Asymmetric Dark Matter & (Self) Interactions

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work w/ Stephen West, James Unwin, & earlier with Lawrence Hall, Matthew McCullough
Dark Matter Genesis?

**Dark matter**

- **WIMPs:** Calculable thermal freeze-out with scale $\nu$
- **FIMPs:** Calculable thermal freeze-in with scale $\nu$
- **Axions:** Mis-alignment or thermal production

**Asymmetric DM & Baryons**

- Sharing
- Co-genesis
Baryons need origin of particle-antiparticle asymmetry

\[ \eta_B = Y_B - Y_{\bar{B}} \]

\[ m_B \eta_B \sim \sin \phi \frac{m^2_M M_{Pl} \Lambda_{QCD}}{\nu^4} \]

CP-violating phase

Usual, unrelated origin of baryons & DM, involving very different physics, makes it hard to understand \( \Omega_{DM}/\Omega_B \approx 4.86 \)

Freeze-out dominates thinking about DM candidates, detection, and LHC phenomenology
Are we being misled?
Alternative: similar physics underlies both $\Omega_B$ and $\Omega_{DM}$

(Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92; Thomas '95; Hooper, JMR, West '04; explosion in last 3yrs esp work of Zurek etal; now many others...)

Baryons: $U(1)_B$  
$u, d, s...$  
$p$ stable  
$\Omega_B \propto m_B \eta_B$

DM: $U(1)_X$  
$X_0, X_1, X_2...$  
$X_0$ stable  
$\Omega_X \propto m_X \eta_X$

At some era

Interactions violate $B$ and $X$ to yield related values for $\eta_B$ and $\eta_X$

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B} \frac{m_X}{m_B}$$
\[
\frac{\Omega_X}{\Omega_B} = \frac{\eta_X m_X}{\eta_B m_B}
\]
only true if X density is determined by the asymmetric part otherwise

\[
\frac{\Omega_X}{\Omega_B} = \frac{Y_X + Y_{\bar{X}}}{Y_B + Y_{\bar{B}}} \frac{m_X}{m_B}
\]

need \[ Y_X + Y_{\bar{X}} = Y_X - Y_{\bar{X}} + \text{small corrections} \]

non-trivial constraint as initially

\[
Y_X + Y_{\bar{X}} = \frac{Y_X - Y_{\bar{X}}}{\epsilon}
\]

where \[ \epsilon \leq \sin(\phi_{eff}) \times \text{loop factor} \] measures CP-violation
Two general categories of theories: “sharing” & “co-generation”

Unspecified primordial generation

\[ \eta_X \sim \eta_B \text{ by sharing} \]

Negligible primordial generation

\[ \eta_X \sim \eta_B \text{ by co-generation} \]

Co-generation is more ambitious: attempts to explain simultaneous origin of B & X asymmetries (if at scale \( \sim \) TeV allowing test at LHC...)}
Sharing:

Assumes presence of some initial asymmetry in (at least) one of B, L & X

A “portal interaction” breaks a combination of B/L & X, such that there is an era when only conserved U(1) is

\[ B - L + X \implies \eta_B : \eta_L : \eta_X = N_1 : N_2 : N_3 \]
Co-generation:

- zero initial asymmetry in B, L & X

“Connector interactions” both break a combination of B/L & X, and lead to generation of asymmetry which is simultaneously shared (further later sharing due to EW anomaly can occur too)
Alternative view (either sharing or co-generation):

- incompatible with standard SUSY Majorana neutralino DM
- changes one or both direct/indirect DM detection

co-generation harder as requires B, X violation & out-of-equilibrium condition (at TeV scale if testable). Requires a new theory of calculable (thermal) DM production....
Must efficiently annihilate away symmetric part to light states

there has to be an efficient $X$-preserving freeze-out process

Three options:

- **direct FO to light SM dof**
  - operators connecting $X$ & SM sectors with strength bounded below

- **direct FO to light dark sector dof**
  - (potentially) new long-range DM interactions

- **FO to dark sector dof which then late decay to SM**
  - late-time energy injection in early universe
direct FO of symm yield to light SM dof

limits from direct detection experiments and monojet searches at Tevatron and LHC are very constraining
Use effective operators to parameterise portal interactions. Some are suppressed by:

- $v$: velocity of
- $q < 0.1 \text{GeV}$ mom’m

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we shall examine CP-violating ops

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### m_q dep’t ops

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### direct detection constrained

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ADM relic density - removal of symmetric component:

\[
\Omega_{\text{DM}} h^2 \simeq 3 \times 10^8 \left( Y_{\text{sym}} + Y_{\text{asym}} \right) \left( \frac{m_{\text{DM}}}{\text{GeV}} \right)
\]

By assumption relic density must be due to the asymmetry, so demand symmetric component <10% of asymmetric part (results relatively insensitive to 0.1% vs 100%)

