Baryons and (Unusual) Light Dark Matter

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with

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Motivation #1: DM and Baryons

- $$\Omega_{DM} \simeq 5\Omega_b$$

  Could this be more than an accident?

- Asymmetric DM [Nussinov '85; . . . , Luty, Terning, Zurek '08;. . .]
  - Distinct DM χ and anti-DM $\bar{\chi}$.
  - More χ created than $\bar{\chi}$.
  - Efficient $\chi\bar{\chi}$ annihilation, no $\chi\chi$ or $\bar{\chi}\bar{\chi}$.

- This is how we get the baryon density.

  DM asymmetry related to the baryon asymmetry?

- Naïve guess: $m_\chi \sim 5\,m_p \sim 5\,\text{GeV}$.

Motivation #2: Moduli

- Many (SUSY) theories contain light scalar "moduli" fields.

  e.g. SUSY flat directions, string compactifications, . . .

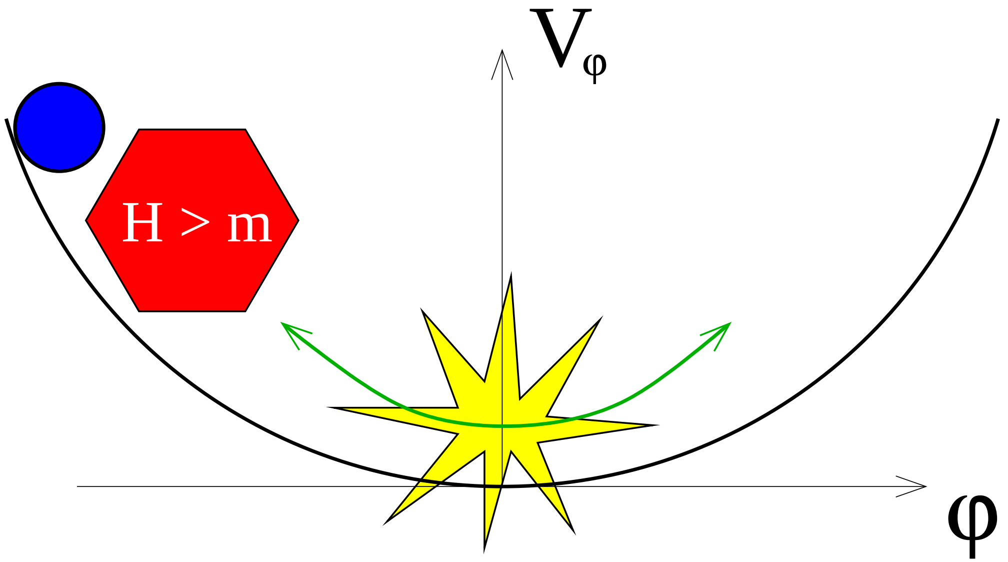
- Moduli masses often related to SUSY breaking:

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

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

- Moduli decay through higher-dimensional operators:

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



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 (*e.g.* moduli decays).
- This is too low for most baryogenesis mechanisms.

  Sphalerons become inactive at $T \sim 100\,\text{GeV}$.

A Unified Approach

- Relate the baryon asymmetry to a DM asymmetry.

  → Asymmetric Dark Matter (ADM)

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

- One step further – hidden antibaryons as DM.

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

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

- Find a low-temperature mechanism for the asymmetry consistent with late moduli decay.

A Sample Mechanism: 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"

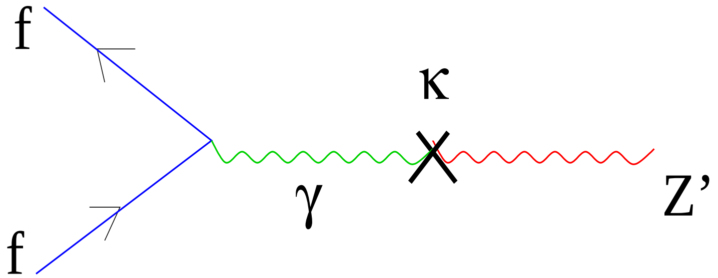
Also used for BG by: Dimopoulos+Hall '87, Cline+Raby '91, Thomas '95, Kitano,Murayama,Ratz '08; Allahverdi,Dutta,Sinha '10.

- 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 $e\, Q_{em}\, c_W \kappa$.



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.

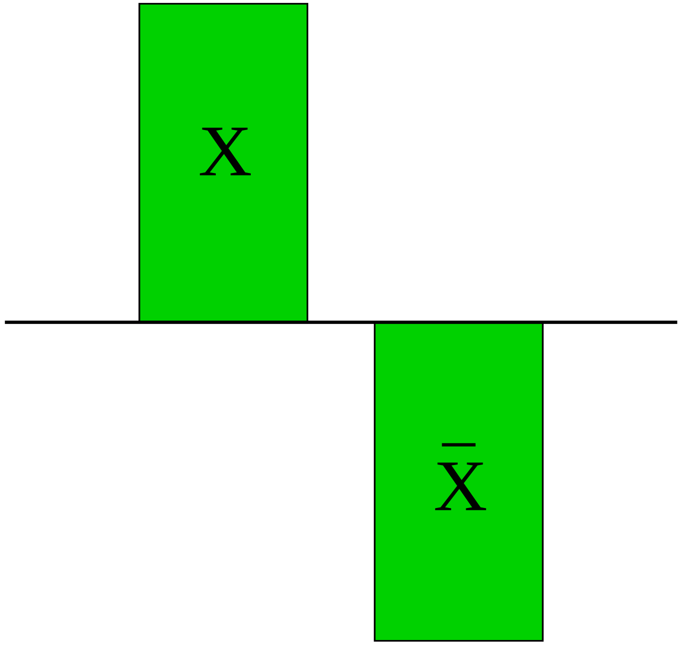
Step #1: X Production

- 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.



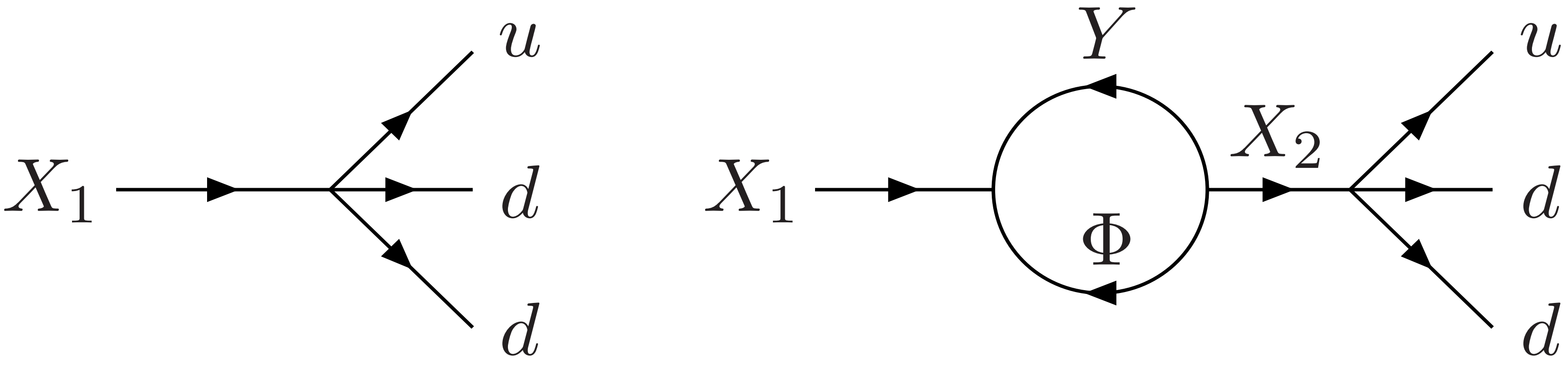
Step #2: X Decay

- $X \to udd$ 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:

