# Probing Baryon Asymmetry of the Universe by Using Lepton Universality

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[arXiv:1410.0432, to appear in PLB]

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# Origin of Neutrino Masses



- Neutrino mass scales from oscillation experiments
  - 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?"***

**Test by Lepton Universality in Kaon Decays**

# Extension by RH neutrinos $\nu_R$

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

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 $\nu$**
  - $\rightarrow$ explain neutrino oscillations
- **Heavy neutral leptons $N$** $(N \simeq \nu_R)$
  - Mass $M_M$
  - Mixing $\Theta = M_D/M_M$

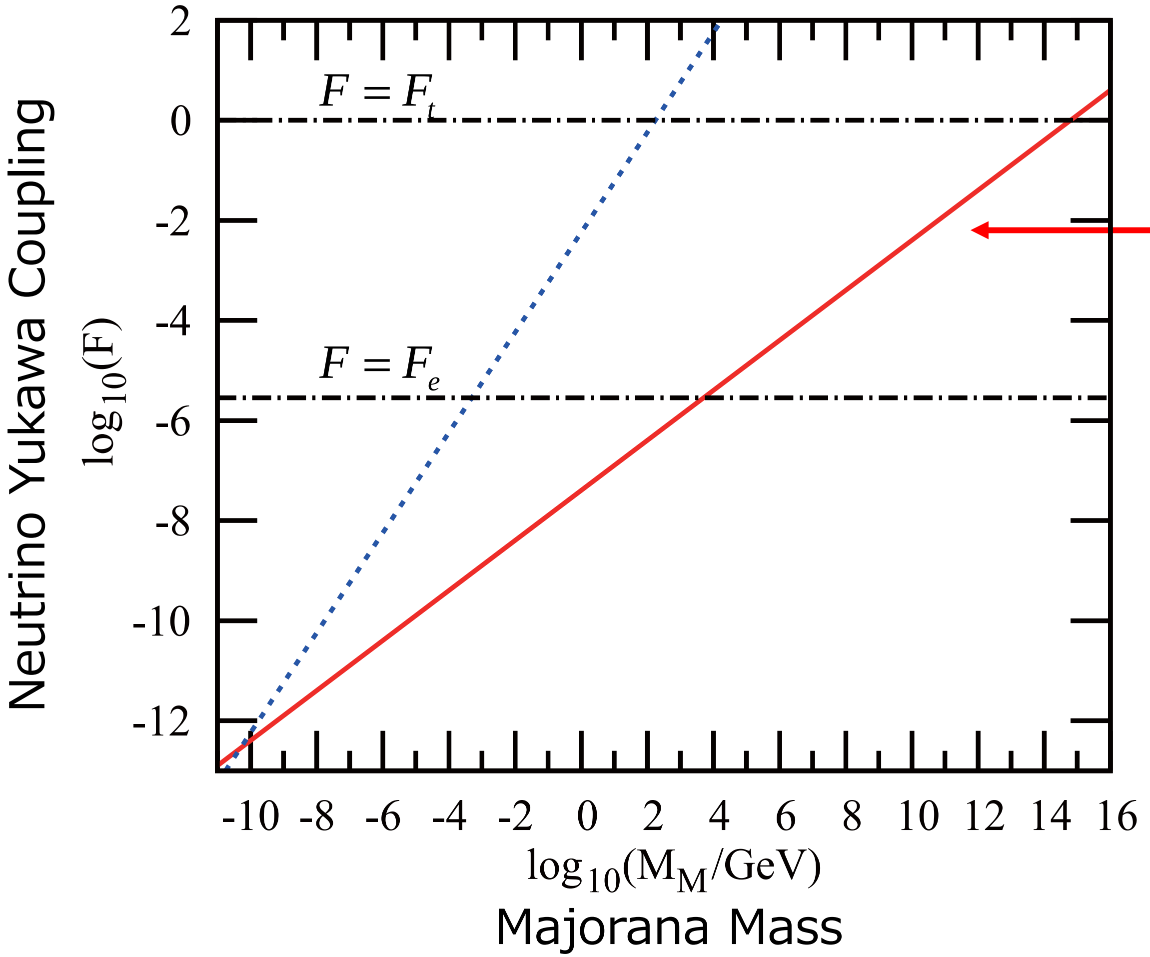
mixing in CC current $\nu_L = U\,\nu + \Theta\, N^c$

# Scale of Majorana mass



- The simplest case: one pair of $\nu_L$ and $\nu_R$

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




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

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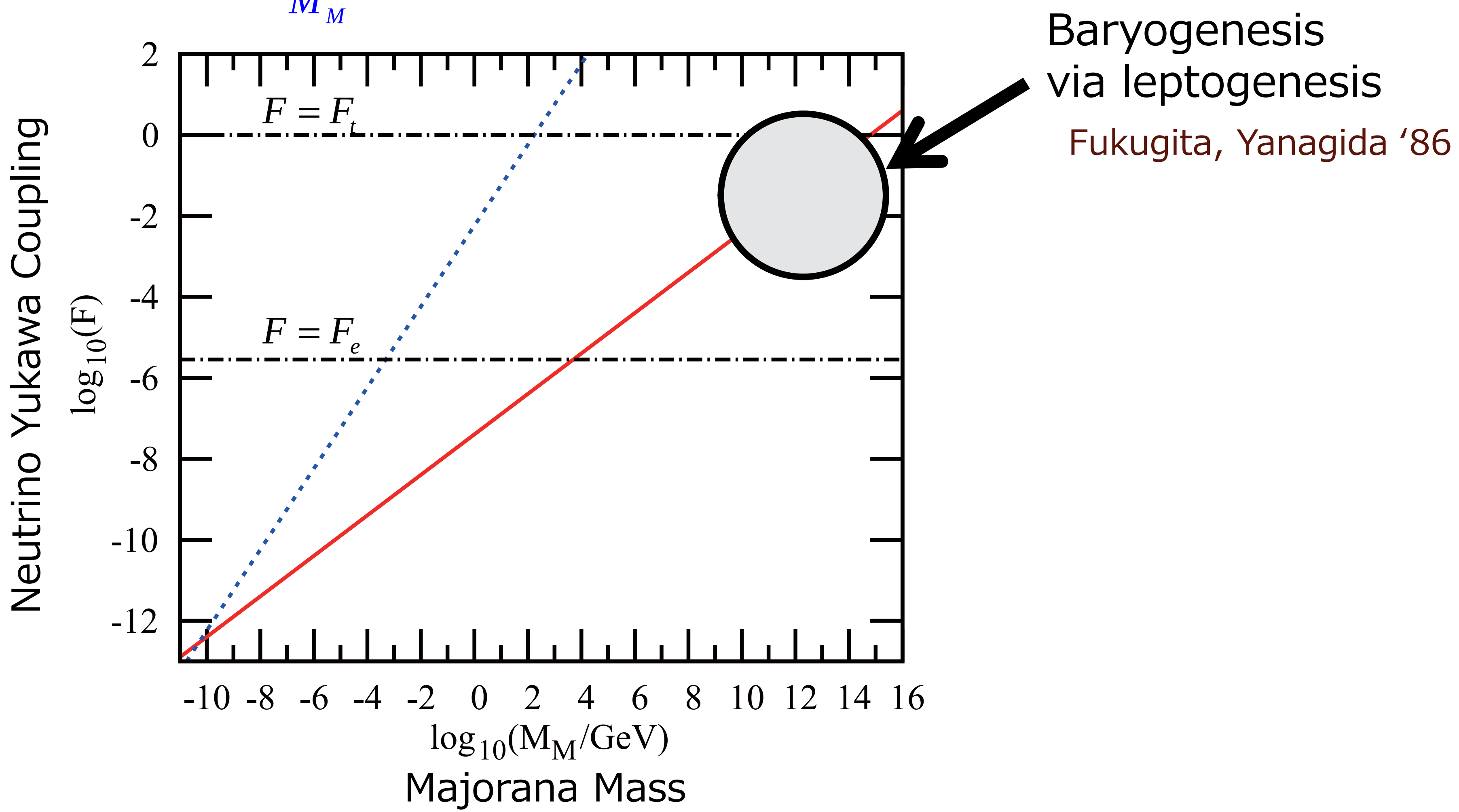

