The νMSM

Neutrino masses, dark matter, and baryon asymmetry of the universe

Takehiko Asaka (Niigata University)

2021/11/07 (Sun)

素粒子現象論研究会2021 (Zoom)

真の強さを学ぶ。
新潟大學
NIIGATA UNIVERSITY

Back to 200X

- In 2005 we published two papers

The νMSM, dark matter and neutrino masses

Takehiko Asaka*, Steve Blanchet, Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

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Takehiko Asaka, Mikhail Shaposhnikov

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I was PD fellow at EPFL (Lausanne, Switzerland).

The first beam in the LHC at CERN was on 10 Sept. 2008.

Thus, they are written in the pre-LHC era.

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

My slides at that time

The νMSM

Neutrino masses, dark matter, and baryon asymmetry of the universe

Takehiko Asaka

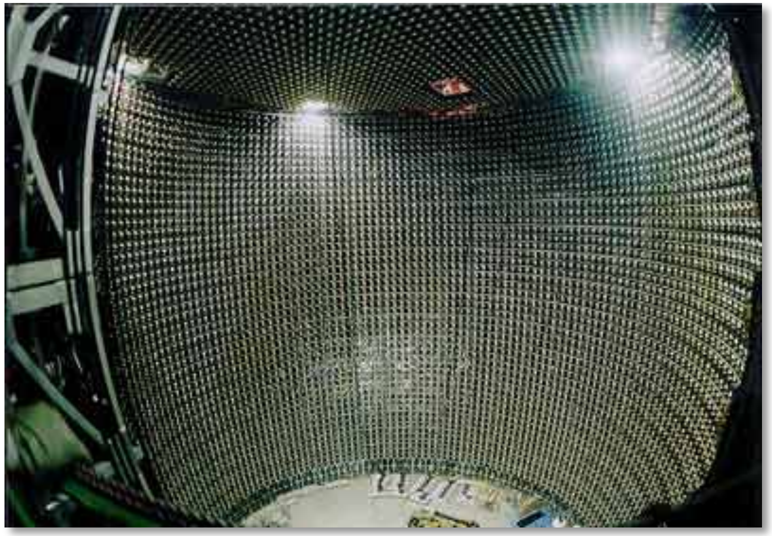
(EPFL: École Polytechnique Fédérale de Lausanne)

@ Freiburg University
10 May 2007

Prologue: Physics beyond the MSM

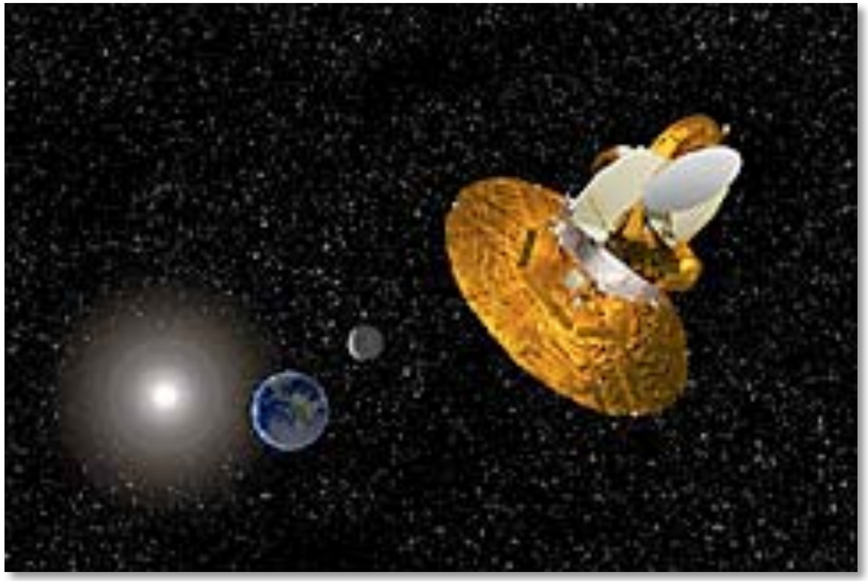
- About 10 years ago …,
  - There was no "convincing" evidence for physics beyond the minimal standard model (MSM)
  - People looked for physics beyond the MSM "mainly" based on theoretical arguments:
    - Hierarchy problem
    - Gravity, String, …
    - Strong CP problem
    - Why 3 generations?
    - Why anomalies cancel?
    - …

Neutrino Oscillations



[SuperK]

Cosmic Microwave Background (CMB)



[WMAP]

Physics beyond the MSM

- In the last decade(s), we have collected quite "convincing" evidences for physics beyond the MSM
  - Neutrino oscillations → non-zero neutrino masses
  - Baryon asymmetry
  - Dark matter
  - Dark energy
  - Scale-invariant density perturbations

Physics beyond the MSM

- In the last decade(s), we have collected quite "convincing" evidences for physics beyond the MSM

  - Neutrino oscillations → non-zero neutrino masses
  - Baryon asymmetry
  - Dark matter
  - ?? Dark energy
  - ?? Scale-invariant density perturbations

- Today, I would like to explain the νMSM, which can solve first three problems!

Contents

■ Motivation

■ The SM with right-handed neutrinos

■ Dark Matter of the Universe

■ Baryon Asymmetry of the Universe

■ Summary

Neutrino oscillations

- Evidence of neutrino oscillations

  → non-zero neutrino masses

  $\Delta m^2_{\rm atm} \simeq 2.5\times10^{-3}\ {\rm eV}^2 \qquad \Delta m^2_{\rm sol} \simeq 7.4\times10^{-5}\ {\rm eV}^2$

- Need for new physics beyond the Standard Model (SM)

- Important questions:
  - What is the origin of neutrino masses ?
  - How can it be confirmed experimentally ?
  - What are the consequences of new physics ?
  - …

The SM with right-handed neutrinos
--the seesaw mechanism

Origin of neutrino masses

■ Adding three right-handed neutrinos $\nu_{R1}, \nu_{R2}, \nu_{R3}$

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

- 18 new parameters
  - 3 Majorana masses (M_M)
  - 15 parameters in Yukawa coupling matrix (F)
    - 3 Yukawa couplings (real positive numbers)
    - 6 mixing angles
    - 6 phases

- Mass term for neutrinos

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

- Dirac type mass $M_D = F\langle\Phi\rangle$
- Majorana type mass M_M

Seesaw mechanism

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

■ If Majorana masses ≫ Dirac masses,

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \Rightarrow \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

- Active neutrinos ν_1, ν_2, ν_3

  $M_\nu = -M_D^T M_M^{-1} M_D = U^* \mathrm{diag}(m_1, m_2, m_3) U^\dagger$

  $\Rightarrow$ **smallness of neutrino masses is naturally explained**

$M_\nu \ll M_D$

- Heavy neutral leptons (HNLs) N_1, N_2, N_3

  $M_N = M_M = \mathrm{diag}(M_1, M_2, M_3)$

■ Mixing in CC current

$$\nu_{L\alpha} = U_{\alpha i}\, \nu_i + \Theta_{\alpha I}\, N_I^c$$

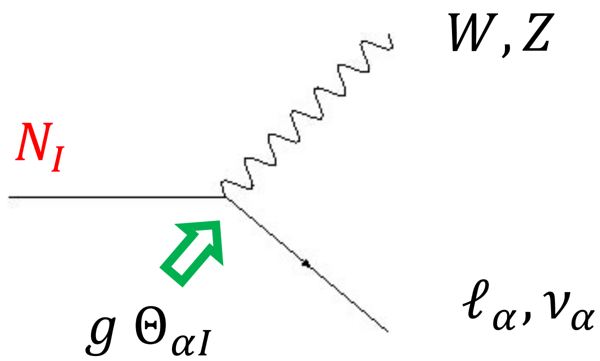
$(\alpha = e, \mu, \tau)$ $(i = 1,2,3)$ $(I = 1,2,3)$

- PMNS mixing for active neutrinos
  $U_{\alpha I}$
- Mixing for HNLs
  $\Theta_{\alpha I} = [M_D]_{\alpha I} / M_I$

Important parameters of HNL

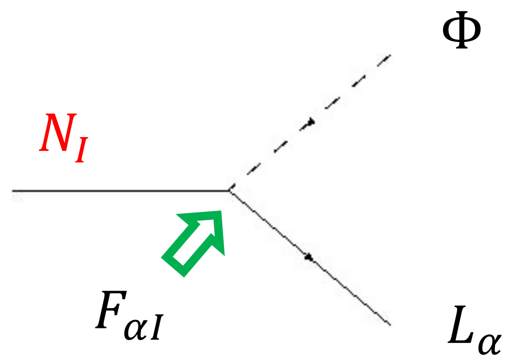
■ Interactions of HNL

gauge interaction through mixing



→ relevant for search experiments

Yukawa interaction



NOTE

$$g\ \Theta_{\alpha I} = g\,\frac{F_{\alpha I}\langle\Phi\rangle}{M_N} \sim F_{\alpha I}\,\frac{m_W}{M_N}$$

