First Dark Matter
Results from LZ

Asher Kaboth
CERN Seminar
9 Aug 2022

https://arxiv.org/abs/2207.03764
Black Hills State University  
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Brown University  
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Lawrence Livermore National Lab.  
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Pennsylvania State University  
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University College London  
University of Liverpool  
University of Oxford  
University of Sheffield
Outline

- Introduction to Dark Matter
- The LZ Experiment
- Looking for WIMPs
- The future is bright
Dark Matter

-0.2-0.6 GeV/cm³ near Earth
Dark Matter Properties

- "Dark"—does not interact electromagnetically
- Stable over lifetime of the universe
- "Cold"—moves slowly enough for galaxy formation
- Local Density is \( \sim 0.3 \text{ GeV/cm}^3 \)
One Candidate: WIMPs

- Weakly Interacting Massive Particle—MeV–100 TeV scale mass
- Weak-scale interactions lead to correct density in present universe
- Motivated by many theories
- Good options for detection!

Lots more, neatly summarized in a Snowmass review
Detecting Dark Matter

Indirect detection Annihilation

Collider Production

Direct Detection Scattering
WIMP Scattering

- Interaction rates are dependent on our model of how the sun and earth move through the galaxy—how fast do we travel relative to WIMPs
- Use a Maxwell-Boltzmann assumption, with cutoff for escape velocity
- Lots of interesting work from new telescopes!
- Potential spin-dependent and spin-independent couplings
- Signal: Falling ~exponential spectrum
Dark Matter Detectors

- Big (many chances to interact)
- Low background (not much SM stuff)
- Good position resolution (fiducialization)
- Low threshold (phase space)
- Event type discrimination (many models)
- Multi-isotope (spin and non-spin dependent interactions)
Liquid Xenon

- Dense
- Easily purified
- Many Isotopes
- Scintillates like a pig
Liquid Xenon

\[ N_{\text{excitons}} \rightarrow Xe_2^* \rightarrow N_Y = N_{\text{excitons}} + r N_{\text{ions}} \]

\[ N_{\text{ions}} \rightarrow Xe^+ + e^- \rightarrow N_e = (1-r) N_{\text{ions}} \]

\[ r, \text{ recombination} \]
Drift time gives z position (~0.5 mm resolution)

S2 light pattern gives x-y position (~few mm resolution)

S1-S2 relative size gives event-type discrimination

S1-S2 relative size gives event-type discrimination
Self-shielding has a bigger impact the bigger the detector is

- 1.5 m diameter
- 1.5 m drift
- 494 PMTs
- 7t Xe in TPC
- PTFE walls for light collection
The TPC walls are made of highly reflective polytetrafluoroethylene (PTFE) panteractions near the TPC walls. The TPC walls are made to nearly circular at the perimeter, thereby optimizing the pattern that transitions from hexagonal near the center for S1 light. The 253 top PMTs are arranged in a hybrid hexagonal pattern to maximize the collection efficiency of LXe. The 241 bottom PMTs are arranged in a close-packed pattern in two arrays viewing the LXe from above and below.

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The active volume of the TPC is a cylinder with both diameter and height equal to 1.46 m, containing 7-tonnes of LXe. Particle interactions in the LXe generate prompt scintillation light ('S1') and release ionization electrons—electrons from the liquid into the gas, and to create an electric field and potential TPC volume. An additional grid below the cathode shields the bottom PMT array from the cathode potential TPC volume. An additional grid below the cathode shields the bottom PMT array from the cathode potential TPC volume.

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Possible Contaminants

- Uranium and Thorium
  - Produce $\alpha$, $\beta$, and $\gamma$
  - Secondary neutron production through $\alpha$-n
  - Long-lived
    - Produce Rn which, as a gas, diffuses
- Krypton and argon dissolved in xenon
  - $\beta$ and $\gamma$ decaying isotopes
- Other radioactive elements—$^{60}$Co and $^{40}$K are most common
- Cosmic activation
- Cavern wall radioactivity
Materials Mitigation

- Enormous screening program for all materials
  - Ge detectors
  - ICPMS
  - Rn emanation
  - Neutron activation analysis
- Clean assembly
  - Rn reduced clean rooms
  - Dust prevention
- Xenon purification
  - Charcoal chromatography
  - Continuous purification in situ
SURF

