Discovering dark matter

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What is the world made of?

Mainly 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’: \[ \Omega_m + \Omega_k + \Omega_\Lambda = 1 \]
(assuming a homogeneous universe)

Baryons (but no anti-baryons)

Both geometrical and dynamical evidence for dark matter (if GR is valid)

Both the baryon asymmetry and dark matter require new physics beyond the Standard \[ SU(3)_c \times SU(2)_L \times U(1)_Y \] Model
... dark energy is even more mysterious (but still lacks compelling dynamical evidence)
What can astrophysics tell us about dark matter interactions?

The ‘Bullet Cluster’ is often cited as evidence that dark matter is \textit{collisionless} ... in actual fact it sets a rather \textit{weak} limit on self-interactions: $\sigma \leq 2 \times 10^{-24}$ cm$^2$/GeV

Moreover it poses a \textit{challenge} for $\Lambda$CDM cosmology: why is the relative velocity so high (>3000 km/s on a scale of 5 Mpc)?

Nine other colliding clusters have been found ... the odds are \textit{tiny} in a Gaussian density field!

But in Abell 520, the inferred dark matter concentration is partly \textit{coincident} with the X-ray emitting gas implying that DM is \textit{self-interacting} with: $\sigma \sim 8 \pm 2 \times 10^{-24}$ cm$^2$/GeV!

This result is contested ... in any case the separation between DM and galaxies will be \textit{time-dependent} and sensitive to whether the self-interactions are contact or long-range (Frandsen \textit{et al}, 1308.3419) ... so data from gravitational lensing can discriminate between particle candidates for dark matter
We can get an idea of what the Milky Way dark matter halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter.

Our galaxy is meant to have resulted from the merger of smaller structures, tidal stripping, baryonic infall, disk formation *et cetera* over billions of years ... not yet fully understood!
What should the world be made of?

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We have a good theoretical explanation for why baryons are massive and stable.

We understand the dynamics of QCD ... and can calculate the mass spectrum.
Nevertheless we get the cosmology of baryons badly wrong!

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

Chemical equilibrium is maintained as long as the annihilation rate exceeds the Hubble expansion rate

‘Freeze-out’ occurs when annihilation rate:

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

becomes comparable to the expansion rate

\[ H \sim \sqrt{\frac{gT^2}{M_P}} \text{ where } g \sim \# \text{ relativistic species} \]

i.e. ‘freeze-out’ occurs at \( T \sim m_N/45 \), with:

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

However the observed ratio is \( 6\times10^9 \) times bigger for baryons, and there seem to be no antibaryons, so we must invoke an initial baryon asymmetry:

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

Why do we not call this the ‘baryon disaster’? (cf. ‘WIMP miracle’!)
To make the baryon asymmetry requires a lot of new physics:

- **B-number violation**
- **CP violation**
- Departure for thermal equilibrium

The SM does allow *B*-number violation (through non-perturbative sphaleron-mediated – processes) ... but *CP*-violation is *too weak* and $SU(2)_L \times U(1)_Y$ breaking is a ‘cross-over’ *(not out-of-equilibrium)*

Hence the generation of the observed matter-antimatter asymmetry requires new BSM physics *(could be related to neutrino mass if this arises from violation of lepton number $\rightarrow$ leptogenesis)*

‘See-saw’: $\mathcal{L} = \mathcal{L}_{SM} + \lambda^* \ell_\alpha \cdot H N_{J} - \frac{1}{2} N_{J} M_{J} N_{J}^{C}$ $\lambda M^{-1} \lambda^T \langle H^0 \rangle^2 = [m_\nu]$

\[\Delta m^2_{atm} = m_3^2 - m_2^2 \approx 2.6 \times 10^{-3} \text{eV}^2 \quad \Delta m^2_{\odot} = m_2^2 - m_1^2 \approx 7.9 \times 10^{-5} \text{eV}^2\]
Asymmetric baryonic matter

Any primordial lepton asymmetry (e.g. from out-of-equilibrium decays of the right-handed \( N \)) would be redistributed by \( B+L \) violating processes in the SM (which conserve \( B-L \)) amongst all fermions – in particular **baryons** - which couple to the electroweak anomaly

