Roles of sterile neutrino in Particle Physics and Cosmology

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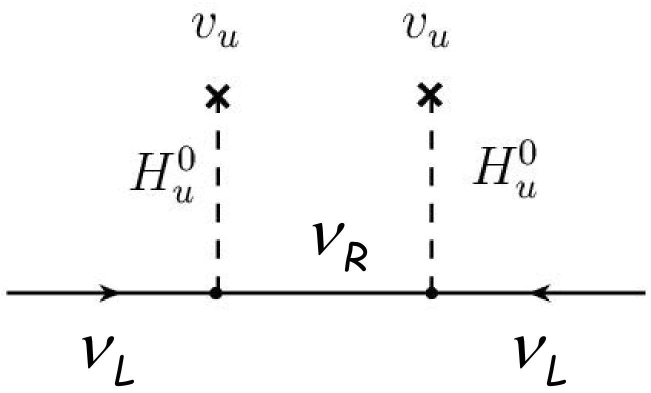
Outline

- Why do we need sterile neutrino ?
- Any hint for sterile neutrino?
- What would sterile neutrino affect ?
- Sterile neutrino as DM
- Roles in baryogenesis

Why do we need sterile neutrino ?

- In theory-
  - massive neutrinos
    - Simple way is to add a Dirac mass term : $m \, \overline{\nu_L} \, \nu_R$
    - This requires ν_R.
    - Then no (SM) principle prevents the occurrence of $M \, \overline{\nu^c_R} \, \nu_R$

Type I see-saw mechanism



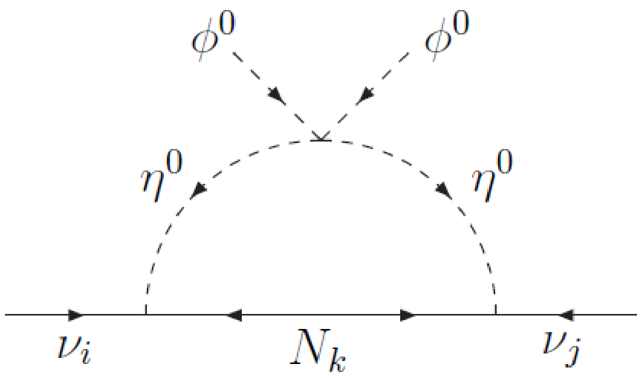
$$m_{LL}^{I} \approx -m_{LR} M_{RR}^{-1} m_{LR}^{T}$$

Why do we need sterile neutrino ?

- Radiative generation of neutrino mass

  - SM be extended to include 3 ν_R and a 2nd scalar doublet (η^+, η^0) : odd under Z_2

  - The usual Yukawa term $(\nu\phi^0 - \ell\phi^+)\,\nu_R$ forbidden but $(\nu\eta^0 - \ell\eta^+)\,\nu_R$ is allowed.



$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik} h_{jk} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right].$$

Why do we need sterile neutrino ?

- In cosmology,
  - We need Dark Matter.
    So, sterile neutrino can be a good DM candidate.
  - Sterile neutrinos can play an essential role in baryogenesis.

Why do we need sterile neutrino ?

- In experiments,
  - To open new phase to search for new physics, we need to find sterile neutrinos
  - Anomalies from neutrino oscillation call for sterile neutrinos

Any Hint for Sterile Neutrino ?

- From neutrino oscillation experiments

"Sterile" neutrinos can mix with active neutrinos

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$\sin^2 2\theta$ ⇒ Gives effective interaction strength of the sterile neutrino relative to the standard ***Weak Interaction***

Any Hint for Sterile Neutrino ?

- From neutrino oscillation experiments

  Oscillations into ν_s are now excluded as the dominant solution in solar and atmospheric neutrinos:

  solar: ~~$\nu_e \rightarrow \nu_s$?~~ no, $\nu_e \rightarrow \nu_{\mu\ \tau}$ (SNO)

  atmo: ~~$\nu_\mu \rightarrow \nu_s$?~~ no, $\nu_\mu \rightarrow \nu_\tau$ (SK, Macro)

Any Hint for Sterile Neutrino ?

- Anomalies from SBL experiments

- LSND : search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with L/E~0.4÷1.5 m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events (LSND, 2001)

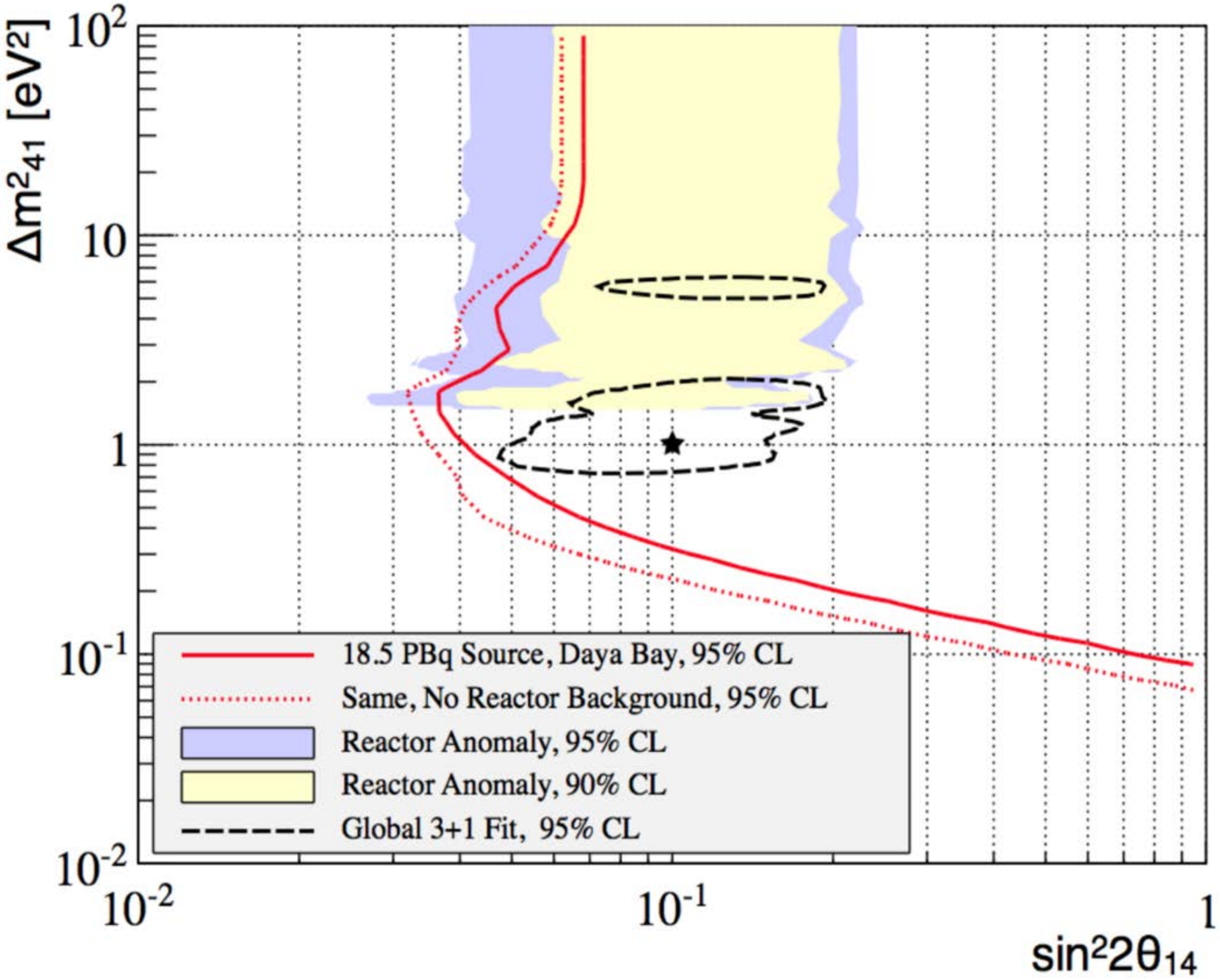
- Gallium : calibration of GALLEX and SAGE Gallium solar ν exp. gives a 2.7 σ anomaly (disappearance of ν_e) (Giunti, Laveder, 2011)

- Reactor : re-evaluation of the expected $\bar{\nu}$ flux shows disapp. of $\bar{\nu}_e$ events compared to predictions (~3 σ) with L<100 m (Azabajan et al., 2012)

- MiniBooNE : search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with L/E = 0.2 ÷2.6 m/MeV. No ν_e excess detected , but $\bar{\nu}_e$ excess observed at 2.8 σ. (MiniBooNE, 2013)

Any Hint for Sterile Neutrino ?

