Noble Status of the Search for WIMP Dark Matter

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(Supported by US DOE HEP)
see information at
http://particleastro.brown.edu/
\[ \Delta T = 100 \, ^{\circ}\text{F} \]

East -> West

Boston, - 8 F

LAX, 92 F
Slide from Hanguo Wang in 2008
• Series of world leading results have been obtained with these instruments

• We can replace many of the 3D renderings with constructed experiments

• A few additional experiments that weren’t listed are about to start operation
  • DEAP
  • Darkside
Noble Experiments

Picture from L. Baudis
Gaitskell (Graduate Work) Superconducting Nb Single Crystal Detector

- 1 cm long - 12 g - 250 eV Threshold - “State of the Art in 1991”
- Superconducting Tunnel Junction arrays detecting phonons and quasiparticles from Nb
Doubling every 2 years

Factor 10 every 6.5 years
Doubling every 2 years

Moore: Factor 10 every 6.5 years
Moore: Factor 10 every 6.5 years

Dark Matter Searches: Past, Present & Future

Limit Scalar Cross-section cm$^2$ [60 GeV WIMP]

- ~ 1 event kg$^{-1}$ day$^{-1}$
- ~ 1 event 100 kg$^{-1}$ yr$^{-1}$

Year

- ~ 1985
- ~ 1990
- ~ 1995
- ~ 2000
- ~ 2005
- ~ 2010
- ~ 2015
- ~ 2020

WIMP Search: Factor 10 every 3.3 years

SuperCDMS also focuses on light WIMPs

LUX
Idealized Dark Matter Direct Detection Experiment

- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - “Platonic ideal”
  - We almost have this in PICO (COUPP) bubble chambers

- However,
  - We will naturally be skeptical of the occasional events - do they fit the pattern
    - CF3I nuclear recoil events were time clustered
  - The absence of a dark matter beam off test means that it is particularly difficult to address the possibility of misidentification of backgrounds/systematic

- So we require more information about each event and for the detector response to be as homogeneous as possible
  - We also want to do physics with recoil energy spectrum / target dependence
  - Maybe we can return to the platonic ideal … reduce competing backgrounds
Reduction in ER Backgrounds

- Electron Recoil Events

![Graph showing background rates vs. energy for different experiments, including LUX, CDMS II Ge, XENON10, XENON100, and SNO.]

- Must also consider naked beta backgrounds, e.g., radon daughters.
- p–p solar neutrinos.
- LUX-ZEPLIN (Xe 5.6 Tonne Fid.) irriducibile pp solar.

Then add discrimination.

Thanks to David Malling, Brown, for preparing slide.

Dark Matter Searches
Expected Neutrino Backgrounds

- Neutrino-electron scattering provides a “conventional” background that will dominate electron recoil rates in inner fiducial region of 10 tonne Xe detector
  - Requires ER rejection at 99.5%+ level to remove
- Neutrino-nucleus coherent scattering (solar, atmospheric and supernovae neutrinos) ultimately becomes WIMP search background
Recent Key Sensitivity Improvements

• Some targets have been scaling in size significantly
  ♦ Provides raw sensitivity for lower cross sections
    - Club Sub Zepto $< 10^{-45}$ cm$^2$ (<1 events/kg/century)
  • In 2 years sensitivity to 50 GeV WIMPs has improved by a factor 10.
    - Recent LUX detector sensitivity $\sim 10$ / kg / Century

• Low Mass WIMPs - energy thresholds very important for sensitivity
  ♦ Improving energy sensitivity/thresholds
    • Greater rate of sensitivity improvement for low mass WIMPs, all the way down to 3 GeV WIMPs
  ♦ Improvements => Potential Signals - seen in multiple detectors, motivated detector energy threshold reduction
  ♦ We have re-spawned quite an industry - smaller mass detectors able to make interesting contributions
Recent Key Sensitivity Improvements

