DECAYING AND STABLE DARK MATTER

Tianjun Li
Institute of Theoretical Physics, Chinese Academy of Sciences

I. Introduction

II. DM decay via Froggat-Nielsen Mechanism

III DM decay via Neutrino Masses and Mixings

IV Summary

Gao, Kang, TL, arXiv:1001.3278 [hep-ph]; in preparation; Kang and TL, arXiv:1008.1621 [hep-ph].

Workshop on Dark Matter and Baryogenesis, ITP, December 13-15, 2010

I. INTRODUCTION

Based on numerous cosmological and astrophysical studies, we believe that our Universe is flat and the total energy density is critical

$$\rho_{\rm tot} \simeq \rho_c \equiv \frac{3H_0^2}{8\pi G_{\rm N}} \;, \quad \Omega_{\rm tot} \equiv \frac{\rho_{\rm tot}}{\rho_c} \simeq 100\% \;.$$

$$\Omega_\Lambda \simeq 72\% \;, \; \Omega_{\rm dm} \simeq 23\% \;, \; \Omega_{\rm b} \simeq 4.6\% \;,$$
$$\Omega_\gamma \simeq 0.005\% \;, \; 0.1\% \leq \Omega_\nu \leq 1.5\% \;.$$

Conditions for Dark Matters:

- $SU(3)_C \times U(1)_{\rm EM}$ singlets.
- Stable due to additional symmetry, or lifetime is longer than the age of the Universe today t_0 about 14 Gyr

$$\tau_{\rm dm} > t_0 \simeq 4.3 \times 10^{17}\ {\rm s}\ .$$

The SM does not have such kind of particles.

Philosophy for Dark Matter Models:

- The simplest Model.
- The SM has some problems, and the dark matter is a particle in the extension of the SM that can solve these problems.
- Experiments inspired the Models.

The simplest Model

A real Klein–Gordon field S with a Z_2 parity.

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!}S^4 \, .$$

To be consistent with the triviality and stability bounds, we find $m_S \simeq 5.5$ GeV–1.8 TeV.

Properties of Dark Matter

- The interaction can not be very strong: Bullet Cluster experiment.
- The collisionless CDM scenario predicts two much power on small scale:

  a large excess of dwarf galaxies, and over-concentration of dark matter in the dwarf galaxies and in large galaxies
- Solutions: Strong self interaction [a], non-thermal dark matter productions via cosmic string [b], etc.

---

[a] D. N. Spergel and P. J. Steinhardt.

[b] W. B. Lin, D. H. Huang, X. Zhang, R. Brandenberger.

- The INTEGRAL experiment detects a 511 KeV emission line from the galactic center, consistent with injection of a few MeV positrons. Exciting dark matter: $\chi_1\chi_1 \to \chi_1\chi_2$ via tree-level and ladder diagrams [a].
- The DAMA signal, which is still compatible with the null results of the other DM experiments within the framework of inelastic DM with splitting about 100 KeV.

Degenerated dark matter candidates.

---

[a] D. P. Finkbeiner, and N. Weiner.

- The ATIC and PPB-BETS collaborations have reported the electron/positron spectrum measurement up to ~ 1 TeV, with an obvious bump above the background at $\sim 300-800\,$GeV and $\sim 500-800\,$GeV, respectively.
- The PAMELA collaboration also released their first cosmic-ray measurements on the positron fraction and the $\bar{p}/p$ ratio. The positron fraction shows a significant excess above $10\,$GeV up to $\sim 100\,$GeV, compared with the background predicted by the conventional cosmic-rays propagation model.

- Fermi-LAT collaboration has released the data on the measurement of the electron/positron spectrum from 20 GeV to 1 TeV with unprecedented precision. HESS from 340 GeV to 700 GeV, and then 700 GeV to 5 TeV.
- DAMA/LIBRA, CDMS II and CoGeNT experiments may be explained by a light DM with mass around 7 GeV and DM-nucleon cross section around $10^{-40}\ \mathrm{cm}^2$.

Particle Physics Dark Matters:

- Unstable DM: fine-tuning.
- Stable DM: Boost Factor (BF) puzzle.

Stable DM: BF solutions

- Sub-halo.
- Non-thermal DM production [a].
- Sommerfeld enhancement [b].
- Breit-Wigner enhancement: the resonent mass is just below the twice dark matter mass [c].
- Strong Interactions.

