Status and Results of the XENON1T Dark Matter Search

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University of California, San Diego
(On behalf of the XENON Collaboration)

NDM2018, IBS, Daejeon, Korea, 2018.6.29-7.4
XENON1T New Results: the most stringent SI limits for WIMP masses above 6 GeV

arXiv:1805.12562, submitted to PRL
The XENON Dark Matter Search Program

XENON10  XENON100  XENON1T  XENONnT

25 kg - 15cm drift  161 kg - 30 cm drift  3.2 ton - 1 m drift  8 ton - 1.5 m drift

~10^{-43} cm^2  ~10^{-45} cm^2  ~10^{-47} cm^2  ~10^{-48} cm^2
The Scientific Goals of the XENON Program

\[ \chi \] incoming DM particles \[ \chi \]

nuclear recoils

\[ M_\chi = 50 \text{ GeV/c}^2, \sigma_{\chi-n} = 1 \times 10^{-46} \text{ cm}^2 \]

15 evt/ton/year > 10 keV
The Scientific Goals of the XENON Program

- **Primary goal**: detecting nuclear recoils from elastic scattering of GeV~TeV scale WIMPs through both SI and SD interactions.

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- **Primary goal**: detecting nuclear recoils from elastic scattering of GeV~TeV scale WIMPs through both SI and SD interactions

- **Other DM channels**:
  - low-mass (GeV-scale) DM through “ionization-only” approach
  - sub-GeV DM via electron scattering
  - axion, ALPs, dark photons etc.

\[
M_\chi = 50 \text{ GeV/c}^2, \quad \sigma_{\chi-n} = 1 \times 10^{-46} \text{ cm}^2
\]

15 evt/ton/year > 10 keV

![Diagram showing incoming DM particles and nuclear recoils](image)
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- **Primary goal**: detecting nuclear recoils from elastic scattering of GeV~TeV scale WIMPs through both SI and SD interactions

- **Other DM channels**:
  - low-mass (GeV-scale) DM through “ionization-only” approach
  - sub-GeV DM via electron scattering
  - axion, ALPs, dark photons etc.

- **Other rare event searches**:
  - 0vbb, DEC
  - solar and supernova neutrinos, etc.

![Diagram](image-url)

\[ M_\chi = 50 \text{ GeV/c}^2, \sigma_{\chi-n} = 1\times10^{-46} \text{ cm}^2 \]

![Graph](graph-url)

- 15 evt/ton/year > 10 keV
The XENON Collaboration: ~165 scientists
Two-phase Xenon Time Projection Chamber for dark matter searches

- Two signals for each event:
  - Energy from S1 and S2 area
  - 3D event imaging: x-y (S2) and z (drift time)
  - Self-shielding, surface event rejection, single vs multiple scatter events
  - Recoil type discrimination from ratio of charge (S2) to light (S1)
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The XENON1T Time Projection Chamber

- 3.2 t LXe @180 K
- 2.0 t active target
- viewed by 248 PMTs
- ~1 meter drift length
- ~1 meter diameter
The XENON1T Dark Matter Experiment at Gran Sasso

Cryogenics & Purification

Kr distillation column & Xe Analytics

Xe Storage & Recovery

DAQ & SC

Muon Veto

Cryostat & LXeTPC

www.xenon1t.org
XENON1T Data taking

- The detector is still running and more data are collected after Feb. 2018

SR0+SR1 combined DM search released: arXiv:1805.12562
The XENON1T Light Detection System

127 PMTs in the top array
121 PMTs in the bottom array
PTFE reflectors & transparent meshes

PMT gain stability
The XENON1T Light Detection System

127 PMTs in the top array
121 PMTs in the bottom array
PTFE reflectors & transparent meshes

PMT gain stability
S1 Position dependence
Improving the liquid xenon purity
Improving the liquid xenon purity

Stability of light and charge yields
Detector Calibrations
Detector Calibrations

$^{83}$mKr: to calibrate the energy response

<table>
<thead>
<tr>
<th>$^8\text{Rb}$</th>
<th>Energy</th>
<th>half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2</td>
<td>347</td>
<td>909</td>
</tr>
<tr>
<td>5/2</td>
<td>338</td>
<td>900</td>
</tr>
<tr>
<td>(3/2)</td>
<td>900</td>
<td>86.2 days</td>
</tr>
<tr>
<td>5/2</td>
<td>571</td>
<td></td>
</tr>
<tr>
<td>5/2</td>
<td>562</td>
<td></td>
</tr>
<tr>
<td>$^{85}$Kr$^{1/2}$</td>
<td>520</td>
<td>41.5</td>
</tr>
<tr>
<td>$^{85}$Kr$^{7/2}$</td>
<td>553</td>
<td>1.83 hours</td>
</tr>
<tr>
<td>$^{85}$Kr$^{9/2}$</td>
<td>530</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>32.1</td>
<td>154 ns</td>
</tr>
<tr>
<td></td>
<td>9.4</td>
<td>stable</td>
</tr>
</tbody>
</table>