- Pointing to possibly another mass squared difference
- Call for O(eV) sterile neutrino



Comments on the analyses in terms of sterile neutrino (Giunti, Schwetz….)

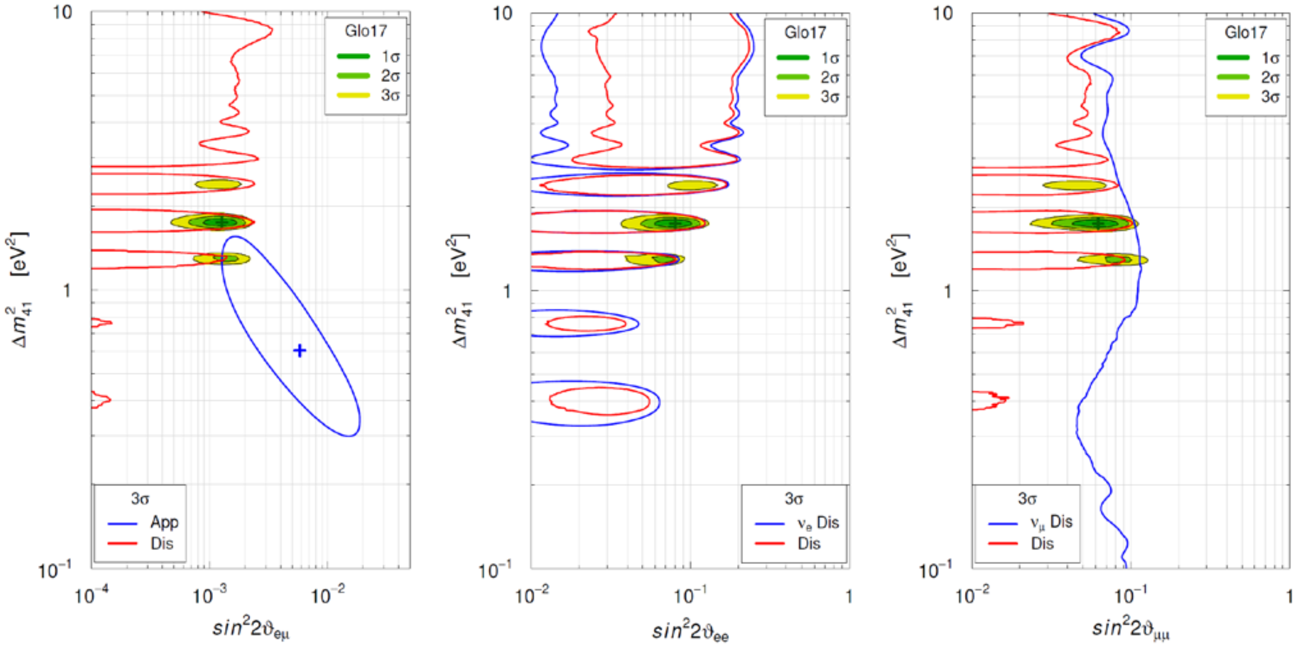
- Two experimental tensions :
  (1) LSND and MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ vs. MiniBooNE $\nu_\mu \rightarrow \nu_e$
  (2) LSND and MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ vs. $\bar{\nu}_e$ and ν_μ disappearance limits

- 3+1 mixing shows tension
- between app. and disapp.

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu 4}|^2$

$\nu_\mu \rightarrow \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]



(a) (b) (c)

- 3+2 mixing can explain tension(1) and reduce tension between app. and disapp.

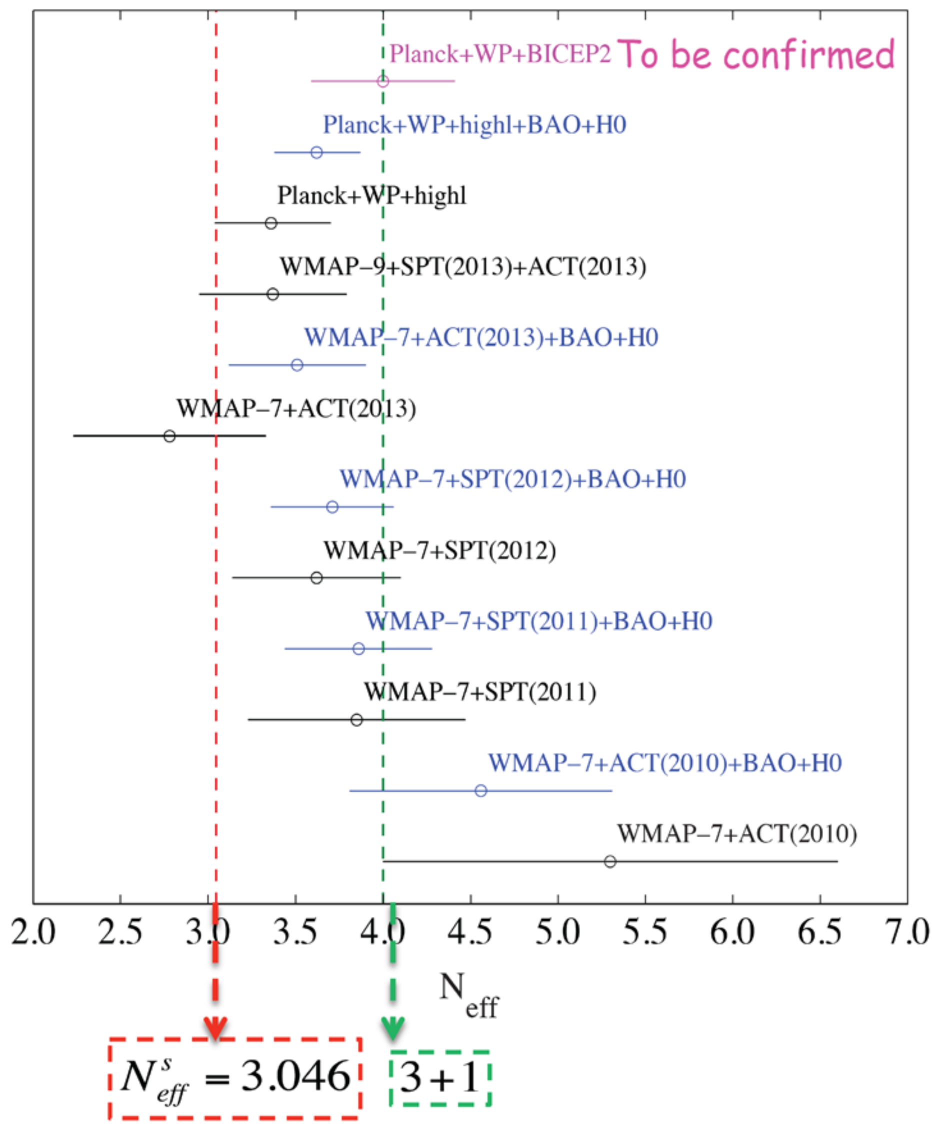
Any Hint for Sterile Neutrino ?

