CERN Academic Training Lectures: Dark Matter Searches

Lecture 2: Direct Searches for Galactic WIMPs

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University of Sheffield
Recap: Dark Matter Searches

• Three main ways to search for evidence of particle DM via non-gravitational interactions

• Indirect: Seek evidence for annihilation or decay products of DM particles trapped in galactic / solar / planetary potential wells
  - X-rays, gamma rays, neutrinos, anti-matter …
  - May prove DM but not identify particle

• Direct: Seek evidence for DM particle interactions with targets in terrestrial detectors
  - Nucleons, nuclei, electrons, photons …
  - May prove DM but not identify particle

• Accelerator/Collider: Seek evidence for invisible particle production in SM particle collisions
  - May identify particle but cannot prove DM

29 Jun – 1 Jul 2021
CERN ATC Lectures: Dark Matter Searches

Search Strategy

10^{-21}eV  peV  neV  μeV  meV  eV  keV  MeV  GeV  TeV  M_p

pre-infl. QCD axion
post-infl. QCD axion
"classical" QCD axion

fuzzy DM

QCD axion

general thermal WIMP
sterile neutrino
ADM

non-thermal WIMP (FIMP)

standard thermal WIMP (e.g. SUSY neutralino)

Searches for Low Energy Nuclear Recoils

- Basic idea (Goodman and Witten 1985): WIMPs couple weakly to baryonic matter so search for anomalous sources of low energy nuclear recoils
- Majority of backgrounds due to electron recoils (beta decay, Compton scattering etc.), from radioactive contamination
- Residual nuclear recoils from neutron scattering from fission and CR spallation so use deep, clean UG lab
- Energy spectrum of recoils driven by kinematics of WIMPs in galactic halo:
  - Assume $m_\chi \sim m_A \sim 100 \text{ GeV}$
  - $E_K(A) \sim E_K(\chi) = \frac{1}{2} m_\chi (v/c)^2 \sim 25 \text{ keV}$
Nuclear Recoil Energy Spectrum

\[
\frac{dR}{dE_R} = \left( \frac{\rho_x}{m_\chi} \right) \left( \sigma_0^{\text{SI}} F_{\text{SI}}^2(E_R) I_{\text{SI}} + \sigma_0^{\text{SD}} F_{\text{SD}}^2(E_R) I_{\text{SD}} \right) \frac{1}{2\mu^2} \int_{v_{\text{min}}}^{v_{\text{esc}}} f(\vec{u}, \vec{v}_E) \frac{d^3\vec{u}}{|\vec{u}|}
\]

• Nuclear recoil energy spectrum obtained by integrating recoil energy spectrum from scattering from WIMP of fixed velocity over WIMP velocity distribution

• Normally assume isothermal (Maxwellian) halo velocity distribution (see Lecture 1):

\[
f(\vec{u}, \vec{v}_E) = \frac{1}{\pi^{3/2} v_0^3} e^{-(\vec{u} + \vec{v}_E)^2/v_0^2}
\]

• If assume target at rest with respect to halo then obtain:

\[
\frac{dR}{dE_R} = \left( \frac{\rho_x}{m_\chi} \right) \left( \sigma_0^{\text{SI}} F_{\text{SI}}^2(E_R) I_{\text{SI}} + \sigma_0^{\text{SD}} F_{\text{SD}}^2(E_R) I_{\text{SD}} \right) \frac{1}{\mu^2 v_0 \sqrt{\pi}} e^{-E_R (m_A/2\mu^2 v_0^2)}
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Nuclear Recoil Energy Spectrum

\[ \frac{dR}{dE_R} = \left( \frac{\rho_\chi}{m_\chi} \right) \left( \sigma_0^{SI} F_{SI}^2(E_R) I_{SI} + \sigma_0^{SD} F_{SD}^2(E_R) I_{SD} \right) \frac{1}{\mu^2 v_0 \sqrt{\pi}} e^{-E_R (m_A/2\mu^2 v_0^2)} \]

- Particle physics:
  - WIMP mass \( m_\chi \)
  - WIMP coupling e.g. scalar, pseudo-scalar (determines coupling to nucleus)
  - WIMP-nucleon cross-sections \( \sigma_0^{SI}, \sigma_0^{SD} \)

- Astrophysics:
  - Local WIMP density \( \rho_\chi \)
  - DM halo velocity dispersion \( v_0 \) (+other params e.g. \( v_E, v_{esc} \))