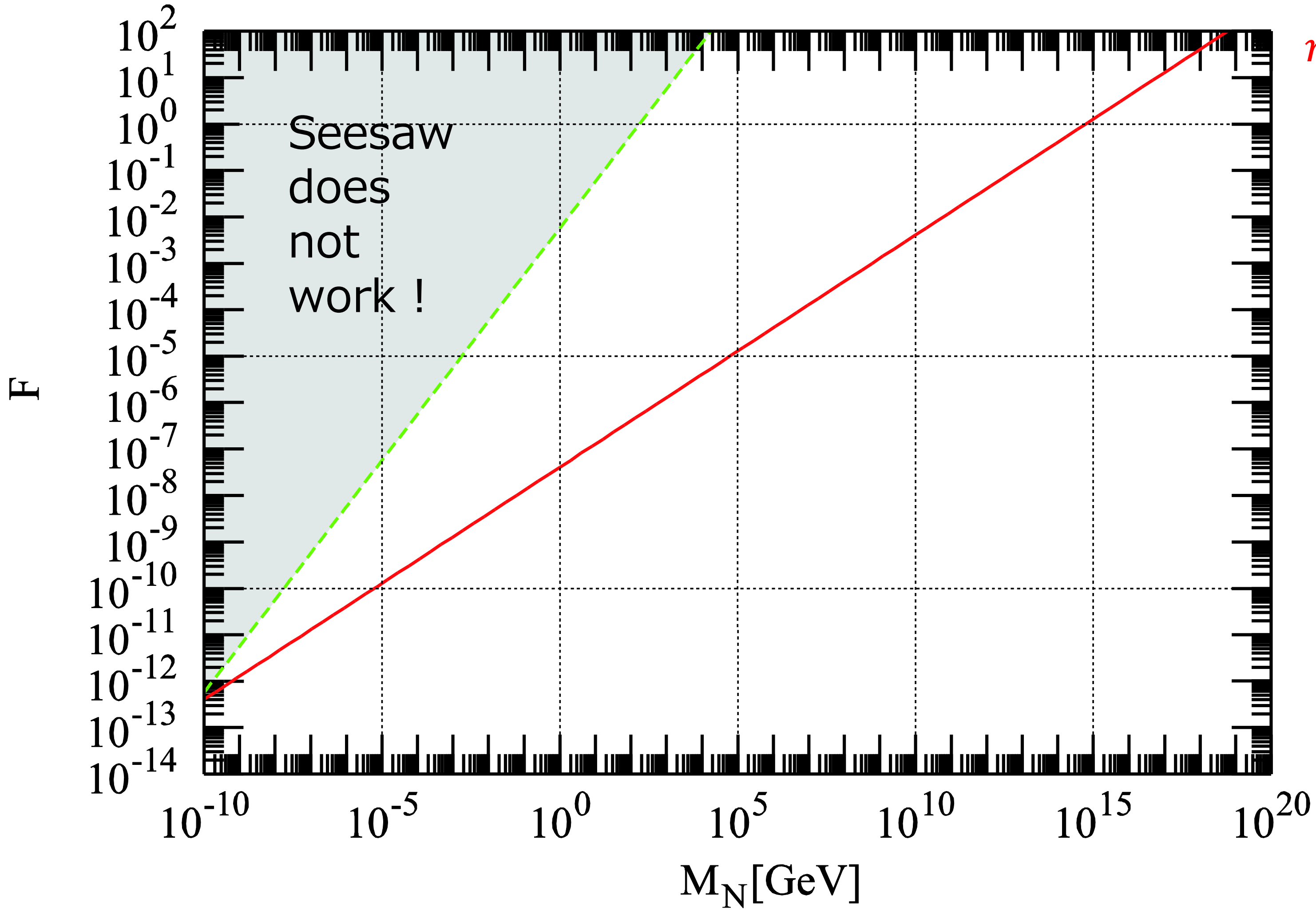
■ Two key parameters of HNL

- Mass M_I
- Mixing $\Theta_{\alpha I}$

Yukawa coupling and Majorana mass for HNL

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

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



Yukawa coupling and Majorana mass for HNL

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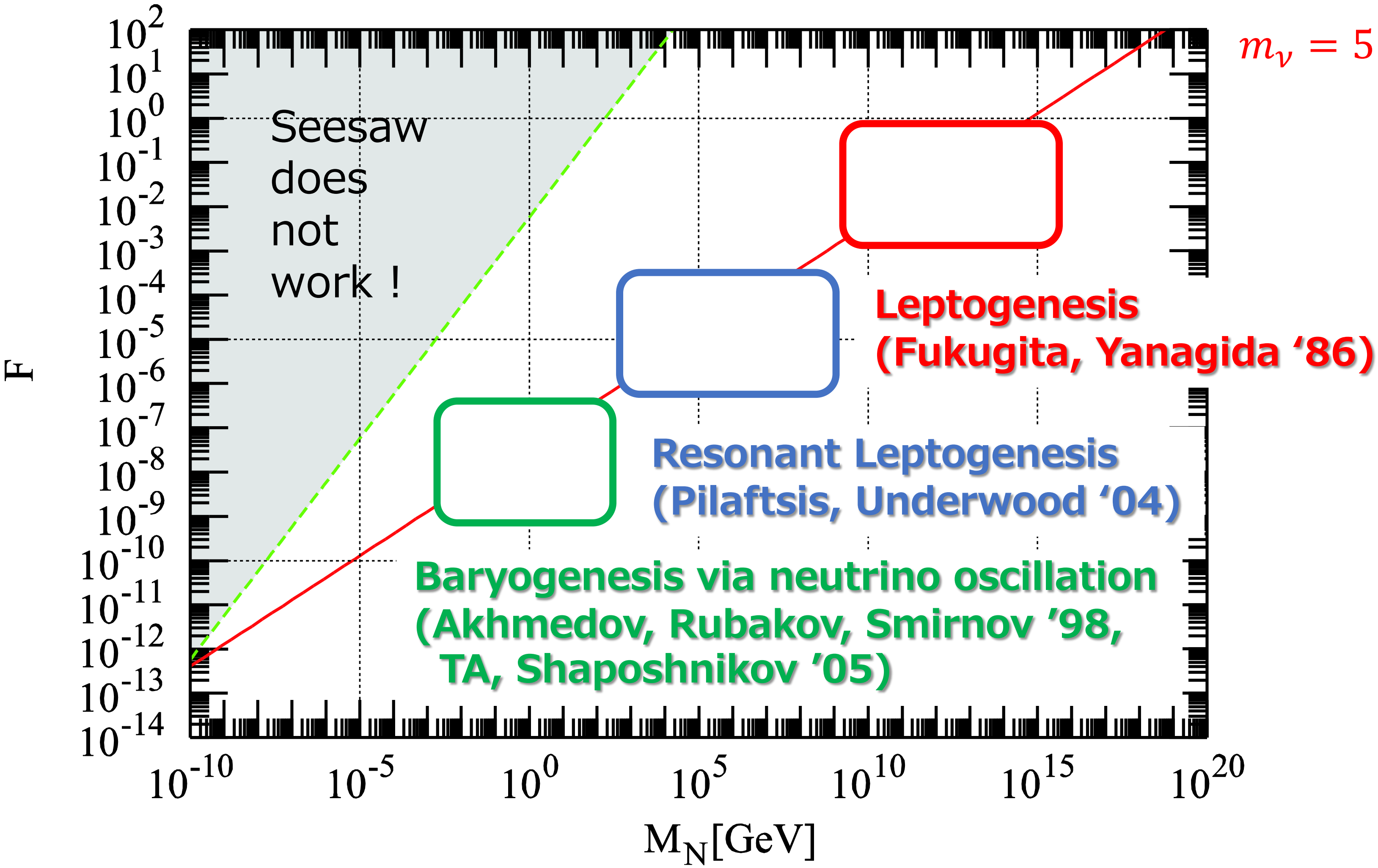
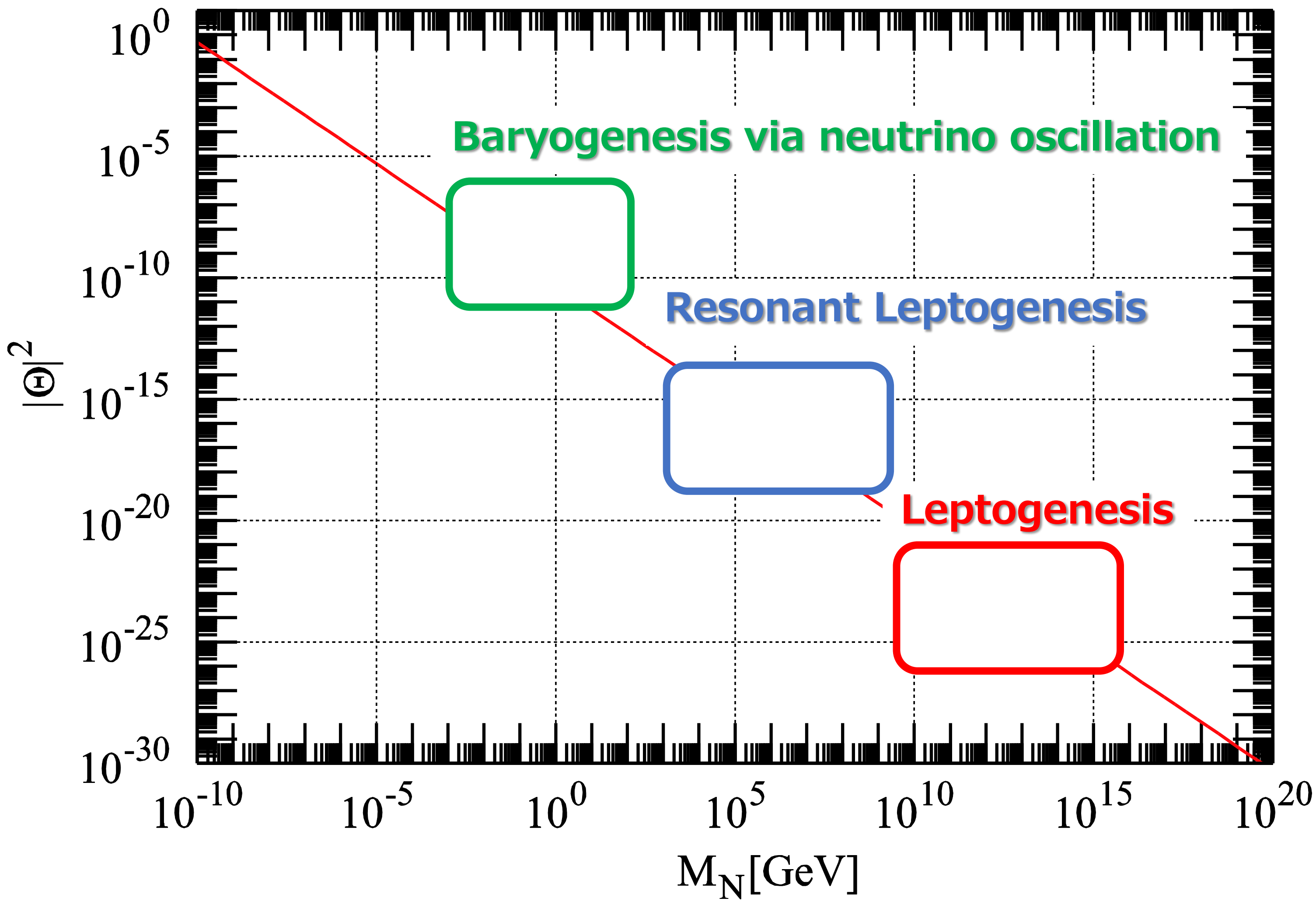
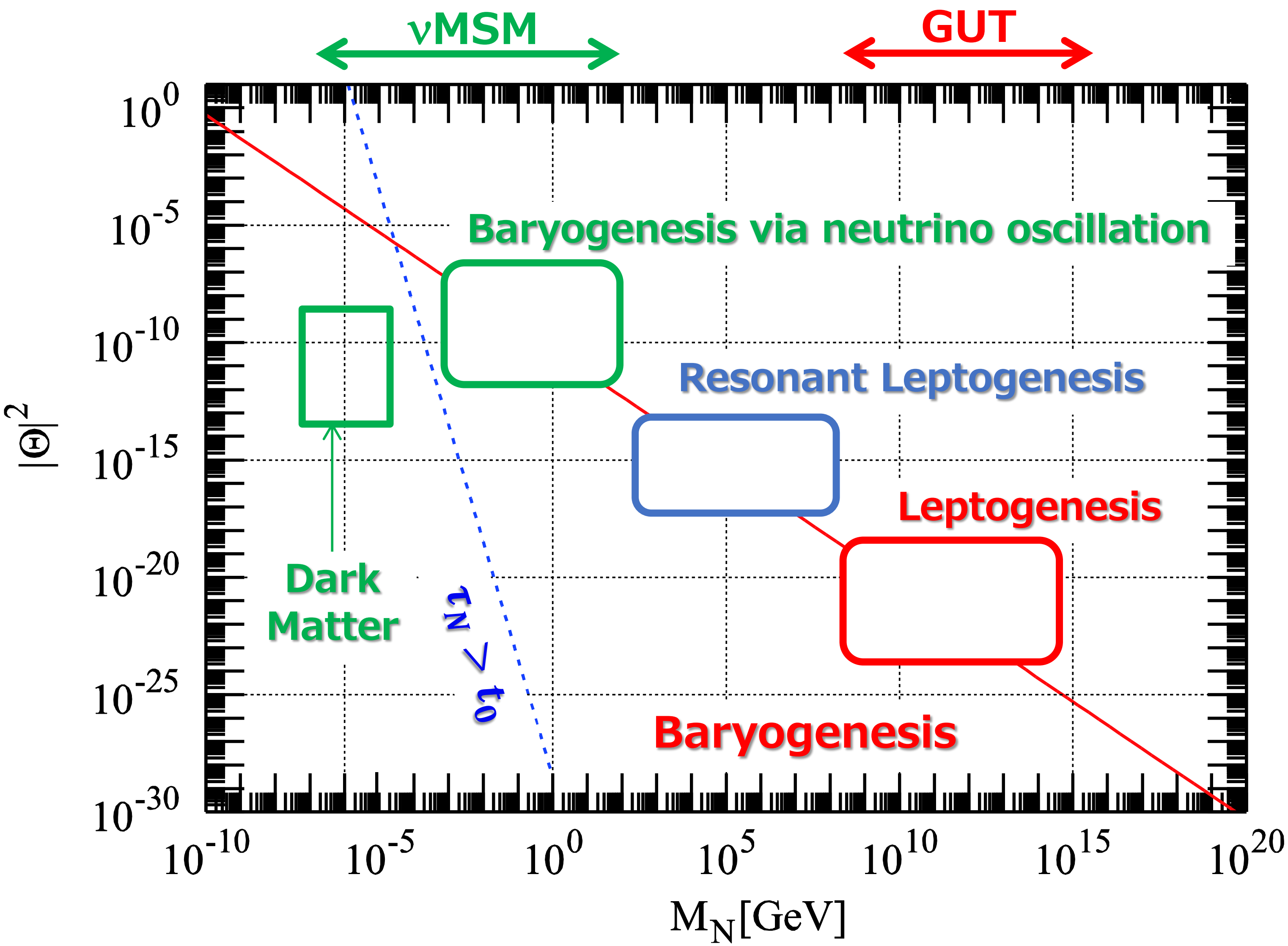


Mixing and Mass of HNL

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



Various Physics of HNL



Dark matter of the Universe

Dark matter

■ Cosmological parameters are well determined now !

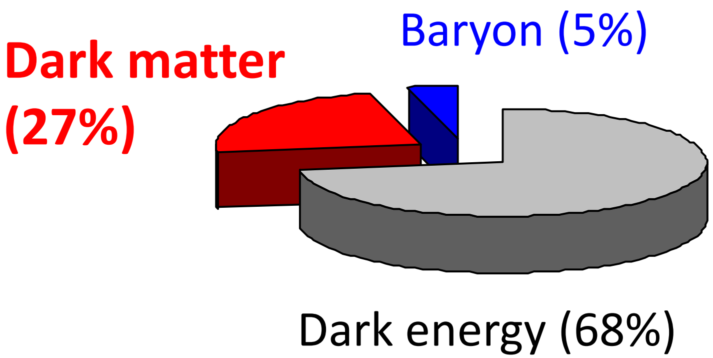
- From CMB anisotropies [Planck '18]

$$\Omega_{\rm dm} h^2 = 0.120 \pm 0.001$$

$$\Omega_{\rm dm} = \rho^0_{\rm dm}/\rho_{\rm cr}, \quad \rho_{cr} = 10.5\, h^2 \text{ GeV m}^{-3}$$

h : H_0 in unit of 100 km/s/Mpc

$$h = 0.674 \pm 0.005$$



■ Particle physics candidate

- "dark" (charge neutral)
- stable within the age of the universe $\tau > t_U = O(10^{17})$ sec
- abundance must be $\Omega_{\rm dm} h^2$
- avoids cosmological constraints

→ No candidate in the SM

Massive Active Neutrinos as Dark Matter

- Massive active neutrinos were classical candidate for dark matter, but they cannot be dark matter since they are too hot !

- Planck 2018: [arXiv:1807.06209]
  - Upper bound on sum of active neutrino masses

    $\Sigma m_i < 0.12$ eV (95%CL)

$$\Omega_\nu h^2 = \frac{\Sigma m_i}{93.14\ \mathrm{eV}} < 0.00129$$

  - Too small to explain the Dark Matter density

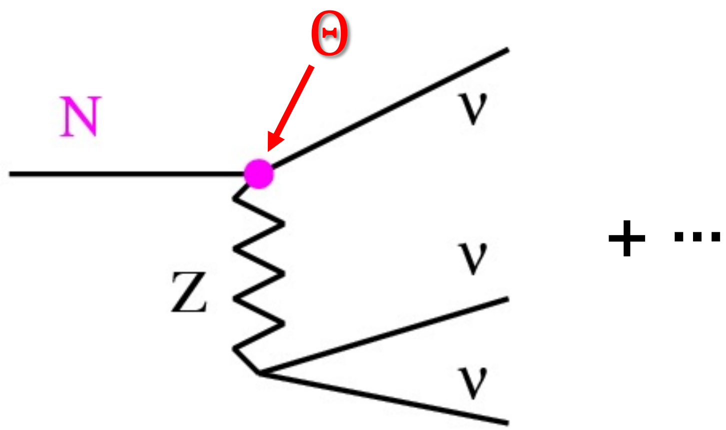
$$\Omega_{\mathrm{dm}} h^2 = 0.120 \pm 0.001$$

Sterile Neutrino (HNL) as Dark Matter

- Sterile neutrino (HNL) N_1 with $M_1 = O(10)$ keV is a good candidate for warm dark matter. [Peebles '82, Olive, Turner '82, ⋯

- DM N_1 is not completely stable (without introducing symmetry)
  - Dominant decay: $N \to 3\,\nu$
  - Lifetime can be very long !

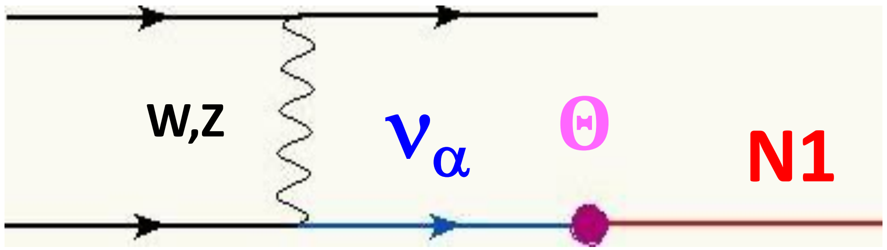
$$\tau_{N_1} = 5\times10^{26}\mathrm{sec}\left(\frac{\mathrm{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$



Production of DM

- Due to smallness of Yukawa couplings, DM N_1 is not thermalized in the early universe

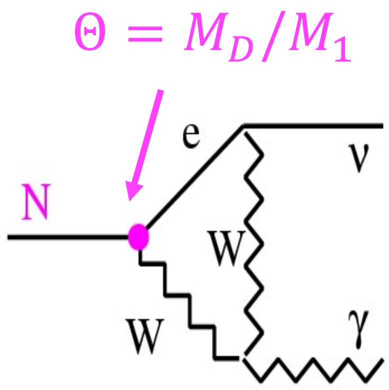
- Production scenarios:
  - **Dodelson-Widrow scenario** [Phys. Rev. Lett. 72, 17, 1994]
    - Production via active-sterile neutrino mixing



    - Dominant production at $T \approx 100\mathrm{MeV}\left(\frac{M_1}{\mathrm{keV}}\right)^{1/3}$

  - **Shi-Fuller scenario** [Phys. Rev. Lett. 82, 2832, 1999]
    - Production is boosted in the presence of lepton asymmetry due to the MSW effect

Cosmological Constraints



■ Radiative decays of DM

- Subdominant decay: $N_1 \to \nu + \gamma$
- Severely restricted from X-ray observations

⇒ **Upper bound on mixing angle !**

■ Structure formation

- DM N_1 plays as WDM and may erase structures on small scales!

