Non-thermal Dark Matter

Rouzbeh Allahverdi

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Outline:

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

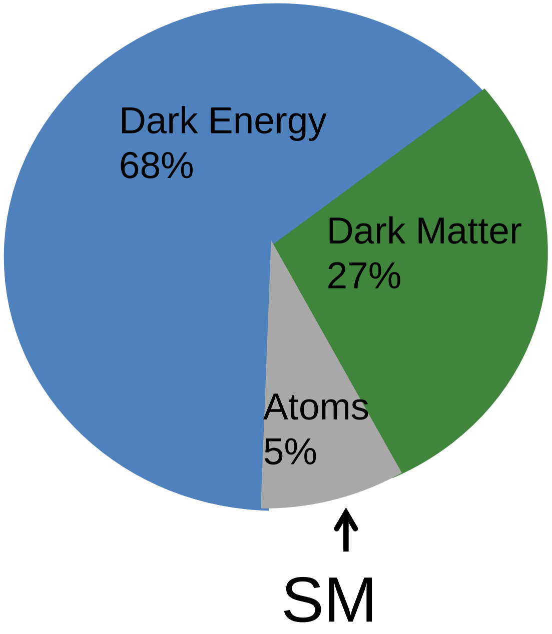
- Non-thermal DM from late decay
  Non-thermal DM form moduli decay
  Necessary conditions for successful models

- 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 $T >> m_\chi$:

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

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

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

$$\Omega_\chi h^2 \approx 10^{-1} \Rightarrow$$

$$\boxed{< \sigma_{ann} v >_f = 3 \times 10^{-26} \ cm^3 s^{-1}}$$

Simple parametrization:

$$< \sigma_{ann} v >_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$$

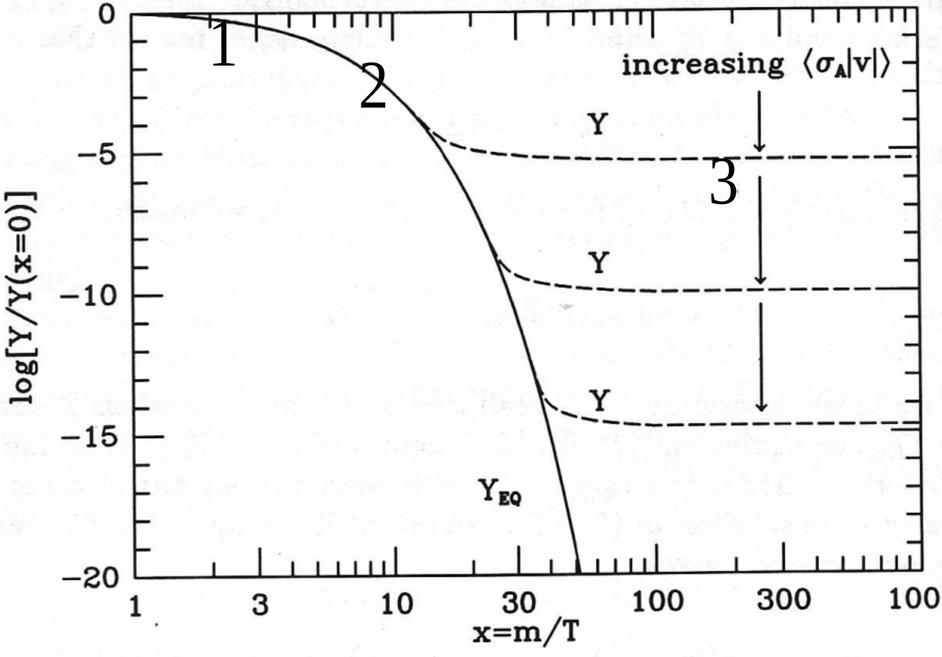
$$T_f \sim \frac{m_\chi}{25} - \frac{m_\chi}{15}$$

WIMP miracle:

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

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

“The Early Universe” Kolb & Turner



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 ~ 10^{-7} sec.

The best experimental probes of the early universe:

1) CMB: t ~ 400,000 yr
2) BBN: t ~ 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)

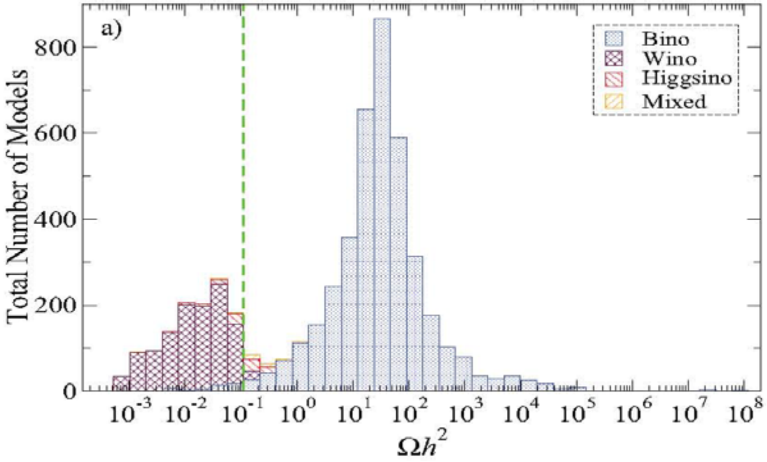
In practice, thermal DM is not a generic scenario.

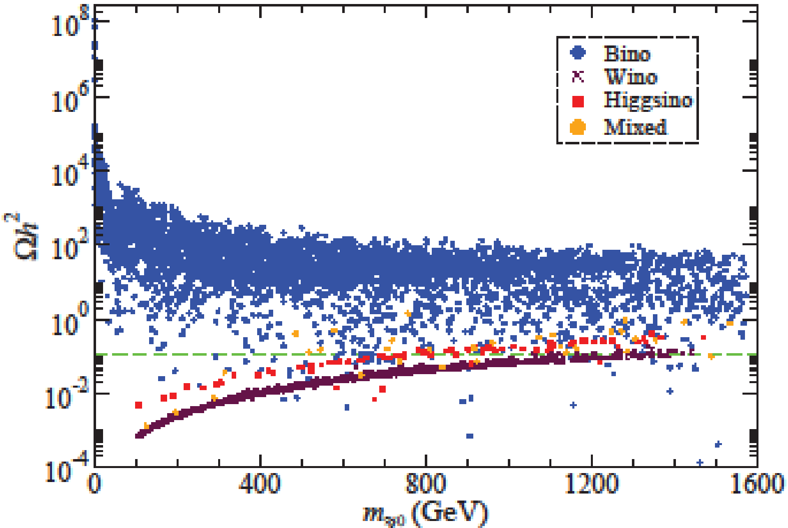
Parametrization of annihilation cross section too simple:
assumes a single mass scale, neglects velocity effects.

