Search for Dark Matter with The XENON1T Experiment

Marie-Cécile Piro
Rensselaer Polytechnic Institute

On behalf of the XENON collaboration
Outlines

• Direct Detection
• XENON1T at LNGS
• Detector principle
• XENON1T Overview
• Expected Backgrounds
• Status
• Summary and Outlook
Direct detection: Interaction Cross Section

- General form of cross section for the WIMP interaction with matter:

\[ \sigma_A = 4 G_F^2 \left( \frac{M_\chi M_A}{M_\chi + M_A} \right)^2 C_A F(q^2) \]

Nuclear enhancement factor

- Depends on the target used for the detector!

Axial-Vector: Spin-Dependent (SD)

Scalar: Spin-Independent (SI)

\[ C_A^{SD} \propto \left( S_{p,n} \right)^2 \]

\[ C_A^{SI} \propto A^2 \]
Direct Detection with Xenon

- **High mass number**: $A \sim 131$
  - SI interactions scale as $A^2$
- **50% odd isotopes**:
  - $^{129}$Xe, $^{131}$Xe for SD interactions
- **High stopping power**:
  - $Z=54$, $\rho = 3 \text{ g cm}^{-3}$
- **Accessible cryogenic temperatures**:
  - Liquid at 182 K at 2 bar.

- **Low intrinsic radioactivity**:
  - No long-lived radioisotopes (with the exception of $^{136}$Xe, $T_{1/2} = 2.2 \times 10^{21}$ y),
  - $^{85}$Kr can be reduced to sub-ppt
- **Efficient scintillator**:
  - High light yield, light output at 178 nm and fast response.
Finally What we need ???

The detection depends of: WIMP mass, spin coupling, background!

\[ 1\, keV \leq \text{Recoil Energy} \leq 100\, keV \quad \rightarrow \quad \text{Low threshold detectors.} \]

Very low Rate \quad \rightarrow \quad \text{Large volume detectors.}

Background is the principal problem of all Dark Matter experiments!

Enemies: muon-induced neutrons, gammas, neutrons, intrinsic betas decays, alpha background, neutrinos!
XENON AT LNGS

- XENON Experiment is located at Laboratori Nazionali del Gran Sasso in Italy.
- Rock coverage from the mountain of 1.4km (3600 m w.e.)

XENON collaboration
- 21 institutions
- ~150 collaborators
XENON as a detector medium

XENON EXPERIMENT:

• **Active target:**
  Double phase Xenon (gas + liquid).
  → Favourable nucleus for SI.

• **Detector:**
  Time Projection Chamber (TPC) within a cryostat.

• **Read-out:**
  Photomultipliers: 248 PMTs from Hamamatsu.
  [PMT model: R11410-21 (3"), 6 R8520 in the veto region]
XENON1T Detector Principle

**Time Projection Chamber (TPC)**

Initial interaction: Prompt scintillation (LXe)

Drifted electrons: Proportional scintillation (GXe)

→ Background discrimination and fiducialization
XENON1T Detector Principle

- **Background discrimination**: \[ \frac{S_2}{S_{1_{ER}}} > \frac{S_2}{S_{1_{NR}}} \]
- **Z-position**: Drift time proportional to interaction depth
- **X-Y position**: Hit pattern on photo-sensors

*From XENON100*
XENON1T Overview and Status
XENON1T Infrastructure

- Cryogenics & purification
- DAQ and control room
- Xe storage & purification
- Water tank with muon veto and XENON1T detector
Water Tank: a Water Cherenkov Muon Veto

- XENON1T cryostat immersed into 700 m$^3$ of demineralised water.
- Tank cladded with high-reflectivity foils and equipped with 84 high QE PMTs.
- Passive shield against external background as neutrons, gammas from the environment.

* XENON1T Muon Veto paper: JINST 9 P11006 (2014)*
XENON1T: Overview

**Purification System**
- 2 parallel lines
- ~ 100 slpm

**Cryogenic System**
- 2 pulse tube refrigerator (PTRs)
- Cools to liquefy up to 7,000 kg of Xe
- Emergency LN$_2$ cooling

**Cryogenic Pipe**
- PMTs signal / HV cables
- Gas line

**Krypton Column Distillation**
- Separation factor: $10^4$ – $10^5$
- Kr removal: $^{^{37}}$Kr/Xe < 0.026 ppt

**Xe Storage ReStoX**
- Store up to 7.6 tons
- Gas and liquid phase

**Cryostat**
- Double wall vacuum insulated
- Hosting TPC
Purification System

- **High flow parallel purifiers:**
  - Purification for electronegative elements ($O_2$, $H_2O$) with hot zirconium oxide getter.
  - Gas cleaned to one part per billion (ppb)

- **HALO+ Analyser:**
  - Monitor performance of purifier
  - Continuously measure $H_2O$ concentration.

- **Charge/light attenuated by impurities**
- **Outgassing continuously contaminates Xe**
  - Continuous recirculation
- **Cleaning of 3.5 tons of xenon**
  - High flow rate: goal 100 SLPM
Slow Control System

• Ensures the complete safety of the experiment.
• Distributed local controllers per subsystem; central monitoring, control and database.
• Based on industrial process control hardware and software (GE)
• Critical operations are guarded and can be executed only if conditions are safe.

Example of the touch screen of the PUR System
First light!

