Dark Matter Searches

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Canada’s Capital University
The Dark Matter Problem

- Rotation curves measure the mass distribution
- Mass density distributed more broadly than visible objects
- Non-luminous halo required to describe rotation curves
- First found in 1933 by Zwicky from Coma Galaxy Cluster analysis
Underground recoil searches for WIMP Dark Matter

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Dark Matter Particle

2 km

rock shields cosmic rays, ν’s and WIMPs remain

detector hardware v. low in radioactivity (~ppb to ppt U,Th)

(Goodman and Witten 1985)

Dark Matter Particle from U, Th in rock (~ppm)

n

γ

(α, n)

n

γ

α

signal is ~10s keV nuclear recoil

H (water, plastic) Shields from n’s (and γ’s) generated in rock wall

underground cavern

Rn

Rn

2 m

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Looking for WIMPs

1. Pick a target, build a detector for low energy nuclear recoils. Detection can include one or more channels (ionization, scintillation, heat, etc.) to aid with background discrimination. Mitigate all sources of backgrounds.

2. Collect data. If no recoils beyond background, rule out regions of mass vs cross-section model space

3. If backgrounds are seen, go back to step 1.

4. If signal is seen, preferably confirm with multiple targets.

(Steps 1 to 3 typically ~10 years. Step 4 TBD.)
LUX & LZ
XENON-100 & 1T
CRESST
PICO
XMASS
DEAP-3600 & beyond
NEWAGE
DMTPC
DAMA/NaI
DAMA/LIBRA
NEWS-SNO
SuperCDMS-Soudan
SuperCDMS-SNOLAB
DAMIC
CDEX
KIMS-NaI
PandaX-II
DarkSide-50 & 20k

SABRE (N&S)
MiniCLEAN
Cogent
DRIFT
DARWIN
Edelweiss
DM-Ice
COSINE
KIMS
ANAIS
TREX-DM
NEWS

… 20 min talk, will try to provide a summary and outlook for recoil DM detectors

not covered here, but equally important are axion searches
SuperCDMS

**Soudan**
Leading limits published on low mass WIMPs

- 15 Ge iZIPs, 0.6 kg each
- Operational Mar. 2012 – Nov. 2015
- In CDMS II location

5 towers all Ge iZIPs

Operation ended late 2015

**Snolab**
Generation-2 experiment, beginning ~2019
Aiming for unique sensitivity to low mass WIMPs

~40 kg mixture of Ge/Si solid state detectors, two detector configurations
iZIPs: Ionization & Phonon Detectors

Simultaneous measurement of ionization and phonons provides better than $1:10^6$ separation between NR and bulk ER.

Operated at low bias (4V) to extract recoil energies on event-by-event basis.

3-D fiducialization in both ionization and phonon energies allows for efficient rejection of external backgrounds down to very low energies.

ICHEP, August 2016
SuperCDMS SNOLAB Projections

Reach at lowest masses accomplished w/ CDMSlite (HV) style detectors with ultra-low (< 100 eV) threshold; will be BACKGROUND limited

start of science runs 2020
Dark Matter in CCDs

Point-like energy deposits from nuclear recoils induced by WIMP interactions

Charge diffuses towards the CCD pixels gates, producing a “diffusion-limited” cluster

1) High-resistivity \(10^{11}\) donors/cm\(^3\), extremely pure silicon, fully-depleted over several 100s \(\mu\)m (typical CCDs few tens of \(\mu\)m)

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CRESST - Detection Principle I

simultaneous read-out of two signals

- **phonon channel:**
  particle independent measurement of deposited energy (= nuclear recoil energy)

- **(scintillation) light:**
  different response for signal and background events for background rejection ("quenching")
Recent result from CRESST-II (arxiv 1509.01515)

CRESST-III Run
LNGS starting
August 2016

Expect x100 increase in sensitivity (arxiv 1503.08065)

Several other projects planning increase in low-mass sensitivity, many good ideas.
Noble liquid detectors

Noble liquid detectors can be scaled to the large target masses needed to probe the low cross-sections for ~high mass WIMPS (20-30+ GeV to TeVs)

Two-phase detectors (TPCs): large target mass, S1+S2 signal allows background discrimination ($\beta/\gamma$ vs recoil) and position reconstruction

Single-phase (scintillation-only): simple detector designs, large target masses with little internal components

