Dark Matter and its Moduli Connection

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Outline

Thermal and Non-thermal Dark Matter (DM)

Moduli Decay and DM

Baryogenesis from the Decay of Moduli

Necessary Conditions for Successful Models

Example of a model

Dark Radiation (DR) and DM correlation

Non-Thermal Scenarios at the LHC

Conclusion

Questions

Important questions:

What is the origin of dark matter?

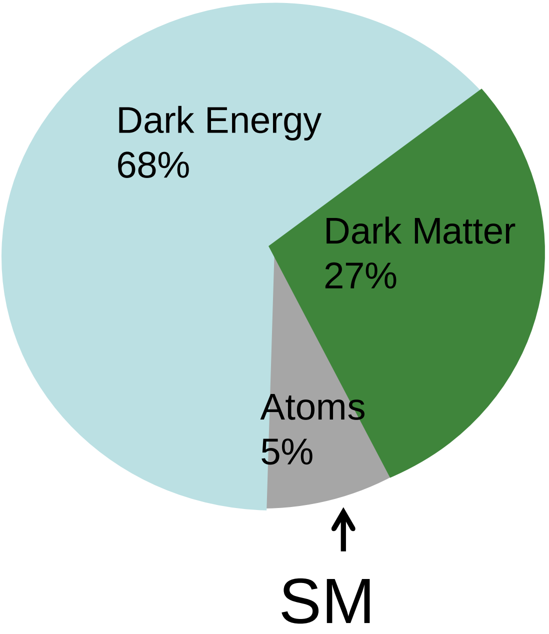
How does it explain the dark matter content?

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:

$$DM + DM \Leftrightarrow f + \bar{f}$$

Non-relativistic

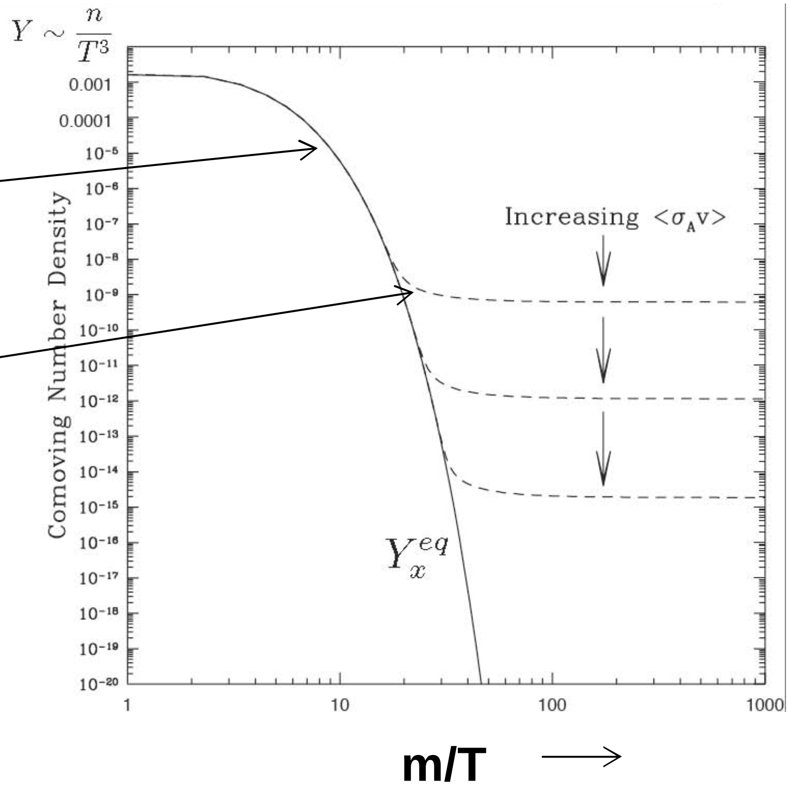
Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content: $\Omega_{\mathrm{DM}} \sim \dfrac{1}{\langle \sigma \mathrm{v} \rangle}$

freeze out ➔ $T_f \sim \dfrac{m_{DM}}{20}$

➔ $\langle \sigma \mathrm{v} \rangle = 3 \times 10^{-26} \dfrac{cm^3}{s}$

Assuming : $\langle \sigma \mathrm{v} \rangle_f \sim \dfrac{\alpha_\chi^2}{m_\chi^2}$



