The Ultimate Dark Matter Observatory: Science Cases and Challenges

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Growth of Direct Detection Community

Dark Matter Direct Detection (Personnel >= Grads)

Scientists (>=Grads)

Year

1997 1999 2001 2003 2005 2007 2009 2011

Non-US
US
How to approach dark matter?

Direct Search

$X \rightarrow X q$

$XENON, \text{DarkSide}$

Indirect Search

$q q \rightarrow X X$

$X X \rightarrow \nu \nu$

$\text{ATLAS, CMS}$

$\text{LHC}$

$\text{Fermi, IceCube}$
How to approach dark matter?

Technology (Experimentalists)

Pure Materials
Photon Detectors...

Science (Theorists)

SUSY, Extra Dimensions...

Funding (Agencies)

DOE, NSF...
Talk Outline

- **Scientific Cases**
  - Origin of the Universe and Mass

- **Detection Methods**
  - Noble Liquid and TPC
  - XENON100 and 1T

- **Sensitivities**
  - SUSY, Extra Dimensions…
  - Comparison with LHC, Indirect searches

- **Ultimate G3 Observatory**
  - Xenon vs. Argon
  - Technological challenges
  - Neutrino Physics
Scientific Cases
Why are we here?

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Seven Phases of Cosmic Evolution

14 billion years ago

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Unification of Forces

Grand Unification

Graph showing the relative strength of forces (strong, electromagnetic, weak, gravity) over temperature (K).

Key points:
- 100 GeV
- $10^{16}$ GeV
- $10^{19}$ GeV

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Unification of Forces

- Strong force
- Electromagnetic force
- Weak force
- Electroweak force
- GUT force

Plank Epoch

Relative strength of force vs. temperature (K):
- 100 GeV
- $10^{16}$ GeV
- $10^{19}$ GeV
- $10^{29}$ K
- $10^{32}$ K

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Physicists’ View of Early Universe

Fiat lux
Let there be light

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Physicists’ View of Early Universe

Lorentz Invariance
Local Gauge Invariance
# Symmetry Breaking

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Temp. (°K)</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻⁴⁵</td>
<td>10³⁰</td>
<td>10¹⁸</td>
</tr>
<tr>
<td>10⁻⁴</td>
<td>10²⁰</td>
<td>10¹⁵</td>
</tr>
<tr>
<td>10⁻³⁵</td>
<td>10²⁵</td>
<td>10¹²</td>
</tr>
<tr>
<td>10⁻³⁰</td>
<td>10¹⁵</td>
<td>10⁹</td>
</tr>
<tr>
<td>10⁻²⁵</td>
<td>10¹⁰</td>
<td>1 PeV</td>
</tr>
<tr>
<td>10⁻²⁰</td>
<td>10⁵</td>
<td>1 TeV</td>
</tr>
<tr>
<td>10⁻¹⁵</td>
<td>10¹</td>
<td>1 GeV</td>
</tr>
<tr>
<td>10⁻¹⁰</td>
<td>10⁹</td>
<td>1 MeV</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>10⁶</td>
<td>1 KeV</td>
</tr>
<tr>
<td>1</td>
<td>10¹⁰</td>
<td>1 eV</td>
</tr>
<tr>
<td>10⁶ sec</td>
<td>10⁵</td>
<td>10⁻³ eV</td>
</tr>
<tr>
<td>1 year</td>
<td>10³</td>
<td></td>
</tr>
<tr>
<td>10³</td>
<td>10⁶</td>
<td></td>
</tr>
<tr>
<td>10⁶ year</td>
<td>10⁹</td>
<td></td>
</tr>
</tbody>
</table>

**Simple Symmetry Break Down**

**Complex**

\[
\begin{align*}
\text{Simple:} & \\
\text{Complex:} & \\
\text{Symmetry Break Down:} & \\
\end{align*}
\]

11/11/2011

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The Beginning

- Everything was the same ↔ Perfect symmetry.
  - All the particles are the same as photons.
  - All four forces are the same.

- The Universe was 10 dimension.
Mass of Particles

Generation

I       II       III
u
\bullet
d
\bullet
\nu_e
\nu_e
\bullet
\nu_{\mu}
\nu_{\tau}
\bullet
\mu
\bullet
\tau

Spin ½
Fermions

Spin 1
Gauge bosons

Spin 0
Higgs boson
Mystery of the Mass (since 1970)

1) How to create mass from energy?

Energy $\rightarrow$ Mass

While maintaining the initial symmetry
Spontaneous Symmetry Breaking

2) Particle mass $\ll$ Plank Mass

MeV – GeV  $\ll$  $10^{19}$ GeV

3) Why so many particles (Generations) with different masses?
Spontaneous Symmetry Breaking
- Higgs Mechanism -

Energy

Vacuum Energy

Mass

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Spontaneous Symmetry Breaking
- Higgs Mechanism -

Energy

Vacuum Energy

Mass

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CERN and LHC in Geneva

27km Circumference
7+7=14 TeV
LHC Higgs search results

Results from the LHC Higgs Cross Section WG by R. Tanaka

ATLAS Preliminary

CLs Limits

- Observed
- Expected

$\int L dt = 1.0-2.3 \, fb^{-1}$

$\sqrt{s} = 7 \, TeV$

CMS Preliminary, $\sqrt{s} = 7 \, TeV$

Combined, $L_{int} = 1.1-1.7 \, fb^{-1}$

95% CL limit on $\sigma/\sigma_{SM}$

145 - 466 GeV excluded.
LHC Higgs search results

ATLAS Preliminary

- Observed
- Expected

\[ \int L dt = 1.0-2.3 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

95% CL Limit on \( \sigma / \sigma_{SM} \)

120 - 145 GeV promising

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LHC Higgs search results

ATLAS Preliminary

120 - 145 GeV promising

\( 1 \)  
\( \int L dt = 1.0-2.3 \text{ fb}^{-1} \)  
\( \sqrt{s} = 7 \text{ TeV} \)

Observed

Expected

120  140  160  180  200  220  240
100

10^{-7}  10^{-6}  10^{-5}  10^{-4}  10^{-3}  10^{-2}  10^{-1}  1

2\sigma  3\sigma  4\sigma  5\sigma
Predicted Sensitivity to Higgs

Projections, \(\sqrt{s} = 7\) TeV

\(95\%\) CL Limit on \(\sigma/\sigma_{SM}\)

120 - 145 GeV

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Formation of Structure in the Universe

Dark Matter is required!
Evolution of Large Structure

(a) Time = 1 second

(b) Time = 1000 years

(c) Time = $10^8$ years
Density of Our Universe

- $\Omega_{\text{Total}} = \Omega_\Lambda + \Omega_{\text{Matter}} = 1.0$

- Universe is Flat.  ⇒  Inflation

- 74% is Dark Energy.  ⇒  Accelerating
Abundance vs. Density

$H_0 = 65 \text{ km/s/Mpc}$

$T_{\text{cmb}} = 2.73 \text{ K}$

$N_v = 3.0$

$\tau_{\text{neutron}} = 886.7 \text{ s}$

$0.03 < \Omega_{\text{Baryon}} < 0.05$
Cosmic Pyramid

Baryonic Matter

Metal
Star

Gas, Dust

Dark Matter

Dark Energy

0.01%

0.4%

4%

23%

73%
Relation between Temperature and Time

T: Temperature
t: time

\[ T = \frac{1.5 \times 10^{10}}{\sqrt{t \text{(sec)}}} ^{\circ} K \]

\[ = \frac{1.3}{\sqrt{t \text{(sec)}}} \text{ MeV} \]
Time = 10^{-10} \text{ sec}, \text{ Temp.} = 10^{15}^\circ\text{K} \approx 100 \text{ GeV}