- Nuclear physics:
  - Spin-dependent / spin-independent coupling enhancements \( I_{SD}, I_{SI} = (\mu/\mu_n)^2 A^2 \) for scalar
  - Form-factors \( F_{SI}^2(E_R), F_{SD}^2(E_R) \) – Fourier Transform of scattering centres
Nuclear Recoil Energy Spectrum

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\frac{dR}{dE_R} = \left( \frac{\rho_\chi}{m_\chi} \right) \left( \sigma_0^{SI} F_{SI}^2(E_R) I_{SI} + \sigma_0^{SD} F_{SD}^2(E_R) I_{SD} \right) \frac{1}{\mu^2 v_0 \sqrt{\pi}} e^{-E_R \left( m_A / 2 \mu^2 v_0^2 \right)}
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  - WIMP-nucleon cross-sections \(\sigma_0^{\text{SI}}, \sigma_0^{\text{SD}}\)

• Astrophysics:
  - Local WIMP density \(\rho_\chi\)
  - DM halo velocity dispersion \(\nu_0\) (+other params e.g. \(v_E, v_{\text{esc}}\))

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First observation of coherent neutrino-nucleus scattering
Nuclear Recoil Energy Spectrum

\[
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Nuclear Recoil Energy Spectrum

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Results typically quoted as limits on WIMP-nucleon cross-section vs. WIMP mass, assuming only one interaction (SI/SD), normalised (for SD) to one type of nucleon.

- Steeply falling spectrum \( \rightarrow \) sensitivity dominated by **detector energy threshold**

- Approximate form:
  \[
  \sigma_0^{\text{lim}} \sim \alpha m_\chi \mu^2 e^{\beta m_\Lambda/\mu^2}
  \]
  - \( \alpha \) determined by limit on yield at threshold
  - \( \beta \) determined by value of threshold
  - Greatest sensitivity when \( m_\chi \sim m_\Lambda \) (kinematics)
  - At high mass, spectrum asymptotically independent of \( m_\chi \). Sensitivity \( \sim 1 / \text{WIMP number density} \sim m_\chi \) for fixed \( \rho_\chi \)

- Spin-dependent limits differ for proton and neutron. Sensitivity \( \sim A^2 \sim 10^4 \) less (coherence)
Halo Signatures

- Motion of terrestrial detector through halo gives further possibilities for signal identification
  
  \[ v_E \approx 244 + 15 \sin(2\pi(t - t_0)) \text{ km s}^{-1} \]
  
- Annual modulation: flux varies annually with max/min in Jun/Dec (depends on energy).
  
- Directional modulation: mean direction of WIMP flux relative to terrestrial detector modulates diurnally \( \rightarrow \) modulation in mean direction of recoils

\[ f(\vec{v}, \vec{v}_E) = \frac{1}{\pi^{3/2} \nu_0^3} e^{-\frac{(\vec{v} + \vec{v}_E)^2}{\nu_0^2}} \]
\[ \vec{v}_E = \vec{u}_R + \vec{u}_S + \vec{u}_E \]

P. Cushman et al, Snowmass 2013

N. Spooner
Energy Calibration

- Added complication – not all kinetic energy of recoiling nucleus visible in detector
  - Visible energy threshold >> recoil energy threshold

- Quantified by energy-dependent Lindhard factor ($\text{keV}_{nr}/\text{keV}_{ee}$)
  - e.g. ~25% for LXe scintillator detectors

- Detector media calibrated with nuclear recoils generated by neutron scattering with (usually) mono-energetic beam.

- Allows run-time calibration with electron recoils

\[ E_e = W(n_\gamma + n_e) \quad E_A = W(n_\gamma + n_e)/\mathcal{L} \]
Backgrounds

- Electron recoils (reducible):
  - Compton scattering of external gammas
  - $\beta$ (and $2\nu-\beta\beta$) decay of contaminants in target volume, e.g. $^{85}\text{Kr}$, $^{39}\text{Ar}$, $^{136}\text{Xe}$, $^{222}\text{Rn}$ daughters

- Nuclear recoils (irreducible):
  - Elastic scattering of neutrons from U/Th chain fission and CR spallation
  - Coherent elastic scattering of solar, atmospheric and SN neutrinos (CEvNS)

- Mitigation:
  - Radiopure target and detector materials
  - Shielding: Pb, Cu, H$_2$O and self-shielding
  - Operation deep underground
  - Veto electron recoil events
  - Veto U/Th chain gammas coincident with neutrons or neutrons themselves

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Coherent Elastic $\nu$-Nucleus Scattering (CE$\nu$NS)

- Irreducible nuclear recoil background to WIMP searches from neutrino scattering
- Observed at Spallation Neutron Source by COHERENT
- Provides the neutrino floor beyond which direct search performance dominated by background systematics (flux, form-factor)
- Substantial progress probably requires use of halo signatures (e.g. directionality)
Low Mass WIMPs