- In Cosmology
  - hint from CMB (radiation energy density ρ_r in the earl Univ.)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

For active neutrinos : $N_{eff} = 3.046$

  - current result : $N_{eff} = 3.36 \pm 0.34$



Any Hint for Sterile Neutrino ?

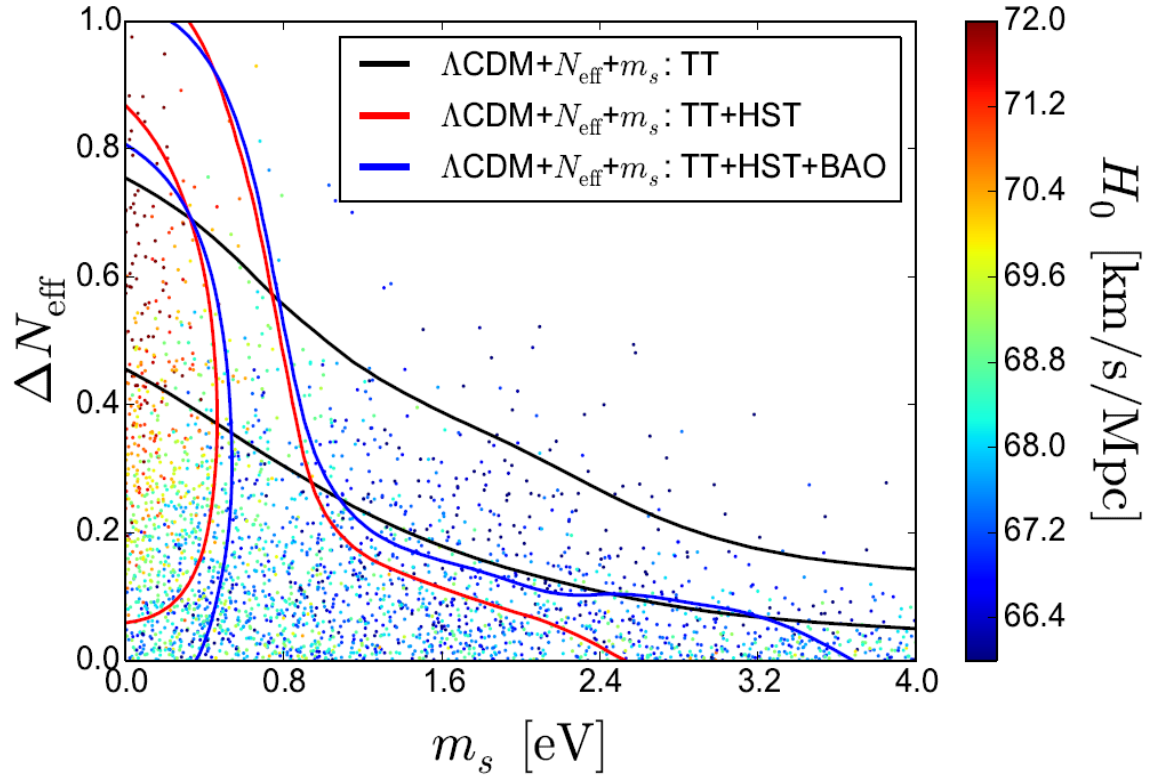
- In Cosmology

-For non-relativistic ν_s (1eV ν_s is non-relativistic today) thermal production →

$$m_s^{\rm eff} = \Delta N_{\rm eff}^{3/4} m_s$$

- From Planck data, $\Delta N_{eff} = 1$ is incompatible with $m_s{\sim}1$ eV.

(Archidiacono et al., JCAP 08, 2016)



What does sterile neutrino affect ?

- Neutrino oscillation
- Pattern of neutrino mixing matrix
- CP violation & unitarity of neutrino mixing matrix
- B & K physics
- Neutrinoless double beta decay
- Solution to reactor neutrino anomaly
- Serve as warm dark matter
- Existence of non-standard interactions
- Affects on lepton flavor violations
- Cosmology and astrophysics observables

- Introduction of ν_s leads to a modification of the leptonic C.C. Lagrangian

$$\frac{g}{\sqrt{2}}\mathbf{U}^{ji}\bar{\ell}_j\gamma^\mu P_L \nu_i W_\mu^- + \text{c.c.}$$

j=physical neutrino states, i=1,2,3 (charged lepton flavor)

-For SM, U corresponds to the 3x3 unitary matrix $U_{\rm PMNS}$

-For SM+ν_s : U is deviated from unitarity

- Non-unitarity of U will induce a departure from the SM expected values of some observables (e.g.: leptonic or semileptonic decays of pseudoscalar mesons like K, B, D…, cLFV process like $\ell \to \ell_1\ell_1\ell_2$, $\ell \to \ell'\gamma$, lepton flavor changing Z decays.

- In the presence of 3 ν_s , the overall 6x6 mass matrix can be diagonalized by a unitary matrix

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} M_{\rm L} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_{\rm N} \end{pmatrix}$$

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \left[\overline{(e,\mu,\tau)_{\rm L}}\, V\gamma^\mu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} W^-_\mu + \overline{(e,\mu,\tau)_{\rm L}}\, R\gamma^\mu \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}_{\rm L} W^-_\mu \right]$$

R **:** production & detection of heavy neutrinos at LHC;

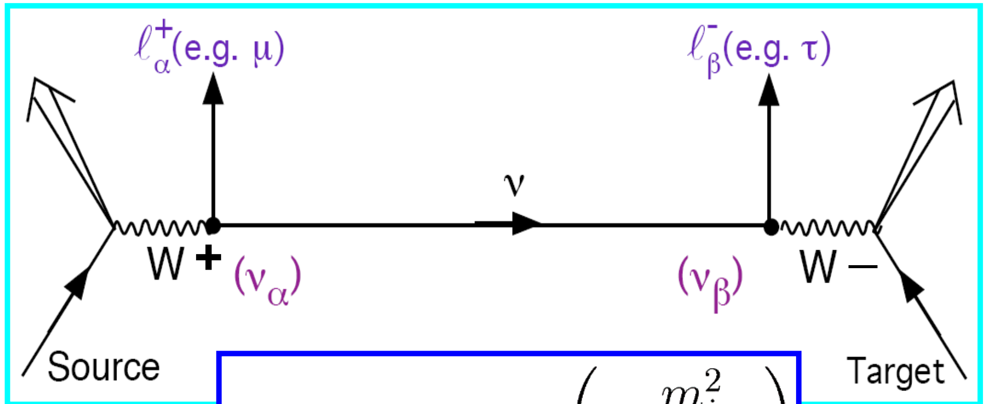
V : oscillations & other phenomena of light neutrinos.

- They are two 3×3 sub-matrices of the 6×6 unitary matrix, hence they must be correlated with each other.
- This correlation characterizes the relationship between neutrino physics and coll ider physics.

Effects on neutrino oscillation (Antusch *et al* 06, Xing. 08):

Production and detection of a neutrino beam via CC weak interactions:

$$A(W^+ \to l_\alpha^+ \nu_i) = \frac{V_{\alpha i}^*}{\sqrt{(VV^\dagger)_{\alpha\alpha}}}$$



$$A(\nu_i W^- \to l_\beta^-) = \frac{V_{\beta i}}{\sqrt{(VV^\dagger)_{\beta\beta}}}$$

$$\sum_i |A(W^+ \to l_\alpha^+ \nu_i)|^2 = 1$$

$$\mathrm{Prop}(\nu_i) = \exp\left(-i\frac{m_i^2}{2E}L\right)$$

$$\sum_i |A(\nu_i W^- \to l_\beta^-)|^2 = 1$$

$$\begin{aligned} A(\nu_\alpha \to \nu_\beta) &= \sum_i \left[A(W^+ \to l_\alpha^+ \nu_i) \cdot \mathrm{Prop}(\nu_i) \cdot A(\nu_i W^- \to l_\beta^-)\right] \\ &= \frac{1}{\sqrt{(VV^\dagger)_{\alpha\alpha}(VV^\dagger)_{\beta\beta}}} \sum_i \left[V_{\alpha i}^* \exp\left(-i\frac{m_i^2}{2E}L\right) V_{\beta i}\right] \end{aligned}$$

Like the case of the *non-standard* interactions in initial & final states.

