DEAP/CLEAN-ing Dark Matter: the Search for Direct Detection with Liquid Argon
Outline

Direct Dark Matter Detection

DEAP/CLEAN Experimental Technique

How Will We Know When Dark Matter is Discovered?
Dark matter is ~23% of the universe.
What do we know about Dark Matter?

- Optically dark
- Density \( \sim 0.3 \text{ GeV/cm}^3 \)
- Dark matter particle mass: \( \sim \text{unknown} \)
- Interactions: very weak, \( \sim \text{collision-less} \)
Dark Matter Candidates

interaction strengths

strong
e.m.

weak

gravity

masses

neutrino?
electron t-quark

mass (GeV)

σ_{int} (pb)

HEPAP/AAAC DMSAG Subpanel (2007)
125 Questions: What don’t we know?

“The quest to elucidate the nature of dark matter and dark energy is at the heart of particle physics—the study of the basic constituents of nature...”

“An answer to the question [what is dark matter] would mark a major breakthrough in understanding the universe and would open an entirely new field of research on its own.”

“an area of world leading science opportunity”
“significant UK leadership”
“UK involvement is essential”

Whoever discovers the nature of dark matter would solve one of modern science's greatest mysteries and be a shoo-in for the Nobel Prize.
Direct Detection

Signal: $\chi N \rightarrow \chi N$

Backgrounds:

$\gamma e^- \rightarrow \gamma e^-$

$n N \rightarrow n N$

$N \rightarrow N' + \alpha, e^-$

$\nu N \rightarrow \nu N$
WIMP Scattering

kinematics: \( v/c \sim 8E-4! \)

\[ r = \frac{4m_Dm_T}{(m_D + m_T)^2} \]

\[ q^2 = 2m_TE_{\text{recoil}} \]

\[ E_{\text{recoil}} = E_Dr\left(1 - \cos \theta\right) \]

Spin Independent:
\( \chi \) scatters coherently off of the entire nucleus \( A: \ \sigma \sim A^2 \)

*D. Z. Freedman, PRD 9, 1389 (1974)*

Spin Dependent:
only unpaired nucleons contribute to scattering amplitude: \( \sigma \sim J(J+1) \)
Measurement

Recoil Nucleus
Kinetic Energy

\[ \chi \]

\[ \chi \]

\[ N \]

\[ \sigma \]

\[ \rho \]

\[ v \]

\[ m \]

\[ Q \]

Scattering rate
Sun's velocity around the galaxy
WIMP velocity distribution

\[ \frac{dR}{dQ} \sim \left( \frac{\sigma_0 \rho_0}{\sqrt{\pi}} v_0 m_\chi m_\text{r}^2 \right) F^2(Q) T(Q) \]

WIMP energy density, 0.3 GeV/cm\(^3\)

Form factor
Backgrounds

Gamma ray interactions:
rate $\sim N_e \times$ (gamma flux), typically 10 million events/day/kg
mis-identified electrons mimic nuclear recoil signals

Neutrons:
(alpha,n), U, Th fission, cosmogenic spallation
nuclear recoil final state

Contamination:
$^{238}$U and $^{232}$Th decays, recoiling progeny and mis-identified alphas mimic nuclear recoils

eg. Study for CDMS-II Detector
Irreducible Backgrounds

impossible to shield a detector from coherent neutrino scattering:

\[ \Phi(\text{solar } B^8) = 5.86 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \]

1 event/ton-year = \( \approx 10^{-48} \text{ cm}^2 \) limit in zero-background paradigm unless you measure the direction!

\[ \begin{array}{c}
\text{V} \\
\text{Z} \\
\text{N} \\
\text{V} \\
\end{array} \]

\[ \text{JM, P. Fisher, PRD76:033007 (2007)} \]
The Low Background Frontier

1 event/kg/day

1 event/100 kg/day

1 event/100 kg/100 days

so far: 3 years/order of magnitude

*only the two leading limits shown
$10^4$ is a lot of $\sigma$

- $10^{-24}$ cm$^2$: $\sigma$(neutron-A elastic scattering)
- $10^{-28}$ cm$^2$: $\sigma$(total inelastic pp at TeVatron)
- $10^{-35}$ cm$^2$: $\sigma$(gg $\rightarrow$ H) at LHC (Standard Model)
- $10^{-39}$ cm$^2$: $\sigma$(single top) at TeVatron
- $10^{-40}$ cm$^2$: $\sigma$(VQE) at T2K
- $10^{-45}$ cm$^2$: $\sigma$(V-e Elastic) for solar $\nu$
- $\sigma$(dark matter coherent scattering)? $10^{-48}$ cm$^2$
Direct Dark Matter Signals?

