Asymmetric dark matter

and the Sun

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What is the world made of?

**Only geometrical evidence:**
\[ \Lambda \sim O(H_0^2), \quad H_0 \sim 10^{-42} \text{GeV} \]
… dark energy is inferred from the ‘cosmic sum rule’:
\[ \Omega_m + \Omega_k + \Omega_\Lambda = 1 \]

**No dynamical evidence**
of dark energy, e.g. late ISW effect due to negative pressure, seen yet (@ $>5\sigma$)
… Is dark energy being faked by inhomogeneity?

Baryons (but no antibaryons)
… the stuff we are made of

**Both geometrical and dynamical evidence found**
(assuming GR)
What **should** the world be made of?

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<td>$\Omega_B \sim 10^{-10}$</td>
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|                       |                       |                     |                    | $\Omega_B \sim 0.05$ | cf. observed |

\[
\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_T^2)
\]

‘Freeze-out’ occurs when annihilation rate:

\[
\Gamma = n\sigma v \sim m_N^{3/2}T^{3/2}e^{-m_N/T} \frac{1}{m^2_{\pi}}
\]

becomes comparable to the expansion rate

\[H \sim \sqrt{gT^2} \quad \text{where } g = \# \text{ relativistic d.o.f.}\]

i.e. freeze-out occurs at $T \sim m_N/45$, with:

\[
\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}
\]

so need to invoke an initial asymmetry:

\[
\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}
\]

Should we not call this the ‘baryon disaster’ (cf. ‘WIMP miracle’)?!
Sakharov conditions for baryogenesis:

1. Baryon number violation
2. \(C\) and \(CP\) violation
3. Departure for thermal equilibrium

Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but \(CP\)-violation is too weak (also out-of-equilibrium conditions are not available since the electroweak symmetry breaking phase transition is in fact a ‘cross-over’)

Thus the generation of the observed matter-antimatter asymmetry requires new BSM physics (could be related to neutrino masses … possibly due to violation of lepton number \(\Rightarrow\) leptogenesis)

‘See-saw’: \( \mathcal{L} = \mathcal{L}_{SM} + \lambda^* \bar{\ell}_\alpha \cdot H N_J - \frac{1}{2} N_J^c M_J N^c_J \quad \lambda M^{-1} \lambda^T <H^0>^2 = [m_\nu] \)

\[ \Delta m^2_{atm} = m^2_3 - m^2_2 \approx 2.6 \times 10^{-3}\text{eV}^2 \quad \Delta m^2_\odot = m^2_2 - m^2_1 \approx 7.9 \times 10^{-5}\text{eV}^2 \]
Asymmetric baryonic matter

\[ Y_{\Delta B} = \frac{n_{N}^{eq}(T \gg M_{1})}{s} \sum_{\alpha} \frac{n_{\ell\alpha} - n_{\bar{\ell}\alpha}}{n_{N}} \times \eta_{\alpha} \times C \]
\[ \sim 4 \times 10^{-3} \sum_{\alpha} \epsilon_{\alpha\alpha} \times \eta_{\alpha} \times \frac{1}{3} \]
\[ \sim 10^{-10} \text{ for reasonable parameter values} \]

Any primordial lepton asymmetry (from the out-of-equilibrium decays of the right-handed $N$) would be redistributed by $B+L$ violating processes (which conserve $B-L$) amongst all fermions which couple to the electroweak anomaly.

Although leptogenesis is not directly testable experimentally (unless the lepton number violation occurs as low as the TeV scale), it is an elegant paradigm for the origin of baryons.

... in any case we accept that the only kind of matter which we know certainly exists originated non-thermally in the early universe.
**What *should* the world be made of?**

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<td>R-parity?</td>
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<td>$\Omega_{\text{LSP}} \sim 0.25$</td>
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For (softly broken) **supersymmetry** we have the ‘WIMP miracle’:

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{ cm}^{-3} \text{ s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle_{T=T_f}} \simeq 0.1$$

, since $\langle \sigma_{\text{ann}} v \rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \simeq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

... Also true for generic hidden sector matter - ‘WIMPless miracle’

(Feng & Kumar 2008) since $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$

But why should the abundance of thermal relics be **comparable** to that of baryons which were born *non*-thermally, with $\Omega_{\text{DM}}/\Omega_B \sim 5$?
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<td>Technibaryon?</td>
<td>(walking) Technicolour</td>
<td>$\tau &gt; 10^{18}$ yr (dim-6 OK)</td>
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A new particle would *share* in the $B/L$ asymmetry if it is charged under a new global $U(1)$ symmetry which has a mixed anomaly with the $SU(2)$ gauge symmetry (Barr *et al* 1990) … *this can* explain the ratio of dark to baryonic matter!