- Go underground to reduce cosmic muon flux—factor of $10^6$
- Depth of 4850 ft (1.48 km)
- Past home of the Homestake experiment, future home of DUNE
Timeline

- Design completed and approved in 2017
- Autumn 2018: above ground assembly work begins at SURF
- October 2019: TPC heads underground
- March 2020: Cryostat closed underground, 2 mo shutdown for COVID
- July 2021: OD complete and filled
- Sept 2021: TPC filled with xenon
- Autumn 2021: Commissioning
- Next up: the photo album
Grids and PMT Arrays
Going Underground
Outer Detector
Let's do some science!
Science Run 1

- Can we operate the detector stably over long periods?
- Can we calibrate the detector response?
- What do the backgrounds look like?
- Can we set a new WIMP cross section limit?
What is an LZ event?

- A WIMP looks like one S1 (photons) followed by one S2 (drifted electrons) with no activity in the veto detectors.
- Pulses are classified into S1 and S2 based on their parameters such as pulse shape and PMT hit patterns.
- Events are categorized into ‘single scatter’ and ‘multiple scatter’ based on the time, ordering, and size of S1 and S2 pulses.
Stable Operations

- PMTs: >97% operational throughout run
- Liquid temperature: 174.1 K (0.02%)
- Gas pressure: 1.791 bar(a) (0.2%)
- Gas circulation: 3.3 t/day

- Drift field: 193 V/cm (32 kV cathode, uniform to 4% in fiducial volume)
- Extraction field: 7.3 kV/cm in gas (8 kV gate-anode ΔV)
Calibration Needs

- Spatial non-uniformity corrections
- ER band response
- NR band response
- Veto efficiencies
- Data selection efficiency
Spatial Non-uniformity

83mKr (32.1 and 9.4 keV ER), 131mXe (164 keV ER), αs (various)

- Electron lifetime (already shown)
- PMT responses
- Light reflection and absorption
- Typically 10% effect in fiducial volume

Relative S2 Light Collection

LZ Preliminary
Use Noble Element Simulation Technique (NEST) to model the relationship between recoil energy and S2-S1 observable space.

- CH$_3$T injection produces a uniformly distributed, well known spectrum over the detector to tune the response model—use identical cuts to the WIMP search.

- Additionally use monoenergetic ER sources to validate model.

- We can test (and validate!) the model of ER leakage into the NR band out to 4$\sigma$.

\[ E = W \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{\text{gas}}^1$</td>
<td>0.0921 phd/photon</td>
</tr>
<tr>
<td>$g_1$</td>
<td>0.1136 phd/photon</td>
</tr>
<tr>
<td>Effective gas extraction field</td>
<td>8.42 kV/cm</td>
</tr>
<tr>
<td>Single electron</td>
<td>58.5 phd</td>
</tr>
<tr>
<td>Extraction Efficiency</td>
<td>80.5%</td>
</tr>
<tr>
<td>$g_2$</td>
<td>47.07 phd/electron</td>
</tr>
</tbody>
</table>
Nuclear Recoil Band Response

Deuterium-Deuterium Neutron Source

- DD source produces a monoenergetic 2.45 MeV neutron, which produces a range of Xe NR energies
- Extrapolate model to NR response—works very well
- Rejection of 99.9% ER leakage below the median quantile of a 40 GeV WIMP.
Looking for WIMPs
All Single-Scatter Events

- There’s a lot going on!
- Lots of stuff above and below the expected ER and NR bands
- This includes
  - Events from walls
  - Accidental coincidence events
  - Physics backgrounds

WIMPs would live here
Fiducial Volume Cuts

- PTFE on TPC walls induces charge loss
- Walls have additional radioactivity relative to the bulk
- Select a fiducial volume with expected <0.01 events
- ...but what’s the rest of this junk?
  - Some physics backgrounds
  - Mostly accidental coincidences!
Electron Trains

- S2s are followed by a large amount of activity in the detector
  - electrons which attach to liquid impurities and then are released or have delayed extraction
  - photons from fluorescence in the detector
- Cut these events with an analysis hold off after S2s which is proportional to the size of the S2
- Very effective, but big effect on livetime

