Identifying the Nature of Dark Matter: What does it take?

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WIMPs?
SUSY?
extra dimensions?
axions?
...
What do we know about Dark Matter?

- Dominates the density of gravitationally attracting matter in the Universe.
- Otherwise weakly interacting - if it interacts at all.
- Stable (or decays with a lifetime >> age of the Universe).
- Mostly cold (non-relativistic/possibly massive).

Nothing in the Standard Model of Particle Physics fits this description.
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Dominates the density of gravitationally attracting matter in the Universe.

Astrophysical observations on the scale of galaxies, clusters and the Universe point to the dominance of dark matter.

What is the density of Dark Matter?

- On average, equivalent to $\sim 1$ H atom per $\text{m}^3$.
- Locally, equivalent to $\sim 0.3$ H atom per $\text{cm}^3$. 

[Diagram showing the relative densities of Ordinary Matter, Dark Matter, and Dark Energy]
Mostly cold (nonrelativistic $\Rightarrow$ massive?).

$2048^3 = 8$ billion DM "particles"
Mass resolution $\sim 10^8 \text{M}_\text{sun}$
$\sim 6$M CPU-hours

Hot dark matter would wipe out density fluctuations.
# A Cross Section ($\sigma$) Cheat Sheet

<table>
<thead>
<tr>
<th>Size of Interactions</th>
<th>Equivalent Units</th>
<th>Cross Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 barn</td>
<td>10^{-24} cm²</td>
<td>(10 fm)^2</td>
<td>nuclear</td>
</tr>
<tr>
<td>1 pb</td>
<td>10^{-36} cm²</td>
<td>weak</td>
<td></td>
</tr>
<tr>
<td>1 fb</td>
<td>10^{-39} cm²</td>
<td>ultra-weak</td>
<td></td>
</tr>
<tr>
<td>1 zeptobarn</td>
<td>10^{-45} cm²</td>
<td>ultra-ultra-weak</td>
<td></td>
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</tbody>
</table>

Size of LHC data sample: 1 event per fb of cross section or 1 fb^{-1}
The Relic Dark Matter Density
(~22%)
and
The “WIMP Miracle”

WIMP = Weakly Interacting, Massive Particles
Using the above relations \( H = 1.66 g^2 T^2 / \text{mpl} \) and the freezeout condition \( r = Y_{\text{eq}}(G^2) \), we find \( n_{\mathcal{X}}^0 = n_{\mathcal{X}} f + 1001 (m/\text{GeV})^2 (A/10^{-27} \text{cm}^3 \text{s}^{-1}) \), \( n_{\mathcal{X}}^0 = 10^{-9} \text{cm}^{-3} \) today.

The current entropy density is \( S = 4000 \text{cm}^{-3} \), and the critical density today is \( \rho_{\text{crit}} = 10^{-5} h^2 \text{GeV cm}^{-3} \), where \( h \) is the Hubble constant in units of \( 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \), so the present mass density in units of the critical density is given by \( \rho_{\text{crit}} = m_X n_{\mathcal{X}} / \rho_{\text{crit}} (3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}) \). \( (3.4) \)

The result is independent of the mass of the WIMP (except for logarithmic corrections), and is inversely proportional to its annihilation cross section.

Fig. 4 shows numerical solutions to the Boltzmann equation. The equilibrium (solid line) and actual (dashed lines) abundances per comoving volume are plotted as a function of \( x = m_{\mathcal{X}} / T_0 \).

Fractional thermal relic density

\[ \approx 0.2 \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

Non-relativistic \( \Rightarrow \sigma(\mathcal{X} \rightarrow \text{SM SM}) \sim \sigma_{\text{weak}} \)

for \( m_{\mathcal{X}} \sim (10 - 1000) \text{ GeV} \)

Figure from Jungman, Kamionkowski, Griest (Phys. Rep. 1996)
In theories beyond the Standard Model, we often find candidates for Dark Matter...

- Characterize candidates according to their
  - mass
  - any SM electroweak interactions?
  - spin?
  - mechanism for stabilizing the DM candidate (e.g., conserved quantum number)
A Popular Model: Supersymmetry

* Phenomenologically viable models of SUSY usually include a conserved quantum number (“R parity”) ⇒
  * insures lightest super-partner is stable and could be DM.

* Other merits of SUSY:
  * Solution to “hierarchy problem” of masses
  * Unification of strong, weak and EM interactions
Each Standard Model particle has a “Super Partner” of the same mass, different spin: squarks and sleptons; gauginos

Supersymmetry is obviously broken...

* ... but if it is broken ‘softly’, masses of superpartners separate while interactions are still determined by supersymmetry.