- Elastic nuclear recoil searches lose sensitivity for $m_\chi$ less than a few GeV (kinematics)
- If WIMPs couple to electrons then kinematics more favourable, but large e-recoil background
- Low energy n-recoil signals accessible by discarding discrimination, or seeking more ‘electron-like’ n-recoil signals due to brem or Migdal effect (Ibe et al.)
  - NB Migdal effect not yet observed in nuclear scattering

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Ibe et al., JHEP 03 (2018) 194
Dark Photon DM

• Motivated by models with extra U(1) gauge symmetry
  - Boson $A'$ mixes with photon $\rightarrow$ weak coupling to matter
  - If light ($m_{A'} < 2m_e$) cosmologically stable. Broad mass range to below $10^{-20}$ MeV

• Dark photon DM constraints:
  - Stellar astrophysics (anomalous cooling in sun, WD, RG, HB stars etc.)
  - Direct searches for electron recoil signals from dark photoionisation

![Graph showing Dark photons and kinetic mixing 1](image-url)
Search Experiments

Background Rejection

Laura Baudis, SUSY 2018
• First experiments based on room temp NaI(Tl)
  - Iodine A=127 (heavy, good A²)
  - Pulse shape discrimination
  - Radiopure
  - Cost-effective

• DAMA + DAMA/LIBRA (Gran Sasso) claims annual modulation in 2-6 keV_{ee} bin at 9.3\sigma
  - Excluded by other targets / methods

• Excluded with same target by COSINE-100 (Yangyang, 2018) and ANAIS-112 (Canfranc, 2021)

• Explanation?
  - Modulation of environment
  - Affects backgrounds e.g. Rn?


COSINE-100 Collaboration, Nature. 564 (7734): 83–86
Liquid Xenon Detectors

- **Liquid Xenon TPC**
  - Recoil generates excitation and ionisation
  - PMT S1 light (VUV 175 nm) read-out
  - Gas-phase charge read-out with electro-luminescence (S2)

- **S2 light measures x-y, drift time S1-S2 z**
  - Allows fiducialisation / self-shielding
  - Veto multi-scatter γ/n background

- **Advantages:**
  - A~131, spin-dependent isotopes
  - Very radiopure
  - ~99.7% e/n-recoil discrimination (50% eff.)
  - Mature, well understood technology

- **Disadvantages:**
  - Xe relatively expensive (~1000 $/kg)
Liquid Xenon Detectors (Scint+Ion)

- LUX (2015/2017):
  - SURF (US)
  - $1.4 \times 10^4$ kg.days (145 kg fiducial)
  - $^{85}$Kr removal by chromatography

- PandaX-II (2017)
  - Jianping (China)
  - Follows PandaX-I
  - $3.3 \times 10^4$ kg.days (300 kg fiducial)

- XENON1T (2018)
  - Gran Sasso (It)
  - Follows XENON-10/100
  - $3.6 \times 10^5$ kg.days (1300 kg fiducial)
  - $^{85}$Kr removal by distillation
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XENON1T Low Energy Excess

- Excess of ~50 electron recoil events near threshold ~2-3 keV_{ee}
  - Possible evidence for solar axion or bosonic DM at >3σ
  - Could be due to additional ^3T β-decay background

- PandaX-II data compatible with both S+B and B-only

- Follow-up from NEST (Szydagis et al.) identifying 2.8 keV γ-rays from ^37Ar EC as a possible cause
  - Good fit to energy spectrum
  - Some evidence for t_{1/2}=35 days in time spectrum

NEST Collaboration, Phys.Rev.D 103(2021)1, 012002

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Future LXe Detectors (Scint+Ion)

• Next generation experiments commissioning / close to operation
  - XENONnT (8.3 t non-fiducial)
  - LUX-ZEPLIN 10 t (non-fid) / 5.6 t (fid)
  - PANDA-4T (4 t non-fiducial)

• Future experiments should approach neutrino floor
  - DARWIN (50 t, EU)
  - G3 (US)
  - MoU for LZ+XENON merger
  - PandaX-xT

• Key challenges:
  - Rn removal
  - Cleanliness
  - Rn chain tagging
  - HV system + Grids
Liquid Argon Detectors

- **Liquid Argon TPC**
  - Recoil generates excitation and ionisation
  - PMT S1 light (VUV 128 nm) read-out
  - Gas-phase charge read-out with electro-luminescence (S2)

- **S2 light x-y, drift time S1-S2 z**
  - Fiducialisation / self-shielding
  - Veto multi-scatter γ/n background

