Light Nonthermal Dark Matter: A Minimal Model & Detection Prospects

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Outline:

- Introduction
- Minimal model (non-supersymmetric version)
- Detection prospects (direct, indirect, collider)
- Minimal model (supersymmetric version)
- Outlook

Based on the following works:

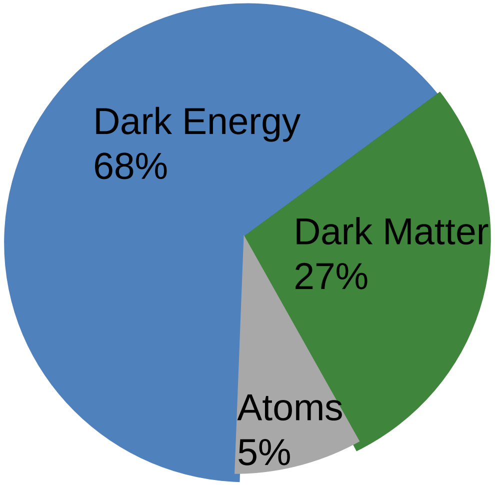
R.A., B. Dutta PRD 88, 023525 (2013)

R.A., B. Dutta, R. N. Mohapatra, K. Sinha PRL 111, 051302 (2013)

R.A., B. Dutta, Y. Gao arXiv:1403.5717

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)

Why is it nonzero?

How was it generated?

Also, the coincidence puzzle:

Why the DM and baryons have comparable energy densities?

Generation of BAU:

$\not{B}$, $\not{C}$ & $C\not{P}$, out of thermal equilibrium (Sakharov conditions):

$$f_L \neq \bar{f}_L,\, f_R \neq \bar{f}_R \qquad f_L \neq \bar{f}_R,\, f_R \neq \bar{f}_L$$

$$f_L = \bar{f}_R,\, f_R = \bar{f}_L \qquad f_L = \bar{f}_L,\, f_R = \bar{f}_R$$

Occurred via out-of-equilibrium decay of some heavy state(s) produced after (or during) inflation

Production of DM:

Thermal freeze-out (WIMP miracle):

$$T_f \sim \frac{m_\chi}{20} \qquad \langle \sigma v \rangle_f = 3\times 10^{-26}\, cm^3/s$$

Nonthermal production:

$$T_r < T_f \qquad \langle \sigma v \rangle_f \neq 3\times 10^{-26}\, cm^3/s$$

A Minimal Model:

We adopt a bottom-up approach.

We consider a minimal extension of the SM with renormalizable $\not{B}$ interactions: R.A., B. Dutta PRD 88, 023525 (2013)

$$L_{new} = \lambda'_{\alpha ij} X_\alpha d_i^c d_j^c + \lambda_{\alpha i} N X_\alpha^* u_i^c + m_\alpha^2 | X_\alpha |^2 + \frac{m_N}{2} NN$$