Yields depend on (presumed known) asymmetry and FO cross section

\[
Y_{\text{DM}} \sim \frac{\eta x}{\exp \left[ \eta x \omega \left( \frac{a}{x_F} + \frac{b}{x^2_F} \right) \right] - 1}
\]

\[
Y_{\text{DM}} \sim \frac{\eta x}{1 - \exp \left[ -\eta x \omega \left( \frac{a}{x_F} + \frac{b}{x^2_F} \right) \right]}
\]

where \( \omega = \frac{4\pi}{\sqrt{90}} m_{\text{DM}} M_{\text{Pl}} \sqrt{g_*} \) and \( \langle \sigma v \rangle = a + \frac{6b}{x} + \cdots \)
Example: relic density requirement on $\frac{m_q \bar{\psi} \psi \bar{q} q}{\Lambda^3}$

$$\hat{O}_S: \frac{m_q}{\Lambda^3} \bar{\psi} \psi \bar{q} q$$

$$a = 0 \quad b = \frac{3 m_X^2}{8 \pi \Lambda^6} \sum_q m_q^2 \left( 1 - \frac{m_q^2}{m_X^2} \right)^{3/2}$$

allowed region is below line
Constraints from direct detection (CRESST, DAMIC, CDMS, XENON100)

\[
\hat{\psi}_s : \frac{m_{\psi}}{\Lambda^3} \bar{\psi} \psi \bar{q} q
\]

allowed region is above coloured lines

ADM in preferred 1-10GeV region excluded with this op
Portal operator \( \frac{m_q}{\Lambda^3} \bar{\psi} \psi \bar{q} q \) is an easy case as direct detection not SD and not v- or q- suppressed

Monojet searches provide complementary constraints on DM with interactions with quarks

(e.g. Bai, Fox, Harnik arXiv:1005.3797)
Constraints on q- or v-suppressed ops

\[ \mathcal{O}_p^q : \frac{1}{N^3} \bar{\psi} \gamma^\mu \psi \bar{q} \gamma^\nu q \]

\[ \mathcal{O}_v^q : \frac{m_q}{N^3} \bar{\psi} \gamma^\mu \psi \bar{q} \gamma^\nu q \]

\[ \mathcal{O}_u^q : \frac{1}{N^3} \bar{\psi} \gamma^\mu \psi \bar{q} \gamma^\nu q \]

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\[ \mathcal{O}_u^q : \frac{1}{N^3} \bar{\psi} \gamma^\mu \psi \bar{q} \gamma^\nu q \]
Constraints on SD operators

\[ \mathcal{O}_1: \frac{1}{\Lambda^2} \overline{\psi} \gamma^\mu \gamma^5 \psi \overline{q} \gamma_\mu \gamma^5 q \]

\[ \mathcal{O}_2: \frac{1}{\Lambda^2} \overline{\psi} \sigma^{\mu \nu} \psi \overline{q} \sigma_{\mu \nu} q \]
Constraints on SI operators

\[
\mathcal{O}_1^\phi: \frac{1}{\Lambda} \phi^i \phi^i q q
\]

\[
\mathcal{O}_2^\phi: \frac{m_q}{\Lambda} \phi^i \phi^i q q
\]

\[
\mathcal{O}_3^\phi: \frac{1}{\Lambda} \bar{\psi} \psi \bar{q} q
\]

\[
\mathcal{O}_4^\phi: \frac{1}{\Lambda} \bar{\psi} \gamma^\mu \psi \gamma_\mu q
\]

\[
\mathcal{O}_5^\phi: \frac{1}{\Lambda} \bar{\psi} \psi \gamma^\mu \gamma_\mu q
\]

Graphs showing constraints on SI operators with different model parameters such as CRESST, DAMIC, XENON 10, CDMS, XENON 100, CMS, and ATLAS.
direct FO of symm yield to light SM dof

limits from direct detection experiments and monojet searches at Tevatron and LHC are very constraining

Main way to avoid these constraints:

Non-minimal flavour structure: e.g. isospin violating or tau-philic, or very special choice of operator...

with ugly exceptions if we want asymmetric DM in natural region $m_X < 10$ GeV then direct FO to SM is disfavoured

eliminating symm yield likely implies new dark-sector dynamics involving further light states
Crucial question

how light?
`Midi’ Mass Mediators

With mediators < few 100 GeV effective operator description breaks-down at LHC and previous results no longer valid

Resonances and mass thresholds are important

Large effects on the monojet limits and relic density calculation

Notably, constraints from monojet limits are greatly relaxed

Direct detection limits are unaffected for mediators >100 MeV as bigger than mom’m transfer & effective op is still good
Example: scalar midi mediator

Consider a scalar mediator with couplings to quarks due to mixing with the SM Higgs $\theta \sim \frac{m_\eta}{m_H}$

$$\mathcal{L} \supset \lambda_X \eta \bar{\psi} \psi + \sum_q (\lambda' \theta y_q) \eta \bar{q} q$$

Monojet constraints relaxed, but direct detection limits remain unless in resonance region
Such midi-mass mediating states logically possible and still marginally allow ADM with some fine-tuning (rather like traditional WIMPs)

However a much more interesting possibility in my opinion is that there are very light states in dark sector, like photon or pion/axion in our sector

\[ \downarrow \]

much richer dark-matter dynamics with astrophysical advantages (and signals)

(also potential signals in direct and indirect detection, and precision particle phys expts)
Light Dark Sector States

This leads to a rich and potentially extremely complicated set of possible consequences.

