Non-thermal Dark Matter and Baryogenesis

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Outline:

- Introduction

- Non-thermal DM from EMD
  the scenario, freeze-out/in production, direct production, the importance of EMD and pre-EMD details, constraints

- EMD and baryogenesis
  a minimal model, baryon-DM coincidence, testable predictions, complementarity of cosmological and experimental constraints

- Conclusion and Outlook

- Possible observable signatures of EMD (Discussion Session?).
Introduction:
The present universe according to observations:

Two big problems to address:
Dark Matter (DM)
What is its nature? How was it produced?

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

Also, a possible coincidence puzzle:
Why the DM and baryons have comparable energy densities?

Answers have profound consequences for:
Particle Physics (BSM), Cosmology (thermal history)
Thermal DM:

Starting in a RD universe:

\[ \dot{n}_\chi + 3Hn_\chi = <\sigma_{ann}\nu >_f (n_{\chi,eq}^2 - n_\chi^2) \]

1) \( T \gg m_\chi: \chi\chi \leftrightarrow f\bar{f} \Rightarrow n_\chi \propto T^3 \)

2) \( T \ll m_\chi: \chi\chi \rightarrow f\bar{f} \Rightarrow n_\chi \propto \exp(-\frac{m_\chi}{T}) \)

3) \( T \approx T_f: \Rightarrow \frac{n_\chi}{S} = \text{const.} \)

WIMP miracle:

\[ <\sigma_{ann}\nu >_f = \frac{\alpha_\chi^2}{m_\chi^2} \]

\( \alpha_\chi \sim O(10^{-2}), m_\chi \sim 10 - 10^3 \text{ GeV} \)

\( \Omega_\chi h^2 \sim 10^{-3} - 1 \)

\( t_f \approx 10^{-7} \text{ s} \)

\[ <\sigma_{ann}\nu >_f = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

“The Early Universe” Kolb & Turner

\[ \log[Y(Y|x=0)] \]

\[ x=m/T \]
In principle, thermal DM is a very attractive scenario:
- Predictive
- Robust

However:
Annihilation rate tightly constrained by indirect detection searches

More importantly:
Freeze-out during RD is an assumption. Currently, we have no observational probe of the early universe prior to one second.

In fact, in a well-motivated class of particle physics models a RD universe is established much later than the freeze-out.

Studying alternatives to thermal DM is well motivated.
Indirect detection experiments


For DM masses < 20 GeV:
\[ <\sigma_{\text{ann}} v>_{f} < 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]  (assuming S-wave annihilation)

Standard thermal history altered in well-motivated models

G. Kane, K. Sinha, S. Watson   IJMPD 8, 1530022  (2015)
Non-thermal DM from Early Matter Domination:

Consider a scalar field $\phi$ with mass $m_\phi$ and decay width $\Gamma_\phi$.

Modulus fields in string theory are natural candidates for $\phi$:

$$\Gamma_\phi = \frac{c \ m_\phi^3}{2\pi \ M_P^2} \quad c \sim O(1)$$

Dynamics of $\phi$ in the early universe:

$H \gg m_\phi$: Displaced from the minimum during inflation

$H \approx m_\phi$: Starts oscillating, behaves like matter, and dominate

$H \approx \Gamma_\phi$: Decays and forms a RD universe

$$T_R \sim 0.1 \ (\Gamma_\phi M_P)^{1/2} \sim \left(\frac{m_\phi}{50 \ TeV}\right)^{3/2} \times 3 \ MeV \ \Rightarrow \ m_\phi \gtrsim 50 \ TeV$$
Evolution of matter and radiation energy densities:

\[ \dot{\rho}_\phi + 3H \rho_\phi = -\Gamma_\phi \rho_\phi \]
\[ \dot{\rho}_r + 4H \rho_r = +\Gamma_\phi \rho_\phi \]

\[ H^2 = \frac{\rho_\phi + \rho_r}{3M_P^2} \]

\[ \rho_r = \frac{\pi^2}{30} g_* T^4 \]

The abundance of non-thermal DM follows:

\[ \dot{n}_\chi + 3Hn_\chi = \langle \sigma_\text{ann}v \rangle_f (n_{\chi,eq}^2 - n_\chi^2) + Br_\chi \Gamma_\phi n_\phi \]