- **Electro-weak Unification**
- Electro-Magnetic force = Weak force
- The highest energy we can study by the accelerators

```
\begin{array}{cccccc}
\text{b} & \overline{s} & \mu^- & W^+ & \gamma & c \\
\overline{\nu}_e & \tau^+ & d & \overline{d} & \tau^- & \nu_e \\
d & e^+ & Z^0 & u & \overline{\nu}_\mu & e^- \\
\overline{u} & \nu_\mu & s & \overline{b} & \nu_\mu & \overline{c} \\
\end{array}
```

Horizon \approx 3 \text{ cm}
WIMP Miracle

\[ \Omega_X = \frac{m_X n_0}{\rho_c} = \frac{m_X T_0^3}{\rho_c} \frac{n_0}{T_0^3} \sim \frac{m_X T_0^3}{\rho_c} \frac{n_f}{T_f^3} \sim \frac{x_f T_0^3}{\rho_c M_{Pl}} \langle \sigma_A v \rangle^{-1} \]

\[ \sigma_A v = k \frac{g_{\text{weak}}^4}{16\pi^2 m_X^2} (1 \text{ or } v^2) \]

\[ \Omega_X \propto M_X^2 \]

\[ M_X \sim 0.1-1 \text{ TeV} \]

\[ \sigma_A \sim \text{pb} \]
What is Dark Matter?
Detection Methods
## Properties of Noble Liquid

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Neon</th>
<th>Argon</th>
<th>Xenon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Z</strong></td>
<td></td>
<td>10</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td></td>
<td>20</td>
<td>40</td>
<td>~132</td>
</tr>
<tr>
<td><strong>Liquid Density</strong></td>
<td>g/cc</td>
<td>1.21</td>
<td>1.4</td>
<td>3.06</td>
</tr>
<tr>
<td><strong>Energy Loss (dE/dX)</strong></td>
<td>MeV/cm</td>
<td>1.4</td>
<td>2.1</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Radiation Length</strong></td>
<td>cm</td>
<td>24</td>
<td>14</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Collision Length</strong></td>
<td>cm</td>
<td>80</td>
<td>80</td>
<td>34</td>
</tr>
<tr>
<td><strong>Boiling Temperature</strong></td>
<td>°K</td>
<td>27.1</td>
<td>87.3</td>
<td>165</td>
</tr>
<tr>
<td><strong>Scintillation Wavelength</strong></td>
<td>nm</td>
<td>85</td>
<td>125</td>
<td>178</td>
</tr>
<tr>
<td><strong>Scintillation</strong></td>
<td>photon/keV</td>
<td>30</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td><strong>Ionization</strong></td>
<td>e-/keV</td>
<td>46</td>
<td>42</td>
<td>64</td>
</tr>
<tr>
<td><strong>Decay time (Fast Component)</strong></td>
<td>nsec</td>
<td>19</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td><strong>Decay time (Slow Component)</strong></td>
<td>nsec</td>
<td>1500</td>
<td>1600</td>
<td>26</td>
</tr>
<tr>
<td><strong>Isotope</strong></td>
<td></td>
<td>No</td>
<td>39Ar (1 Bq/kg)</td>
<td>136Xe</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$/ton</td>
<td>$90k</td>
<td>~$2k</td>
<td>~$1M</td>
</tr>
</tbody>
</table>

**Single Phase Experiments**
- CLEAN
- DEAP/CLEAN
- XMASS

**Double Phase Experiments**
- WARP, ArDM, DarkSide, MAX
- ZEPLIN, XENON, MAX LUX, LZD
Target Mass Dependence of WIMP Cross Section

\[
\text{cross section } 10^{-44} \text{ cm}^2 , \text{ WIMP mass 100 GeV}
\]
XMASS (Single Phase Xe)

100kg Prototype (FV:30kg, 30cm)

800kg Detector (FV:100kg, 80cm)

20ton Detector (FV:10ton, 2.5m)

R&D

Dark Matter

completed

2011 ~

Solar neutrino
Dark Matter

Future

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DEAP/CLEAN (Single Phase Ar/Ne)

360 kg Mini-CLEAN

Water Shield

3.6 ton DEAP/CLEAN

Central volume: 165 cm diameter 2600 litres

217 PMTs

20 cm

Sealed acrylic inner vessel

30 cm acrylic light guides
Double-Phase Noble Liquids

Sensitive volume

WIMP

Phototubes

Anode

Grid

Electron drift

Cathode

S1

S2

$E_{\text{gas}}$

$E_{\text{drift}}$

Drift Time

Nuclear Recoil (WIMP)

Drift Time

Electronic Recoil ($\gamma$, $\beta$)
XENON100 Detector (Double phase Xenon)

161 kg
(48 kg)

PMT HV and Signal Lines
Tube to Cooling Tower
Top Veto PMTs
Top Array PMTs
PTFR Panels
Lower Side Veto PMTs
Bottom Array PMTs
HV Feedthrough
Double Wall Cryostat
Bell Assembly
Upper Side Veto PMTs
Anode
Field Shaping Rings
Cathode
Bottom Veto PMTs

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LUX 300 kg (Double phase Xenon)
WARP 140 kg (Double Phase Argon)
Pulse Shaping Discrimination by Ar

(a) Neutron induced ion recoils

(b) WIMP Exposure of 96.5 kg • day
DarkSide 50 kg (Double phase Argon)

CTF Water Tank

Liquid Scintillator

3” QUPID
(19 top + 19 bottom)

Depleted Ar
(50 kg)
## Comparison of G1 Experiments

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Location</th>
<th>Mass</th>
<th>Photon Detector</th>
<th>Radioactivity</th>
<th>Size</th>
<th>Location</th>
<th>Target</th>
<th>Total</th>
<th>Fiducial</th>
<th>Phase</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>XENON100</td>
<td>Gran Sasso</td>
<td>Xe</td>
<td>Double R8520</td>
<td>1</td>
<td>1</td>
<td>Top/Bot.</td>
<td>162</td>
<td>48</td>
<td>1</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>XMASS</td>
<td>Kamioka</td>
<td>Xe</td>
<td>Single R8778Hex</td>
<td>2</td>
<td>5</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUX</td>
<td>DUSEL</td>
<td>Xe</td>
<td>Double R8778</td>
<td>2</td>
<td>20</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini-CLEAN</td>
<td>SNO</td>
<td>Ar</td>
<td>Single 8&quot; PMT</td>
<td>8</td>
<td>500</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WARP</td>
<td>Gran Sasso</td>
<td>Ar</td>
<td>Double 3&quot; PMT</td>
<td>3</td>
<td>200</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>DarkSide 50</td>
<td>Gran Sasso</td>
<td>Ar</td>
<td>Double 3” QUPID</td>
<td>3</td>
<td>1</td>
<td>0.02</td>
<td></td>
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<td></td>
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</table>
# Single Phase vs. Double Phase