Red dots: S2 times
Grey bands: hold off
Livetime

<table>
<thead>
<tr>
<th>Cause</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot spots</td>
<td>3.1%</td>
</tr>
<tr>
<td>Muon crossings</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Electron Train</strong></td>
<td><strong>29.8%</strong></td>
</tr>
<tr>
<td>High S1 rates</td>
<td>0.2%</td>
</tr>
<tr>
<td>Undetected Muons</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electronics Noise</td>
<td>&lt;0.001%</td>
</tr>
<tr>
<td>Veto Detector Cuts</td>
<td>5%</td>
</tr>
</tbody>
</table>

- We also veto time periods in which there is high activity from other effects in the detector
- Dominant impact on livetime is the electron trains cut
- Total of 60 live days
Other Accidental Coincidences

- Even after the electron train cut, there are remaining accidental coincidences
  - S1 sources include: dark noise pileup, PMT Cerekov light, events above the anode/below cathode, PTFE fluorescence, etc
  - S2 sources include: grid emission, events in the gas region, events where the S1 is missed, etc
- We can use pulse shape, timing, and position to discriminate true scatters from coincidence
WIMPs should never leave energy in both the TPC and veto detectors

We veto both ‘prompt’ coincidence (γ backgrounds) and ‘delayed’ coincidence (neutron backgrounds)

Achieve 88.5% tagging efficiency, measured by inserting AmLi neutron sources in a deployment system between the inner and outer cryostat
Signal Efficiencies

DD, AmLi, CH$_3$T

- Measure trigger efficiency by comparing the DD source trigger to the DAQ trigger
- Requiring 3-fold coincidence dominates the S1 efficiency
- Measure single scatter detection by visual inspection of DD events
- None of our neutron source calibrations are spatially uniform in the detector—stitch together an S1 from CH$_3$T and an S2 from either CH$_3$T or AmLi to make a synthetic event
- Find 50% efficiency at 5.3 keV NR
What’s left?
Backgrounds

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ decays + Det. ER</td>
<td>218 ± 36</td>
</tr>
<tr>
<td>$\nu$ ER</td>
<td>27.3 ± 1.6</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>9.2 ± 0.8</td>
</tr>
<tr>
<td>$^{124}$Xe</td>
<td>5.0 ± 1.4</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>15.2 ± 2.4</td>
</tr>
<tr>
<td>$^8$B  CEνNS</td>
<td>0.15 ± 0.01</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>276 ± 36</strong></td>
</tr>
<tr>
<td>$^{37}$Ar</td>
<td>[0, 291]</td>
</tr>
<tr>
<td>Detector neutrons</td>
<td>0.0$^{+0.2}$</td>
</tr>
<tr>
<td>30 GeV/c$^2$ WIMP</td>
<td>–</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>–</strong></td>
</tr>
</tbody>
</table>

Beta emitters 58%
Beta Emitters

- **214Pb**
  - Comes from $^{222}$Rn in Xe
  - Measure rate of $^{222}$Rn α chain and energy spectrum of elements above WIMP search ROI

- **212Pb**
  - Comes from $^{220}$Rn in Xe
  - Measure rate of $^{220}$Rn α chain and energy spectrum of elements above WIMP search ROI

- **$^{85}$Kr and $^{39}$Ar**
  - Naturally occurring in Kr/Ar
  - Measure total Kr/Ar via sampling

- **Detector components**
  - Predictions from assays and simulation modeling

<table>
<thead>
<tr>
<th>Source</th>
<th>Measured Rate</th>
<th>Predicted Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}$Pb</td>
<td>3.26 μBq/kg</td>
<td>166±35</td>
</tr>
<tr>
<td>$^{212}$Pb</td>
<td>0.137 μBq/kg</td>
<td>18±5</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>0.042 μBq/kg</td>
<td>33±5</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>0.87 nBq/kg</td>
<td>0.6±0.1</td>
</tr>
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<td>Det ER</td>
<td>—</td>
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37Ar

- Produced naturally in air and in Xe by cosmic spallation
- Monoenergetic 2.8 keV peak via electron capture, 35 d half-life
- Predict 97 events from spallation rates and underground decay
- Very large uncertainties from cross sections and details of Xe handling

Phys Rev D 105, 082004 (2022)
ν Backgrounds

- Solar neutrinos can produce both ER backgrounds from ν-e scattering and NR backgrounds from coherent ν-N scattering.
- Rates are predicted from external experimental and theoretical work.
- ν-e scattering produces a flat spectrum.
- ν-N scattering from $^8$B produces a very low energy NR signal that is mostly excluded (0.15 events) due to the S2 threshold.

