Title: Signals of Hidden Antibaryonic Dark Matter

Date: Sep 24, 2011 09:40 AM

URL: http://pirsa.org/11090115

Abstract: Many explanations have been proposed for the origin of dark matter and the creation of the baryon asymmetry, but very few of them address both cosmological puzzles at once. At the same time, the observed energy densities of dark matter and baryons are within a factor of five of each other hinting at a possible common origin. In this talk I will present a novel mechanism that generates both densities at once, with the dark matter species carrying a net baryon number. This gives rise to new and unusual dark matter signals such as the destruction of nucleons by dark matter scattering. I will describe some of these signals, and discuss how they might be detected in current and upcoming experiments and astrophysical observations.

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Hylogenesis*

Signals from Hidden Antibaryonic Dark Matter

David Morrissey

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with

Hooman Davoudiasl, Kris Sigurdson, Sean Tulin

arXiv:1008.2399 [hep-ph]

arXiv:1106.4320 [hep-ph]

Perimeter Institute DM Workshop, September 24, 2011

* hylo = Greek for matter

The "Standard Picture" and a Puzzle

- The Standard Picture for DM and Baryons:
  - Dark Matter comes from thermal freeze-out
  - Baryons come from an asymmetry generated by an independent dynamical mechanism.

e.g. Leptogenesis, Electroweak Baryogenesis, GUT BG, . . .

- But $\rho_{DM} \simeq 5\rho_B$ seems like a funny accident – DM and baryons have completely unrelated origins.

- Could they somehow be related to each other?

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A Second Puzzle: Moduli Oscillations

- Low-energy supersymmetry (SUSY) is well-motivated.
- Many SUSY theories contain light scalar "moduli" fields.
  e.g. SUSY flat directions, string compactifications, ...
- Moduli masses from SUSY breaking:

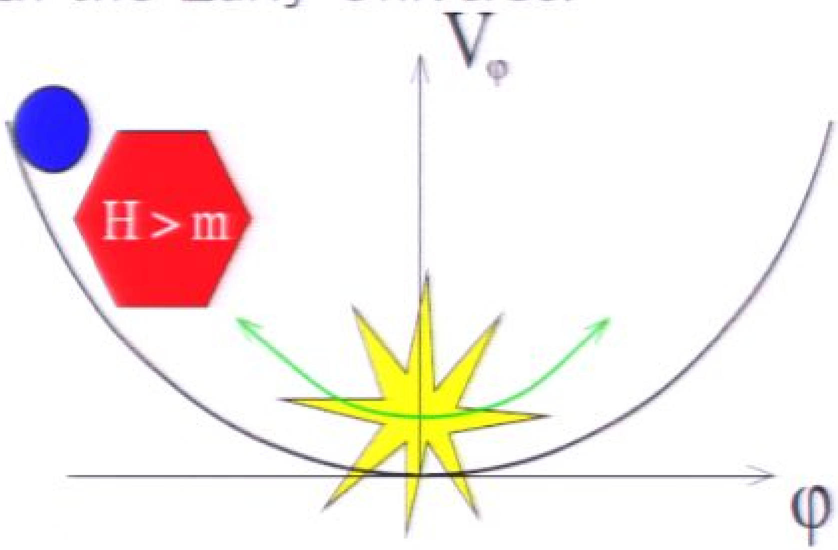
$$m_\varphi \sim m_{3/2}$$

Low-energy SUSY $\Rightarrow m_{3/2} \lesssim 1000\,\text{TeV}$.

- Moduli decay through higher-dimensional operators:

$$\Gamma_\varphi = \frac{m_\varphi^3}{4\pi\Lambda^2}$$

- In the Early Universe:



1. φ is displaced
2. φ oscillates when H ~ m
3. V_φ can dominate ρ
4. φ decays and reheats

- Reheating for $m_\varphi \lesssim 1000\,\text{TeV}$ is relatively late:

$$T_{RH} \simeq 200\,\text{MeV} \left(\frac{10}{g_*}\right)^{1/4} \left(\frac{M_{\text{Pl}}}{\Lambda}\right) \left(\frac{m_\varphi}{1000\,\text{TeV}}\right)^{3/2}$$

- DM can be produced non-thermally.

- This is too low for most baryogenesis mechanisms.
(Sphalerons become inactive at $T \sim 100\,\text{GeV}$.)

A Unified Solution?

- Maybe there is a reason for $\rho_{DM} \sim \rho_B$?

- The DM density could be set by the baryon asymmetry.

  $\rightarrow$ Asymmetric Dark Matter (ADM)

  [Nussinov '85;Kaplan '90; Barr '91; ..., Luty, Terning, Zurek '08]

- One step further – hidden antibaryons as dark matter.

  [Dodelson+Widrow '90; Farrar+Zaharijas '04;Kitano+Low '04;

  Agashe+Servant '04; An,Chen,Mohapatra,Zhang '09,...]

- A Concrete Low-Temperature Mechanism:

  Hylogenesis = Greek for *matter* + *creation*

A Collective Nominal Apology

- Darkogenesis (Ombrogenesis): Shelton+Zurek '10
- Hylogenesis: Davoudiasl,DM,Sigurdson,Tulin '10
- Xogenesis: Buckley+Randall '10
- Baryomorphosis: McDonald '10
- Aidnogenesis: Blennow,Dasgupta,Fernandez-Martinez,Ruis '10
- Cladogenesis: Allahverdi, Dutta, Sinha '10

- Related papers with more tasteful titles:

  Gu+Sarkar '09; Matsumoto+Saba '10; Chun '10; Hall,March-Russell,West '10

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A Simple Model for Hylogenesis

- Expand the SM with new hidden particles:
  - X_1, X_2 heavy (TeV) Dirac fermions, $B = +1$
  - Y light (GeV) Dirac fermion, $B = y$
  - Φ light (GeV) complex scalar, $B = -(1+y)$

- Couplings:

$$-\mathcal{L} \supset \frac{\lambda_a}{M^2} X_{L_a} U^c D^c D^c + \zeta_a^* X_a Y \Phi + (h.c.)$$

→ "neutron portal" coupling

Also used for BG by: Dimopoulos+Hall '87, Cline+Raby '91, Thomas '95,

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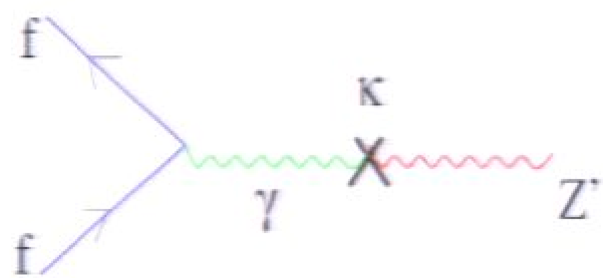
- One more ingredient - a new $U(1)'$ gauge symmetry:
  - Higgsed with $m_{Z'} \sim$ GeV
  - SM fields carry no direct $U(1)'$ charge
  - $X_{1,2}$ are neutral
  - Y and Φ have equal and opposite charges.