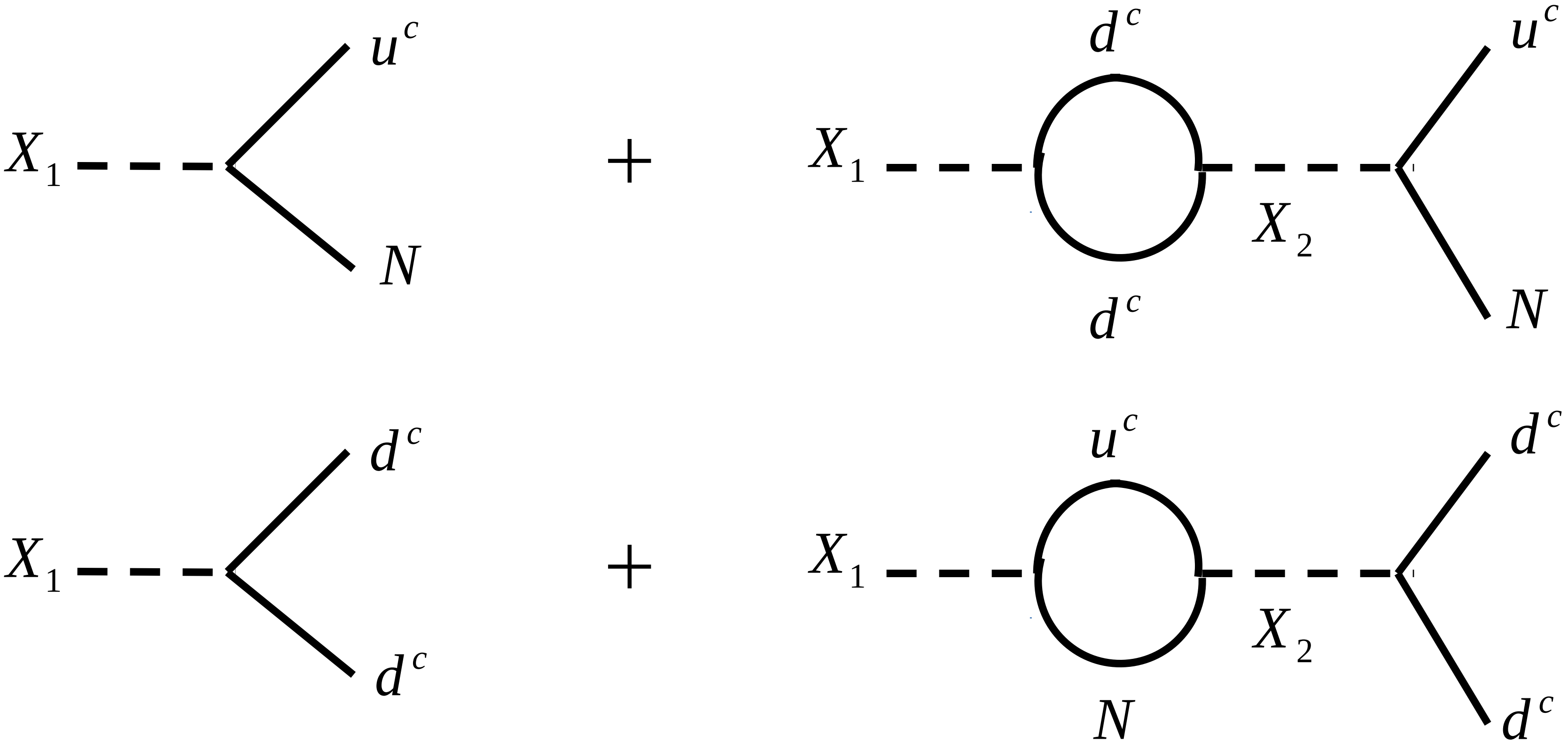
$$+ h.c. + kinetic\ terms$$

X_α : Iso-singlet color triplet scalars with Y =+4/3

N : Singlet fermion

The field content is the minimum required to generate nonzero baryon asymmetry via out-of-equilibrium decay of X

Kolb, Wolfram NPB 172, 224 (1980); Erratum-ibid 195, 542 (1982)



$$\varepsilon_1 = \frac{1}{8\pi}\frac{\sum_{i,j,k}\mathrm{Im}(\lambda_{1k}^*\lambda_{2k}\lambda'_{1ij}\lambda'_{2ij})}{\sum_{i,j}|\lambda'_{1ij}|^2+\sum_{k}|\lambda_{1k}|^2}\frac{m_1^2}{m_1^2-m_2^2}$$

$$\varepsilon_2 = \varepsilon_1(1\leftrightarrow 2)$$

X fields mediate a 4-fermion interaction:

$$\frac{\lambda\lambda'}{m_X^2} N u_i^c d_j^c d_k^c$$

This operator results in the following decays:

$$m_N > m_p + m_e : \; N \rightarrow p + e^- + \overline{\nu}_e \; , \; \overline{p} + e^+ + \nu_e$$

$$m_N < m_p + m_e : \; p \rightarrow N + e^+ + \nu_e \; , \; N + e^- + \overline{\nu}_e$$

N is stable and becomes a viable dark matter candidate if:

$$m_p - m_e \le m_N \le m_p + m_e$$

The condition is stable against radiative corrections for:

$$\lambda \le O(10^{-1})$$

Stability of DM candidate is tied to the stability of proton.

No additional symmetry, like R-parity, is invoked.

Odd & even number of DM particles produced from SM particles.

N quanta produced from/annihilate to SM particles in thermal bath:

$$m_N < T << m_X : \quad \Gamma \sim (|\lambda|^4 + |\lambda|^2 |\lambda'|^2) \frac{T^5}{m_X^4}$$

$$|\lambda|, |\lambda'| \geq O(10^{-2}), m_X \sim O(TeV):$$

$$T \geq m_N (= m_p) \Rightarrow \Gamma \geq H$$

DM reaches equilibrium with the thermal bath at T > O(GeV).

$$m_N \approx 1 GeV, m_X \sim O(TeV):$$

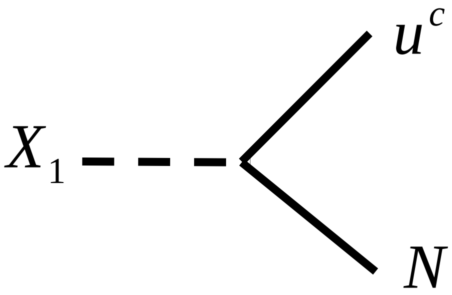
Thermal freeze-out overproduces DM.

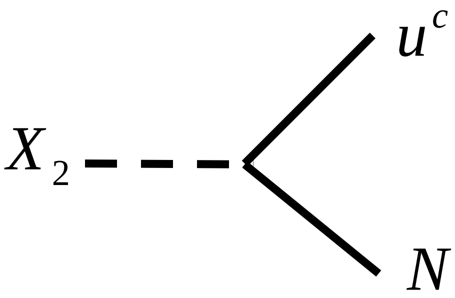
Lee, Weinberg PRL 39, 165 (1977)

Nonthermal mechanism is needed in order to obtain the correct DM relic abundance.

A natural scenario is late decay of a scalar field S that reheats the universe to a temperature $T_r < T_f$.