One of the first S1 and S2 signals from 3 tons of a dual phase Xe TPC

Both charge and light are being detected. The total mass of 3.2 t of LXe is being continuously purified to reach the desired charge yield at the applied field.
**Expected Backgrounds**

*Physics reach of the XENON1T dark matter experiment, JCAP 1604 (2016) no.04, 027"

<table>
<thead>
<tr>
<th>Source</th>
<th>Bgd (eV/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER from materials</td>
<td>~0.07</td>
</tr>
<tr>
<td>$^{222}$Rn (10µBq/kg)</td>
<td>~1.39</td>
</tr>
<tr>
<td>$^{85}$Kr (0.2 ppt of NAT Kr)</td>
<td>~0.07</td>
</tr>
<tr>
<td>$^{136}$Xe 2vβ</td>
<td>~0.02</td>
</tr>
<tr>
<td>Solar neutrinos</td>
<td>~0.08</td>
</tr>
<tr>
<td>Total ER</td>
<td>~1.62</td>
</tr>
<tr>
<td>Total NR</td>
<td>~0.46</td>
</tr>
</tbody>
</table>

Single scatter, 1t FV, [1,12]keVee, [4,50]keVr, 99.75% S2/S1 discrimination, 40% NR acceptance
Total Expected Backgrounds

*Physics reach of the XENON1T dark matter experiment, JCAP 1604 (2016) no.04, 027*

- 3-70 PE S1 region
- 4-50 keV NR energy region
- 2t x y exposure
- 99.75% XENON100- like ER rejection
- 40% NR acceptance

Background estimation:
- Total Nuclear Background: 0.91 events
- Total Electronic Background: 3.25 events
Expected Sensitivity

*Physics reach of the XENON1T dark matter experiment, JCAP 1604 (2016) no.04, 027*
Expected Sensitivity

*Physics reach of the XENON1T dark matter experiment JCAP 1604 (2016) no.04, 027*

Expected to overcome presently world-leading limits just **within 10 days** of data taking in dark matter mode.
Summary and Outlook

• **XENON1T is in commissioning:**
  - Operation of all infrastructures demonstrated.
  - Cherenkov light from muons observed.
  - LXe purification ongoing, electron lifetime increasing.
  - Regular data acquisition / data analysis ongoing.
  - Water tank now is closed and is being filled!

• **First science run expected by this fall**

• **Upgrade to XENONnT:**
  - An order of magnitude better than XENON1T.

* Physics reach of the XENON1T dark matter experiment, JCAP 1604 (2016) no.04, 027"
Thank you for your attention!
Calibrations

Installation in the Water Tank

- Regular PMT gain calibrations with LEDs
- Deployable external and short-lived internal radioisotopes for calibration
- D-D neutron generator for NR band
  → Currently monitoring light yield and Xe purity
Electronic Recoil background

*Physics reach of the XENON1T dark matter experiment, JCAP 1604 (2016) no.04, 027*

ER bkg from material, (1,12) keV

Total ER bkg energy spectrum

ER background in 1 ton FV, (1,12) keV, before ER/NR discrimination

<table>
<thead>
<tr>
<th>Source</th>
<th>Background ([kg·day·keV]⁻¹)</th>
<th>Background [y⁻¹]</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>(7.3 ± 0.7) · 10⁻⁶</td>
<td>30 ± 3</td>
<td>4.1</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>(1.54 ± 0.15) · 10⁻⁴</td>
<td>620 ± 60</td>
<td>85.4</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>(7.7 ± 1.5) · 10⁻⁶</td>
<td>31 ± 6</td>
<td>4.3</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>(2.3 ± 0.3) · 10⁻⁶</td>
<td>9 ± 1</td>
<td>1.4</td>
</tr>
<tr>
<td>Solar neutrinos</td>
<td>(8.9 ± 0.2) · 10⁻⁶</td>
<td>36 ± 1</td>
<td>4.9</td>
</tr>
<tr>
<td>Total</td>
<td>(1.80 ± 0.15) · 10⁻⁴</td>
<td>720 ± 60</td>
<td>100</td>
</tr>
</tbody>
</table>
Nuclear Recoil background

*Physics reach of the XENON1T dark matter experiment, JCAP 1604 (2016) no.04, 027*

<table>
<thead>
<tr>
<th>Source</th>
<th>events / ton / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNNS</td>
<td>$1.8 \pm 0.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>Radiogenic</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>Muon-induced</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

1 t Fiducial volume, (4,50) keV
Before discrimination/NR acceptance
XENON dark matter program

Xenon target = **15 kg**
Sensitivity* (100 GeV, 2007):
\[8.8 \times 10^{-44} \text{ cm}^2\]

Xenon target mass = **62 kg**
Sensitivity* (55 GeV, 2012):
\[2.0 \times 10^{-45} \text{ cm}^2\]

Expected Sensitivity* (50 GeV, 2018):
\[1.6 \times 10^{-47} \text{ cm}^2\]

*S sensitivity increases with exposure (target mass, time) and background reduction

*XENON10
2005 – 2007
Xenon target = 15 kg
Sensitivity* (100 GeV, 2007):
\[8.8 \times 10^{-44} \text{ cm}^2\]

XENON100
2008 – present
Xenon target mass = 62 kg
Sensitivity* (55 GeV, 2012):
\[2.0 \times 10^{-45} \text{ cm}^2\]

XENON1T
2016
Xenon target mass = 2000 kg
Expected Sensitivity* (50 GeV, 2018):
\[1.6 \times 10^{-47} \text{ cm}^2\]

* SI WIMP