Oscillation probability in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \frac{\sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2 + 2\sum_{i<j} \mathrm{Re}\left(V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i}\right) \cos\Delta_{ij} - 2\sum_{i<j} J^{ij}_{\alpha\beta} \sin\Delta_{ij}}{\left(VV^\dagger\right)_{\alpha\alpha}\left(VV^\dagger\right)_{\beta\beta}}$$

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/(2E) \text{ with } \Delta m^2_{ij} \equiv m^2_i - m^2_j \quad |\Delta m^2_{13}| \approx |\Delta m^2_{23}| \gg |\Delta m^2_{12}|$$

Jarlskog invariants of CP violation: $J^{ij}_{\alpha\beta} \equiv \mathrm{Im}(V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i})$

"Zero-distance" (near-detector) effect at *L* = 0 :

$$P(\nu_\alpha \to \nu_\beta)\,|_{L=0} = \frac{|(VV^\dagger)_{\alpha\beta}|^2}{(VV^\dagger)_{\alpha\alpha}(VV^\dagger)_{\beta\beta}}$$

(Langacker , London, '88)

The impact of sterile neutrinos on CP measurements at long baselines

Raj Gandhi,[a,c] Boris Kayser,[b] Mehedi Masud[a] and Suprabh Prakash[a]

$$A_{\nu\bar{\nu}}^{\alpha\beta} = \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \equiv \frac{\Delta P_{\alpha\beta}}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}.$$

The impact of sterile neutrinos on CP measurements at long baselines

$$U_{\text{PMNS}}^{3+1} = O(\theta_{34}, \delta_{34})O(\theta_{24}, \delta_{24})O(\theta_{14})O(\theta_{23})O(\theta_{13}, \delta_{13})O(\theta_{12}). \tag{2.1}$$

Here, in general, $O(\theta_{ij}, \delta_{ij})$ is a rotation matrix in the ij sector with associated phase δ_{ij}. For example,

$$O(\theta_{24}, \delta_{24}) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{24} & 0 & e^{-i\delta_{24}}\sin\theta_{24} \\ 0 & 0 & 1 & 0 \\ 0 & -e^{i\delta_{24}}\sin\theta_{24} & 0 & \cos\theta_{24} \end{pmatrix}; \quad O(\theta_{14}) = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_{14} & 0 & 0 & \cos\theta_{14} \end{pmatrix} \quad \text{etc.}$$

Using the standard formula for a flavour transition oscillation probability, we have, for the $3+1$ case:

$$\begin{aligned} P_{\mu e}^{4\nu} &= 4|U_{\mu 4}U_{e4}|^2 \times 0.5 \\ &\quad -4Re(U_{\mu 1}U_{e1}^*U_{\mu 2}^*U_{e2})\sin^2\Delta_{21} + 2Im(U_{\mu 1}U_{e1}^*U_{\mu 2}^*U_{e2})\sin 2\Delta_{21} \\ &\quad -4Re(U_{\mu 1}U_{e1}^*U_{\mu 3}^*U_{e3})\sin^2\Delta_{31} + 2Im(U_{\mu 1}U_{e1}^*U_{\mu 3}^*U_{e3})\sin 2\Delta_{31} \\ &\quad -4Re(U_{\mu 2}U_{e2}^*U_{\mu 3}^*U_{e3})\sin^2\Delta_{32} + 2Im(U_{\mu 2}U_{e2}^*U_{\mu 3}^*U_{e3})\sin 2\Delta_{32}. \end{aligned} \tag{2.2}$$

How do we find sterile neutrino ?

- Neutrino oscillation

▸ ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

▸ ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2\left(1-|U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

▸ $\nu_\mu \to \nu_e$ experiments:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

▸ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

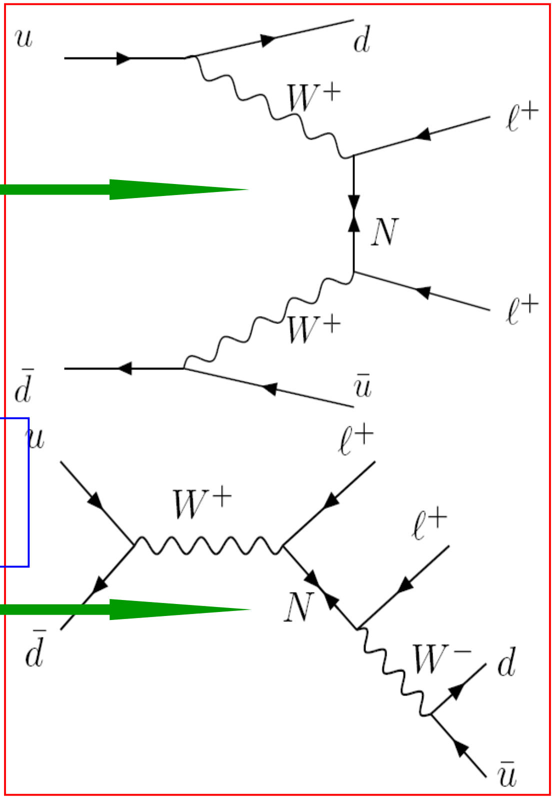
[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

- Collider experiments

Lepton number violation: like-sign dilepton events at hadron colliders such as LHC (~14 TeV).

collider analogue to 0νββ decay

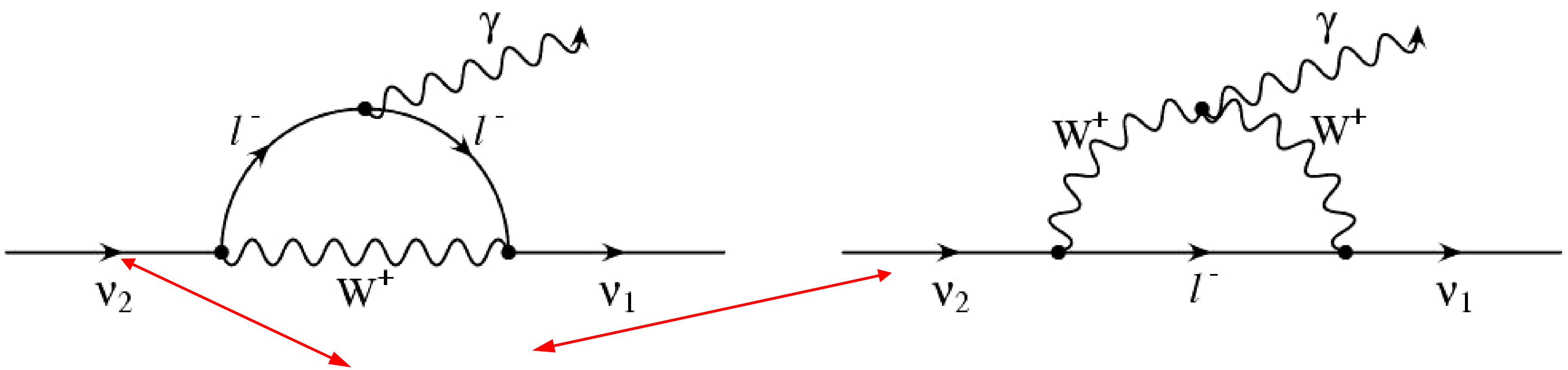
N can be produced on resonance



How do we find sterile neutrino ?

