Inert scalar and fermion doublet dark matters in light of neutrino mass and LUX data

arXiv: 1108.39679[hep-ph] with Chiara Arina (NPB 2012)
arXiv: 1206.0009 [hep-ph] with C. Arina and J.O. Gong (NPB 2012)
arXiv: 1211.0435 [hep-ph] with C. Arina and R.N. Mohapatra (PLB, 2013)
arXiv: 1407.3030[hep-ph] with Arindam Chatterjee (To appear in PRD)
+ work with Nirakar Sahoo & Saptashwa Bhattacharya (students)

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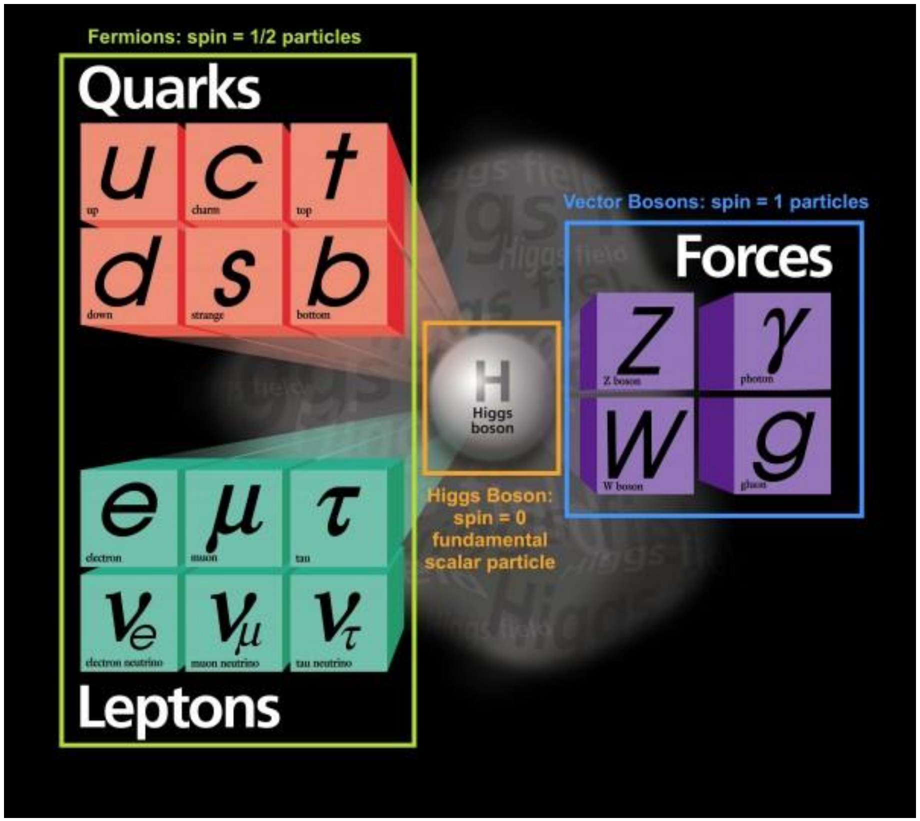
Introduction



(1) Only accommodates 5% of the total energy budget of the Universe.

(2) No neutrino mass

(3) No candidate of dark matter

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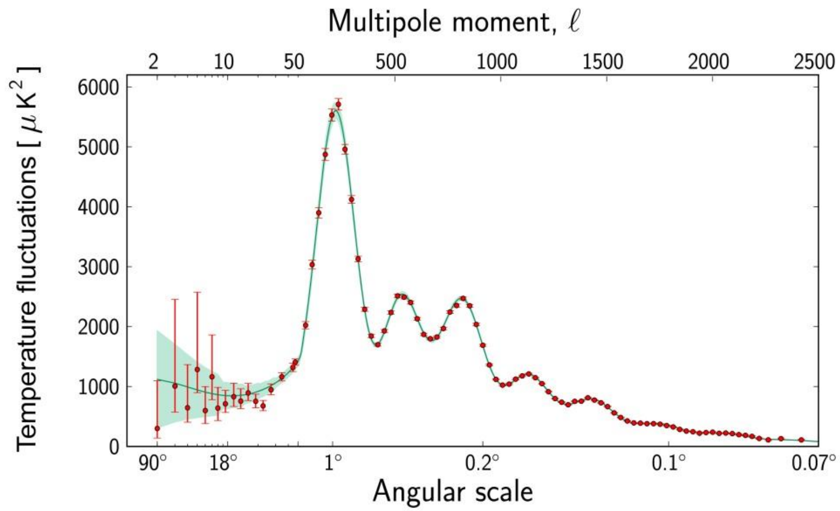
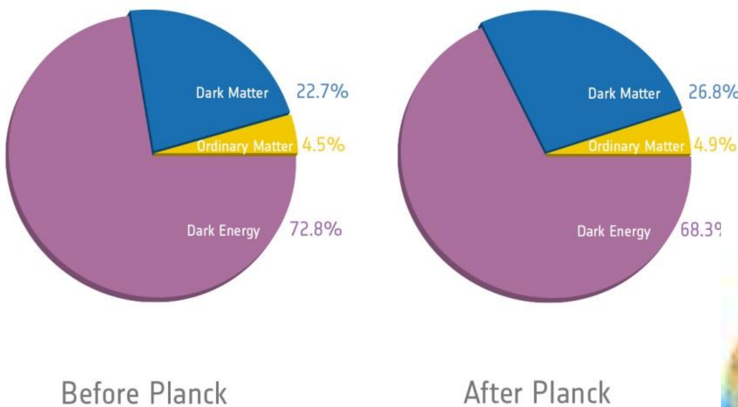
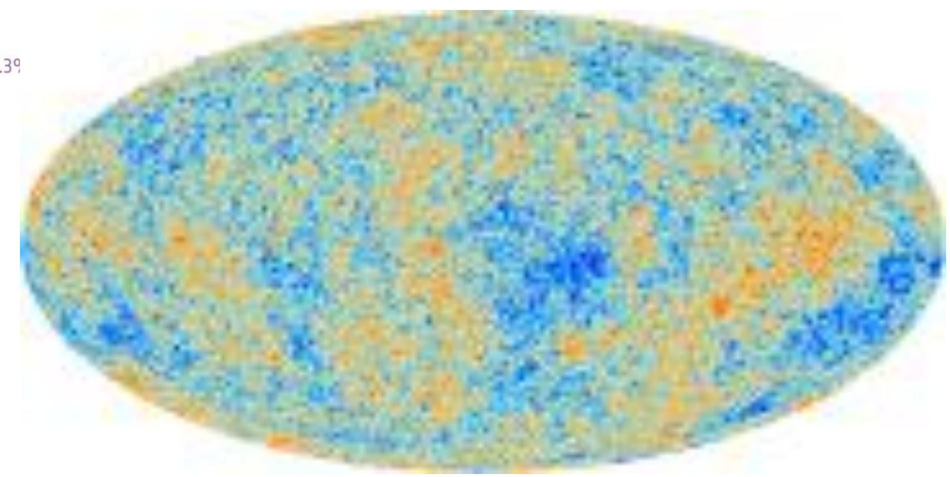

Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
6000
5000
4000
3000
2000
1000
0
Temperature fluctuations [μK^2]
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale


Dark Matter
22.7%
Ordinary Matter
4.5%
Dark Energy
72.8%
Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%
Before Planck
After Planck