<table>
<thead>
<tr>
<th></th>
<th>Single Phase</th>
<th>Double Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HV for electron drift</strong></td>
<td>Not required</td>
<td>Required (~1 kV/cm)</td>
</tr>
<tr>
<td><strong>O$_2$/H$_2$O impurity</strong></td>
<td>Not critical</td>
<td>Critical</td>
</tr>
<tr>
<td><strong>Energy threshold</strong></td>
<td>20 PE</td>
<td>4 PE</td>
</tr>
<tr>
<td><strong>Sensitivity for low mass WIMP</strong></td>
<td>&gt; 20 GeV</td>
<td>&gt; 5 GeV</td>
</tr>
<tr>
<td><strong>Position resolution</strong></td>
<td>~ 10 cm</td>
<td>~ 2 mm</td>
</tr>
<tr>
<td><strong>Gamma rejection by S2/S1</strong></td>
<td>No</td>
<td>Yes (&gt; 99.5%)</td>
</tr>
<tr>
<td><strong>Neutron rejection by Multi-hit cut</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Summary on “Xenon vs. Argon”

**Xenon**
- 5 times more sensitive (per unit mass)
  - due to $A^2$ dependence.
- Ideal for mass range of 10 – 100 GeV
  - Spectrum is independent from mass
- Expensive
  - ~$1M / ton
- Limited by
  - pp-chain solar neutrino: 0.1 event / ton-year
  - $^{136}$Xe Double beta decay: 0.1 event / ton-year
  - $^{85}$Kr: 1 ppt $\rightarrow$ 0.2 event / ton-year

**Argon**
- Free from gamma background
  - $>10^6$ rejection by pulse shaping
- Ideal for mass range of 20 – 200 GeV
  - Insensitive to low mass $<10$ GeV
- $^{39}$Ar is the major source of radioactivity
XENON100
The 1st G1 Experiment
XENON100 Detector

161 kg (48 kg)

Katsushi Arisaka, UCLA
### PMT Arrays

**242 Hamamatsu R8520 PMTs**

- 1"x1", optimized for response @ Xe scintillation light (178 nm)
- Low radioactivity (~ <1 mBq/PMT)

<table>
<thead>
<tr>
<th>Top Array</th>
<th>Bottom Array</th>
<th>Active Veto</th>
</tr>
</thead>
<tbody>
<tr>
<td>98 PMTs</td>
<td>80 PMTs</td>
<td>64 PMTs</td>
</tr>
<tr>
<td>~23% QE</td>
<td>~33% QE</td>
<td>~23% QE</td>
</tr>
</tbody>
</table>

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Energy Spectrum of Real Data vs. MC

Surface Backgrounds

- Teflon, 7.9%
- Steel, 15.6%
- PMT, 62.6%
- Bases, 12.2%

arXiv:1101.3866

Katsushi Arisaka, UCLA
Level of Backgrounds (before S2/S1 cut)

Energy [keV]

Rate [events/keV/kg/day]

- CRESST
- CoGeNT
- CDMS
- XENON10
- DAMA
- XENON100

before fiducial cut

after fiducial cut

Log(S2/S1) vs. Energy

100.9 days, 48 kg

S1 = 4 PE

γ backgrounds

99.75% rejection for γ

Neutron band
(Acceptance 30 – 40%)

3 events
(1.8 ± 0.6 expected)

8.4 keV_{nr}

S2 = 300 PE

-3 σ

44.6 keV_{nr}

arXiv:1104.2549

Katsushi Arisaka, UCLA
Event distribution in z vs. $R^2$

100.9 days, 8.4 – 44.6 keV$_{nr}$

Radius [cm]

<table>
<thead>
<tr>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>15.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>-5</td>
<td></td>
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<td>-10</td>
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<td>-25</td>
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<tr>
<td>-30</td>
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</tr>
</tbody>
</table>

Radius$^2$ [cm$^2$]

$48$ kg

3 events

$(1.8 \pm 0.6$ expected)
Log(S2/S1) vs. Energy

11 keV<sub>nr</sub>
Single Scatter Nuclear Recoil Event Candidate

$11 \text{ keV}_{nr}$

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Summary of XENON100

- Purity of Xenon has achieved the design goal.

<table>
<thead>
<tr>
<th>Actual</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Yield:</td>
<td>2.2</td>
</tr>
<tr>
<td>Electron Drift Time:</td>
<td>400</td>
</tr>
<tr>
<td>Krypton 85:</td>
<td>80</td>
</tr>
<tr>
<td>Radon:</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- 100 days of data published.
  - 3 event observed (1.8 +/- 0.6 events expected)
    - Contaminated by $^{85}$Kr at ~ 700 ppt $\Rightarrow$ 1.1 events
  - $< 7 \times 10^{-45}$ cm² at 50 GeV
  - Low mass (7-10 GeV) WIMP unlikely.
  - Inelastic DM excluded.

- Data taking continues.
  - $^{85}$Kr reduced to $< 80$ ppt
  - $< 2 \times 10^{-45}$ cm² by the end of 2011 expected.
XENON1T
The 1st G2 Experiment
WIMP Mass [GeV/c^2]
WIMP-Nucleon Cross Section [cm^2]

DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
ZEPLIN III

XENON100 (2010)
XENON100 (2011)
XENON100 (2012)
Argon
1 ton-year
Xenon
1 ton-year
Xenon
10 ton-year
Argon
50 ton-year

CMSSM

Buchmueller et al.

DarkSide-50
0.1 ton-year

G1
G2
G3

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XENON1T (G2) at LNGS

Water Tank

Xe (2.2 Ton)
XENON1T Detector Structure
Electric Field of TPC
## Key Parameters of XENON1T

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detector TPC Size</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>20</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Maximum Drift Length (cm)</td>
<td>15</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Operational Field (kV/cm)</td>
<td>0.73</td>
<td>0.53</td>
<td>1.00</td>
</tr>
<tr>
<td>Maximum Drift Time (μs)</td>
<td>72</td>
<td>158</td>
<td>476</td>
</tr>
<tr>
<td>Total Mass (kg)</td>
<td>15</td>
<td>161</td>
<td>2500</td>
</tr>
<tr>
<td>Fiducial Mass (kg)</td>
<td>5.4</td>
<td>48</td>
<td>1100</td>
</tr>
<tr>
<td>Photon Detector</td>
<td>R8520 x 89</td>
<td>R8520 x 242</td>
<td>R11410 x 272</td>
</tr>
<tr>
<td><strong>Detector Material</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon Detector Diameter (inch)</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Cryostat</td>
<td>Stainless Steel</td>
<td>Stainless Steel</td>
<td>Titanium</td>
</tr>
<tr>
<td><strong>Detector Cooling</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling System</td>
<td>PTR</td>
<td>Cu (5cm)</td>
<td>PTR</td>
</tr>
<tr>
<td></td>
<td>Poly (20 cm)</td>
<td>Poly (20 cm)</td>
<td>(Active Muon Veto)</td>
</tr>
<tr>
<td></td>
<td>Lead (20 cm)</td>
<td>Lead (20 cm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>Water</td>
<td>Water (4 m)</td>
</tr>
<tr>
<td><strong>Live Time (days)</strong></td>
<td>58.6</td>
<td>100.9</td>
<td>730</td>
</tr>
<tr>
<td><strong>Exposure (kg × years)</strong></td>
<td>0.37</td>
<td>4.02</td>
<td>880</td>
</tr>
<tr>
<td><strong>Operation and Sensitivity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of observed events</td>
<td>10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Sensitivity&lt;sup&gt;c&lt;/sup&gt; (cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>$5 \times 10^{-44}$</td>
<td>$7 \times 10^{-45}$</td>
<td>$2 \times 10^{-47}$</td>
</tr>
</tbody>
</table>

<sup>a</sup>Observed number of events consistent with the 7 expected background events.