Y becomes constant for $T>T_f$

α_χ~O(10^{-2}) with m_χ ~ O(100) GeV leads to the correct relic abundance

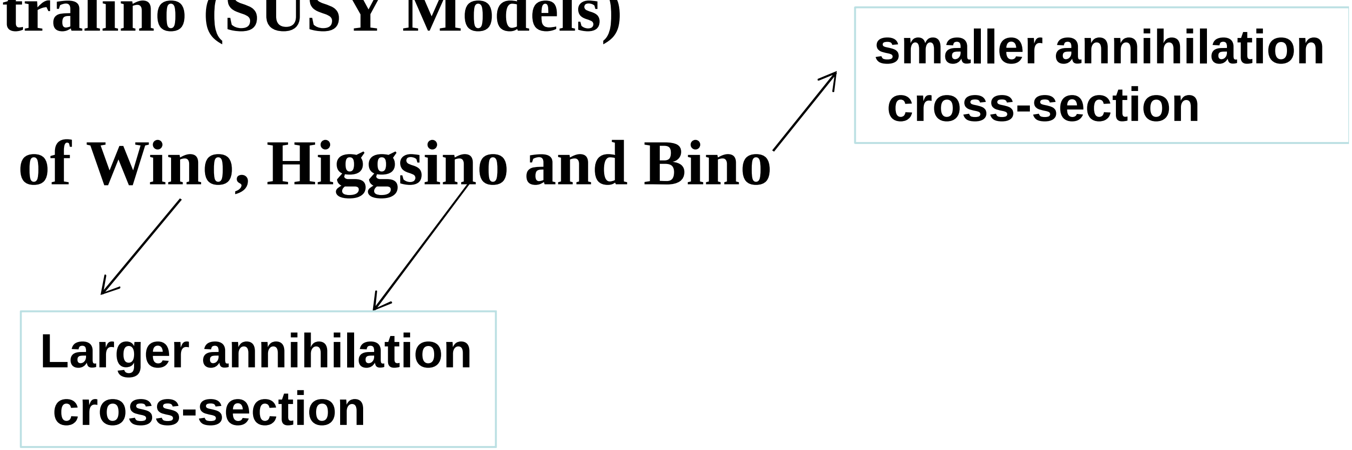
Dark Matter: Thermal

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



smaller annihilation cross-section

Larger annihilation cross-section

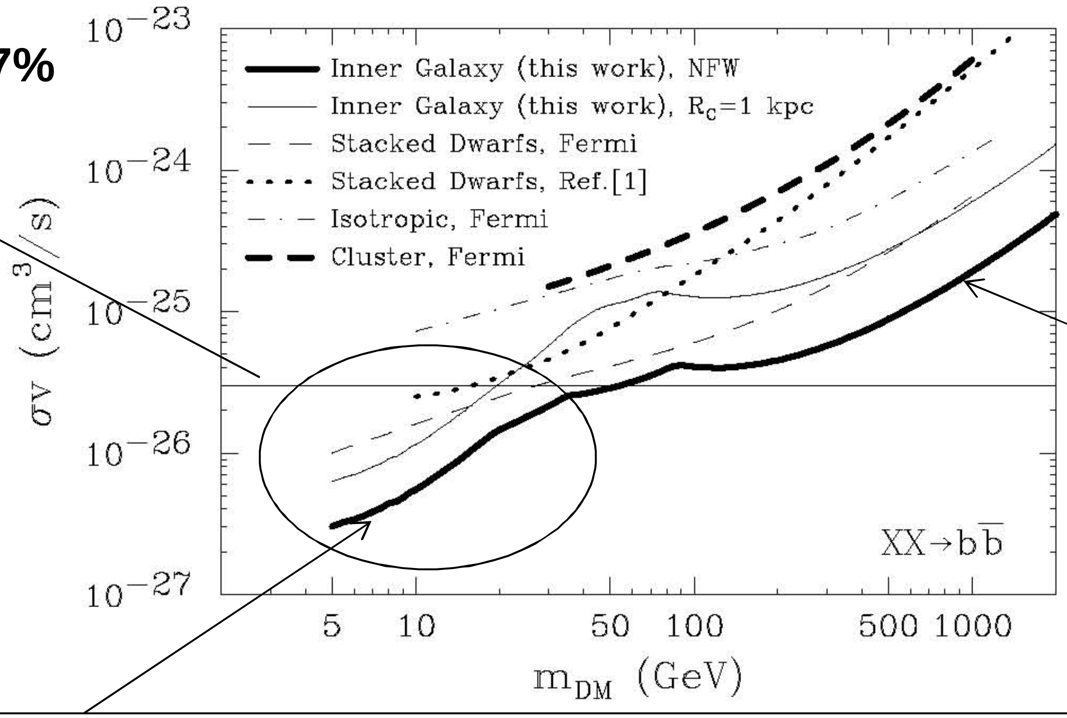
Larger/Smaller Annihilation ➔ Problem for thermal scenario

