DARWIN-LXe: a future large dark matter and neutrino observatory at LNGS

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University of Zurich
for the DARWIN-LXe consortium

LNGS 2020 Meeting
Assergi, April 28, 2015
DARWIN-LXe General Goals

• Build a dark matter detector capable of exploring the experimentally accessible parameter space for WIMP dark matter

• Base this detector on a TPC filled with Xe in its liquid form, a concept successfully proven by the ZEPLIN, XENON, PandaX, and LUX programs

• Reach a low energy threshold and an absolute ultra-low background, and probe a variety of physics channels
DARWIN-LXe Science Goals: Overview

- **Probe WIMP-nucleon interactions for WIMP masses above 6 GeV/c^2**
  - via spin-independent, spin-dependent and inelastic interactions
  - probe even lower WIMP masses by using the charge signal alone

- **Look for signatures of DM scattering off electrons**

- **Detect solar neutrinos: pp-neutrinos via nu-e scattering, ^8B coherent nu scattering**

- **Search for the neutrinoless double beta decay in ^136Xe**

- **Probe interaction of solar axions and axion-like particles, via the axio-electric effect**

- **Probe sterile neutrinos with masses in the > 10 keV range**

- **Probe bosonic SuperWIMPs via their absorption by Xe atoms**
DARWIN-LXe TPC *baseline* concept

- 30-50 tons LXe in total
- \( \sim \) few \( \times 10^3 \) photosensors
- >2 m drift length
- >2 m diameter TPC
- PTFE walls with Cu field shaping rings
- Background goal: dominated by neutrinos
Science reach: WIMP physics with xenon

Probe WIMP-Xe interactions via:

- spin-independent elastic scattering: $^{124}\text{Xe}$, $^{126}\text{Xe}$, $^{128}\text{Xe}$, $^{129}\text{Xe}$, $^{130}\text{Xe}$, $^{131}\text{Xe}$, $^{132}\text{Xe}$ (26.9%), $^{134}\text{Xe}$ (10.4%), $^{136}\text{Xe}$ (8.9%)
- spin-dependent elastic scattering: $^{129}\text{Xe}$ (26.4%), $^{131}\text{Xe}$ (21.2%)
- inelastic WIMP-$^{129}\text{Xe}$ and WIMP-$^{131}\text{Xe}$ scatters

\[
\chi + ^{129,131}\text{Xe} \rightarrow \chi + ^{129,131}\text{Xe}^* \rightarrow \chi + ^{129,131}\text{Xe} + \gamma
\]

1 ns, 0.5 ns 40 keV, 80 keV

SI, elastic WIMP-nucleus

SD, elastic WIMP-nucleus

SD, inelastic WIMP-nucleus


Physics reach: low WIMP masses

- Achieve a lower energy threshold for NRs if the energy is measured by the S2 signal (e\textsuperscript{-}), with ~ 20-25 PE per extracted e\textsuperscript{-} in the gas phase

- **XENON10**: threshold of $E_{nr} \sim 1 \text{ keV}$ reached

- **XENON100**: analysis ongoing

- Loss of S2/S1 discrimination: sensitivity reduction by ~ factor 100, compared to higher WIMP masses; acceptable because at low WIMP masses the solar neutrinos will dominate the NR rate

- **LUX (APS2015)**: ionization signal absolutely measured below 1 keV$_{nr}$
Backgrounds
Backgrounds: nuclear recoils

- **Radiogenic** goal: \(<7 \times 10^{-4}\) events/(t y)
  - active LS veto around cryostat under study

- **Cosmogenic** (MC: \(7.3 \times 10^{-10}\) n/(cm² s) for \(E_n > 10\) MeV)
  - \(<0.01\) events/(t y) in XENON1T/nT shield
  - \(<0.003\) events/(t y) in 14 m diameter water shield

- **XENON1T** muon veto performance must be improved by \(~\) a factor of 10 (very conservative)

- Alternative: line the experimental hall with muon veto (multi-layered proportional tubes, as in Soudan Lab)
Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- $^{222}$Rn in LXe
- $^{85}$Kr in LXe ($^{nat}$Kr contains $2 \times 10^{-11} \ ^{85}$Kr)
- $^{136}$Xe double beta decay
- Solar neutrinos (mostly pp, $^{7}$Be)