- Indirectly from observation of X(γ)-ray from universe

  - A heavy "sterile" neutrino can decay into a light "active" neutrino and a γ
  - The final state light neutrino and the photon *equally share* the rest mass energy of the initial sterile neutrino.
  - producing an emission line amenable to X-ray spectroscopic investigation



$$\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$$

photon line $E_\gamma = m_s/2$

Roles of sterile neutrino in cosmology

- Leptogenesis

  - Seesaw model has been proposed so as to achieve tiny neutrino masses.

  - Another advantage of seesaw model is to provide a nice mechanism of baryogenesis via leptogenesis.

  - However, baryogenesis realized in seesaw model requires very heavy right handed majorana neutrinos which are impossible to probe at collider.

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- Neutrinos as DM candidates/components

- Very light SM neutrinos (hot DM)

CMB bound: $\Omega_\nu h^2 < 0.0067(90\%CL)$

Disfavored by large scale structure formation

- KeV sterile neutrinos (warm DM)

Constraints: X-ray, BBN, Ly-alpha,…

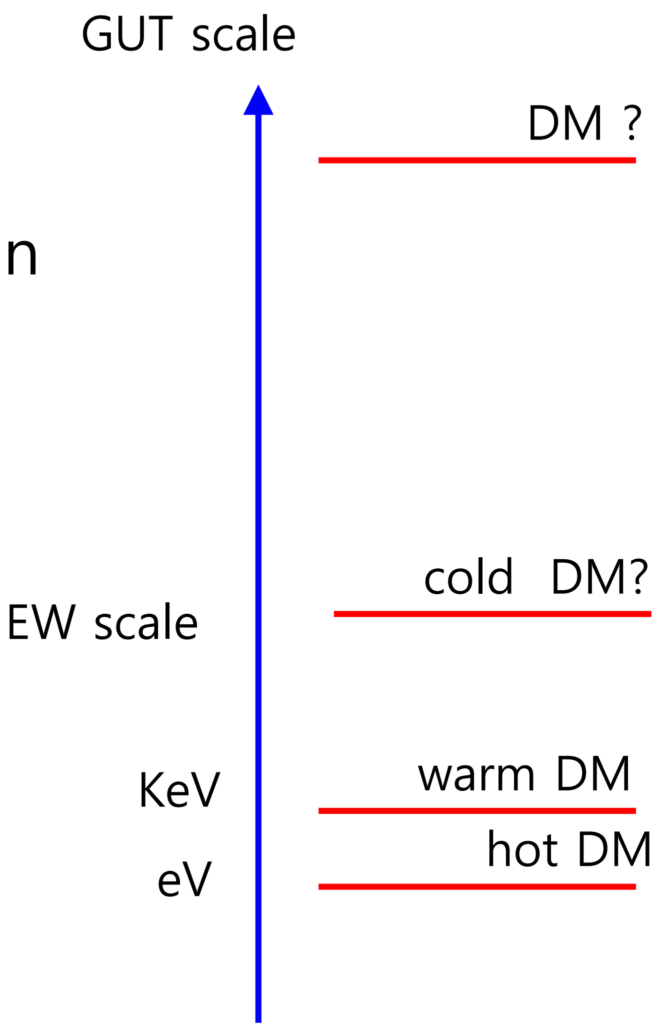
hard to detect directly.

- Heavy neutrinos (cold DM)

Heavy active Dirac/Majorana neutrino

cannot make up the whole DM

Heavy sterile neutrino can be CDM.



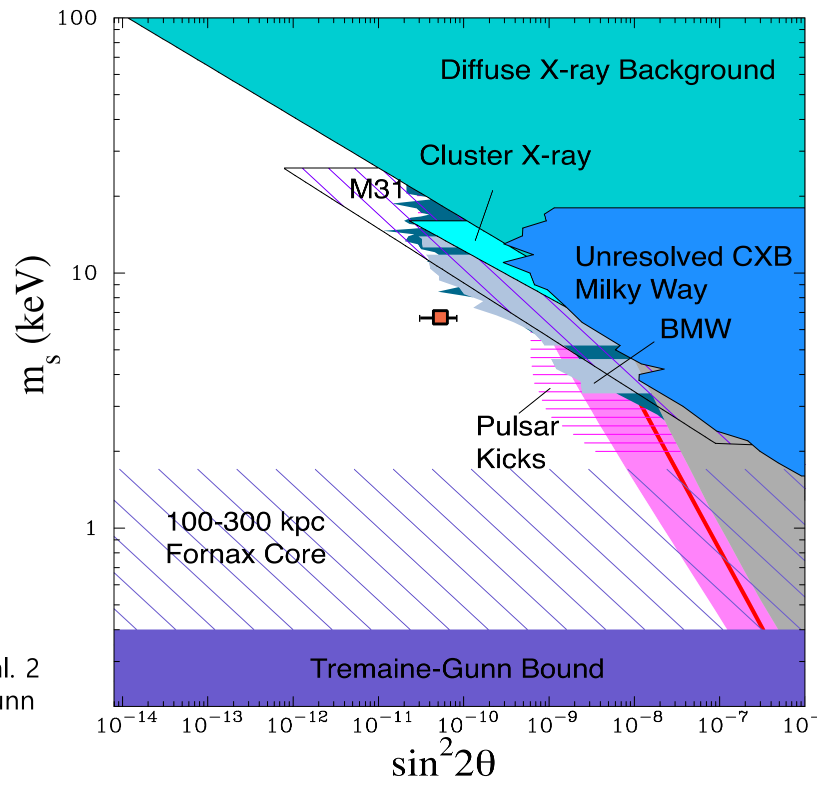
KeV sterile neutrino

- Candidate for warm dark matter
  - could resolve discrepancies between CDM and small scale structure
- Impact on reionization, core-collapse supernovae, leptogenesis…
- Produced and detected through mixing with active neutrino which is very small

-→ constrained by experiments

•If m1< 10^{-5} eV and keV RH neutrino can play the role of warm DM and at the same time the see-saw can explain neutrino mass

(Asaka,Blanchet,Shaposhnikov'05)



The diffuse X-ray background (Boyarsky et al. 2006), cluster X-ray (Boyarsky et al. 2006b), BMW (Boyarsky et al. (2007), M31 (Watson et al. 2006), the Tremaine-Gunn bound (Bode et al. 2001), and Fornax dwarf galaxy (Strigari et al. 2006)

Production of KeV Sterile Neutrino

- Dodelson & Widrow (1994) showed that ν_s could be thermally produced via neutrino oscillations in the early universe at a rate that depends on the ν_a-$\nu_s$mixing angle, θ_{mix} .
- Shi & Fuller showed that ν_s could be resonantly produced via neutrino oscillation in case of sizeable lepton asymmetry existed in the early Univ.
- ν_s could be produced by the decay of heavy scalar fields (Kusenko)

Probe of new interactions via sterile neutrino

Short range interactions

Heavy particle exchange

Long range interactions

Light particles

- New interactions corresponding to high scale physics or low scale physics
- Probe of UV completion for sterile neutrinos with low mass

  - Heavy neutrinos as portal

- An UV model for sterile neutrino we proposed is (SK, Kim, '12)
  "heavy RH neutrino portal"

Dark sector

- SM+ RH neutrino + gauge singlet neutrino & scalar

$$L = M_{R_i} N_i^T N_i + Y_{\nu_{ij}} \bar{L} H N_j + Y_S \bar{N}_i \phi S_j - \mu_{ij} S_i^T S_j + h.c.$$

