Light Nonthermal Dark Matter: A Minimal Model & Detection Prospects

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Outline:

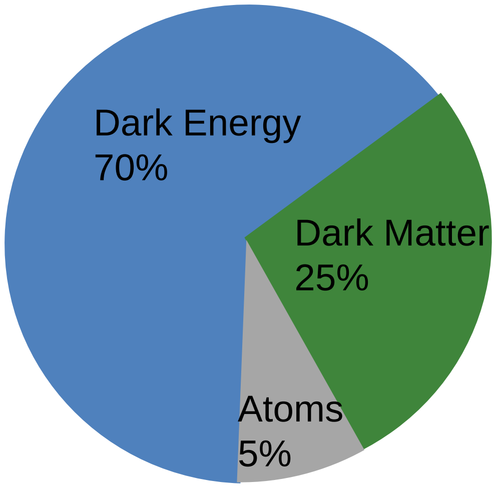
- Introduction
- Minimal model (DM coupled to RH quarks)
- Detection prospects (direct, indirect, LHC)
- Minimal model 2 (DM coupled to LH quarks, monotop chirality)
- SUSY version (new opportunities, multicomponent DM)
- Outlook

Based on recent work:

PRD 88, 023525 (2013) PRL 111, 051302 (2013) PRD 89, 127305 (2014)
PRD 91, 055033 (2015) JHEP 1612, 046 (2016)

Introduction:

Energy budget of the 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, a possible coincidence puzzle:

Why the DM and baryons have comparable energy densities?

A Minimal Model:

B and *L* are accidental symmetries of SM at the perturbative level.

We adopt a bottom-up approach and consider a minimal extension of the SM with renormalizable $\not{B}$ interactions:

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

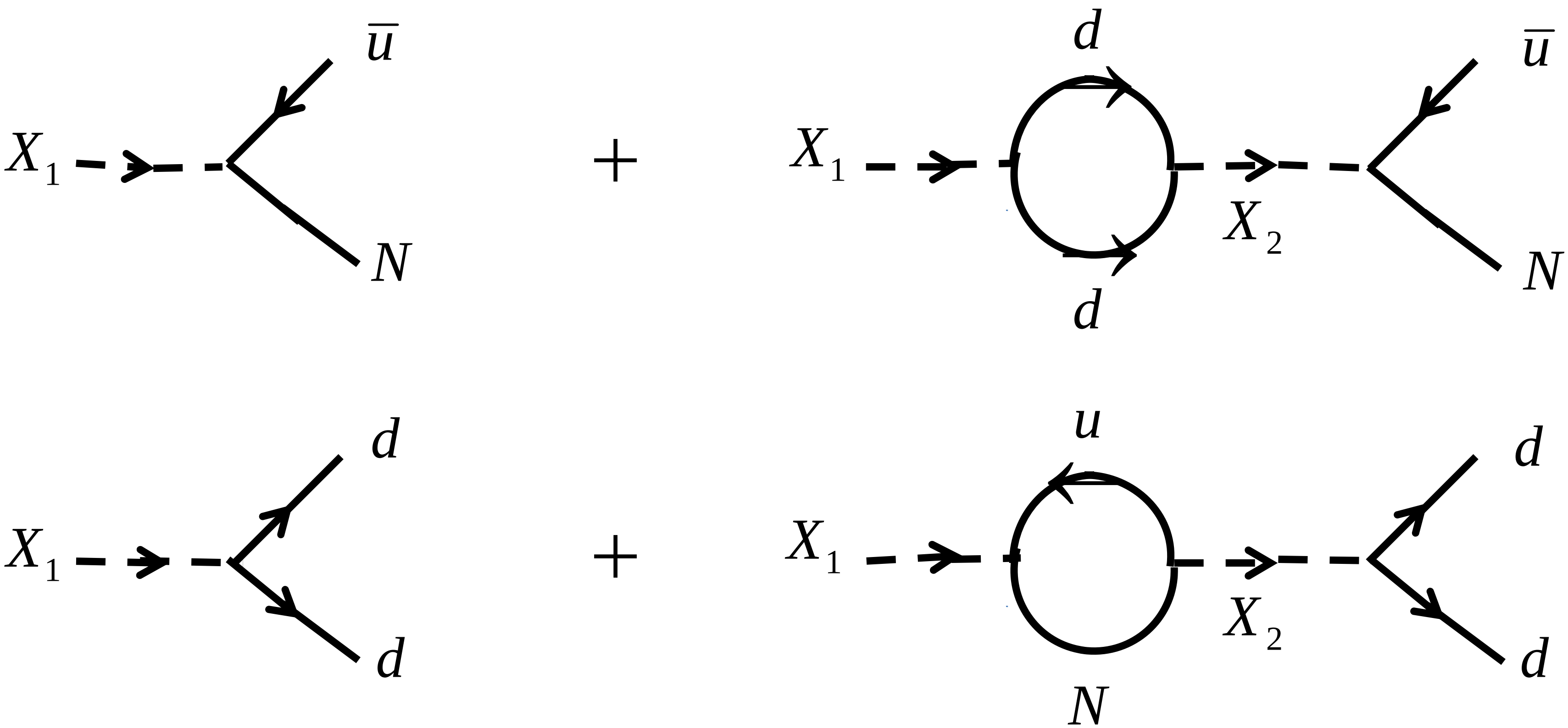
$$L_{new} = \lambda'_{\alpha ij} X_\alpha d_i^c d_j^c + \lambda_{\alpha i} N X_\alpha^* u_i^c + m_\alpha^2 |X_\alpha|^2 + \frac{m_N}{2} NN$$
$$+ h.c. + kinetic\ terms$$

$X_{1,2}$: **Iso-singlet** color-triplet scalars *Y* =+4/3

N : Singlet fermion

This is the minimum field content that is required to generate a nonzero baryon asymmetry via out-of-equilibrium decay of *X*.