• Very Low Energy Calibrations (Electron Recoil + Nuclear Recoil) are being hotly pursued in a range of materials
  ◆ Some calibrations are up-ending previous shibboleths
  ◆ Others are showing convergence in the understanding of response of specific targets

• Importance of Background Calibrations/Discrimination with very High Statistics
  ◆ Allows Convincing Use of Likelihood Models for Signal + Background
  ◆ Accuracy of Monte Carlos has become remarkable good
  ◆ But requires the right detector geometry/calibrations in order to be credible

• Improving understanding of the detector response/physics of target material
  ◆ In 90’s/00’s we saw a lot of pioneering effort in phonon, quasiparticle, electron-hole
  ◆ In 00’s/10’s have seen tremendous progress in photon/ionization, and superheated liquids
Recent Highlights

• Ar Pulse Shape Discrimination (Darkside)
  - By trading off energy threshold to increase scintillation statistics can reject residual 39Ar to allow multiyear running optimized for WIMP searches $m > 100$ GeV

• Underground Ar (UAr) low 39Ar (Darkside)
  - Accumulated stockpile of ~200 kg with demonstrated 1/1400x of Atmospheric Ar (AAr)
  - Presented new WIMP sensitivity limits

• Xe available in quantity on open market in historically low range

• Ar Moving from PMTs -> SiPMs
  - Wavelength shifter into optical allows exploit potentially improved QE at these wavelengths

• XENON100
  - Reported ER annual modulation search - 4.8$\sigma$ in conflict with DAMA
Recent Highlights

• Convergence of low energy nuclear recoil signal yield data
  ◆ Clearer picture of low energy response to NR events - appears to follow ~Lindhard like behavior and absence of energy cutoffs

• New Calibration Data with high stats ER from LUX using 3H injections

• New Low Energy Calibration of LUX using D-D beam and multiple scattering

• LUX reported new search limit using 2013 data but using enhanced calibrations

• LUX New Spin Dependent Limits
  ◆ Xe (nominally odd neutron) but able to make competitive contributions to both neutron and proton spin-dependent - new result from LUX
  ◆ Not available in Ar, Ne, He
Noble Liquid Detectors: Mechanism & Experiments

<table>
<thead>
<tr>
<th></th>
<th>Scintillation Light PSD</th>
<th>Double phase (Liquid + Gas) PSD/Ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon</td>
<td>XMASS</td>
<td>LUX / LZ XENON100+1T, Panda-X</td>
</tr>
<tr>
<td>Argon</td>
<td>DEAP/CLEAN</td>
<td>ArDM</td>
</tr>
<tr>
<td>Neon</td>
<td>CLEAN</td>
<td></td>
</tr>
</tbody>
</table>

- Single phase - scintillation only
  - e-ion recombination occurs
  - singlet (fast)/triplet (slow) ratio enhanced for nuclear vs electron
- Double phase - ionization & scintillation
  - drift electrons in E-field (kV/cm)

Energy Deposition / Partition into various excitations

- Ionisation
- Electron/nuclear recoil
- Excitation

These mechanisms apply to all Nobles

175nm
2Xe
2Xe

Triplet 27ns
Singlet 3ns

Xe 3/27ns
- limited use
- Ar 10/1500ns
- very effective
top hit pattern: x-y localization

S2

Δt: z localization

S1

E

Δt

S2

4540 phe

S1

52 phe

time sample
Pushing Low Mass Search - New LUX Result

Search sensitivity improved significantly to look down to 4 GeV WIMPs with zero background

Talk by Scott Hertel (UC Berkeley)

http://arxiv.org/abs/1512.03506

Coherent Scattering of neutrinos 8B from Sun 0.1-0.16 evts

wrt accelerators sensitivity continues up to 100 TeV+
Xe Target Spin Dependent Limits

• LUX just announced arXiv: 1602.03489 / see also previous XENON100 limit
  ♦ Neutron spin coupling sensitivity is world leading
  ♦ Proton spin is competitive

