Probing origins of neutrino masses and baryon asymmetry

Takehiko Asaka (Niigata Univ.)

In collaboration with
Shintaro Eijima (EPFL, Switzerland)
Atsushi Watanabe (MPIK, Germany)

References: JHEP 1303 (2013) 125
PTEP 113B02 (2013)

Introduction

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

  $\Rightarrow$ **Need for physics beyond the SM !**

- Important questions:
  - ***"What is the origin of neutrino masses?"***
  - ***"How do we test it experimentally?"***

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

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

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

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

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

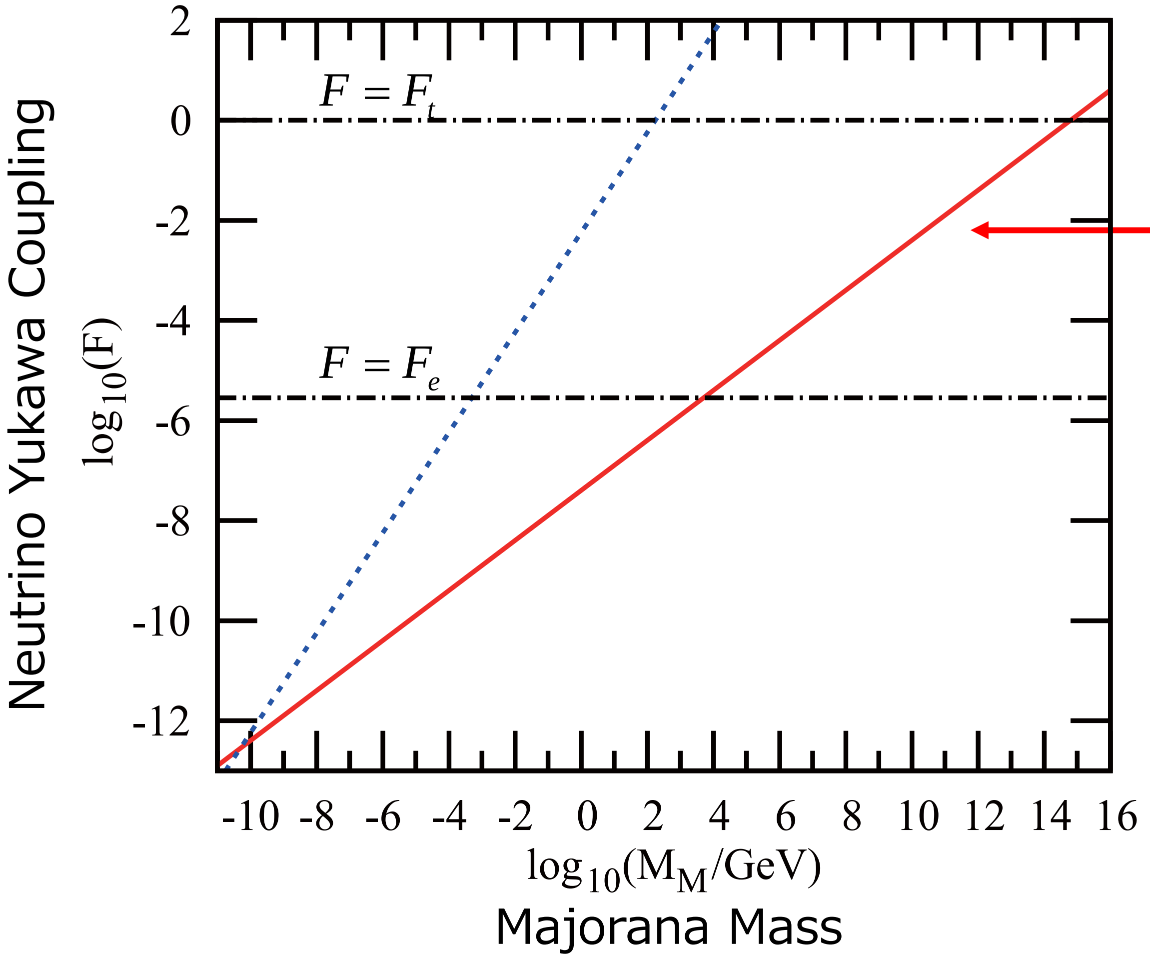
Where is the scale of mass?

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

Scale of Majorana mass

- The simplest case: one pair of ν_L and ν_R

$$M_\nu = -M_D^T \frac{1}{M_M} M_D \quad \Rightarrow F^2 = M_M M_\nu / \langle \Phi \rangle^2$$



$M_\nu = \sqrt{\Delta m^2_{atm}}$

Scale of Majorana mass

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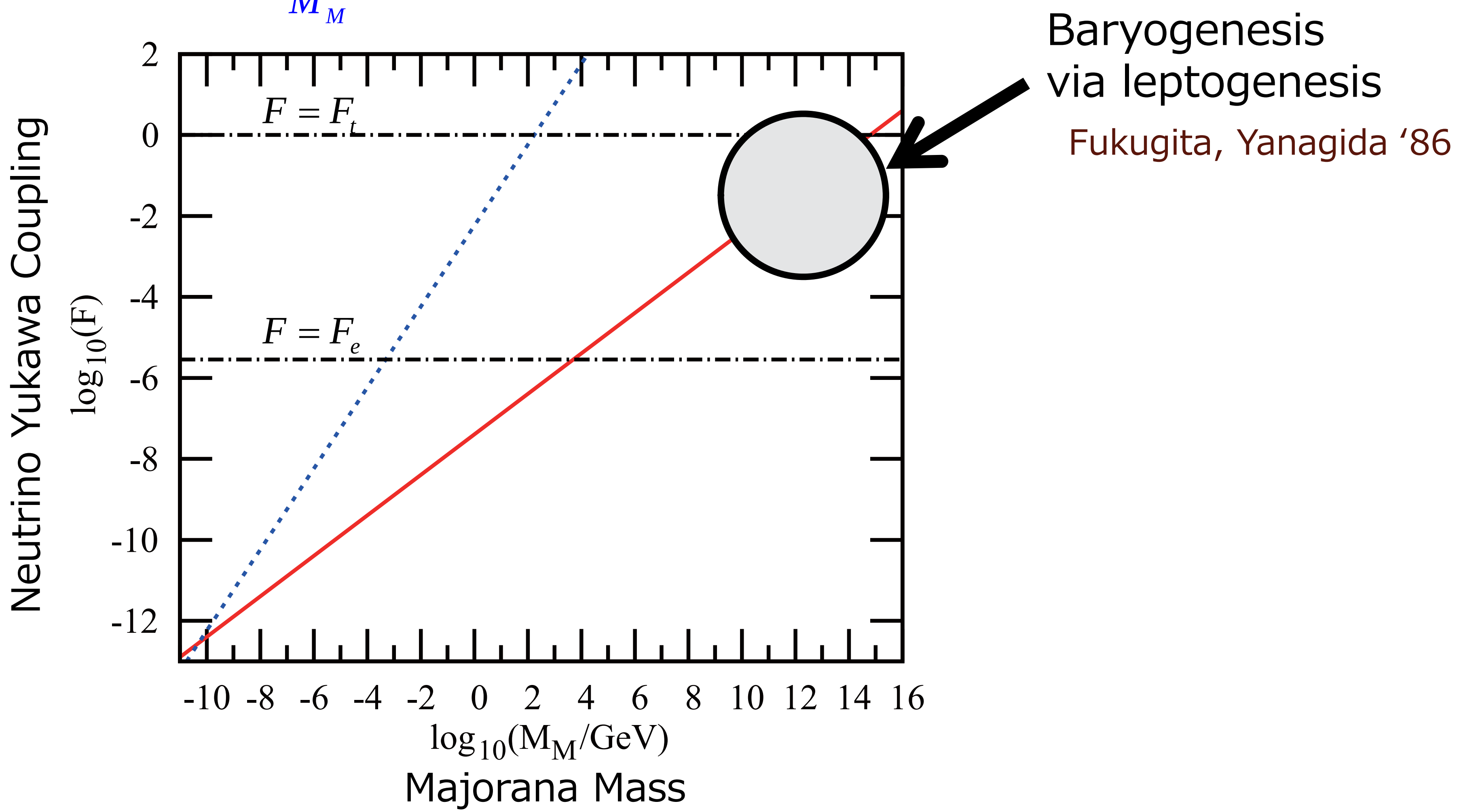

