nuMSM and leptogenesis

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Contents

Introduction

Baryon v.s. antibaryon

Baryon	Antibaryon
proton $(B = +1)$	antiproton $(B = -1)$
neutron $(B = +1)$	antineutron $(B = -1)$

- We find baryons mostly, not antibaryons !
  - Existence of antiproton

    In cosmic rays, $p + p \rightarrow p + p + p + \bar{p}$

    At TEVATRON, $p + \bar{p} \rightarrow X$

- Asymmetry between baryons and antibaryons in our Universe

How large ???

Baryon Asymmetry of the Universe (BAU)

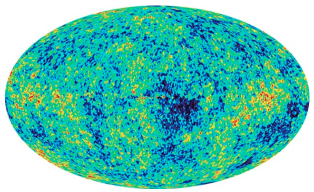
- Observational value

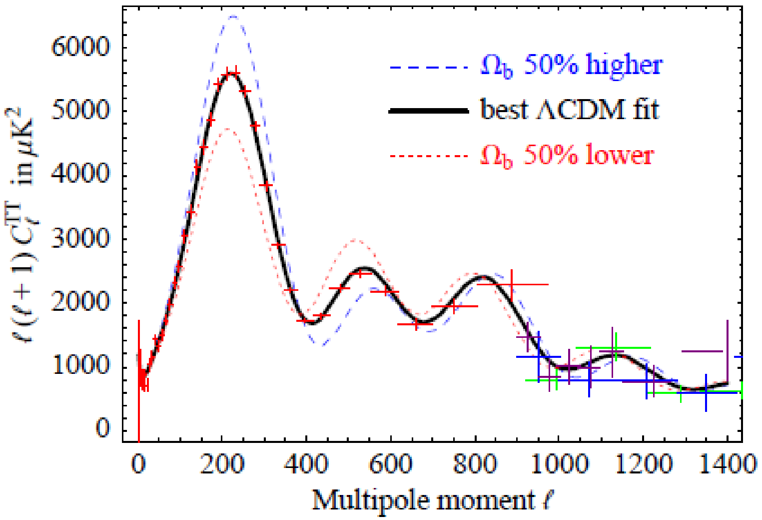
Planck 2018 [1807.06209]

$$Y_B = \frac{n_B}{s} = (0.872 \pm 0.004)\times 10^{-10}$$

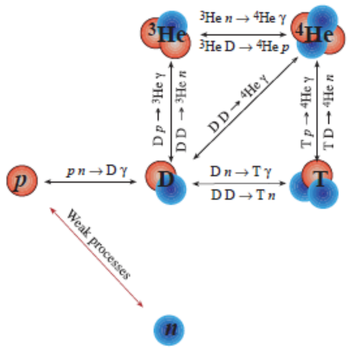
n_B : baryon number density, s : entropy density

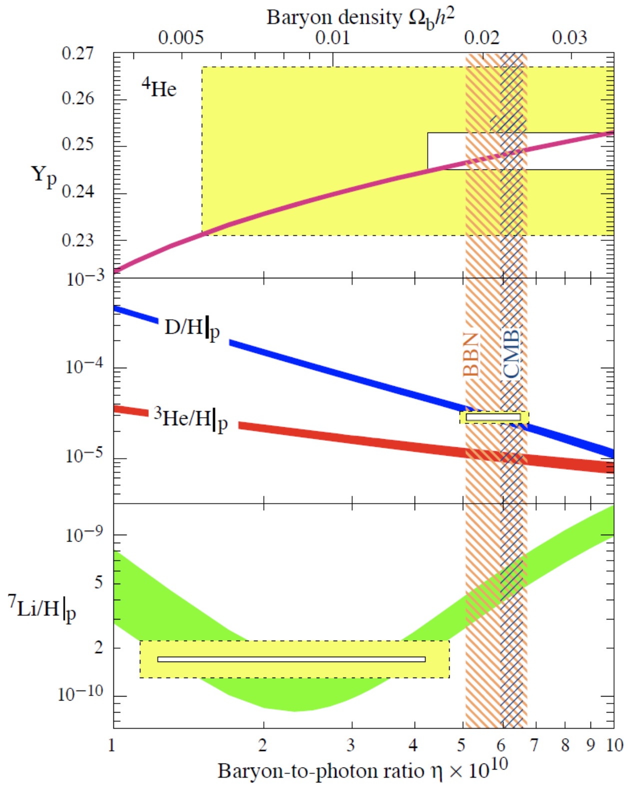
CMBR





BBN





[Strumia 06]

[PDG]

Baryogenesis

- Inflation sets baryon number $B = 0$
  → non-zero B must be generated after the inflation

Baryogenesis

- Conditions for baryogenesis: Sakharov (1967)

  (1) Baryon number B is violated

  (2) C and CP symmetries are violated

  (3) Out of thermal equilibrium

BAU and lepton number violation

- B and L in the Standard Model
  - B and L are accidental symmetries of SM Lagrangian
  - B and L are broken by non-perturbative effects, but $(B-L)$ is conserved.
  - At high temperatures, B and L violations are very rapid.

- Initial value $(B-L)_0$ is distributed to SM particles for high temperatures

$$B = \frac{28}{79}(B-L)_0$$

- Not only B violation, but also L violation can be a source of BAU

Baryogenesis in the Standard Model

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

- CP violation
  - 1 CP phase in the quark-mixing (CKM) matrix

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

→ too small

- **Out of equilibrium** [Kajantie, Laine, Rummukainen, Shaposhnikov]
  - Strong first order phase transition if $m_h < 72$ GeV

but $m_h = 125$ GeV

→ not satisfied

We have to go beyond the SM !

Right-handed neutrinos

$$\nu_R$$

BAU and right-handed neutrinos

Neutrino properties

- Mixing angles and mass squared differences are measured very precisely

$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.012}$ $\Delta m^2_{21} = (7.49^{+0.19}_{-0.17})\times 10^{-5}\ \mathrm{eV}^2$ (NH case)

$\sin^2\theta_{23} = 0.440^{+0.023}_{-0.019}$ $\Delta m^2_{31} = (2.526^{+0.029}_{-0.037})\times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{13} = 0.02163^{+0.00074}_{-0.00074}$

Gonzalez-Garcia, Maltoni and Schwetz (ν-fit, August '16)

- Unknown properties
  - Absolute masses of neutrinos ($m_{\nu\ \mathrm{lightest}}$? Mass ordering ?)
  - CP violations (Dirac phase ? Majorana phase(s) ?)
  - Dirac or Majorana fermions

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**
  - Mass $M_\nu = -M_D^T \frac{1}{M_M} M_D \quad (M_\nu \ll M_D)$

  → smallness of neutrino masses is naturally explained

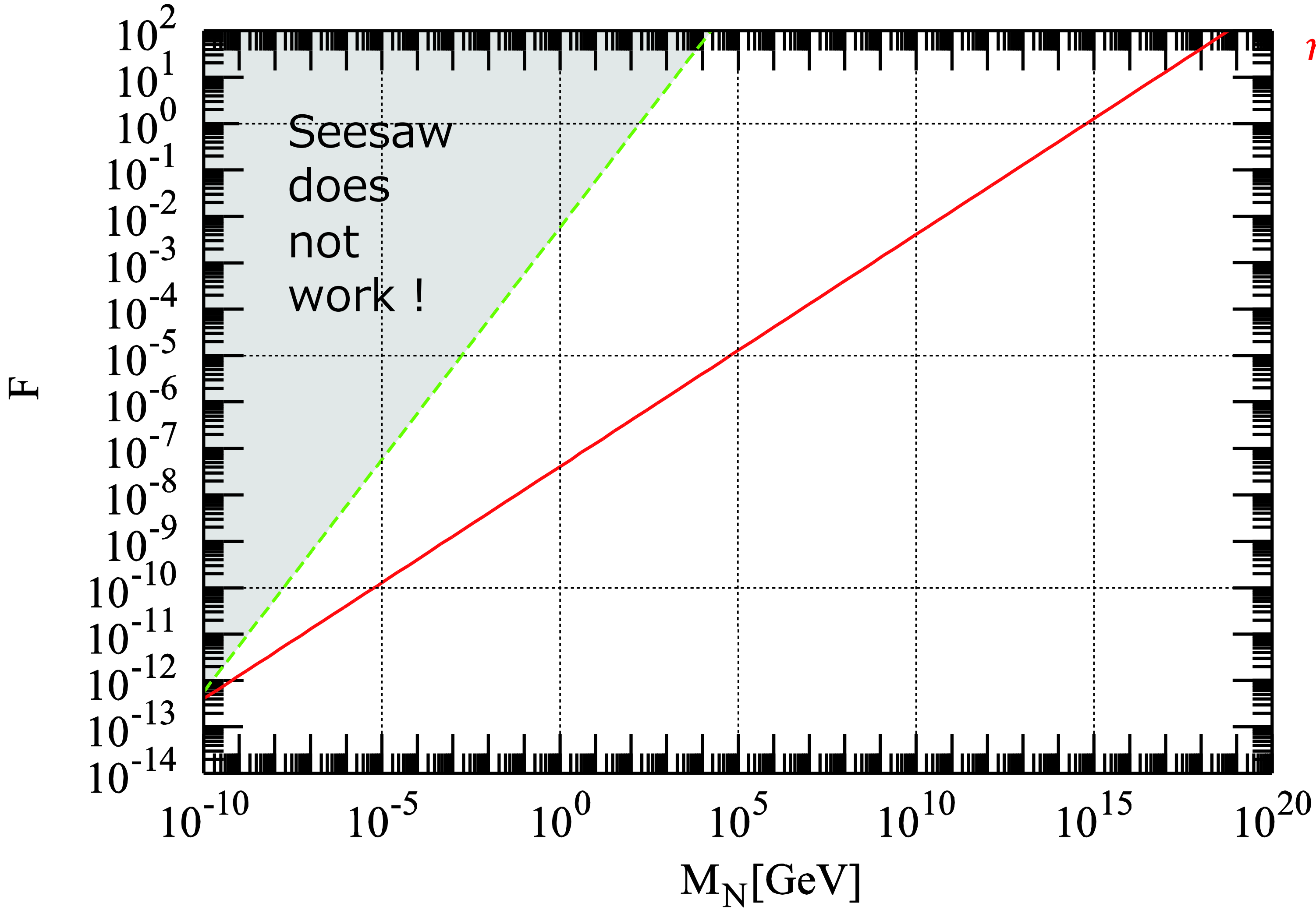
- **Heavy Neutral Leptons (Heavy Neutrinos) N** $(N \simeq \nu_R)$
  - Mass $M_N = M_M$ and mixing $\Theta = M_D/M_M$

