Marc Schumann U Freiburg
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marc.schumann@physik.uni-freiburg.de
www.app.uni-freiburg.de

Top panel: Evolution of the $^{222}$Rn activity concentration in the XENON100 detector during the purification of xenon from traces of the radioactive noble gas radon using a cryogenic distillation column. The seven different phases (roman numerals) show different operational modes of the detector. The gray dashed line shows the expected $^{222}$Rn concentration in the absence of the radon removal system. Bottom panel: Comparison of the $^{222}$Rn activity as determined by the purification method (upper line) and of $^{222}$Rn, $^{220}$Rn, and $^{218}$Po activities in the detector as measured by direct activation.
Dark Matter Searches: Status

spin-independent WIMP-nucleon interactions

![Graph showing cross-section vs. WIMP mass](image)
Dark Matter Searches: Status

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

„neutrino floor“  
PRD 89, 023524 (2014)
Dark Matter Searches: The Limit

COHERENT @ SNS

Observation of coherent elastic neutrino-nucleus scattering

A

Beam OFF

Beam ON

Number of photoelectrons (PE)

Res. counts / 2 PE

0

5

10

15

20

25

30

15

25

35

45

5

10

15

20

Res. counts / 2 PE

1

3

5

7

9

11

1

3

5

7

9

11

Fig. 3. Observation of Coherent Elastic Neutrino-Nucleus Scattering. Shown are residual differences (datapoints) between CsI[Na] signals in the 12 μs following POT triggers, and those in a 12-μs window before,

WIMP mass

1 2 3 4 5 6 8 10 20
spin-independent WIMP-nucleon interactions

Exposure
0.1 t\text{y}
2 t\text{y}
20 t\text{y}
200 t\text{y}

some projects are missing...
Detector? – Dual Phase Xenon TPC

TPC = Time Projection Chamber

Dark Matter WIMP
= single scatter nuclear recoil
S1 – Light

S2 – Charge
→ proportional scintillation

Background ($\beta, \gamma$)

Background (neutron)

• 3d position reconstruction
  → target fiducialization
• background rejection

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Background Sources

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

Only single scatters

- **Muon-induced neutrons**
  - pp+\(^7\)Be neutrinos → ER signature
  - High-E neutrinos → CNNS bg → NR signature

- Neutrons from (α,n) and sf:
  - Neutrons from (α,n) and sf
  - Xe-intrinsic bg: \(^{222}\)Rn, \(^{85}\)Kr, 2νββ
  - Neutrons from (α,n) and sf
  - Natural γ-bg
  - Neutrons from (α,n) and sf
  - Natural γ-bg

- **Electron Recoils** (gamma, beta)
- **Nuclear Recoils** (neutron, WIMPs)
  - Only single scatters
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: \(^{222}\text{Rn}, ^{85}\text{Kr}, 2\nu\beta\beta\)

high-E neutrinos → CNNS bg → NR signature

neutrons from \((\alpha,n)\) and sf

Electronic Recoils (gamma, beta)

Nuclear Recoils (neutron, WIMPs)

only single scatters
Backgrounds

All relevant backgrounds are considered:

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate [events/(t·y·keVₓₓ)]</th>
<th>Spectrum</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-rays materials</td>
<td>0.054</td>
<td>flat</td>
<td>assumptions as discussed in text</td>
</tr>
<tr>
<td>neutrons*</td>
<td>3.8×10⁻⁵</td>
<td>exp. decrease</td>
<td>average of [5.0-20.5] keVnr interval</td>
</tr>
<tr>
<td>intrinsic ⁸⁵Kr</td>
<td>1.44</td>
<td>flat</td>
<td>assume 0.1 ppt of nat Kr</td>
</tr>
<tr>
<td>intrinsic ²²²Rn</td>
<td>0.35</td>
<td>flat</td>
<td>assume 0.1 μBq/kg of ²²²Rn</td>
</tr>
<tr>
<td>²νββ of ¹³⁶Xe</td>
<td>0.73</td>
<td>linear rise</td>
<td>average of [2-10] keVee interval</td>
</tr>
<tr>
<td>pp- and 'Be ν</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

