Direct Searches for WIMP Dark Matter

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Dark Matter Search

Indirect Detection

Direct Detection

Production @Collider
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

$v \sim 230 \text{ km/s}$
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

\[ v \sim 230 \text{ km/s} \]
Elastic Scattering of WIMPs off target nuclei → nuclear recoil

$E_R \sim \mathcal{O}(10 \text{ keV})$

$v \sim 230 \text{ km/s}$

Detectable Signal
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

→ nuclear recoil

WIMP

v \sim 230 \text{ km/s}

Nuclear Recoil

E_R \sim O(10 \text{ keV})

Detectable Signal

gamma- and beta-particles (background) interact with the atomic electrons

→ electronic recoil
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei → nuclear recoil

Recoil Energy:

\[ E_r = \frac{|q|^2}{2m_N} = \frac{\mu^2 v^2}{m_N} (1 - \cos \theta) \sim \mathcal{O}(10 \text{ keV}) \]

Event Rate:

\[ R \propto N \frac{\rho_x}{m_x} \langle \sigma_{\chi-N} \rangle \]

- \( N \) number of target nuclei
- \( \rho_x / m_x \) local WIMP number density
- \( \langle \sigma \rangle \) velocity-averaged scattering X-section

Detector

Local DM Density

\( \rho_x \sim 0.3 \text{ GeV}/c^2 \)

Physics

WIMP

Nuclear Recoil

Detectable Signal

Elastic Scattering of WIMPs off target nuclei

\( v \sim 230 \text{ km/s} \)

\( E_R \sim \mathcal{O}(10 \text{ keV}) \)
Direct WIMP Search

Summary: Tiny Rates

\[ R < 0.01 \text{ evt/kg/day} \]
\[ E_R < 100 \text{ keV} \]

Recoil Energy:
\[ E_r \sim \mathcal{O}(10 \text{ keV}) \]

Event Rate:
\[ R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle \]

Detector

Local DM Density
\[ \rho_\chi \sim 0.3 \text{ GeV/c}^2 \]

Physics

WIMP Expectations
spin-independent interactions

Argon
Xenon

\[ m_\chi = 100 \text{ GeV/c}^2 \]
\[ \sigma = 4 \times 10^{-43} \text{ cm}^2 \]

form factor

1 event/kg/yr
1 event/ton/yr

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A priori, we do not know how dark matter WIMPs interact with ordinary matter.

Parametrization of interactions leading to WIMP-nucleus scattering:

<table>
<thead>
<tr>
<th>Coupling to mass</th>
<th>Coupling to nuclear spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin independent</td>
<td>Spin dependent</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}_S \sim \bar{\chi} \gamma q \bar{q} \propto A^2 \]

\[ \mathcal{L}_A \sim \bar{\chi} \gamma \gamma_5 \chi \gamma \mu \gamma_5 q \propto J(J+1) \]

often: express SD results in proton-only or neutron-only

Form factors describe loss of coherence → mainly for heavy targets and tail of v-distribution

\[ \frac{d\sigma}{d|q|^2} = \frac{C_{\text{spin}}}{v^2} G_F^2 \frac{S(|q|)}{S(0)} \]

\[ C_{\text{spin}} = \frac{8}{\pi} \left[ a_p \langle S_p \rangle + a_n \langle S_n \rangle \right] J + 1 \]

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Summary: Tiny Rates
\[ R < 0.01 \text{evt/kg/day} \]
\[ E_R < 100 \text{keV} \]

How to build a WIMP detector?
- large total mass, high \( A \)
- low energy threshold
- ultra low background
- good signal / background discrimination

We are dealing with
- extremely low rates (1 – 1000 Hz)
- extremely low thresholds (~2 keV)
- extremely low radioactive backgrounds
Background Sources everywhere

Electronic Recoils (gamma, beta)
Nuclear Recoils (neutron, WIMPs)

