Are small neutrino masses unveiling the missing mass problem of the Universe?

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Reference

IS IT POSSIBLE TO EXPLAIN THE NEUTRINO MASSES WITH SCALAR DARK MATTER

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PRD 77 (2008) 43516

Plan of talk

- Dark matter
- Neutrino masses
- Our scenario
- Various possible effects
- Embedding the scenario in a model
- Conclusion

Dark matter

Cosmological observation (CMB) PDG2006

$$\Omega_{DM} = 0.24 \quad \Omega_b = 0.04 \quad \Omega_\Lambda = 0.73$$

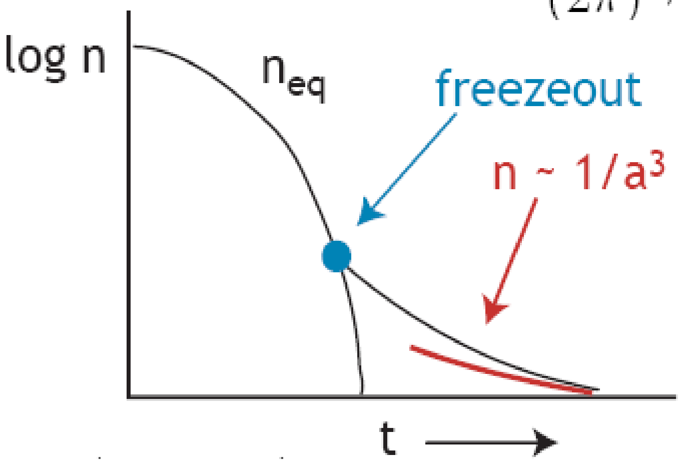
Various DM candidates:
WIMPs (LSP, KK modes, ….)
Axion
Warm Dark matter (Sterile neutrino,…)
….

SLIM Particle

Density of dark matter

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right) \qquad H \sim T^2/m_{\mathrm{Pl}}$$

$$T \ll m \qquad n_{eq} = \frac{g}{(2\pi)^{3/2}} (mT)^{3/2} e^{-m/T}$$



$$e^{-m/T_F} \sim \frac{3\sqrt{T_F/m}(2\pi)^{3/2}}{M_{Pl} m \langle \sigma v \rangle g}$$

Dependence of m/T_f on mass is very weak. Varying Mass from O(MeV) to O(100 GeV) (by 5 orders of magnitude), m/T_f varies only between 10 to 25!

Dependence on parameters

$$\Omega_{DM} = \frac{nm}{\rho_c} \propto \frac{m/T_f}{\langle \sigma v \rangle}$$

m/T_f has a value between 10 to 30. So, the DM density is practically independent of the mass of the DM candidate and is solely determined by its annihilation cross-section.

Neutrino Mass

Neutrino oscillation:

$$m_\nu = U \cdot Diag[m_1, m_2, m_3] \cdot U^T$$

Solar neutrino data: $m_2^2 - m_1^2$

Atmospheric neutrino data: $|m_3^2 - m_1^2|$

Models to explain nonzero but small masses:

Seesaw mechanism: Type I, Type II, Type III,…

Majoron Model(s)

Zee Model; Zee-Babu Model

SUSY without R-parity

……

LINKING the two great mysteries

Krauss, Nasri and Trodden, PRD 67 (03) 85002; Cheung and Seto, PRD 69 (04) 113009; Asaka, Blanchet and Shaposhnikov, PLB 631 (05) 151; Chun and Kim, JHEP 10 (06) 82; Kubo and Suematsu, PLB 643 (06) 336; Ma, PRD73 (06) 77301;Suematsu, PLB 642 (06) 18; Ma, MPLA 21 (06) 1777; Hambye, Kannike, Ma and Raidal, PRD 75 (07) 95003

Boehm, Y. F., Hambye, Palomares-Ruiz and Pascoli, PRD 77 (08) 43516

A scenario Linking these two problems

New fields:

Majorana Right-handed neutrino

SLIM=Scalar as LIght as MeV

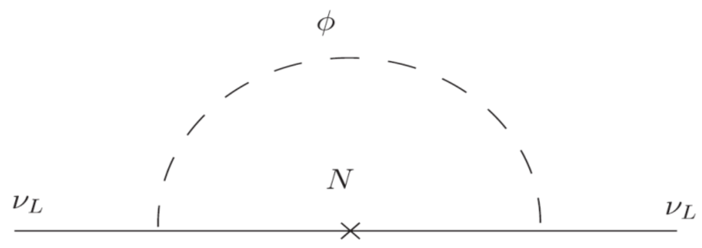
Effective Lagrangian: $$\mathcal{L}_I \supset g\phi\bar{N}\nu$$

New parameters: $g \quad m_\phi \quad m_N$

Explaining the neutrino masses

In this scenario, SLIM does not develop any VEV so the tree level neutrino mass is zero.

Radiative mass in case of real scalar:



Ultraviolet cutoff Λ

Majorana mass:

$$m_\nu = \frac{g^2}{16\pi^2} m_N \left[\ln\left(\frac{\Lambda^2}{m_N^2}\right) - \frac{m_\phi^2}{m_N^2 - m_\phi^2} \ln\left(\frac{m_N^2}{m_\phi^2}\right) \right]$$

SLIM as a real field

For $m_N > m_\phi$, SLIM plays the role of dark matter candidate. Imposing a Z_2 symmetry, the SLIM can be made stable and a potential dark matter candidate:

$$\mathcal{L} = g\phi\bar{N}\nu + (\frac{m_N}{2}NN + H.c) + \frac{m_\phi^2}{2}\phi^2 + ...$$

