

Title: Hylogenesis and Dark Matter Induced Nucleon Decay

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Abstract: I discuss a new scenario called Hylogenesis (hylo=matter) that explains the baryon and dark matter densities of Universe in a unified way. Early universe dynamics generate the baryon asymmetry and an equal antibaryon asymmetry in a GeV-scale hidden sector. The hidden antibaryons are dark matter. Our model has a striking signature that dark matter can annihilate baryons, mimicking nucleon decay. I discuss the effective nucleon decay rates and implications for existing nucleon decay searches.

Hylogenesis: model

	Hidden sector particles	B	$U(1)'$
	TeV-scale Dirac fermions X_1, X_2	1	0
DM	GeV-scale Dirac fermion Y	y	+e'
	GeV-scale complex scalar Φ	-1-y	-e'
	$U(1)'$ vector boson Z' (<GeV)		B = $1/2$ SUSY partners?

Interaction: $-\mathcal{L} \supset \frac{\lambda_a}{M^2} \bar{X}_a P_R d \bar{u}^c P_R d + \zeta_a \bar{X}_a Y^c \Phi^* + \text{h.c.}$

Note: $X_{1,2}$ coupled to “neutron portal” ($u_R d_R d_R$) and to DM states Y and Φ .

Can assign B to hidden sector states such that B is globally conserved

Two component DM: Y and Φ are stable if $|m_Y - m_\Phi| < m_p + m_e$

Proton stable if $m_p < m_Y + m_\Phi + m_e$

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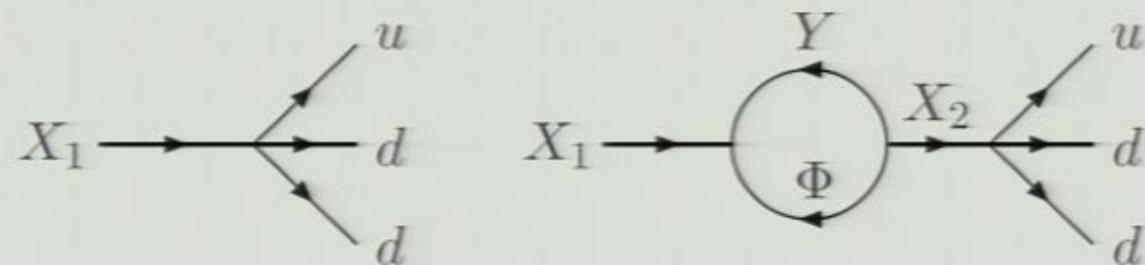
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Hylogenesis in 3 steps

1. X_1 and \bar{X}_1 produced non-thermally in equal amounts
 - ▶ e.g., reheating after inflation, moduli decay
2. CP violating X_1 and \bar{X}_1 decays produce visible B asymmetry and equal and opposite asymmetry in Y, Φ .
3. CP symmetric densities of Y and Φ annihilate into Z'
Residual Y and Φ asymmetries are the DM

CP violation

1. Non-thermal population of X_1 and \bar{X}_1 .
2. X_1 and \bar{X}_1 decay out of equilibrium ($m_{X_1} \gg T_{RH}$)
 - ▶ Two channels: $X_1 \rightarrow \bar{Y}\Phi^*$ $X_1 \rightarrow udd$
 - ▶ Decays violate CP



3. Visible B and equal and opposite B asymmetry in Y, Φ .

$$\rho_{DM}/\rho_B = (n_Y m_Y + n_\Phi m_\Phi) / n_B m_p = (m_Y + m_\Phi) / m_p$$

$$1.7 \text{ GeV} \lesssim m_{Y,\Phi} \lesssim 2.9 \text{ GeV}$$

Compute baryon asymmetry n_B/s

Assume reheating occurs instantaneously

$$\rho_\varphi = m_\varphi n_\varphi \longrightarrow \rho_{\text{rad}} = \pi^2/30 g_* T_{\text{RH}}^{-4}$$

- ▶ Baryon number density $n_B = \epsilon N_X n_\varphi$
 - ▶ ϵ is CP asymmetry (average n_B produced per X_1 decay)
 - ▶ $N_X X_1$ particles produced per φ decay

$$\begin{aligned}\epsilon &= \frac{1}{2\Gamma_{X_1}} [\Gamma(X_1 \rightarrow udd) - \Gamma(\bar{X}_1 \rightarrow \bar{u}\bar{d}\bar{d})] \\ &\simeq \frac{m_{X_1}^5 \text{Im}[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\pi^3 |\zeta_1|^2 M^4 m_{X_2}},\end{aligned}$$

- ▶ Entropy $s = 4/3 \rho_{\text{rad}}/T_{\text{RH}}$  $n_B/s = \frac{\epsilon N_X T_{\text{RH}}}{m_\varphi} f$

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► Additional consideration: no wash out

Transfer operator out of equilibrium

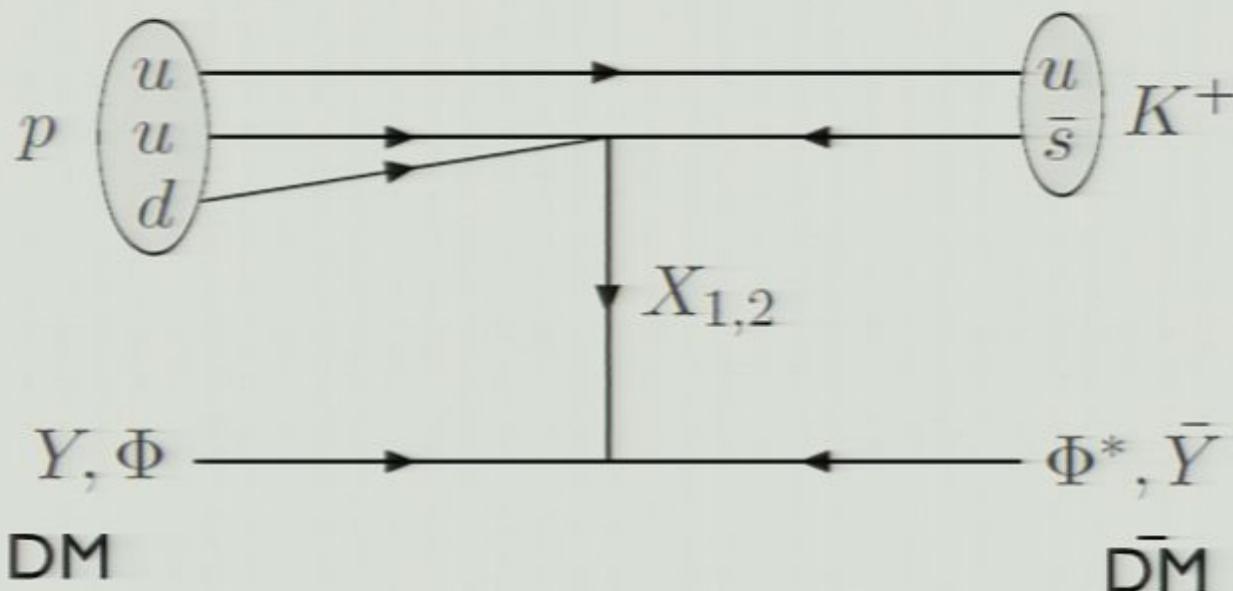
$$T_{RH} \lesssim (2 \text{ GeV}) \left(\sum_{a,b} \frac{\lambda_a \lambda_b^* \zeta_a^* \zeta_b}{M^4 m_{X_a} m_{X_b}} \text{ TeV}^6 \right)^{-1/5}$$

