Self-interacting asymmetric dark matter

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How can we find dark matter?

First, we have to guess the answer!

... Need a strategy ...
Proposed strategy

Focus on DM-related observations:

- DM density $\rightarrow$ Asymmetric DM
- Patterns of gravitational clustering $\rightarrow$ Self-interacting DM
Outline

- Asymmetric DM: general structure and features
- Self-interacting DM
- Self-interacting $\cap$ Asymmetric DM
- Case study: atomic dark matter
A cosmic coincidence

Why $\Omega_{DM} \sim \Omega_{OM}$?

- Unrelated mechanisms $\rightarrow$ different parameters $\rightarrow$ result expected to differ by orders of magnitude.

- Similarity of abundances hints towards related physics for OM and DM production.
Ordinary matter

- Stable particles: $p \ e \ \gamma \ \nu$
- $p^+$ make up most of ordinary matter in the universe.
  
  Only $p^+$, no $p^-$ present today: matter-antimatter asymmetry

\[ \text{Asymmetry} \propto \Omega_{\text{OM}} \]

Ordinary particles $\rightarrow$ conserved today

b/c of global U(1) symmetry of the SM, baryon-number $B_{\text{V}}$

Ordinary anti-particles $\rightarrow$

annihilated in the early universe
A non-coincidence

Ordinary matter

- Atoms: 4.9 %
- Photons: 0.0022 %
- Neutrinos: 0.0016 %

Particle-antiparticle asymmetry

Relativistic thermal relics

Dark Energy (69.1 ± 0.6) %

Ordinary Matter (4.9 ± 0.03) %

Dark Matter (26 ± 0.2) %
A cosmic coincidence

Why $\Omega_{\text{DM}} \sim \Omega_{\text{OM}}$?

- Just a coincidence

  OR

- Dynamical explanation:
  DM production related to ordinary matter-antimatter asymmetry $\rightarrow$ asymmetric DM
The asymmetric DM proposal

[Review of asymmetric dark matter; KP, Volkas (2013)]

- DM density due to an excess of dark particles over antiparticles.
- DM – OM asymmetries related dynamically, by high-energy processes which occurred in the early universe.
- Dark and visible asymmetries conserved separately today.

\[
\begin{align*}
\text{OM asymmetry} & \propto \Omega_{\text{OM}} \\
\text{DM asymmetry} & \propto \Omega_{\text{DM}}
\end{align*}
\]

Ordinary particles \quad Ordinary anti-particles \quad Dark anti-particles \quad Dark particles
**Asymmetric DM**

[Review of asymmetric dark matter; KP, Volkas (2013)]

### Ingredients

#### Low-energy theory:
- Standard Model: Ordinary baryon number symmetry \( B_O \)
  - Dark sector: "Dark baryon number \( B_D \)" [accidental global U(1) symmetry]
- Interaction which annihilates dark antiparticles. How strong?
  - \( \rightarrow \) determines possibilities for DM couplings \( \rightarrow \) low-energy pheno.

#### High-energy theory:
- \( B_O \) violation
- \( B_D \) violation
  - \( \rightarrow \) if correlated \( \rightarrow \) related asymmetries \( \Delta B_O \) & \( \Delta B_D \)
**Low-energy theory:**

- Standard Model: Ordinary baryon number symmetry $B_O$
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**High-energy theory:**

$B_O$ violation $B_D$ violation \[ \text{if correlated} \rightarrow \text{related asymmetries } \Delta B_O \& \Delta B_D \]
Consider

\[ B_{\text{gen}} \equiv B_O - B_D \]
\[ X \equiv B_O + B_D \]

or

\[ B_{\text{gen}} \equiv (B-L)_O - B_D \]
\[ X \equiv (B-L)_O + B_D \]

Need processes which

- violate \( X \rightarrow \Delta X \neq 0 \)
- preserve \( B_{\text{gen}} \rightarrow \Delta B_{\text{gen}} = 0 \)

\[ \Delta(B-L)_O = \Delta B_D = \Delta X / 2 \]

*Side point:* \( B_{\text{gen}} \) remains always conserved \( \rightarrow \) could originate from a gauge symmetry, a generalization of the \( B-L \) symmetry of the SM, coupled to a dark sector \( \rightarrow Z'_{B-L} \) with invisible decay width in colliders