Although **leptogenesis** may never be directly testable, evidence for a **Majorana** neutrino mass from observation of neutrinoless \( \beta\beta \)-decay would provide powerful support for the idea

... in any case we accept that the only kind of matter which we are certain **exists**, originated **non-thermally** in the early universe

\[
\partial_\mu j_\mu^i = \partial_\mu (\bar{\psi}^{i} \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}_{a\mu\nu}^i
\]

(Barr, Chivukula, Farhi, PLB 241:387,1990)
Although vastly overabundant compared to the natural expectation, baryons cannot close the universe (BBN + CMB concordance). … the dark matter must therefore be mainly non-baryonic.
The Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model (viewed as an effective field theory up to some high energy cut-off scale $M$) accurately describes all microphysics!

$$+ M^4 + \left( M^2 \Phi^2 \right) \left( m^2_H \simeq \frac{h_i^2}{16\pi^2} \int_0^M dk^2 = \frac{h_i^2}{16\pi^2} M^2 \right)$$

\text{super-renormalisable}

$$\mathcal{L}_{\text{eff}} = F^2 + \bar{\Psi} \not{D} \Psi + \bar{\Psi} \Psi \Phi + (D\Phi)^2 + \Phi^2$$

\text{renormalisable}

$$+ \frac{\bar{\Psi} \Psi \Phi \Phi}{M} + \frac{\bar{\Psi} \Psi \bar{\Psi} \Psi}{M^2} + \ldots$$

\text{non-renormalisable}

New physics beyond the SM $\Rightarrow$ non-renormalisable operators suppressed by $M^n$ which ‘decouple’ as $M \rightarrow M_P (\ldots$ so neutrino mass is small, proton decay is slow etc)

But as $M$ is raised, the effects of the super-renormalisable operators are exacerbated

One solution for Higgs mass divergence $\rightarrow$ ‘softly broken’ supersymmetry at $M \sim 1$ TeV

This provides new possibilities for baryogenesis as well as a good candidate for dark matter – the lightest supersymmetric particle (typically the neutralino $\chi$), if it is cosmologically stable because of a conserved quantum number ($R$-parity)

This has been the target of most dark matter searches, whether using nuclear recoil detectors or looking for cosmic annihilation products, or missing $E_T$ signals at colliders
### What should the world be made of?

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\[ L_{\text{eff}} \supset M_A A_\mu A^\mu + m_f \bar{f}_L f_R + m_H^2 |H|^2 \]

For (softly broken) **supersymmetry** we have the ‘WIMP miracle’:

\[ \Omega_{\chi} h^2 \sim \frac{3 \times 10^{-27} \text{cm}^{-3} \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle_{T=T_f}} \sim 0.1 \quad \text{since} \quad \langle \sigma_{\text{ann}} v \rangle \sim \frac{g_X^4}{16\pi^2m_X^2} \approx 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \]

But why should a **thermal** relic have an abundance comparable to non thermal relic baryons?
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(GMSB) Hidden sector matter also provides the ‘WIMPless miracle’ (Feng & Kumar, 0803.4196)

... because: $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$

Such dark matter can have any mass: $\sim$0.1 GeV $\rightarrow$ $\sim$few TeV

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{cm}^{-3} \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle_{T=T_f}} \approx 0.1$$, since $\langle \sigma_{\text{ann}} v \rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$

But why should a thermal relic have an abundance comparable to non-thermal relic baryons?
Summary of CMS SUSY Results* in SMS framework

But LHTC sees no such particles!

CMS Preliminary

For decays with intermediate mass,
\[ m_{\text{intermediate}} = x \cdot m_{\text{mother}} + (1-x) \cdot m_{\text{LSP}} \]

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit
A new particle can naturally *share* in the $B/L$ asymmetry if it couples to the $W$ ... linking dark to baryonic matter!

