The XENON Dark Matter Project: Latest Results and Future Prospects

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On behalf of the XENON collaboration

ALPS 2019
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XENON Collaboration
## Timeline

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
<th>XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2005-2007</strong></td>
<td>25 kg - 15 cm drift</td>
<td>161 kg - 30 cm drift</td>
<td>3.2 ton - 1 m drift</td>
<td>8 ton - 1.5 m drift</td>
</tr>
<tr>
<td><strong>2008-2016</strong></td>
<td>~10⁻⁴³ cm²</td>
<td>~10⁻⁴⁵ cm²</td>
<td>~10⁻⁴⁷ cm²</td>
<td>~10⁻⁴⁸ cm²</td>
</tr>
<tr>
<td><strong>2012-2018</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>2019-2023</strong></td>
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</tbody>
</table>
Dual-phase Time Projection Chamber

- Dual-phase xenon time projection chamber:
  - Detect both light (S1) and charge signals (S2)
  - 3D position reconstruction
  - ER-NR identification
  - Light detected by two arrays of 3” PMTs

Data Taking

- 1 tonne x year exposure in a 1.3 tonne fiducial volume
- Results combines both science runs → 278.8 livetime days
- Signal region blinded (SR1+reblind SR0)
Electronic Recoil Background

- Initially $^{85}\text{Kr}$ dominated → distillation campaign → from 1 ppb to 0.66 ppt
- SR1 $^{222}\text{Rn}$ dominated from material emanation: $\sim 10 \, \mu\text{Bq/kg}$
- Lowest ER background in DM detector: $(82^{+5,-3}_{(\text{syst})} \pm 3_{(\text{stat})}) \text{ events/(t \cdot yr \cdot keV_{ee})}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}\text{Rn}$</td>
<td>85.4</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>4.3</td>
</tr>
<tr>
<td>Solar $\nu$</td>
<td>4.9</td>
</tr>
<tr>
<td>Materials</td>
<td>4.1</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Nuclear Recoil Background

- Radiogenic neutrons: from \((\alpha, n)\) reactions in detector materials

- Coherent elastic \(\nu\)-nucleus scattering: \(^8\)B from the sun

- Cosmogenic neutrons: induced by muons interactions

- 9 neutron multiple scatters identified in the ROI

<table>
<thead>
<tr>
<th>Source</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiogenic (n)</td>
<td>96.5</td>
</tr>
<tr>
<td>CE(\nu)NS</td>
<td>2.0</td>
</tr>
<tr>
<td>Cosmogenic (n)</td>
<td>&lt; 2.0</td>
</tr>
</tbody>
</table>

![Diagram](image.png)
Other Backgrounds

• Accidental coincidence:
  • from lone S1s and S2s paired together
  • Model validated on $^{220}$Rn data

• Surface background:
  • $^{210}$Pb and $^{210}$Po from PTFE
  • Smaller S2 signal $\rightarrow$ leak into the ROI
  • Data-driven model based on $^{210}$Po surface control sample
Background Predictions

- Model in 4-dimensional space: S1, S2, R, Z
- Statistical inference in 1.3t fiducial volume
- Reference region between NR median and -2σ quantile

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>(S2, S1)</th>
<th>(S2, S1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3t</td>
<td>Full</td>
<td>Reference</td>
</tr>
<tr>
<td>ER</td>
<td>627 ± 18</td>
<td>1.62 ± 0.3</td>
<td>1.12 ± 0.21</td>
</tr>
<tr>
<td>Neutron</td>
<td>1.43 ± 0.66</td>
<td>0.77 ± 0.35</td>
<td>0.41 ± 0.19</td>
</tr>
<tr>
<td>CEvNS</td>
<td>0.05 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>AC</td>
<td>0.47 +0.27</td>
<td>0.10 +0.06</td>
<td>0.06 +0.03</td>
</tr>
<tr>
<td>Surface</td>
<td>106 ± 8</td>
<td>4.84 ± 0.4</td>
<td>0.02</td>
</tr>
<tr>
<td>BG TOTAL</td>
<td>735 ± 20</td>
<td>7.36 ± 0.61</td>
<td>1.62 ± 0.28</td>
</tr>
<tr>
<td>WIMPs best-fit</td>
<td>3.56</td>
<td>1.70</td>
<td>1.16</td>
</tr>
<tr>
<td>Data</td>
<td>739</td>
<td>14</td>
<td>2</td>
</tr>
</tbody>
</table>
SI-WIMP Results

- Unbinned profile likelihood analysis in (s1, s2, R) and binned in Z. Model uncertainties included as nuisance parameters

- Events after selections represented with best fit probability pie chart from each component and 200 GeV WIMP
SI-WIMP Results

- Unbinned profile likelihood analysis in (s1, s2, R) and binned in Z. Model uncertainties included as nuisance parameters.