Possible Dark Matter Signals

1. Induced nucleon decay: DM-nucleon inelastic scattering that annihilates nucleons
 - ▶ Probes transfer operator (neutron portal)
 - ▶ Unique, novel signal for hylogenesis (not just Asymmetric DM)
2. DM elastic scattering via Z'
 - ▶ Probes annihilation of symmetric DM densities to SM
 - ▶ More generic signal of many DM models.

Induced Nucleon Decay

- DM carries antibaryon number. Can annihilate nucleons.



Several different meson final states possible

$$p \rightarrow K^+, \pi^+, \dots \quad n \rightarrow K^0, \pi^0, \eta, \dots$$

(We only considered lightest pseudo-Goldstone bosons.)

Can have both up-scattering and down-scattering.

Induced Nucleon Decay

- ▶ 5 possible operators coupling DM to u,d,s quarks

$$\mathcal{L}_{\text{int}} = \sum_{i=1}^5 c_i O_i$$

$$c_i = \zeta \lambda / (M^2 m_X)$$

$$\begin{aligned} O_1 &= \epsilon_{\alpha\beta\gamma} (u_R^\alpha d_R^\beta) (d_R^\gamma Y \Phi) \\ O_2 &= \epsilon_{\alpha\beta\gamma} (u_R^\alpha d_R^\beta) (s_R^\gamma Y \Phi) \\ O_3 &= \epsilon_{\alpha\beta\gamma} (s_R^\alpha u_R^\beta) (d_R^\gamma Y \Phi) \\ O_4 &= \epsilon_{\alpha\beta\gamma} (d_R^\alpha s_R^\beta) (u_R^\gamma Y \Phi) \\ O_5 &= \epsilon_{\alpha\beta\gamma} (s_R^\alpha u_R^\beta) (s_R^\gamma Y \Phi) \end{aligned}$$

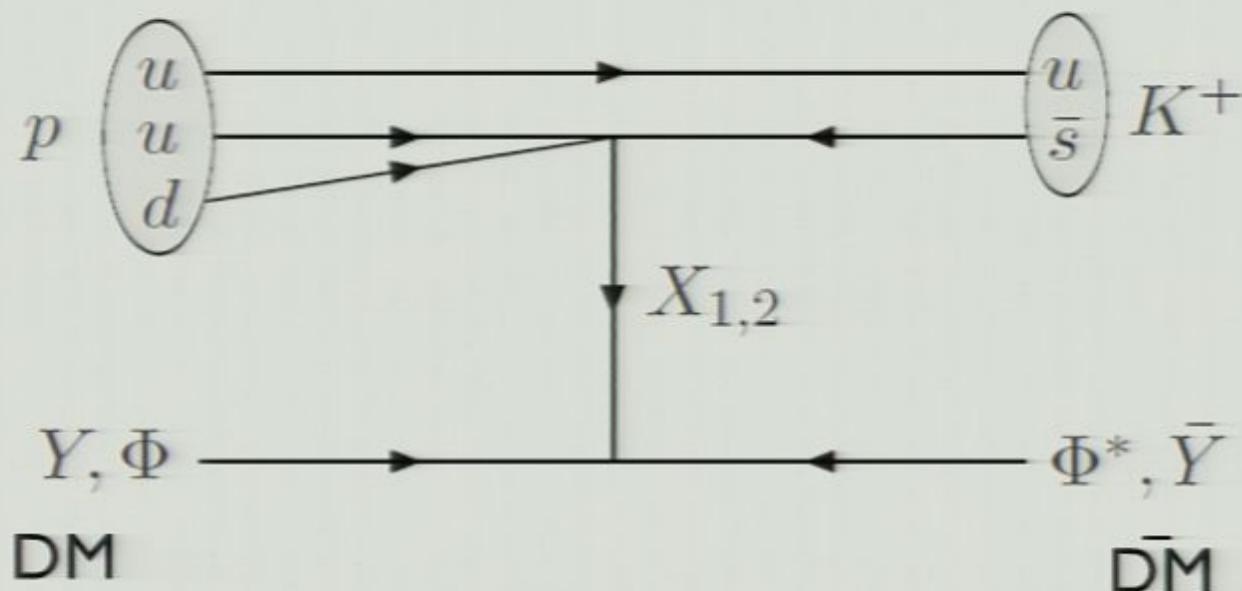
Dimension 7 operators

Lower bound on M, m_X from monojet searches from Tevatron.

Expect $M, m_X > (\text{few}) \times 100 \text{ GeV - TeV}$. (Work in progress.)