Two-phase xenon: XENON-100, XENON-1T, XENON-nT, LUX, LZ, PandaX-II and PandaX-xT

Single-phase xenon: XMASS

Two-phase argon: DarkSide-50, DarkSide-20k, Argo (300 tonnes), ArDM

Single-phase argon: DEAP-3600 (& beyond), miniCLEAN
Scintillation light (S1) and ionization charge from primary event, which is converted to proportional scintillation (S2) in gas phase. Time between S1/S2 and top PMT pattern used to localize event. S2/S1 provides recoil discrimination.

relatively “new” application in DM, about 10 years
PandaX experiment

PandaX = Particle and Astrophysical Xenon Experiments

Phase I: 120 kg DM  
2009-2014

Phase II: 500 kg DM  
2014-2017

PandaX-xt: multi-ton DM future

PandaX-III: 200 kg to 1 ton  
$^{136}$Xe 0vDBD future
China Jinping Underground Laboratory

Deepest in the world (1μ/week/m²) and horizontal access!
PandaX-II

- New inner vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3” PMTs and improved base design
- New separate skin veto region
Run history

- **Series of Engineering runs**
- **Distillation and re-started (Run9, 80 days)**

**2014.10**

- Detector installation at CJPL

**2015**

**2016**

- Nov 22 – Dec 14, Physics commission (Run8, 19 days, stopped due to high Krypton background)

Run8+Run9=98.7 days
Exposure: $3.3 \times 10^4$ kg-day

*Phys. Rev. D. 39, 122009 (2016)*
Final candidates

\[ \log_{10}(S2/S1) \times y,z \text{ corrected} \]

<table>
<thead>
<tr>
<th>ER</th>
<th>Accidental Neutron</th>
<th>Total Expected</th>
<th>Total observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below NR median</td>
<td>1.2</td>
<td>0.84</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Combined results

Minimum upper limit for isoscalar SI elastic cross section reaches $2.5 \times 10^{-46}$ cm$^2$ at 40 GeV.

More than a factor of 2 improvement for high-mass DM compared to the LUX 2015 results.
Large Underground Xenon

- ~1:1 ratio: 50 x 50 cm dodecagonal cylinder of highly reflective PTFE
- 370 kg LXe in total, for all crevices
  - 250 kg in active region (with field)
  - 118, 145, 100 kg fiducial across different analyses (depends on BG)
- 122 phototubes (2 x 61, top and bot)
  - Low BG, sensitive to 175 nm VUV
- Xe pre-purified of Kr-85, plus re-circulated during run for impurities
- Ultra-low BG Ti cryostat, big thermos!
- ~3-4 keV NR threshold (point of 50% efficiency pre-discrimination of ER)
- 0.2% ER leak for ~50% NR accepted (approximate, as PLR used)
Grey within 1 cm of our fiducial volume boundary.

Black: bulk events
Red and blue curves are the ER and NR bands respectively.
Salt identified as blue dots now.

Red and blue curves are the ER and NR bands respectively.
Salt identified as blue dots now.
With salt removed.
A success (!)
After desalinization but prior to limit calculation, events outside of the ER band re-scrutinized 2 populations of rare pathological events were identified contributing 3 sub-NR-band events. Post-unblinding cuts were created, targeting gas S1 events and Cerenkov-like events (light mostly in 1 PMT). S1 quality cuts had been lacking, since focus was on S2 quality cuts.

Loose cuts with flat, high (NR) signal acceptance, defined only on calibration (quite rich!).

2 populations of rare pathological events identified contributing 3 sub-NR-band events.
With the red events from the previous slide included amongst those removed using post-unblinding cuts, the p-value is 40% (BG only).
Our best, lowest exclusion is at 50 GeV: $2.2 \times 10^{-46}$ cm$^2$ (That’s 0.22 zeptobarns in $\sigma$!)

1 order of magnitude off XENON1T

Within < 2 orders of LZ projection

Comparable to LUX 2015 re-analysis of 3 months’ worth of data at low mass but FOUR TIMES better at high mass. (Final G1?)

(LUX. zepto = $10^{-21}$)

(Not preliminary. Analysis/limit is final. Text under internal review.)
A bigger and better version of LUX. Selected!

LZ is now in the midst of its DOE CD-2/3 review. It is already past CD-1 as of last year.

