Leptogenesis

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Online

Contents

Baryon Asymmetry of the Universe (BAU)

Baryon v.s. antibaryon

Baryon

proton $(B = +1)$
neutron $(B = +1)$

Antibaryon

antiproton $(B = -1)$
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)

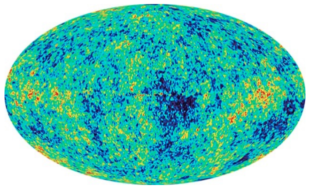
- Observational value

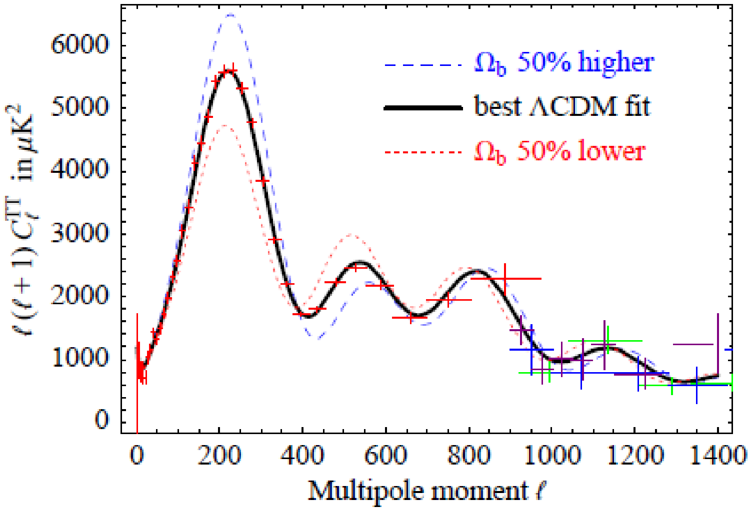
Planck 2018 [1807.06209]

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

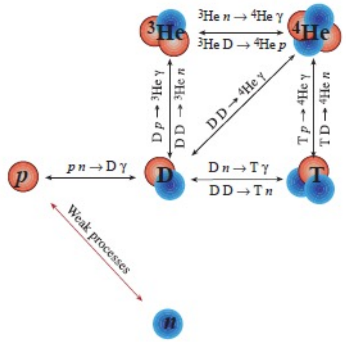
n_B : baryon number density, s : entropy density

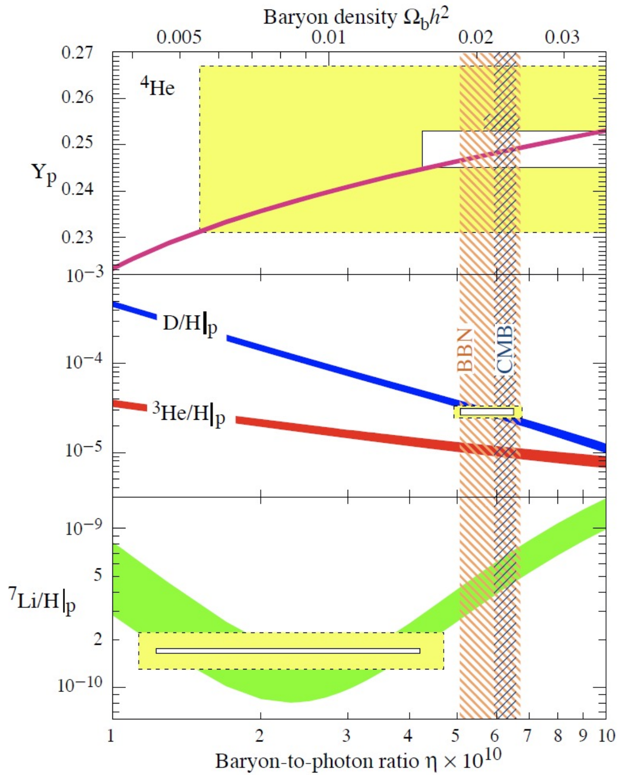
CMBR





BBN

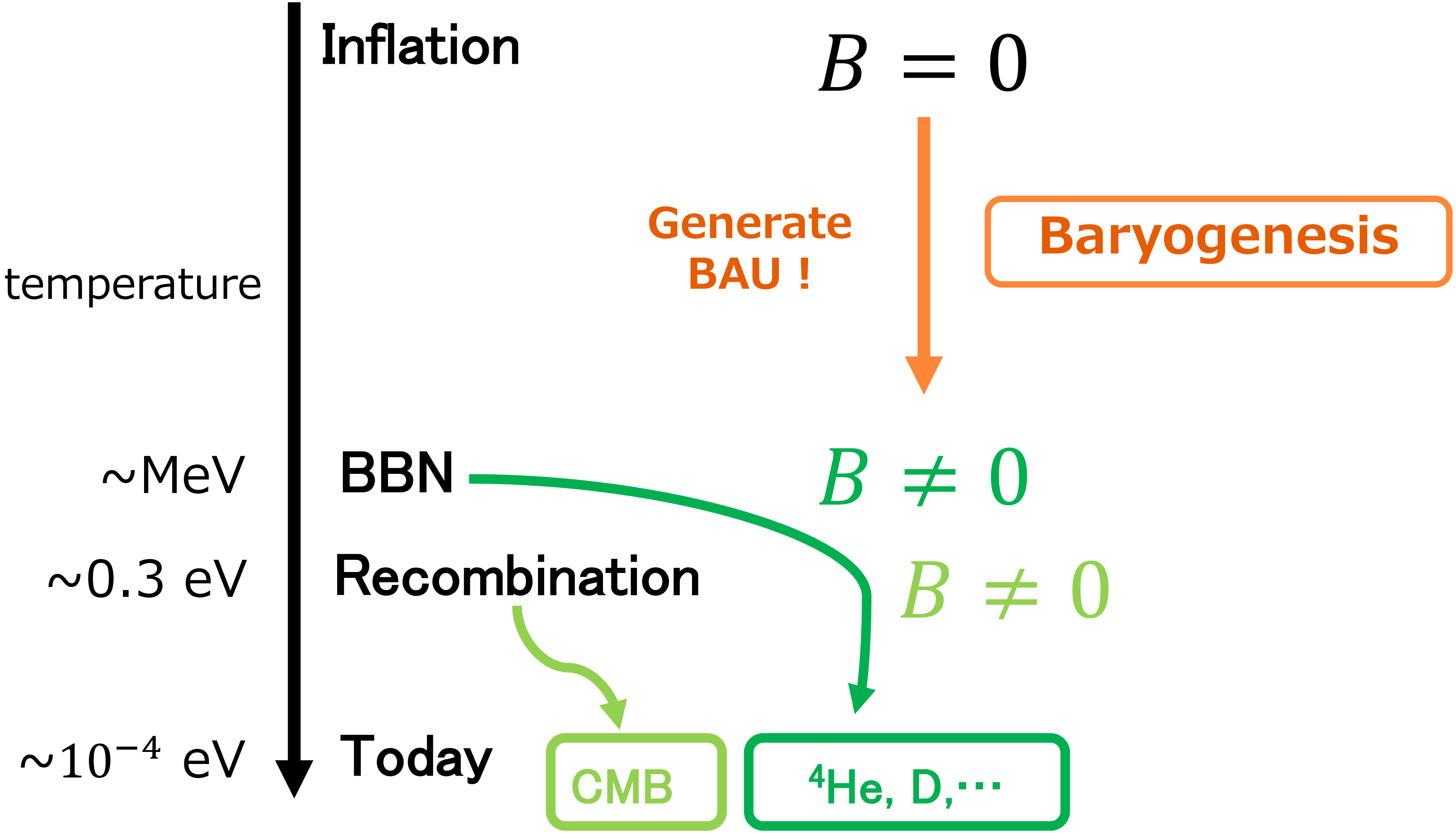




[Strumia 06]

[PDG]

Brief history of the universe



Baryogenesis

- Sakharov （１９６７）

  （１） Baryon number B is violated

  （２） C and CP symmetries are violated

  （３） Out of thermal equilibrium

"According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

Let us see whether the SM satisfies these conditions

B violation in the MSM

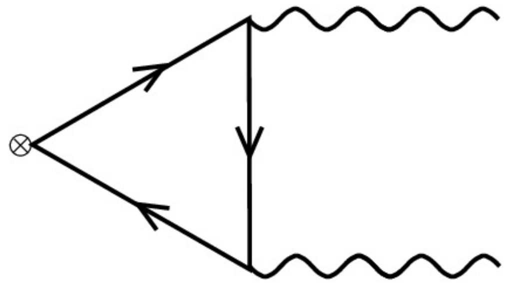
- At classical level, B and L are conserved

$$\begin{cases} \partial_\mu j_B^\mu = 0 \\ \partial_\mu j_L^\mu = 0 \end{cases} \Rightarrow \begin{cases} \text{Baryon number: } B = \int d^3x\, j_B^0 \\ \text{Lepton number: } L = \int d^3x\, j_L^0 \end{cases}$$

accidental symmetries

both charges are conserved

- At quantum level, B and L are violated by non-perturbative anomaly effect



$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = N_F \frac{g^2}{32\pi^2} W_{\mu\nu}^a \widetilde{W}^{a\mu\nu}$$

N_F : number of generations (families)

$$\boxed{\partial_\mu (j_B^\mu - j_L^\mu) = 0}$$

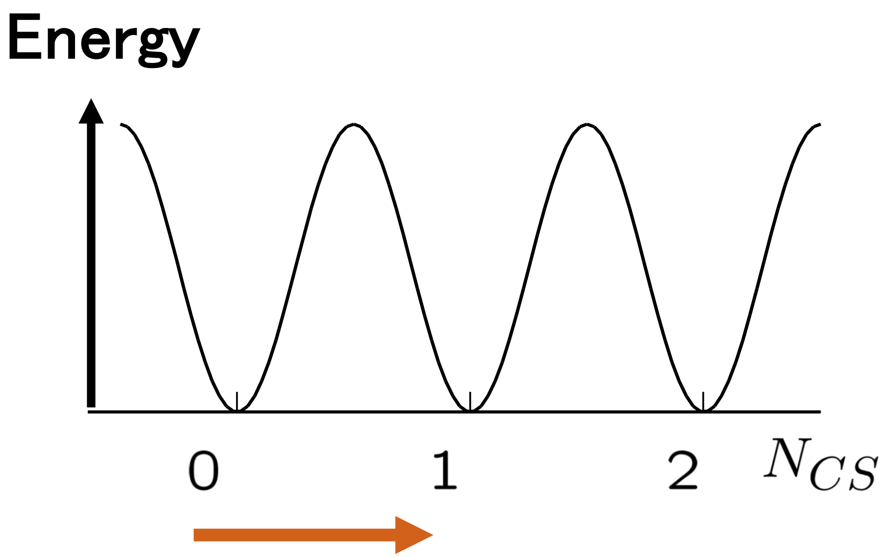
B and L are violated, but $(B - L)$ is conserved !

ΔB and ΔL

- Chern-Simons number (integer)

$$\Delta B = \int_{t_i}^{t_f} dt \int d^3x\ \partial_\mu j_B^\mu = N_F \Delta N_{CS}$$

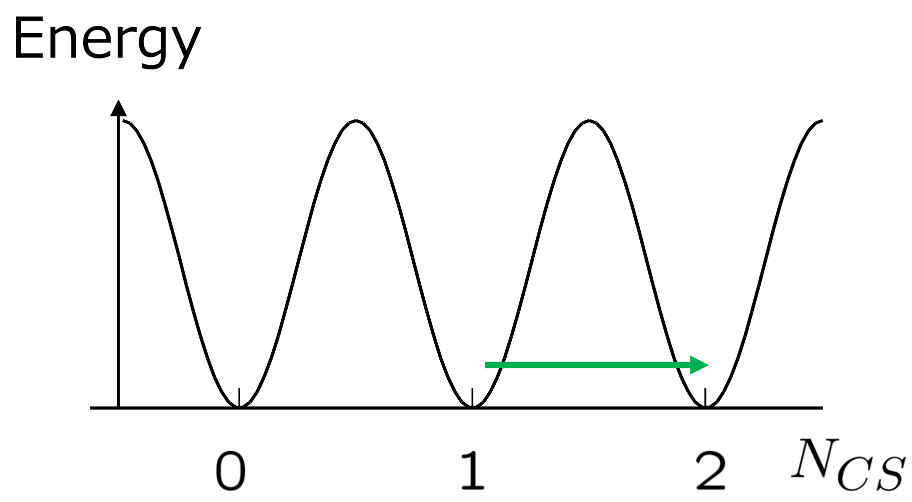
$$N_{CS} = \frac{g^2}{32\pi^2} \int d^3x\ \varepsilon^{ijk} tr\left(A_i \partial_j \partial_k + \frac{2}{3} ig\ A_i A_j A_k\right)$$



$$\Delta B = \Delta L = N_F$$

ΔB and ΔL

- At the vacuum (at temperature $T = 0$)



Instanton

[G. ' t Hooft '76]

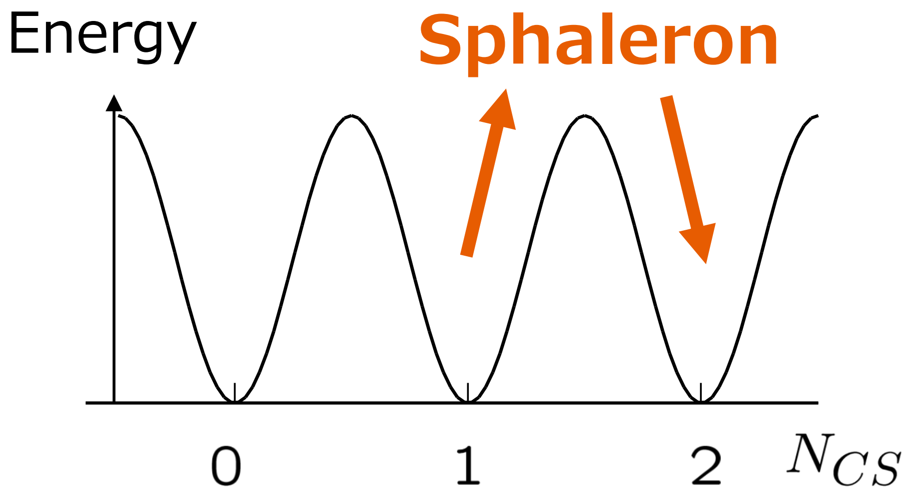
The transition rate

$$\Gamma \sim \exp\left(-\frac{16\pi^2}{g^2}\right) = \mathcal{O}(10^{-170})$$

B+L breaking effect is negligible

ΔB and ΔL

- For high temperatures (at temperature $T > \mathcal{O}(10^2)$ GeV)



$\Delta B = \Delta L = N_F$

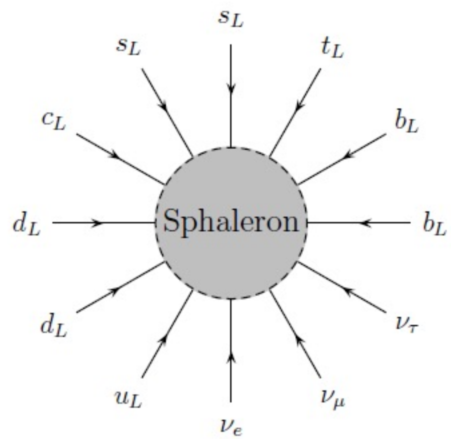
The transition rate
(per unit volume)

$\Gamma \sim \kappa\, \alpha_W^5\, T^5$ [Moore '00]

Sphaleron process is in equilibrium

$$10^{12}\ \mathrm{GeV} > T > 10^2\ \mathrm{GeV}$$

[Kuzumin, Rubakov, Shaposhnikov '85]



Buchmuller

Sphaleron conversion

- Initial $(B-L)$ asymmetry is converted into B

$$\boxed{B_f = \frac{8N_F + 4}{22N_F + 13}(B-L)_i = 0.35\,(B-L)_i}$$

[Khlebnikov, Shaposhnikov '88, Harvey, Turner '90]

- $(B-L)_i = 0$ initially leads to $B = 0$ universe
  → Initial asymmetries B_i and L_i are washed out if $(B-L)_i = 0$

- We have to generate $(B-L)_i > 0$ initially
  in order to explain $B > 0$ universe !

Baryogenesis in the Standard Model

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

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

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

→ too small

- **Out of equilibrium** [Kajantie, Laine, Rummukainen, Shaposhnikov]
  - Strong 1st order phase transition if $m_h < 72$ GeV

but $m_h = 125$ GeV

→ not satisfied

We have to go beyond the SM !

Various baryogenesis scenarios

- GUT baryogenesis, GUT baryogenesis after preheating, Baryogenesis from primordial black holes, String scale baryogenesis, Affleck-Dine (AD) baryogenesis, Hybridized AD baryogenesis, No-scale AD baryogenesis, Single field baryogenesis, Electroweak (EW) baryogenesis, Local EW baryogenesis, Non-local EW baryogenesis, EW baryogenesis at preheating, SUSY EW baryogenesis, String mediated EW baryogenesis, Inflationary via baryogenesis, Baryogenesis without ground unification (leptogenesis), Resonant leptogenesis, Spontaneous baryogenesis, Coherent baryogenesis, Gravitational baryogenesis, Defect mediated baryogenesis, Baryogenesis from cosmic strings, B-ball baryogenesis, Baryogenesis via neutrino oscillations, Monopole baryogenesis, ···

See, for example, talk by M. Shaposhnikov @COSMO 2012

Leptogenesis

Leptogenesis —Motivation

Neutrino properties

- Mixing angles and mass squared differences are measured very precisely

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

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

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

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

Right-handed neutrinos

$$\nu_R$$

Why ν_R ?

- Chiral structure of fermions in the SM

- Hierarchical patterns of fermion masses
  - neutrino masses << masses of quarks and leptons

    $(m_{atm} \simeq 50\ \mathrm{meV} \ll m_e \simeq 0.5\ \mathrm{MeV})$

- Interesting phenomena by right-handed neutrinos
  - Baryogenesis
    - Leptogenesis / Mechanism by oscillations
  - Dark matter
    - keV mass right-handed neutrino is a candidate of WDM
      (it may be irrelevant in the seesaw mechanism)
  - etc.

Standard Model

Higgs Boson	Quarks and Leptons (left-handed)	Quarks and Leptons (right-handed)	Gauge Bosons
h	$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$	$u_R \quad c_R \quad t_R$ $d_R \quad s_R \quad b_R$	g Z^0
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$e_R \quad \mu_R \quad \tau_R$	$W^\pm$ γ

Three right-handed neutrinos

Higgs Boson	Quarks and Leptons (left-handed)	Quarks and Leptons (right-handed)	Gauge Bosons
h	$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$	$u_R \quad c_R \quad t_R$ $d_R \quad s_R \quad b_R$	g Z^0
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$e_R \quad \mu_R \quad \tau_R$ $\nu_{R1} \; \nu_{R2} \; \nu_{R3}$	$W^\pm$ γ

Extension by right-handed neutrinos ν_R

$$\delta\mathcal{L} = i\overline{\nu_R}\gamma^\mu\partial_\mu\nu_R - \left(F\,\bar{L}\nu_R\Phi + \frac{M_M}{2}\overline{\nu_R}\nu_R^c + h.c.\right)$$

Minkowski '77, Yanagida '79
Gell-Mann, Ramond, Slansky '79
Glashow '79,
Mohapatra, Senjanovic '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**

$$M_\nu = -\frac{M_D^T}{M_M} \times M_D$$ $\Leftarrow$ tiny neutrino masses !