Such a decay can produce $X_{1,2}$ with branching ratios $Br_{1,2}$:





$$\frac{n_N}{n_{X_1}} = \frac{Br_1 \sum_k |\lambda_{1k}|^2}{\sum_{i,j} |\lambda'_{1ij}|^2 + \sum_k |\lambda_{1k}|^2} \qquad \frac{n_N}{n_{X_2}} = \frac{Br_2 \sum_k |\lambda_{2k}|^2}{\sum_{i,j} |\lambda'_{2ij}|^2 + \sum_k |\lambda_{2k}|^2}$$

$$\frac{n_B}{s} = \frac{3T_r}{m_S} \times \sum_{i,j,k} \left[\frac{m_1^2 Br_1 \, \mathrm{Im}(\lambda_{1k}^* \lambda_{2k} \lambda'_{1ij} \lambda'_{2ij})}{8\pi (m_1^2 - m_2^2) \sum_{i,j} |\lambda'_{1ij}|^2 + \sum_k |\lambda_{1k}|^2} + (1 \to 2) \right]$$

$$\frac{n_N}{s} = \frac{3T_r}{m_S} \times \left[\frac{Br_1 \sum_k |\lambda_{1k}|^2}{\sum_{i,j} |\lambda'_{1ij}|^2 + \sum_k |\lambda_{1k}|^2} + (1 \to 2) \right]$$

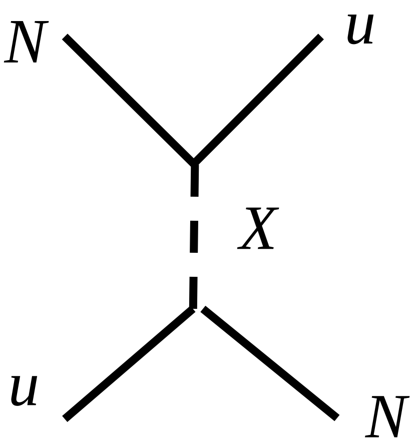
For O(1) couplings and $\cancel{CP}$ phases, it is easy to have:

$$\frac{n_{DM}}{n_B} \sim O(10)$$

$$m_{DM} \approx m_p \Rightarrow \frac{\Omega_{DM}}{\Omega_B} \sim O(10)$$

Detection Prospects:

Direct detection:



Spin-independent interactions:

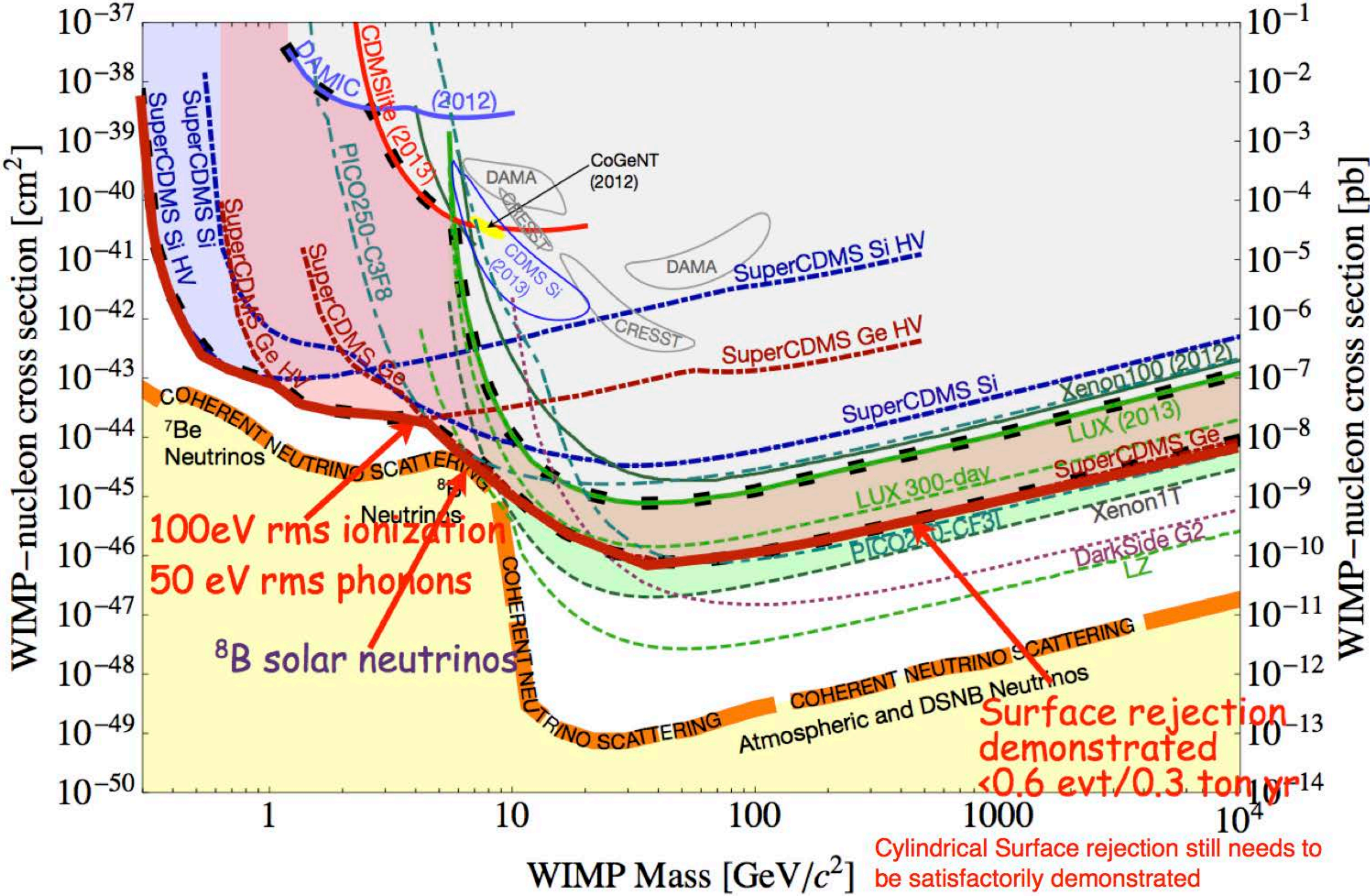
$$\frac{m_N m_u}{m_X^4}(\overline{\psi}_N\psi_N)(\overline{\psi}_q\psi_q)$$

$$\frac{1}{m_X^4}(\overline{\psi}_N\gamma^\mu\partial^\nu\psi_N)(\overline{\psi}_q\gamma_\mu\partial_\nu\psi_q)+h.c.$$

