Outline:

• Introduction
  WIMP miracle in principle & in practice
  Motivations for non-thermal mechanisms

• Non-thermal DM from late decay
  Non-thermal DM from moduli decay
  Necessary conditions for successful models

• Explicit example of a successful realization
  Non-thermal DM in LARGE Volume Scenarios
  DM-DR correlation in LVS

• Summary and Outlook
Introduction:
The present universe according to observations:
BSM needed to explain the remaining 95%.

Important questions about DM:
What is the nature of DM?
How did it acquire its relic density?

Profound consequences for:
Particle Physics (BSM)
Cosmology (thermal history)

Focus of this talk is on WIMP(-like) DM
(will not consider sterile neutrino, axion, gravitino, axino, …)
**Thermal Scenario:**

Thermal equilibrium condition at $T \gg m_\chi$:

1) $T \gg m_\chi$: $\chi\chi \leftrightarrow \bar{f}f, \ldots \Rightarrow n_\chi \propto T^3$, $n_\chi / s = \text{const.}$

2) $T < m_\chi$: $\chi\chi \rightarrow \bar{f}f, \ldots \Rightarrow n_\chi \propto \exp(-m_\chi / T)$

3) $T \approx T_f$: freeze-out $\Rightarrow n_\chi / s = \text{const.}$

**Simple parametrization:**

$$\langle \sigma_{\text{ann}} v \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$$

$$T_f \sim \frac{m_\chi - m_\chi}{25 - 15}$$

**WIMP miracle:**

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

$$\Omega_\chi h^2 \sim 10^{-3} - 10$$

"The Early Universe" Kolb & Turner

![Diagram](image-url)
In principle, thermal DM is a very attractive scenario. DM abundance insensitive to details of thermal history at $T > T_f$.

However, thermal equilibrium above $T_f$ is an assumption.

WIMP freeze-out occurs at $t \sim 10^{-7}$ sec.

The best experimental probes of the early universe:
1) CMB: $t \sim 400,000$ yr
2) BBN: $t \sim 1$ sec

DM will be the strongest probe of the thermal history, but after it is discovered and a model is established.

Moreover, non-standard thermal history at $T < T_f$ is generic in some explicit UV completions of the SM.

Acharya, Kumar, Bobkov, Kane, Shao, Watson JHEP 0806, 064 (2008)
Acharya, Kane, Watson, Kumar PRD 80, 083529 (2009)
In practice, thermal DM is not a generic scenario.

Parametrization of annihilation cross section too simple: assumes a single mass scale, neglects velocity effects.

Example: pMSSM.

Baer, Box, Summy  JHEP 1010, 023 (2010)

WIMP miracle needs real miracle!
Indirect Detection

Stringent bounds from Fermi: Fermi-LAT  
PRL 107, 241302 (2011)

Gamma-rays from dwarf spheroidals

Geringer-Sameth, Koushiappas  
PRL 107, 241303 (2011)

Assuming S-wave:

\[ < \sigma_{ann} v >_0 = < \sigma_{ann} v >_f \]

Consider b final state:

\[ m_\chi < 40 \text{ GeV} \Rightarrow \]

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

Thermal overproduction
LHC:
Various modifications of MSSM proposed after Higgs discovery.

Example: Natural SUSY
Baer, Barger, Huang, Tata JHEP 1205, 109 (2012)
Papucci, Ruderman, Weiler JHEP 1209, 035 (2012)
Hall, Pinner, Ruderman JHEP 1201, 134 (2012)

$3^{\text{rd}}$ generation squarks & EW gauginos $\sim O(\text{TeV})$

Gluinos $\sim 3 - 4 \ TeV$

$1^{\text{st}}$ and $2^{\text{nd}}$ generation squarks & sleptons $\gg 10 \ TeV$

$\mu \sim 150 - 200 \ GeV$

Higgsino DM:

$$<\sigma_{\text{ann}} v> f \sim \frac{\alpha_{\text{EW}}^2}{m_{\chi}^2} > 3 \times 10^{-26} \ cm^3 s^{-1} \ m_{\chi} < 1.2 \ TeV$$