$\rightarrow$ explain neutrino oscillations

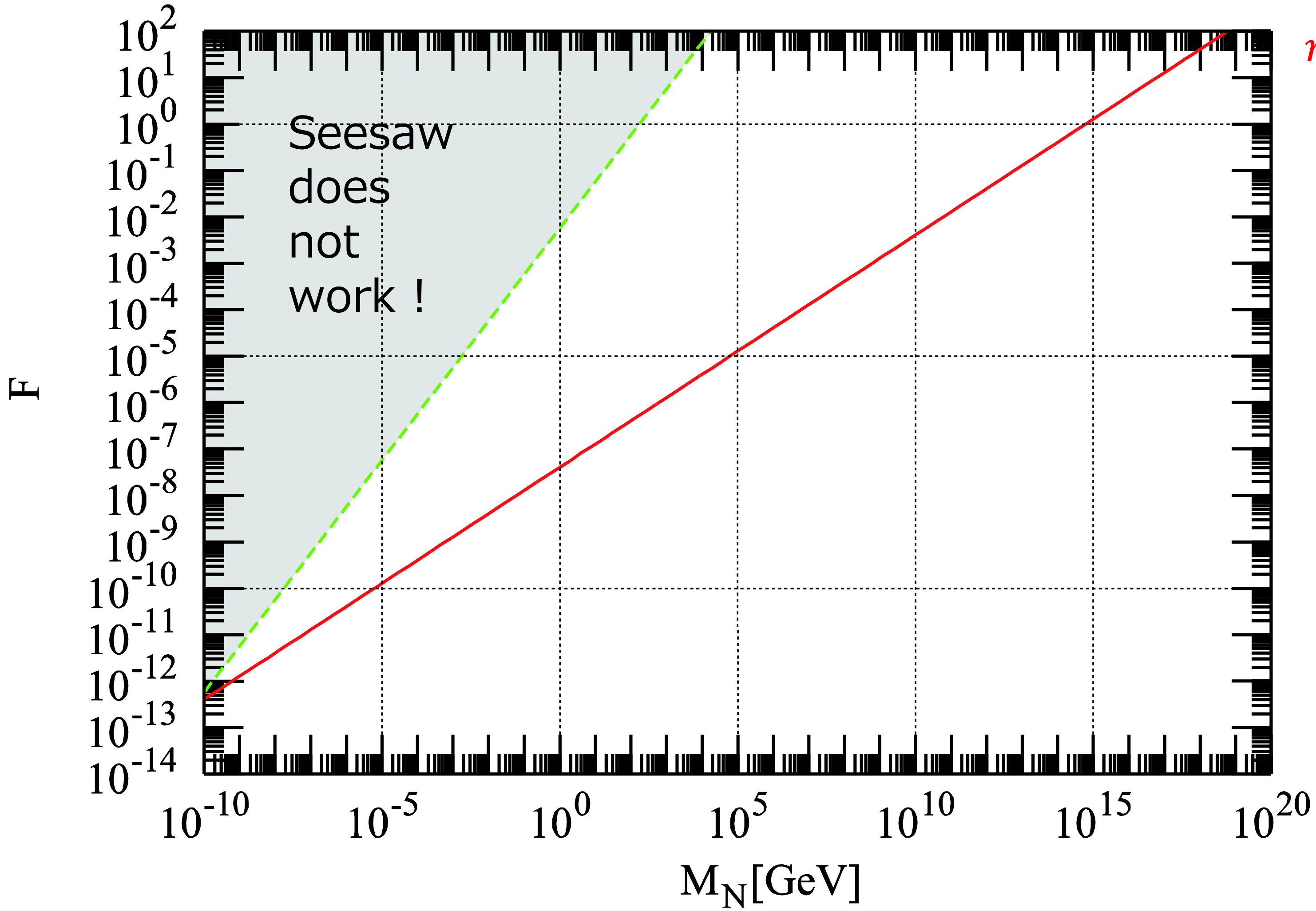
- **Heavy neutral leptons N ($\simeq \nu_R$)**
  - Mass M_M
  - Mixing $\Theta = M_D/M_M$

Neutrino mixing

$$\nu_L = U\,\nu + \Theta\,N^c$$

Yukawa coupling and Majorana mass

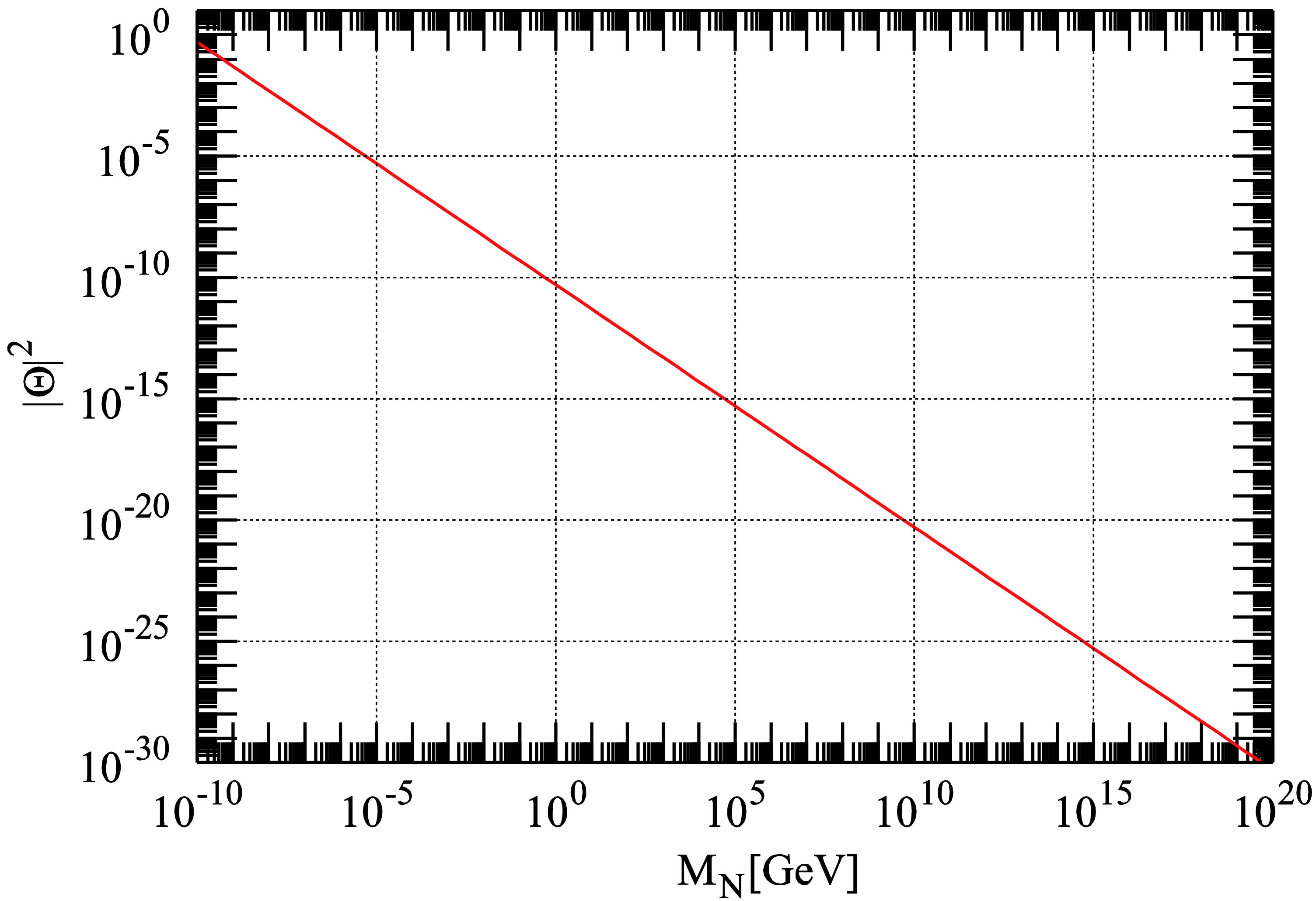
$$m_\nu = \frac{M_D}{M_M} \times M_D = \frac{F^2 \langle \Phi \rangle^2}{M_N} \quad \Rightarrow \quad F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$



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

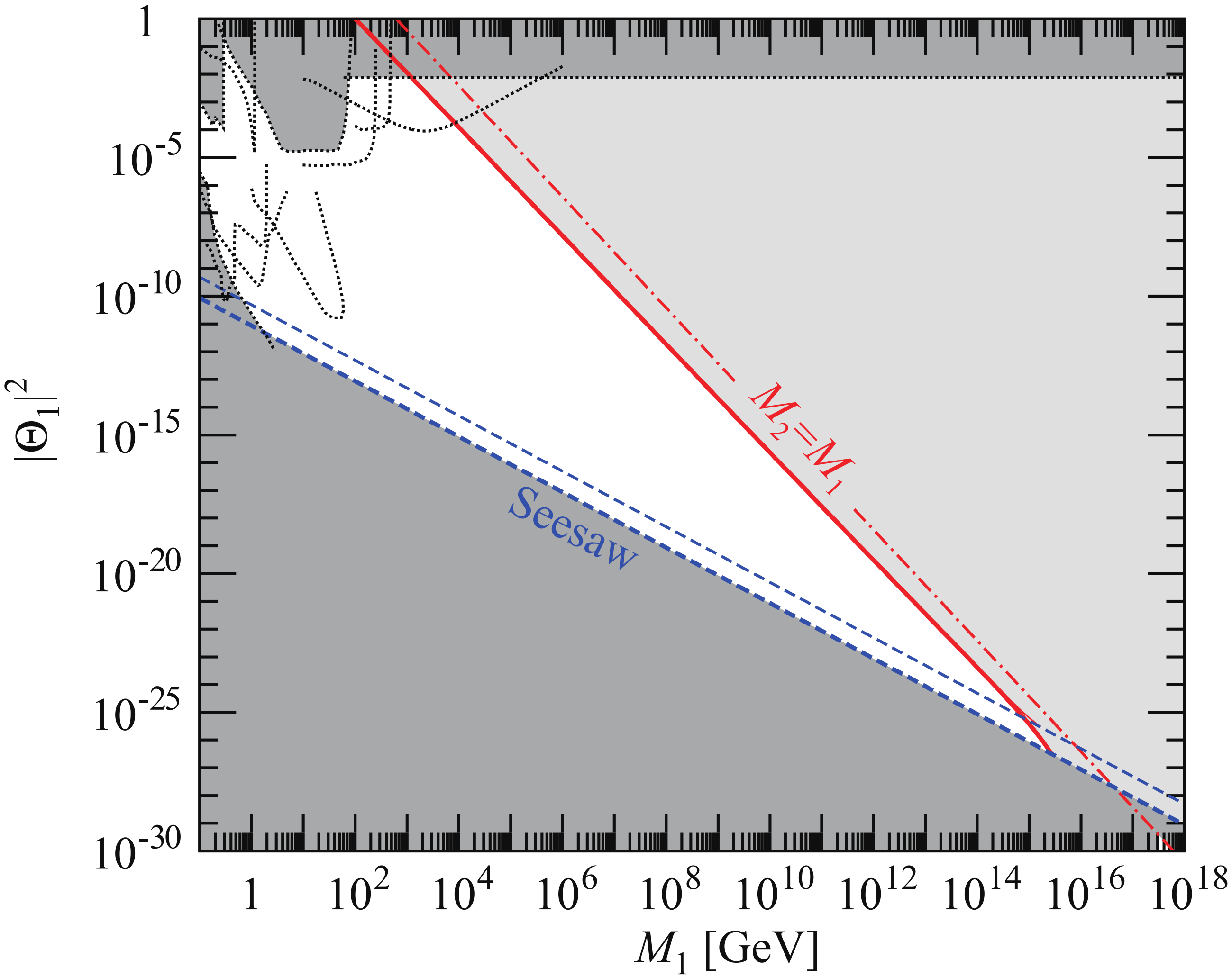
Mixing and mass of heavy neutral lepton

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



Range of parameter space

TA, Tsuyuki '15



Bound from seesaw mechanism

- Mixings of HNL must be sufficiently large to explain masses of active neutrinos !

- Bound on the mixing of the lightest HNL N_1

TA, Tsuyuki '15

$$\boxed{|\Theta_1|^2 \geq \frac{m_l}{M_1}}$$

$$|\Theta_1|^2 \equiv \sum_{\alpha=e,\mu,\tau} |\Theta_{\alpha 1}|^2$$

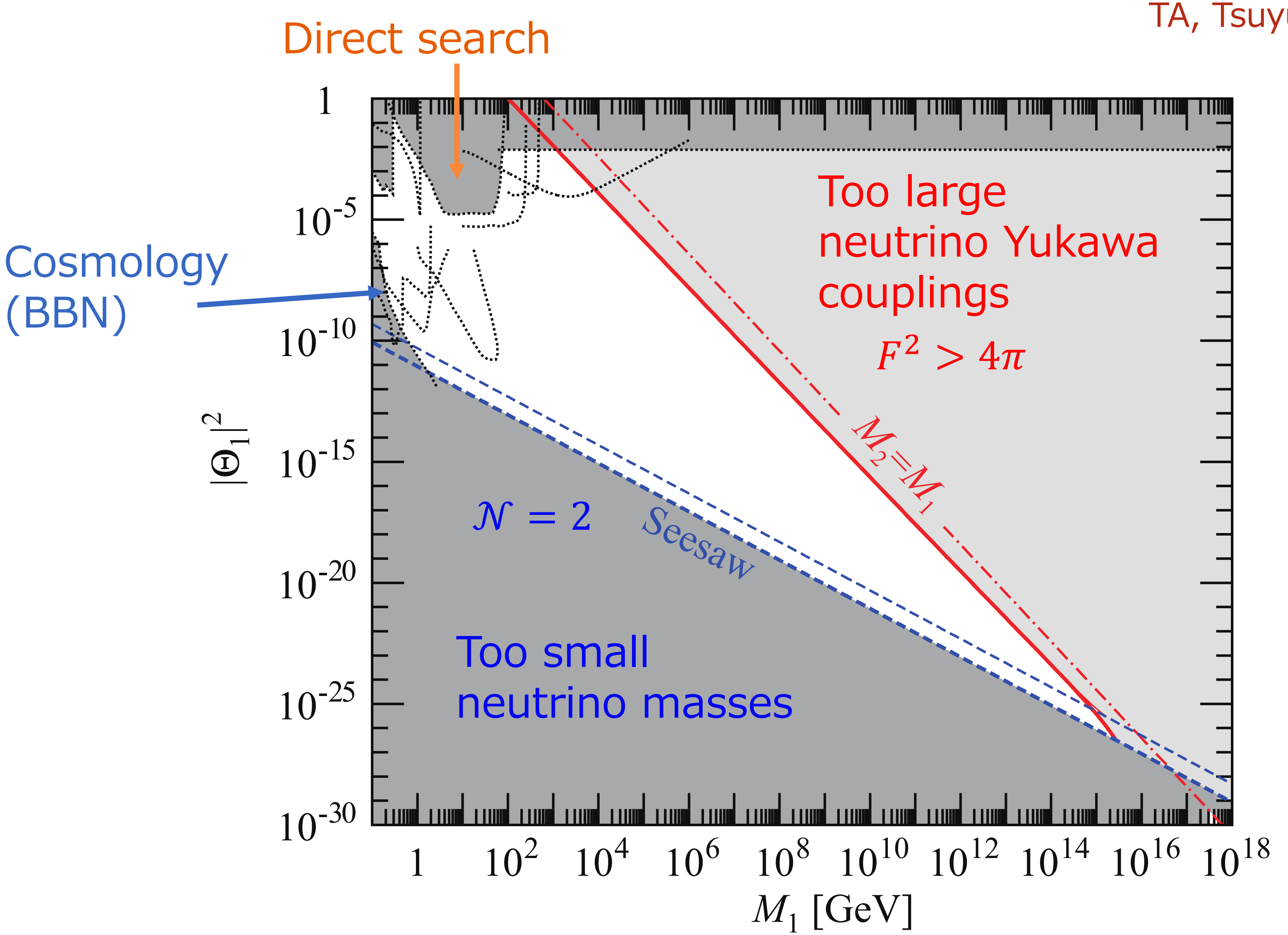
$$m_l = \begin{cases} m_1\ (m_3) \text{ in the NH (IH) for 3RHN } (\mathcal{N}=3) \\ m_2\ (m_1) \text{ in the NH (IH) for 2RHN } (\mathcal{N}=2) \end{cases}$$

NOTE: $|\Theta_1|^2$ can be zero for $\mathcal{N}=3$

(No lower bound for $\mathcal{N}>3$)

Range of parameter space

TA, Tsuyuki '15



RH neutrinos and baryogenesis

Extension by ν_R (seesaw)

L violation
by Majorana mases

CP violation
in neutrino sector

New particles
(HNL/RH neutrinos)

Sakharov's 3 conditions

C1
B, *L* violations

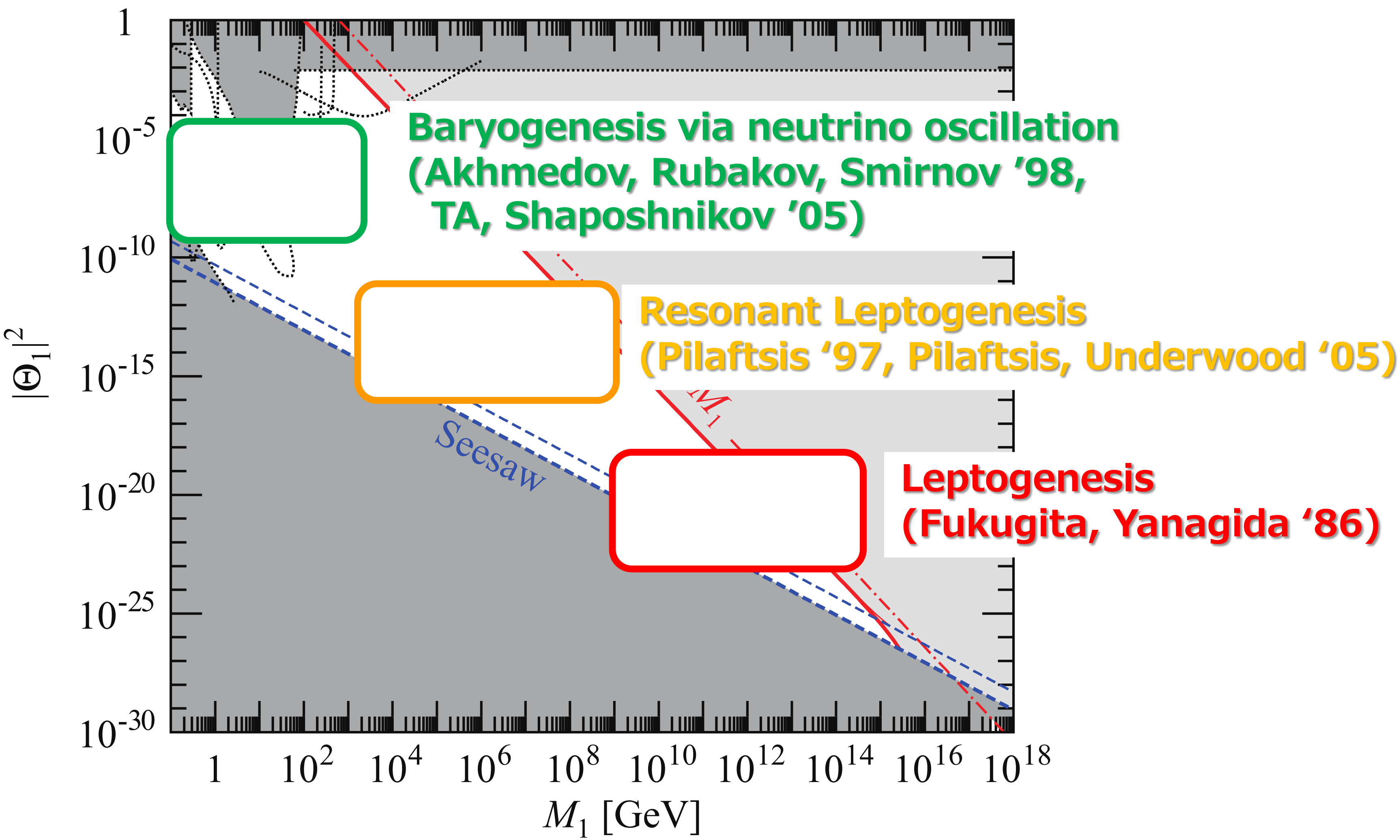
C2
CP violation

C3
Out of equilibrium

ν_R in the seesaw mechanism can satisfy all three conditions for baryogenesis

Baryogenesis regions

TA, Tsuyuki '15



Thermal Leptogenesis

[Fukugita, Yanagida ’86]

