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 $\chi$ and anti-DM $\bar{\chi}$.
  - More $\chi$ 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: $m_\chi \sim 5m_p \sim 5\text{ GeV}$. 
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. $\phi$ is displaced
2. $\phi$ oscillates when $H \sim m$
3. $V_\phi$ can dominate $\rho$
4. $\phi$ decays and reheats

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

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

- 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, $B = y$
  - $\Phi$ light (GeV) complex scalar, $B = -(1 + y)$

- Couplings:
  $$-\mathcal{L} \supset \frac{\lambda_a}{M^2} X_L U^c D^c D^c + \zeta^*_a X_a Y \Phi + (h.c.)$$

→ “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 $m_{Z'} \sim \text{GeV}$
  – SM fields carry no direct $U(1)'$ charge
  – $X_{1,2}$ are neutral
  – $Y$ and $\Phi$ have equal and opposite charges.

• Gauge kinetic mixing:

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

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

![Diagram](image)
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 $\Phi$ annihilate into $Z$'s.

- Leftover $Y$ and $\Phi$ 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

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

- CP violation alters partial decay widths:

\[
\begin{align*}
\Gamma(X \rightarrow 3Q) &= \Gamma_{3Q} + \epsilon \Gamma_{tot} \\
\Gamma(X \rightarrow \bar{Y}\Phi) &= \Gamma_{Y\Phi} - \epsilon \Gamma_{tot} \\
\Gamma(\bar{X} \rightarrow 3\bar{Q}) &= \Gamma_{3\bar{Q}} - \epsilon \Gamma_{tot} \\
\Gamma(\bar{X} \rightarrow Y\Phi) &= \Gamma_{Y\Phi} + \epsilon \Gamma_{tot}
\end{align*}
\]

CPT requires $\Gamma(X \rightarrow all) = \Gamma(\bar{X} \rightarrow all)$. 
Asymmetries come from tree-loop interference:

\[ \epsilon = \frac{\Gamma(X \rightarrow 3Q) - \Gamma(\bar{X} \rightarrow 3\bar{Q})}{\Gamma(X \rightarrow all) + \Gamma(\bar{X} \rightarrow all)} \]

\[ \simeq \frac{Im(\lambda_1^* \lambda_2 \xi_1 \xi_2^*)}{256\pi^3|\xi_1|^2} \frac{m_{X_1}^5}{M^4 m_{X_2}} \]

Final B Asymmetry:

\[ \frac{n_B}{s} \simeq \epsilon \frac{n_X}{s} \bigg|_{RH} \]
• 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:

  \[ q \to g, \gamma \]

- **\( Y, \Phi \)** annihilate to \( Z' \) leaving only the asymmetry:

  \[ Y, \Phi \to Z' \]

- 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.

$3Q + \bar{Y}\Phi^* \rightarrow 3Q + \bar{3Q}$

$\bar{Y}\Phi \rightarrow Y\Phi$

• $Y$ and $\Phi$ 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 \( \Phi \) 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 $\Phi$ 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 $\Phi$ off nuclei via $Z'$.
  - Nucleon destruction from inelastic $Y/\Phi$ 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 $\Phi$ can scatter inelastically off a nucleon.

  e.g.

- A nucleon is destroyed in this process.

\[ Y/\Phi + N \rightarrow \Phi^*/\bar{Y} + M \]
• Inelastic DM scattering will mimic nucleon decay.
  \[ \rightarrow \text{Induced Nucleon Decay (IND)} \]

• Total event rates in a nucleon decay detector:
  \[
  R_{\text{decay}} = \Gamma_{\text{decay}} N_{\text{nuc}}
  \]
  \[
  R_{\text{IND}} = (\sigma v)_{\text{IND}} (F_{DM}/v) N_{\text{nuc}}
  \]
  \[F_{DM} = \text{local DM flux}\]

• Effective IND “lifetime”:
  \[
  \tau_{\text{eff}}^{-1} = (\sigma v)_{\text{IND}} (F_{DM}/v).
  \]
• IND rate:

\[ \tau_{eff} \simeq 10^{32} \text{ yr} \left| \frac{m_X M^2}{\lambda^* \zeta} \right|^2 \]

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

• Nucleon decay searches use a meson momentum window. Meson momenta from IND are larger (for downscattering):

