(Direct) Dark Matter Searches and (some) Implications for Theory

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The cosmic Matter Balance

- dark matter: 26.8%
- something invisible in addition to CvB
- H & He: gas 4%
- stars: 0.8%
- radiation: 0.005%
- chemical elements: (not H & He) 0.025%
- neutrinos = CvB: 0.17%
- dark energy: 68.3%

Many options/questions:
- one or more components?
- gravity or new particles?
- which particle(s)?
- DM+new unstable particles
- ...

M. Lindner, MPIK
Competing Dark Matter Directions

Gravity

**MOND**
a simple one scale modification → fails badly

**Other new GR modifications**
or
a suitable population (mass, number) of black holes

Particles

**BSM physics motivated by SM problems**
- WIMPs (neutralinos)
- axions
- sterile ν’s
- ...

**Models with correct abundance**
- WIMPs
- dark photons
- ALPs
- other new particles

**WIMPs combine both aspects in an attractive way: BSM + abundance**
Hunting WIMPS in different Ways

known Standard Model (SM) particles interact with WIMPs: assumptions…
indirect detection

LHC may detect new particles, but is it DM (lifetime, abundance)?
So far nothing seen…
  ➔ impact on theory…
  ➔ SUSY ➔ higher scale
  ➔ other SB motivated WIMPs
  ➔ new ideas/candidates

colliders

FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…
astronomical uncertainties…
  ➔ is the signal without doubt from DM?
keV lines ➔ atomic physics

direct detection

WIMP wind : 220km/s from Cygnus

  ➔ modelling
  ➔ rare event backgrounds
Generic WIMP Cross Section

• Quantum mechanics: wavelength $\lambda \sim 1/$mass

  “size = area” of a particle: $\pi \lambda^2 = \pi/m^2$

  $\Rightarrow$ cross section: area $\times$ coupling strength

  $\sigma \sim O(0.001-1.0)^2 \cdot g_s^2 \cdot \pi/m^2$ or tuning, symmetry, ...

  - model parameters
  - some weak coupling
  - area

  $\sigma \sim 10^{-42} - 10^{-48}$ cm$^2$

• known DM abundance

  $\Rightarrow$ WIMP flux $\Rightarrow$ known rate @direct detection

  $\Rightarrow$ generic WIMP range $\leftrightarrow$ find it or exclude WIMPs
Pushing into new Territory

- solid state electron recoil
- solid state nuclear recoil
- liquid noble gas experiments
  - growing sensitivity

vanilla WIMP
The XENON Dark Matter Program

The XENON program at Gran Sasso, Italy (3600 mwe)

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T &amp; XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>2005-2007</td>
<td>2008-2016</td>
<td>2012-2018</td>
</tr>
<tr>
<td><strong>Total mass</strong></td>
<td>25 kg</td>
<td>161 kg</td>
<td>3200 kg</td>
</tr>
<tr>
<td><strong>Drift length</strong></td>
<td>15 cm</td>
<td>30 cm</td>
<td>100 cm</td>
</tr>
<tr>
<td><strong>$\sigma_{SI}$ limit (@50 GeV/c^2)</strong></td>
<td>$8.8 \times 10^{-44}$ cm$^2$</td>
<td>$1.1 \times 10^{-45}$ cm$^2$</td>
<td>$1.6 \times 10^{-47}$ cm$^2$ (2018)</td>
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<td></td>
<td></td>
<td></td>
<td>$1.6 \times 10^{-48}$ cm$^2$ (2023)</td>
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XENONnT was prepared while XENON1T took data ➔ switching gears ➔ XENONnT started 2020
→ Goal: two orders of magnitude improvement in sensitivity with respect to XENON100
XENON1T: Nuclear Recoil Searches

Migdal: ...it takes time for the electrons to catch up...