Leptogenesis

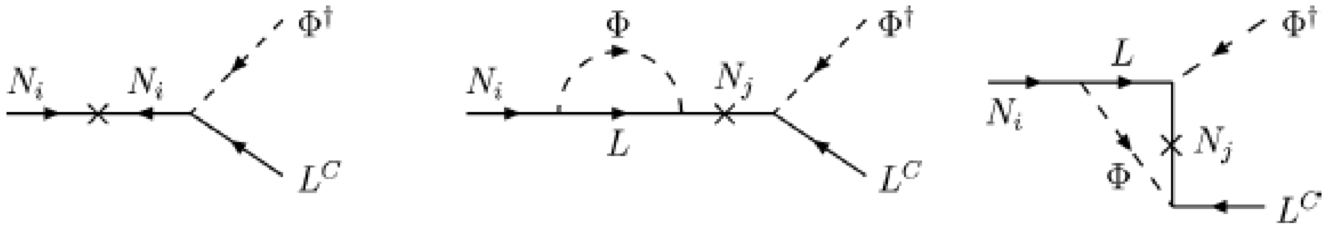
[Fukugita, Yanagida '86]

- ν_R (N) can into LH leptons and also their anti-particles

$$N_1 \to L_L + \overline{\Phi}$$
$$N_1 \to \overline{L_L} + \Phi$$

- When CP is violated in neutrino sector,

$$\varepsilon_1 = \frac{\Gamma(N_1 \to L_L + \overline{\Phi}) - \Gamma(N_1 \to \overline{L_L} + \Phi)}{\Gamma(N_1 \to L_L + \overline{\Phi}) + \Gamma(N_1 \to \overline{L_L} + \Phi)} \neq \mathbf{0}\,!$$



$\Longrightarrow$ generate asymmetry ΔL_L between $\#L_L$ and $\#\overline{L_L}$

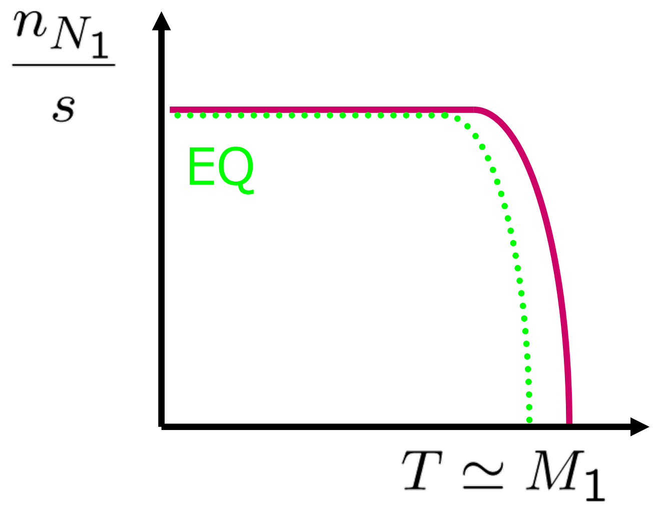
- Asymmetry in L_L is partially converted into baryon asymmetry by EW sphaleron process ($T \gtrsim 10^2$ GeV)

$$\boxed{B = \frac{28}{79}(B-L)_0 = -\frac{28}{79} L_0}$$

Out of Equilibrium Decay

- For $\boldsymbol{T} \gg \boldsymbol{M_1}$, $\boldsymbol{N_1}$ is in thermal equilibrium

$$N_1 \rightarrow L + \overline{\Phi}$$
$$N_1 \leftarrow L + \overline{\Phi}$$



- For $\boldsymbol{T} < \boldsymbol{M_1}$

$$n_{N_1}^{\mathrm{EQ}} \propto \exp(-M_1/T)$$

If $\Gamma_{N_1} < H(T \sim M_1)$

n_{N_1} cannot catch up with $n_{N_1}^{\mathrm{EQ}}$

→ Out of equilibrium decay of $\boldsymbol{N_1}$

Leptogenesis

[Fukugita, Yanagida '86]

- Yield of BAU

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

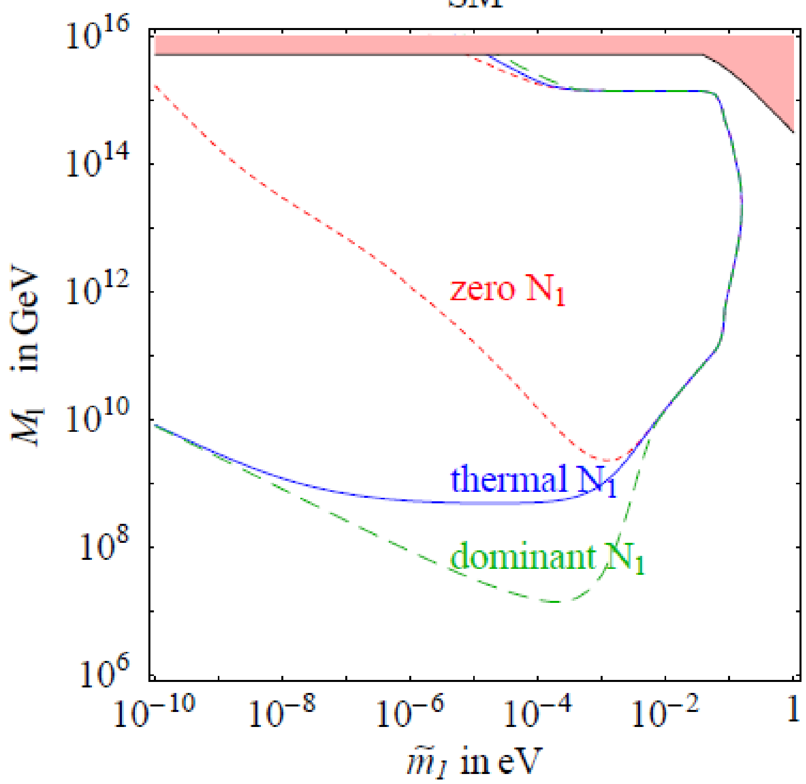
$$\frac{n_B}{s} \propto \varepsilon_1 \propto M_1 \longleftarrow M_1 \ll M_{2,3,\ldots}$$

Lower bound on Majorana mass in order to explain the observed BAU

$$M_1 > O(10^9)\ \text{GeV}$$

→ impossible to test directly such a heavy particle by experiments

[Giudice et al '03]



Resonant leptogenesis

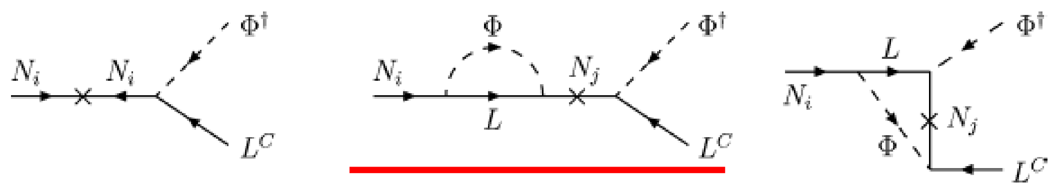
Pilaftsis '97
Pilaftsis, Underwood '04

- 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)

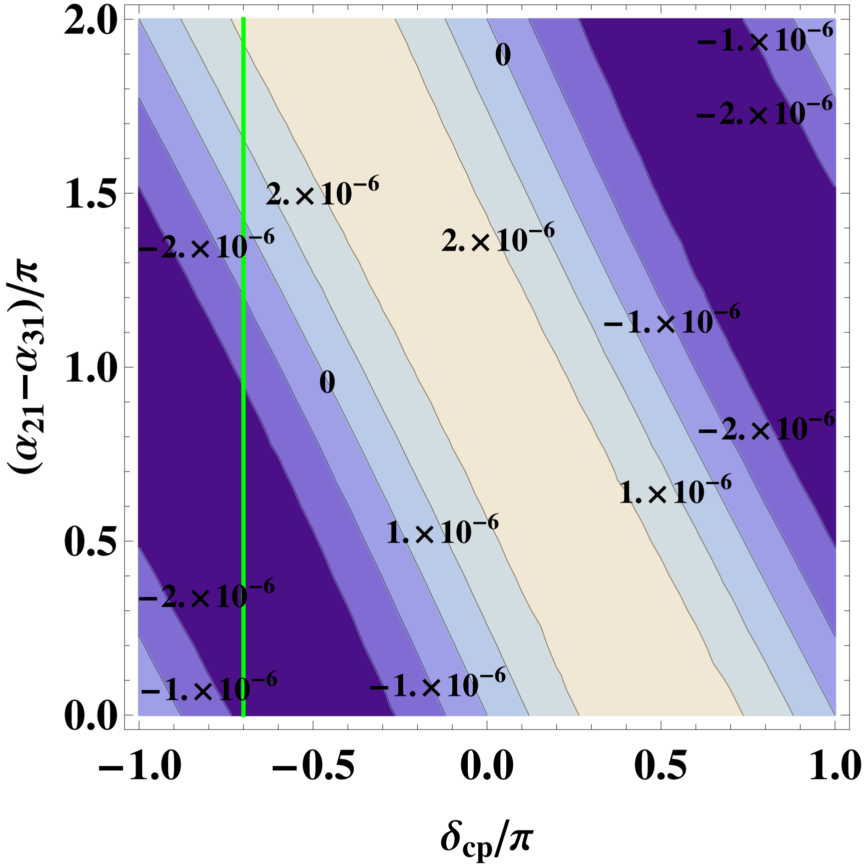
Resonant Leptogenesis

Degenerate RH neutrinos（$M_{1,2} = 10^3$GeV)

Maximum values of YB

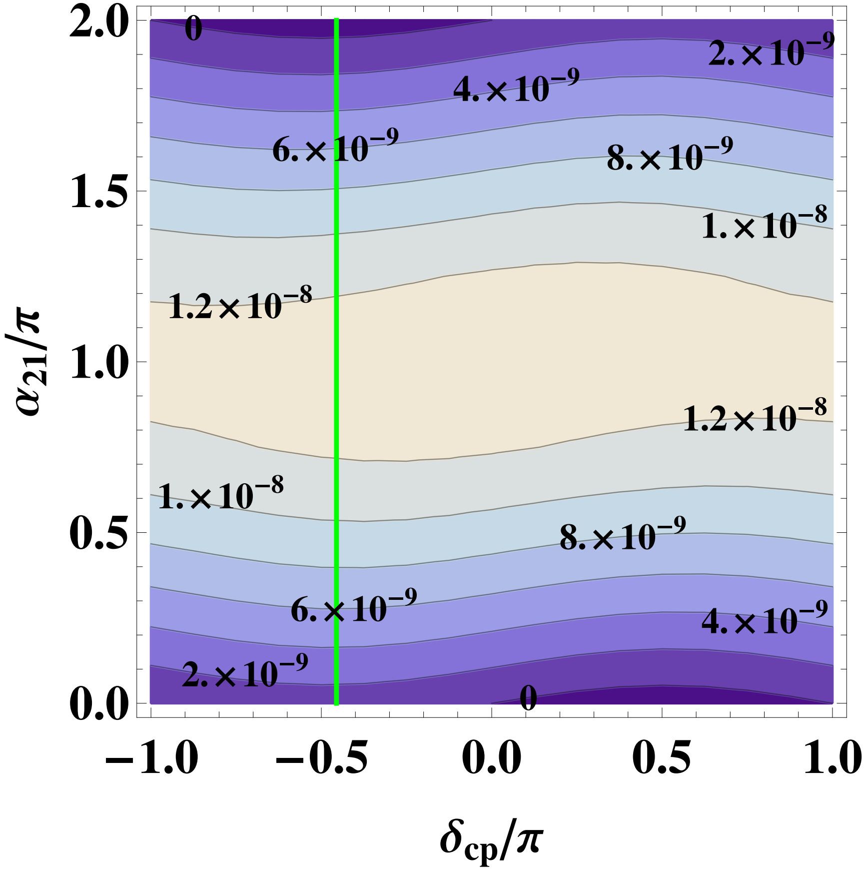
NH Contour of Y_B

Majorana Phase



Dirac Phase

IH Contour of Y_B



TA, Yoshida [arXiv:1812.11323]

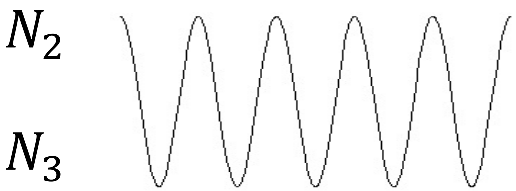
Baryogenesis via neutrino oscillation

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

Baryogenesis via Neutrino Oscillation

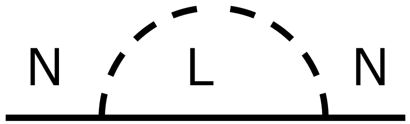
Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)
Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)
...

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

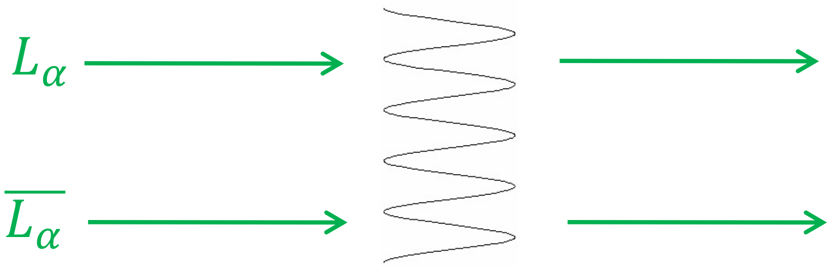


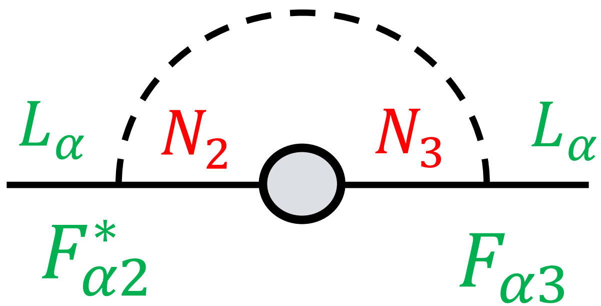
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



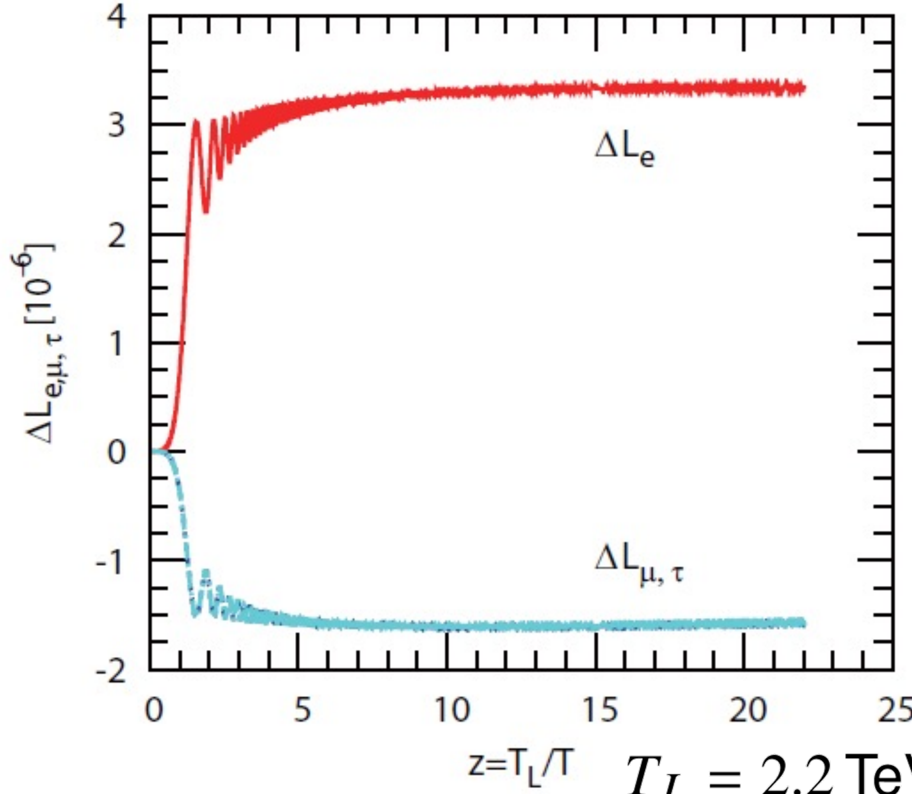
- Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV





Evolution of each asymmetries

LH leptons



$T_L = 2.2$ TeV

Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

RH neutrinos

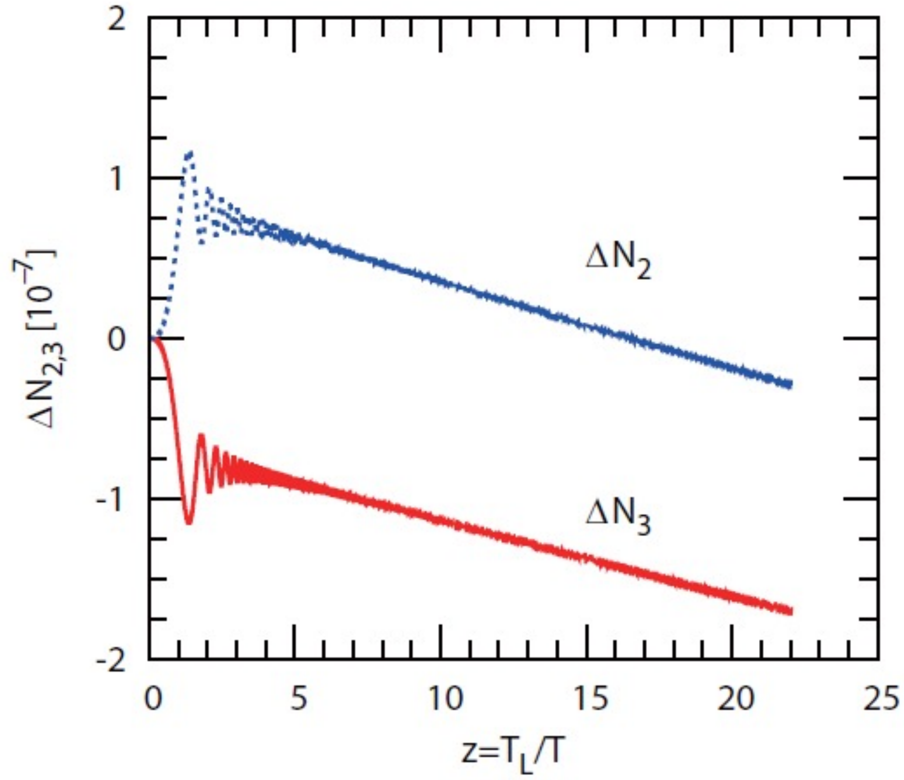
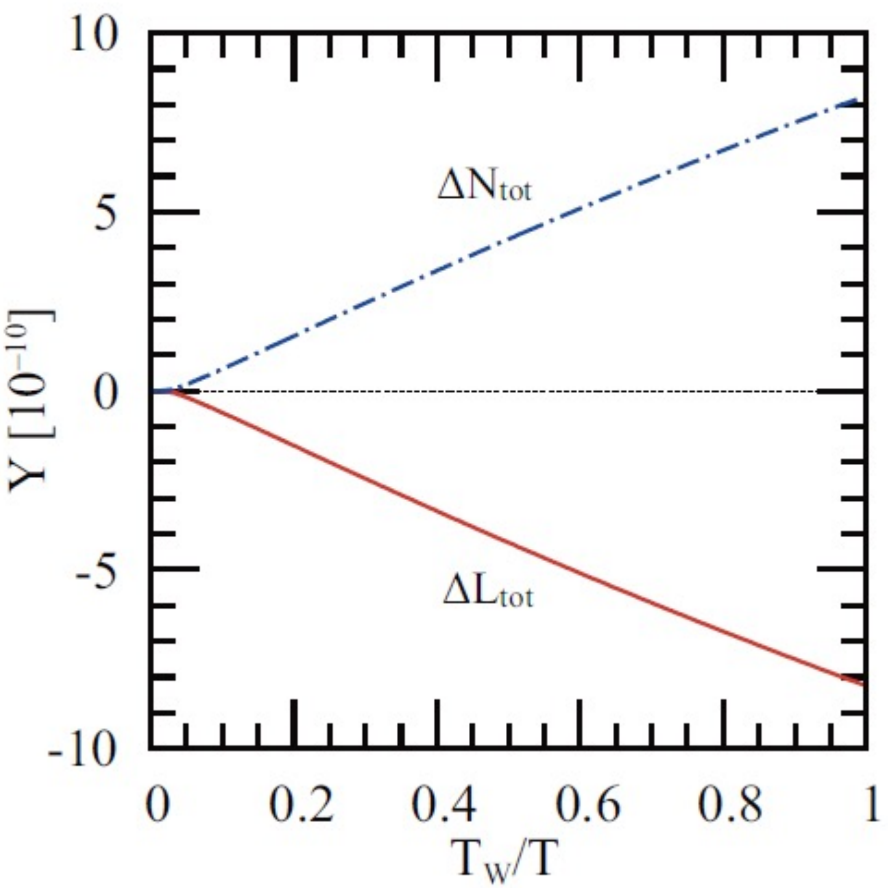


Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Baryogenesis via neutrino osc.

