Dark Matter Detection with large LXe / LAr Detectors

Marc Schumann  University of Freiburg

Dark Matter at the Dawn of Discovery, Heidelberg, April 10, 2018

www.app.uni-freiburg.de
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei → nuclear recoil

WIMP

v ~ 230 km/s

Nuclear Recoil

$E_R \sim 0(10 \text{ keV}_{nr})$

Detectable Signal

Electronic Recoil

Recoil Spectra:

- Xenon
- Germanium
- Argon
- Silicon

Rate [events/(t y keV)]

Recoil energy [keV]$

m_\chi = 100 \text{ GeV}/c^2$

$\sigma = 1 \times 10^{-47} \text{ cm}^2$

form factor

$m_\chi [\text{GeV}]$

- 5
- 10
- 20
- 30
- 40
- 50

Events on Ge [keV] [arb. Units]

$E_{nr} [\text{keV}]$

0 10 20 30 40

0 10 20 30 40

M. Schumann (Freiburg) – Direct Detection with LXe/LAr
Direct WIMP Search

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WIMP

v ~ 230 km/s

Nuclear Recoil

$E_R \sim 0(10 \text{ keV}_{nr})$

Detectable Signal

Electronic Recoil

Recoil Spectra:

Xenon

Argon

tiny!

$A^2$

form factor

$\chi^2 - \chi^2$

$\chi^2 = 100 \text{ GeV} / c^2$

$\sigma = 1 \times 10^{-47} \text{ cm}^2$

$m_\chi [\text{GeV}]$

events on Ge [keV] [arb. Units]

m_\chi = 5, 10, 20, 30, 40, 50

$E_{nr} [\text{keV}]

0 10 20 30 40

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Recoil energy [keV_{\text{eV}}]

0 10 20 30 40

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Rate [events/(t \times y \text{keV})]
The WIMP Parameter Space

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

spin-independent WIMP-nucleon interactions

some results are missing...
Current Status

spin-independent WIMP-nucleon interactions

For higher WIMP masses, simply extrapolate limits

liquid noble gas detectors: best results above ~1.8 GeV/c²

some results are missing...
The ultimate Limit

spin-independent WIMP-nucleon interactions

some results are missing...
The ultimate Limit

Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate → ultimate background for direct detection
## Noble Liquid Targets

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Liquid Noble Gases: Detector Concepts

Single Phase Detector

Time Projection Chamber

PMT

pos HV

neg HV

gas

liq uid target

S1

S2

Amplitude vs. Time
**Liquid Noble Gases: Detector Concepts**

### Single Phase Detector

- **XMASS**

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

### Time Projection Chamber

- **XENON1T**

  - + O(mm) resolution, S2/S1 NR rejection
  - – technical challenges (HV), less light
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Operating Detectors

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<tr>
<td>ZEPLIN-III 0.01t</td>
<td>DarkSide-50 0.04t</td>
</tr>
<tr>
<td>LUX 0.25t</td>
<td>DEAP-3600 3.3t</td>
</tr>
<tr>
<td>XENON100 0.06t</td>
<td>ArDM 0.8t</td>
</tr>
<tr>
<td>XENON1T 2.0t</td>
<td>PandaX-II 0.5t</td>
</tr>
<tr>
<td>XMASS 0.8t</td>
<td></td>
</tr>
</tbody>
</table>

now
Current Status

spin-independent WIMP-nucleon interactions

"neutrino floor"
PRD 89, 023524 (2014)

some results are missing...
New DS-50 Limit @ Low Mass

spin-independent WIMP-nucleon interactions

Charge-only Analysis – DarkSide-50

- no light signal (S1) required
  - reduce threshold
- give up z-fiducialization, ER rejection

some results are missing...
Current Status

spin-independent WIMP-nucleon interactions

some results are missing...