SI WIMP limits down to 3 GeV/c²
[PRL 121, 111302 + PRL 123, 251801]
recently confirmed by PandaX: arXiv:2107.13438

PRL 123, 241803 - Migdal effect
PRL 123, 251801 - light dark matter
Double Electron Capture of $^{124}$Xe

$T = 1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}} \times 10^{22} \text{yr}$

No rejection significant: $4.4\sigma$

⇒ about one trillion times the age of the Universe
⇒ longest half-life ever measured directly

Large exposure: 0.65 tonne-years

Unprecedented low background: 76 ± 2 events/t/yr/keV

Low threshold: 1 keV$_{ee}$

→ excess events!?
Combine light and charge

\[ E = W \cdot (n_{ph} + n_e) \]

\[ = W \cdot \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \]

- detector constants \( g_1 \) and \( g_2 \)

- Anti-correlation between light and charge
  - checked with calibration sources
- Energy resolution < 5 % at 50 keV
The Result

- Exposure: 0.65 t*y
- Single scatter events within [1,210] keV_{ee}
- Nice agreement at higher recoil energies

⇒ Excess between 1-7 keV: 
  285 events observed
  (232 ± 15) expected from best-fit

Explanation #1: 3.5σ fluctuation
- Good fit observed over most of the energy range
- Consistent with expectations
- Unbinned maximum likelihood fit profiling over nuisance parameters:

\[
\mathcal{L}(\mu_s, \mu_b, \theta) = \text{Poiss}(N|\mu_{tot}) \\
\times \prod_i^n \left( \sum_j \frac{\mu_{b,j}}{\mu_{tot}} f_{b,j}(E_i, \theta) + \frac{\mu_s}{\mu_{tot}} f_s(E_i, \theta) \right) \\
\times \prod_m C_{\mu_m}(\mu_{b,m}) \times \prod_n C_{\theta_n}(\theta_n),
\]

\[
\mu_{tot} \equiv \sum_j \mu_{b,j} + \mu_s,
\] 

\( (76 \pm 2) \text{ events } / (t*y*keV) \) in [1,30] keV window

Lowest bg rate ever achieved in this energy range

**Explanation #2:** Some unexpected new background?
Not expected, but being discussed: E.g. Tritium, ...

- Cosmogenic activation of detector materials (surface, UG)
- Cosmogenic activation of Xenon (surface, UG)
- Detector parts: absorption, outgasing
- Chemically bound in LXe: THO, other...?
- Removal: getter, distillation, ...

**Cosmogenic Activation**

- Tritium, other cosmogenic activation products may be present in the detector materials and detector parts, including Xenon.

**Removal**

- Getter, distillation, etc. are methods used for removing cosmogenic activation from the detector materials.

**Tritium Sources and Paths**

- Tritium sources and paths are being discussed in the context of the detector materials and detector parts.

**Graphs**

- The graph on the left illustrates the timeline of Tritium activity and expected concentration, with fitted concentration and expected concentration highlighted.
- The graph on the right shows events per keV and energy distribution, with a peak at 3.2σ.

**No Indication of Tritium**

- There is no indication of Tritium in the current data, and a fit would require less than 3T per kg of LXe.

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New Physics

• A singal from where?

• Sun:
  - neutrinos (exist, but CEνNS too small \(\leftrightarrow\) neutrino floor is close...)
  - some non-standard \(\nu\) interaction with electrons
  - axions or ALPS produced in the sun

• DM density/flow
  - some new particle
    - not WIMPs
    - light and not hot DM? A new light boson?

• Diffuse background of invisible particles
  \(\leftrightarrow\) consistency with other searches/limits

So far >300 citations...

\(\Rightarrow\) mostly theory explanations

\(\Rightarrow\) 3 main directions: Axions, \(\nu\)’s, light bosons
Signal Interpretation: Solar Axions?

Production:

1. ABC

2. Primakoff

3. $^{57}$Fe

Detection via axio-electric effect

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} 3E_a^2 \frac{1 - \beta^2/3}{16\pi\alpha m_e^2}$$

Reconstruction in XENON1T (resolution, efficiency)

Phys. Rev. D 102, 072004

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But: Tension with constraints
- stellar cooling
- solar neutrinos

Ways around?
See e.g.: XENON1T excess from anomaly-free Axion-like Dark Matter and its implications for Stellar Cooling Anomaly,
F. Takahashi, M. Yamada, W. Yin, PRL 125 (2020) 16, 161801
WD and RG explained simultaneously better when ALP constitutes about 10% of DM
Large Neutrino magnetic Moment

Solar neutrino spectrum ➔ MeV-ish

Detection

\[
\frac{d\sigma_\mu}{dE_r} = \mu_\nu^2 \alpha \left( \frac{1}{E_r} - \frac{1}{E_\nu} \right) \sim \frac{1}{E_r}
\]