Spin-dependent interactions:

$$\frac{1}{m_X^2}(\overline{\psi}_N\gamma^\mu\gamma^5\psi_N)(\overline{\psi}_q\gamma^\nu\gamma^5\psi_q)$$

$$\sigma_{SI}\sim|\lambda|^4\frac{O(GeV)^6}{m_X^8}\qquad\qquad\sigma_{SD}\sim|\lambda|^4\frac{O(GeV)^4}{m_X^4}$$



100eV rms ionization
50 eV rms phonons

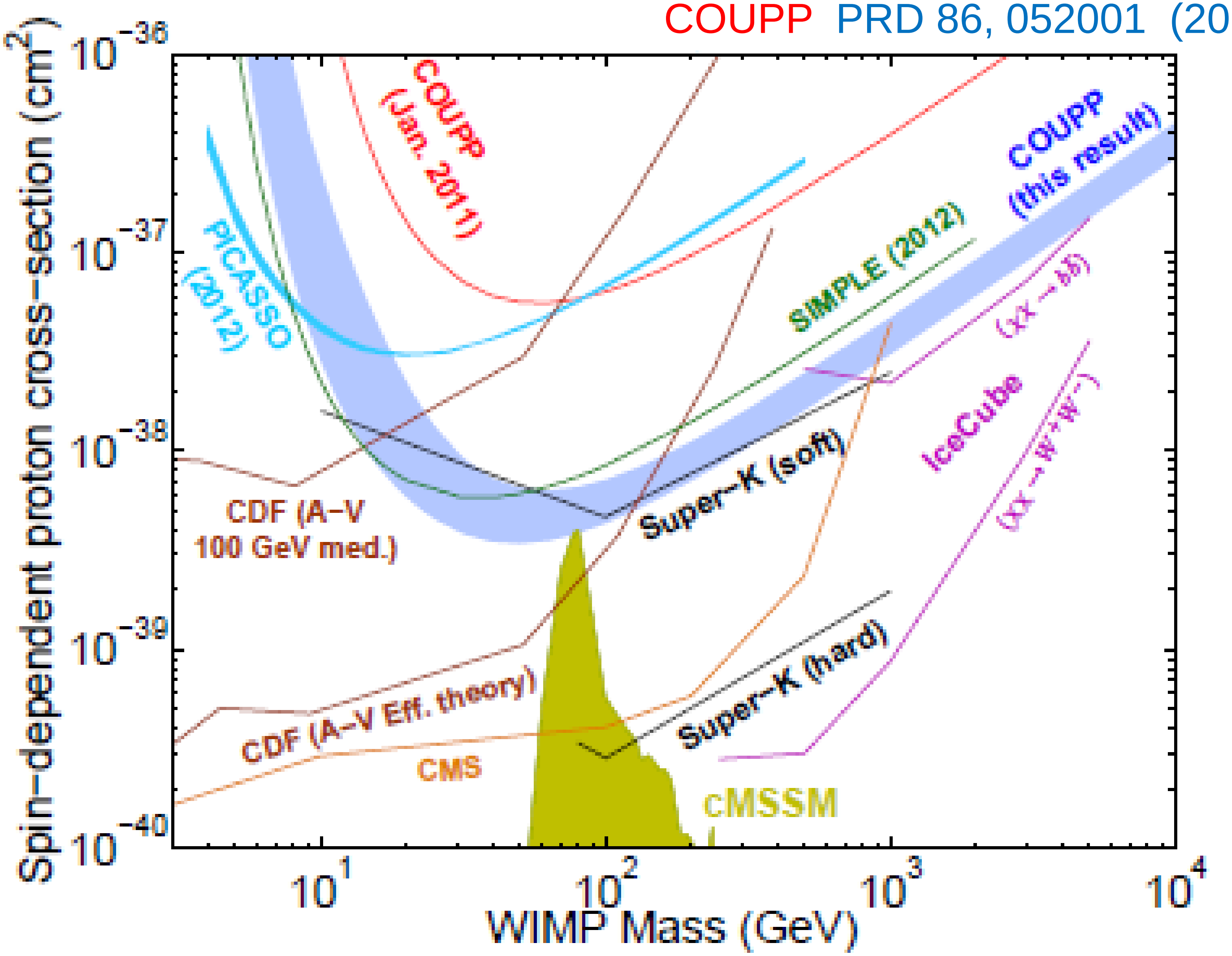
^{8}B solar neutrinos

Surface rejection
demonstrated
<0.6 evt/0.3 ton yr

Cylindrical Surface rejection still needs to be satisfactorily demonstrated

$$m_X \sim O(TeV) \Rightarrow \sigma_{SI} < 10^{-16}\, pb$$

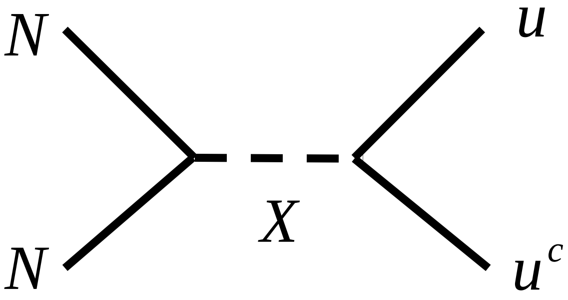
COUPP PRD 86, 052001 (2012)



$$m_X \sim O(TeV) \Rightarrow \sigma_{SD} < 10^{-4}\, pb$$

Indirect detection:

$$<\sigma_{ann}v>\sim|\lambda|^4\frac{|\vec{p}|^2}{m_X^4}$$



$$m_X\sim O(TeV)\Rightarrow<\sigma_{ann}v> \ll 10^{-31}cm^3/s$$

Too low to see any gamma-ray signal.