$^{85}$Kr: to calibrate the energy response
Detector Calibrations

83mKr: to calibrate the energy response

<table>
<thead>
<tr>
<th>J^+</th>
<th>Energy</th>
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<tbody>
<tr>
<td>5/2</td>
<td>347</td>
<td>338</td>
</tr>
<tr>
<td></td>
<td>61%</td>
<td>50%</td>
</tr>
<tr>
<td>(3/2)</td>
<td>520</td>
<td>590</td>
</tr>
<tr>
<td>5/2</td>
<td>530</td>
<td>16%</td>
</tr>
<tr>
<td>45%</td>
<td>60%</td>
<td></td>
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<td>83Kr 1/2</td>
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<td></td>
</tr>
<tr>
<td>83Kr 9/2</td>
<td>9.4</td>
<td>0</td>
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</table>

220Rn: to calibrate the Electronic Recoils (ERs)

220RnPo α-decays: convection & ions
212Pb β-decay: low-energy calibration
212BiPo decay: half-life measurement
Detector Calibrations

### Calibration with $^{83m}$Kr
- **$^{83m}$Kr** is used to calibrate the energy response.
- **Energy and half-life**:
  - $^{83}$Rb: 5/2, $J^e = 5/2$, $347$ 61%, $338$ 30%, $900$ 6%, half-life 909 days (86.2 days).
  - $^{83}$Kr$^*$: 1/2, $J^e = 7/2^+$, $32.1$, half-life 41.5 hours (1.83 hours).
  - $^{83}$Kr: 9/2$, J^e = 9/2^+$, $9.4$, stable.

### Calibration with $^{220}$Rn
- **$^{220}$Rn**: to calibrate the Electronic Recoils (ERs).
- **Calibration Methods**:
  - **$^{220}$RnPo** $\alpha$-decays: convection & ions.
  - **$^{212}$Pb** $\beta^-$-decay: low-energy calibration.
  - **$^{212}$Bi**Po decay: half-life measurement.

### Neutron Calibration
- **AmBe neutrons** are used to calibrate the Nuclear Recoil (NR) signals.

### DD Neutron Generator
- **Detection System**.
Energy \((g_1, g_2)\) calibration with fixed energy gammas

\[
E = (n_{ph} + n_e) \cdot W = \left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right) \cdot W
\]
Low energy responses to Electronic and Nuclear Recoils are obtained using simultaneous fit to the Rn220 and neutron calibration data with detailed detector geometry and LXe physics model.
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Nuclear Recoil Response in XENON1T

XENON Preliminary
Data selection and signal/background definitions before unblinding

- Search region defined within 3-70 PE in cS1
- Detection efficiency dominated by 3-fold coincidence requirement
- Selection efficiencies estimated from control or MC data samples
- Four-component background model: ER, Surface, AC, NR
Reducing the dominant **electronic recoils background**

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<th>Rate [t^{-1} y^{-1}]</th>
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<tr>
<td>Rn222</td>
<td>620 ± 60</td>
<td>85.4</td>
</tr>
<tr>
<td>Kr85</td>
<td>31 ± 6</td>
<td>4.3</td>
</tr>
<tr>
<td>Solar ν</td>
<td>36 ± 1</td>
<td>4.9</td>
</tr>
<tr>
<td>Materials</td>
<td>30 ± 3</td>
<td>4.1</td>
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<tr>
<td>Xe136</td>
<td>9 ± 1</td>
<td>1.4</td>
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<tr>
<td><strong>Total</strong></td>
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(Expectations in 1-12 keV search window, 1t FV, single scatters, *before ER/NR discrimination*)

JCAP04 (2016) 027
Reducing the dominant electronic recoils background

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JCAP04 (2016) 027

XENON1T (Rn222 dominant)
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JCAP04 (2016) 027

XENON1T (Rn222 dominant)

Kr/Xe~0.66 ppt

Kr85 dominant
Surface Background: reduced-S2 events from Rn-daughters on the PTFE surface
A “lone” S1 or S2 signal produced in light and charge insensitive regions of the TPC may be accidentally combined to produce fake events in signal region.

Empirical model shows an overall small rate in the ROI for NRs:

- Select unpaired S1/S2 from data
- Randomly pair to form events
- Apply selection conditions from analysis
- Performance verified with $^{220}$Rn data and background sidebands
Radiogenic neutrons from \((\alpha, n)\) reactions and fission from \(^{238}\text{U}\) and \(^{232}\text{Th}\): reduced via careful materials selection, event multiplicity and fiducialization.