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

Yukawa Coupling and Mass of HNL

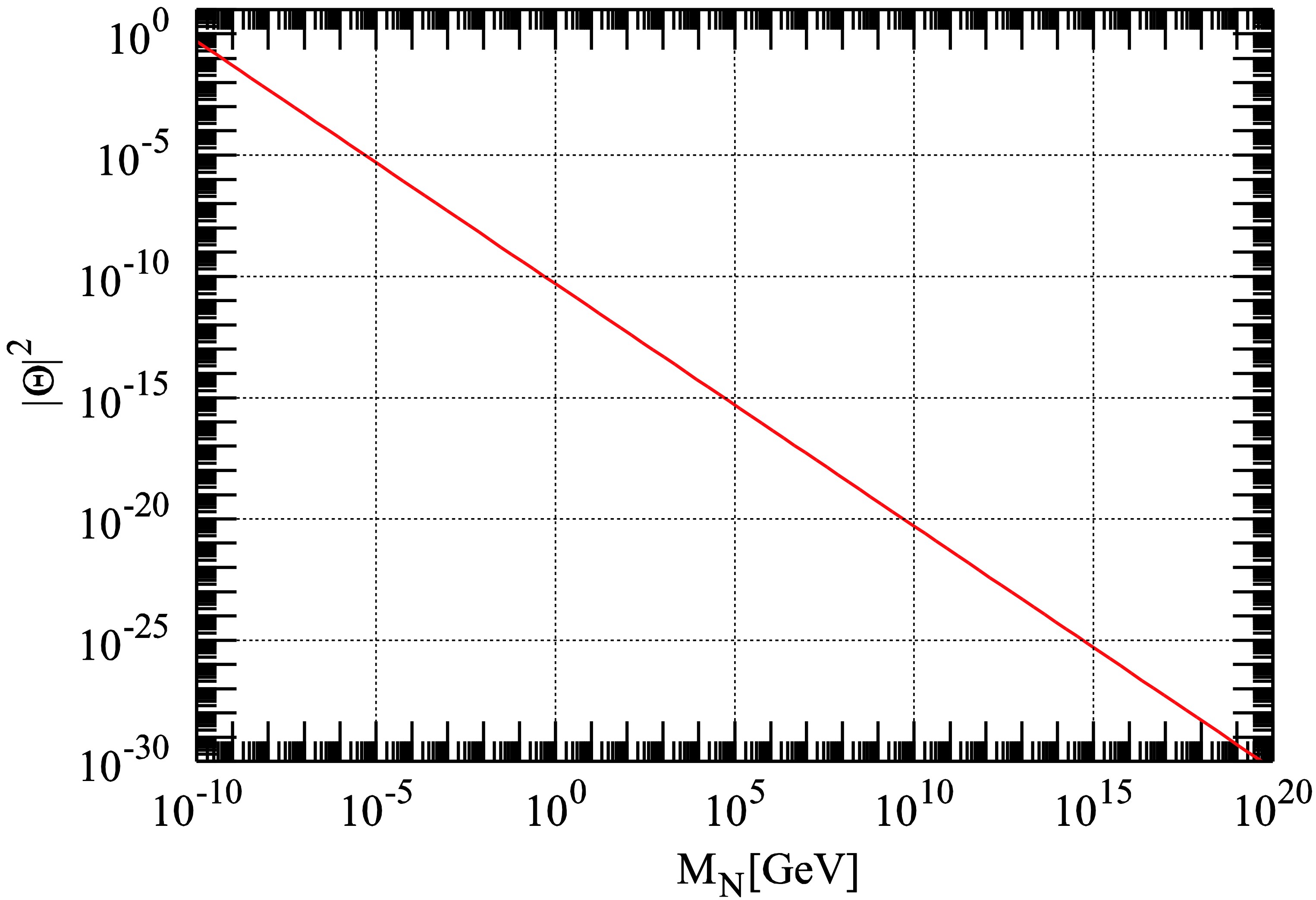
$$F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

