Dark Matter Searches: Status

spin-independent WIMP-nucleon interactions
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spin-independent WIMP-nucleon interactions

\[ m \geq 4.5 \text{ GeV/c}^2 \rightarrow \text{dominated by LXe TPCs} \]
Dark Matter Searches: The Future

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)
The „Neutrino Floor“

There are different definitions on the market...

Billard et al. *PRD 89 (2014) 023524*

„1-CNNS event line“

Billard et al. *PRD 89 (2014) 023524*

„WIMP discovery limit“

= detect a WIMP at 3σ on top of 500 CNNS events above a LXe threshold of 4 keVnr (infinite E resolution)

→ assuming an unrealistic 100% NR acceptance, a 5300 t × y exposure is required to reach this (4-35 keVnr window)

Another possibility

Expected 90% CL exclusion limit

- only CNNS background
- unrealistic 100% NR acceptance
DARWIN The ultimate WIMP Detector

spin-independent WIMP-nucleon interactions

Exposure

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

some projects are missing...

„neutrino floor“

PRD 89, 023524 (2014)
Detector? – Dual Phase Xenon TPC

- 3d position reconstruction → target fiducialization
- background rejection

**TPC = Time Projection Chamber**

- **Dark Matter WIMP**
  - S1 – Light
  - S2 – Charge
  - = single scatter nuclear recoil
  - → proportional scintillation

- **Background**
  - (β, γ)
  - (neutron)

**Parameters**
- pos HV
  - E~10 kV/cm
- neg HV
  - E~0.5 kV/cm
Background Sources

- **Electronic Recoils (gamma, beta)**
  - pp+\(^7\)Be neutrinos → ER signature
  - Xe-intrinsic bg: \(^{222}\)Rn, \(^{85}\)Kr, 2νββ

- **Nuclear Recoils (neutron, WIMPs)**
  - only single scatters

- **Natural γ-bkg**
  - neutrons from (α,n) and sf

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

- **Muon-induced neutrons**

- **Neutrons from (α,n) and sf**
**DARWIN Backgrounds**

Remaining background sources:
- Neutrinos (→ ERs and NRs)
- Detector materials (→ γ, n)
- Xe-intrinsic isotopes (→ e⁻)

(assume 100% effective shield (~15m) against μ-induced background)

**pp+⁷Be neutrinos**
- ER signature

**γ-bg materials**

**Xe-intrinsic bg:**
- ²²²Rn, ⁸⁵Kr, 2νββ

**Neutrons from**
- (α,n) and sf

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

**Electronic Recoils** (gamma, beta)
- only single scatters

**Nuclear Recoils** (neutron, WIMPs)
Backgrounds

All relevant backgrounds are considered:

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate</th>
<th>Spectrum</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-rays materials</td>
<td>0.054</td>
<td>flat</td>
<td>assumptions as discussed in text</td>
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<tr>
<td>neutrons*</td>
<td>$3.8 \times 10^{-5}$</td>
<td>exp. decrease</td>
<td>average of [5.0-20.5] keVnr interval</td>
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<tr>
<td>intrinsic $^{85}$Kr</td>
<td>1.44</td>
<td>flat</td>
<td>assume 0.1 ppt of $^{nat}$Kr</td>
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<tr>
<td>intrinsic $^{222}$Rn</td>
<td>0.35</td>
<td>flat</td>
<td>assume 0.1 $\mu$Bq/kg of $^{222}$Rn</td>
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<tr>
<td>$2\nu\beta\beta$ of $^{136}$Xe</td>
<td>0.73</td>
<td>linear rise</td>
<td>average of [2-10] keVee interval</td>
</tr>
<tr>
<td>pp- and $^7$Be $\nu$</td>
<td>3.25</td>
<td>flat</td>
<td>details see [19]</td>
</tr>
<tr>
<td>CNNS*</td>
<td>0.0022</td>
<td>real</td>
<td>average of [4.0-20.5] keVnr interval</td>
</tr>
</tbody>
</table>

MC simulation of detector made of main components (PTFE, CU, PMTs): subdominant after ~15 cm fiducial cut

$^{85}$Kr: 2x below XENON1T design (0.03 ppt achieved: EPJ C 74 (2014) 2746)

$^{222}$Rn: 100x below XENON1T design

$^{136}$Xe: assume natural xenon

consider all relevant neutrinos

low-E solar neutrinos dominate ER backgrounds...

