Low-scale baryogenesis

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Flavor Physics Conference

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Baryon asymmetry of the universe (BAU)

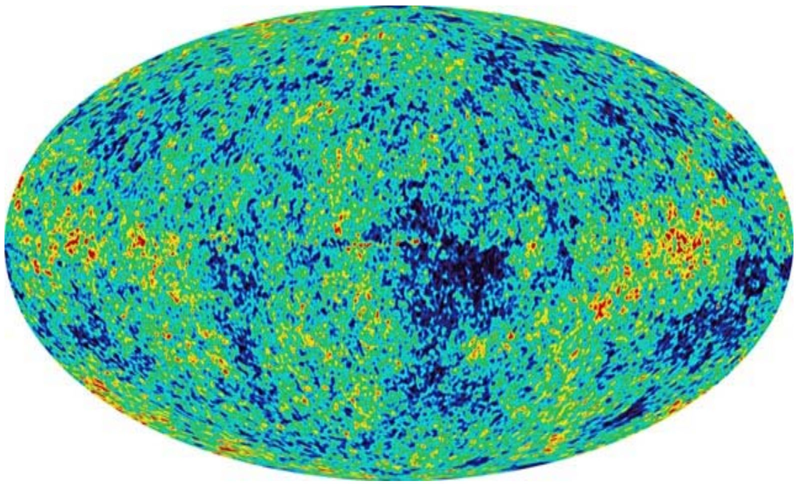
Baryon Number B = (# of baryons) − (# of antibaryons)

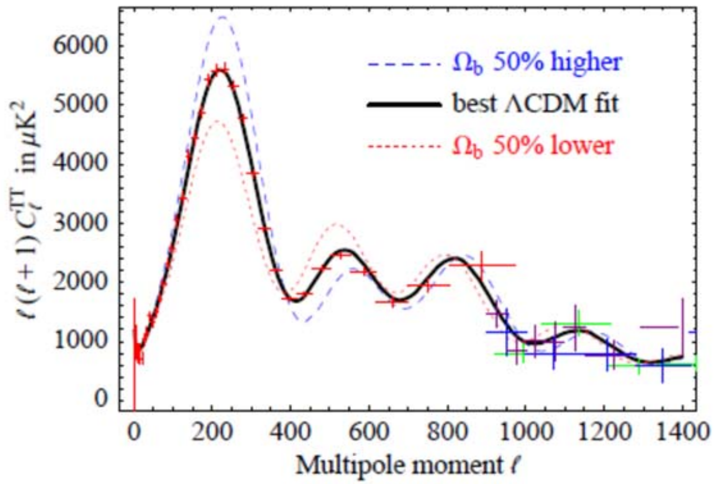
$$\frac{n_B}{s} = (8.579 \pm 0.109) \times 10^{-11}$$

Planck 2013 results
arXiv:1303.5076

n_B : Baryon number density

s : Entropy density





[Strumia 06]

Introduction

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

  ⇒ **Need for physics beyond the SM !**

- Important questions:
  - ***"What is the origin of neutrino masses?"***
  - ***"What is the implications of it?"***
  - ***"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 ($M_D = F\langle\Phi\rangle \ll M_M$)

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

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

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

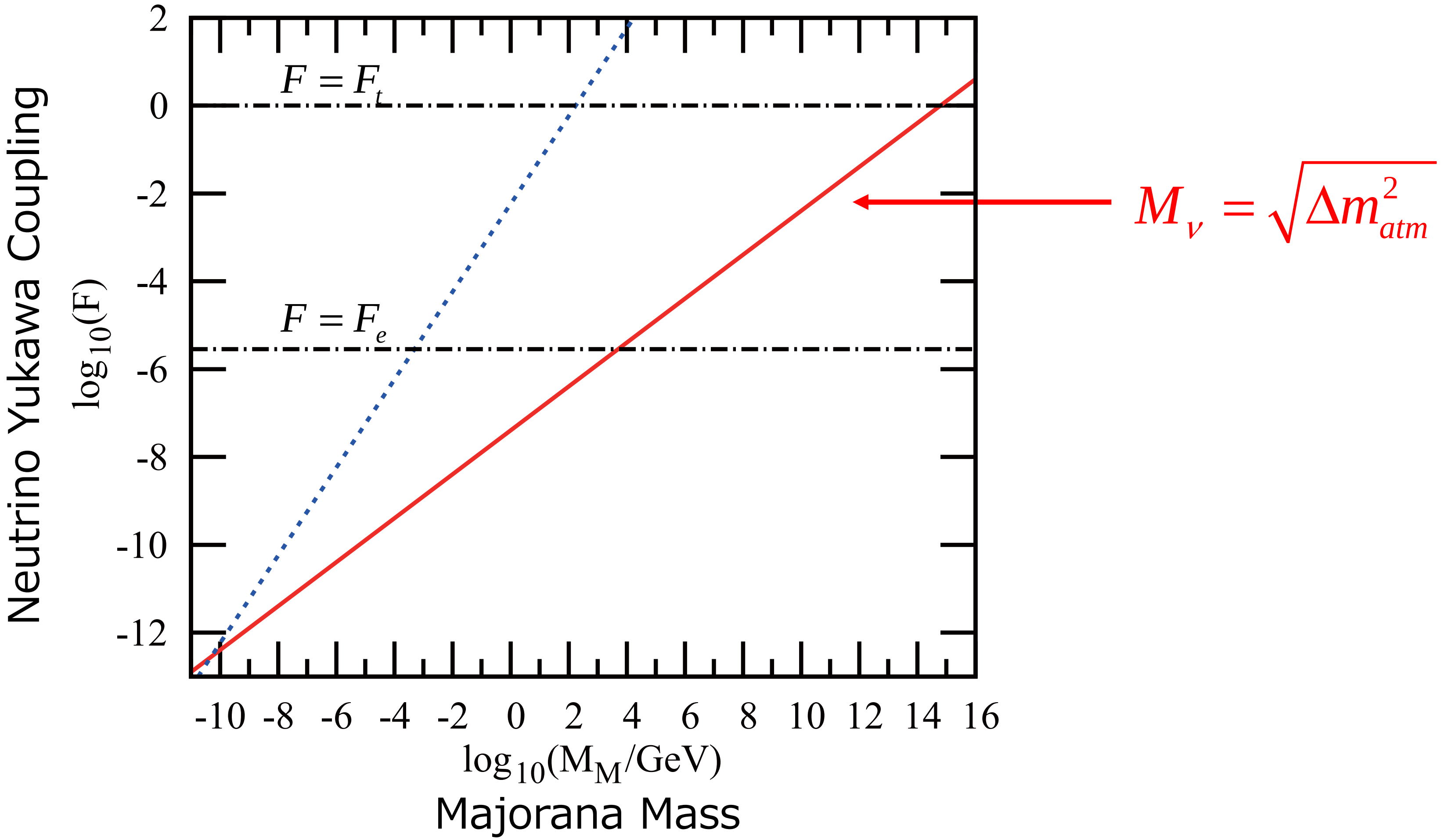
- **Light active neutrinos ν_1, ν_2, ν_3**
  - → explain neutrino oscillations
- **Heavy neutral leptons N_1, N_2, N_3 ($N \simeq \nu_R$)**
  - Mass M_M
  - Mixing $\Theta = M_D/M_M$