* Although there are many (unknown) SUSY parameters, SUSY inherits an enormous structure from the Standard Model.

⇒ Many rates can be calculated in SUSY in terms of the masses of the superpartners.
Other candidates for Dark Matter

\( \sim \sigma_{EW} \)

\( \sim 10^{35} !! \)

\( \sim \left( \frac{m_W}{M_P} \right)^2 \sigma_{EW} \)

Detecting \textbf{WIMP} Interactions with \textbf{SM} Particles

\textbf{Direct Detection}

\textbf{Indirect Detection}

\textbf{Production}

CDMS, CoGeNT in Sudan Mine

\textbf{Fermi Gamma-ray Space Telescope}

ATLAS, LHC
Direct Detection

- local WIMP density: \( \sim 0.3 \text{ GeV/cm}^3 \)
- WIMP-nucleon cross section
- WIMP-nucleus reduced mass (minimized when \( m_{\text{nuc}} = m_\chi \))

\[
\frac{dN}{dE_{\text{recoil}}} = \frac{\sigma \rho_\chi}{2m_\chi \mu^2} \int_{v_{\text{min}}}^{v_{\text{esc}}} f(v) dv
\]

- minimum WIMP velocity able to generate recoil energy \( E_{\text{recoil}} \)
- local escape velocity: \( \sim 550 \text{ km/s} \)
- nuclear form factor
- local relative velocity distribution of WIMPS (assumed to be Maxwellian with \( v_0 \sim 220 \text{ km/s} \))
- assumes spin-independent cross section

(varies annually by \( \sim \pm 6\% \))
Example: Germanium detector

(≤10 kg running now)

\[ m_X = 50 \text{ GeV} \]
\[ m_X = 100 \text{ GeV} \]
\[ m_X = 200 \text{ GeV} \]

\[ m_X = 50, 100, 200 \text{ GeV} \]

exponential (e.g., background)

A. Green (2008), arXiv:0805.1704
Example: Germanium detector; $m_X = 100$ GeV

$\frac{dR}{dE_R} \times q^2$

C. McCabe (2010), arXiv:1005.0579
Range of Sensitivity

WIMP-nucleon cross section (cm$^2$)

- Cross section too low...
- $E_{\text{recoil}}$ too low...
- No sensitivity
- Sensitive to WIMPs (exclude or ‘discover’)

$m_{\chi}$ high $\iff$ number density low...

$m_{\chi}$ (GeV)
Direct Detection Experiments
(currently running or under construction)

**Non-directional:**
- ArDM
- CDMS
- CoGeNT
- COUPP
- CRESST
- DAMA/LIBRA
- DarkSide
- EDELWEISS
- LUX
- MiniCLEAN
- PICASSO
- WArP
- XENON100
- XMASS
- ZEPLIN-III
- ...

**Directional:**
- DRIFT
- DMTPC
- NEWAGE
- MIMAC
- ...

**Requirements:**
- Large Mass
- (currently ≤10 kg for solids, ~100 kg for liquids)
- Long exposure times (years).
- Highly pure materials (low radioactivity).
- Deep underground or under a mountain.
- Possibly cryogenic.
Annual modulation of ±3% in direct detection signal expected.

DAMA/LIBRA => Annual modulation in event rate is observed, over many years.
Search for an Annual Modulation in a p-type Point Contact Germanium Dark Matter Detector
CoGeNT Collaboration


“In addition to the basic estimators presented here, time-stamped CoGeNT data are available by request. These can be used not only for alternative analyses of significance, etc., but also to investigate non-cosmological effects that might generate this modulation and by extension that observed by DAMA/LIBRA.”
Fit performed by Matt Bellis, recently at Stanford University, now at Northern Illinois University.
Unbinned extended maximum likelihood fit to energy and time, using RooFit

Total = 10 cosmogenics + flat (in energy) + exponential (in energy)
CDMS Detector

Illustration: Alan Stonebraker
CRESST Collaboration (CaWO$_4$ crystal detectors)
Data from one of eight modules:

- Oxygen recoil band
- Tungsten recoil band
- Acceptance region
- Lead recoil band
- α band
- e + γ background (internal contamination of crystals)

Contamination from $^{210}$Po $\rightarrow$ $^{206}$Pb + α

G. Angloher et al. (CRESST, 2011), arXiv:1109.0702
Assumptions: $\rho_{\text{DM}} = 0.3$ GeV/cm$^3$; elastic, spin-independent cross section; Maxwellian velocity distribution; $v_0 = 220$ km/s; $v_{\text{esc}} = 544$ km/s.
Anomalies in Direct Detection?