Thermal underproduction
Obtaining correct relic density for $\langle \sigma_{\text{ann}} v \rangle_f \neq 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$:

1) $\langle \sigma_{\text{ann}} v \rangle_f > 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$ (thermal underproduction):

Multi-component DM (WIMP + non-WIMP)
Example: mixed Higgsino/axion DM
Baer, Box, Summy JHEP 0908, 080 (2009)

Asymmetric DM (relic density survives large $\langle \sigma_{\text{ann}} v \rangle_f$)
Zurek arXiv:1308.0338

2) $\langle \sigma_{\text{ann}} v \rangle_f < 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$ (thermal overproduction):

Super/E-WIMP DM from WIMP decay
Examples:
Axino DM Covi, Kim, Roszkowski PRL 82, 4180 (1999)
Non-thermal DM from Late Decay:
DM relic density will be different in non-standard thermal histories (i.e., if there is entropy production at $T < T_f$).

One such scenario can arise from late decay of a scalar field $\phi$ that reheats the universe to a temperature $T_r < T_f$ ($\sim m_\chi / 20$).

$\phi$: Scalar field

$T_r \sim (\Gamma_\phi M_P)^{1/2}$

Decay dilutes existing DM particles, produces new DM particles:

$\frac{n_\chi}{s} = Y_\phi \text{ Br}_\chi$

$Y_\phi \equiv \frac{n_\phi}{s} = \frac{3T_r}{4m_\phi}$

$\text{ Br}_\chi$: Branching ratio to R-parity odd particles
1) Annihilation Scenario:  

\[ \Gamma_{\text{ann}} > H_r \sim \Gamma_\phi \]  

\[
\left( \frac{n_\chi}{s} \right)_{\text{non-th}} = \left( \frac{n_\chi}{s} \right)_{\text{th}} \left( \frac{T_f}{T_r} \right) \left( \frac{n_\chi}{s} \right)_{\text{th}} = \left( \frac{n_\chi}{s} \right)_{\text{obs}} \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma_{\text{ann}} \nu \rangle_f} \]

Kawasaki, Moroi, Yanagida  
PLB 370, 52 (1996)  
Moroi, Randall  
NPB 570, 455 (2000)

2) Branching Scenario:  

\[ \Gamma_{\text{ann}} < H_r \sim \Gamma_\phi \]  

\[
\left( \frac{n_\chi}{s} \right)_{\text{non-th}} = Y_\phi \, Br_\chi \]

Gelmini, Gondolo  
PRD 74, 023510 (2006)  
R.A., Dutta, Sinha  
PRD 83, 083502 (2011)
1) Annihilation works for thermal underproduction, requires:

\[ T_r = T_f \left( \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{<\sigma_{\text{ann}} \nu> f} \right) \]

Experimental constraints on \( <\sigma_{\text{ann}} \nu> f \) restrict \( T_r \).

2) Branching works for thermal under/overproduction, requires:

\[ Br_{\chi} Y_\phi = (5 \times 10^{-10}) \left( \frac{1 \text{ GeV}}{m_\chi} \right) \]

Independent from \( <\sigma_{\text{ann}} \nu> f \), tight restriction for model building.

Challenge: Successful realization within realistic models.
Non-thermal Dark Matter from Moduli Decay:

Modulus fields are natural candidates for $\phi$. Commonly arise in SUSY and string-inspired models, long lived:

$$\Gamma_{\phi} = \frac{c}{2\pi} \frac{m_{\phi}^3}{M_P^2}$$

(typically: $c \sim 0.1 - 1$)

Moduli dynamics in the early universe: ($m_{\phi} \ll H_{\text{inf}}$)

1) Displaced during inflation $\phi_0 \sim M_P$
2) Start oscillating when $H \approx m_{\phi}$
3) Decay and reheat the universe $T_r \sim \left(\frac{m_{\phi}}{50 \text{ TeV}}\right)^{3/2} \times 3 \text{ MeV}$

BBN requires $T_r > 3 \text{ MeV}$.

