Exotic Models of neutrino mass and dark matter

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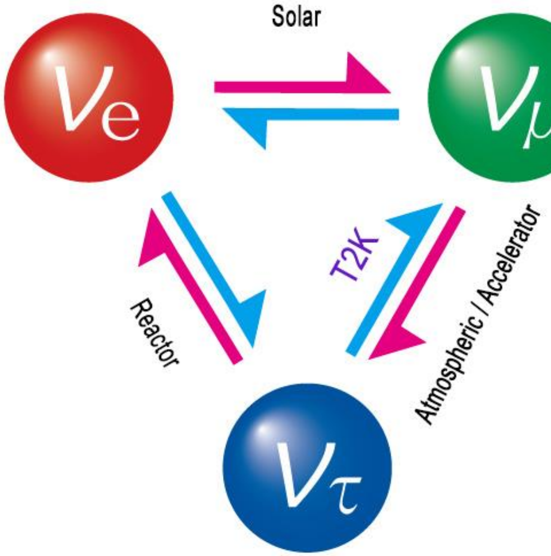
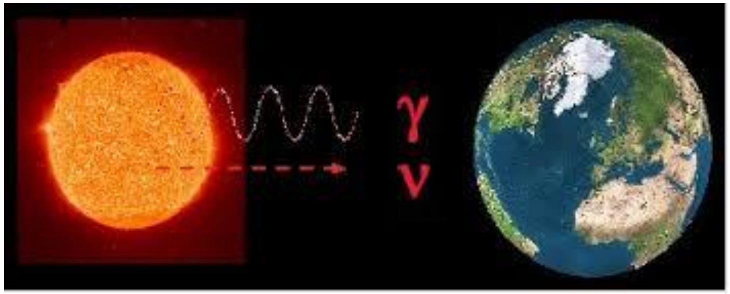
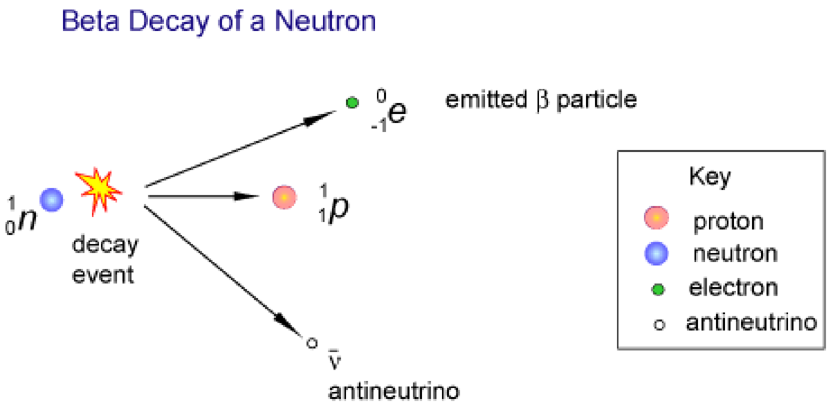
Non-zero neutrino mass

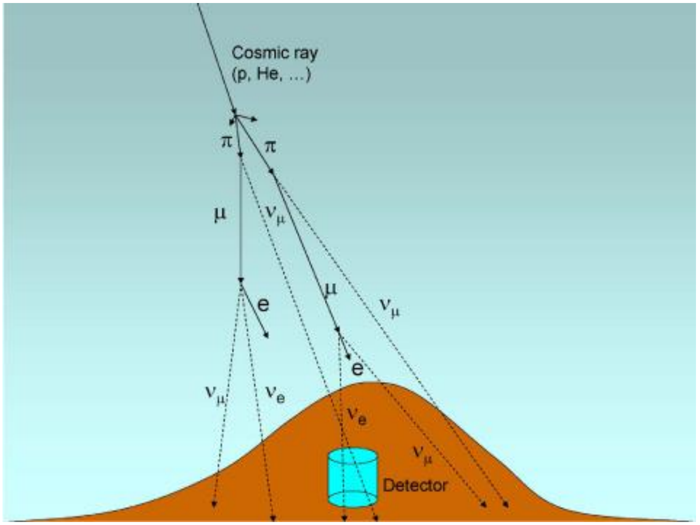


Neutrino oscillation between three generations

At least two of the neutrinos are massive and hence they mix with each other.







$\nu -$ mass: The physics beyond the SM

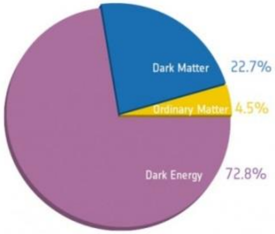
Within the framework of SM, Higgs mechanism does not generate non-zero neutrino masses due to the absence of right-handed neutrinos. Of course one could add three singlet right handed neutrinos to the SM though they are not found yet in the nature. Then the Yukawa coupling:

$$\begin{tikzcd}
Y\overline{\nu}_R\widetilde{H}^+L \arrow[r] \arrow[d] & m_\nu = O(0.1)eV \arrow[d] \\
L \equiv \begin{pmatrix} \nu_l \\ l \end{pmatrix} & Y = 10^{-12}
\end{tikzcd}$$

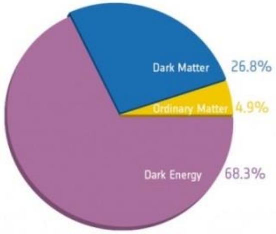
Q. Why the neutrino Yukawa coupling is so small in comparison to other charged fermions ?

Popular solutions: Seesaw mechanisms, which indicates neutrinos are primarily Majorana.

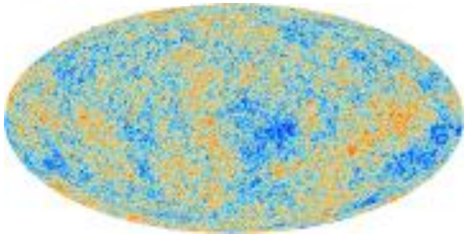
Dark Matter…

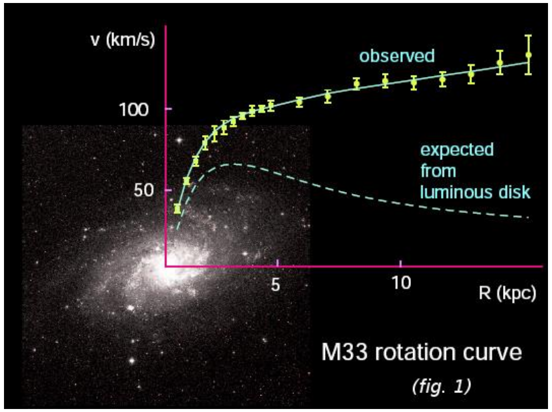


Before Planck

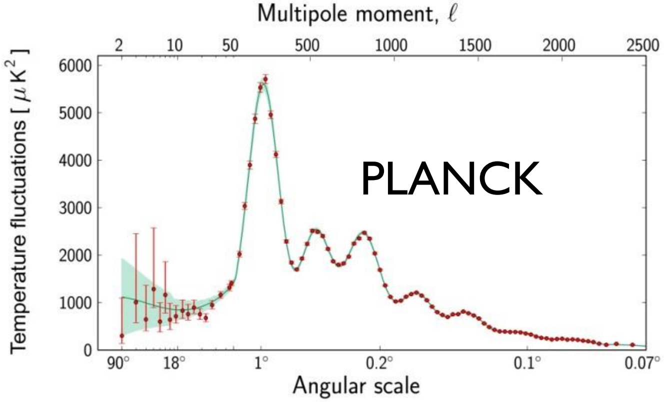


After Planck





Markevitch et.al, Astro Phy J, 2004

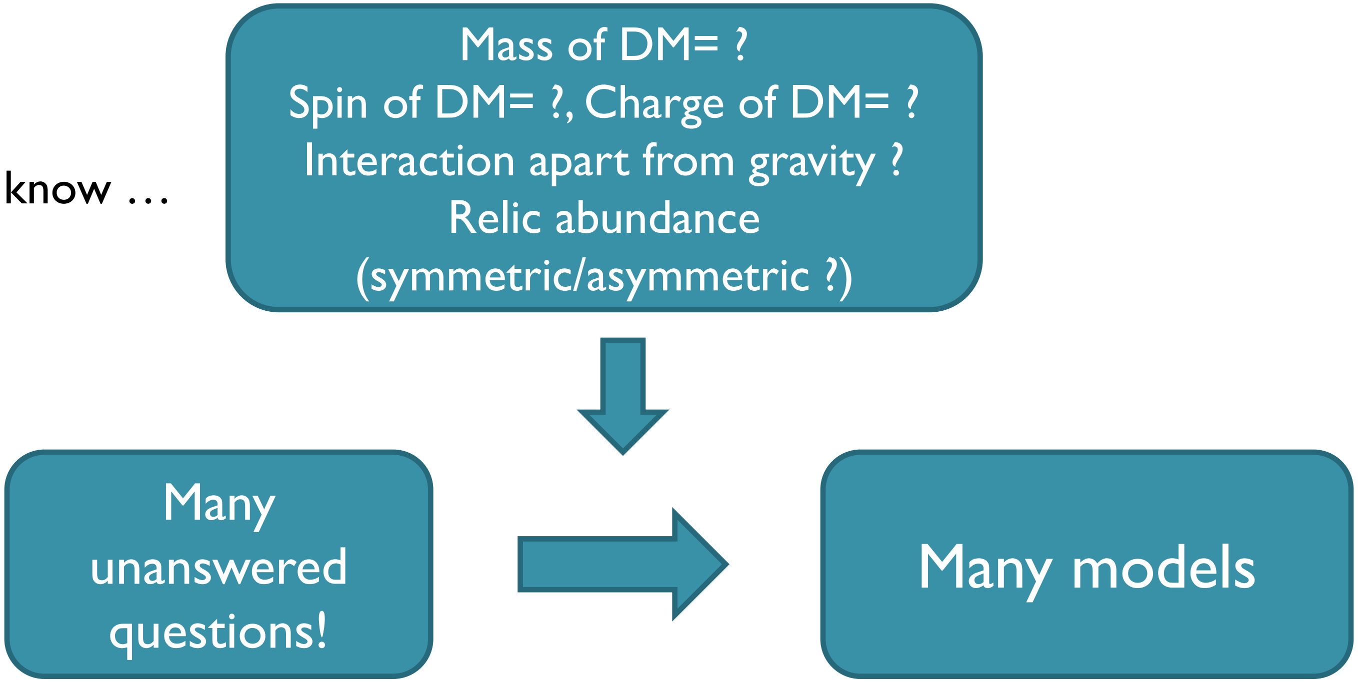


Nature of Dark Matter…

From the astrophysical evidences of dark matter we infer that…

DM should be a massive particle and hence interact gravitationally.
It is electrically neutral and therefore hide itself easily.
It is stable on the cosmological time scale and therefore the large scale structure exists.

However,
We don't know …



Mass of DM= ?
Spin of DM= ?, Charge of DM= ?
Interaction apart from gravity ?
Relic abundance
(symmetric/asymmetric ?)

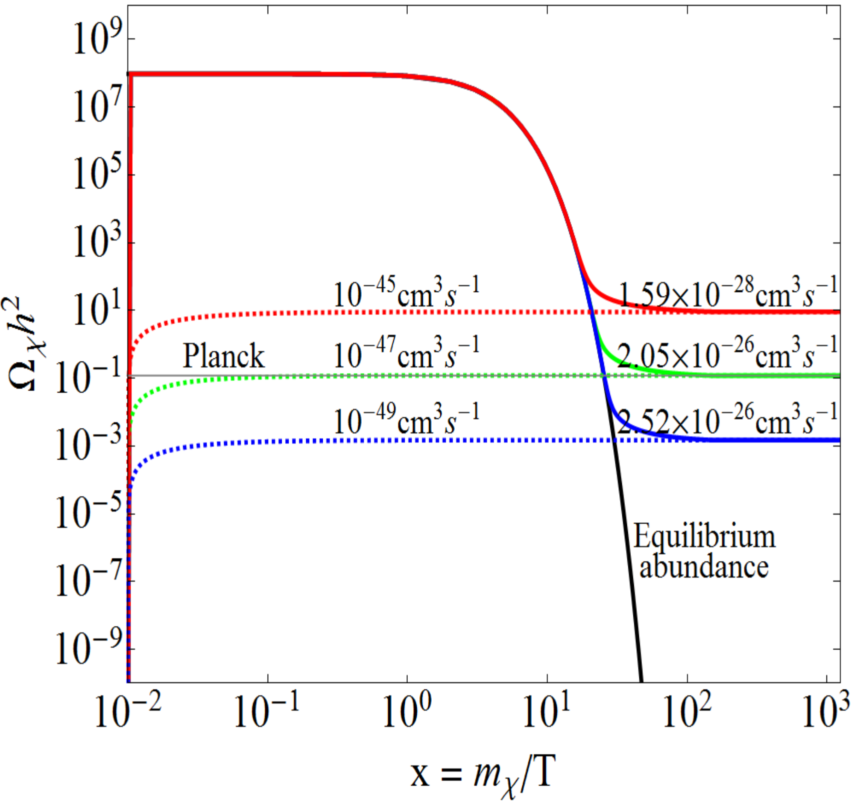
Many unanswered questions!