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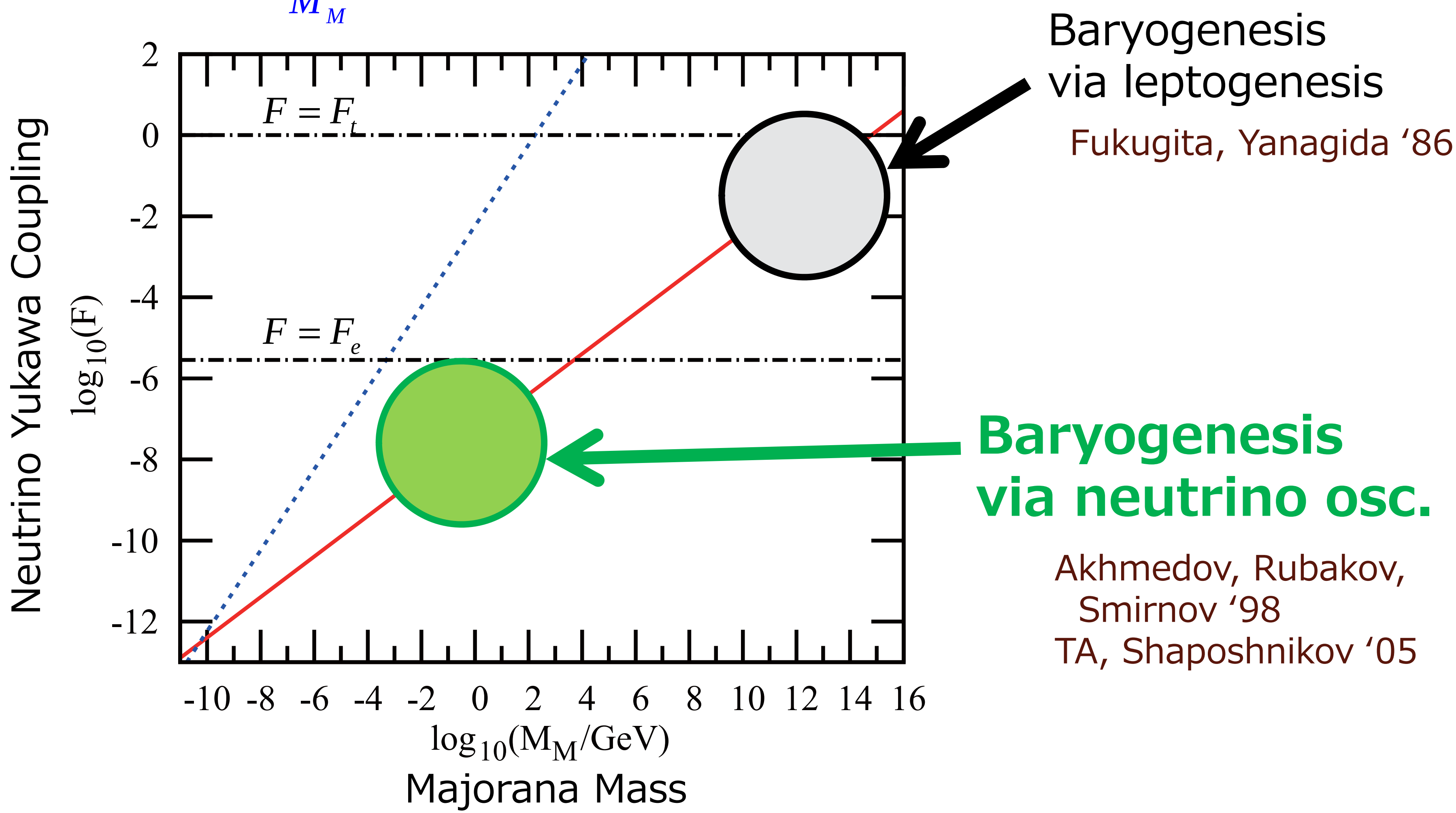


# The νMSM

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



- Three right-handed neutrinos with $M_M \lesssim M_W$

$$F \simeq 4 \times 10^{-7} \left(\frac{M_M}{100\mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{M_\nu}{0.05\mathrm{eV}}\right)^{\frac{1}{2}}$$

**□ $N_1$ (with 10 keV mass)**

- **Dark Matter Candidate**

**□ $N_2$ and $N_3$ (with $M_N = O(0.1)$-$O\left(10^2\right)$ GeV)**

- **Neutrino masses and mixing via seesaw mechanism**
- **Baryon asymmetry of the universe (BAU)**
- **Can be tested by direct search experiments**

