Review on
Future liquid noble gas detectors

Julien Masbou  Subatech – Université de Nantes
**Direct dark matter detection principle**

Nuclear Recoil (NR)

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

Recoil energy \(~1-100\, \text{keV}\)

Electronic Recoil (ER)

\[ \gamma \text{ and } \beta \text{ particles interact with the atomic electrons} \rightarrow \text{background} \]

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
How is evolving the field of Direct Detection?

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

Threshold & atomic mass

Detector size x time matter

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
# Noble gases

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

- Energy deposit produce both:
  - Electron-ion pair
  - Excited atom states

- Anti-correlation between charge and light → Improve energy resolution
- Excitation depends on \( \frac{dE}{dx} \) → Discrimination capabilities

Examples from DarkSide50
Scintillation and ionization in noble liquids

- Energy deposit produces both:
  - Electron-ion pair
  - Excited atom states

- Anti-correlation between charge and light → Improve energy resolution
- Excitation depends on $dE/dx$ → Discrimination capabilities

Phys. Rev. D93, 072009
LXe (LUX)

Phys. Rev. D93, 081101(R)
LAr (DarkSide)
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
How is evolving the field of Direct Detection?

\[ R \sim 0.13 \frac{\text{events}}{\text{kg} \cdot \text{year}} \left[ \frac{A}{100} \times \frac{\sigma_{\chi N}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km.s}^{-1}} \times \frac{\rho_{\odot}}{0.3 \text{ GeV.cm}^{-3}} \right] \]
DM signal rate is expected to be annually modulating
Peak phase 152 days (June 1)

9.3 \( \sigma \) significance only for single hit phase (144 +/- 7) days
No signal above 6 keV, No ER/NR discrimination

Seems to be convincing evidence, HOWEVER...

Probing the DAMA/LIBRA Anomaly with XENON100

DM signal rate is expected to be annually modulating
Peak phase 152 days (June 1)

9.3 σ significance only for single hit phase (144 +/- 7) days
No signal above 6 keV, No ER/NR discrimination

Seems to be convincing evidence, HOWEVER...
... Null results from many experiments more sensitive than DAMA/LIBRA

➔ Reconcile DAMA/LIBRA with the null-results from other experiments assuming leptophilic dark matter?
➔ DAMA/LIBRA might see electronic recoils?

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
Exclusion of leptophilic Dark Matter

- DAMA/LIBRA experiment observes annual modulation interpretable with leptophilic DM

- Selection of 70 live days of electronic recoil XENON100 data, where DAMA signal is highest

- Assume some model of WIMP coupling to $e^-$ to estimate expected signal in XENON100

- XENON100 steady background level lower than DAMA modulation signal

- Exclusion of several types of DM models as the cause of the annual modulation
  
  Kinematically mixed Mirror DM: 3.6σ Exclusion  
  Luminous DM: 4.6σ Exclusion  
  Axial-vector coupling: 4.4σ Exclusion

XENON100: Science 349, 851 (2015)  
Confirmed by XMASS: PLB 759 272 (2016)
Search for Event Rate Modulation

- Time span: 4 years (477 live-days)
- Temporal evolution of relevant detector parameters studied → no significant correlation with event rate observed
- No evident peak crossing the $1\sigma$ global significance threshold!

Discovery potential:


Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
The amplitude of is also too small compared with the expected DAMA/LIBRA modulation signal in XENON100.

The DM interpretation of DAMA/LIBRA annual modulation as being due to WIMPs electron scattering through axial vector coupling is disfavored at 5.7 $\sigma$ from a PL analysis.

LUX 2013 excludes $g_{AE} > 3.5 \times 10^{-12}$ (90% CL)
- $m_A > 0.12$ eV/$c^2$ (DFSZ model)
- $m_A > 36.6$ eV/$c^2$ (KSVZ model)

LUX 2013 excludes $g_{AE} > 4.2 \times 10^{-13}$ (90% CL) across the range 1-16 keV/$c^2$ in ALP mass
How is evolving the field of Direct Detection?

Detector size x time matter

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
The fight against the background

- **Avoid background**
- **External $\gamma$’s** from natural radioactivity
  - Material screening
  - Self shielding (fiducialization)
- **External neutrons**
  - muon-induced ($\alpha,n$) and fission reaction
  - Material screening (low U and Th)
  - Underground experiments
  - Shield & active veto
- **Internal contamination**
  - $^{85}\text{Kr}$: removed by cryogenic distillation
  - $^{222}\text{Rn}$: removed by cryogenic distillation
  - $^{136}\text{Xe}$: $\beta\beta$ decay, long lifetime ($T_{1/2} = 2.2\times 10^{21}$ years)
  - $^{39}\text{Ar}$: $\beta^-$ decay, 1Bq/kg ($T_{1/2} = 269$ years)

• **Use WIMP properties**
  - No double scatter
  - Exponential spectrum
  - Homogeneously distributed  
    $\rightarrow$ *Position reconstruction*
  - Nuclear recoils  
    $\rightarrow$ *ER/NR Discrimination*

\[
\sigma_{XN} = 1 \times 10^{-44} \text{ cm}^2 \quad m_X = 100 \text{ GeV}
\]
Direct detection with noble liquids (2013)