Xenon Isotopes

- Xenon itself has several isotopes that undergo radioactive processes with energy in the ROI
  - $^{136}$Xe is a double $\beta$ decay nucleus with $t_{\frac{1}{2}}=2.1 \times 10^{21}$ y, broad spectrum
  - $^{124}$Xe is a double electron capture nucleus with $t_{\frac{1}{2}}=1.8 \times 10^{22}$ y, monoenergetic peaks
  - $^{127}$Xe is a single electron capture nucleus with $t_{\frac{1}{2}}=36$ d, monoenergetic peaks—reduced 5x by veto detectors
- Predictions are driven by known energy spectra, lifetimes, and isotope fractions
Use knowledge of OD neutron tagging efficiency and events that pass all cuts except OD cuts to predict neutron background.

Find that the prediction of neutron events is $0.0^{+0.2}$.
Accidentals

- DAQ is designed to allow events with drift time longer than the physical region.
- Use the unphysical events to determine the rate of accidentals.
- Use synthetic events from randomly matching S1 and S2 pulses to determine the shape of the PDF.
- Total prediction of 1.2 events overall, and ~0.2 in NR band.
Predicted Spectra

- Grey band shows 1 and 2\(\sigma\) bands for the total predicted background
- Orange shows where 37Ar sits
- Green shows where 8B \(\nu\)-N scattering sits
- Purple shows expected 30 GeV WIMP band
Post-Fit Spectra

- Grey band shows 1 and 2σ bands for the total best-fit background
- Orange shows where 37Ar sits
- Green shows where 8B ν-N scattering sits
- Purple shows expected 30 GeV WIMP band
- We predicted the background pretty well!

335 data events
Data events are uniformly spread throughout the fiducial volume

Red and blue points show events vetoed by veto detectors
For all tested WIMP masses, the best-fit number of WIMP events is zero.

Look at data in 1D reconstructed energy and ‘discrimination variable’ to check validity of background model.

$^{37}$Ar is $\sim 50\%$ of prediction.

Total background rate is $\sim 25$ counts/tonne/year/keVee.

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The dark matter community came together in 2021 to establish statistical conventions for searches—inspired by similar work for the collider community.

We use:

- A profile likelihood ratio test statistic, scanning over possible WIMP masses
- A two-sided test statistic with 90% confidence limits
- A power constrained limit with $\pi_{\text{crit}}=0.32$
- Test statistic distributions generated by simulated toys

In this analysis, we did not blind or salt the data.
Smallest WIMP mass chosen is 9 GeV/c\(^2\) by confidence in Xe response models.

Minimum of limit curve is at (30 GeV/c\(^2\), 6x10\(^{-48}\) cm\(^2\)).
Spin-Dependent Limits

- Consider limiting cases that WIMPs interact only with neutrons and only with protons
- $^{129}$Xe and $^{131}$Xe have 1/2 and 3/2 nuclear spin, respectively, from unpaired neutrons
- Sensitivity to proton interactions are retained through higher order effects—albeit with large uncertainty
What’s Next?
Electron Recoil Models

- Lots of interest in the XENON1T excess... but first results from XENONnT shows it hasn’t persisted
- LZ is limited in that region by $^{37}\text{Ar}$
- Will release similar searches in the near future
Science Run 2 and Beyond

- Currently have an ongoing calibration and detector optimization campaign
- Will begin new science data taking in the near future!
- Many optimizations also can be made for our analyses—expand phase space, better model backgrounds, etc
- Ultimate goal is 1000 live days
Expected Limits: WIMPs

- SR1 got a little lucky around 30 GeV
- Still lots of parameter space to explore
- Begin to reach the neutrino ‘fog’!