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

Scale of Majorana mass

- The simplest case: one pair of ν_L and ν_R

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



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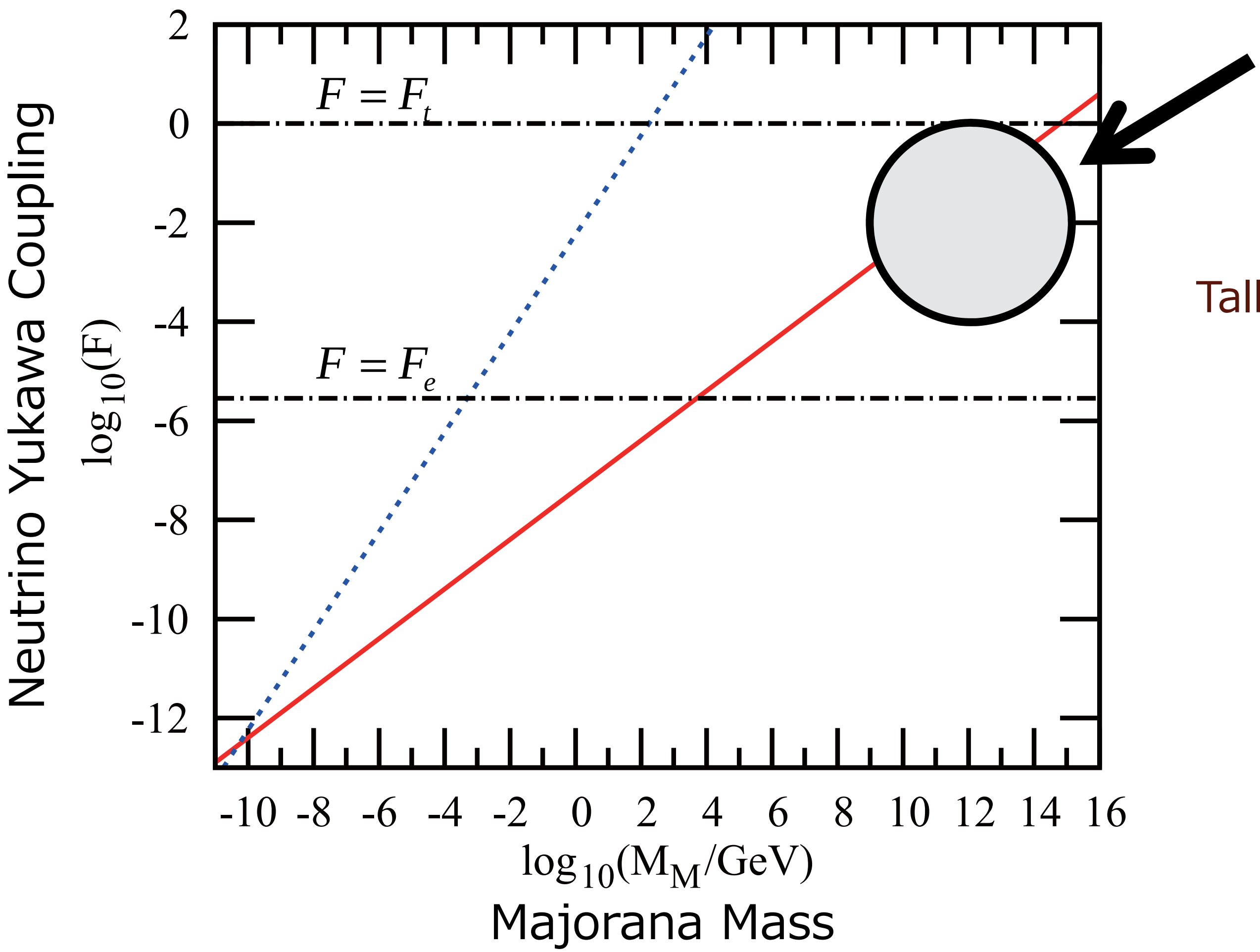

Baryogenesis via leptogenesis

Fukugita, Yanagida '86

Talk by Stephane Lavignac

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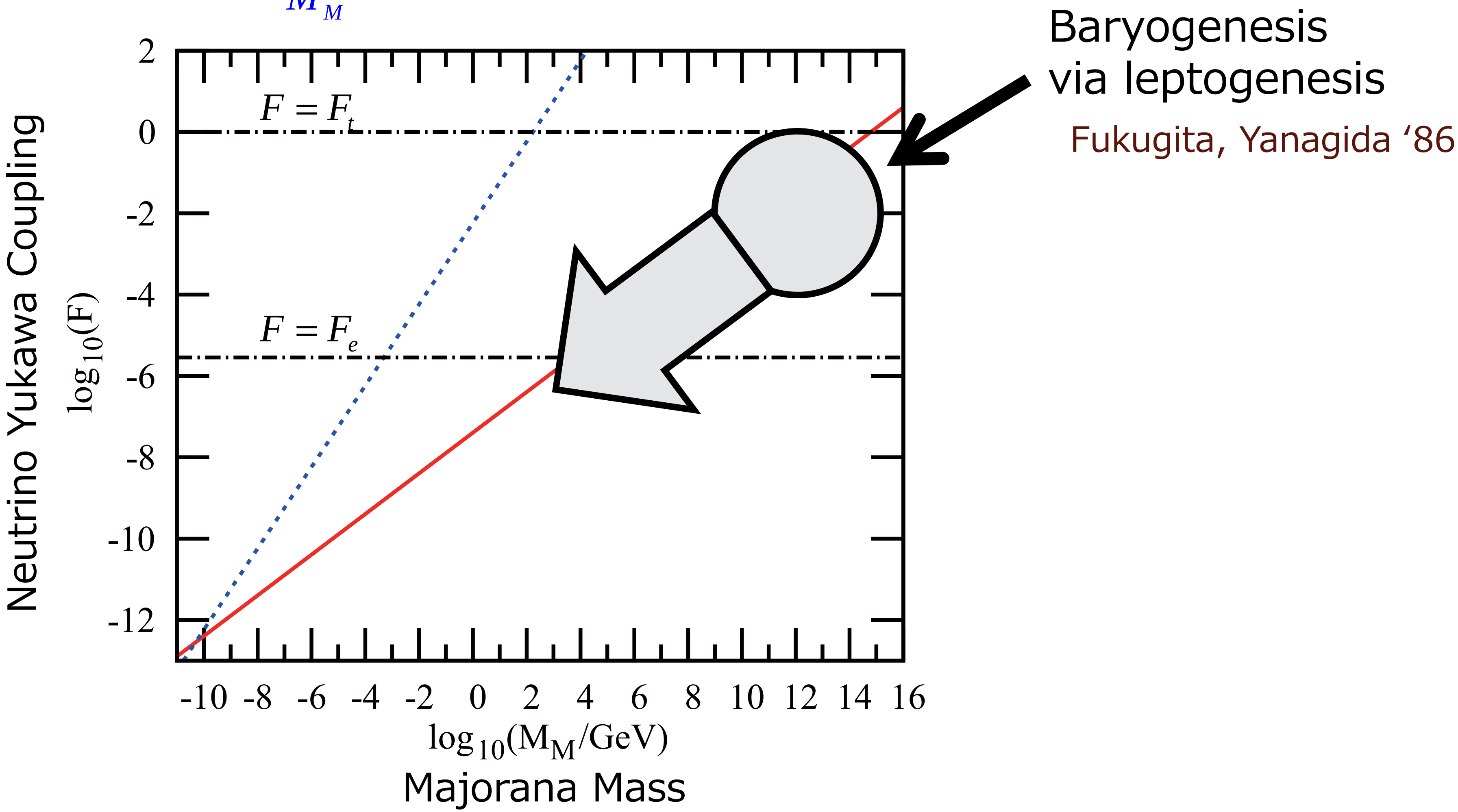