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



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

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

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

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

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

For $m_N \sim O(GeV)$, $m_X \sim O(TeV)$ we must have:

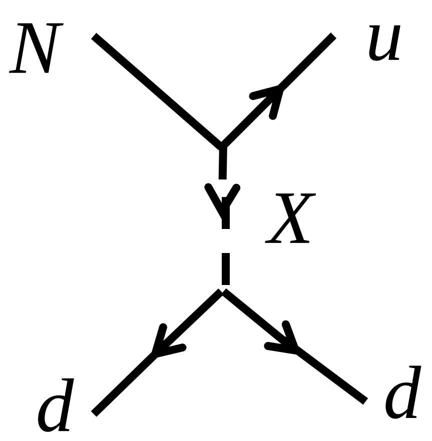
$|\lambda_1 \lambda'_{12}| < 10^{-6}$

Experimental bounds on $K_s^0 - \overline{K}_s^0$ and $B_s^0 - \overline{B}_s^0$ oscillations are satisfied too.

Successful baryogenesis then needs nontrivial flavor structure of $\lambda_i , \lambda'_{ij}$ or degeneracy in m_{X_1}, m_{X_2} .

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

X mediates 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 DM candidate if:

$$m_p - m_e \leq m_N \leq m_p + m_e$$

The condition is stable against radiative corrections for:

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

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 quarks in the early universe:

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

$$H \sim T^2 / M_P \Rightarrow T_{dec} \sim (m_X^4 / \lambda^4 M_P)^{1/3}$$

$$|\lambda|, |\lambda'| < 1, m_X \sim O(TeV):$$

$$T_{dec} > 10 \ MeV$$

Thermal freeze-out results in overproduction of DM.

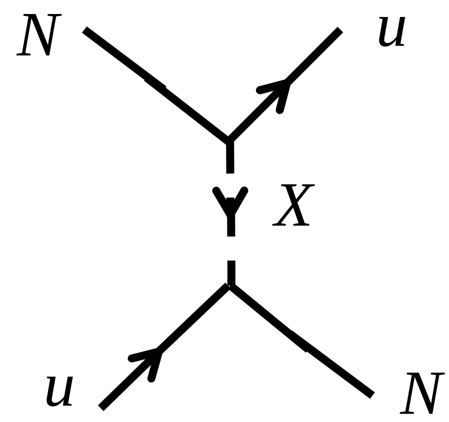
B. Lee, S. Weinberg PRL 39, 165 (1977)

Nonthermal mechanism needed to obtain DM relic abundance.

Detection Prospects:

Direct detection:

Effective interaction:



$$\frac{1}{m_X^2-(p_N-p_u')^2}(\overline{\psi}_N P_L \psi_N)(\overline{\psi}_u P_R \psi_u)$$

Spin-independent piece:

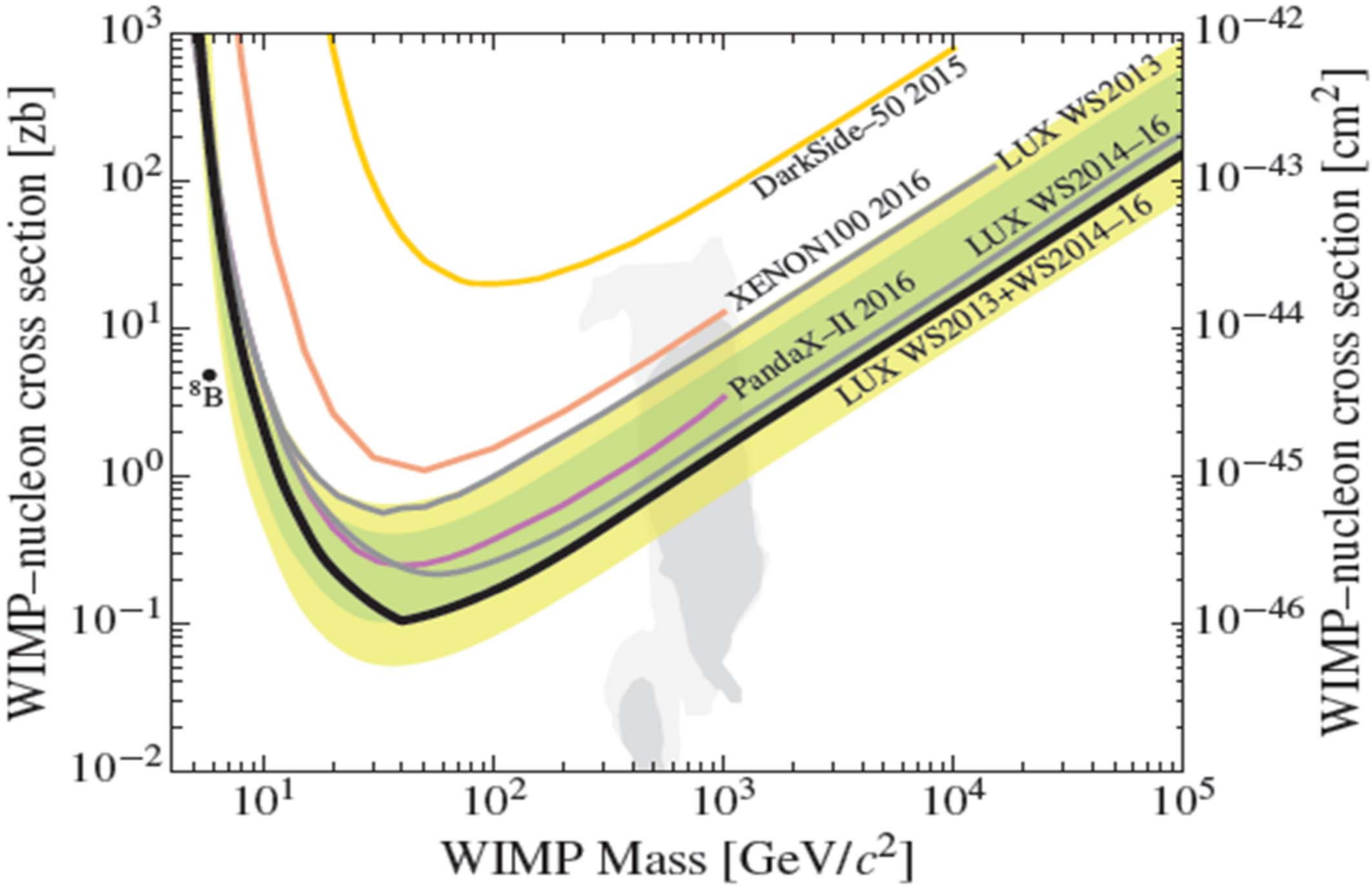
$$\frac{1}{m_X^4}(\overline{\psi}_N \gamma^\mu \partial^\nu \psi_N)\left[(\overline{\psi}_u \gamma_\mu \partial_\nu \psi_u)-(\partial_\nu \overline{\psi}_u \gamma_\mu \psi_u)\right]$$

