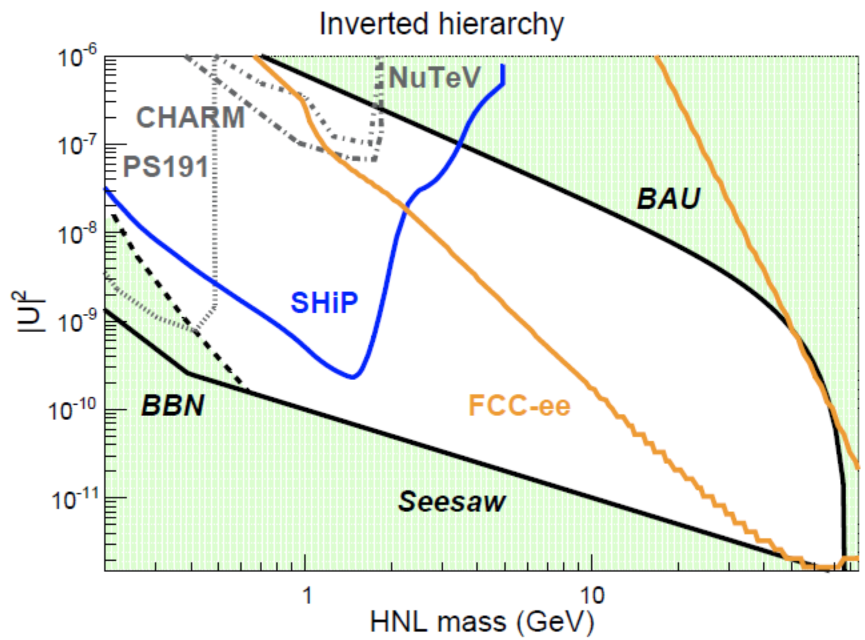
Technical Proposal
arXiv:1504.04956

Search at FCC-ee (TLEP)

- Future Circular Collider at CERN includes e^+e^- collisions as a possible first step toward 100 TeV pp collider.
- At Z-pole, 10^{12}-10^{13} Z bosons
- HNLs are produced in Z boson decays ($Z \to \nu N$)
  → look for a displaced vertex of HNL decay



(b) Decay length 10-100 cm, 10^{13} Z^0

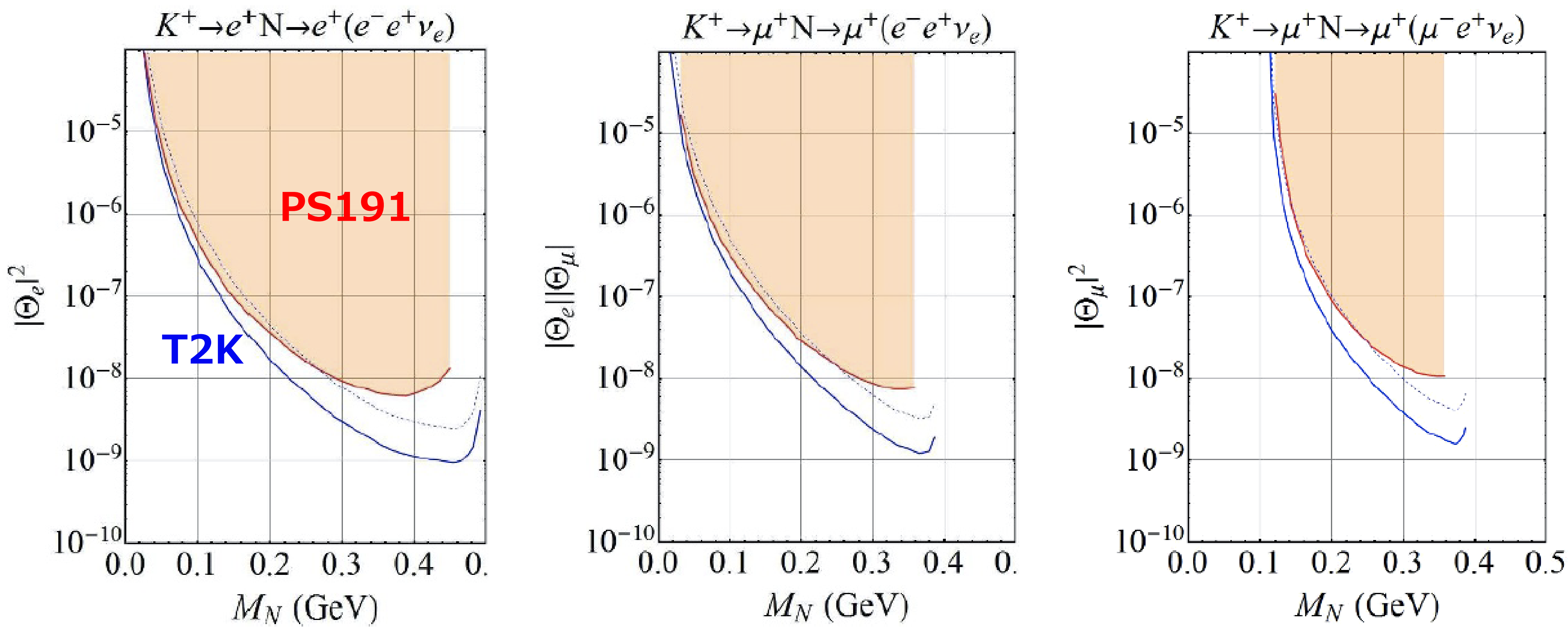


(b) Decay length 10-100 cm, 10^{13} Z^0

Blondel Graverini, Serra, Shaposhnikov (arXiv:1411.5230)

Search at T2K

- HNLs are produced in kaon decays as active neutrinos
  → look for a visible decay of HNLs inside ND280



T2K at 10^{21} POT has a better sensitivity than PS191 (0.86×10^{19} POT) !