- L_i $SU(2)_L$ doublet, N_i : RH singlet neutrinos
- S_i : newly introduced singlet neutrinos

-H : $SU(2)_L$ doublet Higgs

- ϕ : SM singlet scalar field

- Integrating out heavy N

$$-\mathcal{L}_{eff} = \frac{(m_D^2)_{ij}}{4M_R}\nu_i^T\nu_j + \frac{m_{D_{ik}}M_{kj}}{4M_R}(\bar{\nu}_i S_j + \bar{S}_i\nu_j) + \frac{M_{ij}^2}{4M_R}S_i^T S_j + \mu_{ij}S_i^T S_j$$

$$m_\nu \simeq \frac{1}{2}\frac{m_D}{M}\,\mu\,\left(\frac{m_D}{M}\right)^T, \qquad \tan 2\theta_s = \frac{2m_D M}{M^2 + 4\mu M_R - m_D^2}$$

$$\tan 2\theta_s \simeq \sin 2\theta_s \simeq \begin{cases} \frac{2m_D}{M} & (\text{for } M^2 > 4\mu M_R \\ \frac{m_D}{M} & (\text{for } M^2 \simeq 4\mu M_R \\ \frac{m_D M}{2\mu M_R} & (\text{for } M^2 < 4\mu M_R \end{cases} \qquad m_s \simeq \begin{cases} \frac{M^2}{4M_R} \\ 2\mu \\ \mu \end{cases}$$

Low Scale Leptogenesis (SK, CSKim, '12, SK, '16)

- Successful leptogenesis achieved by the decay of the lightest RH neutrino before the Higgs fields get VEVs

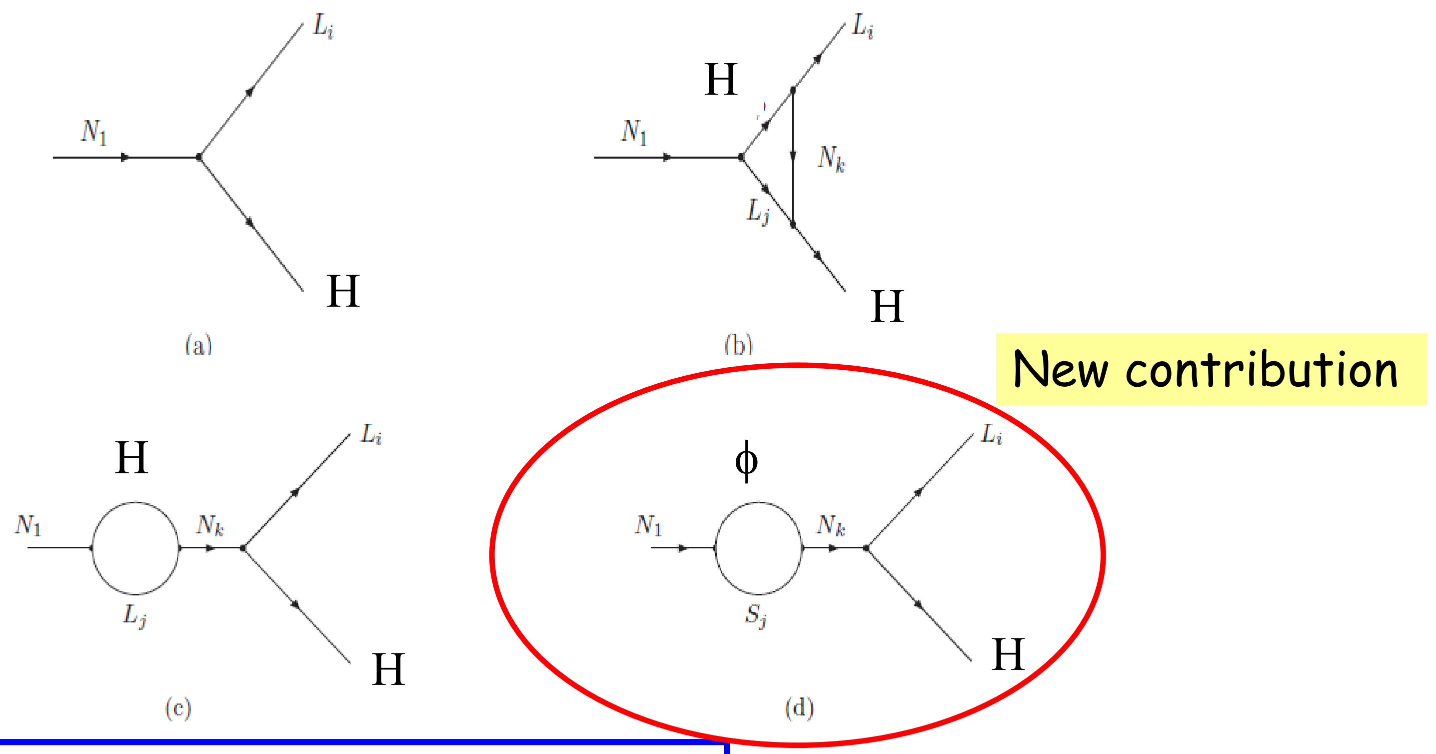
- New contribution mediated by new singlet neutrino S and scalar field ϕ can enhance lepton asymmetry ε_1

- In a basis where M_R and m_S are real and diagonal , the elements of Y_ν and Y_S are complex in general.

- Lepton number asymmetry required for baryogenesis :

$$\varepsilon_1 = -\sum_i \left[\frac{\Gamma(N_1 \to \bar{l}_i H^+) - \Gamma(N_1 \to l_i H)}{\Gamma_{tot}(N_1)} \right]$$

Diagrams contributing to lepton asymmetry



$$\Gamma_{tot}(N_i) = \frac{(Y_\nu Y_\nu^+ + Y_s Y_s^+)_{ii}}{4\pi} M_{R_1}$$

$$\varepsilon_1 = \frac{1}{8\pi} \sum_{k \neq 1} ([g_V(x_k) + g_S(x_k)] T_{k1} + g_S(x_k) S_{k1})$$

g(x) : loop functions

- Since $(Y_s)_{2i}$ is not contrained by the out-of-equilibrium condition, large value of $(Y_s)_{2i}$ is allowed

- The 2nd term of ε_1 can dominate over the 1st one and thus ε_1 can be enhanced.
- Successful leptogenesis can be achieved for M_{R1}~ a few TeV, provided that

$$\kappa = (Y_s)_{2i}/(Y_\nu)^*_{2i} \sim 10^3 \text{ and } M^2_{R_2}/M^2_{R_1} \sim 10.$$

- The generated B-L asymmetry :

$$Y^{SM}_{B-L} = -\eta\varepsilon_1 Y^{eq}_{N_1}$$

where $Y^{eq}_{N_1} \approx \frac{45}{\pi^4}\frac{\varsigma(3)}{g_*\kappa_B}\frac{3}{4}$