# Baryogenesis via neutrino osc.

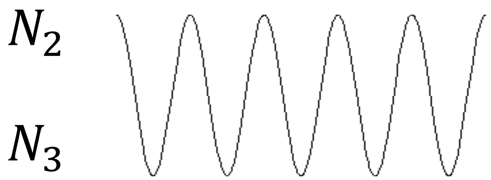


- Oscillation of HNLs can be a source of BAU

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

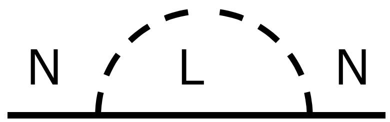
  Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
  TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
  Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)

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

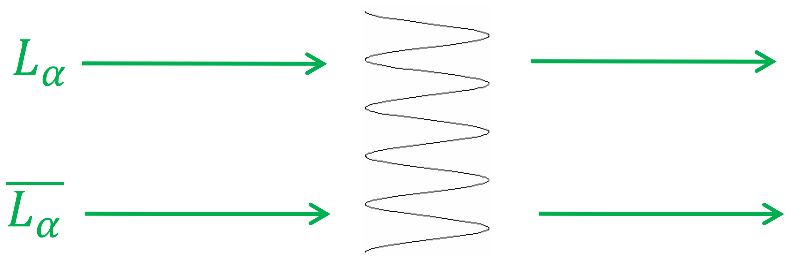


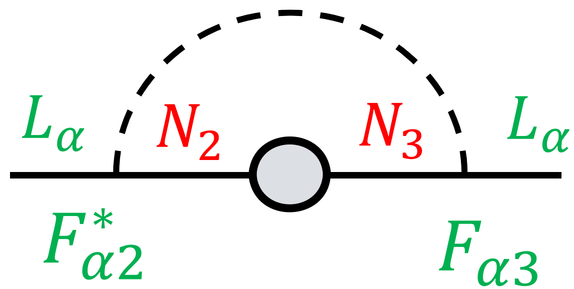

$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects




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

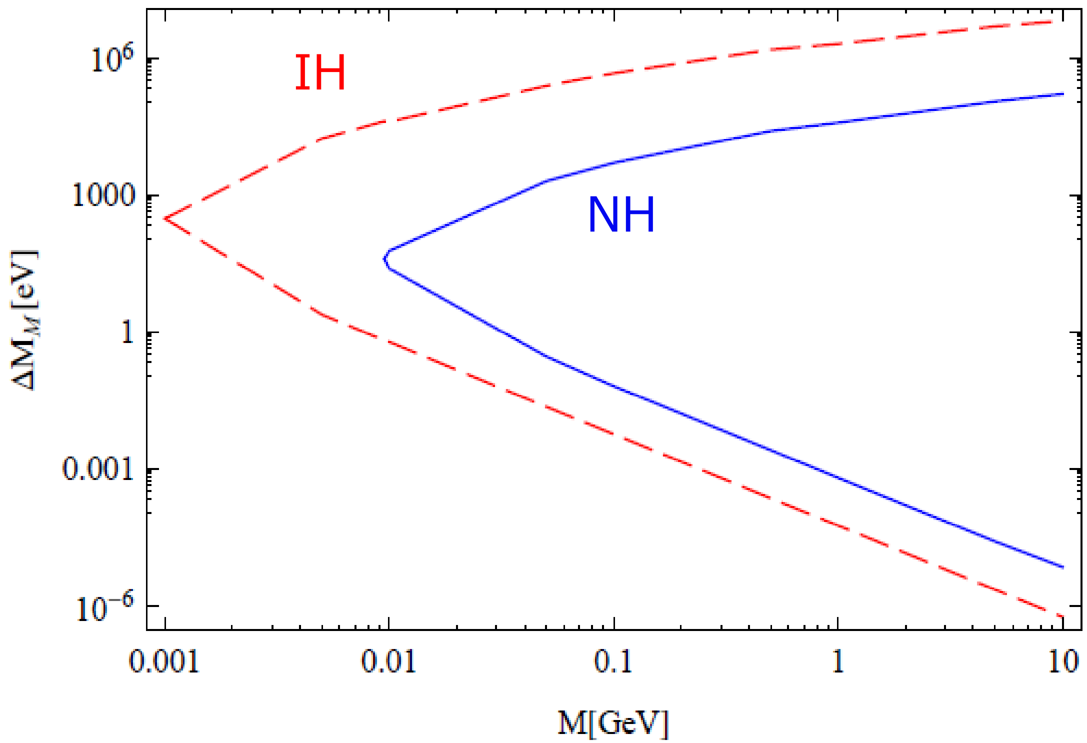


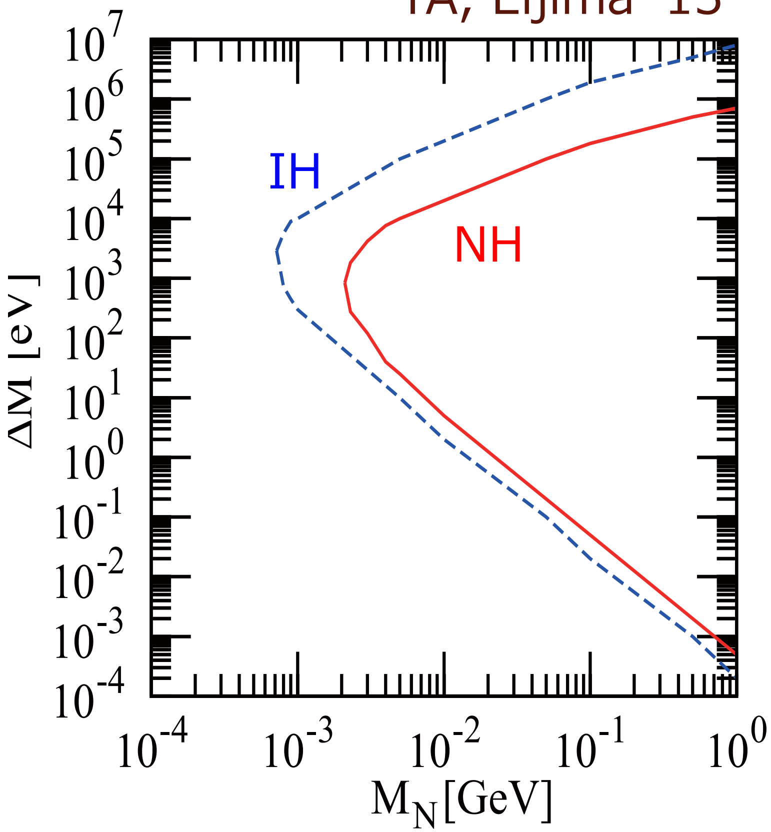
# Baryogenesis via neutrino osc.

