Signals of Hylogenesis

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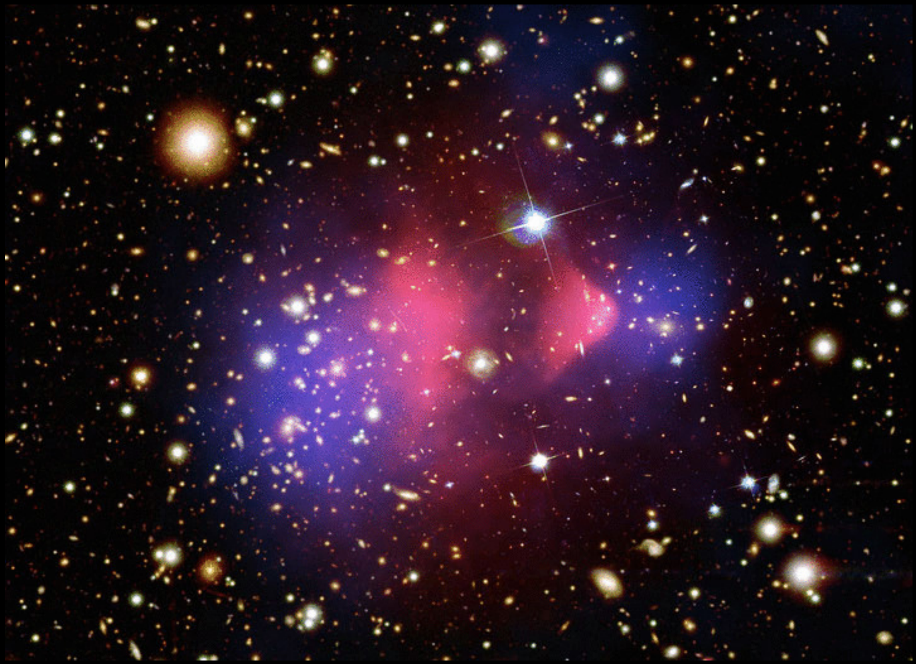


Based on:

H. D., D. E. Morrissey, K. Sigurdson, and S. Tulin

- Phys.Rev.Lett. 105 (2010) 211304, arXiv:1008.2399 [hep-ph]
- Phys. Rev. D 84, 096008 (2011), arXiv:1106.4320 [hep-ph]

Contribution to "Physics Beyond Colliders Working Group Meeting," CERN, March 2, 2017

Introduction

- Open questions:

Nature of dark matter (DM) and the origin of baryon asymmetry

- Observations: $\rho_{\mathrm{DM}} \approx 5\,\rho_{\mathrm{visible}}$

  - Seemingly unrelated sectors

  - Suggests common origin, asymmetric relic densities

Asymmetric Dark Matter:

(I) Charge asymmetry chemical equilibration

(II) Equal and opposite DM and visible sector charges ($\sum \Delta B = 0$)

We will focus on option (II), in the Hylogenesis framework.

(hyle: Greek for matter)

A Concrete Model of Hylogenesis

HD, D. Morrissey, K. Sigurdson, S. Tulin, 2010

- Basic idea
  - Visible and hidden sectors charged under generalized conserved B
  - Non-thermal production of heavy fermions $X, \bar{X}$; $B(X) = +1$
  - CP violation in $X, \bar{X} \to$ quarks, anti-quarks $\Rightarrow \Delta B(q) \neq 0$
  - CPT: $X, \bar{X} \to$ DM, anti-DM $\Rightarrow$ $\Delta B(\mathrm{DM}) = -\Delta B(q)$
  - DM, quarks decoupled to avoid washout: typically low reheat temperature
  - Symmetric populations annihilated efficiently $\Rightarrow n_{\mathrm{DM}} \sim n_{\mathrm{visible}}$
- Implications
  - *Nucleon destruction* via scattering from DM: **Induced Nucleon Decay (IND)**
  - DM masses close to $m_N \sim 1$ GeV

This proposal shares some elements with previous discussions, *e.g.*:

Kitano, Low, hep-ph/0411133, hep-ph/0503112; Farrar, Zaharijas, hep-ph/0510079; Agashe, Servant, hep-ph/0411254; Kaplan, Luty, Zurek, arXiv:0901.4117 [hep-ph]; An, Chen, Mohapatra, Zhang, arXiv:0911.4463 [hep-ph]; Allahverdi, Dutta, Sinha, arXiv:1005.2804 [hep-ph].

