Light Nonthermal Dark Matter: A Minimal Model & Detection Prospects

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Outline:

- Introduction
- Minimal model (non-supersymmetric version)
- Detection prospects (direct, indirect, collider)
- Minimal model (supersymmetric version)
- Outlook

Based on the following works:

Introduction:

The present universe according to observations:

Two big problems to address:

1) Dark Matter (DM)
   - What is the nature of DM?
   - How was it produced?

2) Baryon Asymmetry of Universe (BAU)
   - Why is it nonzero?
   - How was it generated?

Also, the coincidence puzzle:

Why the DM and baryons have comparable energy densities?
Generation of BAU:

B, C & CP, out of thermal equilibrium (Sakharov conditions):

\[ f_L \neq \bar{f}_L, f_R \neq \bar{f}_R \quad f_L \neq \bar{f}_R, f_R \neq \bar{f}_L \]

\[ f_L = \bar{f}_R, f_R = \bar{f}_L \quad f_L = \bar{f}_L, f_R = \bar{f}_R \]

Occurred via out-of-equilibrium decay of some heavy state(s) produced after (or during) inflation

Production of DM:

Thermal freeze-out (WIMP miracle):

\[ T_f \sim \frac{m_\chi}{20} \]

\[ \langle \sigma v \rangle_f = 3 \times 10^{-26} \, cm^3 / s \]

Nonthermal production:

\[ T_r < T_f \]

\[ \langle \sigma v \rangle_f \neq 3 \times 10^{-26} \, cm^3 / s \]
A Minimal Model:
We adopt a bottom-up approach.

We consider a minimal extension of the SM with renormalizable $\beta$ interactions:

$$L_{\text{new}} = \lambda'_{\alpha ij} X_\alpha d^c_i d^c_j + \lambda_{\alpha i} N X_\alpha^* u^c_i + m_\alpha^2 |X_\alpha|^2 + \frac{m_N}{2} NN + \text{h.c. + kinetic terms}$$

$X_\alpha$: Iso-singlet color triplet scalars with $Y = +4/3$

$N$: Singlet fermion

The field content is the minimum required to generate nonzero baryon asymmetry via out-of-equilibrium decay of $X$

Kolb, Wolfram  NPB 172, 224 (1980); Erratum-ibid 195, 542 (1982)
\[ \mathcal{E}_1 = \frac{1}{8\pi} \frac{\sum_{i,j,k} \text{Im}(\lambda^*_1 \lambda^*_2 \lambda'_{i,j} \lambda'_{i,j})}{\sum_{i,j} |\lambda'_{i,j}|^2 + \sum_{k} |\lambda_{i,k}|^2} \frac{m_1^2}{m_1^2 - m_2^2} \]

\[ \mathcal{E}_2 = \mathcal{E}_1(1 \leftrightarrow 2) \]
$X$ fields mediate a 4-fermion interaction:

$$\frac{\lambda \lambda'}{m_X^2} N u_i^c d_j^c d_k^c$$

This operator results in the following decays:

$m_N > m_p + m_e : \ N \rightarrow p + e^- + \bar{\nu}_e , \ \bar{p} + e^+ + \nu_e$

$m_N < m_p + m_e : \ p \rightarrow N + e^+ + \nu_e , \ N + e^- + \bar{\nu}_e$

$N$ is stable and becomes a viable dark matter candidate if:

$m_p - m_e \leq m_N \leq m_p + m_e$

The condition is stable against radiative corrections for:

$$\lambda \leq O(10^{-1})$$
Stability of DM candidate is tied to the stability of proton. No additional symmetry, like R-parity, is invoked.

Odd & even number of DM particles produced from SM particles.

N quanta produced from/annihilate to SM particles in thermal bath:

\[
m_N < T << m_X : \quad \Gamma \sim (|\lambda|^4 + |\lambda|^2|\lambda'|^2) \frac{T^5}{m_X^4}
\]

\[
|\lambda|,|\lambda'| \geq O(10^{-2}), m_X \sim O(\text{TeV}) : \\
T \geq m_N (= m_p) \Rightarrow \Gamma \geq H
\]

DM reaches equilibrium with the thermal bath at \( T > O(\text{GeV}) \).

\[
m_N \approx 1\text{GeV}, m_X \sim O(\text{TeV}) : \\
\text{Thermal freeze-out overproduces DM.}
\]

Lee, Weinberg  PRL 39, 165  (1977)
Nonthermal mechanism is needed in order to obtain the correct DM relic abundance.

A natural scenario is late decay of a scalar field $S$ that reheats the universe to a temperature $T_r < T_f$.