Phys. Rev. D 101, 052002
**Expected Limits: 0νββ**

- Probe very top of degenerate region
- Reasonably competitive with dedicated experiments!
- Potentially enhanced with enrichment after DM analyses complete

![Graph showing projected sensitivity to 0νββ decay](image-url)
Expected Limits: ER-like

- Many different models that can be tested in ER-like signals:
  - Neutrino magnetic moment
  - Hidden photons
  - Axions and ALPs
  - Mirror dark matter
  - DM-e scattering

Phys. Rev. D 104, 092009
XLZD

- Looking even further into the future, the XENON, DARWIN, and LZ collaborations are joining forces for the next generation
- Joint meeting this summer at KIT
- [White paper and website](#)
Conclusions

๏ LZ has successfully completed its first science data taking
๏ The detector is working well, and backgrounds are within the design specifications
๏ New best limits have been set in WIMP searches
๏ There’s much more to come!
Uranium and Thorium
FIG. 1. Left: Cutaway drawing of the LZ detector system. The LXe-TPC is surrounded by the outer detector (OD) tanks (green) and light collection system (white), all housed in a large water tank (blue-grey). Conduits penetrate the various regions and boundaries to deliver services to the LXe-TPC: PMT and instrumentation cables (top and bottom, red); cathode high voltage (lower left with cone); purified LXe (bottom center, green); neutron beam conduit (right, yellow and pitched). Right: Expanded view of the lower right corner. 'OD PMT' indicates an outer detector photomultiplier tube. The xenon skin region is observed by an independent set of PMTs (not depicted) and is surrounded by a room temperature liquid scintillator outer detector (OD). Both are located within a large water tank in the Davis Campus at the 4850-foot level (4300 m w.e.) of the Sanford Underground Research Facility (SURF) [11]. Key dimensions and masses of the experiment are summarized in Table I.

The active volume of the TPC is a cylinder with both diameter and height equal to 1.46 m, containing 7-tonnes of LXe. Particle interactions in the LXe generate prompt scintillation light (‘S1’) and release ionization electrons—the latter drift in an applied vertical ($z$) electric field and are extracted into the gas layer above the surface where they generate electroluminescence photons (‘S2’). The xenon circulation and purification strategies are based on the LUX experience [12–14] and electronegative impurities are suppressed sufficiently to allow electrons to survive, with good efficiency, drifting through the length of the TPC.

Photons are detected by 494 Hamamatsu R11410-300-diameter photomultiplier tubes (PMTs), with a demonstrated low level of radioactive contamination [15,16] and high quantum efficiency [17] at the LXe scintillation wavelength of 175 nm [18]. The PMTs are assembled in two arrays viewing the LXe from above and below. The 241 bottom PMTs are arranged in a close-packed hexagonal pattern to maximize the collection efficiency for S1 light. The 253 top PMTs are arranged in a hybrid pattern that transitions from hexagonal near the center to nearly circular at the perimeter, thereby optimizing the ($x, y$) position reconstruction of the S2 signal for interactions near the TPC walls. The TPC walls are made of highly reflective polytetrafluoroethylene (PTFE) panels that also embed 57 field-shaping rings which define the drift field.

Vertical electric fields in the TPC are created by four horizontal electrode planes, which consist of grids woven from thin stainless steel wires. At the top of the TPC, the gate and anode grids (operating at 5.75 kV, respectively) straddle the liquid surface to extract ionization electrons from the liquid into the gas, and to create an S2-generating region in the gas phase. At the bottom, the cathode grid defines the lower boundary of the active TPC volume. An additional grid below the cathode shields the bottom PMT array from the cathode potential. This creates a reverse field region below the cathode, containing 840 kg of LXe, where energy deposits create S1-only events. The drift field is established between the cathode and gate grid. The nominal cathode operating voltage is 50 kV, delivered from a dedicated conduit penetrating the cryostat laterally. In this work we assume a uniform TPC drift field of $310 \text{ V cm}^{-1}$.

A two-component veto system rejects multi-site backgrounds and asynchronously characterizes the radiation environment around the WIMP target. The innermost veto component is the xenon skin region, formed by instrumenting the outer 2 tonnes of LXe located between the TPC and the inner cryostat vessel. This region is optically segregated from the TPC, and scintillation light produced in the LXe is viewed by 93 Hamamatsu R8520 PMTs mounted near the xenon liquid level and a further 38 Hamamatsu R8778 PMTs mounted near the bottom of the TPC. The inner surface of the inner cryostat vessel is covered by a thin liner of PTFE to improve light collection. The principal role of this skin region is the detection of scattered gamma rays. A 3 phd requirement on the scintillation signal yields an effective...
What’s going on at 30 GeV?