- **Advantages:**
  - Low cost (but requires purification)
  - >10^8 PSD e-recoil rejection
  - Leverage ν experiment expertise

- **Disadvantages:**
  - A = 40 → A^2 factor 10 less than Xe
  - WLS (TPB) required for deep UV readout
  - Background ^39Ar (t_{1/2}=269 y) - CR spallation

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D. Price
LAr Single-Phase (Scint)

- **DEAP-3600 (SNOLAB)**
  - Scintillation signal only – slow charge recombination generates tail in pulse-shape
  - TPB coating on spherical vessel
  - Pulse shape discrimination (PSD)

- 1.9x10^5 kg.days (824 kg) fiducial
- Background dominated by ^{39}\text{Ar}
**LAr Dual-Phase (Scint+Ion)**

- **DarkSide-50 (2018, Gran Sasso)**
  - LAr double-phase read-out
  - ‘Underground’ Ar depleted x1400 in $^{39}\text{Ar}$
  - $1.7 \times 10^4$ kg.days (36.9 kg)
  - Also low mass search 6786 kg.days ionisation only

- **DarkSide-20k under preparation by GADMC**
  - 40 t fiducial with SiPM readout
  - 350 m cryogenic distillation column (ARIA Sardinia)
  - Goal: reduce $^{39}\text{Ar}$ x100 vs. UAr

- **Next stage – ARGO**
  - ~360 t target
Cryogenic Semiconductors (Ion+Heat)

• Mostly Germanium detectors
  - Low threshold – low $m_\chi$
  - A~73 (Ge)
  - Charge+phonon readout
  - Cryogenic – dilution fridge
  - Care with surface events
  - CDMS-II (Si) excess (2014) excluded by other expts.

• SuperCDMS (Soudan, 2014)
  - Follows CDMS-I/II etc.
  - Germanium 577 kg.days
  - CDMSlite (2018) phonon-only – sensitive to low $m_\chi$

• SuperCDMS SNOLAB under construction
  - ~220 kg Ge/Si (75%/25%)
EDELWEISS (Ion+Heat) / CRESST (Scint+Heat)

- **EDELWEISS-III (Modane, 2016)**
  - Ge ion/phonons - similar to CDMS
  - 496 kg.days

- **CRESST-III (Gran Sasso)**
  - CaWO$_4$ - cryogenic scintillator
  - Discrim. with photons+phonons
  - Tungsten A~184
  - Dilution fridge
  - Ultra-low threshold 30 eV$_{nr}$
  - Care with surface events
  - 3.64 kg.days (23.6 g)

- **Next stage – EURECA**
  - EDELWEISS/CRESST merger
  - 1000 kg mixed target

**References**
- EDELWEISS Collaboration, EPJ C (2016) 76:548
CCD Detectors (Ion)

- Very low mass, low $A=28$, but very low threshold
  - ‘Skipper’ CCD – multiple charge measurements reduces noise
  - Segmentation rejects multiple scatter / track background

- SENSEI (2020, Soudan)
  - 0.048 kg.days (2 g)
  - Uses Migdal effect
  - 100 g target planned

- DAMIC (2020, SNOLAB)
  - Larger mass, higher threshold
  - Imaging background tracks
  - 11 kg.days (42 g) (SNOLAB)
  - Plan kg-scale detector at Modane
**NEWS-G (Ion)**

- Spherical gas proportional counter
  - Low energy threshold (~10 eV\(_{ee}\))
  - Flexible target choice (noble gases)
- Prototype 9.6 kg.days (Modane, 2018)
  - Ne (target) + CH\(_4\) (0.7%)
- Installed 1.4 m diameter detector at SNOLAB end 2020
Directional Detectors (Ion)

• Gas TPC to image nuclear recoil tracks

• Advantages:
  - Recoil direction – correlated with WIMP ‘wind’
  - Excellent electron/nuclear recoil discrimination

• Disadvantages:
  - Low density = low mass target
  - Requires excellent position resolution over long drift distances
  - Ideally head/tail discrimination – difficult!