⇒ **Lower bound on mass** (Ly-α forest observations)

$$\lambda_{FS} \sim \mathrm{Mpc} \left(\frac{\mathrm{keV}}{M_1} \right) \frac{\langle |q_N| \rangle}{\langle |q_\nu| \rangle}$$

Boyarsky, Lesgourgues, Ruchayskiy, Viel '09,'09

- $M_1 \gtrsim 8\ \mathrm{keV}$ (DW scenario)

■ Phase-space analysis (Tremaine-Gunn bound)

- $M_1 \gtrsim 1 - 2\ \mathrm{keV}$

Tremaine, Gunn '79
Boyarsky, Ruchayskiy, Iakubovskyi '08
Gorbunov, Khmelnitsky, Ruvakov '08

Mixing angle required for DM abundance

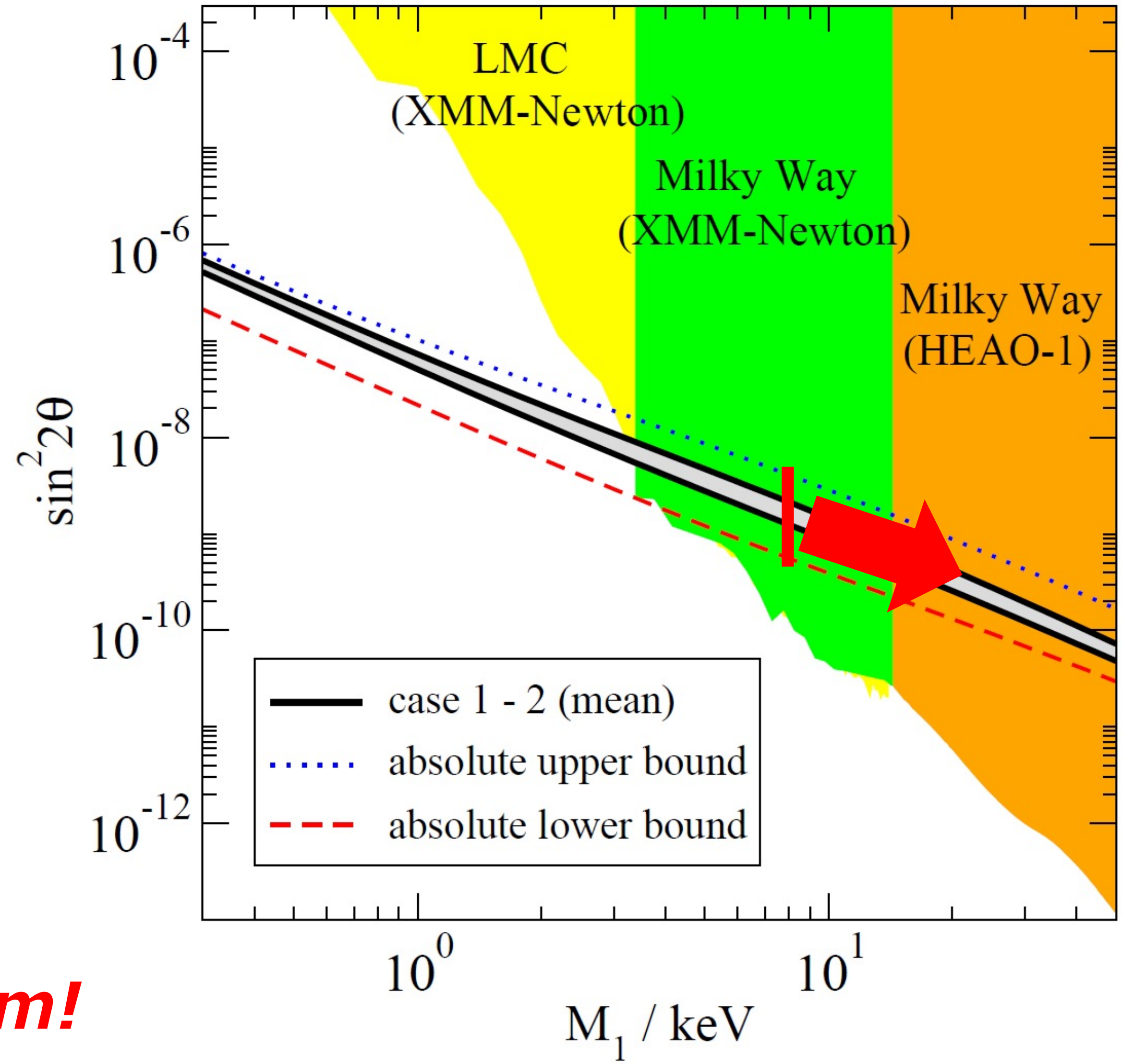
TA, Laine, Shaposhnikov '07

Mixing angle required for
$\Omega_N = \Omega_{dm}$

$$\sin^2 2\theta \simeq 8{\times}10^{-8}\left(\frac{M_N}{1\mathrm{keV}}\right)^2$$

$M_N < 3$ keV is possible !

Not allowed since it is too warm!



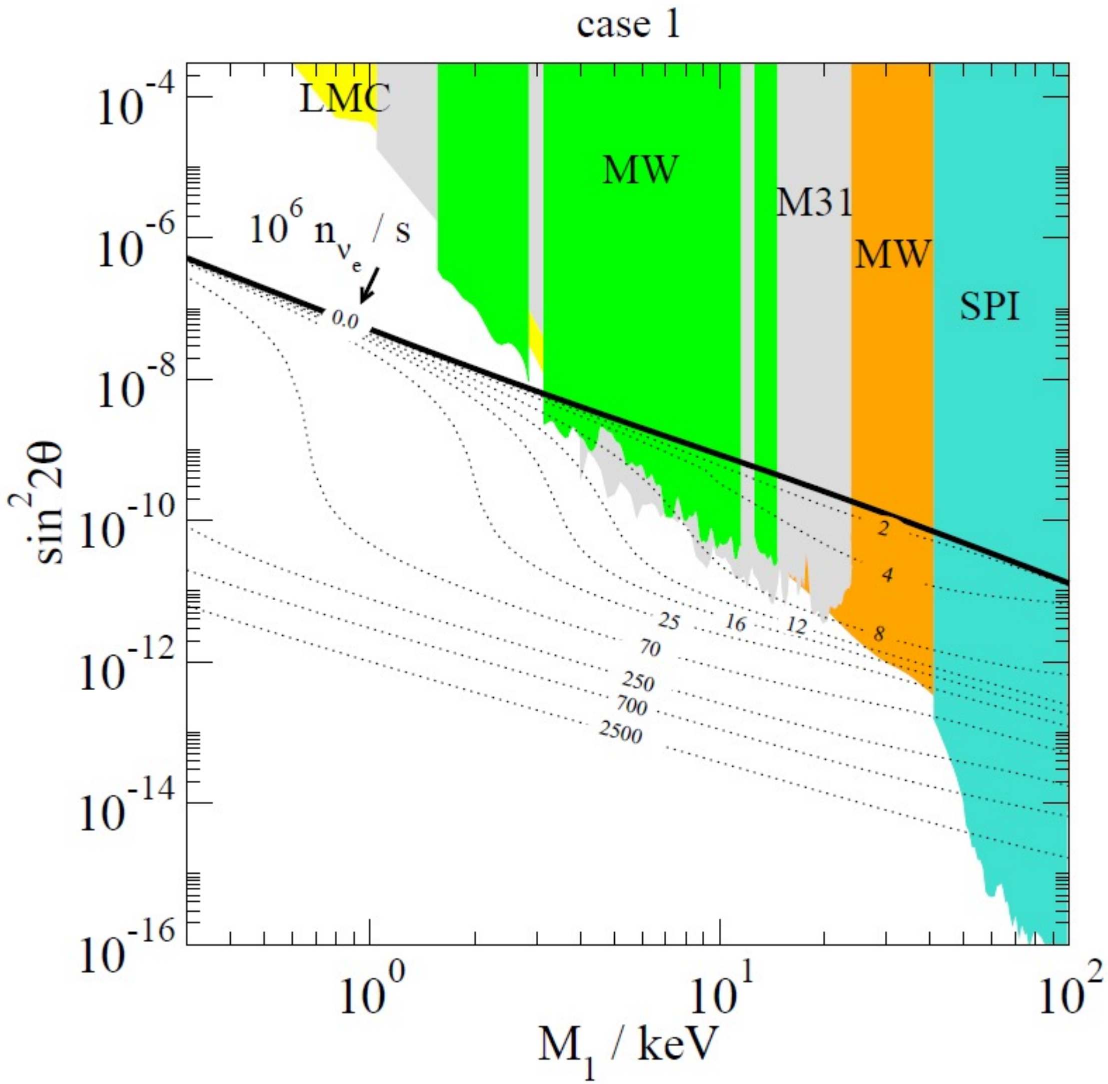
Mixing angle required for DM abundance

Laine, Shaposhnikov '08

- **Resonant production due to lepton asymmetry**

  Smaller mixing can account for the correct dark matter abundance

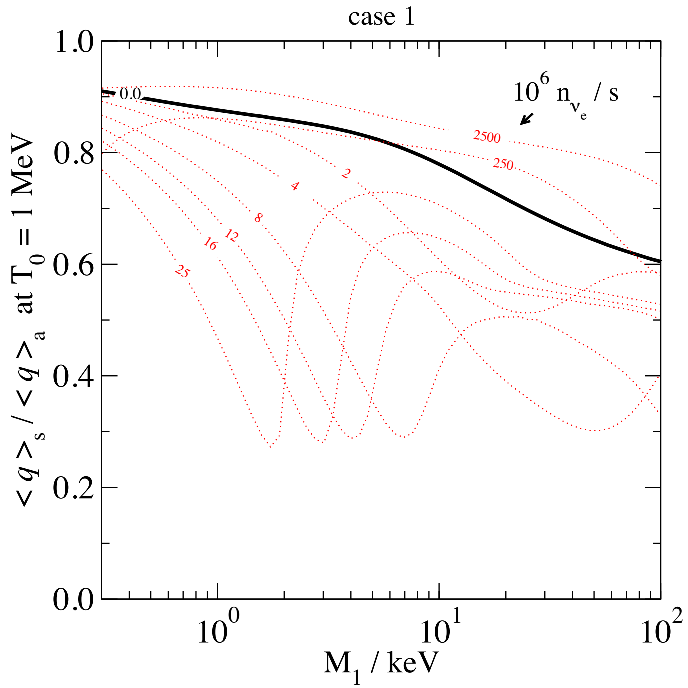
$M_N < 50$ **keV is possible !**

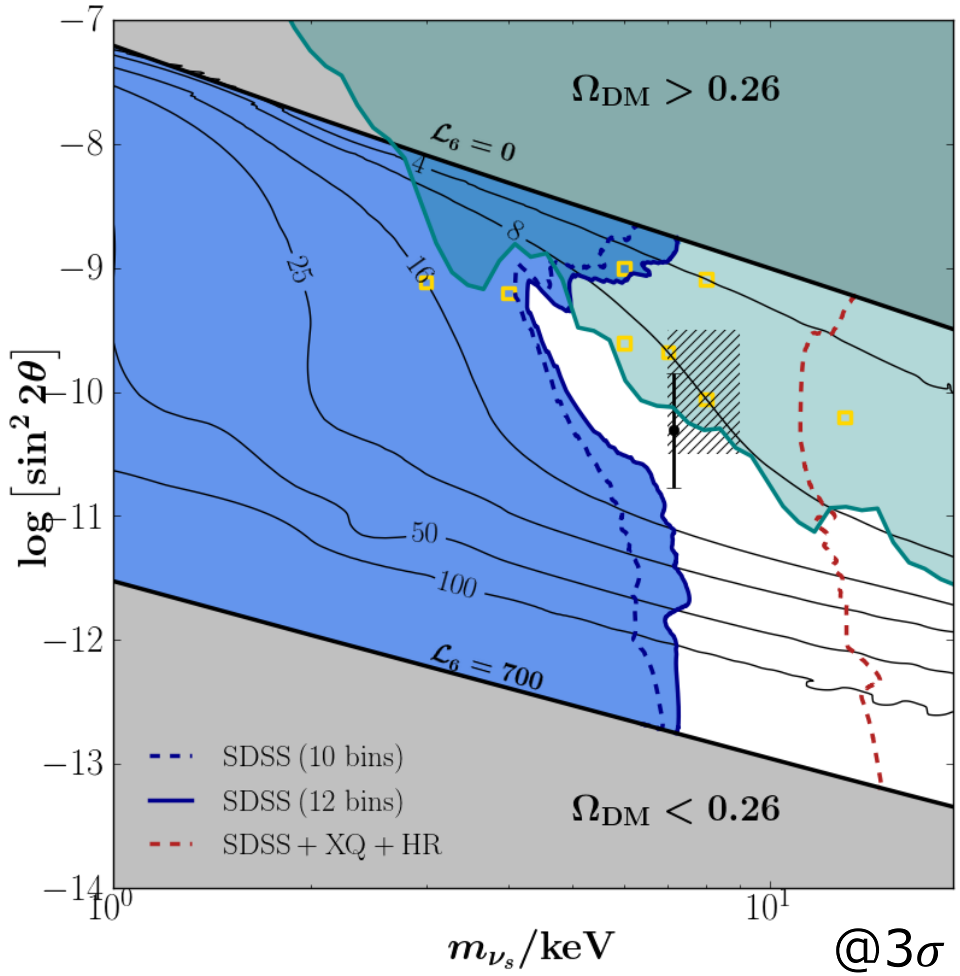


Constraints from Ly-α forests

- Constraints from Ly-α forests for Shi-Fuller scenario is shown by blue region

- Viable region exists!





@3σ

Baur et al [1706.03118]

DM in the νMSM

- Dodelson-Widrow scenario conflicts with cosmological constraints

  $\Rightarrow$ Other production mechanism is needed

  - Shi-Fuller mechanism with large lepton asymmetry

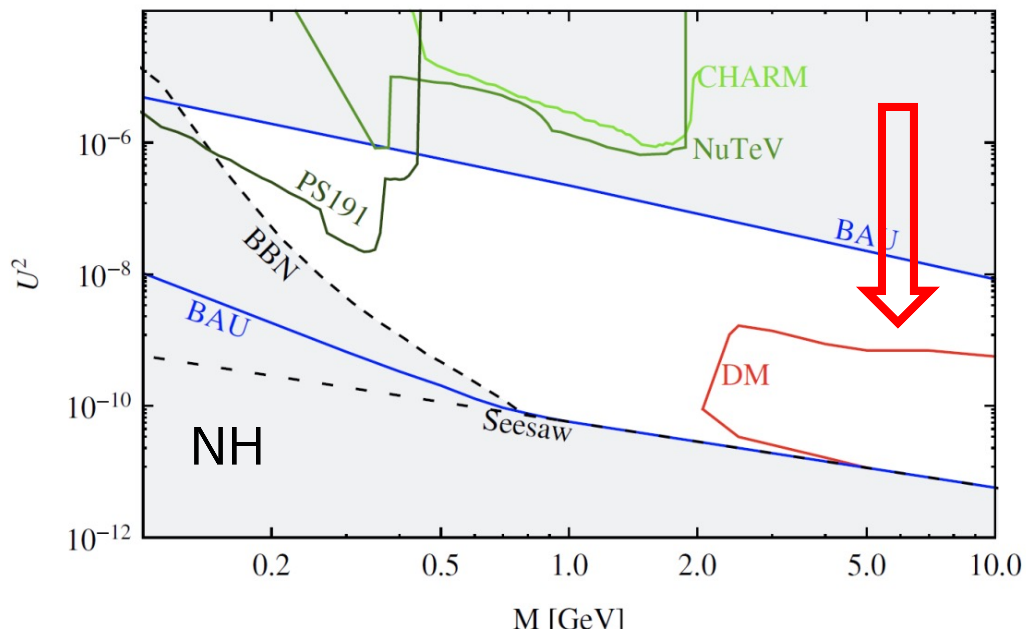
    Laine, Shaposhnikov '08

  - Addition of new d.o.f (scalar, Z', ⋯)

    Shaposhnikov, Tkachev '06, Kusenko '06, Petraki, Kusenko '06
    Bezrukov, Gorbunov '10, Bezrukov, Kartavtsev, Lindner '12,

- Large lepton asymmetry for Shi-Fuller mechanism can be generated by HNL $N_{2,3}$
  - Baryogenesis at $T \gtrsim M_W$
  - Leptogenesis before DM production

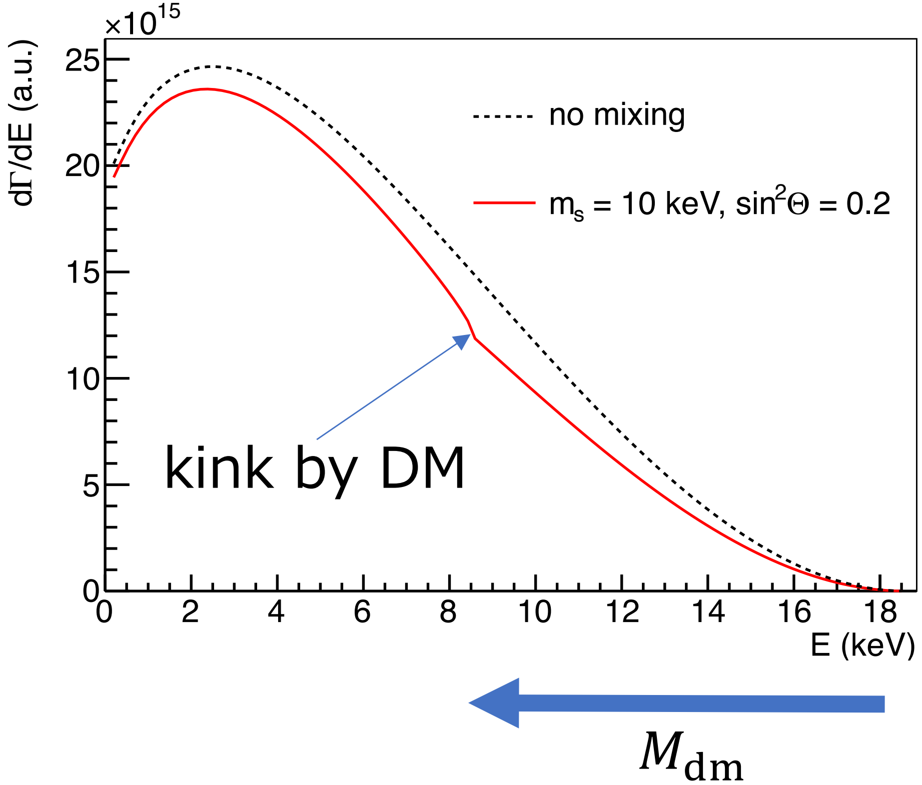
Canetti, Drewes, Shaposhnikov '13
Canetti, Drewes, Frossard, Shaposhnikov '13



