Dark matter searches with liquid xenon

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Seminar, University of Geneva
February 6, 2013
Physics aim of liquid xenon dark matter experiments

- Observe WIMP dark matter via elastic scattering off xenon nuclei

The expected rate is:

\[
R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[ \frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km s}^{-1}} \times \frac{\rho_0}{0.3 \text{ GeV cm}^{-3}} \right]
\]
Why xenon for direct dark matter detection?

- Large mass number \((A=131)\) => large rate for SI-interactions \((\sigma \sim A^2)\)
- Odd isotopes \(^{129}\text{Xe}, \) spin-1/2, 26.4%; \(^{131}\text{Xe}, \) spin-3/2, 21.2%) for SD-interactions
- High stopping power \((Z = 54)\), active volume is self-shielding
- Efficient \((\sim 5 \times 10^4 \text{ photons/MeV})\), fast scintillator and good ionizer in response to the passage of radiation
- Inert, not flammable, good dielectric, easy to purify
- Scalable to large, homogeneous detector masses

<table>
<thead>
<tr>
<th>Material</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionization potential (I) (eV)</td>
<td>15.75</td>
<td>14.00</td>
<td>12.13</td>
</tr>
<tr>
<td>(W) values (eV)</td>
<td>26.4(^a)</td>
<td>24.2(^a)</td>
<td>22.0(^a)</td>
</tr>
<tr>
<td>Liquid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap energy (eV)</td>
<td>14.3</td>
<td>11.7</td>
<td>9.28</td>
</tr>
<tr>
<td>(W) value (eV)</td>
<td>23.6(^b) ± 0.3</td>
<td>18.4(^c) ± 0.3</td>
<td>15.6(^d) ± 0.3</td>
</tr>
</tbody>
</table>

\(^a\) W-value = average energy required to produce an electron-ion pair
Charge and light in liquid xenon

Kubota et al., PRB 20, 1979

- Nuclear recoil
  - holes $\text{Xe}^+$
  - electrons
    - escape
  - localized ions $\text{Xe}^{+2}$
  - thermalized electrons

- Excitons $\text{Xe}^*$
  - recombination $\tau \approx 15\text{ ns}$

- Excited molecular states $\text{Xe}_2^*$
  - $1\Sigma^+_u$
  - $3\Sigma^+_u$
    - fast (3 ns)
    - slow (27 ns)

- UV photons (178 nm)

- $2\text{Xe}$
A liquid xenon time projection chamber

- Particle interaction in the active volume produces *prompt scintillation light (S1)* and ionization electrons.

- Electrons drift to interface (E= 0.53 kV/cm) where they are extracted and amplified in the gas. Detected as *proportional scintillation light (S2)*

  - \((S2/S1)_{\text{WIMP}} \ll (S2/S1)_{\text{Gamma}}\)

- 3-D position sensitive detector with particle ID

\[\text{Xe (A=131); } \lambda = 178 \text{ nm} \]

\[\text{position resolution: } <3\text{mm in x-y}; <0.3 \text{ mm in z}\]

\[
\begin{align*}
\text{PMT array} \\
\text{Anode} & \quad \text{proportional light (S2)} \\
\text{Gate grid} & \quad \text{drift field} \\
\text{Cathode} & \quad \text{direct light (S1)} \\
\text{PMT array} & \quad \text{ground} \quad +4.5 \text{ kV} \\
& \quad \text{ground} \quad -16 \text{ kV}
\end{align*}
\]
Overview: existing and future projects

- Single-phase: $e^-$-ion recombination occurs; only scintillation signal is detected
- Double-phase: ionization and scintillation; $e^-$ are drifted in E-field, $\sim 1$ kV/cm

<table>
<thead>
<tr>
<th>LXe detectors</th>
<th>Current</th>
<th>Future</th>
</tr>
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<tbody>
<tr>
<td>Single phase</td>
<td>XMASS</td>
<td>XMASS (5t)</td>
</tr>
<tr>
<td>Double phase</td>
<td>LUX, XENON100, Panda-X</td>
<td>LZ (7t), Panda-X (1t), XENON1T (3t), DARWIN (20 t)</td>
</tr>
</tbody>
</table>
Overview: existing projects

XMASS: in water Cherenkov shield at Kamioka:
835 kg LXe (100 kg fiducial), single-phase, 642 PMTs taking science data

LUX: In water Cherenkov shield at SURF:
350 kg LXe (100 kg fiducial), dual-phase, 122 PMTs, commissioning, run to start in early 2013

XENON100 in conventional shield at LNGS:
161 kg LXe (~50 kg fiducial), dual-phase, 242 PMTs taking science data