Many models

DM is a WIMP (Gravity+ weak) ?

Steigman and Turner, 1984

The DM is assumed to be in equilibrium in the early Universe via the weak interaction processes. As the temperature, due to expansion of the Universe, falls below the mass scale of DM, the latter gets freeze-out from the thermal bath and gives the correct relic abundance.



$$\frac{dY_\chi}{dx} = \frac{-x\langle\sigma|v|\rangle s}{H(m_\chi)}(Y_\chi{}^2 - Y_{eq}{}^2)$$

$$Y_\chi = \frac{n_\chi}{s}, x = \frac{m_\chi}{T}$$

$$\Omega_{DM} h^2 = \frac{1.1\times 10^9 \, GeV^{-1} x_F}{g_*^{1/2} M_{pl} \langle \sigma | v | \rangle_F} = 0.1198 \pm 0.0026$$

Analytical estimation of a WIMP relic density

The observed relic abundance of DM by WMAP and PLANCK

$$< \sigma | v |>|_F \approx 3\times 10^{-26} cm^3 / \sec \approx 2.6\times 10^{-9} GeV^{-2}$$

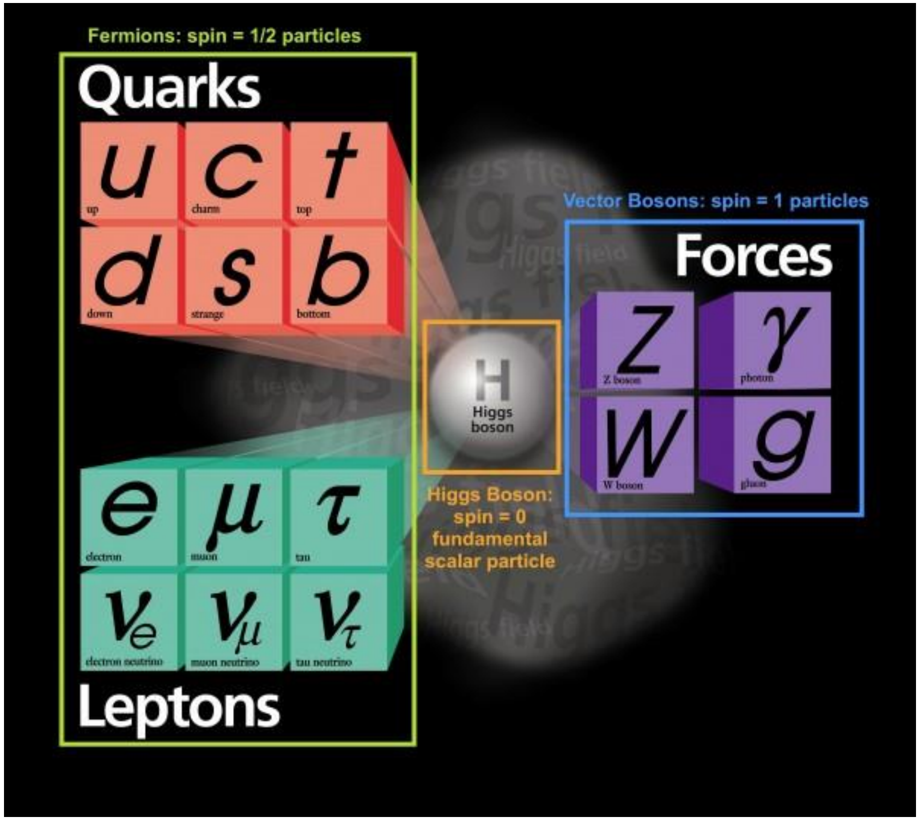
$$\approx O(10^{-36}) cm^2$$

Which is typically a weak interaction cross-section.

WIMP Miracle

Therefore one believes that DM could be a WIMP.

DM: The physics beyond the SM



The only particles in SM which seem to satisfy some properties of DM are neutrinos:

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5eV} \approx 0.0024$$

$$<< \Omega_{DM} h^2$$

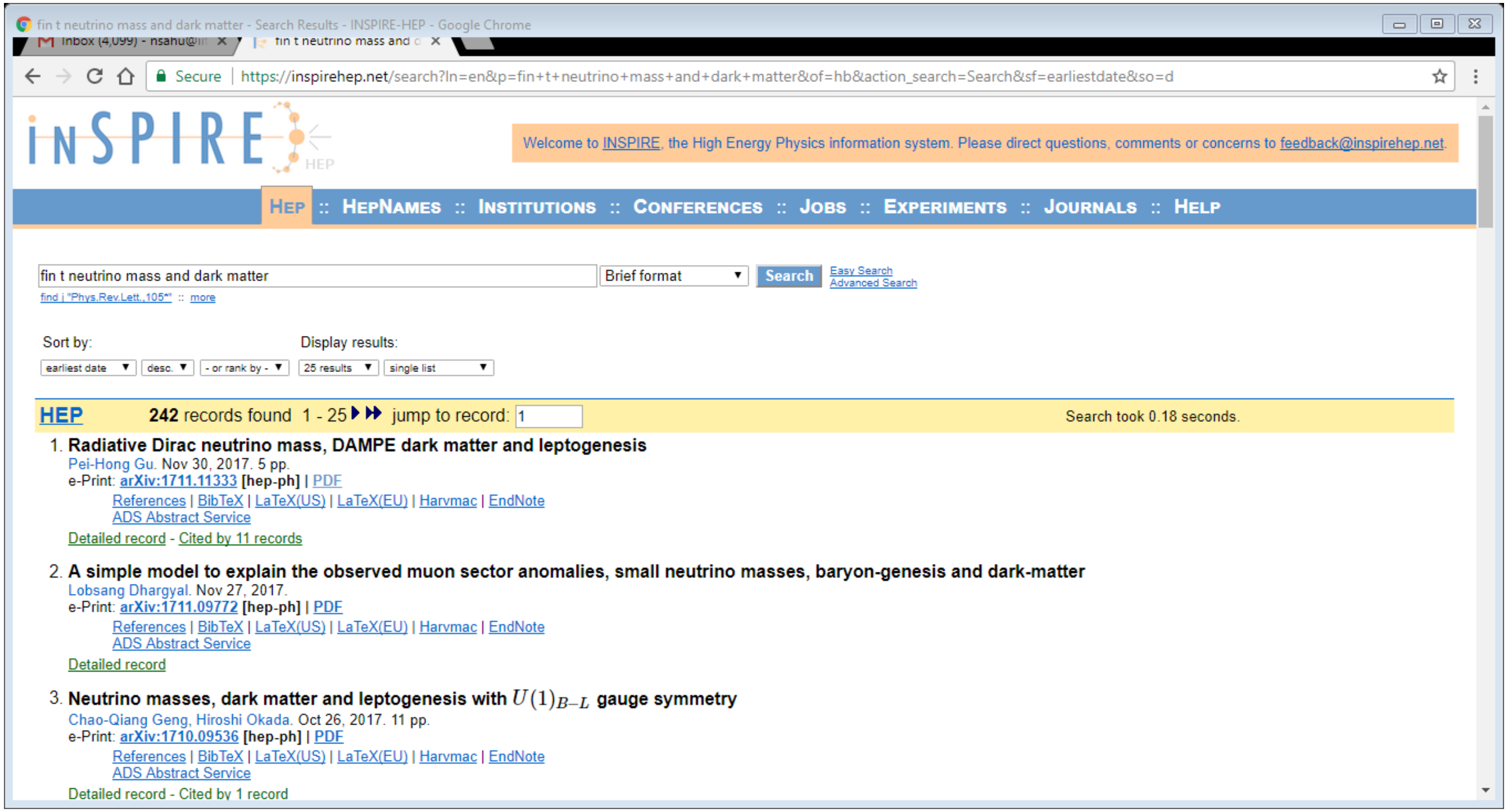
Cowsik and McClelland, PRL 1972

So, we need to look for a candidate of DM in the beyond standard model of particle physics, which is probably heavy (> a few GeV).

Lee and Weinberg, PRL 1977

Objective of this talk:

Models of neutrino mass
+ dark matter



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1. **Radiative Dirac neutrino mass, DAMPE dark matter and leptogenesis**
   Pei-Hong Gu. Nov 30, 2017. 5 pp.
   e-Print: arXiv:1711.11333 [hep-ph] | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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2. **A simple model to explain the observed muon sector anomalies, small neutrino masses, baryon-genesis and dark-matter**
   Lobsang Dhargyal. Nov 27, 2017.
   e-Print: arXiv:1711.09772 [hep-ph] | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
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3. **Neutrino masses, dark matter and leptogenesis with $U(1)_{B-L}$ gauge symmetry**
   Chao-Qiang Geng, Hiroshi Okada. Oct 26, 2017. 11 pp.
   e-Print: arXiv:1710.09536 [hep-ph] | PDF
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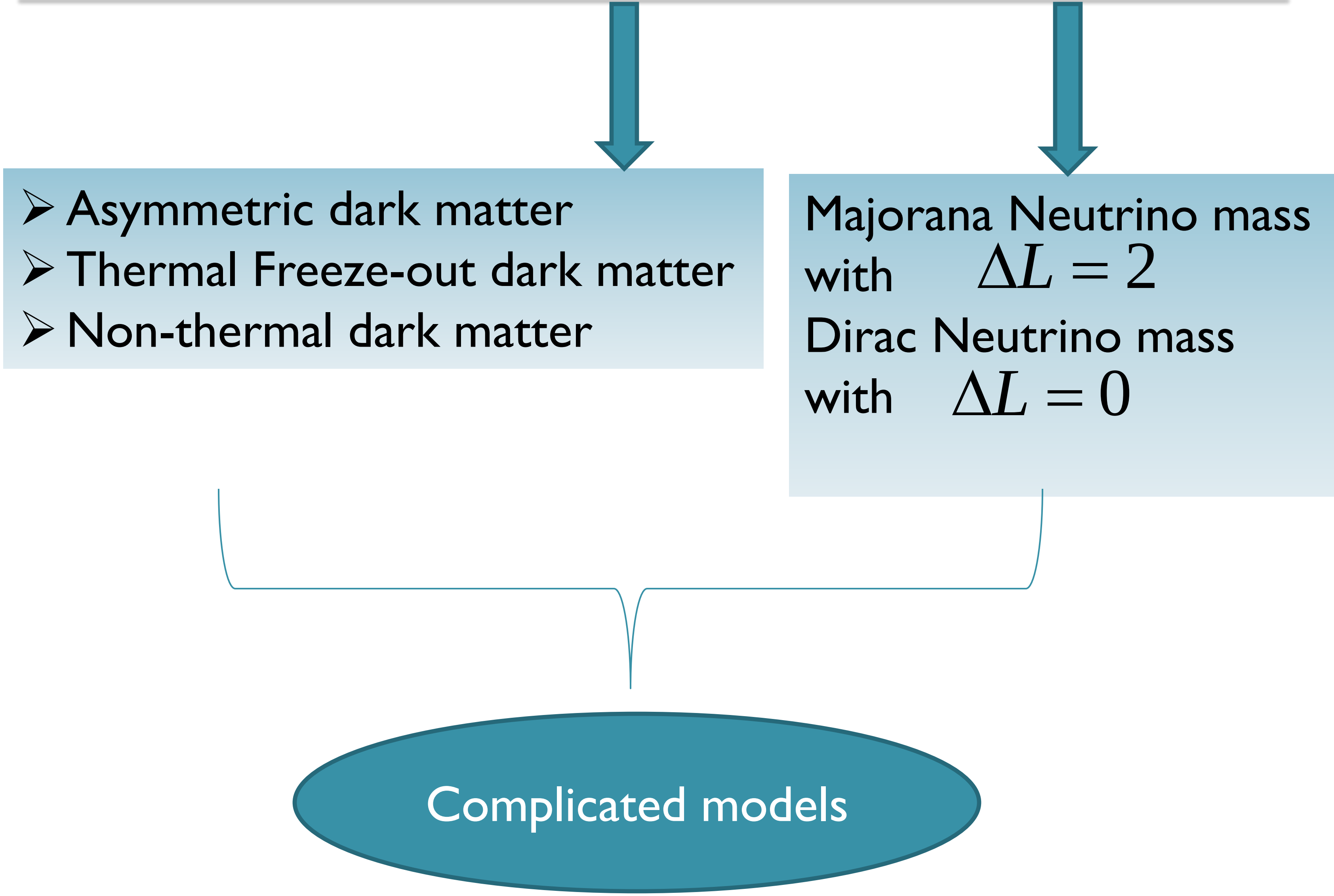
Models of dark matter+neutrino mass