Oscillation of heavy neutrinos can be a source of BAU

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



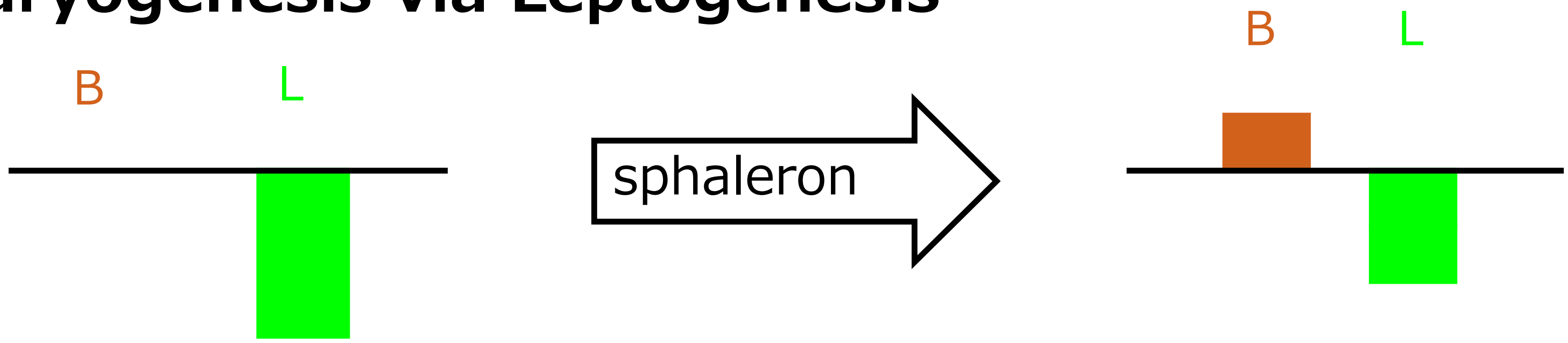
Yield of BAU depends on Yukawa couplings $F_{\alpha I}$ and masses

Especially, CP violating parameters and mass difference

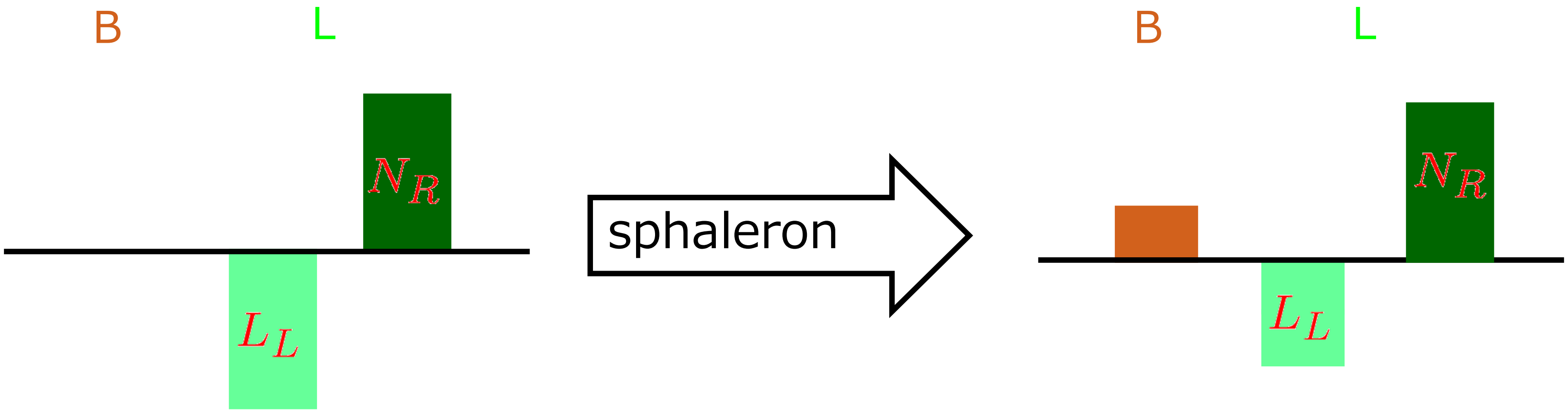
$$T_{osc} \sim (M_0 \; M_N \; \Delta M)^{1/3}$$

Key Point

Baryogenesis via Leptogenesis



Baryogenesis via Neutrino Oscillation



Analytical Formula of BAU

TA, Shaposhnikov '05
TA, Ishida '10

$$\frac{n_B}{s} = 1.8\times 10^{-11}\kappa \frac{M_0^{7/3} M_N^{5/3} m_{\rm atm}^{5/2} m_{\rm sol}^{1/2}}{T_W (\Delta M_{32}^2 / M_N^2)^{2/3} \langle \Phi \rangle^6} \times \delta_{CP}$$

$$= 4.7\times 10^{-10} \left(\frac{M_N}{5\mathrm{GeV}} \right)^{5/3} \left(\frac{10^{-8}}{\Delta M_{32}^2 / M_N^2} \right)^{2/3} \times \delta_{CP}$$

- RH neutrinos N2 and N3 must be quasi-degenerate to get a sizable BAU !

- CP asymmetry parameter for BAU

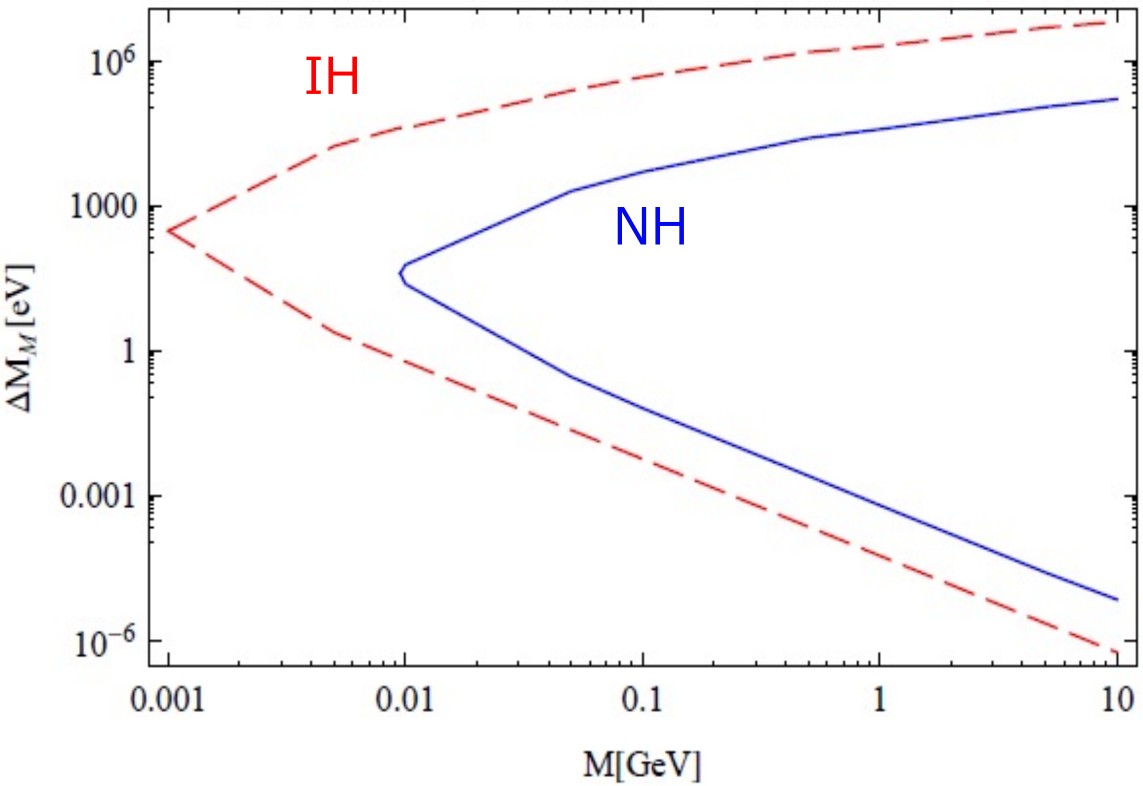
$$\delta_{CP} \propto \sum_{I=2,3} \sum_{\alpha=e,\mu,\tau} \left| F_{I\alpha} \right|^2 \mathrm{Im}\left[F_{\alpha 3} (F^\dagger F)_{32} F_{\alpha 2}^* \right]$$

CPV in neutrino Yukawa couplings

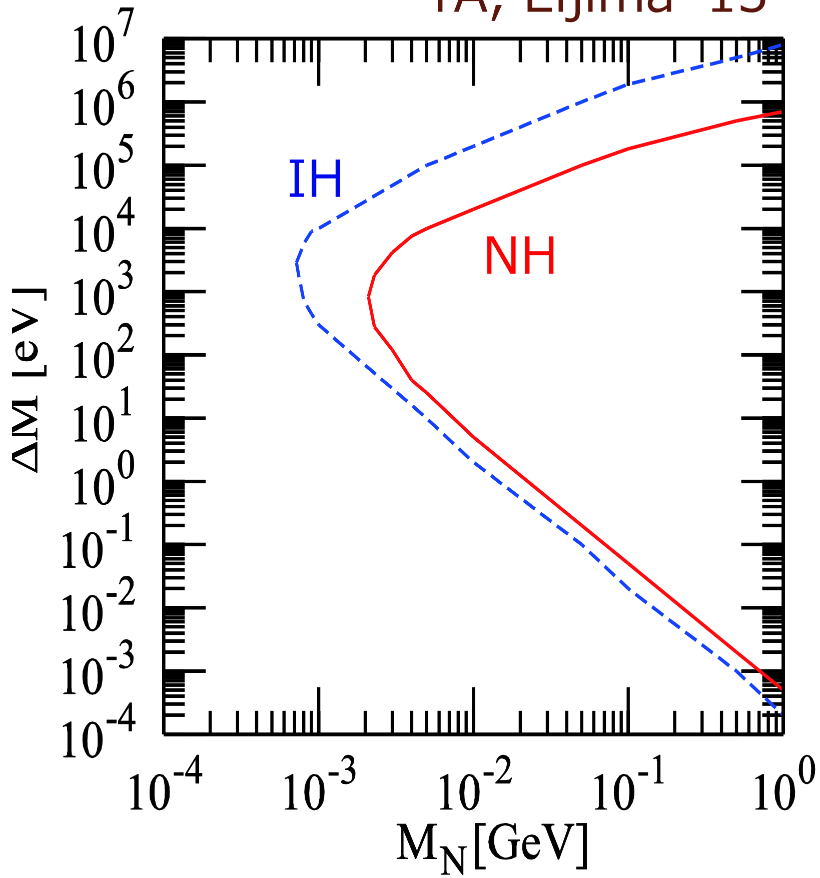
Baryogenesis Region

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

Canetti, Shaposhnikov '10



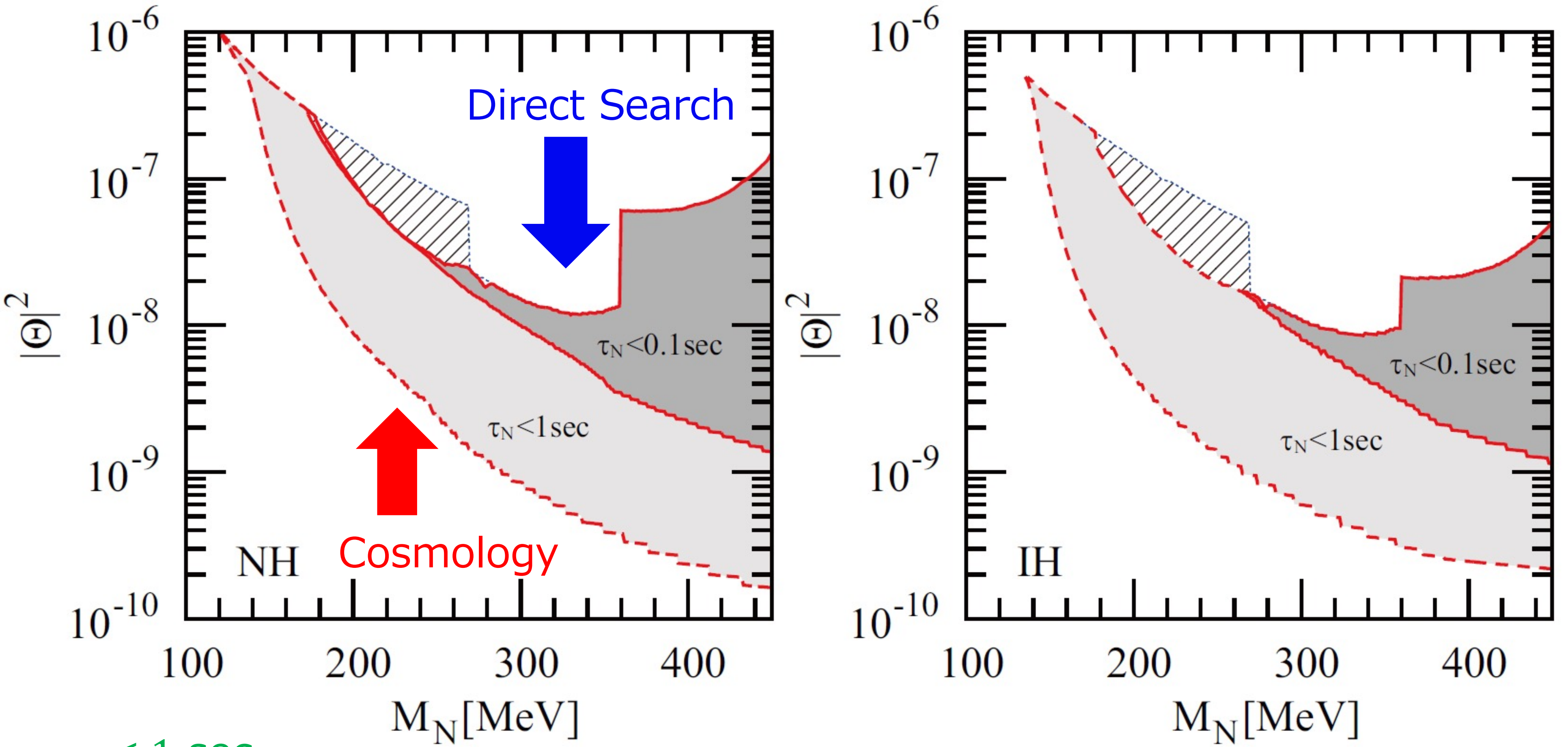
TA, Eijima '13



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

Constraints on HNL

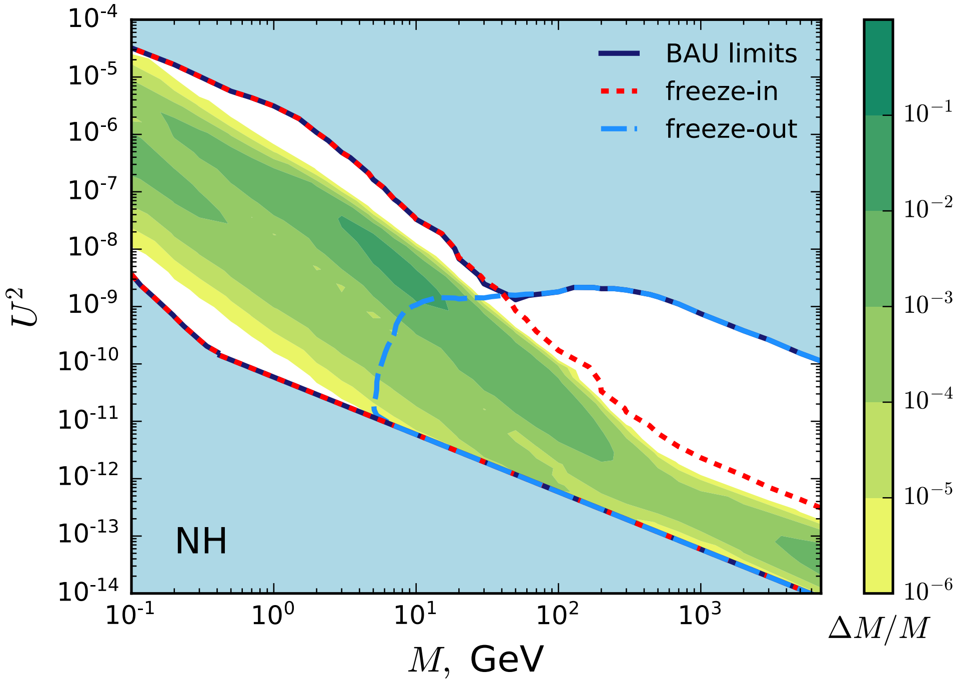
TA, Eijima, Takeda '14

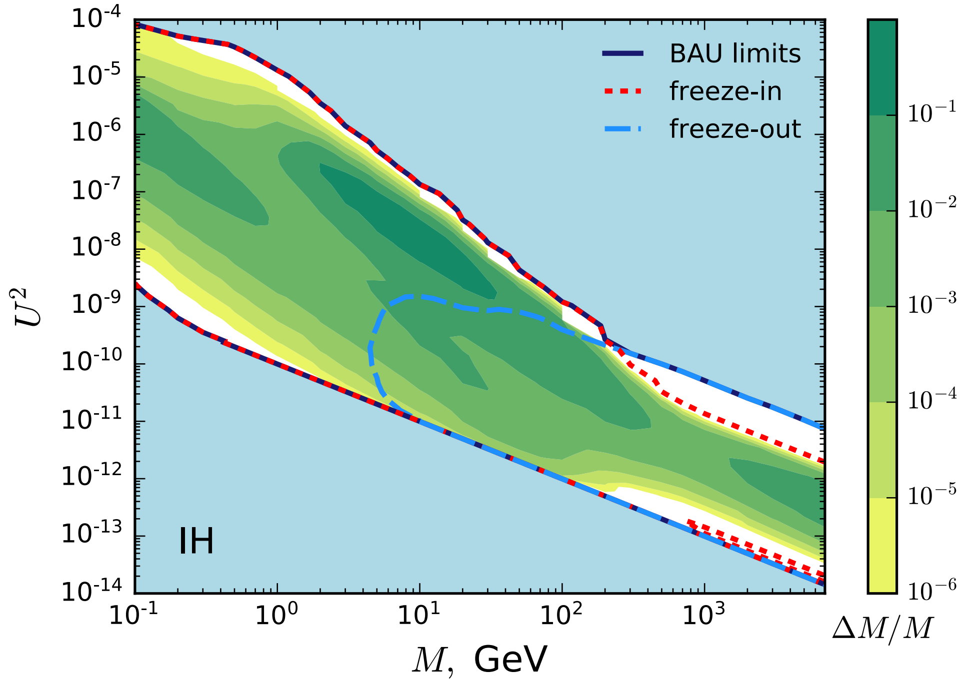


$\tau_N < 1$ sec

$M_N > 122$ MeV (NH) $M_N > 136$ MeV (IH)