---

[a] R. Jeannerot, X. Zhang and R. Branderberger.

[b] N. Arkani-Hamed, D. P. Finkbeiner, T. Slatyer and N. Weiner.

[c] M. Ibe, H. Murayama and T. T. Yanagida; W. L. Guo and Y. L. Wu.

Universal Implications:

- For PAMELA and ATIC experiments, the DM mass is about 700 GeV for annihilation and 1.4 TeV for decay.
- For PAMELA, Fermi-LAT, and HESS experiments, the DM mass is around 2 TeV for annihilation and 4 TeV for decay. The favoured final states are the combination of $\mu^+\mu^-$ and $\tau^+\tau^-$.
- Decay or Stable? The HESS observation of the Galactic center gamma rays gives strong constraints on the annihilation DM scenario while gives weaker constraints on the decay DM scenario.
- Neutralino in (N)MSSM: the DAMA/LIBRA, CDMS II and CoGeNT experiments.

Multicomponent DM: Decaying and Stable DM

Decaying DM:

- DM lifetime about $10^{26}\ s$.
- Decaying into charged leptons.
- DM Density.

Small Number/Hiearchy in Particle Physics:

- Froggatt-Nielsen Mechanism.
- High energy scale: Neutrino Masses and Mixings; proton decay.

II. DM DECAY VIA FROGGATT-NIELSEN MECHANISM

General set-up:

- Z_2 symmetry, and a Z_2 odd field: S.
- Gauged discrete symmetry: annomalous $U(1)_X$ gauge symmetry.
- Decay: S aquires a VEV around M_{SUSY}
- DM Density: extra $U(1)'$/intermediate vector-like particles; non-thermal productions; ....

Details:

- Anomalous gauged $U(1)_X$ symmetry and a flavon field A with charge -1.
- A small parameter: FI-term and D-flatness for SUSY

$$0.171 \leq \epsilon \equiv \frac{\langle A \rangle}{M_{\rm Pl}} \leq 0.221 \,.$$

- $U(1)_X$ charges:

$$\begin{gathered}
X_{Q_1} = 3, \quad X_{Q_2} = 2, \quad X_{Q_3} = 0, \quad X_{U_1^c} = 5, \quad X_{U_2^c} = 2, \quad X_{U_3^c} = 0, \\
X_{D_1^c} = 1, \quad X_{D_2^c} = 0, \quad X_{D_3^c} = 0, \quad X_{L_1} = 1, \quad X_{L_2} = 0, \quad X_{L_3} = 0, \\
X_{E_1^c} = 3, \quad X_{E_2^c} = 2, \quad X_{E_3^c} = 0, \quad X_{H_u} = 0, \quad X_{H_d} = 0.
\end{gathered}$$

SM Fermion Masses and Mixings:

$$\begin{aligned} W \supset & \left(\frac{A}{M_{\mathrm{Pl}}}\right)^{X_{H_u}+X_{Q_i}+X_{U_j^c}} Q_i H_u U_j^c + \left(\frac{A}{M_{\mathrm{Pl}}}\right)^{X_{H_d}+X_{Q_i}+X_{D_j^c}} Q_i H_d D_j^c \\ & + \left(\frac{A}{M_{\mathrm{Pl}}}\right)^{X_{H_d}+X_{L_i}+X_{E_j^c}} L_i H_d E_j^c + \left(\frac{A}{M_{\mathrm{Pl}}}\right)^{X_{H_u}+X_{L_i}+X_{N_j^c}} L_i H_u N_j^c \ . \end{aligned}$$

$$Y_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^7 & \epsilon^4 & \epsilon^2 \\ \epsilon^5 & \epsilon^2 & 1 \end{pmatrix} , \quad Y_d \sim Y_e^T \sim \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^2 & \epsilon^1 & \epsilon^1 \end{pmatrix} , \quad Y_\nu \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \ .$$

Dark Matter Decay:

- A pair of vector-like particles E' and $\overline{E}'$ whose quantum numbers under $SU(3)_C \times SU(2)_L \times U(1)_Y$ are $(\mathbf{1}, \mathbf{1}, -\mathbf{1})$ and $(\mathbf{1}, \mathbf{1}, \mathbf{1})$, respectively.
- S has $U(1)_X$ half-integer charge: discrete gauged Z_2 symmetry after $U(1)_X$ breaking.