- The new process of type $S\phi \leftrightarrow LH$

⟹ wash-out of the produced B-L asymmetry

- wash-out factor for $(Y_s)_{1i} \sim (Y_\nu)_{1i}$, $(Y_s)_{2i}/(Y_\nu)_{2i} \sim 10^3$ and

$$M_{R_1} \sim 10^4 \text{ GeV}$$

similar to the case of the typical seesaw model with

$M_{R_1} \sim 10^4$ GeV and $\tilde{m}_1 \approx 10^{-3}$ eV

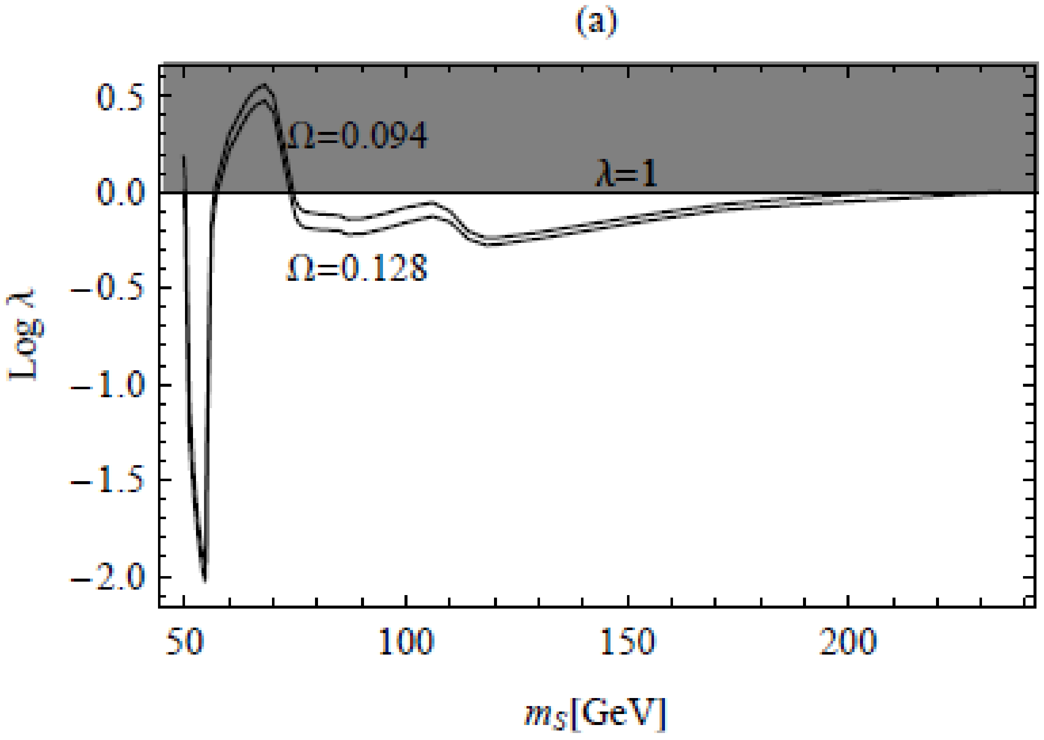
⟹ $\varepsilon_1 \sim 10^{-6}$ enough to explain baryon asymmetry without much severe fine-tuning.

• Possible Dark Matter Candidates

- Sterile neutrino S or/and the singlet scalar ϕ can be DM
- In order to guarantee the stability of DM, we impose Z_2 Symmetry under which S & ϕ: odd, SM+N : even

- S can be a dark matter candidate, provided that $m_S < m_\phi$.

- Possible annihilation processes of the singlet neutrino generate too much relic abundance of S.
- If m_ϕ is close to m_S, it would not be decoupled from thermal equilibrium at the T_f and thus coannihilation processes becomes important.
- It turns out that if $\delta m = m_\phi - m_S \approx T_f$, annihilation processes of ϕ into a pair of the SM particles through the s-channel, can significantly affect the relic abundance of S to be reduced.



Relationship between λ and m_S corresponding to $\Omega_S h^2$ = 0.128 (the lower solid line) and 0.094 (the upper solid line), respectively. The mass difference δm = m_ϕ - m_S has been taken to be 5 GeV and m_ϕ to be 200 GeV. Here the shadowed region is forbidden by breaking of perturbation

• KeV sterile neutrino Dark Matter (SK, Patra, '16, SK'17)

- Relic abundance of sterile neutrino can be achieved via freeze-in through out of equilibrium decay of ϕ
- Decays of ϕ into a pair of sterile neutrino can occur via the interaction term generated after $N_{2(3)}$ decoupled and ϕ got VEV, $\frac{|Y_{S2}|^2 v_\phi}{M_{N2}} \phi SS$

- Decay rate of $\phi \to SS$: $\Gamma(\phi \to SS) = \frac{|Y_{S2}|^4 v_\phi^2}{32\pi m_{N_2}^2} m_\phi$

- Solving Boltzmann Eq. : $\Omega_S h^2 \approx \frac{1.09\times 10^{27} m_S v_\phi^2}{g_*^S \sqrt{g_*^\rho}\, m_\phi m_{N_2}^2} |Y_{S2}|^4$

- BP for relic density : $v_\phi = 100\ GeV$, $m_\phi = 80\ GeV$, $Y_{S2} = 10^{-3}$, $m_{N2} = 15\ TeV$, $m_S = 7\ keV$

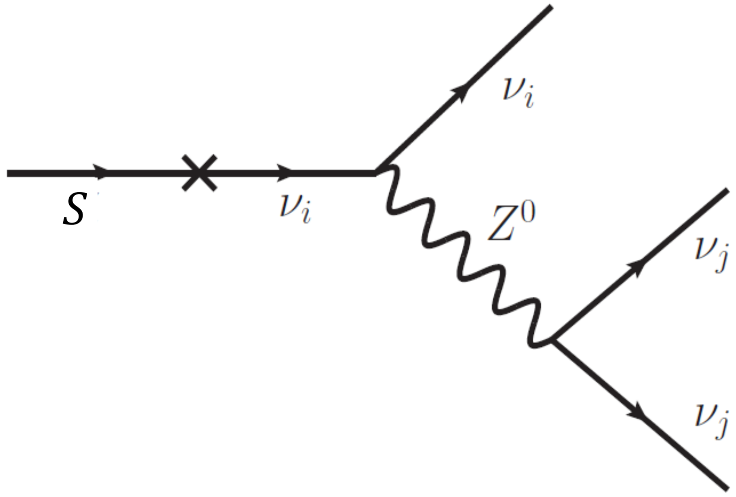
• KeV sterile neutrino Dark Matter

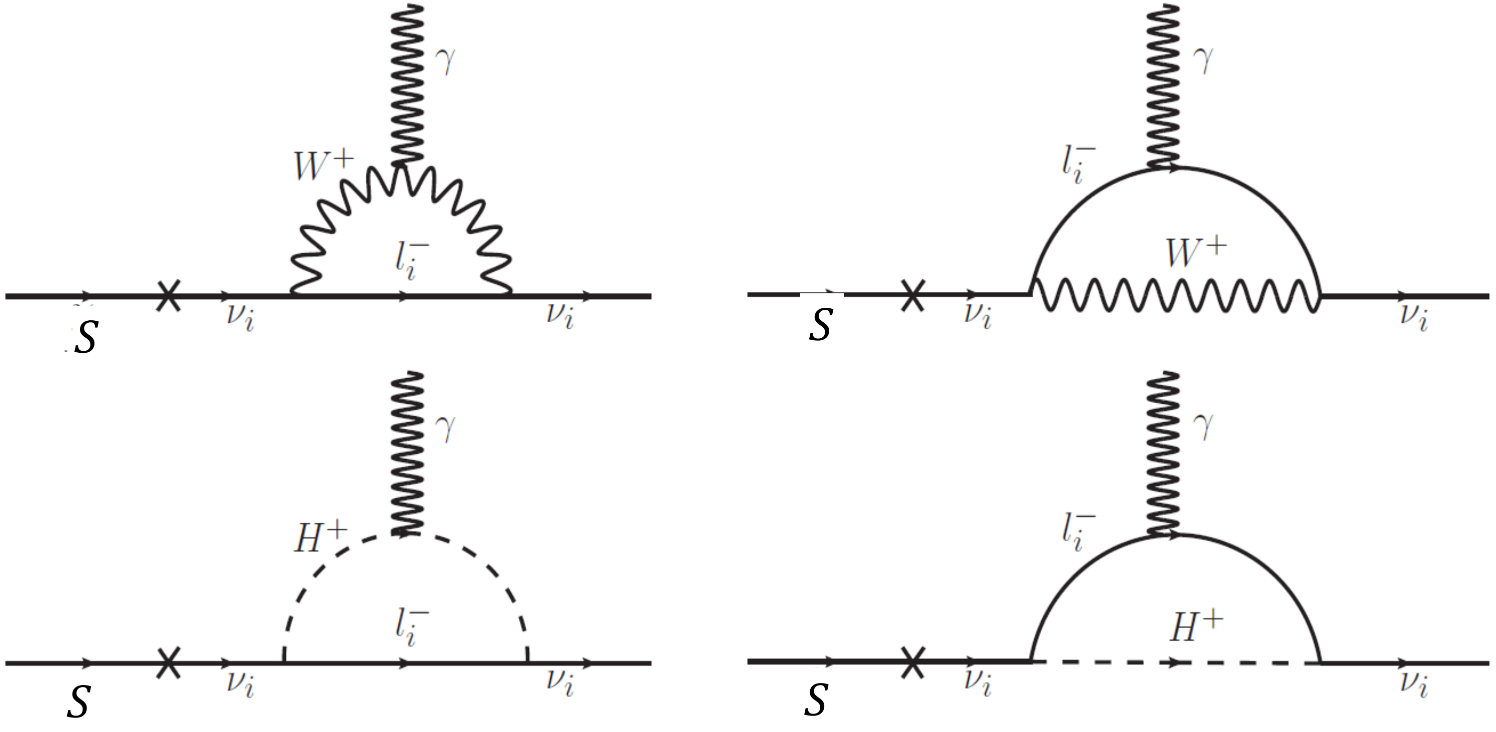
- The decay process takes place out of equilibrium at $T < m_\phi$

