PLANCK, Thermal History, and WIMP Dark Matter

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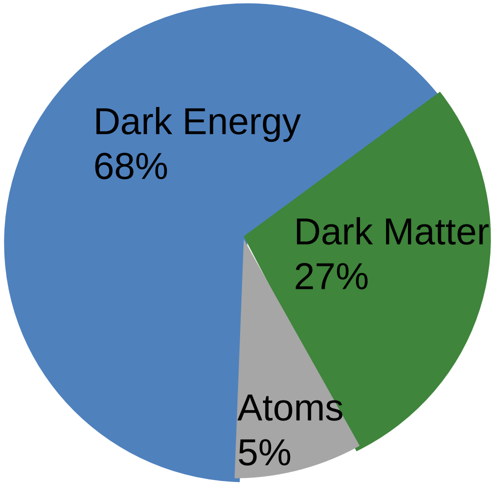
Outline:

- Introduction
- Constraining special models with PLANCK
- Thermal dark matter
- Non-thermal dark matter
- Outlook

Introduction:

The present universe according to observations:



Two big problems to address:

1) Dark Matter (DM)

What is the nature of DM?

How was it produced?

2) Baryon Asymmetry of Universe (BAU)

How was it generated?

Profound consequences for:

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.

In this talk, we will not discuss non-WIMP candidates
(sterile neutrino, axion, axino, gravitino, …)

The best experimental probes of the early universe:

1) CMB, t ~ 400,000 yr

2) BBN, t ~ 1 sec

Confirm **thermal equilibrium condition** of relevant interactions at the onset of <u>recombination</u> & <u>nucleosynthesis</u>.

DM relic density can in principle be measured at colliders.

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

<u>Thermal equilibrium</u> at t ~ 10^{-7} sec

or

<u>Non-thermal mechanisms</u>

DM as the strongest probe of the thermal history of the universe

Constraining Special Models with PLANCK:

The obvious (and most reliable) piece of information is the DM relic abundance.

Other pieces of information may be obtained if:

DM annihilation affects neutrino decoupling N_{eff}

DM annihilation affects recombination and/or reiniozation τ

Important to note:

<u>Very special models</u>

<u>Assumptions needed to connect vastly different time scales</u>

Example: Light WIMP

Steigman arXiv:1303.0049

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

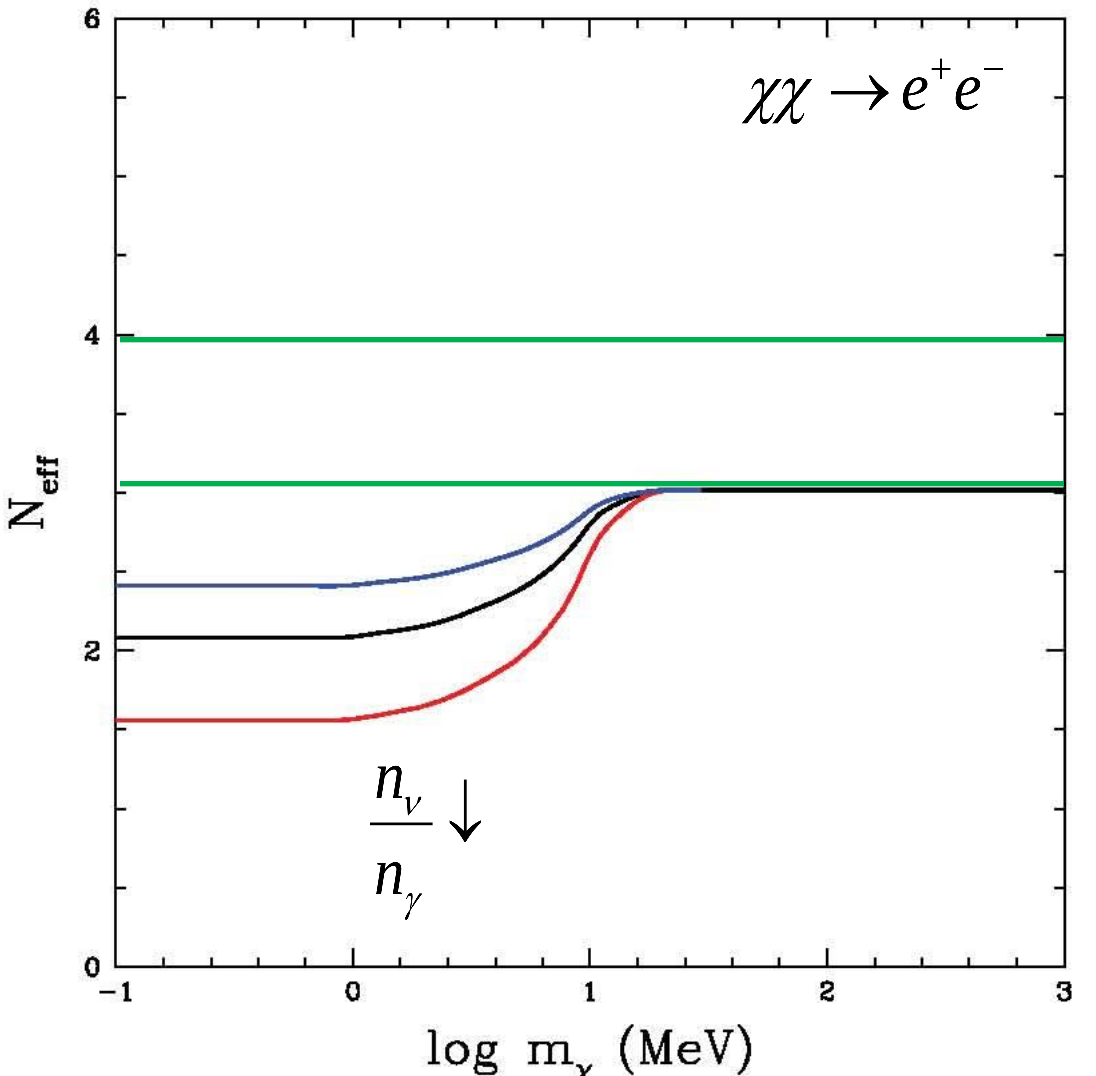
PLANCK+WP+HighL+H+BAO
95% CL

$$N_{eff} = 3.52^{+0.48}_{-0.45}$$

Scalar

Majorana

Dirac



Example: Light WIMP

Steigman arXiv:1303.0049

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