Spin-dependent piece:

$$\frac{1}{m_X^2}(\overline{\psi}_N \gamma^\mu \gamma^5 \psi_N)(\overline{\psi}_u \gamma_\mu \gamma^5 \psi_u)$$

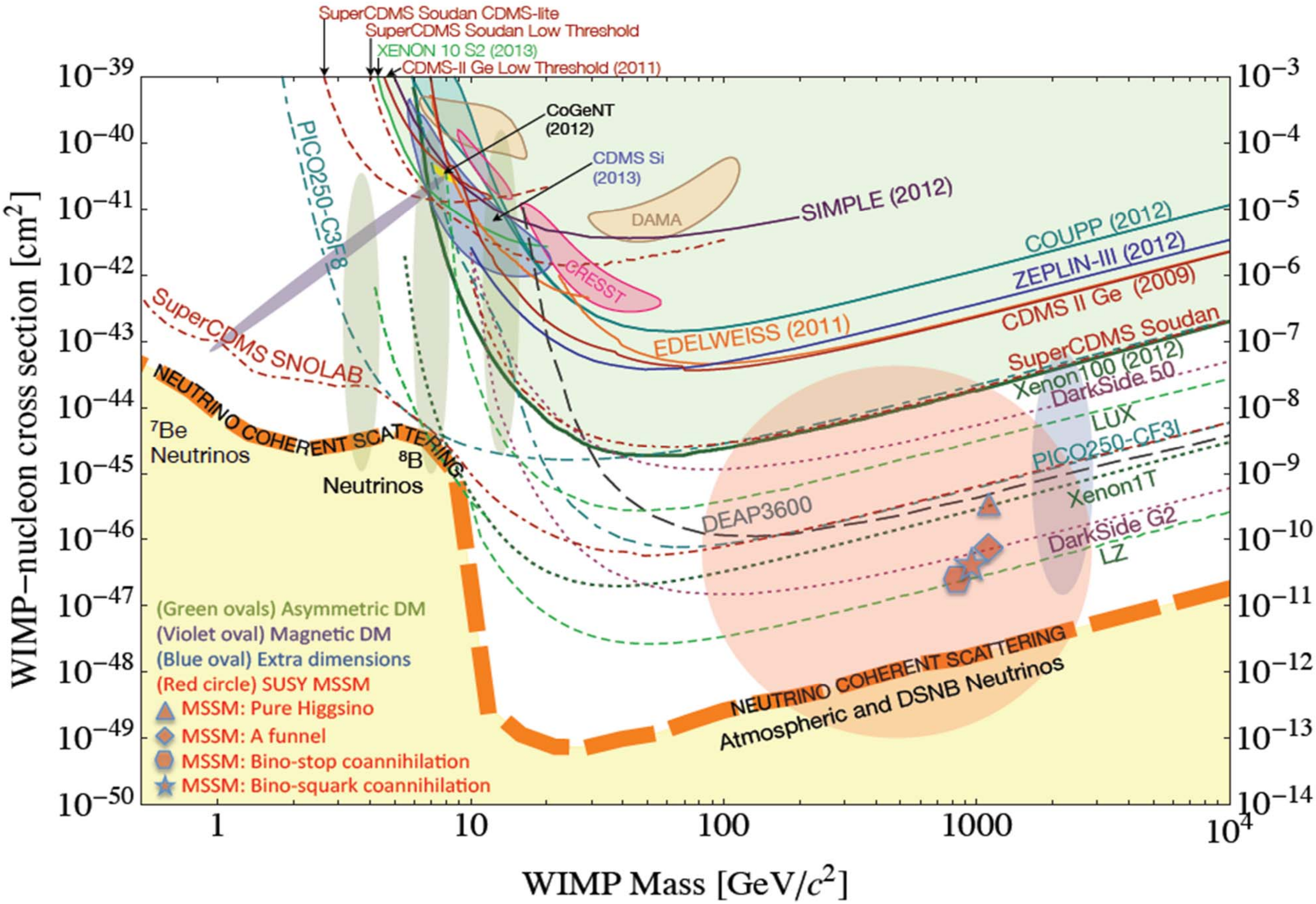
$$\sigma_{SI} \sim |\lambda|^4 \frac{O(GeV)^6}{m_X^8} \qquad \sigma_{SD} \sim |\lambda|^4 \frac{O(GeV)^4}{m_X^4}$$