- Asymmetric dark matter
- Thermal Freeze-out dark matter
- Non-thermal dark matter

Majorana Neutrino mass with $\Delta L = 2$

Dirac Neutrino mass with $\Delta L = 0$

Complicated models

Case-I: Asymmetric DM + Neutrino Mass

$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

Asymmetric DM and neutrino mass in Type-I seesaw models

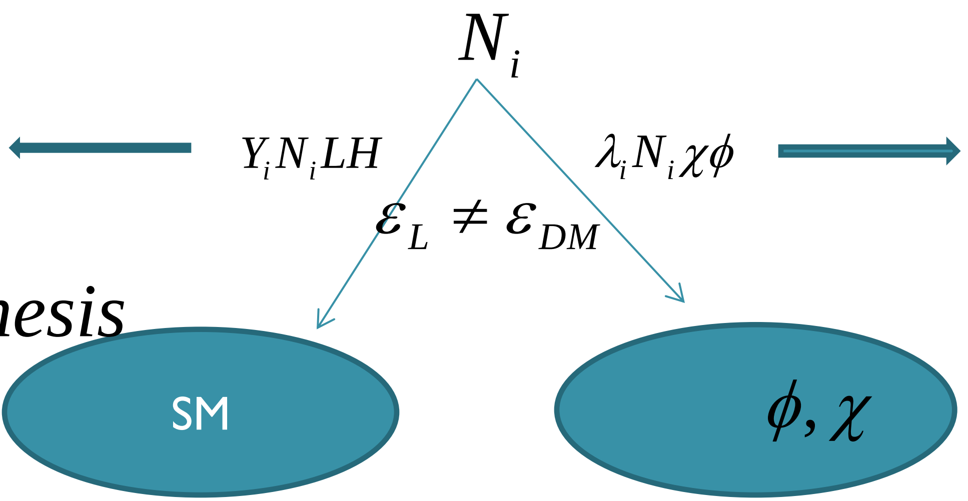
Majorana

$\nu - mass$

$+$

Leptogenesis

$MN_iN_i \rightarrow \Delta L = 2$



N_i

Y_iN_iLH

$\lambda_iN_i\chi\phi$

$\varepsilon_L \neq \varepsilon_{DM}$

SM

ϕ, χ

Dirac Dark matter χ

ϕ, χ are Z_2 odd particles.

$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{1}{S_{\rm DM}}\frac{m_{\rm DM}}{m_p}\frac{\epsilon_{\rm DM}}{\epsilon_L}\frac{\eta_{\rm DM}}{\eta_L}$$

$\Rightarrow$ DM mass keV to TeV is allowed depending on the Yukawa coupling.

Important Note: Symmetric part of Dark matter annihilated to dark sector radiation: $\bar{\chi}\chi \rightarrow \gamma\gamma$

arXiv: 1101.4936 (Falkowski, Ruderman and Volansky)

talk by: Debasish Borah

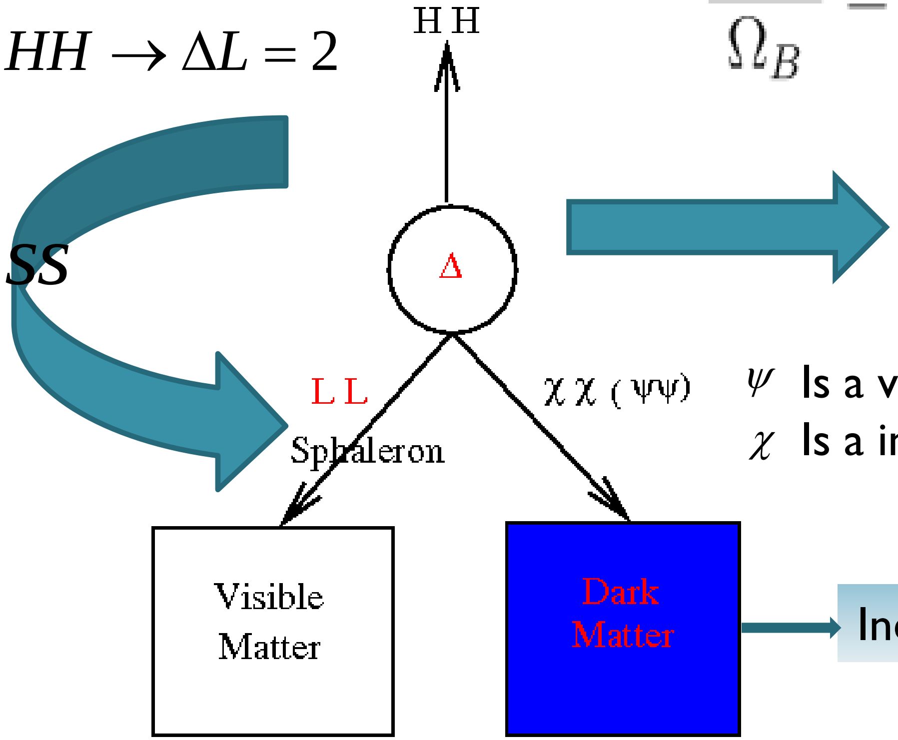
Asymmetric DM and neutrino mass in Type-II seesaw models

$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{1}{S_{\rm DM}}\,\frac{m_{\rm DM}}{m_p}\,\frac{\epsilon_{\rm DM}}{\epsilon_L}\,\frac{\eta_{\rm DM}}{\eta_L}$$

$$\Delta LL + \Delta^{+} HH \rightarrow \Delta L = 2$$

$$\downarrow$$

$$\nu - mass$$



$$\varepsilon_L \neq \varepsilon_{DM}$$

ψ Is a vector-like fermion doublet

χ Is a inert scalar doublet

→ Inelastic dark matter

Large DM masses up to O(TeV) is allowed to satisfy: $\frac{\Omega_{DM}}{\Omega_B} = 4.978 \pm 0.350$

See the details: talk by Debasish Borah

arXiv: 1108.3967 (Arina and Sahu), arXiv: 1206.0009 (Arina, Gong and Sahu), arXiv: 1211.0435 (Arina, Mohapatra and Sahu)

Case-II: Thermal Freeze out dark matter abundance + Neutrino Mass

Here models vary, depending on the nature of neutrino: Dirac or Majorana. In either case, the dark matter abundance can be obtained in tree level as well as radiative neutrino mass models:

Categories:

- Extension of seesaw models for neutrino mass and dark matter.
- Dark matter in radiative neutrino mass models.
- Gauged U(1) extension of SM where anomaly matching conditions provide a common solution to neutrino mass and dark matter.
- Sterile neutrino extension of SM.
- Left-right symmetric models with naturally B-L gauge symmetry
- Flavor symmetric models for neutrino mass and dark matter.

Extended seesaw for $\nu -$ mass+DM

$$\nu - \text{mass} \longleftarrow \frac{LLHH}{\Lambda} + \frac{NNHH}{\Lambda} \longrightarrow \text{DM relic abundance}$$

$$L \equiv \begin{pmatrix} \nu_l \\ l \end{pmatrix} :$$

Left handed fermion doublet

$$H \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} :$$

SM Higgs doublet

$$N \equiv \begin{pmatrix} N^0 \\ N^- \end{pmatrix} :$$

Vector-like doublet fermion whose neutral component serves as a candidate of DM

$$m_\nu = \frac{<H>^2}{\Lambda} = 0.1 eV \Rightarrow \Lambda = O(10^{14}) GeV$$

S.Bhattacharya, N.Sahoo and N. Sahu, 1704.03417
1510.02760

Assured via a Z_2 symmetry under which N is odd.

$$\frac{LLHH}{\Lambda}+\frac{NNHH}{\Lambda} \Longrightarrow$$

Expanded in a type-II seesaw framework

$$-\mathcal{L}= \begin{array}{l} M_\Delta{}^2\Delta^+\Delta+M_N\overline{N}N+f_L\overline{L}^c i\tau_2\Delta L \\ +\, f_H M_\Delta\Delta^+HH+f_N\overline{N}^c i\tau_2\Delta N+h.c. \end{array}$$

Where Δ is a scalar triplet and does not acquire any vev. After electroweak phase transition, it acquires an induced vev. As a result we get a neutrino mass:

$$M_\nu = f_L<\Delta>=-f_L f_H\frac{v^2}{M_\Delta}$$

$$\rho=\frac{M_W{}^2}{M_Z{}^2\cos^2\theta_w}=\frac{\frac{g^2}{4}(<H>^2+2<\Delta>^2)}{\frac{g^2+g'^2}{4\cos^2\theta_w}(<H>^2+4<\Delta>^2)}=1.00037\pm0.00023$$

$$\Rightarrow<\Delta><3.64GeV$$

The scalar triplet also induces a Majorana mass to DM, which does not affect the relic abundance of DM, but it evades the constraints from Z-mediated direct detection. HOW ?

$$-\mathcal{L} = M_N \overline{N^0} N^0 + f_N \overline{(N^0)^c} N^0 \langle \Delta \rangle$$

The Majorana mass splits the DM (Dirac fermion) into two pseudo-Dirac fermions with a small mass splitting:

$$\begin{pmatrix} M_N & m \\ m & M_N \end{pmatrix} \begin{array}{l} \nearrow \; M_N + m \\ \searrow \; M_N - m \end{array}$$

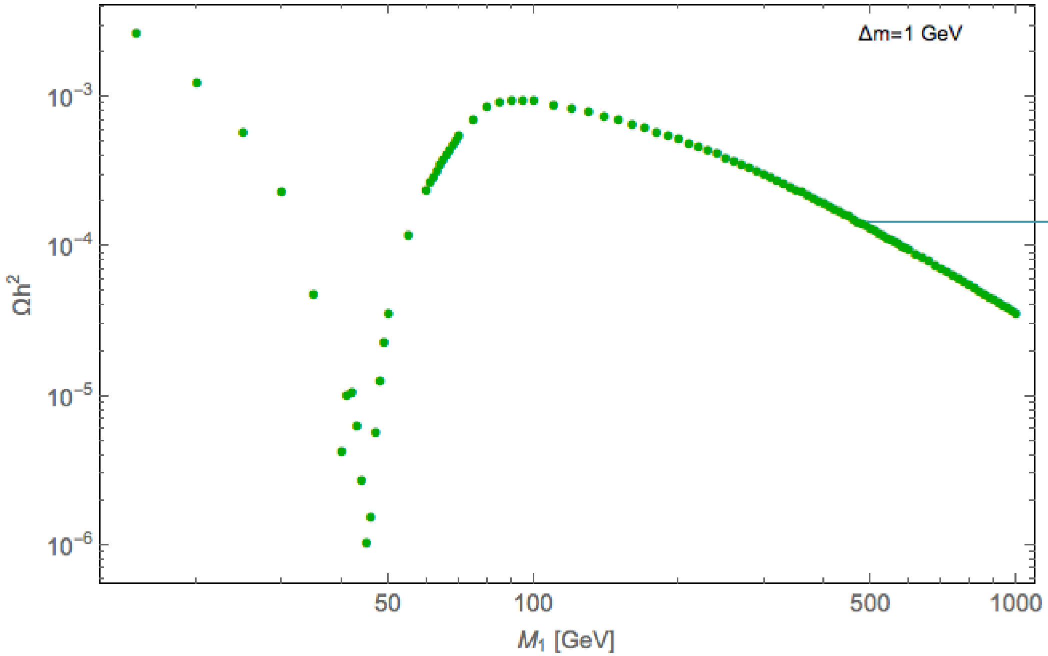
$$\delta = 2m$$

$$= 2 f_N < \Delta > = -2 f_N f_H \frac{v^2}{M_\Delta} = O(MeV - GeV)$$

This forbids the DM-nucleon scattering via Z-mediated process:

But we have another serious problem ?

$$-\mathcal{L} = \frac{g}{\sqrt{2}} \overline{N}^0 \gamma_\mu W^{+\mu} N^- + \frac{g}{2\cos\theta_w} \overline{N}^0 \gamma_\mu Z^\mu N^0$$



Killer process:

$N^0 \overline{N}^0 \to W^+ W^-$

Note: For the same reason, it can be a viable asymmetric DM.

Ref. C. Arina and N. Sahu, 1108.3967, NPB854, 2012.
C.Arina, J.O. Gong and N.Sahu, 1206.0009, NPB 865, 2012.
C.Arina, R.N. Mohapatra and N.Sahu, 1211.0435, PLB720, 2013.