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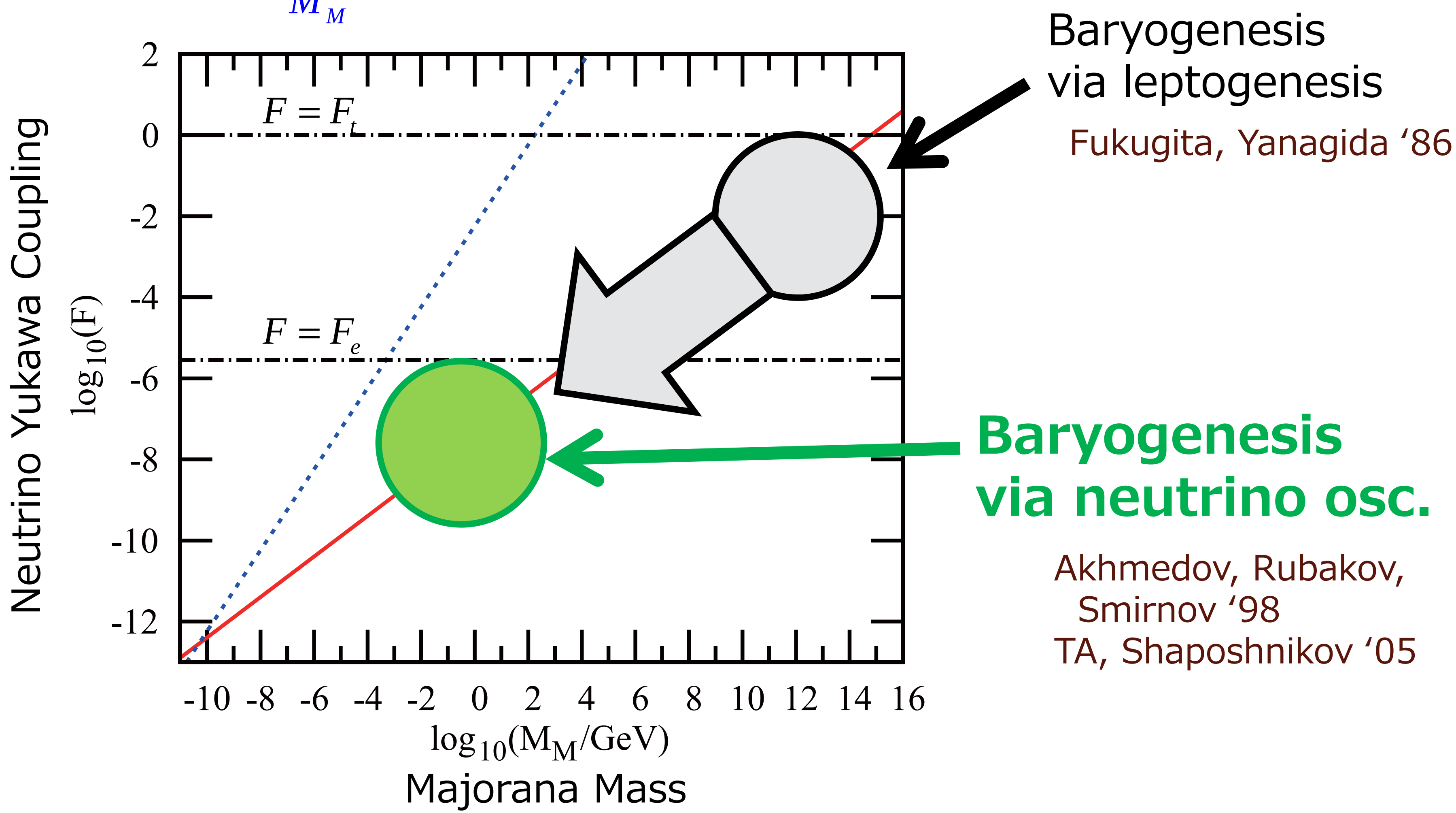

The νMSM

TA, Blanchet, Shappshnikov ‘05,
TA, Shaposhnikov ‘05

- $M_M \lesssim M_W$:no new mass scale between M_W and M_{pl}

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

- Lightest one N_1 among 3 heavy neutral leptons with keV mass can be **dark matter !!**

  Dodelson, Widrow ‘94,⋯

- Oscillation of heavy neutral leptons N_2 and N_3 can generate **baryon asymmetry of the universe !**

  Akhmedov, Rubakov, Smirnov ’98, TA, Shaposhnikov ‘05

- **Dark matter** N_1 can be **tested by cosmic X-ray obs.**

  Talk by Oleg Ruchayskiy

- Physics of heavy neutral leptons N_2 and N_3 can be **tested by experiments !!!**

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Baryogenesis via Neutrino Oscillation

Baryogenesis in the νMSM

Conditions for Baryogenesis (Sakharov '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

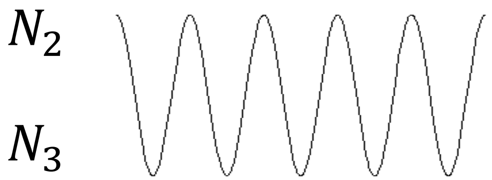
Baryogenesis via neutrino osc.

- Oscillation of HNLs can be a source of BAU

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

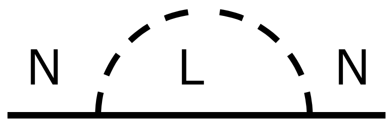
  Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
  TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
  Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)

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

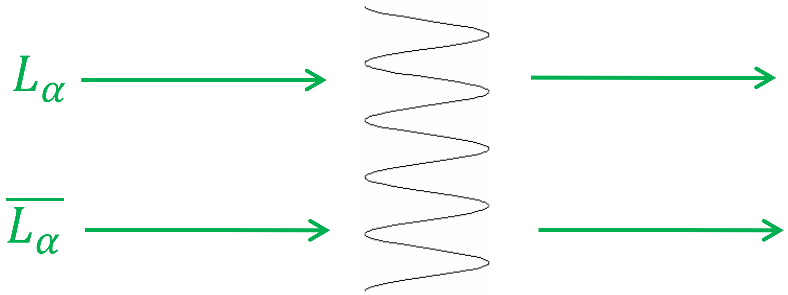


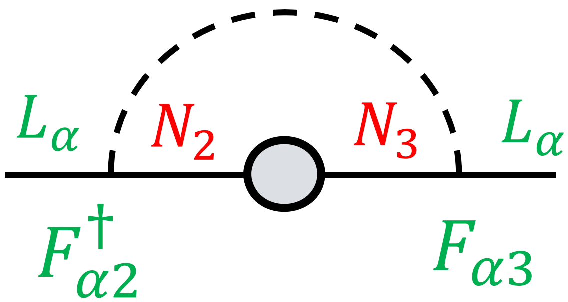
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