- Gauge kinetic mixing:

$$\mathcal{L} \supset -\frac{\kappa}{2} B^{\mu\nu} Z'_{\mu\nu}, \qquad |\kappa| \ll 1.$$

Induces a Z' coupling to the SM with strength $e\, Q_{em}\, c_W \kappa$.



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Matter Production

- Three Easy Steps:

  1. Equal numbers of X_1 and $\bar{X}_1$ are produced non-thermally.
  2. X_1 and $\bar{X}_1$ decay with CP violation into udd and $Y\Phi$.
  3. Non-asymmetric Y and Φ annihilate into Z's.

- Leftover Y and Φ make up the dark matter.

  They carry baryon number and lead to novel DM signals.

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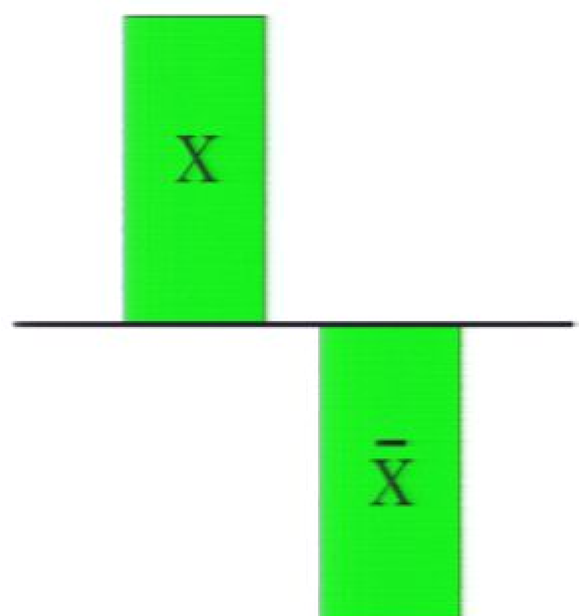
Step #1: X Production

- Equal X_1 and $\bar{X}_1$ densities are produced when $T \ll m_{X_1}$.
  e.g. reheating after moduli oscillation, inflation, ...
- This is the departure from equilibrium ingredient.
- X_1 and $\bar{X}_1$ have $B = \pm 1$, but there is no net B number.



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Step #2: X Decay

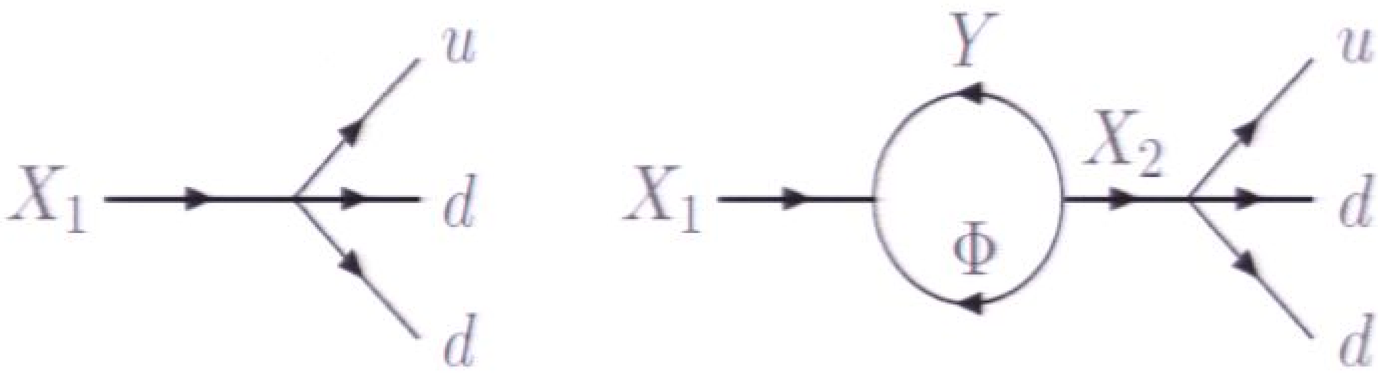
- $X \to udd$ or $\bar{Y}\Phi^*$, $\bar{X} \to \bar{u}\bar{d}\bar{d}$ or $Y\Phi$ instantaneously.

- CP violation alters partial decay widths:

$$\begin{aligned}
\Gamma(X \to 3Q) &= \Gamma_{3Q} + \epsilon\,\Gamma_{tot} \\
\Gamma(X \to \bar{Y}\bar{\Phi}) &= \Gamma_{Y\Phi} - \epsilon\,\Gamma_{tot} \\
\Gamma(\bar{X} \to 3\bar{Q}) &= \Gamma_{3Q} - \epsilon\,\Gamma_{tot} \\
\Gamma(\bar{X} \to Y\Phi) &= \Gamma_{Y\Phi} + \epsilon\,\Gamma_{tot}
\end{aligned}$$

CPT requires $\Gamma(X \to all) = \Gamma(\bar{X} \to all)$.

- Asymmetries come from tree-loop interference:

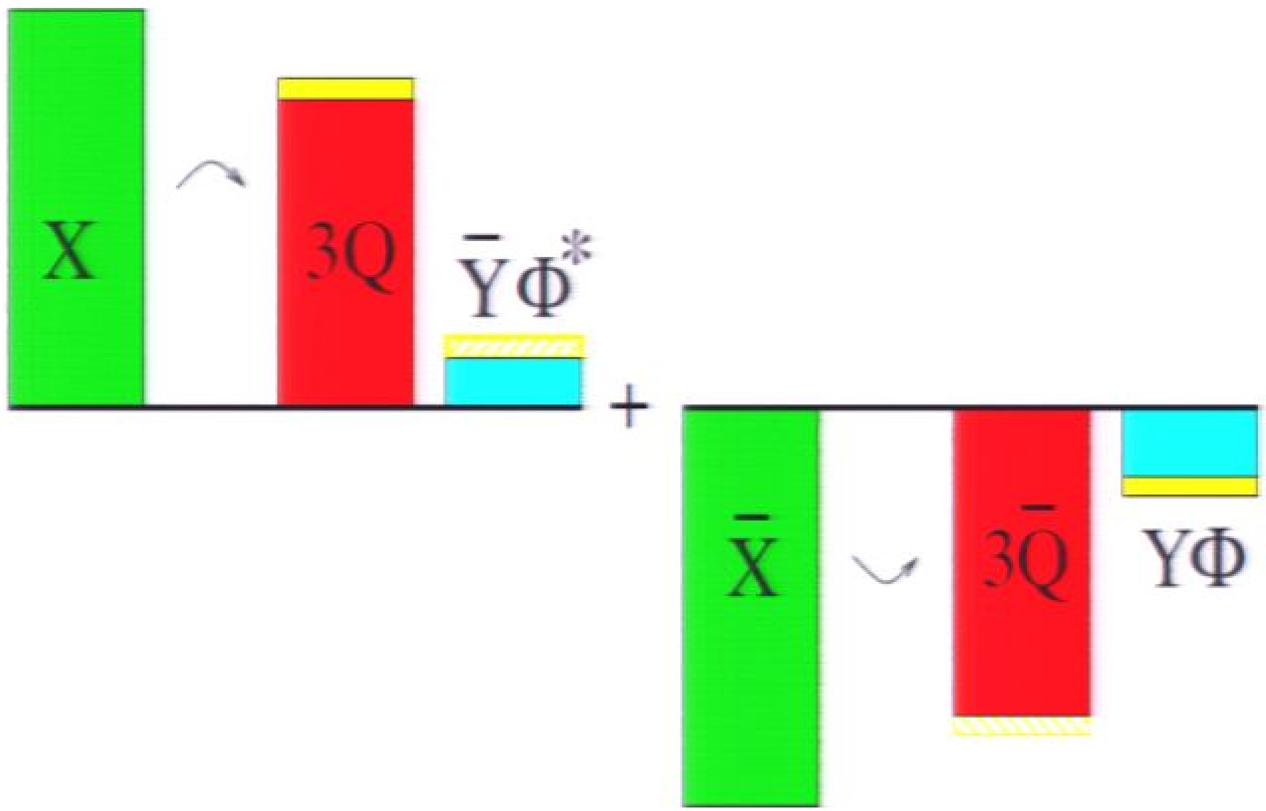


$$\epsilon = \frac{\Gamma(X \to 3Q) - \Gamma(\bar{X} \to 3\bar{Q})}{\Gamma(X \to all) + \Gamma(\bar{X} \to all)}$$

$$\simeq \frac{Im(\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*)}{256\pi^3 |\zeta_1|^2} \frac{m_{X_1}^5}{M^4 m_{X_2}}$$

- Final B Asymmetry: $\frac{n_B}{s} \simeq \epsilon \left. \frac{n_X}{s} \right|_{RH}$.

- Asymmetries split B into $3Q$, $Y\Phi$.



- There is no violation of total (generalized) B number.

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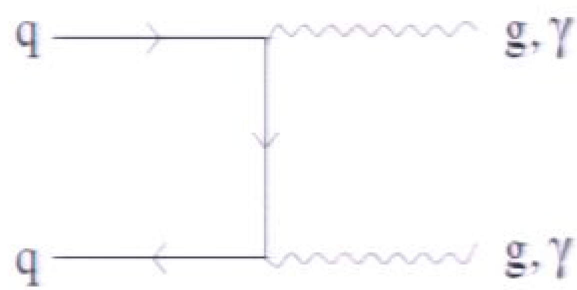
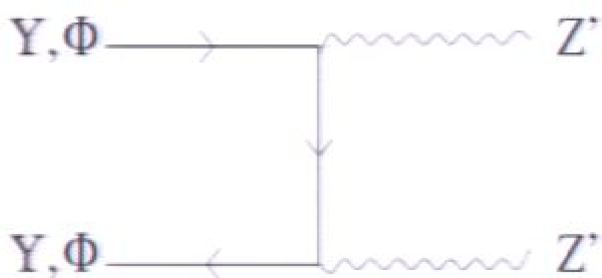
Step #3: Annihilation

- Quarks annihilate until only the asymmetry remains:

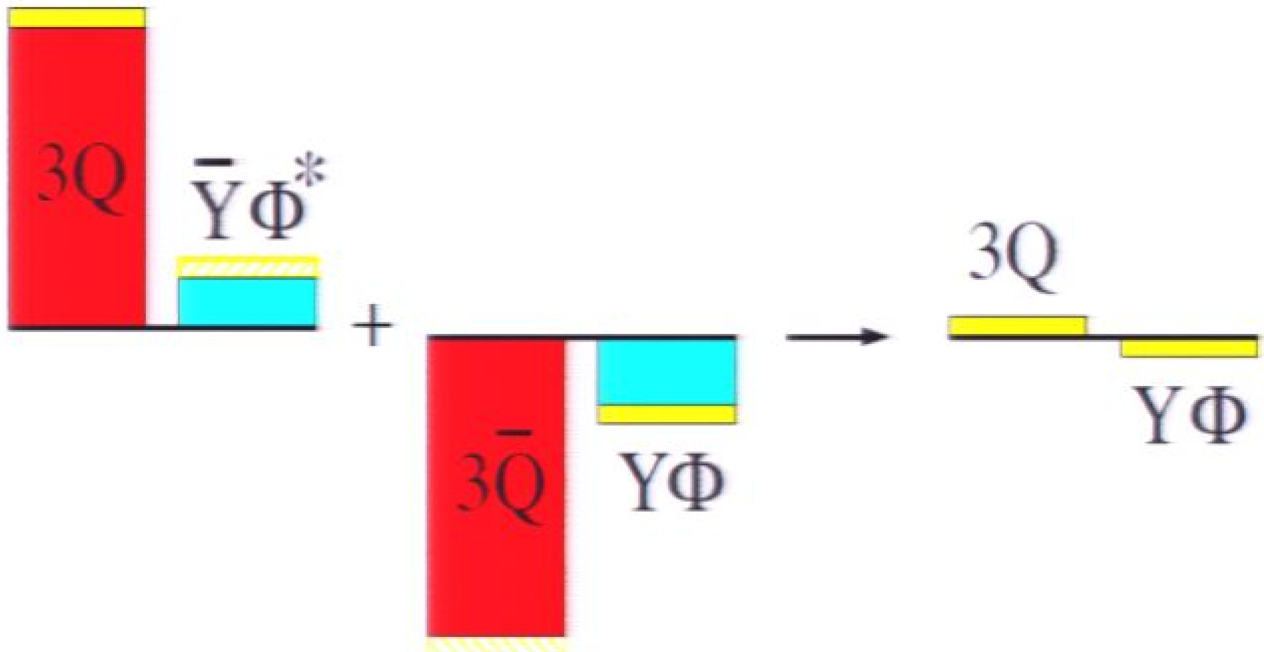


- Y, Φ annihilate to Z' leaving only the asymmetry:



- Very efficient for $m_{Z'} < m_{Y,\Phi}$.