„neutrino floor“
PRD 89, 023524 (2014)
New DAMA Result

spin-independent WIMP-nucleon interactions

R. Bernabei @ LNGS SC Meeting 26.03.2018

\[ \Delta E = 0.5 \text{ keV bins} \]

\[ \chi^2(6-20 \text{ keV})/\text{dof} = 35.8/28 \text{ (P-value=15\%)} \]

\[ \chi^2(6-20 \text{ keV})/\text{dof} = 29.8/28 \text{ (P-value=37\%)} \]
Dark Matter implications of DAMA/LIBRA-phase2 results

Sebastian Baum,1, 2, * Katherine Freese,1, 2, 3, † and Chris Kelso4, ‡

We find that canonical (isospin conserving) spin-independent DM-nucleon interactions are no longer a good fit to the observed modulation signal. The canonical spin-independent case is disfavored by the new data, with best fit points of a DM mass of $\sim 8$ GeV, disfavored by 5.1 $\sigma$, or a mass of $\sim 53$ GeV, disfavored by 3.2 $\sigma$. Allowing for isospin violating interactions, we find new best fit regions for spin-independent scattering with suppressed effective couplings to iodine for DM masses of $\sim 10$ GeV or $\sim 45$ GeV.

$\text{R. Bernabei @ LNGS SC Meeting 26.03.2018}$

DM-nucleon scattering excluded by 5 orders of magnitude!

$\chi^{2}(6-20 \text{ keV})/\text{dof} = 35.8/28 \text{ (P-value=15\%)}$

$\chi^{2}(6-20 \text{ keV})/\text{dof} = 29.8/28 \text{ (P-value=37\%)}$

$\Delta E = 0.5 \text{ keV bins}$
Annual Modulation Searches

- dark matter–electron scattering
- 2-phase LXe TPCs operated stably over long periods
  XENON100: 4 years
  LUX: 2 years
- challenges DAMA/LIBRA
  XENON100: $5.7\sigma$
  LUX: ??
News from XENON1T

- release of new result soon
  - 8x more data than 2016
  - 1 year of stable operation

- larger FV: 1.0t → ~1.3t
  - event position in statistical interpretation

- ROI blinded and salted!
Consolidation of the Field

LXe

LUX 0.25t
ZEPLIN-III 0.01t
LZ 7.0t
XENON100 0.06t
XENON1T 2.0t
XMASS 0.8t
PandaX-II 0.5t
PandaX-4t 4.0t
DarkSide-20k 30t
ArDM 0.8t

LAr

XENONnT 6.0t
DarkSide-50 0.04t
DEAP-3600 3.3t
Background Sources (for ton-scale detectors)

- **Muons**
- **Muon-induced neutrons**
- **Neutrons from (α,n) and sf**
- **Natural γ-bg**
- **Target-intrinsic bg: β-radiation; activation, impurities, 2νββ**

**Background Sources**

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

**High-E neutrinos**
- → CNNS bg
- → NR signature

**Neutrons from**
- (α,n) and sf

**Natural γ-bg**

**pp+⁷Be neutrinos**
- → ER signature

**Background Sources**

- **Neutrons from**
  - (α,n) and sf
- **Natural γ-bg**

- **Muons**
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## Relevant Backgrounds

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<thead>
<tr>
<th></th>
<th>LXe</th>
<th>LAr</th>
</tr>
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<tbody>
<tr>
<td><strong>Radioactivity Laboratory (ER, NR)</strong></td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Muon-induced neutrons</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Detector materials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma (ER)</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Neutrons (NR)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Target Intrinsic isotopes (ER)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>⎯</td>
<td>✓</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Neutrinos</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NR: $^{8}$B, atmospheric</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>ER: pp, $^{7}$Be</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Artefacts</strong></td>
<td>??</td>
<td>??</td>
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- all experiments are underground and sufficiently shielded
- all TPCs employ fiducialization and multiple-scatter rejection
ER Background Rejection

Pulse shape discrimination (PSD):
Lifetimes of singlet and triplet states:
\[
\text{Ar: } 5 \text{ ns, } 1.6 \mu\text{s} \quad \text{Xe: } 4 \text{ ns, } 22 \text{ ns}
\]

Ratio \(N_{\text{trip}}/N_{\text{sing}}\) depends on \(dE/dx\)
→ the interaction type

LAr: excellent \(\sim 3 \times 10^{-8}\)
PRC 78, 035801 (2008)

LXe: irrelevant \(\sim 1 \times 10^{-1}\)
NIM A 612, 328 (2010), arXiv:1803.07935

