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
Other XENON10 / LXe Talks

• Angel Manzur (Yale) - Parallel 3B
  Calibration of Gamma and Neutron response in XENON10

• Eric Dahl (Case) - Parallel 3B
  Liquid xenon discrimination

• Bob Svoboda (Davis/LLNL) - Parallel 1
  LUX 300 kg Dark Matter Detector

• Previous XENON10 APS Talks available at
  http://particleastro.brown.edu & http://xenon.brown.edu

• XENON10 Papers expected ~end May
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
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 $\neq$ 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 $\sigma \sim 10^{-46}$ cm$^2$ $== 1$ 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 Liquid Detectors: Mechanism & Experiments

<table>
<thead>
<tr>
<th></th>
<th>Single phase (Liquid only)</th>
<th>Double phase (Liquid + Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>ZEPLIN I, XENON, 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>
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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

- **Ionisation**
  - $Xe^+$
  - $+Xe$
  - $Xe_{2}^+$
  - $+e^-$ (recombination)

- **Excitation**
  - $Xe^*$
  - $Xe_{2}^*$
  - $+Xe$
  - $Xe^*$

- **Electron/nuclear recoil**
  - $2Xe$
  - $2Xe$

- *Xenon*
  - ZEPLIN I, XENON, XMASS-DM, LUX
  - Time constants depend on gas e.g. Xe 3/27ns, Ar 10/1500ns
  - Wavelength depends on gas e.g. Xe 175nm, Ar 128nm

- *Argon*
  - DEAP, CLEAN
  - WARP, ArDM
  - Clean

- *Neon*
  - CLEAN

These mechanisms apply to all Nobles.

Nigel Smith, RAL
**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

- **γ, e-, μ, (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** >=4 keVr
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)
XENON10 Underground Installation

- Installed March 2006 @ LNGS (~3100 mwe)
- Muon flux ~ 24 \( \mu / m^2/\text{day} \) (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 Underground: Stability of Running

Detector operation and performance shows excellent stability over 9 months

Pressure: $\Delta P < \pm 0.006$ atm

Temperature: $\Delta T < \pm 0.005$ ºC

PMTs gain < ±2%

Start of Blind WIMP Search

End of Blind WIMP Search
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

$\frac{(s_2/s_1)_{ER}}{(s_2/s_1)_{NR}} > 1$

Expect > 99% rejection efficiency of $\gamma/n$ Recoils…
Reduction of Backgrounds $\Rightarrow$
Reduction of Leakage Events
XENON10 Trigger: S2

s1 (~11 phe)  s2 (~2250 phe)

- Noise on individual PMT channels << 0.1 phe equiv
- Zoom on s1

s2 Trigger "catch-all":
- 1 µs RC of \( \sum 34 \) Center-Top PMTs
- Requires look-back for s1

s2 Hit Pattern

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
Event Localization / Double Scatter Event

s1 ~ 27 phe

zoom on s1

R ~ 98mm
s2 ~ 500 phe

R ~ 50mm
s2 ~ 4000 phe

#phe/PMT

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
**Gamma Calibration (Electron Recoils == Background)**

- AmBe (red) and $^{137}$Cs (blue) 4.1 Live–Days (blue)
- Data shown with/without 5.3 kg Fiducial Cuts (QC1)

**Neutron Calibration**

- Sorensen (Brown)
- Note: ER and NR curves shown are not final versions used in 58 day WIMP Blind analysis

- **Fiducial Mass**
- **AmBe**
  - 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)

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE
ER response appears be gaussian in Log10(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

(See Manzur Talk)
Analysis of the ER rejection was performed in energy bins 2-3, 3-4 ..-12 keVee
(See Dahl Talk)
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>- $r &lt; 80 \text{ mm}$</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>
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<tr>
<td>- S2 single peak cut</td>
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<td>- S2 width cut</td>
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<td>- S2 $\chi^2$ cut</td>
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</table>

see Guillaume Plante, Columbia, APS Talk
XENON10 Blind Analysis Cuts

Energy Window: 2-12 keVee (based on 2.2 pe/keVee)

- Basic Quality Cuts (QC0): remove noisy and uninteresting events
- Fiducial Volume Cuts (QC1): capitalize on LXe self-shielding
- High Level Cuts (QC2): remove anomalous events (S1 light pattern)

Fiducial Volume chosen by both Analyses:

15 < dt < 65 us (max drift ~80 us), r < 80 mm

Fiducial Mass= 5.4 kg (reconstructed radius is algorithm dependent)

Overall Background in Fiducial Volume ~0.6 event/(kg d keVee)
XENON10 S1 Pattern Cuts - Removing Tails in S2/S1

Primary Light (S1) Hit Pattern in BOTTOM PMTs

Event with light concentrated locally
=> multiple scatter incl hit near bottom PMTs