We overcome the problem of small relic abundance by introducing a vector-like singlet fermion χ^0, which mixes with the neutral component of the doublet fermion and decreases the annihilation cross-section. As a result we get the correct relic abundance.

$$\mathcal{L}_{DM} = M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + [Y \overline{N} \tilde{H} \chi^0 + h.c.]$$
$$+ \overline{N} i\gamma^\mu D_\mu N + \overline{\chi^0} i\gamma^\mu \partial_\mu \chi^0$$

where $$N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1,2,-1),\ H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \equiv (1,2,1),\ \chi^0 \equiv (1,1,0)$$

For various purpose see: hep-th/0501082, hep-ph/0510064, arXiv: 0705.4493, arXiv:0706.0918, arXiv:0804.4080, arXiv: 1404.4398 arXiv:1109.2604, arXiv:1311.5896, arXiv:1504.07892, arXiv:1505.03867

Under Z_2 symmetry both χ^0 and N are odd. As a result the DM emerges as a mixture of singlet fermion χ^0 and the neutral component of the vector-like doublet fermion N.

After EW phase transition the mass matrix for neutral vector-like fermions is given by

$$\begin{pmatrix} \overline{N^0} & \overline{\chi^0} \end{pmatrix} \begin{pmatrix} M_N & m_D \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} N^0 \\ \chi^0 \end{pmatrix}$$

Where $m_D = Y < H >$

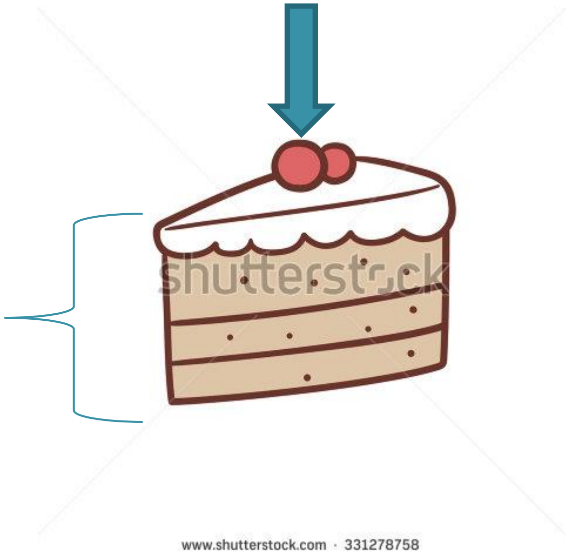
$$M_1 = M_\chi - \frac{m_D^2}{M_N - M_\chi}; N_1 = \cos\theta\chi^0 + \sin\theta N^0$$

$$M_2 = M_N + \frac{m_D^2}{M_N - M_\chi}; N_2 = \cos\theta N^0 - \sin\theta\chi^0$$

$$M^\pm = M_1 \sin^2\theta + M_2 \cos^2\theta = M_N; N^\pm$$

$$\tan 2\theta = \frac{m_D}{M_N - M_\chi}$$

The lightest particle is the N_1, which is candidate of dark matter with appropriate mixing angle θ


DOUBLET

SINGLET

For details: talk by Nirakar Sahoo

Radiative neutrino mass and dark matter

Generic features

(1) Use appropriate symmetry to forbid the coupling :

$$Y\overline{N_R}\widetilde{H}^{+}L \Rightarrow M_\nu = 0 \text{ at tree level}$$

(2) Then generate neutrino mass radiatively using dark matter and other particles in the loop.

Model-I

$$\Rightarrow SM + S_1, S_2, N_R$$

$$Z_2 : S_2 \to -S_2, N_R \to -N_R, S_1 \to S_1$$

Krauss, Nasri, Trodden, hep-ph/0210389

$$-\mathcal{L} = f_{\alpha\beta} L^{T}{}_{\alpha} C i \tau_2 L_{\beta} S_1^{+} + g_{\alpha} N_R S_2^{+} \ell_{\alpha R} + M_R N_R^{T} C N_R + V(S_1, S_2) + H.c.$$

$M_{N_R} < M_{S_2} \Rightarrow N_R$ is dark matter

Relic abundance

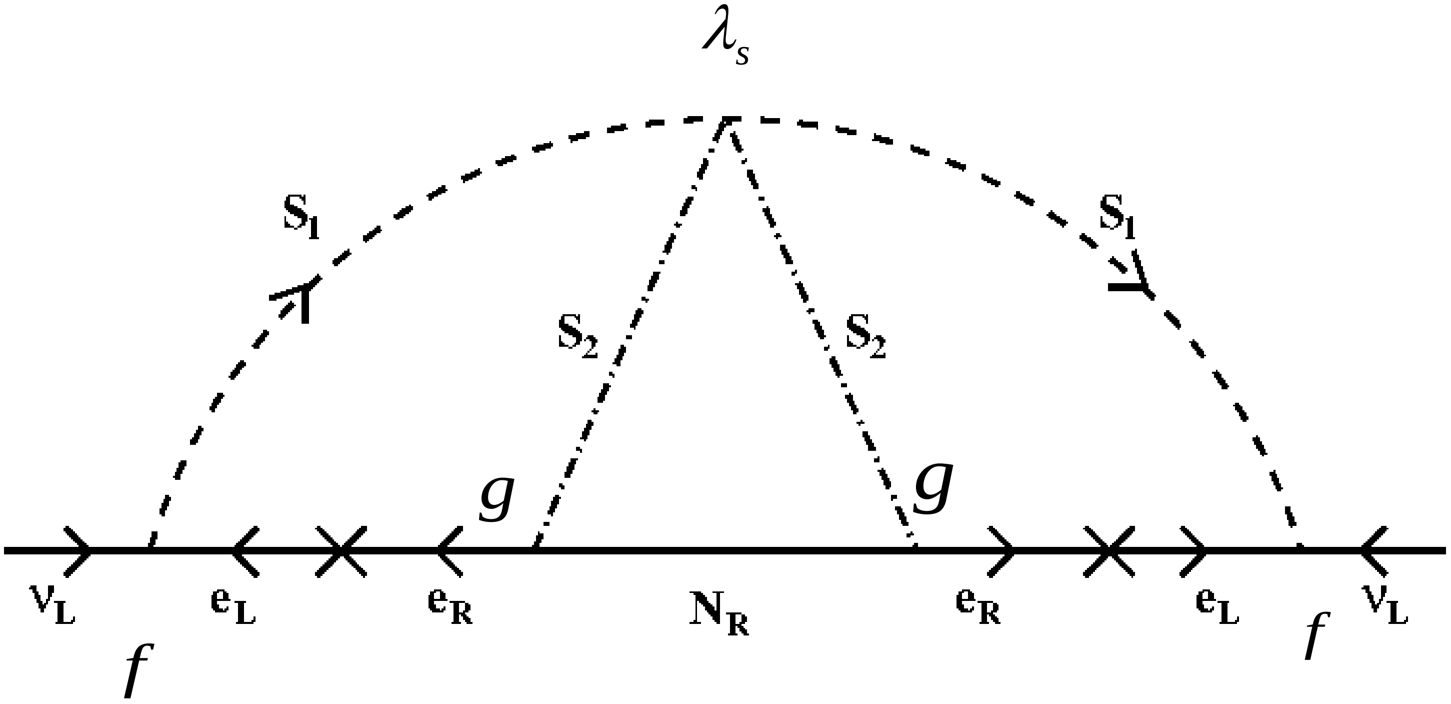
$$N_R N_R \rightarrow \ell_R^{+} \ell_R^{-}$$

$$< \sigma \,|\, v \,|> \approx \frac{g^4}{\pi} \frac{M_R^{2}}{M_{S_2}^{4}}$$

$$\Delta L = 2 \Rightarrow M_{\nu} \neq 0$$

$$M_R \sim TeV, M_{S_2} \sim TeV, g^2 \sim 0.1$$

$$\Omega_{N_R} h^2 \sim 0.1$$



$$M_\nu = \frac{1}{(4\pi)^3} \frac{f^2 g^2 \lambda_s}{M_{S_2}} m_l^2 \qquad M_R < M_{S_1} < M_{S_2} \sim TeV$$

For suitable choice of the coupling the neutrino mass can be obtained in sub-eV scale.

Krauss, Nasri, Trodden, hep-ph/0210389

Model-II

$$\Rightarrow SM + N_i, \eta$$ → Both of them can be dark matter

$$Z_2 : N_i \to -N_i, \eta \to -\eta$$

$$-\mathcal{L} = \frac{1}{2} M_i N_i N_i + f_{ij} \overline{L_i} H l_{jR} + h_{ij} \overline{L_i} \tilde{\eta} N_j + V(H,\eta) + H.c.$$

$$V(H,\eta) = m_1{}^2 H^+ H + m_2{}^2 \eta^+ \eta + \frac{1}{2}\lambda_1 (H^+ H)^2 + \frac{1}{2}\lambda_2 (\eta^+ \eta)^2$$

$$+ \lambda_3 (H^+ H)(\eta^+ \eta) + \lambda_4 (H^+ \eta)(\eta^+ H) + \frac{1}{2}\lambda_5 [(H^+ \eta)^2 + h.c.]$$

Choose the vacuum: $m_1{}^2 < 0, m_2{}^2 > 0$

$$< H >= v, < \eta >= 0$$

Particle spectrum:

$$M_h{}^2 = 2\lambda_1 v^2$$

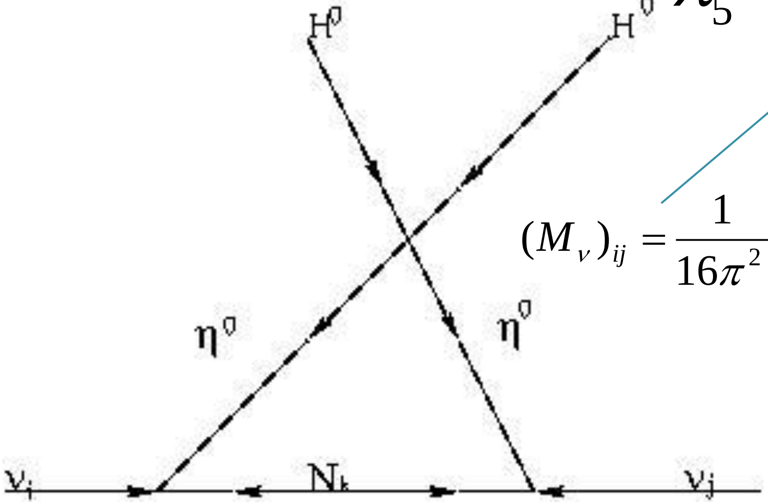
$$M_{\eta^\pm}{}^2 = m_2{}^2 + \lambda_3 v^2$$

$$M_R{}^2 = m_2{}^2 + (\lambda_3 + \lambda_4 + \lambda_5) v^2$$

$$M_I{}^2 = m_2{}^2 + (\lambda_3 + \lambda_4 - \lambda_5) v^2$$

Ernest Ma, hep-ph/0601225,

$$\lambda_5 \to 0 \Rightarrow \Delta L \to 0 \Rightarrow M_\nu \to 0$$



$$(M_\nu)_{ij} = \frac{1}{16\pi^2}\sum_k h_{ik}h_{jk}M_k[\frac{M_R^2}{M_R^2-M_I^2}\ln\frac{M_R^2}{M_k^2} - \frac{M_I^2}{M_I^2-M_k^2}\ln\frac{M_I^2}{M_k^2}]$$

$$M_R^2 - M_I^2 = 2\lambda_5 v^2$$

$$M_R^2 + M_I^2 = 2m_0^2$$

$$(M_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2}\sum_k \frac{h_{ik}h_{jk}M_k}{(m_0^2-M_k^2)}[1-\frac{M_k^2}{m_0^2-M_k^2}\ln\frac{m_0^2}{M_k^2}]$$

$$M_k^2 >> m_0^2$$

$$(M_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2}\sum_k \frac{h_{ik}h_{jk}}{M_k}[\ln\frac{M_k^2}{m_0^2}-1]$$

Inert scalar doublet DM

$$m_0^2 >> M_k^2$$

Barbieri, Hall, Rychkov, hep-ph/0603188

$$(M_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2 m_0^2}\sum_k h_{ik}h_{jk}M_k$$

Right-handed neutrino DM

Ernest Ma, hep-ph/0601225

Gauged $U(1)_{B-L}$ extension of SM for neutrino mass and dark matter

$U(1)_{B-L}$ is an accidental global symmetry in the SM. How ever, if we gauge it, then the triangle anomalies for the SM fermion content turns out to be:

$$A^{SM}[U(1)^3{}_{B-L}] = -3 \qquad A^{SM}[(gravity)^2 \times U(1)_{B-L}] = -3$$

Case-I

This implies new fermions are required to be introduced to cancel this anomaly. The simplest choice is to add three right-handed neutrinos with Y=0 and B-L=-1.

$$A[(gravity)^2 \times U(1)_{B-L}] = A^{SM}[(gravity)^2 \times U(1)_{B-L}] + A^{new}[(gravity)^2 \times U(1)_{B-L}] = 0$$

$$A[U(1)^3{}_{B-L}] = \underset{\substack{\big\downarrow \\ -3 \\ \text{SM}}}{A^{SM}[U(1)^3{}_{B-L}]} + \underset{\substack{\big\downarrow \\ 3 \\ [\nu_{1R}, \nu_{2R}, \nu_{3R}]}}{A^{new}[U(1)^3{}_{B-L}]} = 0$$

Simplest choice for anomaly cancellation

In these models the neutrino mass arises via type-I seesaw and dark matter content can be explained by introducing additional particles (scalar or fermion), non-trivially transforming under new symmetries. Most of the time we use a Z_2 discrete symmetry.