³⁵Kr: 2x below XENON1T design
(0.03 ppt achieved: EPJ C 74 (2014) 2746)
²²²Rn: 100x below XENON1T design
¹³⁶Xe: assume natural xenon

consider all relevant neutrinos

---

At rejection levels ≥99.95%, NRs from CNNS dominate

Exposure: 200 t x y

Low-E solar neutrinos dominate ER backgrounds...
...if ²²²Rn sufficiently low
DARWIN WIMP Sensitivity

- exposure: $200 \, t \times y$; all backgrounds included
- likelihood analysis
- $99.98\%$ ER rejection @ $30\%$ NR acceptance, S1+S2 combined energy scale, $L_Y=8 \, \text{PE/keV}$, $5-35 \, \text{keV}_{nr}$ energy window

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

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

- ER-like (background)
- NR-like (signal)

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

Energy [keVnr]

DARWIN with 30t LXe fiducial target

reconstructed energy, based on S1 and S2 signal
WIMP Detection

60 days

Discriminator $\propto \log_{10} (S2/S1)$ vs. Energy [keVnr]

$5 \times 10^y$
WIMP Detection

![Graph showing energy vs. discriminator with 30 t x y and 1 year](image)

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WIMP Detection

![Graph showing the distribution of WIMP detection results over energy.]
WIMP Detection

Discriminator \[\alpha \log_{10} (S2/S1)\] vs Energy [keVnr]

90 t \times y

3 years
WIMP Detection

Energy [keVnr]

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

150 t × y

5 years
WIMP Detection

exposure goal

200 t × y

6.7 years
WIMP Detection

- CNNS+neutrons
- WIMP: 30 GeV/c², $\sigma = 2 \times 10^{-48}$ cm²
- 40 signal events in box

solar neutrinos, $^{85}$Kr, $^{222}$Rn, $2\nu\beta\beta$, materials
WIMP Spectroscopy

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

**Target Complementarity**

JCAP 11, 017 (2016)

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$^2$

PRD 83, 083505 (2011)

Reconstruction improves considerably by adding Ge-data to Xe.
Only minimal improvement for Ar.
**DARWIN The ultimate WIMP Detector**

- **Goal:** aim at sensitivity of a few $10^{-49}$ cm$^2$, limited by irreducible $\nu$-backgrounds.
- **Collaboration:** international consortium, 24 groups → R&D ongoing.

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

**Timescale:** start after XENONnT

[Link: www.darwin-observatory.org](http://www.darwin-observatory.org)
DARWIN Collaboration

2016 Zürich

2017 Freiburg

(c) HOW Photos
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
  - 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

cohesent 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 **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

**Axion**

arises naturally in the Peccei-Quinn solution of the strong CP-problem

→ well-motivated dark matter candidate

**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

Differential Recoil Spectrum in Xe

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

Neutrino interactions

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

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JCAP 11, 017 (2016)
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 $\nu$ 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
$0\nu$ Double-beta Decay

![Diagram](image.png)

- Current limit
- Inverted Hierarchy
- Normal Hierarchy
- DARWIN
- DARWIN (ultimate)
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 → information on total energy loss in neutrinos → complementary to larger detectors

*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**  
  - spin-independent **mid/high** mass  
  - spin-dependent  
    - complementary with LHC, indirect search  
  - various inelastic models ($\chi$, n, MiDM, ...)

- **Coherent neutrino-nucleon scattering (CNNS)**  
  - $^8\text{B}$ neutrinos (low E), atmospheric (high E)  
  - supernova neutrinos

**Electronic Recoil Interactions**

- **Non-WIMP dark matter and neutrino physics**  
  - axions, ALPs  
  - sterile neutrinos  
  - pp, $^7\text{Be}$: precision flux measurements <1%  

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