TA, Eijima, Watanabe '13

Test by Lepton Universality

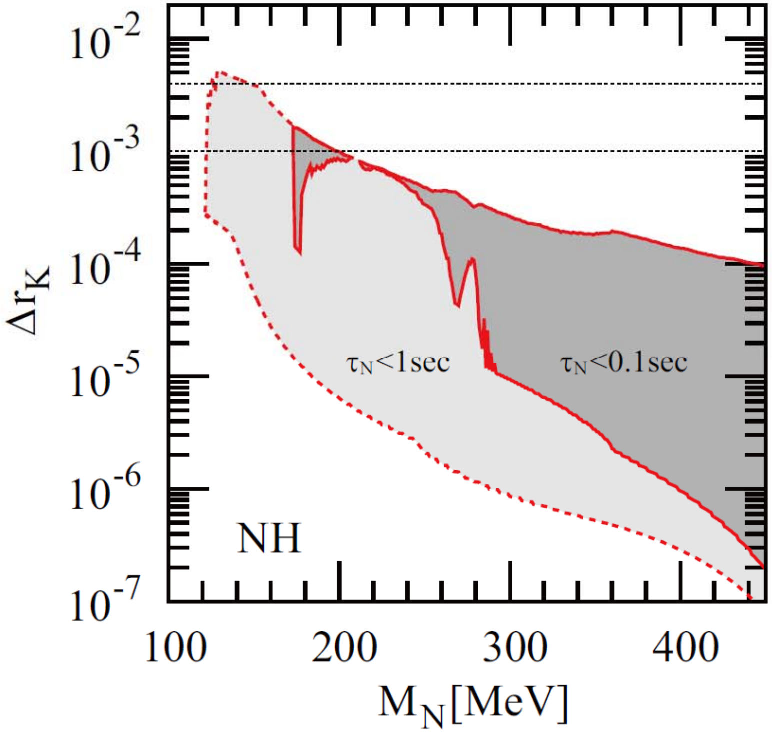
Shrock 1981

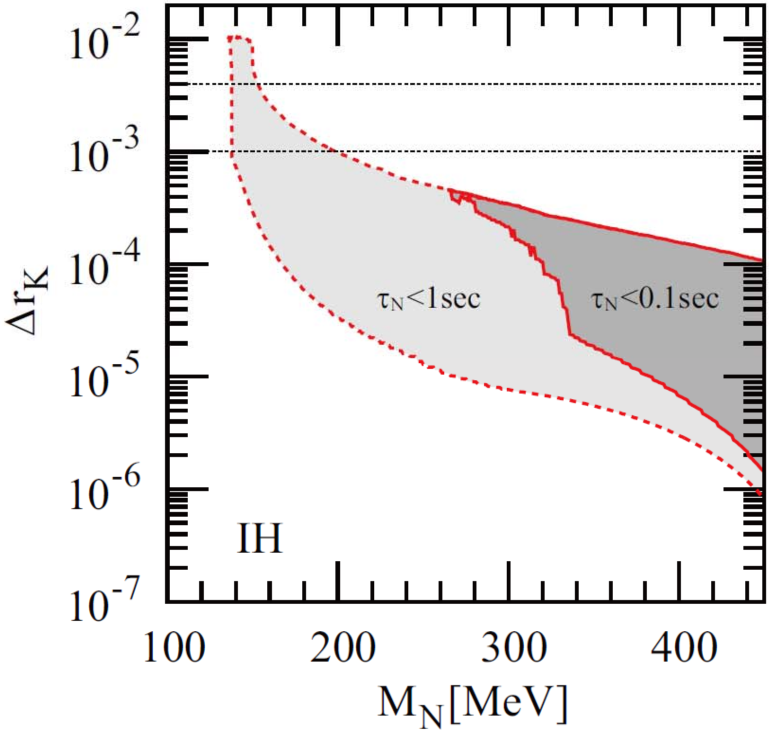
- HNLs may modify lepton universality in kaon decays

$$R_K = \frac{\Gamma(K^+ \to e^+ + \nu)}{\Gamma(K^+ \to \mu^+ + \nu)}$$

$$\Delta r_K = \frac{R_K - R_K^{SM}}{R_K^{SM}}$$

TA, Eijima, Takeda '14





$\Delta r_K = 10^{-3}$ will be probed by near future experiments NA62@CERN and TREK/E36@J-PARC !

Summary

- The νMSM is SM with three RH neutrinos with $M_M \lesssim M_W$
  - **Lightest Heavy Neutral Lepton** N_1
    - **Dark Matter** with M_1 ~keV
  - **Heavier Heavy Neutral Leptons** N_2 and N_3
    - Quasi-degenerate with M_N~100MeV-100GeV
    - Seesaw mass matrix for **masses and mixings of active neutrinos**
    - **Baryon Asymmetry of the Universe (BAU)** through the mechanism via neutrino oscillation

- Heavy neutral leptons in the νMSM can be tested experimentally

Tests of HNLs are crucial to identify the origin of neutrino masses, but also to reveal the mysteries of our universe (DM, BAU, ⋯) !!!