Charge-Light-Ratio (S2/S1):
Signal partition in light/charge depends on \(dE/dx\) → the interaction type
→ works for LXe and LAr (2-phase)
→ significant loss of acceptance

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<th>Edrift [kV/cm]</th>
<th>LY @ 122 keV [PE/keV]</th>
<th>NR acc [%]</th>
<th>ER rej [%]</th>
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<tr>
<td>XENON100</td>
<td>0.53</td>
<td>3.8</td>
<td>40</td>
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<td>30</td>
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<td>0.18</td>
<td>8.8</td>
<td>50</td>
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<td>3.4</td>
<td>4.2</td>
<td>50</td>
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<tr>
<td>K. Ni APP14</td>
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<td>Radioactive Isotopes</td>
<td>$^{136}$Xe (2νββ)</td>
<td>$^{39}$Ar (~1 Bq/kg)</td>
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<tr>
<td>ER Rejection</td>
<td>ok (2-phase only)</td>
<td>excellent</td>
</tr>
<tr>
<td>Odd Isotopes (→ SD couplings)</td>
<td>50% ($^{129}$Xe, $^{131}$Xe)</td>
<td>x</td>
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DarkSide: $^{39}\text{Ar}$-depleted Argon

- extract underground Ar (UAr) in CO$_2$ well in Colorado
- cryogenic distillation @ FNAL

$^{39}\text{Ar}$ reduced by factor $\sim 1400$!

$\rightarrow$ 155 kg UAr produced in 6 years effort

Future: mass-production planned

URANIA @ Colorado
- extract 100 kg/day

Aria @ Sardegna
- column: 350m high, 1.5m OD

Result: DarkSide-50
- 532.4 live-days exposure
- arXiv:1802.07198
November 2017: ARIA top+bottom+1 std module

Final: factor 10 $^{39}$Ar reduction (but lots of UAr lost)
LXe: Krypton Removal

Two methods:
- cryogenic distillation (XMASS, XENON, PandaX)
- chromatography (LUX)

Example:

**XENON1T**

- goal: $^{\text{nat}}$Kr/Xe = 0.2 ppt (below level of pp-neutrinos)
- achieved by novel online distillation: $^{\text{nat}}$Kr/Xe = (0.6±0.1) ppt achieved
- lowest value in LXe experiments ever

XENON1T column has produced a gas sample <0.026 ppt = $2.6 \times 10^{-14}$ (90% CL)
→ 8x cleaner than needed
LXe: Radon Background

Current Strategy
avoid Rn emanation by selecting clean materials

Example:
goal 10 µBq/kg
XENON1T measured (11±2) µBq/kg prelim.

Future Strategy XENONnT
– active Rn removal

– Example: cryogenic distillation
XENON1T distillation column installed @ XENON100
→ demonstrated reduction factor >27 (@ 95% CL)
Upcoming Projects

some results are missing...
DarkSide-20k

G. Fiorillo @ UCLA-DM 2018

- scale up DS-50 by **factor 400**: 30t LAr total
  **20t fiducial**

- focus on high-mass region >400 GeV/c²
- keep strategy for background-free search with 100 t×y exposure
  → depleted underground Ar (URANIA+ARIA)
  → pulse-shape discrimination → high LY needed
  → liquid scintillator n-veto → **NEW: LAr n-veto**
- start @ LNGS within 2021

Readout by two arrays of grouped SiPMs:
14 m² total

Requirements:
- PDE: 45% ✔
- Dark Count Rate: 0.1 Hz/mm² ✔
PandaX-4t

– to be installed at CJPL-II; scale-up by factor 8
– 4t LXe target with $10^{-47}$ cm$^2$ sensitivity to SI interactions
– assembly and commissioning: 2019-2020
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,
● 488 R11410 PMTs
● end 2019: start cold commissioning
  spring 2020: first science data
● goal: 2×10^{-48} cm² @ ~50 GeV/c²
  after 15 t×y exposure
- @ LNGS using existing XENON1T systems
  (existing μ-veto + new n-veto)
→ project funded!