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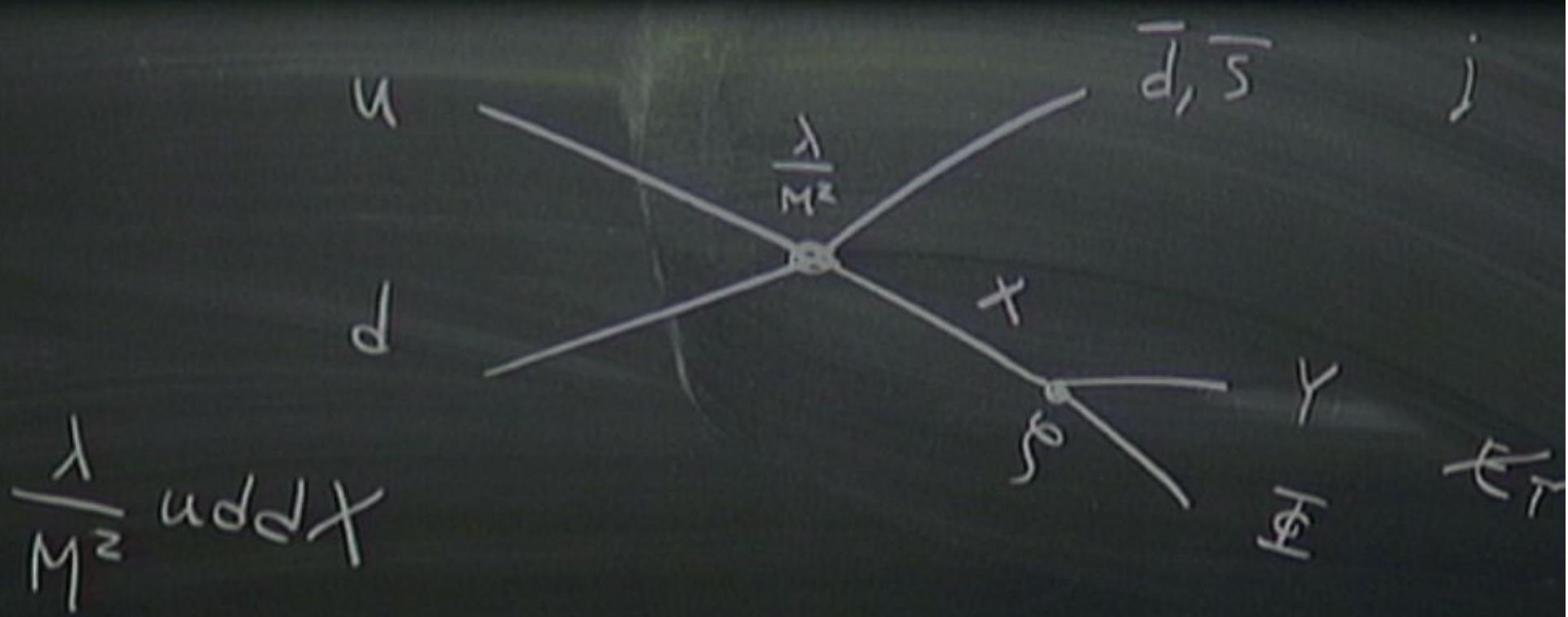
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Induced Nucleon Decay

Looks like standard nucleon decay into meson + neutrino

1. Kinematics is different than in standard nucleon decay
 - ▶ Crucial for experimental searches
2. Effective nucleon lifetime depends on local DM density
 - ▶ How does effective lifetime compare to current limits?
 - ▶ Can Induced Nucleon Decay be observed?

Induced Nucleon Decay: Kinematics

- ▶ $N=(p,n)$ is nucleon, M is meson (pion, kaon, eta)
- ▶ Induced nucleon decay channels are

$$YN \rightarrow \Phi^* M \quad \Phi N \rightarrow \bar{Y} M$$

- ▶ Looks like standard nucleon decay (neutrino undetected)

$$N \rightarrow M\nu$$

Daughter meson momentum:

Decay mode	p_M^{SND} (MeV)	p_M^{IND} (MeV)
$N \rightarrow \pi$	460	800 - 1400
$N \rightarrow K$	340	680 - 1360
$N \rightarrow \eta$	310	650 - 1340

Note: IND final states are monochromatic. Range corresponds to allowed mass range for DM particles. (Assumed down-scattering.)

IND mesons can be much more energetic than that SND mesons!

Nucleon decay searches

- ▶ Consider Kaon modes only at SuperK *Kobayashi et al [SuperK] (2005)*
 - ▶ (Also want to study implications for other searches: pion/eta modes at SuperK, Soudan-2, IMB-3 – work in progress)

$$p \rightarrow K^+ \nu \text{ } 2.3 \times 10^{33} \text{ yr}$$

Two key assumptions:

1. K^+ comes to rest before decaying: Occurs $\sim 50\%$ in IND
2. K^+ below Cerenkov threshold: $\beta < 0.75$ **Not satisfied for IND**

Searches:

1. $K^+ \rightarrow \pi^+ \pi^0 \rightarrow \mu + \gamma\gamma$. Look for one μ -like track, one Michel e, and two e-like tracks, and cut for any additional radiation

2. $K^+ \rightarrow \mu$ with prompt γ from ^{16}O . Look for γ with μ -like track delayed by “quiet” 12 ns. Might be swamped.

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$$n \rightarrow K^0 \nu \bar{\nu} \quad 1.3 \times 10^{32} \text{ yr}$$

Searches:

1. $K^0 \rightarrow \pi^0 \pi^0 \rightarrow \gamma\gamma \gamma\gamma$. Look for four e-like tracks
2. $K^0 \rightarrow \pi^+ \pi^-$ Look for two μ -like tracks.

Both searches reconstruct m_{K^0} and p_{K^0} but cut $200 < p_{K^0} < 500 \text{ MeV}$

Larger p_{K^0} may have problem with separation of $\gamma\gamma$ cones?

Enhanced efficiency for $\pi^+ \pi^-$ modes (probability of having both $\pi^+ \pi^-$ above Cerenkov is low for standard nucleon decay)?

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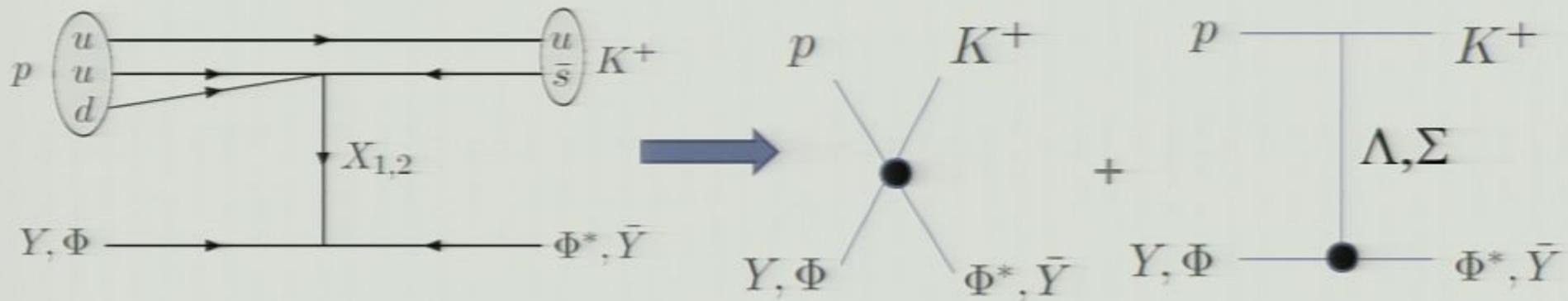
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Induced Nucleon Decay: Lifetime



- ▶ Chiral perturbation theory: effective theory of baryons, mesons, and dark matter particles