$m_{\phi} > 50 \text{ TeV}$:

Handicap (cosmological moduli problem) turned into virtue.
Higgsino DM via “Annihilation” scenario

Obtaining the correct relic density requires:

\[ T_r = T_f \left( \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{< \sigma_{\text{ann}} v >_f} \right) \]

Higgsinos annihilate mainly into W final state, S-wave process:

\[ < \sigma_{\text{ann}} v >_f = < \sigma_{\text{ann}} v >_0 \]

Stringent bounds from Fermi:

\[ m_\chi = 1 \text{ TeV} \quad < \sigma_{\text{ann}} v >_f \leq 4 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1} \]

\[ m_\chi = 100 \text{ GeV} \quad < \sigma_{\text{ann}} v >_f \leq 2 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1} \]

\[ T_f \sim \frac{m_\chi}{20} \Rightarrow T_r \sim O(\text{GeV}) \quad m_\phi \sim \text{few} \times O(1000) \text{ TeV} \]
In models with non-perturbative schemes of moduli stabilization

\( W \sim W_0 + A e^{-a \phi} \) : Conlon, Quevedo JHEP 0606, 029 (2006)

\[ m_\phi : m_{3/2} \sim 4\pi^2 \Rightarrow m_{3/2} > 40 \text{ TeV} \]

Gravitinos escape very tight BBN bounds.
Kawasaki, Kohri, Moroi, Yotsuyanagi PRD 78, 065011 (2008)
Cyburt, Ellis, Fields, Luo, Olive, Spanos JCAP 0910, 021 (2009)

Explicit example: Non-thermal Higgsino DM in mirage mediation
Constraints and Challenges:

1) Gravitino production must be suppressed (in both “Annihilation” and “Branching” scenarios).

\[ \phi \rightarrow \tilde{G}\tilde{G} \] is the main source of gravitino production.
Endo, Yamaguchi, Yoshioka  PRD 72, 015004 (2005)

Helicity-1/2 gravitinos pose the main threat.
Dine, Kitano, Morrise, Shirman  PRD 73, 123518 (2006)

\[ \frac{n_{3/2}}{s} = Y_{\phi} \ Br_{3/2} < \left( \frac{n_{\chi}}{s} \right)_{\text{obs}} \]

\[ Y_{\phi} \sim 7 \times 10^{-8} \ c^{1/2} \left( \frac{m_{\phi}}{50 \ TeV} \right)^{1/2} \left( \frac{n_{\chi}}{s} \right)_{\text{obs}} \approx 5 \times 10^{-10} \left( \frac{1 \ GeV}{m_{\chi}} \right) \]

\[ Br_{3/2} < 7 \times 10^{-4} \quad \text{and/or} \quad c << 1 \]
2) In the “Branching” scenario, the relic density must be just right.

\[
\frac{n_\chi}{s} = Y_\phi \, Br_\chi = \left( \frac{n_\chi}{s} \right)_{\text{obs}}
\]

\[Br_\chi < 7 \times 10^{-4}\] and/or \[c << 1\]

2-body decays to gauginos can be suppressed
Moroi, Randall  NPB 570, 455 (2000)

Decay to Higgsinos can also be suppressed
Cicoli, Burgess, Quevedo  JHEP 1110, 119 (2011)
Cicoli, Mazumdar  JCAP 1009, 025 (2010)

But, 3-body decays produce gauginos/Higgsinos: \[Br_\chi \sim 3 \times 10^{-3}\]

Further suppressing \[Br_\chi\] requires suppression of:
Decay to particles with gauge charges and/or total decay width
3) Generating baryon asymmetry of the universe.

\[
\frac{S_{\text{after}}}{S_{\text{before}}} = \left( \frac{\rho_\phi}{\rho_{\text{rad}}} \right)^{3/4} \leq \frac{(m_\phi M_P)^{1/2}}{T_r}
\]

\[
T_r \sim \left( \frac{m_\phi^3}{M_P} \right)^{1/2} \Rightarrow \left( \frac{S_{\text{after}}}{S_{\text{before}}} \right)_{\text{max}} \sim \frac{M_P}{m_\phi} (\gg 10^{10})
\]

Entropy release washes any pre-existing, even \(O(1)\), asymmetry. BAU must be produced after the decay:

Non-thermal post-sphaleron baryogenesis

Possibility to address the DM-baryon coincidence problem
Question:

Can these constraints be satisfied in explicit string constructions?

