A Brief Introduction to Asymmetric Dark Matter

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1 Asymmetric Dark Matter
1. Asymmetric Dark Matter

2. Type I: Sharing
1. Asymmetric Dark Matter

2. Type I: Sharing

3. Type II: Cogenesis
1. Asymmetric Dark Matter

2. Type I: Sharing

3. Type II: Cogenesis

4. Summary and conclusions
1 Asymmetric Dark Matter

2 Type I: Sharing

3 Type II: Cogenesis

4 Summary and conclusions
Beyond the Standard Model

Hints for physics beyond the Standard Model:
- Dark Matter
- Dark Energy
- Neutrino oscillations
Beyond the Standard Model

- Hints for physics beyond the Standard Model:
  - Dark Matter
  - Dark Energy
  - Neutrino oscillations

- Open questions
  - What is the nature of DM?
  - How is DM created?
  - Why is $\Omega_{DM} \sim \Omega_b$?
Comparing Baryonic and Dark Matter

<table>
<thead>
<tr>
<th>Baryons</th>
<th>Dark Matter</th>
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<tbody>
<tr>
<td><strong>Mass:</strong></td>
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<tr>
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Comparing Baryonic and Dark Matter

**Baryons**

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- **Density:** \( \Omega_b \approx 0.046 \)

**Dark Matter**

- **Mass:** \( m_{DM} = ? \)
- **Abundance:**
- **Density:**
### Motivation

Comparing Baryonic and Dark Matter

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Comparing Baryonic and Dark Matter

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**Abundance:**
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**Density:**
\[ \Omega_b \approx 0.046 \]

**Dark Matter**

**Mass:**
\[ m_{DM} = ? \]

**Abundance:**
\[ n_{DM} = ? \]

**Density:**
\[ \Omega_{DM} \approx 0.23 \]

\[ \frac{\Omega_{DM}}{\Omega_b} \approx 5 \]
WIMP Dark Matter

- Theorists have a (unhealthy) predisposition to expect new physics at the TeV scale
WIMP Dark Matter

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- Assume dark matter at the TeV scale, $m_{DM} \simeq 0.1 - 1$ TeV.
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→ Cross section of weak strength
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  $\implies$ Cross section of weak strength
- Weakly Interacting Massive Particles (WIMPs)
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- Weakly Interacting Massive Particles (WIMPs)
- Great! Or is it?
The WIMP miracle

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

The WIMP miracle!
### The WIMP miracle

#### Baryons

**Mass:**  
\[ m_N \simeq 1 \text{ GeV} \]

**Abundance:**  
\[ \frac{n_b}{n_\gamma} = (6.19 \pm 0.15) \cdot 10^{-10} \]  
*NOT thermal production!*

**Density:**  
\[ \Omega_b \simeq 0.046 \]

#### WIMP Dark Matter

**Mass:**  
\[ m_{DM} \simeq 1 \text{ TeV} \]

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\[ n_{DM} \simeq 10^{-3} n_b \]

**Density:**  
\[ \Omega_{DM} \simeq 0.23 \]

\[ \frac{\Omega_{DM}}{\Omega_b} \simeq 5 \]

*The WIMP miracle!*
Facing the WIMP miracle

If you like WIMPS:
“Just assuming new physics at TeV scale, we derived that DM interacts with a weak scale cross section to the SM. This fits my expectations of how and where new physics should be found.”

If you do not like WIMPS:
“I dont believe that just by coincidence you would get the same DM and baryon abundances when they have so different masses and production mechanisms. I want DM and baryons to be more similar.”
Facing the WIMP miracle

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Let us try to see if we can achieve this: Asymmetric Dark Matter (ADM)
How to make DM similar to baryons

- Baryons are Dirac fermions
- Baryon abundance is tied to baryon number \( B \)
- Baryons asymmetry seeded in early Universe

These assumptions makes DM similar to baryons and have similar number density, thus

\[
\frac{m_{DM}}{m_b} \simeq \frac{\Omega_{DM}}{\Omega_b} \simeq 5
\]
1. Asymmetric Dark Matter

2. Type I: Sharing

3. Type II: Cogenesis

4. Summary and conclusions
Sharing and Cogenesis

There are two main mechanisms behind ADM production:

Sharing:
Baryons and Dark Matter shares a primordial asymmetry produced in an arbitrary sector.