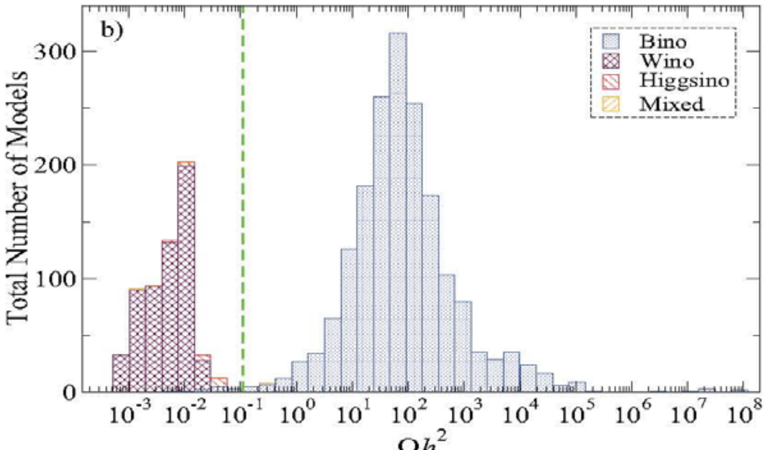
Example: pMSSM.

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:

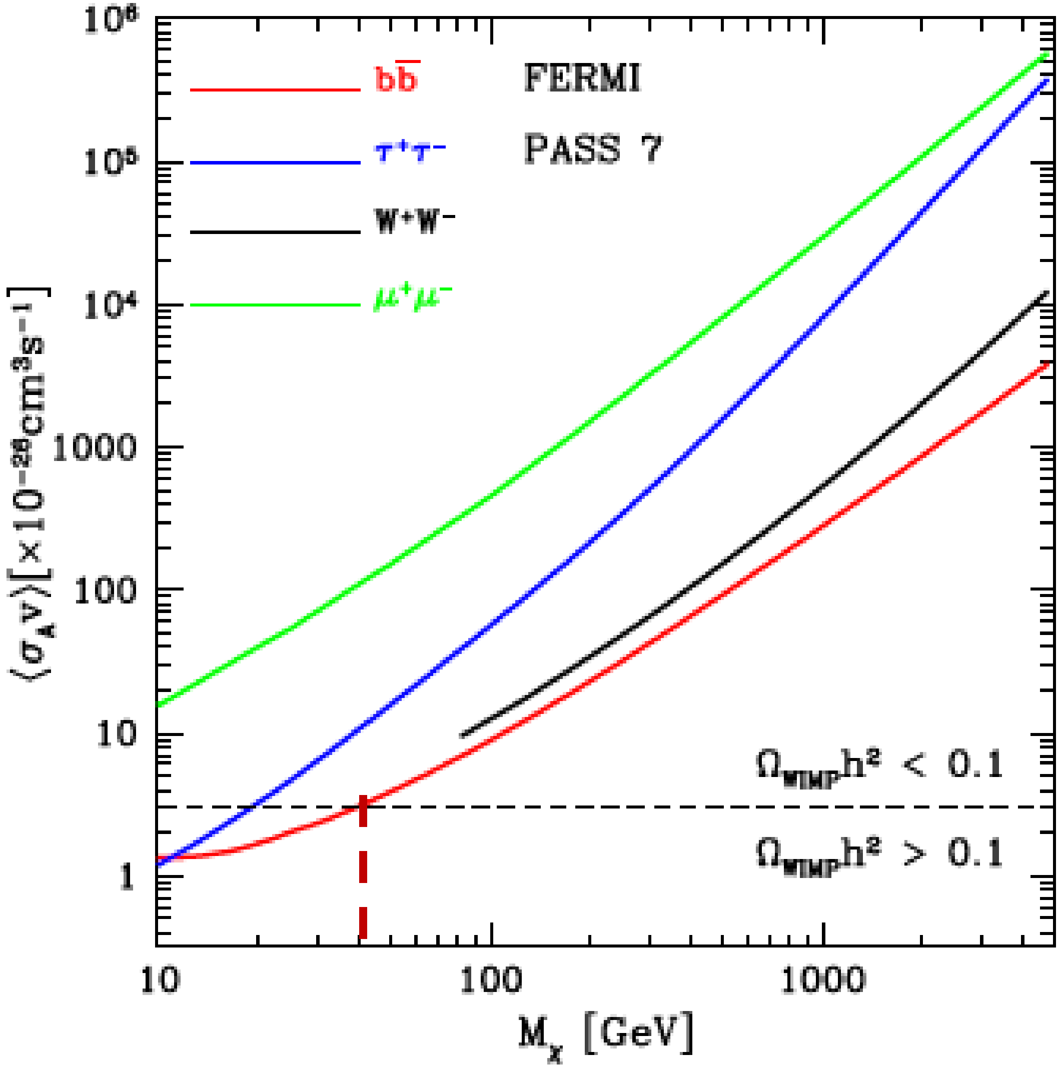
$$<\sigma_{ann} v>_0 = <\sigma_{ann} v>_f$$

Consider b final state:

$$m_\chi < 40\ GeV \Rightarrow$$

$$<\sigma_{ann} v>_f < 3\times10^{-26}\ cm^3 s$$

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)

3rd generation squarks & EW gauginos $\sim O(TeV)$

Gluinos $\sim 3-4\ TeV$

1st and 2nd generation squarks & sleptons $>> 10\ TeV$

$\mu \sim 150-200\ GeV$

Higgsino DM:

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

Thermal underproduction

Obtaining correct relic density for $<\sigma_{ann} v>_f \neq 3\times10^{-26}\ cm^3 s^{-1}$:

1) $<\sigma_{ann} v>_f > 3\times10^{-26}\ cm^3 s^{-1}$ (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 $<\sigma_{ann} v>_f$)
Zurek arXiv:1308.0338

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

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

Gravitino DM Feng, Rajaraman, Takayama PRL 91, 011302 (2003)

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 $T < T_f$).

Barrow NPB 208, 501 (1982)
Kamionkowski, Turner PRD 42, 3310 (1990)

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

m_ϕ : Scalar mass

Γ_ϕ : Scalar decay width

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

Decay dilutes existing DM particles, produces new DM particles:

$$\frac{n_\chi}{s} = Y_\phi \ Br_\chi$$

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

Br_χ : Branching ratio to R-parity odd particles

1) Annihilation Scenario:

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

$$\Gamma_{ann} > H_r \sim \Gamma_\phi$$

$$\left(\frac{n_\chi}{s}\right)_{non-th} = \left(\frac{n_\chi}{s}\right)_{th} \left(\frac{T_f}{T_r}\right) \qquad \left(\frac{n_\chi}{s}\right)_{th} = \left(\frac{n_\chi}{s}\right)_{obs} \frac{3\times 10^{-26} cm^3 s^{-1}}{<\sigma_{ann} v>_f}$$

2) Branching Scenario:

Gelmini, Gondolo PRD 74, 023510 (2006)
R.A., Dutta, Sinha PRD 83, 083502 (2011)

$$\Gamma_{ann} < H_r \sim \Gamma_\phi$$

$$\left(\frac{n_\chi}{s}\right)_{non-th} = Y_\phi \; Br_\chi$$

$$\boxed{\left(\frac{n_\chi}{s}\right)_{non-th} = \min\left[\left(\frac{n_\chi}{s}\right)_{th} \left(\frac{T_f}{T_r}\right), \; Y_\phi \; Br_\chi\right]}$$

1) Annihilation works for thermal underproduction, requires:

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

Experimental constraints on $< \sigma_{ann} v >_f$ restrict T_r .