...if $^{222}$Rn sufficiently low

exposure: 200 t x y

at rejection levels $\gtrsim$99.95%, NRs from CNNS dominate
Background Rejection

ER rejection factors ~99.98% required (@ 30% NR acc)

Experimental achievements:

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{drift}}$ [kV/cm]</th>
<th>LY @ 122 keV [PE/keV]</th>
<th>NR acc [%]</th>
<th>ER rej [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XENON100</td>
<td>0.53</td>
<td>3.8</td>
<td>40</td>
<td>99.75</td>
</tr>
<tr>
<td>XENON100</td>
<td>0.53</td>
<td>3.8</td>
<td>30</td>
<td>99.90</td>
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<tr>
<td>LUX</td>
<td>0.18</td>
<td>8.8</td>
<td>50</td>
<td>99.0-99.9</td>
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<tr>
<td>ZEPLIN-III</td>
<td>3.4</td>
<td>4.2</td>
<td>50</td>
<td>99.987</td>
</tr>
<tr>
<td>K. Ni</td>
<td>0.2-0.7</td>
<td></td>
<td>50</td>
<td>&gt;99.999</td>
</tr>
</tbody>
</table>

Acceptance improves at lower $E$

Simulation

$JCAP 10, 016 (2015)$

2x more light → 7.5x less leakage

M. Schumann (Freiburg) – DARWIN

higher light yield improves signal resolution → better band separation at given mean values

K. Ni, talk at APP2014
DARWIN WIMP Sensitivity

Reference WIMP mass = 40 GeV/c²

**Exposure**

![Exposure Graph](image1)

5.0-20.5 keVnr, CES 8PE, Rej=99.98%, Acc=30%

**Threshold**

![Threshold Graph](image2)

200 t x y, X.20.5 keVnr, CES 8PE, Rej=99.98%, Acc=30%

**ER rejection**

![ER rejection Graph](image3)

200 t x y, 5.0-20.5 keVnr, CES 8PE, Acc=30%

**Energy Scale**

![Energy Scale Graph](image4)

200 t x y, 5.0-20.5 keVnr, Rej=99.98%, Acc=30%

JCAP 10, 016 (2015)
DARWIN WIMP Sensitivity

- exposure: 200 t × 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

excellent complementarity to LHC searches
SUSY Dark Matter

SUSY under pressure because not found at LHC?
→ true for some very constraint models (CMSSM etc.) but looks different when more parameters are left unconstrained

Example: pMSSM10 ← 10 SUSY parameters, e.g. *EPJ C75, 422 (2015)*

WIMP out of reach of HL-LHC (best-fit regions not covered), but accessible by DARWIN
WIMP Detection

reconstructed energy, based on S1 and S2 signal

DARWIN with 30t LXe fiducial target
WIMP Detection

![Graph showing energy vs. discriminator (log(S2/S1)) for 60 days of data. The x-axis represents energy in keVnr, ranging from 0 to 40. The y-axis represents the discriminator, ranging from -8 to 2. The plot includes a region labeled 5 t x y.](image-url)
WIMP Detection

![Graph showing discriminator vs. energy for 30 t x y over 1 year]
WIMP Detection

 Discriminator $[\alpha \log_{10}(S2/S1)]$

 Energy [keVnr]

 $60 \text{ t} \times \text{y}$

2 years
WIMP Detection

Discriminator $[\propto \log_{10}(S2/S1)]$

Energy [keVnr]

$90 \times t \times y$

3 years
WIMP Detection

\[ \text{Discriminator } \propto \log_{10} \left( \frac{S2}{S1} \right) \]

Energy [keVnr]

150 t × y

5 years
WIMP Detection

6.7 years exposure goal

200 t × y
WIMP Detection

- Solar neutrinos, $^{85}\text{Kr}$, $^{222}\text{Rn}$, $2\nu\beta\beta$, materials
- WIMP: $30 \text{ GeV/c}^2$, $\sigma = 2 \times 10^{-48} \text{ cm}^2$
- 27 signal events in box

CNNS+neutrons
WIMP Spectroscopy

Reconstruction: $2 \times 10^{-47} \text{ cm}^2$

Target Complementarity

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

Reconstruction improves considerably by adding Ge-data to Xe.
Only minimal improvement for Ar.