- **3x larger** than XENON1T

- *6.0t active LXe target*
  ~8t total mass

- 494 R11410 PMTs (XENON1T+new)
- start science by *mid 2019*
- goal: factor 10 better than XENON1T

*FC sensitivity estimate @ ~50 GeV/c²*
(conservative, no background subtraction)

*LZ information from: https://idm2016.shef.ac.uk/indico/event/0/contribution/69/material/slides/0.pdf*
DARWIN: The ultimate WIMP Detector

LXe-based

darwin-observatory.org

Exposure:
- 0.1 t\(\times\)y
- 2 t\(\times\)y
- 20 t\(\times\)y
- 200 t\(\times\)y
**DARWIN** The **ultimate** WIMP Detector

*JCAP 11, 017 (2016)*

darwin-observatory.org

---

**Baseline scenario**

~50t total LXe mass  
~40 t LXe TPC  
~30 t fiducial mass

---

**LXe-based**

---

+many other WIMP and non-WIMP channels!

---

Exposure

0.1 t\(\times\)y  
2 t\(\times\)y  
20 t\(\times\)y  
200 t\(\times\)y

---

WIMP mass [GeV/c^2]
WIMP Detection

Backgrounds from JCAP 10, 016 (2015)

- Solar neutrinos, $^{85}$Kr, $^{222}$Rn, 2$\nu$$\beta$$\beta$, materials

- WIMP: $30$ GeV/c², $\sigma = 2 \times 10^{-48}$ cm²

- 40 signal events in box

CNNS+neutrons
DARWIN The ultimate WIMP Detector

Challenges

- Size
  - electron drift (HV)
  - diameter (TPC electrodes)
  - mass (LXe purification)
  - dimensions (radioactivity)
  - detector response (calibration, corrections)

- Backgrounds
  - $^{222}\text{Rn}$: factor 100 required
  - $(\alpha,n)$ neutrons (from PTFE)

- Photosensors
  - high light yield (QE)
  - low radioactivity
  - long-term stability

- etc etc

M. Schumann (Freiburg) – Direct Detection with LXe/LAr
**Outlook: Lots of Science!**

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<td>– spin-independent mid/high mass</td>
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<td>– various inelastic models (χ, n, MiDM, …)</td>
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<td>– $^8$B neutrinos (low E), atmospheric (high E)</td>
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<td>– atmospheric (high E)</td>
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<td>– supernova neutrinos</td>
<td><em>JCAP 1611, 017 (2016)</em></td>
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<td><em>PRD 89, 013011 (2014), PRD 94, 103009 (2016)</em></td>
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<td>– axions, ALPs</td>
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<td>– $^7$Be, pep, CNO flux measurements</td>
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<tr>
<td>– sterile neutrinos</td>
<td><em>JCAP 1611, 017 (2016)</em></td>
<td>2% 10% 15%</td>
<td></td>
</tr>
<tr>
<td>– pp, $^7$Be: precision flux measurements</td>
<td><em>JCAP 01, 044 (2014)</em></td>
<td><em>JCAP 1608, 017 (2016)</em></td>
<td></td>
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<tr>
<td>&lt;1%</td>
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<td><strong>Rare nuclear events</strong></td>
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<td>– $0\nu\beta\beta$ ($^{136}$Xe), 2νEC ($^{134}$Xe), …</td>
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Backup
A priori, we do not know how dark matter WIMPs interact with ordinary matter. Parametrization of interactions leading to WIMP-nucleus scattering:

- **coupling to nucleons**
- **coupling to nuclear spin**

**Spin independent**

\[ L_S \sim \bar{\chi}\chi q\bar{q} \propto A^2 \]

**Spin dependent**

\[ L_A \sim \bar{\chi}\gamma_\mu\gamma_5\chi\gamma^\mu q \propto J(J+1) \]

often: express SD results in **proton-only** or **neutron-only**
Spin-dependent WIMP Couplings

WIMP-neutron scattering:
- dominated by **LXe TPCs**
- also: Ge, NaI, CsI, CF₃I, C₃F₈

WIMP-proton scattering:
- dominated by **bubble chambers** (CF₃I, C₃F₈)
- also: Xe, NaI, CsI

Excellent complementarity to **LHC searches** (ATLAS, CMS)

Excellent complementarity to **indirect searches** (IceCube, SuperK)

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