Noble Travails:
Noble Liquid Dark Matter Detectors

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(Supported by US DOE HEP)
see information at

http://particleastro.brown.edu/
http://gaitskell.brown.edu
Dark Matter Theory and Experiment

- SOME SUSY MODELS
  
  
  
  
Background Challenges

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

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

• Environmental Gamma Activity in unshielded detector
  \begin{align*}
  10^7 \text{ evt/kg/day (all values integrated 0–100 keV)} \\
  \text{This can be easily reduced} \sim & 10^2 \text{ evt/kg/day using 25 cm of Pb}
  \end{align*}

• Moving beyond this
  e.g. High Purity Water Shield 4m gives \ll 1 \text{ evt/kg/day}
  But you have to focus on intrinsic U/Th contamination ppt (10^{-12} \text{ g/g}) levels

• 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
  \begin{align*}
  (\alpha,n) \text{ from rock } 0.1 \text{ cm}^{-2} \text{ day}^{-1} \\
  \text{Since } <8 \text{ MeV use standard moderators (e.g. polyethylene, or water, } 0.1x \text{ flux per 10 cm)} \\
  \text{Cosmic Ray Muons generate high energy neutrons 50 MeV - 3 GeV which are tough to moderate} \\
  \text{Need for depth (DUSEL) - surface muon } 1/\text{hand/sec, Homestake 4850 ft } 1/\text{hand/month}
  \end{align*}
# 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>
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<tr>
<td>Bubble chamber</td>
<td>super-heated bubbles/droplets</td>
<td>COUPP, PICASSO</td>
<td>large mass, good bkg discrimination</td>
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<tr>
<td>Gas detector</td>
<td>ionization track resolved</td>
<td>DRIFT</td>
<td>directional sensitivity, good discrimination</td>
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</table>

Noble Liquids

• Why Noble Liquids?

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

  High Scintillation Light Yields
  • Low energy thresholds can be achieved (although 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 $\sigma \sim 10^{-46}$ cm$^2$ $\Rightarrow$ 1 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 (Tb) at 1 atm [K]</th>
<th>liquid density at Tb [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>
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<td>10 (20)</td>
<td>27.1</td>
<td>1.21</td>
<td>46,000</td>
<td>30,000</td>
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<tr>
<td>Ar</td>
<td>18 (40)</td>
<td>87.3</td>
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<td>54 (131)</td>
<td>165.0</td>
<td>3.06</td>
<td>64,000</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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<tr>
<td><strong>Ne</strong> (A=20)</td>
<td>85 nm Requires wavelength shifter</td>
<td>Low BP (20K) - all impurities frozen out</td>
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<tr>
<td>$60/kg</td>
<td>~100% even-even nucleus</td>
<td>No radioactive isotopes</td>
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<td><strong>Ar</strong> (A=40)</td>
<td>125 nm Requires wavelength shifter</td>
<td>Nat Ar contains ~39Ar 1 Bq/kg == ~150 evts/keVee/kg/day at low energies. Requires isotope separation, low 39Ar source, or very good discrimination ($\sim 10^6$ to match CDMS II)</td>
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<td>$2/kg</td>
<td>~100% even-even</td>
<td></td>
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<tr>
<td>(isotope separation &gt;$1000/kg)</td>
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<td>175 nm UV quartz PMT window</td>
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Recoil Energy, $E_r$ [keVr]

(dash) Rate $> E_r$ [kg/day] (line) $dN/dE_r$ [keVr/kg/day]

$\alpha_{W-N} = 1.0 \times 10^{-42}$ cm$^2$

$\rho_{WIMP}=100$ GeV

Integrated Rates (dash)

Differential Rates (lines)
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Xe is 50% odd n isotope 129Xe, 131Xe
Noble Liquid Detectors: Mechanism & Experiments

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<th>Single phase (Liquid only) PSD</th>
<th>Double phase (Liquid + Gas) PSD/Ionization</th>
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<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>
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<td>Neon</td>
<td>CLEAN</td>
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- 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)

