Dark Matter: Thermal Versus Non-thermal

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Identification of Dark Matter with a Cross-Disciplinary Approach

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Thermal and Non-Thermal Dark Matter (DM)

Various Features of Non-Thermal Scenarios

Example of a Non-Thermal Model

Distinguishing Non-Thermal Scenarios

Conclusion
Important questions:

What is the origin of dark matter?

How does it explain the dark matter content?

Is there any correlation between baryon and dark matter abundance?

Consequences for:

- Particle Physics Models

- Thermal History of the Universe
Dark Matter: Thermal

Production of thermal non-relativistic DM:

\[ DM + DM \leftrightarrow f + \bar{f} \]

Universe cools

\[ DM + DM \Rightarrow f + \bar{f} \]

\[ DM + DM \not\Rightarrow f + \bar{f} \]

\[ \frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle_{eq} [n_{DM}^2 - n_{DM,eq}^2] \]

\[ \langle \sigma v \rangle_{eq} = \frac{\int d^3 p_1 d^3 p_2 \sigma v e^{-(E_1 + E_2)/T}}{\left(2\pi\right)^6} \]

\[ Y \equiv \frac{n}{s} = \frac{n}{g_{*}T^3} \]

\[ Y_{X}^{eq} \]

\[ m/T \]

\[ n = g \int \frac{d^3 p f \left( \vec{p}, t \right)}{(2\pi)^3} \equiv \text{nos. \}/\text{vol} \]
Thermal Dark Matter

Dark Matter content:  \( \Omega_{\text{DM}} \sim \frac{1}{\langle \sigma v \rangle} \)

\[
\langle \sigma v \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}
\]

freeze out  \( T_f \sim \frac{m_{\text{DM}}}{20} \)

\( \Rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s} \)

Weak scale physics:

\[ \alpha_\chi \sim O(10^{-2}) \text{ with } m_\chi \sim O(100) \text{ GeV} \]

leads to the correct relic abundance
Suitable DM Candidate:
Weakly Interacting Massive Particle (WIMP)

Typical in Physics beyond the SM (LSP, LKP, …)

Most Common: Neutralino (SUSY Models)

Neutralino: Mixture of Wino, Higgsino and Bino

Larger/Smaller Annihilation \(\Rightarrow\) Problem for thermal scenario
Status of Thermal DM

Experimental constraints: $<\sigma_{\text{ann}} \nu>$

Gamma-rays constraints:
Dwarf spheroidals, Galactic center

Thermal DM $\Rightarrow$ 27%

$<\sigma_{\text{ann}} \nu>_o$ : smaller than the thermal value

Geringer-Sameth, Koushiappas’11, Hooper, Kelso, Queiroz, Astropart.Phys. ‘13
Latest result from Planck

Dark Matter Pair Annihilation

Dark matter annihilation cross-section:

\[ <\sigma v> = a + b \, v^2 \]

- High \( b/a \) lowers the cross-section at small \( v \) (Present Epoch)
- For \( S \) wave domination, cross-section remains same (constant)

\[ <\sigma v> \text{ is much smaller today compared to the freeze-out time} \]

Thermal Relic Density:
At freeze-out, \[ <\sigma v> = 3 \times 10^{-26} \text{cm}^3/\text{s} \]

- \( \text{Annihilation cross-section can be larger today compared to the Freeze-out time due to Sommerfeld enhancement} \)
LHC constraints on first generation squark mass + Higgs mass:

Natural SUSY and dark matter [Baer, Barger, Huang, Mickelson, Mustafayev and Tata’12; Gogoladze, Nasir, Shafi’12, Hall, Pinner, Ruderman,’11; Papucchi, Ruderman, Weiler’11],

Higgs mass 125 GeV & Cosmological gravitino solution [Allahverdi, Dutta, Sinha’12]

- Higgsino dark matter
  - Higgsino dark matter has larger annihilation cross-section
  - Typically > 3 x 10^-26 cm^3/sec for sub-TeV mass
- Thermal underproduction of sub-TeV Higgsino
- Unnatural SUSY: Wino DM- Larger annihilation cross-section
  - Arkani-Hamid, Gupta, Kaplan, Weiner, Zorawsky’12 (for smaller wino mass)
Recent Higgs search results from Atlas and CMS indicate that $m_h \sim 126$ GeV → in the tight MSSM window <135 GeV