Z_2 symmetry: $\phi \longrightarrow -\phi\ ,\qquad N \longrightarrow -N$

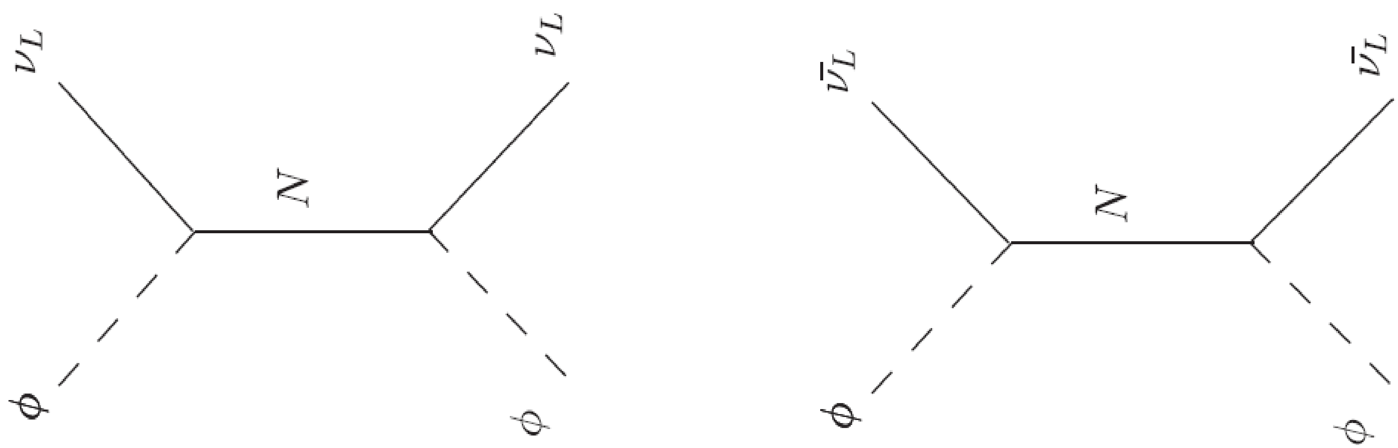
$$\cancel{\bar{N}L\cdot H}$$

SLIM is stable but the right handed neutrino decays:

$$\Gamma_N = g^2 m_N^2/(16\pi E_N)$$

Annihilation cross-section

Pair Annihilation:



$$\langle \sigma(\phi\phi \to \nu\nu)\mathrm{v}_r \rangle = \langle \sigma(\phi\phi \to \bar{\nu}\,\bar{\nu})\mathrm{v}_r \rangle$$

$$\simeq \frac{g^4}{4\pi} \frac{m_N^2}{(m_\phi^2 + m_N^2)^2},$$

$$g \simeq 10^{-3} \sqrt{\frac{m_N}{10\ \mathrm{MeV}}} \left(\frac{\langle \sigma \nu_r \rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right)^{1/4} \left(1 + \frac{m_\phi^2}{m_N^2} \right)^{1/2}$$

Linking dark matter and neutrino mass

$$m_\nu \simeq \sqrt{\frac{\langle \sigma \nu_r \rangle}{128\pi^3}} m_N^2 \left(1 + \frac{m_\phi^2}{m_N^2}\right) \ln\left(\frac{\Lambda^2}{m_N^2}\right)$$

$$\langle \sigma \nu_r \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}.$$

$$\Lambda \sim E_{\mathrm{electroweak}} \sim 200\ \mathrm{GeV}$$

$$0.05\ \mathrm{eV} < m_\nu < 1\ \mathrm{eV},$$

$$O(1)\ \mathrm{MeV} \lesssim m_N \lesssim 10\ \mathrm{MeV}.$$

Bounds on SLIM mass

$$m_\phi < M_N$$

$$O(1)\ \mathrm{MeV} \lesssim m_N \lesssim 10\ \mathrm{MeV}.$$

Ly-α forest power spectrum measured by the Sloan Digital Sky Survey

Viel et al., PRD 71 (05) 63534; PRL 97 (06) 191303;
Miranda et al., Mon Not R. Astron Soc 382 (07) 1225

$$m_s > 14\mathrm{keV}\ \text{at}\ 95\%\ \text{c.l.}\ (10\mathrm{keV}\ \text{at}\ 99.9\%)$$

U. Seljak et al., PRL 97 (06) 191303;

See also, Boyarsky et al., 0812.0010

A way to test the scenario

$$\text{a few keV} < m_\phi < 10 \text{ MeV}.$$

$$g \simeq 10^{-3}\sqrt{\frac{m_N}{10\ \text{MeV}}}\left(\frac{\langle\sigma v_r\rangle}{10^{-26}\ \text{cm}^3/\text{s}}\right)^{1/4}\left(1+\frac{m_\phi^2}{m_N^2}\right)^{1/2}$$

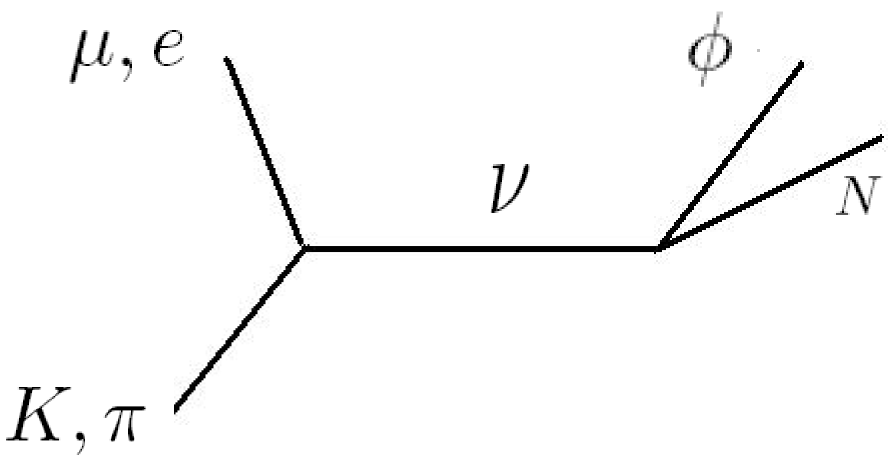
$$3 \times 10^{-4} \lesssim g \lesssim 10^{-3}$$

A lower bound on coupling and upper bounds on m_N and m_ϕ → Model is falsifiable by some terrestrial experiment.

Potential signature

Missing energy in Pion and Kaon decay

Lessa and Peres PRD (07) 94001, Britton et al., PRD 49 (94) 28; Barger et al., PRD 25 (82) 907;Gelmini et al., NPB209 (82) 157