♦ Note that Klos (2013) shows that 2-body currents enhance Xe Proton Spin component at low q - this improves sensitivity of previous 1-body currents (Ressel and Dean structure functions)
  - Factor 2.1x improvement in sensitivity at 50 GeV
LUX Summary

• New LUX Analysis of 2013 data
  ◆ Calibrated response and acceptance efficiencies with low systematics all the way down to 1.1 keVnr
  ◆ Improved by >20x sensitivity at 8 GeV mass, >2x at 33 GeV mass
  ◆ Gives world-leading sensitivity at >=3.7 GeV mass
  ◆ No evidence for WIMP candidate events in data - signal distributions fully consistent with background model
    • Internal Backgrounds (in Xenon): Ar-37, Kr-85m, Xe-127

• LUX has continued to take WIMP Search data in late 2014, 2015 and will do until mid 2016
  ◆ Goal is >300 live days
  ◆ Detector will then be removed from Sanford Lab/Davis Lab to make way for LZ Experiment
Low Energy Calibration - LUX

Plot thanks to **Dongqing Huang, Brown (see talk)**, James Verbus, Brown, Brian Lenardo, UC Davis
Quenching Factor (Summed Excitons/Energy) versus Lindhard Dimensionless Energy - Comparison of Targets

Lindhard QF $\approx \varepsilon^{0.142}$

$\varepsilon^{0.134}$

Si 1 keVnr

Ar 16 keVnr

Quenching factor = keVee / keVnr

$w^*_{\text{total quanta}} / \text{(true recoil energy)}$

- Silicon
- Germanium
- Argon
- LUX
- XENON10 AmBe endpoint

Data compendium thanks to Brian Lenardo, UC Davis

Discussions with James Verbus, Brown, Matthew Szydagis, UAlbany, Peter Sorensen LBL (See Talk)

$\varepsilon = E / (Z^{7/3} 0.087 \text{ keVnr})$
Xe 8B Event Rate - 77 evts/100 kg/year for no threshold based on new NR calibrations

77 evts/100 kg/year for no threshold

Plot thanks to Attila Dobi, LBL
Xe 8B - Surviving existing cuts used in LUX?

2 fold requirement, phe/photon ~ 12%

Total - 0.25 events/(100 kg year) survive efficiency cuts (0.3%)
Xe 8B Event Rate - Lowering S2 cut threshold

Improving the threshold for photons would require increase in QE of photodetectors >> 30%
but must ensure accidental coincidence (due to dark rate) doesn't become the limitation. 2 phe coincidence is likely limit.

77 evts/100 kg/year for no threshold

Plot thanks to Attila Dobi, LBL
• Or we can scale up the target exposure
LZ Detector Overview

- Instrumentation conduits
- Cathode high voltage feedthrough
- Existing water tank
- Gadolinium-loaded liquid scintillator veto
- Liquid Xe heat exchanger
- Outer detector PMTs
- 7 tonne active volume liquid Xe TPC. 10 tonnes total

See talks by Tom Shutt
Maria Elena Monzani
Tomasz Biesiadzinski
Kelsey Oliver-Mallory
Ethan Bernard on PiXYe
WIMP Signal Region

$\log_{10}(S_2/S_1)$ vs. $S_1$ [phd]

- 40 GeV WIMP
- 8B
- 1σ
- 2σ
- ER
XENON1T: status

- Water Cherenkov shield, cryostat support, service building, electrical plant completed
- Cryostat, cryogenics, storage, purification, cables, fibres installed and commissioned
- Central TPC and PMTs Installed and being tested
- Cooling next month

Elena Aprile to follow
Panda-X

- Moved Panda-X equipment into Jinping Lab in Aug 2012
  - 7 cm electron drift length
  - 54 kg fiducial x 80 days
  - 7 events found in the DM search region, however consistent with background expectation due to accidental pileup and ER leakage
  - 60 cm electron drift length, 500 kg active
  - Test Runs in May-Oct 2015
  - Engineering Run started WIMP Search
  - So far 19 days x 300 kg fiducial