[Review of asymmetric dark matter; KP, Volkas (2013)]
Asymmetric DM

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- **High-energy theory:**
  - $B_O$ violation
  - $B_D$ violation
    - if correlated → related asymmetries $\Delta B_O$ & $\Delta B_D$
Non-relativistic thermal relic DM

**Symmetric DM**

\[ \Omega_{\text{DM}} \propto \frac{1}{(\sigma v)_{\text{ann}}} \]

\[ \sigma_{\text{ann}} v_{\text{rel}} \approx 4.4 \times 10^{-26} \text{ cm}^3/\text{s} \]

fixed value

**Asymmetric DM**

\[ \text{excess } \propto \Omega_{\text{DM}} \]

\[ \sigma_{\text{ann}} v_{\text{rel}} > 4.4 \times 10^{-26} \text{ cm}^3/\text{s} \]

no upper limit

For \[ \frac{(\sigma v)_{\text{ann}}}{4.4 \times 10^{-26} \text{ cm}^3/\text{s}} > 2 \rightarrow \frac{n(\chi)}{n(\chi)} < 5\% \]

[Graesser, Shoemaker, Vecchi (2011)]
To get $\Omega_{\text{DM}} \sim 26\%$:

Non-thermal relics e.g. sterile neutrinos, axions

Symmetric (WIMP) DM

Asymmetric DM

4.4 x $10^{-26}$ cm$^3$ / s

increasing $(\sigma v)_{\text{ann}}$

Asymmetric dark matter

- Encompasses most of the low-energy parameter space of thermal relic DM $\rightarrow$ study models and low-energy pheno.
- Provides a suitable host for DM self-interacting via light species.
DM annihilation

Need \((\sigma v)_{\text{ann}} > 4.4 \times 10^{-26} \text{ cm}^3/\text{s}\).

What interaction can do the job?

- \(\bar{\chi} \chi \rightarrow \text{SM SM}\)
  Annihilation directly into SM particles highly constrained via colliders and direct detection (see bounds on symmetric WIMP DM)

- \(\bar{\chi} \chi \rightarrow \phi \phi\)
  Annihilation into new light states:
  - \(\phi \rightarrow \text{SM SM}\): metastable mediators decaying into SM
  - \(\phi\) stable light species, e.g. dark photon (possibly massive, with kinetic mixing to hypercharge), or a new light scalar.
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Asymmetric DM

[Review of asymmetric dark matter; KP, Volkas (2013)]
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Structure

CONNECTOR SECTOR

particles with
$G_{SM}$, $G_D$ and possibly $G_{common}$

Interactions which break one linear combination of global symmetries:

e.g. conserved $B_O - B_D$; broken $B_O + B_D$

$\rightarrow \Delta(B_O + B_D) = 2 \Delta B_O = 2 \Delta B_D$

STANDARD MODEL

gauge group

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$\rightarrow$ accidental global $B_O$

$\rightarrow$ strong $pp$, $nn$ annihilation

DARK SECTOR

gauge group $G_D$

$\rightarrow$ accidental global $B_D$

$\rightarrow$ efficient annihilation

Portal interactions

$B_O$ & $B_D$

preserving
Asymmetric DM

[Review of asymmetric dark matter; KP, Volkas (2013)]

\[ G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y \]

\[ \rightarrow \text{accidental global } B_O \]

\[ \rightarrow \text{strong pp, nn annihilation} \]

\[ G_D \rightarrow \text{efficient annihilation} \]

**Most phenomenological implications determined by low-energy physics.**

**Standard Model**

**Connector Sector**

particles with \( G_{SM}, G_D \) and possibly \( G_{\text{common}} \)

Interactions which break one linear combination of global symmetries:

- e.g. conserved \( B_O - B_D \)
- broken \( B_O + B_D \)

\[ \Delta(B_O + B_D) = 2 \Delta B_O = 2 \Delta B_D \]

**Dark Sector**

**Portal Interactions**

\( B_O \) and \( B_D \) preserving

\[ \rightarrow \text{accidental global } B_D \]

\[ \rightarrow \text{efficient annihilation} \]
Does asymmetric DM pheno have to be unconventional? **No.**

- Many regimes where it behaves as collisionless CDM.
- Could have weak-scale interactions with ordinary matter.
- Main difference in (sufficiently) high-energy physics.
- Scenario still motivated by cosmic coincidence.