Models for PAMELA/Fermi-LAT:

- $U(1)_X$ charges for S, E' and $\overline{E'}$

$$X_S = -1/2, \quad X_{E'} = -1, \quad X_{\overline{E'}} = +1.$$

$$W \supset \left(\frac{A}{M_{\rm Pl}}\right) H_d L_k \overline{E'} + \left(\frac{S^2}{M_{\rm Pl}}\right) E_2^c E' + M_V \overline{E'} E' \ .$$

- Decay operator: $M_*^2 = M_{\rm Pl} \times M_V/\epsilon$

$$W \supset \ -\left(\frac{S^2}{M_*^2}\right) H_d L_k E_2^c \ .$$

- $M_* \sim 10^{17}$ GeV or $M_V \sim 1 \times 10^{15}$ GeV
- The other operators are suppressed by at least ϵ.

Benchmark point:

- The CMSSM soft terms: $\mathrm{sign}(\mu) > 0$

$$m_0 = 310\mathrm{GeV}, \quad m_{1/2} = 250\mathrm{GeV}, \quad A_0 = -1040, \quad \tan\beta = 30\ .$$

- LSP neutralino: stau-neutralino coannhilation region

$$\Omega_{\widetilde{N}_1^0} h^2 \approx 0.08\ .$$

- $m = 101.6$ GeV, and the spin-independent cross section is about $\sigma_{SI} \approx 5 \times 10^{-9}$ pb, which is fine due to the uncertainties of the QCD effects in the calculations.

- χ_1^0 is bino like while $\chi_{3,4}^0$ is Higgsino like.

DM S Three-Body Decays:

$$\begin{aligned}\mathcal{C}_\mu S H_d L E^c + c.c. &= \mathcal{C}_\mu S H_d^0 E E^c - \mathcal{C}_\mu S H_d^- \nu E^c + c.c. \\ &\supset \mathcal{C}_\mu S (H_d^0 \mu_L \mu_R^\dagger + \widetilde{H}_d^0 \mu_L \widetilde{\mu}_R^* + \widetilde{H}_d^0 \widetilde{\mu}_L \mu_R^\dagger) \\ &\quad - \mathcal{C}_\mu S (H_d^- \nu_\mu \mu_R^\dagger + \widetilde{H}_d^- \nu_\mu \widetilde{\mu}_R^* + \widetilde{H}_d^- \widetilde{\nu}_\mu \mu_R^\dagger) \\ &\quad + \mathcal{C}_\mu \widetilde{S} (H_d^0 \mu_L \widetilde{\mu}_R^* + H_d^0 \widetilde{\mu}_L \mu_R^* + \widetilde{H}_d^0 \widetilde{\mu}_L \widetilde{\mu}_R^* + \widetilde{H}_d^0 \widetilde{\mu}_L \widetilde{\mu}_R^\dagger) \\ &\quad - \mathcal{C}_\mu \widetilde{S} (H_d^- \nu_\mu \widetilde{\mu}_R^* + H_d^- \widetilde{\nu}_\mu \mu_R^* + \widetilde{H}_d^- \widetilde{\nu}_\mu \widetilde{\mu}_R^* + \widetilde{H}_d^- \widetilde{\nu}_\mu \widetilde{\mu}_R^\dagger) \ .\end{aligned}$$

After H_d^0 acquires a VEV, the three-body S decay is larger than two-body S decay due to large $\tan\beta$ enhancement: $(M_D/\langle H_d^0\rangle)^2/(96\pi^2) \sim 282.$

$$S \to \widetilde{\chi}^0_{3,4}\mu\widetilde{\mu}_R, \quad \widetilde{\chi}^\pm_{1,2}\nu_\mu\widetilde{\mu}_L, \quad \widetilde{C}_{1,2}\mu\widetilde{\nu}_{\mu_L}, \quad A^0(H^0)\mu\mu, \quad C^-\nu_\mu\mu_R \ .$$

DM lifetime is OK!