PandaX in conventional shield at CJPL:
stage I: 123 kg LXe (25 kg fiducial), dual-phase, 180 PMTs starts in 2013
Design of the XENON100 detector

Requirements:
100 x less background than XENON10
10 x more fiducial mass than XENON10

Solutions:
Cryocooler and FTs outside shield
Materials screened for low radioactivity
LXe scintillator active veto system
Improved passive shield system
Dedicated Kr distillation column

TPC with 30 cm drift x 30 cm diameter
161 kg ultra pure LXe (62 kg as target)
1” square PMTs with ~1 mBq (U/Th)

XENON100 design

- TPC with 30.6 cm height, 15.3 cm radius, made of 24 interlocking teflon panels
- Drift field (0.53 kV/cm) generated between cathode on bottom (-16 kV) and grounded gate grid on top
- Anode at +4.5 kV between two grounded grids: extraction field of $\approx 12$ kV
- Field shaping rings (40) for homogeneous drift field inside the TPC
- Liquid xenon shield (99 kg), 4 cm thick, optically separated from the TPC
- 242 PMTs: 98 on top, 80 on bottom, 64 in the liquid xenon shield
- Because of the 1.69 refractive index of LXe, about 80% of the S1 signal is seen by the bottom PMT array
The photosensors

- 1-inch square R8520 Hamamatsu PMTs, optimized to work at LXe T and P, and of low-radioactivity (< 1 mBq/PMT in $^{238}\text{U}/^{232}\text{Th}$)

- Top array: 98 PMTs (23% quantum efficiency) in concentric circles to improve radial event position reconstruction, teflon holder

- Bottom array: 80 PMTs, closely packed, and of higher quantum efficiency (~ 33% at 178 nm), for efficient S1 light collection

- Liquid xenon veto: 64 PMTs, 23% quantum efficiency
Location and shield

- **Gran Sasso Laboratory:** shield against cosmic rays: 1.4 km of mountain

- **Passive shield:**
  - 5 cm (2 tons) of Cu, 20 cm (1.6 tons) of PE, 20 cm (33 tons) of Pb, plus 20 cm water shield

- Detector housing is continuously purged with boil-off $N_2$, to maintain a radon level $< 0.5$ Bq/m$^3$

- All materials were screened with HPGe detectors at LNGS  
  \[ \text{JINST 6 P08010, 2011} \]
The XENON collaboration
Example of a low-energy event

S1 signal: ~ 100 photons

S2 signal: ~ 23 electrons

S1 signal: 5.14 pe

S2 signal: 459.7 pe
XENON100’s most recent run: 2011-2012

- Data from February 2011 - March 2012, with three maintenance interruptions
- A total of 224.6 live days of dark matter data; region of interest “blind”
Progress compared to previous runs

- Lower trigger efficiency in S2

- Lower $^{nat}Kr$ concentration by a factor of 20, now at $(19\pm4)$ ppt

- Doubled exposure

- Improved noise conditions

- Higher statistics calibration data (35 x science data in region of interest)

- Higher liquid xenon purity ($e^{-}$ mean lifetime from 375 $\mu$s to 611 $\mu$s during this run)

\[ \frac{^{85}Kr}{^{nat}Kr} = 10^{-11} \]
The gamma background in Run10

- Reached background level before S2/S1-discrimination: $5.3 \times 10^{-3}$ events/(kg day keV)

See also PRD 83, 082001 (2011) for a detailed background description
Calibration

- $^{137}\text{Cs}$ data to determine and monitor the charge & light yields in the TPC

- Light yield at 122 keV is interpolated using NEST model and measurements at lower/higher energies with conservative 5% uncertainty

- For Run10 the $\text{LY}_{122\text{keV}} = (2.28 \pm 0.04) \text{ PE/keV}$
Calibration: light and charge yield versus time

Light yield

Charge yield
Calibration of ER and NR bands

- The electronic recoil (ER) band is calibrated with high energy gammas from $^{60}\text{Co}$ and $^{232}\text{Th}$ sources.
- This data is also used to determine the background in the signal region due to low-energy Compton scatters.
- The nuclear recoils band (NR) is calibrated with an AmBe neutron source.
- Single scatters from elastic neutron-xenon collisions are used to define the expected WIMP signal region.
Nuclear recoil energy scale

- Nuclear recoil energy scale is set using the S1 signal

\[ E_{nr} = \frac{S1}{L_y \cdot \mathcal{L}_{\text{eff}}(E_{nr})} \cdot \frac{S_{ee}}{S_{nr}} \]

- \( L_y = 2.3 \text{ pe/keV} \) the light yield for electron recoils of 122 keVee

- \( S_{ee} = 0.58 \) and \( S_{nr} = 0.95 \) represent quenching factors due to the drift field

