Review of liquid noble gas detectors for Dark Matter search and latest results of Xenon1T

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Direct dark matter detection principle

Nuclear Recoil (NR)

$\chi + N \rightarrow \chi + N$
Direct dark matter detection principle

Nuclear Recoil (NR)

\[ \chi + N \rightarrow \chi + N \]

Recoil energy ~1-100 keV

Electronic Recoil (ER)

\( \gamma \) and \( \beta \) particles interact with the atomic electrons → background
How is evolving the field of Direct Detection?

\[ R \sim 0.13 \frac{\text{events}}{\text{kg} \cdot \text{year}} \left[ \frac{A}{100} \times \frac{\sigma_{\chi N}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km.s}^{-1}} \times \frac{\rho_{\odot}}{0.3 \text{ GeV.cm}^{-3}} \right] \]
Direct Detection Techniques

Discrimination is crucial!
- Use technology detecting two signals
- Or if one single signal, it should provide significant discrimination

Phonons/Heat

Ionization

Scintillation

10 meV/ph
100% energy

~1 keV/
few % energy

~10 eV/e
20% energy

Xe, Ar, Ne
Nal

DEAP-3600
CLEAN
XMASS
DAMA, KIMS
DM-Ice
SABRE

CuOre, COupp, PICASSO, PICO

TeO$_2$, Al$_2$O$_3$, LiF, C$_3$F$_8$

CaWO$_4$, BGO

Ge, Si

SuperCDMS
EDELWEISS

Xe, Ar

LUX
LZ
XENON
PandaX
ArDM
DarkSide
Darwin

Ge, CS$_2$, CF$_4$

CoGeNT
CDEX
Malbek
DAMIC
DMTPC
DRIFT

Representative experiments, not meant to be completed
# Noble gases

<table>
<thead>
<tr>
<th></th>
<th>Neon</th>
<th>Argon</th>
<th>Krypton</th>
<th>Xenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Number</td>
<td>10</td>
<td>18</td>
<td>36</td>
<td>54</td>
</tr>
<tr>
<td>Density</td>
<td>1.2</td>
<td>1.4</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>Scintillation ($\gamma$/keV)</td>
<td>30</td>
<td>40</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>85</td>
<td>128</td>
<td>150</td>
<td>178</td>
</tr>
<tr>
<td>Decay Time (ns)</td>
<td>15400</td>
<td>6.3, 1500</td>
<td>2, 91</td>
<td>2.2, 27, 45</td>
</tr>
<tr>
<td>Ionization (e-/keV)</td>
<td>46</td>
<td>42</td>
<td>49</td>
<td>64</td>
</tr>
<tr>
<td>Boiling Point (K)</td>
<td>27.1</td>
<td>87.3</td>
<td>119.8</td>
<td>165.0</td>
</tr>
<tr>
<td>Radioactivity</td>
<td>No</td>
<td>$^{39}$Ar 1Bq/kg (1mBq/kg)</td>
<td>Yes</td>
<td>$^{136}$Xe / Kr can be removed to ppt level</td>
</tr>
<tr>
<td>Price</td>
<td>$$</td>
<td>$ ($$$)</td>
<td>$$$</td>
<td>$$$$$</td>
</tr>
</tbody>
</table>

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Argon main characteristics

- Large abundance
  - Modest price
  - Giant detector are possible

- Relatively compact detectors
  - Self shielding

- Cryogenic feasible: 90K > 77K (LN₂)

- Scalable to large target masses

- Excellent Electronic recoil discrimination event with only light detection

- Need “Shift” Light (128 nm)

- Reduce threshold for detection

- Intrinsic radioactivity (1 - 0.001 Bq/kg)
**Xenon main characteristics**

- Large mass number $A$ (131)
  - Interaction cross section $\propto A^2$

- 50% odd isotopes ($^{129}\text{Xe}$, $^{131}\text{Xe}$)
  - for Spin-Dependent interactions

- Kr can be reduced to ppt levels

- High stopping power
  - active volume is self-shielding

- Efficient scintillator (178 nm)

