Noble Travails:
Noble Liquid Dark Matter Detectors

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Particle Astrophysics Group, Brown University, Department of Physics
(Supported by US DOE HEP)
see information at

http://particleastro.brown.edu/
http://gaitskell.brown.edu
The geocentric pre-Copernican Universe in Christian Europe. At center, Earth is divided into Heaven (tan) and Hell (brown). The elements water (green), air (blue) and fire (red) surround the Earth. Moving outward, concentrically, are the spheres containing the seven planets, the Moon and the Sun, as well as the “Twelve Orders of the Blessed Spirits,” the Cherubim and the Seraphim. German manuscript, c. 1450.

From Joel Primack, UC Santa Cruz
Direct Detection Astrophysics of WIMPs

• Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo
  ▶ “Spherical-cow” assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution
  ▶ \( V_0 = 230 \text{ km/s}, \ v_{\text{esc}} = 650 \text{ km/s}, \)
  ▶ \( \rho = 0.3 \text{ GeV} / \text{cm}^3 \)

• Energy spectrum of recoils is featureless exponential with \( \langle E \rangle \sim 50 \text{ keV} \)

• Rate (based on \( \sigma_{nX} \) and \( \rho \)) is fewer than 1 event per kg of detector per week

• Nucleus recoils (not electron)

“Contains ten 60-GeV WIMPs on average. 20 billion WIMPs pass through each second.”

Coupling to Quarks: SUSY - Supersymmetry
• SOME SUSY MODELS


Background Challenges

• Search sensitivity (low energy region $<<100$ keV)
  
  Current Exp Limit $< 1$ evt/kg/20 days, $\sim 10^{-1}$ evt/kg/day
  
  Goal $< 1$ evt/tonne/year, $\sim 10^{-5}$ evt/kg/day

• Activity of typical Human
  
  $\sim 10$ kBq ($10^4$ decays per second, $10^9$ decays per day)

• Environmental Gamma Activity
  
  Unshielded $10^7$ evt/kg/day (all values integrated 0–100 keV)
  
  This can be easily reduced to $\sim 10^2$ evt/kg/day using 25 cm of Pb

• Moving beyond this
  
  e.g. External Gammas: High Purity Water Shield 4m gives $<<1$ evt/kg/day
  
  Gammas from Internal components - goal intrinsic U/Th contamination toward ppt ($10^{-12}$ g/g) levels
  
  Detector Target can exploit self shielding for inner fiducial if intrinsic radiopurity is good

• Main technique to date focuses on nuclear vs electron recoil discrimination
  
  This is how CDMS II experiment went from $10^2$ $\rightarrow$ $10^{-1}$ evts/kg/day

• Environmental Neutron Activity
  
  $(\alpha,n)$ from rock $0.1$ cm$^{-2}$ day$^{-1}$
  
  Since $<8$ MeV use standard moderators (e.g. polyethylene, or water, $0.1x$ flux per 10 cm
  
  Cosmic Ray Muons generate high energy neutrons 50 MeV - 3 GeV which are tough to moderate
  
  Need for depth (DUSEL) - surface muon 1/hand/sec, Homestake 4850 ft 1/hand/month
# Techniques for dark matter direct detection

<table>
<thead>
<tr>
<th>TYPE</th>
<th>DISCRIMINATION TECHNIQUE</th>
<th>TYPICAL EXPERIMENT</th>
<th>ADVANTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization</td>
<td>None (Ultra Low BG)</td>
<td>MAJORANA, GERDA</td>
<td>Searches for $\beta\beta$-decay, dm additional</td>
</tr>
<tr>
<td>Solid Scintillator</td>
<td>pulse shape discrimination</td>
<td>LIBRA/DAMA, NAIAD</td>
<td>low threshold, large mass, but poor discrim</td>
</tr>
<tr>
<td>Cryogenic</td>
<td>charge/phonon light/phonon</td>
<td>CDMS, CRESST EDELWEISS</td>
<td>demonstrated bkg discrim., low threshold, but smaller mass/higher cost</td>
</tr>
<tr>
<td>Liquid noble gas</td>
<td>light pulse shape discrimination, and/or charge/light</td>
<td>ArDM, LUX, WARP, XENON, XMASS, XMASS-DM, ZEPLIN</td>
<td>large mass, good bkg discrimination</td>
</tr>
<tr>
<td>Bubble chamber</td>
<td>super-heated bubbles/droplets</td>
<td>COUPP, PICASSO</td>
<td>large mass, good bkg discrimination</td>
</tr>
<tr>
<td>Gas detector</td>
<td>ionization track resolved</td>
<td>DRIFT</td>
<td>directional sensitivity, good discrimination</td>
</tr>
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Noble Liquids

• Why Noble Liquids?