More Details:

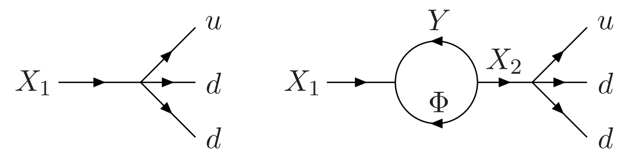
- Dirac fermions X_a, $a=1,2$, Ψ, complex scalar Φ, $B(X_a) = -[B(\Psi)+B(\Phi)] = +1$

$$|m_\Psi - m_\Phi| < m_p + m_e, \quad m_p - m_e < m_\Psi + m_\Phi \quad \text{(Stability)}$$

- X_a couples to quarks via the *neutron portal* (dim-6) and **DM** (Yukawa):

$$-\mathscr{L} \supset \frac{\lambda_a^{ijk}}{M^2}(X_{a,L}^\dagger d_R^k)(u_R^i d_R^j) + \zeta_a (X_{a,L}\Psi_L + X_{a,R}\Psi_R)\Phi + \text{H.C.}$$

- Visible baryon asymmetry:



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

- $U(1)'$, Ψ,Φ charges $\pm e'$, kinetic mixing with $U(1)_Y$: $-(\kappa/2)B_{\mu\nu}Z'_{\mu\nu}$

- GeV-scale Z' coupling to SM $-c_W \kappa Q_{em} e$: Ψ, Φ thermalization, annihilation

- Example: $\Psi\bar{\Psi} \to Z'Z'$

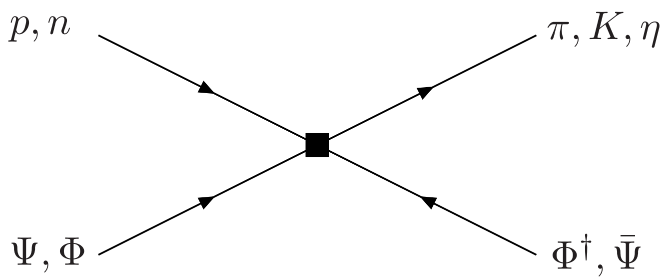
$$\langle \sigma v \rangle = \frac{e'^4}{16\pi}\frac{1}{m_\Psi^2}\sqrt{1 - m_{Z'}^2/m_\Psi^2} \simeq (1.6 \times 10^{-25}\text{cm}^3/\text{s}) \left(\frac{e'}{0.05}\right)^4 \left(\frac{3\,\text{GeV}}{m_\Psi}\right)^2$$

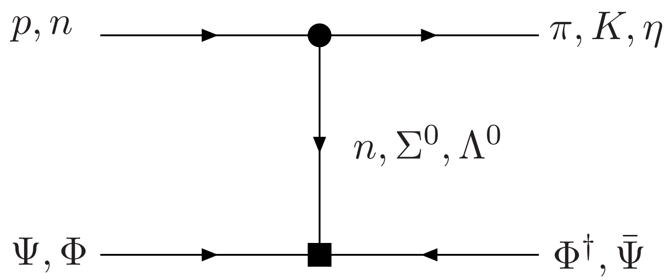
M. Pospelov, A. Ritz, M. Voloshin, 2007

IND and Effective Nucleon Lifetime

HD, D. Morrissey, K. Sigurdson, S. Tulin, 2011

- $\Phi N \longrightarrow \bar{\Psi} M$, $\Psi N \longrightarrow \Phi^\dagger M$





- IND mimics standard nucleon decay (SND) $N \to \text{meson}\ \nu$.
- Transfer operator $O_T \sim \Lambda_{IND}^{-3} u_R^i d_R^j d_R^k \Psi_R \Phi + \text{H.C.}$ (dim-7)