Disentangling the results:

- Are backgrounds understood, including potential annual modulations?
- Sensitivity to local density and velocity distribution?
- Sensitivity to assumptions about nature of interaction?
- Multi-component dark matter?

The way forward in Direct Detection of WIMPS?

- Understand backgrounds => Collaborative effort. (Share data and tools.)
- Build more massive detectors => Collaborative effort.
- Develop high-density directional sensitivity => new technologies.
Production of Dark Matter

Missing Energy $\Rightarrow$ Dark Matter?

SM $\Rightarrow$ Dark Matter?

WIMP

WIMP

Missing Energy $\Rightarrow$ Dark Matter?
**Theory:**

CMSSM = Constrained Minimal Supersymmetric extension of the Standard Model

**Experiment:**

CMS = Compact Muon Solenoidal

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Search Techniques

Favored Region (2008)

Inputs: $g_\mu - 2$, $\Omega_{CDM}$, electroweak measurements, rare $B$ decays.

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CMS, 1.14 fb⁻¹, $\sqrt{s} = 7$ TeV

95% CL limits:

- Observed Limit (NLO), CL_s
- Median Expected Limit ± 1σ

$\tan \beta = 10$, $A_0 = 0$ GeV, $m_1/2 > 0$

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arXiv:0808.4128

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arXiv:1109.2352
**Theory:**
CMSSM = Constrained Minimal Supersymmetric extension of the Standard Model

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**Predicted Region of LHC Sensitivity**

- $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$
- $1/fb$, 14 TeV
- jets + MET (CMS)
- 0 lepton + 4 jets (ATLAS)
- 1 lepton + 4 jets (ATLAS)
- SS $2\mu$ (CMS)
- Higgs ($2/fb$) (CMS)

Full CMSSM parameter space
- 68% C.L.
- 95% C.L.

Inputs:
- $g_\mu - 2$, $\Omega_{CDM}$, electroweak measurements, rare $B$ decays.

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**Favored Region 2008**

Inputs: $g_\mu - 2$, $\Omega_{CDM}$, electroweak measurements, rare $B$ decays.

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**Favored Region 2011**

Inputs: $g_\mu - 2$, $\Omega_{CDM}$, electroweak measurements, rare $B$ decays, LHC searches, XENON100 direct search.

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O. Buchmueller et al. (2011), arXiv:1110.3568

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Indirect Detection

Neutral particles (γ and ν) have advantage of pointing back to the source.

Antiparticles (e^+, p, D) could have higher signal to background.
PAMELA: excess positrons?

**Prediction for diffuse secondary production**
(Moskalenko & Strong 1998)

Possible explanations:
* dark matter -- but why no excess in other antiparticles? Also, rate too high for DM annihilation?
* primary astrophysical sources?
* nonstandard secondary production?
* ???

See review by T. Porter, R. Johnson, P. Graham, arXiv:1104.2836
Also excess in combined e+/e-?
Fermi used Earth’s magnetic field to distinguish $e^+$ from $e^-$.
How about gamma rays?

- Look for sources in regions of high dark-matter density and low expected backgrounds:
  - the Galactic Center (“Hell’s Kitchen” of astrophysical processes);
  - clusters of galaxies;
  - dwarf spheroidal satellite galaxies of the Milky Way: high ratio of DM/regular matter ⇒ potentially high signal to background.

SIX interconnected scientific communities needed to address
“What is the nature of Dark Matter?”

- Astrophysical measurements of dark matter distribution.
  (Abell 2218 - HST image)

- Computational modeling of structure formation.
  (Via Lactea Simulation Project)

- Direct detection of dark matter.
  (CDMS detector illustration: Alan Stonebraker)

- Indirect detection of dark matter annihilations or decays.
  (Fermi Gamma-ray Space Telescope Two-Year Data)

- Accelerator-based searches for dark matter production.
  (ATLAS, CERN)

- Theories for dark matter candidates.
  - WIMPs?
  - SUSY?
  - extra dimensions?
  - axions?
  - . . .
Getting out from under the lamp-post...

1) Detect axion dark matter with molecular interferometry?
   ✴ Can technology from a different discipline (AMO) be brought to bear on a technically challenging new idea with extremely high potential payoff.

2) Sensitivity to dark matter in the MeV mass scale?
   ✴ Need to push the electron-recoil energy threshold down by ~two orders of magnitude. Convert charge signal to thermal signal at high bias voltages? (Luke effect)
Where to go from here?

1. No observed signal is more straightforward to interpret than a signal in direct or indirect detection, or the LHC.

2. Need all three legs of “three-legged stool”:
   - Direct detection
   - Indirect detection
   - Production

   ... plus cross braces!

3. Be careful about looking only under the lamp post...

4. Shared data and tools will lead to faster progress.