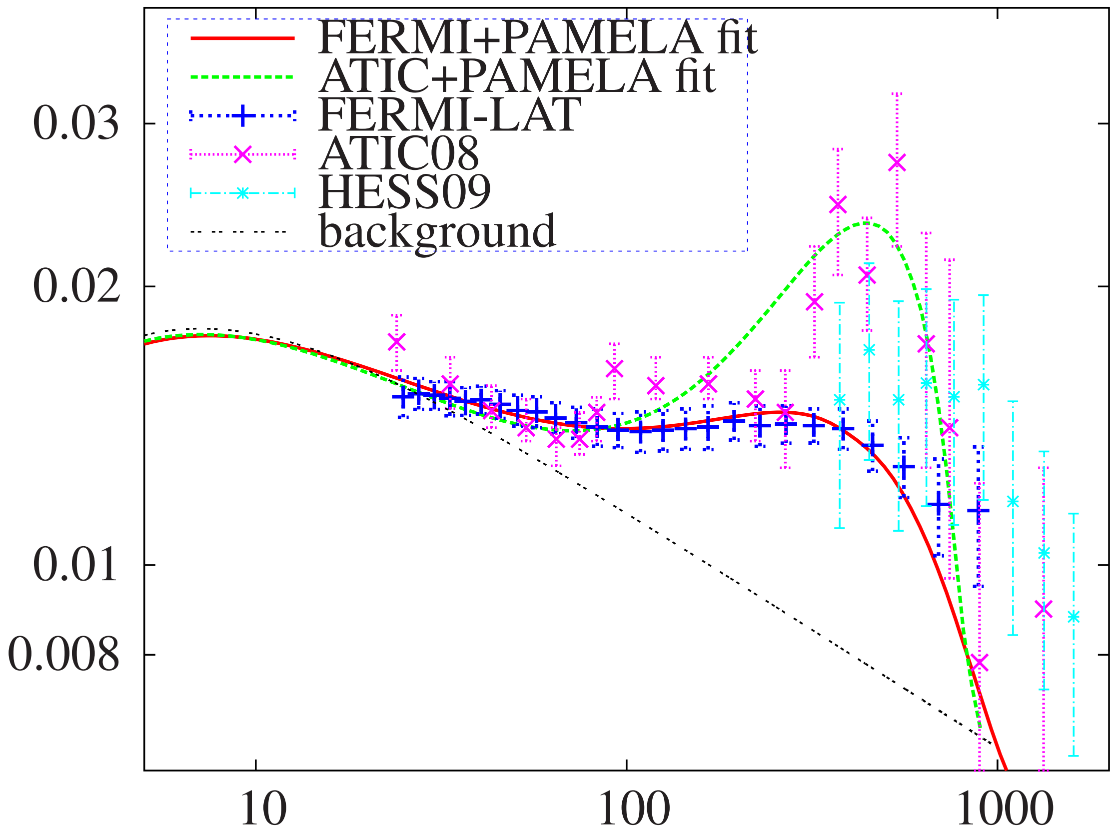

Figure 1: The FERMI data fitting in Model I and the ATIC data fitting in Model II.