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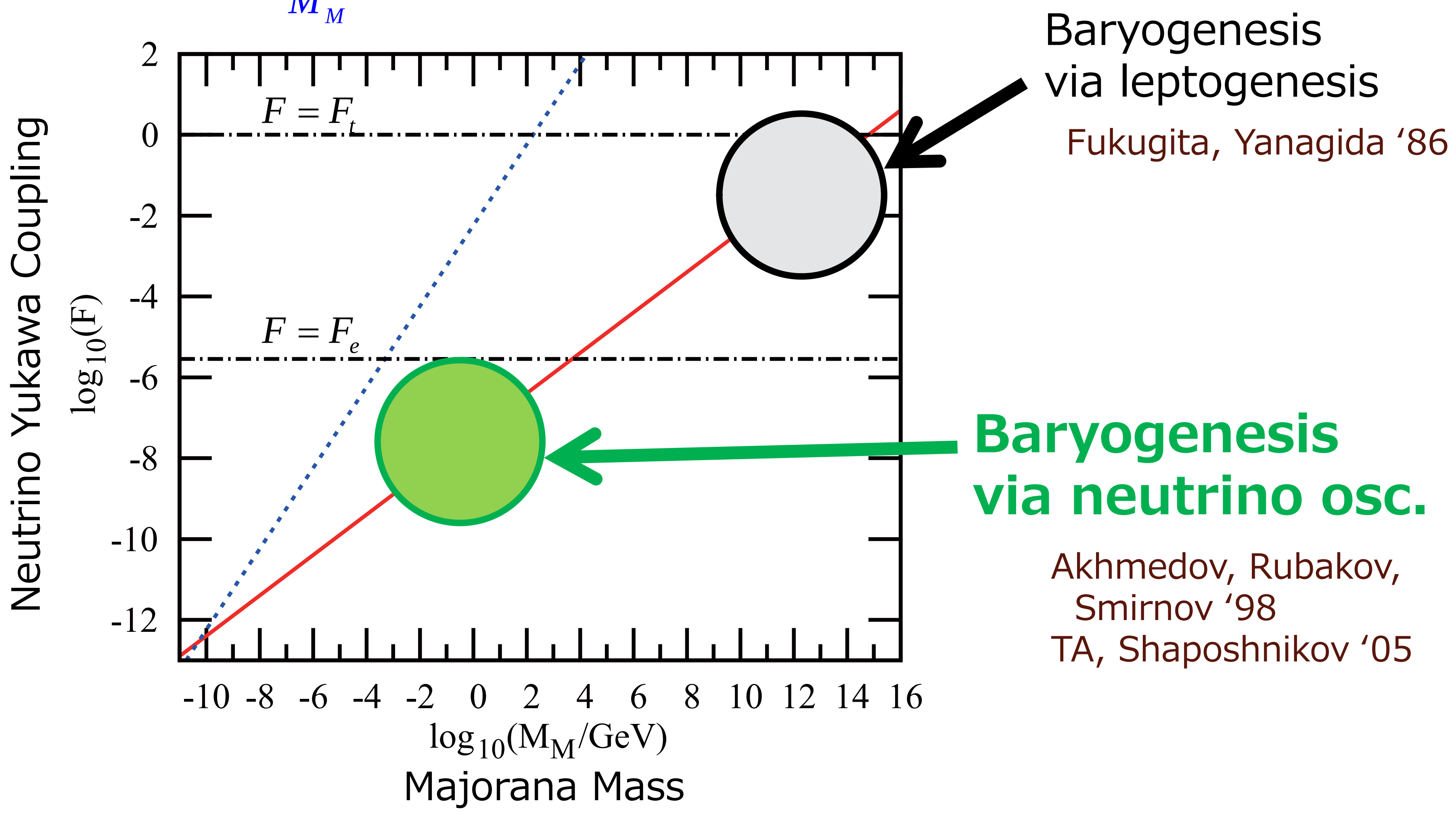

In this talk

Consider the minimal case with two RH neutrinos

- **Lighter than charged kaon $M_{2,3} < m_K$**
  $\longrightarrow$ Test by Kaon decays ($K^+ \to \ell^+ N_I$) is possible

Heavy neutral leptons = Heavy neutrinos

- **Current status of (RH) heavy neutrinos**
  - Region of successful baryogenesis
  - Constraints from direct search and cosmology
- **Implication to $0\nu 2\beta$ decay**
- **Search for (RH) heavy neutrinos at T2K**

When adding one more DM RH neutrino N_1,

the results can be applied to the νMSM !!

TA, Blanchet, Shappshnikov ('05),
TA, Shaposhnikov ('05)

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Current status of heavy neutrinos

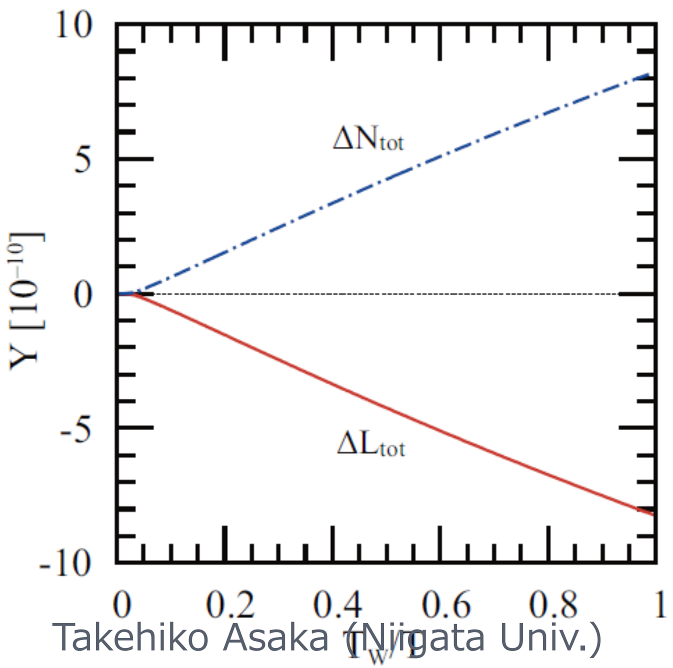
Baryogenesis via neutrino osc.

Oscillation of heavy neutrinos 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)

- CPV in oscillation and production generates asymmetries
- Asymmetries are separated into LH and RH leptons
- Asymmetry in LH leptons is converted into BAU



Yield of BAU depends on Yukawa couplings $F_{\alpha I}$ and masses

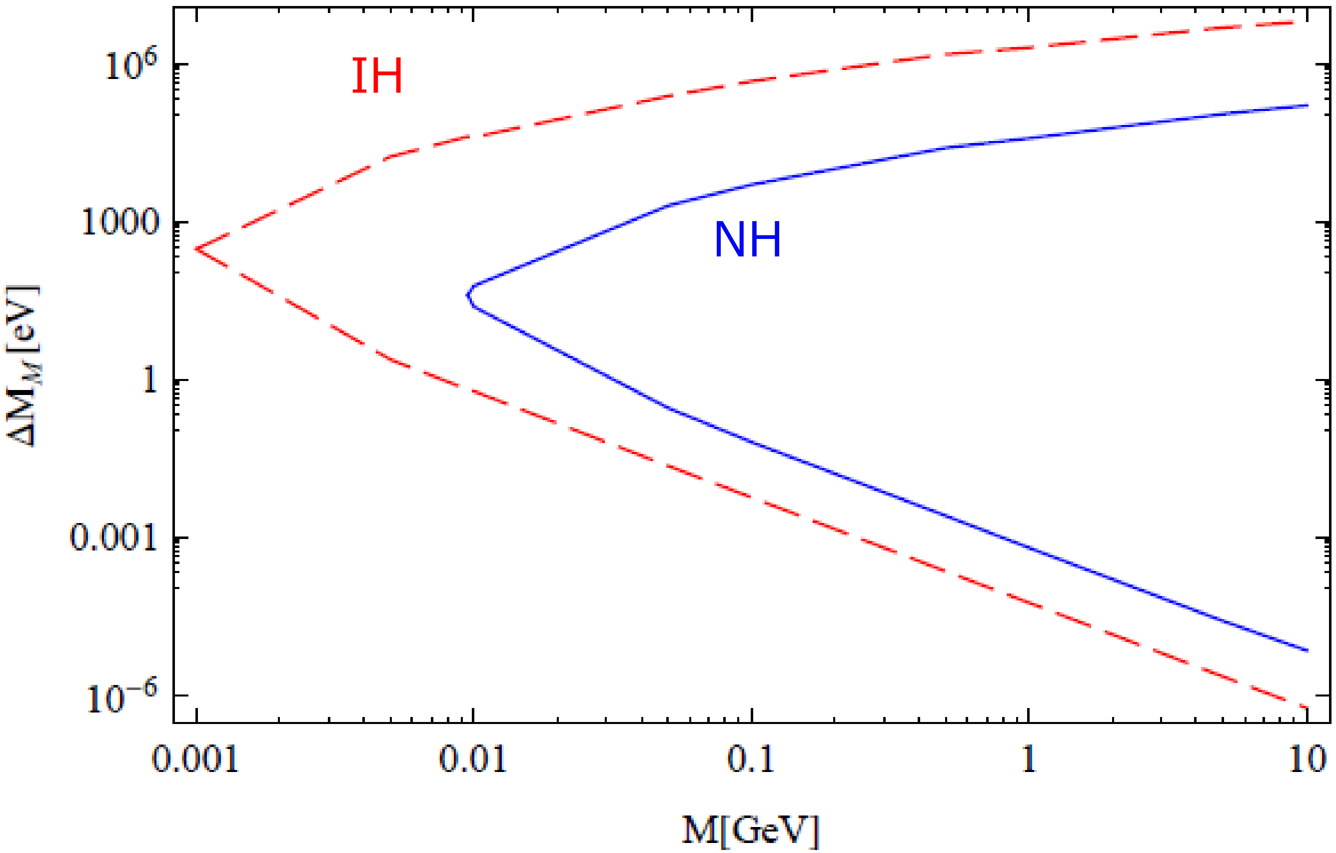
Especially, CP violating parameters and mass difference

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

Baryogenesis via neutrino osc.