Nuclear vs Electron Recoil discrimination readily achieved
  • Scintillation pulse shapes
  • Ionization/Scintillation Ratio

High Scintillation Light Yields / Good Light Transmission (Dimer emission ≠ atomic absorption)
  • Low energy thresholds can be achieved
  • Have to pay close attention to how discrimination behaves with energy

Ionization Drift >>1 m, at purities achieved (<< ppm electronegative impurities)

Large Detector Masses are easily constructed and behave well
  • Shelf shielding means Inner Fiducial volumes have very low activity (assuming intrinsic activity of target material is low)
    – BG models get better the larger the instrument
  • Position resolution of events very good in TPC operation (ionization)
  • Dark matter cross section on nucleons goes down at least to
    \[ \sigma \sim 10^{-46} \text{ cm}^2 = 1 \text{ event/100 kg/year (in Ge or Xe)}, \] so need a large fiducial mass to collect statistics

Cost & Practicality of Large Instruments
  • Very competitive / Simply Increase PMTs

• “Dark Matter Sensitivity Scales As The Mass, Problems Scale As The Surface Area”
Noble Liquids as detector medium

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<tr>
<th></th>
<th>$Z$ (A)</th>
<th>BP ($T_b$) at 1 atm [K]</th>
<th>Liquid density at $T_b$ [g/cc]</th>
<th>Ionization [e-/MeV]</th>
<th>Scintillation [photon/MeV]</th>
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<tr>
<td>He</td>
<td>2 (4)</td>
<td>4.2</td>
<td>0.13</td>
<td>39,000</td>
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<td>Ne</td>
<td>10 (20)</td>
<td>27.1</td>
<td>1.21</td>
<td>46,000</td>
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<td>Ar</td>
<td>18 (40)</td>
<td>87.3</td>
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<td>165.0</td>
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- Scintillation Light Yield comparable to NaI 40,000 phot/MeV
- liquid rare gas gives both scintillation and ionization signals
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- liquid rare gas gives both scintillation and ionization signals
- Scintillation is decreased (~factor 2) when E-field applied for extracting ionization

In LXe ~30% of electron recoil energy appears as scintillation light (7 eV photons)
# Noble Liquid Comparison (DM Detectors)

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<td><strong>Ne</strong> (A=20)</td>
<td>85 nm Requires wavelength shifter</td>
<td>Low BP (20K) - all impurities frozen out No radioactive isotopes</td>
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<td>$60/kg 100%$ even-even nucleus</td>
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<td><strong>Ar</strong> (A=40)</td>
<td>125 nm Requires wavelength shifter</td>
<td>Nat Ar contains $\sim$39Ar 1 Bq/kg $\approx 150$ evts/keVee/kg/day at low energies. Requires isotope separation, low 39Ar source, or very good discrimination ($\sim 10^6$ to match CDMS II)</td>
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<td>$2/kg (isotope separation &gt;$1000/kg) $100%$ even-even</td>
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<td><strong>Xe</strong> (A=131)</td>
<td>175 nm UV quartz PMT window</td>
<td>136Xe double beta decay is only long lived isotope - not a relevant bg for DM search $&gt;10^{46}$ cm$^2$. 85Kr can be removed by charcoal or distillation</td>
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- Ne (A=20): $60/kg, 100% even-even nucleus, requires wavelength shifter.
- Ar (A=40): $2/kg, (isotope separation >$1000/kg), ~100% even-even, requires wavelength shifter.
- Xe (A=131): $800/kg, 50% odd isotope, UV quartz PMT window.