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

Canetti, Shaposhnikov '10



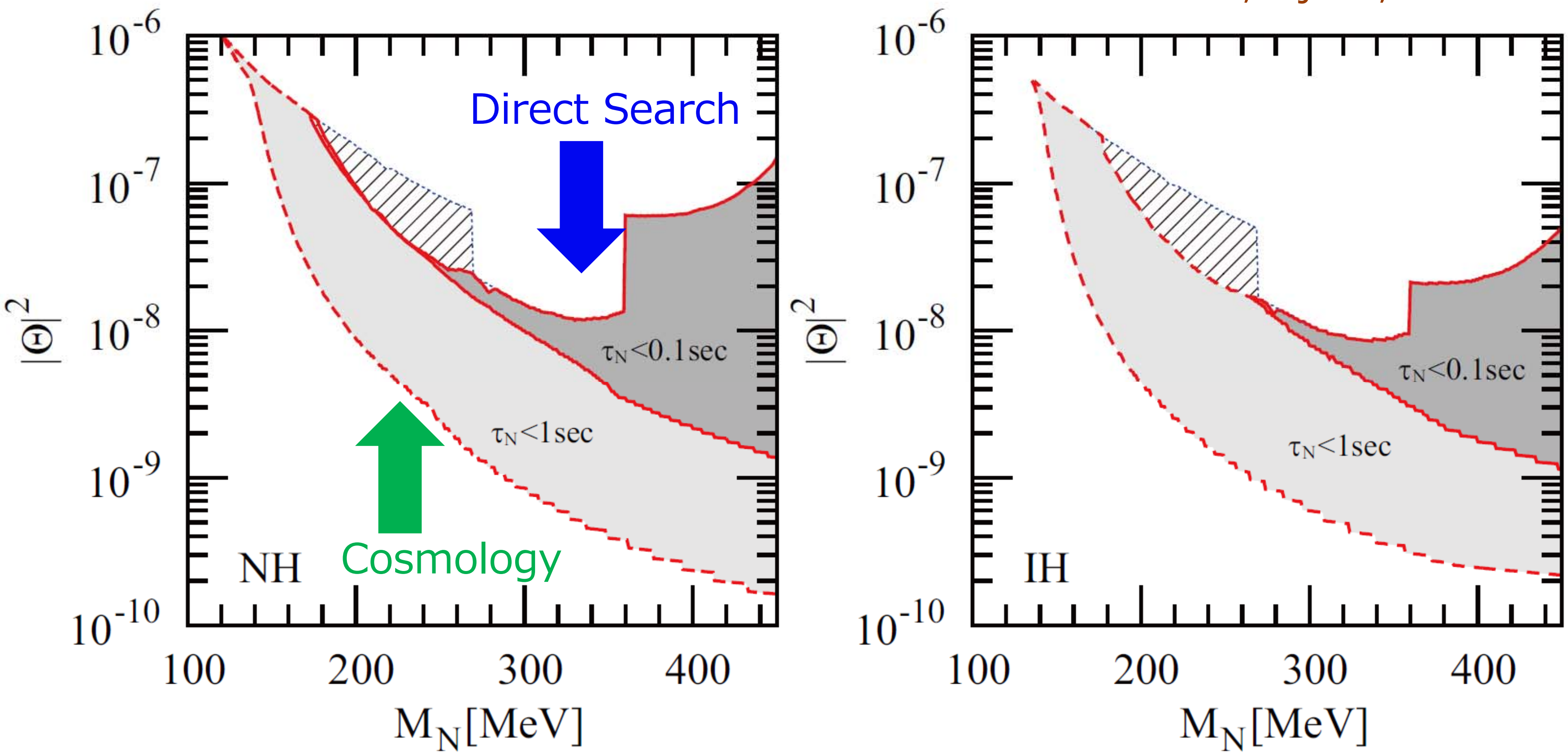

TA, Eijima '13




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

# Constraints on HNLs

TA, Eijima, Takeda '14



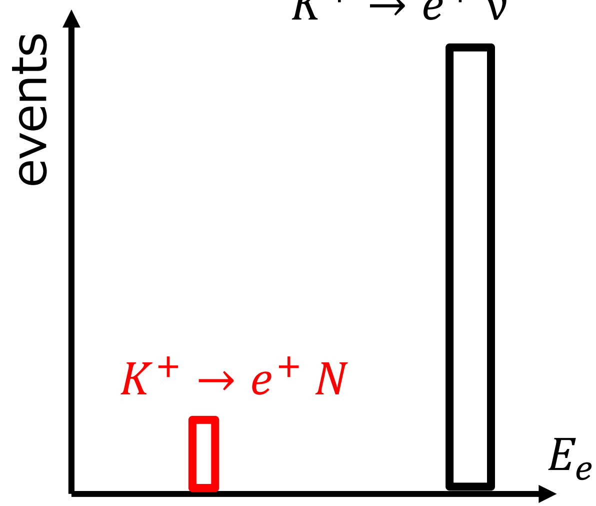
# Search for Heavy Neutral Leptons

- Production by meson decays

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

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

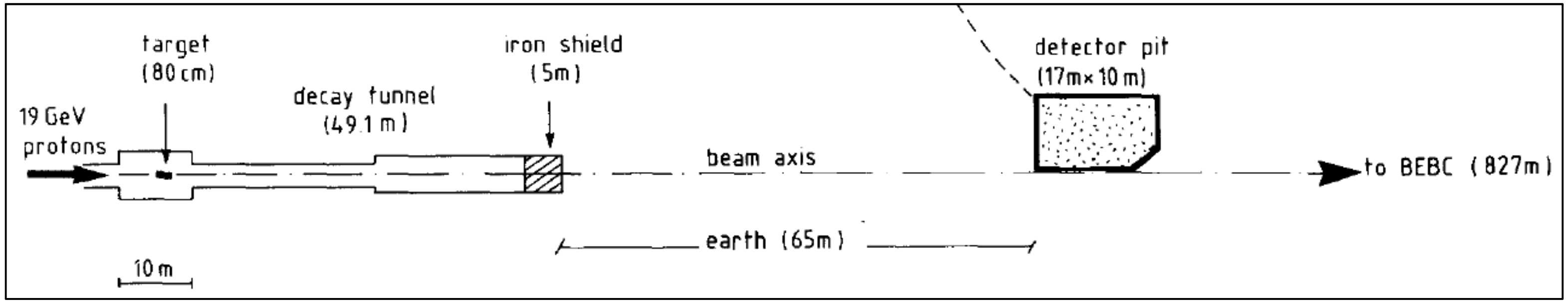
$$E_e = \frac{m_K^2 - m_e^2 - M_N^2}{2\, m_K}$$