For example a TeV mass technibaryon would naturally have (Nussinov 1985):

$$\frac{\rho_{\text{DM}}}{\rho_B} \sim \frac{m_{\text{DM}}}{m_B} \left(\frac{m_{\text{DM}}}{m_B}\right)^{3/2} e^{-m_{\text{DM}}/T_{\text{sphaleron}}} \approx 5$$

For ~5 GeV mass the required abundance is *even* more natural … and there are candidates (Gelmini *et al* 1987, Raby & West 1987, DB Kaplan 1992, Hooper *et al* 2005, Kitano & Low 2005, DE Kaplan *et al* 2009, Kribs *et al* 2009, Frandsen & Sannino 2010, An *et al* 2010, etc) … some with *distinctive collider signatures* (e.g. Bai *et al* 2010, Goodman *et al* 2010)
Nuclear recoil detectors are optimised for heavy WIMPs (motivated by SUSY) and have little sensitivity to low mass particles ($\Rightarrow O(\text{keV})$ recoil energy). Several experiments have recently reported events close to threshold!

A $\sim 5$ GeV dark matter particle may have gone undetected even if its interaction cross-section is as high as $\sim 10^{-39}$ cm$^2$. For spin-dependent interactions the cross-section can be up to $10^{-36}$ cm$^2$. 

Schwetz (talk@IDM2010)

Can get up to $\sim 2 \times 10^{-41} \text{ cm}^2$ spin-independent cross-section through Higgs exchange for an ‘unbaryon’ in walking technicolour (Sannino & Zwicki 2009)
Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_{\chi})^2$, where $\sigma_{nn} \sim 10^{-23} \text{ cm}^2$

... well below the bound of $2 \times 10^{-24} \text{ cm}^2/\text{GeV}$ from the ‘Bullet cluster’
Self-interacting dark matter was invoked (Spergel & Steinhardt 2000) to reduce excessive substructure in simulations of collisionless dark matter ... 

e.g. the Milky Way has only 25 dwarf galaxies, while $\sim 10^5$ are expected
There have been few simulations of *self-interacting* dark matter ... 

Can be tested through observations of cores *vs.* cusps, halo shape *etc*

Presently we *cannot* require that dark matter must have TeV-scale mass, or be collisionless, or very weakly interacting ... or have any annihilation signatures (γ-rays, antiprotons, positrons, neutrinos)!
The Sun has been accreting dark matter particles for $\sim 4.6 \times 10^9$ yr as it orbits around the Galaxy … these will orbit inside affecting energy transport.

The flux of Solar neutrinos is very sensitive to the core temperature and can thus be reduced (Steigman et al 1978, Faulkner et al 1985, Press & Spergel 1985, Gould 1987).
A problem with the standard Solar model

- Asplund, Grevesse & Sauval (2005) have determined new Solar chemical abundances of C, N, O, Ne (‘metals’) using improved 3D hydrodynamical modeling (tested with many surface spectroscopic observations).
- With these new abundances (30-50% lower metallicity), the previous good agreement between the Standard Solar Model & helioseismology is broken.