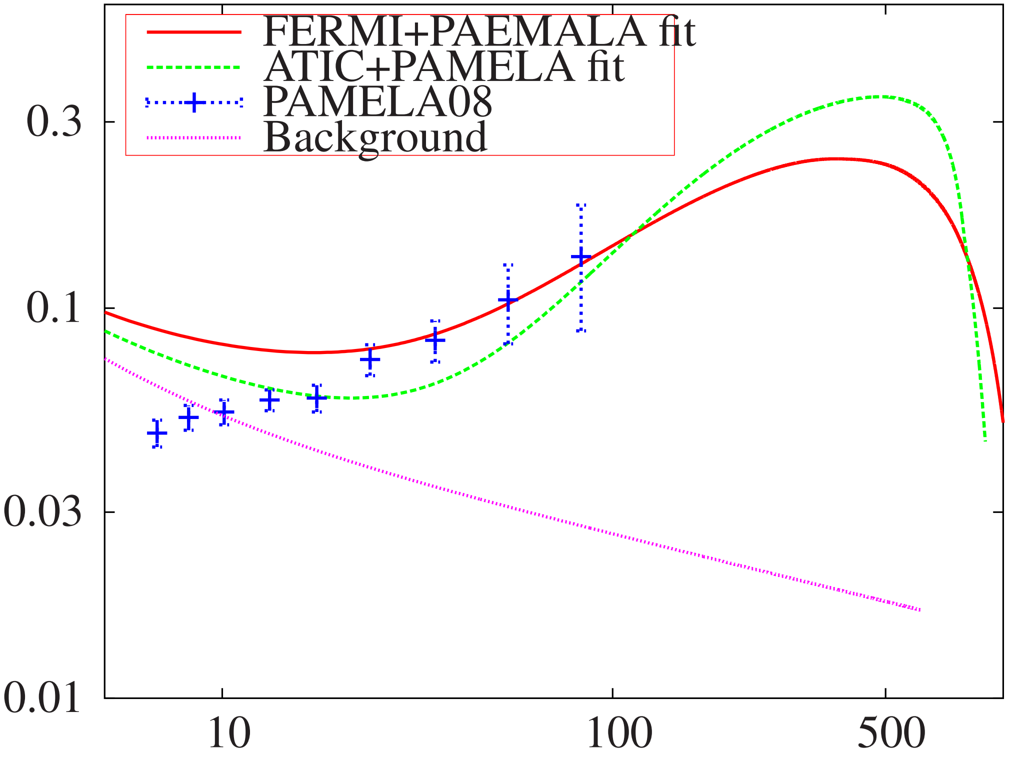

Figure 2: PAMELA data fitting for positron fraction in Model I and Model II.

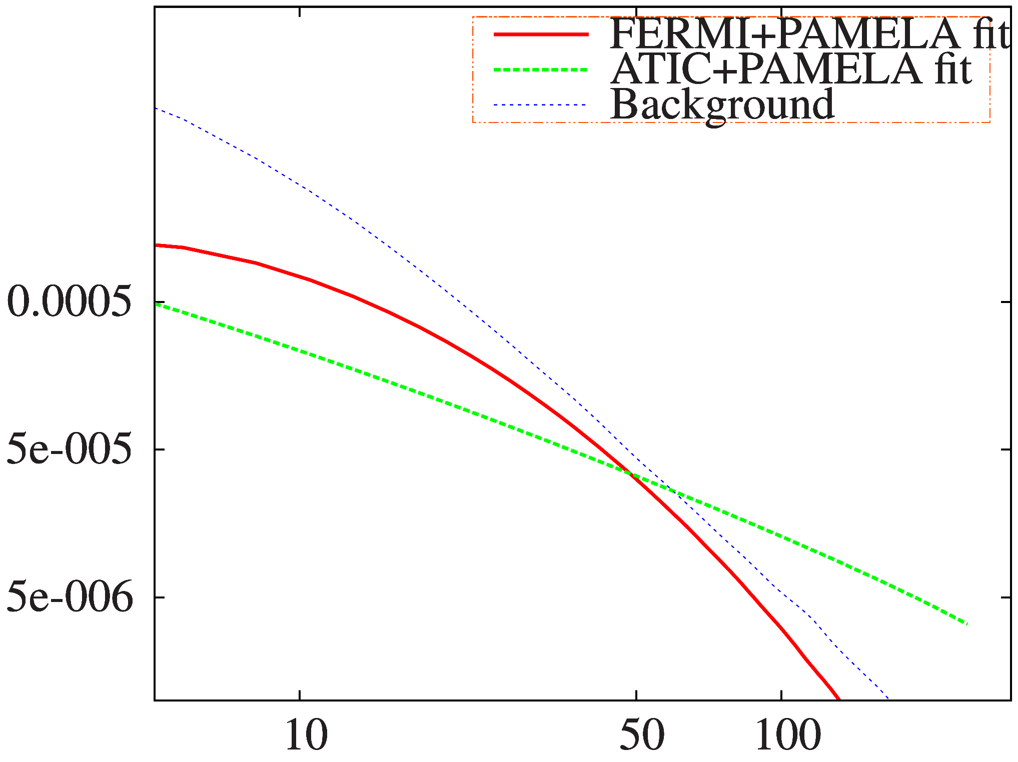

Figure 3: PAMELA data fitting for $\bar{p}/p$ ratio in Model I and Model II. The anti-proton fluxes $\Phi_{\odot}^{\bar{p}}(E)$ is in the unit $\mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$.

III. DM DECAY VIA NEUTRINO MASSES AND MIXINGS

DM decay:

- Operators:

$$\frac{1}{\Lambda^3}\phi_1\phi_2 Y^N_{il} Y^N_{lj} L_i L_j H_u H_u, \quad \frac{1}{\Lambda^2}\phi_1\phi_2 Y^N_{ij} L_i L_j \ .$$

- Neutrino Hierarchies: normal (PAMELA/Fermi-LAT/HESS), inverted (PAMELA/ATIC), degenerated.