Example: Dark matter in type-I seesaw models.
A huge literature exists.

Case-II

Add exotic new fermions with B-L charges 5,-4,-4 and Y=0

$$A[(gravity)^2 \times U(1)_{B-L}] = A^{SM}[(gravity)^2 \times U(1)_{B-L}] + A^{new}[(gravity)^2 \times U(1)_{B-L}]$$
$$= -3 + [-5 - (-4) - (-4)] = 0$$

$$A[U(1)^3{}_{B-L}] = A^{SM}[U(1)^3{}_{B-L}] + A^{new}[U(1)^3{}_{B-L}]$$
$$= -3 + [-5^3 - (-4)^3 - (-4)^3] = 0$$

Montero, Pleitez, arXiv: 0706.0473

Since these are exotic fermions, one of them may be a candidate of dark matter. However, they don't generate neutirno masses. In these models one need to add extra particles such scalar tripelt, doublet to generate neutirno masses either at tree level or at one loop level.

Examples: Sanchez-Vega, Montero, Schmitz (1404.5973),
Ma & Srivastava(1411.5042); Sanchez-Vega, Schmitz (1505.03595) ;
Ma, Pollard,Srivastava, Zakeri (1507.03943);
Singirala, Mohanta, Patra (1704.01107);
Das, Nomura, Okada (1704.02078);
Nomura, Okada (1705.08309)
Bandypadhyay, Chun and Mandal (1707.00874);
Nomura and Okada (1708.08737);
Nomura and Okada (1709.06406);
Singirala, Mohanta, Patra, Rao (1710.05775);
….

Case-III

Add more exotic fermions with B-L charges -4/3,-1/3,,-2/3,-2/3 and Y=0

$$A[(gravity)^2 \times U(1)_{B-L}] = A^{SM}[(gravity)^2 \times U(1)_{B-L}] + A^{new}[(gravity)^2 \times U(1)_{B-L}]$$
$$= -3 + [-(-4/3) - (-1/3) - (-2/3) - (-2/3)] = 0$$

$$A[U(1)^3{}_{B-L}] = A^{SM}[U(1)^3{}_{B-L}] + A^{new}[U(1)^3{}_{B-L}]$$
$$= -3 + [-(-4/3)^3 - (-1/3)^3 - (-2/3)^3 - (-2/3)^3] = 0$$

Patra, Rodejohann, Yaguna, 1607.04029

One of these exotic fermions can be a candidate of dark matter. However, they don’t generate neutirno masses. In these models one need to add extra particles such scalar tripelt, doublet to generate neutirno masses either at tree level or at one loop level.

Examples: Borah and Nanda (1709.08417);
Geng, and Okada(1710.09536);
Nomura and Okada (1711.05115);
…

Case-IV

Even more exotic fermions with B-L charges -17/3,6,-10/3 and Y=0

$$A[(gravity)^2 \times U(1)_{B-L}] = A^{SM}[(gravity)^2 \times U(1)_{B-L}] + A^{new}[(gravity)^2 \times U(1)_{B-L}]$$
$$= -3 + [-(-17/3) - (6) - (-10/3)] = 0$$

$$A[U(1)^3{}_{B-L}] = A^{SM}[U(1)^3{}_{B-L}] + A^{new}[U(1)^3{}_{B-L}]$$
$$= -3 + [-(-17/3)^3 - (6)^3 - (-10/3)^3] = 0$$

See Refs. in Nanda and Borah, 1709.08417

ν-MSM for neutrino mass and DM

The Model

$$\Rightarrow SM + N_1, N_2, N_3$$

$$-\mathcal{L} = \frac{1}{2} M_i N_i N_i + f_{ij} \overline{L_i} H l_{jR} + h_{ij} \overline{N_i} H L_j + H.c.$$

Type-I seesaw

$$m_\nu = -m_D^T M_R^{-1} m_D$$

$$m_D \sim < H >, M_N \sim 10^{14} GeV, m_\nu = 0.1 eV$$

An alternative path:

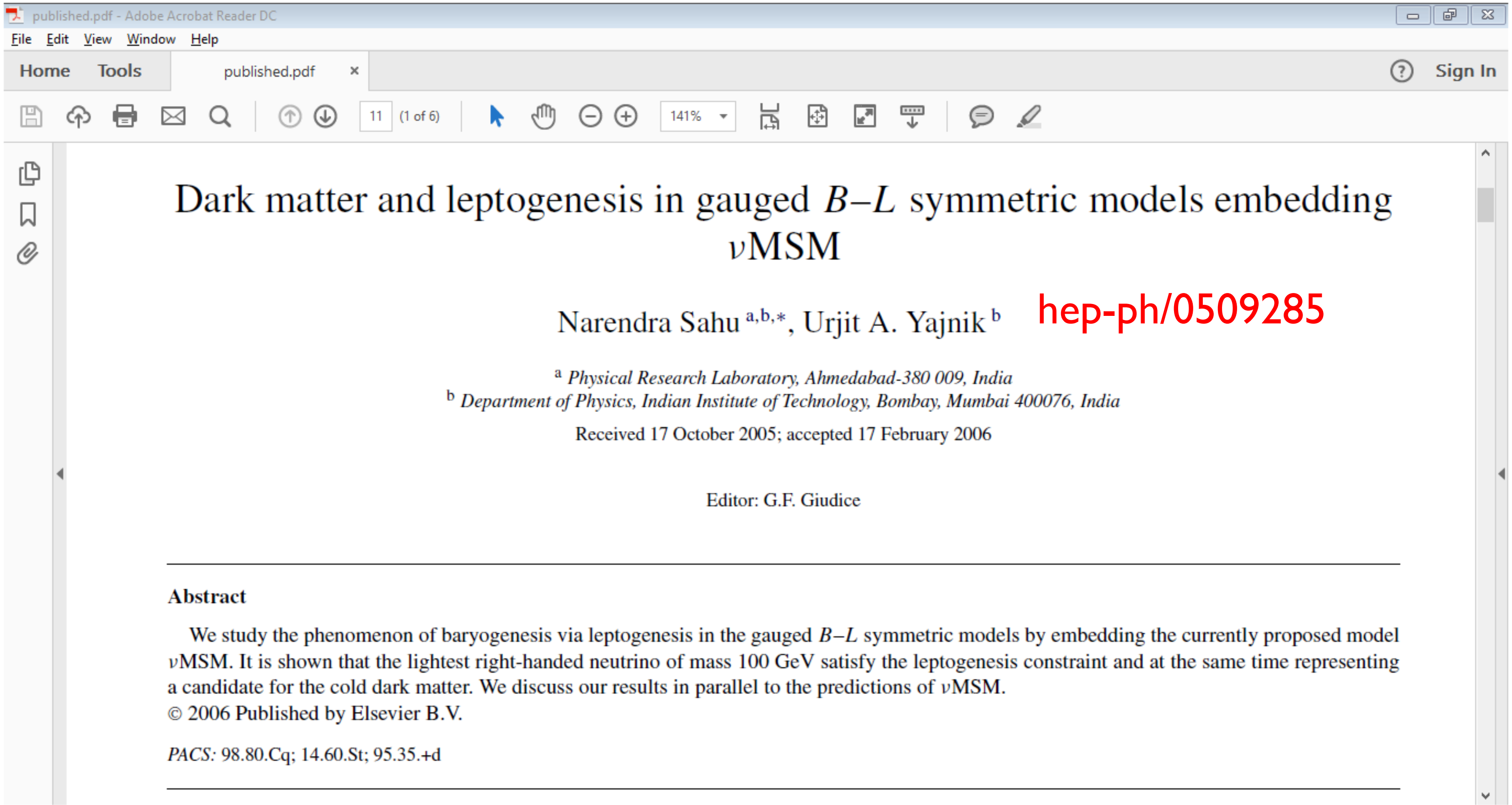
Radiative decays of sterile neutrinos in dark matter halos

$$2keV < M_N < 5keV, h_1 \sim 10^{-10} \Rightarrow m_\nu = 0.1eV$$

CMBR and matter power spectrum

Lightest RHN is a warm dark matter, which is decoupled from thermal bath

Asaka, Shaposhnikov, hep-ph/0505013,
Asaka, Blanchet and Shaposhnikov, hep-ph/0503065



Dark matter and leptogenesis in gauged B–L symmetric models embedding νMSM

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hep-ph/0509285

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Abstract

We study the phenomenon of baryogenesis via leptogenesis in the gauged B–L symmetric models by embedding the currently proposed model νMSM. It is shown that the lightest right-handed neutrino of mass 100 GeV satisfy the leptogenesis constraint and at the same time representing a candidate for the cold dark matter. We discuss our results in parallel to the predictions of νMSM.

PACS: 98.80.Cq; 14.60.St; 95.35.+d

Ingredients are:

(1) A source of lepton asymmetry (say, from domain wall) apart from the decay of right-handed neutrinos.

(2) Limited erasure of the lepton asymmetry by the lepton-number violating processes mediated by lightest RHN, which demands its mass scale to be of order of 100 GeV.

Raw lepton asymmetry: $\eta_L^{raw} = O(10^{-10})$

$$\frac{dY_{N_1}}{dz} = -(D+S)(Y_{N_1} - Y_{N_1}^{eq})$$

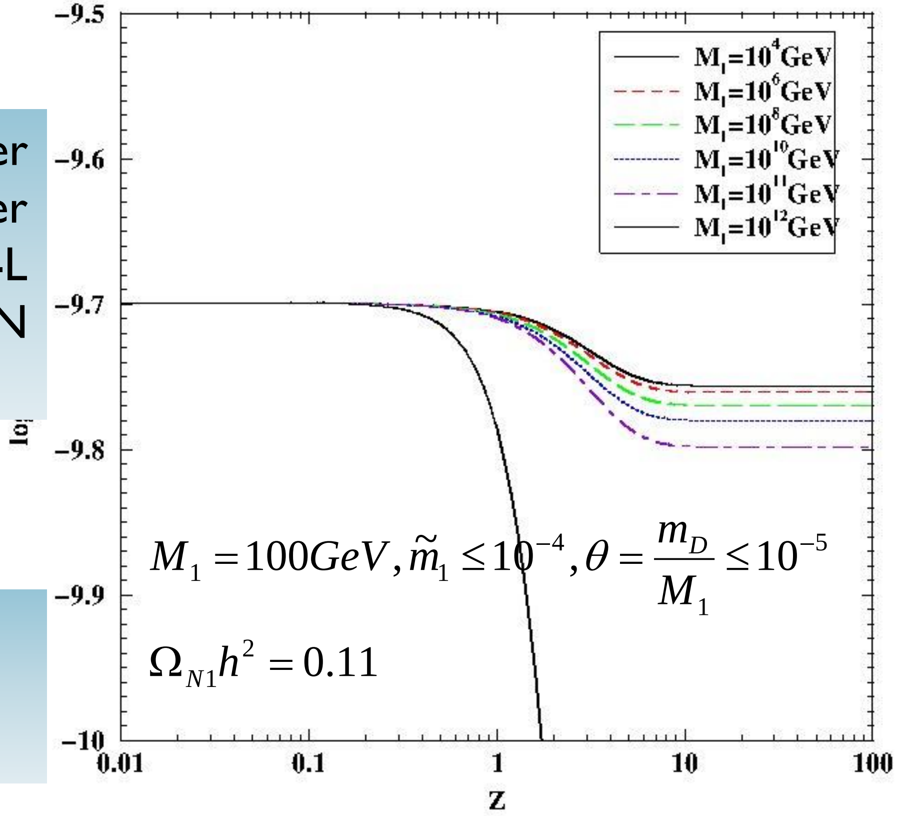
$$\frac{dY_{B-L}}{dz} = -WY_{B-L}$$

$$W, D, S = \frac{\Gamma_{W,D,S}}{zH}, z = \frac{M_1}{T}$$

$$Y_{N_1}^{in} = Y_{N_1}^{eq}, Y_{B-L}^{in} = \eta_{B-L}^{raw}$$

Competition between lepton number violating and lepton number conserving process (mediated B-L gauge boson). Smaller is the RHN mass, less is the wash out.