\( Br_\chi \): number of DM quanta produced per decay of \( \phi \) quanta
Production from thermal processes:
D. Chung, E. Kolb, A. Riotto PRD 60, 063504 (1999)
G. Giudice, E. Kolb, A. Riotto PRD 64, 043512 (2001)

(1) Freeze-out:
\[(\Omega_\chi h^2)_{fo} \sim 1.6 \times 10^{-4} \left(\frac{m_\chi/T_f}{15}\right)^4 \left(\frac{150}{m_\chi/T_R}\right)^3 \left(\frac{3 \times 10^{-26} \text{cm}^3\text{s}^{-1}}{<\sigma v>_f}\right)\]

(2) Freeze-in:
\[(\Omega_\chi h^2)_{fi} \sim 0.062 \left(\frac{150}{m_\chi/T_R}\right)^5 \left(\frac{T_R}{5 \text{ GeV}}\right)^2 \left(\frac{<\sigma v>_f}{3 \times 10^{-26} \text{cm}^3\text{s}^{-1}}\right)\]
Freeze-out/in production of DM during EMD is sensitive to the relation between $H$ and $T$.

The relation depends on the details of EMD and pre-EMD history. For example:

(1) More than one scalar field may be present during EMD
   Multiple string moduli, visible sector fields (AD field)

(2) EMD preceded by other phases
   Prior RD phase after inflationary reheating

In both of these cases, there will be deviation from the $T \propto H^{1/4}$ relation. This will affect freeze-out/in production of DM.

The allowed parameter space may be significantly different from the simple picture.
Two field EMD:
\[ \rho_\phi = f \rho_\phi \quad \Gamma_\phi = \alpha \Gamma_\phi \]
f \ll 1 \quad \beta \equiv \alpha f \gg 1

\[ T_R = 10 \text{ GeV}, \quad \alpha = 10^8, \quad f = 10^{-4} \]
Pre-EMD effect:

\[ H_{\text{tran}} \]

\[ T_{\text{reh}} = 10^{12} \text{ GeV}, \ T_0 = 10^{10} \text{ GeV}, \ T_R = 10 \text{ GeV} \]

RD after inflation \( T \propto H^{1/2} \)

Memory phase \( T \propto H^{2/3} \)

Standard EMD \( T \propto H^{1/4} \)
Production from direct decay:

(1) Annihilation scenario:

\[ < \sigma_{\text{ann}} \nu >_f \ Br_\chi n_\phi \geq \Gamma_\phi \]

M. Kawasaki, T. Moroi, T. Yanagida   PLB 370, 52 (1996)
T. Moroi, L. Randall   NPB 570, 455 (2000)

\[
\left( \frac{n_\chi}{s} \right)_{\text{ann}} = \left( \frac{n_\chi}{s} \right)_{\text{obs}} \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{< \sigma_{\text{ann}} \nu >_f} \frac{T_f}{T_R}
\]

(2) Branching scenario:

\[ < \sigma_{\text{ann}} \nu >_f \ Br_\chi n_\phi \ll \Gamma_\phi \]


\[
\left( \frac{n_\chi}{s} \right)_{\text{br}} = \frac{3 T_R}{4 m_\phi} B r_\chi
\]

DM abundance totally decoupled from annihilation rate!
The observed relic abundance can be obtained from non-thermal production for both small and large annihilation rates:

(1) Large annihilation rate: \( < \sigma_{ann} \nu >_f > 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \)

FO/FI during EMD is negligible, only direct decay matters (either of “annihilation/branching scenario” can work)

\[
\left( \frac{n_\chi}{s} \right)_{\text{non-th}} = \min \left[ \left( \frac{n_\chi}{s} \right)_{\text{obs}} \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{< \sigma_{ann} \nu >_f} \frac{T_f}{T_R} , \frac{3T_R}{4m_\phi} B_{r_\chi} \right]
\]

(2) Small annihilation rate: \( < \sigma_{ann} \nu >_f < 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \)

FO/FI during EMD and direct decay both can be significant (only “branching scenario” can work)

\[
\left( \frac{n_\chi}{s} \right)_{\text{non-th}} = \frac{3T_R}{4m_\phi} B_{r_\chi} + \left( \frac{n_\chi}{s} \right)_{f_0/f_i}
\]
Constraints:

(1) Gravitino production must be suppressed. 
\( \phi \to \tilde{G} \tilde{G} \) is the main source of gravitino production. 
M. Endo, K. Hamaguchi, F. Takahashi  
PRD 96, 211301 (2006)

Helicity-1/2 gravitinos pose the main threat. 
M. Dine, R. Kitano, A. Morisse, Y. Shirman  
PRD 73, 123518 (2006)

(2) \( Br_\chi \) must be small enough for the “branching scenario”. 
2-body decays can be suppressed. 
T. Moroi, L. Randall  
NPB 570, 455 (2000)
M. Cicoli, A. Mazumdar  
JCAP 1009, 025 (2010)

However, saturation from 3-body decays \( Br_\chi \gtrsim 3 \times 10^{-3} \). 
R.A., B. Dutta, K. Sinha  
PRD 83, 083502 (2011)

Challenge: successful realization in explicit models. 
R.A., B. Dutta, K. Sinha  
PRD 86, 095016 (2012)
R.A., B. Dutta, K. Sinha  
PRD 87, 075024 (2013)
R.A., M. Cicoli, B. Dutta, K. Sinha  
PRD 88, 095015 (2013)
R.A., M. Cicoli, B. Dutta, K. Sinha  
JCAP 1410, 002 (2014)
Generation of BAU in Early Matter Domination:

Dilution by modulus decay washes any pre-existing asymmetry:

\[
\left( \frac{s_{\text{after}}}{s_{\text{before}}} \right) \sim \frac{M_P}{m_\phi} \quad (>> 10^{10})
\]

How to generate the desired BAU?

- At the end of EMD:
  Non-thermal post-sphaleron baryogenesis

- Or, from a mechanism that has its associated entropy:
  Affleck-Dine baryogenesis
  G. Kane, J. Shao, S. Watson, H-B Yu  JCAP 1111, 012 (2011)

A non-thermal origin may also help the DM-baryon coincidence.
A Minimal Model:

$B$ and $L$ are accidental symmetries of SM at the perturbative level.

We adopt a bottom-up approach and consider a minimal extension of the SM with renormalizable $\bar{B}$ interactions:

\[ \mathcal{L} \supset (\lambda_{\alpha i} X_{\alpha} \psi u_i^c + \lambda'_{\alpha ij} X_{\alpha}^* d_i^c d_j^c + \frac{m_\psi}{2} \bar{\psi}^c \psi + \text{H.c.}) \]
\[ + \ m_{X_\alpha}^2 |X_{\alpha}|^2 + \text{(kinetic terms)} . \]

$X_{1,2}$: Iso-singlet color-triplet scalars $Y = +4/3$

$\psi$: Singlet fermion

Two color triplets are required in order to generate a nonzero baryon asymmetry via out-of-equilibrium decay of $X$.

E. Kolb, S. Wolfram  NPB 172, 224 (1980); Erratum-ibid 195, 542 (1982)
Baryogenesis:

\[
\begin{align*}
\epsilon_\alpha &= \frac{1}{8\pi} \frac{\sum_{ijk} \text{Im}(\lambda_{\alpha k}^* \lambda_{\beta k}^* \lambda_{\alpha ij}^* \lambda_{\beta ij}')} \left( \sum_i |\lambda_{\alpha i}|^2 + \sum_{ij} |\lambda'_{\alpha ij}|^2 \right) \frac{(m_{X_\alpha}^2 - m_{X_\beta}^2) m_{X_\alpha} m_{X_\beta}} \left( (m_{X_\alpha}^2 - m_{X_\beta}^2)^2 + m_{X_\alpha}^2 \Gamma_{X_\beta}^2 \right) \\
\Delta m_X &\equiv |m_{X_1} - m_{X_2}| \sim \frac{\Gamma_X}{2} \ll m_{X_{1,2}} \rightarrow \epsilon_{\text{max}} \sim O(0.1)
\end{align*}
\]
$|\lambda_1\lambda_{12}'| \text{ severely constrained by } \Delta B = 2, \Delta S = 2 \text{ processes:}$

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

2) Double proton decay $pp \rightarrow K^+K^+$.