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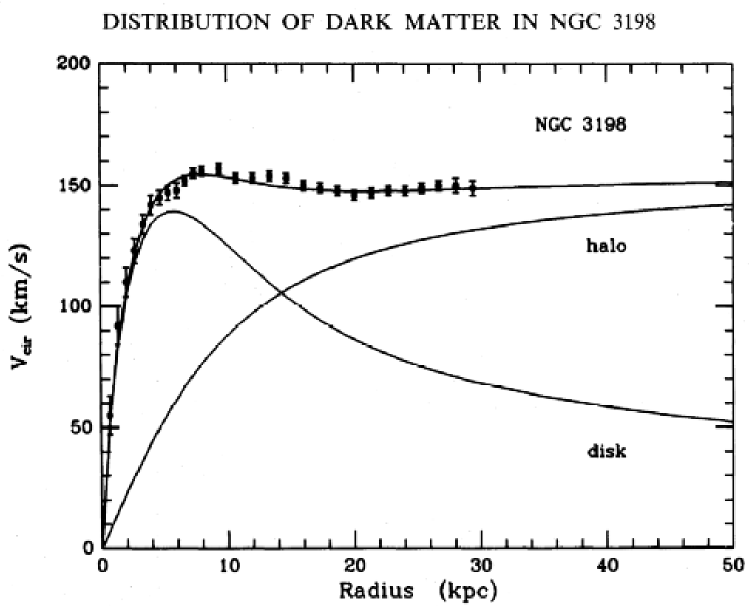


(Bullet cluster)

(Gravitational lensing)

Continued…

From the indirect evidence we infer…

- If DM is a fundamental particle, then it should have mass and hence interact gravitationally.
- It should be electrically neutral.
- It should be stable on the cosmological time scale.

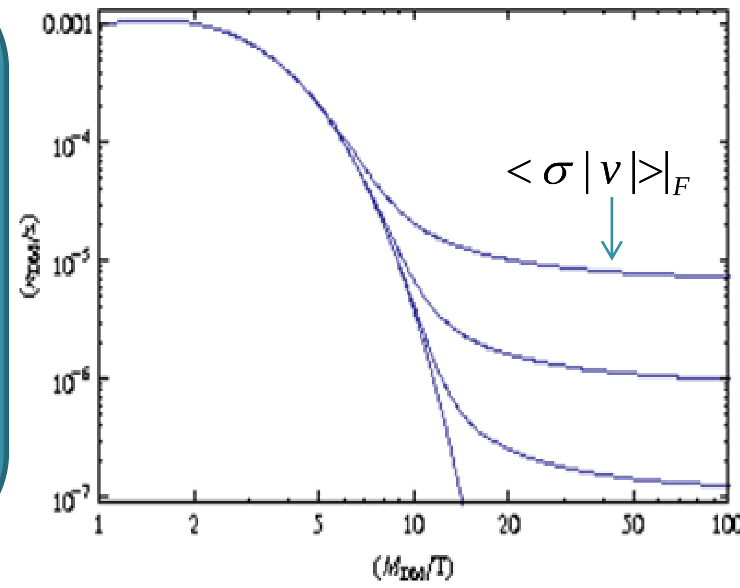
We don't know …

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

→ Many particle physics models !

Usually it is assumed that DM is a weakly interacting massive particle (WIMP) which is stable on cosmological time scale, so that it can fulfill the requirement of relic abundance criteria.

In the standard freeze-out mechanism, the DM is assumed to be in equilibrium in the early Universe. 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.



The observed DM relic abundance: $\Omega_{DM}h^2 = 0.1168 \pm 0.0031$
gives the freeze-out cross-section:

$$<\sigma|v|>|_F \approx 3\times10^{-26}cm^3/\sec \approx 2.6\times10^{-9}GeV^{-2}$$

Note: Relic abundance of DM, obtained through freeze-out mechanism, doesn't depend on its mass directly. Therefore, a wide spectrum of DM mass is allowed, starting from a few GeV (Lee-Weinberg bound).

Motivation

Assuming a thermal freeze-out mechanism

We look for physics beyond the SM to accommodate at least a candidate of DM compatible with LUX data as well as non-zero neutrino mass.

Inert scalar doublet DM

If we extend the SM with a scalar doublet and impose a Z_2 symmetry under which the new particles are odd while all other SM particles are even, then the neutral component of this additional scalar doublet can be a candidate of dark matter.

Ref. A vast literature…

Due to gauge interactions of these additional particles, required relic abundance can be generated. However, the main challenge is to make them compatible with direct detection experiments, such as Xenon-100, LUX…

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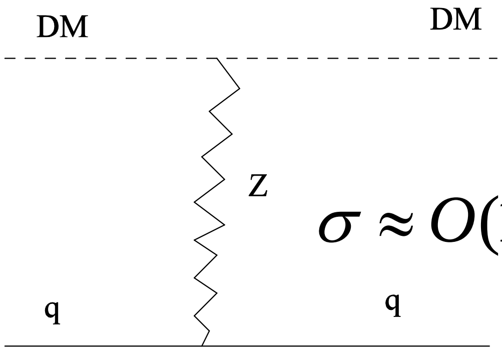
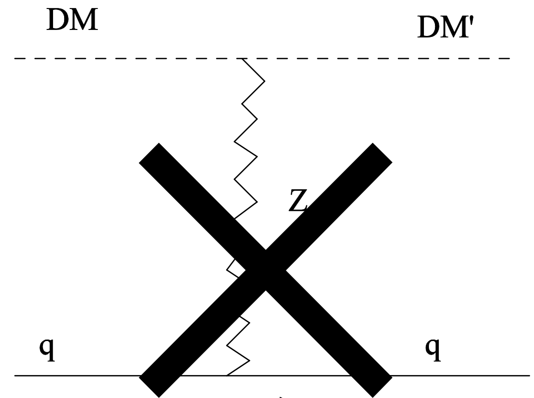
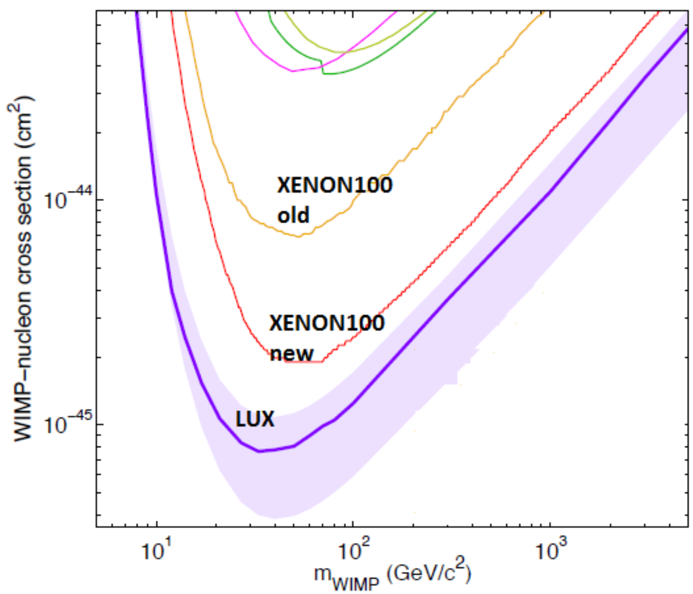
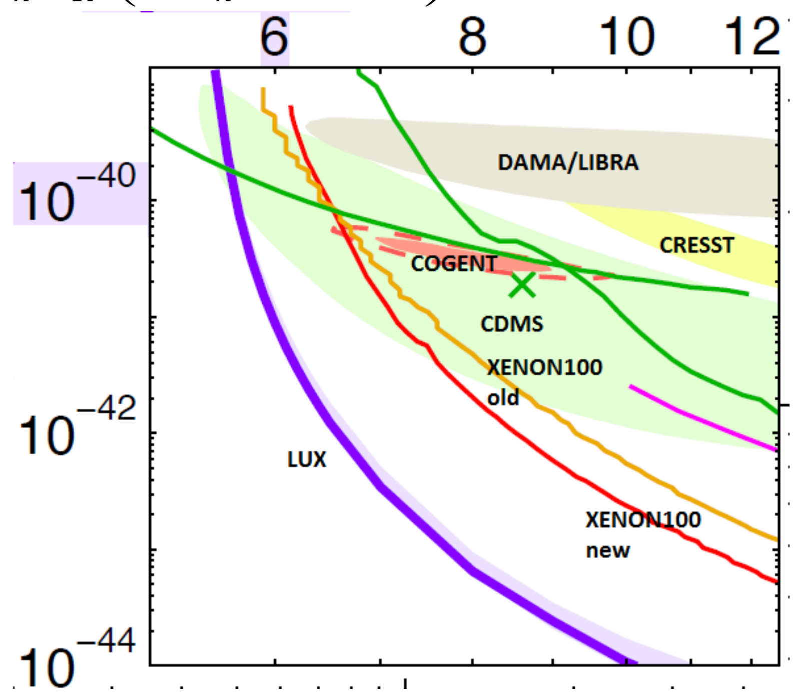