Also, no detectable galactic/extragalactic neutrino signal.

Neutrino signal from solar DM annihilation is negligible too:

1) Capture and annihilation both suppressed,

2) Evaporation efficient for O(GeV) DM.

However, possible indirect signal if two almost degenerate N exist.

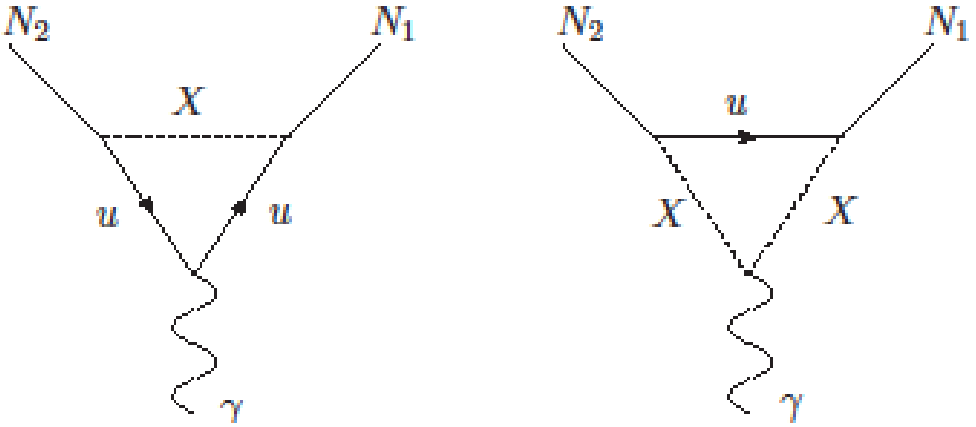
R.A., B. Dutta, Y. Gao arXiv:1403.5717

$$m_p - m_e \leq m_{N_{1,2}} \leq m_p + m_e \Rightarrow N_{1,2}$$

The only allowed decay channel is:

$$N_2 \rightarrow N_1 + \gamma$$

$$\frac{m_N}{m_X^2} \overline{\psi}_{N_2} \sigma^{\mu\nu} \psi_{N_1} F_{\mu\nu} + h.c.$$



$$\Delta m \equiv | m_{N_2} - m_{N_1} |$$

$$\Gamma_{N_2} \approx \frac{|\lambda_1 \lambda_2|^2}{16\pi^4} \alpha_{em} \Delta m^3 \frac{m_N^2}{m_X^4}$$

m_{N_2}, m_{N_1} have same phase

$$\Gamma_{N_2} \approx \frac{|\lambda_1\lambda_2|^2}{16\pi^4}\alpha_{em}\frac{\Delta m^5}{m_X^4}$$

m_{N_2}, m_{N_1} have opposite phase

In general, one can get a photon line at energy:

$$E_\gamma = \Delta m < 2m_e$$

There has been claims of a 3.5 keV photon line from clusters.

Bulbul *et al*. arXiv:1402.2301 Boyarsky *et al*. arXiv:1402.4119

The model can explain this line if:

$$\Delta m \approx 3.5 \ keV \qquad \tau_{N_2} \approx 10^{23} \ s$$

This is satisfied for:

$$O(10^{-6}) < |\lambda_1\lambda_2| < O(10^{-1}) \qquad m_X \sim O(TeV)$$

(Also, see I. Gogoladze talk in this workshop)

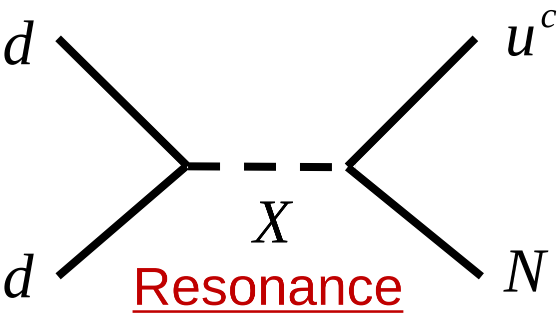
Collider signal:

Both odd & even number of DM particles are produced from the interactions of the SM particles:

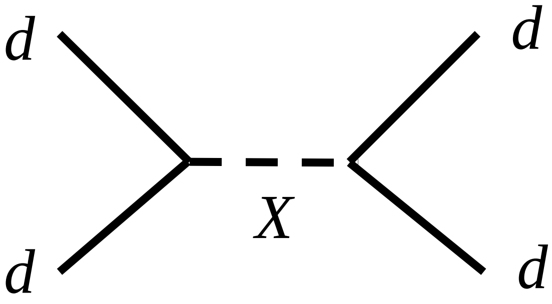
Monojets (including monotops) & dijets plus missing energy.