Recoil Energy, $E_r$ [keVr]

- Integrated Rates (dash)
- Differential Rates (lines)

$m_{WIMP}=100$ GeV, $\alpha_{W-N}=1.0 \times 10^{-42}$ cm$^2$
### Noble Liquid Comparison (DM Detectors)

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<th>WIMP (100 GeV) Sensitivity vs Ge &gt;10 keVr</th>
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<td>No radioactive isotopes</td>
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<td>Axial Coupling: ~5x (model dep)</td>
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### Noble Liquids / Dark Matter

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- **Ar (A=40)**: $2/kg, requires isotope separation >$1000/kg, ~100% even-even, requires wavelength shifter.
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Noble Liquid Detectors: Mechanism & Experiments

### Single phase - scintillation only
- e-ion recombination occurs
- singlet/triplet ratio 10:1 nuclear:electron

### Double phase - ionization & scintillation
- drift electrons in E-field (kV/cm)

<table>
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<tr>
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<th>Single phase (Liquid only) PSD</th>
<th>Double phase (Liquid + Gas) PSD/Ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon</td>
<td>ZEPLIN I, XMASS</td>
<td>ZEPLIN II+III, XENON, XMASS-DM, LUX</td>
</tr>
<tr>
<td>Argon</td>
<td>DEAP, CLEAN</td>
<td>WARP, ArDM</td>
</tr>
<tr>
<td>Neon</td>
<td>CLEAN</td>
<td></td>
</tr>
</tbody>
</table>

Energy Deposition / Partition into various excitations

- Ionisation
- Electron/nuclear recoil
- Excitation

These mechanisms apply to all Nobles

Nigel Smith, RAL
Data taken with Micro-CLEAN (McKinsey, Yale)

CLEAN Ar PSD

Profile of light pulse for electrons and neutrons

Singlet

Triplet

Electronic Recoils

Nuclear recoils

Scintillation Efficiency of Nuclear Recoils

Discrimination in LAr is better than 99.999% above 50 keVr
Gamma Ray - Nuclear Recoil Discrimination Efficiency vs Energy in LAr
Assumes 50% nuclear recoil acceptance

PRELIMINARY
DEAP-1 (being deployed)

- **DEAP-1 (Boulay / Hime)**
  Also based on scintillation PSD alone
  Queen's (Boulay) leading effort - Canadian Groups + Yale/LANL
  7 kg LAr with 2x PMT
  - Have been studying PSD using tagged 22Na source to limit lab neutron contamination
  - Preliminary data showing $\sim 10^{-4}$-$10^{-5}$ discrimination. Will continue to push stats.
  Detector will be taken underground at SNOLab shortly
  Poor position reconstruction and so likely to be limited by surface events

![Graph showing data from DEAP-1](image)
DEAP-1 design

- Quartz windows
- Neck connects to vacuum and gas/liquid lines
- 11” x 6” (8” CF) tee
- Poly PMT supports
- 6” acrylic guide
- Acrylic vacuum chamber
- Inner surface 97% diffuse reflector, covered with TPB wavelength shifter

Mark Boulay
Nov 2006
DEAP & CLEAN “ULTIMATE” designs

“miniCLEAN” 1000 kg

- Design is driven by need for neutron reduction via hydrogenous material
- Vacuum thermal insulation versus ice thermal insulation
- Ice insulation not the preferred design for neon due to heat loads

- Liquid Argon 87 K (greater than LN2), Liquid Neon (27 K)
XMASS 100 kg (Xe) - Japan

• **XMASS**
  
  100 kg Prototype operated
  
  - Limited PMT coverage / Position reconstruction of events near walls at center

  Next step is to 800 kg

  ➢ **Status of 800 kg detector**
    
    - **Basic performances have been already confirmed using prototype detector**
      
      ✓ Method to reconstruct the vertex and energy
      ✓ Self shielding power
      ✓ BG level

    - **Detector design is going using MC**
      
      ✓ Structure and PMT arrangement (812 PMTs)
      ✓ Event reconstruction
      ✓ BG estimation

    - **New excavation will be done soon**
XMASS 800 kg - Japan

- 60 triangles
- 10 PMT/triangle x 60 = 600 PMTs
- + 212 PMTs in triangle boundary region
- Total 812 PMTs
- Photo coverage 67.0%
- Center to photocathode ~45cm
- Fiducial volume is 25cm from center.
- PMTs are inside liquid xenon.