With Argon

With Xenon
DarkSide goals

(New) Argon Collaboration

Researches from

* DarkSide
* DEAP
* ArDM
* MiniCLEAN

DS-20K

multi-100-T

(Argo/DEAP-nT)

DS-20k: Two-phase argon TPC

- 20 T of low-radioactivity Ar:
  Underground and isotopic depletion
- TPC scaled-up from DS-50
- First large-scale use of SiPMs for light readout

More info about future of DarkSide ~20 min ago
(C. Savarese)

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
Dual phase liquid argon TPC, through a **staged** approach:

**Main goal:** a bg-free experiment  
ER background: $\beta$s and $\gamma$s  
NR background: neutrons

**Background suppression**  
- Ultra-low background materials  
- **Depleted Liquid Argon**  
- Low background photo-detectors  
- Low background material components

**Background identification**  
- **Pulse Shape Discrimination**  
  (PSD)  
- Ionization/scintillation ratio  
- Position  
  reconstruction  
  (surface events)  
- **Multiple scatters within the TPC**

**Active Shielding**  
- **Liquid Scintillator Veto** (LSV)  
- Water Cherenkov against muons (WCD)

---

**The DarkSide experiment at LNGS**

**DarkSide program**

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
$^{39}\text{Ar}$, cosmic ray produced, first forbidden $\beta$ decay: endpoint at 565 keV, $t_{1/2} = 269$ years
Pile up in large TPC (drift time: acquisition window of the order of 1 ms)
~150 kg successfully extracted from a CO$_2$ well in Colorado, detector filled in April 2015

AAr: $\sim 1$ Bq/kg

UA$^8\text{Kr}$ (Global Fit)

$^{39}\text{Ar}$ (Global Fit)

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
Goals:

bg-free search with exposure of 100 t.y (possibly 200 t.y) start taking data by 2021

Same detector concept:
Larger TPC (20 t fiducial)
Larger LSV (8 m diameter)
Larger WT (14 m diameter)

Different readout system
14 m² SiPM array (grouped)

Same need for low-background

UAr procurement

URANIA (Colorado) goal: 100 kg/day
ARIA (>300 m distillation column for even larger detector)

Intense calibration and prototyping

DSPProto: 1 m³ TPC to test SiPM
Neutron calibrations:

ARIS (pulsed neutron beam, single phase)
ReD (dual-phase TPC, directionality)
Simulation of several millions of events (ER and NR) to determine the acceptance to WIMPs, assuming NR + ER background < 0.1 events.

+ Nuclear recoil quenching from DS50

Optimization of PSD parameter for the best sensitivity.

Expected $\geq 200 \times 10^6$ events (1400 depletion) from $^{39}$Ar only in [0,50] keV

Asimulation of the full statistics is ongoing.

1.6 CNNS events expected, likelihood approach in progress.
DEAP-3600 First results

3600 kg argon in sealed ultraclean Acrylic Vessel (1.7 m ID)

Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction

255 Hamamatsu R5912 HQE PMTs 8-inch (Light Sensors)

50 cm light guides + PE shielding provide neutron moderation

Steel Shell immersed in 8 m water shield at SNOLAB

LAr experiment
Single phase

very strict control of materials

New results Shown this week at TAUP 2017

3.5 meters

4.4 days DEAP-3600

SI WIMP-nucleon cross section (cm²)

m_\chi (GeV/c²)
PandaX program

• Particle and Astrophysical Xenon Experiments
  – Formed in 2009, ~50 people
• PandaX-II 500kg results published at PRL
  – World-leading sensitivity in 2016
• Plan to build a 4-ton Xenon detector
  – to push the DM SI sensitivity down to $10^{-47}\,\text{cm}^2$
• With exposure reaching 6 ton-year
• DM SI sensitivity could reach
  ~10^{-47} cm^2
**Future: LZ & XENONnT**

**LZ = LUX + ZEPLIN**
- Same location than LUX
- Turning on by 2020 with 1 000 initial live-days
- 10 tons total, 7 tons active, 5.6t fiducial

**XENONnT:**
- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Upgrade starting 2018
- 8 tons total, 6 tons active, 4.5 t fiducial

More info about LZ last Tuesday (H. Lippincott)

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
Background suppression by veto

Two component outer detector:
  - Gd-loaded liquid scintillator
  - instrumented skin

Fiducial mass:
Xe TPC only: 3.3 T
Xe TPC + skin: 4.2 T
TPC + skin + OD: 5.6 T

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
Screening & Cleaning Every materials

2 ways to avoid contamination:
- Use clean materials
- Continuously clean liquid

XENON1T NR origins

LZ Test in clean room

XENON1T PMT Tests

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
• Dedicated gamma counting facilities
  
  – Primary gamma emitting isotopes: $^{40}\text{K}$, $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{238}\text{U}$, $^{235}\text{U}$, $^{232}\text{Th}$, (U and Th chains also responsible for neutron production)

• Intrinsic radioactivity goals for fixed contamination in detector components: single scatter rate less than 0.4 NR counts and less than $37 \times 10^{-6}$ events/keV/kg/d (37 μdru).