<sup>b</sup>Observed number of events consistent with the 1.8 expected background events.

<sup>c</sup>90% CL at 50GeV/c<sup>2</sup> WIMP mass.
Expected Backgrounds vs. Self-shielding cut

![Graph showing expected backgrounds vs. self-shielding cut](image_url)

- **Fiducial Mass [ton]**
  - 2.2
  - 1.6
  - 1.1
  - 0.7

- **No. of evt/ton-year**
  - 10^2
  - 10^1
  - 10
  - 1

- **Thickness of self-shielding cut [cm]**
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12
  - 14

Lines and labels:
- **R11410 (Gamma)**
- **R11410 (Neutron)**
- **Kr at 0.5 ppt**
- **2v2[beta]**
- **QUPID (Neutron)**
- **QUPID (Gamma)**
- **pp Solar**

**11/11/2011**

Katsushi Arisaka, UCLA
# Expected Backgrounds and Sensitivity

<table>
<thead>
<tr>
<th>Fiducial Mass</th>
<th>XENON100</th>
<th>XENON1T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48 kg</td>
<td>30 kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background</th>
<th>ER</th>
<th>NR</th>
<th>ER</th>
<th>NR</th>
<th>ER</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>10^{-3} dru_{ee}</td>
<td>10^{-7} dru_{nr}</td>
<td>10^{-3} dru_{ee}</td>
<td>10^{-7} dru_{nr}</td>
<td>10^{-3} dru_{ee}</td>
<td>10^{-7} dru_{nr}</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>13.5</td>
<td>–</td>
<td>2.0</td>
<td>–</td>
<td>0.01</td>
<td>–</td>
</tr>
<tr>
<td>pp Solar neutrino</td>
<td>0.01</td>
<td>–</td>
<td>0.01</td>
<td>–</td>
<td>0.01</td>
<td>–</td>
</tr>
<tr>
<td>$^{136}$Xe 2vββ</td>
<td>0.008</td>
<td>–</td>
<td>0.008</td>
<td>–</td>
<td>0.008</td>
<td>–</td>
</tr>
<tr>
<td>n from Rock and μ-induced</td>
<td>–</td>
<td>55</td>
<td>–</td>
<td>50</td>
<td>–</td>
<td>0.05</td>
</tr>
<tr>
<td>PMTs with bases</td>
<td>3.59</td>
<td>3.25</td>
<td>1.1</td>
<td>2.87</td>
<td>0.006</td>
<td>0.05</td>
</tr>
<tr>
<td>PTFE</td>
<td>0.02</td>
<td>6.99</td>
<td>0.01</td>
<td>5.04</td>
<td>0.0001</td>
<td>0.02</td>
</tr>
<tr>
<td>Cryostat</td>
<td>0.95</td>
<td>2.01</td>
<td>0.47</td>
<td>1.66</td>
<td>0.0002</td>
<td>0.0007</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>18.1</td>
<td>67</td>
<td>3.6</td>
<td>59</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>Total ER Bkg. after S2/S1 cut</td>
<td>0.045</td>
<td>0.009</td>
<td>&lt; 0.0001</td>
<td></td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Run Time</th>
<th>100 days</th>
<th>200 days</th>
<th>730 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Exposure</td>
<td>13 kg-year</td>
<td>16 kg-year</td>
<td>2.2 ton-year</td>
</tr>
<tr>
<td>Expected number of Bkg. events</td>
<td>1.8 ± 0.6</td>
<td>0.1 ± 0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of Observed events</td>
<td>3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SI $\sigma_{\chi-p}$ reach</td>
<td>$7 \times 10^{-45}$ cm$^2$ (April 2011)</td>
<td>$2 \times 10^{-45}$ cm$^2$ (2012)</td>
<td>$2 \times 10^{-47}$ cm$^2$ (2017)</td>
</tr>
</tbody>
</table>
### XENON1T – Responsibility and Cost

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Photomultiplier Tubes&lt;sup&gt;a&lt;/sup&gt;</td>
<td>UCLA</td>
<td>Columbia</td>
<td>0.07</td>
<td>0.41</td>
<td>1.57</td>
<td>2.05</td>
</tr>
<tr>
<td>Cryostat/Cryogenics Plant</td>
<td>Columbia</td>
<td>UCLA</td>
<td>0.10</td>
<td>–</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>Electronics/DAQ/Computing</td>
<td>Zurich</td>
<td>Columbia</td>
<td>0.50</td>
<td>0.10</td>
<td>–</td>
<td>0.6</td>
</tr>
<tr>
<td>Water Shield</td>
<td>Weizmann</td>
<td>–</td>
<td>–</td>
<td>0.5</td>
<td>–</td>
<td>0.5</td>
</tr>
<tr>
<td>Cherenkov Muon Veto</td>
<td>Bologna, Mainz</td>
<td>–</td>
<td>–</td>
<td>0.65</td>
<td>–</td>
<td>0.65</td>
</tr>
<tr>
<td>LNGS Infrastructure</td>
<td>LNGS</td>
<td>Columbia</td>
<td>–</td>
<td>0.55</td>
<td>0.15</td>
<td>0.7</td>
</tr>
<tr>
<td>(Water Plants, AC, Electrical Systems)</td>
<td></td>
<td>Rice, Purdue</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purification &amp; Cryogenic</td>
<td>Muenster</td>
<td>Columbia/Purdue</td>
<td>0.1</td>
<td>0.6</td>
<td>–</td>
<td>0.7</td>
</tr>
<tr>
<td>Distillation Plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xenon Gas (2.5 ton)</td>
<td>Columbia</td>
<td>Rice</td>
<td>1.25</td>
<td>1.25</td>
<td>–</td>
<td>2.5</td>
</tr>
<tr>
<td>LXe Storage/Recovery Vessel</td>
<td>SubaTech</td>
<td>–</td>
<td>–</td>
<td>0.8</td>
<td>–</td>
<td>0.8</td>
</tr>
<tr>
<td>Internal TPC &amp; PMT Support Structures&lt;sup&gt;a&lt;/sup&gt;</td>
<td>UCLA</td>
<td>Rice</td>
<td>–</td>
<td>0.04</td>
<td>0.52</td>
<td>0.56</td>
</tr>
<tr>
<td>Slow Control</td>
<td>Coimbra, Weizmann</td>
<td>–</td>
<td>–</td>
<td>0.05</td>
<td>–</td>
<td>0.05</td>
</tr>
<tr>
<td>Calibration</td>
<td>Purdue</td>
<td>–</td>
<td>0.05</td>
<td>–</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>Material Screening</td>
<td>MPIK, Zurich</td>
<td>UCLA</td>
<td>–</td>
<td>0.27</td>
<td>0.07</td>
<td>0.34</td>
</tr>
<tr>
<td>Cryostat Support &amp; Platform</td>
<td>Nikhef</td>
<td>Columbia</td>
<td>–</td>
<td>0.25</td>
<td>–</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Total Funds Requested:** 2.07

**Total Proposed:** 5.47

**Total Non-US Funds Secured:** 3.41

**Total Capital Costs:** 10.95

---

*DOE + NSF*
XENON1T – US Responsibility

NSF
E. Aprile
P.I.