Such a decay can produce $X_{1,2}$ with branching ratios $Br_{1,2}$:

$$\frac{n_N}{n_{X_1}} = \frac{Br_1 \sum_k |\lambda_{1k}|^2}{\sum_{i,j} |\lambda_{1ij}|^2 + \sum_k |\lambda_{1k}|^2}$$

$$\frac{n_N}{n_{X_2}} = \frac{Br_2 \sum_k |\lambda_{2k}|^2}{\sum_{i,j} |\lambda_{2ij}|^2 + \sum_k |\lambda_{2k}|^2}$$
\[
\frac{n_B}{s} = \frac{3T_r}{m_S} \times \sum_{i,j,k} \left[ \frac{m_1^2 Br_1 \text{Im}(\lambda_{1k}^* \lambda_{2k} \lambda_{1ij}^* \lambda_{2ij}^*)}{8\pi (m_1^2 - m_2^2) \sum_{i,j} |\lambda_{1ij}'|^2 + \sum_k |\lambda_{1k}'|^2} \right] + (1 \to 2)
\]

\[
\frac{n_N}{s} = \frac{3T_r}{m_S} \times \left[ \frac{Br_1 \sum_k |\lambda_{1k}'|^2}{\sum_{i,j} |\lambda_{1ij}'|^2 + \sum_k |\lambda_{1k}'|^2} \right] + (1 \to 2)
\]

For O(1) couplings and CP phases, it is easy to have:

\[
\frac{n_{DM}}{n_B} \sim O(10)
\]

\[
m_{DM} \approx m_p \Rightarrow \frac{\Omega_{DM}}{\Omega_B} \sim O(10)
\]
Detection Prospects:

Direct detection:

Spin-independent interactions:

\[
\frac{m_N m_u}{m_X^4} \left( \overline{\psi}_N \psi_N \right) \left( \overline{\psi}_q \psi_q \right)
\]

\[
\frac{1}{m_X^4} \left( \overline{\psi}_N \gamma^\mu \partial^\nu \psi_N \right) \left( \overline{\psi}_q \gamma_\mu \partial_\nu \psi_q \right) + h.c.
\]

Spin-dependent interactions:

\[
\frac{1}{m_X^2} \left( \overline{\psi}_N \gamma^\mu \gamma^5 \psi_N \right) \left( \overline{\psi}_q \gamma^\nu \gamma^5 \psi_q \right)
\]

\[
\sigma_{SI} \sim |\lambda|^4 \frac{O(\text{GeV})^6}{m_X^8}
\]

\[
\sigma_{SD} \sim |\lambda|^4 \frac{O(\text{GeV})^4}{m_X^4}
\]
$m_X \sim O(\text{TeV}) \Rightarrow \sigma_{SI} < 10^{-16} \text{ pb}$
$m_X \sim O(\text{TeV}) \Rightarrow \sigma_{SD} < 10^{-4} \, \text{pb}$
Indirect detection:

\[
< \sigma_{\text{ann}} \nu > \sim |\lambda|^4 \frac{\mid \vec{p} \mid^2}{m_X^4}
\]

\[m_X \sim O(\text{TeV}) \Rightarrow < \sigma_{\text{ann}} \nu > \ll 10^{-31} \text{ cm}^3 / \text{s}
\]

Too low to see any gamma-ray signal.

Also, no detectable galactic/extragalactic neutrino signal.

Neutrino signal from solar DM annihilation is negligible too:

1) Capture and annihilation both suppressed,

2) Evaporation efficient for \(O(\text{GeV})\) DM.
However, possible indirect signal if two almost degenerate N exist.


\[ m_p - m_e \leq m_{N_{1,2}} \leq m_p + m_e \Rightarrow N_{1,2} \]

The only allowed decay channel is:

\[ N_2 \rightarrow N_1 + \gamma \]

\[ \frac{m_N^2}{m_X^2} \bar{\psi}_{N_2} \sigma^{\mu\nu} \psi_{N_1} F_{\mu\nu} + h.c. \]

\[ \Delta m \equiv |m_{N_2} - m_{N_1}| \]

\[ \Gamma_{N_2} \approx \frac{\lambda_1 \lambda_2}{16\pi^4} \alpha_{em} \Delta m^3 \frac{m_N^2}{m_X^4} \]

\( m_{N_2}, m_{N_1} \) have same phase
\[
\Gamma_{N_2} \approx \frac{|\lambda_1\lambda_2|^2}{16\pi^4} \alpha_{em} \frac{\Delta m^5}{m_X^4}
\]

\[m_{N_2}, m_{N_1}\] have opposite phase

In general, one can get a photon line at energy:
\[
E_\gamma = \Delta m < 2m_e
\]

There has been claims of a 3.5 keV photon line from clusters.