• Direct measurements of radon emanation from construction materials
  
  – Maximum tolerable activity is 10 mBq throughout LXe, 1 mBq goal for emanation
  
  — $^{210}\text{Pb}$ activity on surfaces < 10 mBq/m², 0.5 for inner TPC surfaces

• Screening programs for cryostat titanium, detector PTFE, PMT bases & components, etc

• Robust cleanliness protocols during assembly

---

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017

From C. Ignarra

arxiv:1703.09144
Mostly outgassing from detector materials

- Constant gas phase circulation/purification to maintain free electron lifetime
  - Requirement: 670 μs, already achieved with LUX
- Heated zirconium getter (commercial) removes non-noble impurities
• Kr-85 is an ER-like background (beta emitter)
  – Present in the atmosphere, half life of 10 years

\[ \sim 10,000 \text{ ppt} \rightarrow 3 \text{ ppt} \rightarrow 0.015 \text{ ppt} \quad (0.300 \text{ ppt}) \]

Commercial Xe  LUX  LZ Goal  (LZ requirement)

• 0.015 ppt corresponds to only a shotglass of air in 10 tons of xenon

• Remove via gas charcoal chromatography (with helium carrier gas)
  – Kr has a faster flow rate through activated charcoal than Xe
Kr Removal R&D System at SLAC

- Upgraded version of LUX Kr removal system
- Run through Chromatography Loop to trap Kr
- Then switch to Recovery Loop to recover purified xenon into condenser
Background Reduction: $^{85}$Kr

- Commercial Xe contains ~ 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:1612.04284
EPJC 74, 2746 (2014)
Background Reduction: $^{222}\text{Rn}$

- Successful demonstration of radon removal by cryogenic distillation at XENON100
- Reduction factor of $R > 27$ (95% C.L.)

XENON1T:
- Minimize leakage into purification system at Xe1T (i.e., hermetically sealed pumps)
- Low radon emanation components
- Dedicated radon emanation measurements

arXiv:1702.06942
DM Detection can be around the corner!

- LZ projected (20 t y)
  - 5σ Median Significance 3σ
  - Median Significance
  - 90% CL Median (Baseline)
  - XENON1T 90% CL (2 t y)

\[ \log_{10}(\sigma_p^S) \text{ [pb]} \]
\[ \sigma_p^S \text{ [cm}^2\text{]} \]

- ν-N coherent scattering
- 1 event
- 3σ significance 1000 tonne-years

Julien Masbou, EDU 2017, Quy Nhong, 28th July 2017
**Far future: DARWIN the ultimate detector**

- Based on proved technologies
- Aim at sensitivity of a few $10^{-49}$ cm$^2$, limited by irreducible $\nu$-backgrounds (200 t y)
- R&D started
- 50 tons total LXe
  - 40 tons TPC
  - 30 tons fiducial

*arXiv:1506.08309*

*JCAP 1611 (2016) no.11, 017 arXiv:1606.07001*

---

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
200t·y exposure

\[ v_{\text{esc}} = 544 \pm 40 \text{ km/s} \]

\[ v_0 = 220 \pm 20 \text{ km/s} \]

\[ \rho_\chi = 0.3 \pm 0.1 \text{GeV/cm}^3 \]

Capability on reconstructing the WIMP mass and cross section for various masses (20, 100, 500 GeV/c^2) and cross sections (reference line: XENON1T sensitivity (20ty))
Science goal: SI and SD limits

Adapted from L. Scotto-Lavina

JCAP 1611 (2016) no.11, 017

200 t·y exposure
E=4-50 keV$_{nr}$
30% NR acceptance
99.98% ERrejection
LY=8PE/keV @ 122 keV

Complementarity with the LHC:
Minimal simplified Model with Dirac fermion
Interacting with an axial-vector mediator $g=g_q=g_{DM}$

S.A. Malik et al., Phys. Dark Univ. 9-10 (2015) 51

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
Estimated Timescale

Adapted from L. Scotto-Lavina

XENON1T/nT
&
LZ

DARWIN

2010

2015

2020

2025

2030

R&D

Construction & Commissioning

XE 1T

Commissioning + Science Data

LUX

R&D Constr.

XENONnT

LZ

R&D

ASPERA funded

R&D and Design Study

Engineering studies

Construction & Commissioning

Physics runs

June 2013: Published ASPERA final report

2018 : TDR

Expected HL-LHC “run4”

Today

Julien Masbou, EDU 2017, Quy Nhon, 28th July 2017
And other analysis already published or to come:
- Axions / ALP
- $2\nu$ double electron capture on $^{124}$Xe
- Low mass
- Effective field theories
- Calibration
- ...
- Stay tuned!

PandaX-II continue data taking with ~400kg

XENON1T has analyzed it first result and data taking continue

XENONnT & LZ construction is about to start...

DARWIN is in design study phase