DAMA/Libra

CDMS

COGENT

CRESST-II

dark matter? backgrounds?

arXiv:1109.2589
Annual Modulation?

June-December event rate asymmetry ~2-10%
Drukier, Freese, Spergel,


CoGeNT modulation result, 2.8σ, ~consistent
with DAMA/Libra
J. Collar, STSI (2011),
arXiv:1106.0650v1

DAMA/Libra positive result, >8σ, inconsistent with many expts

CoGeNT: 442 days, 0.5-3.0 keV
(Dashed line)

42 days

DAMA (solid line)
Indirect Dark Matter Signals?

PAMELA
arXiv:0810.4995

Fermi LAT arXiv:0905.0025

dark matter? local astrophysics?
Outline

Direct Dark Matter Detection

DEAP/CLEAN Experimental Technique

How Will We Know When Dark Matter is Discovered?
current experiments:
10-100 kg detector mass;
zero background paradigm=
any excess of events is candidate signal

goal: measure dark matter properties with
100-1000 events (multi-tonne experiments);
paradigm shift: search for signal above measured
background, in a low background observatory

DEAP/CLEAN Objectives:
1) address scalability to very large detectors,
2) measure all backgrounds in-situ,
while producing a world-leading dark matter result
Sensitivity Projections

- Scalability of Detector Technology
- New Techniques for Backgrounds
- Complementary with High-Energy Frontier

need multiple targets and techniques to verify signals.

need 100-1000 events to measure dark matter mass, cross section.

1 event/kg/day
1 event/100 kg/day
1 event/100 kg/100 days
Neutrino Lesson:
key to scalability is
large, open volume
simple detector design

DEAP/CLEAN Strategy:
draw on design successes of
large neutrino experiments

<table>
<thead>
<tr>
<th>Detector</th>
<th>Cross Section (cm²)</th>
<th>Detector Mass (ktonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MiniBooNE</td>
<td>$10^{-45}$</td>
<td>0.1 (0.8 kt)</td>
</tr>
<tr>
<td>Kamland</td>
<td>$10^{-44}$</td>
<td>3 (3 kt)</td>
</tr>
<tr>
<td>Super-K</td>
<td>$10^{-43}$</td>
<td>100 (55 kt)</td>
</tr>
<tr>
<td>SNO</td>
<td>$10^{-42}$</td>
<td>30 (5 kt)</td>
</tr>
<tr>
<td>DEAP/CLEAN</td>
<td>$10^{-41}$</td>
<td>10 (35 kt)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (10 kt)</td>
</tr>
</tbody>
</table>
DEAP/CLEAN Detector Design

Liquid Argon dark matter target (cold! 87 K)
LAr scintillates at 128 nm

wavelength shift (TPB) to >400 nm

read out with PMTs, digitize at 250 MHz, maximize PE/keVee with $4\pi$ coverage

If there is a signal, verify $A^2$ dependence by Ar/Ne target exchange (MiniCLEAN)
Single Phase Detector

- no electric fields = straightforward scalability
  1) no pile-up from ms-scale electron drift in E
  2) no recombination in E (high photons/keVee)
- but no charge background discrimination either!

- high light yield and self-shielding of liquid noble target

- background discrimination from prompt scintillation timing...

cf. Two Phase Detector: \textit{and} charge (proportional scintillation)
DEAP/CLEAN Program: Single Phase Detectors for Scalability

<table>
<thead>
<tr>
<th>DEAP-1</th>
<th>μCLEAN</th>
<th>MiniCLEAN</th>
<th>DEAP-3600</th>
<th>DEAP/CLEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>(7 kg)</td>
<td>(4 kg)</td>
<td>(300 kg)</td>
<td>(3600 kg)</td>
<td>(&quot;G3&quot;)</td>
</tr>
<tr>
<td>2006</td>
<td>2007</td>
<td>2012</td>
<td>2013</td>
<td></td>
</tr>
</tbody>
</table>