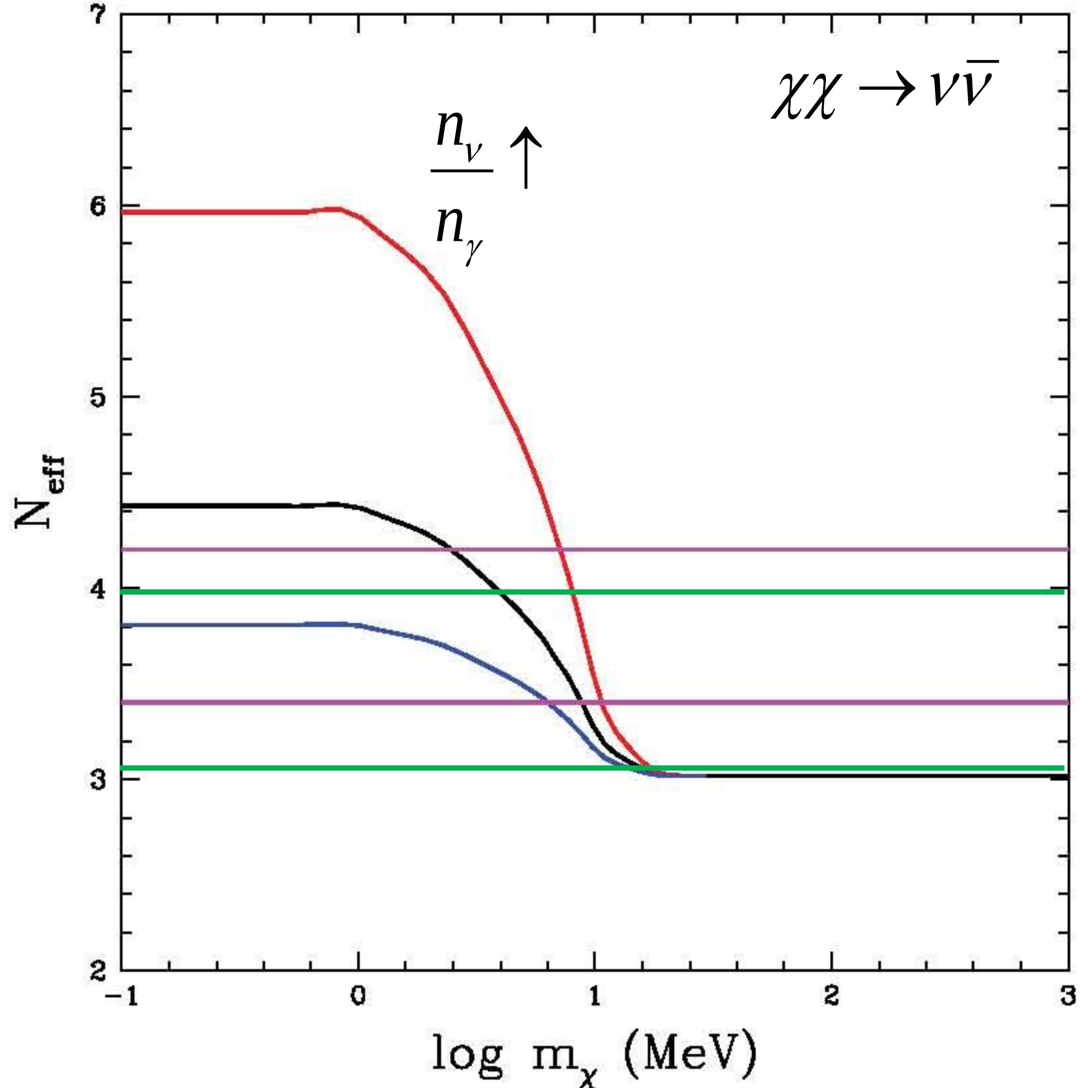
WMAP9
68% CL

PLANCK+WP+HighL+H+BAO
95% CL

Scalar

Majorana

Dirac



Example: Light leptophilic WIMP

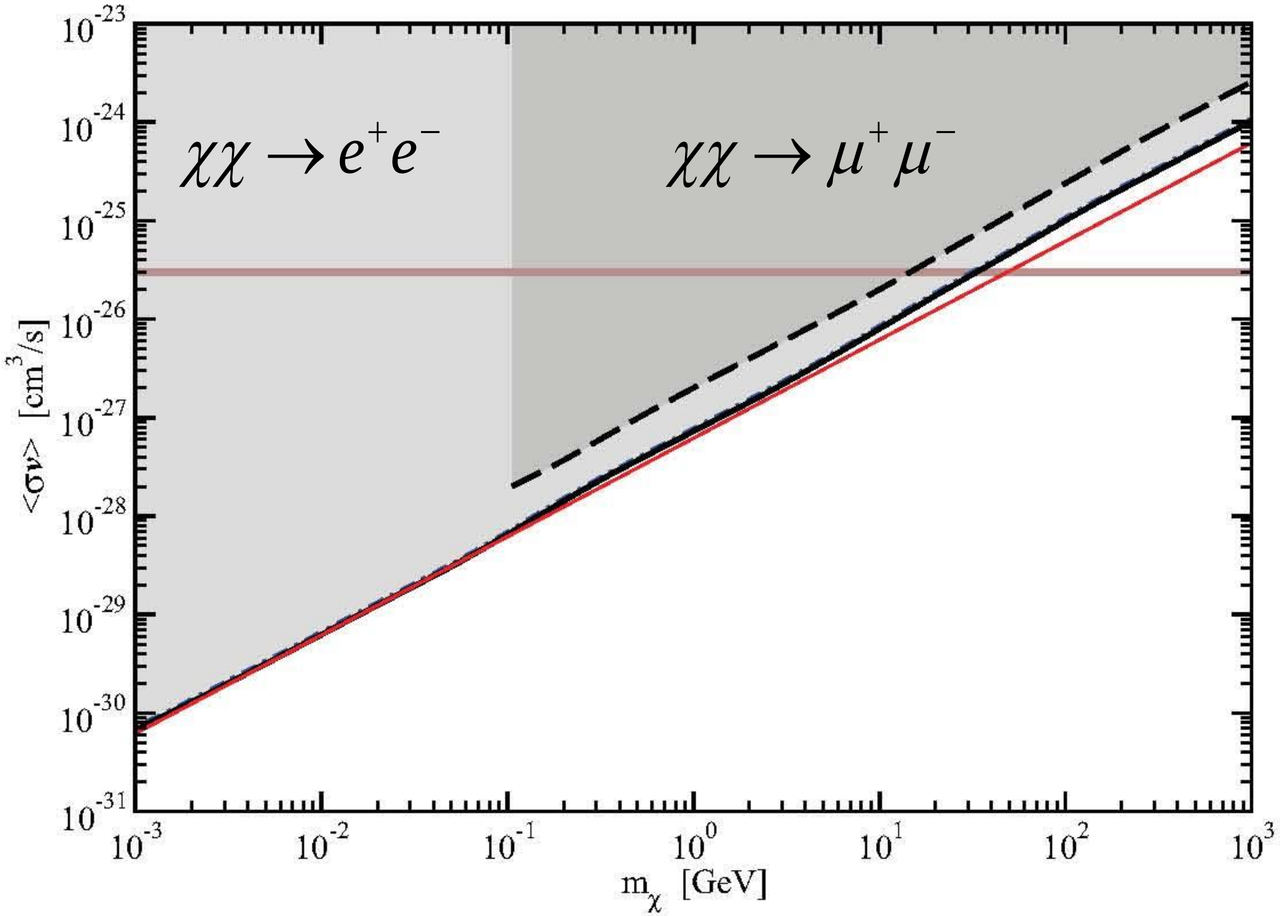
Lopez-Honorez, Mena, Palomares-Ruiz, Vincent arXiv:1303.5094

Assumption: S-wave dominates annihilation

WMAP9+SPT11+H+BAO
95% CL

Perfect energy deposition

Effective energy deposition



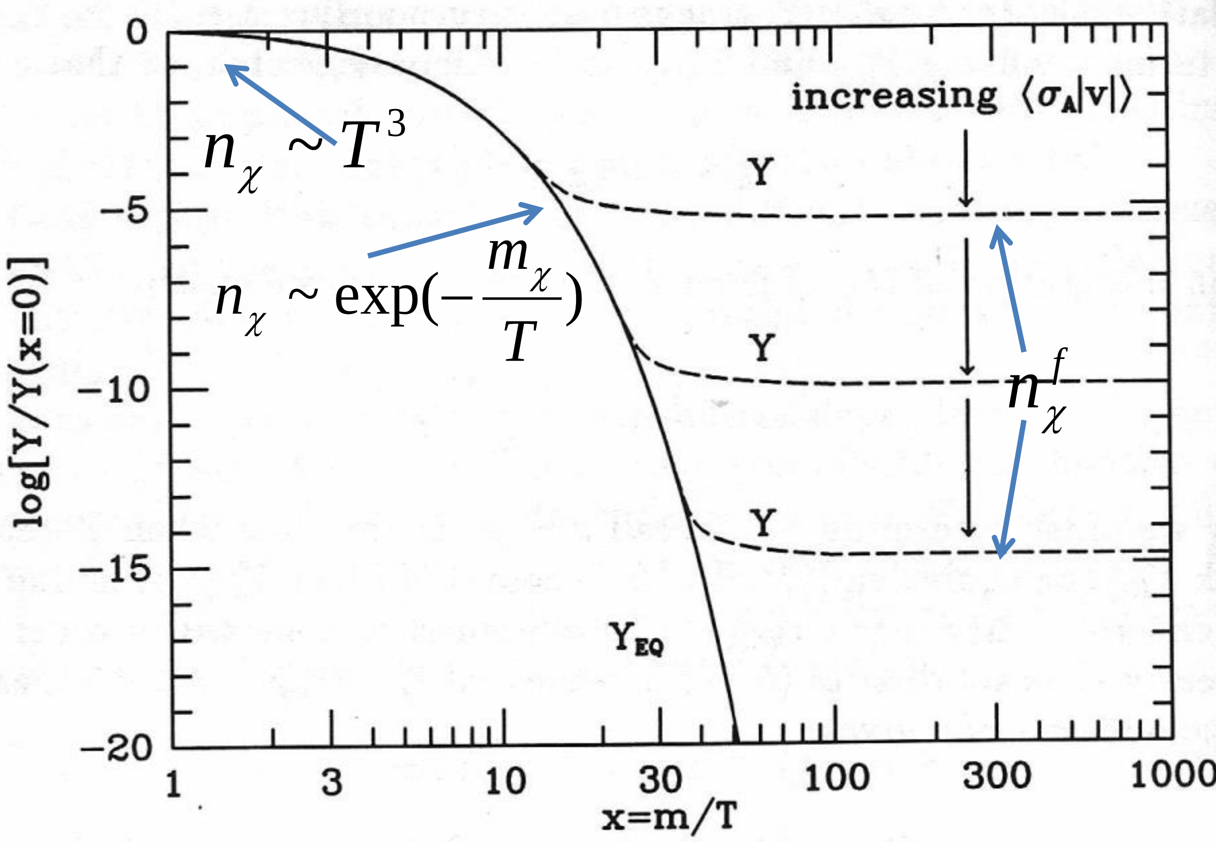
Thermal Dark Matter:

Thermal freeze-out sets the WIMP relic abundance:

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

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

"The Early Universe" Kolb & Turner



Assuming:

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

Correct abundance for:

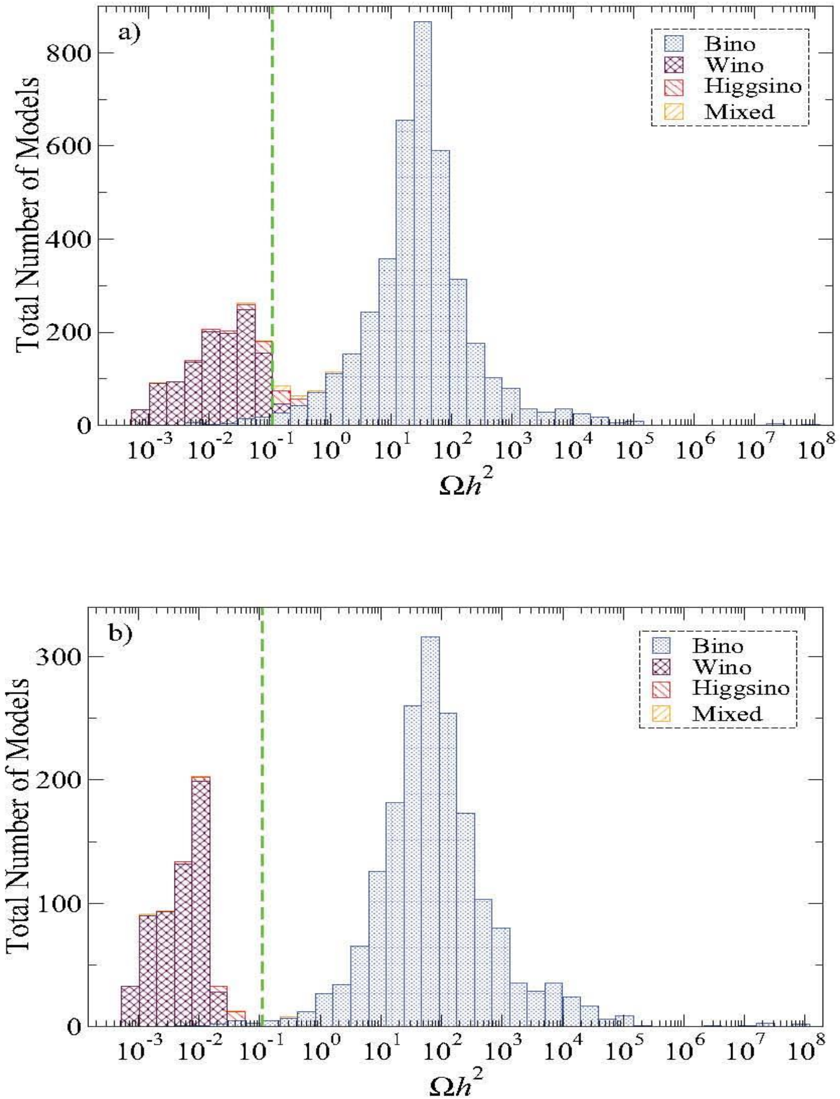
$$\alpha_\chi \sim O(10^{-2})$$

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

Thermal scenario is attractive:

1) Independent from prior thermal history.

2) Predictive.



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!

Higgsino DM

Higgsino is the LSP when other superparticles are very heavy

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 $>> 10\ TeV$

$\mu \sim 150-200\ GeV$

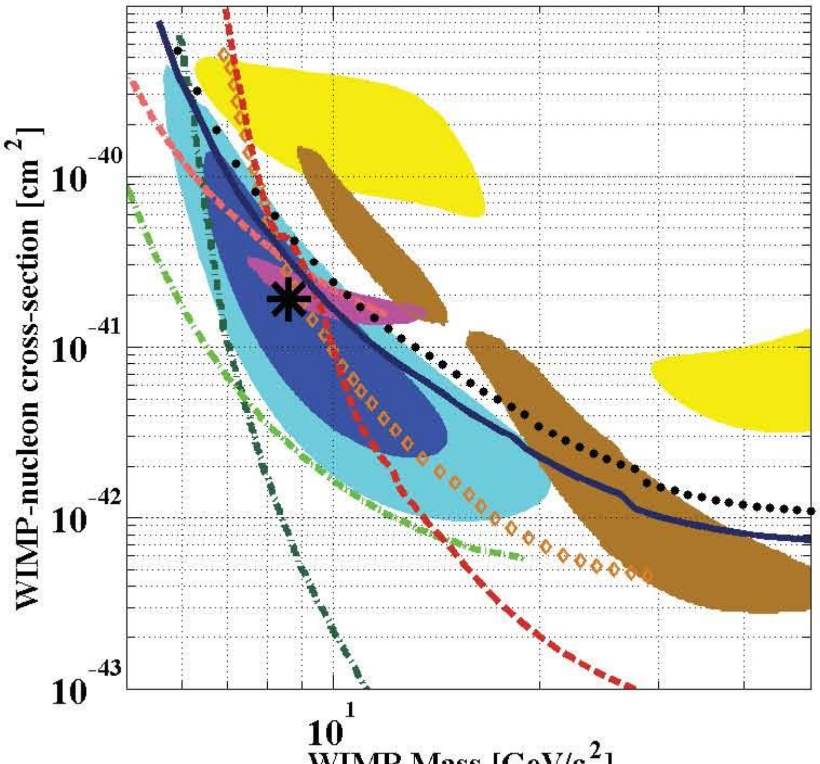
$$< \sigma_{ann} v >_f \sim \frac{\alpha_{EW}^2}{m_\chi^2} > 3\times 10^{-26}\ cm^3 s^{-1} \qquad m_\chi < 3\ TeV$$

Sub-TeV Higgsino DM <u>thermally underproduced</u>

Light DM

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

CDMS Collaboration   arXiv:1304.4279



$$\sigma_{SI} \sim \frac{1}{64\pi}\frac{m_p^2}{M^4} \sim 10^{-41}\ cm^2$$

$$<\sigma_{ann} v>_f \leq \frac{1}{64\pi}\frac{m_\chi^2}{M^4} \sim 10^{-27}\ cm^3 s^{-1}$$

Light DM thermally overproduced

Thermal WIMP still a possibility.