- IND rate estimate based on $SU(3)_L \times SU(3)_R$ chiral Lagrangian

M. Claudson, M. Wise, L. Hall, 1982

- Since $p_{\rm meson} \sim 4\pi f \sim 1$ GeV, only and order-of-magnitude guide

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

[A] Soudan 2, 2000; [B] IMB-3, 1999; [C] Super-Kamiokande, 2005

$$(\sigma v)_{IND} \approx 10^{-39}\ {\rm cm}^3/{\rm s} \times \left(\frac{\Lambda_{IND}}{1\ {\rm TeV}}\right)^{-6} \Rightarrow \boxed{\tau_N \approx 10^{32}\ {\rm yr} \times \left(\frac{\Lambda_{IND}}{1\ {\rm TeV}}\right)^{6} \left(\frac{0.3\ {\rm GeV/cm}^3}{\rho_{DM}}\right)}$$

- Lattice results suggest that the rate can be ~ 10 smaller.

Aoki, Shintani, Soni, arXiv:1304.7424 [hep-lat]; T. Izubuchi and E. Shintani, private communication; E. Shintani talk at "Lattice Meets Experiment 2013," BNL, December 5-6, 2013

★ *IND meson kinematics <u>different</u> from standard nucleon decay; effect on bounds.*

Search for Nucleon Decay Signals

- $p \to K^+ \nu$, $n \to K^0 \nu$
  - Super-Kamiokande (water Čerenkov detector).

  (a) $K^+ \to \pi^+ \pi^0$ and $K^+ \to \mu^+$ (+ prompt γ from ${}^{16}\mathrm{O} \to {}^{15}\mathrm{N}^* \to {}^{15}\mathrm{N} + \gamma$)

  - SND:

    K^+ below Čerenkov threshold, $\beta < 0.75$, decay at rest.

  - IND:

    $\beta > 0.75$ except for *up-scattering* near threshold.

    Extra ring, could make finding prompt γ more challenging.

    Not all K^+'s will be stopped.

  (b) $K^0_S \to \pi^0 \pi^0 \to 4\gamma$ and $K^0_S \to \pi^+ \pi^-$.

  - SND:

    4 e-like rings and 2 μ-like rings, respectively, $200\ \mathrm{MeV} < p_{K^0} < 500\ \mathrm{MeV}$.

  - IND:

    Boost can cause 4 rings to overlap.

    Larger momenta may enhance $\pi^+ \pi^-$ Čerenkov efficiency.

- $p \to \pi^+ \nu$
  - Soudan 2 (iron tracking calorimeter).
    - SND:

      Single π^+ track, ionization consistent with m_π or m_μ.

      Initial $140\ \mathrm{MeV} < p_{\pi^+} < 420$ MeV, visible endpoint decays ($\pi^+ \to \mu^+ \to e^+$).

      Simulations: On average half of initial p_{π^+} lost in iron nucleus.
    - IND:

      Higher p_{π^+} may help because of smaller atmospheric ν background.