- Scalable to large target masses

- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization

- Very expensive
**Dual phase TPC: principle**

**TPC = Time Projection Chamber**

S1:
- Photon (λ = 178 nm) from Scintillation process
- Detected by PMTs (mainly bottom array)

S2:
- Electrons drift
- Extraction in gaseous phase
- Proportional scintillation light

3D reconstruction:
- X, Y from top array
- Z from Drift time

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Dual phase TPC: real life

X and Y position from S2 hit pattern on the top PMTs

Z position from drift time

Δt = 151 µs

S1 light signal

S2 charge signal

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DarkSide-50

Darside-50 (LAr) @ LNGS (Italy)

- 35 cm x 35 cm, ~ 37 kg fiducial
- 47.1 d ARr / 70.9 d UAr
- $1.4 \times 10^3$ kg.day / $2.6 \times 10^3$ kg.day
- No excess
- Data taking continue

More info about future of DarkSide on Friday (C. Savarese)

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Darkside analysis

50 days with Atmospheric Ar (AAr) 07->09/2014

70 days with Underground Ar (UAr) 04->07/2015
*Physical Review D, 93 (2016): 081101(R)*

Today, in taking data
> 1 yr lifetime (still blinded)
Particle and Astrophysical Xenon Experiments

PandaX-II (LXe) @ CJPL (China)
- 60 cm x 60 cm, ~400 kg fiducial
- 2nd largest operating LXe TPC
- $3.3 \times 10^4$ kg.day = 0.1 t.year
- No excess
- Data taking for the 2 next years

More info about future of CJPL on Friday (H. Wong)

PandaX II

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PandaX II new results SI limits

Mar. 9-Jun 30 2016, in total 98.7 live-day of under slightly different conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>live time (day)</th>
<th>$E_{\text{drift}}$ (V/cm)</th>
<th>$E_{\text{extract}}$ (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.76</td>
<td>397.3</td>
<td>4.56</td>
</tr>
<tr>
<td>2</td>
<td>6.82</td>
<td>394.3</td>
<td>4.86</td>
</tr>
<tr>
<td>3</td>
<td>1.17</td>
<td>391.9</td>
<td>5.01</td>
</tr>
<tr>
<td>4</td>
<td>63.85</td>
<td>399.3</td>
<td>4.56</td>
</tr>
</tbody>
</table>

arXiv:1607.07400
LUX (LXe) @ SURF (USA)

- 49 cm x 49 cm, ~100 kg fiducial
- 332 live-days
- $3.4 \times 10^4$ kg.day = 0.1 t.year
- No excess
- Stopped

More info about future (LZ) in 1 hour (H. Lippincott)
Instead of traditional blinding, we employ a technique where fake signal events ("salt") are injected into data stream. NOT SIMULATION!!
LUX recent results on SD limits

- 49 cm x 49 cm, ~100kg fiducial
- 332 live-days
- 3.4 x 10^4 kg.day = 0.1 t.year
- No excess

Improvement of a factor of six compared with the results from the first science run – 95 days (PRL, 116, 161302 (2016))

arXiv:1705.03380
23 Institutions
10 Countries
135 Scientists
**Phases of the XENON Program**

**XENON10**
- 2005 – 2007
- 15 cm drift TPC
- Total: 25 kg
- Target: **14** kg
- Fiducial: 5.4 kg

Achieved (2007)
\[ \sigma_{SI} = 8.8 \cdot 10^{-44} \text{ cm}^2 \]
@ 100 GeV/c^2

**XENON100**
- 2008 – 2016
- 30 cm drift TPC
- Total: 161 kg
- Target: **62** kg
- Fiducial: 34/48 kg

Achieved (2016)
\[ \sigma_{SI} = 1.1 \cdot 10^{-45} \text{ cm}^2 \]
@ 55 GeV/c^2

First Results (2017)
\[ \sigma_{SI} = 7.7 \cdot 10^{-47} \text{ cm}^2 \]
@ 35 GeV/c^2