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

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

Independent from $< \sigma_{ann} v >_f$, tight restriction for model building.

Challenge: Successful realization within realistic models.

Non-thermal Dark Matter from Moduli Decay:

Modulus fields are natural candidates for ϕ .

Commonly arise in SUSY and string-inspired models, long lived:

$$\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2} \qquad \text{(typically: } c \sim 0.1-1\text{)}$$

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

1) Displaced during inflation $\phi_0 \sim M_P$

2) Start oscillating when $H \approx m_\phi$

3) Decay and reheat the universe $T_r \sim \left(\frac{m_\phi}{50\ TeV}\right)^{3/2} \times 3\ MeV$

BBN requires $T_r > 3\ MeV$.

$m_\phi > 50\ TeV$:

Handicap (cosmological moduli problem) turned into virtue.

Higgsino DM via “Annihilation” scenario

Obtaining the correct relic density requires:

$$T_r = T_f \left(\frac{3\times10^{-26}\ cm^3 s^{-1}}{<\sigma_{ann} v>_f} \right)$$

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

$$<\sigma_{ann} v>_f = <\sigma_{ann} v>_0$$

Stringent bounds from Fermi:

$$m_\chi = 1\ TeV \qquad <\sigma_{ann} v>_f \le 4\times10^{-24}\ cm^3 s^{-1}$$

$$m_\chi = 100\ GeV \qquad <\sigma_{ann} v>_f \le 2\times10^{-25}\ cm^3 s^{-1}$$

$$T_f \sim \frac{m_\chi}{20} \Rightarrow T_r \sim O(GeV)$$

$$\boxed{m_\phi \sim\ few\times O(1000)\ TeV}$$

In models with non-perturbative schemes of moduli stabilization

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

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

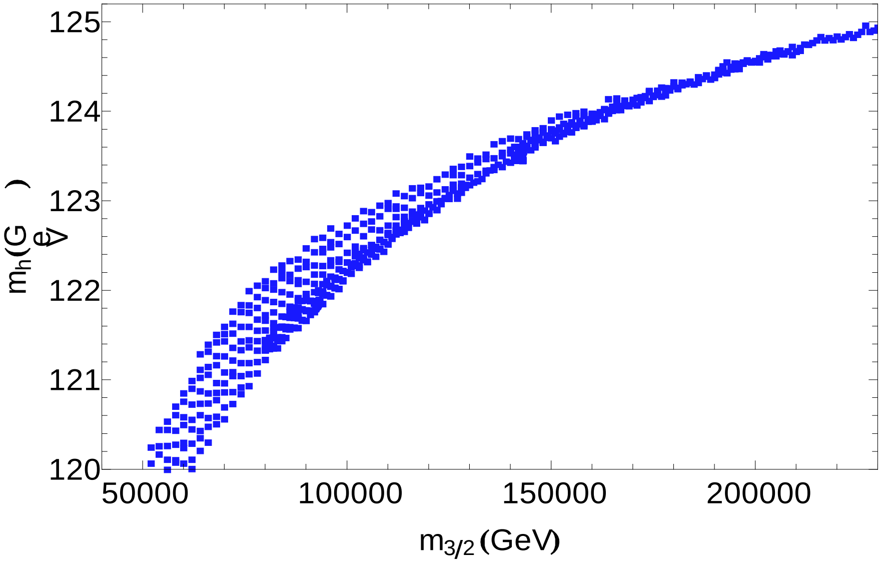
Gravitinos escape very tight BBN bounds.

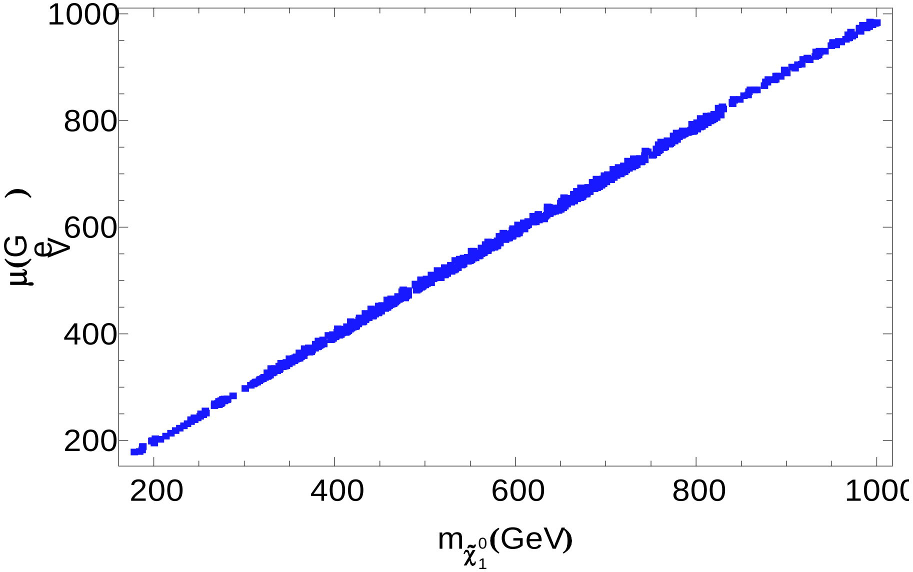
Kawasaki, Kohri, Moroi, Yotsuyanagi PRD 78, 065011 (2008)

Cyburt, Ellis, Fields, Luo, Olive, Spanos JCAP 0910, 021 (2009)

Explicit example: Non-thermal Higgsino DM in mirage mediation

R.A., Dutta, Sinha PRD 86, 095016 (2012)





Constraints and Challenges:

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

$\phi \to \tilde{G}\tilde{G}$ 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)

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

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

$$\boxed{Br_{3/2} < 7 \times 10^{-4}} \quad \text{and/or} \quad \boxed{c << 1}$$

2) In the “Branching” scenario, the relic density must be just right.

$$\frac{n_\chi}{s} = Y_\phi \; Br_\chi = \left(\frac{n_\chi}{s}\right)_{obs}$$

$\boxed{Br_\chi < 7\times10^{-4}}$ and/or $\boxed{c << 1}$

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: $Br_\chi \sim 3\times10^{-3}$.

R.A., Dutta, Sinha PRD 83, 083502 (2011)

Further suppressing Br_χ requires suppression of:

Decay to particles with gauge charges and/or total decay width

3) Generating baryon asymmetry of the universe.

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

$$T_r \sim \left(\frac{m_\phi^3}{M_P}\right)^{1/2} \quad \Rightarrow \quad \left(\frac{s_{after}}{s_{before}}\right)_{\max} \sim \frac{M_P}{m_\phi} \; (>> 10^{10})$$

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

BAU must be produced after the decay:

Non-thermal post-sphaleron baryogenesis

R.A., Dutta, Sinha PRD 81, 053538 (2010)

Possibility to address the DM-baryon coincidence problem

R.A., Dutta, Sinha PRD 83, 083502 (2011)

Question:

Can these constraints be satisfied in explicit string constructions?