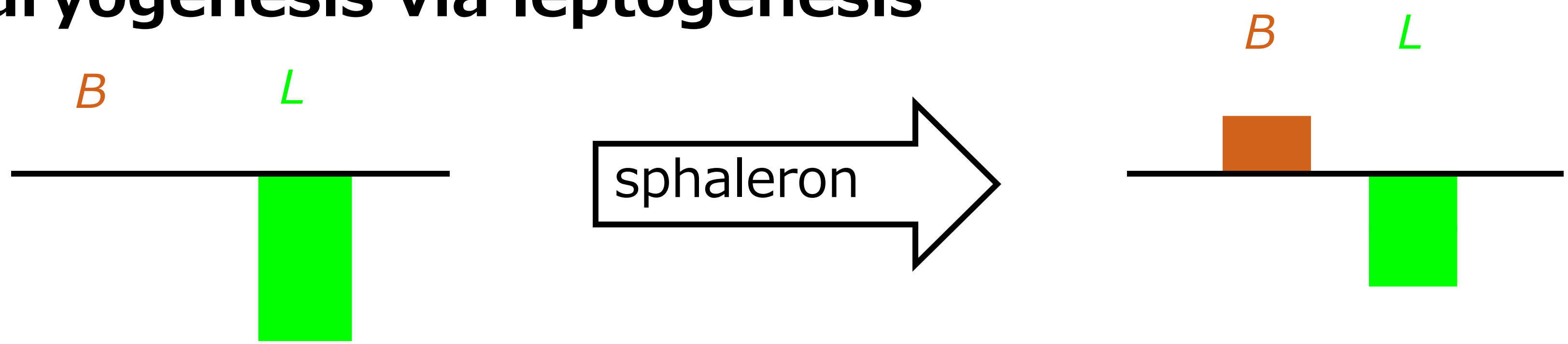
  - Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV



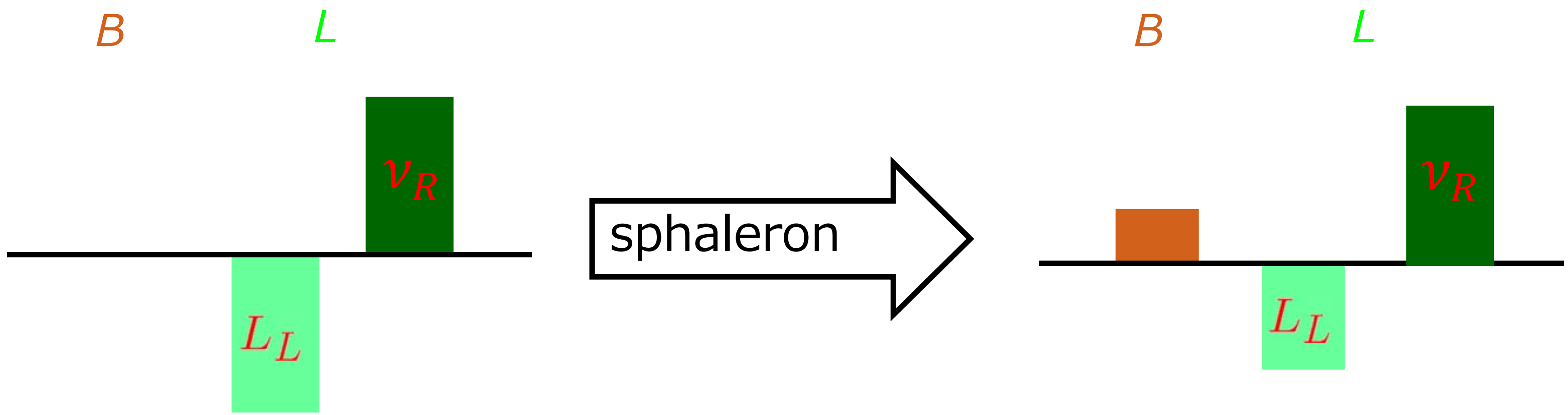


Key points

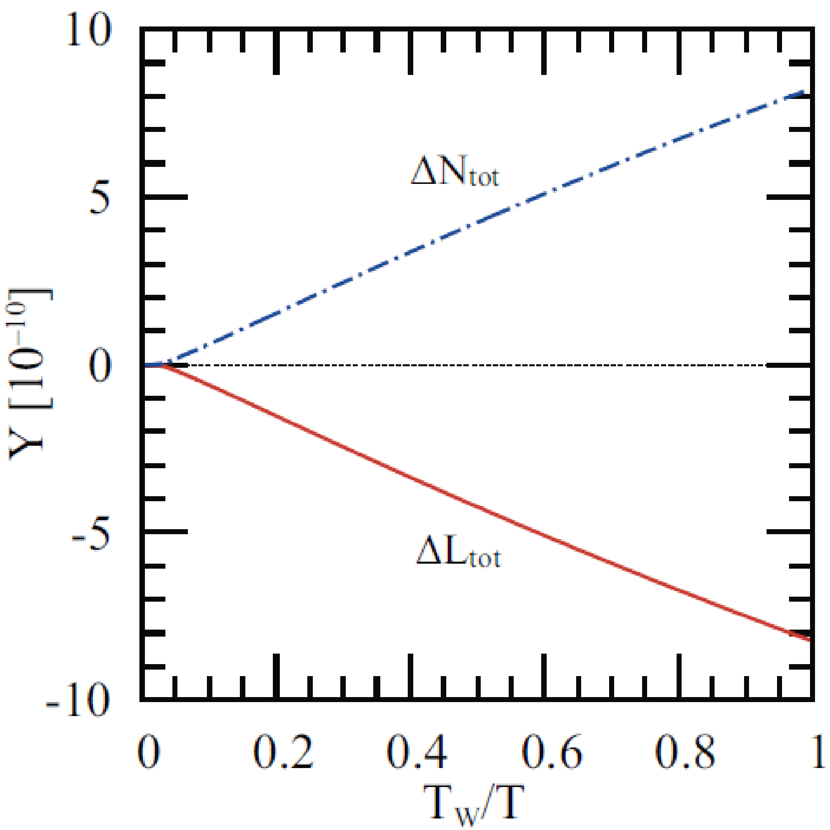
Baryogenesis via leptogenesis



Baryogenesis via neutrino osc.



Evolution of asymmetries



Shaleron converts ΔL_{tot} partially into baryon asymmetry

[Kuzmin, Rubakov, Shaposhnikov]