As an example, let us consider the simplest KKLT model:


\[ G = K + \ln |W|^2 \]

\[ K \supset -3 \ln(\tau + \bar{\tau}) , \quad W \supset W_{\text{flux}} + A e^{-a\tau} \]

The dominant decay mode is to gauge bosons and gauginos:

\[ \Gamma_{\phi \to gg} \sim \frac{N_g}{128\pi} K_{\tau \bar{\tau}}^{-1} <\tau>^2 \frac{m^3_\phi}{M^2_P} \]

\[ \phi = \sqrt{\frac{3}{2}} \ln (\tau + \bar{\tau}) \]

\[ \Gamma_{\phi \to \tilde{g} \tilde{g}} \sim \frac{N_g}{128\pi} K_{\tau \bar{\tau}}^{-1} <\partial_\tau F^\tau >^2 \frac{m^3_\phi}{M^2_P} \]

\[ \Gamma_{\phi \to \tilde{g} \tilde{g}} \sim \Gamma_{\phi \to gg} \sim \frac{1}{10\pi} \frac{m^3_\phi}{M^2_P} \]
The decays to fermions and sfermions are mass suppressed:

\[ \Gamma_{\phi \rightarrow ff} \propto \frac{m_\phi m_f^2}{M_P^2}, \quad \Gamma_{\phi \rightarrow f\tilde{f}} \propto \frac{m_\phi m_{\text{soft}}^2}{M_P^2} \]

\[ \Gamma_\phi \sim 0.4 \frac{m_\phi^3}{2\pi M_P^2} \]

\[ \Gamma_{\phi \rightarrow \tilde{G}\tilde{G}} \sim \frac{1}{288\pi} (|G_\tau|^2 K_{\tau\bar{\tau}}^{-1}) \frac{m_\phi^3}{M_P^2} \sim \frac{1}{288\pi} \frac{m_\phi^3}{M_P^2} \]

\[ Br_{3/2} \sim 10^{-2} \quad \text{Gravitino-induced DM overproduction} \]

\[ c \sim 0.4 \quad , \quad Br_\chi \sim 1 \quad \text{“Branching” scenario not viable} \]

Not a successful set up!
Both problems can be solved if $\phi$ is a visible sector field:

$$W = W_{\text{MSSM}} + h\phi \overline{XX} + \lambda N X u^c + \lambda' \overline{X} d^c d^c + \frac{m_\phi}{2} \phi^2 + m_X X \overline{X} + \frac{m_N}{2} N^2$$

$\phi$ : Singlet  \hspace{1cm} $X, \overline{X}$ : Color triplets  \hspace{1cm} $N$ : Singlet

$m_\phi \sim O(\text{TeV})$

$m_X \sim 10 - 100 \ \text{TeV}$

$m_\chi \leq 500 \ \text{GeV}$

$$\text{Br}_{3/2} \approx 0$$

$$\text{Br}_\chi \sim \frac{1}{2} \left( \frac{g_1}{g_3} \right)^4 \left( \frac{m_\chi}{m_S} \right)^2$$

$$\text{Br}_\chi \sim \frac{1}{16\pi^4} \left( \frac{\lambda_t}{g_3} \right)^4 \left( \frac{m_\chi}{m_S} \right)^2$$
Non-thermal DM in LARGE Volume Scenarios:

As another example, let us consider the volume modulus in the LARGE Volume Scenarios (LVS).

Large volume can be obtained after stabilization of $\tau_b$.