- All that remains are equal and opposite densities of $3Q$ and $Y\Phi$ set by the decay asymmetry.



- Y and Φ are hidden antibaryons.

- We want them to be stable.

Hidden antibaryons as dark matter?

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Hidden Antibaryonic Dark Matter

- We have $n_Y = n_\Phi = n_B$.
- Both Y and Φ can be stable if:

$$|m_Y - m_\Phi| < (m_p + m_e) < m_Y + m_\Phi$$

- They provide the right DM density if:

$$(m_Y + m_\Phi) = m_p \left(\frac{\rho_{DM}}{\rho_B}\right) \simeq 4.5\,\text{GeV}.$$

- Possible mass ranges: $1.7\,\text{GeV} \lesssim m_{Y,\Phi} \lesssim 2.9\,\text{GeV}$.

(The Z' should be even lighter than this.)

- Gratuitous non-physics picture:

Signals of Hylogenesis

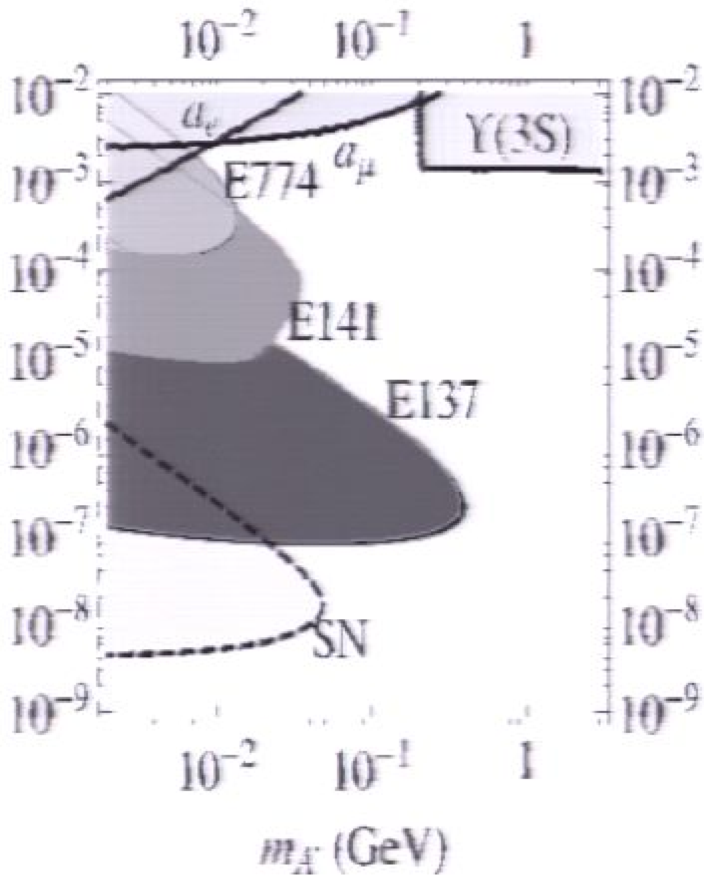
- Y and Φ together make up the dark matter.
  They both couple to a light Z' vector boson.

- Potential Signals:
  - Direct Z' effects in colliders, precision experiments.
  - Elastic scattering of Y and Φ off nuclei via Z'.
  - Nucleon destruction from inelastic Y/Φ scattering.
  - Monojets at colliders from $Xudd$, DM production.

- All four types of signals could be observed soon.

Light Z' Signals

[Pospelov '08; Batell,Pospelov, Ritz '09, Reece+Wang '09; Bjorken *et al.* '09, ...]



[Bjorken,Essig,Schuster,Toro '09]

Fixed target experiments can improve these bounds.

[Bjorken *et al.* '09, APEX '11]

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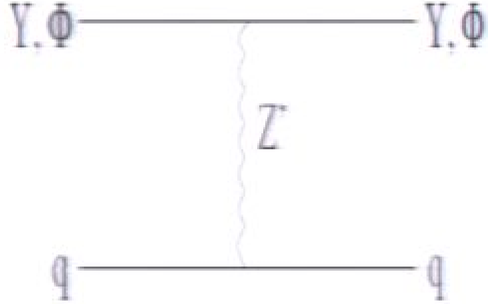
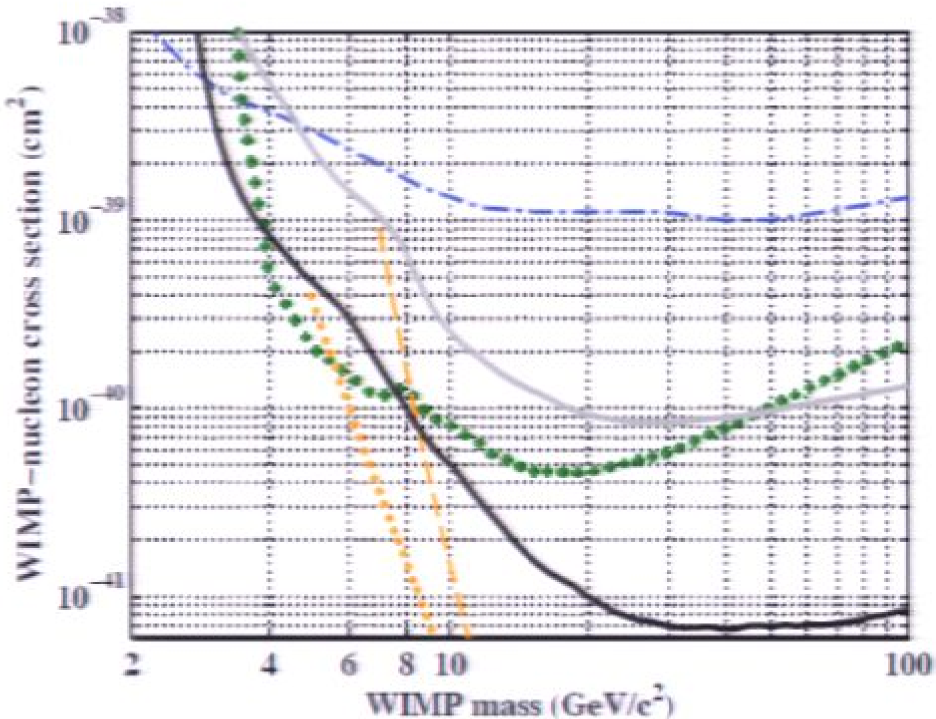
DM-Nucleon Elastic Scattering

- Y and Φ can scatter elastically off nuclei via Z'.