$$\frac{n_B}{s} = -2.5 \times 10^{-4}\, \Delta L_{tot}(T_W)$$

⬍

$$\frac{n_B}{s} = (8.55 \sim 9.00) \times 10^{-11}$$

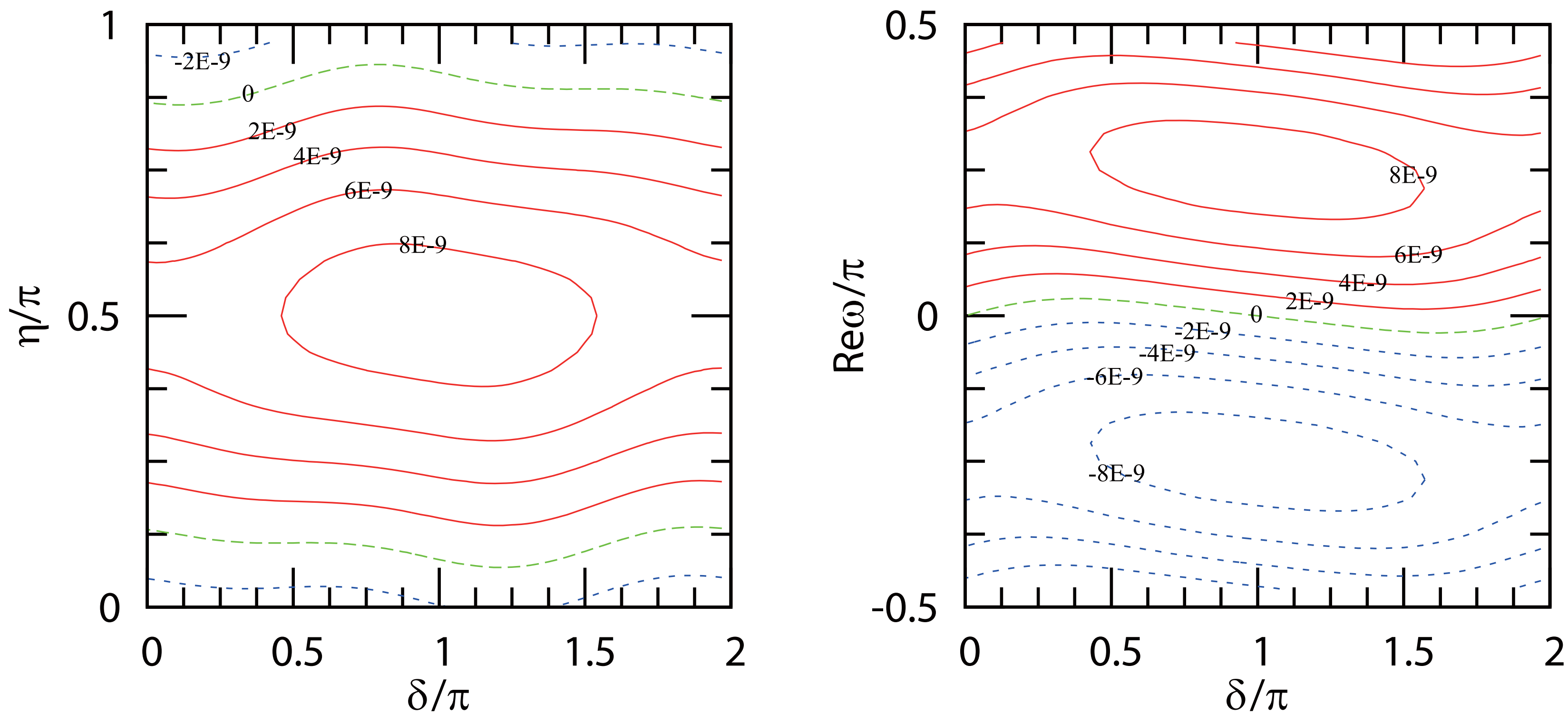
[Planck 2013]

Yield of BAU depends on $F_{\alpha I}$ (even PMNS matrix !!) and masses, especially, CP violating parameters and mass difference

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

BAU and Phases δ and η

IH case



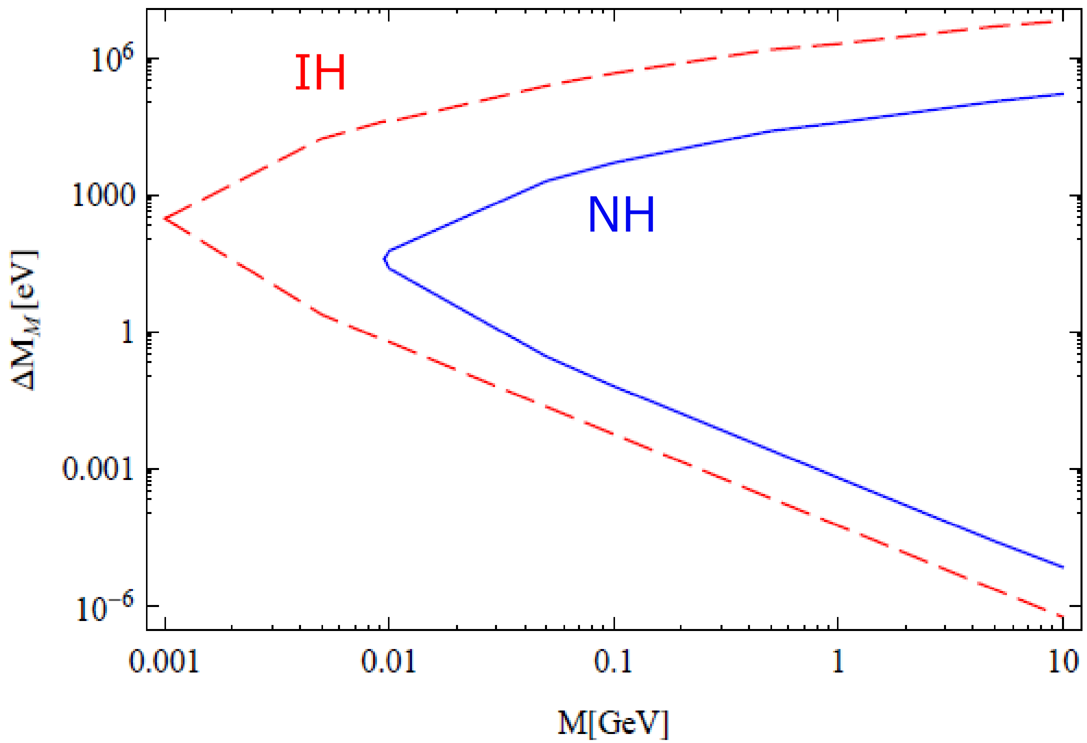
Yield of BAU depends on $F_{\alpha I}$ (even PMNS matrix !!) and masses, especially, CP violating parameters and mass difference

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

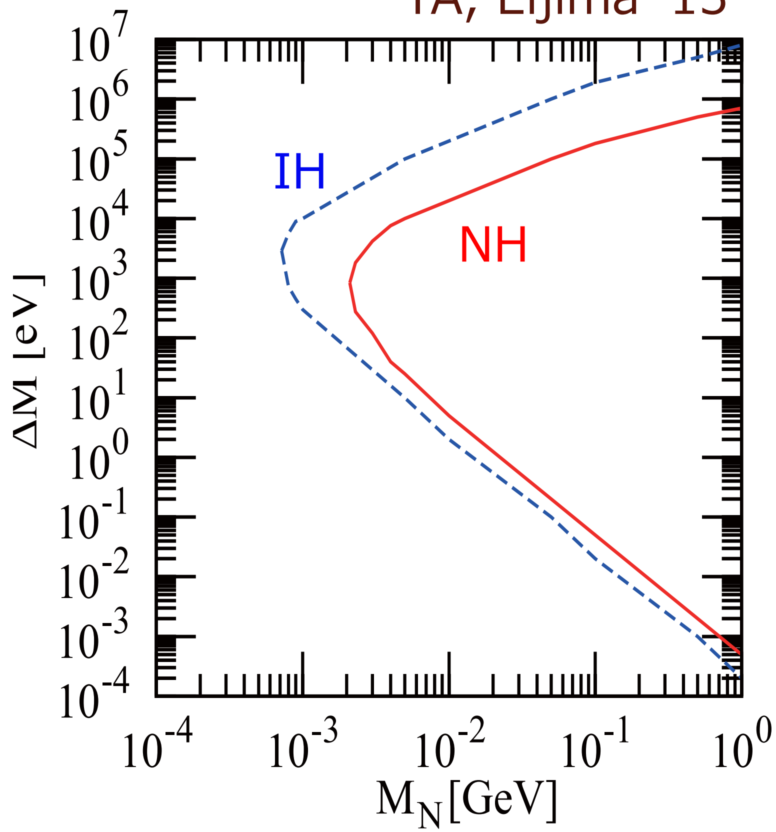
Baryogenesis via neutrino osc.

