Non-thermal Dark Matter and Baryogenesis

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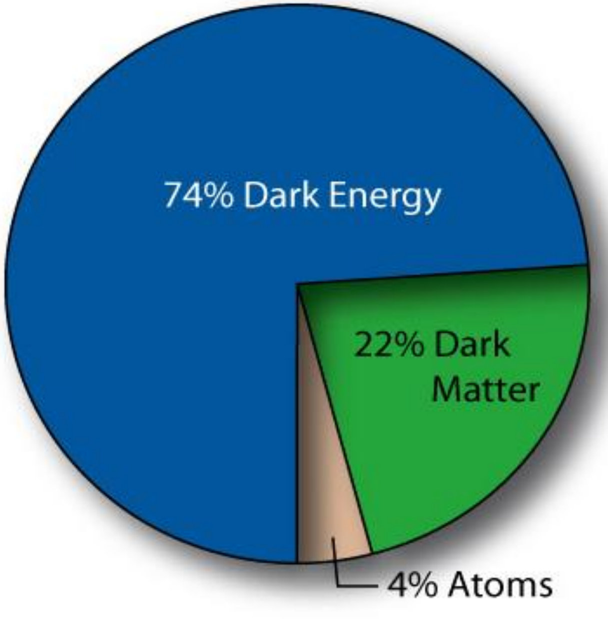
Outline:

- Introduction
- Non-thermal dark matter from moduli decay
- Post-sphaleron baryogenesis
- Non-thermal Higgsino dark matter
- Cladogenesis
- Non-thermal dark matter from visible sector decay
- Summary and outlook

Introduction:

The present universe according to observations:



Two big problems to address:

1) Dark Matter (DM)

What is the nature of DM?

2) Baryon Asymmetry of the Universe (BAU

How is it produced?

Important consequences:

Particle Physics (beyond the SM)

Cosmology (thermal history)

Suitable DM candidate:
Weakly Interacting Massive Particle (WIMP)

Well motivated:
1) Typical in physics beyond the SM (LSP, LKP, …).

2) WIMP miracle.

WIMPs are focus of current worldwide experimental DM searches:
1) Direct detection.

2) Indirect detection.

3) Collider production.

Non-WIMP candidates: sterile neutrino, axion, axino, gravitino, …
In this talk, we will only discuss WIMPs.

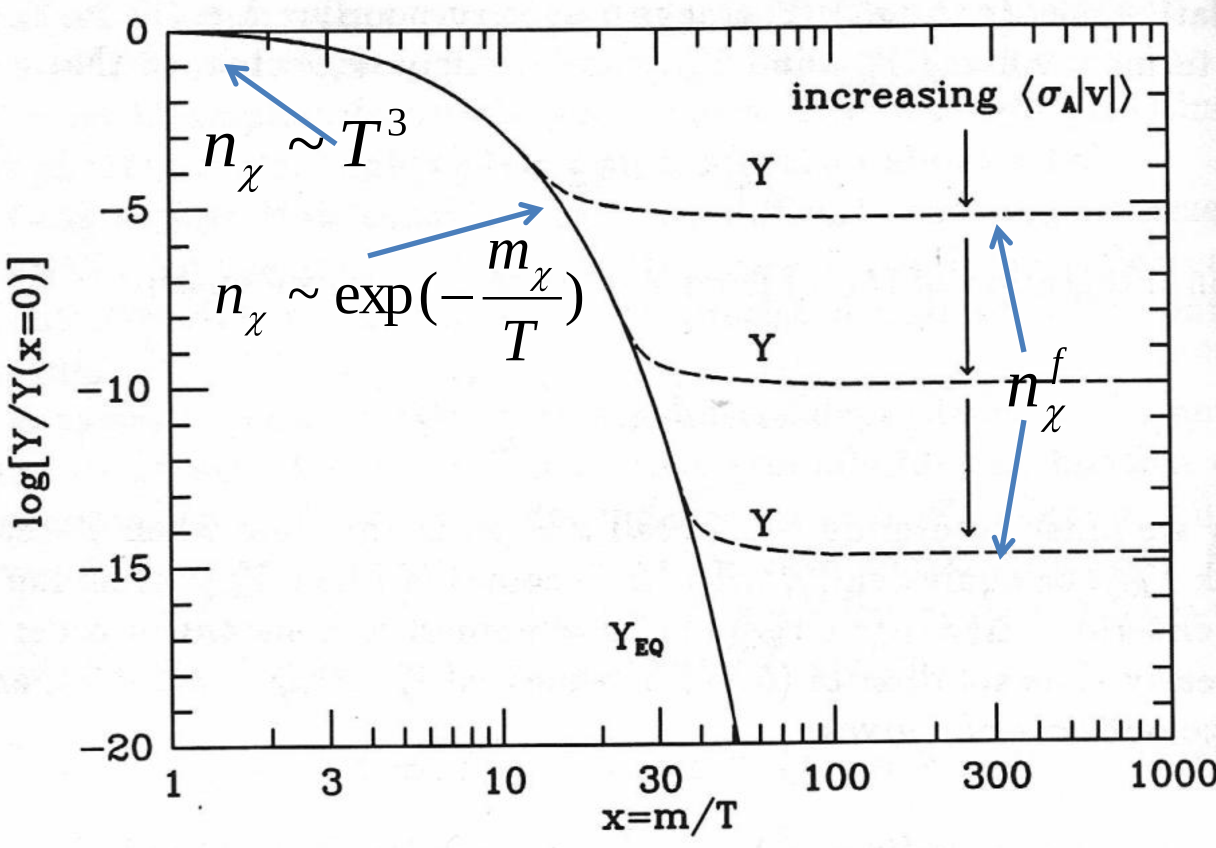
WIMP Miracle:

Thermal freeze-out sets the WIMP relic abundance:

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

$$\Omega_\chi \propto \frac{1}{<\sigma_{ann} v>_f} \quad \Rightarrow <\sigma_{ann} v>_f = 3\times 10^{-26} cm^3/\sec$$

"The Early Universe" Kolb & Turner



Assuming:

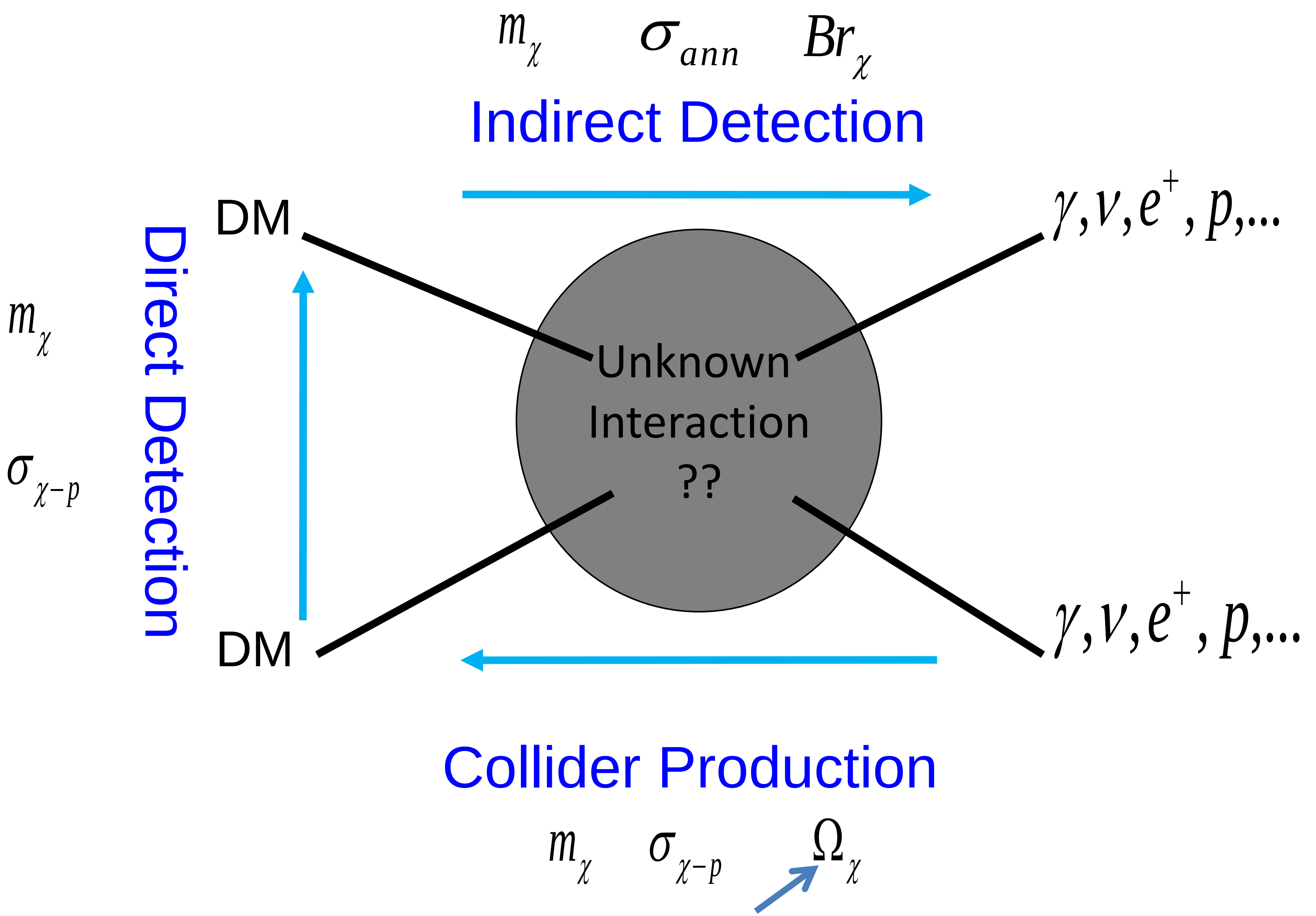
$$<\sigma_{ann} v>_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$$

Correct abundance for:

$$\alpha_\chi \sim O(10^{-2})$$

$$m_\chi \sim (100 - 1000)\ GeV$$

Dark Matter Searches:



Probing thermal history of the universe

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

DM as the strongest probe of the early universe.

Currently, the best experimental probes are:

1) CMB, t ~ 400,000 yr

2) BBN, t ~ 1 sec

Confirm that the universe was in **thermal equilibrium** at the epochs of recombination and nucleosynthesis.

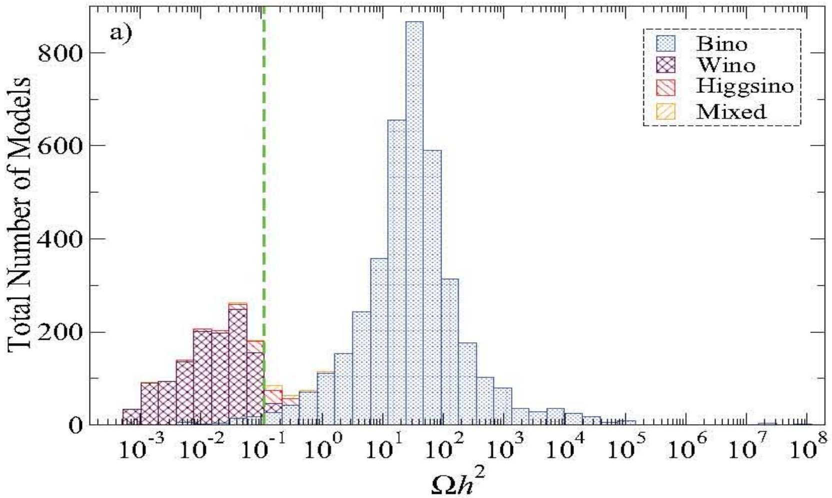
WIMP miracle, if confirmed, will prove that the universe was in thermal equilibrium at t ~ 10^{-7} sec.