- Cross-section per nucleon (spin-independent):

$$\sigma_0^{SI} = (5\times 10^{-39} cm^2)\left(\frac{2Z}{A}\right)^2\left(\frac{e'}{0.05}\right)^2\left(\frac{\kappa}{10^{-5}}\right)^2\left(\frac{0.1\,\mathrm{GeV}}{m_{Z'}}\right)^4$$

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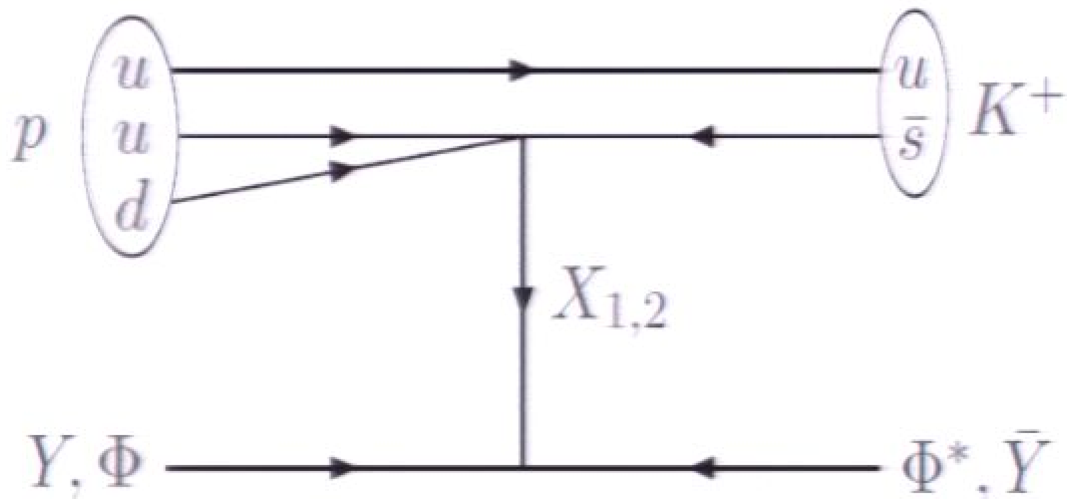
DM-Nucleon Inelastic Scattering

- DM now carries $B = -1$!
- Y or Φ can scatter inelastically off a nucleon.

  e.g.



- A nucleon is destroyed in this process.

$$Y/\Phi + N \to \Phi^*/\bar{Y} + M$$

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- Inelastic DM scattering will mimic nucleon decay.

  → Induced Nucleon Decay (IND)

- Total event rates in a nucleon decay detector:

$$R_{decay} = \Gamma_{decay} N_{nuc}$$
$$R_{IND} = (\sigma v)_{IND} \, (\mathcal{F}_{DM}/v) \, N_{nuc}$$

$\mathcal{F}_{DM}$ = local DM flux

- Effective IND "lifetime":

$$\tau_{eff}^{-1} = (\sigma v)_{IND} \, (\mathcal{F}_{DM}/v) \, .$$

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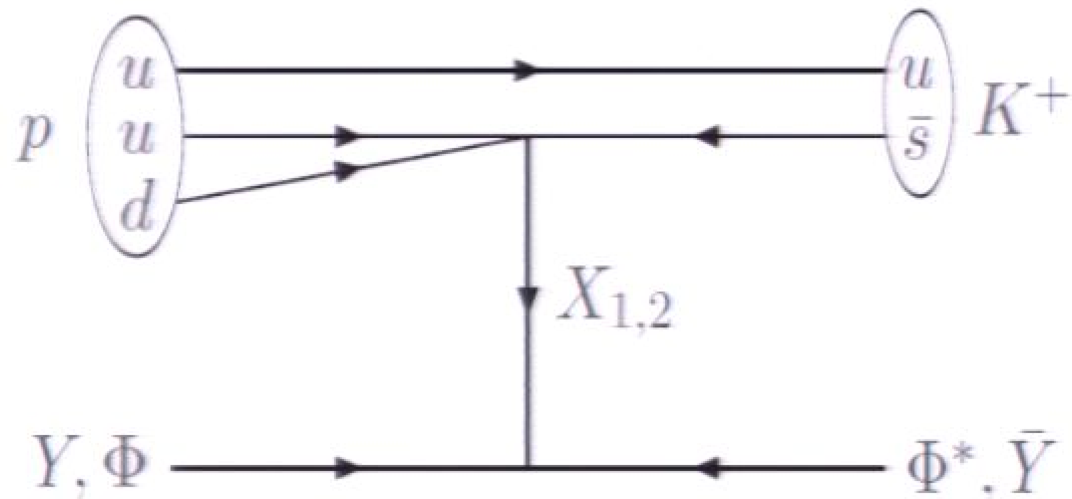

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- IND rate:

$$\tau_{eff} \simeq 10^{32}\,yr \left|\frac{m_X M^2/\lambda^*\zeta}{\text{TeV}^3}\right|^2$$