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

Canetti, Shaposhnikov '10



TA, Eijima '13

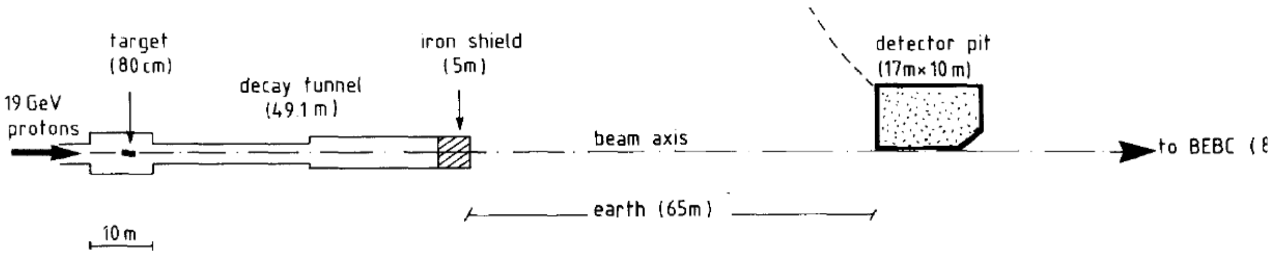


$M_N > 2.1$ MeV (NH) $M_N > 0.7$ MeV (IH)

Direct search experiment

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

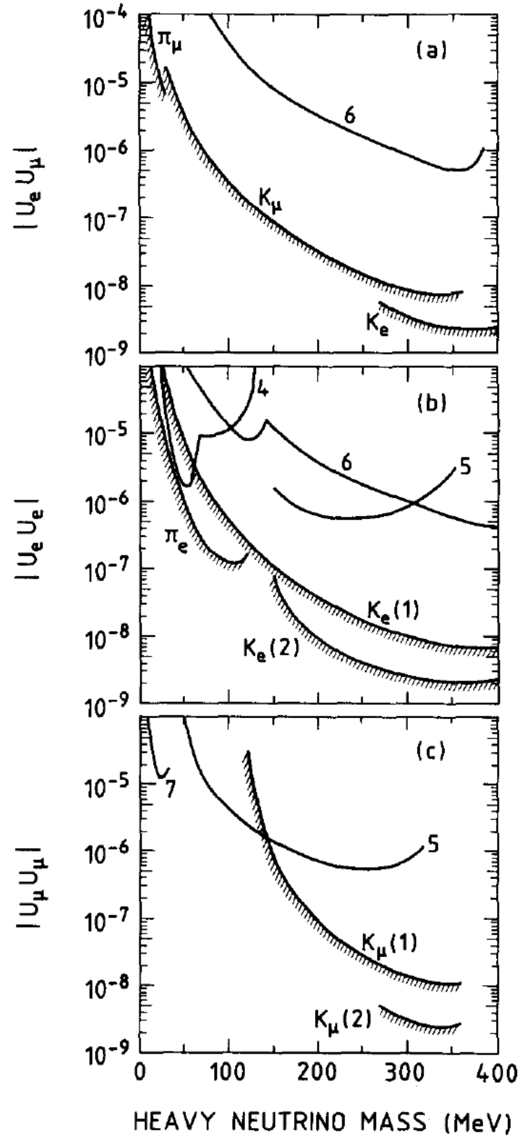
  Beam dump experiment
  performed at CERN in 1984



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

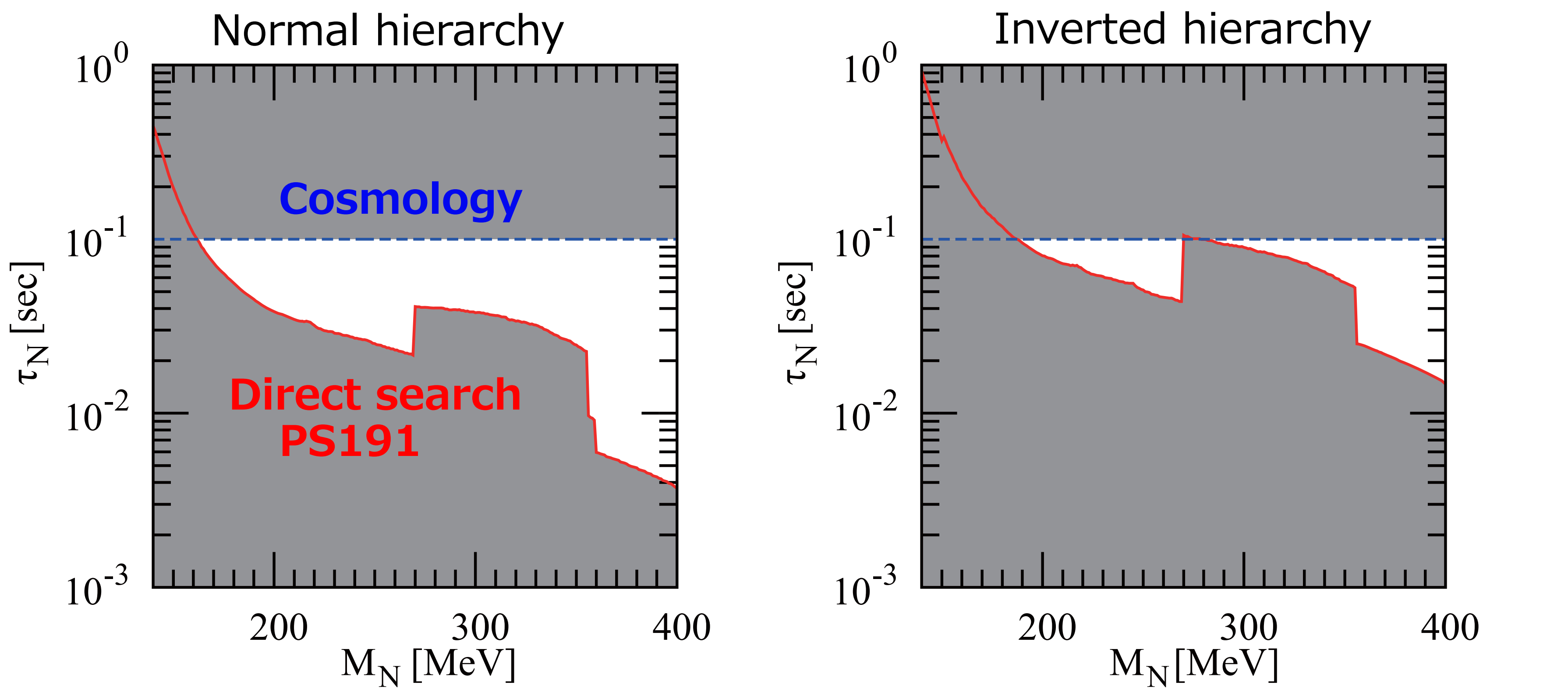
- Upper bounds mixing elements Θ

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



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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Search for heavy neutral leptons (HNLs)