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

Canetti, Shaposhnikov '10



Baryogenesis via neutrino osc.

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

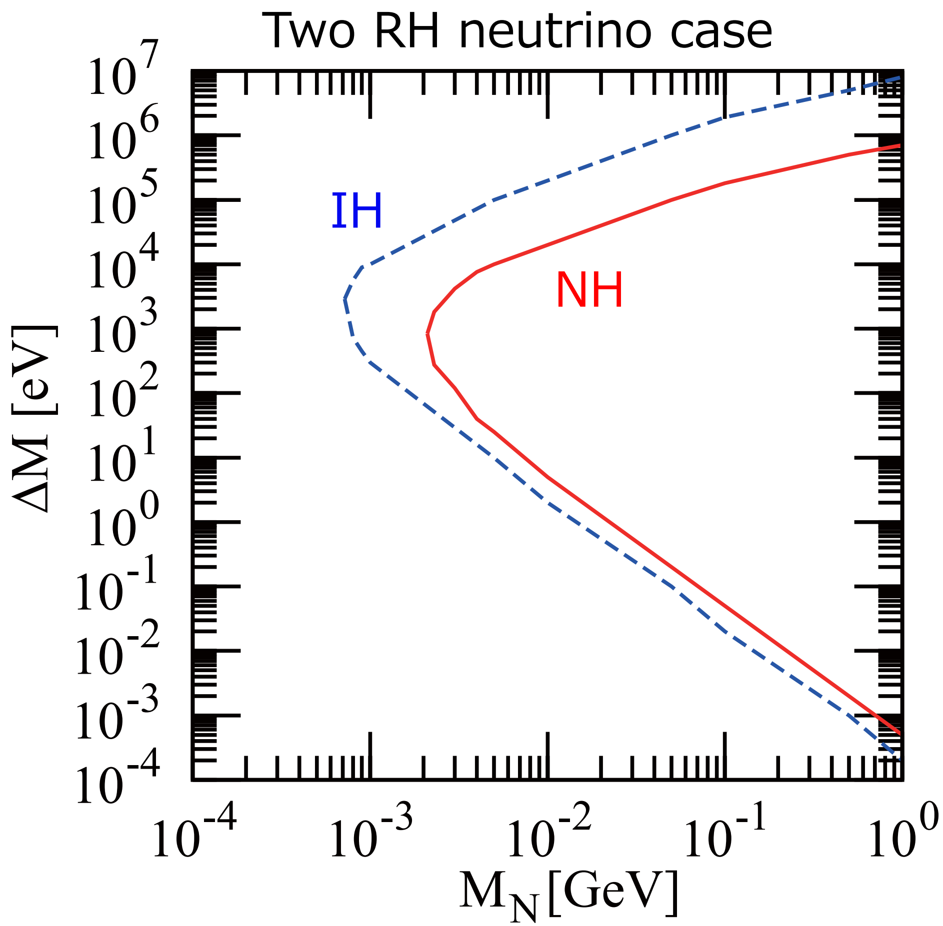
(1) quasi-degenerate

(2) masses are

$M_N > 2.1$ MeV (NH)

$M_N > 0.7$ MeV (IH)

TA, Eijima '13



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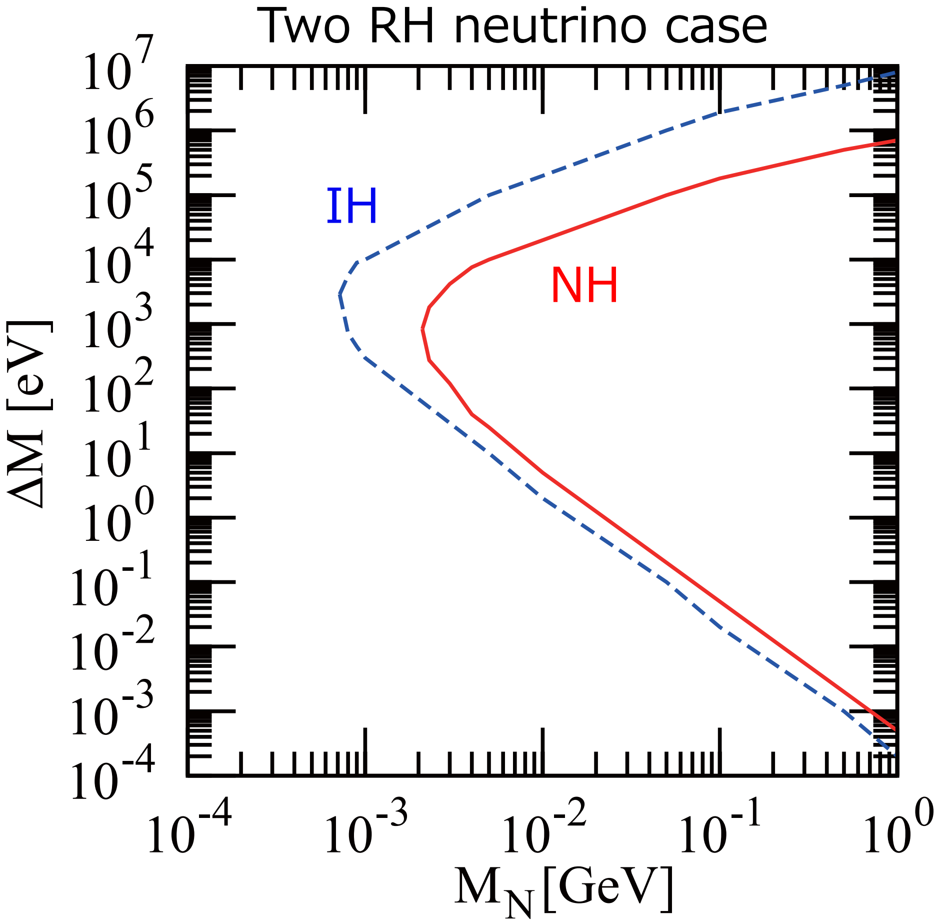
Such light RH neutrinos can be directly tested by experiments!

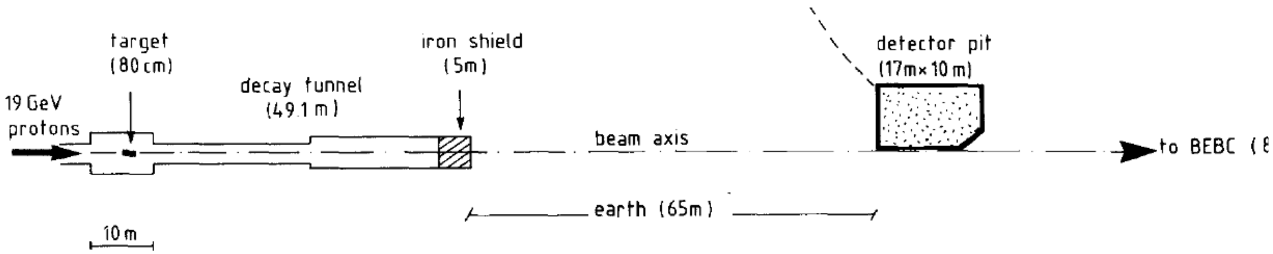
TA, Eijima '13



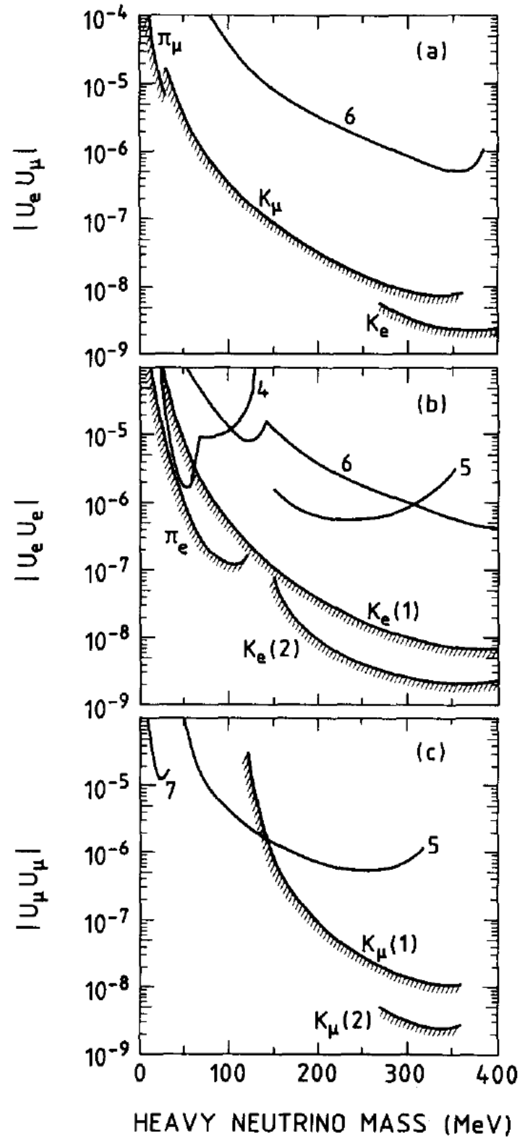
Direct search experiment

- PS191 [Bernardi et al '86, '88]