For example a $O(\text{TeV})$ mass *technibaryon* can be the dark matter (Nussinov 1985) ... another possibility is a $\sim 6$ GeV mass *‘dark baryon’* in a *hidden sector* (Gelmini, Hall & Lin 1986, Kaplan 1992): $\Omega_\chi = (m_\chi N_\chi / m_B N_B) \Omega_B$.

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<td>$\Omega_{\text{TB}} \sim 0.3$</td>
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ATLAS Exotics Searches* - 95% CL Exclusion

ATLAS Preliminary

$\int L \, dt = (1.0 - 20.3) \, fb^{-1}$
$\sqrt{s} = 7, 8$ TeV

But LHC sees no such particles either!
Why may we not have seen these particles yet?

$S_1$ States (constituents) carry weak charges and are connected to sphalerons

$S_2$ States are SM singlets (in a hidden sector/hidden valley) but directly connected to the $S_1$ sector (with scale separation – TeV $\rightarrow$ GeV – because of different $\beta$-function)

$\text{TB} \rightarrow \chi + X$ is in equilibrium until $T \lesssim T_{\text{sph}}$, then $\chi$ decouples and becomes DM

The $S_1$ states do couple to the SM (so should show up at LHC14!)

Frandsen, Sarkar & Schmidt-Hoberg, 1103.4350
Axion dark matter

\[ \mathcal{L}_{\text{eff}} = M^4 + M^2 \Phi^2 + (D\Phi)^2 + \bar{\Psi} iD\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2 + \bar{\Psi}\Phi\Phi + \bar{\Psi}\Psi\bar{\Psi}\Psi + \ldots \]

The SM admits a term which would lead to \( CP \) violation in strong interactions, hence an (unobserved) electric dipole moment for neutrons → requires \( \theta_{QCD} < 10^{-9} \)

To achieve this without fine-tuning, \( \theta_{QCD} \) must be made a dynamical parameter, through the introduction of a new \( U(1)_{\text{Peccei-Quinn}} \) symmetry which must be broken ... the resulting (pseudo) Nambu-Goldstone boson is the axion which acquires a small mass through its mixing with the pion (the pNGB of QCD): \( m_a = m_\pi (f_\pi/f_{PQ}) \)

The coherent oscillations of relic axions contain energy density that behaves like CDM with \( \Omega_a h^2 \sim 10^{11} \) GeV/\( f_{PQ} \) ... however the natural P-Q scale is probably \( f_{PQ} \sim 10^{18} \) GeV

Hence axion dark matter would typically need to be significantly diluted i.e. its relic abundance is not predictable (or seek anthropic explanation for why \( \theta_{QCD} \) is small?)
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<th>Stability ensured?</th>
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<tr>
<td>$\Lambda_{\text{hidden sector}} \sim (\Lambda_F M_P)^{1/2}$</td>
<td>Crypton? hidden valley?</td>
<td>Discrete (very model-dependent)</td>
<td>$\tau \geq 10^{18} \text{ yr}$</td>
<td>Varying gravitational field during inflation</td>
<td>$\Omega_X \sim 0.3$</td>
</tr>
<tr>
<td>$\Lambda_{\text{see-saw}} \sim \Lambda_{\text{Fermi}}^2 / \Lambda_{\text{B-L}}$</td>
<td>Neutrinos</td>
<td>Lepton number</td>
<td>Stable</td>
<td>Thermal (abundance $\sim$ CMB photons)</td>
<td>$\Omega_\nu &gt; 0.003$</td>
</tr>
<tr>
<td>$M_{\text{string}} / M_{\text{planck}}$</td>
<td>? Axions</td>
<td>?</td>
<td>?</td>
<td>Field oscillations</td>
<td>$\Omega_a \gg 1!$</td>
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No definite indication from theory...
Detecting dark matter particles

Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Direct
Detection

Indirect
Detection

Particle
Colliders

Astrophysical
Probes

Snowmass CF1 WG summary, 1310.8327
A passing dark matter particle orbiting in the Galaxy (at \( \sim 300 \text{ km/s} \)) can scatter off a nucleus in an underground detector ... the expected rate is very low (\(< < 1 \text{ event/kg/yr}\))

The recoil is detected via the ionization (charge), scintillation (light), and sound (phonons) \( \rightarrow \) heat

Experiments usually measure more than one channel to discriminate against the much bigger electron recoil background

(Very different techniques required to detect axions)
For ~25 years there has been a world-wide race on to detect dark matter!