- The frozen-in production mechanism at $T{\sim}100$ GeV leads to colder DM compared to typical WDM production via Dodelson-Widrow mechanism.

- Our free streaming length is shorter than typical WDM, but still much larger than that of CDM.

- When ϕ gets VEV, S can decay





$$\Gamma_{3\nu} \cong sin^2 2\theta_S G_F^2 \left(\frac{m_S^5}{768\pi^3}\right)$$

$$\cong 8.7 \times 10^{-31} s^{-1} \left(\frac{sin^2 2\theta_S}{10^{-10}}\right)\left(\frac{m_S}{1\ keV}\right)^5$$

$$\Gamma_{\nu\gamma} \cong 6.8 \times 10^{-33} s^{-1} \left(\frac{sin^2 2\theta_S}{10^{-10}}\right)\left(\frac{m_S}{1\ keV}\right)^5$$

- Radiative decay can lead to 3.55 KeV X-ray line

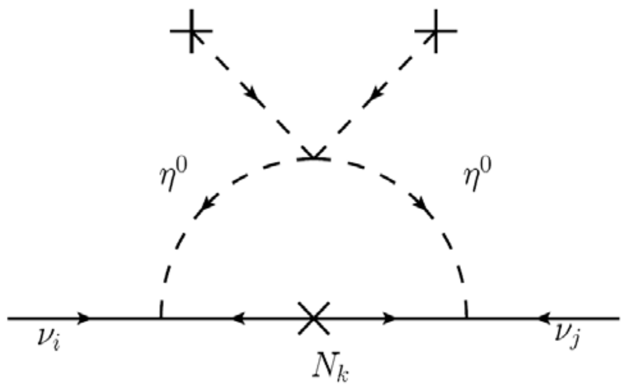
$for\ \ m_S = 7.1\ keV, and\ \ sin^2 2\theta_S \sim 10^{-11}$ $\quad \Gamma_{total} \sim\ 10^{-26}\ \mathrm{s}^{-1}$

- 2-component Dark Matter (Borah, Dasgupta, SK, '18)

  - Incorporating scotogenic idea, we introduce inert doublet scalar

$$L = M_{R_i} N_i^T N_i + Y_{\nu_{ij}} \bar{L} \eta N_j + Y_S \bar{N}_i \phi S_j - \mu_{ij} S_i^T S_j + h.c.$$

- η : SU(2) inert doublet



  - Neutrino masses are generated through 1-loop

$$(m_\nu)_{ij} = \sum_k \frac{Y_{ik} Y_{jk} M_k}{16\pi^2} \left(\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right)$$

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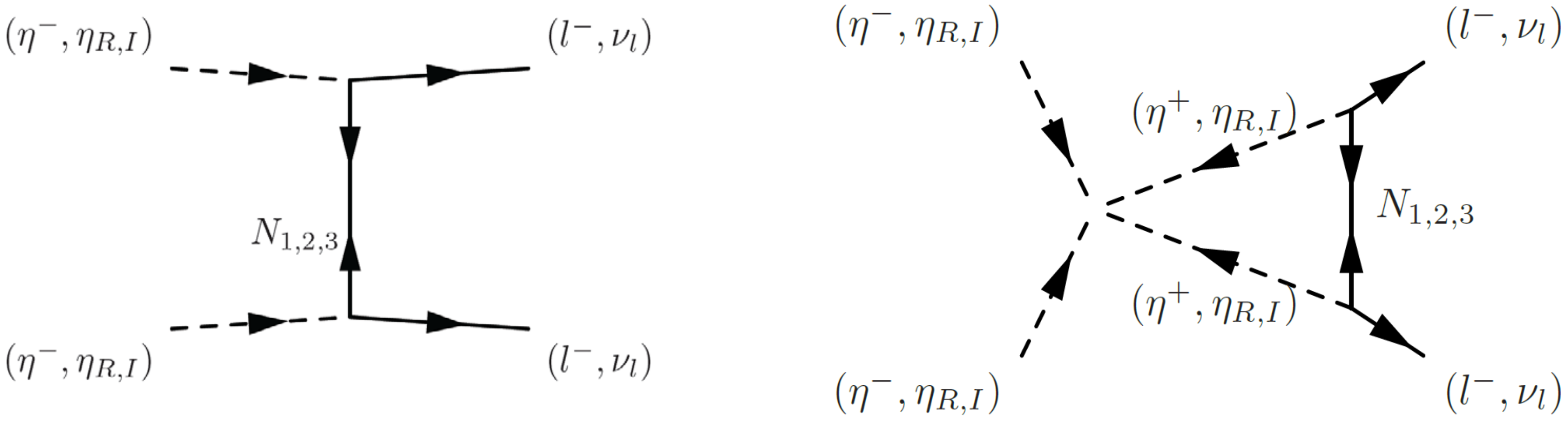
- η : SU(2) inert doublet

- Weak scale scalar η is WIMP, but decays into $\nu\ \phi\ S$ at a late time after freezing out thanks to small Y_S.
- Singlet scalar ϕ becomes CDM after freezing out.
- Sterile neutrino with keV mass can be produced from the decay of η as well as annihilation of ϕ, which is WDM candidate.
- Then, the relic abundance is composed of $\Omega_\phi + \Omega_S$

• 2-component Dark Matter

- In this scenario, leptogenesis can be realized via the annihilation of η (WIMPy leptogenesis)

- Lepton asymmetry ε : interference between



(Borah, Dasgupta, SK, '18)

BP for this scenario : $m_\eta = 5\,TeV,\ m_\phi = 500\,GeV,\ m_S = 7.1KeV,\ Y_S \sim 10^{-7}, \lambda = 0.65$

Conclusion

- Sterile neutrino may be required for deep understanding of our universe.
- Sterile neutrino may affect various phenomena probed in particle physics and cosmology.
- We find no evidence for sterile neutrinos so far.
- We set the present bounds on the mass and mixing.
- Sterile neutrino can be a good dark matter candidate and play an essential role in the existence of our universe.
- Possibility of the existence of sterile neutrino will continue to be studied.