SHIP

Talk by Nicola Serra

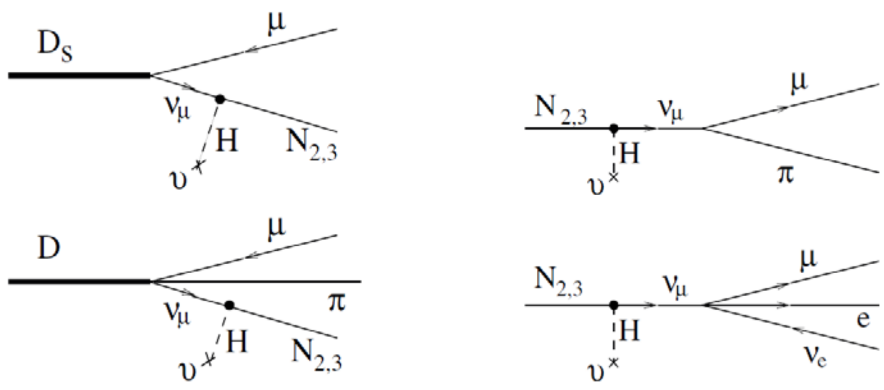
arXiv:1310.1762

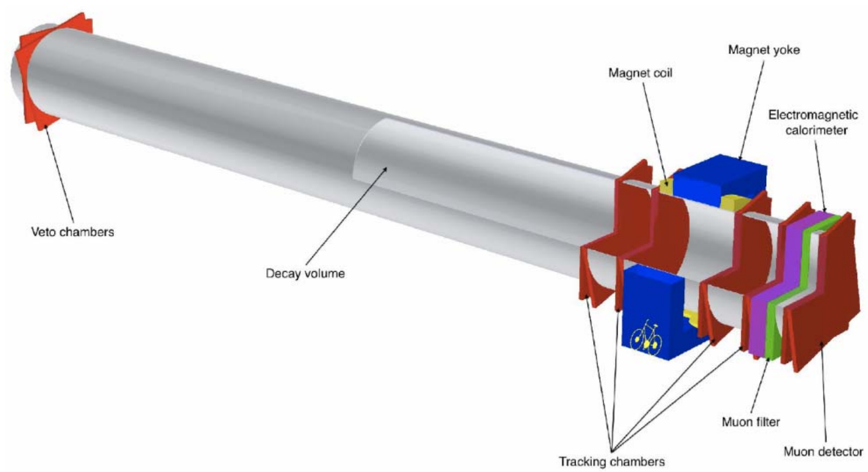
- A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons

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

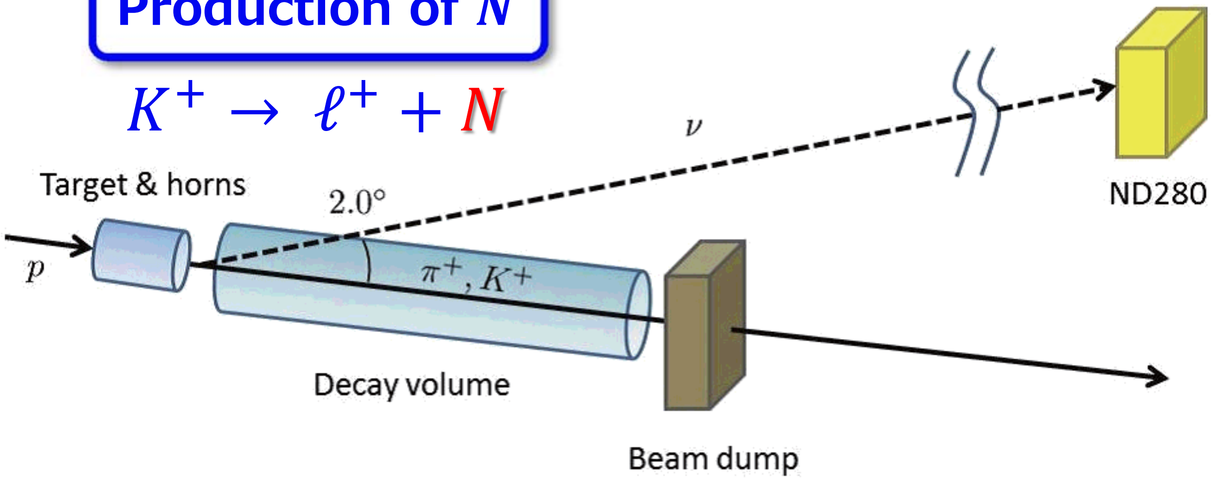
TA, Eijima, Watanabe
[JHEP1303 (2013) 125]