Baryogenesis region

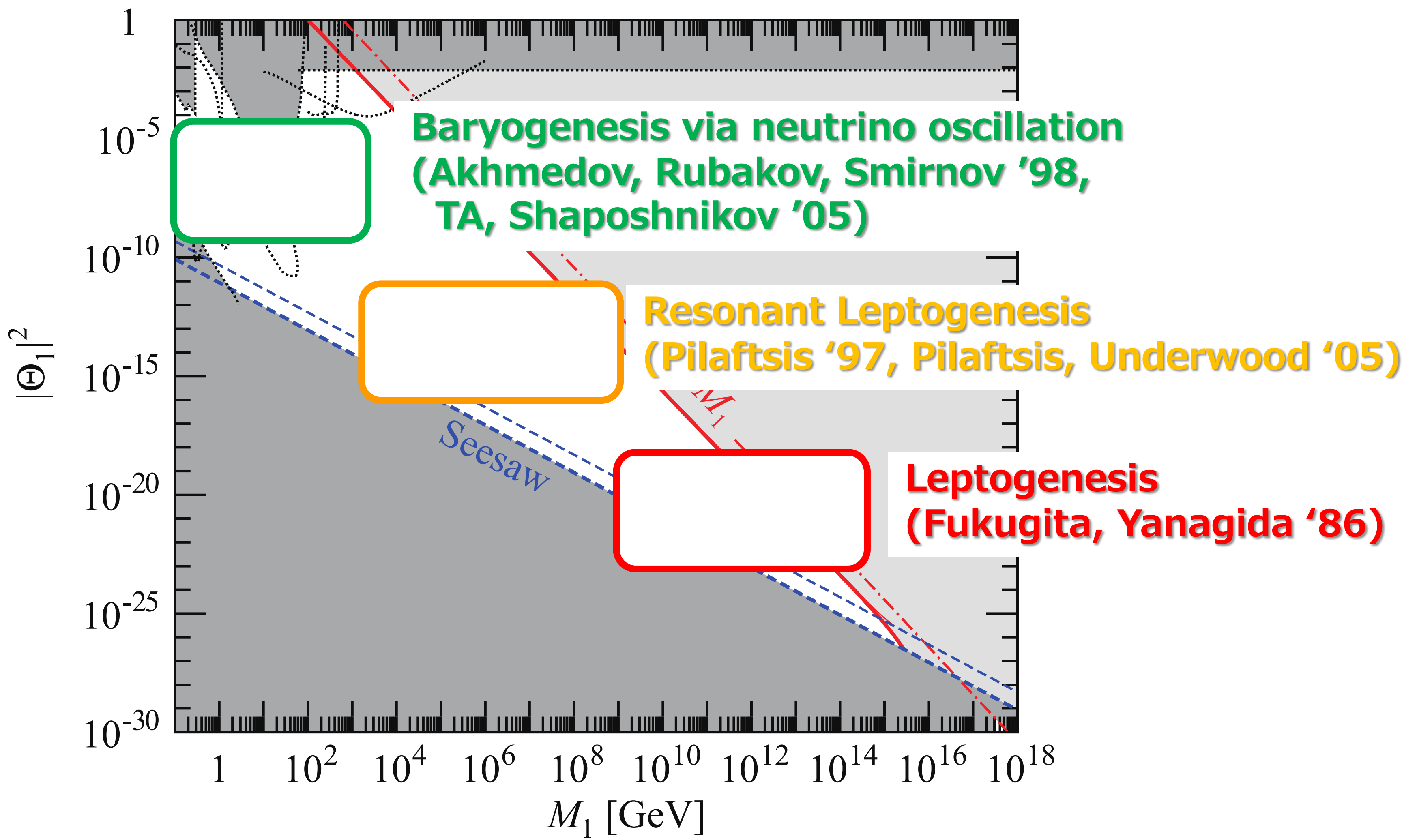




Klaric, Shaposhnikov, Timiryasov '21 [2103.16545]

Leptogenesis scenarios

TA, Tsuyuki '15



Experimental tests for leptogenesis scenarios

RH neutrinos and baryogenesis

Extension by ν_R (seesaw)

L violation
by Majorana mases

- Neutrinoless double beta decay
- Inverse neutrinoless double beta decay
- LNV meson decay
- …

CP violation
in neutrino sector

- CPV neutrino oscillation
- EDM
- …

New particles
(HNL/RH neutrinos)

- Peak searches
- Beam dump experiments
- …

Experimental tests are crucial !!

Lepton number violation in the seesaw mechanism

1) Neutrinoless double beta decay
2) Inverse neutrinoless double beta decay
3) LNV meson decay

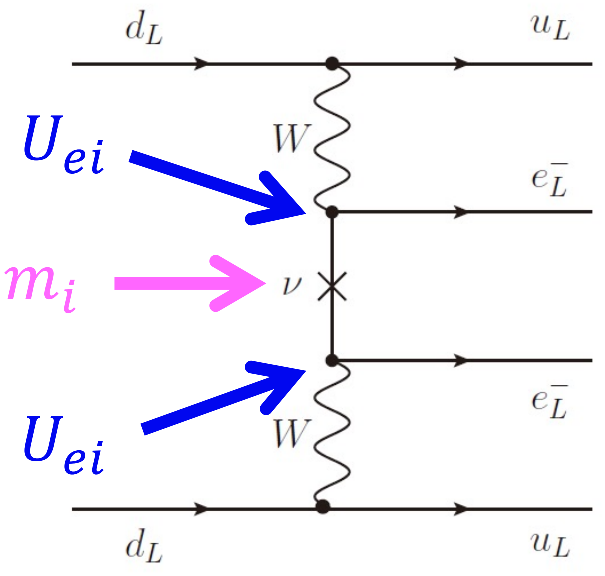
Neutrinoless double beta ($0\nu\beta\beta$) decay

W.H. Furry 1939

- Neutrinoless double beta ($0\nu\beta\beta$) decay

$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

- LNV ($\Delta L = +2$) process mediated by Majorana massive neutrinos

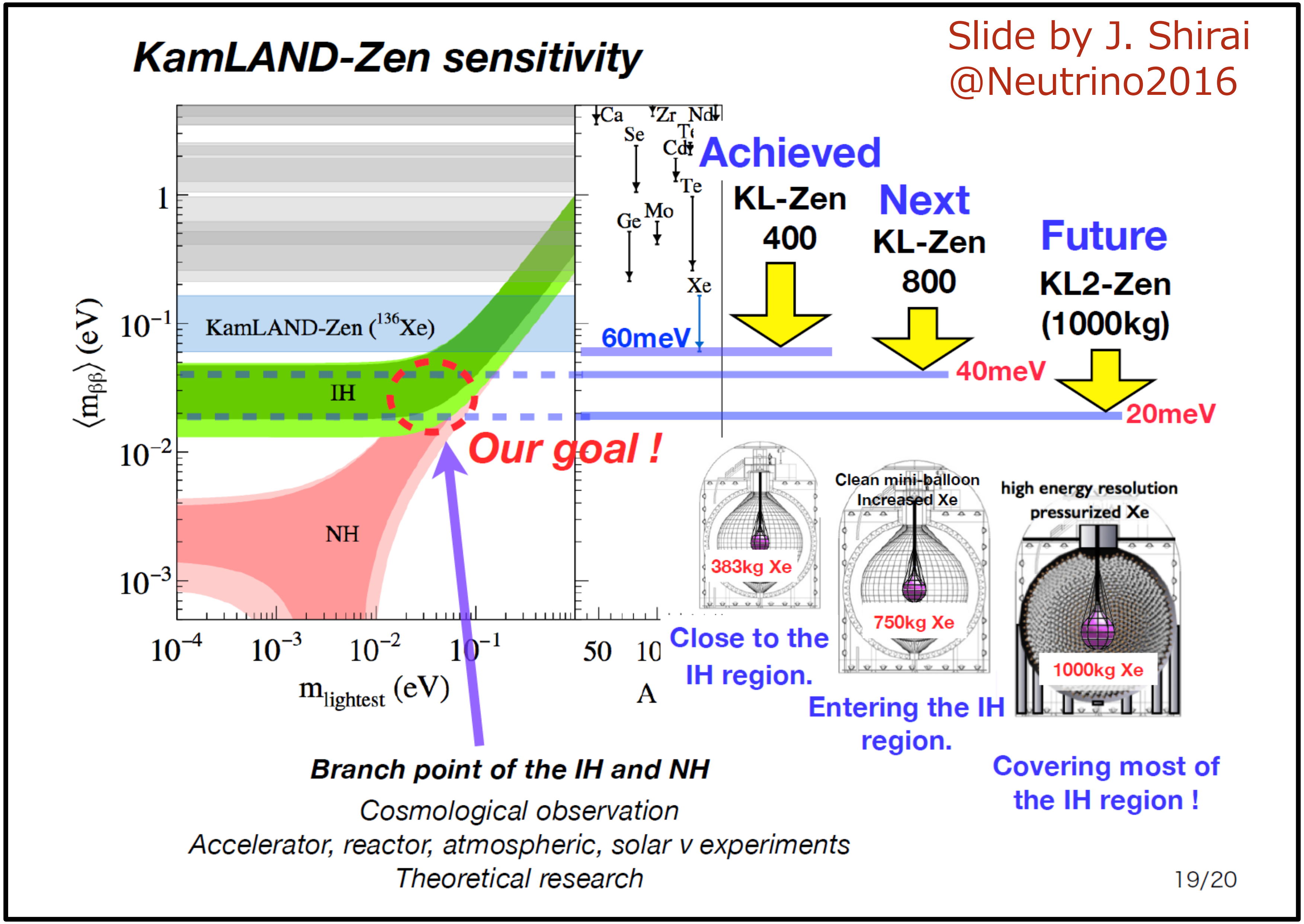


- Half-life of $0\nu\beta\beta$ decay

$$T_{1/2}^{-1} = A \frac{m_p^2}{\langle p^2 \rangle^2} \left| m_{\text{eff}} \right|^2$$

$$\boxed{m_{\text{eff}} = \sum_{i=1,2,3} m_i U_{ei}^2}$$

Future prospects



Effective mass in low-scale seesaw

- Effective mass

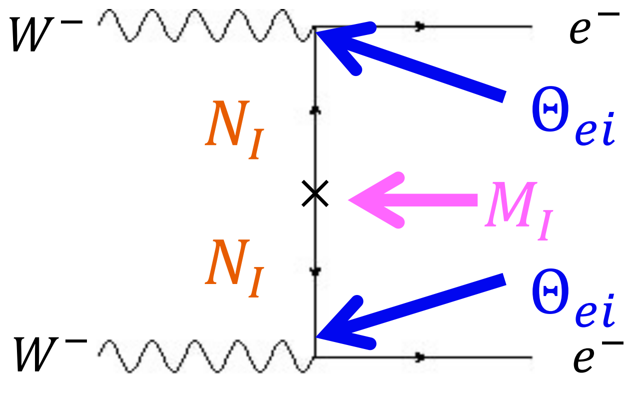
$$m_{\text{eff}} = \underbrace{\sum_{i=1,2,3} m_i \, U_{ei}^2}_{\text{active neutrinos } \nu_{\text{i}}} + \underbrace{\sum_I f_\beta(M_I)\, M_I \; \Theta_{eI}^2}_{\text{HNLs } N_{\text{I}}}$$

m_{eff}^{ν} $\qquad$ m_{eff}^{N}

$$\begin{cases} f_\beta(M_I) = \dfrac{\Lambda_\beta^2}{\Lambda_\beta^2 + M_I^2} \\ \Lambda_\beta \sim 200 \text{ MeV} \end{cases}$$

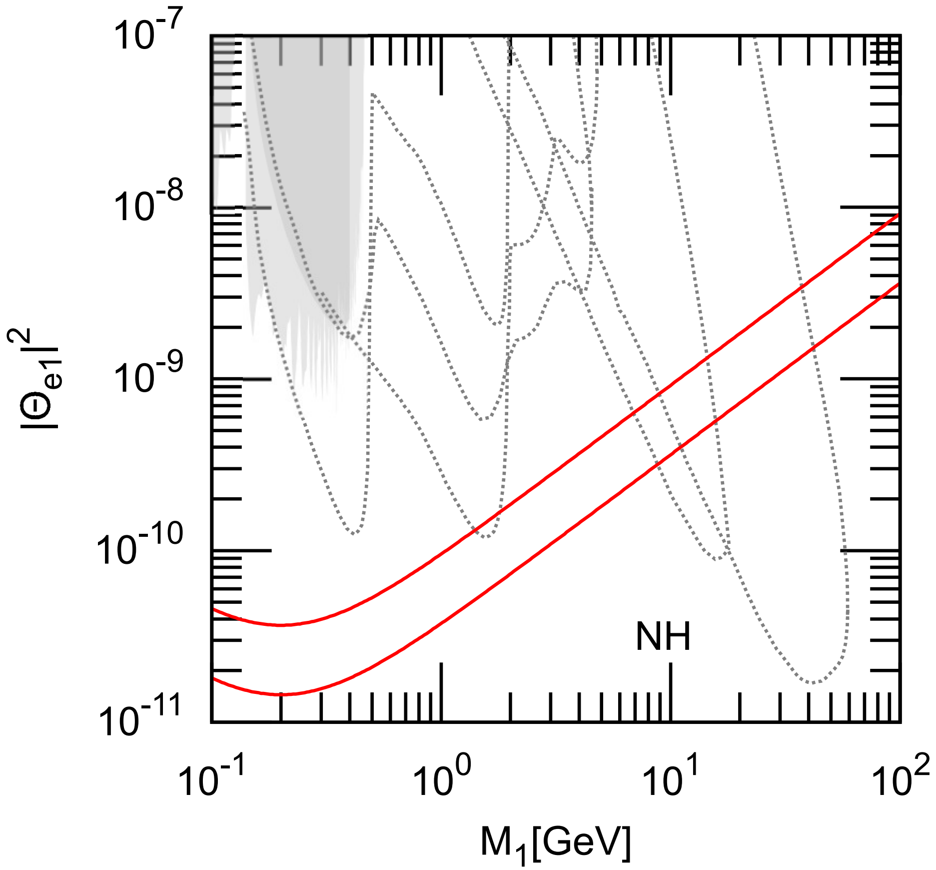
- N_{I} may give a significant contribution to m_{eff} !

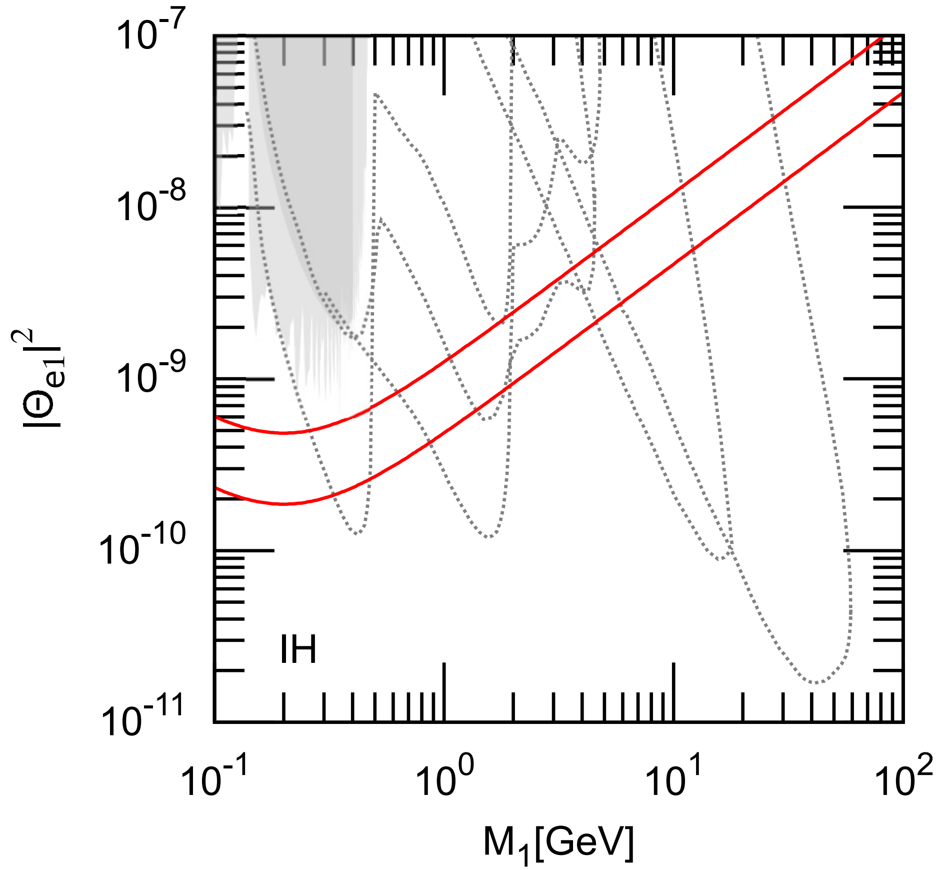
$$m_{\text{eff}}^{N} = \begin{cases} M_I \, \Theta_{eI}^2 & (M_I \ll \Lambda_\beta) \\ \dfrac{{\Lambda_\beta}^2}{M_I^2} M_I \Theta_{eI}^2 & (M_I \gg \Lambda_\beta) \end{cases}$$



HNL may hide NDBD ($m_{\rm eff} = 0$)