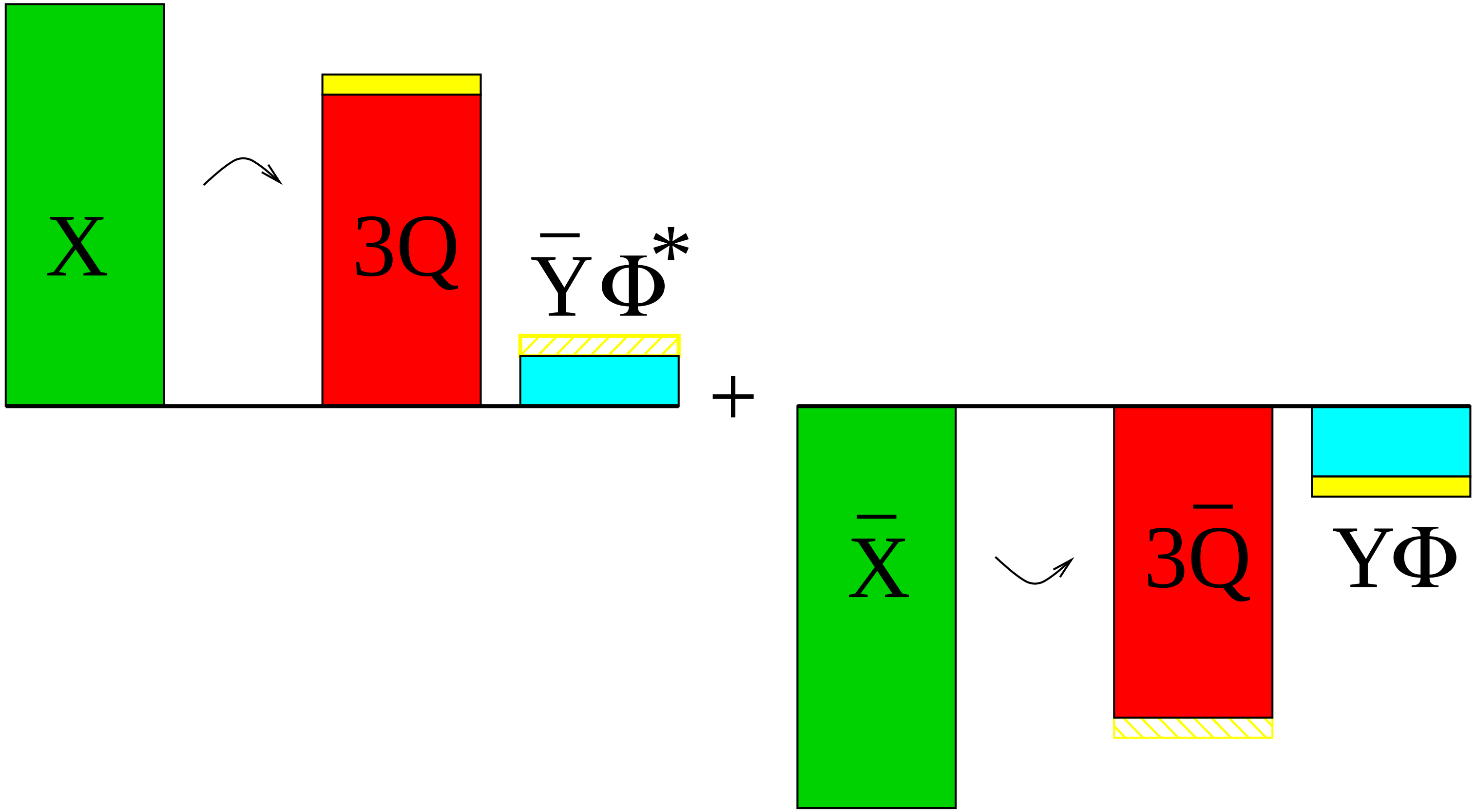


$$\epsilon = \frac{\Gamma(X \to 3Q) - \Gamma(\bar{X} \to 3\bar{Q})}{\Gamma(X \to all) + \Gamma(\bar{X} \to all)}$$

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

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

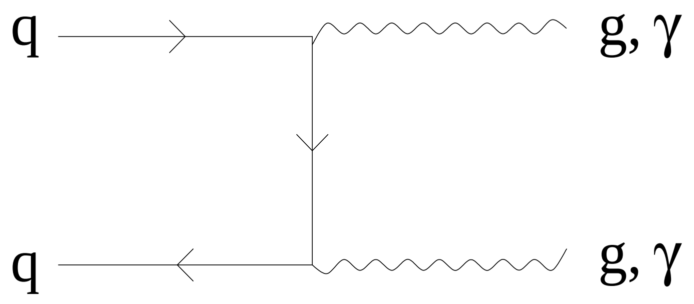
- Asymmetries split B into $3Q$, $Y\Phi$.



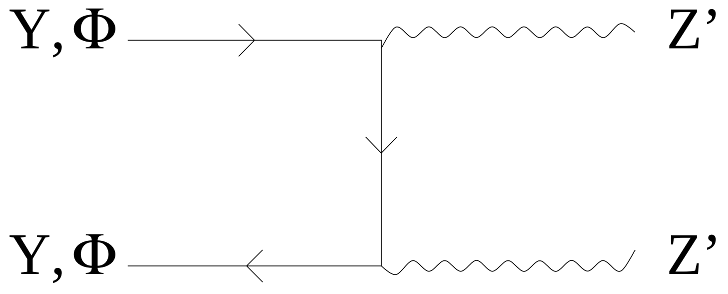
- There is no violation of total (generalized) B number.

Step #3: Annihilation

- Quarks annihilate until only the asymmetry remains:

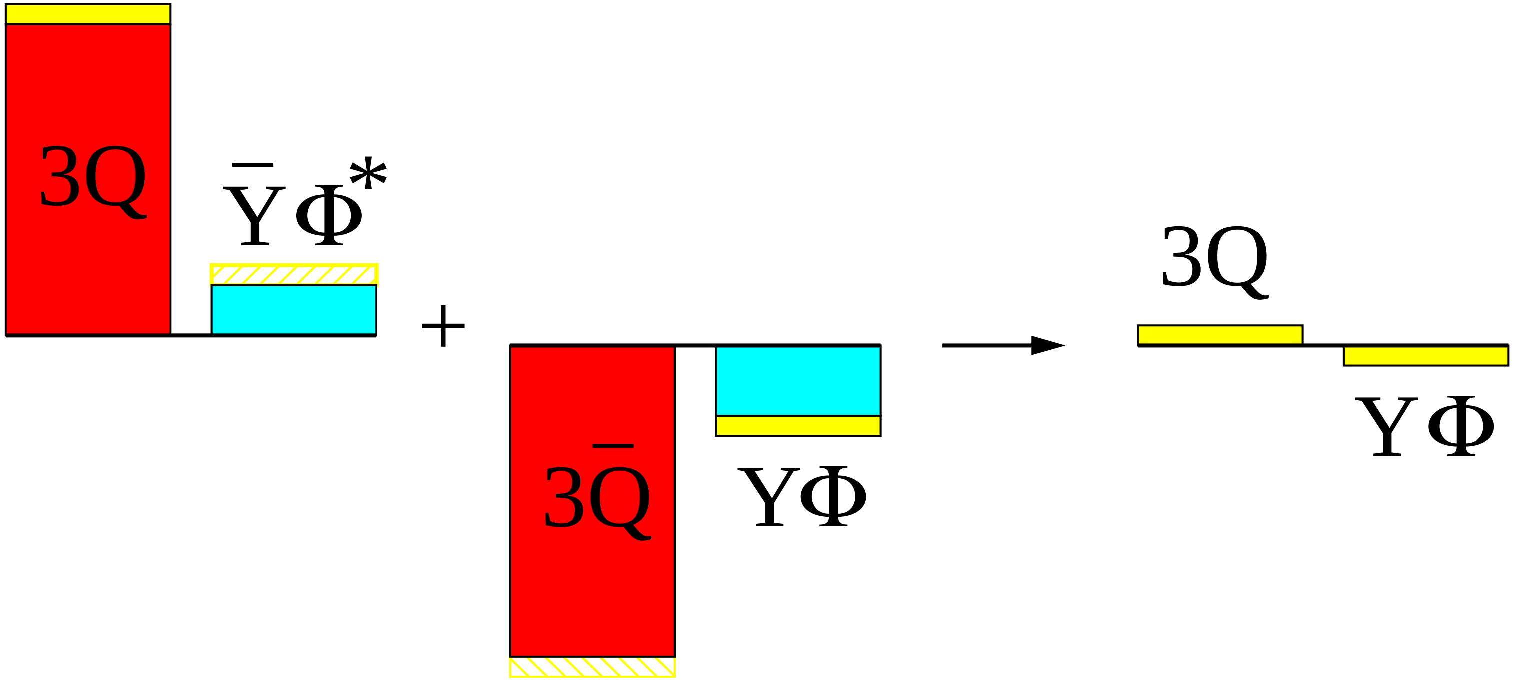


- Y, Φ annihilate to Z' leaving only the asymmetry:



- 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?

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.)

Signals of Hylogenesis

- Y and Φ together make up the dark matter.

  They both couple to a light Z' vector boson.

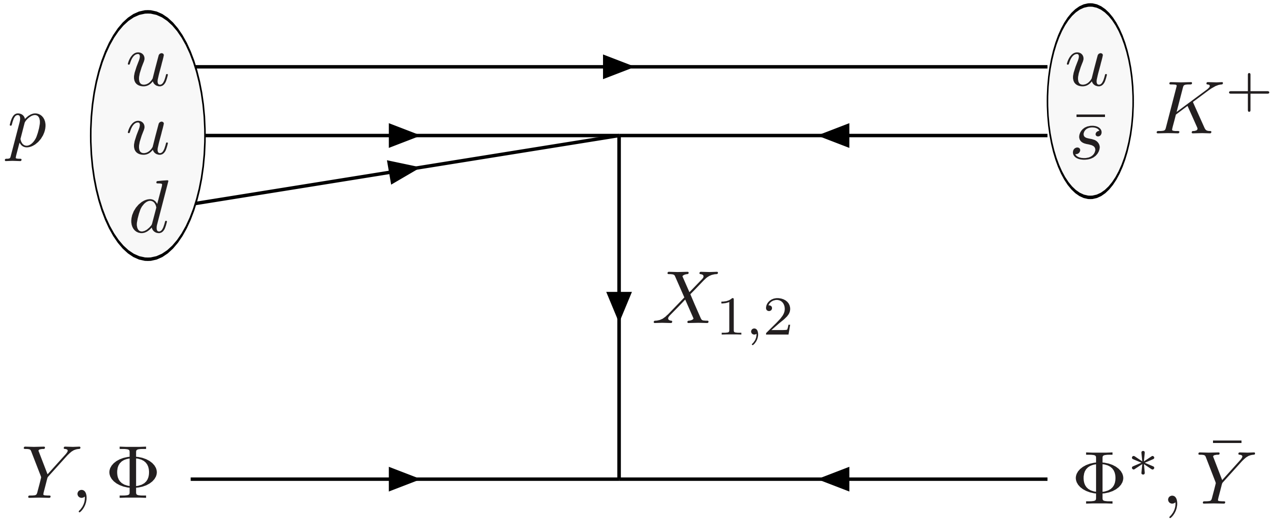
- Potential Signals:
  - Direct Z' effects in colliders, precision experiments.
  - Elastic scattering of Y and Φ off nuclei via Z'.
  - Nucleon destruction from inelastic Y/Φ scattering.
  - Monojets at colliders from $Xudd$, DM production.

- All four types of signals could be observed soon.

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.

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

- Inelastic DM scattering will mimic nucleon decay.

  → Induced Nucleon Decay (IND)

- Total event rates in a nucleon decay detector:

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

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

- Effective IND "lifetime":

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

- IND rate:

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

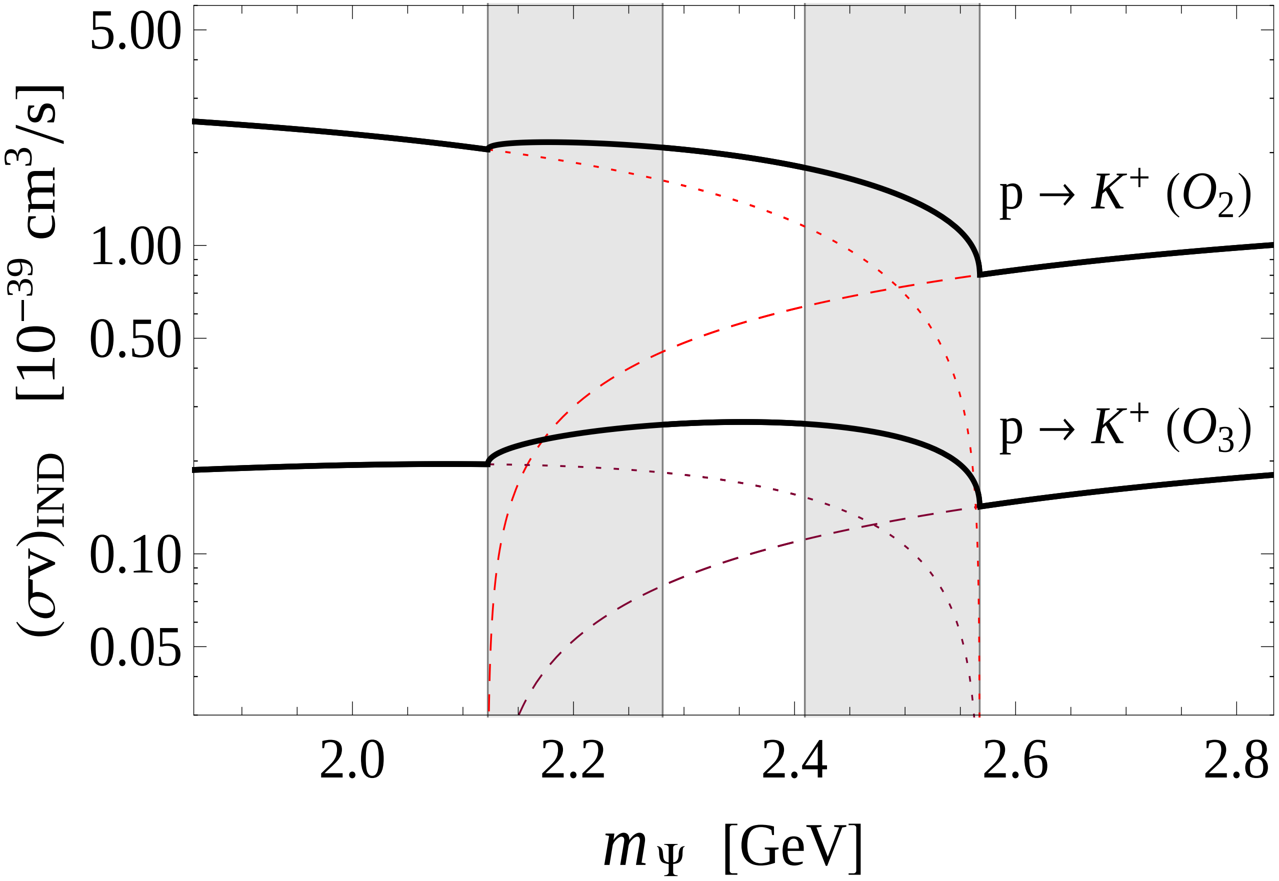
$(\tau_{eff} = 10^{32}\, yr$ corresponds to $(\sigma v)_{IND} \simeq 10^{-39} cm^3/s)$