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

Kachru, Kallosh, Linde, Trivedi PRD 68, 046005 (2003)

$$G = K + \ln |W|^2$$

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

The dominant decay mode is to gauge bosons and gauginos:

$$\Gamma_{\phi\to gg} \sim \frac{N_g}{128\pi} K_{\tau\bar{\tau}}^{-1} < \tau >^2 \frac{m_\phi^3}{M_P^2} \qquad \phi = \sqrt{\frac{3}{2}\ln}\ (\tau + \bar{\tau})$$

$$\Gamma_{\phi\to\tilde{g}\tilde{g}} \sim \frac{N_g}{128\pi} K_{\tau\bar{\tau}}^{-1} < \partial_\tau F^\tau >^2 \frac{m_\phi^3}{M_P^2}$$

$$\Gamma_{\phi\to\tilde{g}\tilde{g}} \sim \Gamma_{\phi\to gg} \sim \frac{1}{10\pi} \frac{m_\phi^3}{M_P^2}$$

The decays to fermions and sfermions are mass suppressed:

$$\Gamma_{\phi\to ff} \propto \frac{m_\phi m_f^2}{M_P^2} \quad , \quad \Gamma_{\phi\to \tilde{f}\tilde{f}} \propto \frac{m_\phi m_{soft}^2}{M_P^2}$$

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

$$\Gamma_{\phi\to\tilde{G}\tilde{G}} \sim \frac{1}{288\pi}\left(|G_\tau|^2 K_{\tau\bar{\tau}}^{-1}\right)\frac{m_\phi^3}{M_P^2} \sim \frac{1}{288\pi}\frac{m_\phi^3}{M_P^2}$$

$$Br_{3/2} \sim 10^{-2}$$

Gravitino-induced DM overproduction

$$c \sim 0.4 \quad , \quad Br_\chi \sim 1$$

“Branching” scenario not viable

Not a successful set up!

Both problems can be solved if ϕ is a visible sector field:

R.A., Dutta, Sinha PRD 87, 075024 (2013)

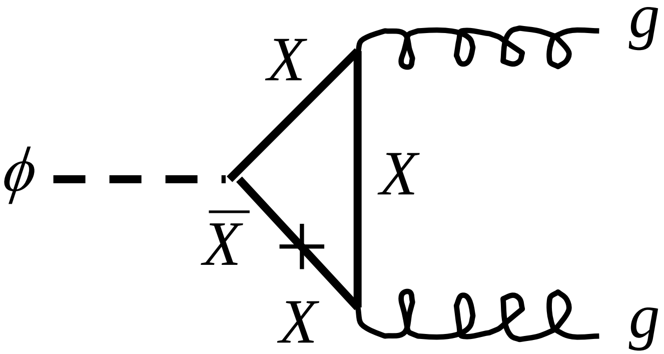
$$W = W_{MSSM} + h\phi\bar{X}X + \lambda N X u^c + \lambda' \bar{X} d^c d^c + \frac{m_\phi}{2}\phi^2 + m_X X\bar{X} + \frac{m_N}{2} N^2$$

ϕ : Singlet $X, \bar{X}$: Color triplets N : Singlet

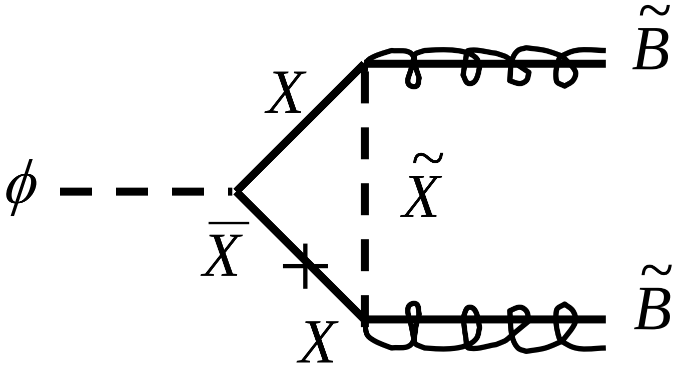
$$m_\phi \sim O(TeV)$$

$$m_X \sim 10 - 100 \ TeV$$

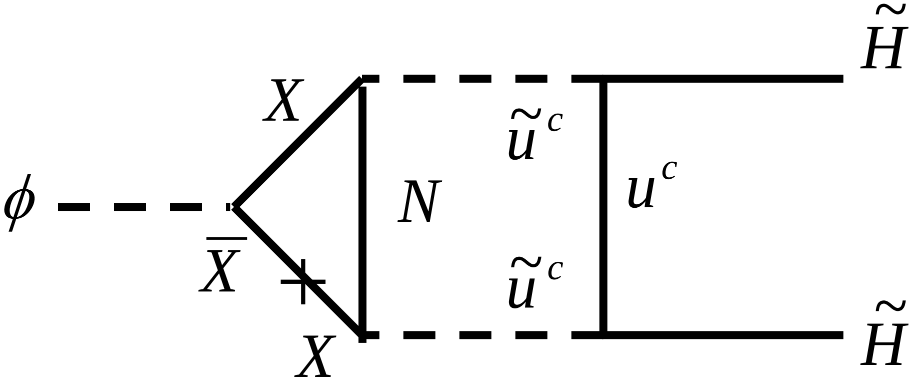
$$m_\chi \leq 500 \ GeV$$



$$Br_{3/2} \approx 0$$



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



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

Non-thermal DM in LARGE Volume Scenarios:

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

Balasubramanian, Berglund, Conlon, Quevedo JHEP 0503, 007 (2005)

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

Large volume can be obtained after stabilization of τ_b.

Cicoli, Conlon, Quevedo JHEP 0801, 052 (2008)

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:

$$m_{3/2} \sim 10^{10}\ GeV \quad , \quad m_{\tau_b} \sim 5\times10^{6}\ GeV \quad , \quad m_{soft} \sim 1\ TeV$$

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

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:

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

$\boxed{c << 1}$ is possible

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.

R.A., Cicoli, Dutta, Sinha PRD 88, 095015 (2013)

DM-DR Correlation in LVS:

The axionic partner of τ_b , denoted by a_b , survives lifting by the non-perturbative effects and being eaten up by anomalous U(1)’s.

R.A., Cicoli, Dutta, Sinha arXiv:1401.4364 [hep-ph]

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 PRD 87, 043520 (2013)

Bulk axions are ultra-relativistic and behave as DR.

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

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

Decay to visible sector mainly produces gauge bosons and Higgs:

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

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

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

$$c = 2Z^2 + 1$$

2σ bound from Planck+WMAP9+ACT+SPT+BAO+HST:

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

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

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

Higaki, Takahashi JHEP 1211, 125 (2012)

$$T_r \approx \frac{1}{\pi}\left(\frac{10Z^2}{288 g_*(T_r)}\right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_P}}$$

$$O(MeV) \le T_r \le O(TeV) \Rightarrow 10.75 \le g_* \le 228.75$$

Abundance of DM particles produced from ϕ decay:

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

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

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

Avoiding excess of DR within LVS prefers “Annihilation” scenario, hence Higgsino-type DM.