**DEAP-3600 (1 tonne fiducial)**
- sensitivity: $1E^{-46}$ cm$^2$

**MiniCLEAN (150 kg fiducial)**
- sensitivity: $1E^{-45}$ cm$^2$

**DEAP/CLEAN (10 tonne fiducial)**
- future goal, $1E^{-47}$ cm$^2$ sensitivity

**Current results**
- only 2 leading results shown

**Astrophysical assumptions:**
- $v_0 = 220$ km/s, $v_{\text{Esc}} = 544$ km/s
- $v_{\text{Sun}} = 12$ km/s, $v_{\text{Earth}} = 15$ km/s
- density = 0.3 GeV/cm$^3$
microCLEAN

4 kg LAr (active), TPB-coated PTFE reflector, TPB-coated acrylic windows; prototyping cold PMTs, PMT bases, LAr and LNe process systems
Example PMT Data

- **Electronic Recoil**: The upper graph shows a high amplitude spike followed by a series of smaller spikes, indicating a quick response to an external stimulus.

- **Nuclear Recoil**: The lower graph features a more gradual and sustained response, indicating a slower, more prolonged interaction.
Light Yield in Liquid Argon

Kr-83m distributed source (32.1±9.4 keV e−) light yield calibration stable over 42-661 keVee yield depends significantly on TPB thickness

FIG. 5: (Color online) Energy spectrum of $^{83}$Kr$^{m}$ runs in argon, with (bottom) and without (top) a background subtraction. The light yield is 6.0 pe/keV and the resolution is 8.2% ($\sigma$/E) at 41.5 keV.

FIG. 6: Light yield versus energy in argon, referenced to the value of 6.0 pe/keV measured for the $^{83}$Kr$^{m}$ peak. There is a 1% systematic error on each point stemming from variations in the position of the $^{83}$Kr$^{m}$ peak from run to run.
Quenching Factor

Gastler et al., arXiv: 1004.0373

mean quenching value above 20 keVr:
0.25 ± 0.02 ± 0.01

FIG. 4: (Color online) Top view of the neutron scattering setup. Shown are the neutron generator and the organic scintillator. The size of the argon cell is not representative.

full Geant4 model of experiment, effect of laboratory geometry is important!
Scintillation Timing

scintillation time constants: $6\pm 1$ ns, $1600\pm 100$ ns


FIG. 7: A scatter plot of $f_p$ vs. energy for tagged electronic and nuclear recoils, where $\xi = 90$ ns.

reject electronic backgrounds by pulse shape vs. time

Pulse Shape Discrimination

fraction of prompt light discriminates between electronic and nuclear recoils

Important for LAr: Ar-39 beta (1 Bq/kg)

Single-phase LAr detectors possible because of rejection power from timing alone: potential for kT scale detectors.
Why Argon?

advantages: x250 difference between singlet and triplet lifetimes: $10^{10}$ electron rejection

favorable form-factor for coherent scattering: higher energy threshold ok

drawbacks: smaller interaction cross section ($A^2$)

$^{39}$Ar, trade-off between background rejection and threshold

low-background Ar sources reduce Ar-39 by a factor of 50 at least

A. Wright, arXiv:1109.2979

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ne</th>
<th>Ar</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield ($\times 10^4$ photons/MeV)</td>
<td>1.5</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td>prompt time constant $\tau_1$ (ns)</td>
<td>2.2</td>
<td>6.0</td>
<td>2.2</td>
</tr>
<tr>
<td>late time constant $\tau_3$ (ns)</td>
<td>15 $\mu$s</td>
<td>1.59 $\mu$s</td>
<td>21 ns</td>
</tr>
<tr>
<td>$I_1/I_3$ for electrons</td>
<td>0.12</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$I_1/I_3$ for nuclear recoils</td>
<td>0.56</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>$\lambda$ (peak)  (nm)</td>
<td>77</td>
<td>128</td>
<td>174</td>
</tr>
<tr>
<td>Rayleigh scattering length (cm)</td>
<td>60</td>
<td>90</td>
<td>30</td>
</tr>
</tbody>
</table>
DEAP-1