$m_{\tilde{q}}$ (1st gen.) $\sim m_{\tilde{g}} \geq 1.7$ TeV

For heavy $m_{\tilde{q}}, m_{\tilde{g}} \geq 1.3$ TeV

$\tilde{t}_1$ produced from $\tilde{g}$, $m_{\tilde{t}_1} \geq 700$ GeV

$\tilde{t}_1$ produced directly, $m_{\tilde{t}_1} \geq 660$ GeV (special case)

$\tilde{e} / \tilde{\mu}$ excluded between 110 and 280 GeV for a mass-less $\tilde{\chi}_1^0$ or for a mass difference >100 GeV, small $\Delta M$ is associated with small missing energy → Can lead to over production of relic abundance

$\tilde{\chi}_1^0$ masses between 100 and 600 GeV are excluded for mass-less $\tilde{\chi}_1^0$ for $\tilde{\chi}_1^\pm$ or for the mass difference >50 GeV decaying into e/$\mu$ → Can lead to over production of relic abundance
Status of Thermal DM

Thermal equilibrium above $T_f$ is an assumption.

Non-standard thermal history at $f$ is generic in some explicit UV completions of the SM.

Acharya, Kumar, Bobkov, Kane, Shao’08
Acharya, Kane, Watson, Kumar’09
Allahverdi, Cicoli, Dutta, Sinha,’13

DM content will be different in non-standard thermal histories (i.e., if there is entropy production at $T < T_f$).

Barrow’82, Kamionkowski, Turner’90

DM will be a strong probe of the thermal history after it is discovered and a model is established.
Thermal, Non-thermal

$<\sigma_{\text{ann}}N>$: Large $\Rightarrow$ multicomponent/non-thermal;
Small $\Rightarrow$ Non-thermal

- LHC: Investigate colorless particles, establish the model
- DM annihilation from galaxy, extragalactic sources
  - Annihilation into photons: Fermi, HAWC, H.E.S.S.
  - Annihilation into neutrinos: IceCube
  - Annihilation into electron-positrons: AMS
Beyond Thermal DM

Obtaining correct relic density for \( <\sigma_{\text{ann}}v>_{f} \neq 3\times10^{-26} \text{ } cm^{3} s^{-1} \):

1) (thermal underproduction): \( <\sigma_{\text{ann}}v>_{f} > 3\times10^{-26} \text{ } cm^{3} s^{-1} \)

- **Multi-component DM (WIMP + non-WIMP)**
  - Example: mixed Higgsino/axion DM

  - **Asymmetric DM (DM content can have large \( <\sigma_{\text{ann}}v>_{f} \) )**
    - \( Zurek’13 \)

2) (thermal overproduction): \( <\sigma_{\text{ann}}v>_{f} < 3\times10^{-26} \text{ } cm^{3} s^{-1} \)

- DM from WIMP decay
  - Ex: Axino DM,
    - **Gravitino DM**
      - \( Covi, Kim, Roszkowski \ ‘99 \)
      - \( Feng, Rajaraman, Takayama’03 \)
Non-Thermal DM

Dark Matter from Moduli decay:

Moduli are heavy scalar fields that acquire mass after SUSY breaking and are gravitationally coupled to matter

The moduli decay width: \[ \Gamma_\phi = \frac{c}{2\pi} \frac{m_\phi^3}{M_p^2} \]

- start oscillating when \( H < m_\tau \)
- dominate the Universe before decaying and reheating it

\[ T_r \approx c^{1/2} \left( \frac{m_\phi}{M_p} \right)^{1/2} m_\phi \]

\( T_r > T_{BBN} \approx 3 \text{ MeV} \)

\( \Rightarrow m_\phi > 50 \text{ TeV} \)

For \( T_r < T_f \): Non-thermal dark matter

Abundance of decay products \[ Y_\phi = \frac{3 T_r}{4 m_\phi} \]

e.g., Moroi, Randall’99; Acharya, Kane, Watson’08, Randall; Kitano, Murayama, Ratz’08; Dutta, Leblond, Sinha’09; Allahverdi, Cicoli, Dutta, Sinha,’13
Dark Matter from Moduli

DM abundance \( \frac{n_{DM}}{s} = \min \left[ \left( \frac{n_{DM}}{s} \right)_{obs} \right] \frac{\langle \sigma v \rangle_f^{Th}}{\langle \sigma v \rangle_f} \frac{T_f}{T_r}, Y_\phi Br_\phi \rightarrow DM \]

