DIRECT DARK MATTER SEARCHES

Jodi Cooley - SMU
OUTLINE

➤ Lecture 1: How to Design a Dark Matter Detector
  ➤ Calculate expected rates
  ➤ Background considerations
  ➤ Expected signal signatures

➤ Lecture 2: Direct Detection Searches
  ➤ Have we already seen a signal?
  ➤ Detecting scattering from the nucleus with existing experiments
  ➤ Reaching lower masses by detecting electron scattering with current experiments
  ➤ Ideas for extending sensitivity to sub-eV dark matter signatures
FURTHER READING

➤ Classic Papers on specific calculations

➤ Lewin, Smith, Astroparticle Physics 6 (1996) 87-112


➤ Books/Special Journal Editions that Overview the Topics in Dark Matter


ABUNDANCE OF EVIDENCE FOR PARTICLE DARK MATTER

- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gravitational lensing
  - Large Scale Structure formation
- Wealth of evidence for a particle solution
  - Microlensing (MACHOs) mostly ruled out
  - MOND has problems with Bullet Cluster
- Non-baryonic
  - Height of acoustic peaks in the CMB \( (\Omega_b, \Omega_m) \)
  - Power spectrum of density fluctuations \( (\Omega_m) \)
  - Primordial Nucleosynthesis \( (\Omega_b) \)
- And STILL HERE!
  - Stable, neutral, non-relativistic
  - Interacts via gravity and (maybe) a weak force

Rotation Curve of Milky Way

Structure Formation

Cosmic Microwave Background

<table>
<thead>
<tr>
<th>Angular scale</th>
<th>Multipole moment, ( \ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>2</td>
</tr>
<tr>
<td>18°</td>
<td>10</td>
</tr>
<tr>
<td>1°</td>
<td>50</td>
</tr>
<tr>
<td>0.2°</td>
<td>100</td>
</tr>
<tr>
<td>0.1°</td>
<td>1500</td>
</tr>
<tr>
<td>0.07°</td>
<td>2500</td>
</tr>
</tbody>
</table>

Plank 2013
Galaxy clusters

Supernovae Ia

Microwave background

Gravitational lensing

Ordinary Matter
4.9%

Dark Matter
26.8%

Dark Energy
68.3%

Big Bang nucleosynthesis
DIRECT DETECTION ENERGY RANGES

<table>
<thead>
<tr>
<th>Energy Units</th>
<th>Detection Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>eV</td>
<td>Absorption (Electronic recoil)</td>
</tr>
<tr>
<td>keV</td>
<td>DM-electron scattering (Electronic recoil)</td>
</tr>
<tr>
<td>MeV</td>
<td>DM-Nucleus scattering (Nuclear recoil)</td>
</tr>
<tr>
<td>GeV</td>
<td>Standard WIMP</td>
</tr>
<tr>
<td>TeV</td>
<td>$^8$B neutrinos (∼ 6 GeV)</td>
</tr>
<tr>
<td></td>
<td>Reactor neutrinos (∼ 2.7 GeV)</td>
</tr>
</tbody>
</table>

Hidden sector Dark Matter and others

SuperConductors: Edelweiss, SuperCDMS, DAMIC, ...

Superfluid He

Semiconductors: XENON10/100/1000T, LUX, LZ, ...

Noble Liquids
CONSIDERATIONS – DETECTING DARK MATTER VIA NUCLEAR SCATTERING
DIRECT DETECTION EVENT RATES

Assume that the dark matter is not only gravitationally interacting (WIMP).