### Materials: strong self-shielding by dense LXe

<table>
<thead>
<tr>
<th>Channel</th>
<th>Before discr</th>
<th>After discr (99.98%)</th>
</tr>
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<tbody>
<tr>
<td>$pp + ^{7}$Be neutrinos</td>
<td>95</td>
<td>0.488</td>
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<tr>
<td>Materials</td>
<td>1.4</td>
<td>0.007</td>
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<td>$^{85}$Kr in LXe (0.1 ppt $^{nat}$Kr)</td>
<td>40.4</td>
<td>0.192</td>
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<td>$^{222}$Rn in LXe (0.1 µBq/kg)</td>
<td>9.9</td>
<td>0.047</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>56.1</td>
<td>0.036</td>
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1 t x yr exposure, 2-30 keVee
200 t x yr exposure 4-50 keVnr, 30% acceptance
Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- $^{222}\text{Rn}$ in LXe
- $^{nat}\text{Kr}$ in LXe ($^{nat}\text{Kr}$ contains $2 \times 10^{-11}$ $^{85}\text{Kr}$)
- $^{136}\text{Xe}$ double beta decay
- Solar neutrinos (mostly pp, $^{7}\text{Be}$)

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1 t x yr exposure, 2-30 keVee
200 t x yr exposure, 4-50 keVnr, 30% acceptance
WIMP physics
WIMP physics: spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses (20, 100, 500 GeV/c²) and a spin-independent cross section of $2 \times 10^{-47}$ cm² (assuming different exposures)

![Graph showing 1 and 2 sigma credible regions after marginalizing the posterior probability distribution over $m_\chi$ and $\sigma_{SI}$ for different exposures.]

$v_{esc} = 544 \pm 40$ km/s
$v_0 = 220 \pm 20$ km/s
$\rho_\chi = 0.3 \pm 0.1$ GeV/cm³

Update: Newstead et al., PHYSICAL REVIEW D 88, 076011 (2013)
WIMP physics: sensitivity

- \( E = [3-70] \text{ pe} \sim [4-50] \text{ keV}_{nr} \)

200 t y exposure, 99.98% discrimination, 30% NR acceptance, \( LY = 8 \text{ pe/keV} \) at 122 keV

Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV
WIMP physics: complementarity with the LHC

- Minimal simplified DM model with only 4 variables: $m_{DM}$, $M_{med}$, $g_{DM}$, $g_q$
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

\[ \sigma_{DD} \propto \frac{g_{DM}^2 g_q^2 \mu^2}{M_{med}^4} \]

**Spin independent**
- 90% CL projected limits
- SuperCDMS (Ge+Si) 90% CL projected limits
- LZ 10 t yr single-GeV limit
- DARWIN 100 t yr single-GeV limit

**Spin dependent**
- 90% CL projected limits
- LZ 10 t yr single-GeV limit
- DARWIN 100 t yr single-GeV limit
Technical challenges
Technical challenge: discrimination

- **A level of 99.98% needs factor of 5 improvement w.r.t. XENON100**

  ➡ high light yield - R&D for high (4-pi) coverage with photosensors is ongoing; options are high QE PMTs, SiPMs and/or GPMs; single-phase TPC

  ➡ strong R&D program in place

  ➡ high stats ER band calibrations - internal sources, for instance tritiated methane à la LUX; also $^{220}$Rn

![LUX Tritium calibration using CH$_3$T (inert)](image)

A. Breskin, L. Arazi: bialkali GPM stable operation at gain of $10^5$
Technical challenge: discrimination

- **Best value in LXe by ZEPLIN-III, 99.987%**
- **LUX: 99.9% - 99% (at 50% NR acceptance)**
- **K. Ni: ER power > 10^5 at 50% acceptance**
  - weak dependance on field strength, but field uniformity crucial

<table>
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<tr>
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<th>Field (kV/cm)</th>
<th>Light yield (pe/keVee, for 122 keV at zero field)</th>
<th>Energy ROI (keVnr)</th>
<th>NR acceptance</th>
<th>ER rejection power</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEPLIN-II</td>
<td>1.0</td>
<td>1.1</td>
<td>14-58</td>
<td>50%</td>
<td>98.5%</td>
</tr>
<tr>
<td>XENON10</td>
<td>0.73</td>
<td>5.4</td>
<td>4.5~26.9</td>
<td>45%~49%</td>
<td>99.9~99.3%</td>
</tr>
<tr>
<td>ZEPLIN-III</td>
<td>3.4</td>
<td>3.1-4.2</td>
<td>7-35</td>
<td>~50%</td>
<td>99.987%</td>
</tr>
<tr>
<td>XENON100</td>
<td>0.53</td>
<td>3.8</td>
<td>6.6-43.3</td>
<td>60%~20%</td>
<td>99.75%</td>
</tr>
<tr>
<td>LUX</td>
<td>0.18</td>
<td>8.8</td>
<td>3-27</td>
<td>50%</td>
<td>99.9~99%</td>
</tr>
</tbody>
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LUX discrimination

K. Ni, AP2014

Nuclear recoil equivalent energy[keVnr]