**XENON1T**
- 2012 – 2019
- 100 cm drift TPC
- Total: 3200 kg
- Target: **2000** kg
- Fiducial: 1000 kg

Achieved (2017)
\[ \sigma_{SI} = 7.7 \cdot 10^{-47} \text{ cm}^2 \]
@ 35 GeV/c^2

Projected (2022)
\[ \sigma_{SI} = 1.6 \cdot 10^{-48} \text{ cm}^2 \]
@ 50 GeV/c^2

**XENONnT**
- 2017 (R&D) – 2023
- 144 cm drift TPC
- Total: 8000 kg
- Target: **6000** kg
- Fiducial: 4500 kg

Projected (2022)
\[ \sigma_{SI} = 1.6 \cdot 10^{-48} \text{ cm}^2 \]
@ 50 GeV/c^2

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**XENON1T facility**

**Water shield:** deionized water as passive radiation shield

**Muon veto:** Active muon veto against muon induced neutrons (84 PMTs)

**Cryogenics:** Stable conditions (3.2t LXe)

**Purification:** LXe flow through getters, remove impurities

**DAQ:** Each channel has its own threshold, Flexible software algorithms

**Readout:** Up to 300MB/s for high rate calibrations

**ReStoX:** Emergency recovery up to 7.6 tons of LXe

**Passive:** No active cooling required to keep Xe contained

**Kr Distillation:** Remove Kr from system during fill or online

**Rn Distillation:** Initial tests show promising reduction for Rn
The largest Xe double-phase TPC ever built!

- Active Xe mass: 2 tons.
- Light sensors: 127+121 3” PMTs average QE = 35%
- Fully covered with high reflectivity PTFE to maximize light collection.
- Drift region: 1m height, 1m diameter.
Water Shield filling

- TPC fully immersed in water since July 2016
- Background studies and calibration runs started

Rate decrease with increasing Water level
Detector Stability

- LXe temperature stable at \(-96.07\, ^\circ C\), RMS 0.04 \(^\circ C\)
- GXe pressure stable at 1.934 bar, RMS 0.001 bar
**Xenon purification**

**Goal:** remove electronegative impurities below 1 ppb (O₂ equivalent) in the Xe gas fill and from outgassing of detector’s components with continuous circulation of Xe gas at high speed through hot getters.

**Performance:** evolution of e-lifetime, monitored regularly with ERs calibration sources, well described by physical model. Current value approaching the max drift time of the LXe TPC.

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Background Reduction: $^{85}\text{Kr}$

- Commercial Xe contains $\sim$ ppb of Kr
- Column principle: remove Kr from Xe by means of cryogenic distillation (gases have different boiling points)
- $>6.4 \times 10^5$ separation, output concentration $< 0.048$ ppt
- 5.5 m column, 6.5 kg/hr,

- New approach: Online Distillation
- Successfully reduced Kr to $(0.62 \pm 0.13)$ ppt measured by RGMS

- Background is now radon dominated

arXiv:1702.06942

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Recovery and Storage System: ReStoX

Goals:
- Store up to 7600 kg of Xe in gaseous or liquid/solid phase under high purity conditions
- Fill Xe in ultra-high-purity conditions into detector vessel
- Recover all the Xe from the detector. In case of emergency all Xe can be safely recovered in a few hours

Double walled, high pressure (72 bar) vacuum insulated sphere of 2.1 meter diameter, cooled by LN2 and by an internal LN-based condenser.
**Science Run: Exposure**

- Dark matter exposure: 34.2 Live days
- Calibration Data:
  - $^{83m}\text{Kr} \Rightarrow$ Spacial Response
  - $^{220}\text{Rn} \Rightarrow$ ER-Bands
  - $^{241}\text{AmBe} \Rightarrow$ NR-Bands
- Interrupted by a 5.5 magnitude earthquake

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$E = (n_{ph} + n_{e^-}) = \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \cdot W$

How much energy is needed to produce a quantum (e- or γ): **13.7 eV**

**Light**

+ **Charge**

= **Total quanta**

Conserved!