DOE
K. Arisaka
P.I.

Columbia
K. Giboni
Cryostat & Cryogenics Systems

Purdue
R. Lang
γ & n Calibration Systems

Rice
P. Shagin
TPC Grids Systems

UCLA
H. Wang
TPC Field Cage & HV Systems

UCLA
C. Ghag
PMT Systems & Calibrations
SUSY and Extra Dimensions
SUSY Neutralino
SUSY Particles and Neutralino

Spin: 1/2, 1, 0
SUSY Particles and Neutralino

Standard particles

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Force particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, c, t</td>
<td>d, s, b</td>
<td>γ, H</td>
</tr>
<tr>
<td>ν_ε, ν_μ, ν_τ</td>
<td>e, μ, τ</td>
<td>Z, W</td>
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</tbody>
</table>

SUSY particles

<table>
<thead>
<tr>
<th>Squarks</th>
<th>Sleptons</th>
<th>SUSY force particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>~u, ~c, ~t</td>
<td>~d, ~s, ~b</td>
<td>~H</td>
</tr>
<tr>
<td>~ν_ε, ~ν_μ, ~ν_τ</td>
<td>~e, ~μ, ~τ</td>
<td>~Z, ~W</td>
</tr>
</tbody>
</table>

Super Symmetry

Spin: 1/2, 1, 0, 0, 1/2, 1/2

Neutralino
Hierarchy Problem

Higgs mass

$$m_b^2 = m_{b_0}^2 + \Delta m_b^2,$$ where $m_{b_0}^2$ is the tree-level mass, and

**SM :**

$$\Delta m_b^2 \sim \frac{\lambda^2}{16\pi^2} \int \frac{d^4 p}{p^2} \sim \frac{\lambda^2}{16\pi^2} \Lambda^2$$

**SUSY :**

$$\Delta m_b^2 \sim \frac{\lambda^2}{16\pi^2} \int \frac{d^4 p}{p^2} \bigg|_{\text{SM}} - \frac{\lambda^2}{16\pi^2} \int \frac{d^4 p}{p^2} \bigg|_{\text{SUSY}}$$

$$\sim \frac{\lambda^2}{16\pi^2} (m_{\text{SUSY}}^2 - m_{\text{SM}}^2) \ln \frac{\Lambda}{m_{\text{SUSY}}}$$

or: new physics at the energy scale of $\Lambda \sim 1$ TeV
Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + sparticles
  \[
  \begin{pmatrix}
  \frac{1}{2} \\
  0
  \end{pmatrix}
  \quad e.g.,
  \begin{pmatrix}
  \ell \\
  \tilde{\ell}
  \end{pmatrix}
  \quad \text{or}
  \begin{pmatrix}
  q \\
  \tilde{q}
  \end{pmatrix}
  \quad \begin{pmatrix}
  \frac{1}{2}
  \end{pmatrix}
  \quad e.g.,
  \begin{pmatrix}
  \gamma \\
  \tilde{\gamma}
  \end{pmatrix}
  \quad \text{or}
  \begin{pmatrix}
  g \\
  \tilde{g}
  \end{pmatrix}
  \]

- 2 Higgs doublets, coupling $\mu$, ratio of v.e.v.’s $= \tan \beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses $m_0$, gaugino masses $m_{1/2}$
  - Trilinear soft couplings $A_\lambda$, bilinear soft coupling $B_\mu$
- Often assume universality:
  - Single $m_0$, single $m_{1/2}$, single $A_\lambda$, $B_\mu$: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity also predicts gravitino mass
  \[m_{3/2} = m_0, B_\mu = A_\lambda - m_0\]
- No-scale supergravity:
  \[m_0 = A_\lambda = B_\mu\]

John Ellis

Katsushi Arisaka, UCLA
MSSM: > 100 parameters

Minimal Flavour Violation: 13 parameters
(+ 6 violating CP)

SU(5) unification: 7 parameters

NUHM2: 6 parameters

NUHM1 = SO(10): 5 parameters

CMSSM: 4 parameters

mSUGRA: 3 parameters

String?
Mass Spectra at the best fit points (before LHC)

Figure 2. The spectra at the best-fit points: left — in the CMSSM with $m_0 = 60$ GeV, $m_{1/2} = 310$ GeV, $A_0 = 240$ GeV, $\tan \beta = 11$, and right — in the NUHM1 with $m_0 = 100$ GeV, $m_{1/2} = 240$ GeV, $A_0 = -930$ GeV, $\tan \beta = 7$, $m_H^2 = -6.9 \times 10^5$ GeV$^2$ and $\mu = 870$ GeV.

Buchmueller et al arXiv: 0808.4218
mSUGRA $m_{1/2}$ vs. $m_0$

$M_x \sim 0.4 \times M_{1/2}$

Katsushi Arisaka, UCLA

SI Cross Section vs. Mass

- **CMSSM**
- **LHC**
- **Pre 2011 2012 2015**
- **XENON100**
- **2011 2012**
- **XENON1T**
- **2017**
- **G1**
- **G2**
- **G3**

*Buchmueller et al. arXiv:1106.2529*

11/11/2011

Katsushi Arisaka, UCLA
SI Cross Section vs. Mass

Ferina et al. arXiv:1104.3573
$M_{1/2}$ vs. $M_0$ & $\mu$

Excluded by XENON100

Excluded by LHC

Ferina et al. arXiv:1104.3573
$M_{1/2} \text{ vs. } M_0$

Buchmueller et al. arXiv:1106.2529
CMSSM $m_{1/2}$ vs. $m_0$

- **Fermi-LAT -- dSph**
- **Xenon 100 (2011)**
- **Neutrino Telescopes - Current**
- **IceCube 80 + DC**
- **ATLAS - Jets**
- **ATLAS - Jets+Lepton**
- **ATLAS - b-Jets**

*Focus Point*

- **Stau Coannihilation**
- **XENON100**

*No Electro-weak Symmetry Breaking*

CMSSM $m_{1/2}$ vs. $m_0$
mSUGRA $m_{1/2}$ vs. $m_0$

Most likely

Excluded by stable charged particle

Coannihilation region $\Omega_\chi > \Omega_{DM}$

Focus point region

Excluded by collider bounds $\Omega_\chi < \Omega_{DM}$

$\tan \beta = 10$

[Graph showing regions of interest for mSUGRA parameters]
KK particles in Extra Dimensions
Origin of Mass in Extra Dimensions

\[ E = mc^2 \rightarrow m = \frac{E}{c^2} \]

- Mass can be generated as kinetic energy in extra dimensions.
  - Origin on mass
  - Dark matter is running in the extra dimensions

- Gravity can escape into the extra dimensions.
  - Why gravity is so small
  - Origin of dark energy
Cyclic Model

“bang”
radiation
matter
dark energy
“contraction”
“crunch”

M theory

Shadow Universe
Our Universe

Katsushi Arisaka, UCLA
Mass Spectrum of the first KK level

Similar to the SUSY mass spectrum

FIG. 1: One-loop corrected mass spectrum of the first KK level in MUEDs for $R^{-1} = 500$ GeV, $\Lambda R = 20$ and $m_h = 120$ GeV.

FIG. 3: Qualitative sketch of the level 1 KK spectroscopy depicting the dominant (solid) and rare (dotted) transitions and the resulting decay product.