Diract Search for DM

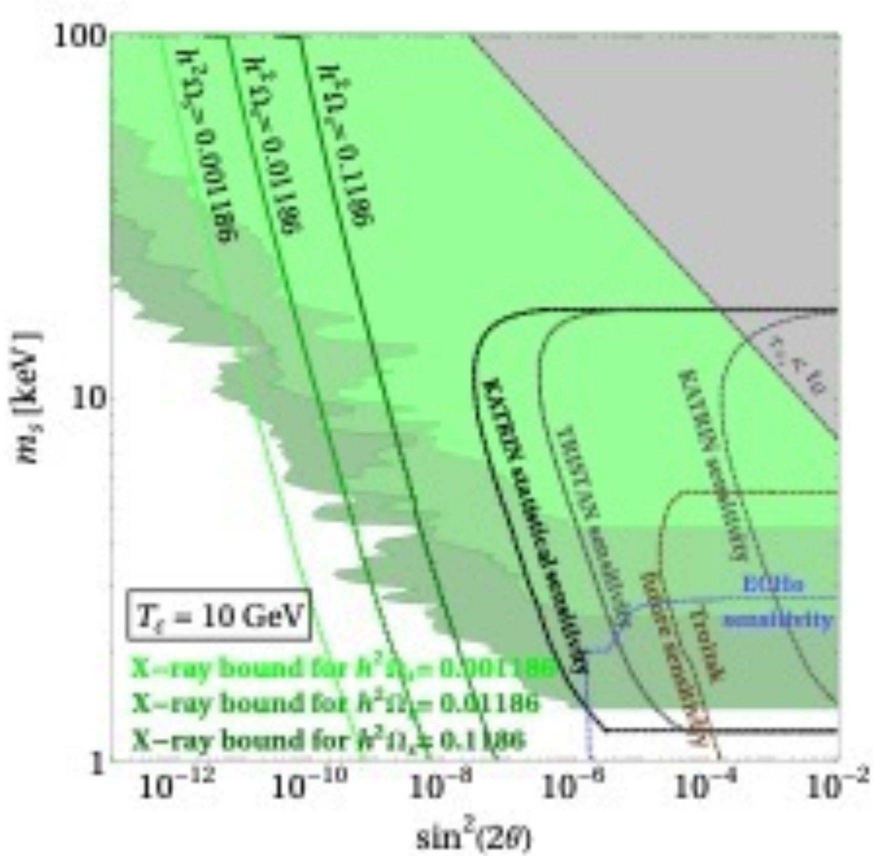
- Tritium beta-decay $\mathrm{T} \to \mathrm{He} + e^- + \bar{\nu}_e$ (KATRIN exp.)

Energy spectrum of e^-



arXiv:1409.0920

Sensitivity

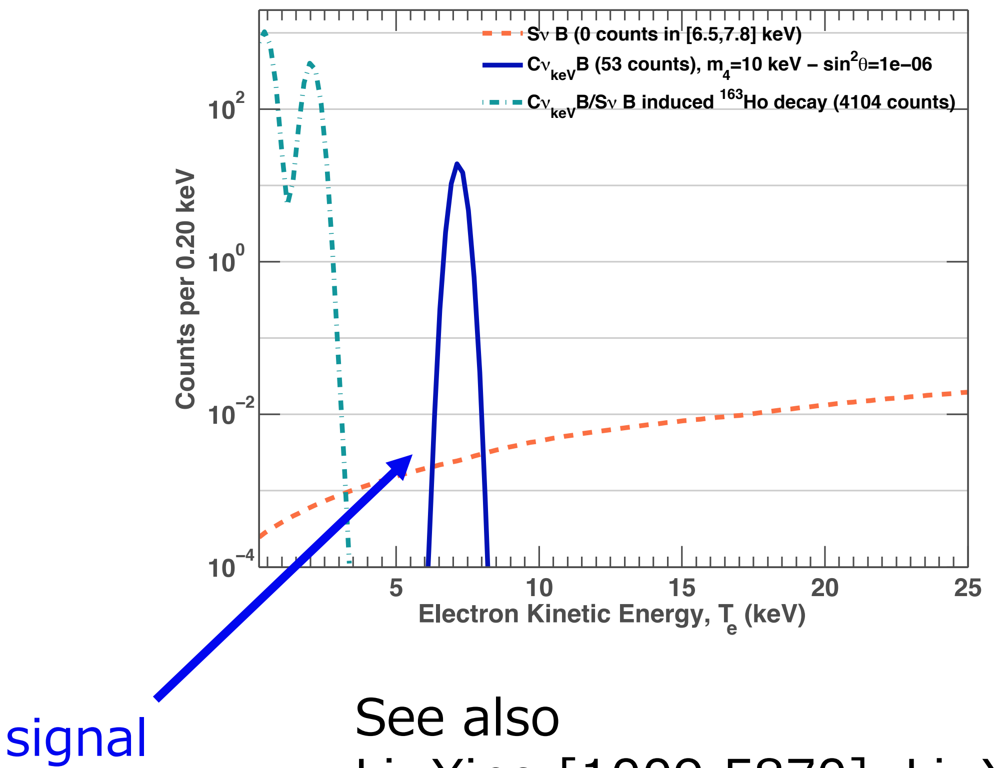


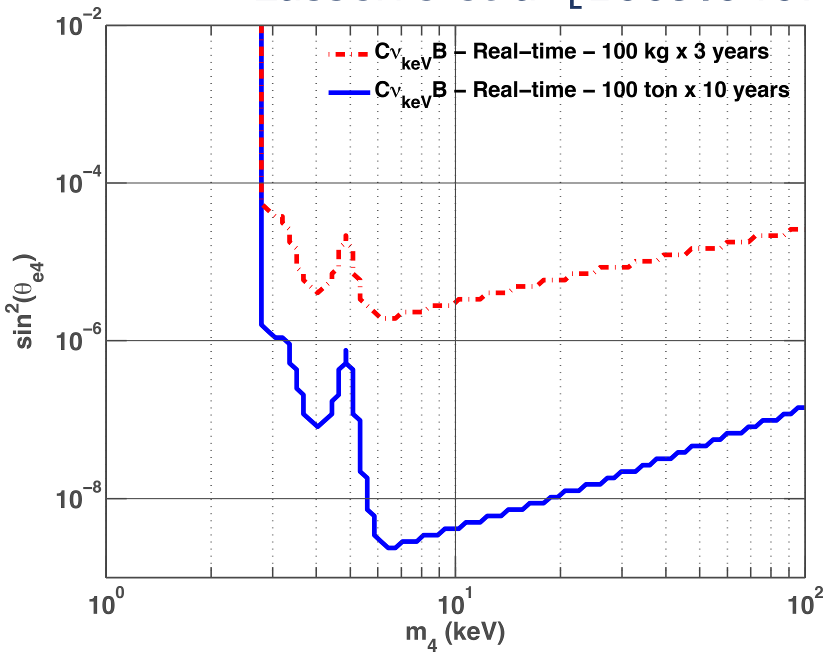
arXiv:1911.00328

Direct Search for DM

- **Laboratory searches**
  - **Beta capture: EX)** ${}^{163}_{66}\mathrm{Dy} + N_1 \rightarrow {}^{163}_{67}\mathrm{Ho}^+ + e^-$

Lasserre et al [1609.04671]





See also
Li, Xing [1009.5870], Li, Xing [1104.4000]
Long et al [1405.7654]

Consequences of DM in the $\boldsymbol{\nu}$MSM

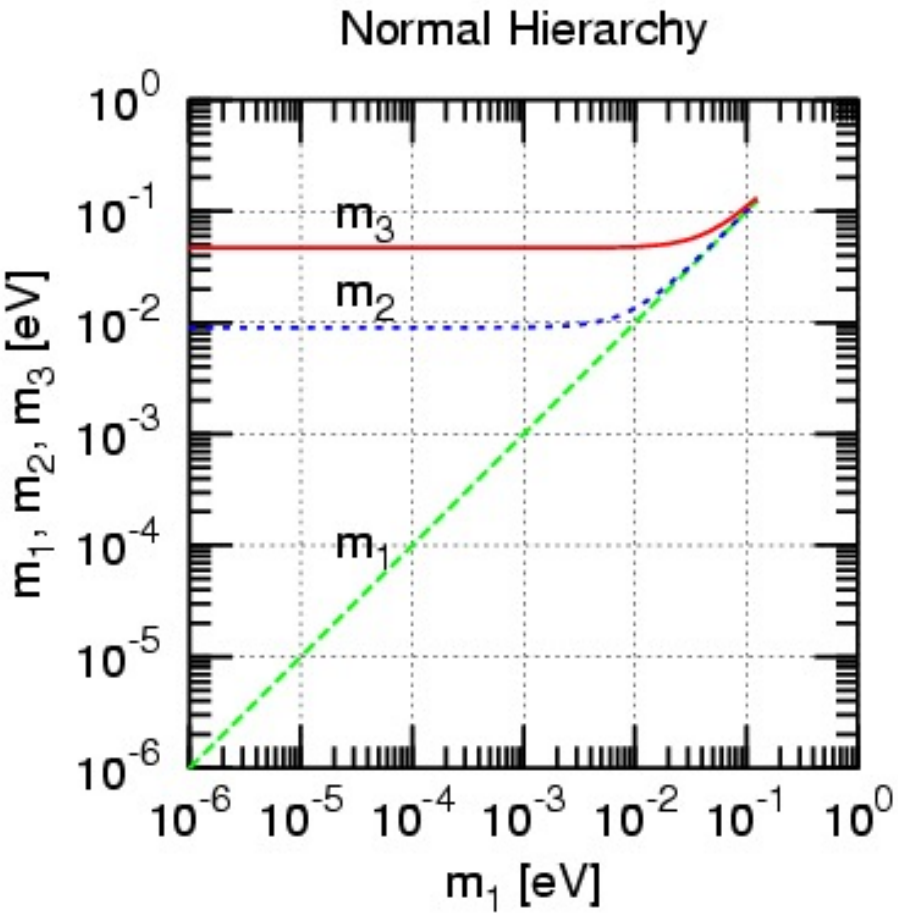
- Yukawa couplings of DM N_1 should be very suppressed
  - DM N_1 decouples from the seesaw mechanism
    - Number of RH neutrinos should be $\# \geq 3$ for explaining neutrino oscillations and dark matter
    - When #=3, the lightest active neutrino $m_1 < O(10^{-5})\mathrm{eV}$

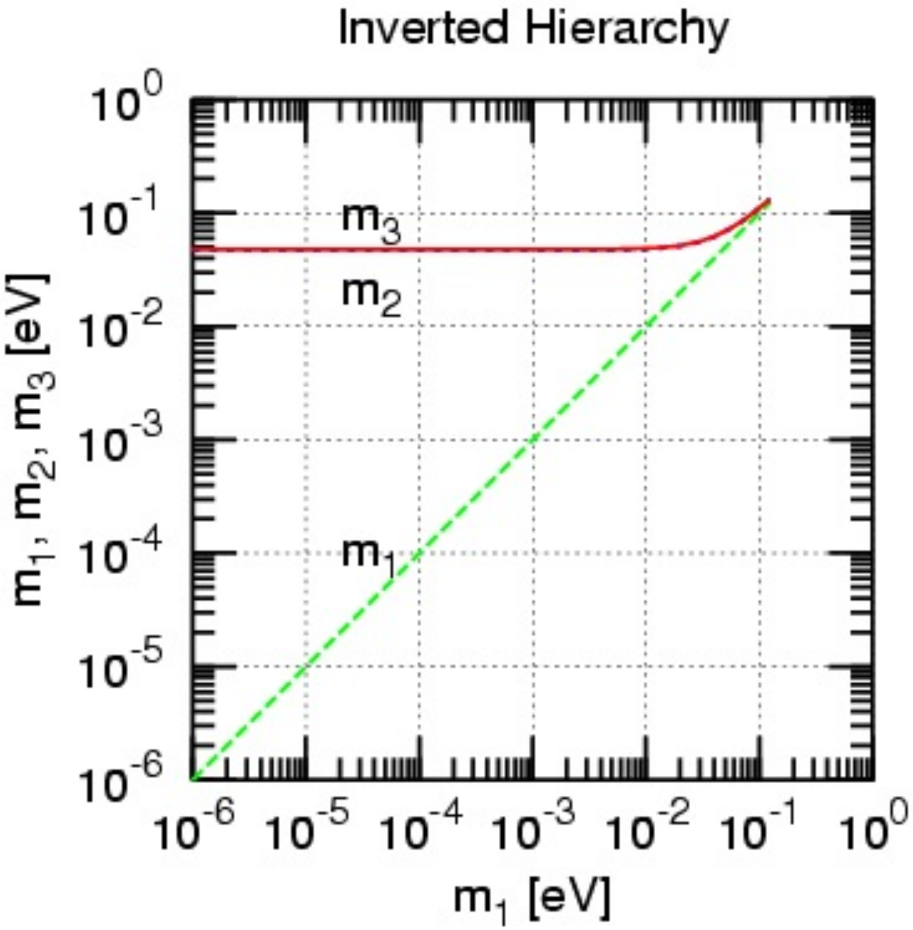
TA, Blanchet, Shaposhnikov '05

  - DM N_1 decouples from baryogenesis
  - DM N_1 decouples from 0ν2β decays   Bezrukov '05

- Heavier HNLs N_2 and N_3 are responsible for
  - Seesaw mass matrix for neutrino masses
  - Baryon asymmetry of the universe

Active neutrino masses





Baryon Asymmetry of the Universe

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, $p + p \to p + p + p + \bar{p}$

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

- Asymmetry between baryons and antibaryons in our Universe

How large ???

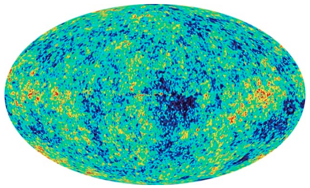
Baryon Asymmetry of the Universe (BAU)

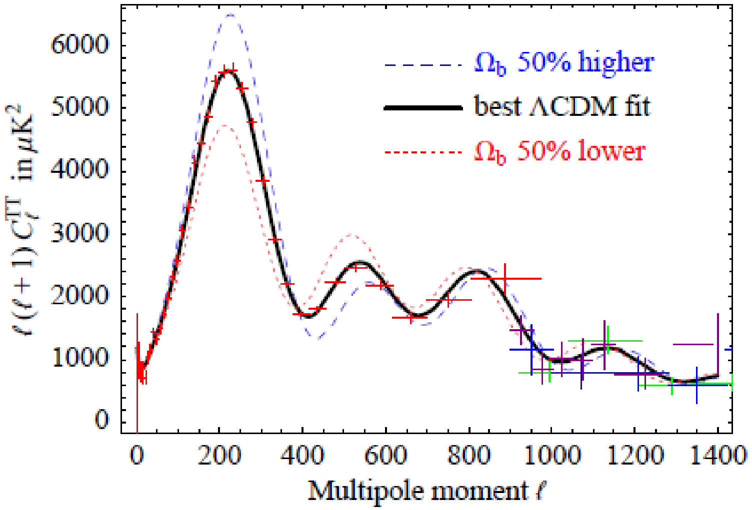
- Observational value   Planck 2018 [1807.06209]

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

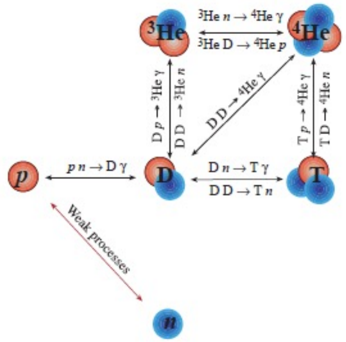
n_B : baryon number density, s : entropy density

CMBR

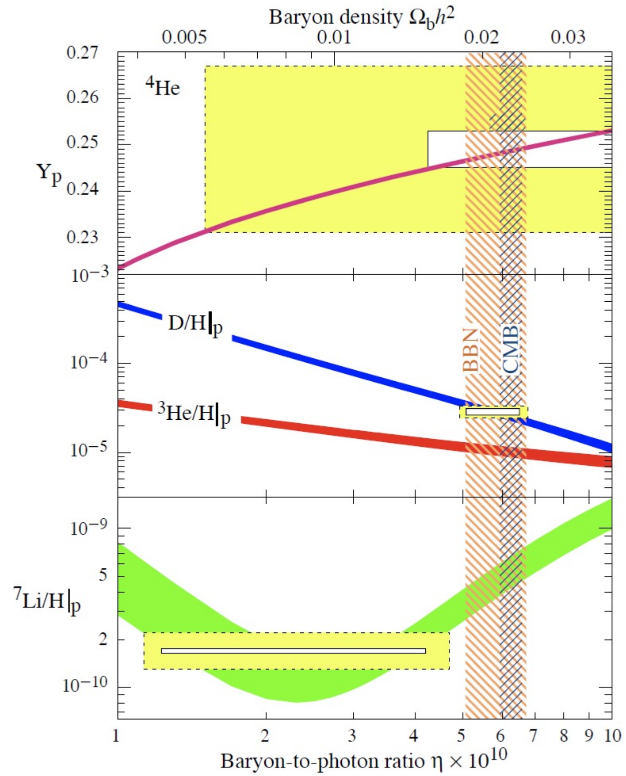




BBN



[Strumia 06]



[PDG]

Baryogenesis

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

  → Baryogenesis

- Conditions for baryogenesis: Sakharov (1967)

  (1) Baryon number B is violated

  (2) Both C and CP symmetries are violated

  (3) Out of thermal equilibrium

Baryogenesis conditions in the MSM

- B and L violation
  - B and L violations in anomalous EW "sphaleron" which is in thermal equilibrium for T>100GeV

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

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

→ too small

- Out of equilibrium
  - Strong 1st order phase transition if $m_H < 72\ \mathrm{GeV}$ but $m_H = 125\ \mathrm{GeV}$

→ not satisfied

[Kajantie, Laine, Rummukainen, Shaposhnikov]

→ We have to go beyond the MSM !!