Non-thermal mechanisms for DM production required otherwise.

Thermal dark matter is an attractive scenario:

1) Predictive.

2) Independent from reheating.

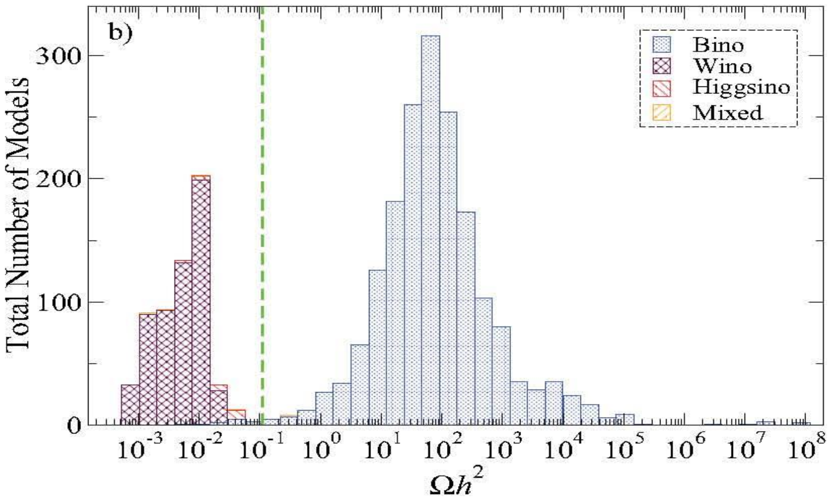


But, not very generic model-wise.

For example, consider MSSM.

A simplified version:
SUGRA with 19 parameters.

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



WIMP miracle needs real miracle!

Non-thermal DM from Moduli Decay:

Thermal freeze-out does not yield the correct density if:

$$<\sigma_{ann} v>_f \neq 3\times 10^{-26} cm^3/\sec$$

Example: Higgsino DM (e.g., arising in natural SUSY)

It is known that:

$$m_\chi < 3\ TeV \ \Rightarrow <\sigma_{ann} v>_f \ > 3\times 10^{-26} cm^3/\sec$$

Thermal underproduction of sub-TeV Higgsino

Question:
How to obtain the correct relic abundance?

Scenario:
Late decay of a scalar field that reheats the universe below T_f .

Dilution factor from decay of a scalar τ with mass m_τ and reheating temperature T_r :

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

The abundance of non-thermally produced DM:

$$\frac{n_\chi}{s} = \min\left[\left(\frac{n_\chi}{s}\right)_{th}\left(\frac{T_f}{T_r}\right),\ Y_\tau\ Br_\chi\right]$$

Decay + Annihilation Decay

$Br_\chi \equiv$ Branching ratio for producing R-parity odd particles

$$\left(\frac{n_\chi}{s}\right)_{th} = \left(\frac{n_\chi}{s}\right)_{obs} \frac{3\times10^{-26}cm^3s^{-1}}{<\sigma_{ann}v>_f} \qquad \left(\frac{n_\chi}{s}\right)_{obs} \approx 5\times10^{-10}\left(\frac{1\ GeV}{m_\chi}\right)$$

Thermal underproduction (e.g., sub-TeV Higgsino DM):

$$<\sigma_{ann}v>_f \; > 3\times 10^{-26}\ cm^3/\sec \Rightarrow \left(\frac{n_\chi}{s}\right)_{th} < \left(\frac{n_\chi}{s}\right)_{obs}$$

1) "Decay + Annihilation" scenario. Requirement:

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

2) "Decay" scenario. Requirement:

$$Br_\chi = \left(\frac{n_\chi}{s}\right)_{obs} Y_\tau^{-1}$$

Typically $Br_\chi \ll 1$ needed.

Thermal overproduction (e.g., Bino DM in the bulk region):

$$< \sigma_{ann} v >_f \; < 3 \times 10^{-26} \; cm^3 / \sec \Rightarrow \left(\frac{n_\chi}{s} \right)_{th} > \left(\frac{n_\chi}{s} \right)_{obs}$$

"Decay + Annihilation" does not work, since it yields:

$$\left(\frac{n_\chi}{s} \right)_{th} \left(\frac{T_f}{T_r} \right) > \left(\frac{n_\chi}{s} \right)_{obs}$$

"Decay" the only viable scenario. Requirement:

$$Br_\chi = \left(\frac{n_\chi}{s} \right)_{obs} Y_\tau^{-1}$$

$Br_\chi << 1$ results in a non-trivial constraint for model building.

Moduli fields a natural candidate for τ :

Commonly arise in SUSY and string-inspired models.

$$\Gamma_\tau = \frac{c}{2\pi}\frac{m_\tau^3}{M_P^2} \qquad\qquad c \sim 0.1-1$$

Moduli dynamics in the early universe:

1) Displaced during inflation

2) Oscillate when $H \approx m_\tau$

3) Reheat the universe

$$T_r \sim \left(\frac{m_\tau}{50\ TeV}\right)^{3/2} (3\ MeV)$$

$T_r > 3\ MeV$ required by BBN

$m_\tau > 50\ TeV \Rightarrow$ Potential handicap turned into virtue

Constraints:

1) BAU should be created after moduli decay.

Substantial dilution of existing asymmetry $Y_\tau \sim 10^{-7}$, necessary if modulus is the inflaton.

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

Post-sphaleron baryognenesis

2) Gravitinos should not be overproduced in moduli decay.

Gravitino decay to DM the major constraint for $m_{3/2} > 40\ TeV$:

$$\left(\frac{n_{3/2}}{s}\right) < 5 \times 10^{-10} \left(\frac{1\ GeV}{m_\chi}\right) \qquad \left(\frac{n_{3/2}}{s}\right) = Y_\tau Br_{3/2}$$

$$\boxed{Br_{3/2} << 1}$$

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 $R = +1$.

