Direct Dark Matter Searches – Status and Perspectives

Marc Schumann, AEC, Universität Bern

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marc.schumann@lhep.unibe.ch
www.lhep.unibe.ch/darkmatter
Dark Matter Search

Direct Detection

Indirect Detection

Production @Collider
Elastic Scattering of WIMPs off target nuclei → nuclear recoil

\[ v \sim 230 \text{ km/s} \]

\[ E_R \sim O(10 \text{ keV}_{nr}) \]

gamma- and beta-particles (background) interact with the atomic electrons → **electronic recoil** [in keVee]
Direct WIMP Search

Direct Detection:

\[ E_r < 100 \text{ keV} \]
\[ R < 1 \text{ evt/kg/year} \]

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

1 event/kg/yr

1 event/ton/yr

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Direct WIMP Search

**Direct Detection:**

- $E_r < 100$ keV
- $R < 1$ evt/kg/year

**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** (O(1) Hz)
- extremely **low thresholds** (∼2 keV)
- extremely **low radioactive** backgrounds

**WIMP Expectations**

- spin-independent interactions

![Graph showing WIMP detection thresholds and expected event rates.](image)
Background Sources

- **muons**
- **muon-induced neutrons**
- **neutrons from (α,n) and sf**
- **natural γ-bg**
- **target-intrinsic bg: α-, β-, γ-radiation, n; activation, impurities, 2νββ**
- **pp+⁷Be neutrinos → ER signature**
- **pp+⁷Be neutrinos → NR signature**
- **high-E neutrinos → CNNS bg → NR signature**

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**Electronic Recoils** (gamma, beta)

**Nuclear Recoils** (neutron, WIMPs)
Background Suppression

Avoid Backgrounds

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

Use of radiopure materials

Use knowledge about expected WIMP signal

WIMPs interact only once
- single scatter selection
  requires some position resolution

WIMPs interact with target nuclei
- 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

CoGeNT
CDEX
Malbek
DAMIC
NEWS (gas)

SuperCDMS
EDELWEISS

Charge

XENON, LUX/LZ
ArDM, Panda-X
DarkSide, DARWIN

Phonons

CRESST
COSINUS

Light

DEAP-3600, CLEAN
DAMA, KIMS
XMASS, COSINE
ANAIS, SABRE

Tracking:
DRIFT, DMTPC
MIMAC, NEWS
NEWAGE

Superheated Liquids:
PICO
SIMPLE

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

- **spin-independent** WIMP-nucleon interactions
- Coupling unknown
- Asymmetric dark matter
- Coupling strength unknown
- WIMP mass unknown
- Generic WIMPs (e.g. from SUSY)
Detections?

spin-independent WIMP-nucleon interactions
Exclusions?

Some results are missing...
Annual Modulation: DAMA/Libra

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

→ recoil spectrum gets harder and softer during the year
→ annually modulating signal (3% effect)
→ does not require many assumptions
Annual Modulation: DAMA/Libra

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

DAMA finds annual modulation @ 9.3σ CL

BUT: no ER/NR discrimination!

Reconcile DAMA/Libra with the null-results from other experiments assuming leptophilic dark matter?

→ DAMA might see electronic recoils

Examples:
- Axial-vector couplings:
  - 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)

interpretation as (spin-(in)dependent, inelastic) WIMP-nucleon scattering challenged by many experiments
XENON100 excludes DAMA as being due to
- WIMP-e⁻ axial-vector couplings at 4.4σ
- luminous dark matter at 4.6σ
- mirror dark matter at 3.6σ

→ exclude DAMA/Libra as being induced by axial-vector WIMP-electron couplings at 4.8σ

DAMA vs XENON

Science 349, 851 (2015)

PRL 115, 091302 (2015)
New **NaI** Projects to test DAMA

aim at testing the DAMA claim using the same target/detector

→ main challenges: crystal purity, low threshold, target mass

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**SABRE**  
Sodium-iodine with Active Background REjection  

*Strategy*:  
- lower background: better crystals ✓, PMTs  
- liquid scintillator veto against $^{40}K$ (factor 10)  
- lower threshold (PMTs directly coupled to NaI)  
- North (LNGS) and South (Australia)  
- Status: tests with 5 kg crystals ongoing at LNGS

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**DM-Ice**: 17 kg @ South Pole  
**COSINE** = KIMS+DM-Ice  
~100 kg @ Yangyang → start soon  
**ANAIS**: 112 kg @ Canfranc  
→ background ~2-3x DAMA  
**COSINUS R&D**:  
EPJ C 76, 441 (2016)  
NaI with bolometric+light readout

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*P. Urquio (COSMO 2016)*

*arxiv:1602.05939*
Cryogenic Detectors

measure charge and heat (phonons) in crystals: 
\[ E \text{ deposition} \rightarrow \text{temperature rise } \Delta T \]
→ requires detectors at mK temperatures