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



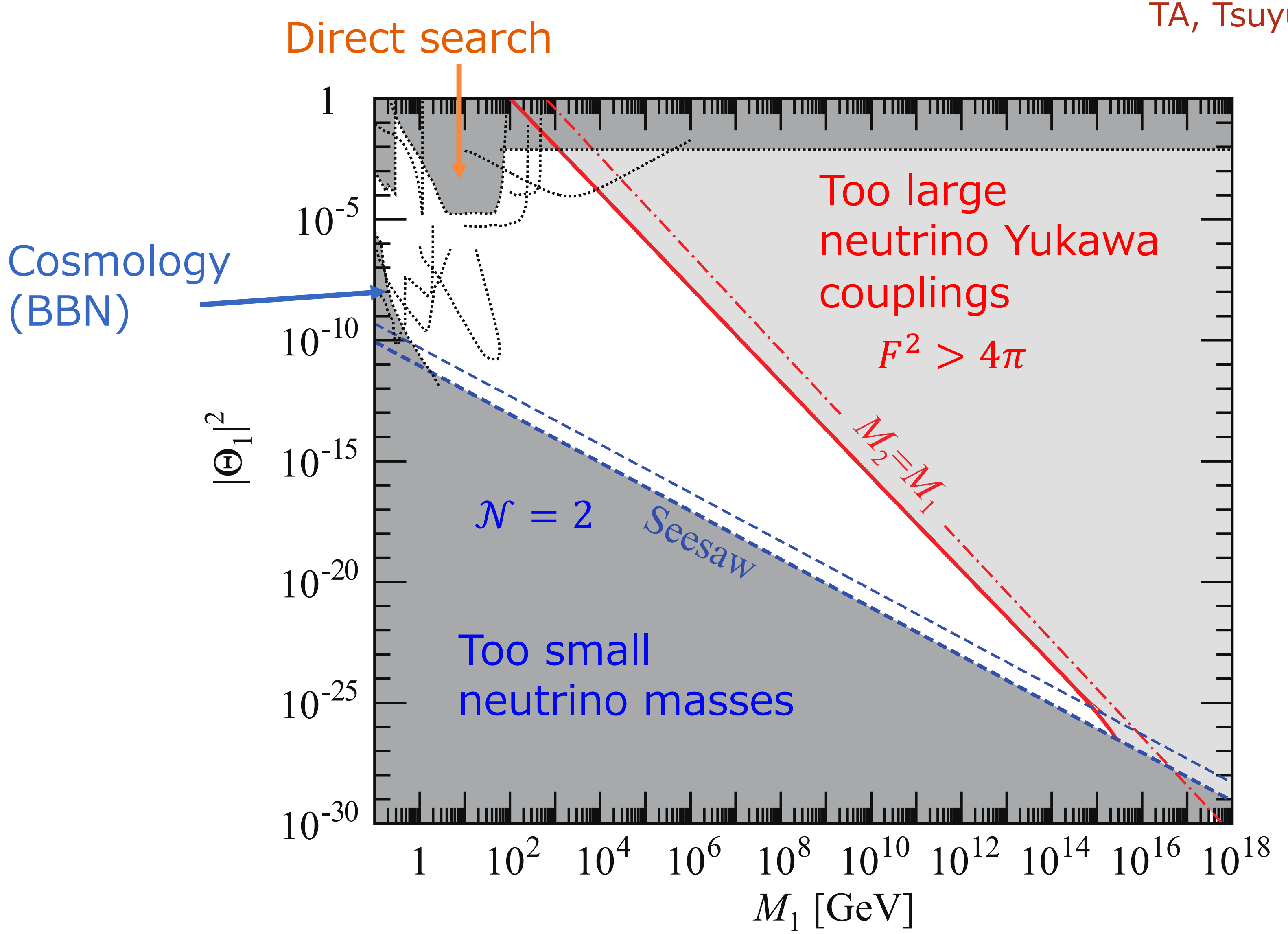
Mixing and Mass of HNL

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



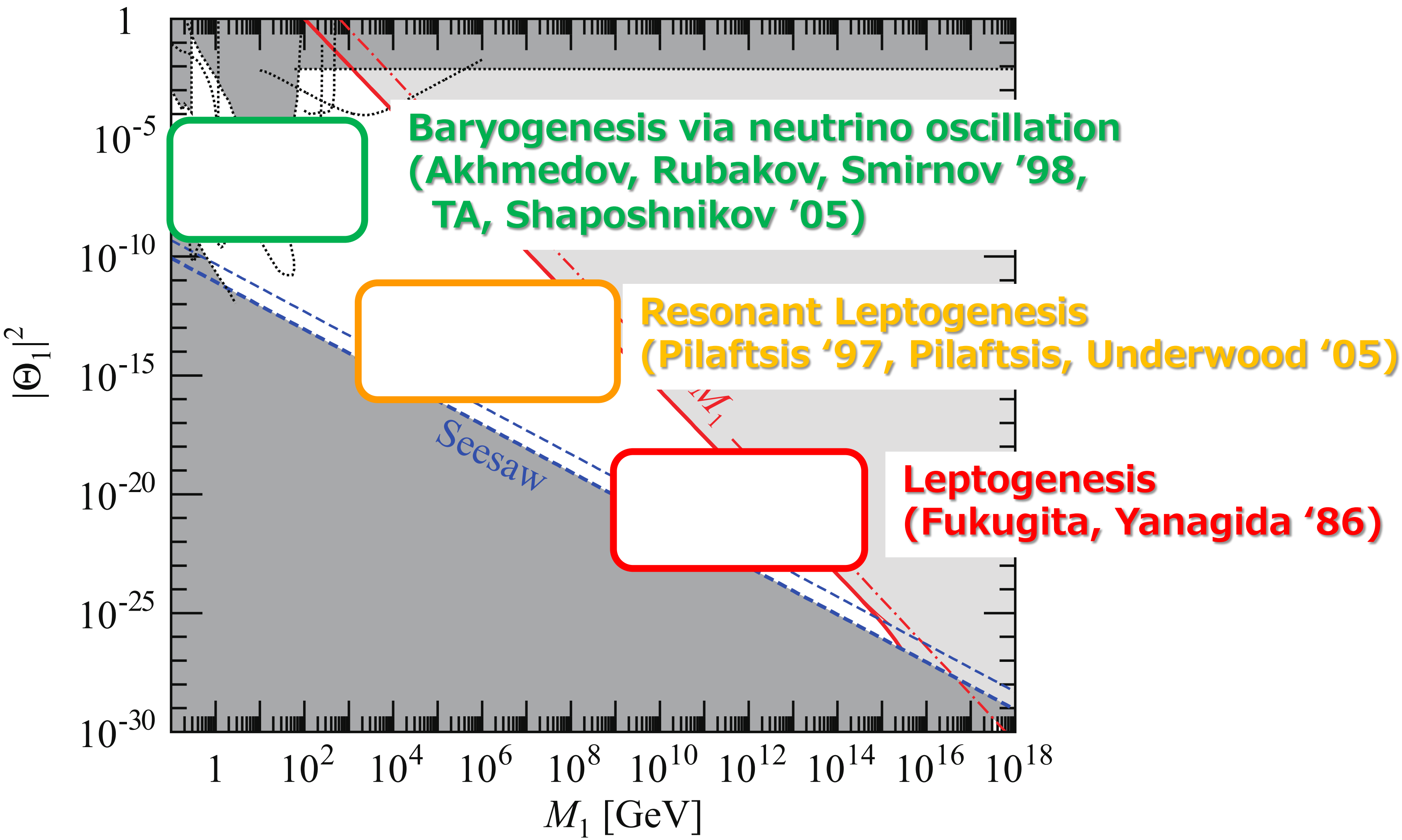
Range of parameter space

TA, Tsuyuki '15



Baryogenesis regions

TA, Tsuyuki '15



Baryogenesis via leptogenesis

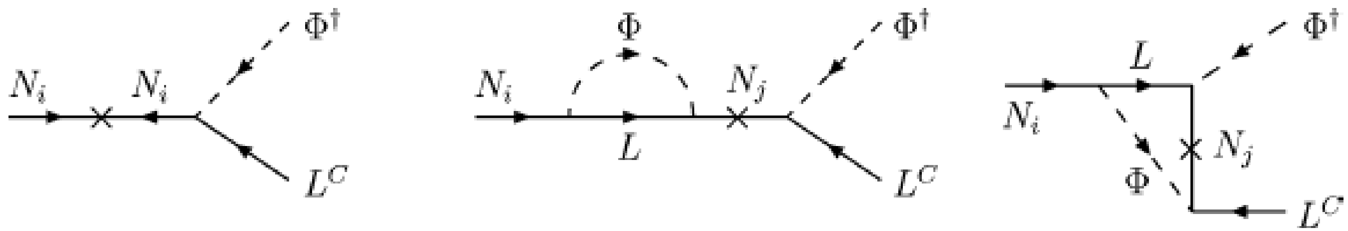
Leptogenesis

[Fukugita, Yanagida '86]

- Attractive idea:
  - Heavy right-handed neutrinos for the seesaw mechanism can provide the mechanism for generating lepton asymmetry .

- Decay of right-handed neutrino N_1

$$\varepsilon_{1\alpha} = \frac{\Gamma(N_1 \to L_\alpha + \bar{\Phi}) - \Gamma(N_1 \to \overline{L_\alpha} + \Phi)}{\Gamma(N_1 \to L_\alpha + \bar{\Phi}) + \Gamma(N_1 \to \overline{L_\alpha} + \Phi)}$$



  - If CP is violated,
    $\varepsilon_{1\alpha}$ can be non-zero and lepton number can be generated
    → source of BAU !

BAU via Leptogenesis

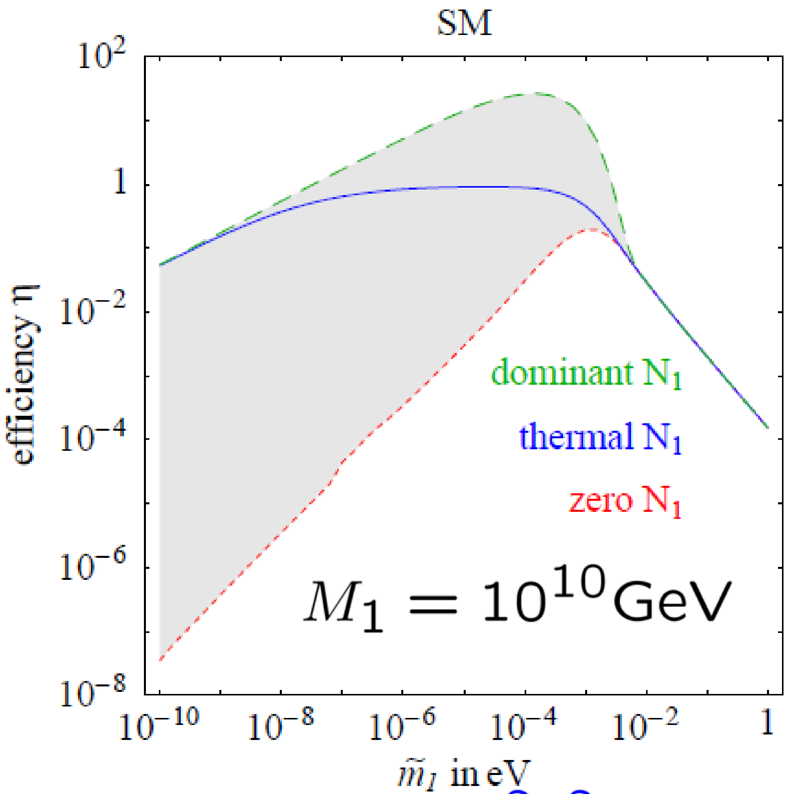
$$\frac{n_B}{s} = \frac{n_{N_1}}{s} \times \epsilon_1 \times 0.35 \times \eta$$

Efficiency factor

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

CP asymmetry $\propto M_1$

Sphaleron conversion



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

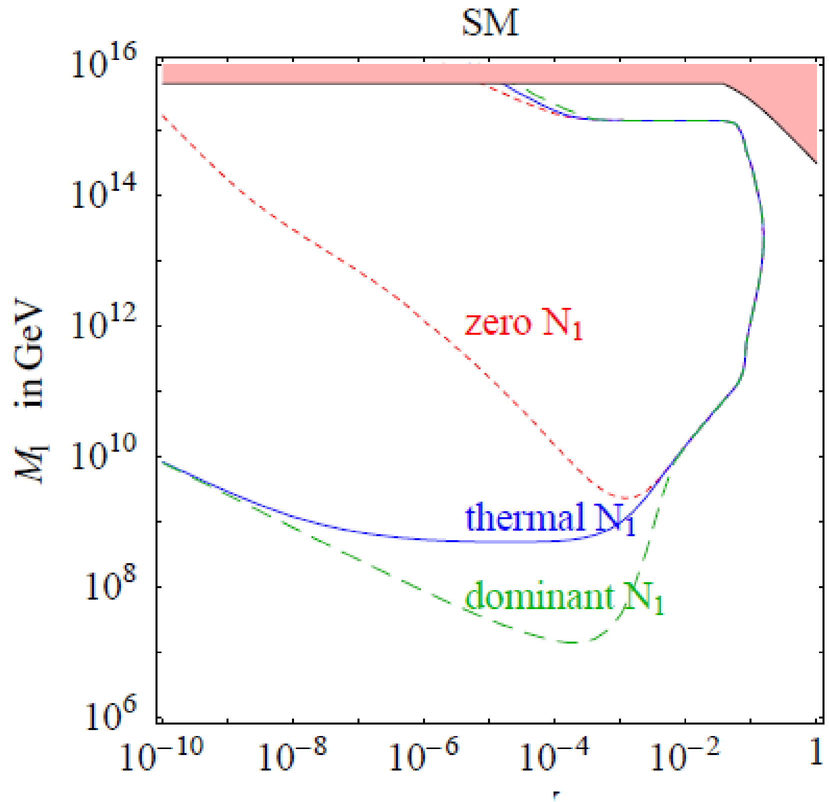
[Giudice et al 03]

Lower Bound on Mass M_1

[Giudice et al '03]

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

Lower bound on mass



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

Resonant leptogenesis

Pilaftsis '97
Pilaftsis, Underwood '04

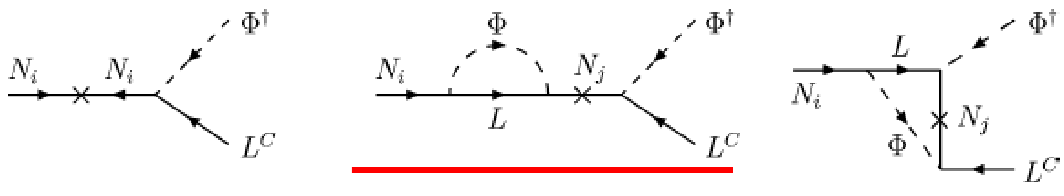
- Resonant production of lepton asymmetry occurs if right-handed neutrinos are quasi-degenerate

$$\varepsilon_1 = \frac{\Gamma(N_1 \to L_L + \overline{\Phi}) - \Gamma(N_1 \to \overline{L_L} + \Phi)}{\Gamma(N_1 \to L_L + \overline{\Phi}) + \Gamma(N_1 \to \overline{L_L} + \Phi)}$$