  Beam dump experiment
  performed at CERN in 1984



  - Production $\pi^+, K^+ \to e^+ N$
  - Detection $N \longrightarrow \ell^+ \ell^- \nu, \ell^- \pi^+$



- Upper bounds mixing elements Θ

  $\to$ Lower bound on lifetime of N

BBN constraint on lifetime

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

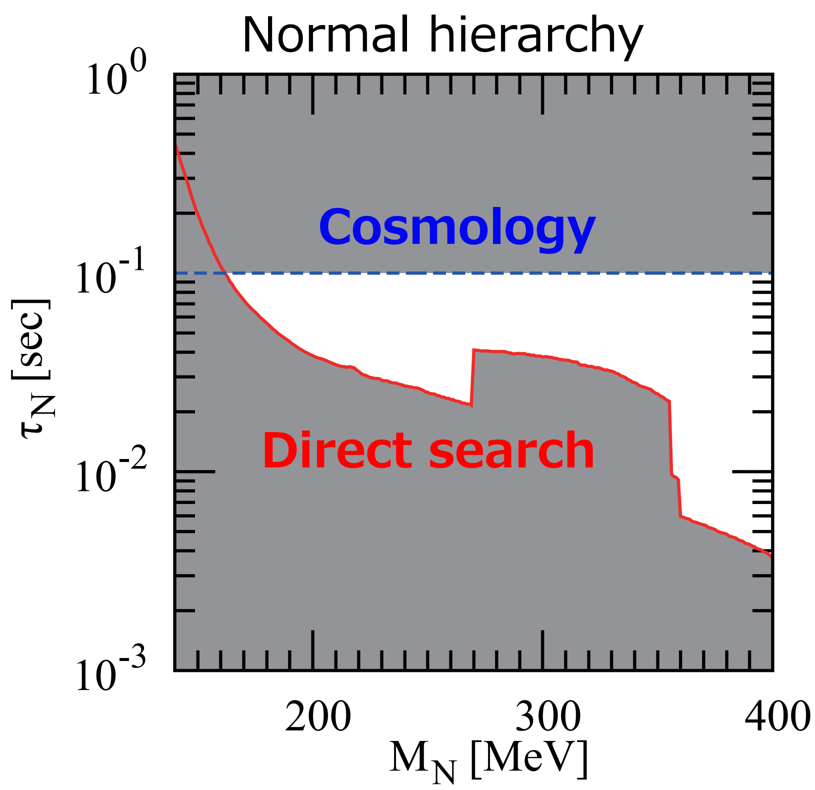
      $n + \nu \leftrightarrow p + e^-, \ldots$
  - Distortion of spectrum of active neutrinos
    - $N_{2,3} \rightarrow \nu\, \bar{\nu}\, \nu,\ e^+\, e^-\, \nu, \ldots$
    - Additional neutrinos may not be thermalized

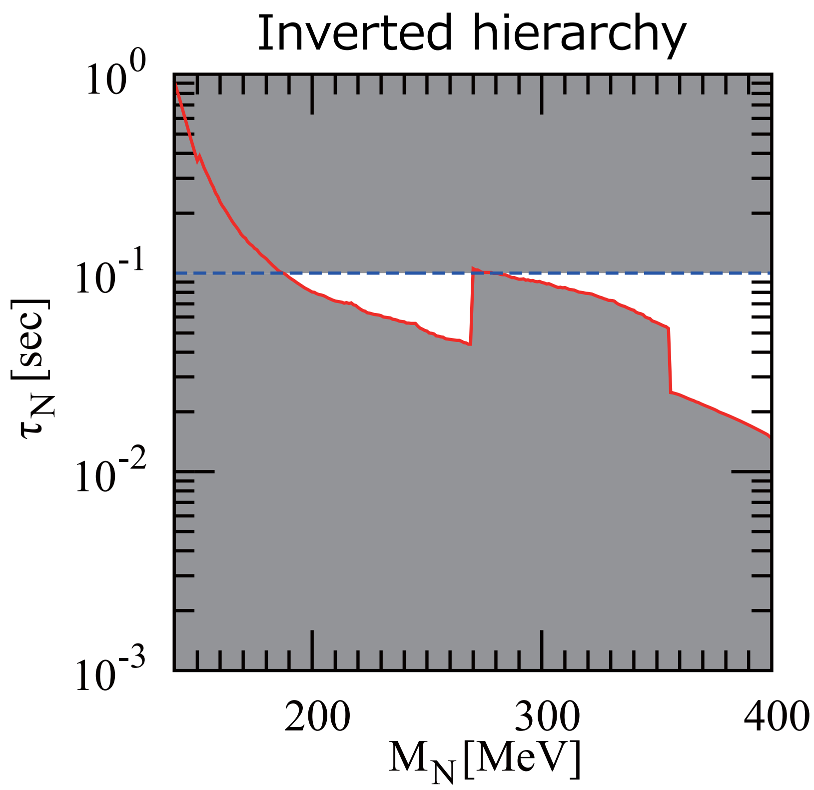
  $\Rightarrow$ Upper bound on lifetime

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

Constraints on light RH neutrinos

TA, Eijima '13





$M_N > 163$ MeV

$M_N = 188 - 269$ MeV
$M_N > 285$MeV

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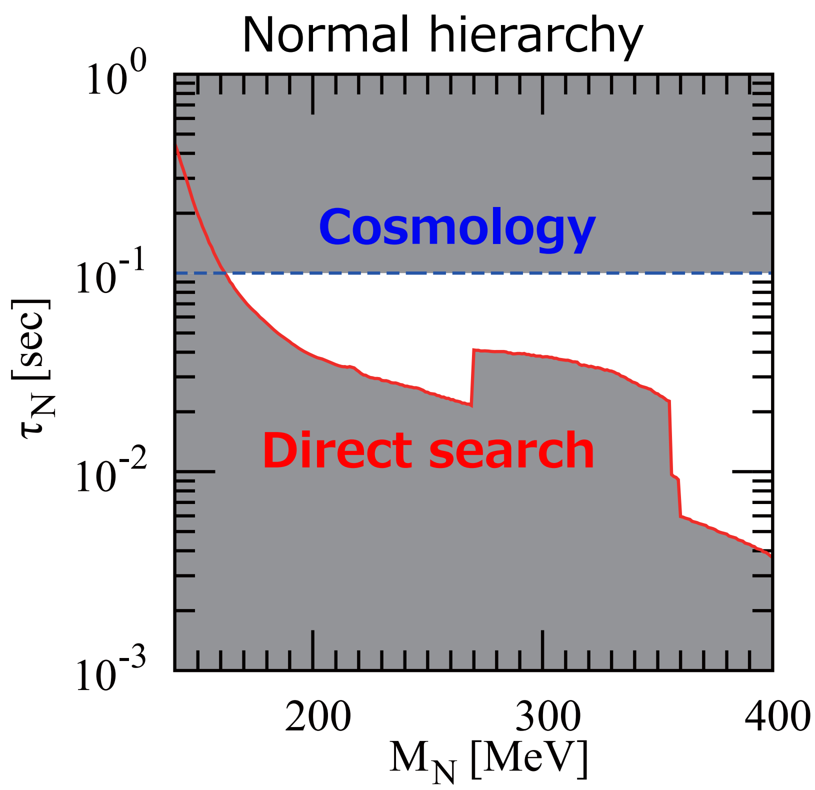
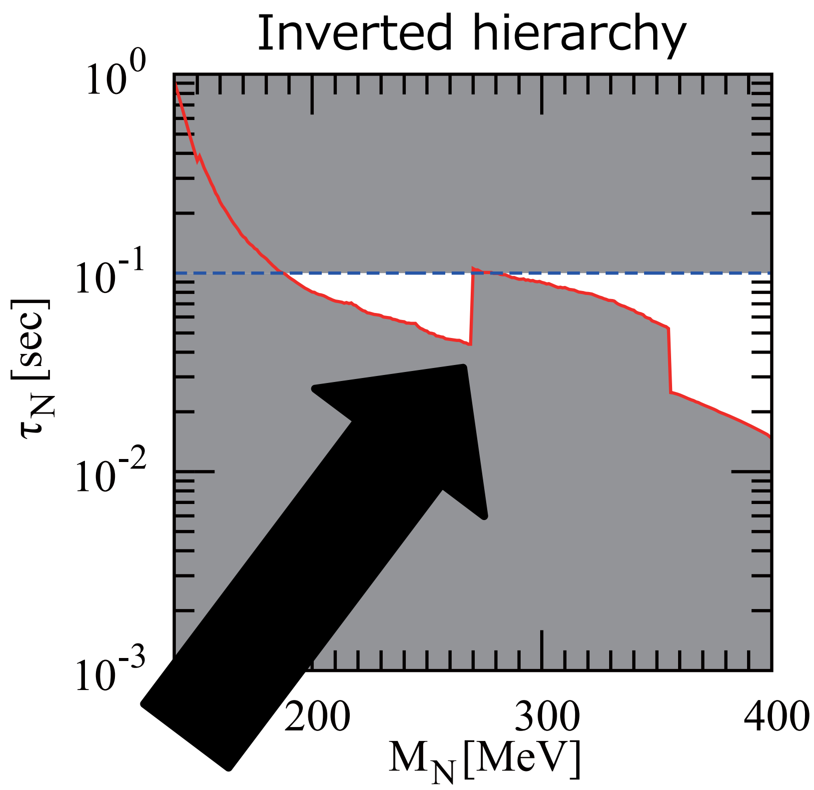
Implication to $0\nu2\beta$ decay