Several claims for putative signals have apparently been ruled out by more sensitive experiments … but are we making a fair comparison?
There are many ambiguities in interpreting the measured recoil rate:

\[
\frac{dR}{dE_R}(E_R, t) = M_{\text{tar}} \frac{\rho \chi}{2 m \mu^2} \left( \frac{f_p Z + f_n (A - Z)}{f_n^2} \right)^2 \sigma_n \int_{v_{\\text{min}}}^{\infty} \frac{f_{\text{local}}(\vec{v}, t)}{v} \ d^3v
\]

- Dark matter may interact \textit{differently} with neutrons and protons (Giulani, hep-ph/0504157) if the mediator is a (new) vector boson, so e.g. the events seen by CDMS-Si can be consistent with the upper limits set by XENON100 or LUX

- Moreover different experiments are sensitive to different regions of the (uncertain) dark matter velocity distribution, hence apparently inconsistent results (e.g. CoGeNT and CRESST) can be reconciled by departing from the \textit{assumed} isotropic Maxwellian form (Fox \textit{et al}, 1011.1915, Frandsen \textit{et al}, 1111.0292, Del Nobile \textit{et al}, 1306.5273)

- Then there are experimental uncertainties (efficiencies, energy resolution, instrumental backgrounds) as well as uncertainties in translating measured energies into recoil energies (channelling, quenching), uncertain nuclear form factors ...

\textbf{No single} experiment can either confirm or rule out dark matter (... also not a good strategy to look just under the supersymmetric lamp post!)
Many techniques for indirect detection ... and many claims!

The PAMELA/AMS-02 ‘excess’ (e⁺), WMAP/Planck ‘haze’ (radio), Fermi ‘bubbles’ + GC ‘excess’ + 130 GeV line (all γ-ray) ... have all been ascribed to dark matter annihilations.

These probe dark matter elsewhere in the Galaxy so complement direct detection experiments ... but we are just beginning to understand the astrophysical backgrounds.
Prospects are good however for probing down to the expected annihilation signal for a thermal relic with Fermi and CTA!

Moreover low energy extensions of IceCube (DeepCore, PINGU) will improve the sensitivity for detecting neutrinos from dark matter trapped in the Sun
However these bounds require the scale $\Lambda$ of the effective operator to exceed $\sim 0.7$ TeV, while perturbative unitarity requires $g_q, g_\chi < \sqrt{4\pi}$ i.e. $m_R < 2$ TeV ... so for higher energy collisions cannot rely on effective operator description (Fox et al, 1203.1662)

NB: For scalar-mediated processes, heavy quark loops can significantly enhance the monojet cross-section (Haisch, Kahlhoefer, Unwin, 1208.4605) – very sensitive probe!

‘Monojet’ events at colliders directly measure the coupling of dark matter to SM particles, e.g.

$$\mathcal{L}_{\chi}^{\text{eff}} = \frac{1}{\Lambda^2} \bar{\chi} \gamma_\mu \chi \gamma^\mu q$$

$$\rightarrow \sigma_p^{\text{SI}} = \frac{f^2 \mu_{\chi n}^2}{\pi \Lambda^4}, \text{ where } f = 3 \text{ for } g_u = g_d$$

$$\Lambda = \frac{m_R}{\sqrt{g_q g_\chi}}$$

$$\rightarrow \sigma (j + \text{MET}) \sim 1/\Lambda^4 \sim \sigma_p^{\text{SI}}$$
Summary

Experimental situation reminiscent of searches in the ’80s for temperature fluctuations in the CMB…

... there were clear theoretical predictions but only upper limits on detection (causing near crisis for theory).

Finally breakthrough in 1992 that transformed cosmology!

Theoretical expectations for dark matter are not as clear but there are several complementary experimental approaches and there has been impressive recent progress.

There are bound to be false alarms but it is a reasonable expectation that the nature of dark matter will soon be determined experimentally.