1. First term on the RHS is the “annihilation scenario”

   Requires: \( \langle \sigma_{ann} v \rangle_f = \langle \sigma_{ann} v \rangle_f^{th} \frac{T_f}{T_r} \)

   Since \( T_r < T_f \), we need \( \langle \sigma_{ann} v \rangle_f > \langle \sigma_{ann} v \rangle_f^{th} \)
   \( \Rightarrow \) wino/Higgsino DM

Gamma-rays constraints: Dwarf spheroidals,
Galactic center \( \Rightarrow M_{DM} > 40 \text{ GeV}, T_f < 30 T_r \Rightarrow T_r > 70 \text{ MeV} \)

2. Second term on the RHS is the “branching scenario”

   Can accommodate large and small annihilation cross-sections

   Bino/Wino/Higgsino are all ok

   \( Y_\phi \) is small to prevent the \( Br_\phi \rightarrow DM \) from becoming too small
   (actually in realistic scenarios: \( Br \geq 5 \times 10^{-3} \Rightarrow T_r < 70 \text{MeV} \))
   
   (for \( m_\phi \sim 5 \times 10^6 \text{ GeV} \))
Dark Matter from Moduli

ϕ Decays dilutes any previous relics

- Thermal DM gets diluted if $T_r < T_f \sim m_{DM}/20 \sim O(10) \text{ GeV}$
- Axionic DM gets diluted if $T_r < \Lambda_{QCD} \sim 200 \text{ MeV}$
  ($f_a \sim 10^{14} \text{ GeV}$ is allowed for $T_r \geq T_{BBN}$) [Fox, Pierce, Thomas’04]
- Baryon asymmetry gets diluted if produced before ϕ decay

Non-thermal DM Production from ϕ decay

- Annihilation scenario for $T_r$ close to $T_f$
  DM production with large cross-section: Wino/Higgsino
- Branching scenario for smaller $T_r$
  (annihilation cross-section does not matter)

Baryon asymmetry from ϕ decay $\Rightarrow$ Cladogenesis of DM and Baryogenesis [Allaverdi, Dutta, Sinha’11]
“Branching scenario” solves the coincidence problem

Baryon abundance in this model: \[ \frac{n_B}{s} = Y_\phi \varepsilon Br_{\phi \rightarrow B} \]

\( Y_\phi \) appears in the DM abundance as well, \( Y_\phi \sim 10^{-7} - 10^{-9} \)

\( \varepsilon Br_{\phi \rightarrow B} \sim 10^{-1} - 10^{-3} \) easy to satisfy for baryogenesis,
\( \varepsilon \) (one loop factor) \( \sim 10^{-1} - 10^{-2} \)

\[
\frac{\Omega_b}{\Omega_{DM}} = \frac{1}{m_{DM}} \frac{Y_\phi \varepsilon Br_{\phi \rightarrow B}}{Y_\phi Br_{\phi \rightarrow DM}} = \frac{1}{m_{DM}} \frac{\varepsilon Br_{\phi \rightarrow B}}{Br_{\phi \rightarrow DM}} = \frac{1}{5}
\]

\[ \Omega = \rho/\rho_c; \rho = \text{mn} \]

For \( m_{DM} \sim 5 m_B \), \( \varepsilon Br_{\phi \rightarrow B} \sim Br_{\phi \rightarrow DM} \) \( \Rightarrow \) \( n_B \sim n_{DM} \)

The DM abundance and Baryon asymmetry are mostly saturated by \( Y_\phi \), Brs contribute to the remaining \( \Rightarrow \) not much particle physics uncertainty
Baryogenesis from Moduli

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

\[ N : \text{SM singlet;} \quad X, \overline{X} : \text{Color triplet, hypercharge } \pm 4/3 \]

Baryogenesis from decays of \( X, \overline{X} \) or \( N \)

\( \tilde{N} : \text{can be the DM candidate: Allahverdi, Dutta, Mohapatra, Sinha’12} \)

\[ \eta_B = \frac{n_b - \overline{n_b}}{s} = Y_\phi Br_N \varepsilon \]

\( Br_N : \text{branching ratio of moduli decay to } N \)