$$\sigma \approx O(10^{-38})cm^2$$



$$v_{\min} = c\sqrt{\frac{1}{2m_n E_R}}\left(\frac{m_n E_R}{\mu_n} + \Delta M\right)$$





Left-handed sneutrino in MSSM as inert scalar doublet DM

Within MSSM, if R-parity is conserved then the lightest left-handed sneutrino can be a viable candidate of dark matter.

$$\begin{pmatrix} \nu_l \\ l \end{pmatrix} \overset{\text{SUSY}}{\Leftrightarrow} \begin{pmatrix} \tilde{\nu}_l \\ \tilde{l} \end{pmatrix}$$

$$R_P = (-1)^{3B+L+2S} = (-1)^L$$

Viable dark matter

However, it is ruled out as a candidate of dark matter due to its large direct detection cross-section mediated through Z-boson.

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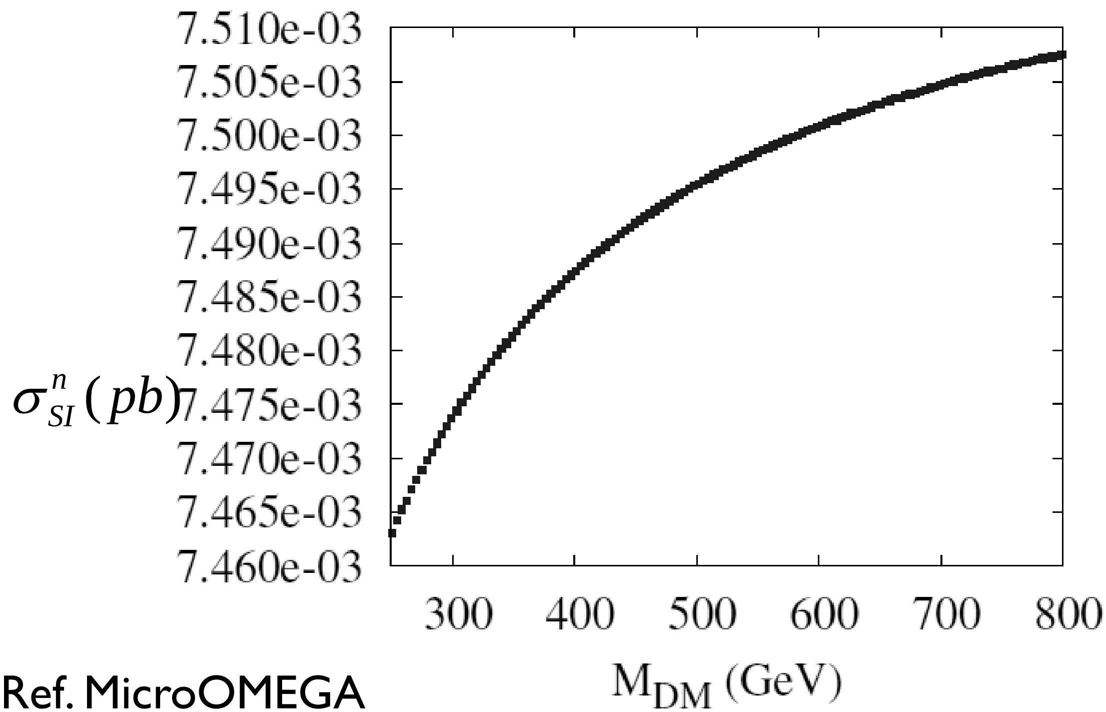
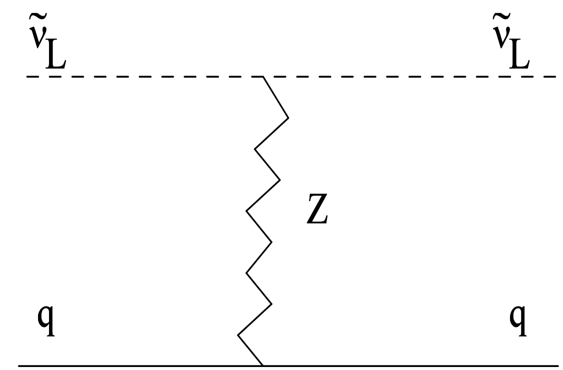
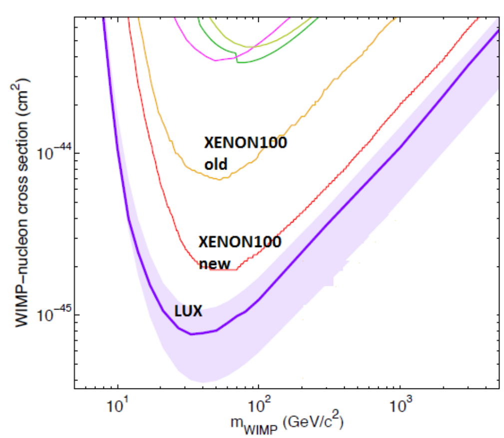
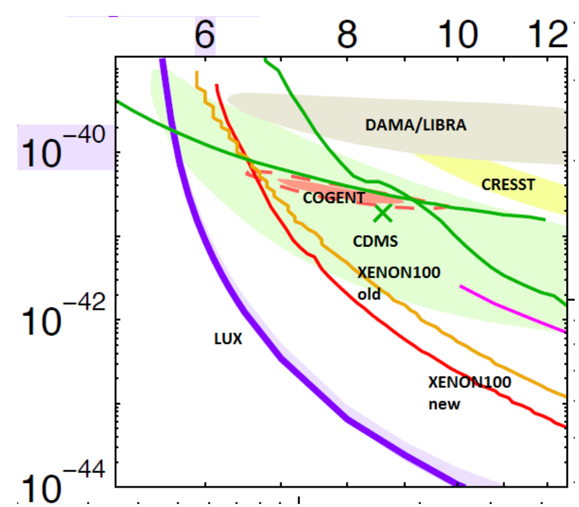




Ref. MicroOMEGA

$$\sigma_n^{SI} \approx O(10^{-38})cm^2$$





LH sneutrino DM in the triplet extension of MSSM

Let us extend the MSSM superpotential with two triplet super fields $\hat{\Delta}_1(1,3,2)$ and $\hat{\Delta}_2(1,3,-2)$, and impose a global symmetry $U(1)_{B-L}$

$$W \supset \mu \hat{H}_u.\hat{H}_d + Y\hat{L}.\hat{H}_d\hat{E}^c + M\hat{\Delta}_1.\hat{\Delta}_2 + f_1\hat{\Delta}_1\hat{H}_d.\hat{H}_d + f_2\Delta_2\hat{H}_u.\hat{H}_u$$