Here I’ll discuss only the very simplest...

Suppose there exists a single v. light self-conjugate DS state \( Y \) coupling to ADM and which is stable or metastable.

What mass should it have?

Maintaining ADM relation for DM density given symm yield

\[
Y_X + Y_{\bar{X}} = \frac{Y_X - Y_{\bar{X}}}{\epsilon}
\]

\[
\downarrow
\]

\[
m_Y < \frac{\epsilon}{10} m_X
\]
symmetric component annihilates to $Y$ and the coupling $\alpha_X \equiv \frac{\lambda^2}{4\pi}$ must satisfy

Minimum for efficient annihilation for scalar (blue), & derivatively coupled pseudoscalar (red) mediator

(in pseudoscalar case $\lambda \equiv m_x/f$)
Constraints on ADM self interactions

The light state implies elastic & inelastic processes for ADM

Existence of elliptical halos implies average time for $O(1)$ changes to DM velocity is bounded below

$$
\Gamma_{\Delta v \sim v} \simeq \int d^3 v_1 d^3 v_2 f(v_1)f(v_2)n_X \sigma_T v_{\text{rel}} \left( \frac{v_{\text{rel}}^2}{v_0^2} \right)
$$

Galaxy NGC720 constrains the DM momentum transfer cross-section,

$$
\sigma_T \lesssim 4.4 \times 10^{-27} \text{ cm}^2 \left( \frac{m_X}{\text{GeV}} \right)
$$

Lin, Yu, Zurek, arXiv:1111.0293
Constraints on ADM self interactions

For fermion ADM with scalar light state

\[
\sigma_T \simeq \frac{32\pi}{m_\phi^2 m_X^2 v_{\text{rel}}^4} \left[ \alpha_X m_\phi \right]^2 \left( \ln(1 + R^2) - \frac{R^2}{1 + R^2} \right)
\]

\[
R \equiv \frac{m_X v_{\text{rel}}}{m_\phi} \quad \beta \equiv \frac{|V(r \sim m_\phi^{-1})|}{m_X v_{\text{rel}}} = \frac{\alpha m_\phi}{m_X v_{\text{rel}}^2}
\]

upper bound for scalar case

\[
\alpha_X \lesssim 2 \times 10^{-3} \left( \frac{m_\phi}{100 \, \text{MeV}} \right)^2 \left( \frac{5 \, \text{GeV}}{m_X} \right)^{1/2}
\]
Pseudoscalars have similar form, but as derivatively coupled

\[
\sigma^{(a)}_T \simeq 24\pi \left(\frac{27}{16}\right)^2 \frac{1}{m_a^2 m_X^2 v_{\text{rel}}^4} \left[\frac{\alpha_X m_a^3}{f_a^2}\right]^2 \left(\ln(1 + R^2) - \frac{R^2}{1 + R^2} \left(1 + \frac{R^2}{2} - \frac{R^4}{6}\right)\right)
\]

leading to approximate upper bound for pseudoscalar case

\[
\alpha_X \lesssim 20 \left(\frac{10^{-2}}{m_a/f_a}\right)^2 \left(\frac{m_a}{100 \text{ MeV}}\right)^2 \left(\frac{5 \text{ GeV}}{m_X}\right)^{1/2}
\]

Significant tension with annihilation in scalar case, whereas pseudoscalar is quite free due to scattering suppression of \((m_a/f_a)^4\)
Bound states

By emitting a light Y quanta the ADM can form WIMPonium bound states

\[
\sigma_{\text{capture}} \sim \begin{cases} 
\frac{\pi \alpha' \beta^2}{m_X^2 v^2} & \text{for } m_X \beta^2 > m_Y \\
\pi \alpha' \beta^2 & \text{for } m_X \beta^2 < m_Y \\
\frac{\pi \alpha' \beta^2}{(m_X^2 m_Y v)^{2/3}} & 
\end{cases}
\]

Depending on model details there can be further transitions to deeper bound states, or even annihilation of ADM via

\[X^2 O_{S.M}\]
Late-time SM indirect detection signals

with possible unusual morphology on sky
Conclusions

ADM is an exciting, constrained, alternative to WIMPs

Requirement that symmetric component removed leads to model independent constraints

Strongly motivates an extended dark sector, with many potential signals