New stainless steel vessel with lower radioactivity
55 R11410 (top)
48 R8520 (veto)
Teflon with better reflectivity
Electrode rings fully covered by Teflon
Overflow chamber inside the vessel

60-cm
500 kg sensitive target
Panda-X Results / Goals

PandaX-II sensitivity assumes:
- 300 kg x 365 day
- 4.4 PE/keV_{ee} (@122 keV)
- S1 range: [3, 47] PE
- ER rejection 99.75%
- NR acceptance 35%
- <3.7 background events
XMASS - Scintillation Only Xe

- **XMASS I**
  - 800 kg with fiducial of 100 kg
  - Commissioning Run 2011-2012
  - Refurbished PMT housing to reduce light coming from activity on seals
- **Continuing Operations**
  - Annual Modulation
- **XMASS 1.5 proposed**
  - Fiducial increase to 1 tonne

Cover around Aluminum seal by Copper ring and protect from scintillation light and low energy beta from dead zone.

Thanks to Masaki Yamashita
XMASS DM - new result

- fixed phase; fit to data

- Annual modulation for two WIMP cases plotted
  - $A^2$ Nuclear recoil signal model

- Full modulation analysis
  - fixed phase
  - Limit consistent with previous xenon results
Darkside DS-50

  - 30 live days, total exposure of 1400 kg-days (47 kg fiducial)
  - Pulse Shape Discrimination (PSD) against β-γ backgrounds > $1.5 \times 10^7$ for WIMPs with masses above ~100 GeV
  - Equivalent to ~5 t yr, with UAr (39Ar @ 0.7 mBq/kg)

- Underground - UAr Substituted, ArXiv 1510.00702
  - 155 kg of UAr used with fiducial of 47 kg
  - 71 live days, exposure of 2600 kg-days (47 kg fiducial)
  - April-July 2015
  - Measured 39Ar absolute 1/1400x AAr 0.7 mBq/kg
  - Also observe 85Kr ~2 mBq/kg
Dark Matter Searches
Rick Gaitskell, Brown University, LZ/LUX/DOE

Darkside

See Talks Alden Fan, UCLA Jeff Martoff, Temple Biagio Rossi, Princeton

• Plans
  - Continue running for 3 year exposure with UAr, PSD discrimination will reject all 39Ar events
  - Construct 30 tonne LAr, 20 tonne fiducial, 5 years running, data taking starts in 2020
  - ARGO - Factor 10 increase again

UAr program today has accumulated ~200 kg. Plans to develop a 100 kg/d production under the URANIA Plant project
• Canfranc - 2 tons LAr operated for >1 year in single-phase - PSD - arXiv: 1505.02443
• AAr so elevated 39Ar - use to study ER rejection
• Installed TPC field cage and SiPM test array
  ♦ Goal is to improve PSD threshold by improving light collection with SiPMs
  ♦ Also evaluating dark rates at 80 K - project acceptable for m² arrays

See talk by Christian Regenfus
Darwin

Design study group for 30-50 tons!

99.98% discrimination, 30% NR acceptance, LY = 8 pe/keV at 122 keV  \( \text{arXiv:1506.08309} \)

\[
\text{WIMP-Nucleon Cross Section} \quad [\text{cm}^2]
\]

\[
\text{WIMP Mass} \quad [\text{GeV/c}^2]
\]

\( \text{arXiv:1506.08309} \)
DEAP-3600 Detector

- 3600 kg argon target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- 50 cm light guides + PE shielding provide neutron moderation
- Steel Shell immersed in 8 m water shield at SNOLAB

See talk by Mark Boulay
DEAP-3600 Detector at SNOLAB

Completed inner detector
255 8” R5912HQE PMTs
installed in water shield tank

Steel Containment Sphere
in 8m diameter water shield tank
DEAP-3600 Dark Matter Search at SNOLAB