Obtaining the correct relic density in “Annihilation” scenario needs:

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

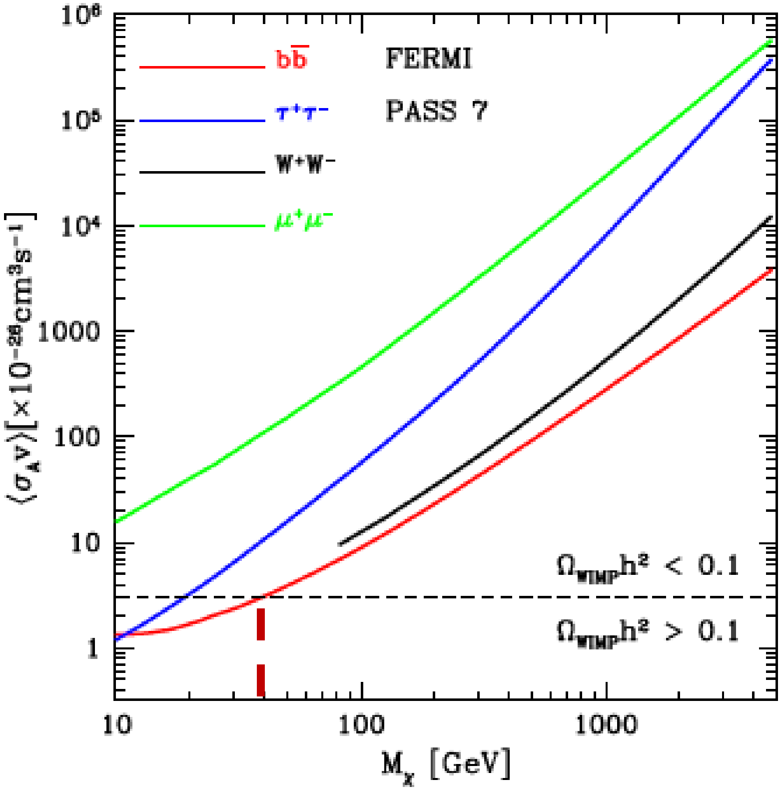
Assuming S-wave annihilation, which is valid for the Higgsino-type DM, $<\sigma_{ann} v>_f$ is directly constrained by Fermi.

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

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

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

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

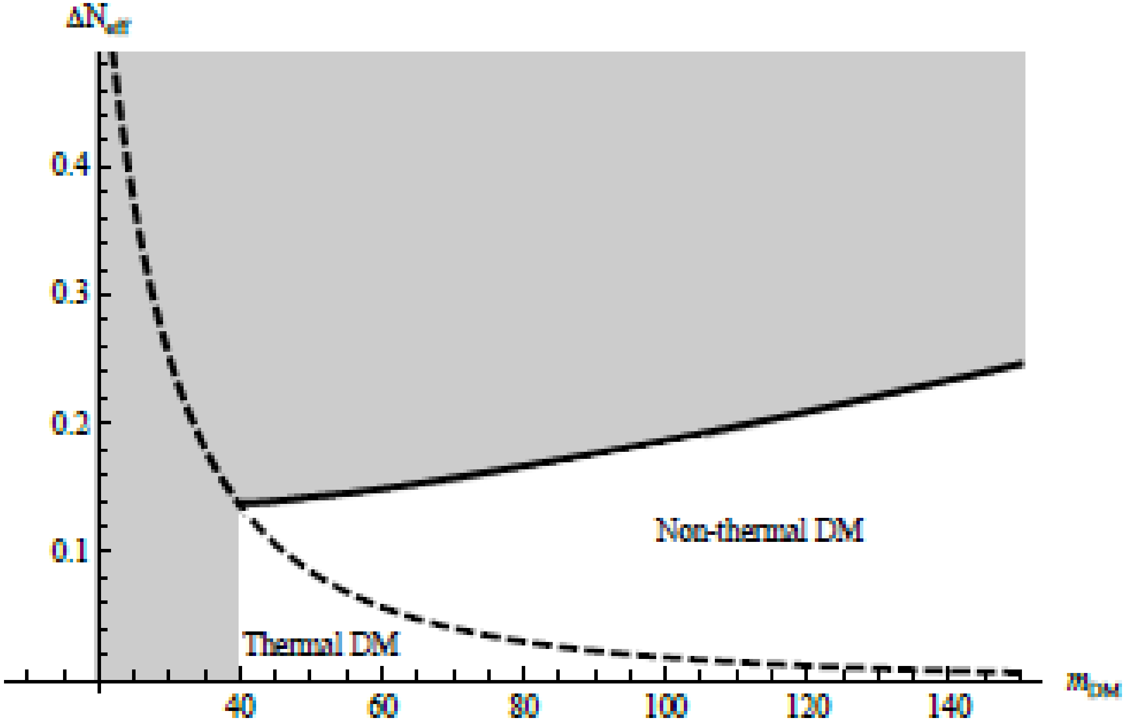


$$T_r \approx \frac{1}{\pi}\left(\frac{10Z^2}{288 g_*(T_r)}\right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_P}} \qquad m_\phi \sim 5\times 10^6\ GeV$$

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

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

R.A., Cicoli, Dutta, Sinha arXiv:1401.4364 [hep-ph]



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, …

Erickcek, Sigurdson PRD 84, 083503 (2011)

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.

Cohen, Wacker JHEP 1309, 061 (2013)
Fukushima, Kelso, Kumar, Sandick, Yamamoto arXiv:1406.4903 [hep-ph]