- Range of mixing element $|\Theta_{e1}|^2$ is predicted



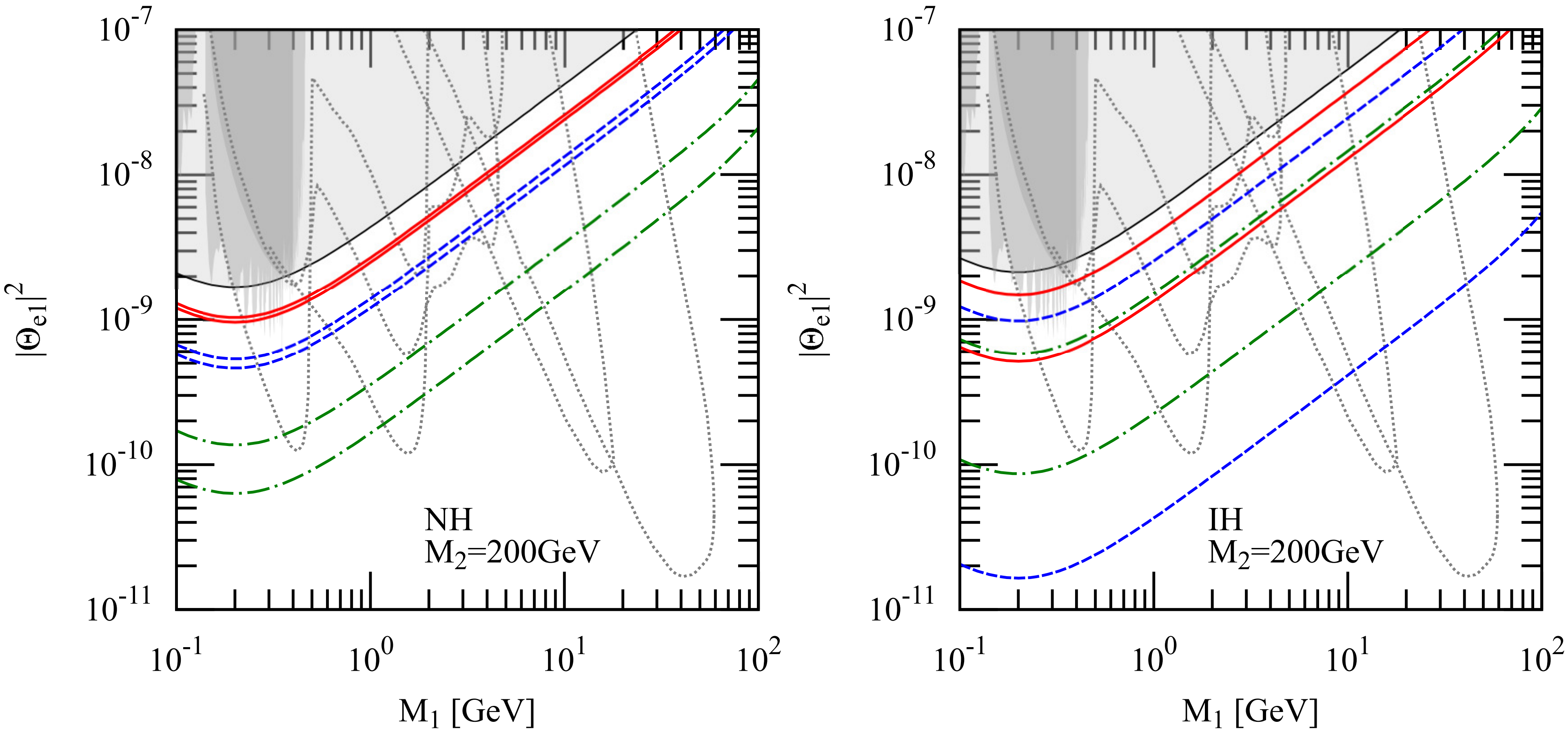


TA, Ishida, Tanaka arXiv:2012.13186

HNL may enhance NDBD ($m_{\rm eff} > m^{\nu}_{\rm eff}$)

- Range of mixing element $|\Theta_{e1}|^2$ is predicted

$m^{\rm obs}_{\rm eff}$=100meV (red), 50meV (blue), 10meV (green)



TA, Ishida, Tanaka arXiv:2101.12498

NDBD in different nuclei

- Effective mass
  - Active neutrino contribution

$$m_{\mathrm{eff}}^{\nu} = \sum_i m_i U_{ei}^2$$

independent on decay nuclei

  - HNL contribution

$$m_{\mathrm{eff}}^{N} = \sum_I f_\beta(M_I)\, M_I\ \Theta_{eI}^2$$

$$f_\beta(M_I) = \frac{\Lambda_\beta^2}{\Lambda_\beta^2 + M_I^2}$$

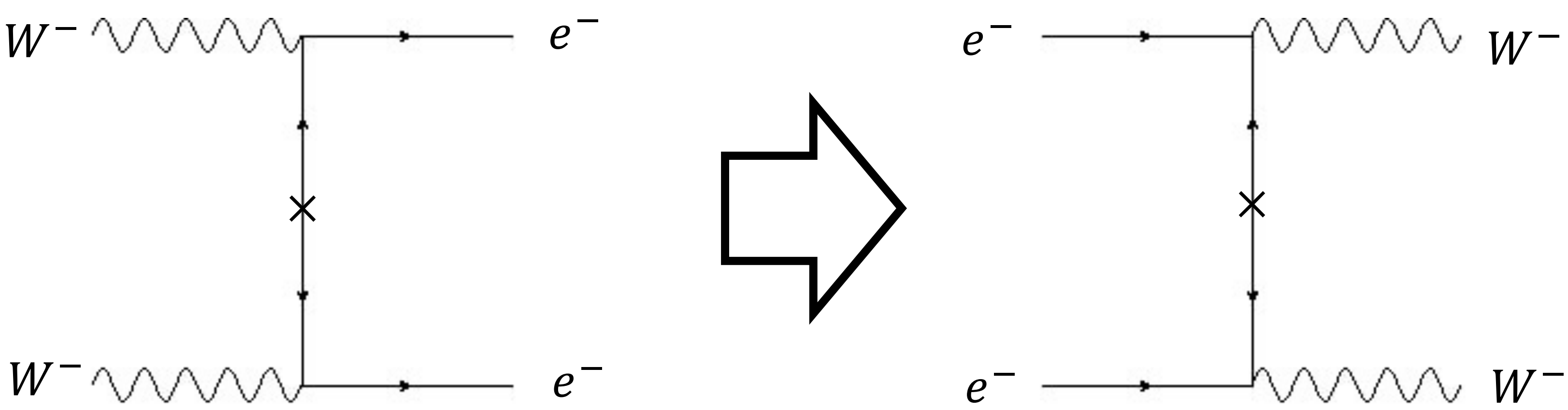
dependent on decay nuclei !

Multiple detection/non-detection by NDBD using different nuclei

is crucial to reveal the properties of HNLs in the seesaw mechanism

Another example of LNV:

$$e^- e^- \rightarrow W^- W^-$$



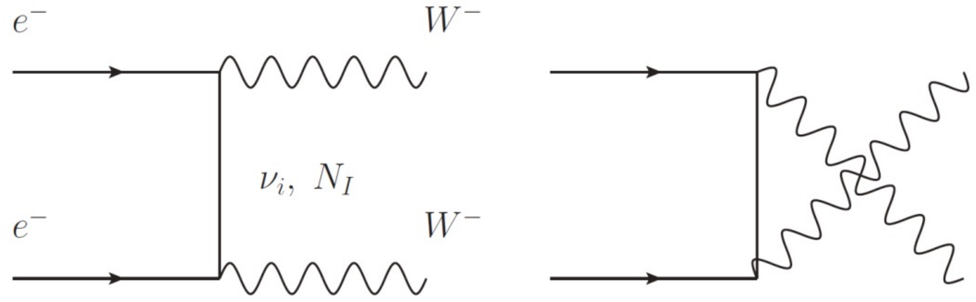
$0\nu\beta\beta$ decay

Inverse $0\nu\beta\beta$ decay

Inverse neutrinoless double beta (i$0\nu\beta\beta$) decay

- $e^-e^- \to W^-W^-$ offers test for LNV

[T. G. Rizzo 1982]



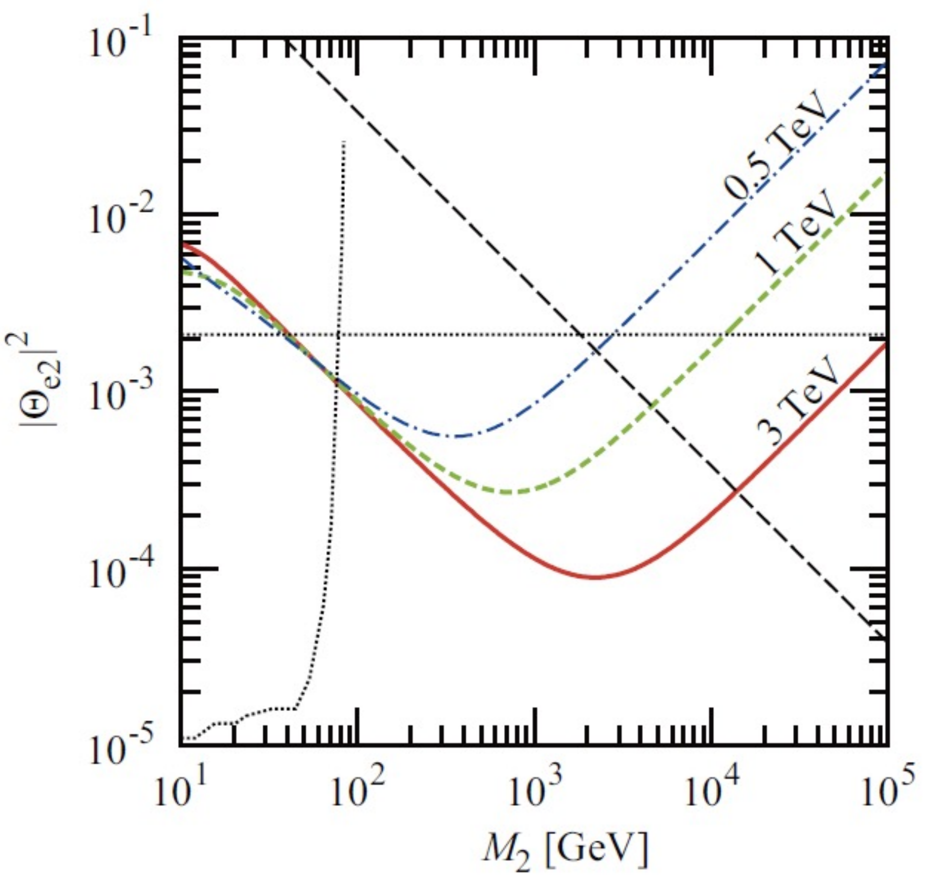
- e^-e^- collision is option of ILC, CLIC
- Advantages over $0\nu\beta\beta$ decay
  - Signal is clean
  - Free from uncertainty in nuclear matrix elements
  - Can occur even if $0\nu\beta\beta$ decay is absent

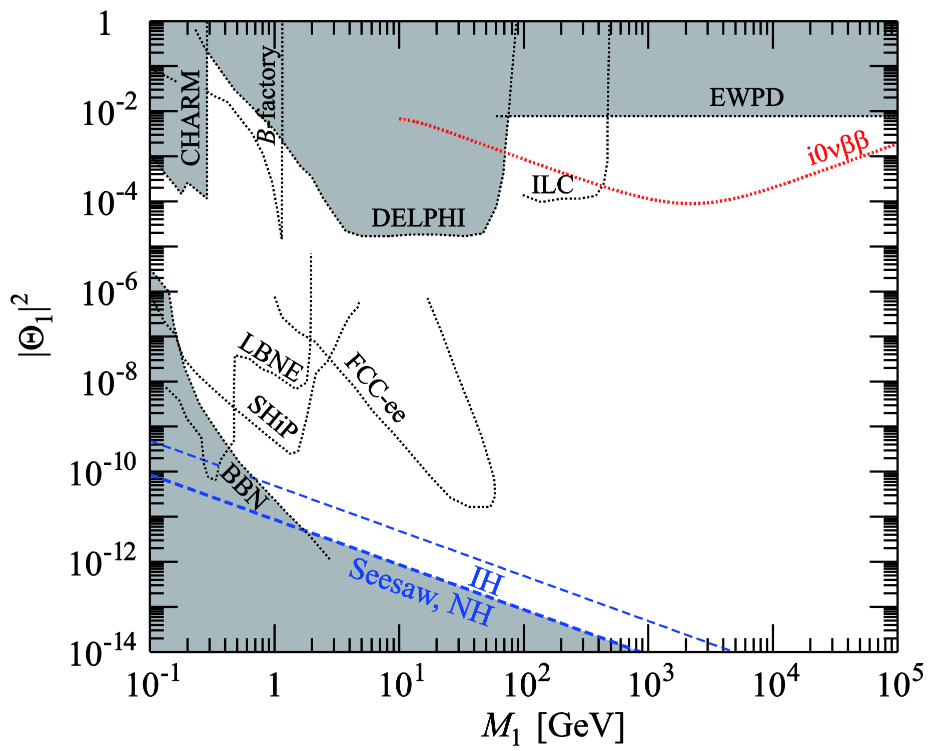
→ Inverse $0\nu\beta\beta$ decay and $0\nu\beta\beta$ decay are complementary tests for LNV in the seesaw mechanism

Inverse $0\nu\beta\beta$ decay in the seesaw

- Sensitivity of mixing ($@100\ \mathrm{fb}^{-1}$)

TA, Tsuyuki '15





Lepton number violation in meson decays

Lepton number violation by heavy Majorana neutrino in B decays

Takehiko Asaka (Niigata Univ.)

In collaboration with
Hiroyuki Ishida (NCTS, Taiwan)

Ref: arXiv:1609.06113
to appear in Physics Letters B

Flavor Physics Workshop 2016
@Iwamuro, Niigata (26-28 October, 2016)

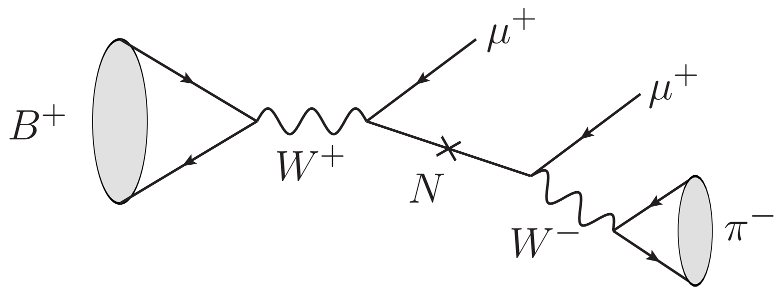
Contents

GeV scale right-handed (RH) neutrinos ν_R

- **Why are such particles interesting?**
  - Seesaw mechanism for neutrino masses
  - Oscillation mechanism for baryon asymmetry of the universe
  - Direct tests by (near) future experiments

- **How do we test such particles?**
  - Lepton number violating decays of B mesons, induced by Majorana properties of such particles

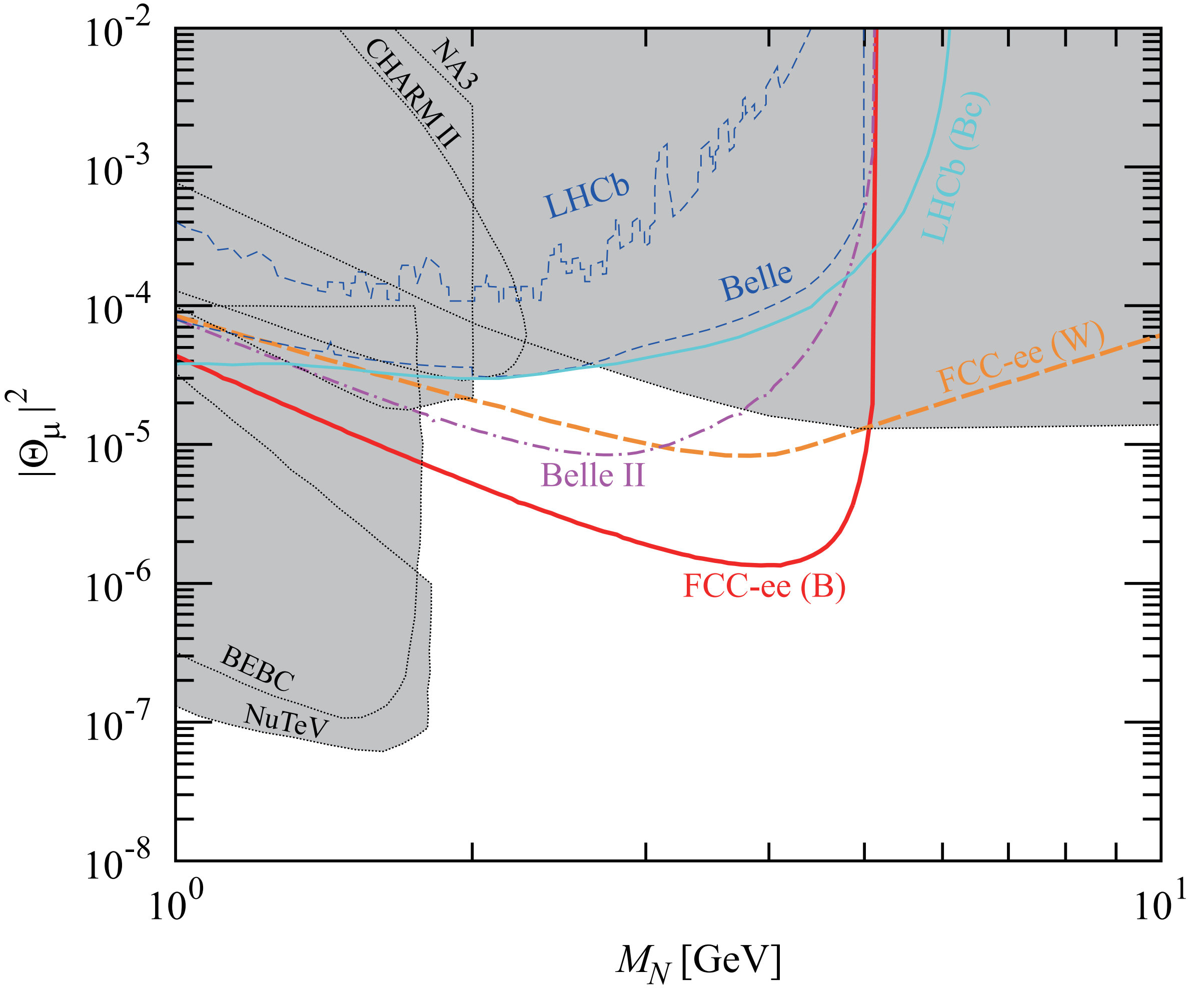
Search for $B^+ \to \mu^+\mu^+\pi^-$ at Belle II and $\cdots$



Sensitivity limits on $|\Theta_\mu|^2$

- FCC-ee ($\sqrt{s} = m_Z$)

TA, Ishida [arXiv:1609.06113]



Sensitivity by using
$B^+ \to \mu^+\mu^+\pi^-$

Belle II with $N_B = 5\times10^{10}$

FCC-ee (B) with $N_Z = 10^{13}$
($Z \to b\,\bar{b} \Rightarrow N_B \simeq 6\times10^{11}$)

Cf. Sensitivity by using
$W^+ \to \mu^+\mu^+\pi^-$
FCC-ee (W)
with $N_W = 2\times10^8$

CPV and Leptogenesis

Decay rate asymmetry

- Leptogenesis

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

$$= \frac{1}{8\pi} \sum_{J \neq 1} \frac{\mathrm{Im}\left(F^\dagger F\right)_{1J}^2}{(F^\dagger F)_{11}} \left[f\left(\frac{M_J^2}{M_1^2}\right) + g\left(\frac{M_J^2}{M_1^2}\right) \right]$$

$$f(x) = x^{\frac{1}{2}} \left[1 + (1+x) \log\left(\frac{x}{x+1}\right) \right] \qquad g(x) = \frac{x^{\frac{1}{2}}}{1-x}$$

ε_1 is determined by Yukawa couplings
and Majorana masses of RH neutrinos

CPV in neutrino Yukawa couplings is important !!

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

Majorana phase(s)

In mixing matrix Ω
of RH neutrinos

Phase(s) for ν_R

These phases are essential for BAU !