- 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.

Supersymmetry for the Light Scalar

- Our mechanism needs a light scalar, $m_\Phi \leq 2.9\,\text{GeV}$.

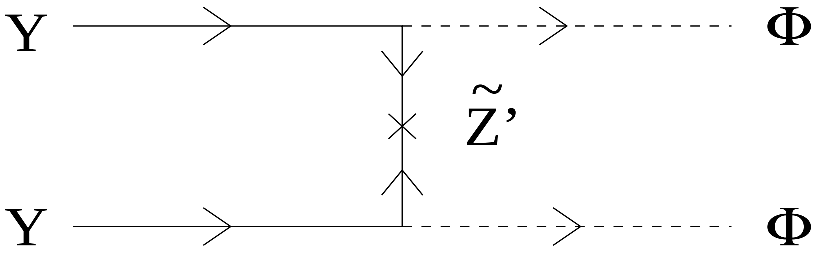
  Why should it be so light?

  Supersymmetry!

- New features of our implementation of supersymmetry:
  - Two Y and Φ multiplets are needed for $U(1)_x$ anomaly.
  - R-parity is extended to $\mathbb{Z}_4^R \subset U(1)_{B\text{–}L}$.
  - The Z' hidden vector has a gaugino superpartner.
  - Suppressed SUSY breaking keeps the dark sector lighter.

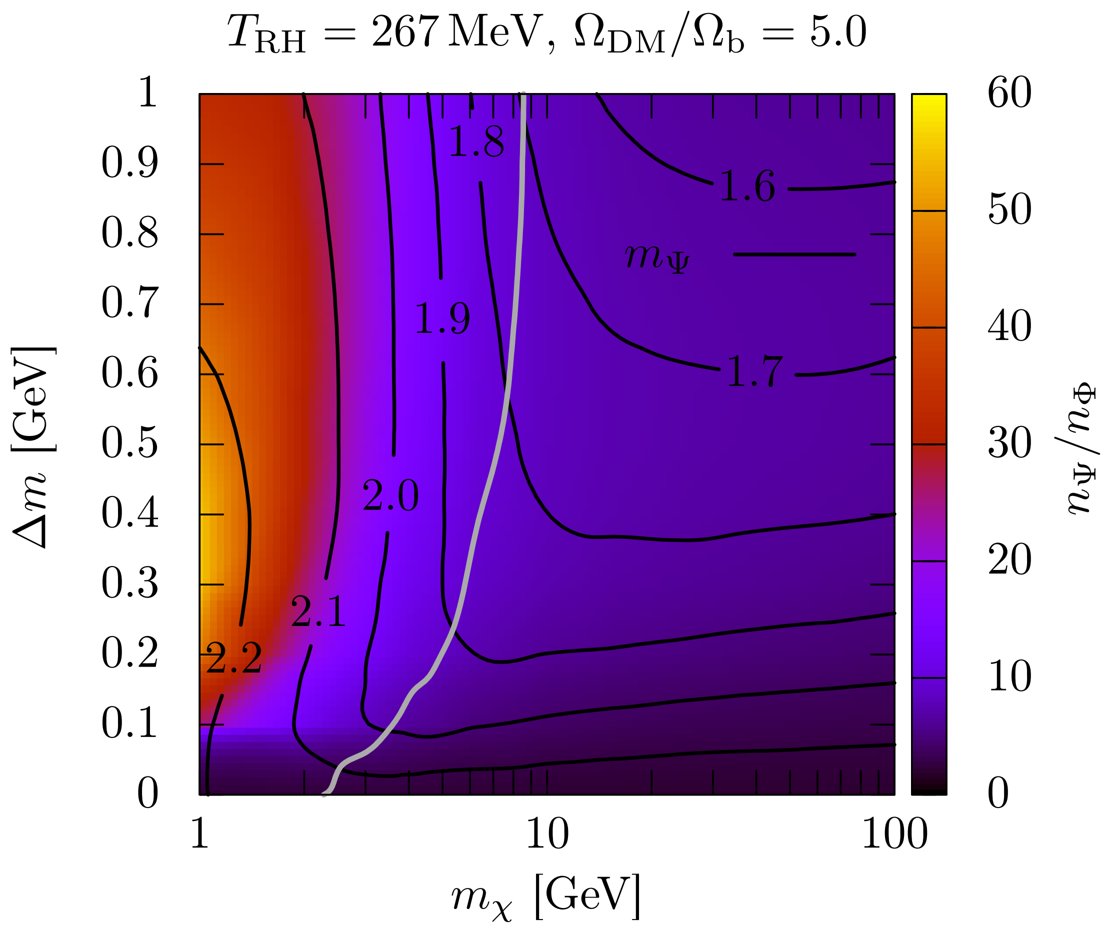
    e.g. AMSB with $e'/g_{SM} \sim 0.1$ [Kumar+Feng 2008]

- Most of the previous story carries over.
- New feature: $YY \leftrightarrow \Phi\Phi$ transfer reactions.



- Implications of transfer:
  - The heavier state is depopulated.
  - A wider range of Y and Φ masses give $\Omega_{DM}/\Omega_b = 5$.
  - IND rates can be suppressed for $\Delta m > m_p - m_K$.
  - Transfer can prevent complete symmetric annihilation.

- Transfer effects:



- Right of the white line is excluded by CMB limits on residual symmetric annihilation. [Lin,Yu,Zurek 2011]

Summary

- Hylogenesis realizes DM as hidden antibaryons.

  Explains DM and the baryon asymmetry simultaneously.