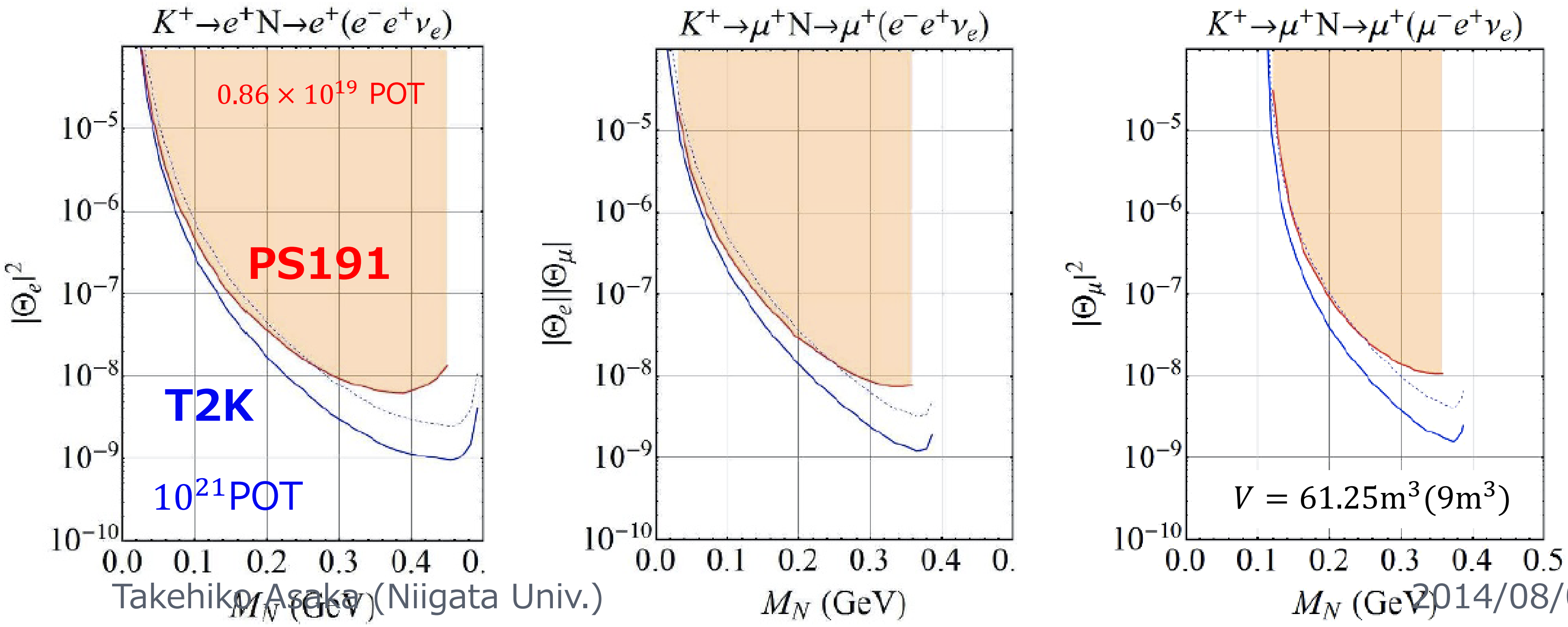
Production of N

$K^+ \rightarrow \ell^+ + N$

Detection of N

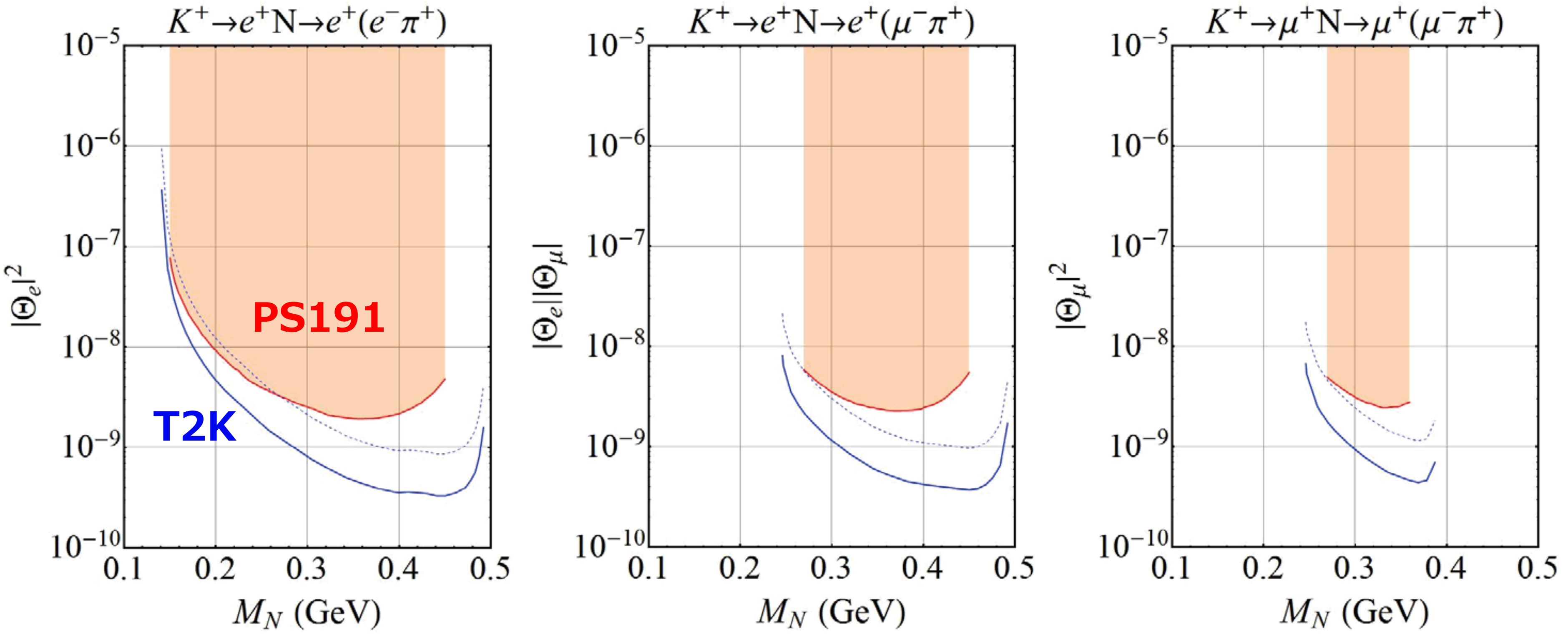
$N \rightarrow \ell^- + \ell^+ + \nu$





Sensitivity: PS191 vs T2K

TA, Eijima, Watanabe '13



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

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 found the possible region for neutrino oscillations and BAU, allowed from search and cosmological constraints.

    - $M_N > 163$ MeV (NH)
      $M_N = 188 - 269$ MeV and $M_N > 285$MeV (IH)

- ***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

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 $\Longrightarrow$ overproduction of $^4\mathrm{He}$

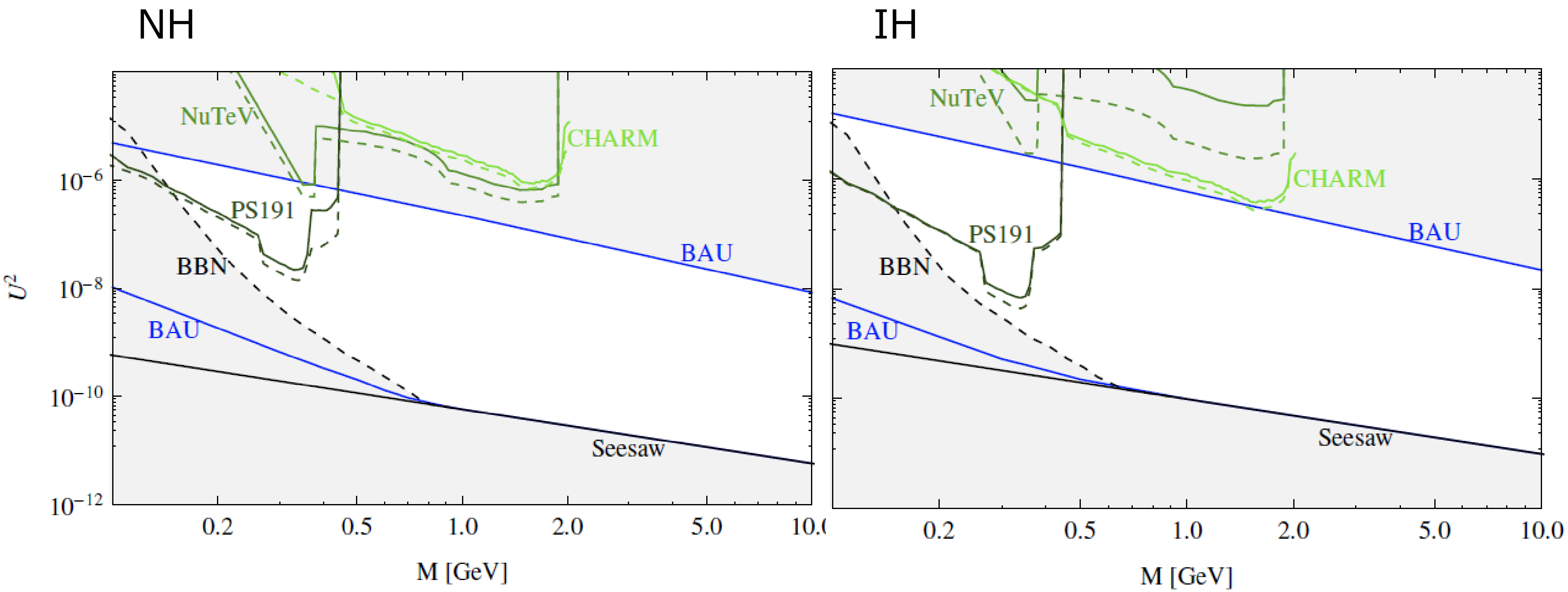
      $n + \nu \;\leftrightarrow\; p + e^-, \ldots$
  - Distortion of spectrum of active neutrinos
    - $N_{2,3} \;\rightarrow \nu\, \bar{\nu}\, \nu,\;\; e^+\, e^-\, \nu, \ldots$
    - Additional neutrinos may not be thermalized

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

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

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]

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