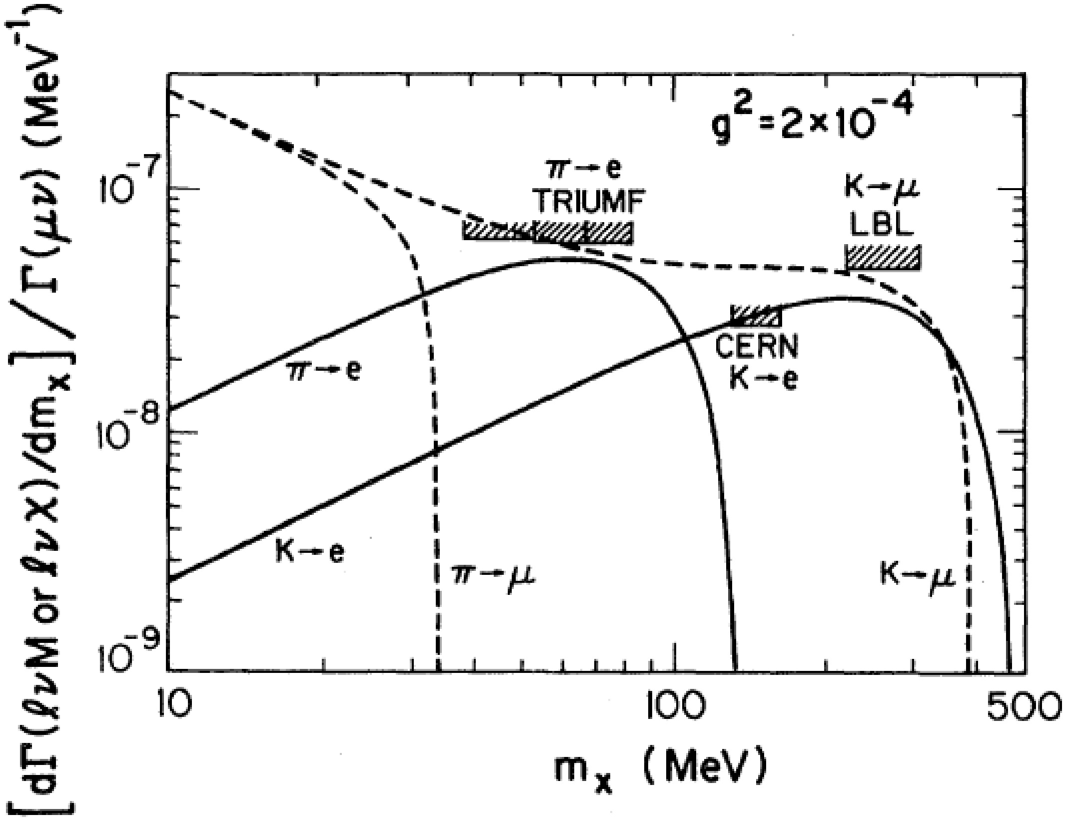


FIG. 2. Predictions for the differential leptonic-decay rates of K or π mesons into final states with $l\nu$ and Majoron or X. The variable m_x is the square root of the virtual-neutrino four-momentum squared. Solid curves represent electron decays and dashed curves represent muon decays. Data are from Refs. 7–9. All $K(\pi)$ differential rates are normalized to the $K(\pi)\to\mu\nu$ rate.

Barger et al., PRD 25 (82) 907

More recent data:

$$g \lesssim 10^{-2}$$

Lessa and Peres , PRD75

Best bound is based on

$$Br(K^+\to\mu^+ + \nu_\mu + \nu + \nu) < 6\times10^{-6}$$

PANG et al., PRD8 (1973!!!) 1989

Looking forward to

KLOE

Complex SLIM

$$\phi = (\phi_1 + i\phi_2)/\sqrt{2}$$

ϕ_1 and ϕ_2 are real fields with masses m_{ϕ_1} and m_{ϕ_2}.

Difference between m_{ϕ_1} and m_{ϕ_2} can be explained by

$$\mathcal{L}_m = -M^2\phi^\dagger\phi - m^2(\phi\phi - H.c.) =$$

$$-\frac{M^2 + \mathrm{Re}[m^2]}{2}\phi_1^2 - \frac{M^2 - \mathrm{Re}[m^2]}{2}\phi_2^2 - i\mathrm{Im}[m^2]\phi_1\phi_2$$

For CP-conserving case, $\mathrm{Im}[m^2] = 0$ and thus there is no mixing between ϕ_1 and ϕ_2

$$\mathcal{L}_I = g\phi\bar{N}\nu = \frac{\phi_1 + i\phi_2}{\sqrt{2}}\bar{N}\nu$$

Without mixing:

$$m_\nu = \frac{g^2}{32\pi^2} m_N \left[\frac{m_{\phi_1}^2}{(m_N^2 - m_{\phi_1}^2)} \ln\left(\frac{m_N^2}{m_{\phi_1}^2}\right) - \frac{m_{\phi_2}^2}{(m_N^2 - m_{\phi_2}^2)} \ln\left(\frac{m_N^2}{m_{\phi_2}^2}\right) \right]$$

No cutoff dependence! With mixing, cutoff would reappear.

In the limit $m_{\phi_1} = m_{\phi_2}$, the neutrino mass vanishes.

In this limit,

$$\mathcal{L}_{m,\phi} = m^2\phi^\dagger\phi + (\cancel{\frac{M^2}{2}\phi\phi + \mathrm{H.c.}})$$

lepton number is conserved:

(L=-1 for ϕ and L=0 for N)

Dark matter candidate

Suppose $m_{\phi_2} < m_{\phi_1}$. Then, $\phi_1 \to \phi_2 \nu\nu$

The lighter one will be DM.

Self annihilation of ϕ_2 (co-annihilation with ϕ_1 !?!)

$$\langle \sigma(\phi_2\phi_2 \to \nu\nu) \rangle = \langle \sigma(\phi_2\phi_2 \to \bar{\nu}\bar{\nu}) \rangle$$

$$= \frac{g^4}{16\pi} \frac{m_N^2}{(m_N^2 + m_{\phi_2}^2)^2}$$

Dark matter candidate

Inserting the couplings:

$$m_\nu = \sqrt{\frac{\langle \sigma v_r \rangle}{128\pi^3}}\left[m_{\phi_1}^2 \ln\left(\frac{m_N^2}{m_{\phi_1}^2}\right) - m_{\phi_2}^2 \ln\left(\frac{m_N^2}{m_{\phi_2}^2}\right)\right],$$

For $10 < \dfrac{m_N}{m_{\phi_1}} < 10^5$, we find

$$(1\ \mathrm{MeV})^2 \lesssim |m_{\phi_1}^2 - m_{\phi_2}^2| \lesssim (20\ \mathrm{MeV})^2.$$

But there is no upper bound on the right-handed neutrino mass in the complex SLIM case.

Remarks

No upper bound on m_N $\Rightarrow$ N can have electroweak interactions.