- Events after selections represented with best fit probability pie chart from each component and 200 GeV WIMP.
SI-WIMP Results

- Median sensitivity 7 times better than previous experiments (LUX and PandaX-II)
- Over-fluctuation at higher WIMP masses compatible with background only hypothesis
- Best 90% CL exclusion limit on SI WIMP interaction above 6 GeV/c²
Spin Dependent WIMP Coupling

- WIMP-quark axial vector coupling
- WIMP-neutron scattering more sensitive for $^{129}$Xe and $^{131}$Xe
- Excluded new parameter space in isoscalar theory with axial vector mediator

WIMP-Pion Coupling

- Coupling of WIMP with virtual pion-current between two nucleons
- Correction to SD WIMP analysis
- Same background model as SI analysis

2ν Double Electron Capture of $^{124}\text{Xe}$
2ν Double Electron Capture of $^{124}$Xe

Observation of two-neutrino double electron capture in $^{124}$Xe with XENON1T

XENON Collaboration*
2ν Double Electron Capture of $^{124}$Xe

$^{124}$Xe + 2e$^-$ → $^{124}$Te + 2ν$\text{e}$

- Electrons filling vacancies → detection of X-rays and Auger electrons
- Total energy for double-K shell capture: (64.3±0.6) keV
- Background from $^{125}$I produced by activation of $^{124}$Xe
- Currently leading lower limit from XMASS collaboration
• Blinded region from 56 keV to 72 keV

• Ellipsoidal 1.5 t inner fiducial volume

• Peak at $E = (64.2 \pm 0.5) \text{ keV}$ and $\sigma = (2.6 \pm 0.3) \text{ keV}$

• Significance $4.4\sigma$

$^{124}\text{Xe}$ Double Electron Capture

Half-life $T_{1/2}^{2\nu\text{ECEC}} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22} \text{ y}$
Ongoing Analyses

XENON1T data can be used to explore various detection channels:

- S2 only analysis technique
- Annual modulation
- Migdal effect
- Light dark matter searches
- $0\nu\beta\beta$ of $^{136}\text{Xe}$
- …

Stay Tuned!
XENON1T Tests

- New radon-free pump → reduction by 45%
- Online radon distillation → another 30% reduction
- Factor 4 above XENONnT goal

- Increased purification of gas flow
- 1 ms “electron lifetime”: mean free path of electrons in liquid xenon
- XENONnT goal reached!
XENONnT

To increase sensitivity by one order of magnitude:

$$\sigma_{SI} \sim 10^{-48} \text{ cm}^2$$

Use most of XENON1T subsystem

Increase fiducial mass by factor 4

Reduce background by factor 10

Construction in 2019
New Features

New TPC:
- PMTs from 248 to 494
- 1.5 m length and 1.3 m diameters

LXe purification:
- Fast cleaning → 2500 slpm

Radon distillation column:
- Already tested in XENON1T

Neutron veto:
- 0.2% Gd-doped water in XENON water tank
The DARWIN Project

- 40t active volume
- 2.6 m length and 2.6 m diameter
- 2025
- Will reach the neutrino floor

Sensitive to several rare physics processes:

- SI and SD WIMP
- Light DM: solar axions and ALPs
- Low energy solar neutrinos: pp, \(^7\)Be
- Neutrinoless double beta decay
- Supernova neutrinos
- Coherent neutrino nucleus scattering

http://darwin.physik.uzh.ch

@DarwinObserv
Conclusions

- Lowest background level for TPC DM experiments
- World leading upper limit on SI WIMP-nucleon interaction for masses > 6 GeV/c²
- First detection of two neutrino double electron capture in $^{124}$Xe
- Many analyses ongoing on XENON1T data

- Fast upgrade to XENONnT
- Works already started
Backup Slides
Energy Reconstruction

\[ E = W \cdot \left( \frac{cS1}{g_1} + \frac{cS2_b}{g_2} \right) \]
**Backup DEC**

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**a) Variable in $T_{1/2}^{ECEC}$ calculation**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial mass $m$</td>
<td>0.6</td>
</tr>
<tr>
<td>ROI cut acceptance $\epsilon$</td>
<td>3.4</td>
</tr>
<tr>
<td>$^{124}\text{Xe}$ abundance $\eta$</td>
<td>1.5</td>
</tr>
</tbody>
</table>