Baryogenesis in the νMSM

■ B and L violations

- EW sphaleron
- L violation due to Majorana masses
  - Now we take Majorana masses $M_N < 100\ \mathrm{GeV}$
    - Its violating effects can be neglected for high temperatures $T > 100\ \mathrm{GeV}$

■ C and CP violations

- 1 CP phase in quark sector
- 6 CP phases in lepton sector
  - Rich CP violation

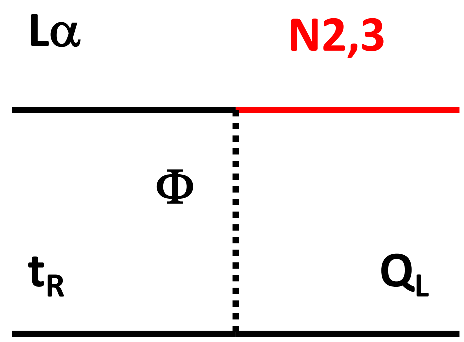
Baryogenesis conditions in the νMSM

- Out of equilibrium
  - No 1st order EW phase transition as in the MSM
  - But, sterile neutrinos can be out of equilibrium
    if Yukawa couplings are small enough
    - To ensure this condition up to T~100GeV

      ➡ $f_{1,2,3} < 2\times10^{-7}$ $[\mathrm{DM}: f_1 \simeq 6\times10^{-13}]$

    - To explain neutrino masses

      ➡ $M \leq 17\mathrm{GeV}$ (atm)



- The νMSM can potentially realize all three conditions for baryogenesis for T>100GeV

Is there a realistic scenario ???

Baryogenesis via neutrino oscillations

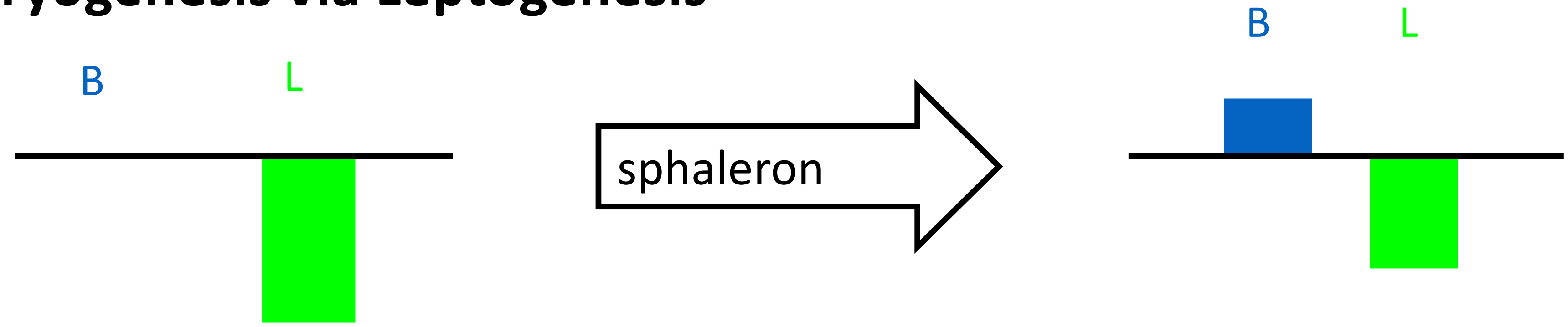
Akhmedov, Rubakov, Smirnov '98

Idea: Sterile neutrino oscillation is a source of BAU

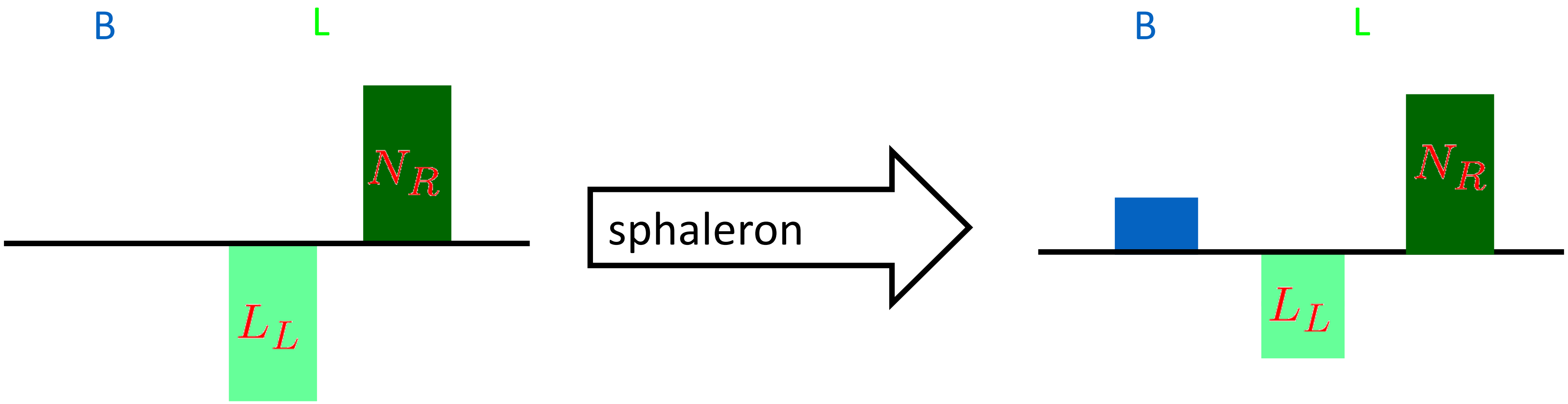
- Sterile neutrinos are created and oscillate with CPV
- The total lepton number is zero but is distributed between active and sterile neutrinos
- The asymmetry of active left-handed neutrinos is transferred into baryon asymmetry by sphaleron effects

Key Point

Baryogenesis via Leptogenesis



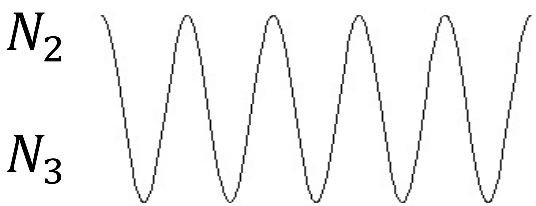
Baryogenesis via Neutrino Oscillation



Baryogenesis via Neutrino Oscillation

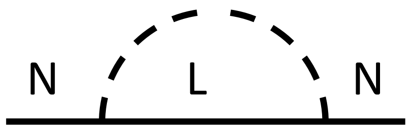
Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)
Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)
…

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

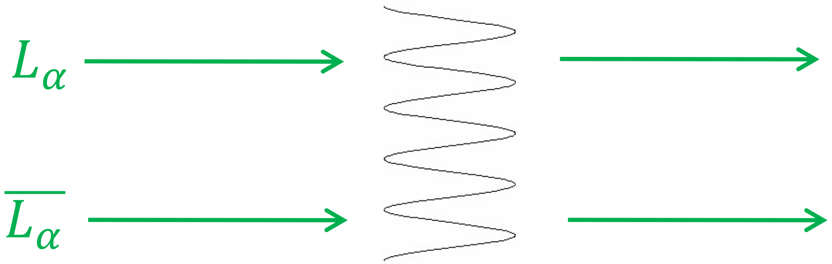


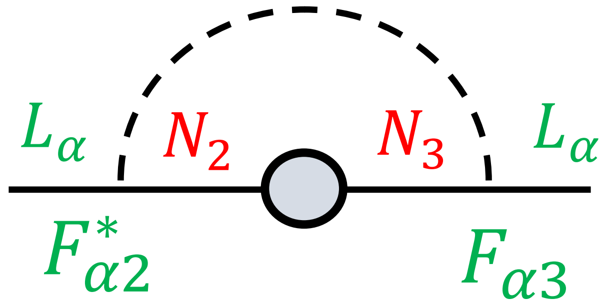
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



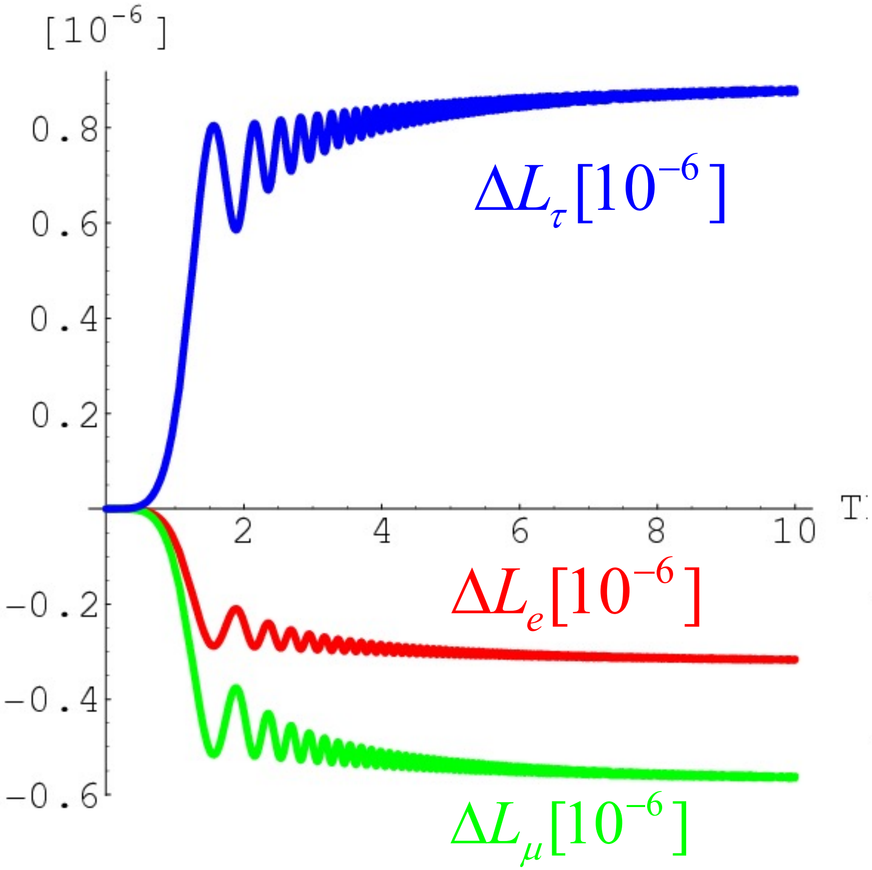
- Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV



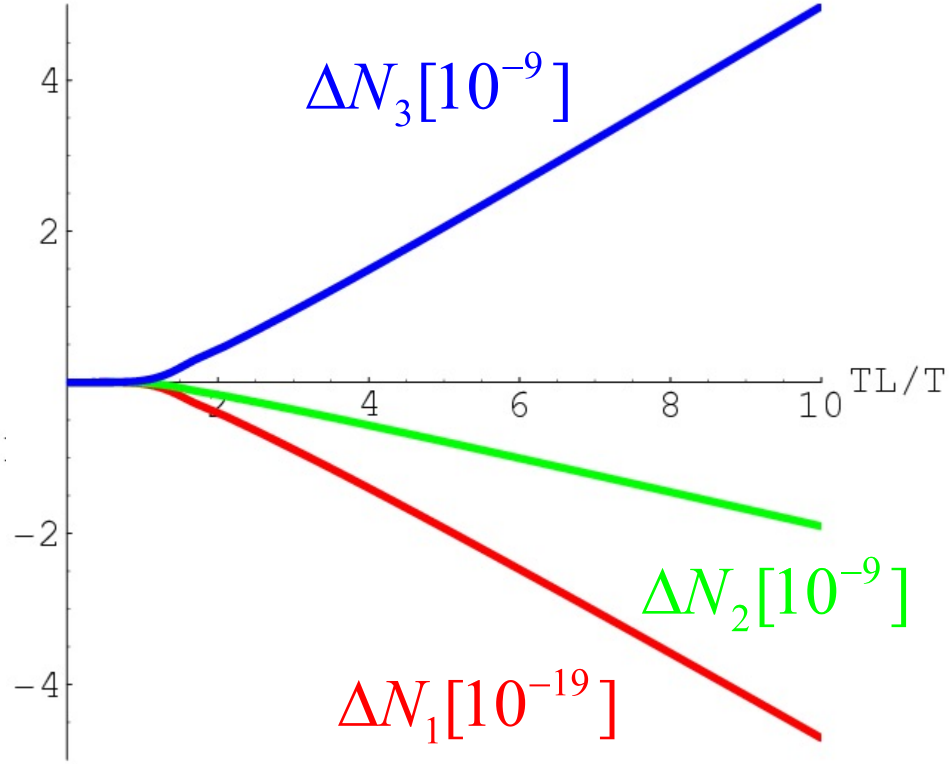


Evolution of asymmetries

Active sector



Sterile sector

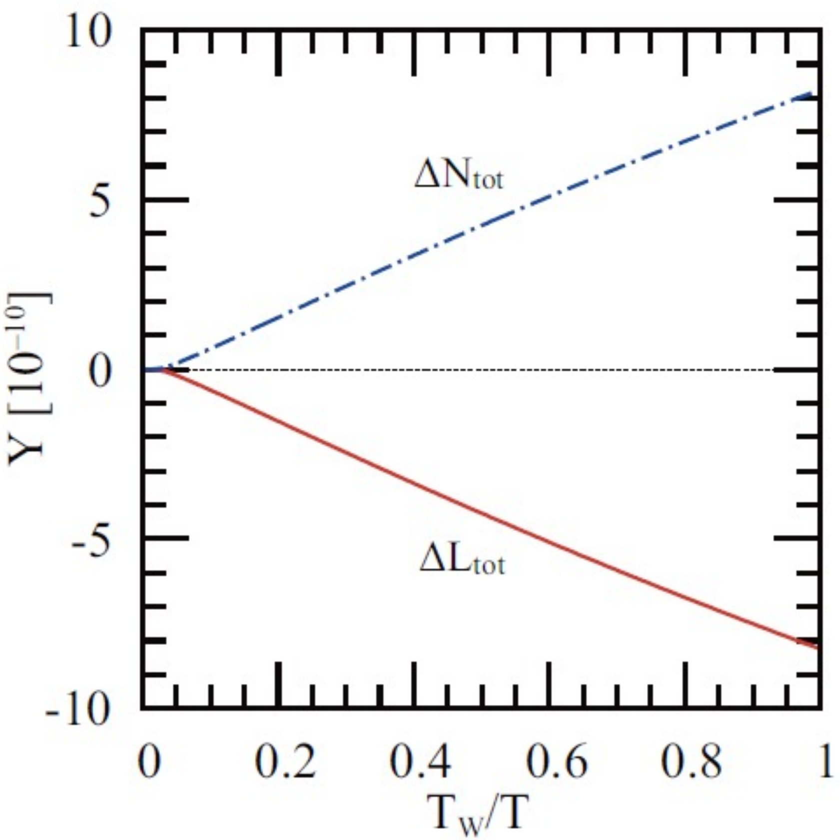


$$T_L \sim 10^4\,\mathrm{GeV}$$

Baryogenesis via neutrino osc.