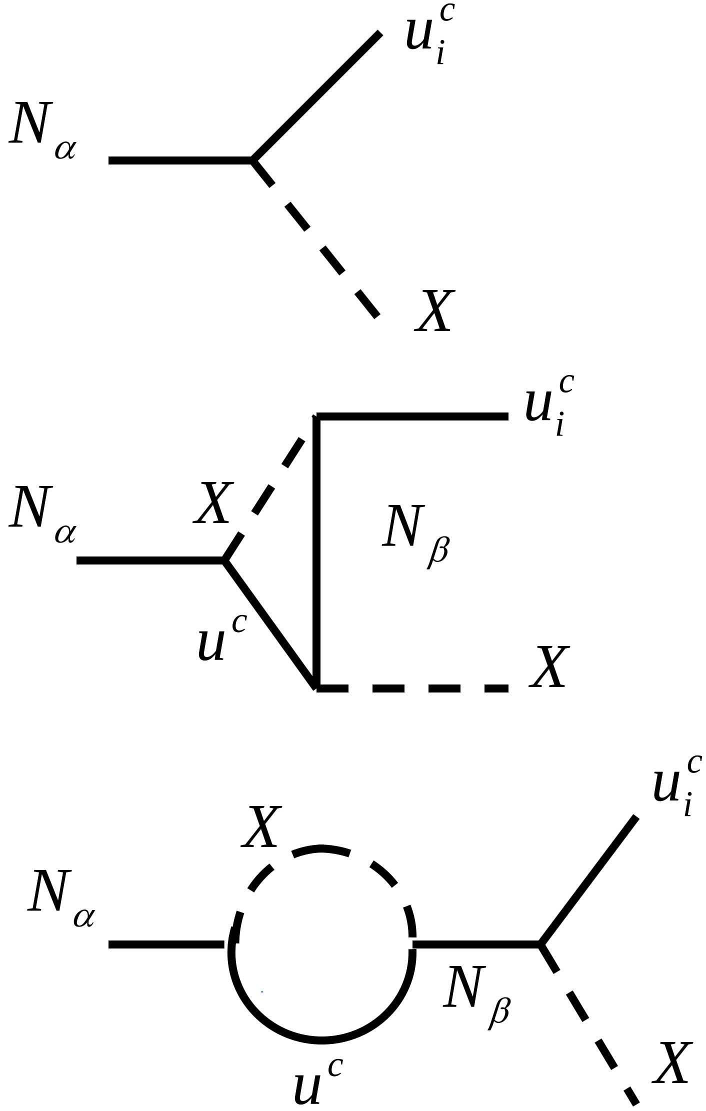
Possibilities:

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)



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

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

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

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

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

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} = Y_\tau \ \varepsilon_N \ Br_N$$

$$Y_\tau \sim 10^{-7} \quad , \quad \varepsilon_N \sim 10^{-1}$$

Observed value $\eta \sim 10^{-10}$ can be obtained if:

$$Br_N \sim 10^{-2}$$

Simplest possibility:

$O(100)$ R-parity even fields in MSSM (plus $N, X, \bar{X}$).

$Br_N \sim 10^{-2}$ arises as a result of democratic decay of modulus.

Non-thermal Higgsino DM:

Sub-TeV Higgsino has small thermal abundance.

Can naturally arise as the DM candidate in mirage mediation.

R.A., Dutta, Sinha arXiv:1208.0115, PRD (in press)

Consider:

$$m_{3/2} > 40\ TeV$$

Will solve the gravitino problem since $\tau_{3/2} < 0.1\ \sec$.

Anomaly mediation contribution to gaugino masses:

$$(4\pi^2)^{-1} m_{3/2} > O(TeV)$$

Giudice, Luty, Murayama, Rattazzi JHEP 9812, 027 (1998)

Bino and Wino masses are above TeV if anomaly and modulus contributions are comparable in size.

Higgsino mass depends on the μ parameter, can be under TeV.

Gaugino masses in mixed anomaly/modulus scenario:

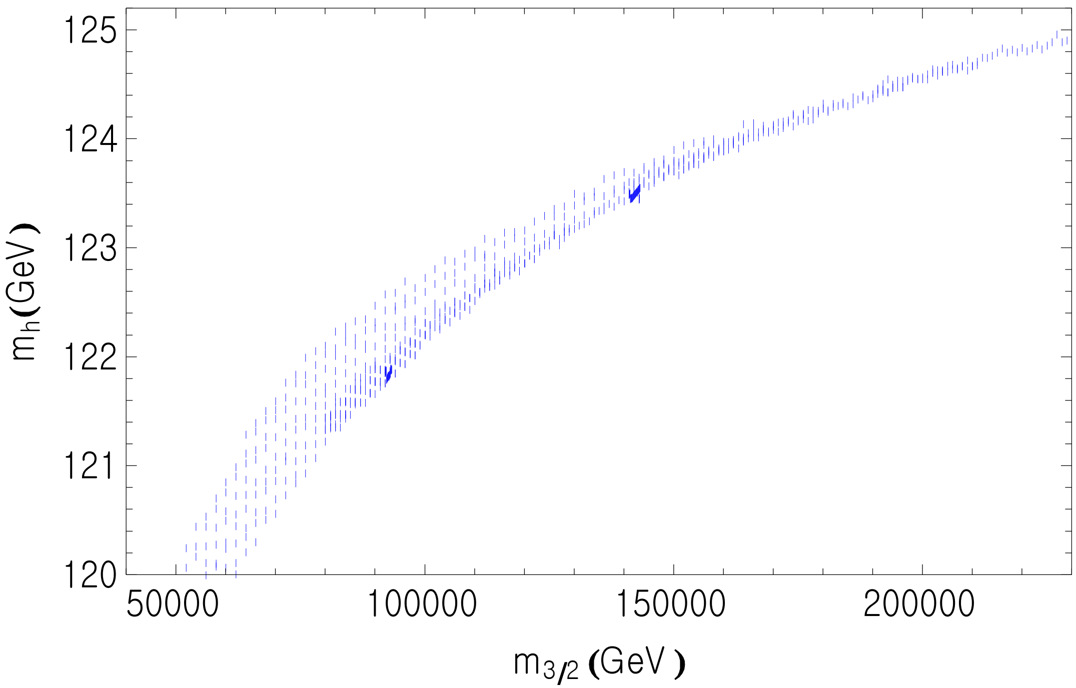
$$M_3 : M_2 : M_1 \ \sim \ (1-0.3\alpha)g_3^2 : (1+0.1\alpha)g_2^2 : (1+0.66\alpha)g_1^2$$