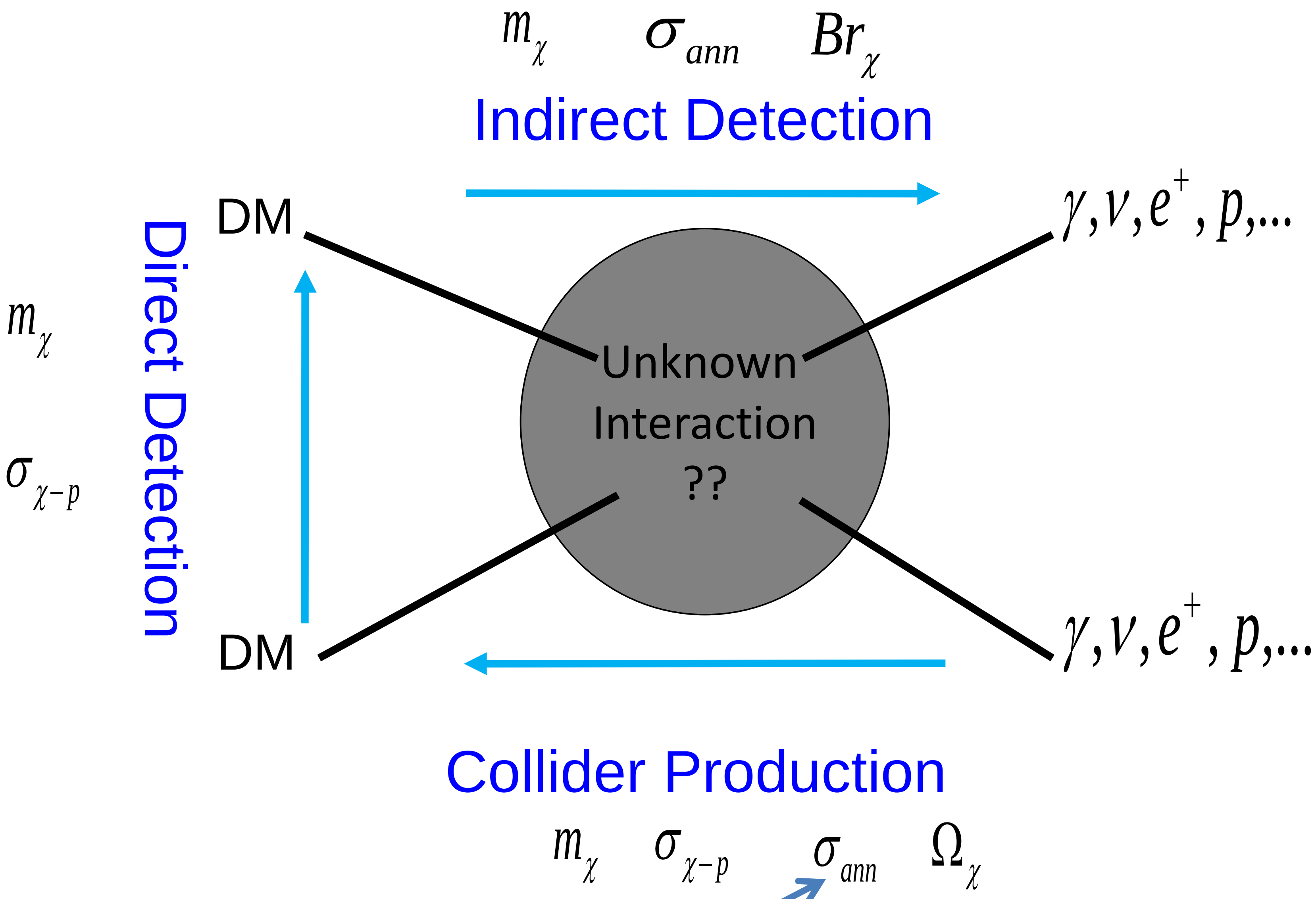
However, latest data from the indirect detection experiments and the LHC keep squeezing the parameter space for thermal DM.

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

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:



m_χ σ_{ann} Br_χ

Indirect Detection

$\gamma, \nu, e^+, p, \ldots$

DM

Direct Detection

m_χ

$\sigma_{\chi-p}$

Unknown Interaction ??

DM

$\gamma, \nu, e^+, p, \ldots$

Collider Production

m_χ $\sigma_{\chi-p}$ σ_{ann} Ω_χ

Probing thermal history once a model is established

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback PRL 100, 231802 (2008)

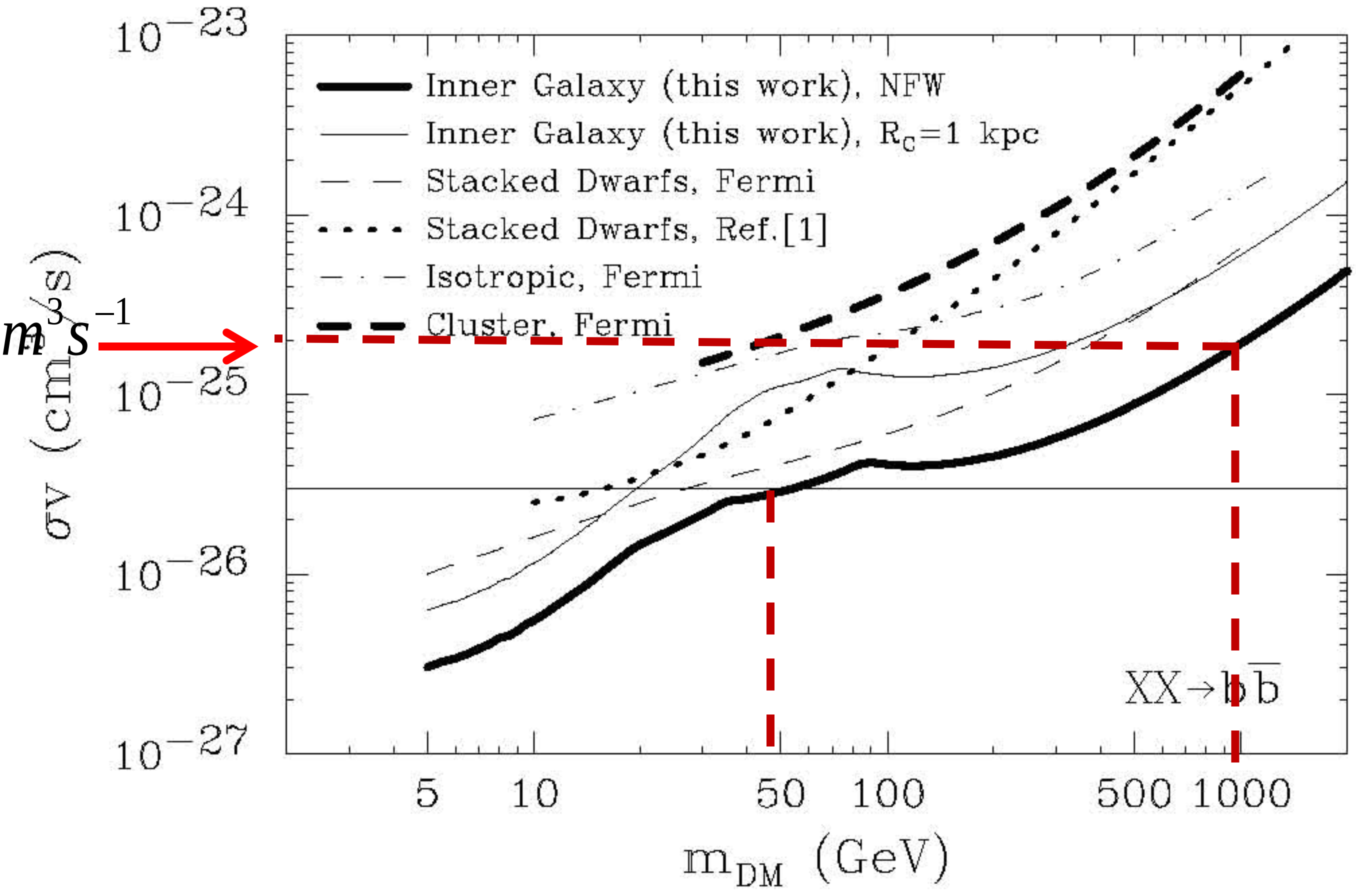
Indirect Detection

Stringent bounds from gammay-rays:

Galactic center

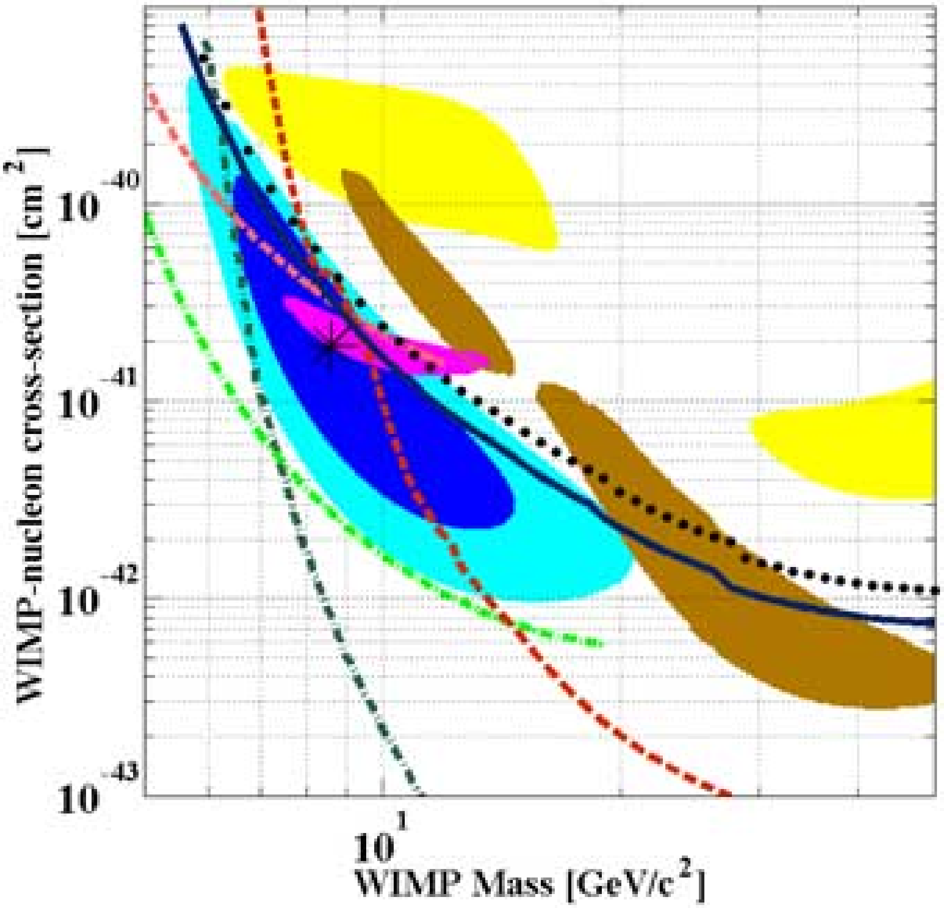
Hooper, Kelso, Quieroz Astropart. Phys. 46, 55 (2013)

$$<\sigma_{ann}v> \le 2\times10^{-25}\ cm^3 s^{-1}$$



Direct Detection:

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



CDMS Collaboration arXiv:1304.4279

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

General estimate
(model-dependent)

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

Thermal overproduction

R.A., Dutta, Mohapatra, Sinha PRL 31, 051302 (2013)

Concrete result
(for specific models)

Obtaining correct relic density for $<\sigma_{ann} v>_f \neq 3\times10^{-26}\ cm^3 s^{-1}$:

1) $<\sigma_{ann} v>_f \ > 3\times10^{-26}\ cm^3 s^{-1}$ (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 $<\sigma_{ann} v>_f$)

Zurek arXiv:1308.0338

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

Super/E-WIMP DM from WIMP decay

Examples:

Axino DM Covi, Kim, Roszkowski PRL 82, 4180 (1999)

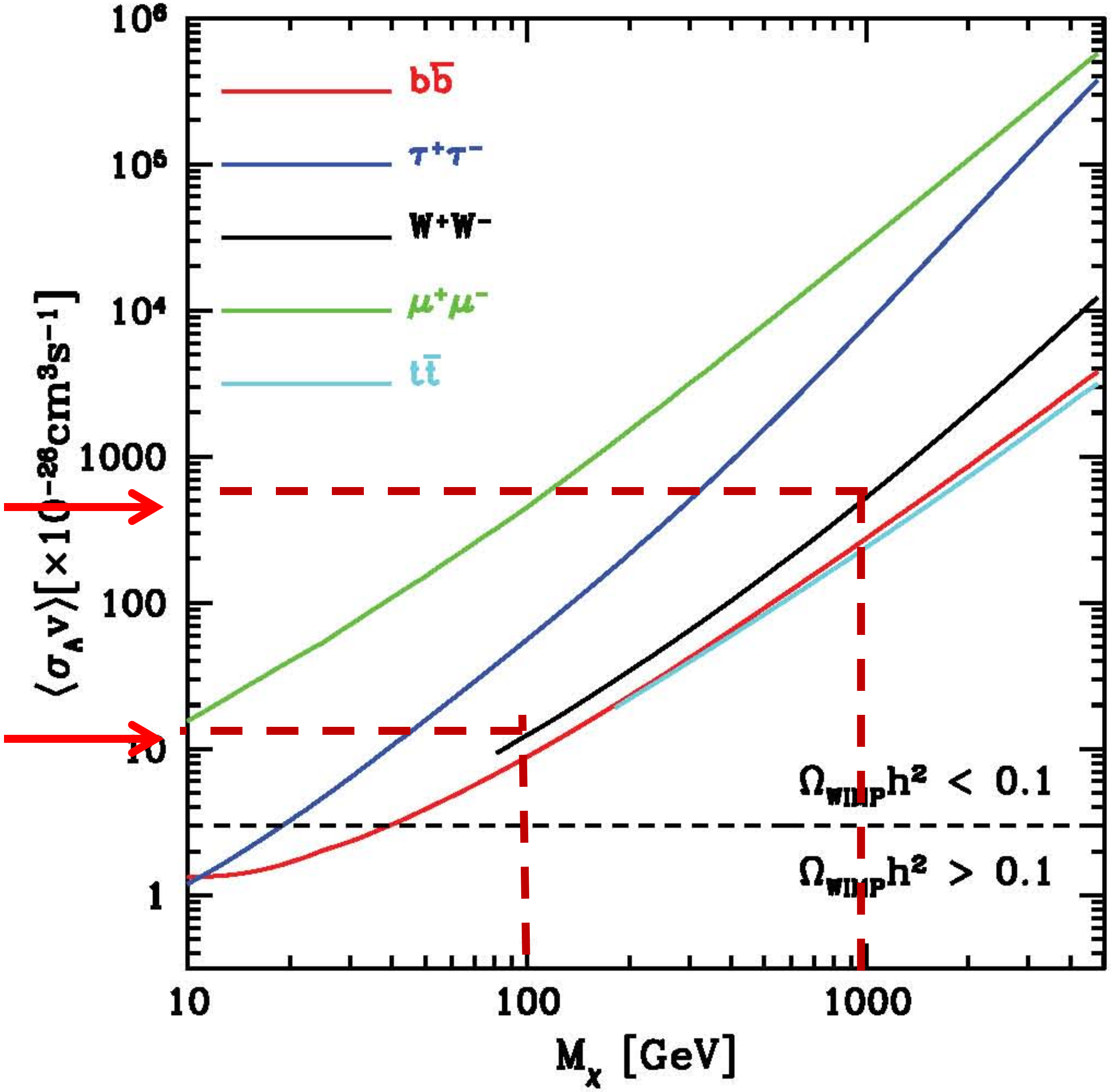
Gravitino DM Feng, Rajaraman, Takayama PRL 91, 011302 (2003)

Fermi constraints on $<\sigma_{ann}v>_0$ from dwarf spheroidals:

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

$$<\sigma_{ann}v> \leq 4\times10^{-24}\ cm^3s^{-1}$$

$$<\sigma_{ann}v> \leq 2\times10^{-25}\ cm^3s^{-1}$$



3) Generating baryon asymmetry of the universe.