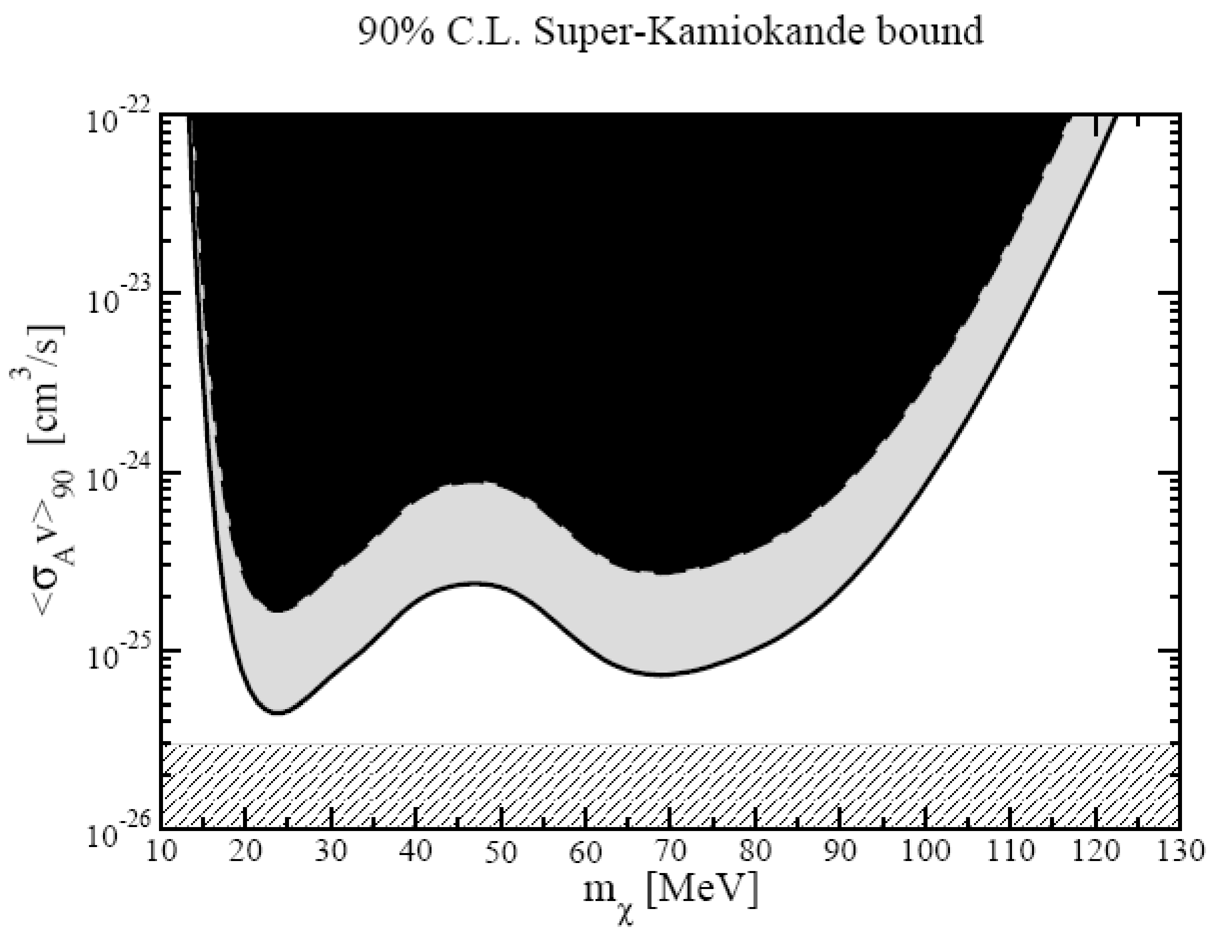
The masses of ϕ_1 and ϕ_2 can be much larger than 10 MeV provided that they are quasi-degenerate.

If the masses are larger than the pion and kaon mass then they cannot be probed by their decay.

Neutrino flux from galactic halo

Self-annihilation of SLIMs in our galaxy can produce a flux of neutrino potentially detectable by neutrino detectors.

S. Palomares-Ruiz and S. Pascoli, PRD 77 (08) 25025



Palomares-Ruiz and Pascoli, PRD77 (08) 25025

Proposed LENA

(50kt scintillator in Finland)

Or

Megaton water detector with Gd

Nucleosynthesis

- For $m_\phi \ll 1\ \mathrm{MeV}$, SLIM is equivalent to 4/7 degrees of freedom. Studying helium abundance alone SLIM lighter than MeV is strongly disfavored.

Serpico and Raffelt, PRD 70 (04) 43526

Other analysis show that 1.5 dof (at 95 % CL) are allowed.

Cyburt et al., Astropart. Phys. 23 (05) 313; Cirelli and Strumina JCAP 12 (06) 13; Hannestad and Raffelt JCAP 11 (06) 16

Both in real and complex cases SLIM can be heavier than MeV.

Real SLIM: $m_\phi < m_N \lesssim 10\ \mathrm{MeV}$

Complex SLIM: $(1\ \mathrm{MeV})^2 \lesssim |m_{\phi_1}^2 - m_{\phi_2}^2| \lesssim (20\ \mathrm{MeV})^2.$

Nucleosynthesis

For masses above ~10 MeV, there is no effect on BBN.

For masses between 1 MeV and 10 MeV, the SLIM density is suppressed at the time of nucleosynthesis

but its annihilation to neutrinos increases the entropy and thus the temperature of the neutrino which affects nucleosynthesis.

For masses in the range 4-10 MeV, they can even improve the overall agreement between the predicted and observed $^2\mathrm{H}$ and $^4\mathrm{He}$ abundances.

Serpico and Raffelt, PRD 70 (04) 43526

Supernova Bounds

- Energy loss consideration: binding energy

$E_b = (1.5 - 4.5) \times 10^{53}$ erg. Sato and Suzuki, PLB196 (87)

Exotic extremely weekly interacting particles can carry away energy leaving no energy for neutrinos which is in contradiction with SN1987a.

Choi and Santamaria, PRD42 (90)293; Berezhiani and Smirnov

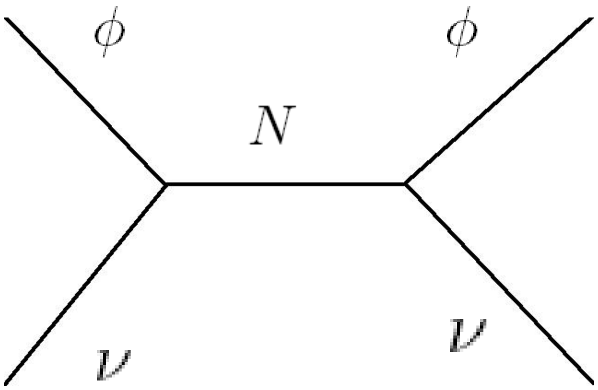
PLB 220 (89)279; Kachelriess, Tomas and Valle, PRD 62 (00) 23004; Giunti et al., PRD45 (92) 1556; Grifols et al, PLB215 (88) 593.