7 kg LAr (active), warm PMTs, quartz windows; prototyping reflectors, acrylcs, operation underground
Pulse Shape Discrimination

high intensity tagged gamma source, integrated $6.3 \times 10^7$ tagged gammas in surface lab detector light yield at surface: $2.8 \pm 0.1$ PE/keVee

no events observed with prompt fraction $> 0.7$ in 120-240 PE, leakage $< 6 \times 10^{-8}$ @ full recoil acceptance, in 45-88 keVee

*Boulay et al., arXiv:0904.2930*
Pulse Shape Discrimination, Underground

high intensity tagged gamma source deployed with DEAP-1 at SNOLAB
detector light yield: 2.8±0.1 PE/keVee; statistics: integrated 1.1E8 tagged gammas

1 event observed with prompt fraction > 0.7 in 120-240 PE

leakage < 3E-8 @ 90% CL, studies ongoing now with higher light yield

simple model of photon statistics predicts 1E-10 leakage at 120 PE
(20 keVee threshold at 6 PE/keVee)
M. Boulay, TAUP 2011

C. Jilling, CAP 2011
This gets easier with smaller surface-to-volume ratio (large, spherical detectors).
## Alpha Reduction R&D in DEAP-1

### Background rates in DEAP-1 (low-energy region 120-240 p.e.)

<table>
<thead>
<tr>
<th>Date</th>
<th>Background Rate (in WIMP ROI)</th>
<th>Configuration</th>
<th>Improvements for this rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2006</td>
<td>20 mBq</td>
<td>First run (Queen’s)</td>
<td>Careful design with input from materials assays (Ge γ counting)</td>
</tr>
<tr>
<td>August 2007</td>
<td>7 mBq</td>
<td>Water shield (Queen’s)</td>
<td>Water shielding, some care in surface exposure (&lt; a few days in lab air)</td>
</tr>
<tr>
<td>January 2008</td>
<td>2 mBq</td>
<td>Moved to SNOLAB</td>
<td>6000 m.w.e. shielding</td>
</tr>
<tr>
<td>August 2008</td>
<td>400 μBq</td>
<td>Clean v1 chamber at SNOLAB</td>
<td>Glove box preparation of inner chamber (reduce Rn adsorption/implantation on surfaces)</td>
</tr>
<tr>
<td>March 2009</td>
<td>150 μBq</td>
<td>Clean v2 chamber at SNOLAB</td>
<td>Sandpaper assay/selection, PTFE instead of BC-620 reflector, Rn diffusion mitigation, UP water in glove box, documented procedures; Rn Trap.</td>
</tr>
<tr>
<td>March 2010</td>
<td>130 μBq</td>
<td>Clean v3 chamber at SNOLAB</td>
<td>Acrylic monomer purification for coating chamber. TPB purification.</td>
</tr>
<tr>
<td>Feb 2011</td>
<td>~10 μBq (PRELIMINARY)</td>
<td>Clean v4 chamber at SNOLAB</td>
<td>Inner chamber redesign to remove “Neck Light” events</td>
</tr>
</tbody>
</table>

Mark Boulay, Queen’s
DEAP/CLEAN Detector Simulation

**RAT:** simulation and analysis program for PMT-based experiments (Braidwood, DEAP/CLEAN, SNO+, CLEAR)

- **GEANT4:** detector geometry and particle propagation, physics validation collaboration (AARM)
- **ROOT:** Event input and output.
- **GLG4Sim:** custom scintillation physics, PMT model, DAQ
  - $dE/dx$ dependent quenching and singlet/triplet ratios for different particle types, based on measurements in microCLEAN
  - Full optical transport of individual photons through detailed 3D model of the detector, optics based on ex-situ measurements

Gastler et al., arXiv: 1004.0373

![Histogram of photoelectrons](image1.png)

Position reconstruction resolution

![Graph of resolution vs. radius](image2.png)
MiniCLEAN Design

- Water shield surrounds by $\geq 1\text{ m}$
- 300 kg Argon inside WLS, project 150 kg fiducial
- 92 8" R5912mod PMTs (cold)