Status of Thermal DM

Experimental constraints: $< \sigma_{ann} v >$

Gamma-rays constraints:
Dwarf spheroidals, Galactic center

Thermal DM ➔ 27%



Large Cross-section is constrained

$< \sigma_{ann} v >_o$ **: smaller than the thermal value**

Geringer-Sameth, Koushiappas'11, Hooper, Kelso, Queiroz, Astropart.Phys. '13

LHC Constraints and Status of DM

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]

➔ **Higgs**i**no 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, Kapla, Weiner, Zorawsky'12 (for smaller wino mass)

Status of Thermal DM

Thermal equilibrium above T_f is an assumption.

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

Acharya, Kumar, Bobkov, Kane, Shao’08
Acharya, Kane, Watson, Kumar’09

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.

Beyond Thermal DM

Obtaining correct relic density for $<\sigma_{ann} v>_f \neq 3\times 10^{-26}\ cm^3 s^{-1}$:

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

Baer, Box, Summy'09

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

Asymmetric DM (DM content can have large $<\sigma_{ann} v>_f$ **)**

Zurek'13

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

DM from WIMP decay
Ex: Axino DM,

Covi, Kim, Roszkowski '99

Gravitino DM

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_τ**
- **dominate the Universe before decaying and reheating it**

$$T_r \sim c^{1/2}\left(\frac{m_\phi}{M_p}\right)^{1/2} m_\phi$$

$$T_r > T_{BBN} \approx 3\,\text{MeV}$$

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

Inflation

↓

Radiation domination

↓

moduli domination

Decay of moduli → ↓

radiation domination

↓

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<u>For T_r<T_f: Non-thermal dark matter</u>

Abundance of decay products $Y_\phi \equiv \frac{3T_r}{4m_\phi}$

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

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 $\langle \sigma_{ann} v \rangle_f > \langle \sigma_{ann} v \rangle_f^{th}$ **➔ wino/Higgsino DM**

Gamma-rays constraints: Dwarf spheroidals,

Galactic center ➔ $M_{DM} > 40$ GeV, $T_f < 30\ T_r$➔$T_r > 70$ MeV

[Hooper, Kelso, Queiroz,; Geringer-Sameth, Koushiappas]

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_ϕ is small to prevent the Br $_{\phi \to DM}$ from becoming too small

   (actually in realistic scenarios: Br $\geq$ 5 x10^{-3} => $T_r < 70$MeV)

(for $m_\phi \sim 5$ x10^6 GeV)

Dark Matter from Moduli

ϕ Decays dilutes any previous relics

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

Dark Matter from Moduli

"Branching scenario" solves the coincidence problem

Baryon abundance in this model: $$\frac{n_B}{s} = Y_\phi \varepsilon Br_N$$

Y_ϕ appears in the DM abundance as well~ 10^{-7}- 10^{-9}

$\varepsilon Br_N \sim 10^{-3}$ easy to satisfy for baryogenesis

$$\frac{\Omega_b}{\Omega_\chi} = \frac{1}{m_\chi}\frac{\varepsilon BR_N}{BR_\chi}$$ **For $m_{DM} \sim m_B$, $n_B \sim n_{DM}$ ➔ ε $BR_N \sim BR_{DM}$**