Let us add a soft term: $\mu_L \Delta_1 \widetilde{L}\widetilde{L}$ which not only breaks $U(1)_{B-L}$ to $(-1)^L \equiv Z_2$ but also breaks supersymmetry. Ma & Sarkar, PRD, 2012

Now the relevant soft potential is:

$$V_{soft} \supset \boxed{M_{\tilde{L}}^2 \widetilde{L}^*.\widetilde{L}} + MB\Delta_1\Delta_2 + A_1\Delta_1 H_d H_d + A_2\Delta_2 H_u H_u + \boxed{\mu_L \Delta_1 \widetilde{L}.\widetilde{L}} + h.c.$$

After EW-phase transition Δ_1 acquires an induced vacuum expectation :

$$< \Delta_1 > \equiv u = -(A_1 v_d^2 + f_2^* M v_u^2)/2M^2$$

Continued…

$$-\mathcal{L}_{\tilde{\nu}-mass} = \begin{pmatrix} \tilde{\nu}_L{}^* & \tilde{\nu}_L \end{pmatrix} \begin{pmatrix} M_{\tilde{L}}{}^2 + \frac{1}{2} M_Z{}^2 \cos 2\beta & \delta M_{\tilde{\nu}}{}^2 \\ \delta M_{\tilde{\nu}}{}^2 & M_{\tilde{L}}{}^2 + \frac{1}{2} M_Z{}^2 \cos 2\beta \end{pmatrix} \begin{pmatrix} \nu_{\tilde{L}} \\ \nu_{\tilde{L}}{}^* \end{pmatrix}$$

Let us define: $\tilde{\nu}_L = \tilde{\nu}_1 + i\,\tilde{\nu}_2$ then in the basis of $\begin{pmatrix} \tilde{\nu}_1 & \tilde{\nu}_2 \end{pmatrix}$ we get

$$-\mathcal{L}_{\tilde{\nu}-mass} = \begin{pmatrix} \tilde{\nu}_1 & \tilde{\nu}_2 \end{pmatrix} \begin{pmatrix} M_{\tilde{L}}{}^2 + \frac{1}{2} M_Z{}^2 \cos 2\beta + \delta M_{\tilde{\nu}}{}^2 & 0 \\ 0 & M_{\tilde{L}}{}^2 + \frac{1}{2} M_Z{}^2 \cos 2\beta - \delta M_{\tilde{\nu}}{}^2 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Thus we get a mass splitting between the real and imaginary parts of $\tilde{\nu}_L$

$$\Delta M_{\tilde{\nu}} \equiv \sqrt{M_{\tilde{\nu}_2}{}^2 - M_{\tilde{\nu}_1}{}^2} = 2\sqrt{|\mu_L u|} = O(500)keV$$

Continued…

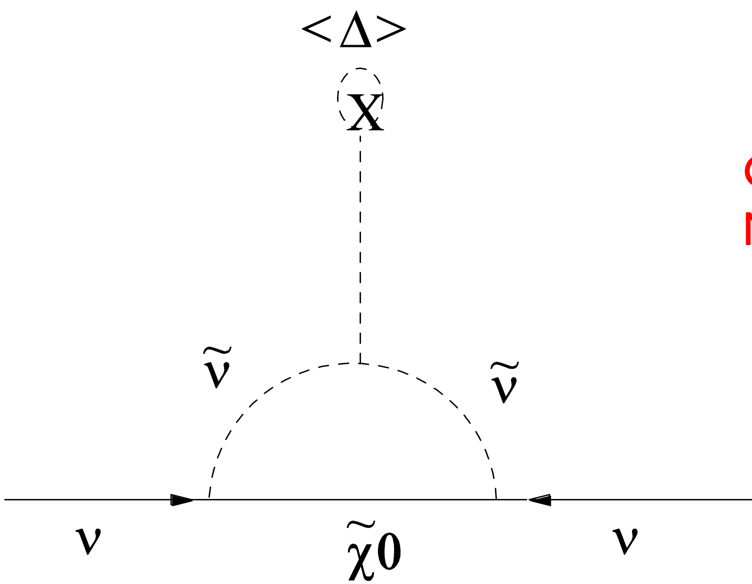
(1)Because of a residual symmetry $Z_2 \equiv (-1)^L$ either the real or imaginary part of lightest sneutrino is stable and hence becomes a candidate of dark matter.

(2)The next to lightest stable particle decays: $\tilde{\nu}_2 \to \tilde{\nu}_1 \nu \overline{\nu}$ whose life time can be estimated to be $10^4 - 10^9 s$ for a mass splitting of 100 keV to 1 MeV.

(3) Since the mass splitting is order of 500 KeV, the Z-boson mediated process in the direct detection of DM is forbidden.

(4) Therefore, the lightest sneutrino remained a viable candidate of DM.

Radiative neutrino mass



Grossman & Haber, PRL, 1997
Ma & Sarkar, PRD, 2012

$$M_\nu = \frac{g^2 \Delta M_{\tilde{\nu}}}{32\pi^2 \cos^2\theta_w} \left\{ \frac{\sin^2\theta_w r_1}{r_1^{\,2}-1}\left(1-\frac{r_1^{\,2}}{r_1^{\,2}-1}\ln r_1^{\,2}\right) + \frac{\cos^2\theta_w r_2}{r_2^{\,2}-1}\left(1-\frac{r_2^{\,2}}{r_2^{\,2}-1}\right)\ln r_2^{\,2} \right\}$$

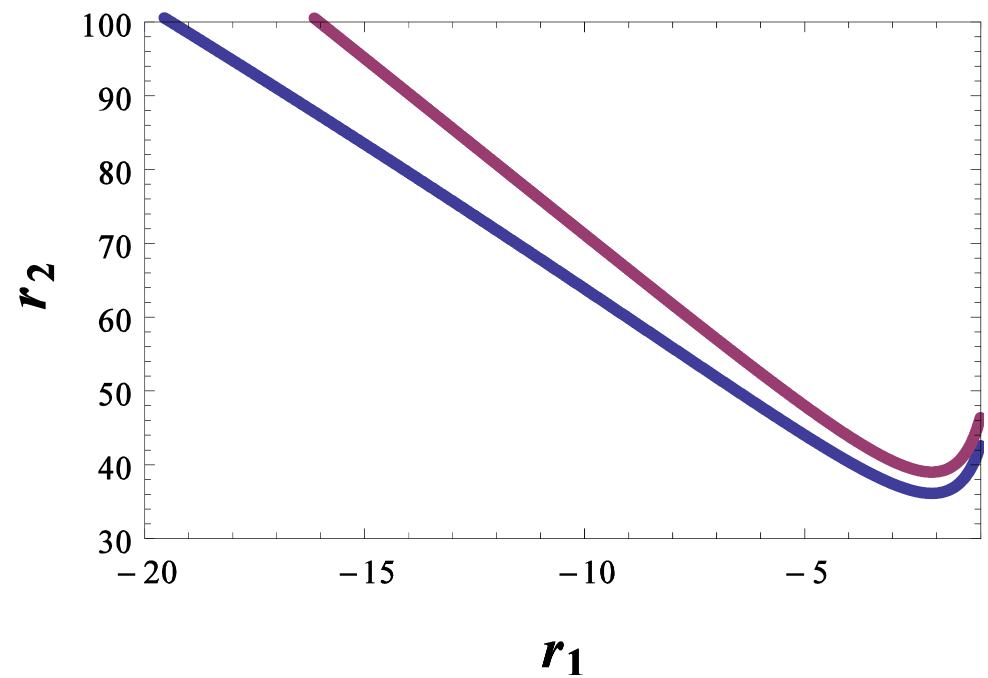
$$r_1 = \frac{M_1}{M_{\tilde{\nu}}}$$

$$r_2 = \frac{M_2}{M_{\tilde{\nu}}}$$

Where M_1 and M_2 are soft-susy breaking parameters for $U(1)_Y$ and $SU(2)$ gauginos.