Light guides optically isolate PMTs
- 10 cm acrylic plug shields LAr from PMT
- Glass neutrons
Electron Backgrounds

strategy:
-reject using scintillation light timing

-projected light yield in MiniCLEAN: 6-8 pe/keVee, from full optical simulation

-simulate MiniCLEAN, using DEAP-1 measurement as a constraint, predict <1 event/year @ 20 keVee using Fprompt cut (@ 50% nuclear recoil acceptance)

-likelihood ratio estimator, Lrecoil, uses observed times of arrival for all PE in an event

-Lrecoil reduces effect of broad PMT charge distribution, statistic has less variance than Fprompt producing better separation between nuclear recoils and electrons

-Lrecoil simulation allows 12.5 keVee threshold with <1 electron background event (50 keVr)

Boulay, et al., arXiv:0904.2930
Alpha Backgrounds

Strategy:
- reject using fiducial volume cut
- dangerous background from Rn daughters plating out on materials
- control radiopurity $O(100 \text{ ppb U, Th})$, minimize radon exposure ($< 1\alpha/m^2/day$)
- simulate alphas with full reconstruction, find $R<30 \text{ cm}$ (150 kg fiducial mass) = $<1 \text{ event/yr}$ above 12.5 keVee (50 keVr)

V. Giuseppe et al., arXiv:1101.0126

Simulation

Data
Alpha Scintillation in TPB

Strategy:
- TPB wavelength-shifts from 128 nm to visible (fluorescence) ex-situ test benches for spectrum, efficiency, angular dist. V. M. Gehman et al., arXiv:1104.3259

- alpha scintillation in TPB has rejection power, ex-situ test stand finds 11\(\pm\)5 and 275\(\pm\)10 ns fast and slow time constants, and fast:total intensity ratio of 0.67\(\pm\)0.03 (cf. 7 ns and 1600 ns, and 0.75) T. Pollmann et al., arXiv:1011.1012
Neutron Backgrounds

Strategy:
- reject using energy, radius, timing (multiple scatters)

- dangerous background from U, Th (alpha, n) in PMT glass (assayed 1.27/0.69/3.62 U/Th/K Bq/kg)

- major effort to validate Geant4 neutron physics, >90% of neutrons scatter inelastically, different time signature than single nuclear recoils (K. Palladino, APS’11)

- simulate neutrons with reconstruction, estimate radius, energy, fprompt cuts leave ~2 events/yr in E>20 keVee; with tagging multiple scatters and Lrecoil cut, project <1/yr in E>12.5 keVee (50 keVr)
Neutron Calibration: Pulsed Source

d-d source:
-Schlumberger Minitron: 2.4 MeV ~monoenergetic neutrons, $10^5$/s

calibration of n-induced $^{40}$Ar recoils at energy threshold, measure neutron tagging efficiency

-characterizing source intensity, energy with liquid scintillator fast neutron detector

-UK: HV distribution/monitoring, deployment
External Backgrounds

**Strategy:**
- Shield external gammas and neutrons using water (1m on all sides), and active muon veto
- Dangerous background from cosmogenic neutrons (high energy, large uncertainty)
- UK: mechanical, HV&electronics, trigger, DAQ, simulation, analysis

70-yr simulation: 0.08 n-induced backgrounds/yr
Experimental Technique

WIMP signal:
- plan two types of (blind) analyses:
  1) counting, with signal box defined by:
     radius < 30 cm, 12.5 < energy < 25 keVee, f\text{prompt} > 0.7 (or L\text{recoil}), single scatters
  2) likelihood-based PDF fit for signal above measured background PDFs (using in-situ calibration data), a la SNO

- current simulation of reconstructed background distributions, in energy (left), radius (center, fraction of prompt photons (right), with no cuts
MiniCLEAN Status

Outer Vessel

SNOLab Infrastructure

Practice!
Inner Vessel

Cassette Test Stand

Veto Assembly Test
DEAP-3600 Detector

85 cm radius acrylic sphere contains 3600 kg LAr
(55 cm, 1000 kg fiducial, sealed vacuum vessel to control backgrounds)

255 8” PMTs
(Hamamatsu R5912 HQE)

50 cm acrylic light guides and fillers for neutron shielding (from PMTs)

Steel shell for safety to prevent cryogen/water mixing (AV failure)