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

N : **SM singlet**; $X, \overline{X}$: **Color triplet, hypercharge** $\pm$4/3

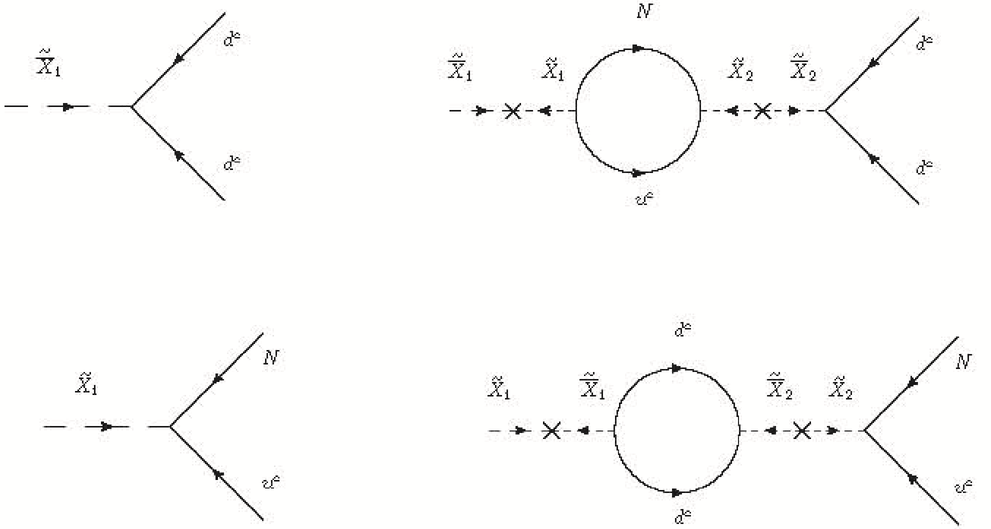
Baryogenesis from decays of $X, \overline{X}$ or N

$\tilde{N}$**: can be the DM candidate with small mass large spin-independent cross-section: Allahverdi, Dutta, Mohapatra, Sinha'12**

Baryogenesis from ϕ

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

From X decay



$$\epsilon_1 \simeq \frac{1}{8\pi} \frac{\sum_{i,j,k} \mathrm{Im}(\lambda_k^{1*} \lambda_k^2 \lambda_{ij}'^{1*} \lambda_{ij}'^2)}{\sum_{i,j} |\lambda_{ij}'^1|^2 + \sum_k |\lambda_k^1|^2} \frac{B_1 B_2 M_1 M_2 m_{\tilde{X}_1}^2}{(m_{\tilde{X}_1}^2 - m_{\tilde{X}_2}^2)^3}.$$

Typically, $\varepsilon_{1,2}$ is O(10^{-2}) for CP violating phase O(1) and λ~O(1)

$$\eta_B \simeq \frac{1}{2} Y_S (\epsilon_1 + \epsilon_2).$$

Conditions for Models

Two typical problems for moduli decay

- **Gravitino Problem:**

  [Endo,Hamaguchi,Takahashi'06][Nakamura,Yamaguchi'06]

  If $m_{3/2}<40$ TeV ➔ Gravitino decays after the BBN

  $m_\phi>m_{3/2}$ can lead to DM overproduction

- **Large branching ratio of moduli into light Axions➔ N_{eff}**

  [Cicoli,Conlon,Quevedo'12][Higaki,Takahashi'12]

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

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

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

Ex: NT DM in Large Volume Scenarios

$$K \supset -3\ln(\tau_b + \bar{\tau}_b) \quad , \quad W \supset W_{flux} + Ae^{-a\tau_s}$$

Balasubramanian, Berglund, Conlon, Quevedo'05

Large volume can be obtained after stabilization of τ_b

Cicoli, Conlon, Quevedo'08

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

$$m_{soft} << m_{\tau_b} << m_{3/2} \qquad (m_{soft} m_{3/2} \sim m_{\tau_b}^2)$$

For example, TeV scale SUSY can be obtained for:

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

NT DM in Large Volume Scenarios

$$m_{\tau_b} < m_{3/2} \Rightarrow \boxed{Br_{3/2} = 0}$$

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

$$\Gamma_{\phi \to gg} \sim \left(\frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2} \qquad \phi = \sqrt{\frac{3}{2}\ln}\ (\tau_b + \bar{\tau}_b)$$

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

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

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

$$\Gamma_{\phi \to \tilde{g}\tilde{g}} \propto \frac{m_\phi m_{soft}^2}{M_P^2} \Rightarrow \boxed{Br_\chi << 1}$$

LVS set up can successfully accommodate non-thermal DM.