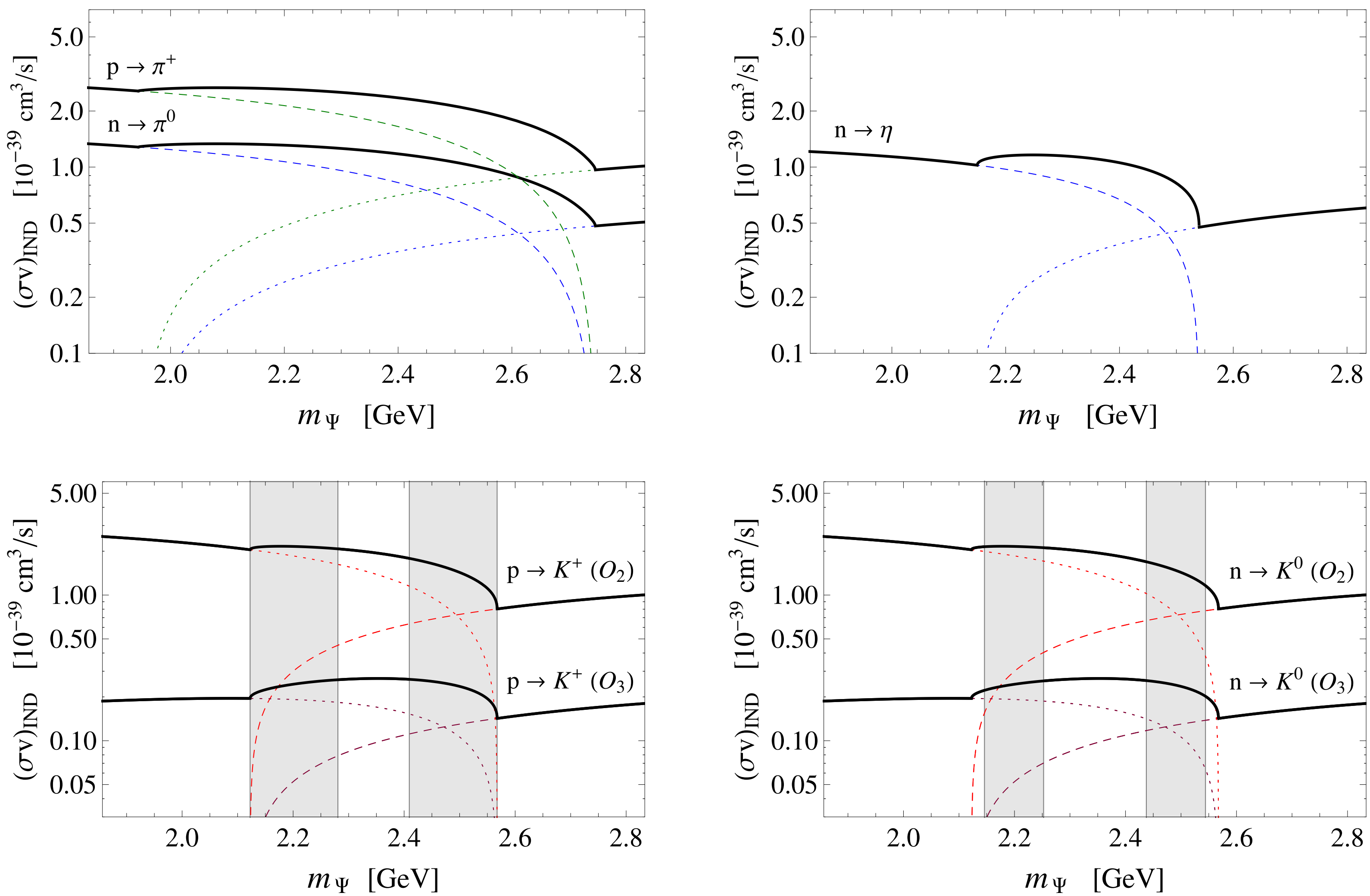
      Open questions: momentum loss in iron and possible nuclear fragmentation.

- $n \to \pi^0 \nu$, $n \to \eta \nu$
  - IMB-3 (water Čerenkov detector).
    - IND:

      Photons could overlap for $\pi^0 \to \gamma\gamma$; better prospects for $\eta \to \gamma\gamma$.

      Similar rates into π^0 and η; probe same underlying IND operator.

Dotted (dashed) lines $N\Phi \to \bar{\Psi}M$ ($N\Psi \to \Phi^{\dagger}M$); $\Lambda_{IND} = \mathrm{TeV}$



- Gray regions: Super-Kamiokande bounds for up-scattering near thershold:
  - $p \to K^+$ for $\beta_{K^+} < 0.75$ (below Čerenkov threshold).
  - $n \to K^0$ for 200 MeV $< p_{K^0} <$ 500 MeV.