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>( p_{SM}^{SND} )</th>
<th>( p_{SM}^{IND} ) [down]</th>
<th>( \tau_N ) bound (( \times 10^{32} ) yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N \to \pi )</td>
<td>460</td>
<td>800 (-) 1400</td>
<td>( \tau_p &gt; 0.16, \tau_n &gt; 1.12 )</td>
</tr>
<tr>
<td>( N \to K )</td>
<td>340</td>
<td>680 (-) 1360</td>
<td>( \tau_p &gt; 23, \tau_n &gt; 1.3 )</td>
</tr>
<tr>
<td>( N \to \eta )</td>
<td>310</td>
<td>650 (-) 1340</td>
<td>( \tau_n &gt; 1.58 )</td>
</tr>
</tbody>
</table>
• 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, $m_\Phi \leq 2.9$ GeV.
  
  Why should it be so light?
  
  Supersymmetry!

- New features of our implementation of supersymmetry:
  
  – Two $Y$ and $\Phi$ multiplets are needed for $U(1)_x$ anomaly.
  – $R$-parity is extended to $\mathbb{Z}_4^R \subset U(1)_{B-L}$.
  – 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 \( \Phi \) 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:

\[ T_{RH} = 267 \text{ MeV}, \Omega_{DM}/\Omega_b = 5.0 \]

- 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.

\[ \rho_{DM} \approx 5 \rho_B \Rightarrow \sum_i m_{DM_i} \approx 5 m_p. \]

- A distinctive new DM signal is Induced Nucleon Decay. \( M \approx 1 \) 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.
Extra Slides
Light $Z'$ Signals

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

Fixed target experiments can improve these bounds.

[Bjorken, Essig, Schuster, Toro '09]

[Bjorken et al. '09, APEX '11]
DM-Nucleon Elastic Scattering

- $Y$ and $\Phi$ can scatter elastically off nuclei via $Z'$. 

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

$$\sigma_0^{SI} = (5 \times 10^{-39} \text{cm}^2) \left( \frac{2Z}{A} \right)^2 \left( \frac{e'}{0.05} \right)^2 \left( \frac{\kappa}{10^{-5}} \right)^2 \left( \frac{0.1 \text{ GeV}}{m_{Z'}} \right)^4$$
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 $\Phi$ DM can’t self-annihilate, but can yield IND:
  – DM collects in the stellar core by elastic scattering.
  – IND: $Y/\Phi + N \rightarrow \Phi^*/\bar{Y} + M$
  – $\Phi^*$ annihilates with $\Phi$, $\bar{Y}$ 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:

  \[ \begin{array}{c}
  U \\
  X \\
  D \\
  \end{array} \begin{array}{c}
  \rightarrow \Phi^* \\
  \rightarrow Y \\
  \rightarrow D \\
  \end{array} \]

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

- Analogous 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:

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

  $\Gamma = \text{unknown mediator width}$

• Look at different values of $\Gamma$ to estimate UV dependence.
- Tevatron (CDF) Monojet Search:
  jet with $p_T > 80$ GeV, $|\eta| < 1.0$, ...

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

![Graph showing the relationship between M (GeV) and $\sigma$ (fb) for different masses and decay widths.](image-url)
- 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: $\sigma \lesssim 7 \, fb$. 

![Graph showing the sensitivity of the signal cross-section ($\sigma$) as a function of the mass ($M$) for different mass values ($m_x$) and widths ($\Gamma$). The graph includes lines for $m_x = 0.75 \, M$, $\Gamma = M/50$ (red), $m_x = 0.75 \, M$, $\Gamma = M/5$ (green), $m_x = 1.50 \, M$, $\Gamma = M/50$ (blue), and $m_x = 1.50 \, M$, $\Gamma = M/5$ (magenta).]
Monojets can also come from $Z'$ Drell-Yan with ISR/FSR:

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

$$A_\mu \rightarrow A_\mu - \epsilon X_\mu + \mathcal{O}(\epsilon^2)$$

$$X_\mu \rightarrow X_\mu + \mathcal{O}(\epsilon^2)$$

• This induces a coupling between $X_\mu$ and SM states:

$$eQ A_\mu \bar{f} \gamma^\mu f \rightarrow eQ A_\mu \bar{f} \gamma^\mu f - eQ \epsilon x_\mu \bar{f} \gamma^\mu f.$$  

SM-$U(1)_x$ coupling strength = $-eQ \epsilon \ll 1$

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

• DM DOES NOT get an electric charge!
Hylogenesis = double rainbow + double unicorn!