Oscillation of heavy neutrinos can be a source of BAU

- 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

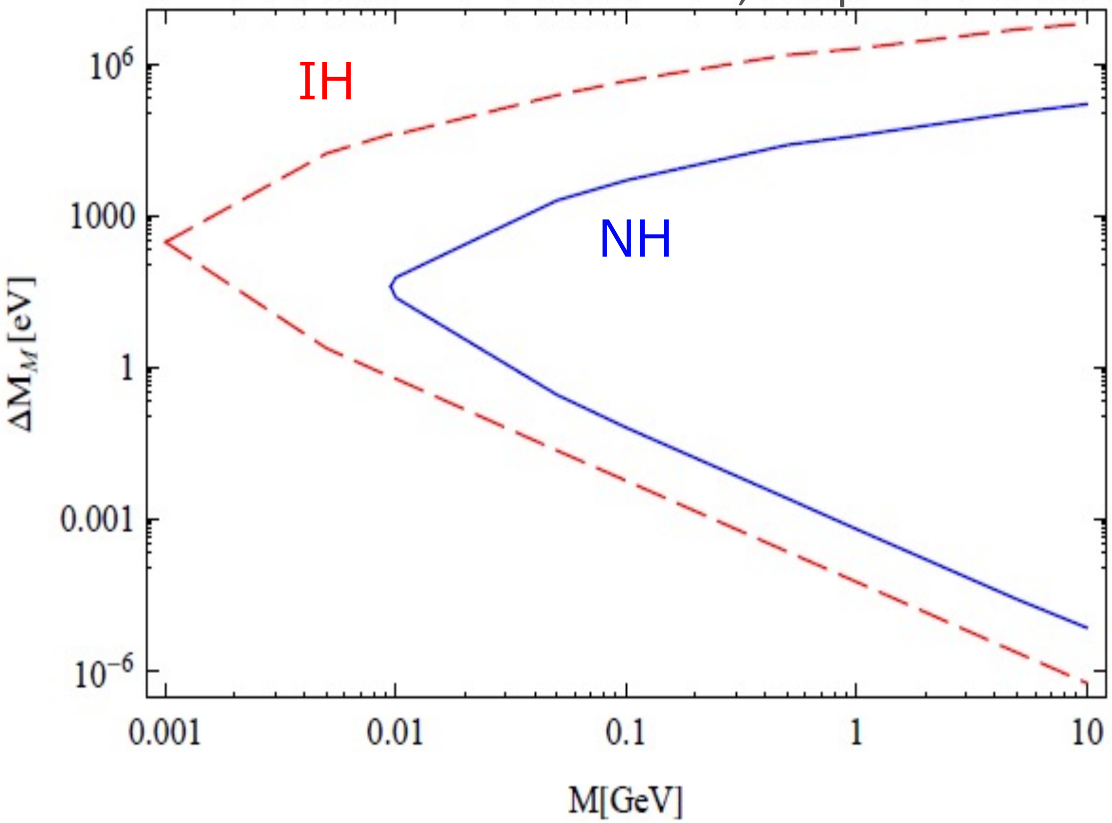
Especially, CP violating parameters and mass difference

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

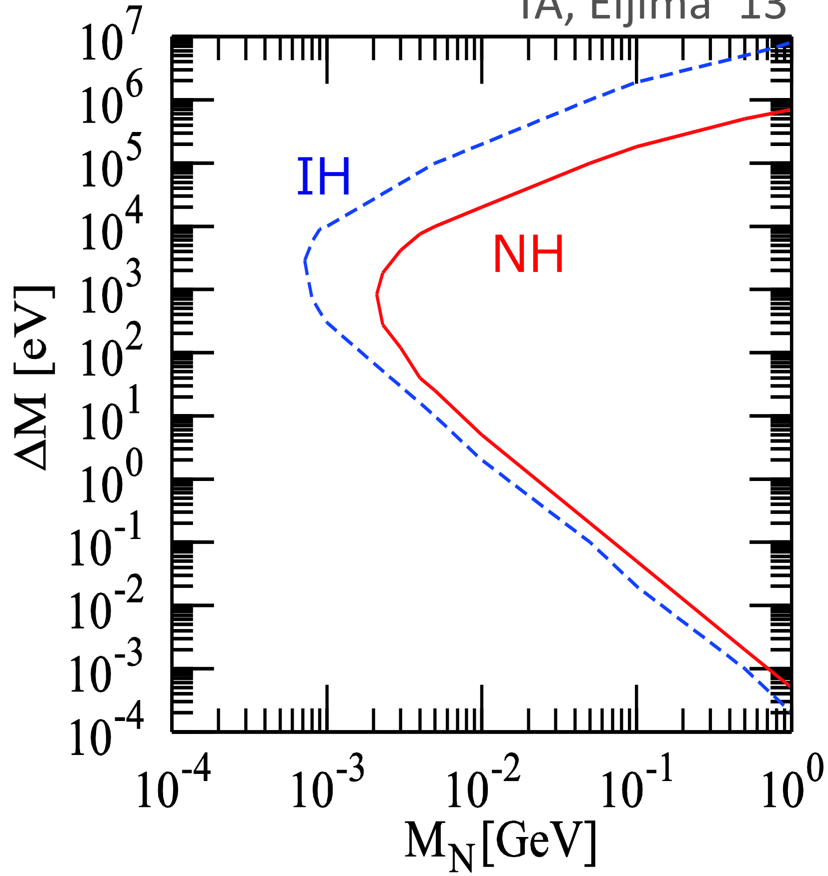
Baryogenesis Region

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

Canetti, Shaposhnikov '10



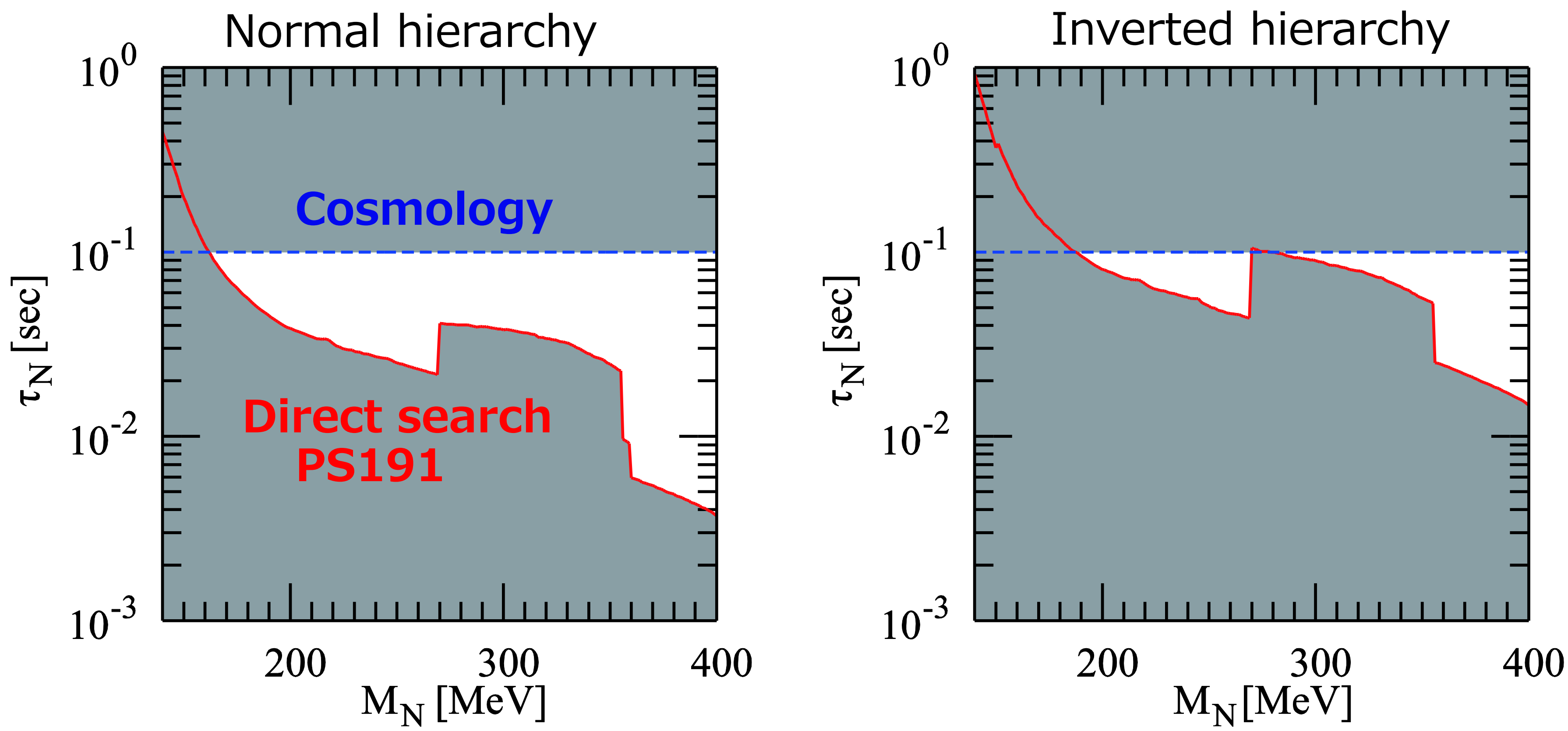
TA, Eijima '13



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

Constraints on light RH neutrinos

TA, Eijima '13

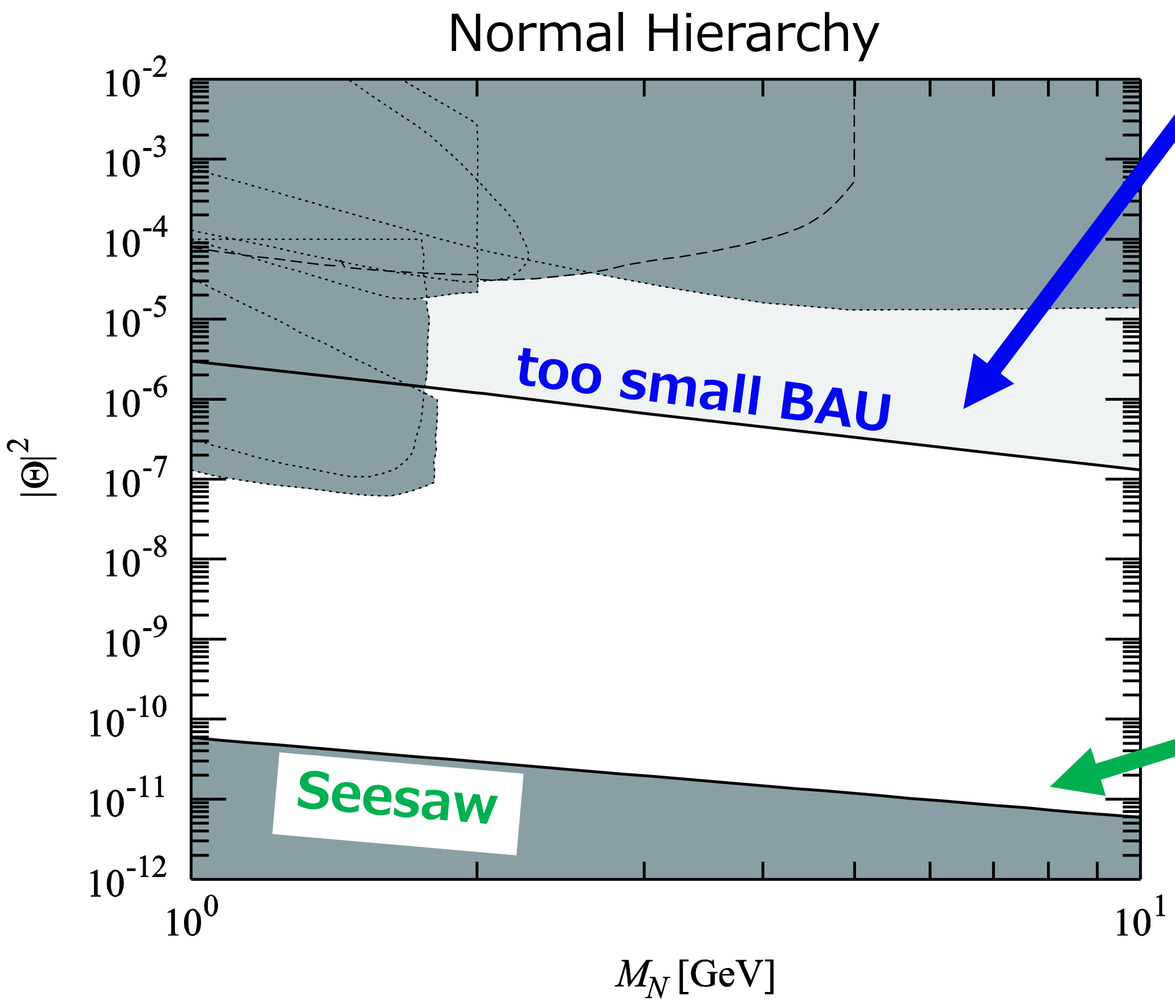


$M_N > 163$ MeV

$M_N = 188 - 269$ MeV

$M_N > 285$MeV

Baryogenesis region



Bound from BAU

to avoid strong washout

Canetti, Shaposhnikov '10 [arXiv:1006.0133]

Drewes, Garbrecht, Gueter, Klaric '16 [arXiv:1609.09069]

TA, Eijima, Ishida, Minogawa, Yoshii '17 [arXiv:1704.02692+α]

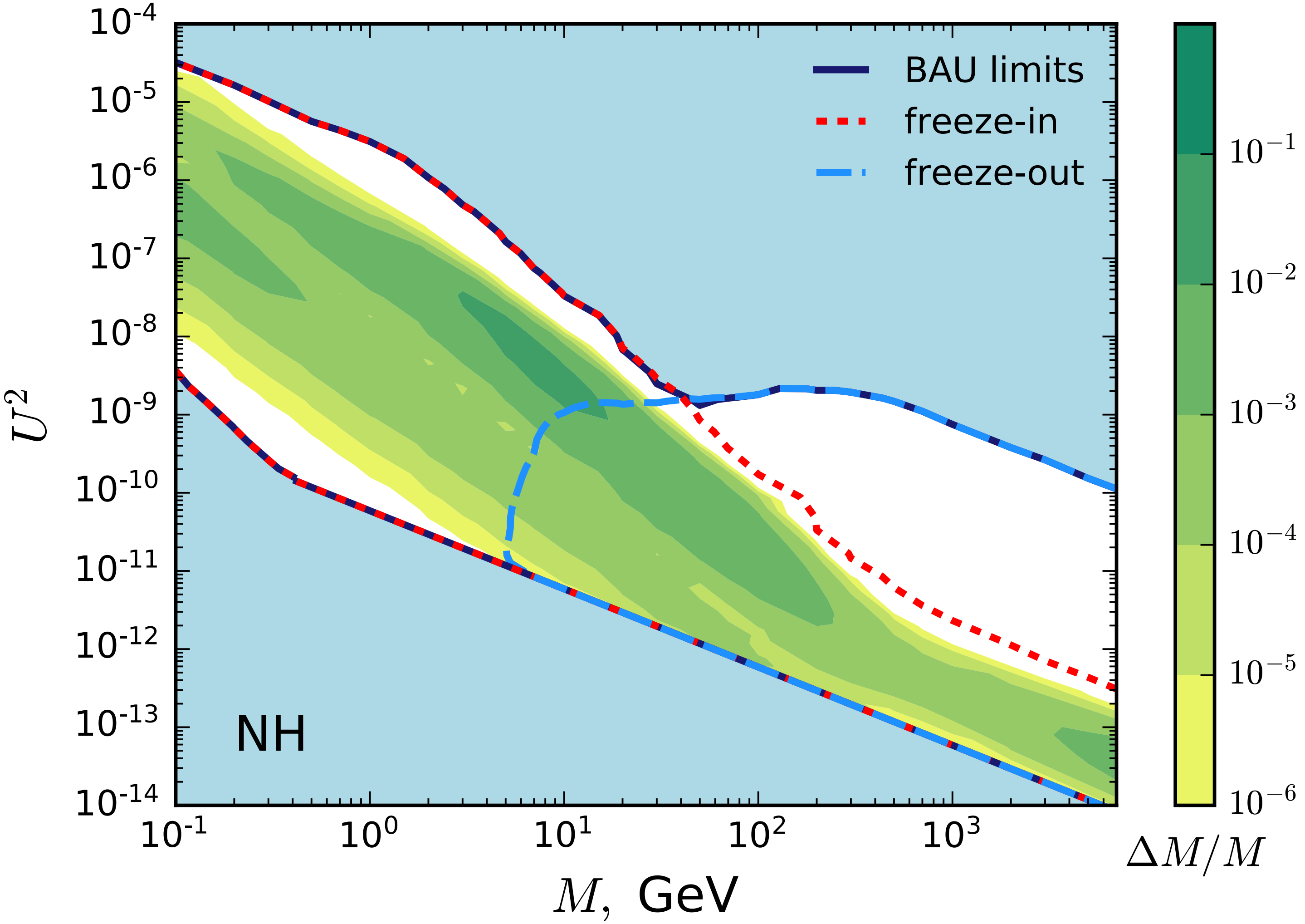
Bound from Seesaw

to explain neutrino masses

$$|\Theta|^2 > \frac{\Sigma m_i}{2\, M_N}$$

Baryogenesis Region (recent progress)