SLIM production in the supernova core

SLIM production

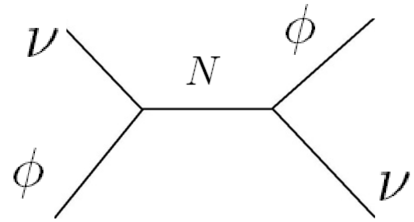
in core (for relatively Light SLIM)

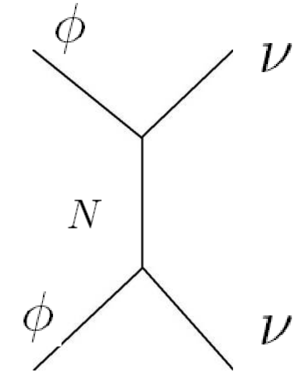
Available mode:



Thermalization

SLIMs will be trapped in the core.





In the outer core with T~30 MeV

$$\sigma(\phi\nu \to \nu\phi) \sim \frac{g^4}{4\pi}\frac{T^2}{(T^2+m_N^2)^2} \sim 10^{-37}(\mathrm{cm}^2)\left(\frac{m_N/10\ \mathrm{MeV}}{T/30\ \mathrm{MeV}}\right)^2$$

Mean free path: $(\sigma n_\nu)^{-1} = 10\ \mathrm{cm}$

The effect of SLIMs on cooling can be tolerated within present uncertainties of supernova models.

Other supernova approaches

In the case of future supernova observations, one may be able to test this scenario by studying the neutrino energy spectra.

Palomares-Ruiz, WIN07, Kolkata (India), 2007;

T.J. Weiler, 6th Recontres du Vietnam, Hanoi (Vietnam) 2006

Realization of the scenario

For real SLIM, m_N <10 MeV ⇒ N has to be singlet.

Therefore, $\mathcal{L}_I \supset g\phi\bar{N}\nu$ must be effective and can obtain this form only after electroweak symmetry breaking.

By promoting ϕ to be a doublet one can complete.

E. Ma, Annales Fond. Broglie 31 (06) 285.

For Complex SLIM, m_N can be larger than electroweak scale so N can have electroweak interaction; e.g., as a component of SU(2) doublet.

Embedding SLIM in a cozy model (work in progress)

Content:

1) A singlet of SU(2): $\phi \equiv (\phi_1 + i\phi_2)/\sqrt{2}$

2) Fermionic doublets:

$$\begin{bmatrix} \nu_R \\ E_R^- \end{bmatrix} \quad Y = -\frac{1}{2} \qquad \Big| \qquad \begin{bmatrix} E_R'^+ \\ \nu_R' \end{bmatrix} \quad Y = \frac{1}{2}$$

3) A scalar triplet of SU(2) with hypercharge=1

$$\Delta = \begin{bmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{bmatrix}$$

4) A fermionic singlet N_L

Summary and conclusions

- SLIM scenario can establish a link between neutrino masses and dark matter. Two possibilities:

1) Real SLIM:

$3 \times 10^{-4} \lesssim g \lesssim 10^{-3}$. stable by meson decay

$m_\phi < m_N \lesssim 10 \text{ MeV}$

2) Complex SLIM: No upper bound on m_N

$$(1 \text{ MeV})^2 \lesssim |m^2_{\phi_1} - m^2_{\phi_2}| \lesssim (20 \text{ MeV})^2.$$

If m_{ϕ_1} is 20-100 MeV, LENA experiment can indirectly detect it.

SLIM affects supernova cooling and energy spectrum of neutrinos from SN

Z_2 symmetry

SM fields $\Rightarrow$ SM fields

New fields $\Rightarrow$ -(New fields)

The lightest of new particles is stable and a suitable dark matter candidate.

The new scalars do not develop VEV so despite the Z_2 symmetry, there is no domain wall problem.

Mass terms for ϕ

$(\phi_1 + i\phi_2)/\sqrt{2}$

$$\mathcal{L}_{m,\phi} = m^2\phi^\dagger\phi + (\frac{M^2}{2}\phi\phi + \mathrm{H.c.}) =$$
$$m_1^2\phi_1^2 + m_2^2\phi_2^2 - \mathrm{Im}[M^2]\phi_1\phi_2,$$

$$m_1^2 = \frac{m^2 + \mathrm{Re}[M^2]}{2}$$ and $$m_2^2 = \frac{m^2 - \mathrm{Re}[M^2]}{2}.$$

CP $\Longrightarrow$ M^2 is real. $\Longrightarrow$ No mixing

Mass term for fermions

$$-m_{RR}\epsilon_{\alpha\beta}R'^{T}_{\alpha}cR_{\beta} + \text{H.c} = -m_{RR}\left[(\nu'_R)^T c\nu_R - (E'^{+}_R)^T cE^{-}_R\right] + \text{H.c}$$

No need for extra fermions (not like fourth generation)

$$\mathcal{L} = -g' N_L^{\dagger} R_{\alpha}\epsilon_{\alpha\beta}H_{\beta} - \tilde{g}' N_L^{\dagger} H^{\dagger}\cdot R' + M_M N_L^T cN_L$$

$$\begin{bmatrix}\nu_R^T c & \nu'^T_R c & N_L^{\dagger}\end{bmatrix}\begin{bmatrix} 0 & m_{RR} & m_D \\ m_{RR} & 0 & m'_D \\ m_D & m'_D & m_M\end{bmatrix}\begin{bmatrix}\nu_R \\ \nu'_R \\ cN_L^*\end{bmatrix}$$

$$m_D = -g'\langle H^0\rangle = -g'v/\sqrt{2} \text{ and } m'_D = \tilde{g}'\langle H^0\rangle = \tilde{g}'v/\sqrt{2}.$$

Mass term for Δ

$$\mathcal{L}_\Delta = m_0^2 \mathrm{Tr}(\Delta^\dagger \Delta) + G_{H\Delta} H^\dagger \cdot H \mathrm{Tr}[\Delta^\dagger \Delta] + g_{H\Delta} H^\dagger \Delta^\dagger \Delta H + g'_{H\Delta} H^\dagger \Delta \Delta^\dagger H$$