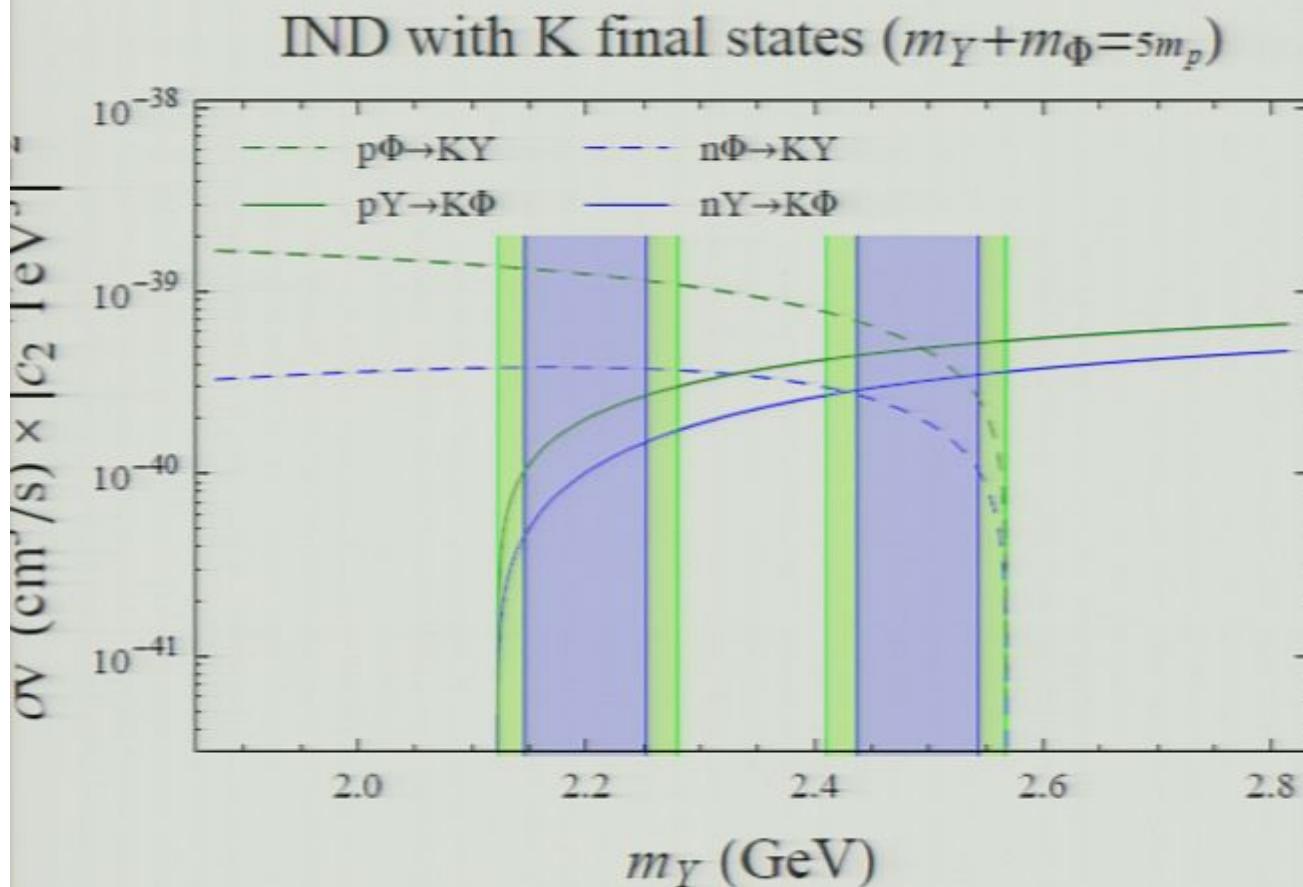
$$\begin{aligned}\mathcal{L}_{\text{eff}}^{|\Delta B|=1} \supset & \beta Y \Phi \left(c_1 n_R + \frac{-2c_2 + c_3 + c_4}{\sqrt{6}} \Lambda_R^0 + \frac{-c_3 + c_4}{\sqrt{2}} \Sigma_R^0 \right) \\ & + \frac{i\beta}{f} Y \Phi \left(-c_1 (p_R \pi^- + \sqrt{3/2} n_R \eta - \sqrt{1/2} n_R \pi^0) + (c_3 - c_2) n_R K^0 + (c_4 - c_2) p_R K^- \right)\end{aligned}$$