\( \varepsilon : \text{asymmetry factor in the N decay} \)

\[ Y_\phi \sim 10^{-9} - 10^{-7}, \quad \varepsilon < 0.1, \quad Br_N \sim 10^{-2} - 1 \Rightarrow \eta_B = 9 \times 10^{-11} \]
Baryogenesis from Moduli

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

From X decay

Typically, $\epsilon_{1,2}$ is $O(10^{-2})$ for CP violating phase $O(1)$ and $\lambda \sim O(1)$
Conditions for Models

Two typical problems for moduli decay

- Gravitino Problem:
  
  [Endo, Hamaguchi, Takahashi’06][Nakamura, Yamaguchi’06]
  
  If $m_{3/2} < 40$ TeV $\Rightarrow$ Gravitino decays after the BBN
  $m_\phi > 2m_{3/2}$ can lead to DM overproduction

- Large branching ratio of moduli into light Axions $\Rightarrow N_{\text{eff}}$
  
  [Cicoli, Conlon, Quevedo’12][Higaki, Takahashi’12]

\[
\rho_{\text{rad}} = \rho_\gamma \left( 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right)
\]

Current bound from Planck+WMAP9+ACT+SPT+BAO+HST

(at 95% CL) : $N_{\text{eff}} = 3.52^{+0.48}_{-0.45}$

Ex: NT DM in Large Volume

\[ K \supset -3 \ln(T_b + \overline{T}_b) \quad , \quad \gamma/I \rightarrow W^+_{j\nu} \rightarrow \nu \tau^\pm \epsilon^{-aT_s} \]

Balasubramanian, Berglund, Conlon, Quevedo’05

Large volume can be obtained after stabilization of \( \tau_b \equiv (T_b + \overline{T}_b) / 2 \)

\[ \nu = \tau_b^{3/2} - \tau_{np}^{3/2} - \tau_{vis}^{3/2} \]

Cicoli, Conlon, Quevedo’08

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

\[ m_{soft} \ll m_{\tau_b} \ll m_{3/2} \quad (m_{soft} m_{3/2} \sim m_{\tau_b}^2) \]

For example, TeV scale SUSY can be obtained for:

\[ m_{3/2} \sim 10^{10} \, \text{GeV} \quad , \quad m_{\tau_b} \sim 5 \times 10^6 \, \text{GeV} \quad , \quad m_{soft} \sim 1 \, \text{TeV} \]

[Detailed Mass spectra, Aparicio, Cicoli, Krippendorf, Maharana, Quevedo’14]

\( \Rightarrow \) No Gravitino Problem
The decay to gauge bosons arises at one-loop level:

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

\[ \phi = \sqrt{\frac{3}{2}} \ln(\tau_b) \]

The decay to Higgs:

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

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

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

LVS set up can successfully accommodate non-thermal DM.

\[ Y_\phi \] can be quite small \( \sim 10^{-10} \): branching and annihilations are ok

Allahverdi, Cicoli, Dutta, Sinha’13
NT DM in Large Volume

If the dominant decay mode is to gauge boson final states, \( \phi \) decays into DM particle via 3-body:  
\[ \phi \rightarrow g\tilde{g}\tilde{g} \]

\[ BR_{\phi \rightarrow DM} \geq 10^{-3} \]

Since \( \tilde{g} \) produces dark matter at the end of the decay chain.

The 3 body decay width larger than the 2-body decay width of moduli into gauginos

\[ [\phi \rightarrow g\tilde{g}\tilde{g} \text{ is suppressed by } (m_{\text{gaugino}}/m_{\phi})^2 \text{ compared to } \phi \rightarrow gg \] \]

\[ \Rightarrow Y_\phi \sim 10^{-10} \text{ (using } m_\phi \sim 5 \times 10^6 \text{ GeV)} \]

\[ \Rightarrow Y_{DM}: Y_\phi \cdot BR_{\phi \rightarrow DM} \sim 10^{-12} \Rightarrow m_{DM} \sim O(100) \text{ GeV is allowed} \]

\[ \Rightarrow \text{Solves the coincidence problem} \]
DM-DR Correlation in LVS:
The axionic partner of \( \tau_b \), denoted by \( a_b \) is not eaten up by anomalous U(1)’s.

\( a_b \) acquires an exponentially suppressed mass \( m_{a_b} \approx 0 \).