Cogenesis
The Baryon and Dark Matter asymmetries are produced by the same processes.

Conditions for Sharing

A few ingredients necessary for generating ADM in sharing models

\[ B \quad \bar{B} \]
\[ \chi \quad \bar{\chi} \]
Conditions for Sharing

A few ingredients necessary for generating ADM in sharing models

1. Asymmetry generation in arbitrary sector
Conditions for Sharing

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1. Asymmetry generation in arbitrary sector
2. Asymmetry transfer
Conditions for Sharing

A few ingredients necessary for generating ADM in sharing models

1. Asymmetry generation in arbitrary sector
2. Asymmetry transfer
3. Annihilation of symmetric (thermal) component
Asymmetry generation

- **Baryon number** $B$
  - Baryogenesis  Sakharov 1967

- **Lepton number** $L$
  - Leptogenesis  Fukugita, Yanagida 1986

- **Dark matter number** $X$
  - Xogenesis  Buckley, Randal, arXiv:1009.0270

...
Asymmetry transfer

The transferring processes need to be:
- Fast and active in the early Universe
- Inactive at lower energies
Asymmetry transfer

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Effective operators

$O^6$
Asymmetric transfer

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- Inactive at lower energies

Effective operators

Sphaleron processes

Mattias Blennow
A Brief Introduction to Asymmetric Dark Matter
Thermal component annihilation

- ADM has a mass in the few GeV region
- WIMPs get the correct relic abundance with a weak scale cross section
- Annihilation of lighter species require larger cross sections
  \[ \Rightarrow \text{Larger annihilation cross section than weak} \]

ADM mass is higher, but abundance is Boltzmann suppressed compared to \( B \)

Thermal component does not annihilate directly into SM particles
Cosmological phenomenology

ADM generally has different cosmology than WIMP DM

- Only consisting of particles (no anti-particles) ⇒ no indirect detection
- Accumulates in stellar bodies – what is the effect on stellar evolution?
- Short range self-interacting ADM could alter halo evolution (to the better)
  Spergel, Steinhard, astro-ph/9909366
How asymmetric is ADM?

- Cross section close to what is required
- Annihilation is not complete
- Residual component of anti-ADM
- Phenomenological consequences?

Graesser, Shoemaker, Vecchi, JHEP 1110 (2011) 110
An example of sharing

Standard leptogenesis

Generation of lepton number asymmetry by $CP$ violating decays of heavy Majorana fermion singlets $N_R$ (typically type-I seesaw)

- Seeds a lepton number asymmetry $L$
- Transfers to baryon sector through $SU(2)_L$ sphalerons conserving $B - L$
Asymmetry transfer from $L$

- The asymmetry in $L$ could transfer to both $B$ and $X$
Asymmetric Dark Matter

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Summary and conclusions

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Asymmetry transfer from $L$

- The asymmetry in $L$ could transfer to both $B$ and $X$

- Couple $X$ to $SU(2)_L$ like baryons and leptons

Asymmetric transfer from \( L \)

- The asymmetry in \( L \) could transfer to both \( B \) and \( X \)

- Couple \( X \) to \( SU(2)_L \) like baryons and leptons

- Implies weakly interacting light \( X \), excluded by LEP
Aidnogenesis via Leptogenesis

- The basic idea: New gauge group to provide new sphalerons

- Extend the gauge sector of the SM
- Additional sphaleron processes
- Is this possible to achieve?

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Cogenesis

Necessary ingredients for generating ADM in cogenesis models:
Cogenesis

Necessary ingredients for generating ADM in cogenesis models:

1. DM-SM interactions violating both $B$ and $\bar{B}$

\[ B \quad \bar{B} \]
\[ X \quad \bar{X} \]
Cogenesis

Necessary ingredients for generating ADM in cogenesis models:

1. DM-SM interactions violating both
2. Out of thermal equilibrium

[Diagram showing four regions: B, B, X, X]
Necessary ingredients for generating ADM in cogenesis models:

1. DM-SM interactions violating both
2. Out of thermal equilibrium
3. Annihilation of symmetric (thermal) component
Asymmetric production in Cogenesis