- ▶ One unmeasurable coefficient β

- ▶ same as in standard nucleon decay *Claudson, Hall, Wise (1982)*

- ▶ computed on the lattice *Aoki et al [JLQCD](2000)*

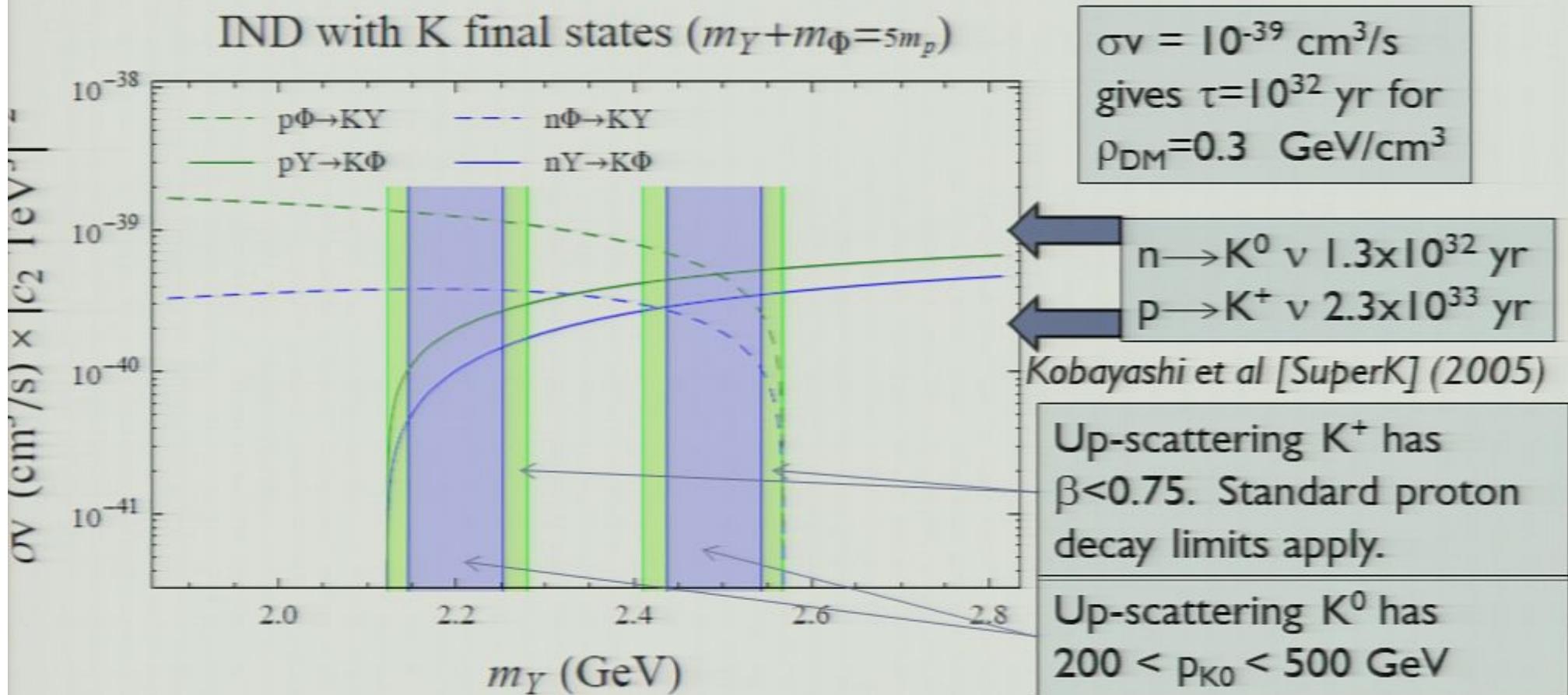
Induced Nucleon Decay lifetime



$\sigma v = 10^{-39} \text{ cm}^3/\text{s}$
gives $\tau = 10^{32} \text{ yr}$ for
 $\rho_{\text{DM}} = 0.3 \text{ GeV/cm}^3$

For TeV-scale mediator particles, IND lifetime relevant for existing searches!

Induced Nucleon Decay lifetime



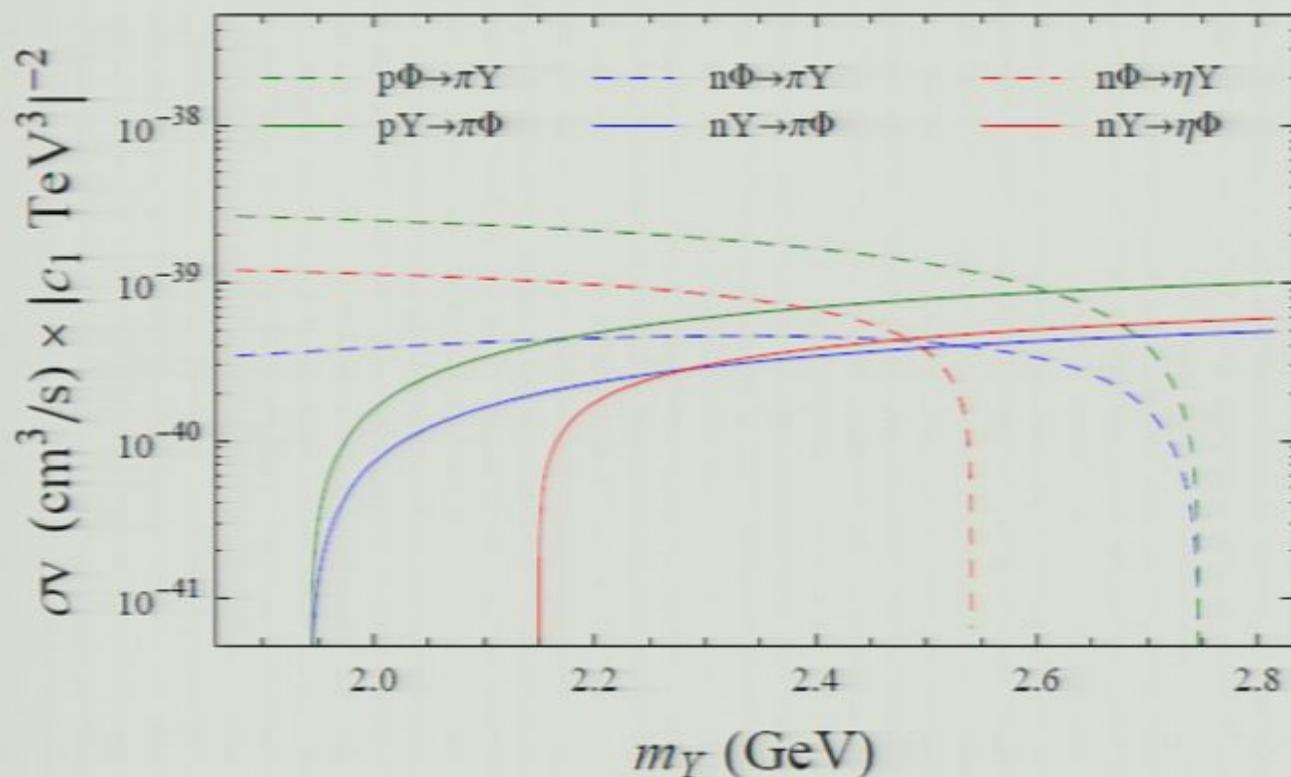
K^+ above Cerenkov threshold for most of parameter space

K^0 outside of momentum window for most of parameter space

Induced Nucleon Decay lifetime

π/η decay channels have comparable lifetimes

IND with π, η final states ($m_Y + m_\Phi = 5m_p$)



$\sigma v = 10^{-39} \text{ cm}^3/\text{s}$
gives $\tau = 10^{32} \text{ yr}$ for
 $\rho_{\text{DM}} = 0.3 \text{ GeV/cm}^3$

All three channels probe a single coefficient c_1 .

K modes probe different linear combinations of c_2, c_3, c_4 .

Induced Nucleon Decay: Summary

- ▶ IND is a novel signature of dark matter motivated by explaining $\rho_B \sim \rho_{DM}$.
- ▶ IND can mimic nucleon decay
 - ▶ Lifetime comparable with present limits for TeV-scale mediators
 - ▶ Kinematics can be much different (more energetic)
- ▶ Standard nucleon decay limits apply in some regions of parameter space
- ▶ We are working on how current searches apply in other regions of parameter space. Really a job for experimentalists.