- Relative scintillation efficiency (measured in dedicated experiment) given as:

\[ \mathcal{L}_{\text{eff}}(E_{nr}) = \frac{L_{y,er}(E_{nr})}{L_{y,er}(E_{ee} = 122 \text{ keV})} \]

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![Graph showing data points and error bars with fit lines and shaded uncertainty regions.](attachment:image.png)
Nuclear recoils: data and MC

- Matching the AmBe data with MC simulations

129Xe  Inelastic collisions
Data; Monte Carlo

131Xe  19F  19F

Elastic collisions, S1
Data; Monte Carlo

Elastic collisions, S2
Data; Monte Carlo for optimized charge yield

Manuscript in preparation: XENON collaboration
Gammas from neutron calibrations

- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: \(^{129,131}\text{Xe} + n \rightarrow ^{129,131}\text{Xe} + n + \gamma\) (40 keV, 80 keV)
- Inelastic n-scattering on F (in PTFE): \(^{19}\text{F} + n \rightarrow ^{19}\text{F} + n + \gamma\) (110 keV, 197 keV)
- Also Xe activation lines: \(^{129\text{m}}\text{Xe}\) (236 keV) and \(^{131\text{m}}\text{Xe}\) (164 keV)

All gammas from the neutron irradiation of XENON100 are used to check/correct signal dependency with position and also to infer the LY at 122 keV
Position-dependent signal correction

- S1 light collection depends on the event position in the TPC: a 3D map of the light collection efficiency (LCE) is inferred from irradiation with $^{137}$Cs (662 keV) at different positions, from the 40 keV neutron inelastic scattering line, and the 164 keV line from n-activated $^{131m}$Xe (all agree within 3%)

- S2 response measured with the 40 keV gamma line

- Shown are relative changes compared to the mean
From raw data to results

Majority trigger, efficiency > 99% for S2>150 pe

Data acquisition: sample PMT traces @ 100 MS/s in windows around signals > 0.35 pe

Raw data processing, baseline and noise measurement; S1, S2 signal recognition; signal integration; position reconstruction; signal correction (gain, spatial)

Event selection, remove “bad” events:
- noise
- S1/S2 not matching
Select single interaction events

Physics analysis input: astrophysics, nuclear physics, DM data sidebands, NR and ER calibration => response, background

Profile likelihood

Acceptances!

Profile likelihood results
Nuclear recoil acceptance

- Data quality cuts acceptance estimated from AmBe and $^{60}$Co calibration data, MC simulations and ERs outside the WIMP search energy range.

- A priori decision to use profile likelihood (PL) approach and test both background only and signal + background hypotheses.

- The PL approach does not use an “$S2/S1$-based rejection cut”.

- A cross check based on the standard approach, where a “benchmark WIMP region” is defined:
  - 3 - 20 photoelectrons in S1
  - 99.75% ER rejection line
  - 150 pe S2 threshold
  - 97% NR band quantile
Background prediction for Run10

- Expected background in: 34 kg inner region, 224.6 live days, 99.75% rejection of electronic recoils

- **Electronic recoil background:**
  - 0.79±0.16 events
  - from ER calibration data, scaled to non-blinded ER band background data

- **Nuclear recoil background**
  - 0.17±0.12-0.07 events
  - from cosmogenic and radiogenic neutrons

- **Total:** 1.0±0.2 events

- benchmark WIMP region (not used in PL analysis)
Before/after unblinding
After unblinding
After unblinding

- Two events observed in signal region (there is a 26.4 % chance for upward fluctuation): at 7.1 keV\(_{\text{nr}}\) (3.3 pe) and at 7.8 keV\(_{\text{nr}}\) (3.8 pe)

- Both events at low S2/S1 with respect to NR calibration data

- Visual inspection: waveforms of high quality
What if?

- How would signal claims of other experiments look like in XENON100’s Run10 data?

Light WIMP: $m_W = 8$ GeV

CRESST-like WIMP; $m_W = 25$ GeV

WIMP-nucleon cross section: $3 \times 10^{-41}$ cm$^2$

WIMP-nucleon cross section: $1.6 \times 10^{-40}$ cm$^2$
Run10 SI Results

• No evidence for WIMPs

• Upper limit on SI WIMP-nucleon cross section is $2 \times 10^{-45}$ cm$^2$ at $M_W = 55$ GeV

![Graph showing the WIMP-nucleon cross section comparison for various experiments, with XENON100 (2012) showing the observed limit and regions for 90% confidence level exclusion limits.]
Run10 SD results

- $^{129}$Xe (spin-1/2) and $^{131}$Xe (spin-3/2), two isotopes with $J \neq 0$ and abundance of 26.2% and 21.8% in XENON100