LUX Collaboration PRL 118, 021303 (2017)



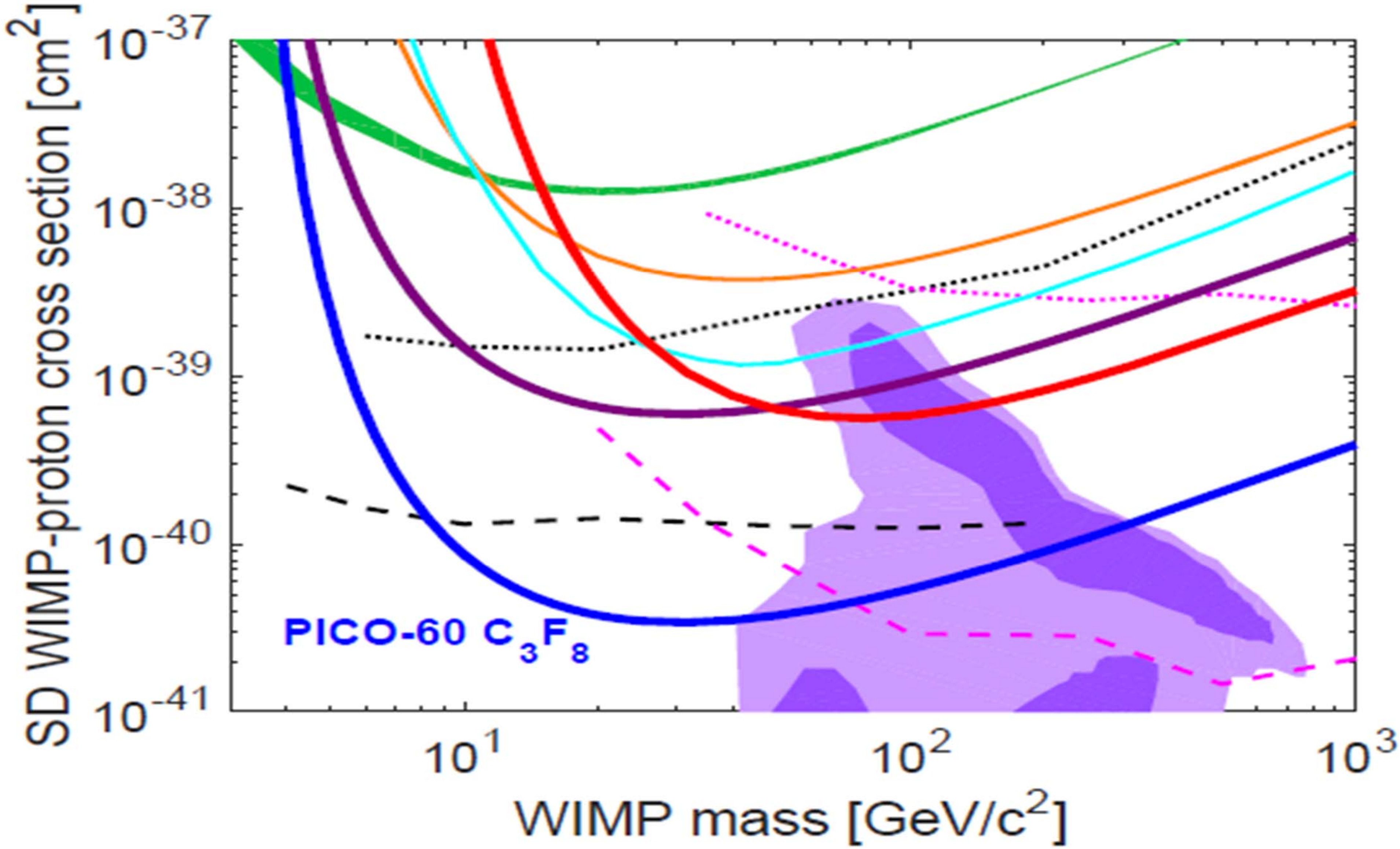
$$m_X \sim O(TeV) \Rightarrow \sigma_{SI} < 10^{-52} cm^2$$

Snowmass CF1 Summary (2013)