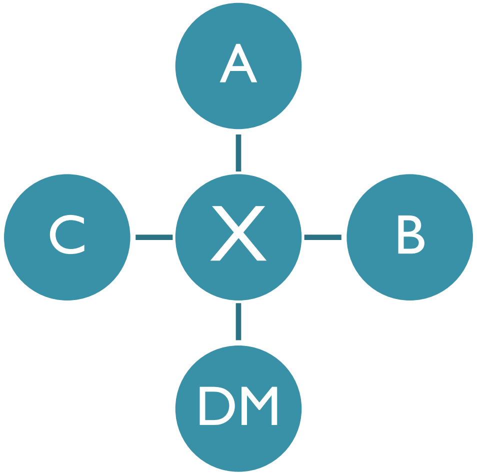
Lightest RHN with mass 100 GeV is a decaying DM, with life time larger than the Universe.



$$M_1 = 100GeV, \tilde{m}_1 \le 10^{-4}, \theta = \frac{m_D}{M_1} \le 10^{-5}$$

$$\Omega_{N1}h^2 = 0.11$$

Non-thermal DM and neutrino mass



If X is in thermal equilibrium then:

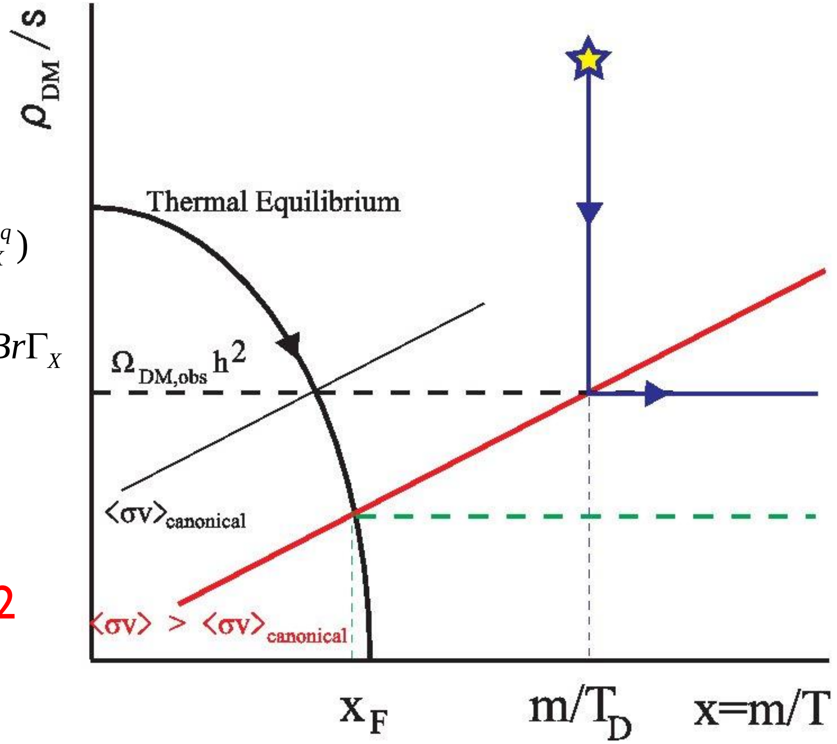
$$\frac{dn_X}{dt}+3n_X H=-<\sigma|v|>_{XX\to AA}(n_X^2-n_X^{eq\,2})-\Gamma_X(n_X-n_X^{eq})$$

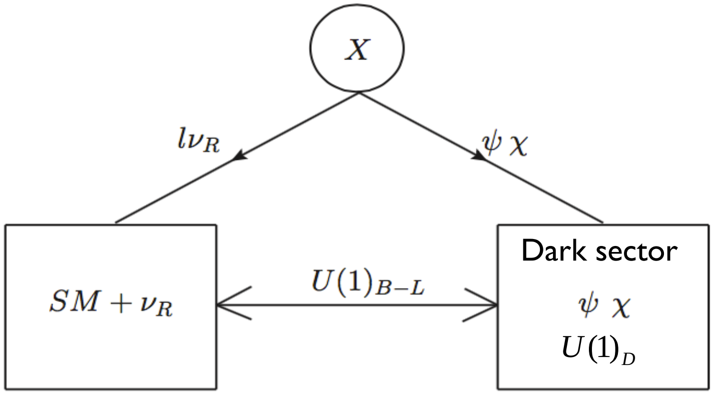
$$\frac{dn_{DM}}{dt}+3n_{DM} H=-<\sigma|v|>_{DMDM\to ff}(n_{DM}^2-n_{DM}^{eq\;2})+n_X Br\Gamma_X$$

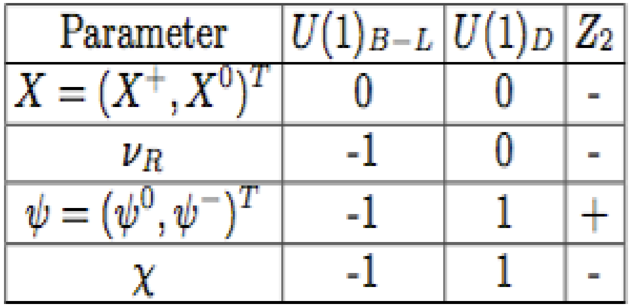
Kohri, Mazumdar, Sahu, Stefens, 0907.0622

If X is out-of-thermal equilibrium, then

$$Y_{DM}\equiv\frac{n_{DM}}{s}=\frac{3}{4}Br\frac{T_D}{M_X}$$







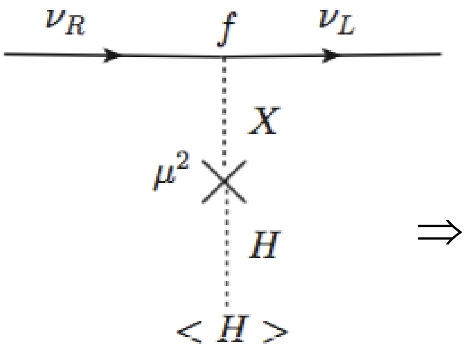
Parameter	$U(1)_{B-L}$	$U(1)_D$	Z_2
$X=(X^+,X^0)^T$	0	0	-
ν_R	-1	0	-
$\psi=(\psi^0,\psi^-)^T$	-1	1	+
χ	-1	1	-

N.Narendra, N.Sahoo and N.Sahu, 1712.02960

$$-\mathcal{L} \supset M_\psi \overline{\psi}\psi + M_\chi \overline{\chi}\chi + \overline{L}\tilde{X}\nu_R + \overline{\psi}\tilde{X}\chi + h.c.$$

The Z_2 symmetry forbids: $Y\overline{N_R}\tilde{H}^+L \;\Rightarrow M_\nu = 0$

We allow a soft Z_2 symmetry breaking $\mathcal{L}_{soft} = -\mu^2 H^\dagger X + \text{h.c.}$



$M_\chi < M_\psi \Rightarrow \psi$ is dark matter

$$\Rightarrow M_\nu = f <H> \frac{\mu^2}{M_X^2}$$

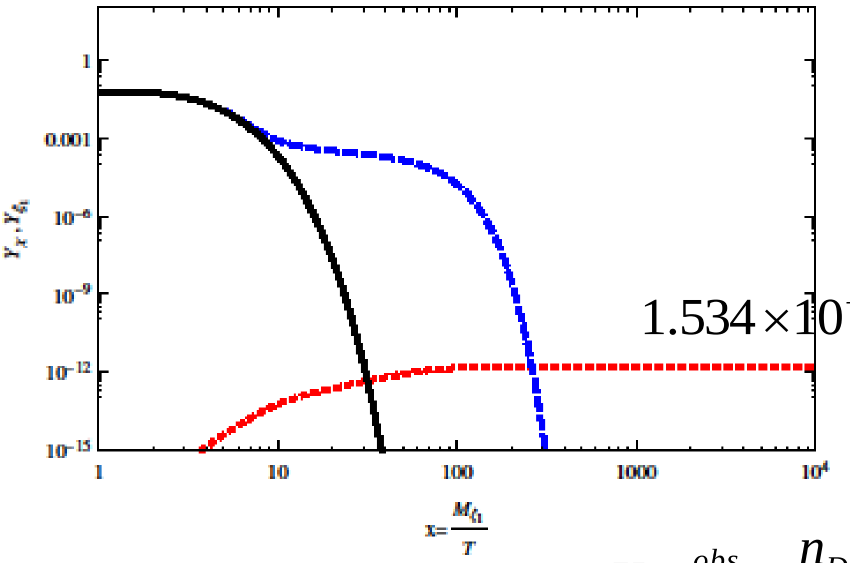
The relevant Boltzmann equations for non-thermal production of DM are:

$$\frac{dY_{\xi_1}}{dx} = -\frac{x}{H(M_{\xi_1})} s\langle\sigma|v|_{(\xi_1\xi_1\to All)}\rangle[Y_{\xi_1}{}^2 - Y_{\xi_1}{}^{eq2}] - \frac{x}{H(M_{\xi_1})}\Gamma_{(\xi_1\to all)}[Y_{\xi_1} - Y_{\xi_1}{}^{eq}]$$

$$\frac{dY_\chi}{dx} = \frac{1}{H(M_{\xi_1})} B_\chi (Y_{\xi_1} - Y_{\xi_1}{}^{eq})$$

$$B_\chi = Br\Gamma(\xi_1 \to \psi\chi) = 10^{-8}$$

$$M_\chi = 100GeV$$



1.534×10^{-12}

$$Y_{DM}{}^{obs} \equiv \frac{n_{DM}}{S} = 4\times10^{-12}\left(\frac{100GeV}{M_{DM}}\right)\left(\frac{\Omega_{DM}h^2}{0.11}\right)$$

DM and neutrino mass in left-right symmetric model

$$\begin{tikzcd} SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[d, "<\Delta_R>"] \\ SU(2)_L \times U(1)_Y \times Z_2 \arrow[d, "<\Phi>"] \\ U(1)_{em} \times Z_2 \end{tikzcd}$$

$$\left.\begin{array}{l} l_L \sim (2,1,-1) \\ l_R \sim (1,2,-1) \\ q_L \sim (2,1,1/3) \\ q_R \sim (1,2,1/3) \end{array}\right\} \text{fermions}$$

$$\left.\begin{array}{l} \Delta_L \sim (3,1,-2) \\ \Delta_R \sim (1,3,-2) \\ \Phi \sim (2,2,0) \end{array}\right\} \text{scalars}$$

Under the remnant Z_2 symmetry all the fermions are odd and scalars are even.

Heeck and Patra, 1507.01584

$$Z_2 \equiv (-1)^L$$

Possible ways of introducing dark matter:

(1) **Introducing new fermion multiplet, even under B-L ,and scalar multiplet, odd under B-L.**

(2) **Introduce new multiplets that are stable only at the renormalizable level, which will not allow DM to decay.**

Example: B-L Even Fermion multiplet

$$\psi_L \sim (2n+1,1,0) + \psi_R(1,2n+1,0), n \in N$$

Example: B-L Odd Scalar multiplet

$$\chi_L \sim (2k,1,2m+1) + \chi_R \sim (1,2k,2m+1), m \in N$$

Neutrino mass arises through lepton number violating coupling:

$$-\mathcal{L} \supset \quad \Delta_L \overline{l_L} l_L{}^c + \Delta_R \overline{l_R} l_R{}^c + \Delta_L \overline{\psi_L} \psi_L{}^c + \Delta_R \overline{\psi_R} \psi_R{}^c$$

Heeck and Patra, 1507.01584

Flavored singlet-doublet dark matter and leptonic non-zero θ_{13}

Forbid the dimension -5 operator: $\frac{LHLH}{\Lambda}$

Ma & Rajasekharan: 2001
Babu, Ma & Valle: 2003
Altarelli & Feruglio: 2005

Here the lepton doublet transform as A_4 triplet while Higgs doublet is a A_4 singlet.