**Summary**

- XMASS 800kg detector
  - 1 ton liquid xenon, 90cm diameter, 60 triangles, 812 PMTs
  - BG level $10^{-4}$ dru(day$^{-1}$kg$^{-1}$keV$^{-1}$)
  - Dark matter search $10^{-45}$ cm$^2$
- Detector design by simulation
  - Resolution of event reconstruction
    - 10keV ~3cm 5keV ~5cm at boundary of fiducial volume
  - Background from PMT
    - $^{238}$U, $^{60}$Co $\sim 10^{-5}$ dru inside fiducial volume
  - Water shield for ambient $\gamma$ and fast neutron
    - 200cm shield is enough

Background from PMT $^{238}$U

Funding of 800 kg phase has been recently been approved. Two year build planned 2007-2009.

Concern for DM reach relates to tails in position reconstruction for low energy events.

20 phe = 25 keVr
**XENON Event Discrimination: Electron or Nuclear Recoil?**

**Within the xenon target:**

- **Neutrons, WIMPs** => Slow nuclear recoils => strong columnar recombination
  
  => Primary Scintillation (S1) preserved, but Ionization (S2) strongly suppressed

- \( \gamma, e^-, \mu \) (etc) => Fast electron recoils =>
  
  => Weaker S1, Stronger S2

Ionization signal from nuclear recoil too small to be directly detected => extract charges from liquid to gas and detect much larger proportional scintillation signal => dual phase

Simultaneously detect (array of UV PMTs) primary (S1) and proportional (S2) light =>

Distinctly different S2 / S1 ratio for e / n recoils provide basis for event-by-event discrimination.

**Challenge:** ultra pure liquid and high drift field to preserve small electron signal; efficient extraction into gas; efficient detection of small primary light signal

- S1: \(~1\) phe /keVr in PMTs
- S2: \(~5\) liquid electrons / keVr, \(~100\) phe / keVr in PMTs

**(HIGH EFFICIENCY ANALYSIS \(\geq 4\) keVr)**
Two-phase Argon Detectors: WARP and ArDM

- PSD and secondary scintillation from ionization drift
- WARP (Carlo Rubbia)
  - 3.2 kg prototype running at Gran Sasso
  - Preliminary results reported
  - 140-kg detector w/800-kg active veto under construction
- ArDM (Andre Rubbia)
  - LEMs for ionization readout
  - PMTs for primary scintillation
  - 1 ton prototype in construction
WARP - Dual Methods of Discrimination

- **PSD**
  
  Nuclear Recoil "Ion" has larger prompt component as in single phase

- **S2/S1**
  
  Also have Ionization/Scintillation

---

**Figure 2.**

**Figure 3.**

**Figure 4.**
• Analysis with no events above 55 keV (energy threshold selected a posteriori) yields limit at cyan line (5x above CDMS).
  
  At this threshold energy Ar is 1/10 as sensitive to WIMPs per unit mass as Ge E>10 keV
  
  The 40 keVr cyan dashed line is a simple a “what if” there were no events above 40 keVr

• Have new data run of ~50 kg-days with improved electronics - suggest that it will remove some/all of low energy events. (Announce soon)
39Ar Beta Background - Event Rejection vs Removal

- Note that regular Ar contains 39Ar ~1 Bq/kg, which gives beta spectrum (end point ~500 keV) with a low energy tail of ~150 evts/keVee/kg/day
- This means that in order to match current best CDMS II sensitivity an Ar experiment must deliver at least ~10^6 rejection.
  - Fiducialization/multiple scatter cuts don’t help in reducing this rate
- Possible ways of dealing with it
  - Improve discrimination so it become irrelevant (although still have to deal with the event rate 1 kHz in 1 tonne)
  - Isotopic reduction (WARP have taken delivery of 3 liters of Ar with ~1/50 activity for running in WARP prototype)
  - Extraction of Ar from underground wells
    - However, underground (n,p) process in 39K will generate 39Ar. (n > 3 MeV are generated by U/Th decays)
    - An initial sample that was tested from an underground well had 50x (larger) than usual 39Ar:Ar concentration - large survey will be required to understand factors effecting levels.
**ZEPLIN-II Detector**