- Consider a heavy field $H$ with a $CP$ violating decay

$$\Gamma(H \rightarrow BX) \neq \Gamma(H \rightarrow \bar{B}\bar{X})$$

- If the decays are out of thermal equilibrium (cf. Leptogenesis), asymmetries can result in both $B$ and $X$

- Typically, it will be possible to assign $X$ such that $X = -B$

- Dark Matter can be viewed as being anti-baryonic and carry the missing baryon number with $B_{SM} + B_{DM} = 0$  
Cogenesis versus Sharing

There are pros and cons with both Cogenesis and Sharing:

- Cogenesis typically relates $B$ and $X$ through some fundamental interaction
- Typically $B$-$X$ relation at a relatively low energy scale
- Problems consolidating with current bounds
- Difficulty of model building

- Sharing does not imply strong $B$-$X$ interactions, just communication between the sectors
- Asymmetry production not related to $B$-$X$ relation
- Asymmetry production can be put at very high scales
- More possibility of separating the physics of the two sectors
An example of Cogenesis

**Hyloegenesis**

- **Use the following ingredients:** Davoudiasl, et al, arXiv:1008.2399
  - Two heavy Dirac fermions $X_1, X_2$ ($M_{X_a} \gtrsim \text{TeV}$)
  - A GeV scale Dirac fermion $Y$
  - A GeV scale scalar $\Phi$

- With proper assignment of Baryon numbers,
  $B_{X_a} = 1 = -(B_Y + B_{\Phi})$:

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

![Diagram of interactions]

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4. Summary and conclusions
We have . . .

- discussed the general principles of ADM
- discussed how different ADM models can be constructed
- discussed the two dominant ways of generating ADM
- seen selected examples
Incomplete set of references

Nussinov, 1985
Barr, et al, 1990
Kaplan, 1992
Kitano, Low, hep-ph/0411133
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5 Asymmetric Dark Matter via Leptogenesis

6 A model of Asymmetric Dark Matter
Standard leptogenesis

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- Seeds a lepton number asymmetry $L$
- Transfers to baryon sector through $SU(2)_L$ sphalerons conserving $B - L$
Direct production

One way of producing ADM is to let the two sectors be seeded at the same time, i.e.,

- In addition to $N_R \rightarrow L\Phi$, we have $N_R \rightarrow X\phi$
- $X$ can belong to a mirror world \textsuperscript{(An, et al., arXiv:0911.4463)} or be the ADM itself \textsuperscript{(Falkowski, et al., arXiv:1101.4936)}
- The mirror world has problems with extra radiation and neutrinos mixing between worlds
- The pure ADM model needs extra symmetries to prevent DM-neutrino mixing
- It is also a Majorana fermion $\rightarrow$ small or no window \textsuperscript{(Buckley, Profumo, arXiv:1109.2164)}
Asymmetry transfer from $L$

- The asymmetry in $L$ could transfer to both $B$ and $X$
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- The basic idea: New gauge group to provide new sphalerons
- Extend the gauge sector of the SM
- Additional sphaleron processes
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5 Asymmetric Dark Matter via Leptogenesis

6 A model of Asymmetric Dark Matter
Extending the SM gauge group

- We want to introduce new spalerons $\Rightarrow$ extend the gauge group
Extending the SM gauge group

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- We want (part of) the extended group to couple to both SM and DM
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\[ G_{ADM} = G_{SM} \times SU(2)_H \]

- Horizontal chiral symmetry providing new spalerons
Extending the SM gauge group

- We want to introduce new spalerons ⇒ extend the gauge group.
- We want (part of) the extended group to couple to both SM and DM.
- We want to prevent mixing between neutrinos and DM.

\[ G_{ADM} = G_{SM} \times SU(2)_H \times SU(3)_{dc} \]

- Horizontal chiral symmetry providing new spalerons.
- Charge DM under additional “dark color” group to prevent mixing with singlets.
Introduction of new fermion fields

For each SM generation, we also introduce:

■ A right handed fermion singlet $N_R$ (type-I seesaw) $\Rightarrow$ leptogenesis, neutrino masses