After electroweak symmetry breaking:

$$m_\Delta^2(|\Delta^0|^2 + |\Delta^+|^2 + |\Delta^{++}|^2) + \frac{v^2}{2} g_{H\Delta}(|\Delta^{++}|^2 + \frac{|\Delta^+|^2}{2}) + \frac{v^2}{2} g'_{H\Delta}(|\Delta^0|^2 + \frac{|\Delta^+|^2}{2})$$

$$m_{\Delta^+}^2 = \frac{m_{\Delta^{++}}^2 + m_{\Delta^0}^2}{2} \ .$$

Mixing of Δ^0 and ϕ

Electroweak symmetry breaking

$$-g_{\phi\Delta}\phi(H^\dagger\Delta)_\alpha H^*_\beta\epsilon_{\alpha\beta} \Longrightarrow$$

$$\mathcal{L}^m_\phi = -\frac{1}{2}[\phi_1\ \phi_2\ \Delta_1\ \Delta_2]\begin{bmatrix} m_1^2 & 0 & m^2_{\phi\Delta} & 0 \\ 0 & m_2^2 & 0 & -m^2_{\phi\Delta} \\ m^2_{\phi\Delta} & 0 & m^2_\Delta & 0 \\ 0 & -m^2_{\phi\Delta} & 0 & m^2_\Delta \end{bmatrix}\begin{bmatrix}\phi_1 \\ \phi_2 \\ \Delta_1 \\ \Delta_2\end{bmatrix}$$

$$\Delta^0 = (\Delta_1 + \Delta_2)/\sqrt{2}, \qquad m^2_{\phi\Delta} = g_{\phi\Delta}v^2/2.$$

Mass eigenstates

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix} = \begin{bmatrix} \cos\alpha_1 & 0 & \sin\alpha_1 & 0 \\ 0 & \cos\alpha_2 & 0 & \sin\alpha_2 \\ -\sin\alpha_1 & 0 & \cos\alpha_1 & 0 \\ 0 & -\sin\alpha_2 & 0 & \cos\alpha_2 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \Delta_1 \\ \Delta_2 \end{bmatrix}$$

The lightest is supposed to play the role of dark matter

Yukawa couplings and lepton number

$$- g_\alpha \phi^\dagger R^\dagger L_\alpha - (g_\Delta)_\alpha R'^\dagger \Delta L_\alpha + \mathrm{H.c.}$$

Lepton number of ϕ = 1

Lepton number of Δ = -1

$$\cancel{\boxed{\phi^\dagger (H^\dagger \Delta)_\alpha H^*_\beta \epsilon_{\alpha\beta}}} \qquad \cancel{\boxed{\phi R^\dagger \cdot L_\alpha}}$$

Source of lepton number violation: $m_1^2 - m_2^2$

$$\boxed{m_1^2 \phi_1^2 + m_2^2 \phi_2^2}$$

Invisible decay modes of the Z boson

$$\frac{ie\sin\alpha_1\sin\alpha_2}{\sin\theta_w\cos\theta_w}[\delta_2\partial_\mu\delta_1-\delta_1\partial_\mu\delta_2]Z^\mu$$

in case that $M_1+M_2<m_Z$

$$\Gamma(Z\to\delta_1\delta_2)=\frac{e^2\sin^2\alpha_1\sin^2\alpha_2}{48\pi\sin^2\theta_w\cos^2\theta_w}m_Z$$

$$\Gamma(Z\to\delta_1\delta_2)<0.3\%\Gamma_{invisible}\Rightarrow\sin\alpha_1\sin\alpha_2<0.07$$

Neutrino masses

$$-g_\alpha \phi^\dagger R^\dagger L_\alpha - (g_\Delta)_\alpha R'^\dagger \Delta L_\alpha + \mathrm{H.c.}$$

$$m_\nu = \eta_1 g_\alpha g_\beta + \eta_2 (g_\Delta)_\alpha (g_\Delta)_\beta + \eta_3 [(g_\Delta)_\alpha g_\beta + g_\alpha (g_\Delta)_\beta]$$

$$m_\nu \propto (m_2^2 - m_1^2)$$

$\mathrm{Det}[m_\nu] = 0$ $\Longrightarrow$ Hierarchical neutrino mass scheme

Anomaly cancelation $\Longleftrightarrow$ Hierarchical neutrino mass scheme

Annihilation of dark matter

$$\sigma(\delta_1\delta_1 \to \nu_\alpha\nu_\beta) \;=\; \sigma(\delta_1\delta_1 \to \bar{\nu}_\alpha\bar{\nu}_\beta)$$

$$= \frac{\left|\sin 2\alpha_1 (g^*_\alpha (g^*_\Delta)_\beta + g^*_\beta (g^*_\Delta)_\alpha)\right|^2}{8\pi m^2_{RR}}$$

$$2\sum_{\alpha,\beta}\sigma(\delta_1\delta_1 \to \nu_\alpha\nu_\beta) = 10^{-36}\ \mathrm{cm}^2$$

$$\mathrm{Max}[g^2_\alpha (g_\Delta)^2_\beta] \sim 10^{-3}\left(\frac{0.07}{\sin^2\alpha_1}\right)^2\left(\frac{m_{RR}}{300\ \mathrm{GeV}}\right)^2.$$

LFV rare decay modes

$$\mathrm{Br}(\mu \to e\gamma) = 10^{-6} \left(\frac{310 \text{ GeV}}{m_{RR}}\right)^4 \left| g_\mu^* g_e + K(\frac{m_\Delta^2}{m_{RR}^2})(g_\Delta^*)_\mu (g_\Delta)_e \right|^2$$

$$\mathrm{Br}(\tau \to \alpha\gamma) = 5 \times 10^{-9} \left(\frac{310 \text{ GeV}}{m_{RR}}\right)^4 \left| g_\tau^* g_\alpha + K(\frac{m_\Delta^2}{m_{RR}^2})(g_\Delta^*)_\tau (g_\Delta)_\alpha \right|^2$$

$$\mathrm{Max}[g_\alpha^2 (g_\Delta)_\beta^2] \sim 10^{-3} \left(\frac{0.07}{\sin^2 \alpha_1}\right)^2 \left(\frac{m_{RR}}{300 \text{ GeV}}\right)^2 .$$

$$\begin{aligned} \mathrm{Br}(\mu \to e\gamma) &< 1.2 \times 10^{-11} \\ \mathrm{Br}(\tau \to e\gamma) &< 1.1 \times 10^{-7} \\ \mathrm{Br}(\tau \to \mu\gamma) &< 6.8 \times 10^{-8} . \end{aligned}$$

To satisfy the bound, there should be a small hierarchy:

$g_e \sim 0.1 g_\mu, 0.1 g_\tau$ $\qquad$ $(g_\Delta)_e \sim 0.1 (g_\Delta)_\mu, 0.1 (g_\Delta)_\tau$