The model can explain this line if:
\[
\Delta m \approx 3.5 \text{ keV} \quad \tau_{N_2} \approx 10^{23} \text{ s}
\]

This is satisfied for:
\[
O(10^{-6}) < |\lambda_1\lambda_2| < O(10^{-1}) \quad m_X \sim O(\text{TeV})
\]

(Also, see I. Gogoladze talk in this workshop)
Collider signal:
Both odd & even number of DM particles are produced from the interactions of the SM particles:
Monojets (including monotops) & dijets plus missing energy.
Combined collider bounds (assuming single value for $\lambda$ and $\lambda'$):

Also, possibilities with monotops (see the paper).
Supersymmetric Version:

Extension to supersymmetry is straightforward:

\[ W_{\text{new}} = \lambda'_{\alpha ij} X_\alpha d_i^c d_j^c + \lambda_{\alpha i} N\bar{X}_\alpha u_i^c + m_\alpha X_\alpha \bar{X}_\alpha + \frac{m_N}{2} N\bar{N} \]

\[ X_\alpha, \bar{X}_\alpha : \text{ Iso-singlet color triplet superfields } Y = +4/3, Y = -4/3 \]

\[ N : \text{ Singlet superfield} \]

The model can lead to thermal and non-thermal baryogenesis.

Babu, Mohapatra, Nasri  PRL 98, 161301  (2007)


It also has a real scalar DM candidate \( \tilde{N} \) protected by R-parity.

\[ m_{\tilde{N}}^2 = m_N^2 + \tilde{m}^2 \pm B m_N \]

The lighter of the two components of \( \tilde{N} \) can be DM candidate.
In order to address the coincidence puzzle, one can have:

\[ m_{\tilde{N}} \leq O(10 \ GeV) \]

The model allows for multi-component DM coming from the same superfield \( N \).

The prospect for direct detection of \( \tilde{N} \) is high.


Spin-independent interactions:

\[
\frac{1}{m_X^2} (\bar{\psi}_q \gamma^\mu \partial_\mu \psi_q) (\tilde{N}\tilde{N})
\]

\[
\sigma_{SI} \sim |\lambda|^4 \frac{m_p^2}{m_X^4}
\]

\[
m_X \sim O(\text{TeV}) \Rightarrow \sigma_{SI} < 10^{-5} \text{ pb}
\]
\[ \sigma_{SI} < 10^{-5} \text{ pb} \]
Outlook:

- A minimal BSM with colored states to explain baryogenesis.
- Model can give rise to $O(\text{GeV})$ DM candidate.
- Nonthermal DM and baryon production needed.
- Direct & indirect DM detection unlikely in the minimal model.
- Sub-GeV Photon line possible with two copies of DM.
- DM particles can be produced singly and doubly at colliders.
- Distinct monojet signal is possible due to resonance.
- SUSY version allows new DM candidates.
- Direct detection signal possible, multi-component DM possible.
Coincidence problem (?)

The DM and BAU densities are of similar order:

$$\Omega_{DM} \sim 6\Omega_B$$

How serious is the issue?

$$\Omega_{DM}, \Omega_B$$ have the same EOS, $$\Omega_{DM} / \Omega_B$$ is constant in time.

Different from the DE coincidence problem:

EOS of DM and DE different, why $$\Omega_{DE} / \Omega_{DM} \sim O(1)$$ today?

Nevertheless, one can explore the possibility that $$\Omega_{DM}, \Omega_B$$ may be related dynamically.

Relation between baryogenesis and DM production mechanisms.

D. B. Kaplan   PRL 68, 741 (1992)
severely constrained by processes:

\[ \Delta B = 2, \Delta S = 2 \]

1) \( n - \bar{n} \) oscillations.

2) \( pp \rightarrow K^+ K^+ \) double proton decay.

\[
m_N \sim O(\text{GeV}) , \ m_X \sim O(\text{TeV}) : \quad |\lambda_1 \lambda'_1| < 10^{-6}
\]

Successful baryogenesis then needs nontrivial flavor structure of \( \lambda_i, \lambda'_{ij} \) and/or degeneracy in \( m_{X_1}, m_{X_2} \).

Monojet and monotop signals are still possible:

\[
|\lambda'_1|, |\lambda'_{12}|, |\lambda'_{13}|, |\lambda'_{23}| \sim 1
\]

\[
|\lambda_1| \sim 10^{-6} , \ |\lambda_2|, |\lambda_3| \sim 1
\]