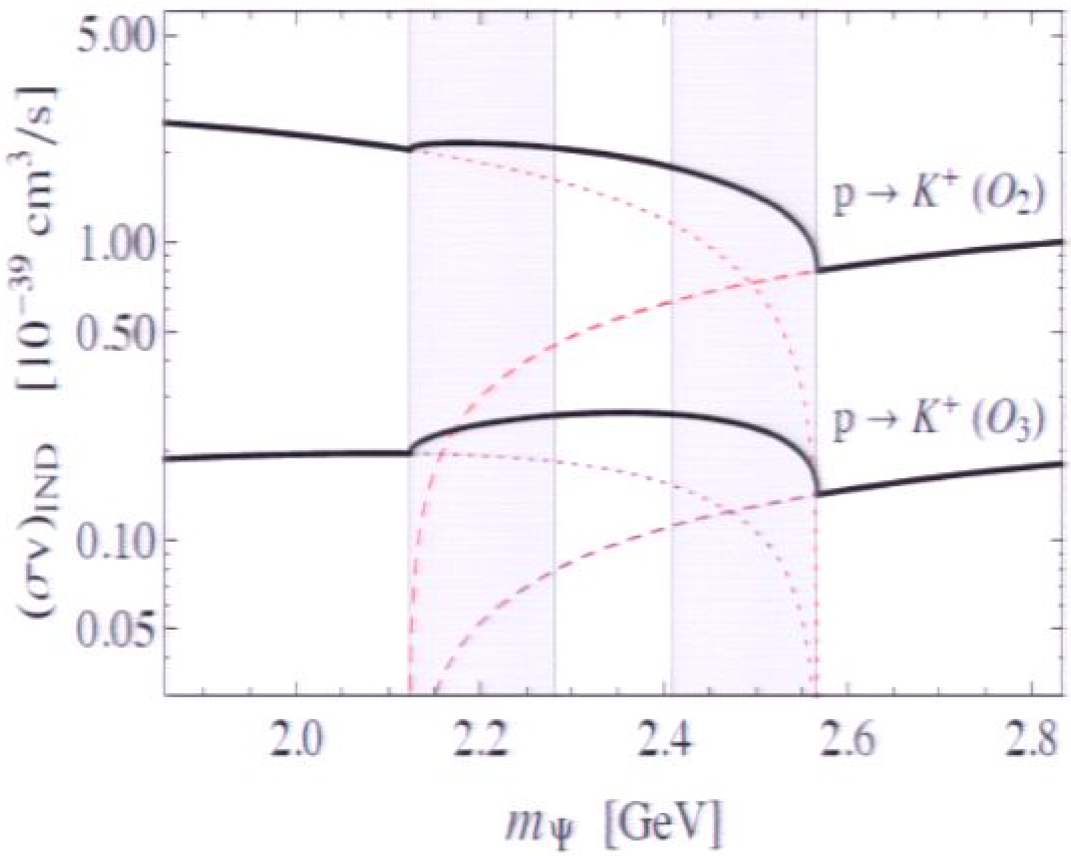
($\tau_{eff} = 10^{32}\,yr$ corresponds to $(\sigma v)_{IND} \simeq 10^{-39} cm^3/s$)

- Nucleon decay searches use a meson momentum window.

  Meson momenta from IND are larger (for downscattering):

Decay mode	p_M^{SND}	p_M^{IND} [down]	τ_N bound ($\times 10^{32}$ yr)
$N \to \pi$	460	800 – 1400	$\tau_p > 0.16$, $\tau_n > 1.12$
$N \to K$	340	680 – 1360	$\tau_p > 23$, $\tau_n > 1.3$
$N \to \eta$	310	650 – 1340	$\tau_n > 1.58$

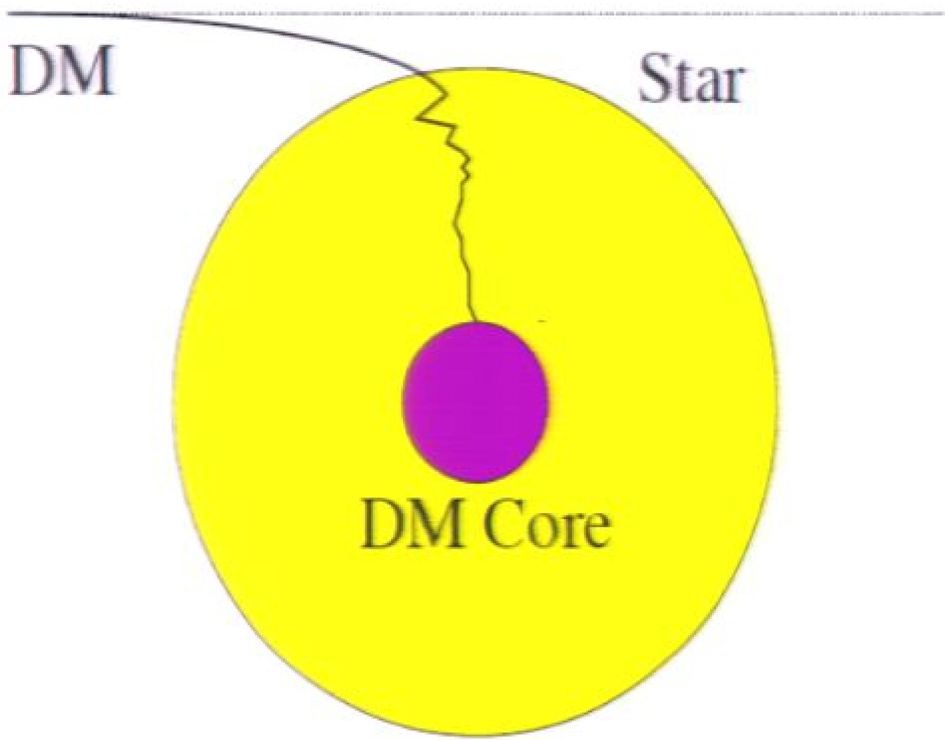
- Results for $U^c D^c S^c X$ operator:



- Shaded bands are covered by existing (SuperK) analyses.

IND and Stars

- DM can collect in stars and build up a large density.



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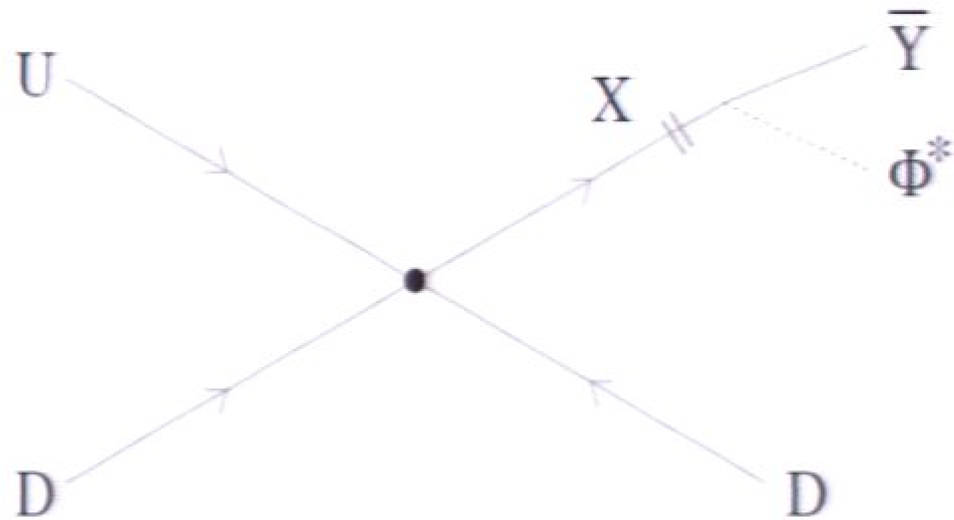
- Regular DM self-annihilates and can heat up a star.
- Y and Φ DM can't self-annihilate, but can yield IND:
  - DM collects in the stellar core by elastic scattering.
  - IND: $Y/\Phi + N \rightarrow \Phi^*/\bar{Y} + M$
  - Φ^* annihilates with Φ, $\bar{Y}$ annihilates with Y
- Largest effects in dense neutron stars, white dwarfs.