Y_ϕ can be quite small ~ 10^{-10} : branching and annhilations are ok

Allahverdi, Cicoli, Dutta, Sinha'13

NT DM in Large Volume Scenarios

If the dominant decay mode is to gauge boson final states
ϕ decays into DM particle via 3-body: $\phi \to g\tilde{g}\tilde{g}$ ➔

$$BR_{\phi\to DM} \geq 10^{-3}$$

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

➔ $Y_{\phi} \sim 10^{-10}$ **(using** $m_{\phi} \sim 5 \times 10^{6}$ **GeV)**

➔ Y_{DM}: $Y_{\phi}\ BR_{\phi\to DM} \sim 10^{-12}$ ➔ $m_{DM} \sim O(100)$ **GeV is allowed**

➔ **Solves the coincidence problem**

DM-DR Correlation

DM-DR Correlation in LVS:

The axionic partner of τ_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 ϕ decay:

$$\Gamma_{\phi \to a_b a_b} = \frac{1}{48\pi} \frac{m_\phi^3}{M_P^2}$$

Cicoli, Conlon, Quevedo'13

Bulk axions are ultra-relativistic and behave as DR.

contribute to the effective number of neutrinos N_{eff}:

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

DM-DR Correlation

Decay to visible sector mainly produces gauge bosons and Higgs:

$$\Gamma_{\phi\to gg} \sim \left(\frac{\alpha_{SM}}{4\pi}\right)^2 \frac{m_\phi^3}{M_P^2} \qquad \Gamma_{\phi\to gg} << \Gamma_{\phi\to a_b a_b}$$

$$K \supset \frac{Z H_u H_d}{\tau_b + \bar{\tau}_b} + h.c. \qquad \Gamma_{\phi\to H_u H_d} = \frac{Z^2}{24\pi}\frac{m_\phi^3}{M_P^2}$$

$$\Gamma_{tot} = \Gamma_{\phi\to H_u H_d} + \Gamma_{\phi\to a_b a_b}$$

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

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

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

DM-DR Correlation

$$T_r \approx \frac{1}{\pi}\left(\frac{5C_{vis}C_{tot}}{288\,g_*(T_r)}\right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_P}} \qquad \Gamma_{tot} = \frac{C_{tot}}{24\pi}\frac{m_\phi^3}{M_P^2}, \Gamma_{vis} = \frac{C_{vis}}{24\pi}\frac{m_\phi^3}{M_P^2}$$

$$O(MeV) \le T_r \le O(TeV) \qquad C_{vis} = 2Z^2, C_{tot} = 1 + 2Z^2$$

$$\Rightarrow 10.75 \le g_* \le 228.75$$

Abundance of DM particles produced from ϕ decay:

$$Y_\varphi = \frac{n_\chi}{s} = \frac{3T_r}{4m_\phi} Br_\chi$$ **: Branching scenario**

$$Z > \sqrt{3}\ ,\ \ m_\phi \sim 5\times 10^6\ GeV \quad \Rightarrow T_r \ge O(GeV) \Rightarrow Y_\phi \ge 10^{-6}$$

$$Br_\chi > 3\times 10^{-3} \ \Rightarrow \frac{n_\chi}{s} > \left(\frac{n_\chi}{s}\right)_{obs}$$ **: Branching scenario does not work**

Avoiding excess of DR within LVS prefers "Annihilation" scenario ➔ Higgsino-type DM.