B. Dutta, Y. Gao, T. Kamon arXiv:1401.1825

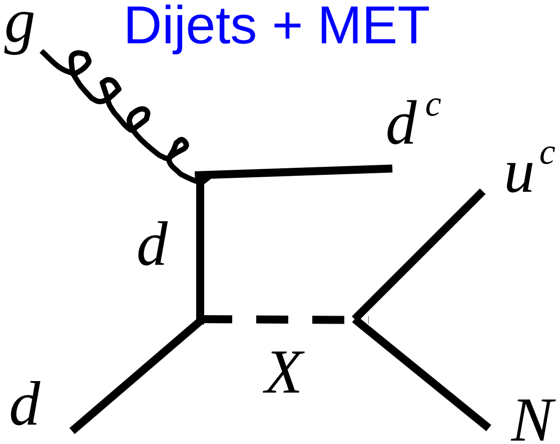
Monojets + MET



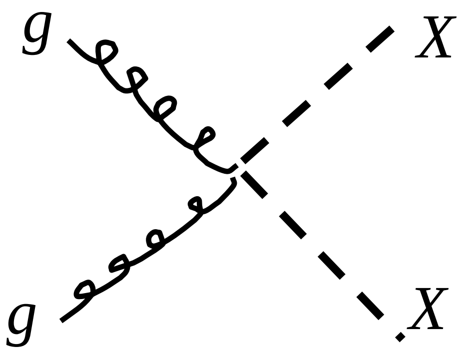
Dijets



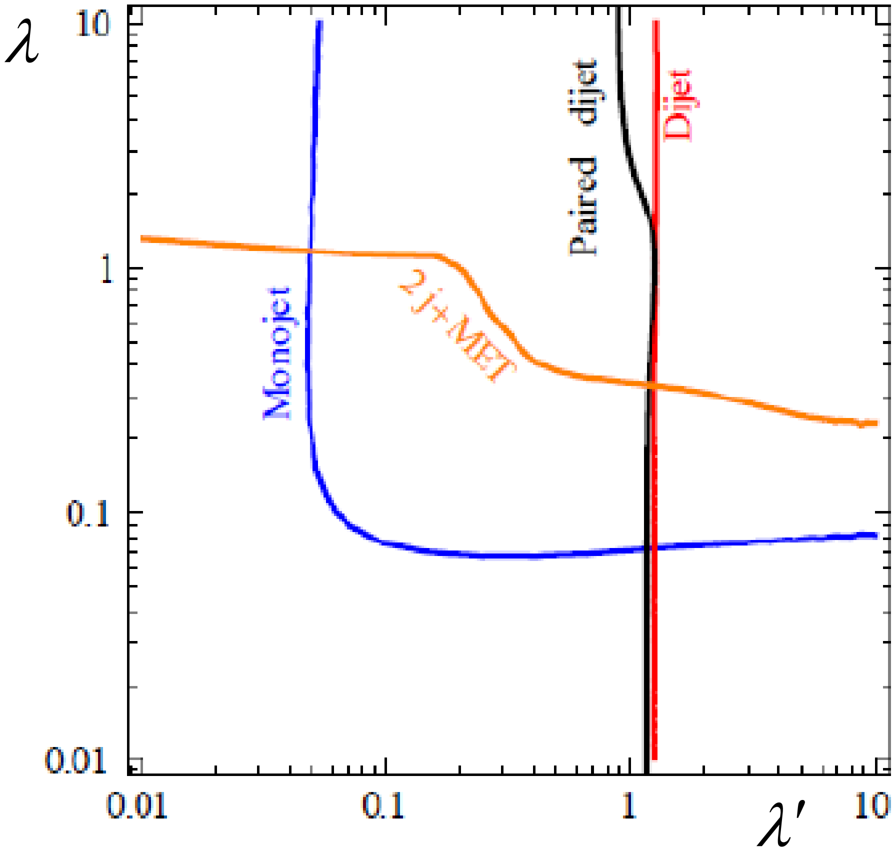
Dijets + MET



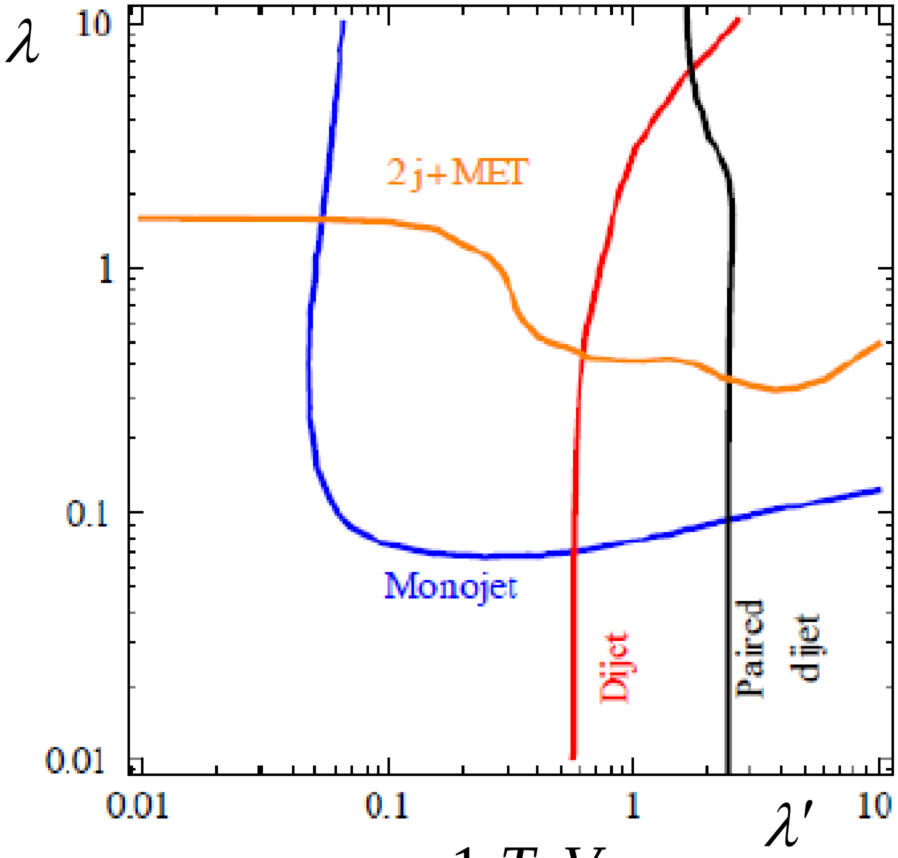
Paired dijets + MET



Combined collider bounds (assuming single value for λ and λ'):



$m_1 = 500\ GeV$



$m_1 = 1\ TeV$

Also, possibilities with monotops (see the paper).

Supersymmetric Version:

Extension to supersymmetry is straightforward:

$$W_{new} = \lambda'_{\alpha ij} X_\alpha d_i^c d_j^c + \lambda_{\alpha i} N \bar{X}_\alpha u_i^c + m_\alpha X_\alpha \bar{X}_\alpha + \frac{m_N}{2} NN$$

$X_\alpha, \bar{X}_\alpha$: Iso-singlet color triplet superfields Y =+4/3, Y=-4/3