  Main effect is stellar heating, not nucleon destruction.

  [Kouvaris '08; Bertone+Fairbairn '08; McCullogh+Fairbairn '10; Hooper *et al.* '10]
- Solar bounds are weak due to evaporation ($m_{DM} \leq 2.9$ GeV).

Collider Searches

- The operator $XU^cD^cD^c/M^2$ will produce monojets:



- Tevatron + LHC are sensitive to $M \sim$ TeV.
  $\Rightarrow$ same scale probed by nucleon decay experiments

- Analagous to monojet bounds on "ordinary" dark matter.

[Rai, Fox, Harnik '10; Goodman *et al* '10; Graesser, Shoemaker, Vecchi '11]

- Slight problem: $M \sim \sqrt{\hat{s}}$ for relevant collisions.

  $\Rightarrow$ details depend on the UV completion

- But DM/baryon production and IND do not (have to).

- Quasi-model-independent fix:

$$-\frac{1}{M^2} \to \begin{cases} \frac{1}{\hat{s}-M^2-i\sqrt{\hat{s}}\,\Gamma} & (X \text{ contracts with final } q) \\ \frac{1}{\hat{t}-M^2} & (X \text{ contracts with initial } q) \end{cases}$$

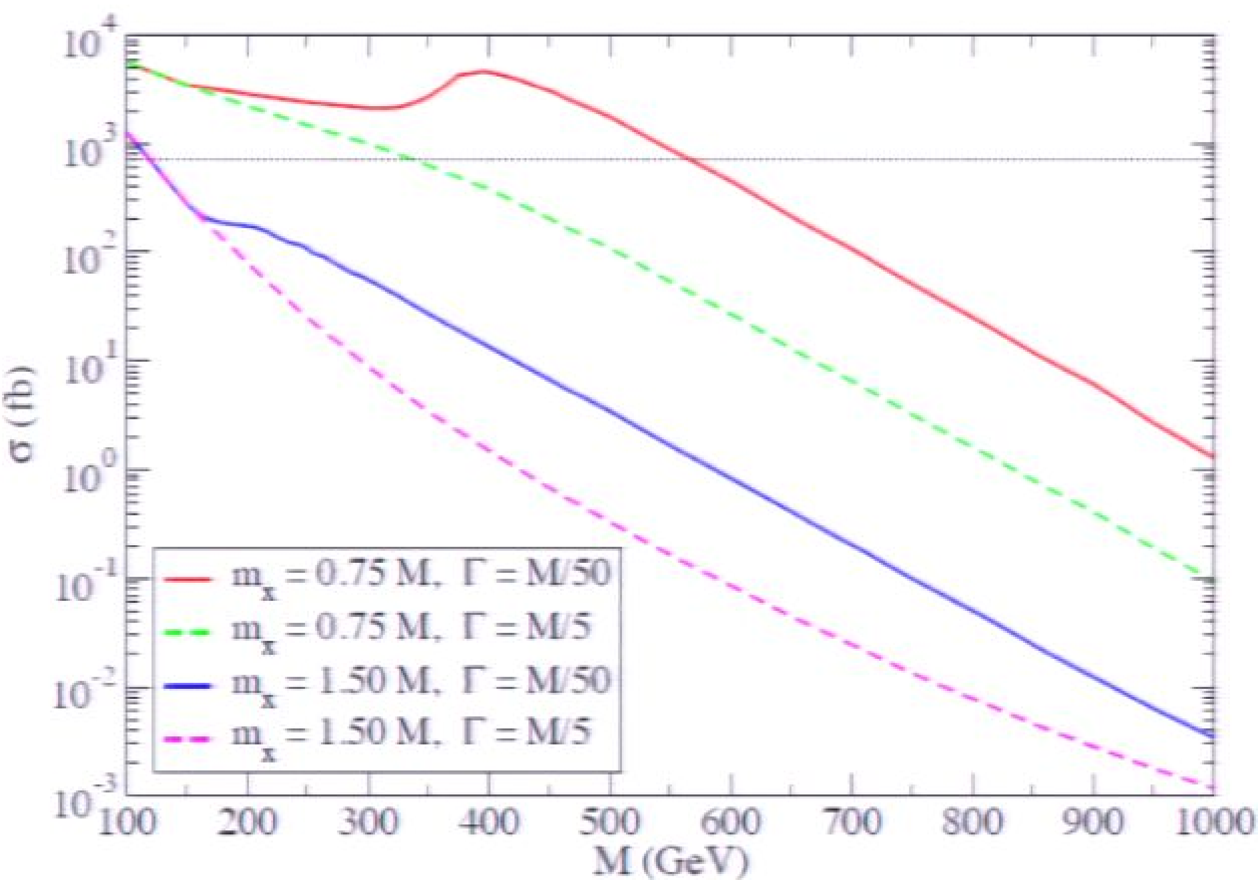
  Γ = unknown mediator width

- Look at different values of Γ to estimate UV dependence.

• Tevatron (CDF) Monojet Search:

jet with $p_T > 80\,\text{GeV}$, $|\eta| < 1.0$, ...