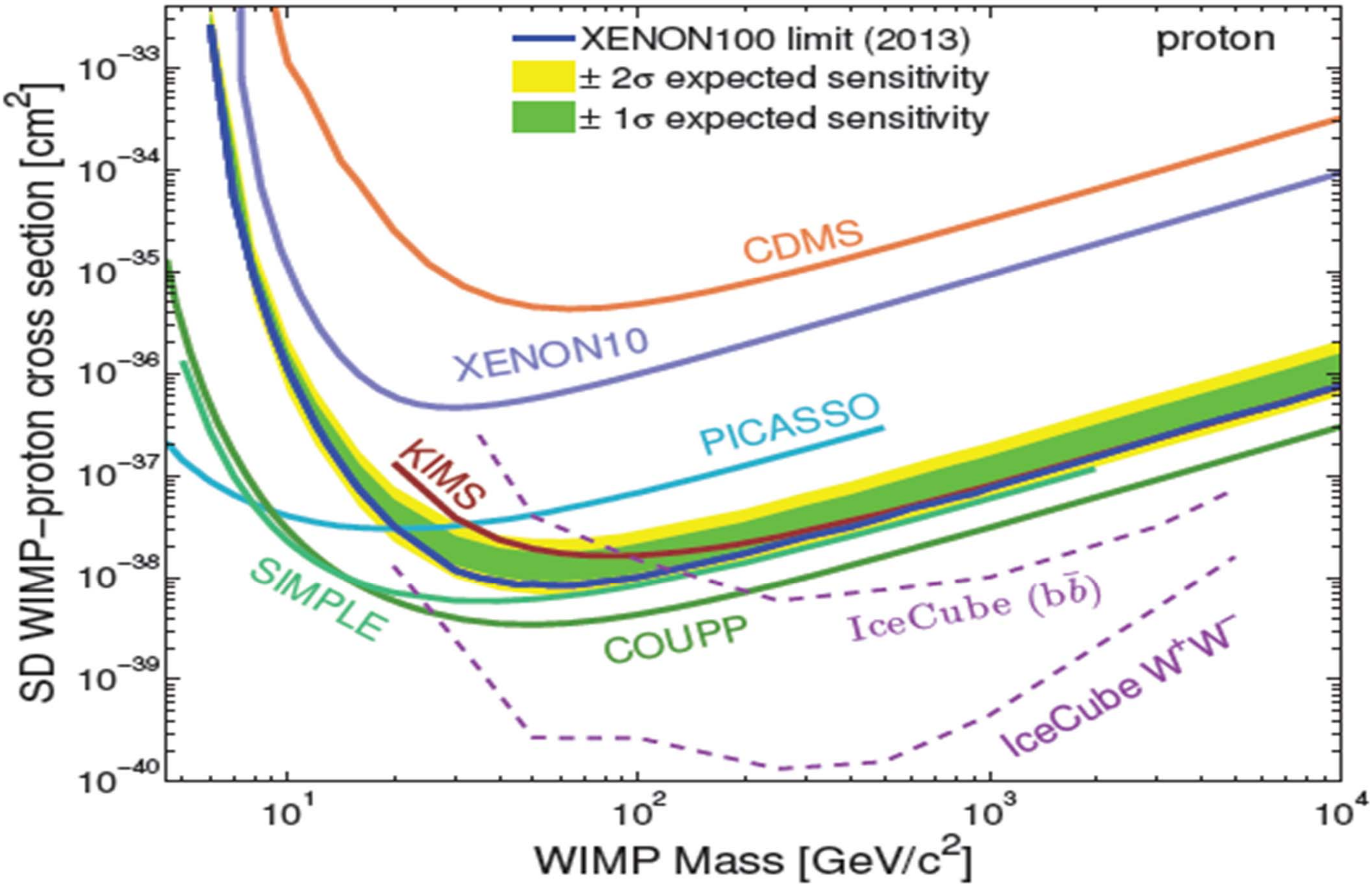
$$m_X \sim O(TeV) \Rightarrow \sigma_{SI} < 10^{-52}\, cm^2$$

PICO Collaboration PRD 93, 052014 (2016)