Collider Signals

- Monojet (mono t/b) from the neutron portal: $q_i q_j \to \bar{q}_k X_{1,2}$
- Focus on the lighter $X_1 \equiv X$ and

$$-\mathscr{L} \quad \supset \quad \frac{\lambda}{M^2}(X_L^\dagger s_R)(u_R d_R) + \zeta\, X \Psi \Phi + H.C.,$$

- $q(p_1)\, q'(p_2) \;\to\; \bar{q}''(p_3)\, \bar{\Psi}(p_4)\, \Phi^\dagger(p_5)$

$$|\mathscr{M}|^2 = \begin{cases} \frac{2}{3}\left|\frac{\lambda\,\zeta}{M^2}\right|^2 \left|\frac{1}{q^2 - m_x^2 + i\Gamma_x m_x}\right|^2 (p_1\cdot p_2)\left[2(p_3\cdot q)(p_4\cdot q) - (q^2 - m_X^2)(p_3\cdot p_4)\right] \;; & s\text{-like} \\ \frac{2}{3}\left|\frac{\lambda\,\zeta}{M^2}\right|^2 \left|\frac{m_x}{q^2 - m_x^2 + i\Gamma_x m_x}\right|^2 (p_1\cdot p_3)\left[2(p_2\cdot q)(p_4\cdot q) - (q^2 - m_X^2)(p_2\cdot p_4)\right] \;; & t\text{-like} \end{cases}$$

$q = (p_4 + p_5) = (p_1 + p_2 - p_3)$; $\Gamma_x = \zeta^2 m_X / 16\pi$

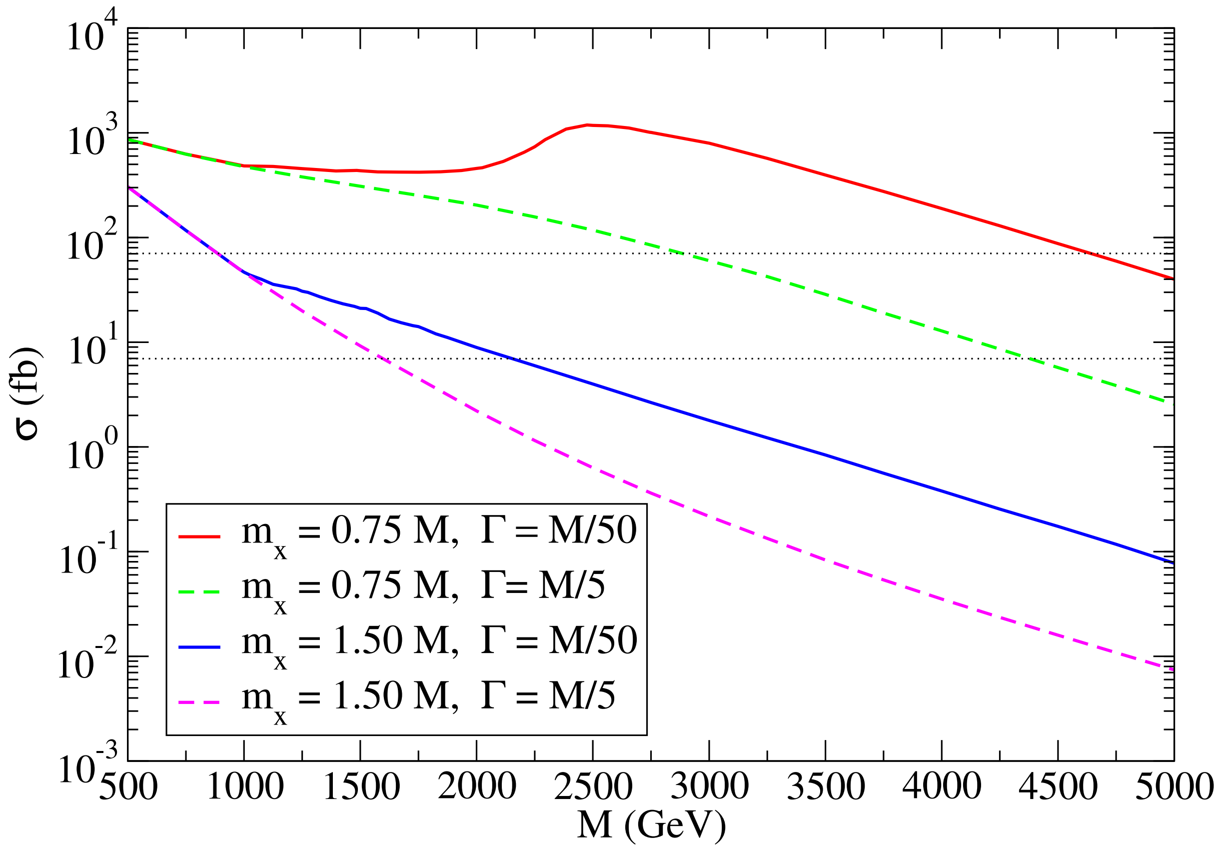
- Enhancement near X pole, but $m_X \lesssim M$ (hylogenesis): loss of effective theory.
- Mimic UV physics by boson exchange with mass M and width $\Gamma = \mathscr{C} M$, $\mathscr{C} = 1/5,\, 1/50$.