Even in the simplest scenarios, like mSUGRA, there are allowed pockets of parameter space.

Cohen, Walker arXiv:1305.2914

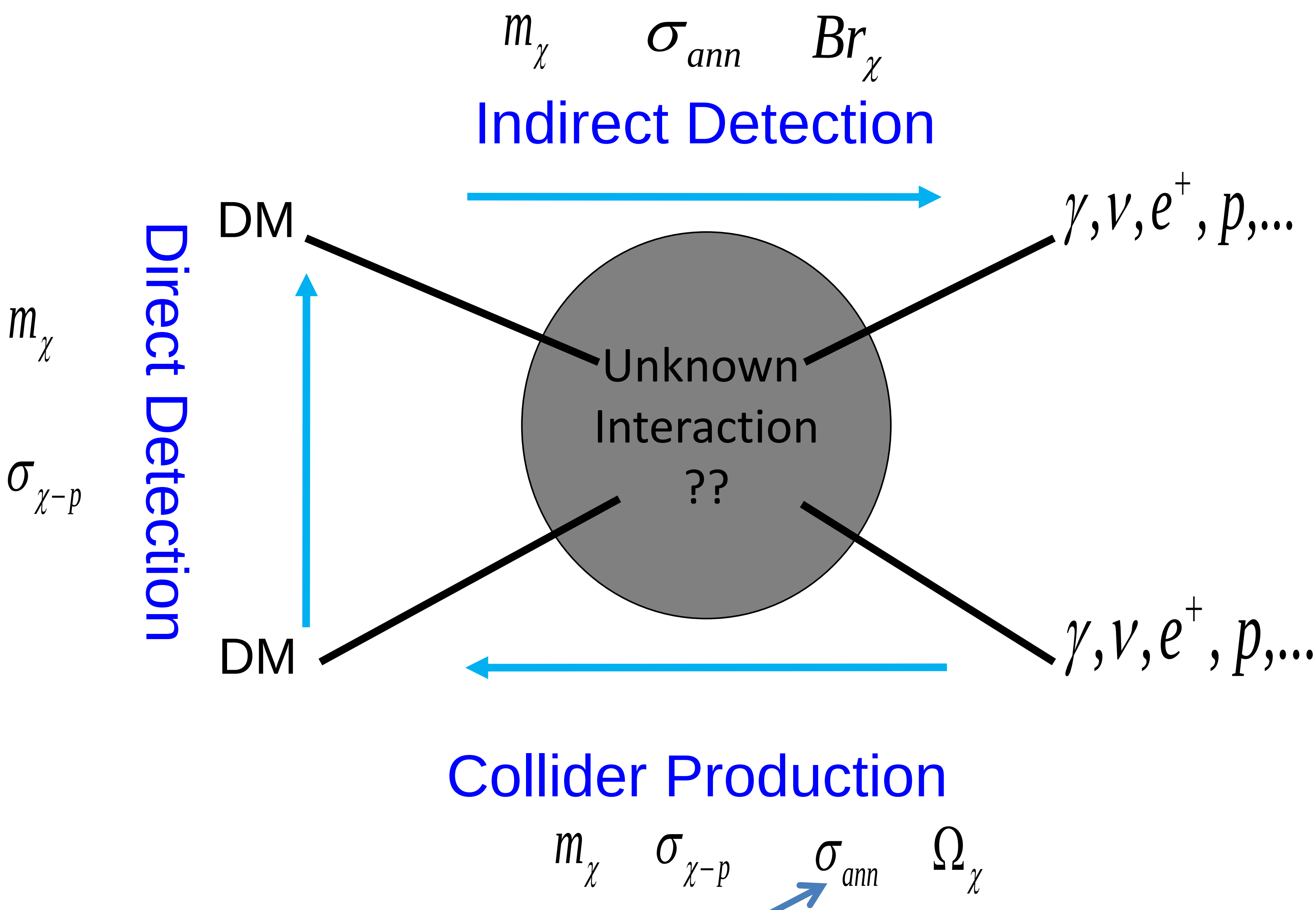
However, current data and emerging hints motivate scenarios of non-thermal DM as a serious alternative.

Eventually, after a model is discovered and then established at colliders, we will be able to calculate $<\sigma_{ann} v>_f$.

Indirect search bounds should also be interpreted with care.

It is important to keep open and study different scenarios.

Dark Matter Searches:



Probing thermal history once a model is established

Non-thermal Dark Matter:

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

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

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

Thermal underproduction

Example: Sub-TeV Higgsino DM

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

Thermal overproduction

Example: Bino DM in bulk region, Light DM

Scenario:

Late decay of a scalar S with mass m_S that reheats the universe to a temperature $T_r < T_f \sim m_\chi / 25$.

Dilution factor due to entropy release is $Y_S \equiv \dfrac{n_S}{s} = \dfrac{3T_r}{4m_S}$.

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

Annihilation Branching

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

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

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) “Annihilation” scenario requires:

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

2) “Branching” scenario requires:

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

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

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

"Annihilation" scenario does not work:

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

"Branching" scenario the only option, requires:

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

Non-thermal scenario can also help with N_{eff} .