\( a_b \) is produced from \( \phi \) decay:

\[
\Gamma_{\phi \rightarrow a_b a_b} = \frac{1}{48\pi} \frac{m_{\phi}^3}{M_P^2}
\]

Bulk axions are ultra-relativistic and behave as DR.

\( T_r \sim 100 \text{ MeV} \text{ or larger} \Rightarrow \text{annihilation scenario} \)

Contribute to the effective number of neutrinos \( N_{\text{eff}} \):

\[
\Gamma_{\phi} = \left( c_{\text{vis}} + c_{\text{tot}} \right) \frac{m_{\phi}^3}{48\pi M_P^2} \Rightarrow \Delta N_{\text{eff}} = \frac{43c_{\text{hid}}}{7c_{\text{vis}}} \quad (\Delta N_{\text{eff}} = N_{\text{eff}} - 3.04)
\]
The Fermi bound is translated to constraint in $\Delta N_{\text{eff}} - m_\chi$ plane:

$$m_\phi \sim 5 \times 10^6 \text{ GeV}$$

$\Delta N_{\text{eff}}, m_\phi$ : set lower bound on DM mass

$T_r \approx \frac{1}{\pi} \left( \frac{5 C_{\text{vis}} C_{\text{hid}}}{288 g_*(T_r)} \right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_p}}$

using

$$\Delta N_{\text{eff}} = \frac{43}{7} \frac{C_{\text{hid}}}{C_{\text{vis}}}$$

$$\approx \kappa \sqrt{\frac{C_{\text{hid}}}{\Delta N_{\text{eff}}}} \left( \frac{68.5}{g_+} \right)^{1/4} \left( \frac{m_\phi}{5 \times 10^6 \text{ GeV}} \right)^{3/2} 0.72 \text{ GeV} \Rightarrow m_{\text{DM}} \gtrsim \frac{\Delta N_{\text{eff}}}{C_{\text{hid}}} \sqrt{\frac{g_+}{68.5} \left( \frac{5 \times 10^5 \text{ GeV}}{m_\phi} \right)^3} \frac{625 \text{ GeV}}{\kappa^2}$$
Non-thermal Scenarios in CMSSM

Suppose $\phi$ decays into CMSSM for $T_r > 100$ MeV scenario/annihilation scenario

Large cross-section for smaller $T_r \rightarrow$

More Higgsino Domination

$T_r = 2$ GeV satisfies all data

Apparicio, Cicoli, Dutta, Kippendorf, Maharana, Muia, Quevedo, ‘15
Non-thermal Scenarios in CMSSM

Planck Constraints

\[ m_h = 125 - 126 \text{ GeV} \]
\[ \Omega h^2 \leq (\Omega h^2)_{\text{Pl}} \]
\[ T_R = 2 \text{ GeV} \]
Non-thermal Scenarios in CMSSM

\[ R = \frac{\Omega_{NT} h^2}{0.12} \], \rho \rightarrow R\rho

More multicomponent DM parameter space is recovered

Assume: Multicomponent fraction in the early epoch is same as the present epoch.

- More simulation work is needed
- Free up more parameter space for wino, Higgsino types of DM
Probe the DM sector directly: \[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \]

One interesting way:

Preselection:
- missing \( E_T > 50 \) GeV,
- 2 leading jets \( (j_1, j_2): p_T(j_1), p_T(j_2) > 30 \) GeV
- \( |\Delta \eta(j_1, j_2)| > 4.2 \) and \( \eta_{j1} \eta_{j2} < 0 \).

Optimization:
- Tagged jets: \( p_T > 50 \) GeV, \( M_{j1j2} > 1500 \) GeV;
- Events with loosely identified leptons (\( l = e; \mu; \tau_h \)) and b-quark jets: rejected.
- Missing \( E_T \): optimized for different value of the LSP mass.

