Dark matter search with noble gas two-phase emission detectors
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The widely accepted hypothesis is Particle Dark Matter - elementary particles (relic from Big Bang) with a weak interaction only:

**WIMPs - (Weakly Interacting Massive Particles)**

From astrophysical observations and modern cosmology we know:

\[
\sigma \sim A^2 \quad \text{spin-independent (SI) interaction}
\]

\[
\sigma \sim J(J+1) \quad \text{spin-dependent (SD) interaction}
\]
Two-phase emission detection technique is very suitable for Dark Matter search

This method was proposed by Russian scientists in MEPhI 50 y ago!


Electrons are partly pulled out from the track: recombination is suppressed

Suppression depends on dE/dX

Ratio of SC/EL is different for different kind of particles

Photodetectors (photomultipliers)

Image by LUX Collaboration
Advantages of two-phase noble gas emission detectors for WIMP search

• No long-life own radioactive isotopes (Xe). Ar has cosmogenic $^{39}$Ar, but production of depleted Ar is well developed
• Very low contamination by U/Th, K (can be easily purified by filtering)
• Possibility of discrimination by simultaneous measurements of scintillation and ionization signals in a two-phase mode
• Possibility to build large and even very large (ton-scale) detectors
• 3D position sensitivity => “WALL-LESS” detector!!!
Particle identification is based on comparison of SC and EL signals (on example of XENON10 experiment)

Exclusion plots are produced on the basis of collected statistics
Progress of setting limits on SI WIMP-proton interaction cross-section

In Dark Matter search experiments, the progress of setting limits has increased significantly when liquid noble gas two-phase detectors started operation

Original fig. from L. Baudis 2014
ZEPLIN program

ZEPLIN II – the 1st two-phase emission DM detector
31 kg; 7.2 kg FV

ZEPLIN III – “pancake” geometry; 50 kg total,
12 kg active, 6 kg FV

Boulby mine, U.K. ‘Palmer lab’
1100m, 2.8km water equiv.
10^6 reduction in muon flux
# XENON program
at the Gran Sasso National lab., Italy

![XENON logo](image)

<table>
<thead>
<tr>
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<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
<th>XENONnT</th>
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<tbody>
<tr>
<td>Xe mass [kg]</td>
<td>25</td>
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<td>2300</td>
<td>8400</td>
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<tr>
<td>Target m [kg]</td>
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<td>62</td>
<td>2000</td>
<td>5900</td>
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<tr>
<td>Drift [cm]</td>
<td>15</td>
<td>30</td>
<td>96</td>
<td>150</td>
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<tr>
<td>VETO</td>
<td>NO</td>
<td>NO</td>
<td>Muons</td>
<td>Muons+Neutrons</td>
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<tr>
<td>$\sigma_{SI}$ [cm$^2$]</td>
<td>$8.8 \times 10^{-44}$ @ 100 GeV/c$^2$</td>
<td>$1.1 \times 10^{-45}$ @ 55 GeV/c$^2$</td>
<td>$4.1 \times 10^{-47}$ @ 30 GeV/c$^2$</td>
<td>$1.4 \times 10^{-48}$ @ 50 GeV/c$^2$</td>
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</tbody>
</table>

From A. Giovanni talk @ICHEP 2020
XENON program

DARWIN

<table>
<thead>
<tr>
<th>VETO</th>
<th>Muons+Neutrons</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Fiducial m [kg]</td>
<td>Up to 30000</td>
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<tr>
<td>Drift [cm]</td>
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<tr>
<td>$\sigma_{SI}$ [cm$^2$]</td>
<td>Few $10^{-49}$ @ 50 GeV/c$^2$</td>
</tr>
</tbody>
</table>

Sensitivity to Spin Independent models

Assumed an exposure 200 t (30t FV)

99.98% ER rejection (30% NR acceptance)

Combined (S1+S2) energy scale

Energy window 5-35 keV

Light yield 8 p.e./keV

From A. Giovanni talk @ICHEP 2020
LUX

Large Underground Xenon detector

250 kg in active volume (TPC); 100 kg in FV
LUX-ZEPLIN - LZ

Sensitivity to Spin Independent models
Assumed an exposure 200 t x y (30t FV)
99.98% ER rejection (30% NR acceptance)
Combined (S1+S2) energy scale
Energy window 5-35 keV NR
Light yield 8 p.e. / keV