Example: (quasi)Dirac neutrinos with gauge interactions for ν_R

A simple and well-motivated model includes a gauged $U(1)_{B-L}$.

LEP & Tevatron set bounds on Z'_{B-L} mass (and ν_R interactions).

Carena, Daleo, Dobrescu, Tait PRD 70, 093009 (2004)

$$T_d^{\nu_R} \sim 200 \ MeV$$

In a thermal scenario this results in $N_{eff} \approx 3.87$.

However, late decay with $1 \ MeV << T_r << T_d^{\nu_R}$ leads to:

$$\frac{n_{\nu_R}}{n_\gamma} \propto \left(\frac{T_r}{T_d^{\nu_R}} \right)^3 \quad \Rightarrow \quad N_{eff} \approx 3$$

Non-thermal Dark Matter from Moduli Decay:

Moduli fields are natural candidate for S .

Commonly arise in SUSY and string-inspired models.

$$\Gamma_S = \frac{c}{2\pi}\frac{m_S^3}{M_P^2} \qquad\qquad c \sim 0.1 - 1$$

Moduli dynamics in the early universe:

1) Displaced during inflation

2) Starts oscillating when $H \approx m_S$

3) Decays and reheats the universe to $T_r \sim \left(\frac{m_S}{50\ TeV}\right)^{3/2} \times 3\ MeV$

BBN requires $T_r > 3\ MeV$

$m_S > 50\ TeV \Rightarrow$ Potential handicap turned into virtue

Example: Higgsino DM via “Annihilation” scenario

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

Obtaining the correct relic density requires:

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

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

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

$< \sigma_{ann} v >_0$ is subject to bounds from indirect searches:

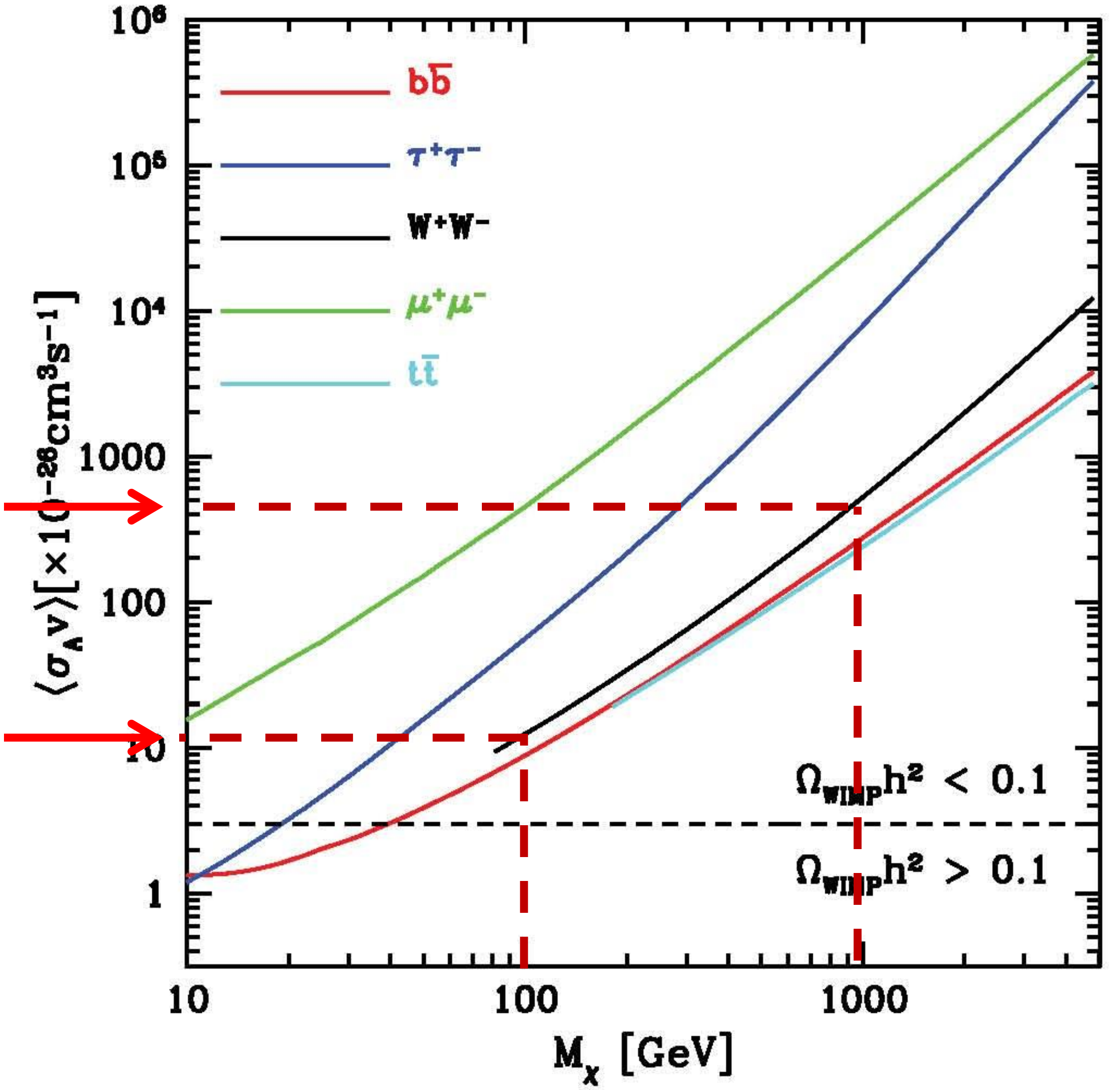
Strongest bounds provided by Fermi.