Muons

Muon-induced neutrons

Natural gamma background

Neutrons from $(\alpha,n)$ and sf

Target-intrinsic bg: activation, impurities

$2\nu\beta\beta$

High-E neutrinos

$\rightarrow$ CNNS bg

$\rightarrow$ NR signature

Muons

Neutrons from $(\alpha,n)$ and sf

Natural gamma background

Natural gamma background
A  Avoid Backgrounds

Use of radiopure materials

Shielding
  deep underground location
  large shield (Pb, water, poly)
  active veto (μ, γ coincidence)
  self shielding → fiducialization
Background Suppression

A. Avoid Backgrounds

Use of radiopure materials

Shielding
- deep underground location
- large shield (Pb, water, poly)
- active veto (µ, γ coincidence)
- self shielding \(\rightarrow\) fiducialization

B. Use knowledge about expected WIMP signal

WIMPs interact only once
- \(\rightarrow\) single scatter selection
  requires some position resolution

WIMPs interact with target nuclei
- \(\rightarrow\) nuclear recoils
  exploit different \(dE/dx\) from signal and background

Examples:
- scintillation pulse shape
- charge/light ratio
- ionization yield
Direct WIMP Detection

Crystals (NaI, Ge, Si)
Cryogenic Detectors
Liquid Noble Gases

SuperCDMS
EDELWEISS

CoGeNT
CDEX
Texono
Malbek
DAMIC

Phonons

CRESST-I
CUORE

XENON, LUX
ArDM, Panda-X
Darkside, DARWIN

Charge

Light

DEAP-3600, CLEAN
DAMA, KIMS
XMASS, DM-Ice,
ANAIS, Sabre

too many experimental efforts to report on → you will see a biased selection
The current WIMP landscape

The plot shows the spin-independent WIMP-nucleon interactions with the current landscape. The graph compares different experiments such as DAMA/Na, CDMS-Si (2013), XENON10 (2013), CRESST-II (2014), SuperCDMS (2014), EDELWEISS (2011/12), PandaX-I (2014), DarkSide-50 (2014), CDMS (2010/11), XENON100 (2012), and LUX (2013). Some results are missing as indicated by the text "some results are missing..."
Annual Modulation

\[
\frac{dR}{dE_{nr}} = \frac{\rho_0}{m_{Xe}} \frac{M}{m_X} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_{nr}} dv
\]

- recoil spectrum gets harder and softer during the year
- search for annually modulating signal \((3\%\) effect\)
- does not require many physical assumptions

Drukier, Freese, Spergel, PRD 33, 3495 (1986)
Annual Modulation: DAMA/Libra

- PMTs coupled to $\text{NaI(Tl)}$ Scintillators @ LNGS → extremely clean background necessary
- looks for annual modulation
- large mass and exposure: $1.17 \text{ t} \times \text{y}$

- DAMA finds annual modulation @ $9.3\sigma$ C.L.
- BUT: no ER/NR discrimination!

Interpretation as Dark Matter interaction is in conflict with numerous other experiments → KIMS, ANAIS, DM-Ice, Sabre will check directly

$E_{\text{ur. Phys. J. C 73, 2648 (2013)}}$

$S \approx S_0 + S_m \cos(\omega(t - t_0))$

$\text{DAMA/Libra} = 250 \text{ kg } (1.04 \text{ ton} \times \text{yr})$

$\begin{align*}
2-4 \text{ keV} & \\
\text{what is here?} & \\
\text{no modulation} & \text{above 6 keV}
\end{align*}$

$\begin{align*}
\text{no modulation} & \text{above 6 keV} \\
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Reconcile DAMA/Libra with the null-results from other experiments assuming leptophilic dark matter?
→ DAMA might see electronic recoils

Examples:
Kopp et al., PRD 80, 083502 (2009)
Changet al., PRD 90, 015011 (2014)
Bell et al., PRD 90, 035027 (2014)
Mirror dark matter:
Luminous dark matter:
Feldstein et al., PRD 82, 075019 (2010)

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DAMA vs XENON: Average Rates

XENON100, Science 349, 851 (2015)

even if dark matter only interacts with electrons at tree-level, loop induced dark matter-hadron interactions dominate → back the the usual NR limits PRD 80, 083502 (2009)