Allowed Region of Minimum Universal Extra Dimensions

1/R (GeV)

m_\rho (GeV)

Excluded (charged LKP)

WMAP constraint

Kakizaki 2006
\[ \Omega h^2 \text{ vs. } m_{KK} \]

**ν\(^{(1)}\)**
- Overclosure Limit
- Three Flavors
- One Flavor

\[ \Omega h^2 = 0.16 \pm 0.04 \]

**B\(^{(1)}\)**
- 5d
- 1 Flavor
- 3 Flavors

\[ \Omega h^2 = 0.110 \pm 0.006 \]

\[ \Delta = 0.05 \]
\[ \Delta = 0.01 \]

Predicted Cross Section of Kaluza-Klein Dark Matter


Katsushi Arisaka, UCLA
Discovery Potential by LHC

\[ L \text{(fb}^{-1}) \]

\[ R^{-1} \text{(GeV)} \]

\[ 41E_T \]

\[ \Lambda R = 20 \]

Sensitivity to KK particles

My favorite

Arrenberg 2008
Summary on “Science Cases”

- XENON program (~$10M) is extremely timely and competitive to LHC (~$10B)
  - XENON100 ~ Current LHC
  - XENON1T ~ Future LHC

- If new physics at 100 – 1000 GeV (as it should be), both LHC and XENON1T will discover WIMPs.
  - SUSY - Neutralino
  - Extra Dimensions – KK particles

- By combining LHC and XENON1T, we have a better chance to untangle large parameter spaces.
Target Mass Dependence of WIMP Cross Section

cross section $10^{-44}$ cm$^2$, WIMP mass 100 GeV

$\text{dru} / \text{kg/day/keV}$ vs. $E_r(\text{keV})$

- Xe-132
- Ge-73
- Ar-40
- Si-28
- Ne-20

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11/11/2011
(SI) WIMP Energy Spectrum for LXe
(Cross Section = $10^{-45}$ cm$^2$)

(SI) WIMP Recoil Energy Spectrum for LXe ($\sigma = 10^{-45}$ cm$^2$)

Xenon

- Event rate (kg/day/keVr)
- $E_r$ (keVr)
- $E_r$ (keV) markers: 7 keVr, 45 keVr
- Energy levels: 20 GeV, 50 GeV, 100 GeV, 200 GeV, 500 GeV, 1000 GeV

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(SI) WIMP Energy Spectrum for LAr
(Cross Section = $10^{-45}$ cm$^2$)

(PI) WIMP Recoil Energy Spectrum for LAr ($\sigma = 10^{-45}$ cm$^2$)

Argon

Event rate (kg/day/keVr)

$E_r$ (keVr)

- $M = 20$ GeV
- 50 GeV
- 100 GeV
- 200 GeV
- 500 GeV
- 1000 GeV

$E_r$ (keVr) range:
- 45 keVr
- 200 keVr
1-σ Error of WIMP Mass vs SI Cross Section
(1 ton*year Xe and 5 ton*year Ar)

1-σ Error of WIMP Mass and SI Cross Section

Cross Section (cm$^2$)

Mass (GeV$^{10^3}$)

- 1 ton*year Xenon
- 5 ton*year Argon
- 1 ton*year Xe + 5 ton*year Ar

10$^{-45}$ cm$^2$

G2

11/11/2011

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$1-\sigma$ Error of WIMP Mass vs SI Cross Section (1 ton*year Xe and 5 ton*year Ar)

- Xenon (56 events)
- Argon (42 events)

100 GeV

G2

$10^{-45}$ cm$^2$

1 ton*year Xe + 5 ton*year Ar

1 ton*year Xenon

5 ton*year Argon

Cross Section (cm$^2$)

Mass (GeV)$^{10^3}$
1-σ Error of WIMP Mass vs SI Cross Section
(1 ton*year Xe and 5 ton*year Ar)

1-σ Error of WIMP Mass and SI Cross Section

- 1 ton*year Xenon
- 5 ton*year Argon
- 1 ton*year Xe + 5 ton*year Ar

Xenon (5.6 events)
Argon (4.2 events)

10^{-46} cm^2

100 GeV

G2

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1-σ Error of WIMP Mass vs SI Cross Section

(10 ton*year Xe and 50 ton*year Ar)

1-σ Error of WIMP Mass and SI Cross Section

Cross Section (cm²)

10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷

1 ton*year Xenon
5 ton*year Argon
1 ton*year Xe + 5 ton*year Ar

10⁻⁴⁶ cm²

Xenon
(56 events)

Argon
(42 events)

G3
100 GeV

11/11/2011
Katsushi Arisaka, UCLA
(SI) WIMP Energy Spectrum for LXe
(Cross Section = $10^{-45}$ cm$^2$)

(SI) WIMP Recoil Energy Spectrum for LXe ($\sigma = 10^{-45}$ cm$^2$)

Xenon

Event rate (kg/day/keVR)

- $M = 20$ GeV (Summer)
- 20 GeV (Winter)
- 50 GeV
- 100 GeV
- 200 GeV
- 500 GeV
- 1000 GeV

$E_r$ (keVR)

- 7 keVr
- 45 keVr

- 20 GeV
- 50 GeV
- 100 GeV
- 200 GeV
- 500 GeV
- 1000 GeV

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(SI) WIMP Energy Spectrum for LAr
(Cross Section = $10^{-45}$ cm$^2$)

(SI) WIMP Recoil Energy Spectrum for LAr ($\sigma = 10^{-45}$ cm$^2$)

Argon

- M = 20 GeV (Summer)
- 20 GeV (Winter)
- 50 GeV
- 100 GeV
- 200 GeV
- 500 GeV
- 1000 GeV

Event rate ($\text{kg/day/keVr}$) vs. $E_r$ (keVr)

- 45 keVr
- 200 keVr

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±1 $\sigma$ Error of Annual Modulation Amplitude vs WIMP Mass
(10 ton*year Xe and 50 ton*year Ar, Cross Section = $10^{-45}$cm$^2$)

1-Sigma Error of Annual Modulation Amplitude vs WIMP Mass ($\sigma = 1E-45$cm$^2$)
DUSEL at Homestake, started in 2007

DUSEL: Deep Underground Science and Engineering Laboratory at Homestake, SD

Six and a half Empire State Buildings for scale

Shallow Lab

Mid-level

Deep Campus

300 ft

4,850 ft

8,000 ft

Engineering

Geoscience

Biology

Physics

Astrophysics
XAX (Xenon-Argon-Xenon)  

**14 m**

**12 m**

**Water Tank Veto**

- **WIMP (Spin even)**
  - Double Beta Decay
  - Solar Neutrino

- **WIMP (Spin odd)**

- **WIMP (Spin even)**

- **129/131 Xe**
  - 12 ton (6 ton)

- **136 Xe**
  - 7 ton (4 ton)

- **40 Ar**
  - 70 ton (50 ton)

**2 m**

**12 m**

**14 m**

**1.2 m**

arXiv:0808.3968

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### G2 and G3 facilities defined by PASAG (2009)

<table>
<thead>
<tr>
<th></th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>$&lt; 10^{-44}$ cm²</td>
<td>$&lt; 10^{-46}$ cm²</td>
<td>$&lt; 10^{-47}$ cm²</td>
</tr>
<tr>
<td>Target Mass</td>
<td>10 – 100 kg</td>
<td>~ 1 Ton</td>
<td>~ 10 Ton</td>
</tr>
<tr>
<td>Cost</td>
<td>$1M – 5M</td>
<td>$10 – 20M</td>
<td>~ $100M</td>
</tr>
</tbody>
</table>

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Comparison of Xenon Detector Size

XENON100
161 kg
(48 kg)
2010
30 cm
30 cm
1 m

XENON10
14 kg
(5.4 kg)
2007
15 cm
30 cm
1 m

ZEPLIN-II
31 kg
(7.2 kg)
2007
14 cm
30 cm

G1
XENON 1ton
2.5 ton (1 ton)

G2
MAX, LZD, XAX
20 ton (10 ton)

G3
2019
2 m

2014
1 m

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DarkSide 5T (G2) at LNGS

CTF Water Tank

Liquid Scintillator

2 m

\[ ^{40}\text{Ar} \]

10 ton (5 ton)

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MAX (G3) (at DUSEL)

MAX Layout in Homestake 4850ft

Xe 6 ton

$^{40}$Ar 20 ton
LUX and LZD (at DUSEL)

G1

G2

G3

DARWIN in Europe (LNGS?)