$\Delta M \ll M_N$

$$\Delta M = M_2 - M_1$$

$$M_N = (M_2 + M_1)/2$$



$$\varepsilon_1 \propto \frac{M_N^2}{\Delta M^2} \qquad (\text{for } \Delta M^2 > O(M_N \Gamma_N))$$

huge enhancement

$\Longrightarrow$ Leptogenesis is possible even for $M_1 \ll 10^9$ GeV

Note that $M_1 \gtrsim 10^2$ GeV in this case in order to convert lepton asymmetry into baryon asymmetry by EW sphaleron process ($T \gtrsim 10^2$ GeV)

BAU and CPV in neutrino sector

- Neutrino Yukawa couplings

$M_\nu = -M_D^T \, M_{N,\mathrm{diag}}^{-1} \, M_D$ → Casas, Ibarra ('01)

$$F = \frac{i}{\langle \Phi \rangle} \, U \, M_{\nu,\mathrm{diag}}^{1/2} \, \Omega \, M_{N,\mathrm{diag}}^{1/2}$$

In mixing matrix U
of active neutrinos

Dirac phase δ

Majorana phase(s) η (η')

In mixing matrix Ω
of RH neutrinos

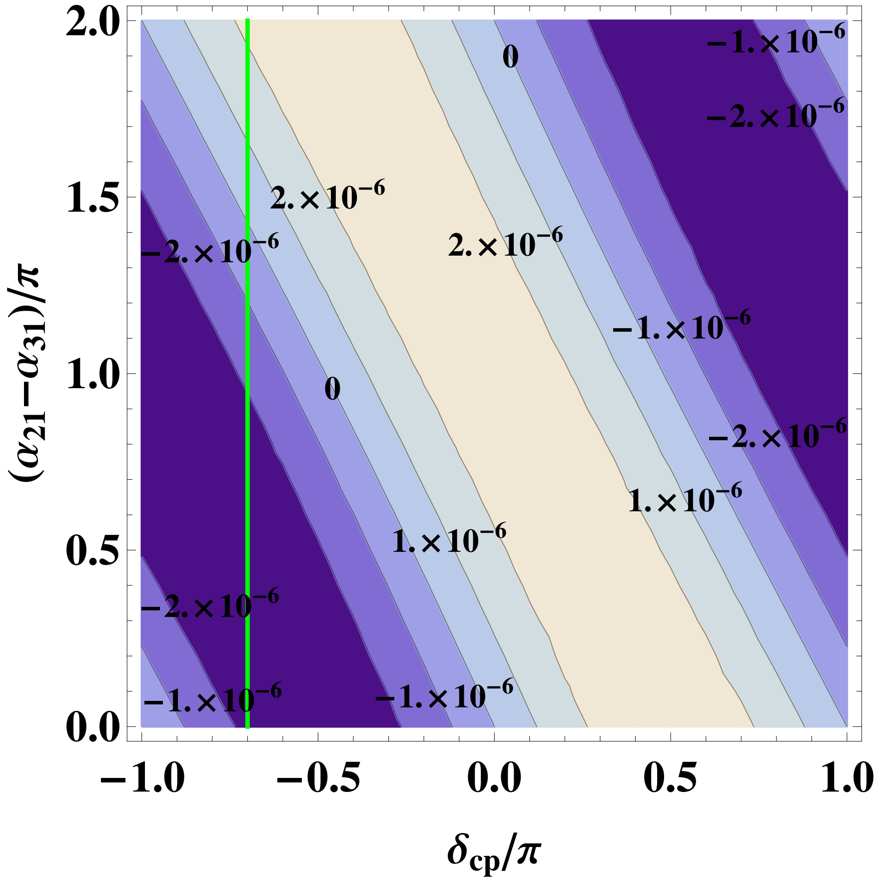
Phase(s) for ν_R

These phases are essential for BAU !

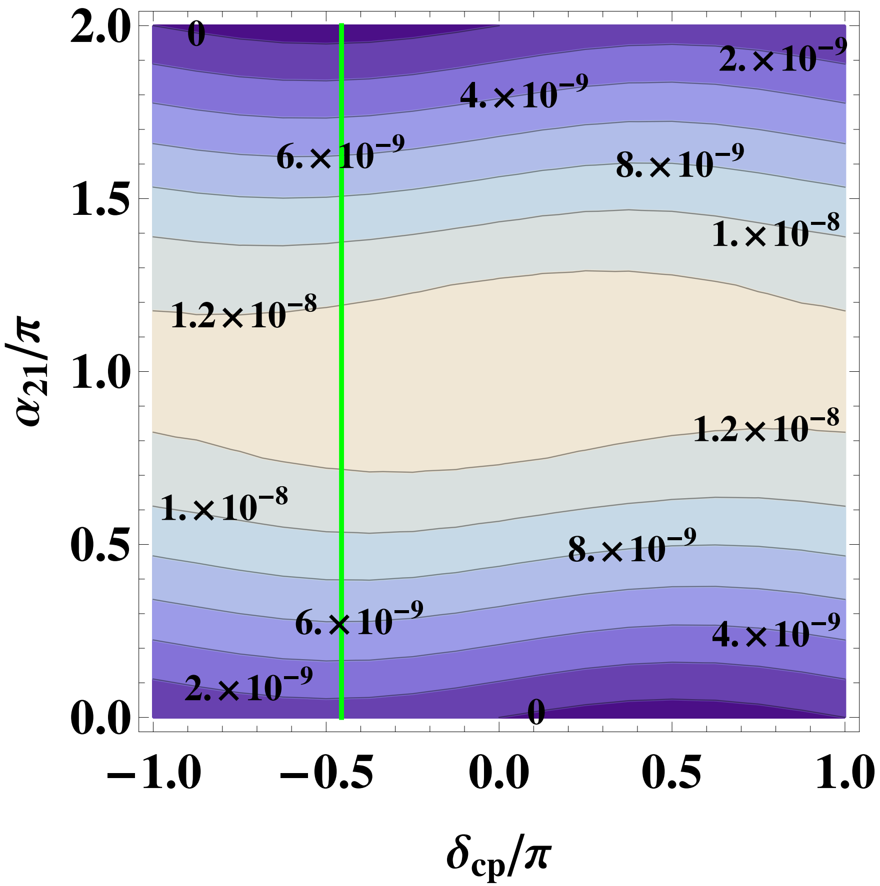
BAU vs Dirac and Majorana phases

Degenerate right-handed neutrinos with $M_1 = 10^3$GeV

NH
Contour of Y_B



IH
Contour of Y_B

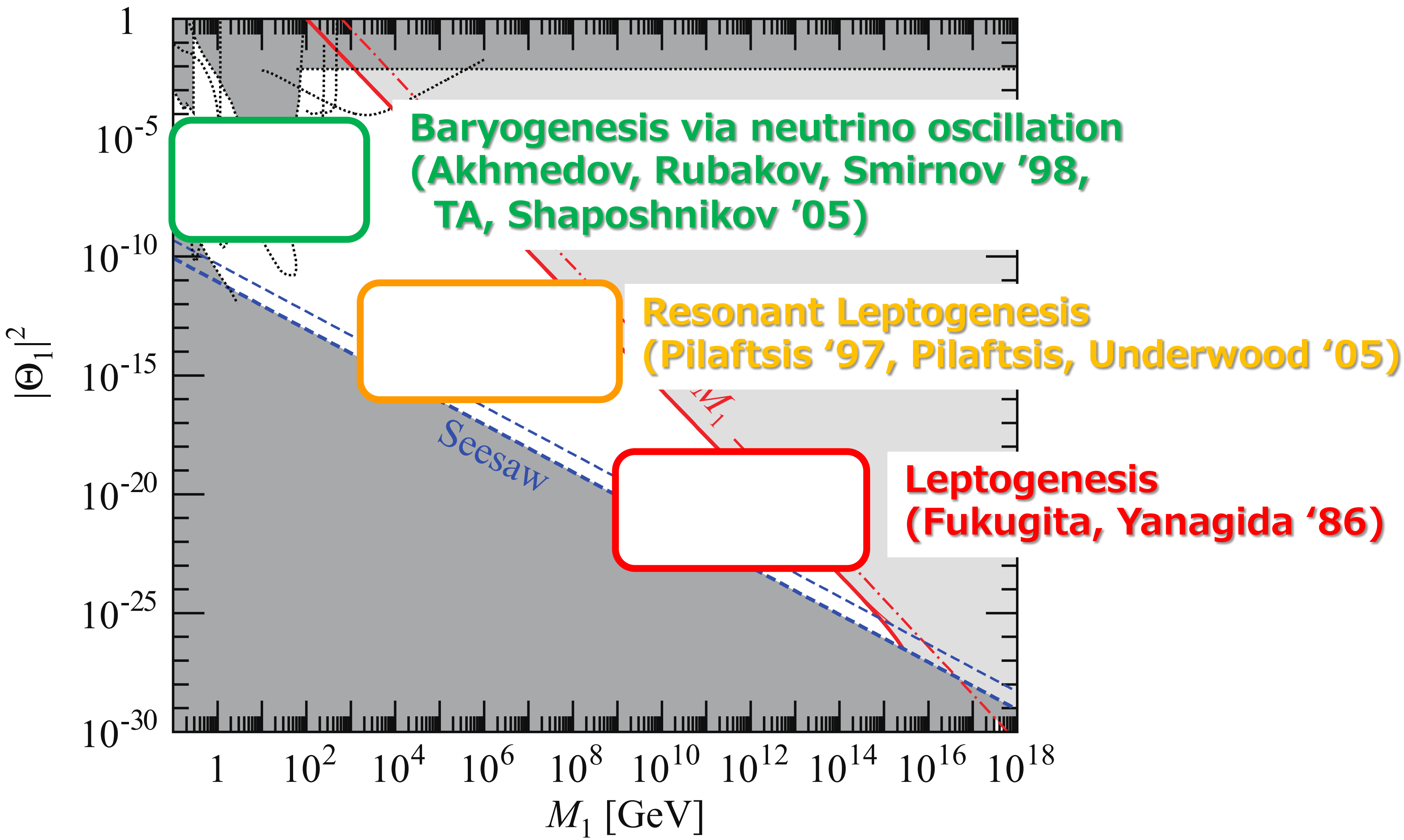


--> impact on 0νββ decay
(See Yoshida-san's talk.)