■ A dark sector of fermions $x_R$, $x_L$, which will form a Dirac fermion $\Rightarrow$ ADM

■ Put different flavors of right handed fields in doublets of $SU(2)_H$:

$$
\begin{pmatrix}
e \\
\mu \\
u \\
c
\end{pmatrix}_R,
\begin{pmatrix}
u \\
c
\end{pmatrix}_R,
\begin{pmatrix}
d \\
s
\end{pmatrix}_R,
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix}_R
$$

■ Make $x_R$ and $x_L$ triplets under $SU(3)_{dc} \Rightarrow x_L$ does not mix with $N_R$ (and some interesting phenomenology)
Complete fermion content

<table>
<thead>
<tr>
<th>Field</th>
<th>Y</th>
<th>L</th>
<th>H</th>
<th>C</th>
<th>dc</th>
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<tr>
<td>$L_{L\alpha} (\nu_{\alpha L}, \ell_{\alpha L})$</td>
<td>$-1/2$</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$L_H (e_R, \mu_R)$</td>
<td>$-1$</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\tau_R$</td>
<td>$-1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\nu_{\alpha R}$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>$Q_{\alpha L} (u_{\alpha L}, d_{\alpha L})$</td>
<td>$1/6$</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
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<tr>
<td>$Q^u_H (u_R, c_R)$</td>
<td>$2/3$</td>
<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>$t_R$</td>
<td>$2/3$</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$b_R$</td>
<td>$-1/3$</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
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<tr>
<td>$X_H (x_{1R}^1, x_{2R}^2)$</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
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<tr>
<td>$x_{3R}, x_{L}^{\alpha}$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
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Removing the thermal component

\[ \bar{X} \]
Removing the thermal component

\[ \bar{X} \]

\[ SU(3)_{dc} \]

\[ \bar{XX} \]
Removing the thermal component
Removing the thermal component

\[ \bar{X} \]

\[ SU(3)_{dc} \]

\[ SU(2)_H \]

\[ SM \]
Dark matter properties

- The $SU(2)_H$ sphalerons satisfy $\Delta B = 2\Delta L = 2\Delta X$
- Along with SM sphalerons, $B - L - X$ remains non-anomalous and conserved
- After sphaleron freezout

$$X = -\frac{11}{14}B \Rightarrow m_{DM} = 5.94 \pm 0.42 \text{ GeV}$$

- $SU(3)_{dc}$ is confining $\Rightarrow$ DM consists of dark baryons
- We expect a thermal abundance of both DM and anti-DM in the early Universe
- Below the $SU(3)_{dc}$ phase transition, the thermal component goes into dark mesons
- Dark mesons decay to SM via $SU(2)_H$
In the early Universe

- We want the dark mesons to decay before BBN $\Rightarrow$ lower bound on $G_F^H$
- The $SU(2)_H$ is going to induce FCNC, from $K^0 \rightarrow e\mu$:
  $$G_F^H < 3.6 \cdot 10^{-12} \text{ GeV}^2$$
- Too low for dark mesons to decay fast enough
- Could couple to second and third generation where bounds are weaker
Breaking $SU(2)_H$ in stages

- Another possibility: $SU(2)_H$ is broken to a flavor conserving $U(1)$
- Break $SU(2)_H$ by a scalar triplet vev in the flavor conserving direction

For $\tau < 10^{-2} \text{ s}$

\[ G_F^H > \]

\[ 5 \cdot 10^{-11} \text{ GeV}^2 \]
\[ 10^{-10} \text{ GeV}^2 \]
\[ 5 \cdot 10^{-10} \text{ GeV}^2 \]
\[ 10^{-9} \text{ GeV}^2 \]
With $\tau$ in the doublet
Our model has the following “nice” features:

- Anomaly free extension of the SM gauge group
- Dark matter and baryon abundances similar
- Dark matter and baryon masses similar and given by similar processes
- Dark matter is stable without any additional parity
- Allows for some interesting phenomenology at low energies, such as flavor violation or possible direct detection

In fairness, also some “ugly” features must be mentioned:

- Why a horizontal $SU(2)$?
- The assignment of flavors to $SU(2)_H$ doublets is artificial
- Difficult to extend to, e.g., $SU(3)$ flavor symmetry