Ar
20 ton
(10 ton)

Xe
8 ton
(5 ton)
MAX+LZD = "Ultimate G3" Detector (at DUSEL)

Xe
20 ton (10 ton)

40Ar
70 ton (50 ton)

2 m

4 m

3” QUPID x 595 (Top)
3” QUPID x 595 (Bottom)

3” QUPID x 2644 (Top)
3” QUPID x 2644 (Bottom)
MAX+LZD = “Ultimate G3” Detector (at DUSEL)

Xe 20 ton (10 ton)  
Liquid Scinti

40Ar 70 ton (50 ton)  
Liquid Scinti

Water Tank

8 m

18 m

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US Dark Matter Programs

G3 = Xe (10T) + Ar (50T)
Technological Challenges
Where backgrounds come from?

• External
• Detector materials
• Internal impurity

Underground or Under high mountains

Cosmic Rays

Radio Activities (U, Th, K...)

Water Tank (Liquid Scintillator)
QUPID (QUartz Photon Intensifying Detector)

Photo Cathode (-6 kV)

Quartz

Al coating

APD (0 V)

Quartz

APD (0 V)

arXiv:1103.3689

Max: -100
-100
-300
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
-2500
-2700
-2900
-3100
-3300
-3500
-3700
-3900
-4100
-4300
-4500
-4700
-4900
-5100
-5300
-5500
-5700
-5900

Min: -5900

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Comparison of Low-radioactive Photon Detectors from Hamamatsu

R8520 1 inch
R8778 2 inch
QUPID 3 inch

XENON10
XENON100
LUX (XMASS)

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QE of two types of QUPID

Quantum Efficiency [%] vs. Wavelength [nm]

Xenon type
- Xenon (178 nm)

Argon type
- Argon + TPB (420 nm)
1, 2 and 3 PE Distribution with 2m cable
Expected Background from Gammas and pp Solar Neutrinos
(100 Year, Multi-hit Cut, S2/S1 Cut)

\[ \text{2 } \gamma /10 \text{ ton-year (pp solar neutrino} \quad + \text{2v double beta decay)} \]

\[ \text{Xenon 10 ton} \]

\[ 5 \times 10^{-8} \text{ DRU} \]
Xe 10 ton Neutron Background (100 Years)

Before Cuts

Multi Hit Cut

Liquid Scinti. Veto

0.81 n / year

0.10 n / year

0.03 n / year

Xenon 10 ton

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Ar 50 ton Neutron Background (100 Years)

Before Cuts

Multi Hit Cut

Liquid Scint. Veto

1/20

1/6

42 n / year

2.1 n / year

0.39 n / year

Argon 50 ton

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Princeton Prototype Plant for Depleted Argon:

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Technological Challenges

- **External Backgrounds**
  - Deep underground
  - 4 m water shielding
  - LNGS, SNOLab, DUSEL

- **Detector Materials**
  - Photon detectors
  - Cryostat
  - Titanium
  - QUPID
  - Copper, PTFE

- **Purity of Liquid Xe/Ar**
  - Radon
  - $^{85}\text{K}$ (0.5 ppt in Xe)
  - $^{39}\text{Ar}$ (in Ar)
  - 1 event / 10 ton-year
  - Depleted Ar from underground

- **Physics Backgrounds (in Xe)**
  - pp-chain solar neutrinos
  - Double beta decays from $^{136}\text{Xe}$
  - 1 event / 10 ton-year
  - 1 event / 10 ton-year

- **Neutron Vetos**
  - B (or Gd) doped Liquid Scintillator
Some Remarks

- **Xenon** is optimum up to 1 Ton scale
  - Largest discovery potential
  - Background \( \sim 1 / \text{ton-year} \)
  - Good sensitivity to low mass WIMP

- At > 10 ton scale, **Argon** is more appealing
  - No gamma ray backgrounds
  - Mass determination up to 200 GeV
  - Large annual modulation
Neutrino Physics

- Neutrinoless Double Beta Decay
- pp-chain Solar Neutrino
- Supernova Neutrino
Energy Spectrum (Natural Xe)

- 100 GeV WIMP (10^{-44} cm^2)
- 2ν DBD (10^{22} yrs)
- pp Solar
- Be7 Solar
- B8 Solar
- 0ν DBD (10^{27} yrs)

Events (keV/day/kg)

Energy (keV)

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XAX (Xenon-Argon-Xenon) arXiv:0808.3968

14 m

12 m

Water Tank Veto

WIMP (Spin even)
Double Beta Decay

WIMP (Spin odd)
Solar Neutrino

WIMP (Spin even)

129/131Xe
12 ton
(6 ton)

136Xe
7 ton
(4 ton)

40Ar
70 ton
(50 ton)

1.2 m

2 m

4 m

14 m

12 m

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Double Beta $\beta\beta(0\nu)$ Decay

$\beta\beta(0\nu) : 2n \rightarrow 2p + 2e^-$

$\Delta L = 2$ Process

- Majorana Neutrino $\nu = \bar{\nu}$
- Right-handed current in weak interaction
- Majoron emission
- SUSY particle exchange

$n \rightarrow p + e^-$

$W^- \rightarrow \bar{\nu}_{eR} + h$

$h \rightarrow \nu_{eL} + h$

$\nu_{eL} \rightarrow W^- + e^-$

$\nu_{eL} \rightarrow W^- + e^-$

$\nu_{eL}$

$\nu_{eR}$

$\nu_M$

$\beta\beta0\nu$

$\beta\beta2\nu$

$0.2$ $0.4$ $0.6$

$0.5$ $(T_1 + T_2)/Q_{\beta\beta}$ $(Q_{\beta\beta} \sim \text{MeV})$ $1$

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Neutrino Mass Differences

Normal Scheme

Inverted Scheme

Laurent SIMARD, LAL - Orsay
Sensitivity of Neutrinoless Double Beta Decay to Neutrino Mass

Normal Scheme

Inverted Scheme

Laurent SIMARD, LAL - Orsay

(Figure from C. Giunti)
$^{136}$Xe Double Beta Decay and Gamma Background
(1 mBq / QUPID, 2m Xenon Detector)
Double Beta Decay Experiments

![Graph showing the relationship between mass and number of backgrounds for various experiments.]