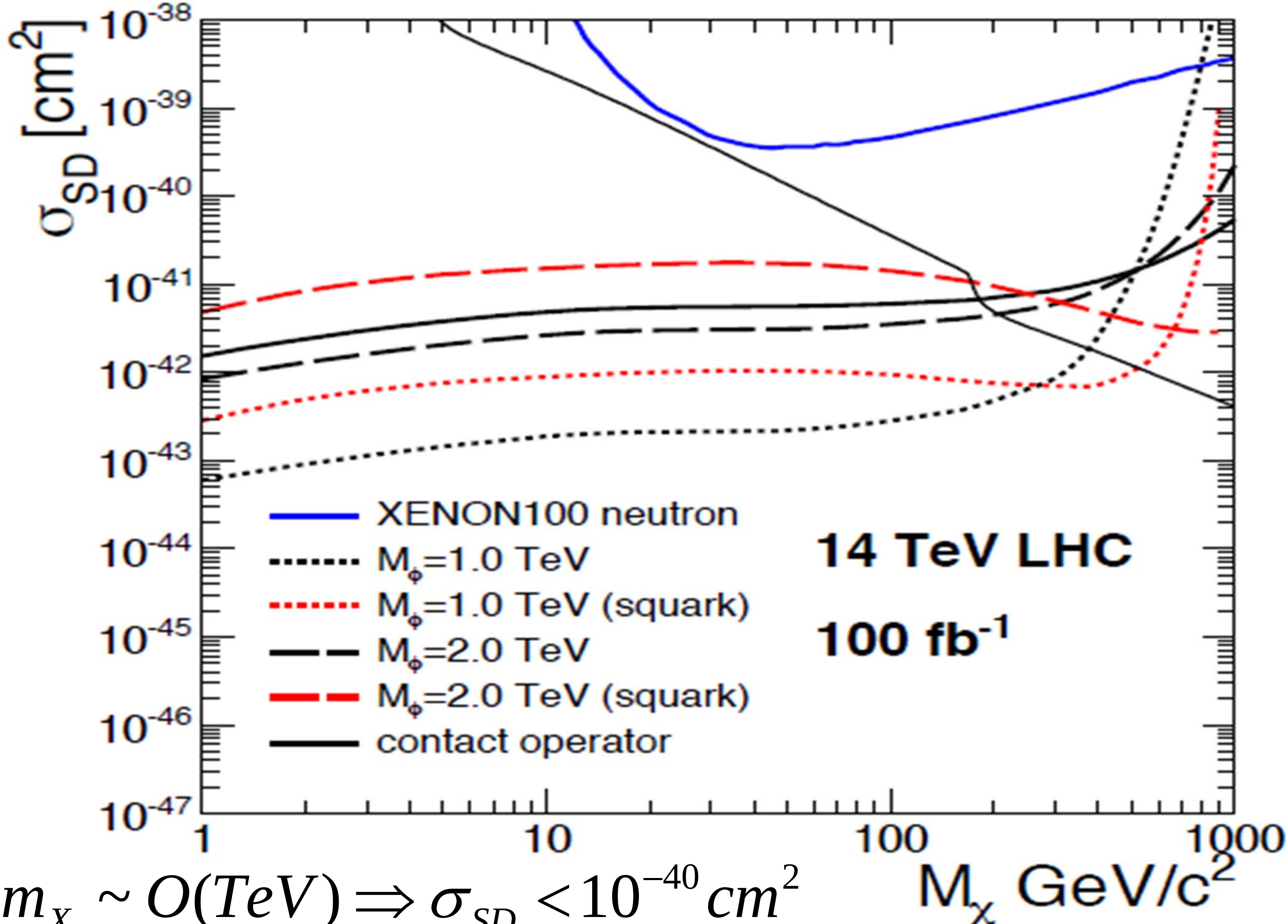
$$m_X \sim O(TeV) \Rightarrow \sigma_{SD} < 10^{-40} cm^2$$

Snowmass CF1 Summary (2013)



$$m_X \sim O(TeV) \Rightarrow \sigma_{SD} < 10^{-40} cm^2$$

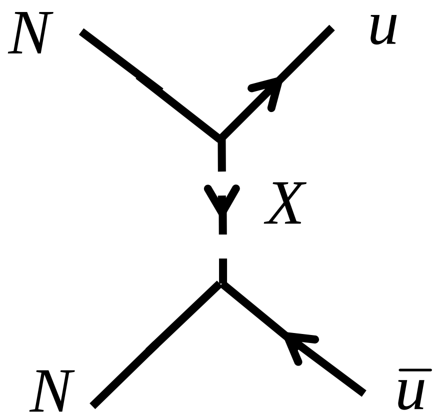
H. An, L-T. Wang, H. Zhang PRD 89, 115014 (2014)



$$m_X \sim O(TeV) \Rightarrow \sigma_{SD} < 10^{-40} cm^2$$

Indirect detection:

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



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

Much smaller than limits on galactic/extragalactic DM annihilation into gamma-rays and neutrinos.

Neutrino signal from solar DM annihilation depends on $\sigma_{SD,SI}$ and σ_{ann}. However, it is negligible too since:

1) Both capture and annihilation are suppressed.

2) Evaporation dominates for $O(GeV)$ DM mass.

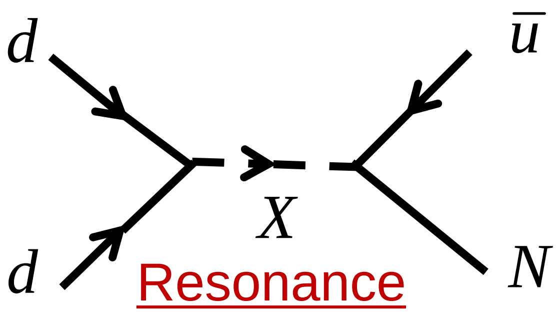
Collider signals: (see the talk by S. Undleeb)

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

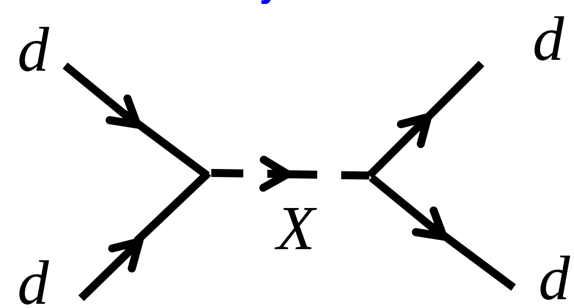
Monojets (including **monotops**) & dijets plus missing energy.