Axial-vector couplings $\bar{A} \otimes \bar{A}$: loop-effects vanish, WIMP-electron couplings are not suppressed

Analysis
– assume 100% modulation (conservative but hard to find a model)
– convert DAMA modulation spectrum to Xe; I and Xe have very similar electron structure
– compare rates during 70 days in Summer

XENON100 excludes DAMA as being due to
– WIMP-electron axial-vector couplings at $4.4\sigma$
  (interpreting all XENON100 events as signal)
– luminous dark matter at $4.6\sigma$
– mirror dark matter at $3.6\sigma$
DAMA vs XENON: Modulation

- 225 live days acquired over 13 months
- first demonstration that 2-phase TPCs can be operated stably for modulation analysis
- did not find significant correlation with operation/detector parameters
- single scatters: no significant modulation at $P=365$ days; phase disfavors DM interpretation
- multiple scatters: similar modulation ($\phi_{\text{ms}} \approx \phi_{\text{ss}}$)

→ exclude DAMA/Libra as being induced by axial-vector WIMP-electron couplings at $4.8\sigma$
Cryogenic Detectors: SuperCDMS

@ Soudan Lab (USA) → later: SNOLAB
measure charge and heat (phonons): 
\[ E \text{ deposition} \rightarrow \text{temperature rise } \Delta T \]

Crystals: Ge, (Si) cooled to few mK
– low heat capacity
– \( \Delta T \sim \mu K \)

Very good discrimination
→ BUT: need to reject surface events

similar: EDELWEISS @ Modane
new low-mass limit also challenges CDMS-II-Si

arXiv:1504.00820
SuperCDMS @ SNOLAB

- selected by US NSF-DOE downselection in 2014
- aim for 50 kg-scale experiment (cryostat can accommodate 400 kg)
  low threshold → focus on 1-10 GeV/c² mass range
- Improvements: deeper lab, better materials, better shield, improved resolution, upgraded electronics, active neutron veto?
- 100 x 33.3 mm IZPs (1.4 kg Ge, 0.6 kg Si) → fabrication protocol established
Towards lowest WIMP masses

**CRESST @ LNGS**
- reads phonons and scintillation light
- target: CaWO$_4$ → multi-element material
- successful background reduction;
data taking since 2013
- EPS-HEP preliminary result:
detector with 300 eV threshold
- focus on low-mass WIMPs

**DAMIC @ SNOLAB**
- target: Si → use thick CCDs
  → need only 3.6 eV to create e$^-$-hole pair
- low target mass but very low thresholds
  → low mass WIMPs
- particle ID via track information

**CRESST-II**
- lowest threshold
  EPJ C 74, 3184 (2014)
- lowest background
  Reindl (EPS-HEP)
- CRESST excludes CRESST

**DAMIC**
- preliminary result:
  - 36 days of 3 CCDs up to 675 µm thick (2.9 g)
    → @ 3 GeV/c$^2$: 10x better than DAMIC (2012)
  - DAMIC100 will start data taking in 2015

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Spin dependence: Threshold Detectors

PICO @ SNOLAB
- PICO = PICASSO + COUPP
- bubble chamber filled with superheated C$_3$F$_8$
  → very good sensitivity to \textit{spin-dependent} interactions
  → bubble forms only above a threshold energy
- almost „immune“ to electronic recoils; reject alphas by acoustic discrimination \textit{N. J. Phys.10, 103017 (2008)}
- challenge: correlation of candidate events with events in previous expansions
- PICO-2L: low threshold down to 3 keVnr

PICO-60: CF$_3$I data analysis ongoing → C$_3$F$_8$
Upgrade plan: PICO-250 → SD reach $\sim$10$^{-42}$ cm$^2$

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Liquid Noble Gases: Detector Concepts