Constraints on light RH neutrinos

TA, Eijima '13





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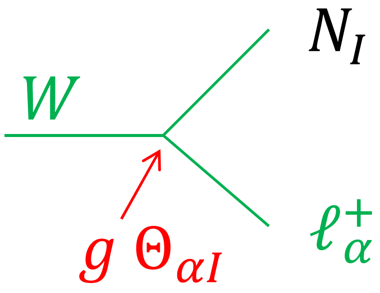
Mixing elements in IH case

Mixing elements of heavy neutrinos $\Theta_{\alpha I}$



$$\Theta_{\alpha I} = \frac{\langle\Phi\rangle F_{\alpha I}}{M_I}$$

- Mixing elements strongly depend on "$\xi \sin\eta$"

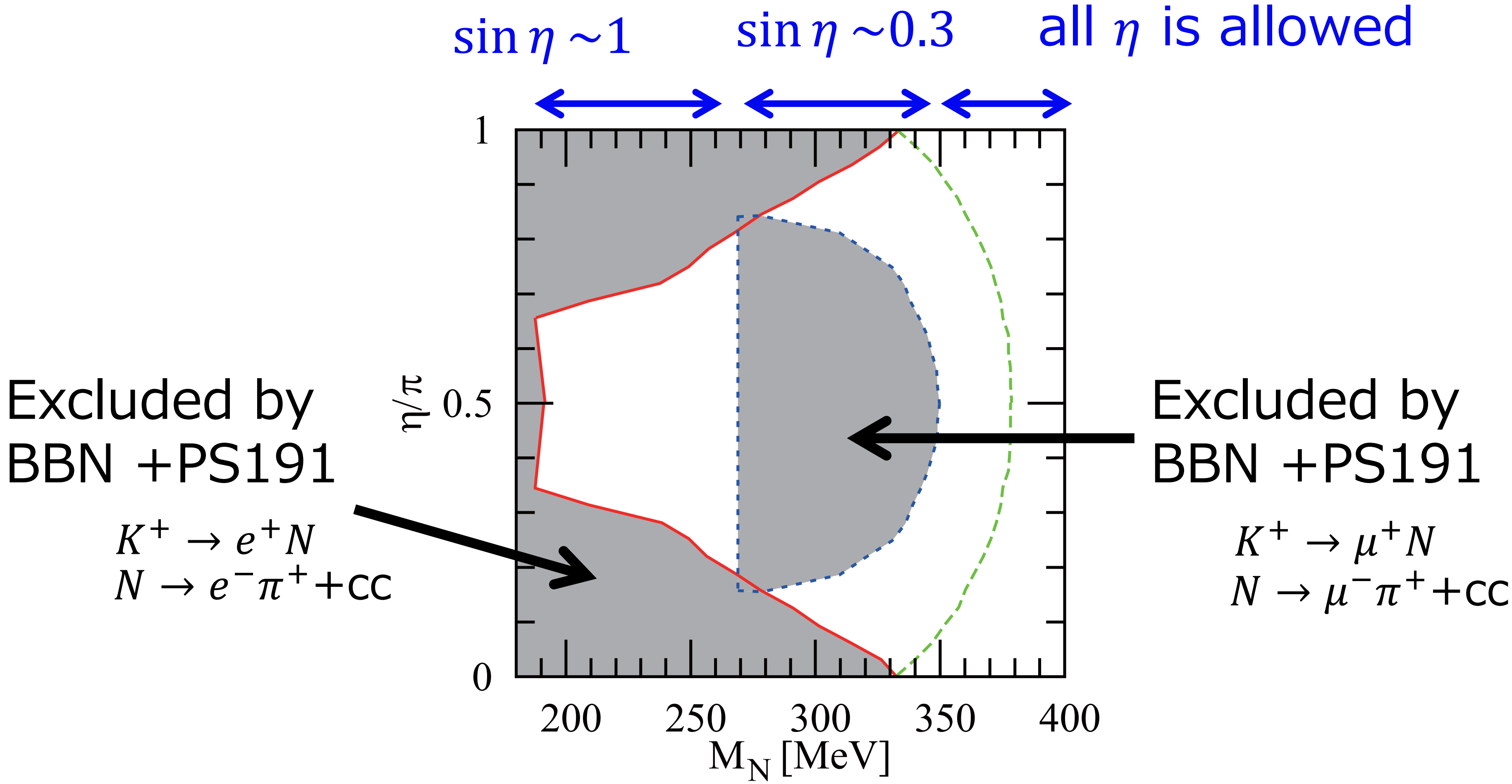
$$|\Theta_e|^2 \simeq 1.20\times 10^{-8}\left(\frac{\mathrm{MeV}}{M_N}\right)(1.000 - 0.925\xi\sin\eta)X_\omega^2,$$

$$|\Theta_\mu|^2 \simeq 0.76\times 10^{-8}\left(\frac{\mathrm{MeV}}{M_N}\right)(1.000 + 0.895\xi\sin\eta - 0.250\xi\cos\eta\sin\delta + 0.092\xi\sin\eta\cos\delta)X_\omega^2,$$

$$|\Theta_\tau|^2 \simeq 0.50\times 10^{-8}\left(\frac{\mathrm{MeV}}{M_N}\right)(1.000 + 0.860\xi\sin\eta + 0.380\xi\cos\eta\sin\delta - 0.140\xi\sin\eta\cos\delta)X_\omega^2.$$

We find allowed range of Majorana phase !

Majorana phase in IH case



Majorana phase is restricted for $M_N < 350$ MeV!

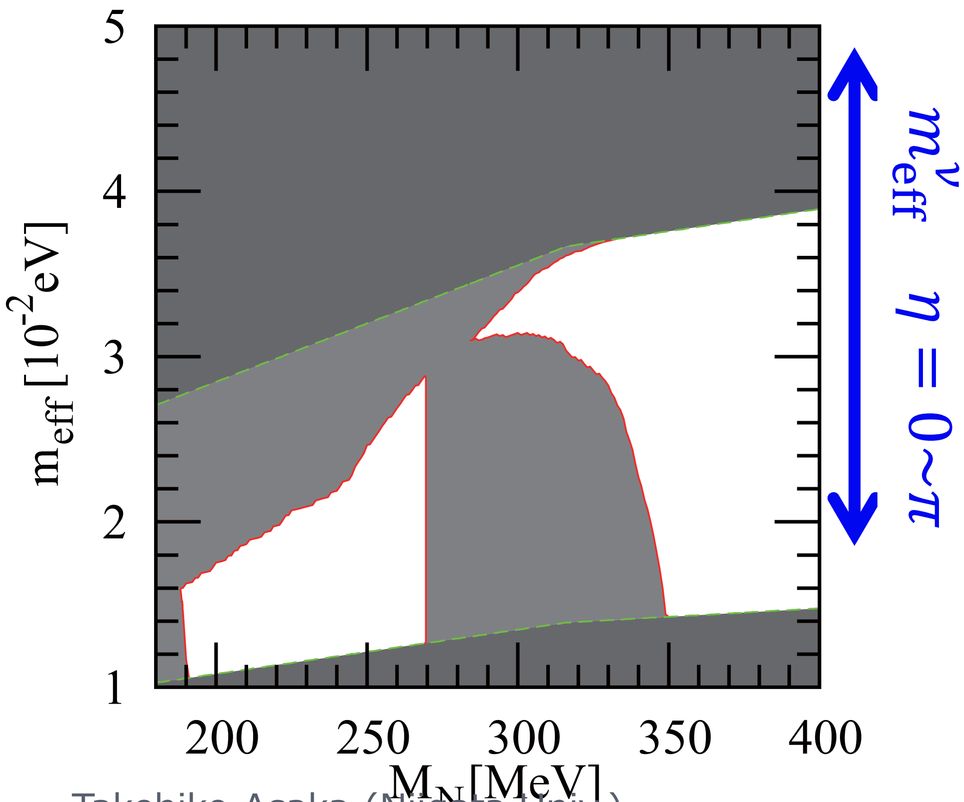
$0\nu2\beta$ decays in IH

Effective neutrino mass from light and heavy neutrinos

$$m_{\text{eff}} = m_i U_{ei}^2 + f_\beta(M_I) M_I \Theta_{eI}^2 = [1 - f_\beta(M_N)] m_{\text{eff}}^\nu$$