$$\alpha \equiv \frac{m_{3/2}}{M_0 \ln(M_P / m_{3/2})}$$: Ratio of anomaly to modulus mediated contribution

Modulus mediated contribution at GUT scale

Choi, Lee, Shimizu, Kim, Okumura JCAP 0612, 017 (2006)

Sub-TeV Higgsino comptible with $\sim 125\ GeV$ Higgs can be obtained for suitable values of α .

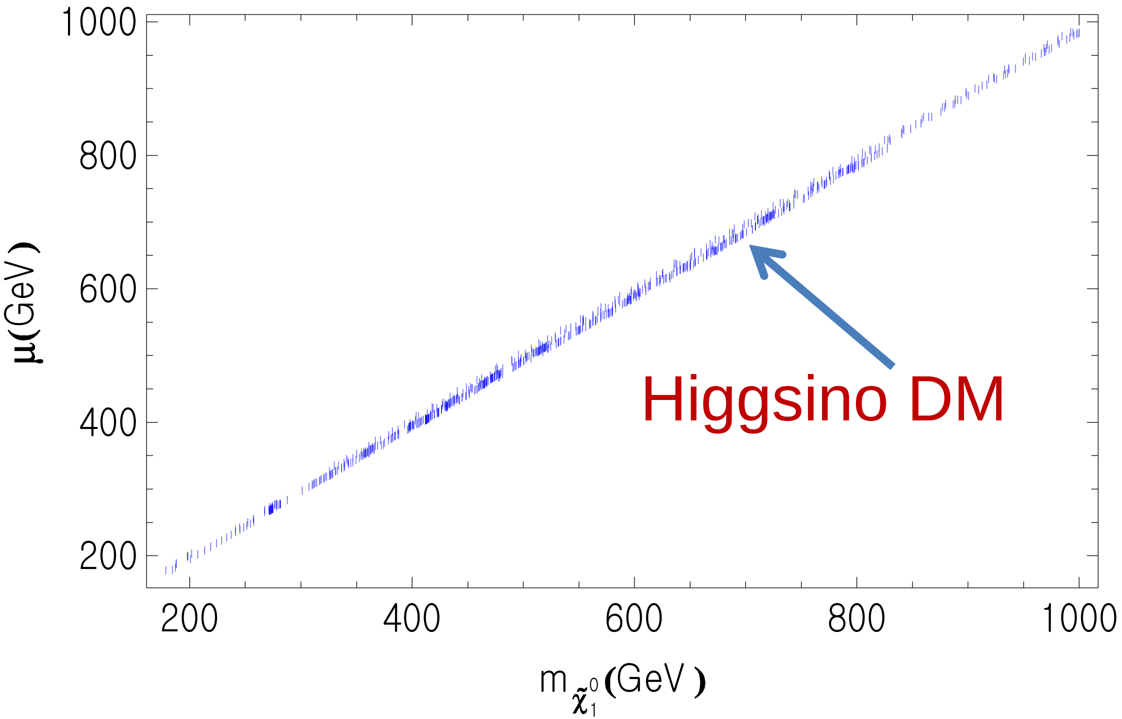


Parameter scan:

$$0.1 < \alpha < 1.6$$

$$\tan\beta = 50 \ , \ n_m = \frac{1}{2}$$

Similar behavior for other values of $\tan\beta, n_m$



R.A., Dutta, Sinha
arXiv:1208.0115, PRD (in press)

Thermal underproduction of sub-TeV Higgsino:

$$<\sigma_{ann} v>_f \; > 3\times 10^{-26}\ cm^3/\sec \Rightarrow \left(\frac{n_\chi}{s}\right)_{th} < \left(\frac{n_\chi}{s}\right)_{obs}$$

"Decay + Annihilation" scenario can work. Correct relic density if:

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

Annihilates mainly into W final state. S-wave process, implying:

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

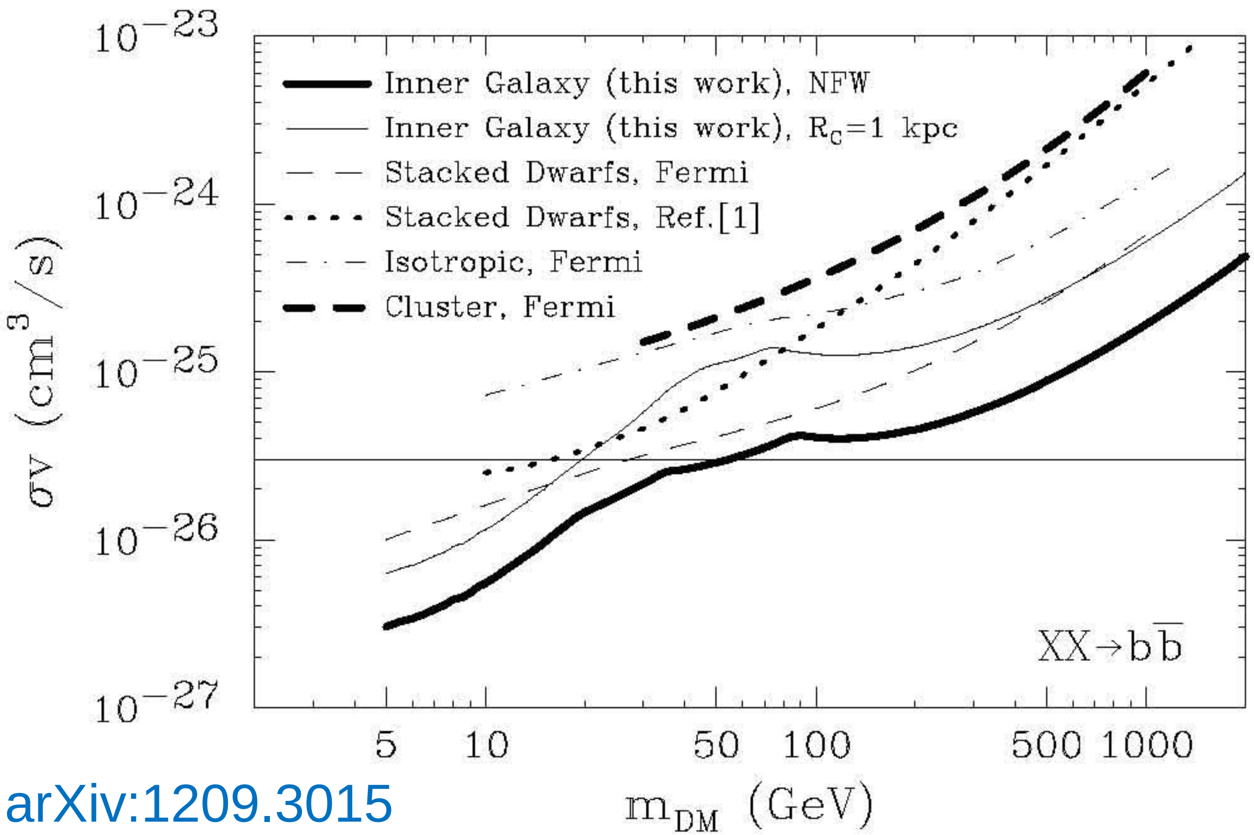
$<\sigma_{ann} v>_f$ is subject to bounds from indirect searches.

$< \sigma_{ann} v >_0$ is constrained by indirect searches:

Fermi (gammay-ray signal)
IceCube (neutirno signal)

Strongest bounds provided by Fermi:

Gamma-rays from:
Dwarf spheroidals
Galactic center
Clusters



Hooper, Kelso, Quieroz arXiv:1209.3015

Fermi bounds from dwarf spheroidals:

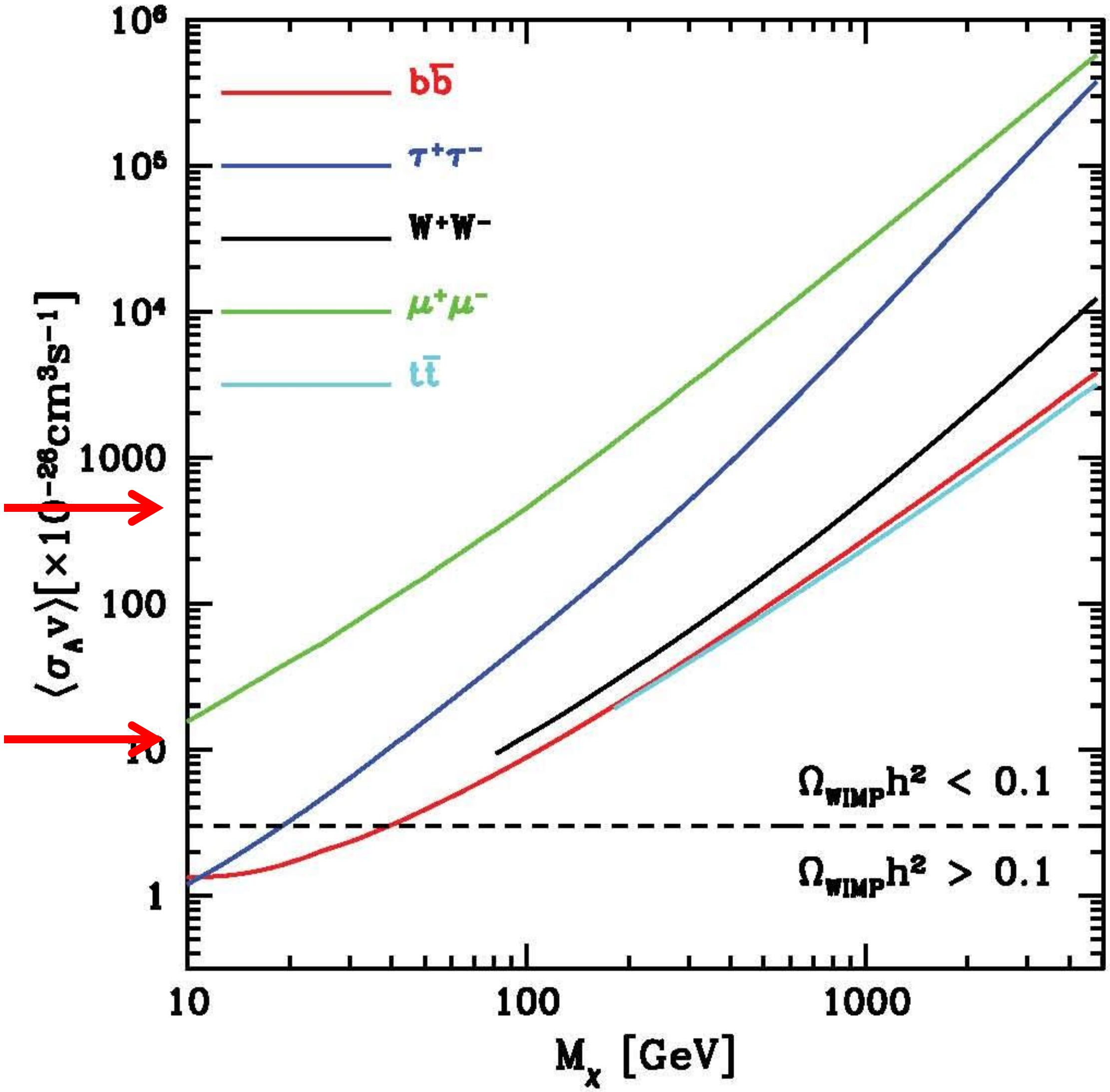
Geringer-Sameth, Koushiappas PRL 107, 241303 (2011)