- Instrumentation conduits will go here
- Separate project from LUX

**LUX-ZEPLIN Collaboration**

(A merger of 2 collaborations)

- Existing water tank
- Gd-loaded liquid scintillator
- LXe heat exchanger

**Diagram Details**

- Cathode high voltage feedthrough
- 120 outer detector PMTs
- 2-phase XeTPC
- 494 (131) TPC (Xe skin) PMTs
LZ’s Reach

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial mass
- Due to unique triple veto
- GOALS: < $3 \times 10^{-48}$ cm$^2$, at 40 GeV. Clip $\nu$ shoulder

*plot and models from LZ’s Conceptual Design Report, arXiv:1509.02910
XENON1T

- Reduce background 100X from XENON100
- Goal: 2 t-yr exposure
- Increase sensitivity by factor 100 compared to XENON100
- $1.6 \times 10^{-47} \text{ cm}^2$ @ 50 GeV WIMP

- Located in LNGS
- Many systems upgraded from successful operation of XENON100
- 3.2 tons Xe (2.0 t active volume)
- Water Cherenkov muon veto
- Cryogenics plant for high purity xenon (~10t)
- Largest DM detector ever built!
- Filled with LXe since April 2016
- 248 PMTs
- 96 cm drift x 96 cm diameter
- High reflectivity teflon walls

- TPC now operational!
- In conjunction with commissioning of remaining systems
Projected Sensitivity

- Only need 20 days to reach LUX/PandaX sensitivity!
- Commissioning nearly complete
- Operations of TPC and other systems already underway

- $2.0 \times 10^{-47} \text{ cm}^2$
- @ 50 GeV WIMP
- 2 t-yr data
Upgrade: XENONnT

- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Start data taking by 2019
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DEAP-3600 Detector

3600 kg argon in sealed ultraclean Acrylic Vessel (1.7 m ID)

Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction

255 Hamamatsu R5912 HQE PMTs 8-inch (Light Sensors)

50 cm light guides + PE shielding provide neutron moderation

Scintillation light only – PSD for background discrimination

very strict control of materials

3.5 meters

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Pulse shape discrimination (PSD)

Ar singlet and triplet excited states have well separated lifetimes (7ns vs. ~1.5us)

PMT signal:

Neutron (AmBe)

γ(22Na)

Prompt: 0-150ns
Late: 150ns-10μs

Single phase LAr: scintillation channel is sufficient, no ionization channel
SNOLAB

DEAP-3600, MiniCLEAN
NEWS-SNO Cube Hall
Cube Hall in 2009

Halo
SuperCDMS

PICO, DEAP-1, DAMIC

2009: Low Background Counting

original SNO exp.

Cave Hall

SNO Cavern

South Drift

Personnel facilities

Utility Area

SNO+
All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM).

Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ.

Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)

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DEAP Acrylic Vessel with Light Guide “Stubs” July 2012, U Alberta

Ultrapure acrylic vessel, controlled exposure to radon
Bonding light guides to the DEAP AV, underground at SNOLAB.
DEAP Acrylic Vessel (2013)
Moving the AV into temporary assembly room
Acrylic Vessel Resurfacer

- Mechanical sander to clean inner surface
- Components selected for low radon emanation
- Remove 0.5-mm surface *in situ* with N₂ purge
- Cleans surface to bulk-level impurities
Completed Detector and Shield Tank

Completed Detector: Steel Shell, calibration tubes, muon veto in Shield Tank (fall 2015)

Shield Tank and emergency vent lines, tank was filled with water Oct 2015, cooldown started Feb 2016

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DEAP-3600 argon filling

Argon remains pure during filling, 3600 kg level within 1-2 weeks marks the start of the DM search running (1000 kg-days collected per day)

- Continuous filling for the past month.
- The process system can be run in re-circulation model, to further purify the argon.

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“Concept for future single phase”:
100’s tonnes of argon

Reaches ultimate DM sensitivity (limited by neutrino backgrounds)

Requires low-radioactivity argon (pioneered by DarkSide)

Planned R&D

• photodetector development, characterization
• background reduction
• engineering design and safety
Dark Matter: Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, as well as the ability to confirm or refute current anomalous results.
Summary

Many experiments targeting low-mass and high-mass regions, several new ideas in low-mass region. Vibrant field with new ideas and developments, many new supporting and enabling techniques developed. Apologies for omissions, only a v. small fraction has been discussed here.

Large noble liquid detectors exploring high mass region, possibility of seeing “SUSY” from low-energy nuclear recoils underground.

Many exciting new results, including recent limits from LUX and PandaX-II! Expect new results from XENON-1T and DEAP-3600.

Many projects aiming for sensitivity near neutrino “floor” in the next 5-10 years. Important to develop experimental sensitivity with multiple targets and range of mass sensitivity.

Field has a healthy mix of projects, some with sensitivity right around the corner, some that will take us into mid-2020s and beyond. Discovery can be anywhere along the way – should use the new measurements to guide the future program, and wherever possible … collaborate!

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END