Continued…

The required ratio: $R \equiv \frac{M_\nu}{\Delta M_{\tilde{\nu}}} < 10^{-5}$



This implies that the parameter space allows a heavy Wino, while the Bino mass can be close to the sneutrino mass. Therefore, the co-annihilation of sneutrino with Bino is important while calculating the relic abundance.

Sneutrino DM and Thermal relic abundance

In the usual thermal freeze-out mechanism, the annihilation cross-section:

$$\Omega_{DM} h^2 \quad \alpha \frac{1}{<\sigma_{ann} |v|>}$$

The effect of co-annihilation can be obtained by substituting:

$$\sigma_{ann} \rightarrow \sigma_{eff} = \sum_{i,j} \frac{g_i g_j}{g_{eff}^2} (1+\delta_i)^{3/2} \times (1+\delta_j)^{3/2} e^{-x(\delta_i+\delta_j)} \sigma_{ij}$$

Where

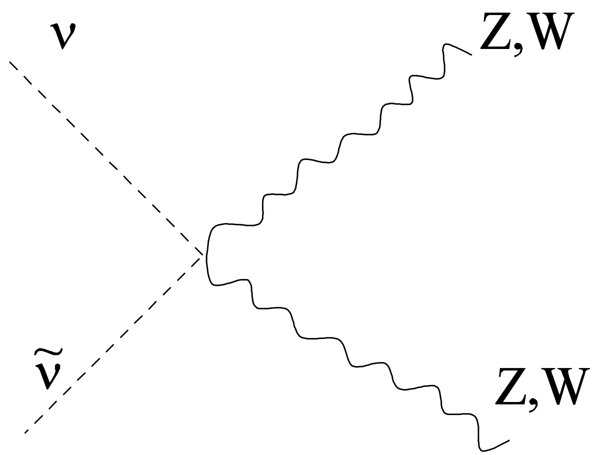
$$\delta_i = \frac{m_i}{m_{DM}} - 1$$

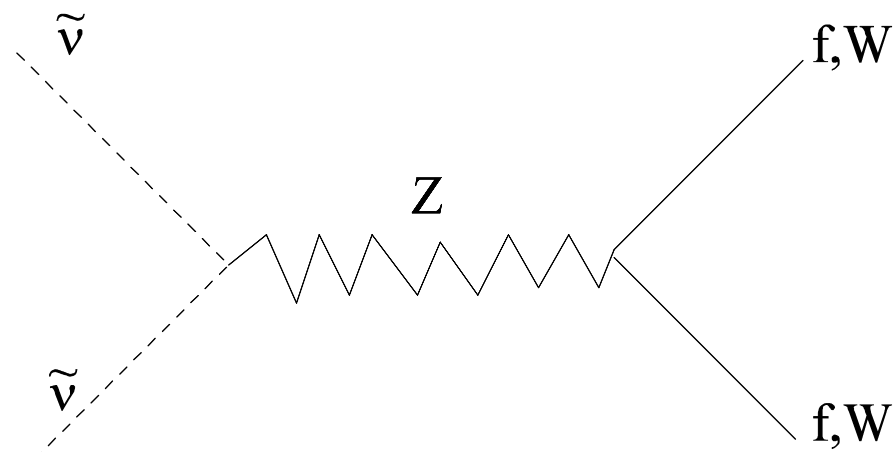
$$x = \frac{m_{DM}}{T}$$

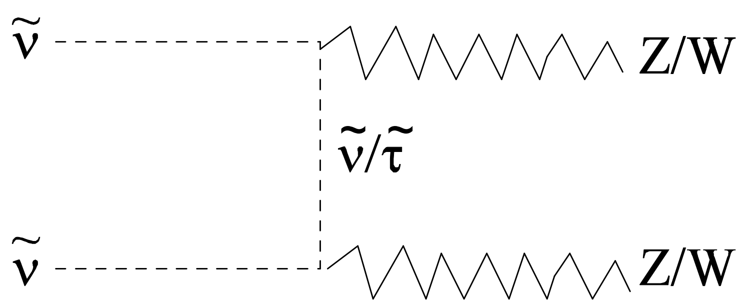
$$g_{eff} = \sum_i g_i (1+\delta_i)^{3/2} e^{-x\delta_i}$$