- Elastic scatter of a WIMP off a nucleus
  - Imparts a small amount of energy in a recoiling nucleus
  - Can occur via spin-dependent or spin-independent channels
  - Need to distinguish this event from the overwhelming number of background events
**ELEMEENS OF IDEAL EVENT RATE IN DIRECT DETECTION**

**Differential Event Rate:**
\[ \frac{dR}{dE_r} = \frac{\rho_0}{m_Nm_\chi} \int_{v_{\text{min}}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_r} dv \]

- Local WIMP density
- WIMP-nucleon scattering cross section
- WIMP speed distribution in detector frame
- Nuclear mass
- WIMP mass
- need input from astrophysics, particle physics and nuclear physics

Elastic scattering happens in the extreme non-relativistic case in the lab frame.

\[ E_R = \frac{\mu^2 N v^2 (1 - \cos \theta_R)}{m_N} \]

where \( \mu = \frac{m_\chi m_N}{m_\chi + m_N} \) and \( \theta_R = \) scattering angle.
Event rate is found by integrating over all recoils:

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{W_N}}{dE_r}(v, E_R) dv$$

Minimum WIMP velocity which can cause a recoil of energy $E_R$.

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

The WIMP-nucleon cross section can be separated:

$$\frac{d\sigma_{W_N}}{dE_R} = \left[\left(\frac{d\sigma_{W_N}}{dE_R}\right)_{SI}\right] + \left(\frac{d\sigma_{W_N}}{dE_R}\right)_{SD}$$

Spin-Independent + Spin-Dependent

SI arise from scalar or vector couplings to quarks.

SI arise from scalar or vector couplings to quarks.

To calculate, add coherently the spin and scalar components

$$\frac{d\sigma_{W_N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2} \left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right]$$

Particle Theory

Nuclear Structure

F$(E_R)$ = Form factor encodes the dependence on the momentum transfer.
\[
\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2v^2} \left[ \sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right]
\]

\textbf{Spin Independent - Woods-Saxon Form Factor}

\[ F(E_R) = \left( \frac{3j_1(qR_1)}{qR_1} \right)^2 \exp \left[ -q^2s^2 \right] \]

- \(j_1 = \text{spherical Bessel Function}\)
- \(q = \text{momentum transfer}\)
- \(s = \text{nuclear skin thickness} \approx 1 \text{ fm}\)
- \(R_1 = \text{effective nucleus radius}\)

\textbf{Spin Dependent Interactions}

\[ F^2(E_R) = \frac{S(E_R)}{S(0)} \]

\[ S(E_R) = a_0^2 S_{00}(E_R) + a_1^2 S_{11}(E_R) + a_0 a_1 2 S_{01}(E_R) \]

\(a_0 = a_p + a_n\) and \(a_1 = a_p - a_n\)

\(S_{ij} \rightarrow \text{isoscalar, isovector and interference form factors}\)

\(a_{i,j} \rightarrow \text{isoscalar, isovector coupling}\)
Assume low momentum transfer:

- In most models $f_n \sim f_p$
- Scattering adds coherently with $A^2$ enhancement

\[
\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2v^2} \left[ \sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right]
\]

- **Spin-Independent**

\[
\sigma_0^{SI} = \frac{4\mu^2}{\pi} \left[ Zf_p + (A - Z)f_n \right]^2 \propto A^2
\]

- **Spin-Dependent**

\[
\sigma_0^{SD} = \frac{32G_F^2\mu^2}{\pi} \frac{J + 1}{J} \left[ a_p < S_p > + a_n < S_n > \right]^2
\]

- **Scales with spin of the nucleus**
- **No coherent effect!**
CHOOSING A TARGET MATERIAL:
SPIN DEPENDENT CASE