Log # phe/PMT

Regular Event
for comparison

0.5 phe
1 phe
2 phe

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XENON10 S1 Pattern Cuts - Removing Tails

Event with light concentrated locally
=> multiple scatter incl hit near bottom PMTs

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Log # phe/PMT

0.5 phe

1 phe

2 phe

Regular Event for comparison

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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.
Performance of QC2 Cut (S1 RMS Cut) on Cs Data

**137Cs Data**

![Graph showing S1 RMS vs. Energy](image)

**PRIMARY ANALYSIS**

QC2 cut based on RMS of S1 scintillation light signal in 10 bottom PMTs with largest signals

This technique was refined further in the secondary analysis designed to look for specific patterns PMTs for S1

- 137Cs data (1.3 x WIMP search data) + Not Blind WIMP search data used to optimize QC2 cuts.
- Define S1-RMS parameter to reject “Events with Anomalous S1 light pattern”: events with most S1 signal in a few bottom PMTs are likely to have scattered first in the LXe layer above bottom PMTs and below cathode grids, or other “dead” LXe regions.

- S1-RMS for bottom PMTs array: events with high S1-RMS parameter coincide with the non-Gaussian events from the ER-band distribution.
• The coincidence of 2 PMT hits is used in Primary Analysis and the S1 analysis threshold is set to 4.4 photoelectrons (=2 keVee) were efficiency is > 99% for correctly tagging S1

• The QC2 cuts efficiency varies between 95% and 78% in the 2-12 keVee energy window for single scatter nuclear recoil (NR) events in Neutron Calibration data
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 - see Manzur Talk
Gamma Calibration (Electron Recoils == Background)

- Q01-QC1 (5.3 kg)
- ER centroid
- ER 99.5% rejection
- NR Centroid
- NR 3σ
- Software Threshold
- S2 ~ 300 phe

Neutron Calibration

- Sorensen (Brown)

DM Results Analysis

- Effect of S2 Trigger Efficiency

S2 300 phe ~ 12 drift electrons

Note: ER and NR curves shown are not final versions used in 58 day WIMP Blind analysis
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 (S2 / S1) vs S1

“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

Δlog (S2 / S1) vs S1
“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)
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 effect of varying low energy QFs >30% - <10%

See Manzur Talk
(NOT) Subtracting Gamma Leakage Estimate

- If gamma response was perfectly known ...
- Current estimate is 2.1 leakage ER events in energy range 2-7 keVee
- We see no WIMP candidate events in the same energy range
- Taking account of this in WIMP sensitivity analysis would improve limit by factor 2
- However, since current statistical errors in gamma calibration are comparable to leakage estimate we will not use an ER leakage subtraction in current result.
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

See de Viveiros Talk
• Dark Matter Goals
  o XENON10
    • 136 kg-days net exposure
  o LUX - Sensitivity curve at $2 \times 10^{-45}$ cm$^2$ (100 GeV)
    • Exposure: Gross Xe Mass 300 kg
      Limit set with 120 days running
      $\times$ 100 kg fiducial mass $\times$ 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 $7 \times 10^{-4}$ /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
  o Comparison
    • SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg
      (x 50% fid mass+cut acceptance)
      Limit set for 1000 days running $\times$ 7 SuperTowers

(XENON10 curve no background subtraction)
Factors Affecting ZEPLIN II vs XENON10

• ZEPLIN II
  PMTs all above liquid
  • S1 0.55 phe/keVee with drift field applied
  • This limits S2/S1 discrimination due to Poisson fluctuations in S1
  7 x 5” PMTs - xy position reconstruction is poor (relative to diameter of target) so
  fiducial volume fraction is smaller (7.2 kg/35 kg) and some leakage in reconstruction of
  surface events
  Room temp getter - introducing Rn into Xe (~1 Hz alphas seen in bulk)
  Overall Gamma Background ~0.8 dru in Fiducial Volume

• XENON10
  PMTs above and below LXe
  • S1 2.2 (3.0) phe/keVee @662 (122) keVee with drift field applied
  • 0.9 phe/keVr (assuming 19% QF for zero field)
  89 x 1” PMTs - xy position reconstruction very good <<5 mm. No apparent leakage due
  to poor position reconstruction.
  High temp getter - not introducing significant levels of Rn (<0.04 Hz alpha seen in bulk)
  Overall Gamma Background ~0.8 dru in Fiducial Volume
In situ Neutron Calibration agreed very closely with calibrations of above ground prototypes.

*Refining QF light yield for nuclear recoil events*

High Stats Gamma Calib and WIMP search data show very similar performance in ER rejection using 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
- 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

**XENON10 Modifications**

A number of components will be replaced in XENON10 to improve radioactive backgrounds

**OPTIONS FOR LARGER LIQUID XENON EXPERIMENTS** are currently being explored