Ref. Griest & seckel, PRD, 1991

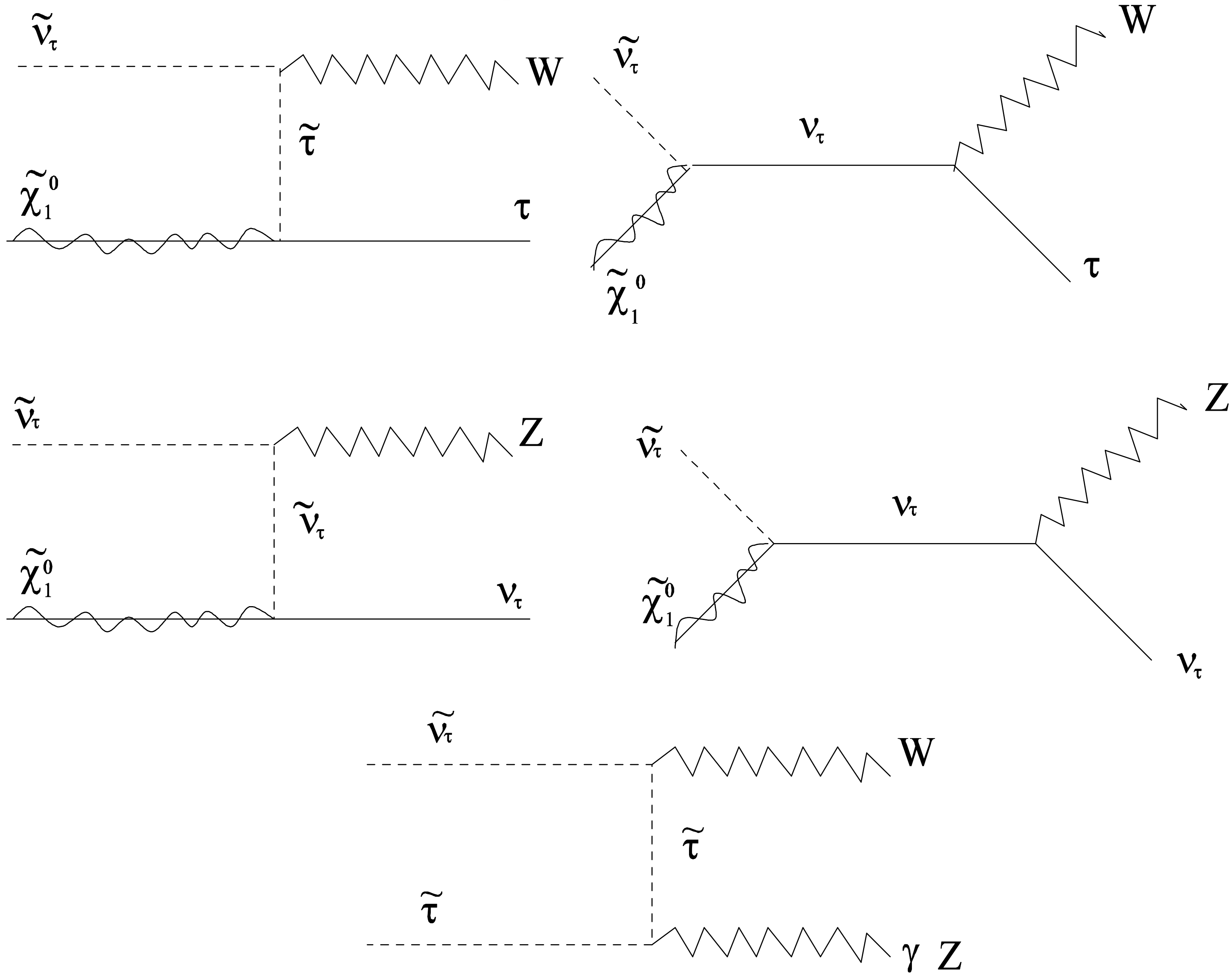
Mutual annihilation processes







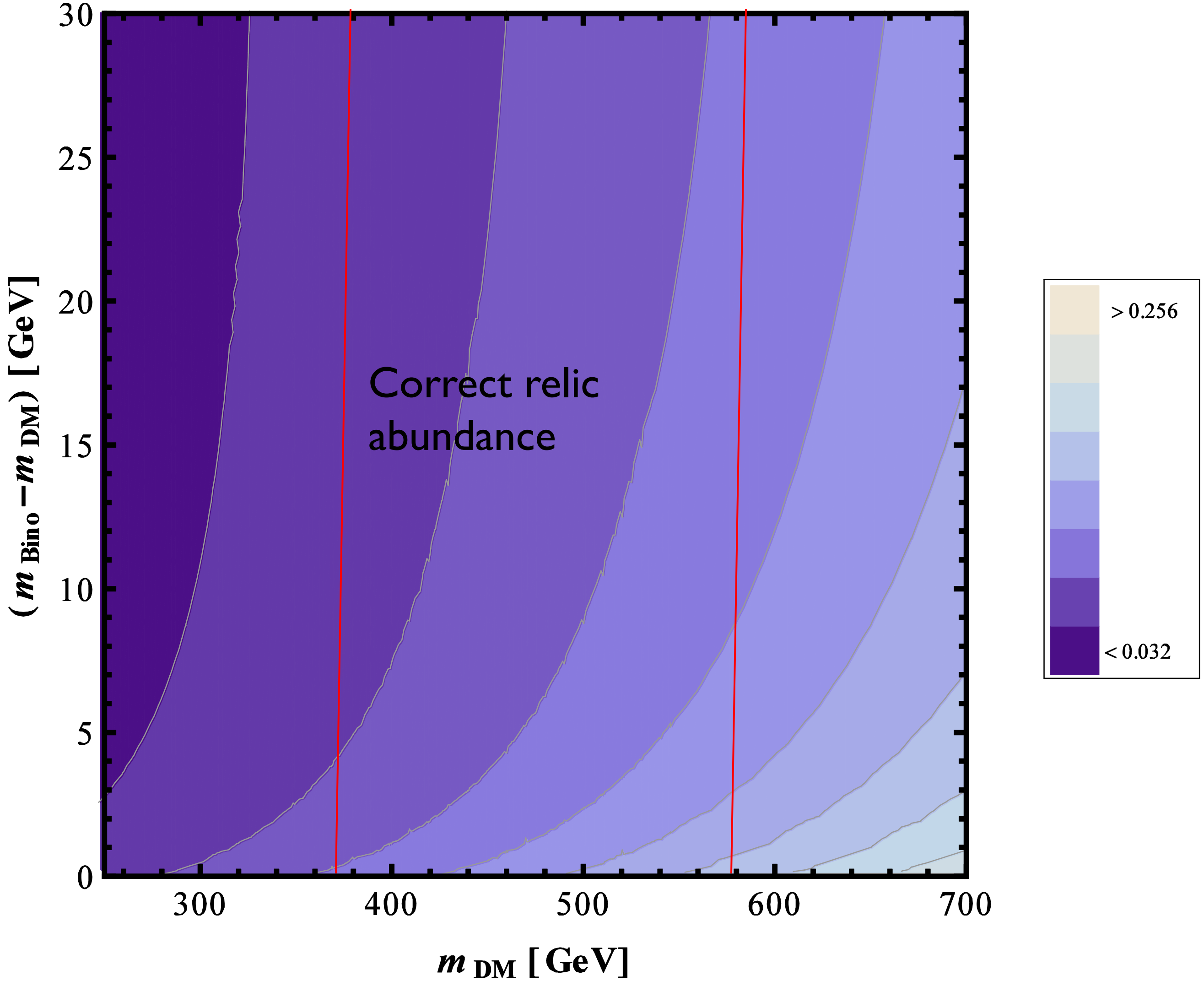
Coannihilation processes



Parameter selection:

(1) First two generations of squark masses are assumed to be 2 TeV
(2) 3rd generation left(right) handed squarks masses are assumed to be 3 (1.5) TeV.
(3) Gluino masses are assumed to be 1.5 TeV.
(4) Tri-linear soft-SUSY breaking terms At=-3.7 TeV and Ab=-3.7TeV
(5) Atau=0 TeV (Soft-SUSY breaking slepton masses are assumed to be flavor diagonal.
(6) CP odd scalar mass is 1 TeV
(7) Mu-term is taken to be -1TeV
(8) Heavy CP even scalar mass is taken to be 2 TeV
(9) $\tan\beta = 10; m_t = 173.1 GeV; m_h = 125 GeV$