- **NEMO3 (Mo)**
- **NEMO3 (Se)**
- **Cuoricino**
- **GERDA I**
- **GERDA II**
- **GERDA III**
- **Super-NEMO (Se)**
- **CANDLES III**
- **CUORE I**
- **CUORE II**
- **CUORE III**
- **EXO200**
- **EXO 1Ton**
- **XENON1T**
- **COBRA**
- **XAX (Natural)**
- **XAX (Enriched)**
- **XAX (Natural) (Ba tag)**
- **EXO 1Ton (Ba tag)**

The graph illustrates the sensitivity of different experiments in detecting double beta decay events, with axes representing mass in kilograms and the number of backgrounds in background events per year.
Solar Neutrino (by XMASS group)

- **Motivation**
  
  ➞ 99% of solar neutrinos are from pp chain
  
  ➞ Measurement of $\theta_{12}$ with ~1% precision
  
  ➞ Confirmation LMA solution

M. Nakahata

11/11/2011

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Sular Neutrino Detection

\[ 10 \text{pp} / 5 \ ^7\text{Be} \text{ events/day/10ton} \]

SK 13 events/day

\[ 10 \text{ ton LXe} \]

= \[
50 \text{ kton}
\]

M. Yamashita
Solar Neutrino Study by XMASS Group

- Expected region using pp neutrinos (90% C.L.):
  - 10 ton Liq. Xe
  - $\nu_e$ scattering
  - 5 years data
  - Statistical error and SSM prediction error (1%)

- Accuracy of mixing angle:
  $$\sin^2 2\theta = 0.77 \pm 0.03 \text{(stat.+SSM)}$$

KamLAND and pp solar neutrinos will determine precise oscillation parameters.

M. Nakahata

11/11/2011

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PHYSICAL REVIEW D 68, 023005 (2003)

Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

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(Received 5 February 2003; published 28 July 2003)

Development of large mass detectors for low-energy neutrinos and dark matter may allow supernova detection via neutrino-nucleus elastic scattering. An elastic-scattering detector could observe a few, or more, events per ton for a galactic supernova at 10 kpc (3.1×10^{20} m). This large yield, a factor of at least 20 greater than that for existing light-water detectors, arises because of the very large coherent cross section and the sensitivity to all flavors of neutrinos and antineutrinos. An elastic scattering detector can provide important information on the flux and spectrum of νμ and ντ from supernovae. We consider many detectors and a range of target materials from 4He to 208Pb. Monte Carlo simulations of low-energy backgrounds are presented for the liquid-neon-based Cryogenic Low Energy Astrophysics with Noble gases detector. The simulated background is much smaller than the expected signal from a galactic supernova.

DOI: 10.1103/PhysRevD.68.023005

PACS number(s): 97.60.Bw, 95.85.Ry
Neutrinos from a Supernova

➢ Assumptions:
  ▪ 10 kpc away.
  ▪ Total energy radiated in neutrinos = $3 \times 10^{53}$ ergs
  ▪ Equal partition of energy among the 6 neutrinos

➢ Temperatures of neutrinos:
  ▪ $\nu_e$  \hspace{2cm} $k_B T = 3.5$ MeV
  ▪ $\bar{\nu}_e$ \hspace{2cm} $k_B T = 5$ MeV
  ▪ $\nu_\chi$ ($\chi = \mu, \bar{\mu},\tau, \text{and} \bar{\tau}$) \hspace{1cm} $k_B T = 6\sim8$ MeV
Energy Spectrum of SN Nuclei Scattering

Yield of recoiling nuclei (d = 10kpc, $T_{v_x} = 8$ MeV)

- **Xenon**
- **Argon**
- **Neon**

Yield ($\text{ton/keV}_n$) vs. Recoil Energy $E$ (keV$_{nr}$)
Temperature Dependence of Energy Spectrum

Yield of recoiling nuclei (Xenon, $d = 10\text{kpc}$)

**Xenon**

- $T_{\nu_e} = 4\text{ MeV}$
- 6 MeV
- 8 MeV
- 10 MeV

Yield ($\text{ton/keV}_{\text{nr}}$)

Recoil Energy $E$ (keV$_{\text{nr}}$)

- 10
- 1
- 10$^{-1}$
- 10$^{-2}$
- 10$^{-3}$

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

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Temperature Dependence of Energy Spectrum

Event rate and Background rate for 5 ton Ar (d = 10kpc)

Argon

Yield (keV\textsubscript{nr})

Recoil Energy E (keV\textsubscript{nr})

- No pulse shape cut
- Pulse shape cut

ν Event rate (T\textsubscript{ν} = 4MeV, 50% NR acceptance)
- 6 MeV
- 8 MeV
- 10 MeV
- \textsuperscript{39}Ar BG rate (99% S2/S1 cut)
- \textsuperscript{39}Ar BG rate (99% S2/S1 cut, 95% depleted Ar)
Estimate of Total Energy vs. Temperature

1-σ and 2-σ CL of T_{ν_s} and total neutrino energy (d=10kpc, T_{ν_s} = 8MeV, E_{ν_i} = 3*10^{65}J, 1 Ton Xenon)

Xenon (1 Ton)

G2

1-σ and 2-σ CL of T_{ν_s} and total neutrino energy (d=10kpc, T_{ν_s} = 8MeV, E_{ν_i} = 3*10^{65}J, 5 Ton Argon)

Argon (5 Ton)

G2

1-σ and 2-σ CL of T_{ν_s} and total neutrino energy (d=10kpc, T_{ν_s} = 8MeV, E_{ν_i} = 3*10^{65}J, 10 Ton Xenon)

Xenon (10 Ton)

G3

1-σ and 2-σ CL of T_{ν_s} and total neutrino energy (d=10kpc, T_{ν_s} = 8MeV, E_{ν_i} = 3*10^{65}J, 50 Ton Argon)

Argon (50 Ton)

G3
Summary
"Ultimate G3" Detector (at DUSEL)

- Xe 20 ton (10 ton)
- $^{40}$Ar 70 ton (50 ton)
US Dark Matter Programs

G3 = Xe (10T) + Ar (50T)
Dark Matter Experiments

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Detection of Cosmic Radiation

- XENON10
- IMB
- Kamiokande
- AMANDA
- Super-K
- HiRes
- AGASA
- XENON1T
- G3
- LBNE (Water)
- ICECUBE
- AMANDA
- JEM-EUSO
- Pierre-Auger
- HiRes
- AGASA
- XENON100
- XENON1T
- CDMS-II
- XENON10

Larger Volume
Lower Threshold

Past
Ongoing
Future

Cosmic Ray
Neutrino
Dark Matter

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Conclusions

Science cases
- Stronger than ever - SUSY, Extra Dimensions...
- Competitive and complementary to LHC
- Extremely timely

Technical challenges
- Xe-G1 (100 kg) well demonstrated by XENON100
- New photon detector (QUPID) developed
- Radioactivity (\(^{39}\)Ar, \(^{85}\)Kr, Rn) major challenges

Future directions
- G2: XENON 1T and DarkSide 50 / 5T at Gran Sasso.
- G3: MAX + LZD (Xe 10T + Ar 50T) at DUSEL
Katsushi’s Speculations

- **2012** LHC (ATLAS+CMS) announces
  - 120 GeV Higgs (at 3σ)

- **2016** XENON1T announces
  - Observation of 5 WIMP signals (> 200 GeV)

- **2021** G3 (Xe+Ar) and LHC jointly confirm
  - Extra Dimensions
  - WIMP = 600 GeV KK Photon (Δ = 5%)
  - No SUSY
  - Katsushi happily retires at age 65.