  - **Beam dump experiments**

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

CERN PS191



# Lepton Universality in Kaon Decays



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

- Helicity suppression $\Gamma \propto m_\ell^2$
- Hadronic uncertainties are cancelled

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$
Finkemeier '96,
Cirigliano, Rosell '07

$R_K^{exp} = (2.488 \pm 0.010) \times 10^{-5}$
NA62, '13

- Good probe of new physics

$$\Delta r_K = \frac{R_K - R_K^{SM}}{R_K^{SM}} = (4 \pm 4) \times 10^{-3}$$

- In the νMSM,

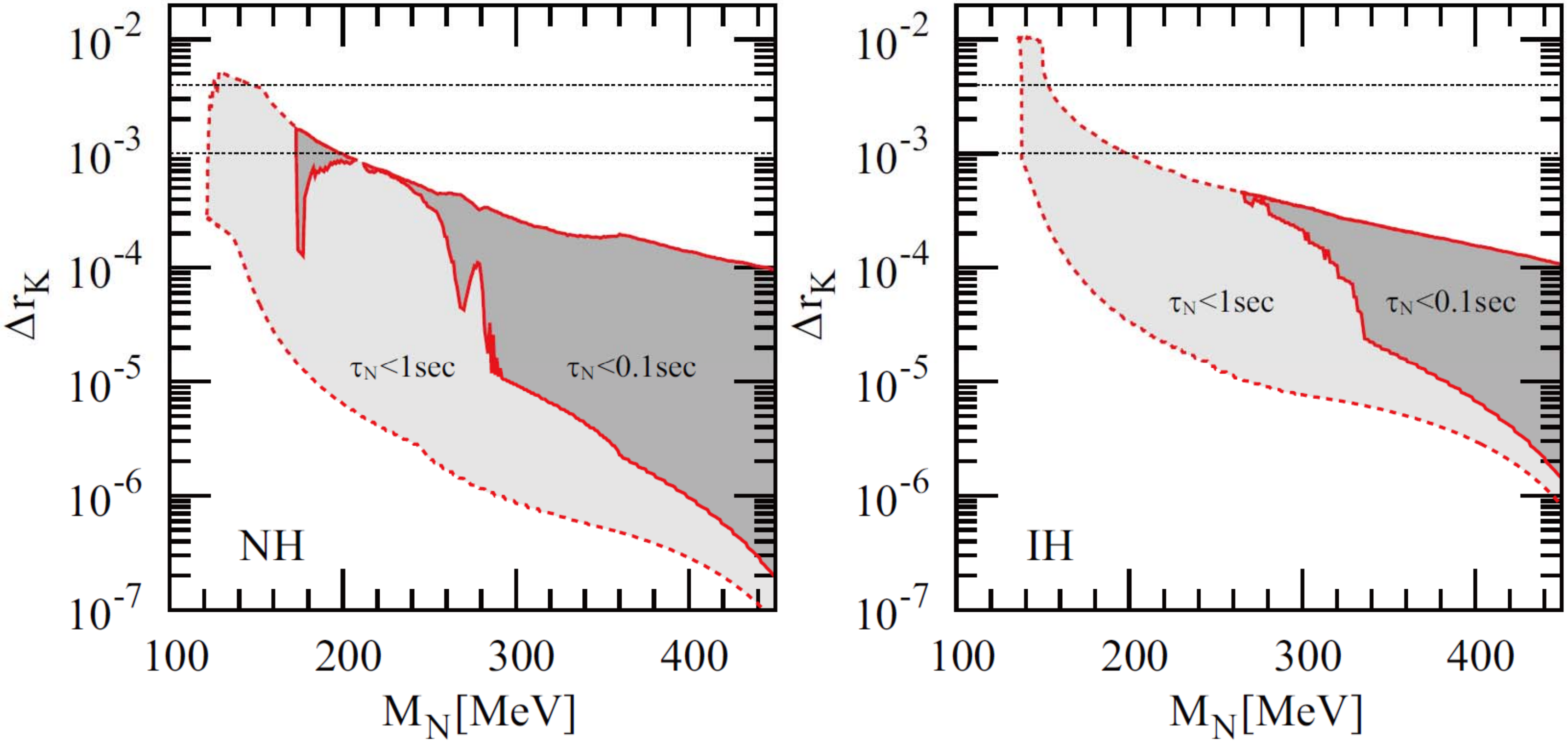
$$R_K = \frac{\sum_i \Gamma(K^+ \to e^+ + \nu_i) + \sum_I \Gamma(K^+ \to e^+ + N_I)}{\sum_i \Gamma(K^+ \to \mu^+ + \nu_i) + \sum_I \Gamma(K^+ \to \mu^+ + N_I)}$$

$$\Delta r_K \simeq \sum_I |\Theta_{eI}|^2 \left(\frac{M_N}{m_e}\right)^2 \left(1 - \frac{M_N^2}{m_K^2}\right)^2$$

Electron mode is enhanced due to helicity suppression, which leads to $\Delta r_K > 0$

# Prediction of the νMSM

TA, Eijima, Takeda '14




$\Delta r_K = 10^{-3}$ will be probed by future experiments,
ORKA@Fermilab, NA62@CERN, TREK/E36@J-PARC, ⋯

# Summary

- We have considered the νMSM with three right-handed neutrinos which are lighter than weak scale.
  - Neutrino masses by seesaw mechanism
  - Dark matter (lightest HNL $N_1$ with ~keV mass)
  - Baryogenesis via neutrino oscillations of $N_{2,3}$
  - Direct search of $N_{2,3}$ is possible

- We have considered the lepton universality in Kaon decays

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

  - $\Delta r_K \leq O(10^{-3}) - O(10^{-2})$
  - Good target for future searches (NA62@CERN, ORKA@Fermilab, TREK/E36@J-PARC...)