\[ \sigma_{SD}^0 = \frac{32G_F^2\mu^2}{\pi} \frac{J + 1}{J} \left[ a_p < S_p > + a_n < S_n > \right]^2 \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Z</th>
<th>Odd Nucleon</th>
<th>J</th>
<th>\langle S_p \rangle</th>
<th>\langle S_n \rangle</th>
<th>\frac{C_A^p}{C_p}</th>
<th>\frac{C_A^n}{C_n}</th>
</tr>
</thead>
<tbody>
<tr>
<td>^{19}\text{F}</td>
<td>9</td>
<td>p</td>
<td>\frac{1}{2}</td>
<td>0.477</td>
<td>-0.004</td>
<td>9.10 \times 10^{-1}</td>
<td>6.40 \times 10^{-5}</td>
</tr>
<tr>
<td>^{23}\text{Na}</td>
<td>11</td>
<td>p</td>
<td>\frac{3}{2}</td>
<td>0.248</td>
<td>0.020</td>
<td>1.37 \times 10^{-1}</td>
<td>8.89 \times 10^{-4}</td>
</tr>
<tr>
<td>^{27}\text{Al}</td>
<td>13</td>
<td>p</td>
<td>\frac{5}{2}</td>
<td>-0.343</td>
<td>0.030</td>
<td>2.20 \times 10^{-1}</td>
<td>1.68 \times 10^{-3}</td>
</tr>
<tr>
<td>^{29}\text{Si}</td>
<td>14</td>
<td>n</td>
<td>\frac{1}{2}</td>
<td>-0.002</td>
<td>0.130</td>
<td>1.60 \times 10^{-5}</td>
<td>6.76 \times 10^{-2}</td>
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<tr>
<td>^{35}\text{Cl}</td>
<td>17</td>
<td>p</td>
<td>\frac{3}{2}</td>
<td>-0.083</td>
<td>0.004</td>
<td>1.53 \times 10^{-2}</td>
<td>3.56 \times 10^{-5}</td>
</tr>
<tr>
<td>^{39}\text{K}</td>
<td>19</td>
<td>p</td>
<td>\frac{3}{2}</td>
<td>-0.180</td>
<td>0.050</td>
<td>7.20 \times 10^{-2}</td>
<td>5.56 \times 10^{-3}</td>
</tr>
<tr>
<td>^{73}\text{Ge}</td>
<td>32</td>
<td>n</td>
<td>\frac{9}{2}</td>
<td>0.030</td>
<td>0.378</td>
<td>1.47 \times 10^{-3}</td>
<td>2.33 \times 10^{-1}</td>
</tr>
<tr>
<td>^{93}\text{Nb}</td>
<td>41</td>
<td>p</td>
<td>\frac{9}{2}</td>
<td>0.460</td>
<td>0.080</td>
<td>3.45 \times 10^{-1}</td>
<td>1.04 \times 10^{-2}</td>
</tr>
<tr>
<td>^{125}\text{Te}</td>
<td>52</td>
<td>n</td>
<td>\frac{1}{2}</td>
<td>0.001</td>
<td>0.287</td>
<td>4.00 \times 10^{-6}</td>
<td>3.29 \times 10^{-1}</td>
</tr>
<tr>
<td>^{127}\text{I}</td>
<td>53</td>
<td>p</td>
<td>\frac{5}{2}</td>
<td>0.309</td>
<td>0.075</td>
<td>1.78 \times 10^{-1}</td>
<td>1.05 \times 10^{-2}</td>
</tr>
<tr>
<td>^{129}\text{Xe}</td>
<td>54</td>
<td>n</td>
<td>\frac{1}{2}</td>
<td>0.028</td>
<td>0.359</td>
<td>3.14 \times 10^{-3}</td>
<td>5.16 \times 10^{-1}</td>
</tr>
<tr>
<td>^{131}\text{Xe}</td>
<td>54</td>
<td>n</td>
<td>\frac{3}{2}</td>
<td>-0.009</td>
<td>-0.227</td>
<td>1.80 \times 10^{-4}</td>
<td>1.15 \times 10^{-1}</td>
</tr>
</tbody>
</table>

Tovey et al., PLB 488 17 (2000)
WIMPs are distributed in isothermal spherical halos with Gaussian velocity distribution (Maxwellian):

\[ f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|\vec{v}|^2}{2\sigma^2}} \]

The speed dispersion is related to the local circular speed by

\[ \sigma = \sqrt{\frac{3}{2}} v_c \quad \text{where} \quad v_c = 220 \text{ km/s} \]

The density profile of the sphere is

\[ \rho(r) \propto r^{-2} \quad \text{and} \quad \rho_0 = 0.3 \text{ GeV/c}^2 \]

Particles with speeds greater than \( v_{esc} \) are not gravitationally bound. Hence, the speed distribution needs to be truncated.

\[ v_{esc} = 650 \text{ km/s} \]
The local dark matter density is \( \rho_0 = 0.3 \text{ GeV/cm}^3 \)

Pick your favored mass for the dark matter particle

- \( m = 5 \text{ GeV/c}^2 \)
- \( m = 60 \text{ GeV/c}^2 \)

What is the number density?