B. Dutta, Y. Gao, T. Kamon PRD 89, 096009 (2014)

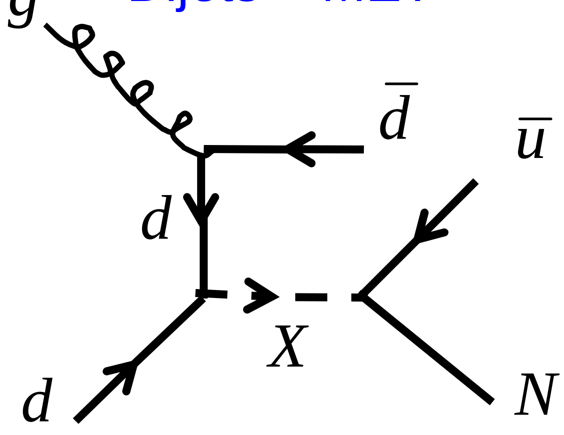
Monojets + MET



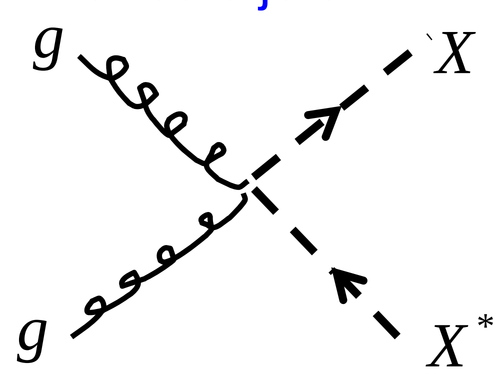
Dijets



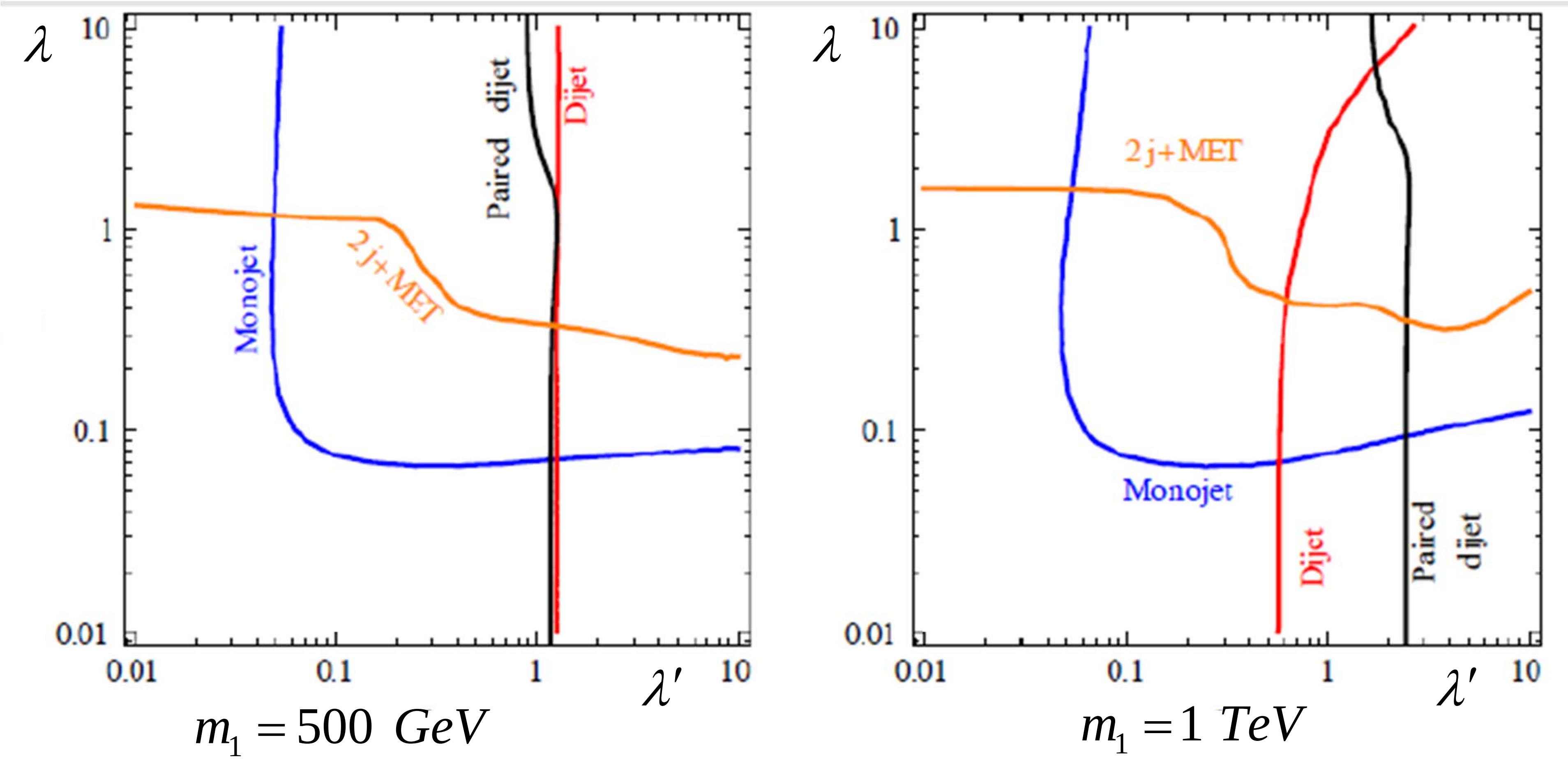
Dijets + MET



Paired dijets + MET



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



B. Dutta, Y. Gao, T. Kamon PRD 89, 096009 (2014)

Another Minimal Model:

In this model the DM is coupled to **LH quarks**.
The model has a slightly larger field content.