DM-DR Correlation

Obtaining the correct relic density in "Annihilation" scenario needs:

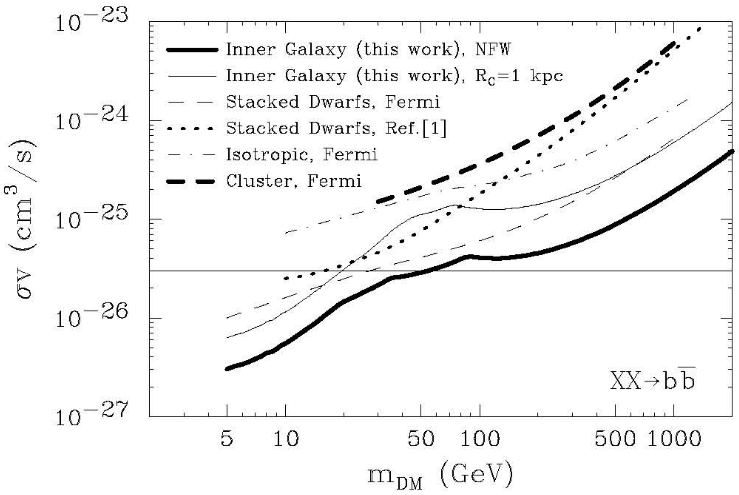
$$T_r = T_f \left(\frac{3 \times 10^{-26} \ cm^3 s^{-1}}{< \sigma_{ann} v >_f} \right) \qquad T_f \sim \frac{m_\chi}{20}$$

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

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

$$m_\chi \geq 40 \ \ GeV$$

$$T_r \geq (18 \ \ GeV) \sqrt{\frac{1 \ GeV}{m_\chi}}$$



Upper bound on $< \sigma_{ann} v >_f$ **➔** $\mathbf{T_r}$ **gets bounded from below**

DM-DR Correlation

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

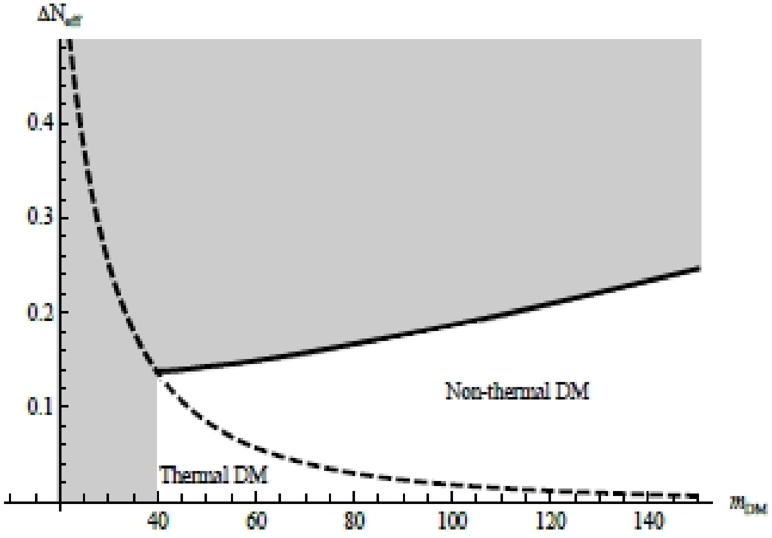
using

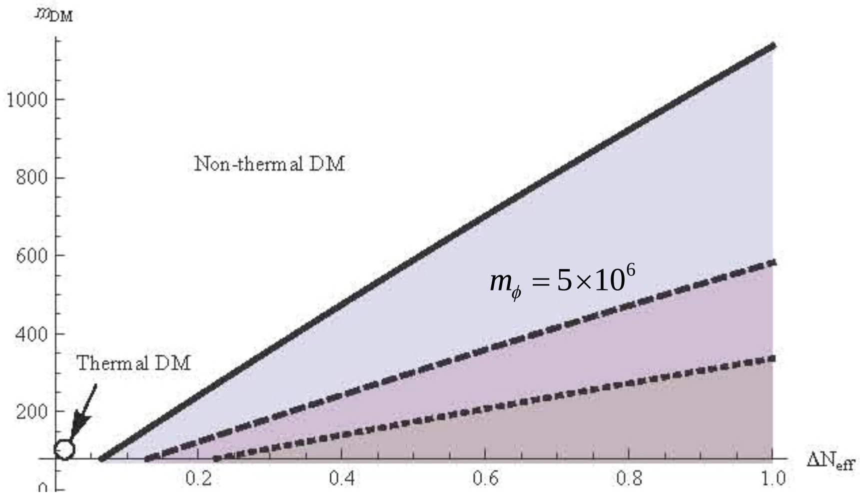
$$\Delta N_{eff} = \frac{43}{7}\frac{C_{hid}}{C_{vis}}$$