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<tr>
<td>200V/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700V/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000V/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Preliminary
Technical challenge: HV, drift field

- Electron drift length of >2 m, high purity, and uniform field at the 1% level

- HV to bias the cathode must be -100 to -200 kV to have a drift field of 0.5 - 1 kV/cm
  - build long, >2m TPC demonstrator(s)

- Robust, and transparent grid or wire electrodes with >2 m diameter

- Challenge is to combine thin wires O(100 µm) to ensure high LCE
  - build shallow, >2m diam. TPC demonstrator(s)

- Very precise, 3D field simulations based on the BEM technique
Technical challenge: liquid target

- Procurement, storage, cooling, high-speed purification of 30-50 t of LXe
  - coordinate procurement among institutions, funding agencies and companies
- Storage: à la ReStoX, developed for XENON1T/nT, acts as a demonstrator
  - possible solution: a network of connected ReStoX, with a main storage directly connected to the cryostat
  - study a different mechanism for recovery, based on gravity (recovery pipe below cryostat)
Technical challenge: backgrounds

• **ER dominance by solar neutrinos needs:**
  
  ➡ low intrinsic levels of $^{85}$Kr and $^{222}$Rn

- $^{85}$Kr: 0.1 ppt $^{nat}$Kr (0.2 ppt $^{nat}$Kr => same background level as solar neutrinos)
  - 0.2 ppt is goal for XENON1T, factor 20 better than this already achieved by Münster group*: separation factor $> 120000$!

- $^{222}$Rn: 0.1 µBq/kg (1 µBq/kg => same background level as solar neutrinos)
  - 1 µBq/kg is goal for XENON1T: control Rn levels with low-emanation materials & cryogenic distillation (use different vapour pressure), adsorption

*M. Murra, Münster, DPG 2015: Purified liquid out: $^{nat}$Kr/Xe < 26e-15 = 26 ppq (90% CL); measured with MPIK RGMS system
Other physics channels
Physics reach: solar neutrinos \( \nu + e^- \rightarrow \nu + e^- \)

- Rate of solar neutrinos > 2 keV
  \[ R_{pp} \approx 1.05 \text{ events/(t d)} \]
  \[ R_{7\text{Be}} \approx 0.51 \text{ events/(t d)} \]

- \text{pp} neutrinos (2-30 keV):
  - 1714 events/(20 t x yr)

- \text{7Be} neutrinos (2-30 keV):
  - 214 events/(20 t x yr)
    - \( ^{220}\text{Rn} \): 0.1 µBq/kg; \( ^{\text{nat}}\text{Kr} \): 0.1 ppt
    - Reach ~ 1% precision after 5 years

Details see: L. Baudis et al, JCAP01 (2014) 044
Physics reach: solar neutrinos \( \nu + e^- \rightarrow \nu + e^- \)

- Reach \( \sim \) 1\% precision after 5 years
- Test different oscillation scenarios, for instance non-standard neutrino interactions that can modify the \( P_{ee} \) of electron neutrinos as a fct of energy
- Even higher stats can be reached with:
  - increased energy range (Xe depleted in \(^{136}\)Xe)
  - larger fiducial mass

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Borexino, Nature 512 (2014) 383
Physics reach: solar axions

Look for solar axions via their couplings to electrons, $g_{ae}$, through the axio-electric effect

$$\sigma_{ae} = \sigma_{pe}(E_A) \frac{g_{ae}^2}{\beta_A} \frac{3E_A^2}{16\pi\alpha_{em}m_e^2} \left(1 - \frac{\beta_A^2/3}{3}\right)$$

$$\phi_A \propto g_{ae}^2 \implies R \propto g_{ae}^4$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- Factor of ~10 improvement with DARWIN
Physics reach: galactic axion-like particles (ALPs)

Look for ALPs via their couplings to electrons, $g_{AE}$, through the axio-electric effect

Expect line feature at ALP mass

assume $\rho_{dm} = 0.3 \text{ GeV/cm}^3$

$$\phi_A = c \beta_A \times \frac{\rho_{dm}}{m_A}$$

$$R \propto g_{AE}^2$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- **Factor of ~100 improvement with DARWIN**
Physics reach: double beta decay

- $^{136}$Xe: Q-value = 2458.7 ± 0.6 keV
- Fiducial mass of 6 t of xenon
- sensitivity to the neutrinoless double beta decay of $^{136}$Xe:
  - $T_{1/2} > 5.6 \times 10^{26}$ yr (95% CL) in 30 t yr
  - $T_{1/2} > 8.5 \times 10^{27}$ yr (95% CL) in 140 t yr, assuming negligible backgrounds from detector materials
Physics reach: bosonic SuperWIMPs