CPV in active neutrino sector

- PMNS mixing matrix of active neutrinos

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

  - Dirac phase δ
  - Majorana phases α_{21} and α_{31}

- CPV in PMNS matrix can be source of BAU
  - Decay rate asymmetry ε_1 does NOT depend on U
  - But, the flavor effects (for $M_1 \lesssim O(10^{13})$GeV) give the connection between CPV in PMNS matrix and BAU

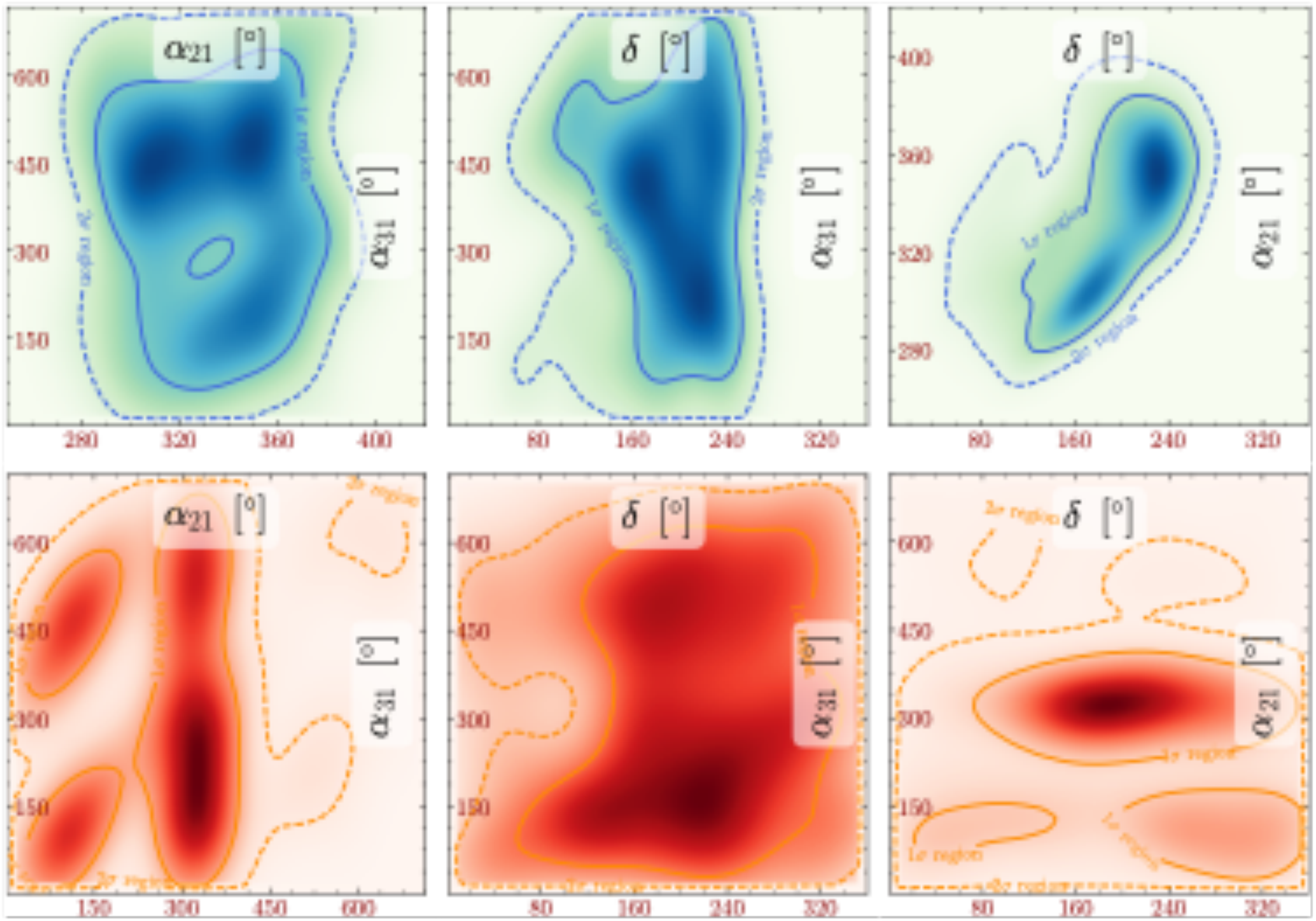
$\rightarrow$ Dirac and Majorana phases in PMNS matrix can be a source of BAU !!

Thermal Leptogenesis

- $M_1 = 10^{10}$ GeV (Hierarchical masses for RH neutrinos)

NH

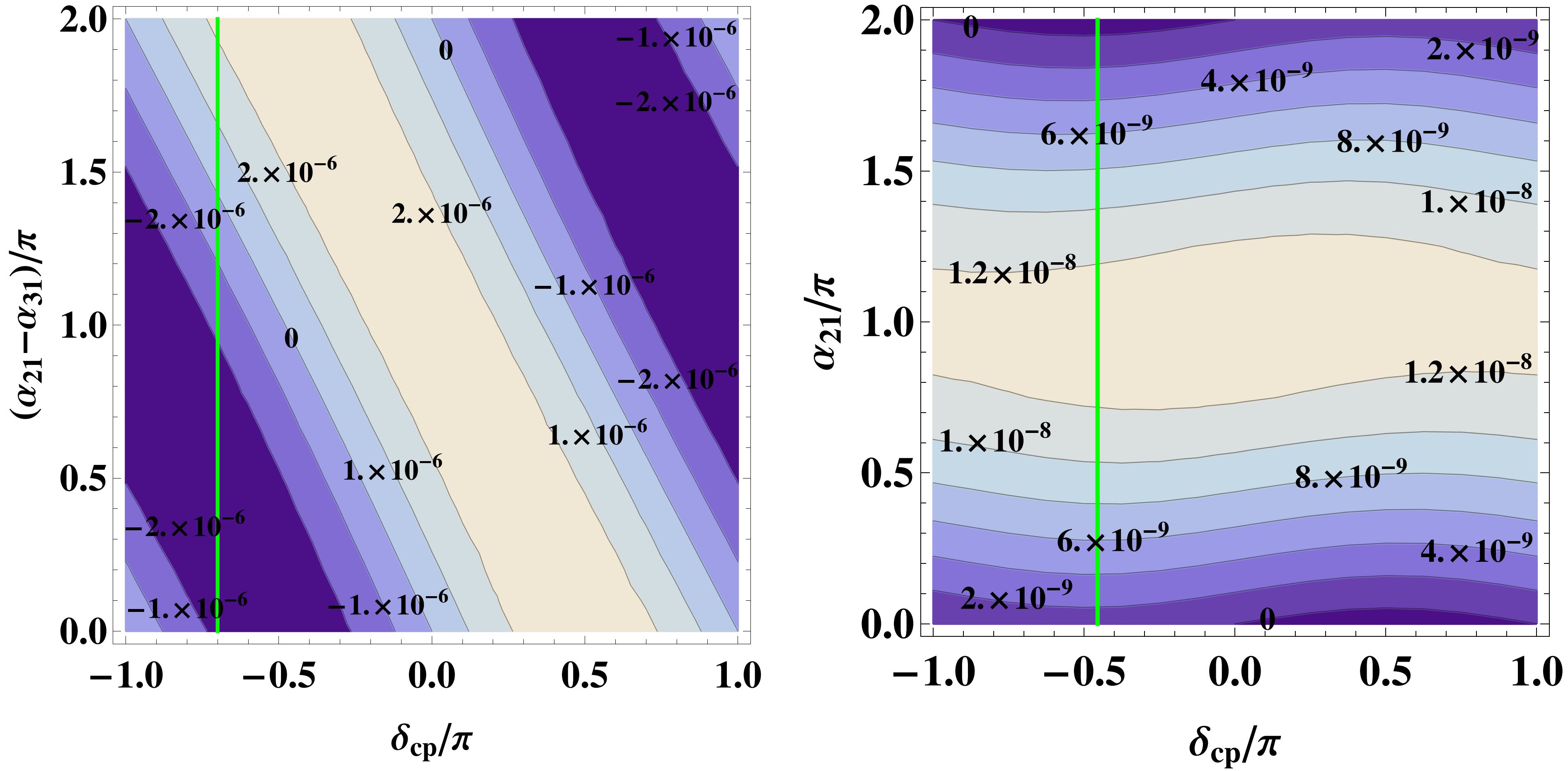
IH



Moffat, Pascoli, Petcov, Turner '19

Resonant Leptogenesis

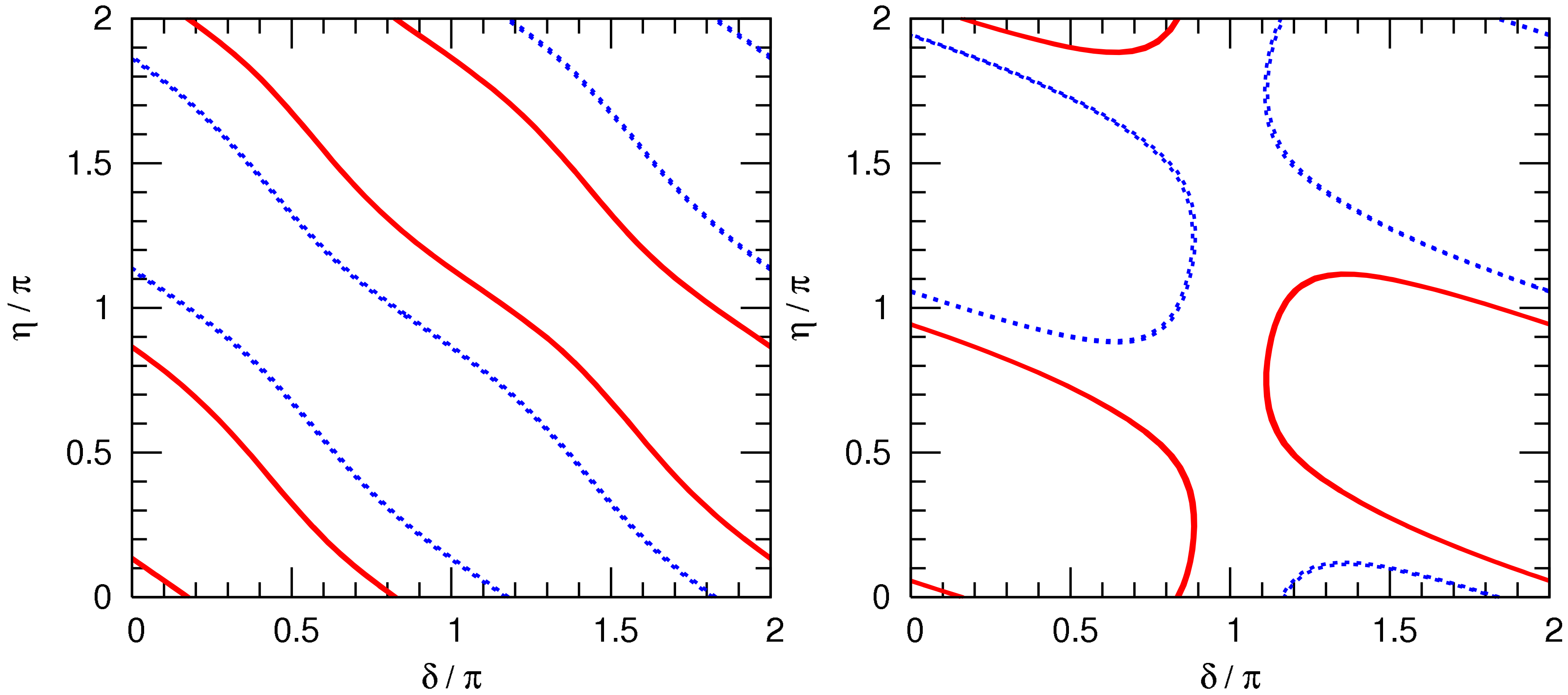
- $M_{1,2} = 1$ TeV (quasi-degenerate)



TA, Yoshida ’19

Baryogenesis via RH neutrino oscillation

- $M_{1,2} = 5$ GeV (quasi-degenerate)

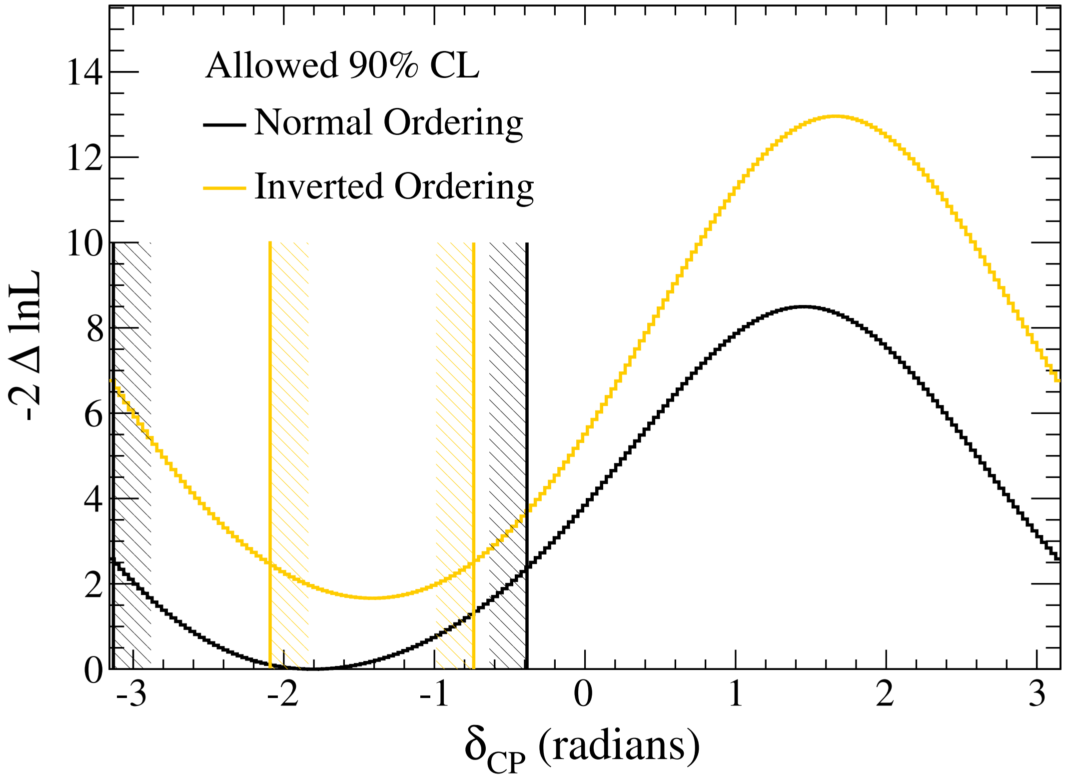


TA, Ishida '10

BAU and CPV in neutrino sector

- T2K and NOvA indicate CPV in neutrino sector

T2K, PRL 118, 151801 ('17)

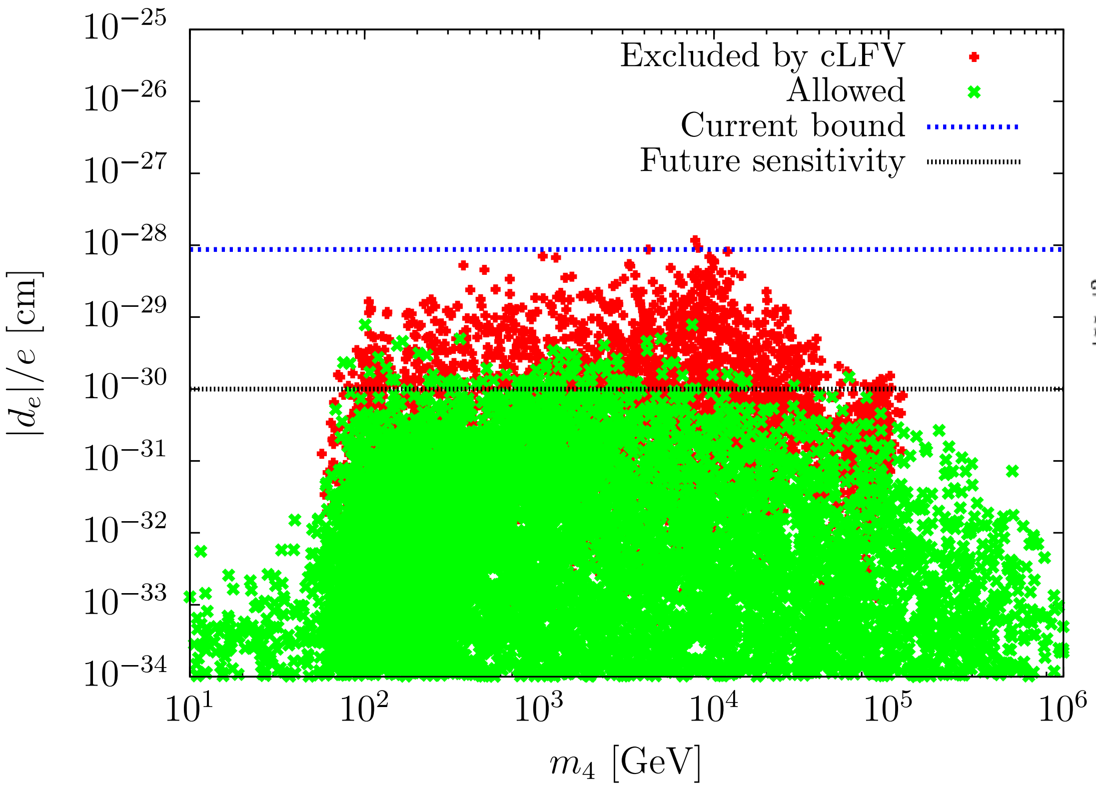


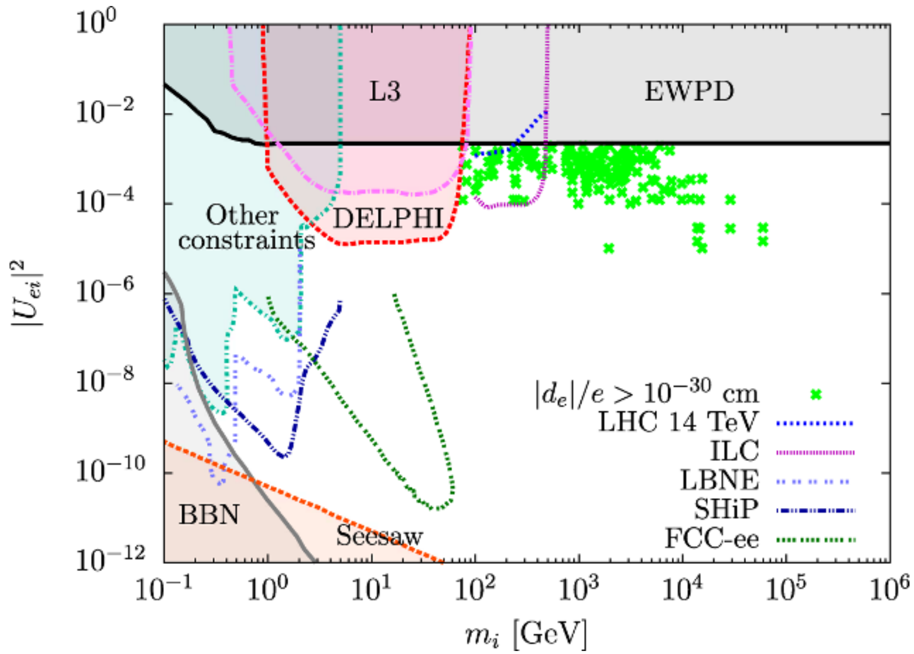
Non-zero Dirac phase

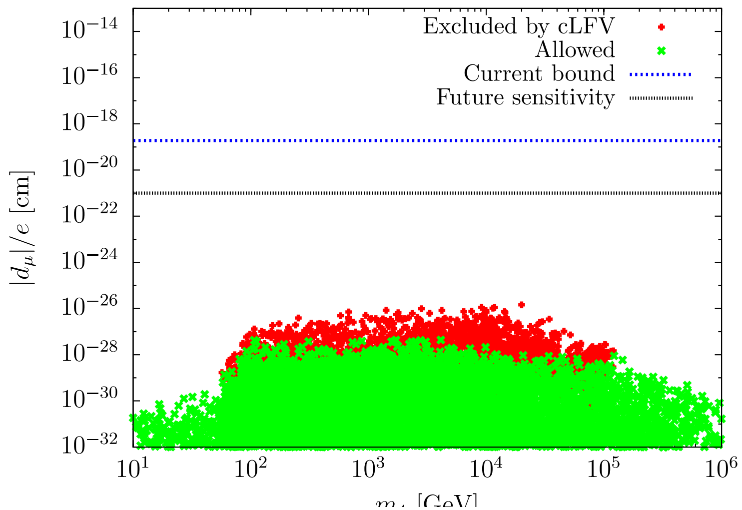
$$\delta \sim -\frac{\pi}{2} \left(or \ \frac{3\pi}{2} \right)$$

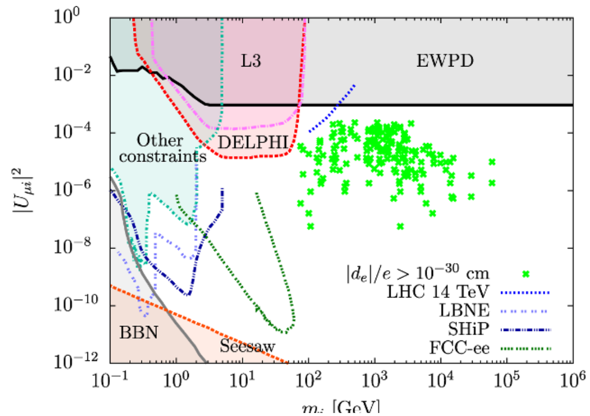
Important step to understand baryogenesis by RH neutrinos !