- 5 months continuous operation
- 1.0t*day of raw DM data
Discrimination Power

- AmBe calibration (upper)
- Co-60 Calibration (lower)
  Used to define acceptance window
  50% n.r. acceptance shown
  lower S2/S1=40 bound fixed
  Box defined 5-20keVee
- Uniform population across plots
  high rate calibrations (esp Co-60)
  coincidences between events and ‘dead-region’ events
- 98.5% $\gamma$ discrimination at 50% n.r. acceptance
ZEPLIN II

- 31 live days running, 225 kg-days exposure
  - Red Box is 5-20 keVee, 50% NR acceptance based on neutron calibration
  - 29 candidate events seen
    - Estimate 50% from ER leakage from upper band
    - Other 50% from lower band which are Radon daughters plating on PTFE side walls
  - Both populations have been modeled and subtraction performed
  - Final results is <10.4 events (90% CL) consistent with WIMP
The XENON10 Detector

- 22 kg of liquid xenon
  - 15 kg active volume
  - 20 cm diameter, 15 cm drift
- Hamamatsu R8520 1”×3.5 cm PMTs
  - bialkali-photocathode Rb-Cs-Sb,
  - Quartz window; ok at -100°C and 5 bar
  - QE + CE > 12% @ 178 nm
- 48 PMTs top, 41 PMTs bottom array
  - x-y position from PMT hit pattern; σx-y≈ 1 mm
  - z-position from Δtdrift (vd,e- ≈ 2mm/µs),
  - σZ≈0.3 mm
- Cooling: Pulse Tube Refrigerator (PTR),
- 90W, coupled via cold finger (LN2 for emergency)
The XENON10 Collaboration

**Columbia University** Elena Aprile, Karl-Ludwig Giboni, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli and Masaki Yamashita

**Brown University** Richard Gaitskell, Simon Fiorucci, Peter Sorensen and Luiz DeViveiros

**RWTH Aachen University** Laura Baudis, Jesse Angle, Joerg Orboeck, Aaron Manalaysay and Stephan Schulte

**Lawrence Livermore National Laboratory** Adam Bernstein, Chris Hagmann, Norm Madden and Celeste Winant

**Case Western Reserve University** Tom Shutt, Peter Brusov, Eric Dahl, John Kwong and Alexander Bolozdynya

**Rice University** Uwe Oberlack, Roman Gomez, Christopher Olsen and Peter Shagin

**Yale University** Daniel McKinsey, Louis Kastens, Angel Manzur and Kaixuan Ni

**LNGS** Francesco Arneodo and Alfredo Ferella

**Coimbra University** Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos
XENON10 (August 2006)
Detector installation in Shield - Brown Personnel
XENON10 Underground Installation

- Installed March 2006 @ LNGS (~3100 mwe)
- Muon flux ~ 24 $\mu$m$^2$/day (10$^6$ reduction from sea level)
- Began detector calibration end of March
- Began shield installation May 2006
- (bottom left) Installing steel frame on top of 15 cm External HDPE
XENON10: Ready for Low Background Operation

Installation of the Detector... ...and we are operational
XENON10 Live time at Gran Sasso

- High Statistics Gamma Calibs + 1 Neutron Calib
- NON BLIND WIMP search data ~20 live days (Sept) + 20 live days dispersed (Oct-Feb)
- BLIND WIMP Search results from 60 live day (Oct-Feb)
XENON10 Detector

89 PMTs: Hamamatsu R8520-AL 2.5 cm square
Example: Low Energy Compton Scatter

- $S_1 = 15.4$ phe $\sim 6$ keVee
- Drift Time $\sim 38 \mu s \Rightarrow 76$ mm

$s_1$: Primary Scintillation Created by Interaction LXe
$s_2$: Secondary Scintillation Created by e-extracted & accelerated in GXe

$\frac{s_2}{s_1}$: ER $> \frac{s_2}{s_1}$: NR

Expect $> 99\%$ rejection efficiency of $\gamma/n$ Recoils...
Reduction of Backgrounds $\Rightarrow$
Reduction of Leakage Events
Event Localization / Double Scatter Event