- ***Search for these heavy neutral leptons are crucial to solve the origin of neutrino masses as well as the mysteries of our universe, DM and BAU !!!***

# Backup

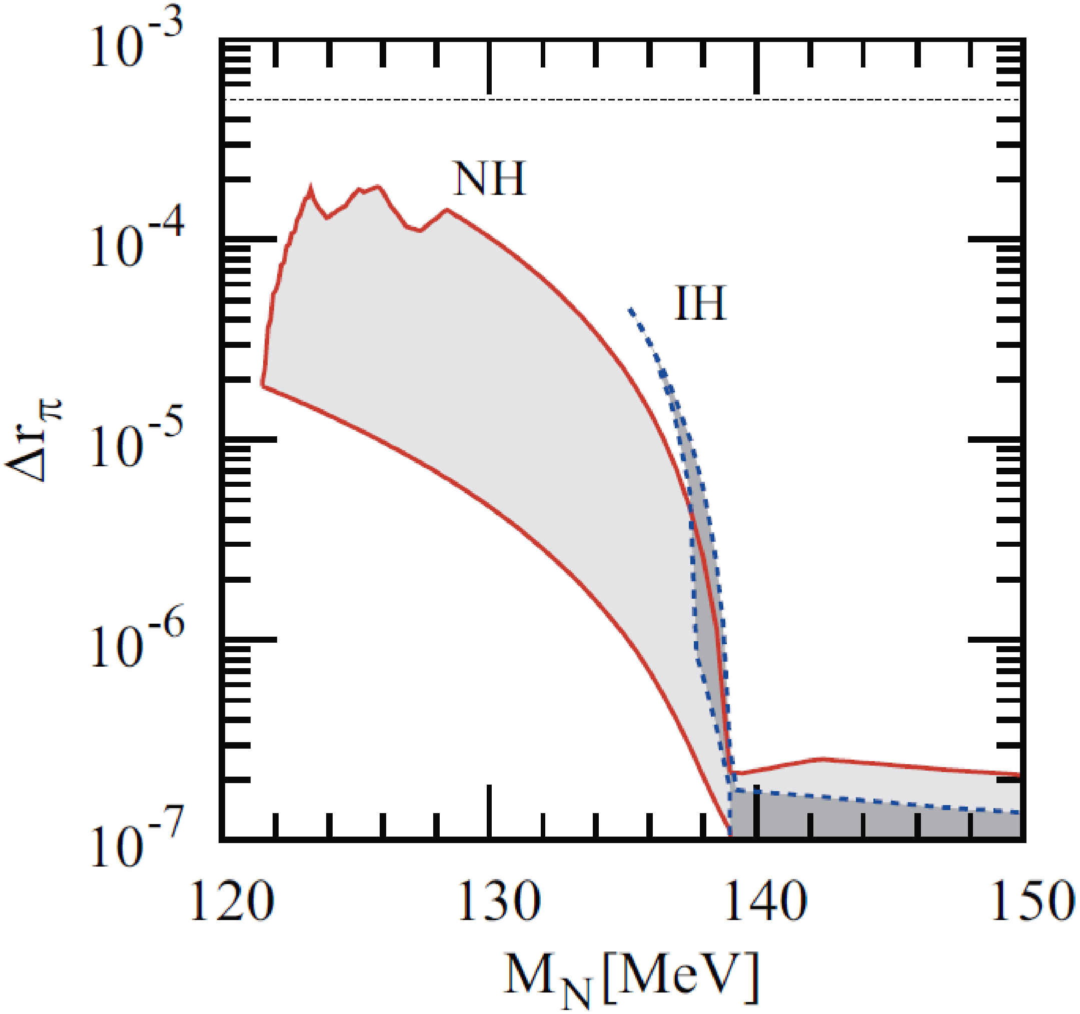
# Lepton Universality in Pion Decay

$$R_\pi = \frac{\Gamma(\pi^+ \to e^+ + \nu)}{\Gamma(\pi^+ \to \mu^+ + \nu)}$$

$$\Delta r_\pi = \frac{R_\pi - R_\pi^{SM}}{R_\pi^{SM}}$$
$$= (-4 \pm 3) \times 10^{-3}$$

Cirigliano, Rosell '07
PDG '12

TA, Eijima, Takeda '14



# Baryogenesis in the νMSM



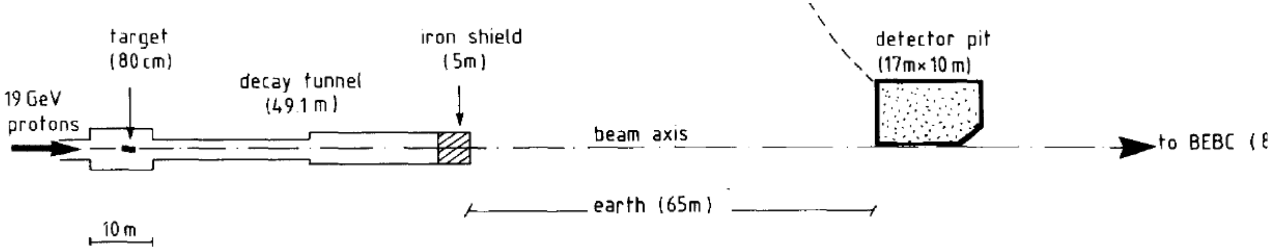
**Sakharov's Conditions for Baryogenesis ('67)**

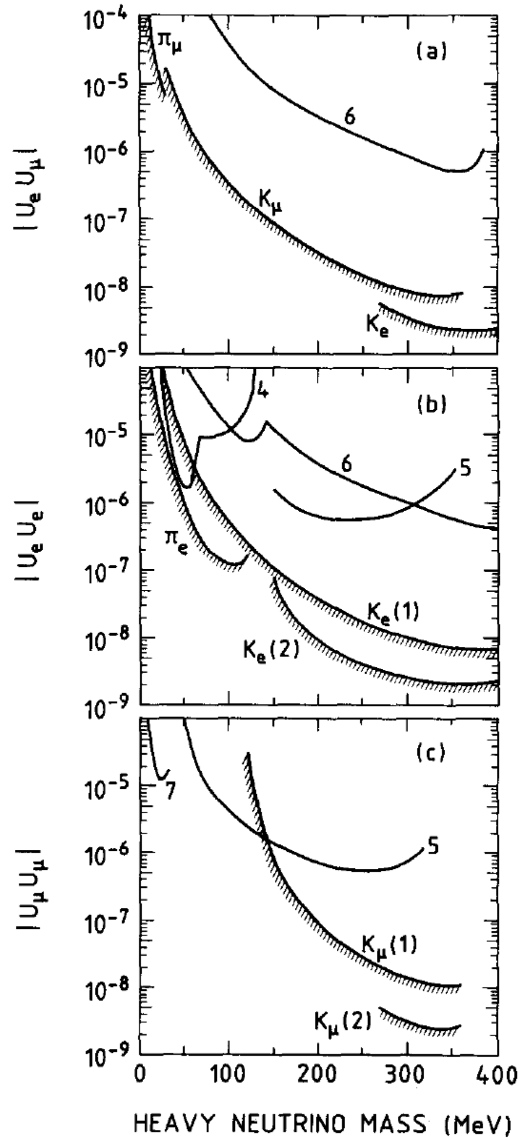
- ***B* and *L* violations**
  - *B* violation due to EW sphaleron
  - *L* violation due to Majorana masses
    - negligible for baryogenesis temperature since $M_M \lesssim M_W$
- **C and CP violations**
  - 1 CP phase in quark sector
  - 6 CP phases in lepton sector
    - 3 CP phases associated with $N_{2,3}$ are relevant for baryogenesis
- **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