Annihilation and Hidden U(1)'

- ▶ We need symmetric DM density to annihilate
 - ▶ Introduce Z' vector boson $\Phi^*\Phi$ $Y\bar{Y} \rightarrow Z'Z'$

- ▶ Z' decays to SM through kinetic mixing with $U(1)_Y$

Holdom (1986)

$$-\frac{\kappa}{2} B_{\mu\nu} Z'_{\mu\nu}$$

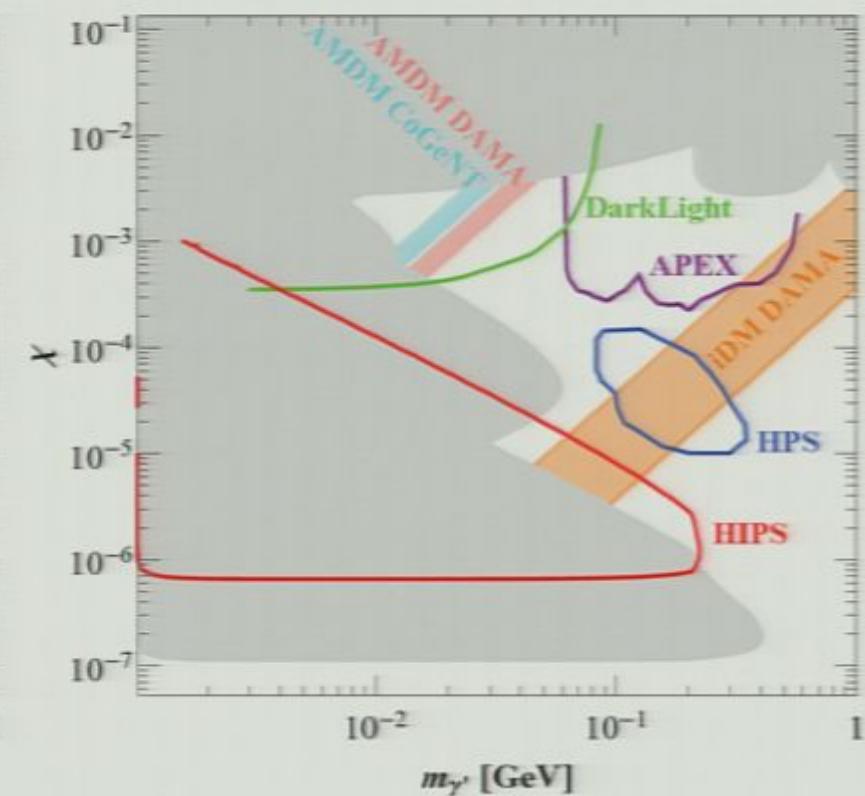
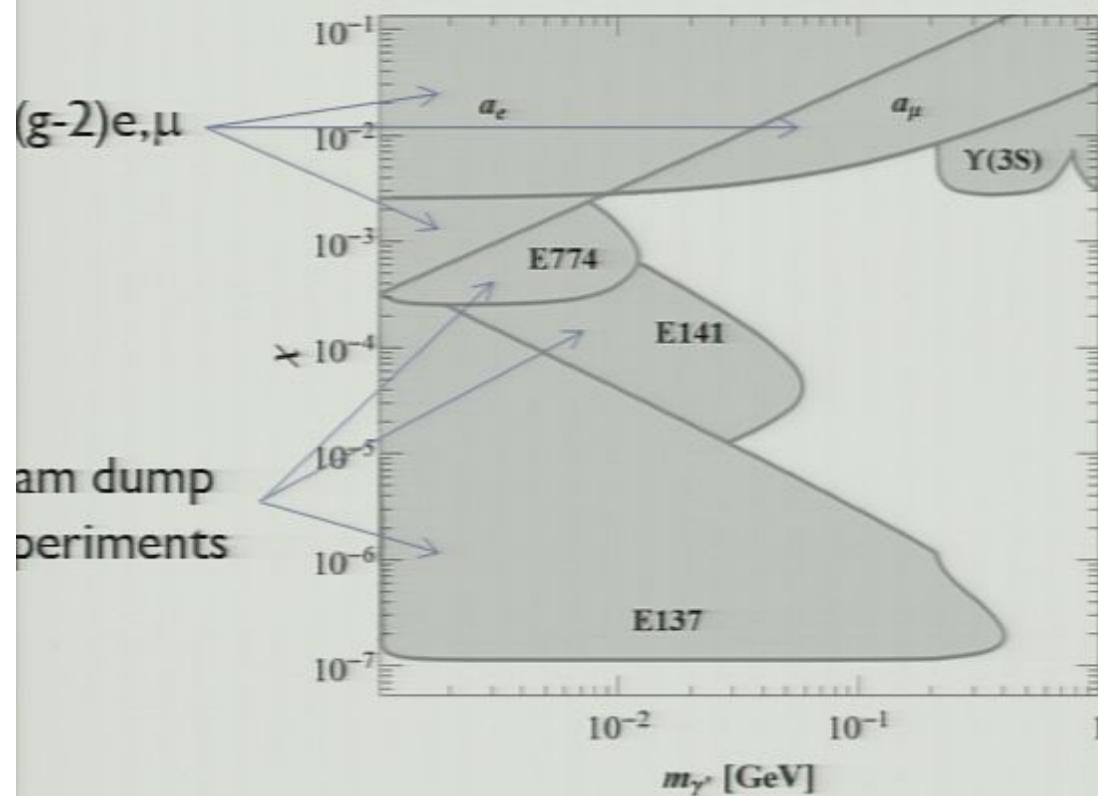
- ▶ SM fields develop a charge $c_W \kappa Q_{eme}$ coupling them to Z'
- ▶ Allows $Z' \rightarrow e^+e^-$, etc. Z' decays to SM fermions.
- ▶ No DM electromagnetic charge coupling it to the photon

Annihilation sufficient for

$$\kappa > 1.5 \times 10^{-8} \left(\frac{g}{10}\right)^{1/2} \left(\frac{m_{Z'}}{\text{GeV}}\right)^{-1} \left(\frac{T}{\text{GeV}}\right)^{3/2}$$

Searches for hidden U(1)'

► Current and prospective future constraints



Andreas, Ringwald (2010)