![Graph showing SD WIMP-neutron and proton cross section vs. WIMP mass](image)
The near future: XENON1T at Gran Sasso

- 1m drift TPC with ~3 ton LXe
- Water shield as Cherenkov Muon Veto
- 100 x less background than XENON100
- Based on proven technology

- Project approved and funded
- Management and WGs in place
- Design of major infrastructures completed
- Construction in Hall B starts April 2013
The XENON1T detector at LNGS

Dual phase time projection chamber
~ 3 ton liquid xenon; 1 ton fiducial mass
100 x lower background than XENON100

1m³ = 3 tons LXe

0.07 gammas/year
0.1 neutrons/year

1 ton LXe
1 ton LXe
XENON1T schedule

• Commissioning and start of physics run in 2015
• Goal: $\sim2 \times 10^{-47}$ cm$^2$ SI cross section after 2 years of data

XENON1T: 3 tons LXe

In a $\sim$10 m x 10 m water Cherenkov shield
XENON1T goal

A statistically significant WIMP signal after 2 ton-years of data:

~100 events if cross section at $10^{-45}$ cm$^2$

$2 \times 10^{-47}$ cm$^2$ for 50 GeV WIMP in 2 ton-year

Two orders of magnitude improvement in SI cross-section sensitivity w/r to XENON100
The far future

- DARWIN: dark matter search with noble liquids
- Physics channels of 20t LXe detector:
  - dark matter searches
  - real-time detection of solar pp-neutrinos:
  - search for neutrinoless double beta decay in $^{136}$Xe

![Graph](graph.png)

L. Baudis, Physics of the Dark Universe 1, 94 (2012)
DARWIN goal

FIG. 1 (color online). The joint 68% and 95% posterior probability contours in the (middle column) and the prior constraint adopted (rightmost column) are shown. See Secs. II and III for further details. Let us stress as well that the 250 GeV WIMP benchmark proves very difficult to constrain in terms of mass and cross section. For reference, the (marginalized) mass accuracy extraction of the correct mass to better than 1% with Galactic model parameters, as discussed in Sec. II. Taking into account the differences in adopted values and procedures, our results are in qualitative agreement with those of previous analyses for Xe. In this work, we extend these analyses to Xe + Ge and Xe + Ge + Ar targets.

The left frame of Fig. 1 shows the results for the three benchmarks and for Xe, Ge, and Ar together, whereas in the right frame the combined data sets are used to reconstruct the posterior for the DM benchmarks. The reconstruction capabilities of Xe, Ge, and Ar configurations separately, whereas in the right frame the combined data sets are shown. See Secs. II and III for further details.

There are several other recent results that determine the results for the three benchmarks and for Xe, Ge, and Ar together, whereas in the right frame the combined data sets are shown. See Secs. II and III for further details.

TABLE II. The parameters used in our analysis, with their fiducial values, prior range (middle column) and the prior constraint adopted (rightmost column) are shown. In the left frame we show the results for the three benchmarks and for Xe, Ge, and Ar together, whereas in the right frame the combined data sets are shown. See Secs. II and III for further details.

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<tr>
<th>Parameter</th>
<th>Prior range</th>
<th>Prior constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_\chi )</td>
<td>(16, 50) ( \text{GeV} )</td>
<td>(16, 50) ( \text{GeV} )</td>
</tr>
<tr>
<td>( v_0 )</td>
<td>(230, 544) ( \text{km/s} )</td>
<td>(230, 544) ( \text{km/s} )</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>(0.4, 2.3) ( \text{GeV/cm}^3 )</td>
<td>(0.4, 2.3) ( \text{GeV/cm}^3 )</td>
</tr>
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</table>

For completeness Table II summarizes the information. With the experimental capabilities of Xe, Ge, and Ar configurations separately, whereas in the right frame the combined data sets are shown. In the left frame we show the results for the three benchmarks and for Xe, Ge, and Ar together, whereas in the right frame the combined data sets are shown. See Secs. II and III for further details.

KINOSHIRO/08: \( \sigma_\chi \approx 10^{-30} \text{cm}^2 \), \( m_\chi \approx 1 \text{GeV} \). The Galactic model parameters, i.e., fixed astrophysical parameters, are shown. In the left frame we show the results for the three benchmarks and for Xe, Ge, and Ar together, whereas in the right frame the combined data sets are shown. See Secs. II and III for further details.

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Direct detection: sensitivity versus time

Factor ~ 10 every two years!

Spin-independent cross section (at $m_W \sim 50$-100 GeV) [cm$^2$]

- Ge ionization
- CsI and NaI
- mk-Ge current
- XENON
- ZEPLIN
- mK-Ge future
- noble liq. single
- noble liq. double

L. B., Physics of the Dark Universe 1, 94 (2012)