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

- A distinctive new DM signal is Induced Nucleon Decay.

  $M \sim 1\,\mathrm{TeV}$ probed by existing nucleon decay searches.

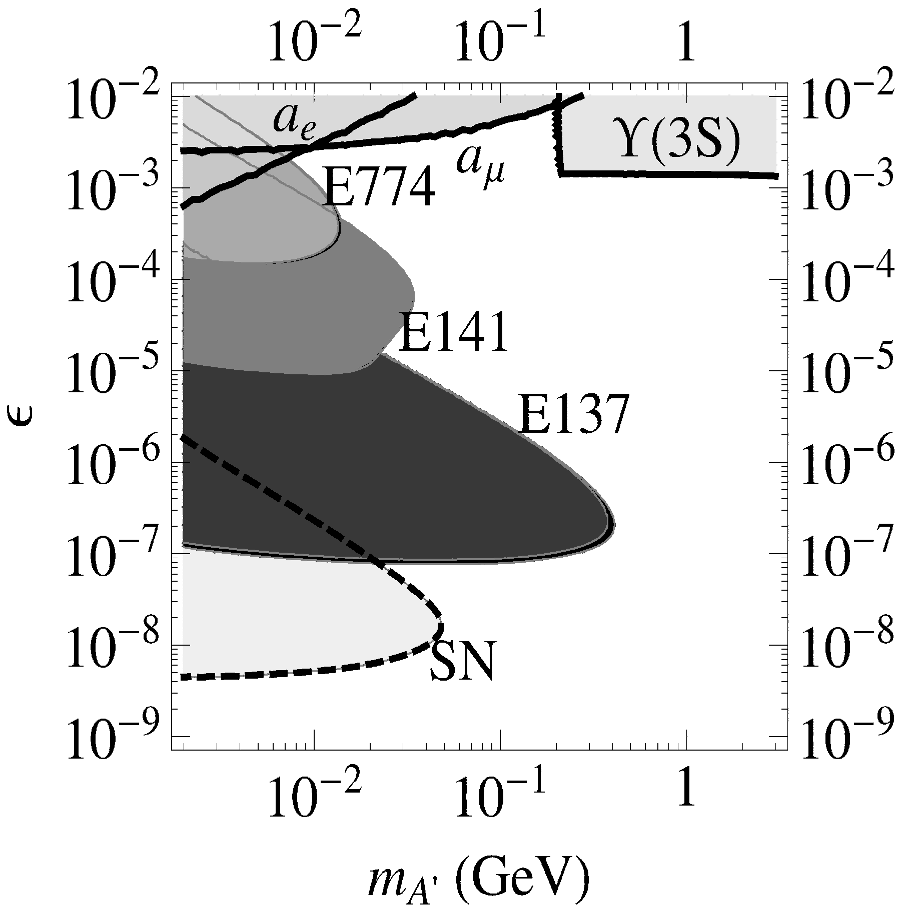
- The scenario is also be testable at the LHC via monojets.

- A natural mass hierarchy could arise from SUSY.

Extra Slides

Light Z' Signals

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



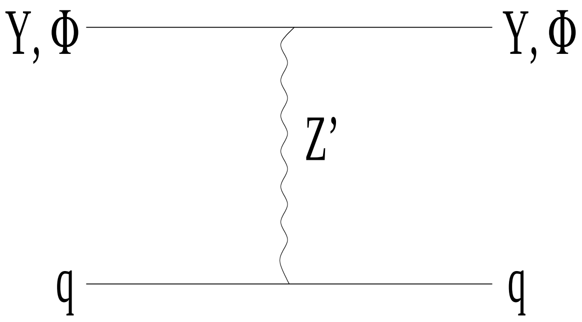
[Bjorken,Essig,Schuster,Toro '09]

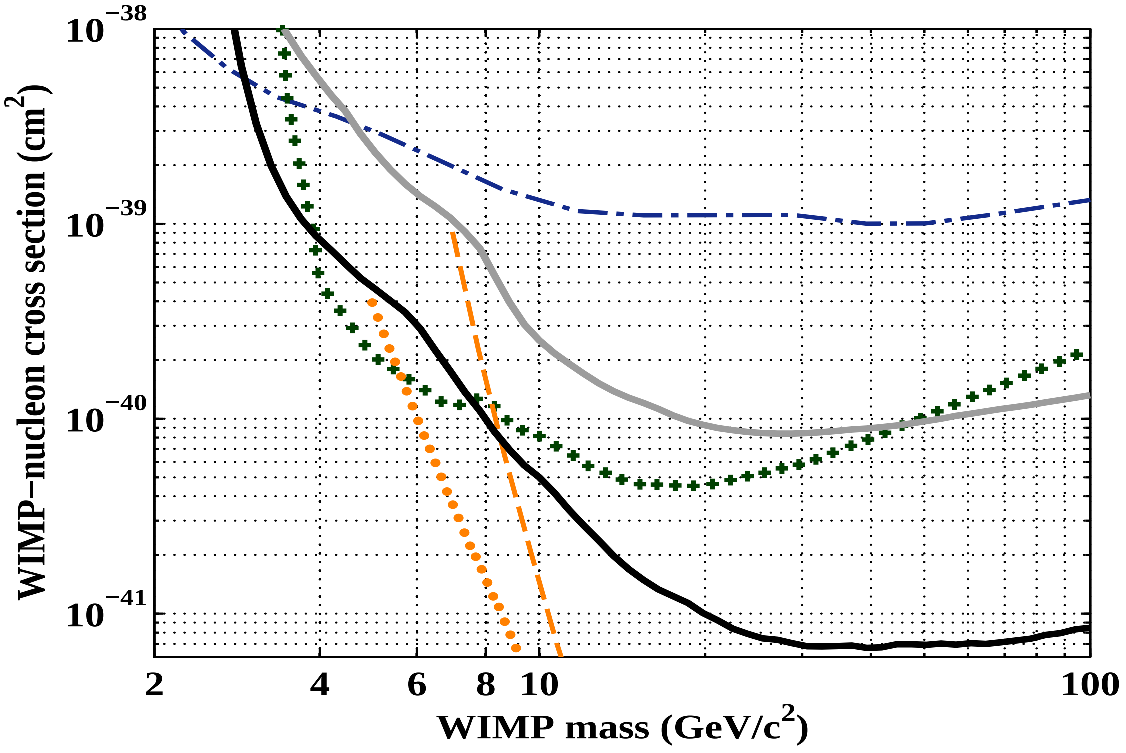
Fixed target experiments can improve these bounds.