# 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 $\Theta$

$\Rightarrow$ **Lower bound on lifetime of $N_{2,3}$**

# 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
    - $N_{2,3} \;\to \nu\,\bar{\nu}\,\nu,\;\; e^+\, e^-\, \nu, \ldots$
    - Additional neutrinos may not be thermalized

$\Rightarrow$ **Upper bound on lifetime of $N_{2,3}$**

- Dolgov, Hansen, Rafflet, Semikoz ('00)
  - One family case:

$$\tau_N < 0.1\,\mathrm{sec}\;\; \mathrm{for}\; M_N > m_\pi$$

# SHiP

Talk by Nicola Serra

**arXiv:1310.1762**

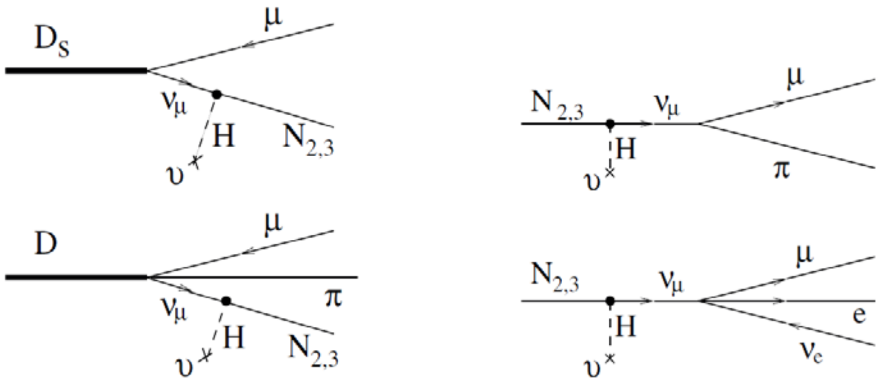
- A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons

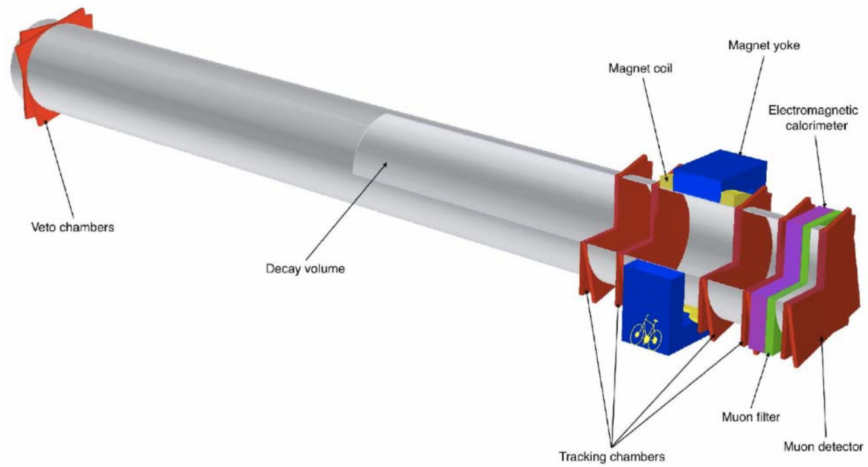
SHiP

*Search for Hidden Particles*

**SHIP - Search for HIdden Particles**

**CERN, Universität Zürich, EPFL Lausanne, INFN Cagliari, Università Federico II and INFN Napoli, Imperial College London**