Electric dipole moments of charged leptons









Abada, Toma '16
[1511.03265]

Search for HNL (ν_R)

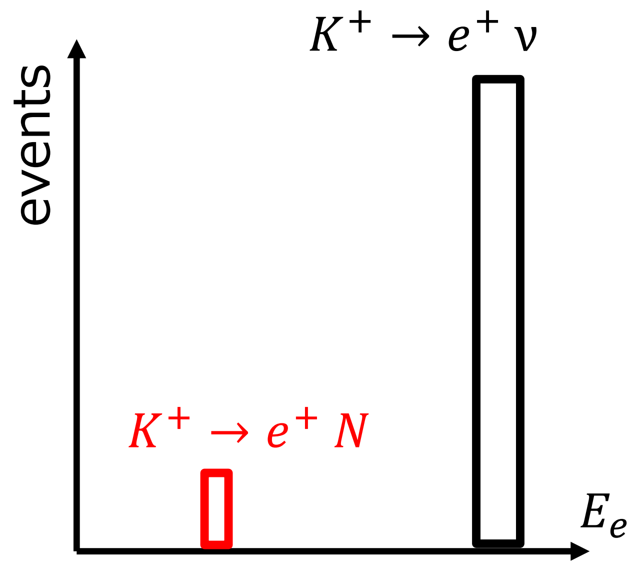
Search for Heavy Neutral Leptons

- Production by meson decays

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

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

[Shrock '80]

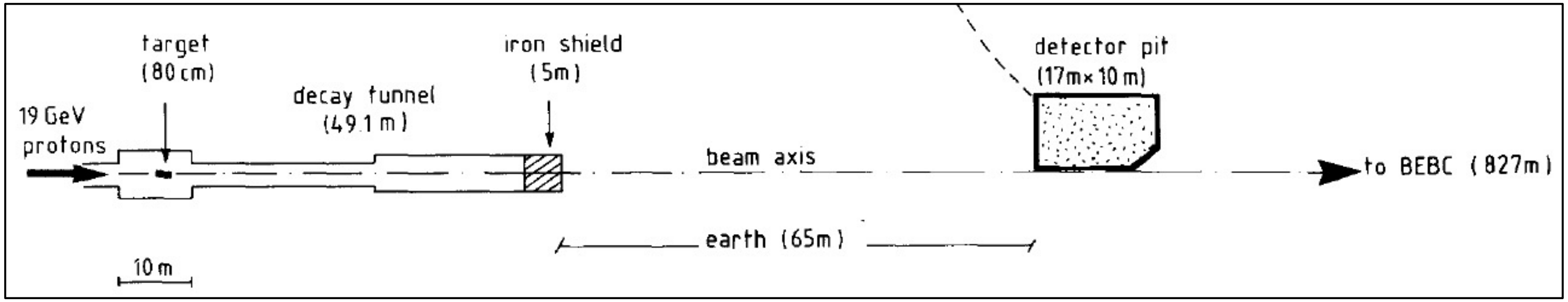


$$E_e = \frac{m_K^2 - m_e^2 - M_N^2}{2\, m_K}$$

  - **Beam dump experiments**

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

CERN PS191



Search for HNLs at T2K

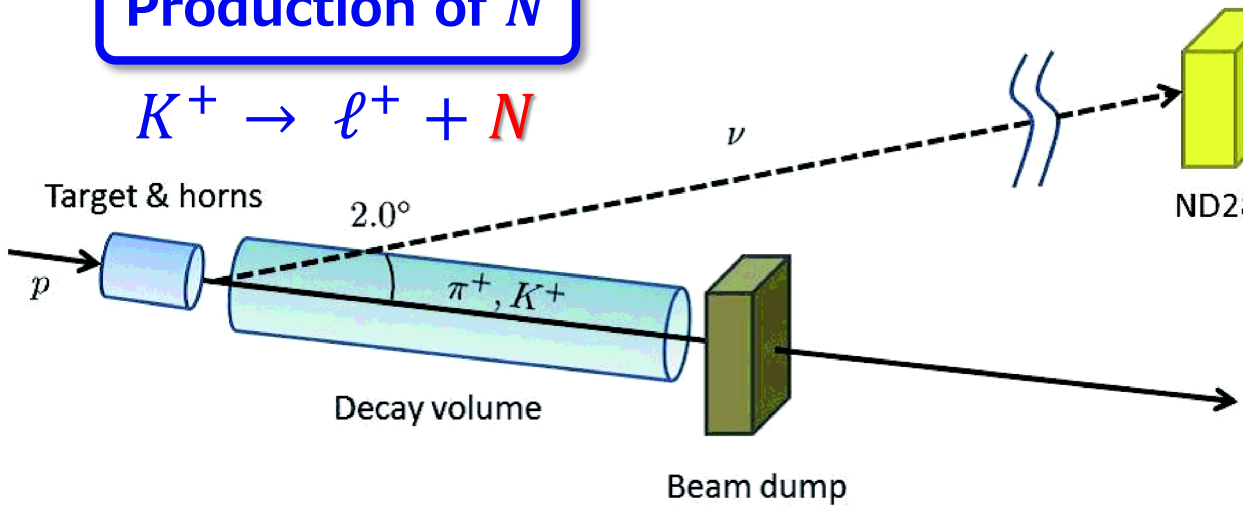
TA, Eijima, Watanabe
[JHEP1303 (2013) 125]

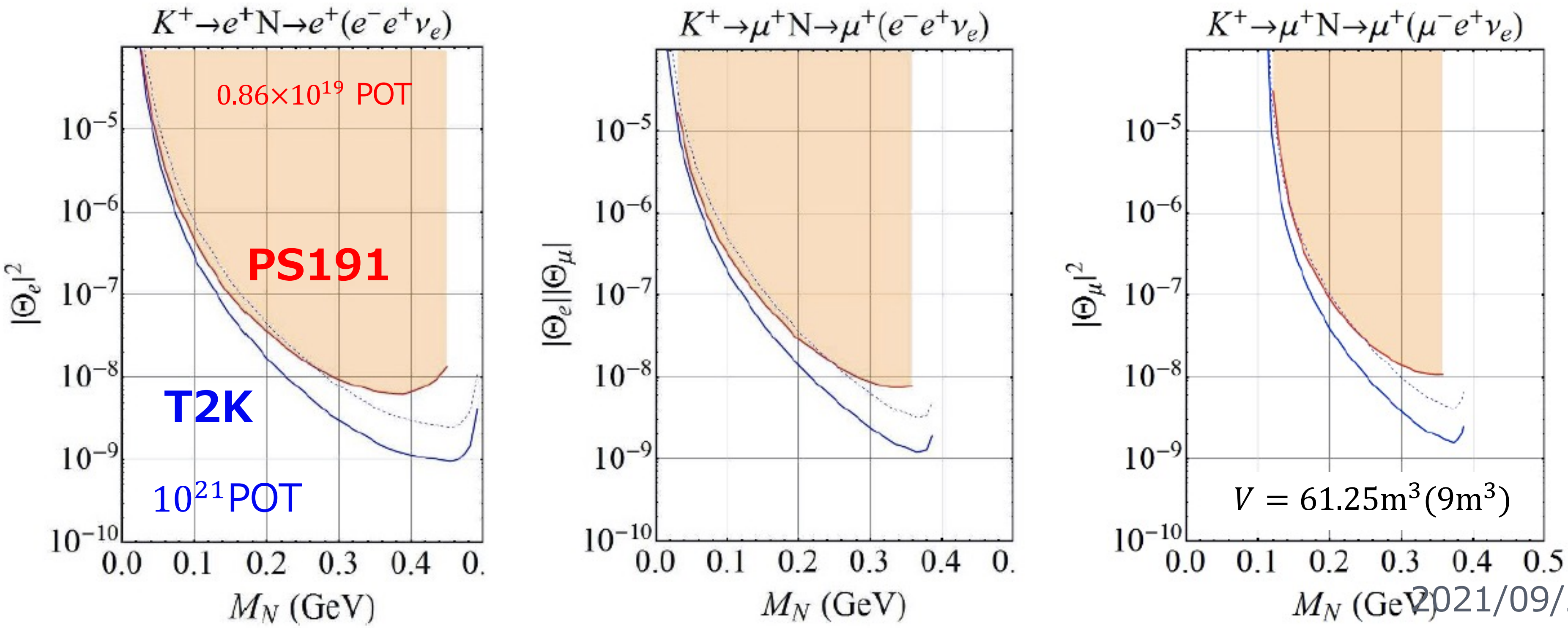
Production of N

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

Detection of N

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





(The T2K Collaboration)

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

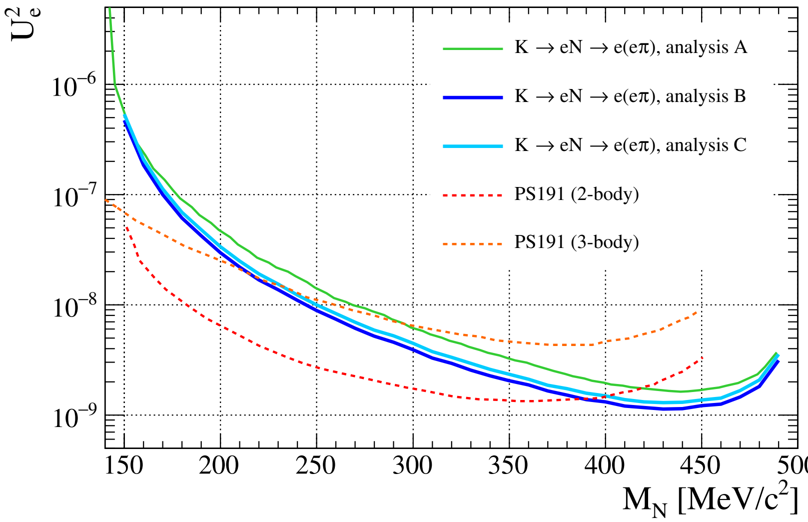


FIG. 5. 90% upper limits on the mixing element U_e^2 as a function of heavy neutrino mass using the single-channel approach, considering only the contribution from $K^\pm \to e^\pm N, N \to e^\pm \pi^\mp$, with the three methods **A**, **B** and **C**. The limits are compared to the ones of PS191 experiment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

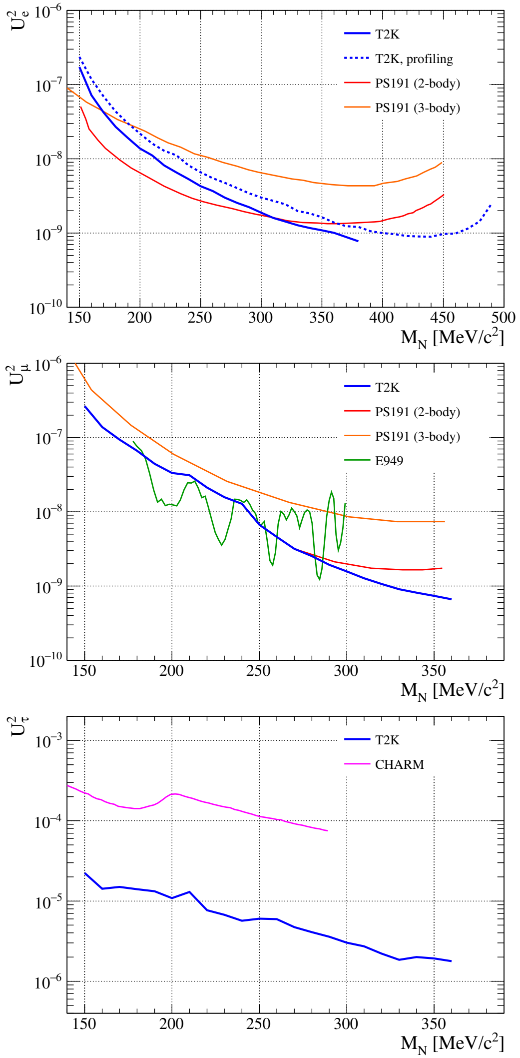
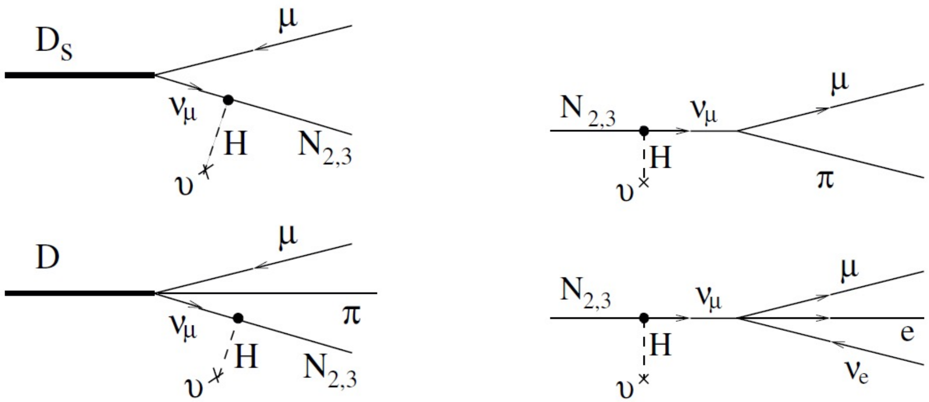


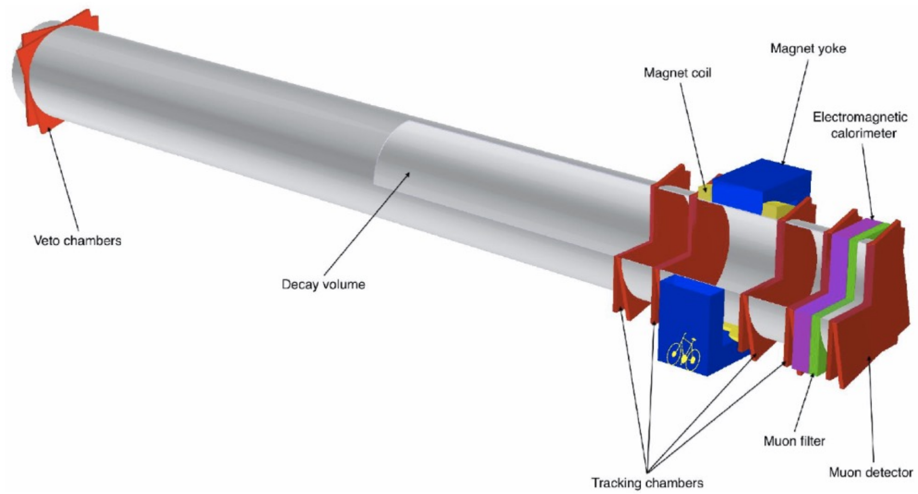
FIG. 6. 90% upper limits on the mixing elements U_e^2 (top), U_μ^2 (middle), U_τ^2 (bottom) as a function of heavy neutrino mass, obtained with the combined approach. The blue solid lines are obtained after marginalisation over the two other mixing elements. In the top plot, the additional blue dashed 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].

SHiP

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

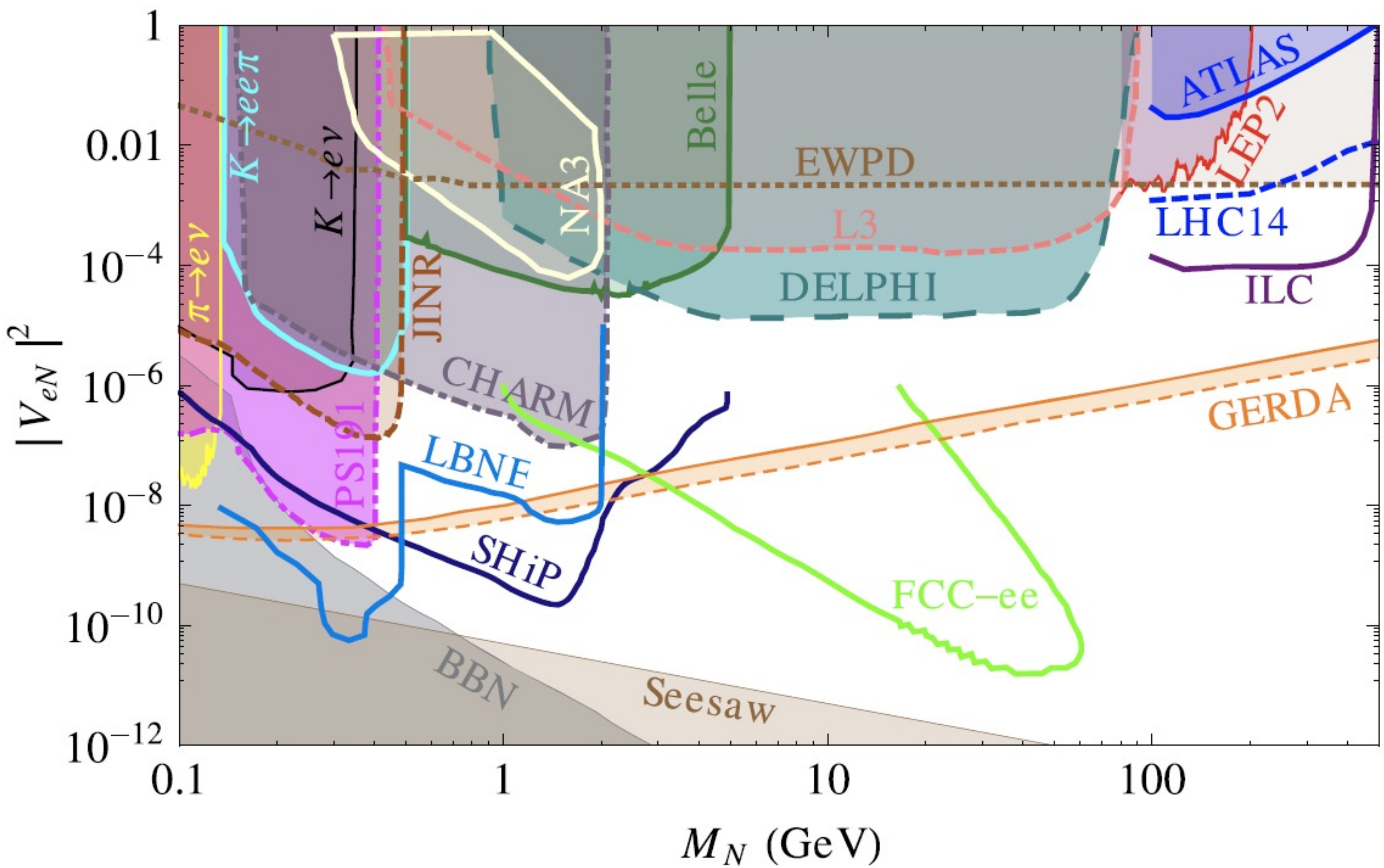




Limits on mixing of HNL

- Limits on mixing Θ_{eI}

Deppisch, Dev, Pilaftsis '15



Summary

- Leptogenesis
  → Connection between neutrino masses and BAU is attractive and important idea
  → Various scenarios are possible depending on RH neutrino masses

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

- Connection can be obtained even lighter mass region
  [Seesaw + Baryogenesis via RH neutrino osc.]
  → Such RH neutrinos might be tested!