Flavor Structure in Normal Hierarchical Scheme

$$g_\alpha = |g|(\hat{3})_\alpha \quad \text{and} \quad (g_\Delta)_\alpha = |g_\Delta|[\cos\psi(\hat{3})_\alpha + \sin\psi(\hat{2})_\alpha] \; ,$$

$$\alpha = e \; , \; \mu \; , \; \tau$$

$$\hat{2} = \left(s_{12}c_{13}c - s_{13}se^{-i\delta}e^{i\phi} \; , \; cc_{12}c_{23} - cs_{12}s_{23}s_{13}e^{i\delta} - ss_{23}c_{13}e^{i\phi} \; , \; -cc_{12}s_{23} - cs_{12}s_{13}c_{23}e^{i\delta} - sc_{23}c_{13}e^{i\phi}\right)$$
$$\hat{3} = \left(s_{12}c_{13}s + cs_{13}e^{i(\phi-\delta)} \; , \; c_{12}c_{23}s - s_{12}s_{23}s_{13}se^{i\delta} + s_{23}c_{13}ce^{i\phi} \; , \; -c_{12}s_{23}s - s_{12}s_{13}c_{23}se^{i\delta} + c_{23}c_{13}ce^{i\phi}\right)$$

where $c = \cos\theta$ and $s = \sin\theta$ in which

$$\theta = \tan^{-1}\left(\sqrt[4]{\Delta m^2_{sol}/\Delta m^2_{atm}}\right) \simeq 0.4 \; .$$

$$\sin\psi \gtrsim 0.2.$$

Flavor Structure in Inverted Hierarchical Scheme

$$g = |g|\hat{2}' \ , \quad g_\Delta = |g_\Delta|(\hat{1}' \sin\psi' + \hat{2}' \cos\psi')$$

$$[\hat{1}' \ \hat{2}' \ \hat{3}'] = U_{PMNS} \cdot \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\theta \quad = \quad \arctan \sqrt[4]{\Delta m^2_{atm}/(\Delta m^2_{atm} + \Delta m^2_{sol})} \simeq \pi/4$$

Exciting prediction

Accommodating the neutrino data without fine tuning:

$$g_e \sim 0.1 g_\mu, 0.1 g_\tau \qquad (g_\Delta)_e \sim 0.1 (g_\Delta)_\mu, 0.1 (g_\Delta)_\tau$$

$\mathrm{Br}(\mu \to e\gamma)$ is very close to present bound

$\Downarrow$

MEG will detect abundant number of events.

Scale of neutrino mass

$$g g_{\Delta} \frac{m_2^2 - m_1^2}{m_{RR}} \frac{\sin\alpha_1 \cos^3\alpha_1}{16\pi^2} \sim \sqrt{\Delta m^2_{atm}}$$

As in SLIM scenario:

$$m_2^2 - m_1^2 \sim (10\ \mathrm{MeV})^2 \frac{m_{RR}}{300\ \mathrm{GeV}} \frac{0.054}{g g_{\Delta}}$$

Scale of new physics

Dark matter abundance:

$$\mathrm{Max}[g_\alpha^2 (g_\Delta)_\beta^2] \sim 10^{-3} \left(\frac{0.07}{\sin^2\alpha_1}\right)^2 \left(\frac{m_{RR}}{300\ \mathrm{GeV}}\right)^2$$

$\mu \to e\gamma$ $\Rightarrow$ upper bound on g_α and $(g_\Delta)_\alpha$

$m_{RR} \sim 300$ GeV $\Rightarrow$ $E_R'^{+}$ E_R^{-} ν_R' ν_R

At LHC

$$\mathrm{Br}(E_R^- \to \ell_\alpha^- \delta_{1,2}) \propto |g_\alpha|^2.$$

$$\Gamma(\Delta^{++} \to \ell_\alpha^+ \ell_\beta^+ \delta_1, \delta_2) \propto |(g_\Delta)_\alpha g_\beta + (g_\Delta)_\beta g_\alpha|^2$$

One can cross check the direct measurement of $(g_\Delta)_\alpha$ and g_α at the LHC, with the derivation from neutrino data combined with $\mathrm{Br}(\mu \to e\gamma)$

Signatures at LHC

1)

$$m_{\Delta^+}^2 = \frac{m_{\Delta^{++}}^2 + m_{\Delta^0}^2}{2}$$

2) Missing Higgs: $\lambda_{\phi H}\phi\phi^\dagger H^\dagger H$

If $\lambda_{\phi H} > 4\ \mathrm{GeV}/\langle H\rangle$, the invisible decay modes,

$H \to \delta_1\delta_1, \delta_2\delta_2$, can dominate over $H \to b\bar{b}$.

Summary and conclusions

A model that embeds the low energy scenario:

A high signal for $\mu \to e\gamma$ to be discovered by MEG.

Rich phenomenology in LHC

Upper limit on the new physics scale:

Discovery of $\begin{bmatrix} \nu_R \\ E_R^- \end{bmatrix}$ and $\begin{bmatrix} E_R'^+ \\ \nu_R' \end{bmatrix}$

Summary and Conclusions

LHC $\Rightarrow$ $\boxed{g}$ and $\boxed{g_\Delta}$ $\Leftarrow$ $\left\{ \begin{array}{l} \text{Neutrino mass} \\ \boxed{\mathrm{Br}(\mu \to e\gamma)} \end{array} \right.$

An example

Boehm and Fayet, NPB683 (04) 219

$$D = \begin{bmatrix} N \\ E_R \end{bmatrix} \qquad g\phi\epsilon_{\alpha\beta} D^*_\alpha L_\beta \qquad \phi = (\phi_1 + i\phi_2)/\sqrt{2}$$

Since this time N carries quantum numbers it cannot have Majorana mass. Majorana mass can be achieved after electroweak symmetry breaking. Adding a new singlet, N_L , there will be a "mirror seesaw":

$$Y N_L H \cdot D \qquad \frac{M_L}{2} N_L^T c N_L \qquad M_L \sim m_{EW} \qquad Y \sim 1$$

Z_2 Symmetry: $D \to -D\ , \quad N_L \to -N_L\ , \quad \phi \to -\phi$

Comparison with Majoron

Interaction of Majorons, J : $J\nu^T c\nu$

Reminder: $\mathcal{L}_I \supset g\phi\bar{N}\nu$

Majoron is a massless pseudo-scalar Goldstone boson.

The effects of Majoron have been extensively studied in the context of

CMB,

Structure formation,

Meson decay,

supernova

…

Bounds from CMB

Acoustic peaks of the CMB ➡ neutrinos must be freely streaming at T ~ 0.3 eV. ➡ limits on interactions of J

Hannestad and Raffelt, PRD 72 (05)103514

$$\nu \to \nu' J \qquad \nu\bar{\nu} \to JJ \qquad \nu\nu \to \nu\nu \qquad \nu\phi \to \nu\phi$$

Parallels in the SLIM model:

Kinematics forbids $\nu \to \nu' \phi$

For T<eV, there is nc $\nu\nu \to \phi\phi$

$\nu\nu \to \nu\nu$ contribute only through a box diagram.