$m_\chi = 1\ TeV:$

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

$m_\chi = 100\ GeV:$

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



These bounds together with $T_f \sim m_\chi / 25$ require that:

$$T_r \sim O(GeV)$$

Resulting modulus mass:

$$m_\tau \sim O(1000)\ TeV$$

Within the expected range in mirage mediation:

$$m_\tau : m_{3/2} : M_{\tilde{g}} \sim 4\pi^2$$

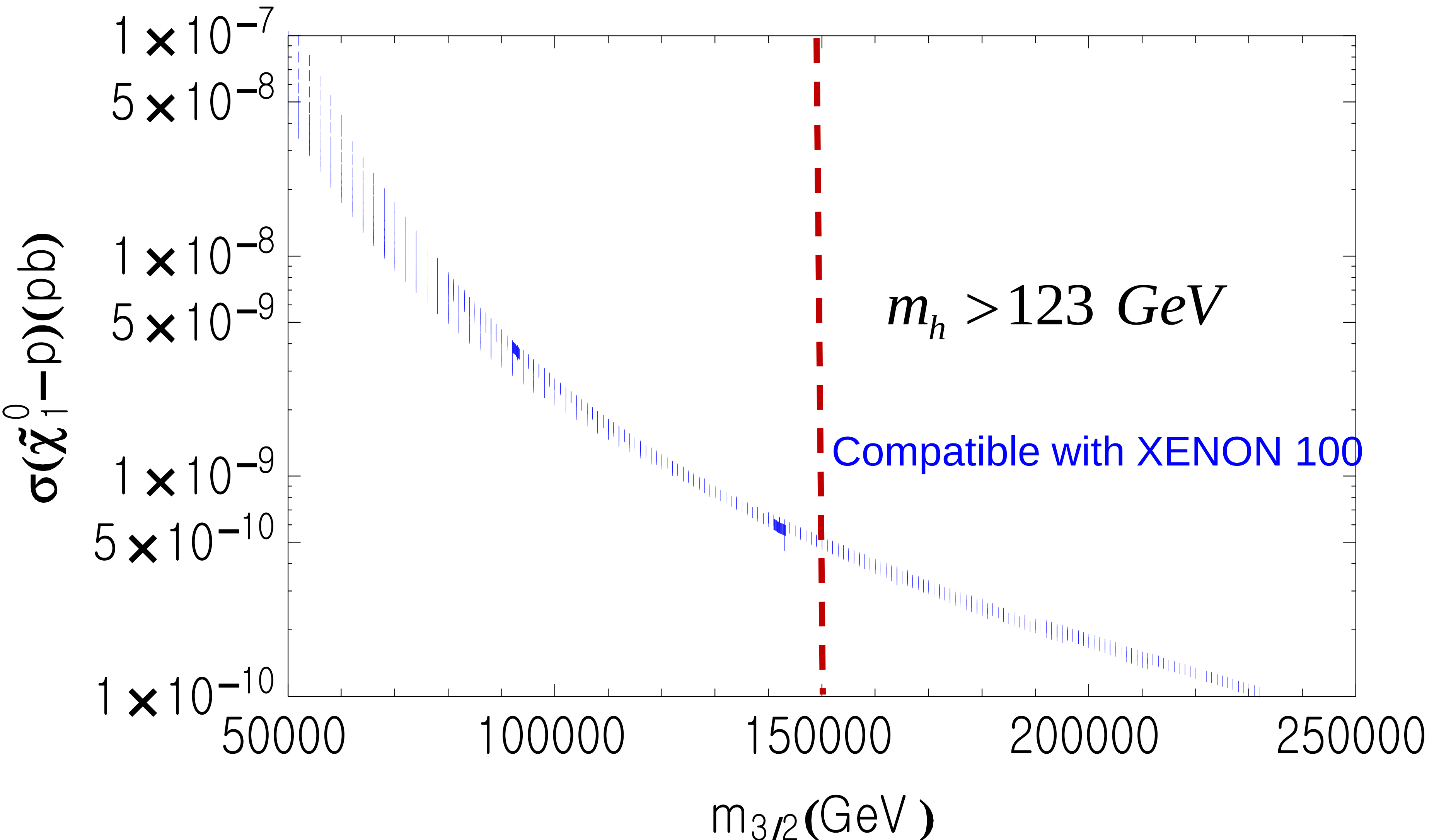
Such $m_\tau / m_{3/2}$ typical in non-perturbative stabilization schemes.

Conlon, Quevedo JHEP 0606, 029 (2006)

Successful non-thermal Higgsino DM within mirage mediation.