Continued…



Ref. MicroOMEGA

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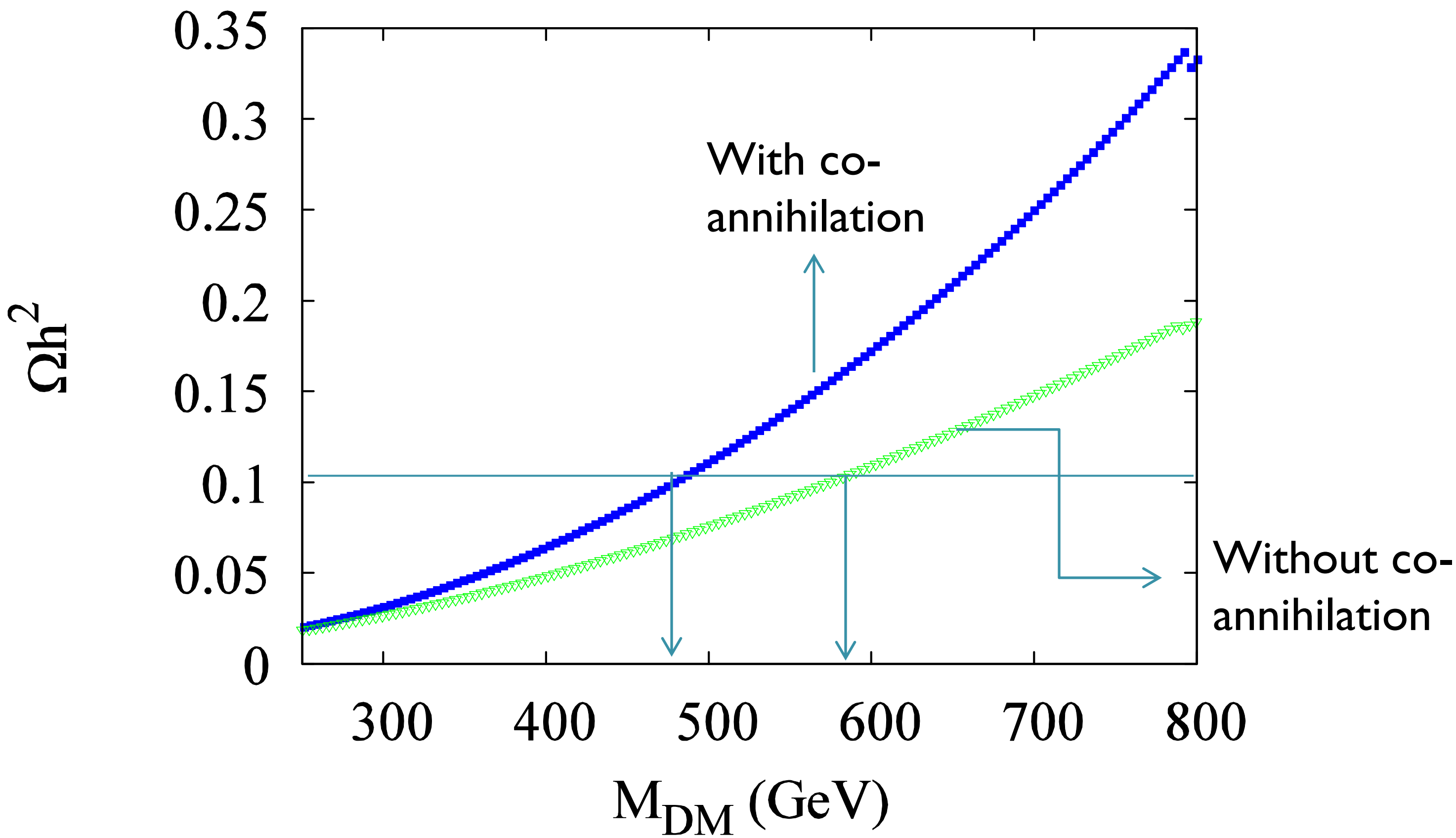
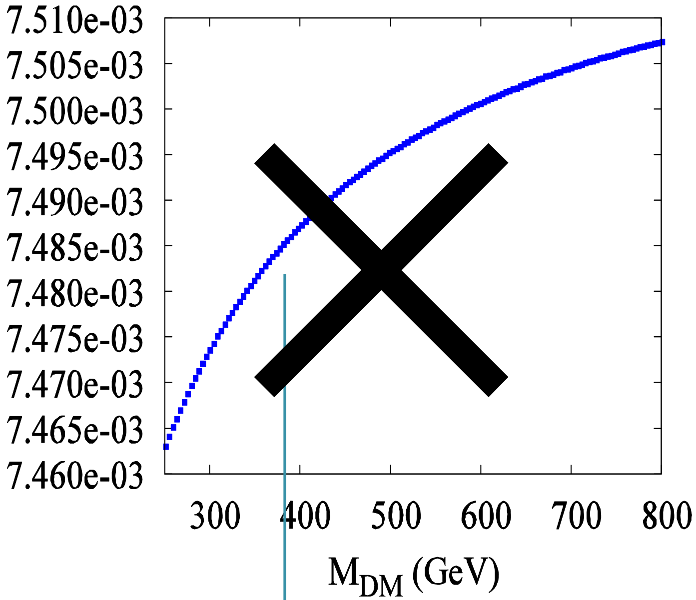
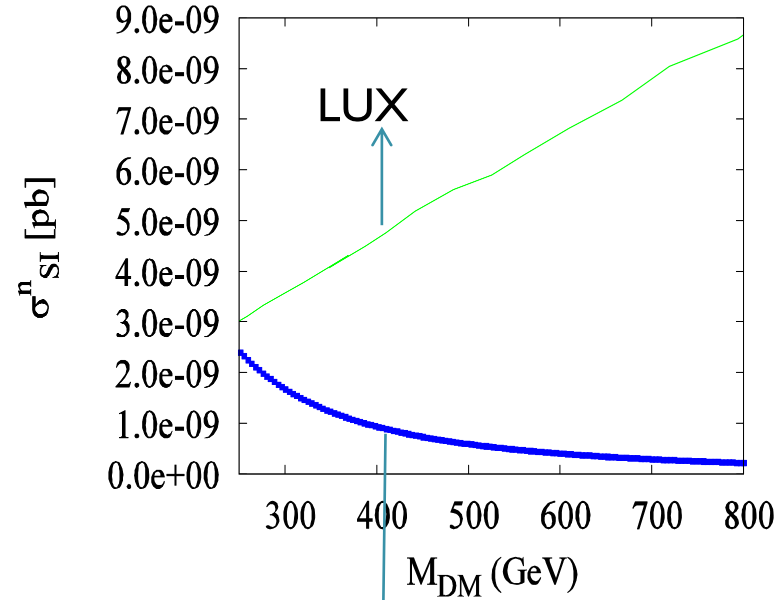
$$M_{Bino} - M_{DM} = 5GeV$$



Direct detection of sneutrino DM





Z-boson exchange process
Forbidden.

$$v_{\min} = c\sqrt{\frac{1}{2m_n E_R}}\left(\frac{m_n E_R}{\mu_n} + \Delta M_{\tilde{\nu}}\right)$$

Heavy scalar exchange process

$$\tan\beta = 15$$

$$m_H = 2000GeV$$

Inert fermion doublet DM

If we extend the SM with a vector-like fermion doublet and impose a Z_2 symmetry under which the new particles are odd while all other SM particles are even, then the neutral component of this additional fermion doublet can be a candidate of dark matter.

Ref. Some Works with Chiara Arina, Rabi Mohapatra and Jinn-Ouk Gong

Due to gauge interactions of these additional particles, required relic abundance can be generated. However, the main challenge is to make them compatible with direct detection experiments, such as Xenon-100, LUX…

Some ongoing work
With my students

Vector-like fourth generation neutrino as Inert fermion doublet DM

Let us extend the SM by including a vector-like fourth lepton doublet $L_4 = (N_4 E_4)^T$ and a scalar triplet $\Delta \equiv (1,3,2)$ and impose a Z_2 symmetry under which L_4 is odd while all other particles are even. Then the relevant Lagrangian is:

$$-\mathcal{L} \supseteq \overline{L}_4 i\gamma^\mu D_\mu L_4 + M_D \overline{L}_4 L_4 + \frac{1}{\sqrt{2}}\left((f_L)_{\alpha\beta}\overline{L_\alpha{}^c} i\tau_2 \Delta L_\beta + f_4 \overline{L_4{}^c} i\tau_2 \Delta L_4 + h.c.\right)$$

$$V(\Delta, H) = M_\Delta{}^2 \Delta^+\Delta + \frac{\lambda_\Delta}{2}\left(\Delta^+\Delta\right)^2 - M_H{}^2 H^+H + \lambda_H\left(H^+H\right)^2 + \lambda_{\Delta H}\left(H^+H\Delta^+\Delta\right)$$

$$+\frac{1}{\sqrt{2}}\left(\mu_H \Delta^+ HH + h.c.\right)$$

After EW phase transition

$$\langle\Delta\rangle = -\mu_H \frac{v^2}{M_\Delta{}^2}$$

$$M_\nu = \sqrt{2} f_L \langle\Delta\rangle$$

$$m = \sqrt{2} f_4 \langle\Delta\rangle$$

Continued…

$$-\mathcal{L}_{DM-mass} = M_D\left[\overline{N_{4L}}N_{4R} + \overline{N_{4R}}N_{4L}\right] + m\left[\overline{N_{4L}{}^{c}}N_{4L} + \overline{N_{4R}{}^{c}}N_{4R} + h.c.\right]$$

So the mass matrix in the basis $\begin{pmatrix} N_{4L} & N_{4R}{}^{c} \end{pmatrix}$ is:

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

So the mass splitting between the two states is order of m. Assuming m=500 keV, the direct detection of DM through Z mediation can be forbidden. Then look for other channels which are compatible with direct detection.