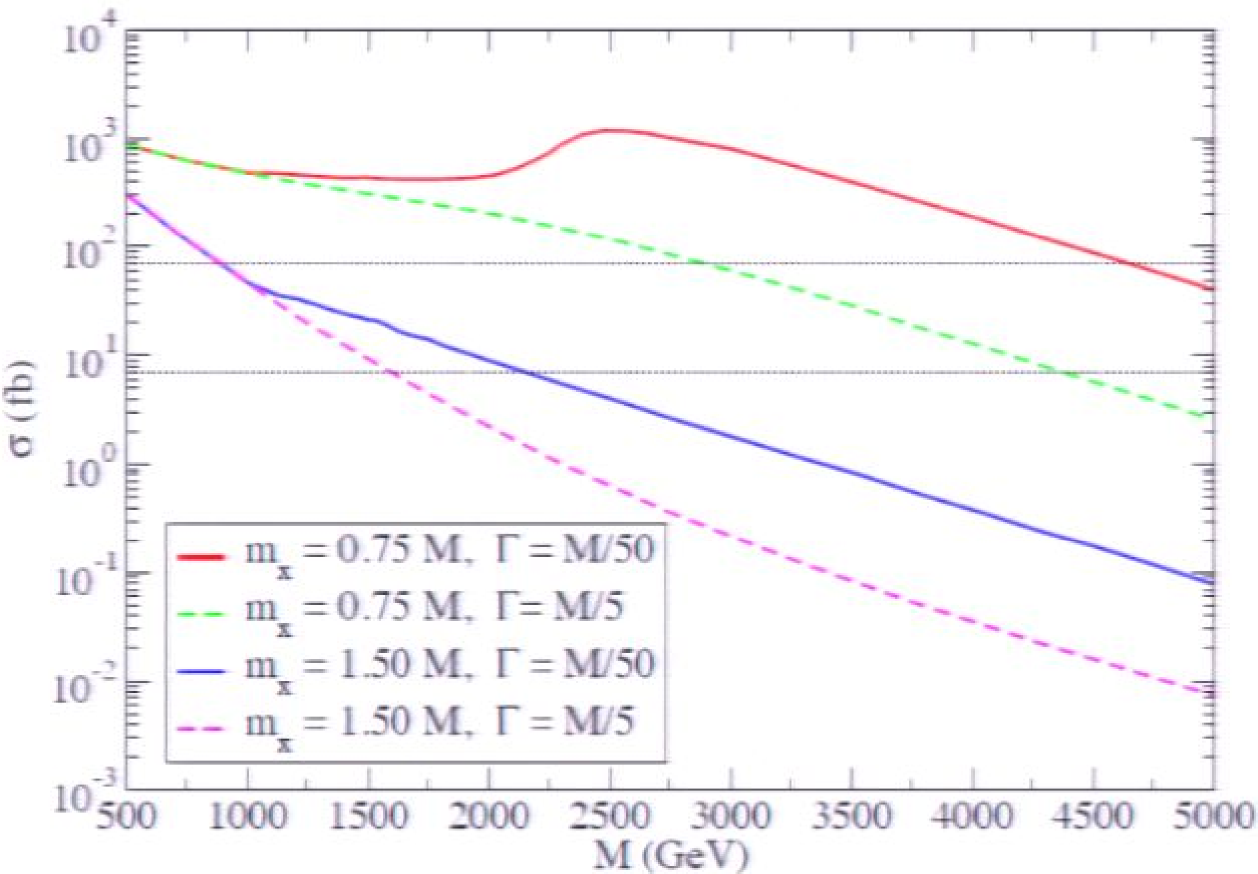
• CDF search ($1.0\,fb^{-1}$) implies $\sigma < 0.66\,pb$.



- LHC $j + \not{E}_T$ Search: jet with $p_T > 500$ GeV, $|\eta| < 3.2$, ...

  [Vacavant+Hinchliffe '01]

- Sensitivity with 100 fb^{-1} at 14 TeV: $\sigma \gtrsim 7\ fb$.



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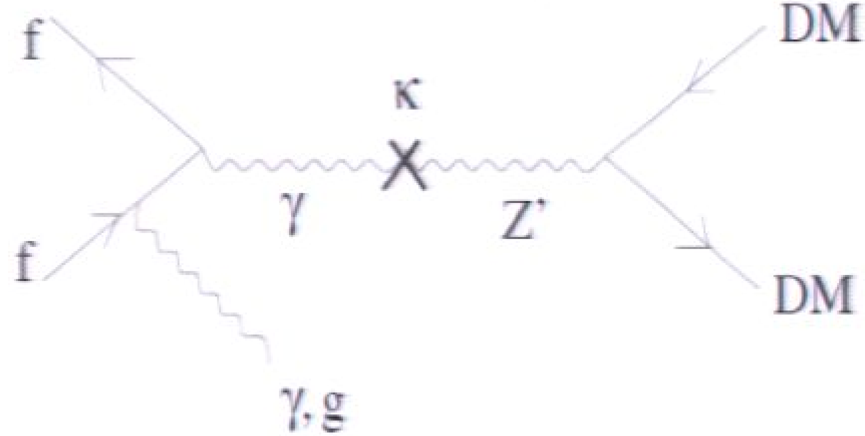
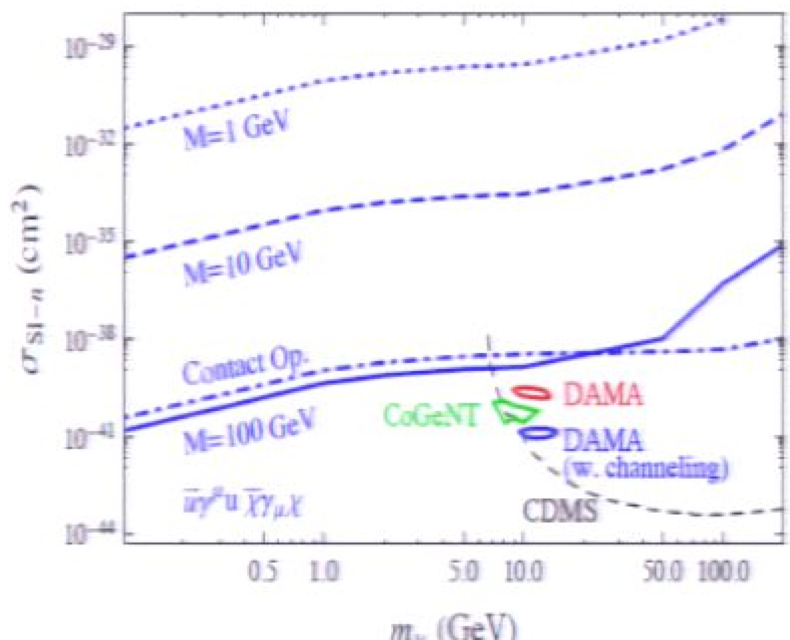
- Monojets can also come from Z' Drell-Yan with ISR/FSR:



Could be observable at the LHC: [Bai,Fox,Harnik '10; Goodman '10]



Summary

- Hylogenesis realizes DM as hidden antibaryons.

  Explains DM and the baryon asymmetry simultaneously.

- $\rho_{DM} \simeq 5\rho_B \Rightarrow \Sigma_i m_{DM_i} \simeq 5\, m_p$.

- A distinctive new DM signal is Induced Nucleon Decay.

  $M \sim 1$ TeV probed by existing nucleon decay searches.

- The scenario is also be testable at the LHC via monojets.

- A natural mass hierarchy could arise from SUSY (in progress).