- **s1**: ~27 phe
- **s2 hit pattern TOP PMTs**: 
  - R ~ 50mm
  - s2 ~ 4000 phe
- **s2 hit pattern TOP PMTs**: 
  - R ~ 98mm
  - s2 ~ 500 phe

Zoom on s1

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
Neutron Calibration

- 8400 events in range 2-12 keVee
- Characterize single scatter neutron response == WIMP nuclear recoils

Gamma Calibs
- ~3000 events in range 2-12 keVee
  - (15 days but only ~1.5x single scatter ER in WIMP search stats, future calibrations will have higher stats)

Note: ER and NR curves shown are not final versions used in 58 day WIMP Blind analysis

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
Nuclear Recoil (NR), Electron Recoil (ER) Discrimination

ER response appears to be Gaussian in \( \log_{10}(S2/S1) \) down to better than <0.1%.

This is an empirical observation.

We have characterized the discrimination performance using separation of means of ER and NR and sigma of Gaussian.

To date we have collected <~2x number of ER calibration events as ER WIMP search events.

Any subtraction of ER leakage is therefore dominated by “statistics” of calibration.

However, gamma calibration shows improvement of leakage at lower energies. Completely consistent behavior is seen in the WIMP search data.

Analysis of the ER rejection was performed in energy bins 2-3, 3-4 ..-12 keVee.

Note that discrimination improves from 99.0% -> 99.9% at lowest energies.

Errors bars shown are only those from fits of Log-Gaussian hypothesis.
Cuts Explanation

<table>
<thead>
<tr>
<th>QC0: Basic quality cuts</th>
<th>QC1: Fiducial volume cuts</th>
<th>QC2: High level cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed to remove noisy events, events with unphysical parameters or events which are not interesting for a WIMP search</td>
<td>Because of the high stopping power of LXe, fiducialization is a very effective way of reducing background.</td>
<td>Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns</td>
</tr>
<tr>
<td>■ S1 coincidence cut</td>
<td>■ $r &lt; 80$ mm</td>
<td>■ S1 top-bottom asymmetry cut</td>
</tr>
<tr>
<td>■ S1 single peak cut</td>
<td>■ $15 \mu s &lt; dt &lt; 65 \mu s$</td>
<td>■ S1 top RMS cut</td>
</tr>
<tr>
<td>■ S2 saturation cut</td>
<td></td>
<td>■ S1 bottom RMS cut</td>
</tr>
<tr>
<td>■ S2 single peak cut</td>
<td></td>
<td></td>
</tr>
<tr>
<td>■ S2 width cut</td>
<td></td>
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<tr>
<td>■ S2 $\chi^2$ cut</td>
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</tr>
</tbody>
</table>

see Guillaume Plante, Columbia, APS Talk

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
Event with light concentrated locally
=> multiple scatter incl hit near bottom PMTs

Regular Event for comparison

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
**Anomalous S1 Hit Patterns & Leakage**

**Multiple scatter events**

- But only one S2 signal ... second vertex is in LXe where we are not collecting charge e.g. Reverse Field Region below cathode

S2/S1 ratio is reduced since S1 has two contributions, but S2 has only one.
Neutron MC

Very good agreement of observed single scatter neutron calibration events compared with Monte Carlo
Absolute rate consistent with quoted AmBe source strength
Using normalization on neutron event rate 30-80 keVee
If we assume quenching factor is energy independent 19%
  • Spectrum statistically consistent 8-30 keVee
  • ~20% lower event rate in region 2-7 keVee range
Consistent with modest drop in QF at lowest energies
Applying the Gamma-X Cuts to XENON10 Data

XENON10 Blind Analysis – 58.6 days

- WIMP “Box” defined at
  - ~50% acceptance of Nuclear Recoils (blue lines):
    - Centroid -3σ
  - 2-12keVee
    (2.2phe/keVee scale)

- 23 Events in the Nuclear Recoil Acceptance Window

- 13 events are removed from box by Primary Gamma-X Cuts (+)

- 10 events in the “box” after all primary cuts (o)

- 5 of these are not consistent with Gaussian distribution of ER Background

\[ \log \left( \frac{S_2}{S_1} \right) \] vs \( S_1 \)

“Straightened Y Scale” – ER Band Centroid => 2.5
Applying the Gamma-X Cuts to XENON10 Data