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

DM-Nucleon Elastic Scattering

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



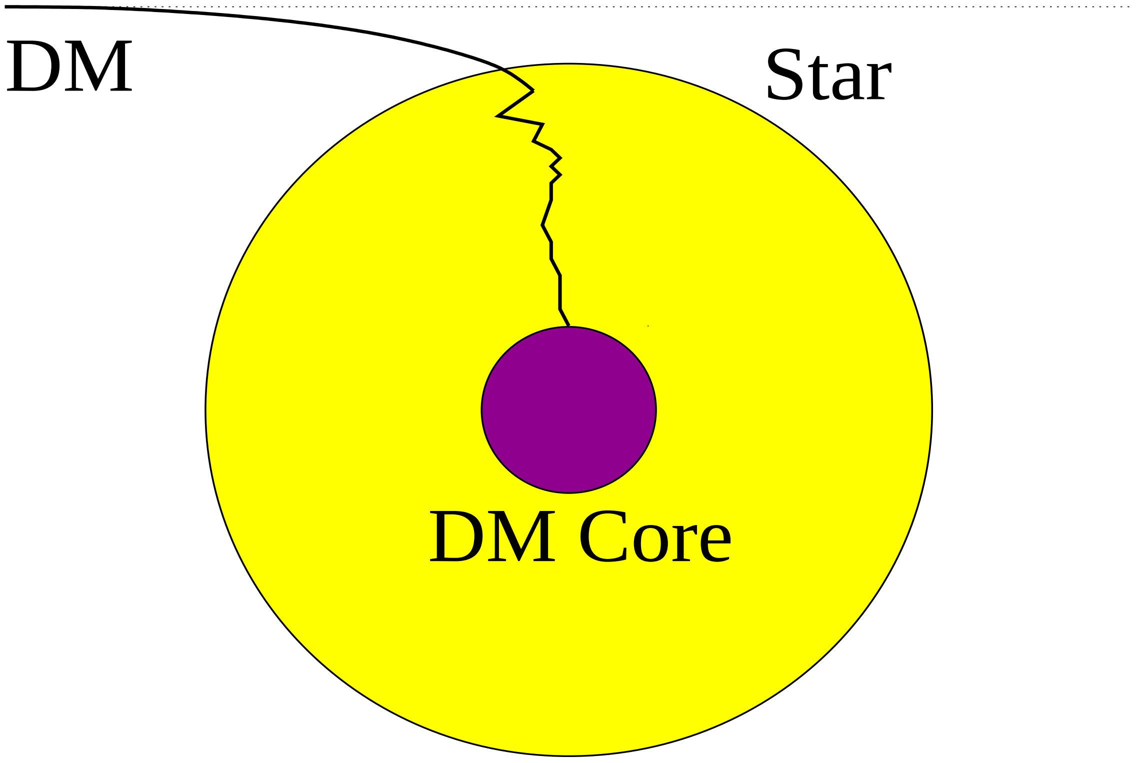


- Cross-section per nucleon (spin-independent):

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

IND and Stars

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

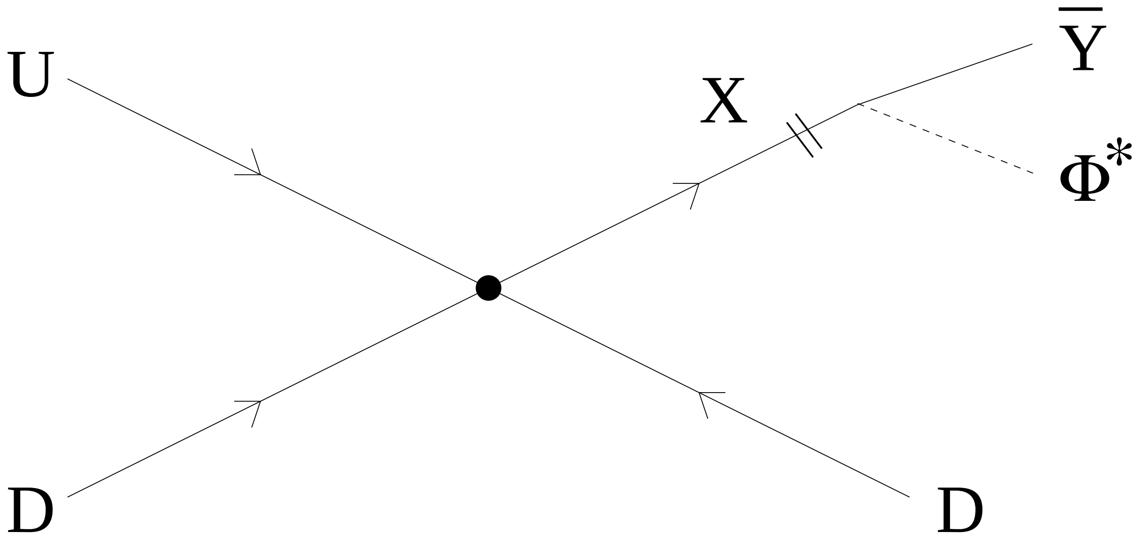


- Regular DM self-annihilates and can heat up a star.
- Y and Φ DM can't self-annihilate, but can yield IND:
  - DM collects in the stellar core by elastic scattering.
  - IND: $Y\,/\,\Phi \;+\; N \;\;\rightarrow\;\; \Phi^*\,/\,\bar{Y} \;+\; M$
  - Φ^* annihilates with Φ, $\bar{Y}$ annihilates with Y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

  [Bai, 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:

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

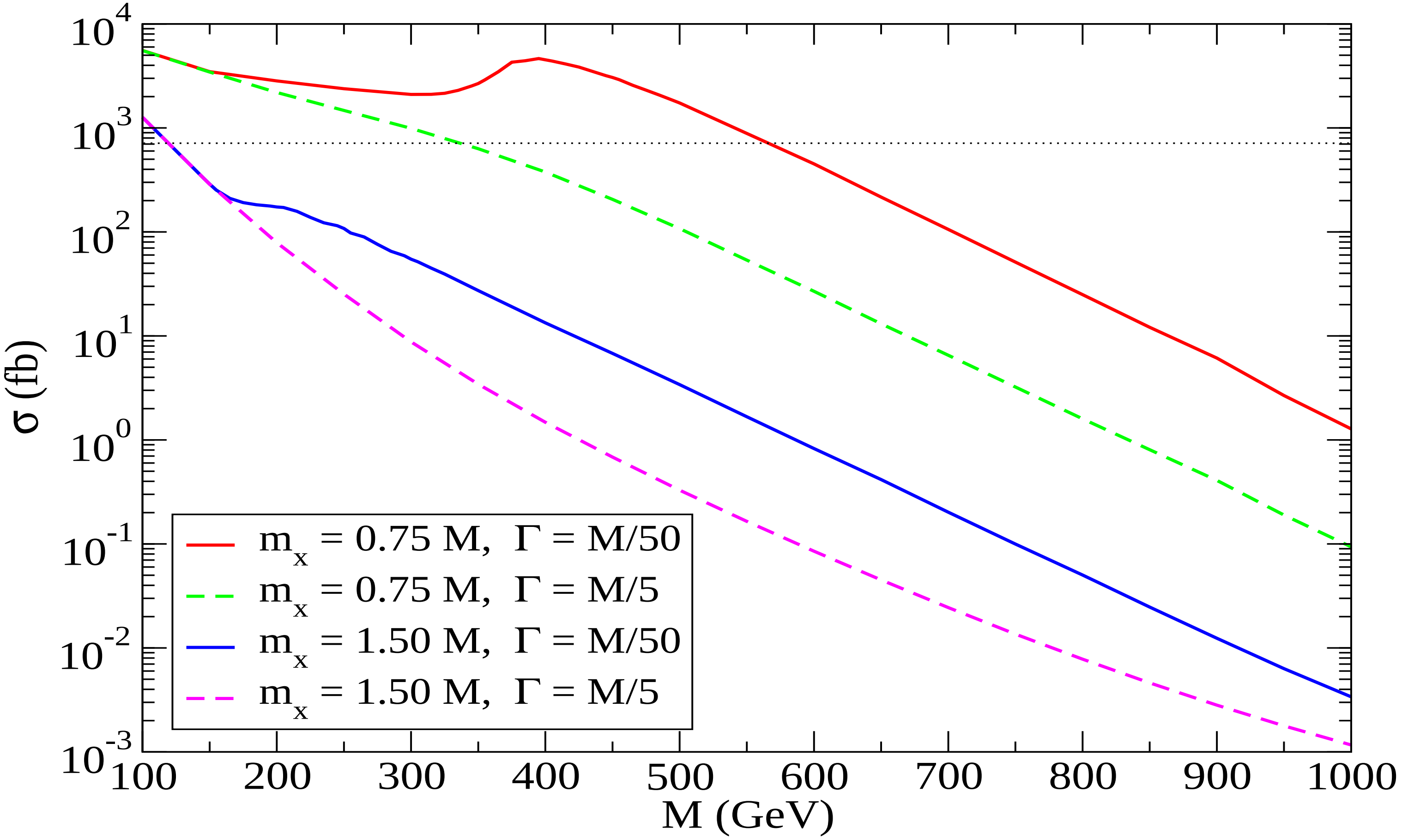
  Γ = unknown mediator width

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

- Tevatron (CDF) Monojet Search:

  jet with $p_T > 80$ GeV, $|\eta| < 1.0, \ldots$

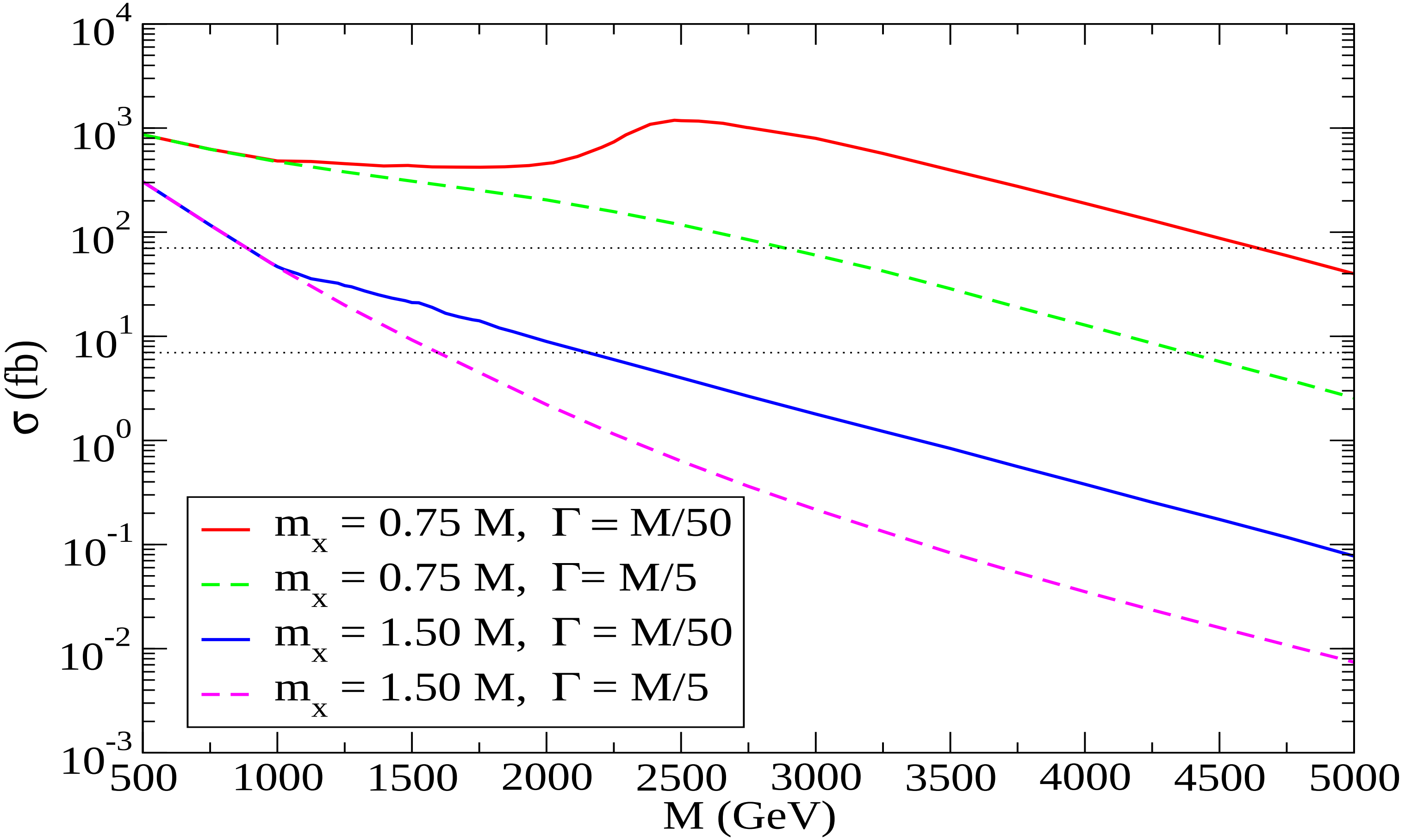
- CDF search ($1.0\, fb^{-1}$) implies $\sigma < 0.66\, pb$.



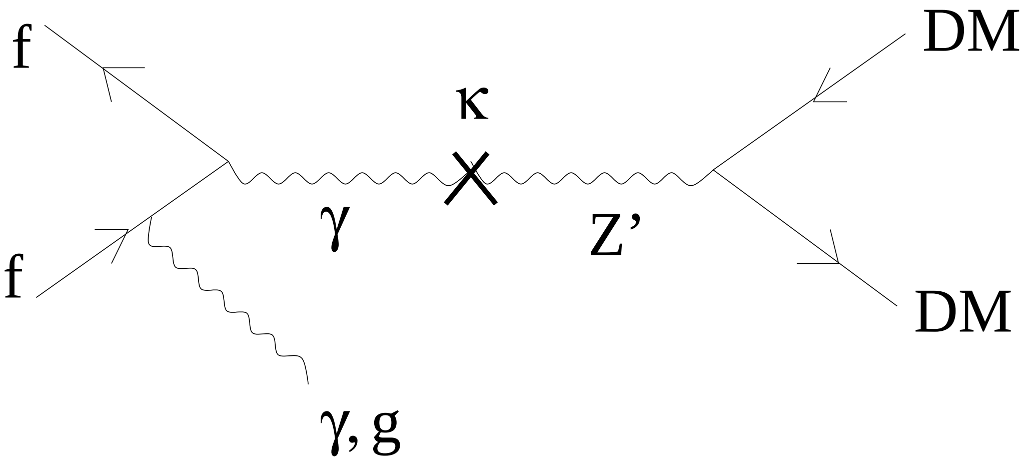
- LHC $j+\not{E}_T$ Search: jet with $p_T > 500$ GeV, $|\eta| < 3.2$, . . .