10 t, 7 t active
PandaX program

China Jinping underground laboratory (CJPL)

PandaX-4T
6 t, 4 t active

PandaX-I
250kg, 120 kg active;
580 kg, 270 active

PandaX-II
2400 m = 6500 m.w.e

5-cm inner & outer copper vessels
20-cm inner PE
40-cm Pb
20-cm outer PE

In Table IV. In the final background numbers, we have also assumed that the final ER rejection efficiency is 99.75% with 40% NR acceptance. After a two-year exposure, the final expected background is 2.5 (ER) and 2.3 (NR) events.

PHYSICS REACH OF THE PANDAX-4T

Given a WIMP mass and WIMP-nucleon scattering cross section, the NR rate and spectrum are calculated using identical formalism as in Refs. [11]. The NR efficiency in PandaX-II (Figure 10) is adopted for the WIMP NR events as well. For simplicity, we assume simple counting experiment with the so-called CLs method [24].

Under the expected background in Table IV, the 90% C.L. WIMP median sensitivity corresponds to a signal of 5 events after selection. The sensitivities for WIMP-nucleon spin-independent and spin-dependent interactions are shown in Figure 12 and Figure 13, respectively, with a 5.6-ton-year exposure. For a WIMP mass of $m_\chi = 40 \text{ GeV}/c^2$, the sensitivity on the interaction cross section reaches a minimum at $6 \cdot 10^{-48} \text{ cm}^2$ for spin-independent interaction. For the spin-dependent interaction, the strongest sensitivity reaches $9 \cdot 10^{-43} \text{ cm}^2$ for the WIMP-neutron-only coupling and $3 \cdot 10^{-41} \text{ cm}^2$ for the WIMP-proton-only coupling.

CONCLUSION
PandaX-4T is a next generation dark matter direct detection experiment with a multi-ton dual phase liquid xenon detector. In this paper we present a comprehensive simulation study of the background from radioactivity in the materials, intrinsic contaminations in the liquid xenon and neutrinos through. The WIMP candidate selection is chosen to be between 1 keV and 10 keV electron equivalent energy, single scattering in anti-coincidence with the veto compartment, and a vertex located in a 2.8-ton fiducial volume. In the NR signal region (with $S_2/S_1$ cut), we estimate the background to be $2.5 \pm 0.3$ ER events and $2.3 \pm 0.4$ NR events for an exposure of 5.6 ton-year. The expected WIMP 250kg, 120 kg active; 580 kg, 270 active...
DarkSide program, LAr two-phase detectors

DarkSide-50 @ Borexino TF in Gran Sasso

~ 46 kg active

Water tank
Veto sphere with LSc inside

URANIA and ARIA projects to obtain large amounts of $^{39}$Ar-free argon

Over 15 published papers, more are coming.

The 532 live days x 46 kg results ($16660 \pm 270$) kg d exposure.

Cuts are studied on 70 live days + AAr data.

The DarkSide-50 is running with UAr since Aprile 2015.

High Mass Analysis
Physical Review D 98 (10), 102006 (2018)

Low Mass Analysis
Physical Review Letters 121 (8), 081307 (2018)

Spin-independent DM-nucleon cross section 90% C.L. exclusion limits
In the range of (1.8-3.5) GeV/c$^2$
Summary

- We can see now a very rapid development over ~ two decades of a two-phase emission detection technology stimulated by Dark Matter search race.
- The Dark Matter search experiments with noble gas two-phase emission detectors have produced the best limits on WIMP-nucleon interaction (from $\sim 10^{-42}\, \text{cm}^2$ by ZEPLIN-II in 2007 to $4.1 \cdot 10^{-47}\, \text{cm}^2$ by XENON1t in 2018)
- The development of two-phase emission detection technology have stimulated the progress in other areas:
  - development of new low-background, low-temperature photodetectors (including new large area SiPMs),
  - development of noble gas purification methods,
  - development of new calibration methods (by $^{83}\text{Kr}$, by $T$),
  - development of new position reconstruction methods,
  - detailed study of the energy transfer processes in liquid noble gases at low energies,
  - etc.