JCAP 11, 017 (2016)

PRD 83, 083505 (2011)
DARWIN The ultimate WIMP Detector

- aim at sensitivity of a few $10^{-49}$ cm$^2$, limited by irreducible $\nu$-backgrounds
- international consortium, 21 groups → R&D ongoing

Baseline scenario
- $\sim$50t total LXe mass
- $\sim$40 t LXe TPC
- $\sim$30 t fiducial mass

Timescale: start after XENONnT

www.darwin-observatory.org
DARWIN The **ultimate** WIMP Detector

*JCAP 11, 017 (2016)*

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**Challenges**

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

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

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

- etc etc
Challenges

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- R&D within XENON collaboration
- new: two ERC projects
  - ULTIMATE (Freiburg)
  - Xenoscope (Zürich)
DARWIN The **ultimate** WIMP Detector

What (else) can we do with these instruments? other than WIMPs
Interactions in LXe Detectors

from XENON100
Interactions in LXe Detectors

- Coherent scattering off xenon nucleus → nuclear recoil
  - Dark Matter
  - CNNS

SM process, not yet measured. Deviation from expectation → new physics?
Interactions in LXe Detectors

scattering off atomic electrons, excitations etc.
→ electronic recoil
- rare processes detectable if ER background is low

coherent scattering off xenon nucleus
→ nuclear recoil
- Dark Matter
- CNNS

Many science channels are accessible with a multi-ton DARWIN detector thanks to its extremely low ER background.
Axions and ALPs couple to xenon via \textit{axio-electric-effect}
\[\sigma_{AE}(E_A) = \sigma_{pe}(E_A) \frac{g_{AE}^2}{\beta_A} \frac{3E_A^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta_A}{3}\right)\]
→ axion ionizes a Xe atom

\textbf{Axion}
arises naturally in the Peccei-Quinn solution of the strong CP-problem
→ well-motivated dark matter candidate

\textbf{Axion-like particle (ALP)}
generalization of the axion concept, but without addressing strong CP problem
(ALPs = Nambu-Goldstone bosons from breaking of some global symmetry)
Axions and ALPs couple to xenon via *axio-electric-effect*

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pp-Neutrinos in DARWIN

• Neutrinos interact with Xe electrons → electronic recoil signature
• Continuous recoil spectrum → largest rate at low E
pp-Neutrinos in DARWIN

A background for the WIMP search

- Neutrinos interact with Xe electrons → electronic recoil signature
- Continuous recoil spectrum → largest rate at low E

- ER rejection efficiencies ~99.98% at 30% NR efficiency are required to reduce to sub-dominant level
pp-Neutrinos in DARWIN

a new physics channel!

- Neutrinos interact with Xe electrons → electronic recoil signature
- Continuous recoil spectrum → largest rate at low E
  ~0.26 ν evts/t/d in low-E region (2-30 keV)

- 30t target mass, 2-30 keV window → 2850 neutrinos per year (89% pp)
  → achieve 1% statistical precision on pp-flux (→ P_{ee}) with 100 t x y

Differential Recoil Spectrum in Xe

Neutrino interactions
0ν Double-beta Decay

\[ |\text{m}_{\beta\beta}| [\text{eV}] \]

\[ m_{\text{lightest}} [\text{eV}] \]

- **Current limit**
- **Inverted Hierarchy**
- **Normal Hierarchy**
- **DARWIN**
- **DARWIN (ultimate)**

*JCAP 11, 017 (2016)*
Supernova Neutrinos

- $\nu$ from supernovae could be detected via CNNS as well
- signal from accretion phase of a $\sim 18$ $M_{\odot}$ supernova @ 10 kpc is clearly visible in DARWIN
- signal: NRs plus precise time information
- challenge: threshold

*Chakraborty et al., PRD 89, 013011 (2014)*
*Lang et al., PRD 94, 103009 (2016)*
DARWIN – exciting prospects

Science with a 40 t LXe TPC

Nuclear Recoil Interactions

WIMP dark matter  \( \text{JCAP 10, 016 (2015)} \)
- spin-independent mid/high mass
- spin-dependent
  \( \rightarrow \) complementary with LHC, indirect search
- various inelastic models \( (\chi, n, \text{MiDM}, ...) \)

Coherent neutrino-nucleon scattering \( (\text{CNNS}) \)
- \(^8\text{B}\) neutrinos \((\text{low E})\), atmospheric \((\text{high E})\)
- supernova neutrinos
  \( \text{PRD 89, 013011 (2014), PRD 94, 103009 (2016)} \)

Electronic Recoil Interactions

Non-WIMP dark matter and neutrino physics
- axions, ALPs  \( \text{JCAP 1611, 017 (2016)} \)
- sterile neutrinos
- pp, \(^7\text{Be}\): precision flux measurements
  \(<1\%\)
  \( \text{JCAP 01, 044 (2014)} \)

Rare nuclear events
- \(0\nu\beta\beta\ (^{136}\text{Xe})\), \(2\nu\text{EC}\ (^{134}\text{Xe})\), ...