Reconstruction in XENON1T (resolution, efficiency, 

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\[ \text{Dirac: } \mathcal{L} \supset \mu_\nu \bar{\nu}_L \sigma_{\mu\nu} \nu_R F_{\mu\nu}^{\mu\nu} + m_\nu \bar{\nu}_L \nu_R + \text{H.c.} \]

\[ \mu_\nu \text{ and } \nu \text{ mass operators have the same chiral structure } \Rightarrow \mu_\nu \text{ typically proportional to } m_\nu \]

\[ \text{SM+R: } \]

\[ \mu_\nu = \frac{eG_F m_\nu}{8\sqrt{2}\pi^2} = 3 \times 10^{-20} \mu_B \left( \frac{m_\nu}{0.1 \text{ eV}} \right) \]

\[ \text{Transition mag. moment for Majorana } \nu \text{'s: } \]

\[ \mu_{ij} = -\frac{3eG_F}{32\sqrt{2}\pi^2} (m_i \pm m_j) \sum_{\ell=e,\mu,\tau} U_{\ell i}^* U_{\ell j} \frac{m_\ell^2}{m_W^2} \]

\[ \Rightarrow \mathcal{O}(10^{-23}) \mu_B \]

\[ \Rightarrow \text{all orders of magnitude too small!} \]
BSM models significantly enhance $\mu_\nu$
eq e.g. MSSM with L violation by R-parity violation $\sim \lambda'$

$$\mu_\nu \sim \lambda'^2/(16\pi^2)m_\ell^2A_\ell/M_\ell^4$$

$A_\ell \leftrightarrow$ SUSY breaking
trilinear coupling

$M_\ell \leftrightarrow$ slepton mass

BUT $\Rightarrow \mu_\nu \leq 10^{-13} \mu_B$

Rather general: Most BSM models with TeV-ish scales allow/predict $\mu_\nu \leq 10^{-13} \mu_B$

Pushing higher often leads to two problems:
- light new particles that should have been discovered
- intrinsic relation between magnetic moment and radiative neutrino masses

$\Rightarrow$ neutrino mass shifts which are much bigger than allowed
However: Symmetries can decouple $\mu$ and neutrino masses
See e.g.: ML, B. Radovčić, J. Welter, JHEP 07 (2017) 139
symmetries for $\nu$ mass patterns $\Rightarrow$ non-trivial $m_\nu \leftrightarrow \mu_\nu$ relation

K.S. Babu, S. Jana, ML, JHEP 10 (2020) 040 $\Rightarrow$ see talk by S. Jana
Horizontal $SU(2)_H$ broken by muon Yukawa coupling

$$\mathcal{L}_{\text{mag.}} = (\nu_e^T \nu_\mu^T) C^{-1} \sigma_{\mu \nu} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} F^{\mu \nu} \quad \leftrightarrow \quad \mathcal{L}_{\text{mass}} = (\nu_e^T \nu_\mu^T) C^{-1} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$\mathcal{L}_{\text{mass}}$ is not invariant $\Rightarrow m_\nu = 0$ in the $SU(2)_H$ limit while $\mu_\nu$ is allowed
+ corrections $\Rightarrow$ elegantly generates the correct $\nu$ mass scale

$\Rightarrow$ LHC prospects
Bosonic Dark Matter

E.g. axion-like particles (ALPs) – not related to strong CP problem, but interesting ➔ avoids strict mass-coupling relation ➔ more freedom

\[ R \approx \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left( \frac{m_a}{\text{keV}/c^2} \right) \left( \frac{\sigma_{pe}}{b} \right) \text{kg}^{-1} \text{d}^{-1} \]

➔ Expect a monoenergetic peak around the rest mass

![Graph showing monoenergetic peaks for different energy levels]
Many Solutions: Hidden Dark Sectors

Recipe: Dark sector + light particles + weak coupling

A few examples:
- Light new physics in XENON1T
- Light vector mediators facing XENON1T data
  D. Aristizabal Sierra, V. De Romeri, L.J. Flores, D.K. Papoulias, PLB 809 (2020) 135681
- Shining dark matter in Xenon1T
- Mirror Dark Matter and Electronic Recoil Events in XENON1T
- XENON1T Anomaly: A Light Z’
- Boosted Dark Matter Interpretation of the XENON1T Excess