# Search for HNLs at T2K

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

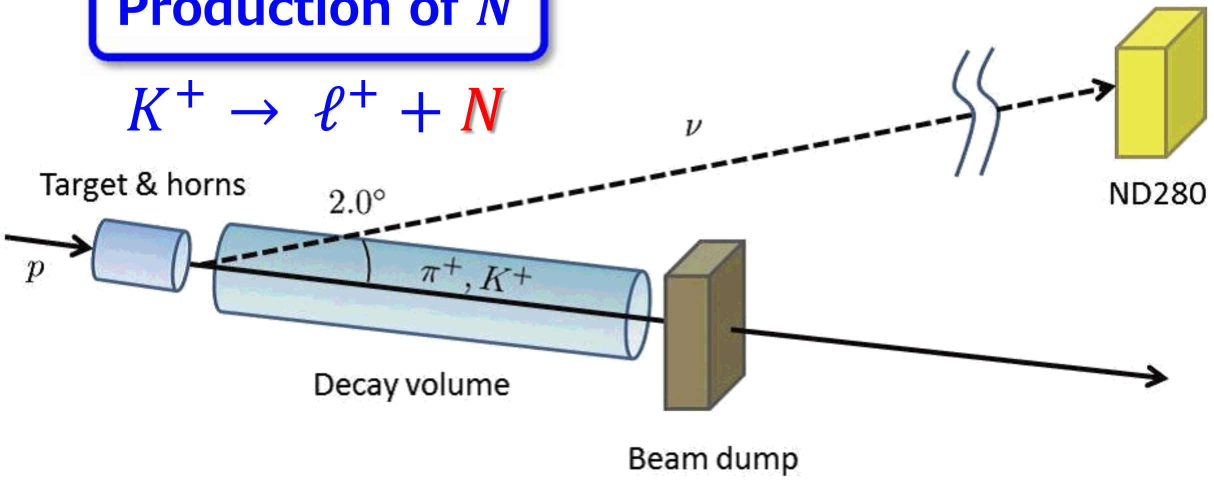


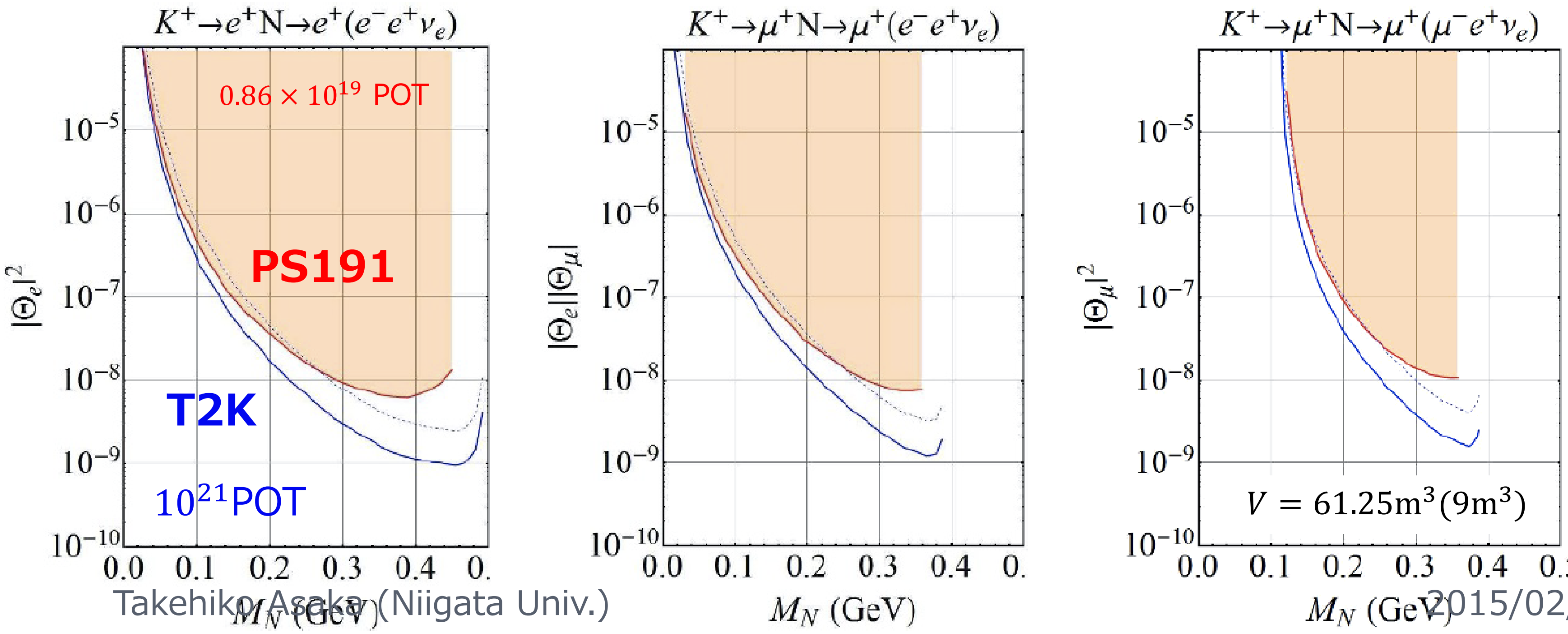
**Production of $N$**

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

**Detection of $N$**

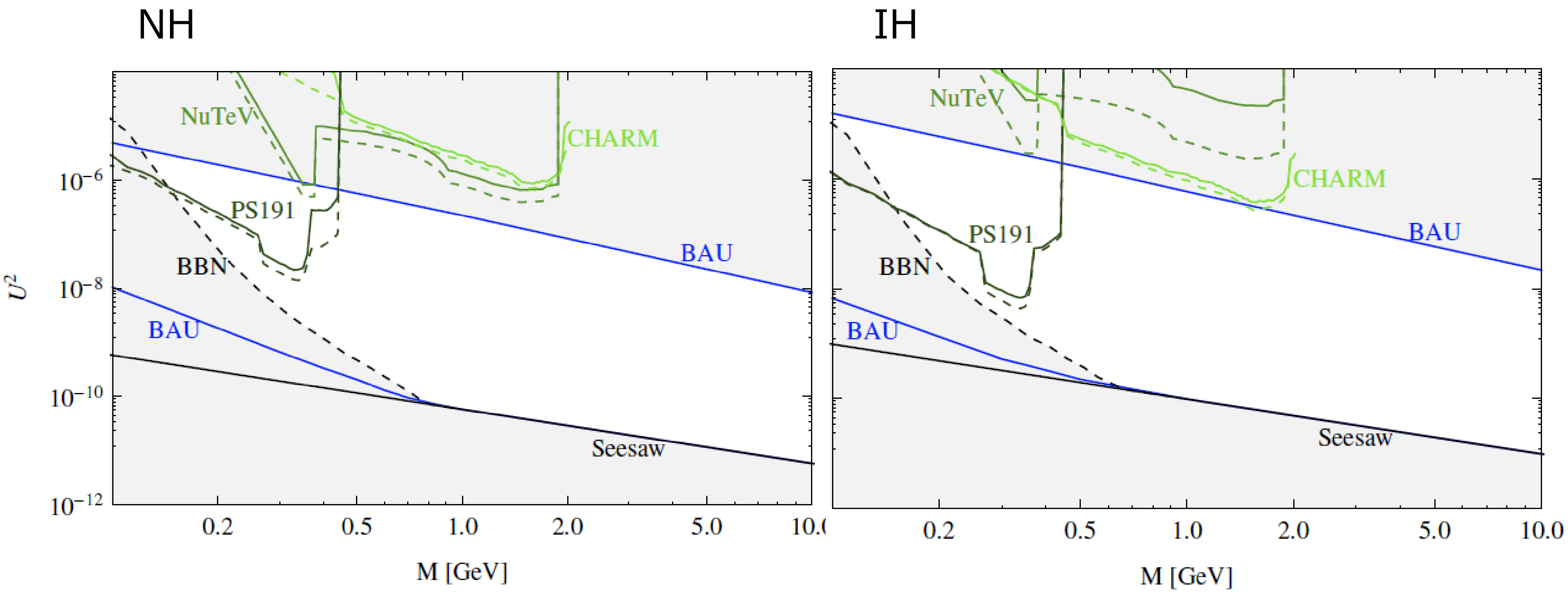
$$N \to \ell^- + \ell^+ + \nu$$



# Constraints on HNLs $N_2$ and $N_3$

Canetti, Drewes, Frossard, Shaposhnikov ‘13




See Gorbunov and Shaposhnikov ’07 [arXiv:0705.1729]
Atre, Han, Pascoli, Zhang ‘09 [arXiv:0901.3589]