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

Very good discrimination
→ BUT: need to reject surface events

EDELWEISS (Modane)
→ new low-mass limit \textit{arXiv:1607.03367}

SuperCDMS @ SNOLAB

• selected by NSF-DOE downselection
• \(~50 \text{ kg (upgrade to 400 kg possible)}\)
• low threshold
→ focus on 1-10 GeV/c² mass range
• deeper lab, better materials & shield, improved resolution, electronics, ...
• 100 x 33.3 mm IZPs (1.4 kg Ge, 0.6 kg Si)

First results on low-mass WIMPs

PRL 112, 241302 (2014)
Ge / Si: Status and Prospects

spin-independent WIMP-nucleon interactions

some projects are missing...
Very low WIMP masses

Exremely low threshold for sensitivity to very low-mass WIMPs: amplify signal → HV operation: Neganov-Luke effect to amplify charge signal

\[ E_{\text{tot}} = E_r + E_{\text{Luke}} = E_r + n_{\text{eh}} eV_b \]

\[ = E_r \left( 1 + \frac{eV_b}{e_{\text{eh}}} \right) \]

Initial recoil: 3 eV/pair

Bias voltage

CDMSlite  
*PRL 116, 071301 (2016)*

- 625 g iZIP detector, 70 kg\(\times\)d exposure
- \(V_b=69\) V, **56 eV\text{ee}** threshold! 14 eV\text{ee} resolution
- no ionization measured
  → no ER rejection

EDELWEISS plans:
- 2017: 350 kg\(\times\)d in HV mode
- Afterwards:
  join forces with CDMS

SuperCDMS plans:
- 2018-20: construction
- 2020: begin data taking
CRESST: the low-mass record

CRESST-II @ LNGS
- read phonons and scintillation light
- target: CaWO₄ → multi-element material
- successful background reduction; data taking 2013-2015, 52 kg×d
- new result *EPJ C, 76, 25 (2016)*
  detector with 300 eVnr threshold
**CRESST: the low-mass record**

**CRESST-II @ LNGS**
- read phonons and scintillation light
- target: CaWO$_4$ → multi-element material
- successful background reduction; data taking 2013-2015, 52 kg×d
- new result *EPJ C, 76, 25 (2016)*
detector with 300 eV$_{nr}$ threshold

**CRESST-III: lower threshold to 100 eV$_{nr}$**
- smaller crystals (250 g → 24 g)
- all-scintillating detector design → avoid partial energy depositions
- improve signal-to-noise

**Status:**
- Prototype exceeds design goal: 50 eV$_{nr}$ threshold
- commissioning and calibration started July 2016

*arXiv:1503.08065*
*Reindl @ Lake Louise 2016*
CRESST: Status and Prospects

spin-independent WIMP-nucleon interactions

some projects are missing...
Single Phase Detector

- No high voltage, very high light yield
- \( O(\text{cm}) \) resolution, no double scatter rejection
**Noble Gas: Single Phase Detectors**

**XMASS @ Kamioka (JP)**
- 832 kg LXe target, 642 PMTs
- very high light yield, low threshold (0.5 keVee)
  - **BUT:** no possibility to reject NRs

- background reduced after commissioning run
  - stable data taking since >2 years
- plans towards XMASS-1.5t and XMASS-II (24t)

**DEAP-3600 @ SNOLAB (CA)**
- 3.6t liquid argon target;
  - high $^{39}$Ar background when using $^{nat}$Ar (~1 Bq/kg)
  - filled with LAr since a few weeks
  - start data taking...
  - sensitivity: $1 \times 10^{-46}$ cm$^2$ @ 100 GeV/c$^2$
  - light pulse-shape for discrimination
    - $3 \times 10^{-8}$ achieved in 43-86 keVee
    - prediction: $10^{-10}$ above 15 keVee in DEAP-3600

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Noble Gas: Single Phase Detectors

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**LXe**

**DEAP-3600 @ SNOLAB (CA)**

- Light pulse-shape for discrimination
  - $3 \times 10^{-8}$ achieved in 43-86 keVee
- Prediction: $10^{-10}$ above 15 keVee in DEAP-3600

**LAr**

- $^{nat}$Ar (~1 Bq/kg)

**M. Kuzniak (IDM 2016)**

- Background reduced after commissioning run
- Stable operation since 2 years
- Plans towards XMASS-1.5t and XMASS-II (24t)

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Liquid Noble Gases: Detector Concepts

Single Phase Detector

+ no high voltage, very high light yield
– O(cm) resolution, no double scatter rejection

Time Projection Chamber

+ O(mm) resolution, S2/S1 NR rejection
– technical challenges (HV), less light
Existing dual phase detectors