General set-up:

- DM sector: two SM singlet fields $\phi_{1,2}$ and a discrete Z_3 symmetry

$$\phi_1 \longrightarrow w\phi_1 \ , \qquad \phi_2 \longrightarrow w^2\phi_2 \ .$$

- Superpotential and SUSY breaking soft terms

$$\begin{aligned} W_{DM} =& \frac{\lambda_1}{3}\phi_1^3 + \frac{\lambda_2}{3}\phi_2^3 + M_\phi \phi_1 \phi_2 \ , \\ -\mathcal{L}_{soft}^{DM} =& m_{\phi_1}^2 |\phi_1|^2 + m_{\phi_2}^2 |\phi_2|^2 \\ & + \left(\frac{A_{\lambda_1}}{3}\lambda_1 \phi_1^3 + \frac{A_{\lambda_2}}{3}\lambda_2 \phi_2^3 + B_\phi M_\phi \phi_1 \phi_2 + h.c. \right) \ . \end{aligned}$$

- Type I seesaw

$$W \supset \frac{M_{N_i}}{2} N_i^2 + Y_{ij}^N L_i H_u N_j + \frac{\lambda_{Xi}}{2} X N_i N_i$$
$$+ \lambda_{X\phi} \phi_1 \phi_2 X + \left(\frac{M_X}{2} X^2 + \text{irrevelant terms} \right) .$$

- Integrating out X and N_i

$$\mathcal{C}_{ij} \phi_1 \phi_2 (L_i H_u)(L_j H_u) , \quad \text{where } \mathcal{C}_{ij} = - \frac{\lambda_{X\phi} \lambda_{N_l}}{M_X} \frac{Y_{il}^N Y_{jl}^N}{M_{N_l}^2} .$$

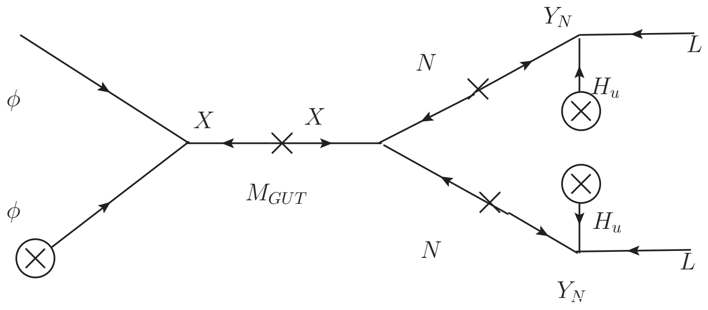

Figure 4: Feymann diagram for the dimension-7 operators $\mathcal{C}_{ij}\phi_1\phi_2(L_iH_u)(L_jH_u)/M_XM_{N_l}^2$ generated by integrating out X and N_i at tree level.

Z_3 **Symmetry Breaking:**

- Potential

$$V(\phi_i) = |\lambda_1 \phi_1^2 + M_\phi \phi_2|^2 + |\lambda_2 \phi_2^2 + M_\phi \phi_1|^2 + m_{\phi_1}^2 |\phi_1|^2 + m_{\phi_2}^2 |\phi_2|^2$$
$$+ \left(\frac{A_{\lambda_1}}{3} \lambda_1 \phi_1^3 + \frac{A_{\lambda_2}}{3} \lambda_2 \phi_2^3 + B_\phi M_\phi \phi_1 \phi_2 + h.c. \right) \ .$$

- Concrete example

$$\lambda_1 = \lambda_2 = 0.3, \quad M_\phi = 1.0\,\mathrm{TeV},$$
$$m_{\phi_i}^2 = 200\,\mathrm{GeV}^2, \quad B_\phi = -600\,\mathrm{GeV}, \quad A_{\lambda_i} = 600\,\mathrm{GeV}.$$

$$\langle \phi_1 \rangle \equiv v_1 \approx -6.06\,\mathrm{TeV}, \quad \langle \phi_2 \rangle \equiv v_2 \approx -6.57\,\mathrm{TeV}.$$