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

$m_\phi \sim 5\times10^6\ GeV$

Allahverdi., Cicoli, Dutta, Sinha'14

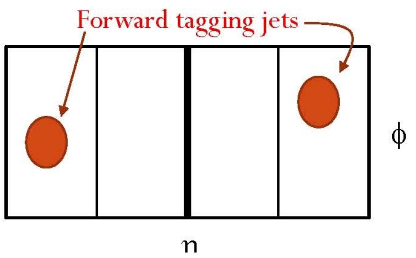




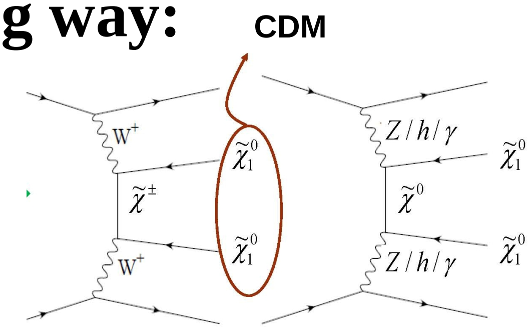
$\Delta N_{eff}, m_\varphi$ **: set lower bound on DM mass**

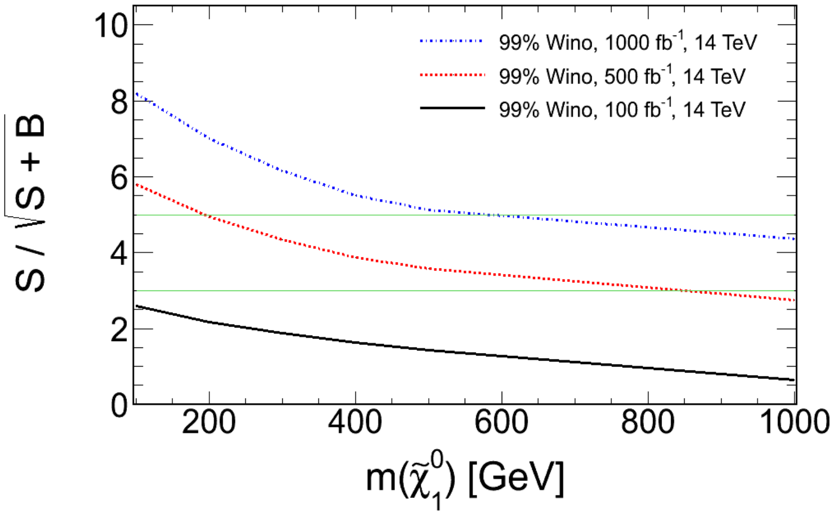
Non-thermal scenarios at the LHC

Probe the DM sector directly: $pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj$



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

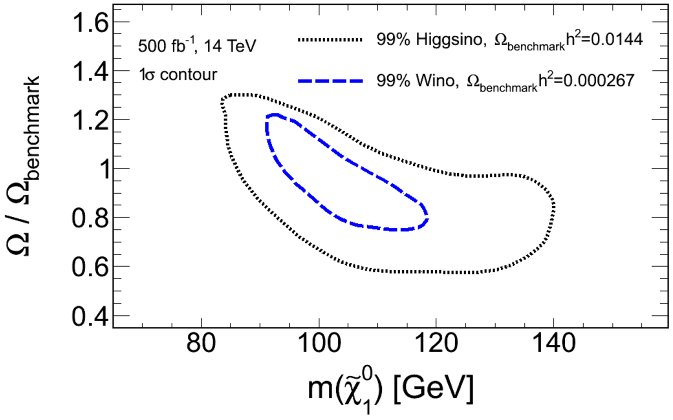
$|\Delta\eta(j_1, j_2)| > 4.2$ and $\eta_{j1}\eta_{j2} < 0$.

Optimization:

Tagged jets : p_T > 50 GeV, M_{j1j2} > 1500 GeV;

Events with loosely identified leptons(l = e; μ ; τ_h) and b-quark jets: rejected.

Missing E_T : optimized for different value of the LSP mass.



Delannoy, Dutta, Gurrola, Kamon, Sinha et a'13

Conclusion

- **The origin of DM content is a big puzzle**
  We will be able 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
  Successful realization in explicit constructions is nontrivial