Coherent elastic \(\nu\)-nucleus scattering, constrained by \(^8\text{B}\) neutrino flux and measurements, is an irreducible background at very low energy (1 keV).

Cosmogenic \(\mu\)-induced neutrons significantly reduced by rock overburden and muon veto.

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<tr>
<td>Radiogenic (n)</td>
<td>0.6 ± 0.1</td>
<td>96.5</td>
</tr>
<tr>
<td>CE(\nu)NS</td>
<td>0.012</td>
<td>2.0</td>
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<td>Cosmogenic (n)</td>
<td>&lt; 0.01</td>
<td>&lt; 2.0</td>
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(Expectations in 4-50 keV search window, 1t FV, single scatters)

JCAP04 (2016) 027
Fiducial volume optimization

- new surface background model allowed inclusion of radius, R, in statistical inference to maximize useful volume. Analysis space became cS1, cS2b, R, and Z
after unblinding

Piecharts indicate the relative PDF of background and the best-fit of 200 GeV/c^2 WIMPs at cross-section of 4.7x10^{-47} cm^2
- unbinned profile likelihood analysis in cS1, cS2, R space
- Example show the best-fit of **200 GeV WIMPs at cross-section of $4.7 \times 10^{-47} \text{ cm}^2$**
- p-value for background-only hypothesis: $\sim 0.2$ for high WIMP masses
- No significant (>3 sigma) excess at any scanned WIMP masses

**Statistical Interpretation**

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**Graphs showing:

1. Events / (bin width x t)
2. SR0+SR1 Discovery p-value**

- Local p-value vs WIMP mass [GeV/c^2]
- Global discovery significance

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**Legend:**
- ER
- Surface
- neutron
- CEvNS
- AC
- WIMP
- Total BG (1.3 t)
- Data (1.3 t)
- Total BG (0.9 t)
- Data (0.9 t)
PandaX/LUX sensitivity
XENON1T sensitivity

- x7 improvement in sensitivity compared to LUX/PandaX-II
- Most stringent SI limits for all WIMP masses above 6 GeV
- ~ 1sigma upper fluctuation at high WIMP masses
What’s the current status of XENON1T?
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- Many physics analysis topics being explored:
  - extending to higher energy: EFT, inelastic DM, DEC, 0vbb, etc.
  - lowest ER rate ever achieved to probe leptophilic dark matter, ER annual modulation, etc.
  - ionization-only search: low-mass (1-10 GeV), light (sub-GeV), and hidden sector dark matter, etc.
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- **XENON1T keeps taking science data** with better detector performance following upgrades (for XENONnT)
  - improved electron lifetime (now reaching ~1 ms)
  - reduced radon in the bulk!
Location/Cost:
Capital cost ~20M$ (50% from non-US groups)

Detector:
1m- drift dual-phase TPC with 3.3 t LXe viewed by 250 3-inch PMTs
Cryostat/Cryogenics built with the idea to upgrade detector by 2018: replace TPC with one of larger sensitive mass (7 tons of Xe) using larger diameter PMT arrays (~400 PMTs) but same drift length.

Shield: 10 m diameter water tank instrumented as Cherenkov muon veto.

Background goal: 100 x lower than XENON100, ~5 x 10^{-2} events/(t-d-keV)

Status: commissioning of all cryogenic plants under way. Detector installation by end of Summer. Start first science run within 2015.

Projected Sensitivity:
10^{-47} cm^2 for 50 GeV WIMP with 2 ton x yr data   (10^{-48} cm^2 for XENONnT)

Upgrading XENON1T to XENONnT
Upgrading XENON1T to XENONnT
Upgrading XENON1T to XENONnT
XENONnT: our detector gets larger and better!

XENON1T Infrastructure and sub-Systems already operative

Some upgrades already implemented and working!

1/10 reduction of background and x10 sensitivity improvement

Fast turnaround: commissioning in 2019

New TPC
5.9-ton Time Projection Chamber

LXe Purification
To achieve fast cleaning of the large LXe volume (5000 SLPM)

Radon Distillation
To online remove the $^{222}$Rn emanated inside the detector

Neutron Veto
To tag and measure in situ neutron-induced background
Summary

• XENON1T placed the most stringent SI limits for all WIMP masses above 6 GeV
• XENON1T keeps taking science data with improved detector performance
• XENONnT is on track, commissioning in 2019, with a x10 boost in sensitivity
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XENON1T keeps taking science data with improved detector performance.

XENONnT is on track, commissioning in 2019, with a x10 boost in sensitivity.

detect this dark matter by 2025!