  [Vacavant+Hinchliffe '01]

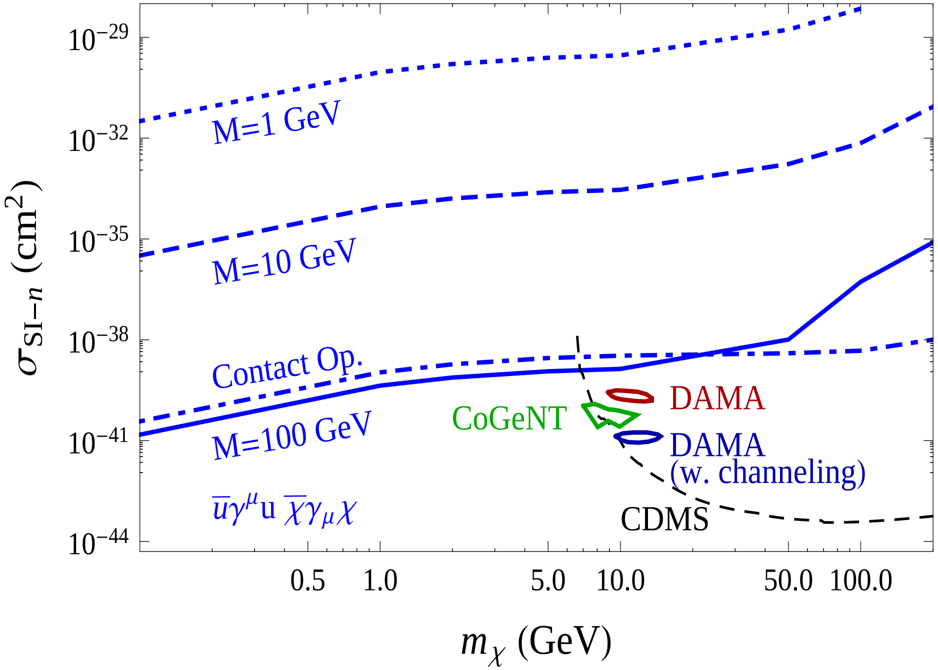
- Sensitivity with 100 fb^{-1} at 14 TeV: $\sigma \lesssim 7\, fb$.



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



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



[Bai,Fox,Harnik '10]

Gauge Kinetic Mixing

- Standard Gauge Boson Kinetic Terms:

  $(A = U(1)_{em}, \quad X = U(1)_x)$

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu},$$

  with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$.

- Gauge Kinetic Mixing:

$$\mathcal{L} \supset -\frac{1}{2}\epsilon\, F_{\mu\nu}X^{\mu\nu}.$$

- $\epsilon \sim 10^{-4}$–10^{-2} from integrating out heavy states charged under both $U(1)_{em}$ and $U(1)_x$. [Holdom '86]

- Assume DM carries a $U(1)_x$ charge x_{DM}, SM states do not.

- Rotate gauge fields to get canonical kinetic terms:

$$\begin{aligned} A_\mu &\to A_\mu - \epsilon\, X_\mu + \mathcal{O}(\epsilon^2) \\ X_\mu &\to X_\mu + \mathcal{O}(\epsilon^2) \end{aligned}$$

- This induces a coupling between X_μ and SM states:

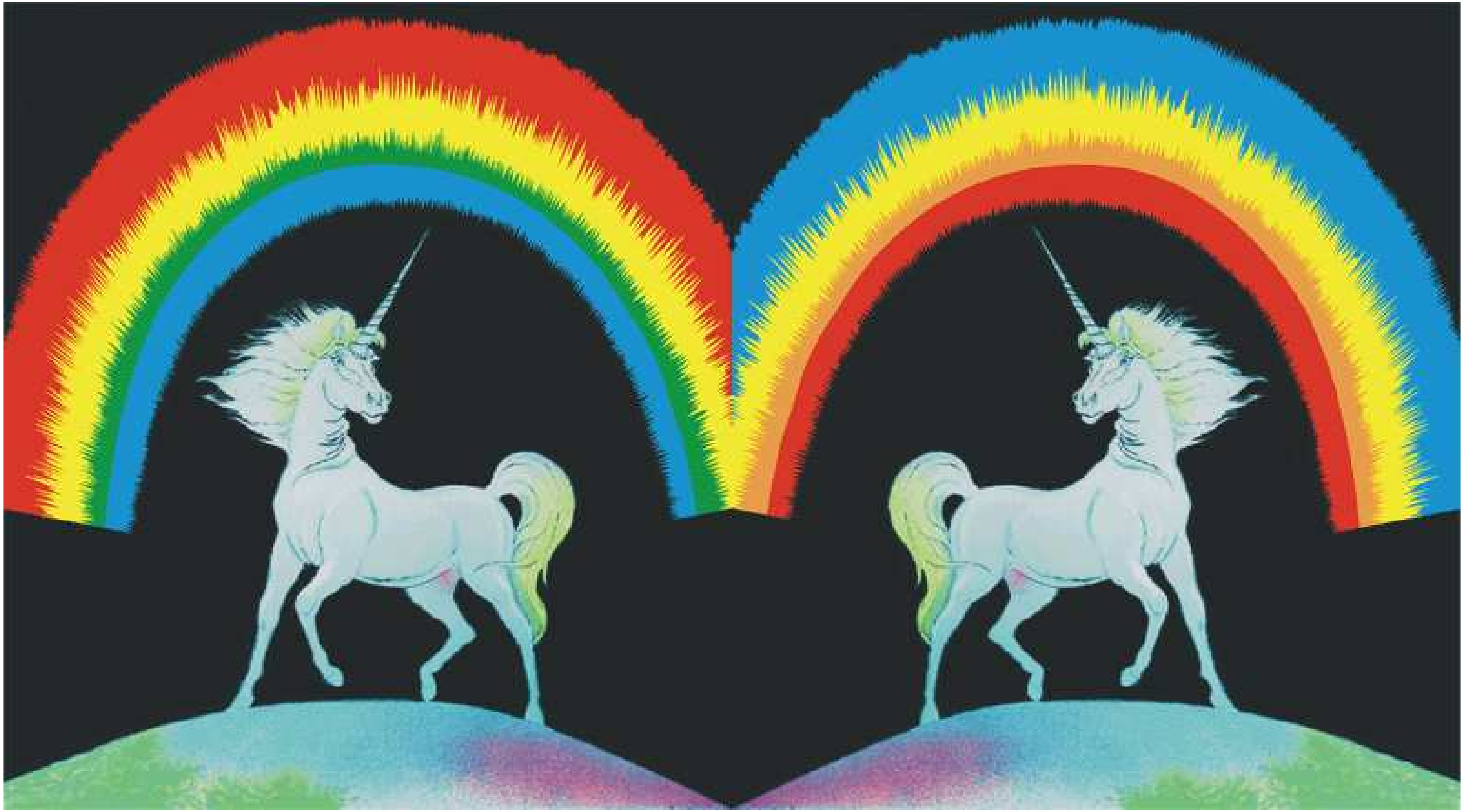
$$eQ\, A_\mu\, \bar{f}\gamma^\mu f \to eQ\, A_\mu\, \bar{f}\gamma^\mu f - eQ\epsilon X_\mu\, \bar{f}\gamma^\mu f.$$

SM-$U(1)_x$ coupling strength $= -e\,Q\,\epsilon \ll 1$

DM-$U(1)_x$ coupling strength $= g_x\, x_{DM} \sim 1$

- DM DOES NOT get an electric charge!

- Hylogenesis = double rainbow + double unicorn!



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