α	$m_{3/2}$	m_h	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$\langle \sigma_{\rm ann} v \rangle_0$ (cm^3/s)	$\langle \sigma_{\rm ann} v \rangle_f$ (cm^3/s)	T_f/T_d	$\sigma_{\tilde{\chi}_1^0 - p}$ (pb)
1.49	$143 \cdot 10^3$	123.5	248.4	250.8	3828	2441	2781	$1.49 \cdot 10^{-25}$	$1.63 \cdot 10^{-25}$	~ 6	$5 \cdot 10^{-10}$
1.46	$200 \cdot 10^3$	124.5	258.9	260.6	5536	3564	3991	$1.38 \cdot 10^{-25}$	$1.52 \cdot 10^{-25}$	~ 3.4	$1.4 \cdot 10^{-10}$
1.44	$232 \cdot 10^3$	125	306	308	6505	4197	4677	$1.01 \cdot 10^{-25}$	$1.01 \cdot 10^{-25}$	~ 3.2	$8.9 \cdot 10^{-11}$

R.A., Dutta, Sinha arXiv:1208.0115, PRD (in press)



DM from Gravitino Decay:

$$\left(\frac{n_{3/2}}{s}\right) = Y_\tau Br_{3/2} < 5\times 10^{-10}\left(\frac{1\ GeV}{m_\chi}\right)$$

$$m_\chi \sim O(100)\ \ GeV \quad , \quad Y_\tau \sim 10^{-6} \Rightarrow Br_{3/2} < 10^{-5}$$

Modulus decay the main source of gravitinos.

Endo, Yamaguchi, Yoshioka PRD 72, 015004 (2005)

For mirage mediation in the KKLT model:

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

$$\Gamma_{\tau\to\tilde{G}\tilde{G}} \sim \frac{1}{288\pi}\frac{m_\tau^3}{M_P^2} \Rightarrow Br_{3/2} \sim 10^{-2}$$ Too large

The simplest model (KKLT) is not quite successful.

One needs to modify this model in order to suppress $Br_{3/2}$.

The main issue is with helicity 1/2 gravitinos.

Dine, Kitano, Morrise, Shirman PRD 73, 123518 (2006)

In general, we have:

$$\Gamma_{\tau \to \tilde{G}\tilde{G}} \sim \frac{1}{288\pi}\left(|G_{\tau}|^2 K^{-1}\right)\frac{m_{\tau}^2}{m_{3/2}^2}\frac{m_{\tau}^3}{M_P^2} \quad , \quad G = K + \ln|W|^2$$

Modulus contribution to soft masses have a different functional dependence on K, G .

Modifying K can successfully suppress $Br_{3/2}$.

Cladogenesis:

BAU and DM densities correlated in "Decay" scenario:

$$\eta_B = Y_\tau \; Br_N \; \varepsilon_N \qquad\qquad \frac{n_\chi}{s} = Y_\tau \; Br_\chi$$

Densities mainly controlled by Y_τ .

Ratio of Ω_{DM} and Ω_B determined by branching ratios:

$$\frac{\Omega_{DM}}{\Omega_B} \sim 10 \; \frac{Br_\chi}{Br_N} \left(\frac{m_\chi}{1 \; GeV} \right) \qquad\qquad (\varepsilon_N \sim 0.1)$$

The coincidence puzzle addressed for $m_\chi \sim 5 - 500 \;\; GeV$ if:

$$Br_\chi \sim (10^{-3} - 10^{-1}) Br_N$$

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

How natural is this relation?

Recall:

$$Br_N \sim (10^{-2} - 1)$$

The coincidence problem can be solved for:

$$Br_\chi \geq 10^{-3}$$

2-body decays to R-parity odd particles can be suppressed.

Moroi, Randall NPB 570, 455 (2000)

3-body decays inevitably produce R-parity odd particles.

Phase space suppression $Br_{3-body} \sim O(10^{-3})$, yielding a lower bound $Br_\chi \geq O(10^{-3})$.

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

Requirements to get the correct DM relic abundance:

$$Y_\tau \sim (10^{-9} - 10^{-7}) \quad , \quad Br_\chi \sim (10^{-3} - 10^{-1})$$

How to suppress Y_τ ?

$$Y_\tau \sim c^{1/2} \left(\frac{m_\tau}{50 \ TeV} \right)^{3/2} 10^{-7}$$

Recall that $m_\tau \geq 50 \ TeV$ required by BBN, hence:

$$Y_\tau \sim 10^{-9} \Rightarrow c << 1$$

Geometrical suppression of modulus decay

How to suppress Br_{χ} from 2-body decays?

For example, consider τ decay to gauge fields and gauginos:

$$\frac{\Gamma_{\tau\to\tilde{g}\tilde{g}}}{\Gamma_{\tau\to gg}} = \frac{<\partial_{\tau}F^{\tau}>^2}{<\tau>^2} \qquad F^{\tau} = e^{K/2} D_{\tau^+} K^{\tau\tau^+}$$

Suppression of gaugino production: $<\partial_{\tau}F^{\tau}> << <\tau>$

Suppression of gravitino production: $Br_{3/2} < 10^{-3}$

For $m_{\chi} \sim O(100)\ GeV$ the total decay rate, as well as gaugino/gravitino production, must be suppressed.

Non-thermal DM from Visible Sector Decay:

DM from moduli decay requires:

1) Suppression of gravitino production

2) Suppression of R-parity odd particles

May be achieved naturally if τ is a visible sector field:

$Br_{3/2} << 1$ due to gravitationally suppressed coupling

$Br_{\chi} << 1$ due to kinematic suppression

For example, consider the case $2m_{\chi} < m_{\tau} < m_{\chi} + m_{NLSP}$.

1) Decay to gravitinos forbidden.

2) Decay to χ suppressed by loop/phase space factors.

R.A., Dutta, Sinha in preparation

Summary and Outlook:

- Thermal WIMP scenario attractive, but under increasing stress.
- Non-thermal DM production from late decay a viable scenario.
- Decay scenario typically requires late-time baryogenesis also.
- Moduli decay a natural candidate for DM production.
- Possible scenarios: “Decay + Annihilation” and “Decay”.
- Constraints from indirect searches and gravitino production.
- Explicit model: non-thermal Higgsino DM in mirage mediation.
- Cladogenesis as a possible solution to the coincidence puzzle.
- Visible sector decay can relax some of the constraints.