For $m_\psi \sim O(\text{GeV}), m_X \sim O(\text{TeV})$ double proton decay requires:

$|\lambda_1\lambda_{12}'| < 10^{-6}$

Experimental bounds on $K_s^0 - \bar{K}_s^0$ and $B_s^0 - \bar{B}_s^0$ oscillations are also satisfied (loop suppressed).

EDM constraints not strong since the new interactions involve only one chirality of quarks.
4-fermion interaction at low energies:

\[ \frac{\lambda \lambda'}{m_X^2} \psi u d d \]

This operator results in the following decays:

- If \( m_\psi > m_p + m_e \), then \( \psi \rightarrow p + e^- + \bar{\nu}_e \), \( \bar{p} + e^+ + \nu_e \)
- If \( m_\psi < m_p - m_e \), then \( p \rightarrow \psi + e^+ + \nu_e \), \( \psi + e^+ + \bar{\nu}_e \)

\( \psi \) is stable and becomes a viable dark matter (DM) candidate if:

\( m_p - m_e < m_\psi < m_p + m_e \)

Stability of DM is tied to the stability of the proton.

Vicinity of DM and proton mass also useful for the DM-baryon coincidence puzzle.
Direct Detection:

Effective interaction at low energies:

\[
\frac{1}{m_X^2 - (p_\psi - p'_u)^2} (\overline{\psi} P_L \psi_\psi) (\overline{\psi}_u P_R \psi_u)
\]

Spin-independent piece:

\[
\frac{1}{m_X^4} (\overline{\psi} \gamma^\mu \partial^\nu \psi_\psi) \left[ (\overline{\psi}_u \gamma_\mu \partial_\mu \psi_u) - (\partial_\nu \overline{\psi}_u \gamma_\mu \psi_u) \right]
\]

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

Spin-dependent piece:

\[
\frac{1}{m_X^2} (\overline{\psi} \gamma^\mu \gamma^5 \psi_\psi) (\overline{\psi}_u \gamma_\mu \gamma^5 \psi_u)
\]

\[\sigma_{SD} \sim |\lambda|^4 \frac{O(GeV)^4}{m_X^4}\]
$m_X \sim O(\text{TeV}) \Rightarrow \sigma_{SI} < 10^{-52} \text{cm}^2$
$m_X \sim O(\text{TeV}) \Rightarrow \sigma_{SD} < 10^{-40} \text{ cm}^2$
Indirect Detection:

\[ \langle \sigma_{\text{ann}} \nu \rangle \sim \frac{|\lambda_{\alpha 1}|^4}{8\pi} \frac{m_{\psi}^2}{m_{X,\alpha}^4} \]

\[ m_X \sim O(TeV) \Rightarrow \langle \sigma_{\text{ann}} \nu \rangle \ll 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]

Neutrino or gamma-ray signals from galactic or extragalactic DM annihilation far below detectable levels.

Neutrino signal from solar DM annihilation also negligible:

1) \( \sigma_{\text{ann}} \) and \( \sigma_{SD,SI} \) are very small.

2) Evaporation dominates for \( O(GeV) \) DM mass.

Low prospect for direct or indirect detection of DM in the model.
Relic Abundance:

Thermal freeze-out results in overproduction of DM.

A non-standard thermal history with EMD can help.

Consider a scenario where a scalar field $\phi$ drives an era of EMD.

$\phi$ decay reheats the universe to a temperature $T_R \ll 1 \; GeV$.

The decay also produces $\psi$ (DM) and $X$ particles.

Subsequent decay of $X$ generates the BAU.

\[
\frac{n_\psi}{s} = \frac{n_\phi}{s} \frac{n_\psi}{n_\phi} = \frac{3T_R}{m_\phi} \text{Br}_{\phi \rightarrow \psi} \equiv Y_\phi \text{Br}_{\phi \rightarrow \psi}
\]

\[
\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq Y_\phi \sum_{\alpha} \text{Br}_{\phi \rightarrow X_\alpha} \epsilon_\alpha
\]
\[
\Omega_{\text{DM}} \sim \frac{\text{Br}_{\phi \to \psi}}{\sum_{\alpha} \epsilon_{\alpha} \text{Br}_{\phi \to X_{\alpha}}}
\]