Single Phase Detector

PMT

liquid target

Amplitude

Time

S1
**Noble Gas: Single Phase Detectors**

+ no high voltage, very high light yield

**XMASS @ Kamioka (JP)**
- 832 kg LXe target, 642 PMTs
- very high light yield, low threshold (0.5 keVee)
- **BUT: no possibility to reject NRs**
- results: (low-mass) WIMPs, inelastic WIMP scat., axions, bosonic superWIMPs, rare decays
- background reduced after commissioning run
- **stable operation since 2 years**
- plans towards XMASS-1.5t and XMASS-II (24t)

→ summary:

- [arXiv:1506.08939](http://arxiv.org/abs/1506.08939)
- background reduced after commissioning run
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**DEAP-3600 @ SNOLAB (CA)**
- **light pulse-shape for discrimination**
  - 3×10⁻⁸ acheived 43-86 keVee
  - prediction: 10⁻¹⁰ above 15 keVee in DEAP-3600
- 3.6t liquid argon target;
  - high ⁴⁰Ar background when using natAr (~1 Bq/kg)
  - under commissioning; fill with LAr in summer first data by late 2015; first DM result in 2016
- sensitivity: 1×10⁻⁴⁶ cm² @ 100 GeV/c²
  - if experiment successful → „upgrade“ to 50t

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Noble Gas: Single Phase Detectors

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Liquid Noble Gases: Detector Concepts

**Single Phase Detector**

- PMT
- Gas
- Liquid target

**Time Projection Chamber**

- Positive HV
- Negative HV
- $E$

**Amplitude vs. Time**

- Single phase detector: S1
- Time projection chamber: S1, S2
Dual Phase TPC

Top

Bottom

3dim vertex reconstruction

double-scatter rejection

151 µs


charge signal S2

light signal S1

XENON100

NR

ER

log_{10}(S2/S1)-ER mean

Energy [keVnr]

S1 [PE]

5 10 15 20 25 30

-1.2 -0.8 -0.4 0.0 0.4

5 10 15 20 25 30 35 40 45 50

NR

ER

charge signal S2

light signal S1

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LXe: Existing dual phase detectors

**XENON100 @ LNGS (IT)**
*Astropart. Phys. 35, 573 (2012)*
- 62 kg LXe, 225×34 kg exposure
- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, ...
- still running as testbench

**LUX @ SURF (USA)**
*NIM A 704, 111 (2013)*
- best sensitivity above ~6 GeV/c²
- 250 kg LXe: 85d×118 kg exp.
- high LY, inside water shield
- currently taking data

**PandaX-I @ CJPL (CN)**
- optimized for low-mass WIMPs
- 120 kg LXe: 80d×54 kg exposure
- final low-mass limit published;
- experiment stopped for upgrade

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LAr TPC: **DarkSide-50 @ LNGS**
*PLB 743, 456 (2015)*
→ working towards a $^{39}$Ar-depleted target (factor ~300)**
Upcoming Detectors

**PandaX-II @ CJPL**
- New SS cryostat with lower radioactivity
- 1.3 tons total mass
- TPC: 60cm × 60cm, 600 kg active target
- ~300 kg fiducial target
- 110 R11410 PMTs, active veto
- Aim for improved light yield
- Under commissioning → science data in 2015

**LZ @ SURF**
- LZ = LUX+ZEPLIN
  - Selected by 2014 US DOE-NSF downselection
- 50× larger than LUX
  - 10t total, 7t active target, 5.6t fiducial target
- 488 R11410 PMTs
- 2015: started procurement of Xe, PMTs, ...
  - 2019: expected start of commissioning
- Goal: $2 \times 10^{-48}$ cm$^2$ @ ~50 GeV/c$^2$ after 15 t×y exp

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XENON1T

dual-phase LXe TPC
- total mass ~3.2 t
- active mass ~2.0 t
- fiducial mass: ~1 t

TPC made from OFHC and PTFE

248 photomultipliers
- Hamamatsu R11410-21
- low background
  arXiv:1503.07698
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments
  JINST 8, P04026 (2013)

Low-background stainless steel cryostats
**XENON1T → XENONnT**

**XENON1T**
- 2t active target
- under construction
- first data 2015

**XENONnT**
- >5t active target
- most components already in place from XENON1T
- projected to start data taking 2018
The XENON Future