Excellent linearity with electronic recoil energy from 40 keV to 2.2 MeV
From Kr83m and activated Xe131m, variation in LY and CY is at ~1% level.
Fitting Models to Calibration

• Full modeling of LXe and detector response in cS2_b vs cS1 space

• All parameters fitted with no significant deviation from priors

Novel $^{220}\text{Rn}$ internal source (from $^{228}\text{Th}$)

Efficiencies

- **Detection efficiency** dominated by 3-fold PMTs coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- **Selection efficiencies** estimated from control samples or simulation
  - Data quality and selection cuts tuned to calibraton data of single scarrer (WIMP-like) events
- **Search region** defined within 3-70 PE in corrected S1

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Events remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events (cS1&lt;200 PE)</td>
<td>128144</td>
</tr>
<tr>
<td>Data Quality &amp; Selection</td>
<td>48955</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>180</td>
</tr>
<tr>
<td>3 PE &lt; cS1 &lt; 70 PE</td>
<td>63</td>
</tr>
</tbody>
</table>

**Results:**
- **1042 kg**
### Background Model

- ER and NR spectral shapes derived from models fitted to calibration data
- Other background expectations are data-driven, derived from control samples

<table>
<thead>
<tr>
<th>Background</th>
<th>Total</th>
<th>NR median - 2σ, 3-70pe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic Recoil</td>
<td>(62 ± 8)</td>
<td>0.26 (+0.11)(-0.07)</td>
</tr>
<tr>
<td>Radiogenic neutrons (n)</td>
<td>(0.05 ± 0.01)</td>
<td>0.02</td>
</tr>
<tr>
<td>CNNS (ν)</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Accidental coincidences (acc)</td>
<td>(0.22 ± 0.01)</td>
<td>0.06</td>
</tr>
<tr>
<td>Wall leakage (wall)</td>
<td>(0.52 ± 0.32)</td>
<td>0.01</td>
</tr>
<tr>
<td>Anomalous (anom)</td>
<td>0.09 (+0.12)(-0.06)</td>
<td>(0.01 ± 0.01)</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td><strong>(63 ± 8)</strong></td>
<td><strong>(0.36 ± 0.09)</strong></td>
</tr>
<tr>
<td>50 GeV/c², 10⁻⁴⁶cm² WIMP</td>
<td><strong>(1.66 ± 0.01)</strong></td>
<td><strong>(0.82 ± 0.06)</strong></td>
</tr>
</tbody>
</table>
• Extended unbinned profile likelihood analysis
• Most significant ER & NR shape parameters included from calibration fits
• Normalization uncertainties for all components
XENON1T Results

arXiv:1705.06655

World Best sensitivity
Minimum @ 35 GeV/c² : 7.7x10⁻⁴⁷cm²

WIMP mass [GeV/c²]

WIMP-nucleon σ [cm²]

XENON100 (2016)
PandaX-II (2016)
LUX (2017)
XENON1T (this work)
From XENON1T to XENONnT

Cross Section [cm²] vs. WIMP mass [GeV/c²] plot showing XENON1T, XENONnT, and other experiments.
Upgrade: XENONnT

- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Upgrade starting 2018
Conclusion

- **XENON1T** first results demonstrate that the detector is performing very well

- The measured background is the lowest ever achieved in a DM detector: \((1.93 \pm 0.25) \times 10^{-4}\) events/(kg day keV)

- With only 34.2 days of exposure we have already obtained the best exclusion limit in the world: \(7.7 \times 10^{-47}\) cm\(^2@ 35\) GeV/c\(^2\)

- Up to now, > 100 days additional days of science run have been acquired (and detector still running) and are currently under analysis

- The foreseen sensitivity of **XENON1T** in 2 years is \(1.6 \times 10^{-47}\) cm\(^2\)

- LXe & LAr TPC are leading this field

More info about future of noble liquid on Friday