Klaric, Shaposhnikov, Timiryasov arXiv:2103.16545

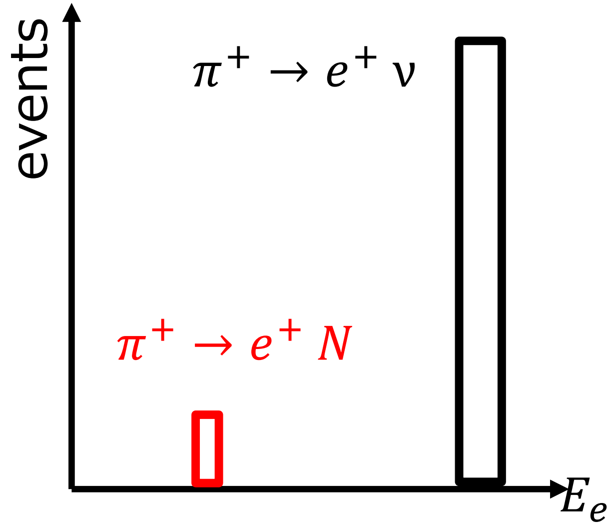


Direct searches

■ Peak search in meson decays ($M^+ \to \ell^+ N$) [Shrock '80]

- Measure E_e in $\pi^+ \to e^+ N$

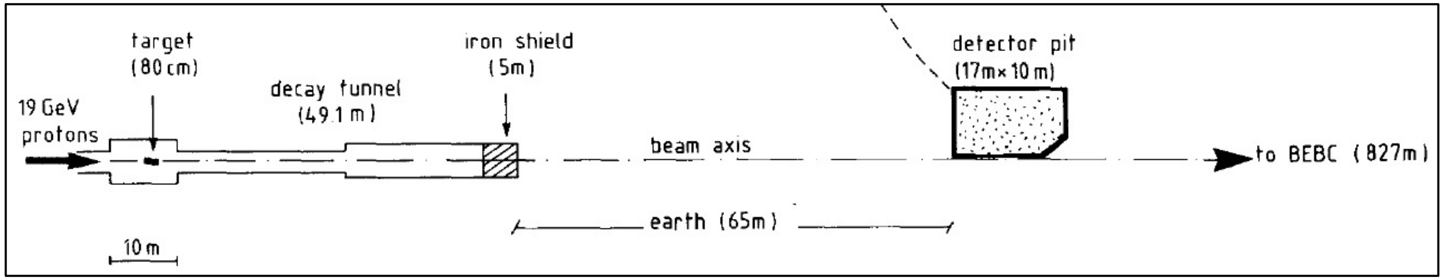
$$E_e = \frac{m_\pi^2 - m_e^2 - M_N^2}{2\, m_\pi}$$



■ Beam dump experiments

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

CERN PS191



→ SHiP, LBNE (now DUNE)

Direct searches @colliders

- Search @LEP
  - $Z \to \nu N \quad (3.3\times 10^6\ Z)$

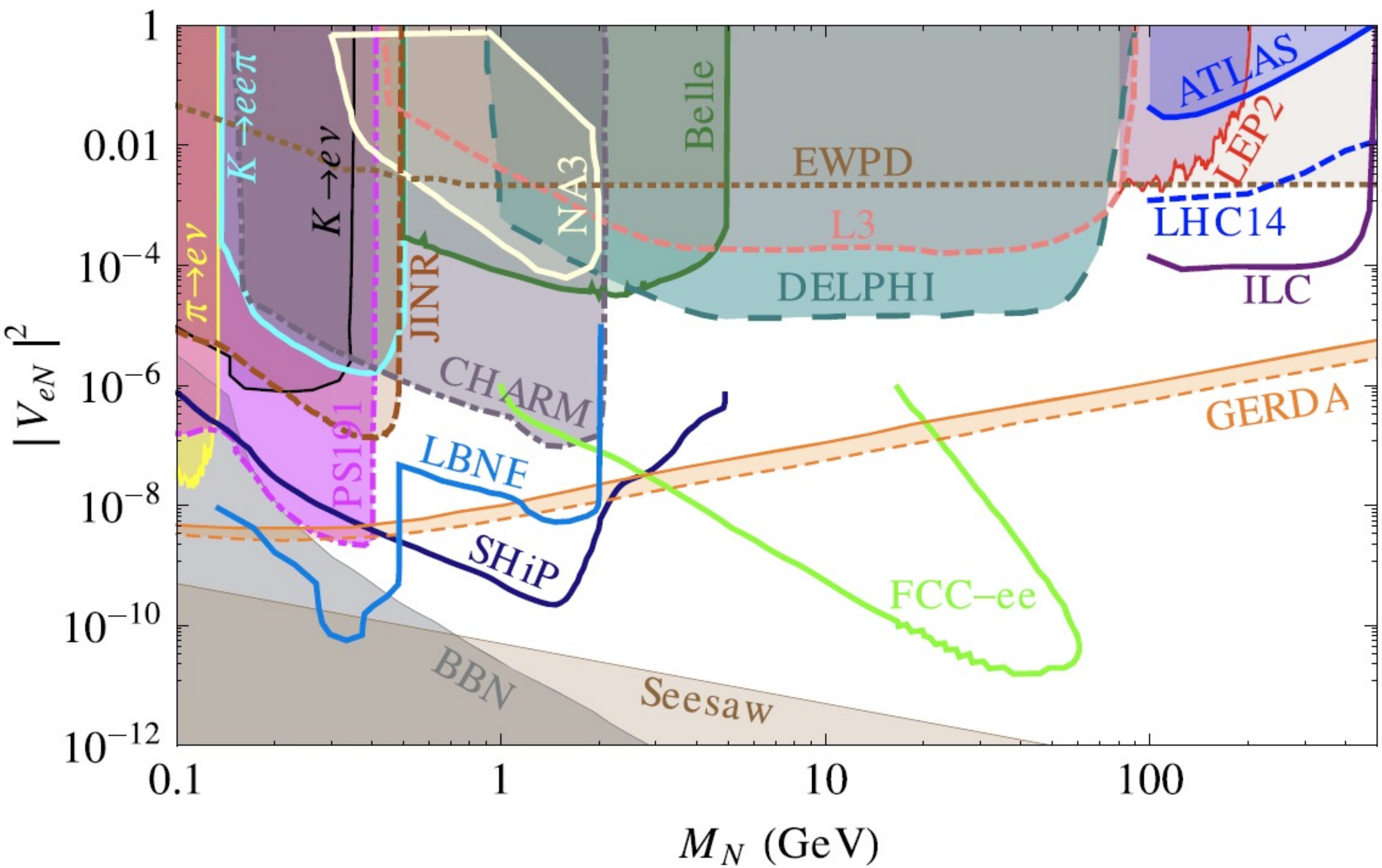
    → FCC-ee $(10^{12}\ Z)$
- Search @LEPII
  - $e^+ e^- \to \nu N\ (N \to e\, W$ with $W \to jets)$

    → ILC $(\sqrt{s} = 500\ \mathrm{GeV}, 500\ \mathrm{fb}^{-1})$
- Search @LHC
  - $pp \to \ell^+ N \to \ell^+\ \ell^+ j\, j$
- Search @LHCb
  - $B^- \to N\,\mu^- \to\ \pi^+\ \mu^-\ \mu^-$
- Search @Belle/Belle II
  - $B^- \to X \ell N,\ N \to e^\pm \pi^\mp,\ \mu^\pm \pi^\mp$

Limits on mixing of HNL

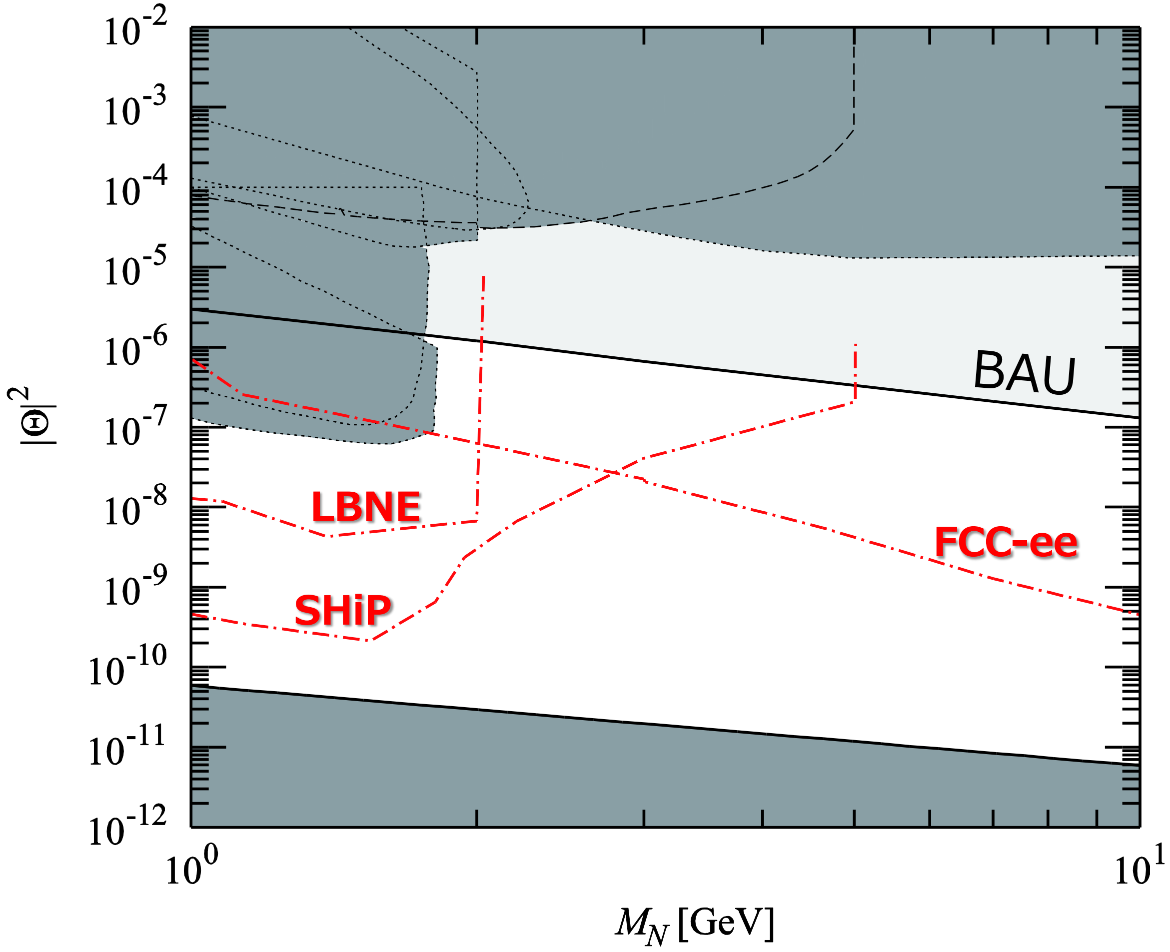
- Limits on mixing Θ_{eI}

Deppisch, Dev, Pilaftsis '15



Sensitivities by future searches

Normal Hierarchy



Sensitivity for $|\Theta_\mu|^2$

- **LBNE (DUNE)**
  N decay inside near detector
  Adams et al '13 [arXiv:1307.7335]

- **SHiP**
  beam dump exp.
  Anelli et al '13 [arXiv:1504.04956]

- **FCC-ee at Z-pole**
  displaced vertex of N decay
  Blondel, Graverini, Serra, Shaposhnikov (FCC-ee study team) '14 [arXiv:1411.5230]

Search for HNLs at T2K

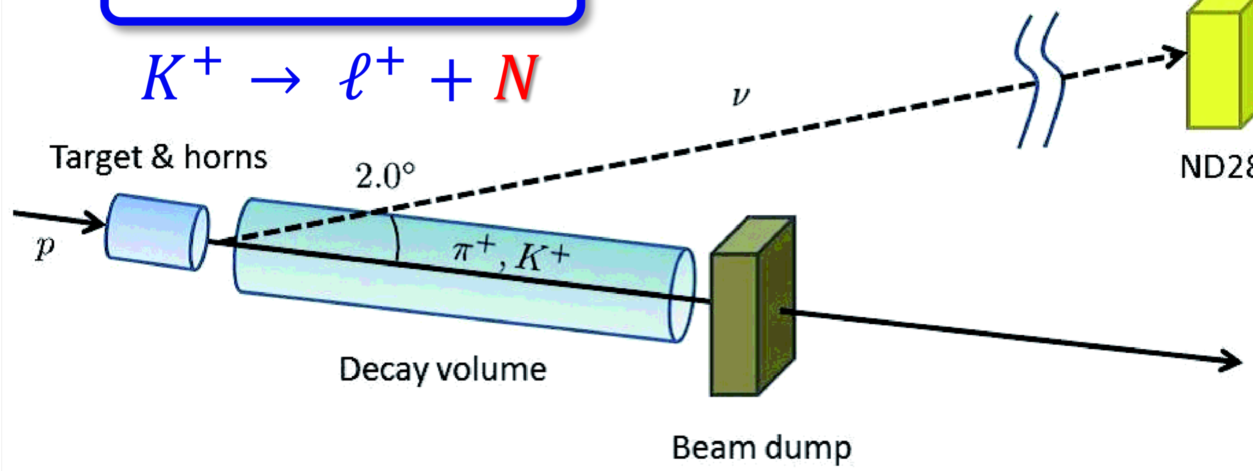
TA, Eijima, Watanabe
[JHEP1303 (2013) 125]