$$
\begin{aligned}
&m_{\phi_R} \approx 2.60\,\mathrm{TeV}, \quad m_{\phi'_R} \approx 4.81\,\mathrm{TeV},\\
&m_{\phi_I} \approx 2.91\,\mathrm{TeV}, \quad m_{\phi'_I} \approx 4.83\,\mathrm{TeV},\\
&m_{\widetilde{\phi}} \approx -4.80\,\mathrm{TeV}, \quad m_{\widetilde{\phi}'} \approx -2.78\,\mathrm{TeV}. \qquad (1)\\
&\phi_R = 0.70\phi^0_{1,R} + 0.71\phi^0_{2,R}, \quad \phi'_R = 0.71\phi^0_{1,R} - 0.70\phi^0_{2,R},\\
&\phi_I = 0.82\phi^0_{1,I} + 0.58\phi^0_{2,I}, \quad \phi'_I = -0.58\phi^0_{1,I} + 0.82\phi^0_{2,I},\\
&\widetilde{\phi} = -0.65\widetilde{\phi}^0_1 + 0.76\widetilde{\phi}^0_2, \quad \widetilde{\phi}\,' = 0.76\widetilde{\phi}^0_1 + 0.65\widetilde{\phi}^0_2.
\end{aligned}
$$

- DM lifetime $\phi_R \to \widetilde{\nu}_i \ell_j \widetilde{H}_u$: Freeze-in DM scenario

  $M_{N_i}/M_X \sim 10^{-11}$

$$\tau \approx 768\pi^3 \times \frac{1}{(\mathcal{C}^5_{ij})^2} \frac{1}{m^3_{\phi_R}}$$

$$= 3.6 \times 10^{26} \times \left(\frac{M_X}{10^{15}\,\mathrm{GeV}}\right)^2 \times \left(\frac{0.05\,\mathrm{eV}}{(M_{LL})_{ij}}\right)^2 \times \left(\frac{M_{N_2}}{10^4\,\mathrm{GeV}}\right)^2$$

$$\times \left(\frac{5\,\mathrm{TeV}}{v_\phi}\right)^2 \times \left(\frac{2\,\mathrm{TeV}}{m_{\phi_R}}\right)^3 s.$$

DM Density from Freeze-in Mechanism:

$$\begin{aligned}\Omega_\phi h^2 \sim& \frac{6.0\times 10^{22} g^2_{\widetilde{N}_i}}{g_*^S\sqrt{g_*^\rho}}\left(\frac{m_\phi}{M_{N_i}}\right)\lambda^2_{N_i}\\ =&0.065\left(\frac{m_\phi}{2.5\mathrm{TeV}}\right)\left(\frac{10\mathrm{TeV}}{M_{N_i}}\right)\left(\frac{229^{3/2}}{g_{*MSSM}}\right)\left(\frac{M_{N_i}/M_X}{5\times 10^{-11}}\right)^2 \ .\end{aligned}$$

Small scale problem:

Both ϕ_R and $\widetilde{\phi}$ are generated with equal number densities via the freeze-in mechanism. Because $\widetilde{\phi}$ is a relatively heavy metastable R_p-odd state, it will decay and produce some relativistic particles.

$$\widetilde{\phi} \to \widetilde{G} + \phi_R \to \ldots .$$

Baryon Asymmetry: Soft Leptogenesis

$$
\begin{aligned}
-\mathcal{L} \supset & \frac{1}{\sqrt{2}}\widetilde{N}_{2+}(Y^N_{i2})^*(M_{N_2}+A^*_{i2})\widetilde{L}^\dagger_i H^\dagger_u + \frac{1}{\sqrt{2}}\widetilde{N}_{2-}(Y^N_{i2})^*(M_{N_2}-A^*_{i2})\widetilde{L}^\dagger_i H^\dagger_u \\
& + (Y^N_{i2})^*(\widetilde{N}_{2+}-\widetilde{N}_{2-})L^\dagger_i \widetilde{H}^\dagger_u + \frac{1}{2}M_2\widetilde{\lambda}_2\widetilde{\lambda}_2 + h.c.,
\end{aligned}
$$