For large volume, one can have a sequestered scenario such that:

$$m_{soft} << m_{\tau_b} << m_{3/2} \quad \left( m_{soft} m_{3/2} \sim m_{\tau_b}^2 \right)$$

For example, TeV scale SUSY can be obtained for:

$$m_{3/2} \sim 10^{10} \text{ GeV} \quad , \quad m_{\tau_b} \sim 5 \times 10^6 \text{ GeV} \quad , \quad m_{soft} \sim 1 \text{ TeV}$$
\[ m_{\tau_b} < m_{3/2} \Rightarrow Br_{3/2} = 0 \]

The decay to gauge bosons arises at one-loop level:

\[ \Gamma_{\phi \rightarrow gg} \sim \left( \frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2} \]

\[ \phi = \sqrt{\frac{3}{2} \ln (\tau_b + \bar{\tau}_b)} \]

The decay to Higgs controlled by the Giudice-Masiero term:

\[ \Gamma_{\phi \rightarrow H_uH_d} = \frac{Z^2}{24\pi} \frac{m_\phi^3}{M_P^2} \]

\[ c \ll 1 \text{ is possible} \]

The decay to gauginos (and Higgsinos) is mass suppressed:

\[ \Gamma_{\phi \rightarrow \tilde{g}\tilde{g}} \propto \frac{m_\phi}{M_P^2} \frac{m_{soft}^2}{M_P^2} \Rightarrow Br_\chi \ll 1 \]

LVS set up can successfully accommodate non-thermal DM.

DM-DR Correlation in LVS:
The axionic partner of $\tau_b$, denoted by $a_b$, survives lifting by the non-perturbative effects and being eaten up by anomalous U(1)'s.

Bulk axions are ultra-relativistic and behave as DR. They contribute to the effective number of neutrinos $N_{\text{eff}}$:

$$\Gamma \propto \frac{c}{M_P^2} \frac{m_\phi^3}{48\pi} \Rightarrow \Delta N_{\text{eff}} = \frac{43}{7(c-1)} \quad (\Delta N_{\text{eff}} = N_{\text{eff}} - 3.04)$$

Cicoli, Conlon, Quevedo PRD 87, 043520 (2013)

Decay to visible sector mainly produces gauge bosons and Higgs:

\[
\Gamma_{\phi \to gg} \sim \left( \frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2}
\]

\[
K \supset \frac{Z H_u H_d}{\tau_b + \bar{\tau}_b} + h.c.
\]

\[
\Gamma_{\phi \to H_u H_d} = \frac{Z^2}{24\pi} \frac{m_\phi^3}{M_P^2}
\]

Giudice-Masiero term needed to avoid a DR-dominated universe.

\[c = 2Z^2 + 1\]

2\(\sigma\) bound from Planck+WMAP9+ACT+SPT+BAO+HST:

\[\Delta N_{\text{eff}} = 0.48^{+0.48}_{-0.45}\]

\[\Delta N_{\text{eff}} < 1 \Rightarrow Z > \sqrt{3}\]

Cicoli, Conlon, Quevedo  PRD 87, 043520 (2013)

Higaki, Takahashi  JHEP 1211, 125 (2012)
\[
T_r \approx \frac{1}{\pi} \left( \frac{10Z^2}{288g_*(T_r)} \right)^{1/4} \frac{m_\phi}{m_\phi} \sqrt{\frac{m_\phi}{M_P}}
\]

\[
O(\text{MeV}) \leq T_r \leq O(\text{TeV}) \Rightarrow 10.75 \leq g_* \leq 228.75
\]

Abundance of DM particles produced from \( \phi \) decay:

\[
\frac{n_\chi}{s} = \frac{3T_r}{4m_\phi} Br_\chi
\]

\[
Z > \sqrt{3}, \quad m_\phi \sim 5 \times 10^6 \text{ GeV} \Rightarrow T_r \geq O(\text{GeV})
\]

\[
Br_\chi > 3 \times 10^{-3} \Rightarrow \frac{n_\chi}{s} > \left( \frac{n_\chi}{s} \right)_{\text{obs}}
\]

Avoiding excess of DR within LVS prefers “Annihilation” scenario, hence Higgsino-type DM.
Obtaining the correct relic density in “Annihilation” scenario needs:

\[ T_r = T_f \left( \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{<\sigma_{\text{ann}}v>_f} \right) \]

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

Assuming S-wave annihilation, which is valid for the Higgsino-type DM, \(<\sigma_{\text{ann}}v>_f\) is directly constrained by Fermi.