XENON10 Blind Analysis – 58.6 days

- WIMP “Box” defined at
  - ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -3σ]
  - 2-12keVee (2.2phe/keVee scale)
  - Assuming QF 19% 4.5-27 keVr

- 10 events in the “box” after all primary analysis blind cuts (o)

- 5 of events are consistent with gaussian tail from ER band
  - Fits based on ER calibrations projected 7.0 +2.1-1.0 events

- 5 of these are not consistent with Gaussian distribution of ER Background

\[ \Delta \log \left( \frac{S_2}{S_1} \right) \text{ vs } S_1 \]

“Straightened Y Scale” – ER Band Centroid normalized => 2.5
Absence of Low Energy Candidate Events (2-7 keVee)

Why are there fewer events in the box in low energy?

- Discrimination improves at lowest energies - NR and ER bands move apart in log(S2/S1) plot
- Missing S2 events less frequent for low energies, (multiple scatters, boost S1)
Applying the SECONDARY Gamma-X Cuts to XENON10

§XENON10 Blind Analysis – 58.6 days

§ WIMP “Box” defined at
  • ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -3σ]
  • 2-12keVee (2.2phe/keVee scale)
  • Assuming QF 19% 4.5-27 keVr

§ 10 events in the “box” after all primary analysis blind cuts (o)

§ 5 of events are consistent with gaussian tail from ER band
  • Fits based on ER calibrations projected 7.0 +2.1-1.0 events

§ 5 of these are not consistent with Gaussian distribution of ER Background
  • 4 out of 5 events removed by Secondary Blind Analysis (looking for missing S2/Gamma-X events)
  • Remaining event would have been caught with 1% change in cut acceptance: WIMP SIGNAL UNLIKELY

log (S2 / S1) vs S1

“Straightened Y Scale” – ER Band Centroid => 2.5

See de Viveiros Talk

De Viveiros - Brown University

APS April Meeting

April 2007 v01 <>
Dark Matter Results and (some of Goals)

- **Dark Matter Goals**
  - **XENON10**
    - Two month run
    - 136 kg-days net exposure
  - **LUX - Sensitivity curve at 2x10^{-45} cm^2 (100 GeV)**
    - Exposure: Gross Xe Mass 300 kg
      - Limit set with 120 days running x 100 kg fiducial mass x 50% NR acceptance
        - If candidate DM signal is observed, run time can be extended to improve stats
    - ~1 background event during exposure assuming most conservative assumptions of ER 7x10^{-4} /keVee/kg/day and 99% ER rejection
      - Intrinsic BG rejection ->99.9% at low energy
      - Improvements in PMT bg will extend background free running period, and DM sensitivity
      - Curve shown is conservative - could improve by factor 10, but this would require 1200 days running to fully exploit... bigger detector
  - **Comparison**
    - SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg (x 50% fid mass+cut acceptance)
      - Limit set for 1000 days running x 7 SuperTowers

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LUX Dark Matter Collaboration
LUX Dark Matter Experiment - Summary

- Brown [Gaitskell], Case [Shutt], LBNL [Lesko], LLNL [Bernstein], Rochester [Wolfs], Texas A&M [White], UC Davis [Svoboda/Tripathi], UCLA [Wang/Arisaka/Cline]
  - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - (Also ZEPLIN III Groups after their current program trajectory is established)
  - Co-spokespersons: Shutt (Case)/Gaitskell (Brown)

- 300 kg Dual Phase liquid Xe TPC with 100 kg fiducial
  - Using conservative assumptions: >99% ER background rejection for 50% NR acceptance, E>10 keV
    (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial

- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - Can achieve BG γ+β < 7x10^-4 /keVee/kg/day, dominated by PMTs (Hamamatsu R8778 or R8520).
    - Neutrons (α,n) & fission subdominant
  - External: large water shield with muon veto.
    - Very effective for cavern γ+n, and HE n from muons
    - Very low gamma backgrounds with readily achievable <10^-11 g/g purity.