- Bosonic, light, super weakly interacting cold dark matter (mass in the 10-100 keV range)
- Scattering cross section is many orders of magnitude below the weak-scale cross section, but such particles could be absorbed in LXe and produce a detectable signal

- Signature: a line at the rest mass of the boson

\[
R \simeq \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \frac{m_a}{\text{keV}} \frac{\sigma_{\text{photo}}}{b} \text{ kg}^{-1} \text{ d}^{-1}
\]

\[
g_{aee} = \frac{2m_e}{f_a}
\]

\[
R \simeq \frac{4 \times 10^{23}}{A} \frac{\alpha}{\alpha'} \frac{\text{keV}}{m_V} \frac{\sigma_{\text{photo}}}{b} \text{ kg}^{-1} \text{ d}^{-1}
\]

M. Pospelov, A. Ritz, M. Voloshin, PRD 78, 2008
Physics reach: heavy sterile neutrinos

- DARWIN-LXe can explore physics scenarios in which neutrino interactions with electrons are enhanced due to BSM processes:
  - new interactions between neutrinos and $e^-$ mediated by a very light or massless particle (these would dominate the SM rates at low energies relevant for DD)
- A: nu with magnetic moment of $0.32 \times 10^{-10} \mu_B$
- B, C, D: $A'$-mediated nu-$e^-$ scattering (sterile neutrinos heavier than $\sim 10$ keV)
- $A'$ is a new light gauge boson ("dark photon") that has a small kinetic mixing with the photon

**Exploring $\nu$ signals in dark matter detectors**

Roni Harnik, Joachim Kopp and Pedro A.N. Machado
Risks, costs, requests, timeline, consortium
Technical risks

• A good mix of scaling up our present know-how (XENON10->XENON1T/nT) and higher risk activities, with well-established fallbacks

• **Lower risk:**
  
  • cooling, purification and storage of large amount of cryogenic liquids - experience from GERDA and XENON1T/nT at LNGS

• **Higher risk:**
  
  • development of alternative signal readout methods (some technologies seem promising, but were not yet demonstrated to be practical in large noble-liquid detectors)
    
  • development of single-phase TPC
  
  • use of stable, high drift field (1 kV/cm)
  
  • development of 4-pi readout
Estimated Construction/Investment Costs

The costs will be dominated by the costs of LXe, followed by the ones of the photosensors, cryostat, electronics, etc.

Here an example, based on extrapolating the XENON1T/nT costs:

<table>
<thead>
<tr>
<th>Item</th>
<th>Total costs [in 10^6 CHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosensors, 1000 units</td>
<td>7.0</td>
</tr>
<tr>
<td>Xenon, 30 t</td>
<td>22.5</td>
</tr>
<tr>
<td>Detector (TPC, grids, HV)</td>
<td>1.5</td>
</tr>
<tr>
<td>Cryostat</td>
<td>4.5</td>
</tr>
<tr>
<td>Cryostat support</td>
<td>0.5</td>
</tr>
<tr>
<td>Cherenkov shield</td>
<td>0.5</td>
</tr>
<tr>
<td>Water tank</td>
<td>0.4</td>
</tr>
<tr>
<td>Xenon storage</td>
<td>1.6</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>1.4</td>
</tr>
<tr>
<td>Electronics, DAQ, cables</td>
<td>1.8</td>
</tr>
<tr>
<td>Calibration system</td>
<td>0.3</td>
</tr>
<tr>
<td>Slow control</td>
<td>0.3</td>
</tr>
<tr>
<td>Screening (HPGe, ICP-MS)</td>
<td>0.4</td>
</tr>
<tr>
<td>LXe purification (Rn, Kr)</td>
<td>1.5</td>
</tr>
<tr>
<td>Demonstrator vertical (drift, HV)</td>
<td>0.5</td>
</tr>
<tr>
<td>Demonstrator horizontal (grids)</td>
<td>0.5</td>
</tr>
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Sum: 54.2
Requests for laboratory space

- Minimum water tank dimensions: 14 m diameter
- Space in Hall B (that belonged to ICARUS)
- Or space in Hall C (Borexino shield or other), or Hall A

Example: space in hall B

**DARWIN-LXe**

**XENON1T/nT**

Water shield
14 m ø

Infrastructure building
+ clean room

Xe storage
Estimated timescale

2010 - 2013
First R&D phase, Aspera funded
June 2013: Aspera final report

2014 - 2018
R&D and design study
2018: CDR/TDR

2018 - 2020
Engineering studies

2018-19: demonstrators at home institutions
2020: construction/integration at UL

2020 - 2030
Construction, commissioning, science run

2020: construction/integration at UL
2021: commissioning
2022: physics runs
The DARWIN-LXe consortium

In total: 22 groups from 9 countries
Outlook
End