N : Singlet superfield

The model can lead to thermal and non-thermal baryogenesis.

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

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

It also has a real scalar DM candidate $\tilde{N}$ protected by R-parity.

$$m_{\tilde{N}}^2 = m_N^2 + \tilde{m}^2 \pm B m_N$$

The lighter of the two components of $\tilde{N}$ can be DM candidate.

In order to address the coincidence puzzle, one can have:

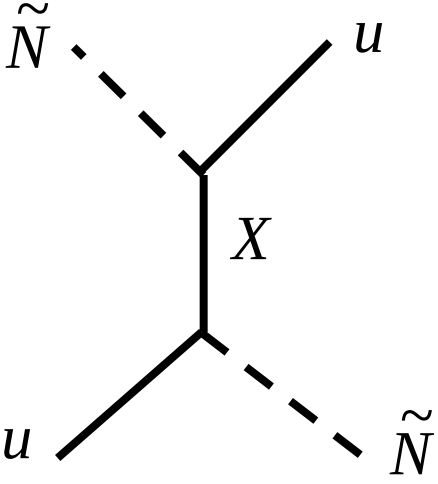
$$m_{\tilde{N}} \leq O(10\ GeV)$$

The model allows for multi-component DM coming from the same superfield N.

The prospect for direct detection of $\tilde{N}$ is high.

R.A., B. Dutta, R. N. Mohapatra, K. Sinha PRL 111, 051302 (2013)

Spin-independent interactions:

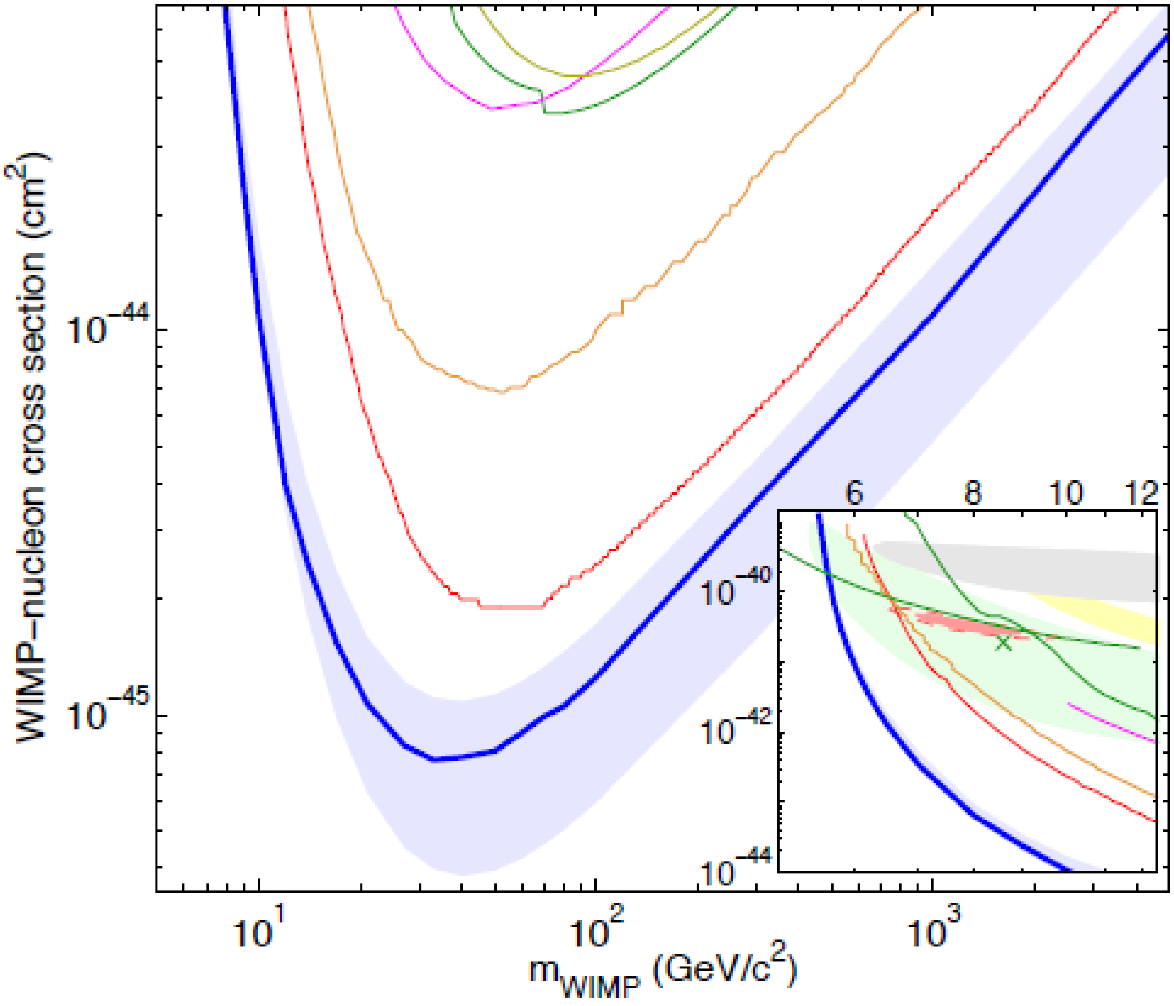


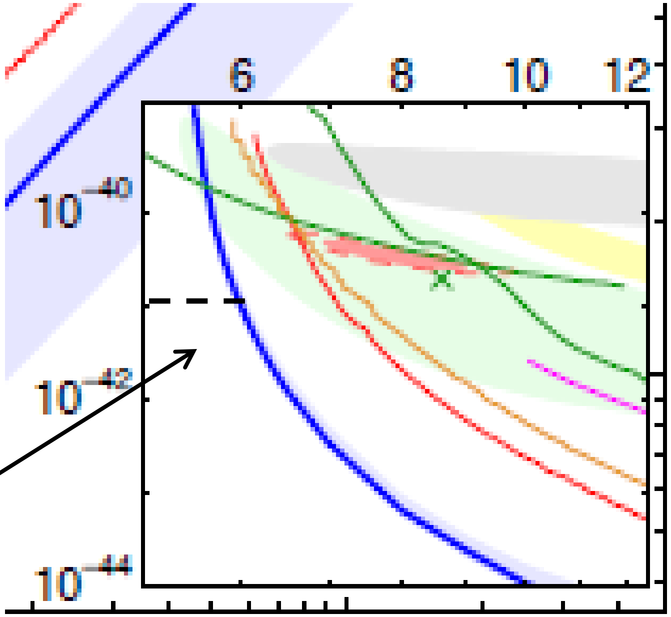
$$\frac{1}{m_X^2}(\overline{\psi}_q \gamma^\mu \partial_\mu \psi_q)(\tilde{N}\tilde{N})$$

$$\sigma_{SI} \sim |\lambda|^4 \frac{m_p^2}{m_X^4}$$

$$m_X \sim O(TeV) \Rightarrow \sigma_{SI} < 10^{-5}\ pb$$

LUX PRL 112, 001303 (2014)





$\sigma_{SI} < 10^{-5}\, pb$

Outlook:

- A minimal BSM with colored states to explain baryogenesis.
- Model can give rise to O(GeV) DM candidate.
- Nonthermal DM and baryon production needed.
- Direct & indirect DM detection unlikely in the minimal model.
- Sub-GeV Photon line possible with two copies of DM.
- DM particles can be produced singly and doubly at colliders.
- Distinct monojet signal is possible due to resonance.
- SUSY version allows new DM candidates.
- Direct detection signal possible, multi-component DM possible.

Coincidence problem (?)

The DM and BAU densities are of similar order:

$$\Omega_{DM} \sim 6\Omega_B$$

How serious is the issue?

Ω_{DM}, Ω_B have the same EOS, Ω_{DM} / Ω_B is constant in time.

Different from the DE coincidence problem:

EOS of DM and DE different, why $\Omega_{DE} / \Omega_{DM} \sim O(1)$ today?

Nevertheless, one can explore the possibility that Ω_{DM}, Ω_B may be related dynamically.

Relation between baryogenesis and DM production mechanisms.

D. B. Kaplan PRL 68, 741 (1992)

…

$|\lambda_1 \lambda'_{12}|$ severely constrained by $\Delta B = 2$, $\Delta S = 2$ processes:

1) $n - \bar{n}$ oscillations.

2) $pp \to K^+ K^+$ double proton decay.

$$m_N \sim O(GeV) \ , \ \ m_X \sim O(TeV):$$

$$|\lambda_1 \lambda'_{12}| < 10^{-6}$$

Successful baryogenesis then needs nontrivial flavor structure of λ_i, λ'_{ij} and/or degeneracy in m_{X_1}, m_{X_2}.

Monojet and monotop signals are still possible:

$$|\lambda'_{12}|, |\lambda'_{13}|, |\lambda'_{23}| \sim 1$$

$$|\lambda_1| \sim 10^{-6} \ , \ \ |\lambda_2|, |\lambda_3| \sim 1$$