TA, Yoshida [arXiv:1812.11323]

Baryogenesis regions

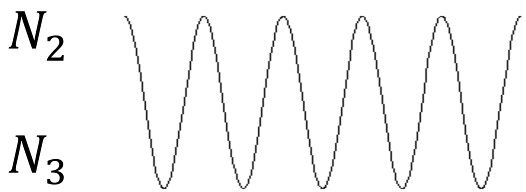
TA, Tsuyuki '15



Baryogenesis via Neutrino Oscillation

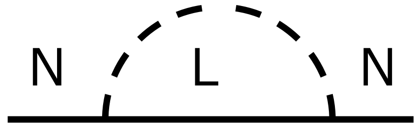
Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)
Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)
…

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

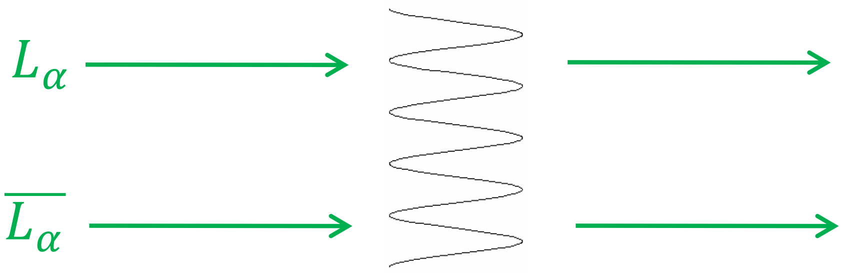


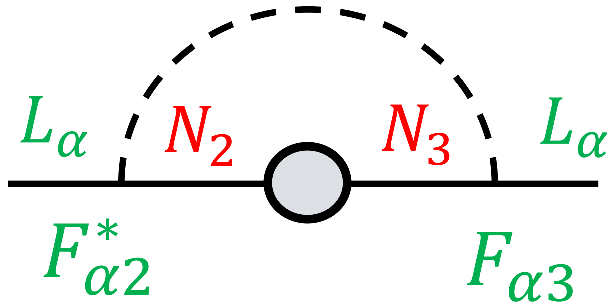
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



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

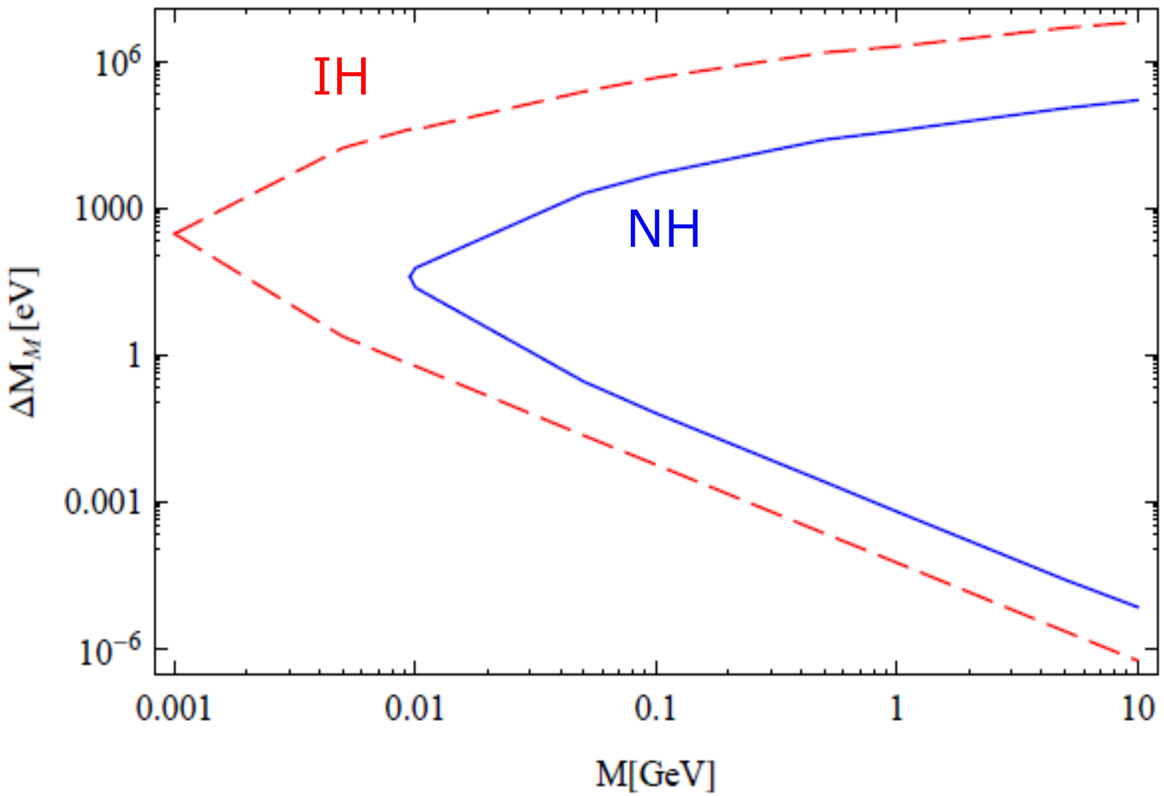




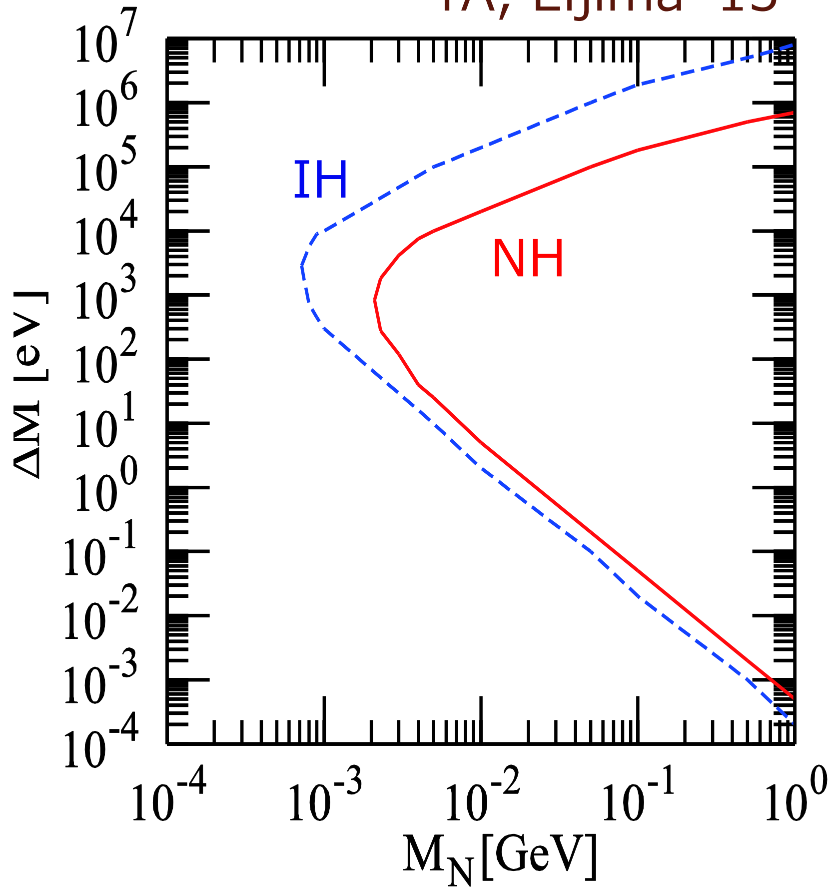
Baryogenesis Region

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

Canetti, Shaposhnikov '10



TA, Eijima '13

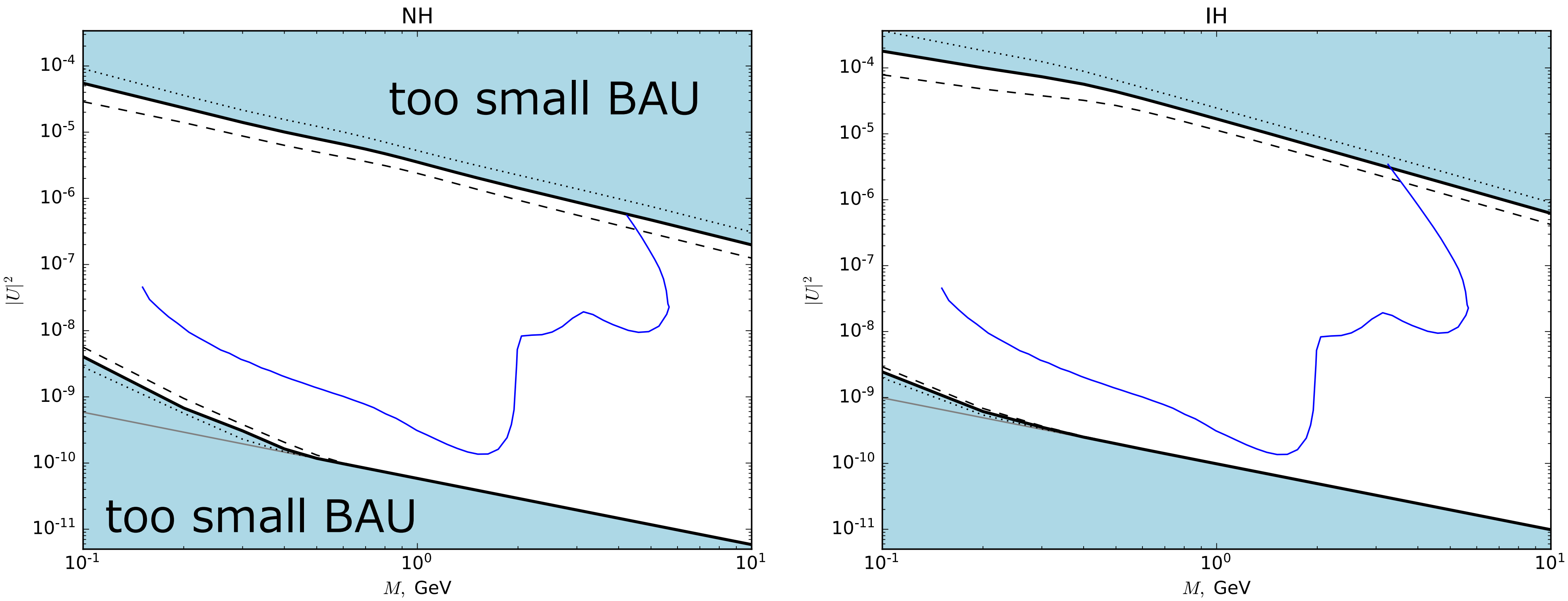


$M_N > 2.1$ MeV (NH) $\quad M_N > 0.7$ MeV (IH)