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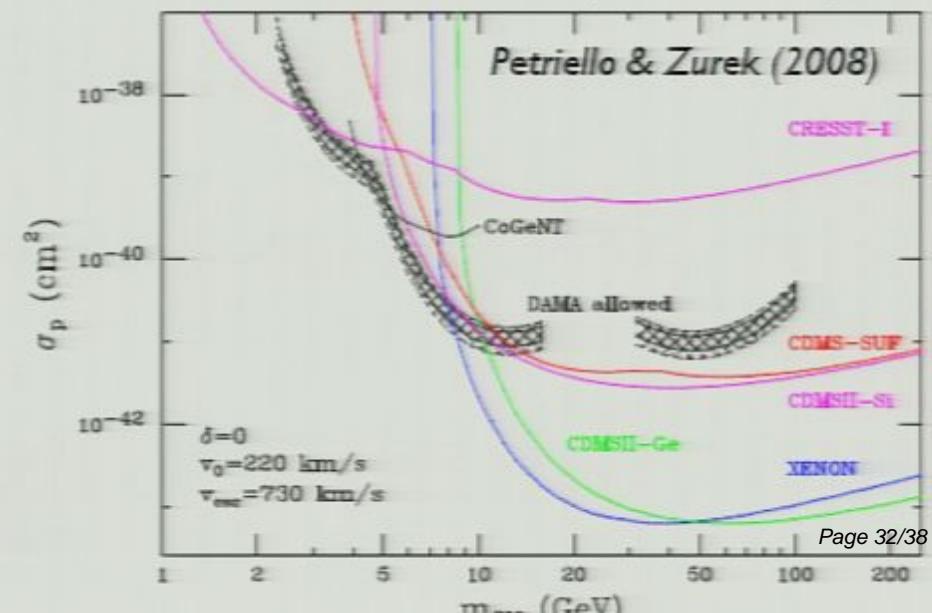
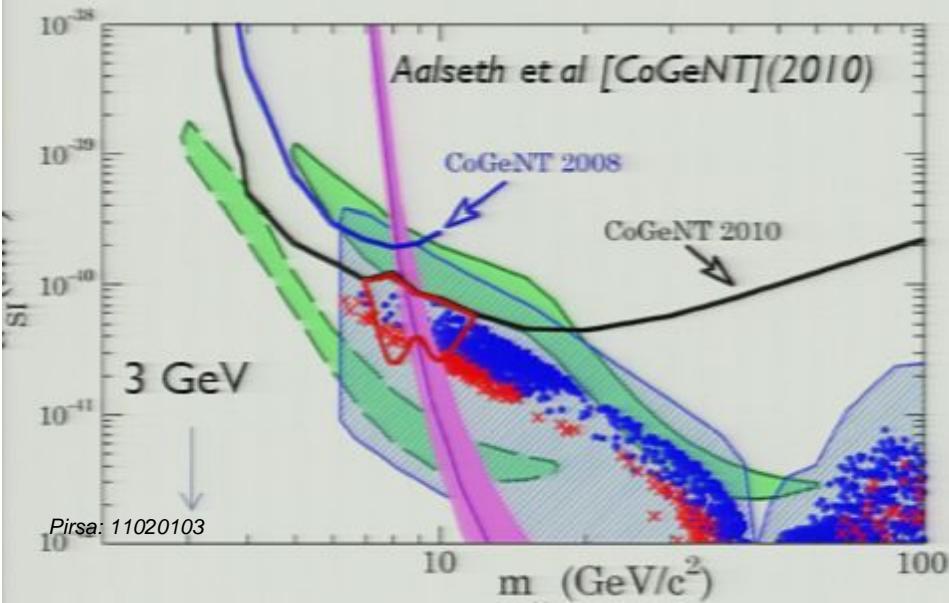
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Dark matter elastic scattering

► Spin independent cross section

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

Below (by factor of 2) current bounds for 3 GeV DM (CRESST)