Introduce SM singlets (flavons): $\phi_s \sim 3, \phi_T \sim 3, \xi \sim 1$

Generate the neutrino mass via the dimension -6 operator: $\frac{LHLH\,(y_1\xi - y_2\phi_s)}{\Lambda^2}$

$$< \phi_s > = v_s\,(1,1,1)^T$$
$$< \phi_T > = v_T\,(1,0,0)^T$$
$$< \xi > = v_\xi$$

$$(m_\nu)_0 = \begin{pmatrix} a - 2b/3 & b/3 & b/3 \\ b/3 & -2b/3 & a + b/3 \\ b/3 & a + b/3 & -2b/3 \end{pmatrix} \longrightarrow$$

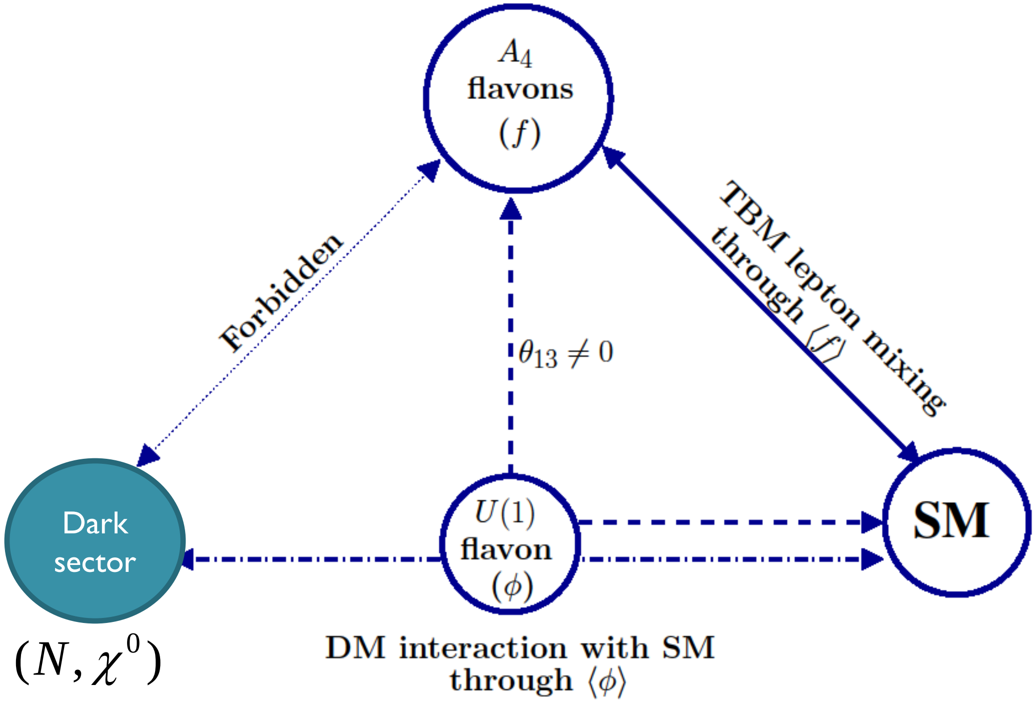
$$Tribi\max imal\ mixing \Rightarrow \theta_{13} = 0$$

$$a = y_1(v^2/\Lambda)\varepsilon$$
$$b = y_2(v^2/\Lambda)\varepsilon$$
$$\varepsilon = \langle \phi_s \rangle / \Lambda = \langle \xi / \Lambda \rangle$$

But observed $\theta_{13} = 8^0 - 9^0$

Daya-Bay, Reno, T2K, Double-CHOOZ

We introduce a flavor symmetry in the dark sector to explain non-zero theta_13



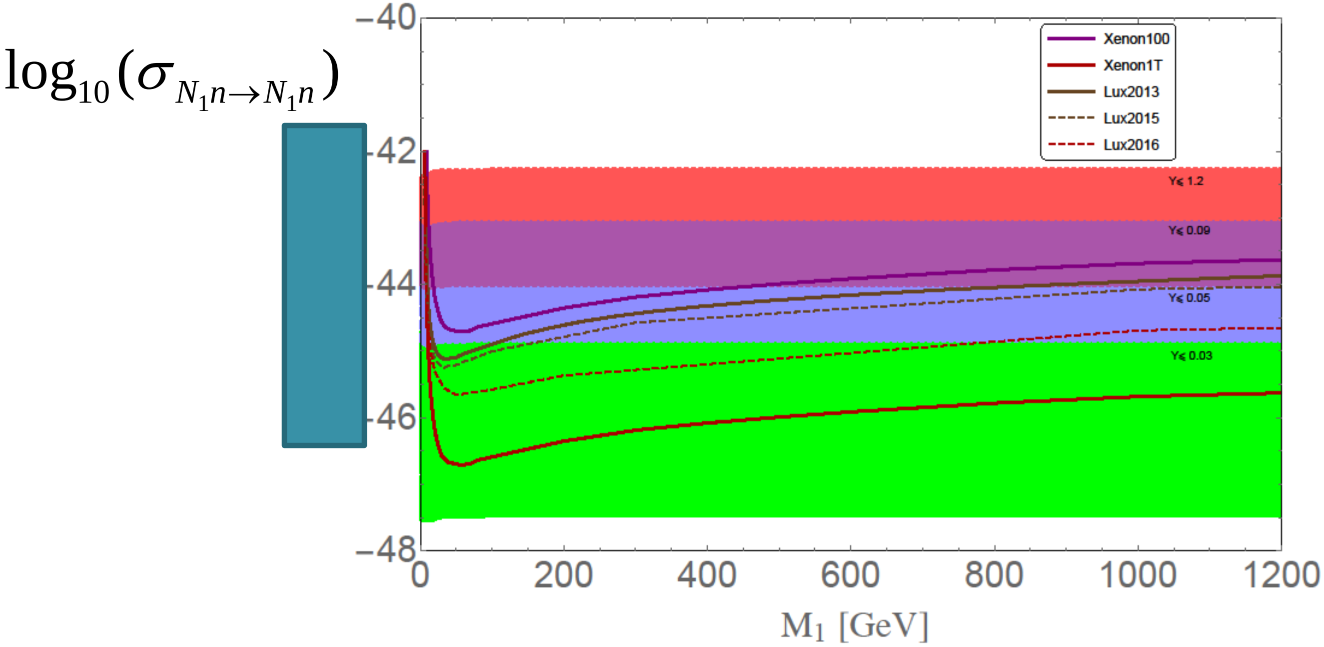
Bhattacharya, Karmakar, Sahu and Sil, arXiv:1603.04776, PRD93, 2016;
Bhattacharya, Karmakar, Sahu and Sil: arXiv: 1611.07419, JHEP,2017

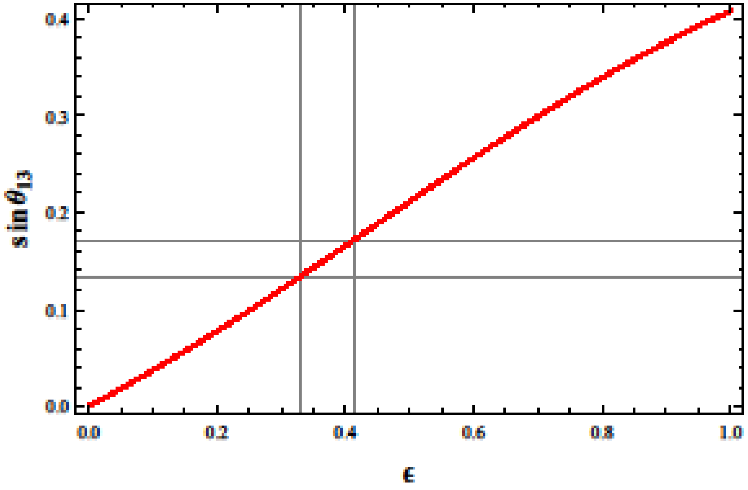
Introduce U(1) flavor symmetry, so that the allowed Lagrangian is

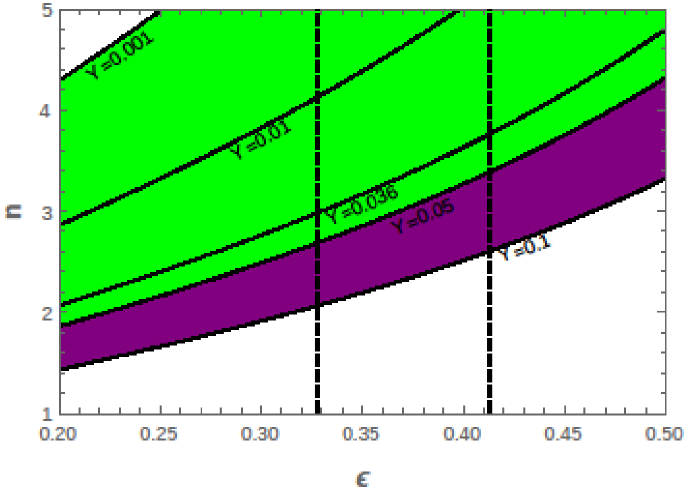
$$\mathcal{L}_{int} = \underbrace{M_N \overline{N} N + M_\chi \overline{\chi}\chi + \left(\frac{\phi}{\Lambda}\right)^n \overline{N}\tilde{H}\chi}_{\text{Mixed singlet –doublet DM sector}} + \underbrace{\frac{LHLH\phi\eta}{\Lambda^3}}_{\text{Gives correction to neutrino masses and mixing}}$$

ϕ and η have opposite U(1) flavor charge but neutral under A_4 symmetry. U(1) charge of N and χ Cancels the U(1) charge of ϕ^n

Yukawa coupling: $$Y = \left(\frac{\langle\phi\rangle}{\Lambda}\right)^n = \varepsilon^n$$


$\log_{10}(\sigma_{N_1 n\to N_1 n})$
−40
−42
−44
−46
−48
0
200
400
600
800
1000
1200
M₁ [GeV]
Xenon100
Xenon1T
Lux2013
Lux2015
Lux2016
Y≤ 1.2
Y≤ 0.09
Y≤ 0.05
Y≤ 0.03


$\sin\theta_{13}$
0.0
0.1
0.2
0.3
0.4
0.0
0.2
0.4
0.6
0.8
1.0
ϵ


n
1
2
3
4
5
0.20
0.25
0.30
0.35
0.40
0.45
0.50
ϵ
Y=0.001
Y=0.01
Y=0.036
Y=0.05
Y=0.1

Conclusions

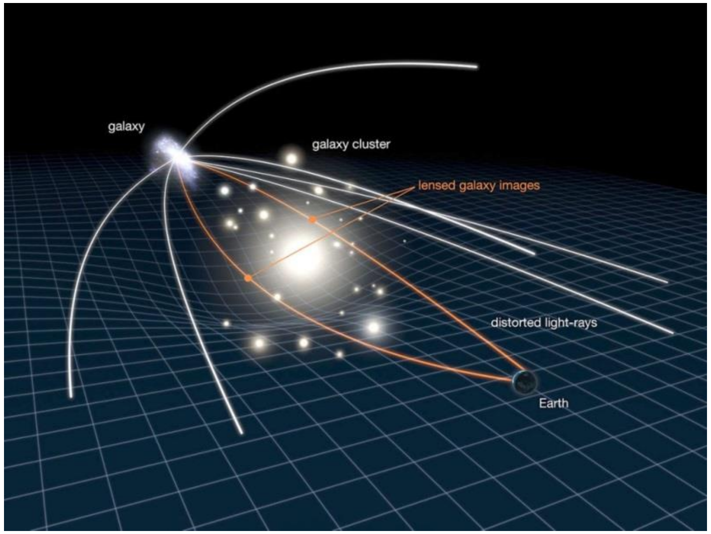
(1)Compelling evidences of dark matter (DM) arising via gravitational interaction suggest that DM exists in nature. However, we don't know how to probe it.

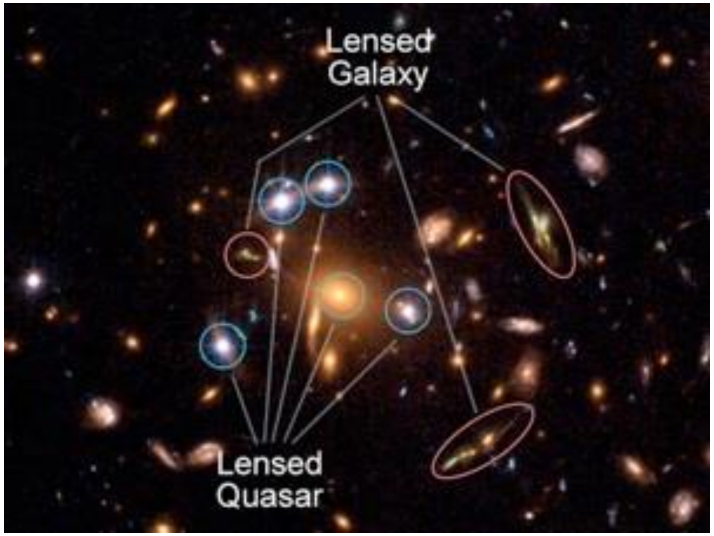
(2)The observed relic abundance of DM implies that its freeze-out cross-section (~0.1pb) is typically a weak interaction cross-section. So it is largely believed that the DM is a WIMP.

(3)Oscillation experiments imply that neutrinos are massive, which can not be explained within the framework of SM.