Only LAr, acrylic, and WLS (10 g) inside of neutron shield

8.5 m diameter water shielding sized for reduction of ($\alpha$,n) from rock

UK: calibration system
DEAP-3600 Construction and Prototyping
Goal: DEAP/CLEAN “G3” 100T Scale

Cryogenic Low Energy Astrophysics with Noble Liquids

Dark matter search (Argon) and precision measurements of pp solar neutrinos (Neon), supernova neutrinos

<table>
<thead>
<tr>
<th></th>
<th>MiniCLEAN (G1)</th>
<th>DEAP-3600 (G2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Capability</td>
<td>LAr / LNe</td>
<td>LAr</td>
</tr>
<tr>
<td>Target Radius</td>
<td>500 kg / 150 kg</td>
<td>3600 kg / 1000 kg</td>
</tr>
<tr>
<td>Target / Fiducial Volume</td>
<td>45 cm / 30 cm</td>
<td>85 cm / 55 cm</td>
</tr>
<tr>
<td>Cryogen Containment</td>
<td>Code-Stamped SS Pressure Vessels</td>
<td>Monolithic Acrylic Sphere</td>
</tr>
<tr>
<td>Light Collection</td>
<td>92 Optical Modules PMTs Submerged “Cold”</td>
<td>266 “Warm” PMTs Outside of Cryogen</td>
</tr>
<tr>
<td>Neutron Shielding</td>
<td>10 cm Acrylic + 20 cm Cryogen</td>
<td>50 cm Acrylic</td>
</tr>
<tr>
<td>Surface Background Mitigation</td>
<td>Modular Cassettes Assembled under Vacuum</td>
<td>In Situ Resurfacing of Inner Acrylic Surface</td>
</tr>
<tr>
<td>Process Systems</td>
<td>Pulse Tube Refrigerators With Heat Exchangers</td>
<td>LN-Cooled Thermal Siphon</td>
</tr>
<tr>
<td>Magnetic Compensation</td>
<td>Active</td>
<td>Passive + Active</td>
</tr>
<tr>
<td>G3 Scientific Program</td>
<td>Dark Matter pp-Solar Neutrinos Supernovae Neutrinos</td>
<td>Dark Matter</td>
</tr>
</tbody>
</table>

DEAP/CLEAN “G3” design will build on experience with MiniCLEAN and DEAP3600, testing different technical choices.
DEAP/CLEAN “G3” Physics Reach

1. dark matter
2. pp solar neutrinos
3. supernova neutrinos
4. rare event searches

\[ \text{Neutrino Energy (MeV)} \]

\[ \text{Solar v Flux (cm}^{-2}\text{s}^{-1}\text{bin}^{-1}) \]

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

\[ \text{SI WIMP-nucleon Cross Section (cm}^2\text{)} \]

\[ \text{Horowitz et al, astro-ph/0302071} \]

\[ \text{McKinsey et al, astro-ph/0402007} \]
Outline

Direct Dark Matter Detection

DEAP/CLEAN Experimental Technique

How Will We Know When Dark Matter is Discovered?
3. directional detection...
Conclusions & Outlook

This is a very interesting time in dark matter direct detection!

The DEAP/CLEAN collaboration is developing single-phase detectors with emphasis on scalability and in-situ background measurement, 5-year program of prototype single-phase detector development.

MiniCLEAN (O(100 kg)) and DEAP-3600 (O(1000 kg)) detectors under construction, starting operations at SNOLab from 2012 and 2013. UK leads calibration systems and neutron background analysis.

Definitive discovery of dark matter in direct detection will require multiple targets and multiple technologies.

Stay tuned!
Extra Slides
Depleted Argon

- $^{39}$Ar beta decays with 565 keV endpoint, at ~1 Bq/kg with half-life 269 years
- $^{39}$Ar production supported by cosmogenic activation, underground Ar has less!
- low-background Ar sources reduce Ar-39 by a factor of 50 at least (counting-only analysis)

Figure 2: Left: Schematic diagram of the “Low Background Detector.” Right: The depleted argon spectra obtained in various detector configurations. In the measurement at KURF, the total event rate in 300-400 keV is ~0.002 Hz, about 2% of the rate expected from $^{39}$Ar in atmospheric argon. Data taken with atmospheric argon is shown for comparison (green) - in this data the $^{39}$Ar spectrum is clearly visible.