TA, Eijima, Ishida ('11)

$$m_{\text{eff}}^\nu = \cos^2\theta_{13} \left(m_1^2 \cos^4\theta_{12} + m_2^2 \sin^4\theta_{12} + 2 m_1 m_2 \cos^2\theta_{12} \sin^2\theta_{12} \, \mathbf{\cos 2\eta}\right)^{1/2}$$



- Heavy neutrinos give negative contribution to m_{eff}
- Constraint on η restricts the predicted range of m_{eff}

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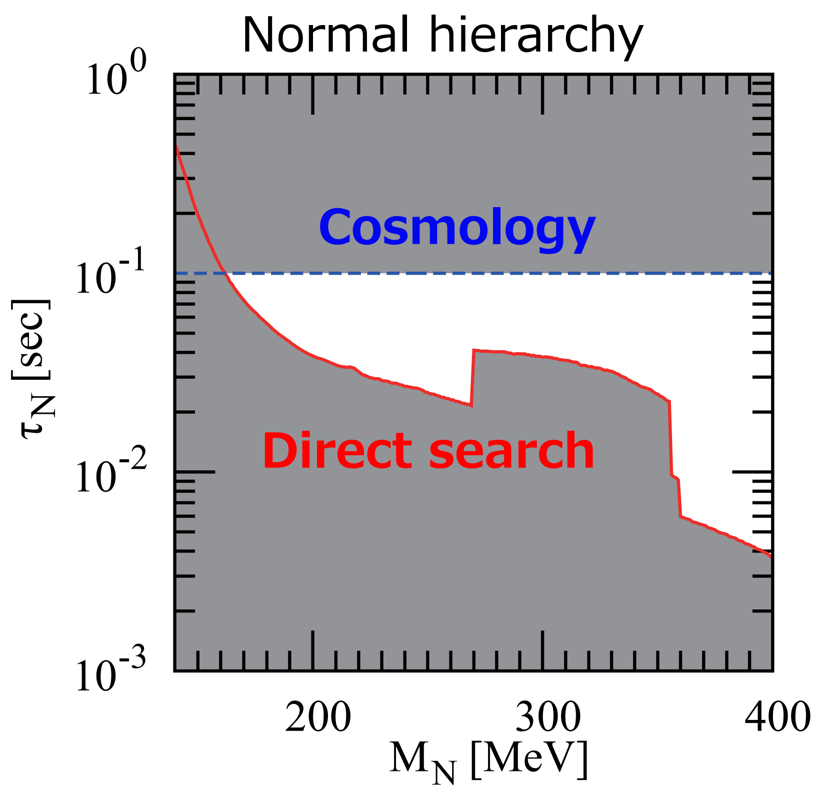
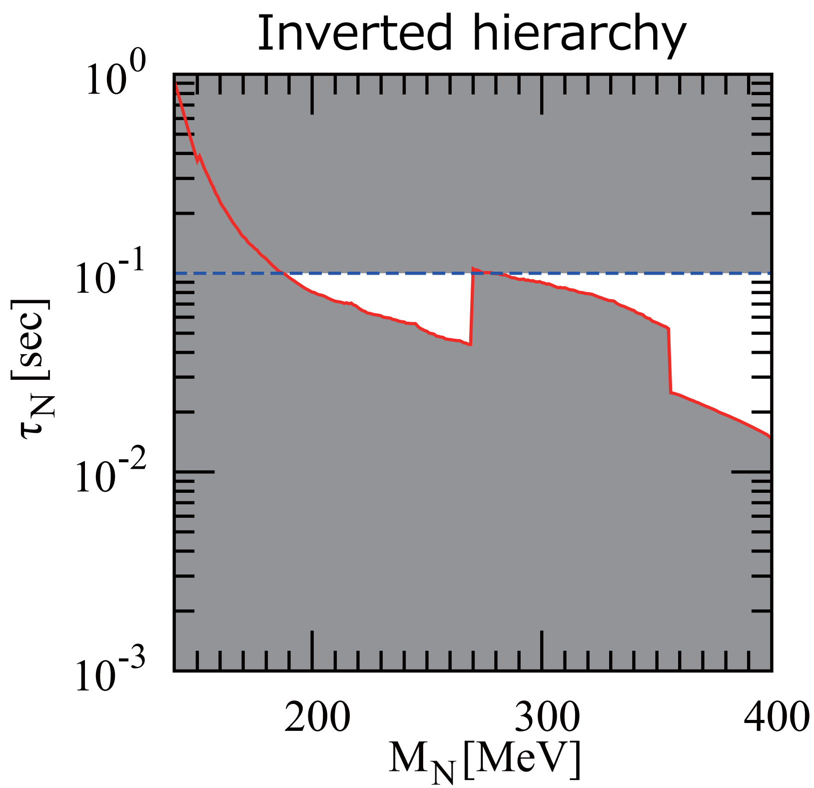
Search for heavy neutrinos at T2K

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

Constraints on light RH neutrinos

TA, Eijima '13





$M_N > 163$ MeV

$M_N = 188 - 269$ MeV
$M_N > 285$MeV

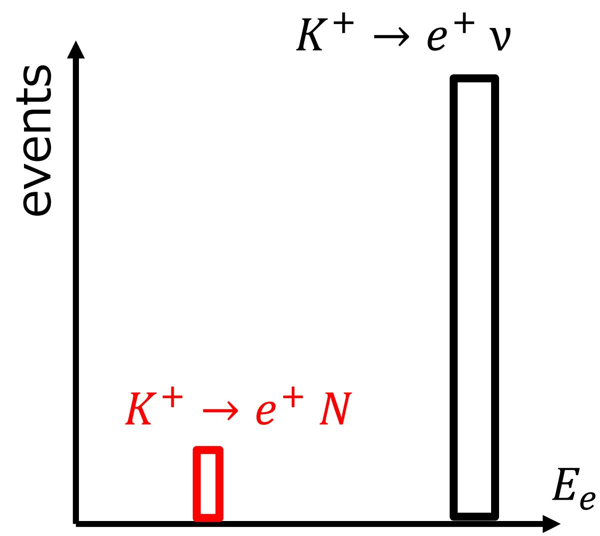
Search for light sterile neutrinos

- Production by meson decays

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

  - **Peak search** [Shrock '80]
    - Measure E_e in $K^+ \to e^+ N$

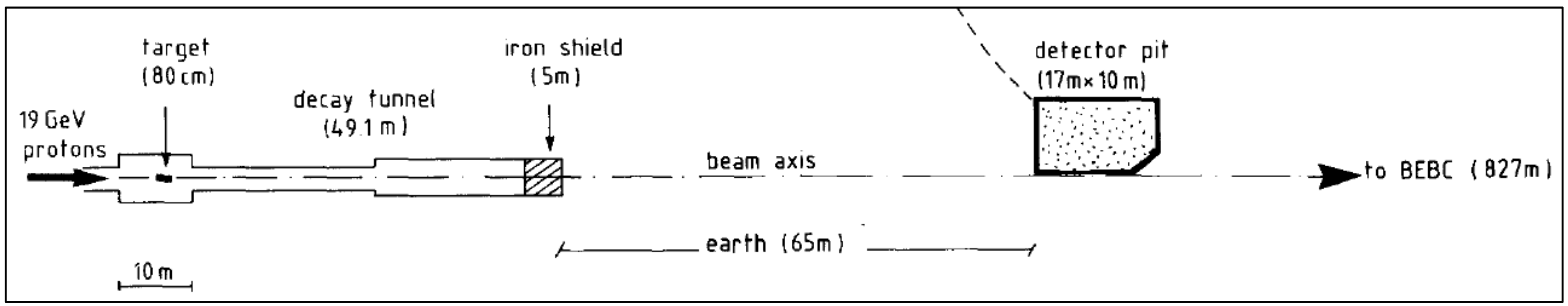
$$E_e = \frac{m_K^2 - m_e^2 - M_N^2}{2\, m_K}$$