- DM reach: 2x10^-45 cm^2 in 4 months
  - Possible <5x10^-46 cm^2 reach with recent PMT activity reductions, longer running.

http://www.luxdarkmatter.org

LUX Dark Matter Collaboration
Topography of Gamma Events That Deposit Energy in FV

- The rate of ER events in FV is determined by small angle scattering Compton events, that interact once in the FV.
  The rate of above events is suppressed by the tendency for the γ's to scatter a second time. Either on the way in, or way out.
  The chance of no secondary scatter occurring is more heavily suppressed the more LXe there is.
  - The important optimization is to maximize the amount of LXe that lies along a line from the greatest sources of radioactivity (PMTs?) that pass through the FV.

- Example for 1.5 MeV γ from outside LXe volume
  Energy Spectrum for part of energy deposited in FV
  Energy spectrum for all energy in detector
  Additional application of multiple scatters cut has little additional effect on low energy event rate

- Conclusion for Event Suppression
  xyz resolution of detector is important simply in defining FV. Little additional reduction from locating vertices.
  (Full xyz hit pattern does assist in bg source identification)
Scaling LXe Detector: Fiducial BG Reduction /1

• Compare LXe Detectors (factor 2 linear scale up each time)
  15 kg (ø21 cm x 15 cm) -> 118 kg (ø42 cm x 30 cm) -> 1041 kg (ø84 cm x 60 cm)

Monte Carlos simply assume external activity scales with area (from PMTs and cryostat) using XENON10 values from screening

Low energy rate in FV before any ER vs NR rejection /keVee/kg/day

Gross Mass 15 kg 118 kg 1041 kg
x2 linear x10 reduction x2 linear
x200 reduction

Fiducial Mass [kg] Fiducial Mass $10^3$ kg
LUX program: exploit scalability

• LUXcore: Final engineering for large-scale detector
  ◦ Cryostat, >100 kV feedthrough, charge drift, light collection over large distance
  ◦ Full system integration, including ~1m water shield
  ◦ 40 kg narrow “core”, 14 PMTs, 20 cm Ø x 40 cm tall.
    • Radial scale-up requires full-funding.
  ◦ Under construction, Jan 2007, operations at Case: June 2007.

• LUX in ~ 6m Ø water shield
• Very good match to early-implementaion DUSEL (e.g., Homestake “Davis” cavern)
  ◦ SNOLAB LOI
• System scalable to very large mass.
Water Shield - Homestake - Davis Cavern
Homestake / Potential DUSEL Site (Lesko, LBL)

- DUSEL process for new national underground lab.
  
  Site Decision mid 2007 (Full DUSEL lab 2010->)

- 4850 mwe depth at Homestake - early program.

- Water Shield: >4 m shielding / 10 module system
Summary
- Past two years we have seen rapid progress in demonstrated performance (NR-ER discrimination/energy resolution/light yields) of Noble Liquid Detectors in low energy regime
- Competitive WIMP Search Results from WARP (Ar), ZEPLIN II (Xe), XENON10 (Xe)

Single Phase (Liquid only) - Pulse Shape Discrimination (ER)
- Ar/Ne demonstrating $>10^5:1$ discrimination at 50 keVr, limitations not fundamental.
  - Will push these tests to $10^8:1$ using higher light yields/shielding in test facilities (required for $10^{-45}$ cm$^2$ dm reach)
- Position reconstruction based on photoelectron hit patterns (timing not useful in <=10 tonne scale). Mis-reconstruction
  - 39Ar (160 evts /keVee/kg/day) / Rn daughters on surfaces (major issue)

Dual Phase (Liquid Target/Ioniz Readout in Gas) - Discrim. Ionization/Photons+PSD (Ar)
- Xe TPC Operation: ZEPLIN II / XENON10 (20-35 kg target)
  - Discrimination established $\sim10^2:1$ (50% NR acceptance), fiducialize to get further bg reduction
    - Xe intrinsically very low activity (cf XMASS), so scaling works
- Ar TPC (WARP) - studying use of Ionization + PSD
  - Discrimination Ionization $\sim10^2:1$ + PSD $>10^4:1$ (energy threshold should be improved with better elec.)

Scaling of Technology
- Detector WIMP sensitivity improves very significantly with size
- Designs are very scalable - 1 event/100 kg/month ($10^{-45}$ cm$^2$) in a few years seems very realizable
- Future instruments for $10^{-46} - 10^{-47}$ cm$^2$ also realistic (performance & cost)