• Low pressure CS$_2$ negative ion drift
  - DRIFT Collaboration (Boulby)

• Low pressure He-CF$_4$ electron drift
  - NEWAGE (Kamioka)
  - MIMAC (Modane)
  - DMTPC (MIT)
Bubble Chambers (Heat)

• Superheated bubble chamber
  - Technology used in nuclear industry
  - Insensitive to low LET electron recoils
  - Acoustic and optical detection of bubbles
  - Energy-integrated signal (no spectral info)
  - $C_3F_8$ target rich in $^{19}F$ – superior target for spin-dep. WIMP-proton interactions

• COUPP+PICASSO → PICO

• PICO-60L (2019, SNOLAB)
  - $1.4 \times 10^3$ kg.days (49 kg)
  - 1-3 keV$_{ee}$ threshold

• Future scale-up:
  - PICO-40L (57 kg) commissioning
  - PICO-500 (250 litres) proposed

• NB: Indirect searches with neutrinos competitive

PICO Collaboration, Phys. Rev. D 100, 022001

Super-K indirect
ICECube Indirect
SD WIMP-proton cross section [pb]
Higgsino/Wino Dark Matter

- Direct detection challenging in pure higgsino case (nature has not been kind!)


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**Diagram:**

- **x-axis:** $m_h$ (GeV)
- **y-axis:** $\sigma_{SI}$ (cm$^2$)

- **Regions:**
  - Pure higgsino
  - Pure wino
  - Triplet
  - Doublet

Table 27.1: Best constraints from direct detection experiments on the SI (at high >5 GeV and low < 5 GeV masses) and SD DM-nucleon couplings.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>Fiducial mass [kg]</th>
<th>Cross section [cm²]</th>
<th>DM mass [GeV]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spin independent high mass (&gt;5 GeV)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XENON1T</td>
<td>Xe</td>
<td>1042</td>
<td>4.1 × 10⁻⁴⁷</td>
<td>30</td>
<td>[145]</td>
</tr>
<tr>
<td>PandaX-II</td>
<td>Xe</td>
<td>364</td>
<td>8.6 × 10⁻⁴⁷</td>
<td>40</td>
<td>[144]</td>
</tr>
<tr>
<td>LUX</td>
<td>Xe</td>
<td>118</td>
<td>1.1 × 10⁻⁴⁶</td>
<td>50</td>
<td>[143]</td>
</tr>
<tr>
<td>SuperCDMS</td>
<td>Ge</td>
<td>12</td>
<td>1.0 × 10⁻⁴⁴</td>
<td>46</td>
<td>[135]</td>
</tr>
<tr>
<td>DarkSide-50</td>
<td>Ar</td>
<td>46</td>
<td>1.14 × 10⁻⁴⁴</td>
<td>100</td>
<td>[146]</td>
</tr>
<tr>
<td>DEAP-3600</td>
<td>Ar</td>
<td>2000</td>
<td>3.9 × 10⁻⁴⁵</td>
<td>100</td>
<td>[147]</td>
</tr>
<tr>
<td><strong>Spin independent low mass (&lt;5 GeV)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUX (Migdal)</td>
<td>Xe</td>
<td>118</td>
<td>6.9 × 10⁻³⁸</td>
<td>2</td>
<td>[149]</td>
</tr>
<tr>
<td>XENON1T (Migdal)</td>
<td>Xe</td>
<td>1042</td>
<td>3 × 10⁻⁴⁰</td>
<td>2</td>
<td>[150]</td>
</tr>
<tr>
<td>XENON1T (ionisation only)</td>
<td>Xe</td>
<td>1042</td>
<td>3.6 × 10⁻⁴¹</td>
<td>3</td>
<td>[151]</td>
</tr>
<tr>
<td>DarkSide-50 (ionisation only)</td>
<td>Ar</td>
<td>20</td>
<td>1 × 10⁻⁴¹</td>
<td>2</td>
<td>[152]</td>
</tr>
<tr>
<td>SuperCDMS (CDMSlite)</td>
<td>Ge</td>
<td>0.6</td>
<td>2 × 10⁻⁴⁰</td>
<td>2</td>
<td>[138]</td>
</tr>
<tr>
<td>CRESST</td>
<td>CaWO₄ - O</td>
<td>0.024</td>
<td>1 × 10⁻³⁹</td>
<td>2</td>
<td>[137]</td>
</tr>
<tr>
<td>NEWS-G</td>
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<td>0.3</td>
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<td>2</td>
<td>[169]</td>
</tr>
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<td><strong>Spin dependent proton</strong></td>
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<td>PICO60</td>
<td>C₃F₈ - F</td>
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<td>3.2 × 10⁻⁴¹</td>
<td>25</td>
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<td><strong>Spin dependent neutron</strong></td>
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<td>XENON1T</td>
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<td>[192]</td>
</tr>
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<td>Xe</td>
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</tr>
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</table>

L. Baudis and S. Profumo, PDG 2020
Direct WIMP Search Summary

We have come a long way!

Laura Baudis, LHCP 2021, after Rick Gaitskell (2020)
To Be Continued ...