  - **Decays inside the detector**

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

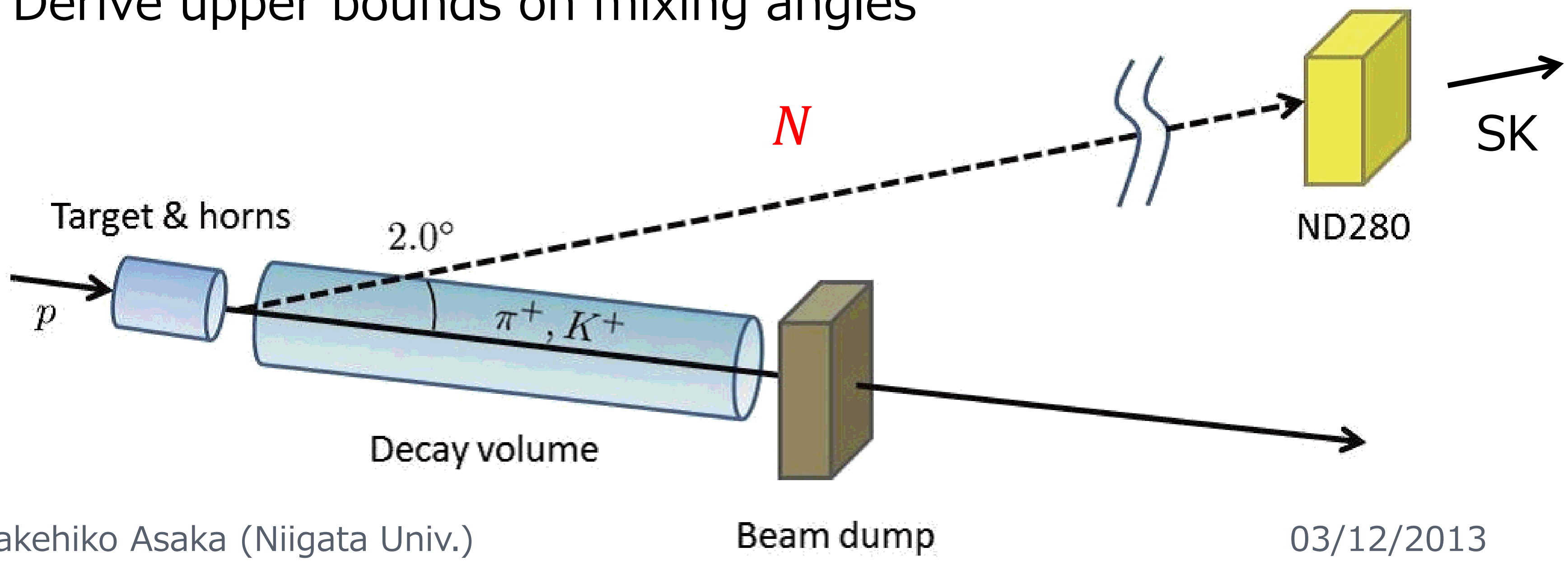
CERN
PS191



Search for heavy neutrinos at T2K

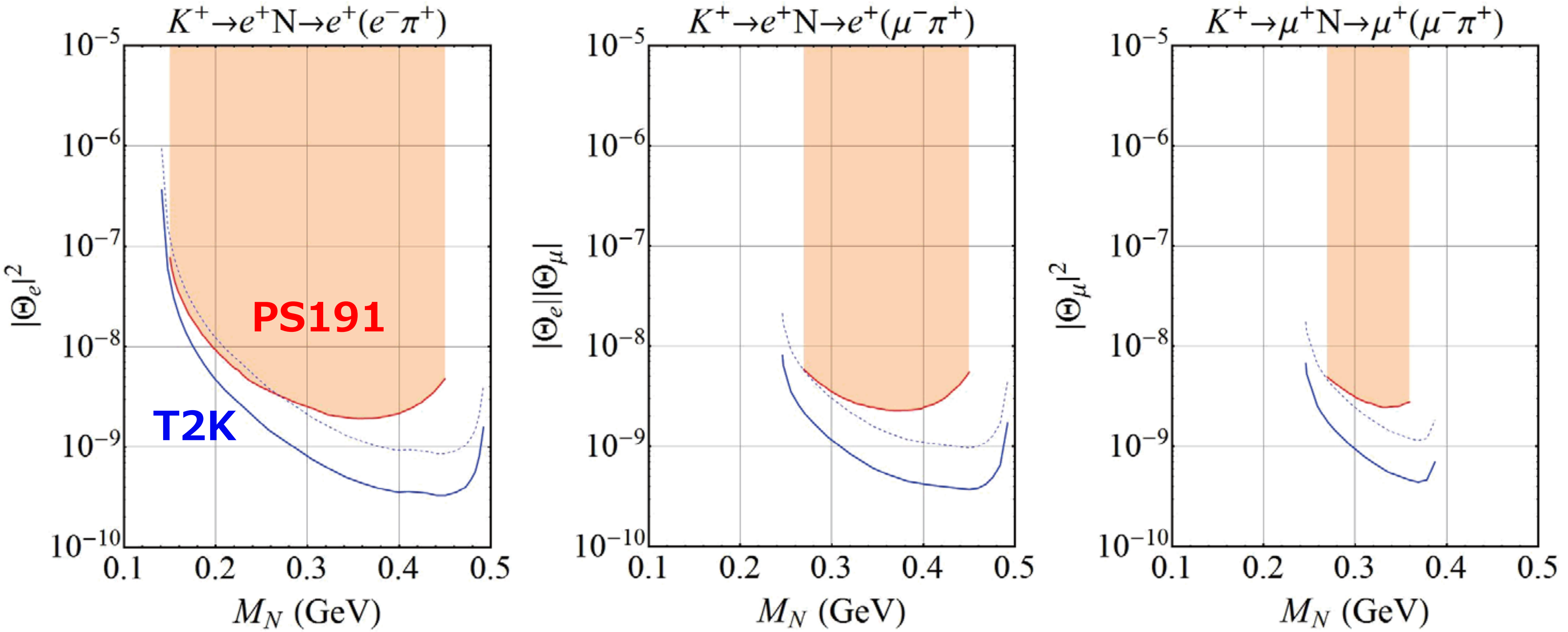
Production of N	Detection of N
$K^+ \to \ell^+ + N$	$N \to \ell^- + \pi^+$
	$(\ell^- = e^-, \mu^-)$

- Estimate flux of N at ND280
- Count # of signal decay inside ND280
- Derive upper bounds on mixing angles



Sensitivity: PS191 vs T2K

TA, Eijima, Watanabe '13



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

Signal vs Background

- Signal events: $N \to \ell^- + \pi^+$
- BG events: $\nu_\mu + n \to \mu^- + \pi^+ + n$ (CC-$n\pi^+$)

  $\nu_\mu +^{16} \mathrm{O} \to \mu^- + \pi^+ +^{16} \mathrm{O}$ (CC-coherentπ^+)

To reduce BG,

- Use the invariant mass distribution of ℓ^- and π^+ since it has a peak at M_N for signal decay
- Use the low density part of detector filled with argon gas (9m^3) out of 61.25m^3

See also the recent proposal to search for heavy neutrinos at the CERN SPS. arXiv:1310.1762

Summary

- We have considered the model with two right-handed neutrinos which are lighter than charged Kaon.
  - Neutrino masses by seesaw mechanism
  - Baryogenesis via neutrino oscillations
  - Search in Kaon decays

- We have found the possible region for neutrino oscillations and BAU, allowed from search and cosmological constraints.
  - Majorana phase is restricted in IH
    $\rightarrow$ Distinctive feature in $0\nu 2\beta$ decay

- We have discussed search for such right-handed neutrinos at near detector ND280 of T2K experiment
  - Signal: $N \rightarrow e^- + \pi^+,\ \mu^- + \pi^+$ inside ND280
  - T2K at 10^{21} POT has a better sensitivity than PS191

Backup

Comparison

	PS191 [55, 56]	T2K [61]	MINOS [62]	MiniBooNE [63]	SciBooNE [64]
POT	0.86×10^{19}	10^{21}	10^{21}	10^{21}	10^{21}
$(\mathrm{Distance})^{-2}$	$(128\,\mathrm{m})^{-2}$	$(280\,\mathrm{m})^{-2}$	$(1\,\mathrm{km})^{-2}$	$(541\,\mathrm{m})^{-2}$	$(100\,\mathrm{m})^{-2}$
Volume	$216\,\mathrm{m}^3$	$88\,\mathrm{m}^3$	$303\,\mathrm{m}^3$	$524\,\mathrm{m}^3$	$15.3\,\mathrm{m}^3$
Events	1	9.9	2.7	15.8	13.5

Table 1. A comparison between PS191 and recent accelerator experiments. The item "Distance" means the distance between the beam target and the detector for each experiment. The item "Events" shows POT$\times$(Distance)$^{-2}\times$Volume in units of PS191. The POTs for the oscillation experiments are assumed to achieve 10^{21}.