Geringer-Sameth, Koushiappas  PRL 107, 241303 (2011)

For Higgsino-type DM, and the b final state, the bound reads:

\[ m_\chi \geq 40 \text{ GeV} \]

\[ T_r \geq (18 \text{ GeV}) \sqrt{\frac{1 \text{ GeV}}{m_\chi}} \]
\[ T_r \approx \frac{1}{\pi} \left( \frac{10Z^2}{288g_*(T_r)} \right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_P}} \]

\[ \Delta N_{\text{eff}} = \frac{43}{7(\sqrt{2}Z - 1)} \]

The Fermi bound is translated to constraint in $\Delta N_{\text{eff}} - m_\chi$ plane:

Outlook and Summary:

• The origin of DM relic abundance is an important question
  DM will be the strongest probe of the early universe

• Thermal DM is an attractive scenario
  However, it relies on certain assumptions about thermal history

• Alternatives with a non-standard thermal history are motivated
  Typically arise in UV completions
  Can ease the tension with tightening experimental limits

• Non-thermal DM from moduli decay is a viable scenario
  Can yield the correct density for large & small annihilation rates
  Successful realization in explicit constructions is nontrivial

• Non-thermal scenarios: observational signatures
  DM-DR correlation, Enhancement of DM substructure, …
Thermal DM is still a possible scenario.

Even in the simplest scenarios, like CMSSM, there are regions of the parameter space that are compatible with all experimental constraints.

However, latest data from the indirect detection experiments and the LHC keep squeezing the parameter space for thermal DM.

There are potential hints pointing to \( <\sigma_{\text{ann}}v> \neq 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \).

This motivates consideration of scenarios beyond thermal DM.

Therefore, as more data become available, it is important to keep open and study scenarios of non-thermal and their predictions.
Experimental Constraints:

Indirect Detection

Direct Detection

Collider Production

Probing thermal history once a model is established

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback  PRL 100, 231802 (2008)
Indirect Detection
Stringent bounds from gammay-rays:
Galactic center

$$\langle \sigma_{\text{ann}} \nu \rangle \leq 2 \times 10^{-25} \text{ cm}^2 \text{ s}^{-1}$$

Hooper, Kelso, Quieroz  Astropart. Phys. 46, 55 (2013)
Direct Detection:

Hint for $O(10)$ $GeV$ DM from some experiments:

$\sigma_{SI} \sim \frac{1}{16\pi} \frac{m_p^2}{M^4} \sim 10^{-41} \, cm^2$

CDMS Collaboration arXiv:1304.4279

General estimate (model-dependent)

$<\sigma_{\text{ann}} v>_{f} \leq 10^{10} \frac{1}{8\pi} \frac{m_\chi^2}{M^4} \sim 10^{-28} \, cm^3 s^{-1}$

Thermal overproduction


Concrete result (for specific models)
Obtaining correct relic density for $<\sigma_{\text{ann}} v>_f \neq 3 \times 10^{-26} \ \text{cm}^3 \text{s}^{-1}$:

1) $<\sigma_{\text{ann}} v>_f > 3 \times 10^{-26} \ \text{cm}^3 \text{s}^{-1}$ (thermal underproduction):

Multi-component DM (WIMP + non-WIMP)
Example: mixed Higgsino/axion DM
Baer, Box, Summy  JHEP 0908, 080 (2009)

Asymmetric DM (relic density survives large $<\sigma_{\text{ann}} v>_f$)
Zurek  arXiv:1308.0338

2) $<\sigma_{\text{ann}} v>_f < 3 \times 10^{-26} \ \text{cm}^3 \text{s}^{-1}$ (thermal overproduction):

Super/E-WIMP DM from WIMP decay
Examples:
Axino DM  Covi, Kim, Roszkowski  PRL 82, 4180 (1999)

Fermi constraints on $\langle \sigma_{\text{ann}} v \rangle_0$ from dwarf spheroidals:

Geringer-Sameth, Koushiappas  
*PRL 107, 241303 (2011)*

\[ \langle \sigma_{\text{ann}} v \rangle \leq 4 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1} \]

\[ \langle \sigma_{\text{ann}} v \rangle \leq 2 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1} \]
3) Generating baryon asymmetry of the universe.

\[
\frac{S_{\text{after}}}{S_{\text{before}}} = \left( \frac{\rho_\phi}{\rho_{\text{rad}}} \right)^{3/4} \leq \frac{(m_\phi M_P)^{1/2}}{T_r}
\]

\[T_r \sim (\Gamma_\phi M_P)^{1/2}, \quad \Gamma_\phi \sim \frac{m_\phi^3}{M_P^2} :\]

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

Entropy release washes any pre-existing, even \(O(1)\), asymmetry.