Energy Deposition / Partition into various excitations

These mechanisms apply to all Nobles

Xenon
- ZEPLIN I
- XMASS
- ZEPLIN II+III
- XENON
- XMASS-DM
- LUX

Argon
- DEAP
- CLEAN
- WARP
- ArDM

Neon
- CLEAN

Xe
- Ionisation
- Excitation
- Electron/nuclear recoil
- +Xe
- Xe\textsuperscript{+}
- Xe\textsuperscript{+} (recombination)

Xe\textsuperscript{2+}
- +e\textsuperscript{-}
- Xe\textsuperscript{2+}
- Xe\textsuperscript{2+} + Xe

Xe\textsuperscript{*}
- 175nm
- Triplet 27ns
- Singlet 3ns

Xe
- 175nm

Excitation
- Electron/nuclear recoil
- +Xe
- Xe\textsuperscript{+}
- Xe\textsuperscript{2+}
- Xe\textsuperscript{2+} + Xe

Energy Deposition
- Wavelength depends on gas
  - e.g. Xe 175nm
  - Ar 128nm

Time constants
- Depend on gas
  - e.g. Xe 3/27ns
  - Ar 10/1500ns

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

CLEAN Ar PSD

Profile of light pulse for electrons and neutrons

**Time Dependence of Liquid Argon Scintillation**
- Singlet
- Triplet
- Electronic Recoils

**Scintillation Efficiency of Nuclear Recoils**
- LAr (Mini-CLEAN collaboration, Summer 2006)
- LXe (Aprile et al., Phys. Rev. D 72, 072006 (2005))

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

Electronic Recoil Acceptance

Mini-CLEAN requirement

6 pe/keV

4 pe/keV

2 pe/keV

Nuclear Recoil Energy (keVr)
miniCLEAN (proposed)

- 100 kg miniCLEAN
  - WIMP Goal \( \sim 5 \times 10^{-45} \text{ cm}^2 \)
  - 10 events/year

- Backgrounds
  - PMT Gammas
    - Requires better than \( 10^{-8} \)
      rejection of ER at 50 keVr
    - Currently demonstrated \( 10^{-5} \)
      \( >50 \text{ keVr} \) (limited by neutron bg
      in lab)
  - PMT neutrons
    - Studies on going, but these are
      expected to be limitation to
      sensitivity of smaller instrument
    - Less of problem in larger target

Position Reconstruction
- How well can events leaking from outer

Mini-CLEAN
Active mass: 100 kg of LAr or LNe. Expected signal yield > 6 pe/keV
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
DEAP-1 design

Quartz windows

poly PMT supports

11" x 6" (8" CF) tee

Neck connects to vacuum and Gas/liquid lines

ET 9390 PMT 5"

6" acrylic guide

Acrylic vacuum chamber

inner surface 97% diffuse reflector, Covered with TPB wavelength shifter
DEAP & CLEAN “ULTIMATE” designs

“miniCLEAN” 1000 kg

DEAP-3

- 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.

Background from PMT $^{238}$U

- 1.8 x 10^{-3} Bq/PMT
- Reconstructed Energy (keV)
- Drüz (day^{-1}kg^{-1}keV^{-1})

Decision on funding of 800 kg phase currently be considered

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 $~10^{-5}$ dru inside fiducial volume
  - Water shield for ambient $\gamma$ and fast neutron
    - 200cm shield is enough

All volume
- 5cm self shield 40cm from center
- 10cm shield 35cm
- 20cm shield 25cm

Reconstructed Energy (keV)
- 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
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 (~20 electrons); efficient extraction into gas; efficient detection of small primary light signal (~200 photons) associated with 16 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 1: Integrated S1 signal (\(\theta = 40\) \(\mu s\))](image1)

- (a) e-like event, \(F = 0.29\)
- (b) ion recoil event, \(F = 0.74\)

![Figure 2: Neutron induced ion recoils](image2)

- Log (S2/S1) 40-60 keV
- Log (S2/S1) 60-130 keV
WARP Recent Results (Jan 07) astro-ph/0701286

- 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

N.J.T.Smith
ILIAS/ASPERA Paris Workshop
January '07
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 5-20keVee, 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
  - Quantum efficiency > 20% @ 178 nm
- 48 PMTs top, 41 PMTs bottom array
  - x-y position from PMT hit pattern; $\sigma_{x-y} \approx 1$ mm
  - z-position from $\Delta$tdrift ($v_{d,e-} \approx 2$mm/µs), $\sigma_Z \approx 0.3$ 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: Ready for Low Background Operation