Is it interesting to consider regimes with unconventional pheno? **Yes!**

- Disagreement between collisionless CDM predictions and observations of galactic structure: May be telling us something non-trivial about DM.
- Potential for interesting signatures (not yet fully explored).
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Collisionless ΛCDM and galactic structure

- Very successful in explaining large-scale structure.

- At galactic and subgalactic scales: simulations predict too rich structure. Various problems identified: “cusps vs cores”, “missing satellites”, “too big to fail”.

  too much matter in central few kpc of typical galaxies.

[an overview: Weinberg, Bullock, Governato, Kuzio de Naray, Peter; arXiv: 1306.0913]
Small-scale galactic structure: How to suppress it

- **Baryonic physics**

- **Shift in the DM paradigm:**
  Retain success of collisionless $\Lambda$CDM at large scales, suppress structure at small scales
  - Warm DM, e.g. keV sterile neutrinos
  - Self-interacting DM

Continuum of possibilities:
How warm or how self-interacting can / should DM be?
The energy & momentum exchange between DM particles:

- **Heats up the low-entropy material**
  -suppresses overdensities [cusps vs cores]
  -suppresses star-formation rate [missing satellites, “too big to fail”]

- **Isotropises DM halos**
  -constrained by observed ellipticity of large haloes.

\[0.2 \text{ barn/GeV} < \frac{\sigma_{\text{scatt}}}{m_{\text{DM}}} < 2 \text{ barn/GeV}\]

DM coupled to a light or massless force mediator (long-range interaction)

- $\sigma_{\text{scatt}} / m_{\text{DM}} \sim$ nuclear interaction strength
- If mediator sufficiently light: $\sigma_{\text{scatt}} \sim 1 / v^n$, $n > 0$:
  - Significant effect on small halos (small velocity dispersion)
  - Negligible effect on large halos (large velocity dispersion)
Sizable self-interactions via light mediators imply minimum contribution to DM annihilation; annihilation cross-section could exceed canonical value for symmetric thermal relic DM

→ consider **asymmetric DM** (also motivated by $\Omega_{\text{DM}} \sim \Omega_{\text{OM}}$)
Asymmetric dark matter with (long-range) self-interactions
Self-interacting asymmetric dark matter

How to go about studying it?

Many studies of long-range DM self-interactions (in either the symmetric or asymmetric regime) employ a Yukawa potential

\[ V_{\chi\chi} (r) = \pm \alpha \exp (- m_\phi r) / r \]

[upper bound on \( \sigma_{\text{scatt}} \) → lower bound on \( m_\phi \) / upper bound on \( \alpha \)]

However, typically reality is often more complex for asymmetric DM with (long-range) self-interactions.
Self-interacting asymmetric dark matter

- **Complex early-universe dynamics**
  - Formation of stable DM bound states $\rightarrow$ Multi-species DM, e.g. dark ions, dark atoms, dark nuclei.

- **Implications for detection**
  - Variety of **DM self-interactions** $\rightarrow$ affect kinematics of halos.
  - Variety of **DM-nucleon interactions** $\rightarrow$ direct detection.
  - Variety of **radiative DM processes** $\rightarrow$ indirect detection.

- Consider classes of models, calculate cosmology + phenomenology self-consistently
A minimal self-interacting asymmetric DM example:

atomic dark matter
Atomic DM

Minimal assumptions

- DM relic density: dark particle-antiparticle asymmetry
- DM couples to a gauged $U(1)_{D}$ [dark electromagnetism]
  - DM self-scattering in halos today via dark photons.
  - DM annihilation in the early universe into dark photons.

Atomic DM

Minimal assumptions → rich dynamics

• DM relic density: dark particle-antiparticle asymmetry
• DM couples to a gauged $U(1)_D$ [dark electromagnetism]
  → DM self-scattering in halos today via dark photons.
  → DM annihilation in the early universe into dark photons.