Baryogenesis region

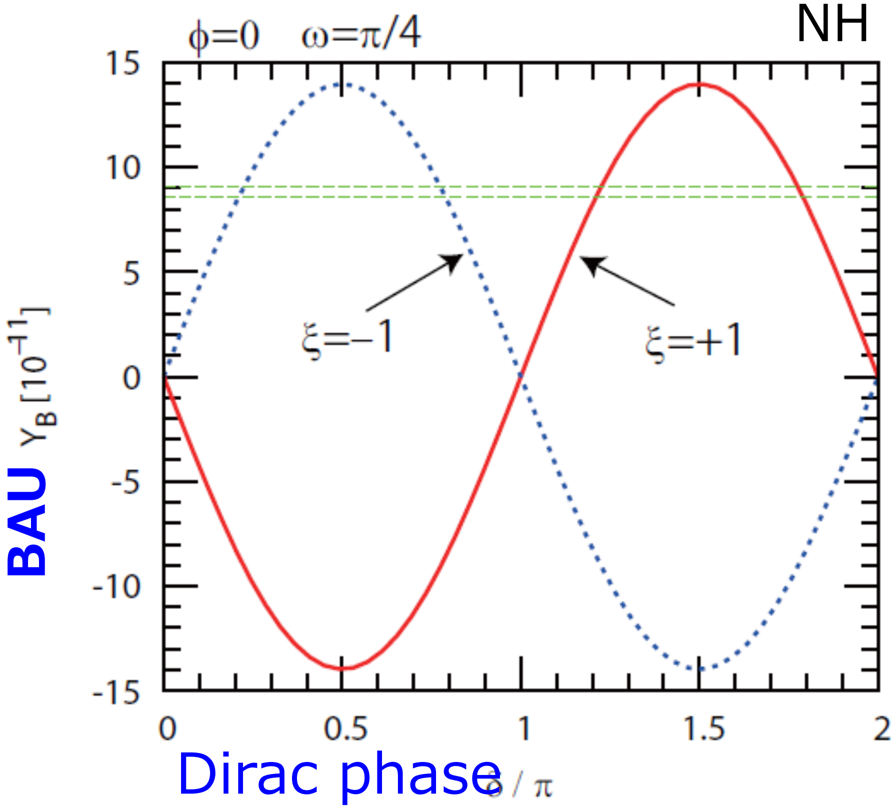
- Range of mixing angle

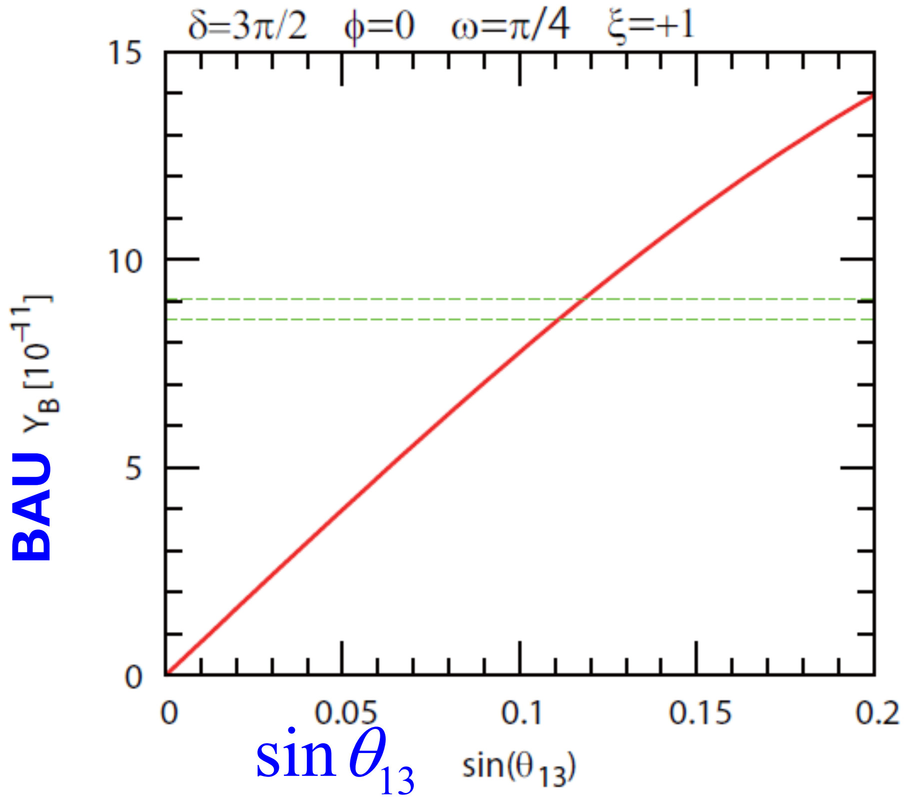
Eijima, Shaposhnikov, Timiryasov '18
[arXiv:1808.10833]



Dirac phase δ and baryogenesis via oscillation

TA, Ishida ('10)





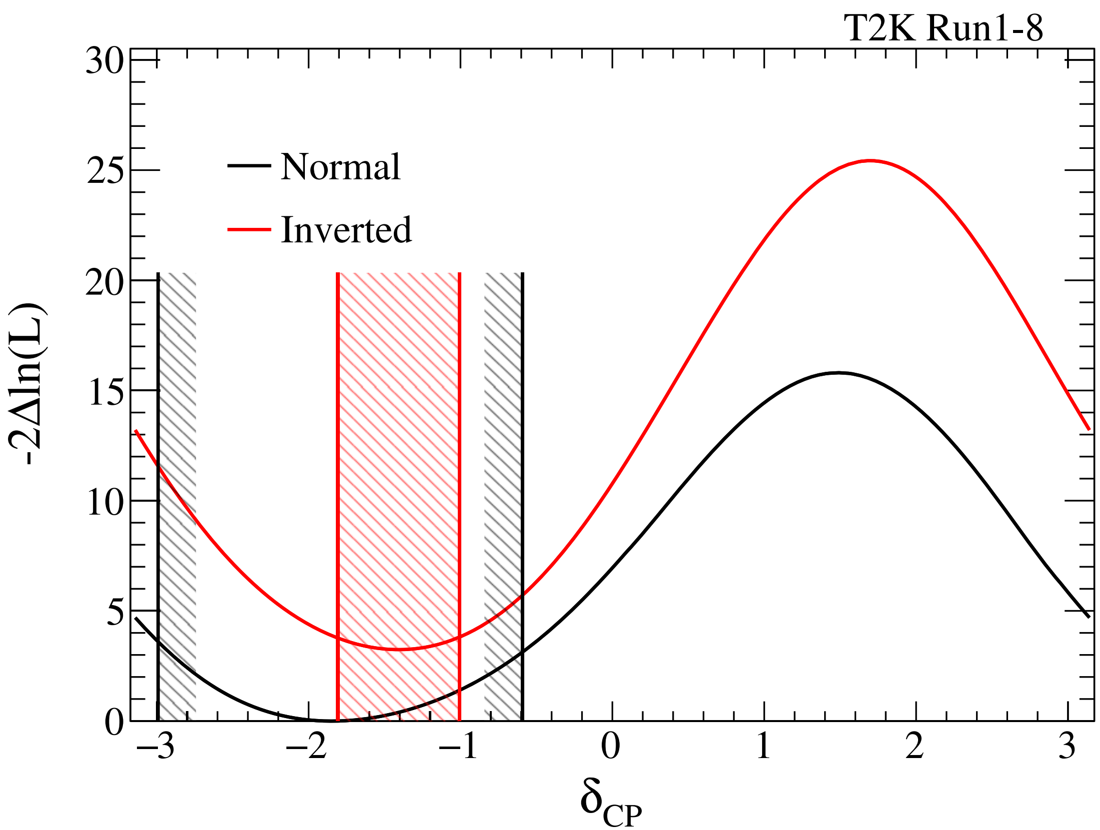
$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13}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

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

BAU and CPV in neutrino sector

- T2K and NOvA indicate CPV in neutrino sector

T2K, PRL 121, 171802 ('18)



Non-zero Dirac phase

$$\delta \sim -\frac{\pi}{2} \left(or \ \frac{3\pi}{2} \right)$$

Important step to understand baryogenesis by RH neutrinos !