For $m_\phi \gg T$, $\nu\phi \to \nu\phi$ vanishes.

No bound on SLIM from CMB

Product of SLIM annihilation

In this scenario, SLIMs annihilate only into neutrinos.

Electron-positron pair is not produced by SLIM annihilation. As a result:

No 511 keV line

No radiation from bremsstrahlung, Compton scattering …

Restoring the Flavor indices

$$\mathcal{L} = g_{i\alpha}\phi\bar{N}_i\nu_\alpha$$

Real SLIM

$$(m_\nu)_{\alpha\beta} = \sum_i \frac{g_{i\alpha}g_{i\beta}}{16\pi^2} m_{N_i}\left(\log\frac{\Lambda^2}{m_{N_i}^2} - \frac{m_\phi^2}{m_{N_i}^2 - m_\phi^2}\log\frac{m_{N_i}^2}{m_\phi^2}\right).$$

Complex SLIM

$$(m_\nu)_{\alpha\beta} = \sum_i \frac{g_{i\alpha}g_{i\beta}}{32\pi^2} m_{N_i}\left[\frac{m_{\phi_1}^2}{(m_{N_i}^2 - m_{\phi_1}^2)}\ln\left(\frac{m_{N_i}^2}{m_{\phi_1}^2}\right) - \frac{m_{\phi_2}^2}{(m_{N_i}^2 - m_{\phi_2}^2)}\ln\left(\frac{m_{N_i}^2}{m_{\phi_2}^2}\right)\right].$$

Two or more N are necessary.

In two N case, one of the neutrino mass eigenvalues will vanish.

Just Like canonical seesaw

Fitting the neutrino data

$$m_\nu = U \cdot \mathrm{Diag}[m_1, m_2 e^{2i\phi_2}, m_3 e^{2i\phi_3}]U^T.$$

$$g = \mathrm{Diag}(X_1, \ldots, X_n) \cdot O \cdot \mathrm{Diag}(\sqrt{m_1}, \sqrt{m_2} e^{i\phi_2}, \sqrt{m_3} e^{i\phi_3})U^T,$$

where O is an arbitrary $n \times 3$ matrix that satisfies $O^T \cdot O = \mathrm{Diag}(1, 1, 1)$.

For real SLIM

$$X_i = 4\pi\left(\frac{1}{m_{N_i}}\right)^{1/2}\left(\log\frac{\Lambda^2}{m_{N_i}^2} - \frac{m_\phi^2}{m_{N_i}^2 - m_\phi^2}\log\frac{m_{N_i}^2}{m_\phi^2}\right)^{-1/2},$$

For complex SLIM

$$X_i = \sqrt{\frac{32\pi^2}{m_{N_i}}}\left(\frac{m_{\phi_1}^2}{m_{N_i}^2 - m_{\phi_1}^2}\log\frac{m_{N_i}^2}{m_{\phi_1}^2} - \frac{m_{\phi_2}^2}{m_{N_i}^2 - m_{\phi_2}^2}\log\frac{m_{N_i}^2}{m_{\phi_2}^2}\right)^{-1/2}.$$

$$\langle\sigma(\phi\phi \to \nu_\alpha\nu_\beta)v_r\rangle = \langle\sigma(\phi\phi \to \bar{\nu}_\alpha\bar{\nu}_\beta)v_r\rangle = \frac{1}{4\pi}\left|\sum_i \frac{g_{i\alpha}g_{i\beta}m_{N_i}}{m_\phi^2 + m_{N_i}^2}\right|^2.$$

For real case: $(m_\nu)_{\alpha\beta} = \sum_i \frac{g_{i\alpha}g_{i\beta}}{16\pi^2} m_{N_i}\left(\log\frac{\Lambda^2}{m_{N_i}^2} - \frac{m_\phi^2}{m_{N_i}^2 - m_\phi^2}\log\frac{m_{N_i}^2}{m_\phi^2}\right).$

At least one of the right-handed neutrinos has to have a mass in the 1-10 MeV range.

$$\text{a few keV} < m_\phi < 10\ \text{MeV}.$$

Some solutions for real scalar

a few keV $< m_\phi <$ 10 MeV.

TABLE I. Some possible solutions in the framework of real ϕ. "N" and "I," respectively, denote normal and inverted mass scheme. We have taken $\langle \sigma v_r \rangle = 10^{-26}$ cm^3/s, $\Delta m^2_{\rm atm} = 2.6 \times 10^{-3}$ eV^2, $\theta_{12} = 34°$, $\theta_{13} = 0$, and $\theta_{23} = 45°$ and have set the Majorana phase equal to zero.

	M_{N_1} [MeV]	M_{N_2} [MeV]	m_ϕ [MeV]
N	1.2	1.2	0.85
I	1.4	1.4	1.0
N	100	1.2	0.85
I	100	1.3	0.97

Complex case

TABLE II. The same notation as in Table I, but with complex ϕ.

	M_{N_1} [MeV]	M_{N_2} [MeV]	m_{ϕ_1} [MeV]	m_{ϕ_2} [MeV]
N	10^5	10^5	3.3	1
I	10^5	10^5	3.7	1
N	5.8	5.8	2.6	1.8
I	6.6	6.6	2.9	2.0

$$\langle\sigma(\phi\phi \to \nu_\alpha \nu_\beta) v_r\rangle = \langle\sigma(\phi\phi \to \bar{\nu}_\alpha \bar{\nu}_\beta) v_r\rangle = \frac{1}{4\pi}\left|\sum_i \frac{g_{i\alpha} g_{i\beta} m_{N_i}}{m_\phi^2 + m_{N_i}^2}\right|^2.$$

For complex case:

$$m_\nu = \frac{g^2}{32\pi^2} m_N \left[\frac{m_{\phi_1}^2}{(m_N^2 - m_{\phi_1}^2)} \ln\left(\frac{m_N^2}{m_{\phi_1}^2}\right) - \frac{m_{\phi_2}^2}{(m_N^2 - m_{\phi_2}^2)} \ln\left(\frac{m_N^2}{m_{\phi_2}^2}\right)\right]$$

No upper bound on the right-handed neutrino mass

$$(1\ \mathrm{MeV})^2 \lesssim |m_{\phi_1}^2 - m_{\phi_2}^2| \lesssim (20\ \mathrm{MeV})^2.$$