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

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

$$\left(\frac{s_{after}}{s_{before}}\right)_{\max} \sim \frac{M_P}{m_\phi} \ (>>10^{10})$$

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

BAU must be produced after the decay:

Non-thermal post-sphaleron baryogenesis

R.A., Dutta, Sinha PRD 81, 053538 (2010)

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

R.A., Cicoli, Dutta, Sinha PRD 88, 095015 (2013)

1) Annihilation scenario:

$$T_r \sim O(GeV) \qquad\qquad m_\chi \leq O(TeV)$$

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

2) Branching scenario:

$$3\ MeV \leq T_r < 70\ MeV \qquad\qquad m_\chi \leq 200\ GeV$$

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:

$$W = W_{MSSM} + W_{extra}$$

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

SM singlet

Color triplet $Y = \pm\frac{4}{3}$

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

R-parity conservation: N fermions & $X, \overline{X}$ scalars have $R = +1$.

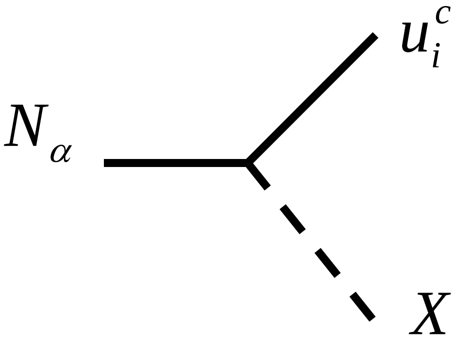
Possibilities:

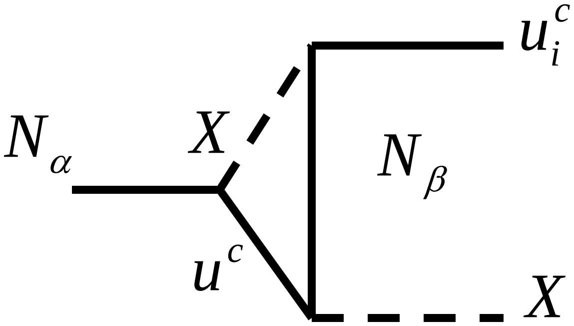
1) Baryogenesis from decays of N

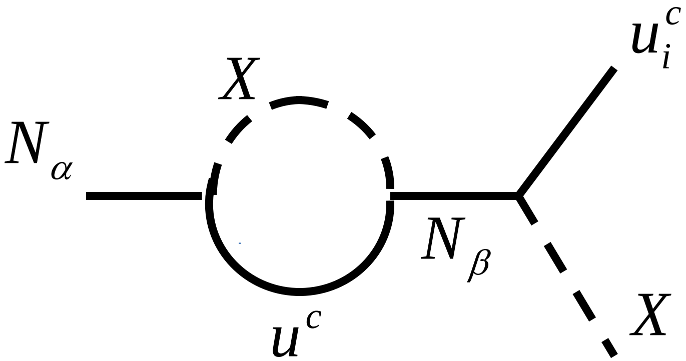
2) Baryogenesis from decays of $X, \overline{X}$

Consider decay of N fermions, assuming $M_N > M_X$:

R.A., Dutta, Sinha PRD 82, 035004 (2010)







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

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

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

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

$$\Rightarrow \varepsilon_\alpha \sim O(0.1)$$

Visible sector scalar can solve both of these issues.

If ϕ 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 ϕ.
2) Suitable kinematic relations.

Example: ϕ 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 χ suppressed by loop and/or phase space factors.

R.A., Dutta, Sinha PRD 87, 075024 (2013)

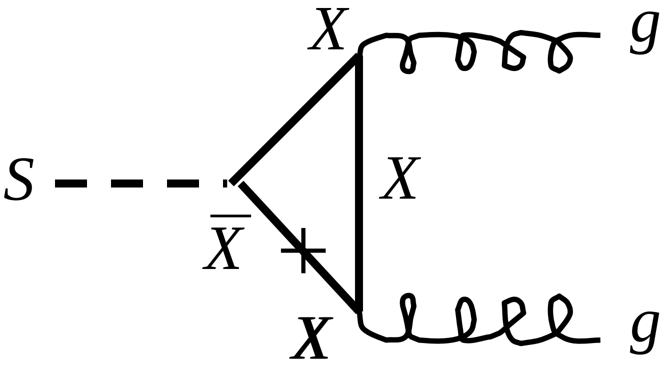
Question: How does ϕ fit in a realistic extension of the SM?

$$W = W_{MSSM} + hS\bar{X}X + \lambda N X u^c + \lambda' \bar{X} d^c d^c + \frac{m_S}{2} S^2 + m_X X\bar{X} + \frac{m_N}{2} N^2$$

R.A., Dutta, Sinha arXiv:1212.6948

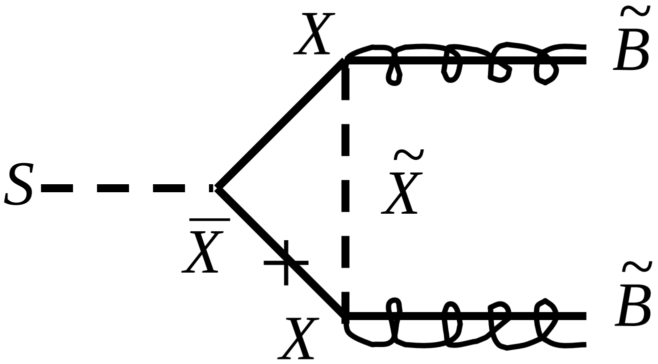
Singlet Color Triplet Singlet

$Y = \pm 4/3$



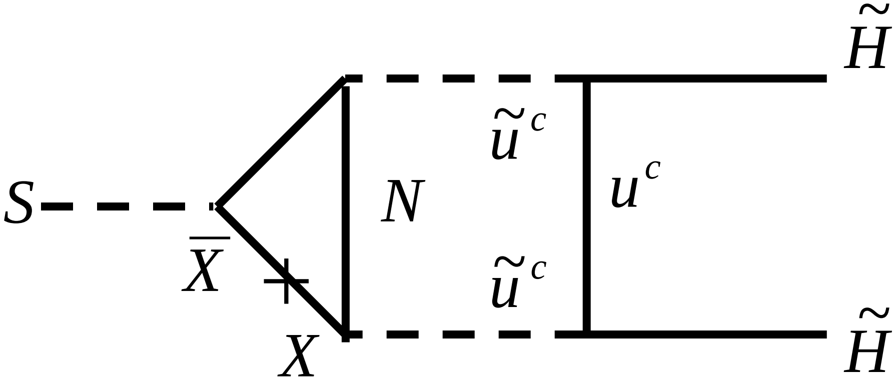
$m_S \sim O(TeV)\ ,\ m_\chi \leq 500\ GeV$

$m_X \sim 10 - 100\ TeV$



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

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



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