Project Overview

3.6 tonne liquid argon target in 85-cm radius ultraclean acrylic vessel, 255 8-inch HQE PMTs

1 tonne fiducial mass designed for < 0.2 background events/year

10^{-46} cm^2 sensitivity for 100-GeV WIMP with 3-year exposure
with 15 keV_{ee} (60 keV_{r}) threshold

Future Project

Planning for development of future 50-tonne argon experiment (photo-detector development, low-background argon and engineering proposal)

Project Status

PMT commissioning Throughout
inner AV, calibration 2015

Water tank fill Aug. 2015

Cryogenic and purification Aug 2015-
System commissioning Feb 2016

Start of AV cooldown Feb 2016

3 months for cool down and filling with liquid argon
MiniCLEAN at SNOLAB: A prototype for CLEAN

- Single phase Liquid Argon
  - Fiducial volume 150 kg / inner volume 500 kg
  - Detector construction complete
  - Expect to cool and operate in 2016
  - Natural Ar & Ar Spike Run

- $4\pi$ coverage to maximize light-yield at threshold ...
  - 3D Position Reconstruction
  - Particle-ID via Pulse-shape discrimination (PSD)

- Radon-reduced assembly ...

- No electric fields (better PSD)
  - PMTs only active component ...

- “Cold” design allows both LAr & LNe

- Simple design scalable to 50–150 tonnes

IFIC Northwest National Laboratory
by Battelle Since 1965
The Practical Matter of a Low Energy Rare Event Search

• Dark Matter signals will be expected to appear first in the lowest energy bins of an experiment that is still in search mode.
• Unfortunately, that is also where the first indications that systematics are starting to dominate.

Thresholdinos

• You should be ready to be skeptical of the results from your uppermost and lowermost bins of your histogram - Attributable, in spirit to Lord Rutherford (I believe).
• It is difficult to control systematics that may cause events to be in edge bins/tails.
  • This is particularly important when a result is dependent on subtle effects.
• And we will need to push the detectors by another $10^3$ before we reach the irreducible coherent scattering atm. neutrino backgrounds.
The Practical Matter of a Rare Event Search

• In 28th year of searching - now at a sensitivity that $10^5$ better than the first round - we need detectors with a Low Sisyphean Index †

• They must want to work correctly / do so without misleading us / low complexity - mustn’t roll back down the hill when we stop paying attention for a moment

• And we will need to push them (pun indented) by another $10^4$ before we reach the irreducible coherent neutrino backgrounds

† Experimentalist’s Perspective of the Technology itself, not the definition that the task can never be completed
Conclusions - Noble - Direct Detection

• DM2016 - Friday will see plethora of Direct Detection Talks starting 8 am
  ◆ LZ CD2/3B in April 2016
• New Results Expected in 2016
  ◆ DEAP3600 preliminary WS results from early running
  ◆ XENON1T preliminary WS results from early running
  ◆ LUX >300 day exposure WS results
  ◆ XENON100 >500 like days for new annual mod, and WS
• Low Mass WIMP signal(s) - sensitivity has improved by three orders of magnitude since 2012
  ◆ Critically there has also been an improvement in our understanding of potential systematics in detector response
  ◆ This Focus - Has brought the best out of people. Yes, we are combative, but that is the spice that makes the best sauce, and it has caused us to hone our arguments, and improve our detailed understanding of the detectors/backgrounds
  ◆ Calibration strategies that can provide abundant statistics, and have low systematic uncertainties are critically important
• We have improved the sensitivity to 50 GeV WIMPs by over an order of magnitude in the last two years (Compare 5 orders of magnitude in the last 25 years => we are accelerating progress)
  ◆ Let us look forward to doing something similar over coming years
• The Spectre of Discovery is always upon us, and is a great responsibility