R.A., *et al* JHEP 1612, 046 (2016)

$$L_{new} = y_{1\alpha j} N X^*_\alpha Q_i + y_{2\alpha i} X_\alpha \overline{Y} d^c_i + y_{3\alpha i} X_\alpha Y d^c_i + m_Y Y\overline{Y}$$

$$+ m^2_\alpha |X_\alpha|^2 + \frac{m_N}{2} NN + h.c. + kinetic\ terms$$

$X_{1,2}$: **Iso-doublet** color-triplet scalars Y =+1/3

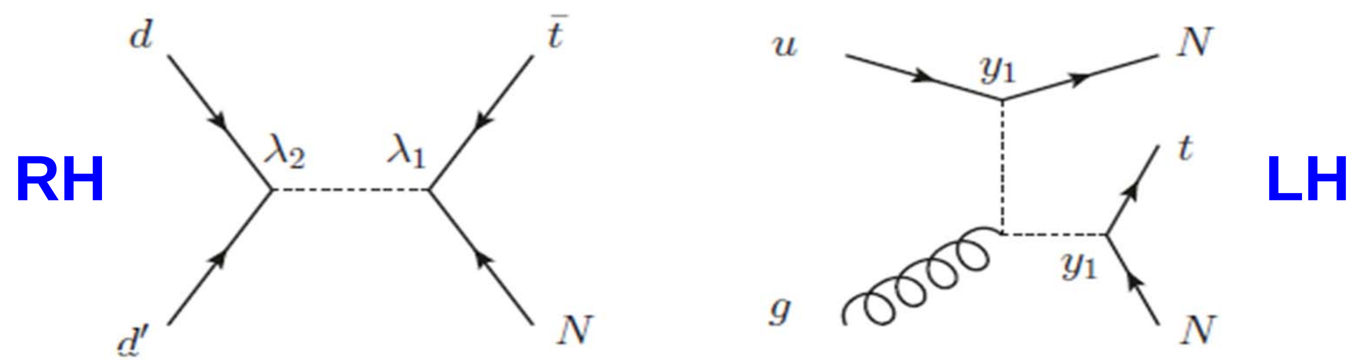
$Y, \overline{Y}$: Iso-doublet fermions Y =+1,-1 $m_Y > 45\ GeV$

N : Singlet fermion

N is the DM candidate if $m_N < m_Y$.

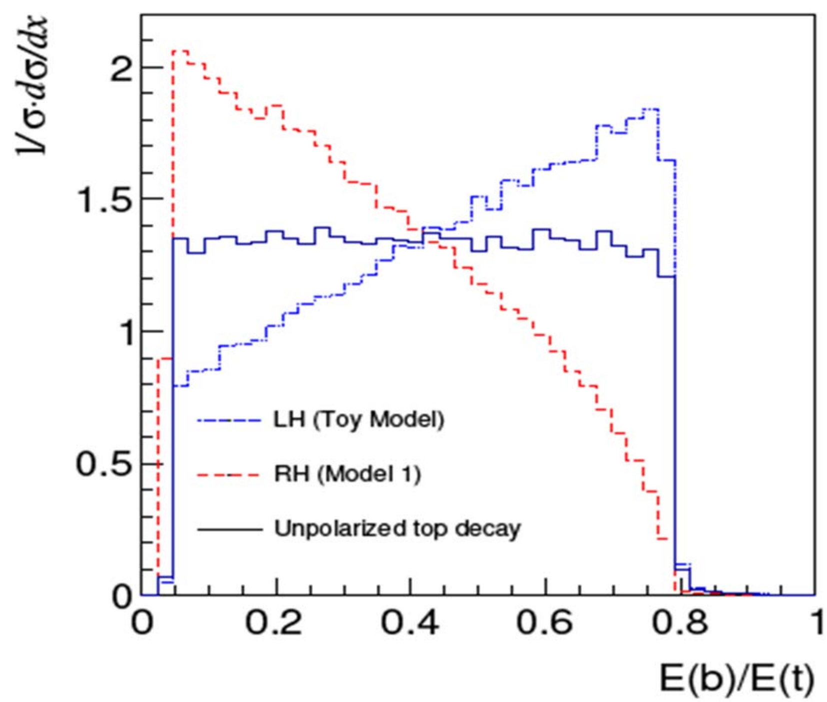
This model predicts **LH** monojet/monotop events.

This is different from most of the simplified DM models.



Top chirality can be used as a discriminator between the models:

$$t_{R,L} \rightarrow W^{+} + b_{L}$$



R.A., *et al* JHEP 1612, 046 (2016)

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 $\tilde{N}$ is a DM candidate.

$m_{\tilde{N}}$ can have any value irrespective of m_N .

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

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

The model allows natural realization of the multicomponent DM scenario if $m_N \approx 1\ GeV$.

Two components of DM arise from the same superfield, both of which can in principle be detected.

Prospects for direct and indirect detection of $\tilde{N}$ are good.

N may be detected at the LHC through monojet/monotop events.

Both components of DM are produced in nonthermal fashion.
For example, from invisible decay of the gravitinos.

R.A., B. Dutta, F. S. Queiroz, L. E. Strigari, M-Y Wang PRD 91, 055033 (2015)

Outlook:

- A minimal SM extension for TeV scale baryogenesis presented.
- It can accommodate an $O(GeV)$ fermionic DM candidate.
- DM coupled to RH quarks, abundance produced non-thermally.
- Distinct monojet/monotop signals detectable at the LHC.
- A second model with DM coupling to LH quarks presented.
- Monotop chirality can be sued to distinguish the two models.
- SUSY version has improved direct/indirect detection prospects.
- It can lead to a natural realization of multicomponent DM.