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

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

$$<\sigma_{ann} v> \leq 4\times 10^{-24}\ cm^3 s^{-1}$$

$$<\sigma_{ann} v> \leq 2\times 10^{-25}\ cm^3 s^{-1}$$



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

$$T_r \sim O(GeV)$$

Required modulus mass:

$$m_S \sim few \times O(1000)\ TeV$$

$m_S : m_{3/2} \sim 4\pi^2$ in models with non-perturbative schemes of moduli stabilization $W \sim W_0 + Ae^{-aS}$:

Conlon, Quevedo JHEP 0606, 029 (2006)

$m_{3/2} > 40\ TeV \Rightarrow$ Gravitinos escape very tight BBN bounds

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

Explicit realization: Non-thermal Higgsino DM in mirage mediation

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

“Annihilation” scenario does not work if:

indirect searches result in more stringent bounds $<\sigma_{ann} v>_f \downarrow$,

or

models with thermal overproduction.

In these case, the “Branching” scenario will be the only option:

$$\frac{n_\chi}{s} = Y_S \; Br_\chi \approx 5 \times 10^{-10} \left(\frac{1 \; GeV}{m_\chi} \right)$$

If $m_\chi \geq 10 \;\; GeV$, the correct abundance is obtained for:

$$Y_S \; Br_\chi \leq 5 \times 10^{-11}$$

Constraints and Challenges:

1) Gravitino production must be suppressed:

$$\frac{n_\chi}{s} > \frac{n_{3/2}}{s}$$

$S \rightarrow \tilde{G}\tilde{G}$ 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)

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

$\boxed{Br_{3/2} < 7 \times 10^{-4}}$ or kinematic blocking required.

2) The relic density in the "Branching" scenario must be just right:

$$\frac{n_\chi}{s} = Y_S \; Br_\chi \approx 5\times10^{-10} \left(\frac{1 \; GeV}{m_\chi} \right)$$

$$Y_S \sim 7\times10^{-8} c^{1/2} \left(\frac{m_S}{50 \; TeV} \right)^{1/2} \geq 7\times10^{-8} \; c^{1/2}$$

$$Y_S \; Br_\chi \leq 5\times10^{-11} \quad (m_\chi \geq 10 \; GeV)$$

$\boxed{Br_\chi < 10^{-3}}$ suppressing R-parity odd particle production

$\boxed{c << 1}$ suppressing modulus decay

Typically, the main decay mode is to gauge/Higgs bosons.

2-body decays to gauginos may 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)

However, 3-body decays produce gauginos: $Br_{\chi} \sim 3\times 10^{-3}$.

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

<u>Suppressing modulus decay to particles with gauge charges</u>

and/or

<u>Suppressing its total decay rate</u>

3) Generating baryon asymmetry:

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

For moduli:

$$\left(\frac{s_{after}}{s_{before}}\right)_{\max} \leq \frac{M_P}{m_S} \quad (>> 10^{10})$$

S decay washes out any pre-existing, even $O(1)$, asymmetry.

BAU must be produced after the decay, hence post-sphaleron

Non-thermal baryogenesis

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

The simplest model based on KKLT scenario not quite successful:

$$G = K + \ln |W|^2 \;,\quad K = -3\ln(S+\bar{S}) + (S+\bar{S})^{-n_m}\Phi\Phi^+$$

$$Br_{3/2} \sim \left(|G_S|^2 K^{-1}\right)\frac{m_S^2}{m_{3/2}^2} \sim 10^{-2}$$

Modifications to K in order to suppress $Br_{3/2}$.

Three-body decays yield $Br_\chi \sim 3\times 10^{-3}$.

Suppressed modulus decay $c << 1$ to save "Branching" scenario.

Possible solution in Large Volume Compactification (LVC) models:

$$m_S << m_{3/2} \quad , \quad Br_\chi << 10^{-3}$$

R.A., Cicoli, Dutta, Sinha (in preparation)

Non-thermal DM from Visible Sector Scalar:

Overproduction of DM may be solved if S is a visible sector field.

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

Ensured by S belonging to the visible sector

$$Br_{\chi} << 1$$

Achieved by proper charge assignments, interactions, kinematics

Example: S an R-parity even scalar coupled to colored fields.

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

1) Decay to gravitinos gravitationally suppressed.

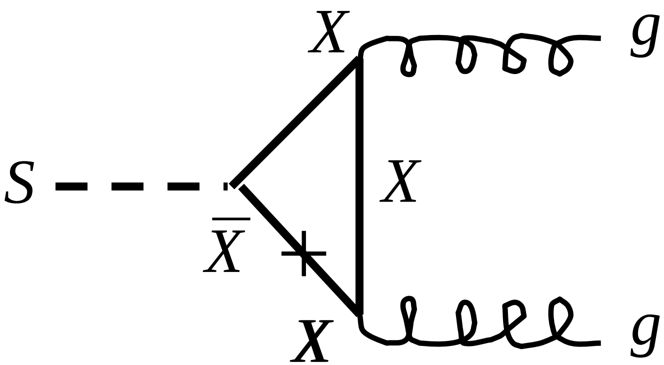
2) Decay to χ suppressed by loop and/or phase space factors.