Constraints

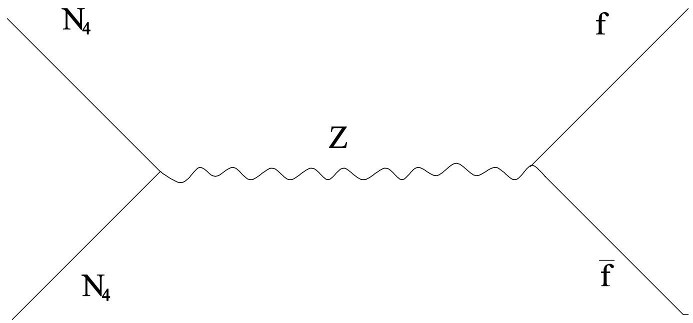
(1) Invisible Z-decay width: $M_{N_4} > 45 GeV$

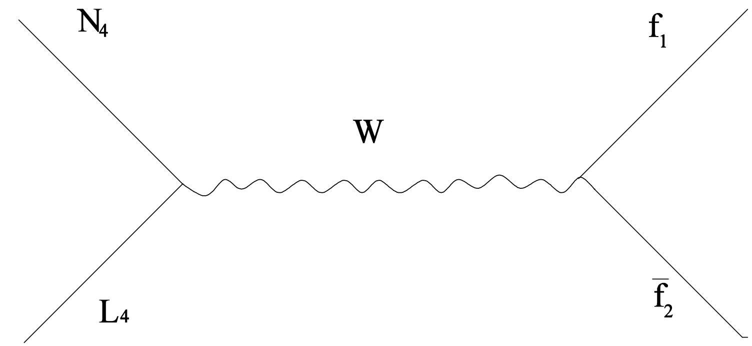
(2) The ratio of neutrino mass to mass splitting between the DM states:

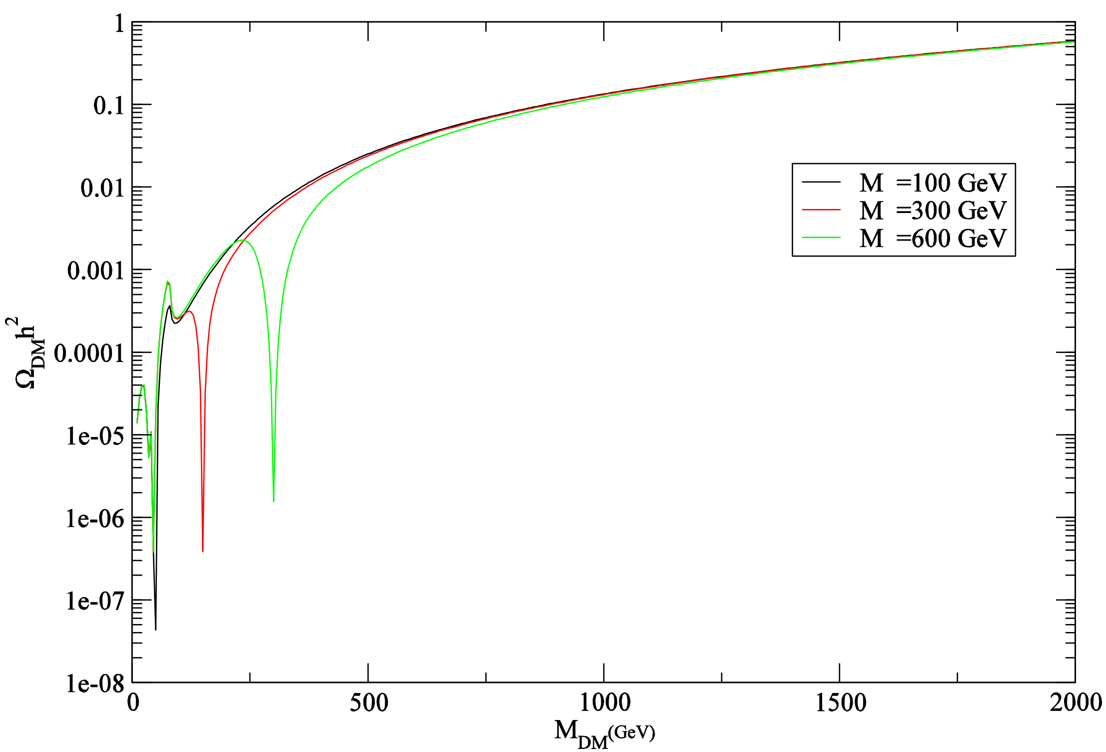
$$R \equiv \frac{M_\nu}{m} = \frac{f_L}{f_4} < 10^{-5}$$

This implies that if the mass of scalar triplet is twice or more than the mass of DM, then the triplet dominantly decays to dark matter sector. On the other hand, if the triplet mass is less than twice the mass of dark matter then it will decay to two leptons.

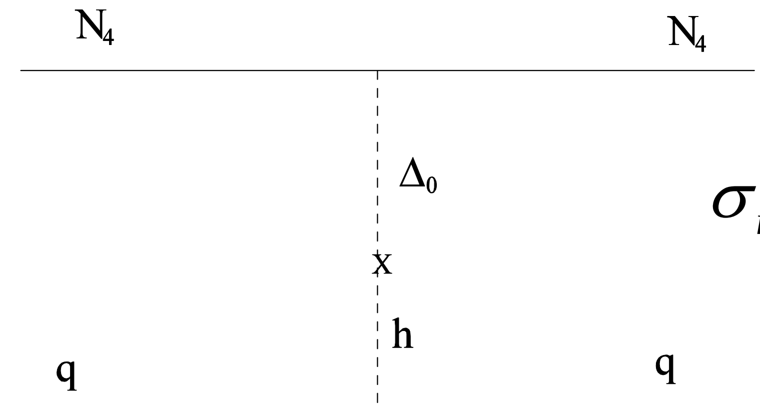
Relic abundance of 4th generation neutrino DM







Direct detection of 4th generation neutrino DM



$$\sigma_n^{SI} = \frac{\mu_n^2}{4\pi} f_n^2 \left(\frac{m_n^2}{v^2}\right) f_4^2 \frac{\theta_{H\Delta}^2}{M_\Delta^4}$$

$$\sigma_n^{SI} \approx O(10^{-46})cm^2 \left(\frac{f_4}{1}\right)^2 \left(\frac{\theta_{H\Delta}}{0.01}\right)^2 \left(\frac{1TeV}{M_\Delta}\right)^4$$

Conclusions…

1. We showed that left-handed sneutrino is a viable candidate of dark matter in the triplet extension of MSSM, otherwise it is ruled out.

2. In the low energy, the triplet extension of MSSM resembles with the pure MSSM with a $(-1)^L \equiv Z_2$ symmetry. If this notion is extended to baryon number, then $(-1)^{3B}$ should be considered. In that case it is an exact R-parity.

3. Neutrino mass is a by-product of the theory.

4. Collider signatures are novel and soon be reported.