Delannoy, Dutta, Gurrola, Kamon, Sinha et al’13
Non-Thermal scenario @ LHC

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

Final states at the LHC

New Particles: Heavy colored states: \(X, \bar{X}\)

SM Singlet: \(N\)

LHC signals: new colored states -spin 0- are pair produced

\[ \Rightarrow \text{high } E_T \text{ four jets in the final states} \]

new colored states –spin \(\frac{1}{2}\)- are pair produced,

\[ \Rightarrow \text{high } E_T \text{ four jets + missing energy} \]

[via cascade decays into squarks etc]

Distinguishing Feature:

4 high \(E_T\) jets and 4 high \(E_T\) jets + missing energy
If $N$ is the DM candidate, i.e., $m_N \sim m_p$

**Monojet**

**Dijet**

**Dijet pair**

**Dijet + Missing Energy**

*Dutta, Gao, Kamon’14*
DM via Monojet at LHC

Monojet $p_T$ distribution for $M_{X_1}=1$ TeV

Also, Mono-top, di-tops in this model

Combining various observable, we can probe ann. cross-section
Direct Detection

Dark Matter Candidates: $\tilde{N}, N, \tilde{\chi}_1^0$

Direct detection scattering cross-section: $\lambda_i \tilde{N} X u_i^c$

Suppose: $\tilde{N}$ is the DM particle (spin-0)

$\tilde{N}$ Scatters off a quark via s-channel exchange of X

$$\sigma^{SI}_{\tilde{N}_1-p} \sim \frac{|\lambda_1|^4 m_p^2}{16\pi M_X^4}$$

For $\lambda_i \sim 1$, $M_X \sim 1$ TeV,

$$\sigma^{SI}_{\tilde{N}_1-p} \sim \mathcal{O}(10^{-41}) \text{ cm}^2.$$  

If $N$ (spin $1/2$) is DM, $M_N \sim m_p$ (to prevent N decay and p-decay), $\sigma_{N-p}$ is $10^{-51} \text{ cm}^2$ (SI) and $10^{-42} \text{ cm}^2$ (SD)
Neutrino floor needs to be understood!
The origin of DM content is a big puzzle ➔ key to understand the history of the early universe

Thermal DM is a very attractive scenario
However, it contains 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 arising from moduli decay is a viable scenario
can yield the correct density for large & small annihilation rates

Direct, Indirect detection and LHC experimental results in tandem will probe the origin of DM

Need: simulation studies of multicomponent DM and understanding the neutrino floor
Extra: DM-DR Correlation

Decay to visible sector mainly produces gauge bosons and Higgs:

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

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

\[ \Gamma_{tot} = \Gamma_{\phi \rightarrow H_u H_d} + \Gamma_{\phi \rightarrow a_b a_b} \]

Bound from Planck+WMAP9+ACT+SPT+BAO+HST at 95%:

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

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

We get a lower bound on \( T_r \)
Abundance of DM particles produced from $\phi$ decay:

\[
Y_\phi = \frac{n_\chi}{s} = \frac{3T_r}{4m_\phi} Br_\chi : \text{Branching scenario}
\]

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

\[
Br_\chi > 3 \times 10^{-3} \implies \frac{n_\chi}{s} > \left( \frac{n_\chi}{s} \right)_{\text{obs}} : \text{Branching scenario does not work}
\]

⇒ Small annihilation cross-sections will be hard to accommodate

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

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

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

Assuming S-wave annihilation, which is valid for the Higgsino-type DM, \( \langle \sigma_{\text{ann}} \nu \rangle_f \) is directly constrained by Fermi.

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

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

\[ T_r \geq (18 \text{ GeV}) \sqrt{\frac{1 \text{ GeV}}{m_\chi}} \]

Upper bound on \( \langle \sigma_{\text{ann}} \nu \rangle_f \) \( \Rightarrow T_r \) gets bounded from below
\( \phi \) can be a visible sector field \( S \) (moduli is a hidden sector field)

\[
W_s = h S X \alpha \bar{X}_\alpha + \frac{1}{2} m_s S^2
\]

\[
W_{N,X} = \chi' d^c d^c \bar{X} + \chi N u^c X + \frac{m_N}{2} NN + m_X X \bar{X}
\]

\( m_c \sim \mathcal{O}(1) \) TeV, \( m_X \sim \mathcal{O}(10) \) TeV, \( m_N \sim \mathcal{O}(0.5) \) TeV

\[
W = W_s + W_{N,X}
\]

\[
\text{BR}_{\phi \rightarrow \text{DM}} \sim 10^{-6}
\]

\[
Y_s = \frac{(3/4) T_r}{m_s} \sim 10^{-4}
\]

\( \Rightarrow n_{\text{DM}}/s \sim 10^{-10} \)

S Decay + DM Annihilation or no annihilation works

Allahverdi, Dutta, Sinha, ‘13