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

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

Singlet   Color Triplet   Singlet

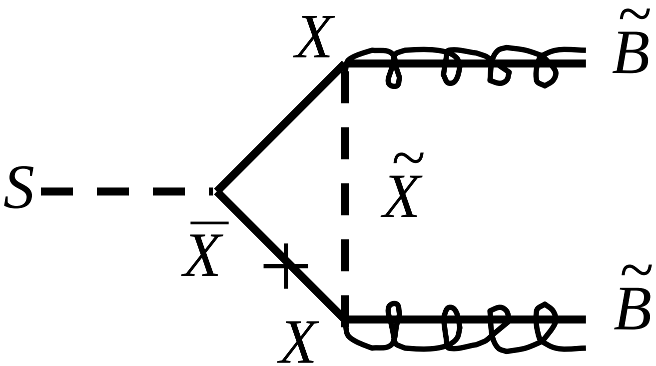
$Y = \pm 4/3$



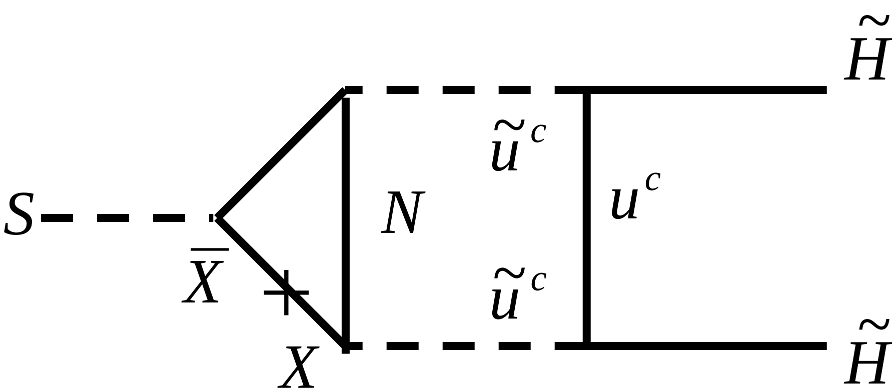
$$m_S \sim O(TeV)\ ,\ m_\chi \le 500\ GeV$$

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

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



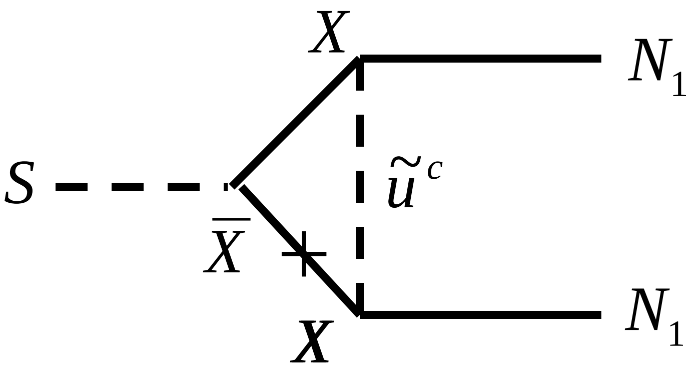
$$Br_\chi \sim \frac{1}{2}\left(\frac{g_1}{g_3}\right)^4 \left(\frac{m_\chi}{m_S}\right)^2 \ (\sim 10^{-5})$$



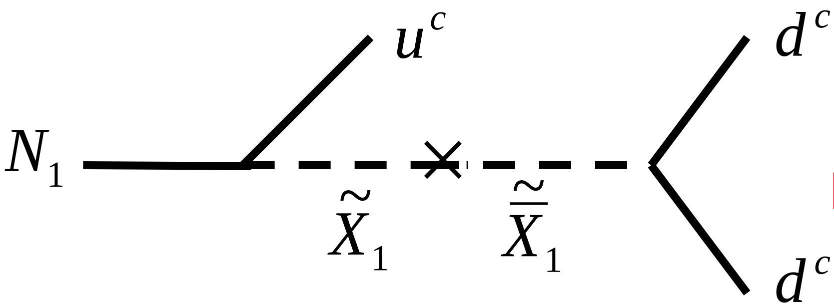
$$Br_\chi \sim \frac{1}{16\pi^4}\left(\frac{\lambda}{g_3}\right)^4 \left(\frac{m_\chi}{m_S}\right)^2 \ (\sim 10^{-8})$$

Model can also generate BAU, address baryon-DM coincidence:

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

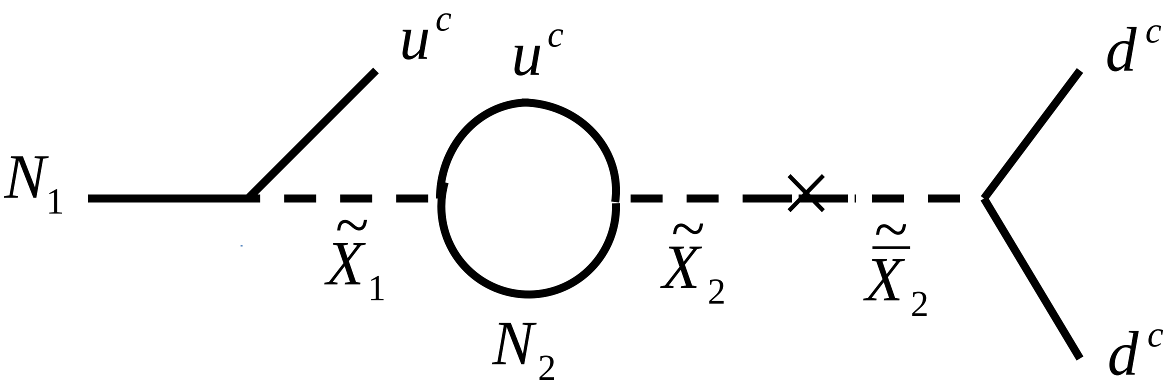


$$Br_{N_1} \sim \left(\frac{\lambda}{g_3}\right)^4 \left(\frac{m_{N_1}}{m_S}\right)^2$$



"Cladogenesis": $\frac{\Omega_\chi}{\Omega_B} \propto \frac{Br_\chi}{Br_{N_1}}$

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



Outlook:

- DM as strongest probe of thermal history, after discovery.
- CMB sets relic density, other limits rely on assumption/models.
- WIMP miracle is attractive, how seriously should we take it?
- Late decay scenarios motivated, observational consequences?
- Moduli decay natural candidate, embedding in explicit models?
- Decay may overproduce DM, challenge for model building?
- Visible sector decay can help, building realistic models?
- Apparent baryon-DM coincidence, motivation for light DM?
- Complementarity of experiments, multi-component DM etc?