+ many more
Light Dark Sectors $\leftrightarrow E_R$ Spectrum

Also:
A. Bally, S. Jana, A. Trautner, PRL 125 (2020) 16, 161802

$\Rightarrow$ new neutrino interactions with leptons mediated by a light vector particle

$\Rightarrow 1\sigma$ allowed, $2\sigma$ excluded regions in the $m_V - g_V$ plane

comparison to limits from:
- TEXONO
- GEMMA
- Borexino
- astrophysics
DM with a fast Component


elastic DM+e → DM+e' scattering
DM with initial velocity: \( \vec{v}_{DM} \)
initial/final e velocity: \( \vec{v}_e \rightarrow \vec{v}'_e \)
⇒ Momentum transfer:
⇒ \( E_R \approx 2.4 \text{keV} \) for \( m_{DM} \gg m_e \) with \( v_{DM} \approx 0.1 \)

Favoured region

Fast component gravitationally not bound to galaxy \( \rightarrow \ldots \) decays, sub-halo, ...
Explain signal by the MeV-scale dark matter heated inside the Sun ($\approx 1.5 \times 10^7$ K)

- high-temperature plasma inside the Sun
  - heat-up light DM particles to keV energies


$$\Phi_{\text{heat}} \sim \frac{\Phi_{\text{halo}}}{4} \times \left\{ \frac{4S_g}{3} \left( \frac{R_{\text{core}}}{d} \right)^2 \frac{R_{\text{core}}}{\lambda} , \quad R_{\text{core}} \ll \lambda \right\} \left\{ \frac{S_g}{R_{\text{scatt}}} \right\}^2 , \quad R_{\text{core}} \gg \lambda$$

- same DM-electron interaction in the detector
  - Best fit, F(...), XENON1T limits
  - Expect annual modulation w/o $\nu$’s or axions
Boosted Dark Matter

B. Fornal, P. Sandick, J. Shu, M. Su, Y. Zhao, PRL 125 (2020) 16

BDM: particles with velocities $\gg$ typical of virialized dark matter
$n$ naturally produce keV electron recoils

- BDM flux $\Rightarrow$ could originate from the Galactic Center or from halo DM annihilation
- daily modulation of the BDM signal expected for mediator masses $< 10$-100 GeV

\[ L_{fs,E} \approx 60 \text{ m} \times \left( \frac{10^{-28} \text{ cm}^2}{\sigma_{\text{elec}}} \right) \]
More Directions

- non-relativistic particles gravitationally bound to the Milky Way
- DM particles “store” energy, which they release in the detector

- Exothermic DM \((X^* + e^- \rightarrow \text{strong signal preference } X + e^-)\)
  Baryakhtar et al., arXiv:2006.13918

- Luminous DM \((X^* \rightarrow \text{strong signal preference } X + \gamma)\)
  Bell et al., arXiv:2006.12461

This would require a slightly heavier state
  \(\rightarrow\) populated either in the early Universe or via up-scattering

- millicharged neutrinos
  Kahn, arXiv:2006.12887, ...
Summary of the current Situation

Excess between 1-7 keV:  
285 events observed 
(232 ± 15) expected from best-fit

Interpretations:

a) A fluctuation

b) Some new background
   - Tritium
   - $^{37}$Ar
   - ...

c) New physics
   - solar axions
   - large ν mag. Moment
   - bosonic DM, dark Z, ...

>100 papers in 2 months

All $\sim 3\sigma \Rightarrow$ more data soon from XENONnT
Changes, re-assembly, filling, commissioning done last year! data taking → SR0 results... soon... → more data & checking
Conclusions

• The WIMP search will continue
  - XENONnT...

• Direct detection will make good progress soon
  (XENONnT, LZ, ...)
  - even better WIMP sensitivity
  - sensitivity to axions, neutrino physics (DEC, 0νββ, solar ν’s, SN, coherent scattering,...)
  - low $E_R$ excess may be statistics, background or new physics
    ➔ more pronounced with more data from XENONnT?
    ➔ annual modulation?
    ➔ ...

• Results on low $E_R$ excess have a substantial impact
  ➔ a hot signal to explain or unique limits on many ideas