**PandaX-II @ CJPL (CN)**
*arXiv:1607.07400*
- 60cm×60cm, **500 kg** target
- 2nd largest operational LXe TPC

**LUX @ SURF (USA)**
*arXiv:1608.07648*
- 48cm×48cm, **251 kg** target
- in-situ NR calibration studies

**DarkSide-50 @ LNGS (IT)**
- **46 kg** LAr, which is 39Ar-depleted by a factor 1400
- 71d×37kg exposure
- no event in search region
- taking data
- proposal for DarkSide-20k

New result July 2016:
- combines data from 2 runs (85Kr differs by factor 10)
- 3.3×10^4 kg×d = 0.1 t×y exposure
- no signal excess
- best limit above ~4.5 GeV/c^2
- taking more data

New result July 2016:
- 332d exposure:
  - 3.4×10^4 kg×d = 0.1 t×y
  - no signal excess
  - 2.2×10^{-46} cm^2 @ 50 GeV/c^2

50 PE ~ 25 keVr
High WIMP-masses TPC dominated

≥4.5 GeV/c²

spin-independent WIMP-nucleon interactions

some projects are missing...
XENON1T @ LNGS
**XENON1T → XENONnT**

**XENON1T**
- 2t active LXe target
- largest LXe TPC
- @commissioning
- first science data in 2016

**XENONnT**
- 6t active target
- projected to start in 2018

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Already existing:
- Muon Veto
- Cryostat Support
- Outer Cryostat
- in-LXe Cabling
- LXe storage system
- Cryogenic system
- Purification system
- Kr removal
- DAQ
- 95% of Electronics
- Calibration System
- >300 PMTs
- >4.5t of LXe
- Screening Facilities
- first nT funding
LZ = LUX+ZEPLIN
selected by 2014
US DOE-NSF downselection
● to be installed @ SURF (USA)
● 50× larger than LUX

10t total LXe mass,
7t active target,
5.6t fiducial target

● 488 R11410 PMTs
● 2015: started procurement of xenon gas, PMTs, ... 2020: start operations
● goal: $2 \times 10^{-48}$ cm$^2$ @ ~50 GeV/c$^2$
after 15 t×y exposure
XENON Science Goals

spin-independent WIMP-nucleon interactions

some projects are missing...
Dark Matter Searches: The Future

spin-independent WIMP-nucleon interactions

some projects are missing...
Dark Matter Searches: The Limit

spin-independent WIMP-nucleon interactions

some projects are missing...
Dark Matter Searches: The Limit

Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate → **ultimate background** for direct detection

"neutrino floor"

PRD 89, 023524 (2014)

some projects are missing...
DARWIN: The ultimate WIMP Detector

spin-independent WIMP-nucleon interactions

"neutrino floor"

PRD 89, 023524 (2014)

some projects are missing...
DARWIN The **ultimate** WIMP Detector

- aim at *sensitivity of a few* $10^{-49}$ cm$^2$, limited by *irreducible v-backgrounds*
- international consortium, 21 groups → R&D ongoing
- DARWIN is sensitive to
  - spin-independent,
  - spin-dependent,
  - inelastic WIMP interactions;
  - axions, ALPs
  - supernova neutrinos
  - CNNS
  - low-$E$ solar neutrinos
  - neutrinoless double-beta decay
  - other rare nuclear processes...
- Timescale: start after XENONnT

Illustration only!

**Baseline scenario**
- ~50t total LXe mass
- ~40 t LXe TPC
- ~30 t fiducial mass

**Timescale**

www.darwin-observatory.org
exposure: 200 t \times y; \textbf{all backgrounds included}

200 \ t \times y: \sigma < 2.5 \times 10^{-49} \text{ cm}^2 @ 40 \text{ GeV}/c^2

excellent complementarity to LHC searches

\textbf{if detection before DARWIN} \rightarrow \textbf{“WIMP spectroscopy“}

\textbf{Phys.Dark Univ. 9-10, 51 (2015)}

\textbf{arXiv:1606.07001}
Spin dependence: Threshold Detectors

**PICO** = PICASSO + COUPP @ SNOLAB

- bubble chambers filled with superheated C₃F₈ or CF₃I
  - very good sensitivity to **spin-dependent** interactions
  - bubble forms only above a threshold energy
- almost “immune” to electronic recoils;
  - reject alphas by acoustic discrimination
- challenge: particulate contamination, hysteresis effects

**Recent results:**

PICO-60: largest chamber; >2000 bg events

PICO-2L: cleaning solved bg problem in Run-2

![Images of bubble chambers with tracks and scatters](image1.jpg)

**Upgrade plan:** PICO-500 → SD reach $\sim 10^{-42}$ cm²

![Graph showing WIMP-proton cross section](image2.jpg)
Spin-dependent: Neutron-Only

Liquid xenon detectors dominate neutron-only parameter space

![Graph showing SD WIMP-neutron cross-section vs. WIMP Mass (GeV/c²)]

*PRL 116, 161302 (2016)*

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Exciting times ahead of us