Gauge invariance mandates DM be multi-component:

• Massless dark photon:
  Dark electric charge carried by dark protons $p_D^+$ compensated
  by opposite charge carried by dark electrons $e_D^-$. They can
  bind in dark Hydrogen atoms $H_D$.

• Mildly broken $U(1)_D$, light dark photon:
  Similar conclusion in most of the parameter space of interest.

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[KP, Pearce, Kusenko (2014)]
\[ G = G_{SM} \times U(1)_{B_{gen}} \times U(1)_D \]

same as \((B-L)_V\) for SM particles

- Efficient annihilation
- DM self-scattering in halos

\[
\begin{align*}
\delta L_{\text{low}} &= \mathcal{L}_{SM} + \bar{p}_D (i\not{D} - m_p) p_D + \bar{e}_D (i\not{D} - m_e) e_D + \left(\varepsilon/2\right) F_{\mu\nu} F_D^{\mu\nu} \\
\delta L_{\text{high}} &\supset \left(1/\Lambda^8\right) (\bar{u}^c d \bar{s}^c u \bar{d}^c s) \bar{e}_D^c p_D 
\end{align*}
\]

preserves \( B_{gen} = (B-L)_V - B_D \)

breaks \( X = (B-L)_V + B_D \)

\[ \Delta (B-L)_V = \Delta B_D \]

[e.g. via Affleck-Dine mechanism in susy models; von Harling, KP, Volkas (2012)]

Direct / Indirect detection

accidental global \((B-L)_V \& B_D\)
**Dark asymmetry generation** in \( U(1)_D - \)neutral op \((p_D e_D)\)

\[
T_{\text{asym}} > m_{p_D} / 25
\]

**Freeze-out of annihilations**

\[
\bar{p}_D p_D \rightarrow \gamma_D \gamma_D \quad \text{&} \quad \bar{e}_D e_D \rightarrow \gamma_D \gamma_D
\]

\[
T_{\text{FO}} \approx m_{p_D, e_D} / 30
\]

**Dark recombination,**

\[
p_D + e_D \rightarrow H_D + \gamma_D
\]

\[
T_{\text{recomb}} \lesssim \text{binding energy} = \alpha_D^2 \mu_D / 2
\]

**Residual ionisation fraction**

\[
x_{\text{ion}} \equiv \frac{n_{p_D}}{n_{p_D} + n_{H_D}} \sim \min \left[ 1, 10^{-10} \frac{m_{p_D} m_{e_D}}{\alpha_D^4 \text{ GeV}^2} \right]
\]

**[If dark photon massive] Dark phase transition**

\[
T_{\text{PT}} \sim m_{\gamma_D} / (8\pi\alpha_D)^{1/2}
\]

[Kaplan, Krnjaic, Rehermann, Wells (2009); KP, Trodden, Volkas (2011); Cyr-Racine, Sigurdson (2012); KP, Pearce, Kusenko (2014)]
Atomic DM with a massive dark photon

Asymmetric DM coupled to a dark photon is multicomponent \((p_D, e_D)\), and possibly atomic \((H_D)\) in much of the parameter space where the dark photon is light enough to mediate sizable (long-range) DM self-interactions

[KP, Pearce, Kusenko (2014)]

- Bound-state formation cannot be ignored.
- The formation of atomic bound states screens the DM self-interaction.
- Force mediator need not be “sufficiently massive” to satisfy constraints.
- Interplay between cosmology and strength of the interactions.
Multi-component DM with different inter- and intra-species interactions

\[ H_D - H_D, \ H_D - p_D, \ H_D - e_D, \ p_D - p_D, \ e_D - e_D, \ p_D - e_D \]

Strong velocity dependence of scattering cross-sections

\[ \sigma_{\text{ion-ion}} \propto v^{-4}, \text{ screened at } \mu_{\text{ion-ion}} v < m_{\gamma_D} \]

\[
\sigma_{H_D - H_D} \approx (\alpha_D \mu_D)^{-2} \left[ b_0 + b_1 \left( \frac{m_{H_D} v^2}{4 \mu_D \alpha_D^2} \right) + b_2 \left( \frac{m_{H_D} v^2}{4 \mu_D \alpha_D^2} \right)^2 \right]^{-1}
\]

(valid away from resonances; \(b_0, b_1, b_2\) : fitting parameters, depend mildly on \(m_p/m_e\))

[Cline, Liu, Moore, Xue (2013)]
Non-monotonic behavior in $\alpha_D$, because of the formation of bound states ($\rightarrow$ no upper limit on $\alpha_D$, or lower limit on $m_{\gamma_D}$).