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

- Discuss data from High Statistics Gamma Calib, Neutron Calib and NON BLIND WIMP search data ~20 live days
- WIMP Search results (from 80 live day) will be announced at April APS Meeting
XENON10 Detector

89 PMTs: Hamamatsu R8520-AL 2.5 cm square

Grid-Anode-Grid
Top PMTs
GXe
Field Shaping Wires
Bottom PMTs

z = 15 cm

R = 10 cm
Example: Low Energy Compton Scatter

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

$s_1$: Primary Scintillation Created by Interaction LXe

$s_2$: Secondary Scintillation Created by e- extracted & accelerated in GXe

$\frac{(s_2/s_1)}{ER} > (s_2/s_1)_{NR}$

Expect > 99% rejection efficiency of $\gamma/n$ Recoils...
Reduction of Backgrounds => Reduction of Leakage Events
Gamma Calibration (Electron Recoils == Background)

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
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

![Graph](image)

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

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

See Aprile / Manalaysay Talk

log ( S2 / S1 ) vs S1

“Leakage” Events

Removed by Primary Gamma-X cuts
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
- 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

See de Viveiros Talk
Absence of Low Energy Candidate Events (2-7 keVee)

Why are there fewer events in 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)

Manalaysay Talk
Setting Limit

- Effect on dm sensitivity associated with varying assumption of “best fit” to nuclear recoil light yield

  Low energy QF: assume 19% constant as default
  Also consider low energy asymptote >30% - <10%

See Dahl Talk

Yellin Maximum Gap Analysis
PRD 66 (2002) 032005
Allows fit to Sig+Known BG+Unknown BG

XENON10 (w Yellin Maximum Gap Meth.)
070412v4 djt/rjg

Text

Based on 10 events
Based on 10, allowing for 7 BG events

Noble Liquids / Dark Matter
Rick Gaitskell, Brown University, DOE
XENON10

- In situ Neutron Calibration agreed very closely with calibrations of above ground prototypes.
- High Stats Gamma Calib and Preliminary non-blind WIMP search (20 live days) shows performance very similar performance
- Discrimination (S2/S1) - Behavior very encouraging
  
  Gaussian Component
  
  - Due to Recombination fluctuations, and Poisson stats at lowest energies (<5 keVee)
  
  Non-gaussian (systematics) Contribution
  
  - Non-gaussian “LOW TAIL” component is being eliminated at better than 1000:1
    - Tail events removed using cuts tuned on gamma calib (but this is NON blind analysis)
  
  Main Cuts used to
  
  - Fiducial Volume - eliminate events at edge Teflon where charge (S2) collection is poor
  - More than one S2 pulse indicating multiple scatter
  - S1 light hit pattern unusual - e.g. if most of signal is concentrated in few adjacent bottom PMTs, indicates additional scattering in Xe below cathode grid
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
Topology 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

- 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

![Graph showing low energy rate vs fiducial mass for different detector sizes.

Gross Mass 15 kg, 118 kg, 1041 kg with corresponding reductions.

- x10 reduction
  - 15 kg
  - 118 kg

- >10^2 reduction
  - 1041 kg

- x2 linear
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.

• 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

LUX Dark Matter Collaboration
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
Dark Matter Results and (some of Goals)

• Dark Matter Goals
  • LUX - Sensitivity curve at $2 \times 10^{-45} \text{ cm}^2$ (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 $7 \times 10^{-4} \text{ /keVee/kg/day}$ and 99% ER rejection
      — ER bg assumed is dominated by guaranteed Hamamatsu PMT background (R8778 or R8520)
        recent PMTs from Hamamatsu achieving lower backgrounds, but not guaranteed
      — Improvements in PMT bg (and rejection power) will extend background free running period, and DM sensitivity
  • Comparison
    • SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg
      (x 50% fid mass+cut acceptance)
      Limit set for 1000 days running x 7 SuperTowers
Noble Liquids for Dark Matter

• 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 $\sim 10^2:1$ (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 $\sim 10^2:1$ + 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)