BAU must be produced after the decay:

Non-thermal post-sphaleron baryogenesis

In principle, both of the “Annihilation” and “Branching” scenarios of non-thermal DM can be accommodated within the LVS set up.


1) Annihilation scenario:

\[ T_r \sim O(GeV) \quad m_\chi \leq O(TeV) \]

This scenario works in the presence of \( a_b \) or in its absence. It exploits the Giudice-Massiero term.

2) Branching scenario:

\[ 3\ MeV \leq T_r < 70\ MeV \quad m_\chi \leq 200\ GeV \]

This scenario works if \( a_b \) could be removed from the spectrum, and the Giudice-Masiero term is suppressed.
Post-Sphaleron Baryogenesis:

New fields needed:

\[ W = W_{\text{MSSM}} + W_{\text{extra}} \]

\[ W_{\text{extra}} = \lambda_{i\alpha\beta} N_\beta u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \bar{X}_\alpha + M_\alpha X_\alpha \bar{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta \]

SM singlet \quad Color triplet \quad \quad Y = \pm \frac{4}{3}

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

R-parity conservation: \( N \) fermions & \( X, \bar{X} \) scalars have \( R = +1 \).

Possibilities:

1) Baryogenesis from decays of \( N \)
2) Baryogenesis from decays of \( X, \bar{X} \)
Consider decay of $N$ fermions, assuming $M_N > M_X$:


$$\varepsilon_\alpha = \frac{1}{24\pi} \frac{\text{Im}[(\lambda^+ \lambda)_{\alpha\beta}]^2}{(\lambda^+ \lambda)_{\alpha\alpha}} [3F_s(x) + F_V(x)]$$

$$F_s = \frac{2\sqrt{x}}{x-1}, \quad F_V = \sqrt{x} \ln(1 + \frac{1}{x})$$

$$x = \left(\frac{M_\beta^2}{M_\alpha^2}\right)$$

$$\lambda \sim O(1), \quad x \sim O(1)$$

$$\Rightarrow \varepsilon_\alpha \sim O(0.1)$$
Visible sector scalar can solve both of these issues.
If $\phi$ is a visible sector field, then naturally $Br_{3/2} << 1$.

Moreover, $Br_\chi << 1$ can be achieved by choosing:
1) Proper charge assignments and couplings for $\phi$.
2) Suitable kinematic relations.

Example: $\phi$ an R-parity even singlet coupled to (new) colored fields that give rise to baryogenesis.

$$2m_\chi < m_\phi < m_\chi + m_{NLSP}$$

1) Decay to gravitinos gravitationally suppressed.
2) Decay to $\chi$ suppressed by loop and/or phase space factors.


Question: How does $\phi$ fit in a realistic extension of the SM?
\[
W = W_{\text{MSSM}} + h S \bar{X} X + \lambda N X u^c + \lambda' \bar{X} d^c d^c + \frac{m_S}{2} S^2 + m_X \bar{X} X + \frac{m_N}{2} N^2
\]

R.A., Dutta, Sinha  

Singlet  Color Triplet  Singlet

\[Y = \pm 4/3\]

\[m_S \sim O(\text{TeV}), \quad m_\chi \leq 500 \text{ GeV}\]

\[m_X \sim 10-100 \text{ TeV}\]

\[m_{3/2} \sim O(\text{TeV}) \Rightarrow Br_{3/2} \leq 10^{-6}\]

\[Br_\chi \sim \frac{1}{2} \left( \frac{g_1}{g_3} \right)^4 \left( \frac{m_\chi}{m_S} \right)^2\]

\[Br_\chi \sim \frac{1}{16\pi^4} \left( \frac{\lambda_t}{g_3} \right)^4 \left( \frac{m_\chi}{m_S} \right)^2\]