- Strong velocity dependence of scattering cross-sections allows for ellipticity constraints to be satisfied, while having a sizable effect on small scales.

- Collisionless CDM limits:
  - Large $m_{H_D} \rightarrow$ small number density
  - Large $\alpha_D \rightarrow$ tightly bound atoms
  - Small $\alpha_D \rightarrow$ small interaction
  - Small $m_{\gamma_D} \rightarrow$ atom formation
  - Large $m_{\gamma_D} \rightarrow$ no atoms, ion-ion screening

[KP, Pearce, Kusenko (2014)]
Self-scattering in halos

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[KP, Pearce, Kusenko (2014)]
Self-scattering in halos

- DM in bound states: even massless mediators viable (and very interesting: $v$-dependent scattering)

- If DM mostly ionized, and $m_{\text{DM}} < 500 \text{ GeV} \rightarrow$ sizable mediator mass needed

- Even if DM mostly ionized, very light / massless mediators still good, if $m_{\text{DM}} > 500 \text{ GeV}$

$$\text{ionisation fraction } x_{\text{ion}} = 0.6$$
$$\text{dark proton mass } m_{p_D} = \text{dark electron mass } m_{e_D}$$

[KP, Pearce, Kusenko (2014)]
Indirect detection: $\delta \mathcal{L} = (\varepsilon/2) F_Y F_D$

- **Bound-state formation** in galaxies today from ionized component

  \[ p_{D^+} + e_{D^-} \rightarrow H_D + \gamma_D \]

  \[ \gamma_D \rightarrow e^+ e^- \text{ (for } m_\gamma > 1.022 \text{ MeV)} \]

  [Pearce, KP, Kusenko (2015)]

- **Level transitions** (dark Hydrogen excitations and de-excitations)

  \[ H_D + H_D \rightarrow H_D + H_D^*, \quad H_D^* \rightarrow H_D + \gamma_D, \quad \gamma_D \rightarrow e^+ e^- \]
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\[ H_D + H_D \rightarrow H_D + H_D^*, \quad H_D^* \rightarrow H_D + \gamma_D, \quad \gamma_D \rightarrow e^+ e^- \]
Indirect detection: dark-atom formation in halos

**Bound – state formation:**
\[
\frac{d \Gamma_{BSF}}{d \nu} = \left( \sigma_{BSF} v_{rel} \right) x_{ion}^2 \frac{\rho_{DM}^2}{m_{H_D}^2}
\]

**Annihilation of symmetric DM:**
\[
\frac{d \Gamma_{ann}}{d \nu} = \left( \sigma_{ann} v_{rel} \right) \frac{\rho_{DM}^2}{m_{DM}^2}
\]

Interplay between early universe cosmology and strength of interaction → min and max signal strength

[ Pearce, KP, Kusenko (2015) ]
Indirect detection:
atomic DM vs annihilating DM

atomic DM: \( \delta E = \text{binding energy} \ll m_{H_0} \)

annihilating DM: \( \delta E = 2m_{DM} \)

[Pearce, KP, Kusenko (2015)]
Atomic DM

511 keV line in the Milky Way from dark-atom formation

\[ m_\gamma^D = 2 \text{ MeV}; \] contracted NFW profile (\( \gamma = 1.4 \))

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**Fully Ionized DM**

- Insufficient annihilation in early universe
- No value of \( \sigma_D \) produces signal

**Partially Ionized DM**

- Overproduction of photon continuum

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[Pearce, KP, Kusenko (2015)]
Conclusion

- Symmetric thermal-relic WIMP DM ↔ collisionless CDM
  Asymmetric (thermal relic) DM ↔ self-interacting DM
  independently motivated

- Dark-sector dynamics can be complex. Interplay between cosmology and strength of fundamental interactions determines low-energy phenomenology:
  The early universe regulates any manifestation of DM we may hope to detect today.

- Lots more to think about and to calculate!