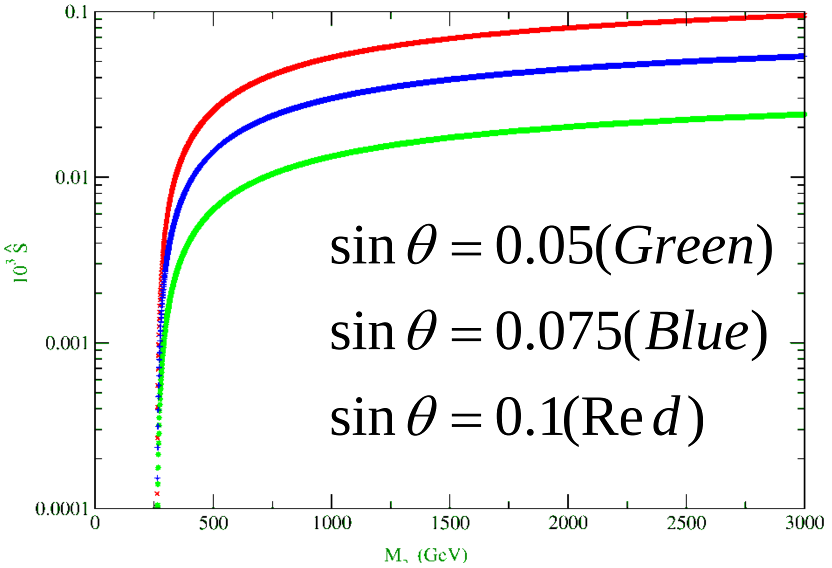
(4)We studied various models in the beyond SM framework which can explain neutrino mass (Dirac or Majorana) and dark matter simultaneously.

Thank you


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth


Lensed Galaxy
Lensed Quasar

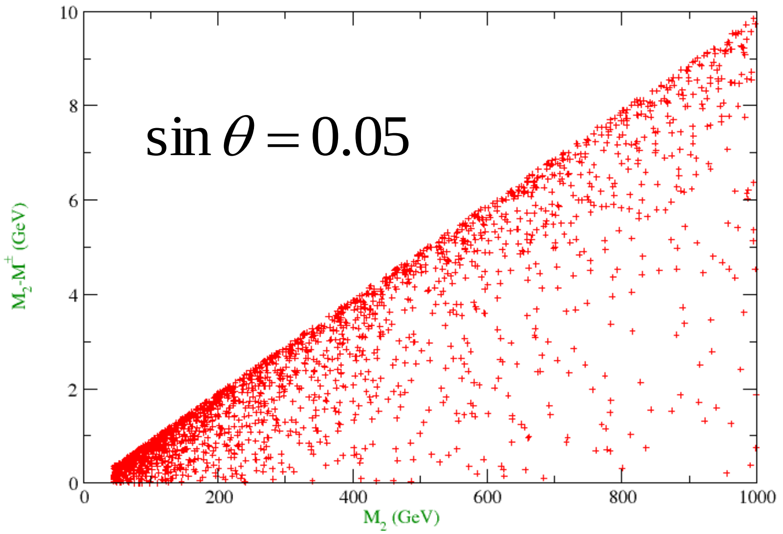
Constraint from EW precision test



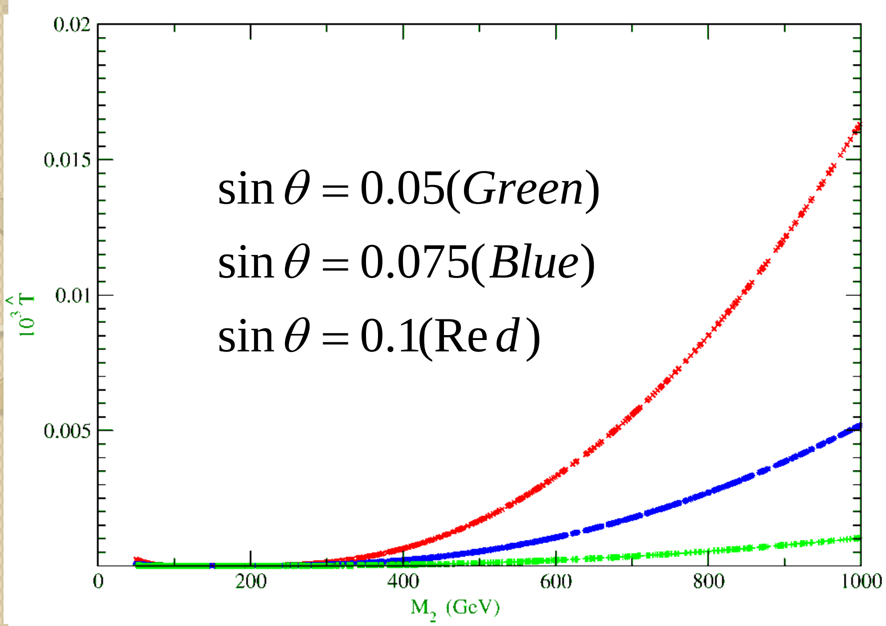
$$\hat{S} = \frac{\alpha S}{4\sin^2\theta_w}$$

$$10^3\hat{S} = 0.0 \pm 1.3$$

Barbieri et.al. NPB 703, 2004



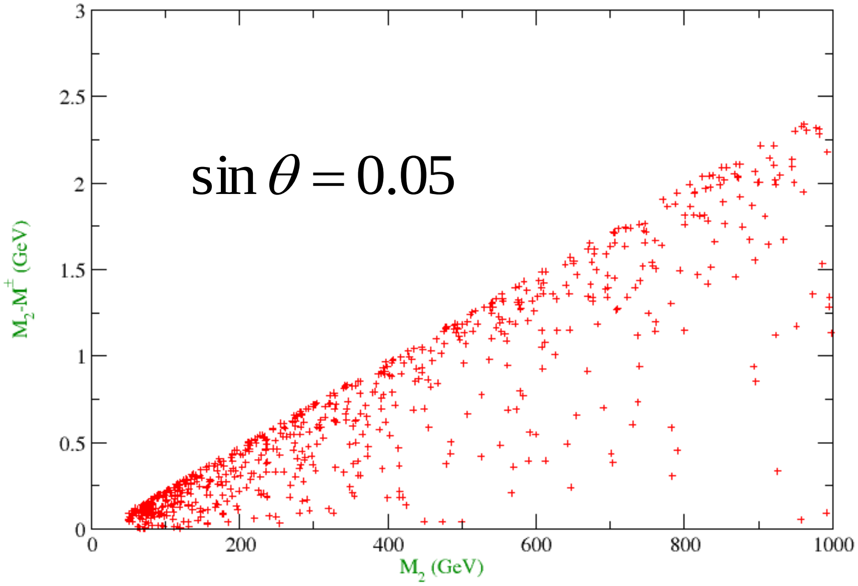
So for small mixing angle, vector-like lepton masses above 100 GeV are in compatible with the Electroweak precision parameter S.



$$\hat{T} = \alpha T$$

$$10^3\hat{T} = 0.1 \pm 0.9$$

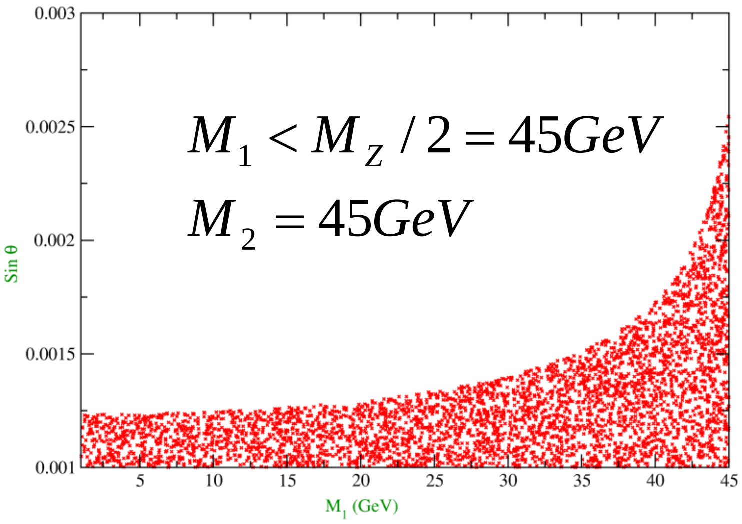
Barbieri et.al. NPB703,2004



So for small mixing angle, vector-like lepton masses above 100 GeV are in compatible with the Electroweak precision parameter T.

Constraints from Invisible Higgs and Z-decay

LEP Constraints from Z-decay



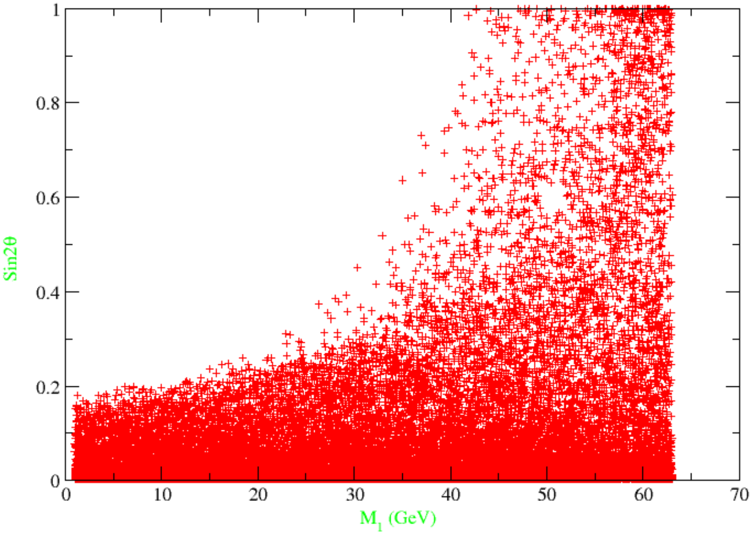
$$M_1 < M_Z / 2 = 45 GeV$$

$$M_2 = 45 GeV$$

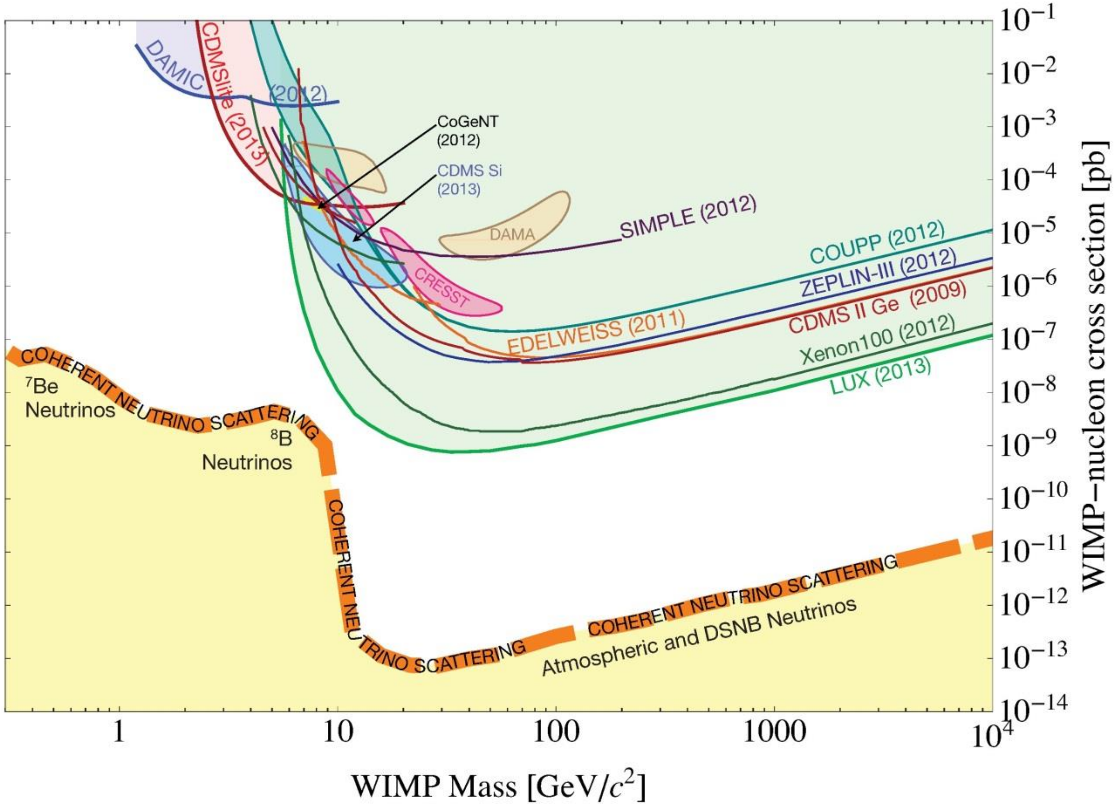
$$Br_{inv} = \frac{\Gamma_h^{inv}}{\Gamma_h^{SM} + \Gamma_h^{inv}} < 0.3$$

ATLAS collaboration
1508.07869 (hep-ex)

Constraints from invisible Higgs decay keeping all possible values of M_2 that allow Higgs decay.



Future DM experiments challenging the neutrino background ?



Billard, Figueroa-Feliciano and Strigari, 1307.5458