We see a downward fluctuation near 30 GeV/c²

This is caused by a lack of background events under the $^{37}$Ar

We have plenty of efficiency there in both ER (CH₃T) and NR (DD)

Conclusion: this is likely a statistical fluctuation

Also see M-shell $^{127}$Xe tagged with skin
What’s a Power Constraint?

- The power of a statistical test is the probability that the test correctly detects an effect when it is there.
- As the number of background events increases, this asymptotically reaches the $-1\sigma$ sensitivity band.
- When the number of background events is small, this breaks down.
‘Doke’ plot

\[
\langle S_{1c}/E \rangle \quad \text{[phd/keV]}
\]

\[
\langle S_{2c_{bottom}}/E \rangle \quad \text{[phd/keV]}
\]

- $^{85m}$Kr: 41.5 keV
- $^{125}$I: 67.3 keV
- $^{129m}$Xe: 164 keV
- $^{127}$Xe: 208 keV
- $^{127m}$Xe: 235 keV
- $^{125m}$Xe: 276 keV
- $^{127}$Xe: 380 keV
- $^{127m}$Xe: 408 keV
- $^{211}$Bi: 609 keV
- $^{225}$Ac: 911 keV
- $^{60}$Co: 1173 keV
- $^{60}$Co: 1332 keV
- $^{40}$K: 1460 keV
- $^{214}$Bi: 1764 keV
- $^{214}$Bi: 2204 keV
- $^{208}$Tl: 2614.5 keV
'Pies' Plot

\[ \log_{10}(S2c \, [{\text{phd}}]) \]

\[ \text{S1c \, [{\text{phd}}]} \]

- 0.9 keV\text{ee}
- 2.9 keV\text{ee}
- 5.1 keV\text{ee}
- 7.4 keV\text{ee}
- 5 keV\text{nr}
- 15 keV\text{nr}
- 25 keV\text{nr}
- 35 keV\text{nr}

- 9.8 keV\text{ee}
- 45 keV\text{nr}
- 60 keV\text{nr}
- 13.4 keV\text{ee}
Kr Removal

- LXe can be contaminated with air or cosmic ray activation
- Light elements like N or O can be removed with ‘standard’ purification
- Most dangerous contamination is Kr—needs to be removed before Xe goes underground
Other Couplings

- Consider all couplings of the form
- SI and SD are just two of the many possible couplings
- Signal: Nuclear Recoil with many possible spectra

\[ O_1 = 1 \chi_1 N \]
\[ O_3 = i \vec{S}_N \cdot \left[ \vec{q} \times \vec{v} \right] \]
\[ O_4 = \vec{s}_x \cdot \vec{s}_N \]
\[ O_5 = i \vec{s}_x \cdot \left[ \vec{q} \times \vec{v} \right] \]
\[ O_6 = \left[ \vec{s}_x \cdot \frac{\vec{q}}{m_N} \right] \left[ \vec{s}_N \cdot \frac{\vec{q}}{m_N} \right] \]
\[ O_7 = \vec{s}_N \cdot \vec{v} \]
\[ O_8 = \vec{s}_x \cdot \vec{v} \]
\[ O_9 = i \vec{s}_x \cdot \left[ \vec{s}_N \times \frac{\vec{q}}{m_N} \right] \]
\[ O_{10} = i \vec{S}_N \cdot \frac{\vec{q}}{m_N} \]
\[ O_{11} = i \vec{S}_x \cdot \frac{\vec{q}}{m_N} \]
\[ O_{12} = \vec{s}_x \cdot \left[ \vec{s}_N \times \vec{v} \right] \]
\[ O_{13} = i \left[ \vec{s}_x \cdot \vec{v} \right] \left[ \vec{s}_N \cdot \frac{\vec{q}}{m_N} \right] \]
\[ O_{14} = i \left[ \vec{s}_x \cdot \frac{\vec{q}}{m_N} \right] \left[ \vec{s}_N \cdot \vec{v} \right] \]
\[ O_{15} = - \left[ \vec{s}_x \cdot \frac{\vec{q}}{m_N} \right] \left( \vec{s}_N \times \vec{v} \right) \cdot \frac{\vec{q}}{m_N} \]
Expected Discovery: Cv NS

- This is as close to a ‘sure thing’ signal as we can imagine
- Excellent practice for discovering dark matter!