T2K
2013/4/12: 6.39x10^20 POT
2013/5/8: 6.63x10^20 POT

GOAL: 7.8x10^21 POT

Neutrino Yukawa couplings for $N_{2,3}$

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

[Casas, Ibarra '01]

- Parameters of active neutrinos

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

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

Dirac phase δ

Majorana phase η

- Parameters of sterile neutrinos

$D_N^{1/2} = {\rm diag}(\sqrt{M_2}, \sqrt{M_3})$: sterile ν masses

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

ω: complex number

$\xi = \pm 1$

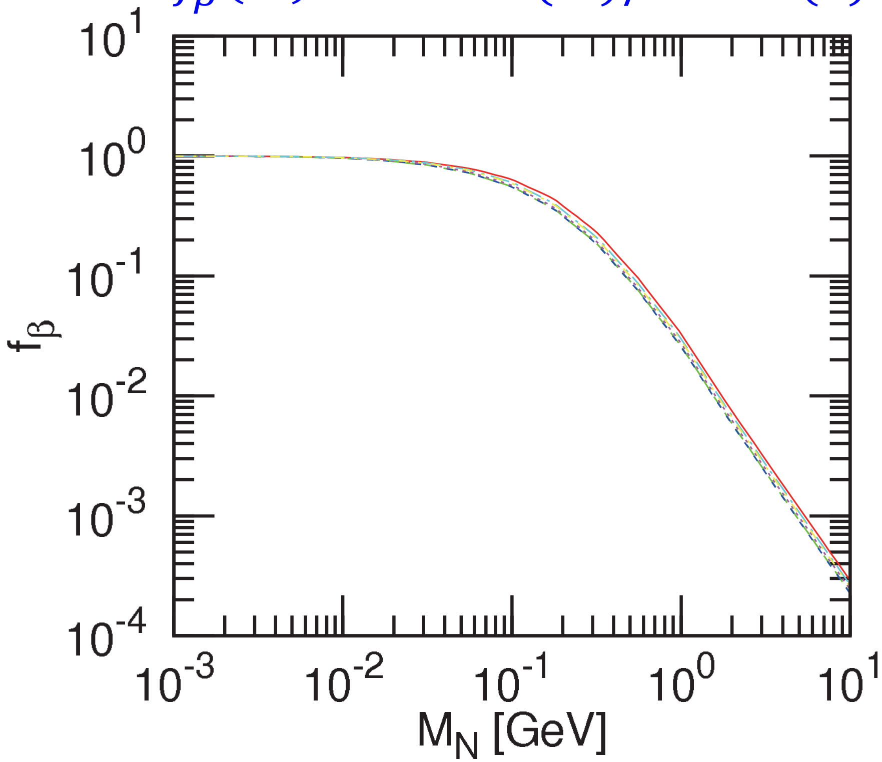
Imω

Effective neutrino mass

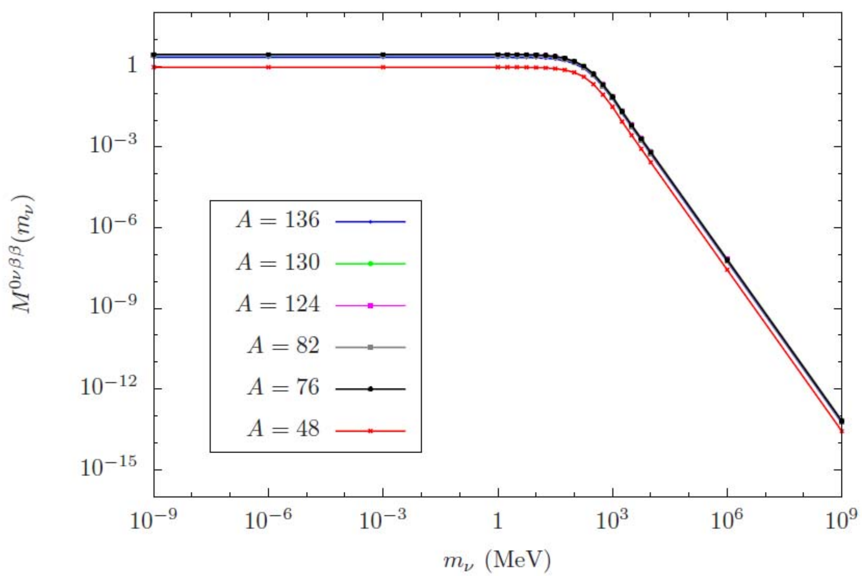
- $$m_{\rm eff} = \sum_{i=1,2,3} m_i\, U_{ei}^2 + \sum_{I=1,2,3} f_\beta(M_I)\, M_I\ \Theta_{eI}^2$$

  active neutrinos — sterile neutrinos

$f_\beta(M) = M^{0\nu\beta\beta}(M)/M^{0\nu\beta\beta}(0)$

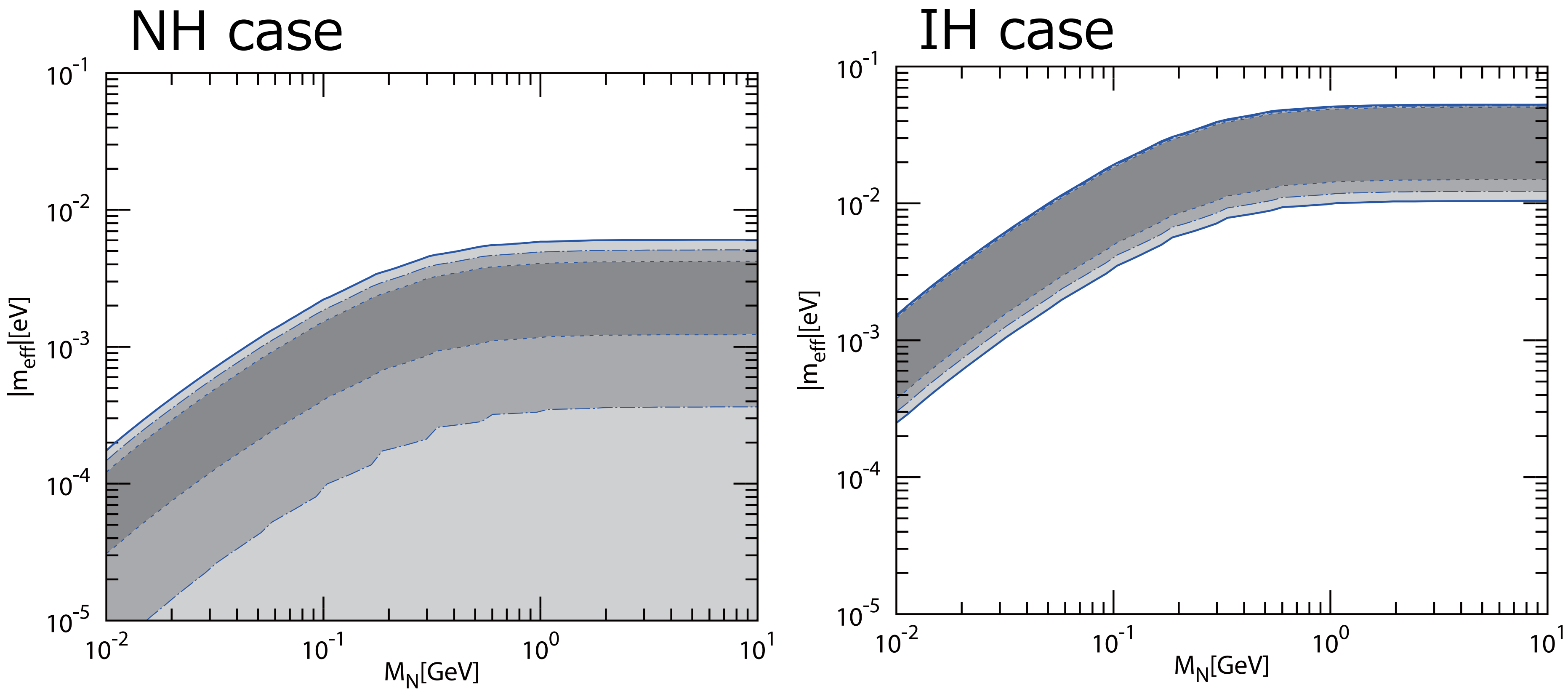


[Blennow, Frenandez-Martinez, Pavon, Mnendez '10]



m_{eff} in the νMSM

[TA, Eijima, Ishida '11]



- m_{eff} in the νMSM is smaller than active ν's one
- No significant constraint on Θ_{eI} in the νMSM !