$$\frac{\lambda}{M^2} \to \frac{\lambda}{\hat{s} - M^2 + i\sqrt{\hat{s}}\Gamma} \quad ; \quad \frac{\lambda}{M^2} \to \frac{\lambda}{\hat{t} - M^2},$$

- LHC, $\sqrt{s} = 14$ TeV; $\lambda = 1$ and $\zeta = 0.7$
  - Cuts: $p_T > 500$ GeV, $|\eta| < 3.2$; efficiency factor: 85%

Background estimate: L. Vacavant, I. Hinchliffe, 2001
J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. Tait, H.-B. Yu, 2010

  - $S/\sqrt{B} > 5$ for $\int L dt = 1, 100$ fb^{-1}



From HD, D. Morrissey, K. Sigurdson, S. Tulin, arXiv:1106.4320 [hep-ph]

- LHC sensitivity to $M = 1 - 4$ TeV.

- IND in nucleon decay searches: $M \sim 1$ TeV.

- IND and collider mono-jet signals <u>correlated</u>.

- Hylogenesis may also go through *heavy quark* flavors.

- $M \sim 1$ TeV $\Rightarrow$ mono-top or mono-bottom signals: $s\,d \to X\,\bar{t}$, . . .

See also

J. Andrea, B. Fuks, F. Maltoni, 2011; J. Kamenik, J. Zupan, 2011

Potential Fixed Target Signals

- DM states, Z' (or other light annihilation mediator) at the GeV scale
- Quark coupling to DM suppressed by $\Lambda_{IND} \gtrsim 1$ TeV
- Proton beam fixed target experiments (SHiP) could produce DM, Z'
- DM-SM interactions mediated by IND (quarks) and Z' (kinetic mixing)
- Dominant scattering interaction model-dependent
- Z' could be long-lived (DM pair annihilation set by "dark coupling" α')
- Feasibility determination requires quantitative analysis

Conclusions

- Hylogenesis:
  - DM and ordinary baryons (nucleons) generated by asymmetry.
  - No net cosmic asymmetry: $\Delta B_{\rm DM} = -\Delta B_n$.
  - *DM can destroy nucleons through inelastic scattering processes*
- Signals
  - *Nucleon decay experiments*
  - *Collider physics*
  - *Astrophysics* (See arXiv:1106.4320 [hep-ph])
- UV completion at the TeV-scale:
  - *Nucleon decay signal correlated with mono-jets at the LHC*
  - Mono-top/bottom signals generally present in Hylogenesis
- Potential signal at proton beam fixed target experiments (~ 1 GeV scale states; prospects require quantitative examination)