\[
\text{Br}_{\phi \to \psi} = \text{Br}_{\phi \to \psi}^{\text{direct}} + \sum_{\alpha} \text{Br}_{\phi \to X_{\alpha}} \text{Br}_{X_{\alpha} \to \psi}
\]

\[
\geq \sum_{\alpha} \text{Br}_{\phi \to X_{\alpha}} \text{Br}_{X_{\alpha} \to \psi},
\]

\[
\mathcal{L} \supset (\lambda_{\alpha i} X_{\alpha} \psi u_i^c + \lambda'_{\alpha ij} X_{\alpha}^* d_i^c d_j^c + \frac{m_{\psi}}{2} \bar{\psi}^c \psi + \text{H.c.})
\]

\[
+ m_{X_{\alpha}}^2|X_{\alpha}|^2 + \text{(kinetic terms)}.
\]

\[
\text{Br}_{X_{\alpha} \to \psi} = \frac{\sum_i |\lambda_{\alpha i}|^2}{\sum_{ij} |\lambda'_{\alpha ij}|^2 + \sum_i |\lambda_{\alpha i}|^2}
\]

\[
\frac{\Omega_{\text{DM}}}{\Omega_B} \gtrsim \frac{\text{Br}_{X_{\alpha} \to \psi}}{\epsilon_{\alpha}}
\]

We need \( \frac{\Omega_{DM}}{\Omega_B} \approx 5 \).
General constraint on the couplings:

\[ \lambda \equiv |\lambda_1| = |\lambda_2| = |\lambda_3| \quad \lambda' \equiv \sqrt{|\lambda'_{13}|^2 + |\lambda'_{23}|^2} \]
Further constraints obtained by considering a modulus field:

\[ \Gamma_\phi = \frac{c_\phi m_\phi^3}{2\pi M_{Pl}^2} \]

\[ T_R \sim c_\phi^{1/2} \left( \frac{10.75}{g_*} \right)^{1/4} \left( \frac{m_\phi}{50 \text{ TeV}} \right)^{3/2} (3 \text{ MeV}) \]

\[ \eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq Y_\phi \sum_{\alpha} \text{Br}_{\phi \rightarrow X_\alpha} \epsilon_\alpha \]

\[ Y_\phi \equiv \frac{3T_R}{4m_\phi} \quad \varepsilon \geq 0.1 \]

Low-energy Signals:

\( n - \bar{n} \) Oscillations:

\[
G_{n\bar{n}} \sim \frac{\lambda^2 \lambda_{13}^4 m_\psi}{16\pi^2 m_X^6} \ln\left(\frac{m_X^2}{m_\psi^2}\right) \quad \tau_{n\bar{n}} \sim (\Lambda_{QCD}^6 G_{n\bar{n}})^{-1}
\]

Note that only \( \lambda'_{13} \) matters for \( n - \bar{n} \) oscillations.

Current experimental limits:

\( \tau_{n\bar{n}} \geq 3 \times 10^8 \) s

SNO Collaboration arXiv:1705.00696

Next generation experiments:

\( \tau_{n\bar{n}} \geq 5 \times 10^{10} \) s

Collider Signals:

Both odd & even number of DM particles are produced from the interactions of the SM particles:
Monojets (including monotops) & dijets plus missing energy.

Complementarity of cosmological considerations and experimental limits to constrain the parameter space of the model.

CMS & ATLAS dijet constraints
CMS Collaboration arXiv:1611.03568
ATLAS Collaboration arXiv:1711.02692

ATLAS analysis of pair-produced resonances
ATLAS Collaboration arXiv:1710.07171

A dedicated CMS monojet analysis

We have also included the constraints from $n - \bar{n}$ oscillations and DM and baryogenesis, with $\lambda'_{13}$ set to zero.
Conclusion and Outlook:

- Thermal DM is an attractive scenario
  Coming under increasing scrutiny, relies on certain assumptions

- EMD provides a suitable framework for non-thermal DM
  Typically arises in a well-motivated class of UV complete models

- Can yield the correct relic abundance for large and small $\sigma_{\text{ann}}$
  Details of EMD and pre-EMD important for precise predictions

- EMD requires non-thermal baryogenesis
  Same origin for DM & BAU may explain baryon-DM coincidence

- A minimal predictive model for baryogenesis and DM presented
  Novel complementarity of experimental and cosmological limits