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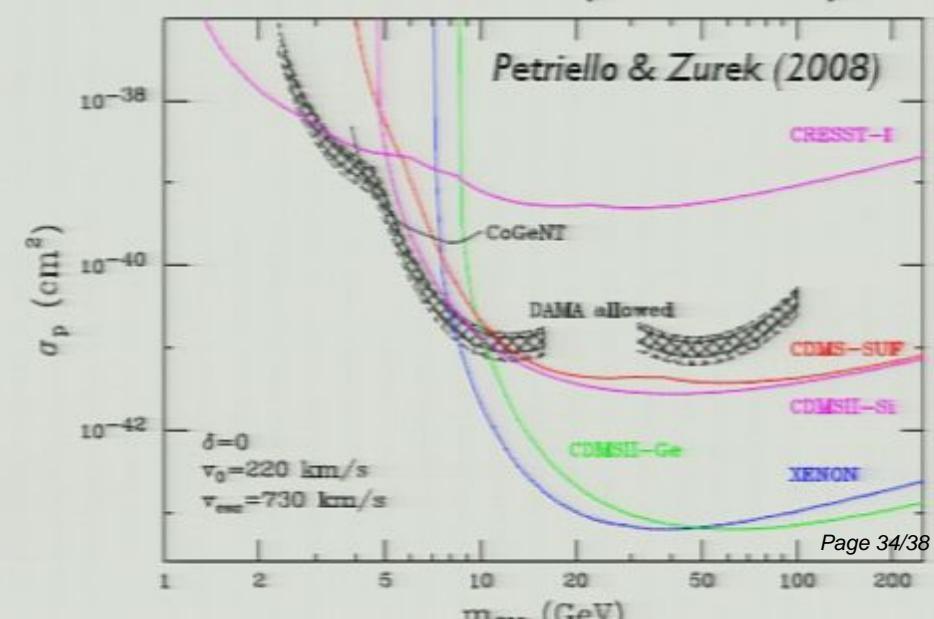
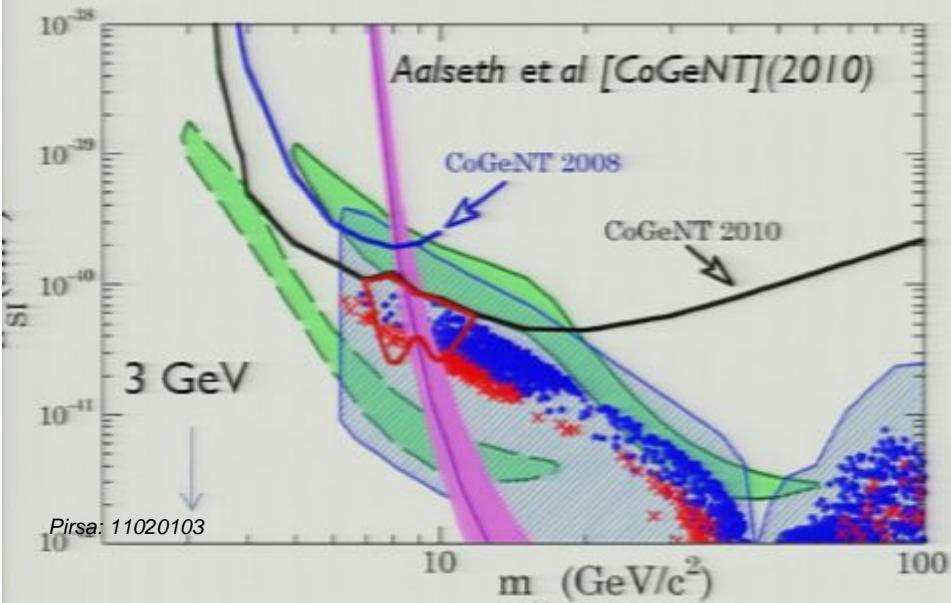
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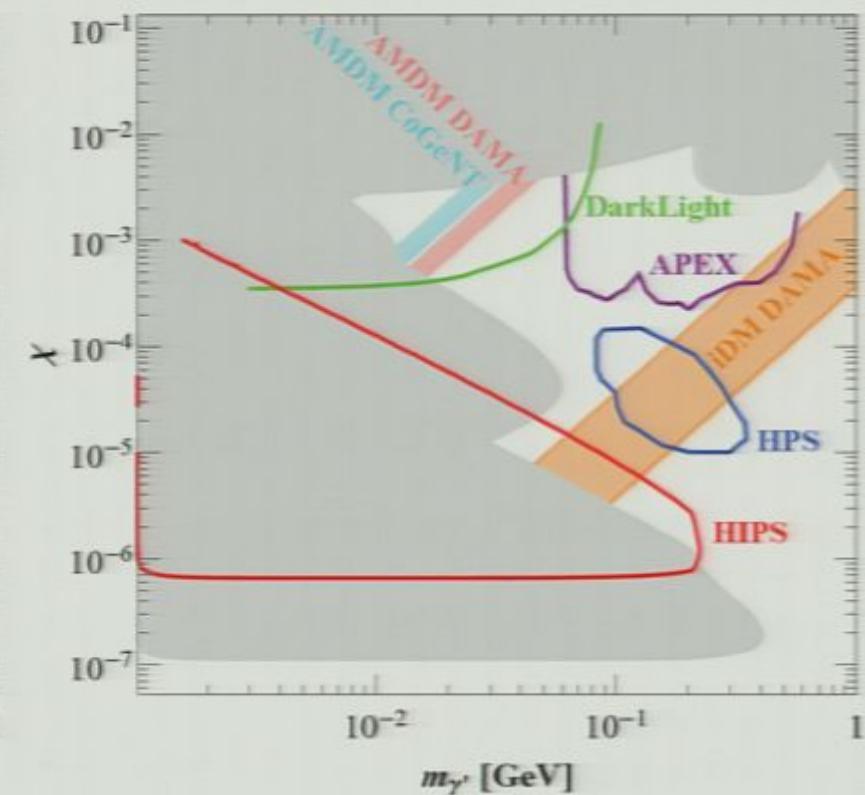
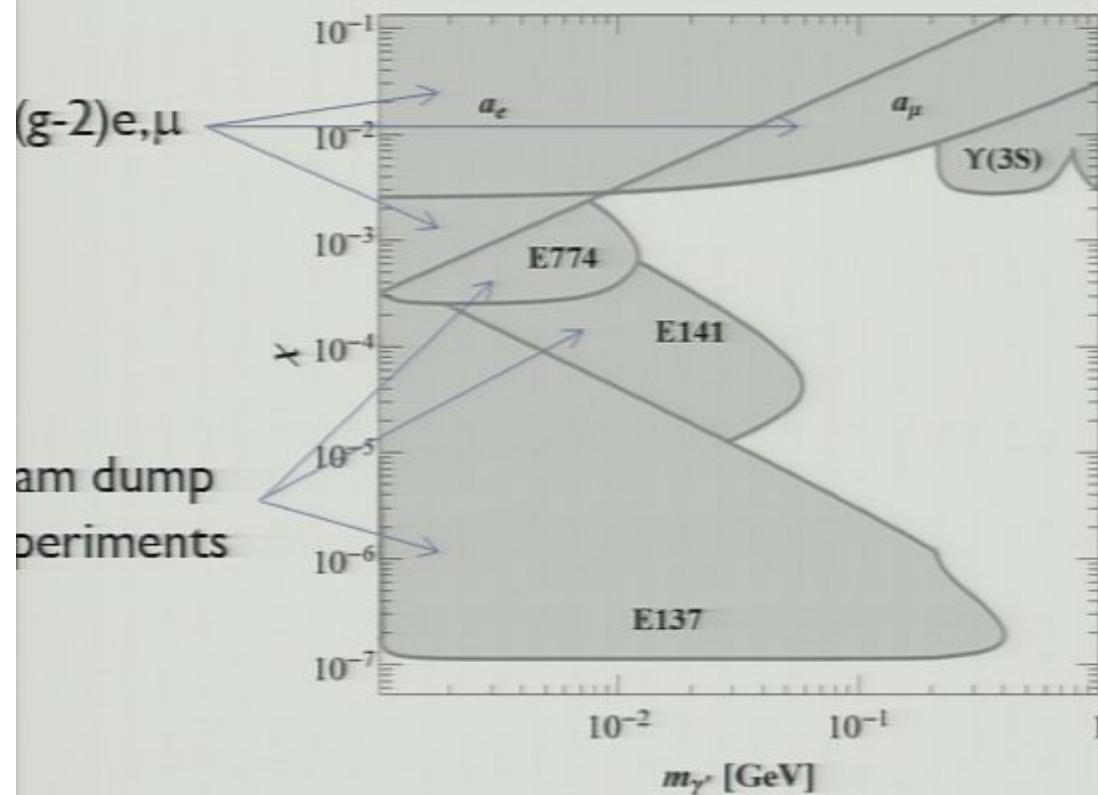
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Induced Nucleon Decay: Astrophysics

- ▶ Dark matter accumulates in stars. Effective nucleon lifetime decreases. Does DM devour/destroy stars?
- ▶ Some preliminary calculations:
 - ▶ DM can be captured through elastic scattering, but IND rate too small to destroy appreciable fraction of nucleons
 - ▶ Although DM does not annihilate with other DM, in stars it can annihilate through two step process: (1) IND transforms DM to anti-DM, (2) anti-DM annihilates with DM
 - ▶ Main effect is stellar heating through DM annihilation, not nucleon annihilation
 - ▶ Consistent with known constraints (BBN OK)

Conclusions

1. Cosmological puzzle: why $\rho_B \sim \rho_{DM}$? May be coincidence, or may be hint for asymmetric dark matter
2. Hylogenesis: a unified mechanism for generating the baryon and dark matter asymmetries simultaneously
3. Toy model: baryogenesis without B violation
4. Novel signature: Induced Nucleon Decay
 - ▶ Dark matter is antibaryonic
5. Elastic DM-nucleon scattering: required at some level in all ADM models due to requirement that DM annihilate efficiently to SM particles but may be unobservable

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