Could light dark matter particles accreted by the Sun solve this problem? (Villante, talk@TAUP’09, Frandsen & Sarkar 2010)
The particle mass must be \( \sim 5-10 \text{ GeV} \) to have an effect on energy transport (too light and they ‘evaporate’, too heavy and their orbits do not extend out far enough)

Convective zone boundary from helioseismology: \( R_{\text{CZ}}/R_\odot = 0.713 + 0.001 \) … too high (by \( >10\sigma \)) in SSM but can be lowered by the required \( \sim 1\% \) if

\[
(\sigma_{\chi N}/\sigma_\odot)(N_\chi/N_\odot) \gtrsim 10^{-14}, \quad \text{where} \quad \sigma_\odot \equiv (m_N/M_\odot)R_\odot^2 \sim 4 \times 10^{-36} \text{ cm}^2
\]
The abundance of *asymmetric* dark matter is not depleted by annihilation … so grows exponentially (until geometric limit set by Solar radius)

Also self-interactions will *increase* capture rate in the Sun *(Zentner 2009)*

\[
\frac{dN_\chi}{dt} = C_{\chi N} + C_{\chi \chi} N_\chi \ \Rightarrow \ \ N_\chi(t) = \frac{C_{\chi N}}{C_{\chi \chi}} \left(e^{C_{\chi \chi} t} - 1\right)
\]

Self-capture rate: \(C_{\chi \chi} = \sqrt{\frac{3}{2}} \rho_{\text{local}} s_\chi \frac{v^2_{\text{esc}}(R_\odot)}{\bar{v}} \langle \phi \rangle \frac{\text{erf}(\eta)}{\eta}\)

\(\sigma_{\chi N}^{\text{SI}} \sim 10^{-39} \text{ cm}^2\)

\(\sigma_{\chi N}^{\text{SD}} \sim 10^{-36} \text{ cm}^2\)

‘black disk’ limit

*(Frandsen & Sarkar 2010)*
ADM will transport heat outward in the Sun:
\[ L_x \sim 4 \times 10^{12} L_\odot \frac{N_x}{N_\odot} \frac{\sigma_x}{\sigma_\odot} \sqrt{\frac{m_N}{m_x}} \]

... thus affecting the effective opacity:
\[
\delta L(r) \sim -\delta \kappa r \gamma (r) \equiv -\frac{\kappa_x (r)}{\kappa r \gamma (r)}
\]

(Bottino et al 2002)

According to the ‘Linear Solar model’ (Villante & Ricci 2009) a ~10% reduction of the opacity in the core lowers the convective boundary by ~0.7% so will (largely) restore agreement with helioseismology.

Modification of the luminosity profile will also reduce neutrino fluxes:
\[
\delta \Phi_B = -17\%, \quad \delta \Phi_{Be} = -6.7\%,
\]
\[
\delta \Phi_N = -10\%, \quad \delta \Phi_O = -14\%
\]

... testable by Borexino & SNO+

(Frandsen & Sarkar 2010)
Forthcoming precision measurements of Solar neutrinos by Borexino and SNO can test the model.

SNO: $\Phi(^{8}\text{B}) = 5.18 \pm 0.29 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$; Borexino: $\Phi(^{7}\text{Be}) = 5.18 \pm 0.51 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$

Measurement of $^{13}\text{N}$ and $^{15}\text{O}$ fluxes by SNO will provide additional constraint, but it may be hard to distinguish between effects of metallicity and dark matter.
Using the ‘GENEVA code’, Taoso et al (2010) confirm that the effect on energy transport within the Sun is negligibly small for annihilating dark matter… but can be significant for asymmetric dark matter!

However they (also Cumberbatch et al 2010) obtain a smaller effect than we do from the analytic ‘linear Solar model’… this is under investigation
Summary

Asymmetric dark matter is motivated by the observed asymmetry of baryonic matter and the desire to explain why $\Omega_{DM}/\Omega_B \sim O(1)$

- ~ GeV scale ADM can arise from hidden/mirror/unbaryon sectors
  - Such particles are naturally self-interacting
  ... may solve problems of collisionless CDM on galactic scales

- Direct detection will require $O(\text{keV})$ threshold recoil detectors
  ... efforts already under way using Xenon, CCDs etc
  - Interesting signatures at LHC (‘monojets’ …)

➤ Large capture rate in Sun ⇒ may solve ‘Solar composition problem’
  ... magnitude of effect is presently disputed (under study)

➤ Can probe through precision measurements of Solar neutrino fluxes
  ... expect $^7\text{Be}$ data soon from Borexino, later $^{13}\text{N} + ^{15}\text{O}$ from SNO+

Interesting alternative to dark matter in supersymmetry ... experiment will tell!