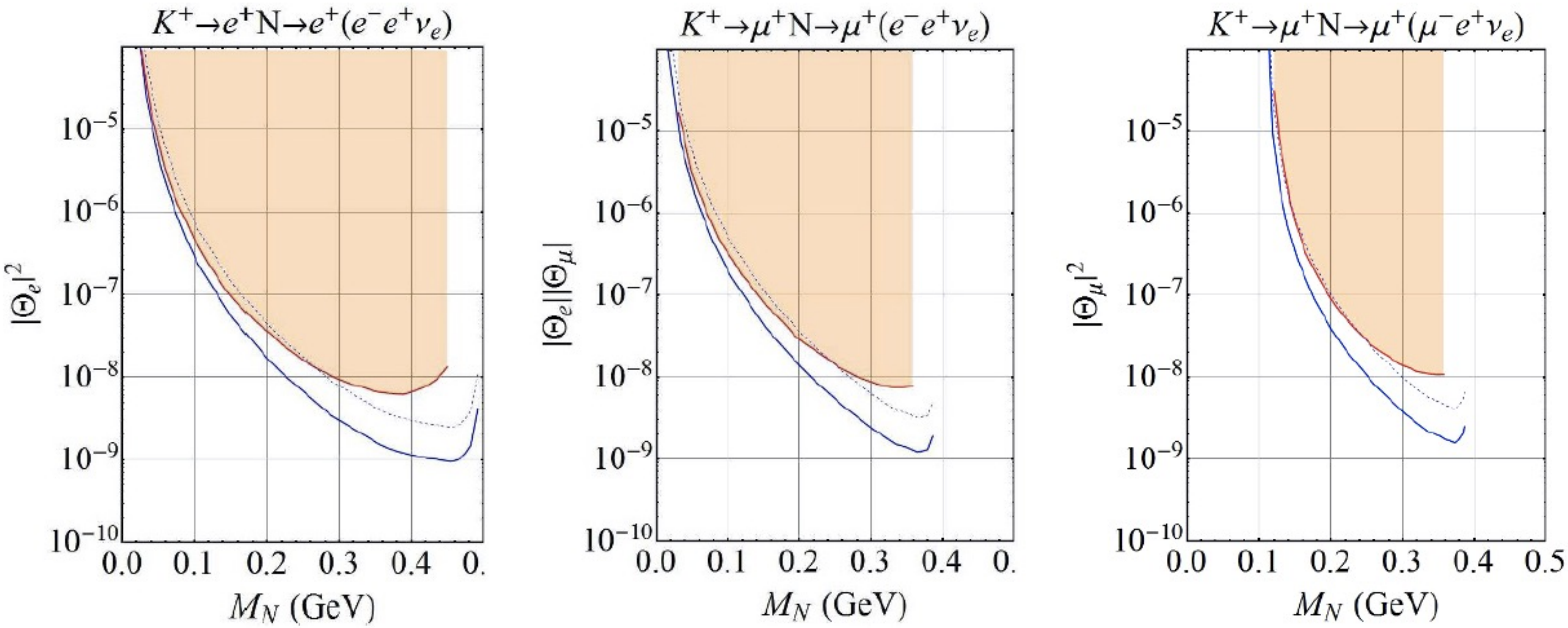
Production of N

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

Detection of N

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





Search for heavy neutrinos with the T2K near detector ND280

(The T2K Collaboration)

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

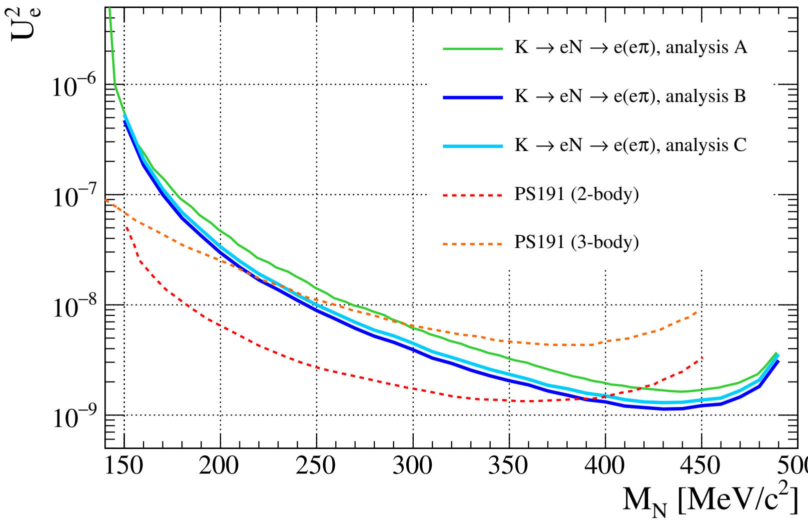


FIG. 5. 90% upper limits on the mixing element U_e^2 as a function of heavy neutrino mass using the single-channel approach, considering only the contribution from $K^{\pm} \to e^{\pm}N, N \to e^{\pm}\pi^{\mp}$, with the three methods **A**, **B** and **C**. The limits are compared to the ones of PS191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

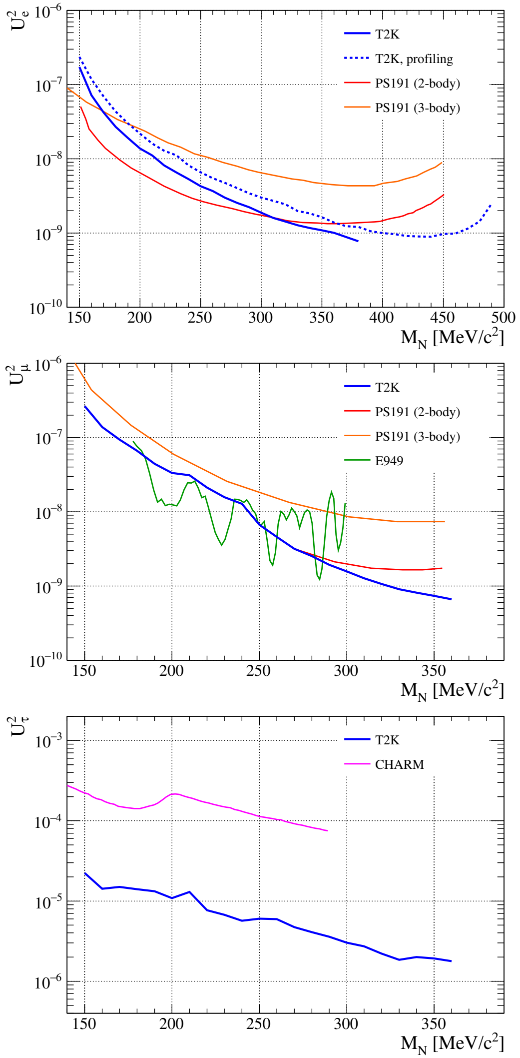


FIG. 6. 90% upper limits on the mixing elements U_e^2 (top), U_μ^2 (middle), U_τ^2 (bottom) as a function of heavy neutrino mass, obtained with the combined approach. The blue solid lines are obtained after marginalisation over the two other mixing elements. In the top plot, the additional blue dashed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

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

W.H. Furry 1939

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

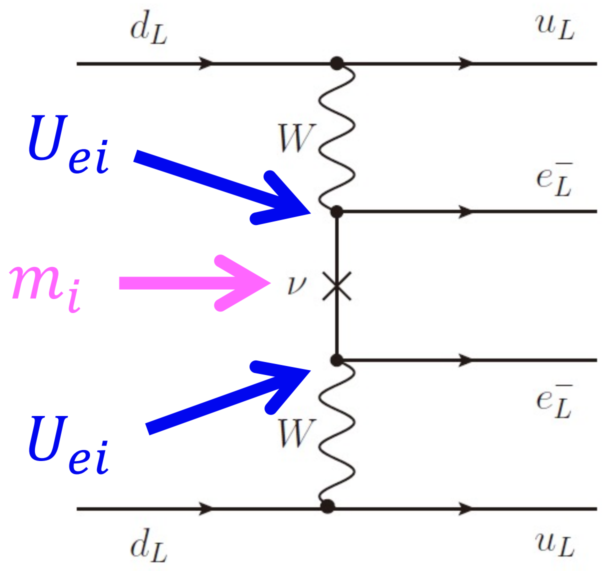
  $(Z, A) \rightarrow (Z+2, A) + 2e^-$

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

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

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

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



Summary

Summary

- The νMSM is SM with three RH neutrinos with $M_M \lesssim M_W$
  - **Lightest Heavy Neutral Lepton (N1)**
    - **Dark Matter** with M_1 ~keV
    - Simple production scenario conflicts with cosmological obs.
  - **Heavier Heavy Neutral Leptons (N2 and N3)**
    - Quasi-degenerate with M_N~100MeV-10GeV
    - Seesaw mechanism for **masses of active neutrinos**
    - **Baryon Asymmetry of the Universe (BAU)** through the mechanism via neutrino oscillation

- Heavy neutral leptons in the νMSM can be tested experimentally

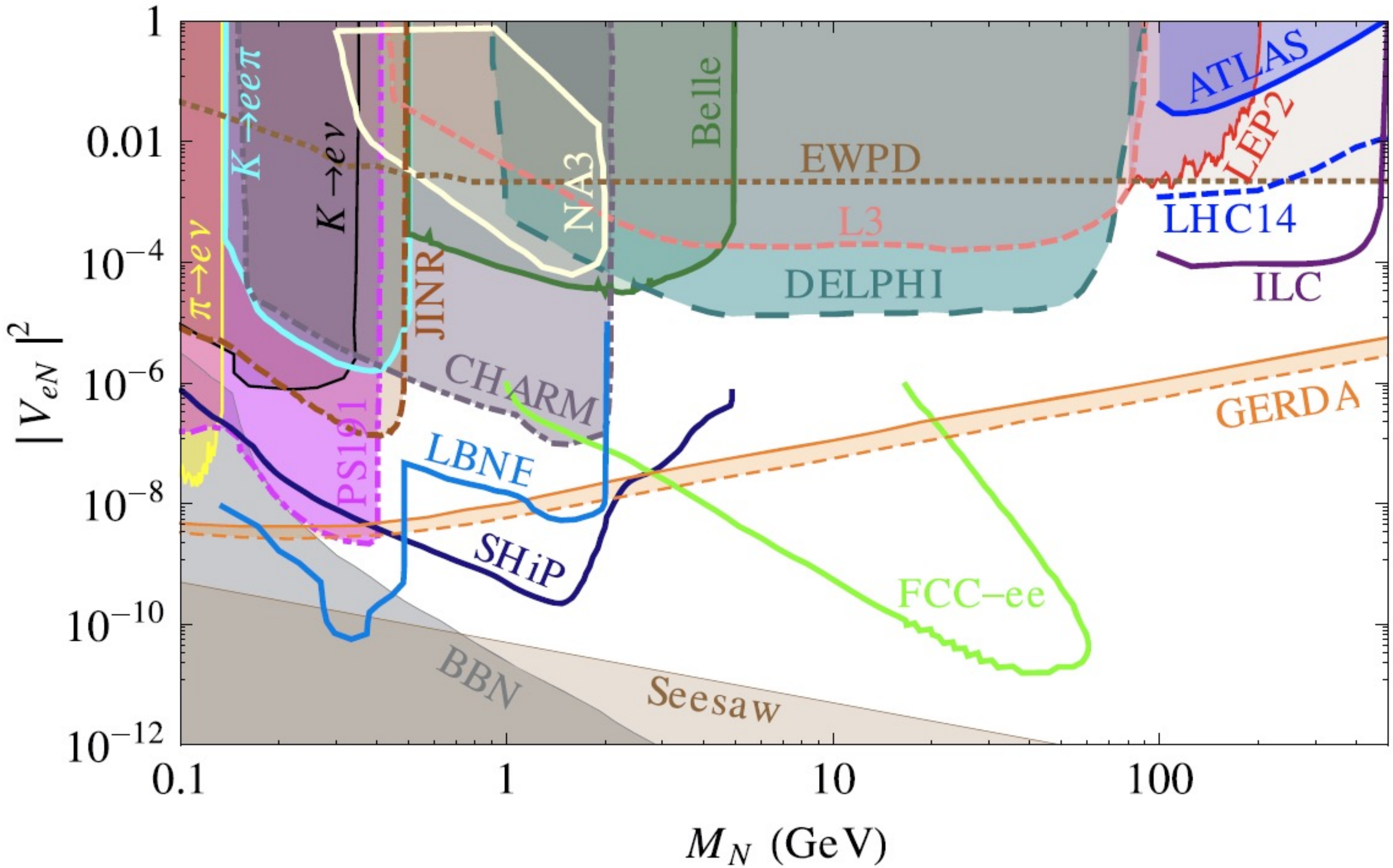
Hunting, Discovering, Producing and Measuring HNLs are crucial to identify the origin of neutrino masses, but also to reveal mysteries of our universe (DM, BAU, ⋯) !!!

Backup

Limits on mixing of HNL

- Limits on mixing Θ_{eI}

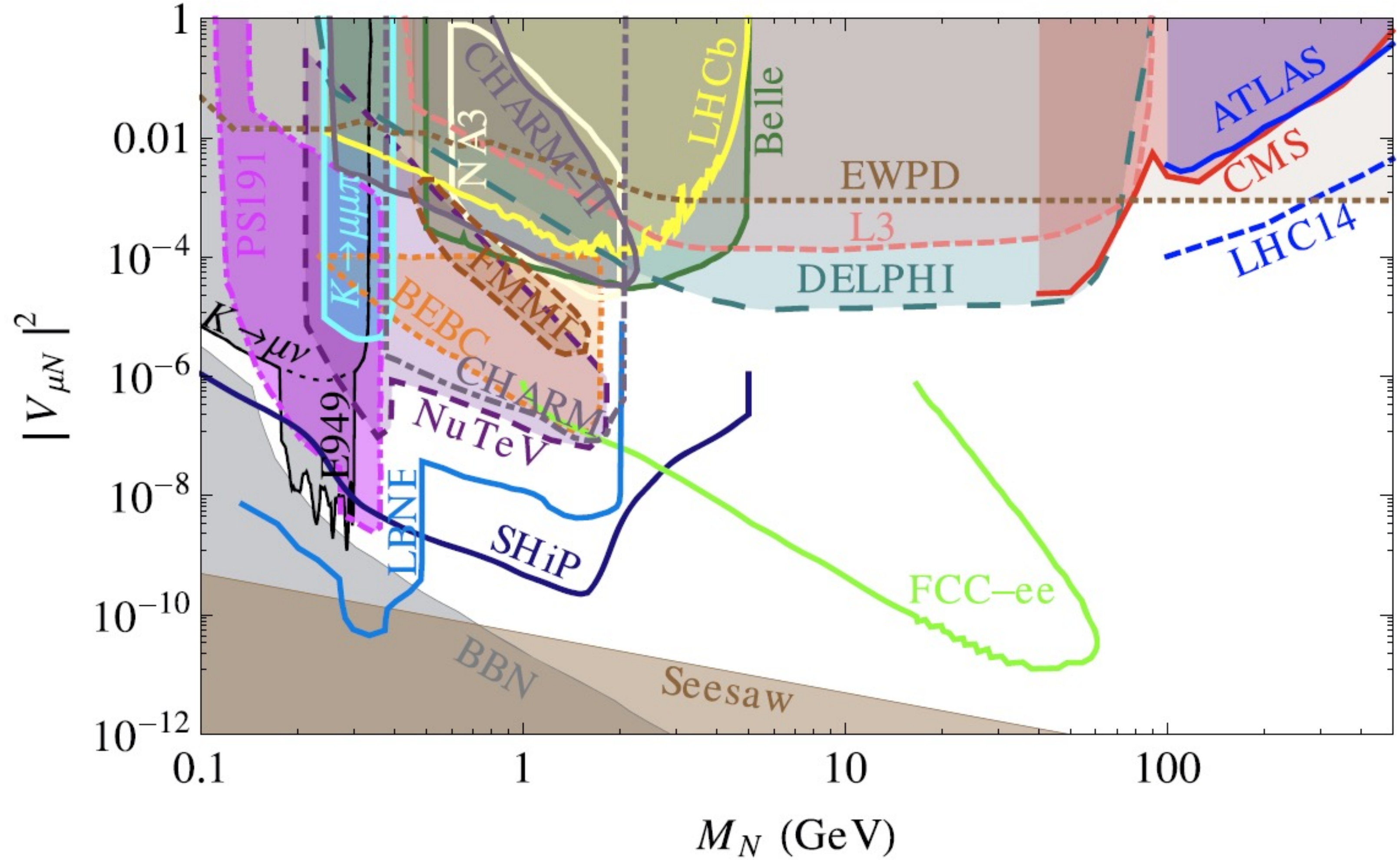
Deppisch, Dev, Pilaftsis '15



Limits on mixing of HNL

- Limits on mixing $\Theta_{\mu I}$

Deppisch, Dev, Pilaftsis '15



Limits on mixing of HNL

- Limits on mixing $\Theta_{\tau I}$

Deppisch, Dev, Pilaftsis '15