Search for HNL (ν_R)

Search for Heavy Neutral Leptons

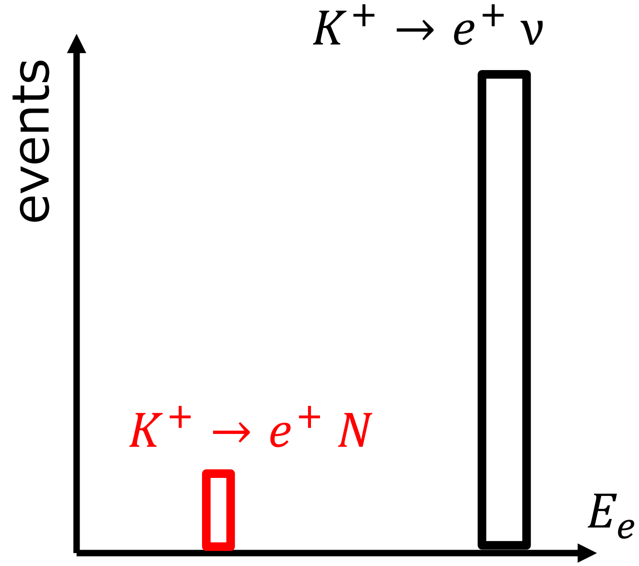
- Production by meson decays

  $K^+ \to e^+ N, K^+ \to \mu^+ N, \ldots$

  - **Peak search experiments**
    - Measure E_e in $K^+ \to e^+ N$

$$E_e = \frac{m_K^2 - m_e^2 - M_N^2}{2\, m_K}$$

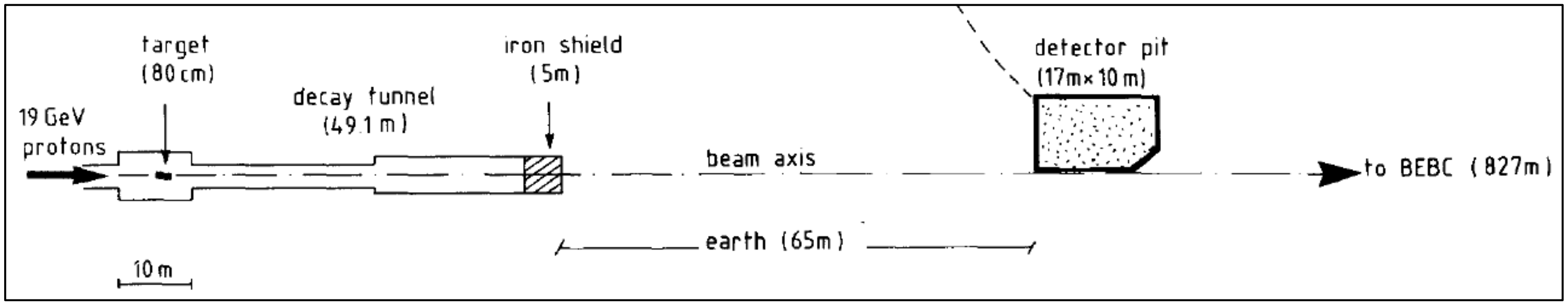
[Shrock '80]



  - **Beam dump experiments**

$K^+ \to e^+ N$ $\quad N \to \ell^+ \ell^- \nu + c.c.$

CERN PS191



Search for HNLs at T2K

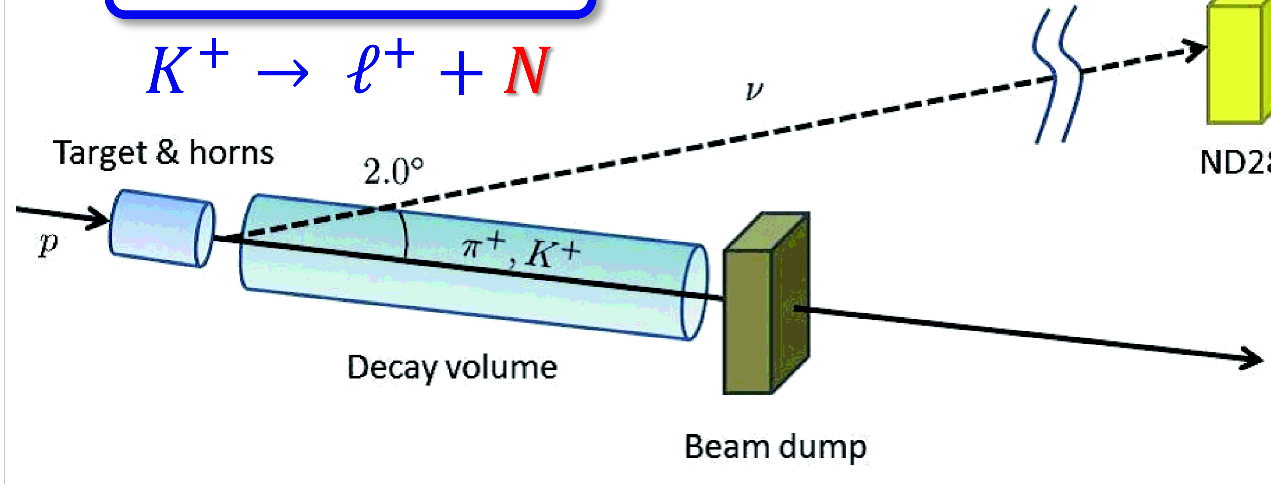
TA, Eijima, Watanabe
[JHEP1303 (2013) 125]

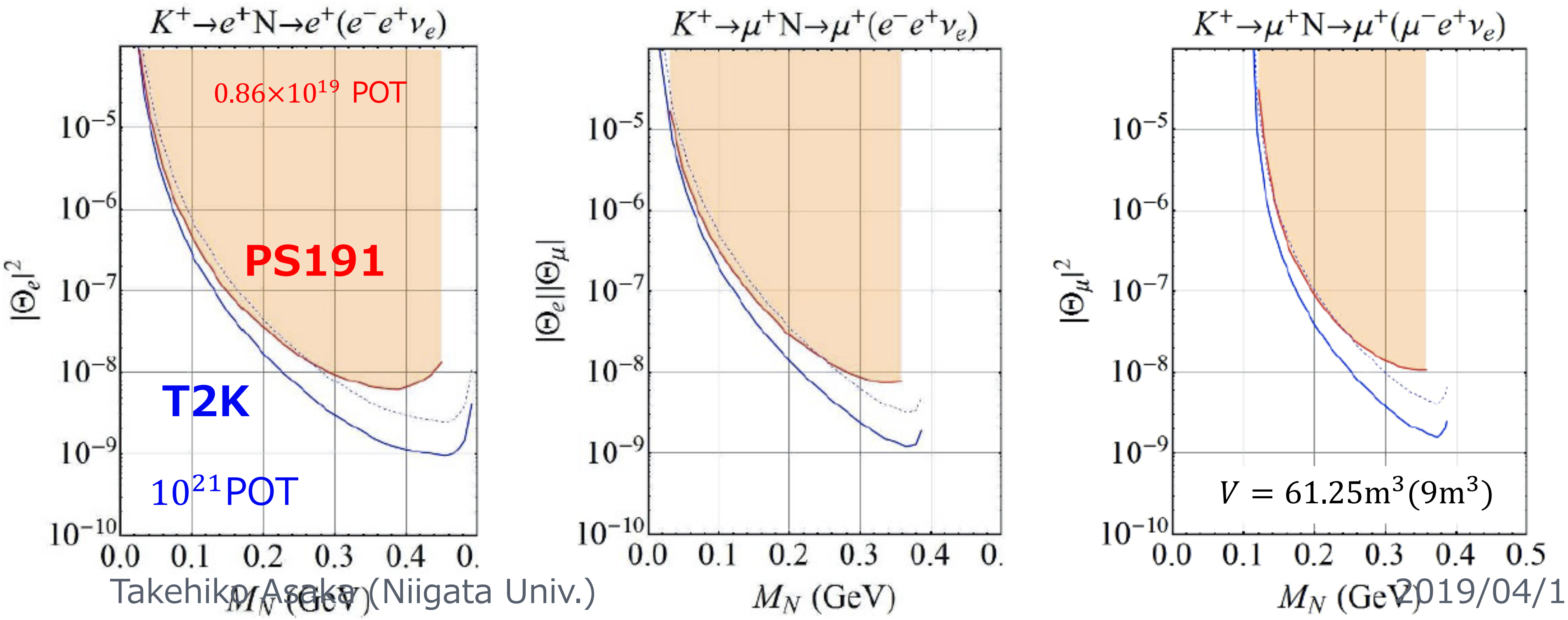
Production of N

$K^+ \to \ell^+ + N$

Detection of N

$N \to \ell^- + \ell^+ + \nu$





(The T2K Collaboration)

arXiv:1902.07598v1 [hep-ex] 20 Feb 2019

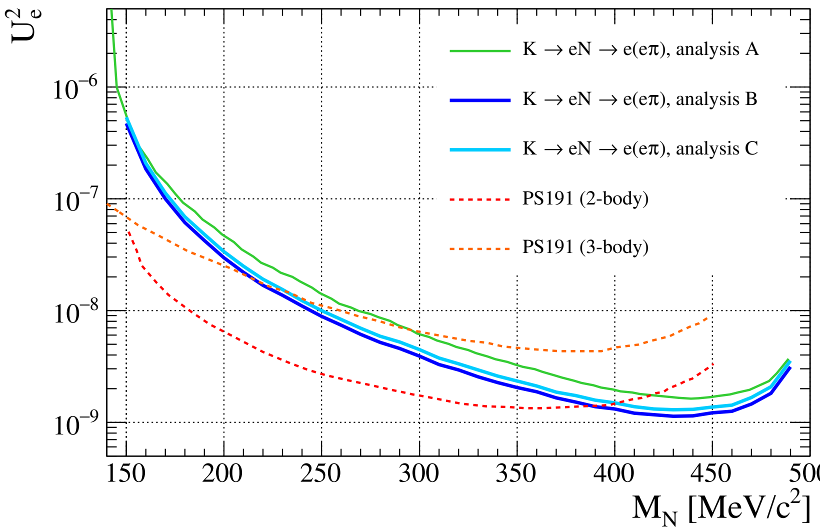


FIG. 5. 90% upper limits on the mixing element U_e^2 as a function of heavy neutrino mass using the single-channel approach, considering only the contribution from $K^\pm \to e^\pm N, N \to e^\pm \pi^\mp$, with the three methods **A**, **B** and **C**. The limits are compared to the ones of PS191 experiment [6, 7].