![Graph showing WIMP-Nucleon Cross Section vs. WIMP Mass]

- CoGeNT (2013)
- CDMS-Si (2013)
- DAMA/I
- CRESST-II (2012)
- ZEPLIN-III (2012)
- CDMS (2009)
- XENON100 (2012)
- LUX (2013)
- XENON1T
- LZ / XENONnT

"neutrino detection limit"


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate → **ultimate background** for direct detection.
DARWIN: The ultimate WIMP Detector

- Aim at sensitivity of a few $10^{-49}\, \text{cm}^2$, limited by irreducible $\nu$-backgrounds → many non-WIMP science channels (e.g., neutrinos, axions, SN, ...)
- International consortium, 21 groups → R&D ongoing
- DARWIN is on the European astroparticle physics APPEC roadmap and endorsed by the Swiss State Secretariat (SERI)
- Timescale: start after XENONnT

Baseline scenario
- $\sim 40\, \text{t LXe TPC}$
- $\sim 30\, \text{t fiducial mass}$

Illustration only!
- exposure: 200 t x y; **all backgrounds included**
- **likelihood analysis** (~99.98% ER rejection @ 30% NR acceptance)
- S1+S2 combined energy scale, LY=8 PE/keV, 5-35 keVnr energy window

200 t×y: σ < 2.5 x 10^{-49} cm² @ 40 GeV/c²

→ also sensitive to inelastic WIMP interactions

**DARWIN WIMP Sensitivity**

arXiv:1506.08309

accepted by JCAP
**WIMP Spectroscopy**

**Update of Newstead et al., PRD 8, 076011 (2013)**

- Capability to reconstruct WIMP parameters
  - $m_\chi = 20, 100, 500$ GeV/c$^2$
  - $1\sigma/2\sigma$ CI, marginalized over astrophysical parameters
  - due to flat WIMP spectra, no target can reconstruct masses >500 GeV/c$^2$

**Observations:**

- CNNS + neutrons
- solar neutrinos, $^{85}$Kr, $^{222}$Rn, $2\nu\beta\beta$, materials

- WIMP: 30 GeV/c$^2$, $\sigma = 2 \times 10^{-48}$ cm$^2$
- 27 signal events in box

**Exposure:**

- 100 t y; 200 t y
- $2 \times 10^{-48}$ cm$^2$
- $2 \times 10^{-47}$ cm$^2$
- **num. events:** $77,154, 112,224, 29,60$
The WIMP Landscape today

adapted from arXiv:1310.8327
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Exciting times ahead of us

adapted from arXiv:1310.8327
Backup
CoGeNT: excess gone

440 g HPGe p-type detector

CoGeNT: NULL result excluded by $1.9\sigma$
Kelso: best fit achieved w/o signal
(no improvement when considering streams)
Davis: detection crucially depends on equally-well motivated choices for the fraction of bulk events
→ marginalize over possibilities
→ end up with $<1\sigma$ evidence
LXe: Non-WIMP Channels

- **Coherent Neutrino Nucleus Scattering**
  - not observed yet
  - $200 \text{ t} \times \text{y}$: $\sim 200$ evts $> 3 \text{ keVnr}$
    $\sim 25$ evts $> 4 \text{ keVnr}$

- **Low E solar neutrinos: pp, $^7\text{Be}$**
  - test solar model; test neutrino models
  - 1% stat. precision in $100 \text{ t} \times \text{y}$

- **Solar axions and dark matter ALPs**
  - alternative dark matter candidates
  - couple to electrons via axio-electric effect

- **Supernova Neutrinos**
  - sensitive to all neutrino species (CNNS)
    - *complementary information to large-scale neutrino detectors*
  - $O(10)$ events for $\sim 18 \text{ M}_\odot \text{ SN @ 10 kpc}$

- **Neutrinoless Double-Beta Decay**
  - lepton number violating process
  - access to neutrino mass, neutrino hierarchy
  - no $^{136}\text{Xe}$ enrichment required