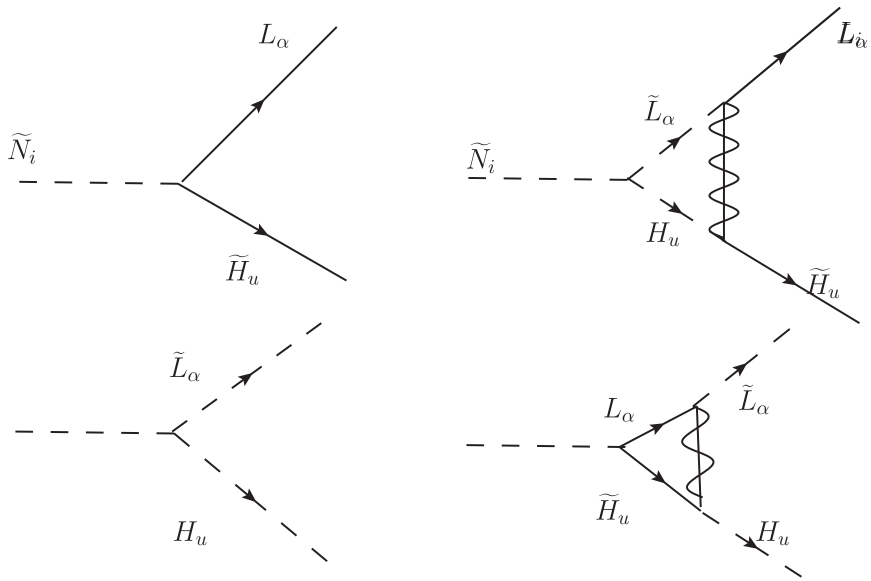

Figure 5: Lepton number and CP-violation decays of $\widetilde{N}_i$ with gaugino running in the vertex correction loop. Self-energy contributions are ignored since they are suppressed by the extra Yukawa couplings Y^{N_i}.

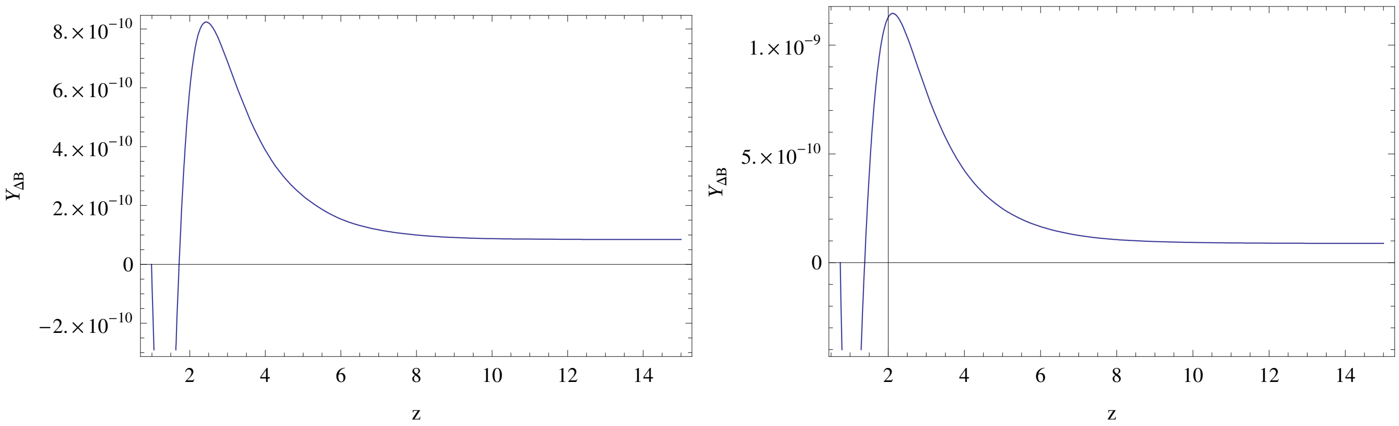

Figure 6: Baryon asymmetry $Y_{\Delta B}(z)$ versus $z = M_{N_2}/T$. Left: $M_{N_2} = 10^4$ GeV, $M_2 = 250$ GeV and $|A_{N_{22}}| = 300$ GeV with $\theta_{A_{22}} = -1/4$. Right: $M_{N_2} = 4 \times 10^3$ GeV, $M_2 = 250$ GeV, $|A_{N_{22}}| = 100$ GeV, $\theta_{A_{22}} = -1/5$. Initial density of $\widetilde{N}_2$ is taken as thermal density.

SUMMARY

Decaying and Stable DM Matter

- Decaying DM: long lifetime and leptonical decay modes
- Froggatt-Nielsen mechanism or neutrino masses and mixings.
- Stable DM: LSP in the SSM
- SM fermion masses and mixings, small scale problem, baryon asymmetry, etc.