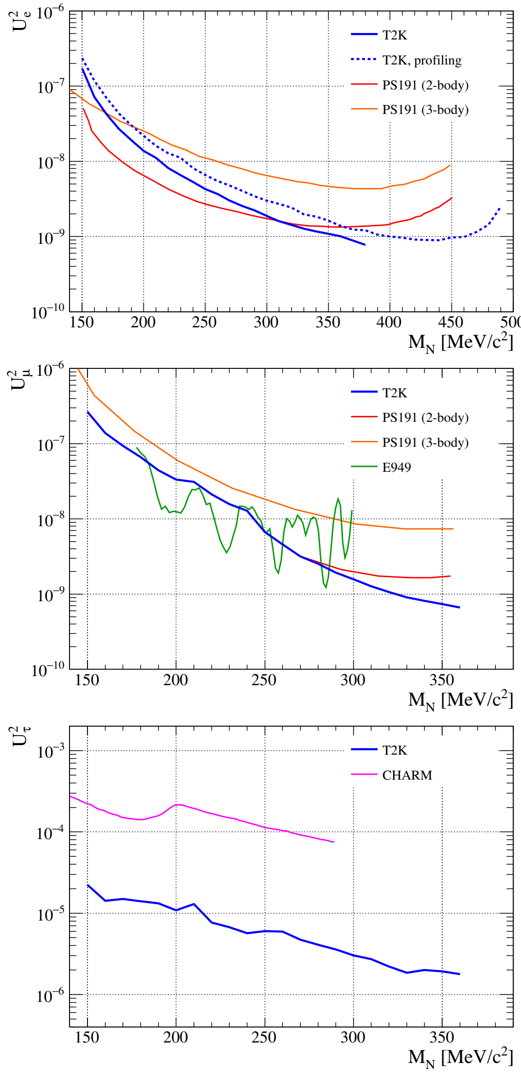
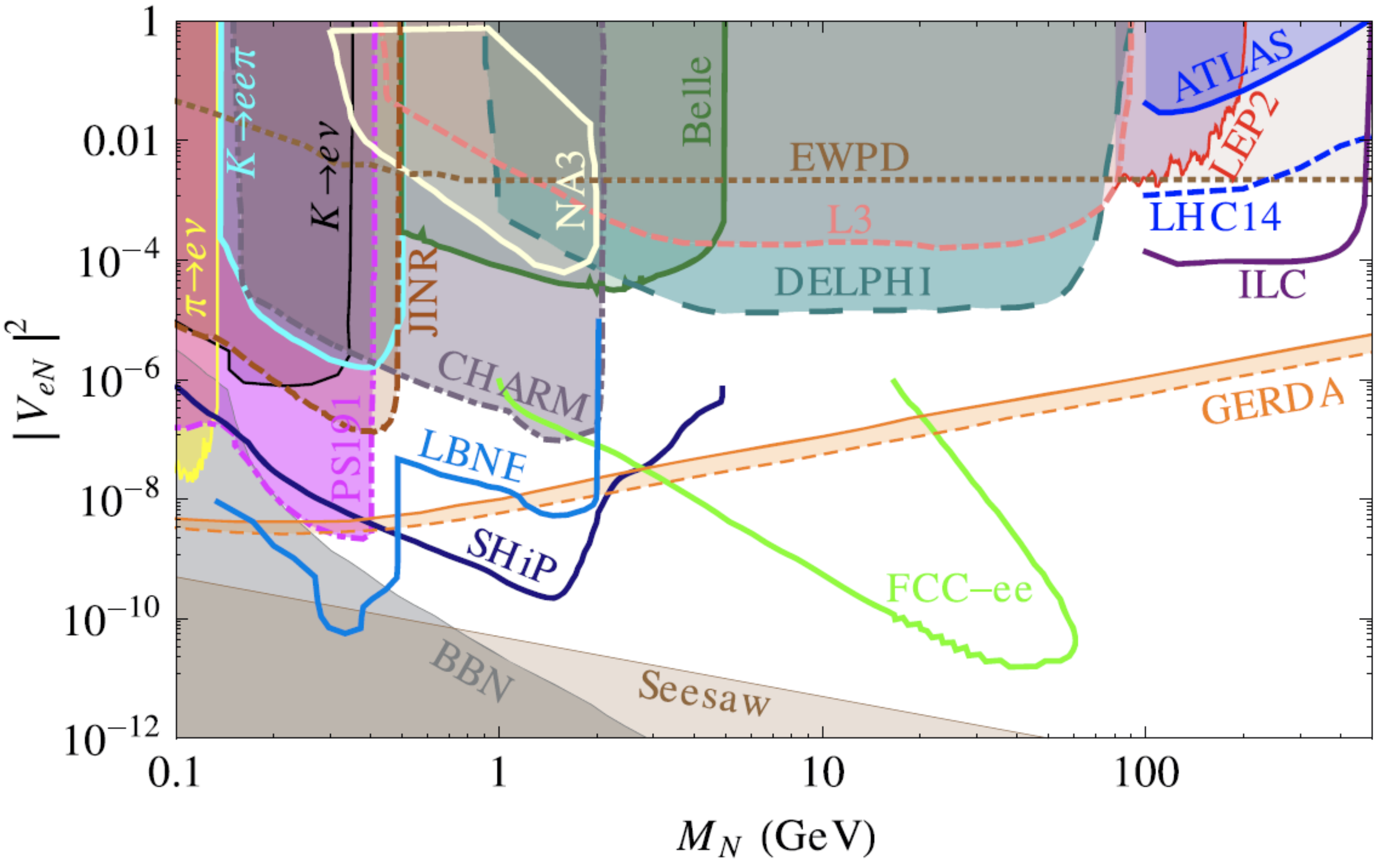


FIG. 6. 90% upper limits on the mixing elements U_e^2 (top), U_μ^2 (middle), U_τ^2 (bottom) as a function of heavy neutrino mass, obtained with the combined approach. The blue solid lines are obtained after marginalisation over the two other mixing elements. In the top plot, the additional blue dashed line corresponds to the case where profiling is used ($U_\mu^2 = U_\tau^2 = 0$). The limits are compared to the ones of other experiments: PS191 [6, 7], E949 [5], CHARM [25].

Limits on mixing of HNL

- Limits on mixing Θ_{eI}

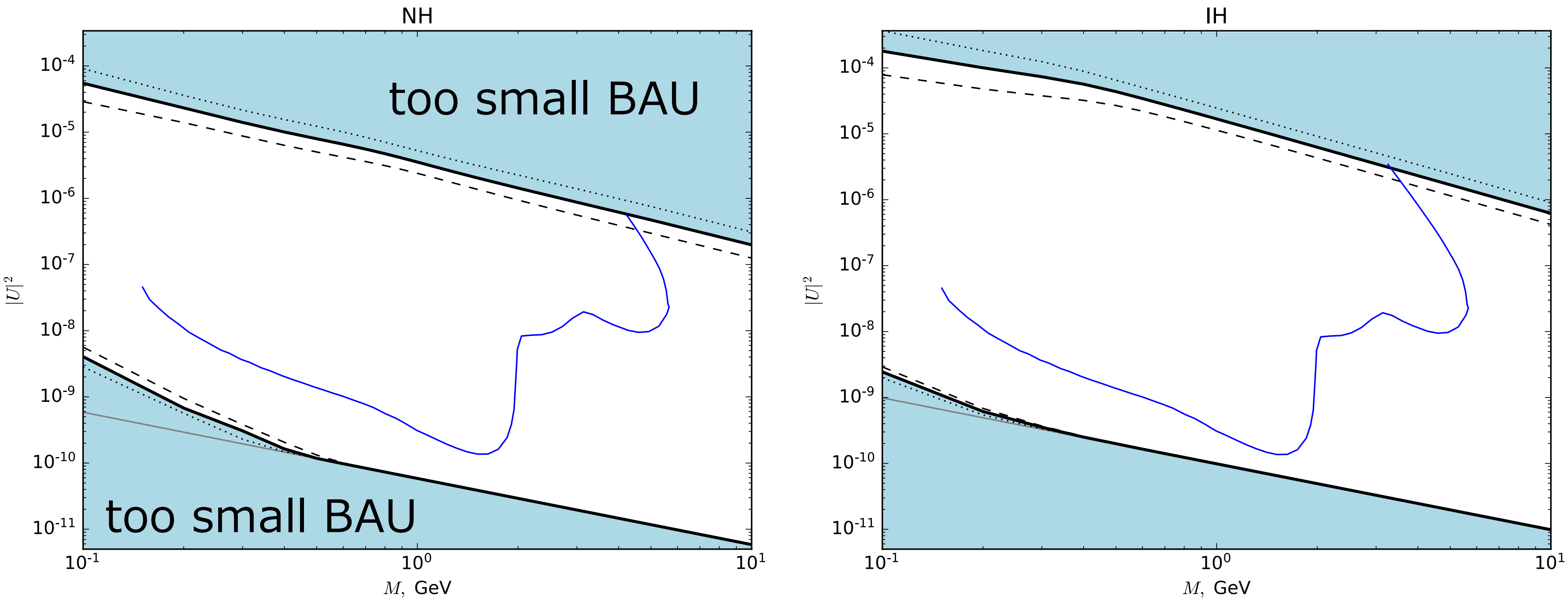
Deppisch, Dev, Pilaftsis '15



Baryogenesis region

- Range of mixing angle

Eijima, Shaposhnikov, Timiryasov '18
[arXiv:1808.10833]



Summary

- Neutrinos may provide the mechanism for generating the matter-antimatter asymmetry of the universe

- Conventional seesaw scenario ($M>10^9$GeV)
  [Seesaw + Leptogenesis]
  → natural framework of SUSY GUT ⋯
  → Exp. test for RH neutrinos is impossible

- Connection can be obtained even with $M<10^2$GeV
  [Seesaw + Baryogenesis via RH neutrino osc.]
  → Such RH neutrinos might be tested!