- \( 60,000 \text{ particles/m}^3 \) \( \longrightarrow \) for 5 GeV/c\(^2\)
- \( 5,000 \text{ particles/m}^3 \) \( \longrightarrow \) for 60 GeV/c\(^2\)

How many dark matter particles in a 2 liter bottle?

- \( \text{recall that 1 liter} = 0.001 \text{ m}^3 \)
  - 120 particles \( \longrightarrow \) for 5 GeV/c\(^2\)
  - 10 particles \( \longrightarrow \) for 60 GeV/c\(^2\)
MAYBE NOT THAT SIMPLE?

➤ Effective Field Theory considers leading order and NLO operators that can occur in the effective Lagrangian that describes the WIMP-nucleon interactions.

➤ Contains 14 operators, that rely on a range of nuclear properties in addition to the SI and SD cases. They combine such that the WIMP-nucleon cross section depends on six independent nuclear response functions:
  ➤ One “Spin independent”
  ➤ Two “Spin Dependent”
  ➤ Three “Velocity-Dependent”

➤ Two pairs of these interfere, resulting in eight independent parameters that can be probed

The effective field theory of dark matter direct detection

A. Liam Fitzpatrick, a Wick Haxton, b Emanuel Katz, a,c,d Nicholas Lubbers, c Yiming Xu c

http://arxiv.org/abs/1308.6288
http://arxiv.org/abs/1405.6690
DARK MATTER COULD LOOK DIFFERENT IN DIFFERENT TARGETS

- Nuclear responses for different target elements vary. Some EFT operations have momentum dependance. EFT Operators can interfere.
- Example illustrates differences using the fluorine eigenvector and using the germanium eigenvector for selected targets.
- Results in different rates between targets AND different spectral shapes.
- A robust dark matter direct detection program with different target materials will be needed to nail down which operators are contributing to any detected signal.
- Take home message: We will need multiple targets to map out the physics of WIMP-nucleon interactions!

arxiv: 1503.03379
EVENT RATES ARE EXTREMELY LOW!

- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.
- Radioactive background of most materials is higher than the event rate.

Need large exposures (mass x time)!
THE LOW-MASS WIMP CHALLENGE

A WIMP must have a minimum velocity to produce a recoil.

\[ E_R = \frac{p^2}{2m_N} = \frac{m_\mu^2v^2}{m_N}(1 - \cos \theta_R) \]

Need Low Energy Threshold!
THE EVENT RATES ARE EXTREMELY LOW!

➤ Expected WIMP Spectrum

\[ \sigma_{N,SI} = 10^{-45} \text{ cm}^2 \]

\[ \text{Mass} = 20 \text{ GeV/c}^2 \]

➤ Measured Banana Spectrum

Gamma measurements with a 3-inch NaI detector

THE EVENT RATES ARE EXTREMELY LOW!

➤ Expected WIMP Spectrum

- Mass = 20 GeV/c²
- $\sigma_{N,SI} = 10^{-45}$ cm²

~1 event per kg per year
(nuclear recoils)


➤ Measured Banana Spectrum

~100 events per kg per year
(electron recoils)
BACKGROUNDS
BACKGROUND SOURCES

- Environmental radioactivity
  - includes airborne radon and its daughters
- Radio-impurities in materials used for the detector construction and shield
- Radiogenic neutrons with energies below 10 MeV
  - Neutrons from (α,n) and fission reactions
- Cosmic rays and their secondaries
- Activation of detector materials near Earth’s surface
- Others that we have not yet identified?
Worldwide 17 underground sites for physics research
UNDERGROUND FACILITIES

- Worldwide 17 underground sites for physics research
- Hadronic component of the cosmic ray flux is negligible with a few 10 mwe overburden.
- Muons that penetrate deep and produce high energy neutrons (fast neutrons) can produce keV recoils in detectors when attenuated by rock or shields.
- Processes to produce fast neutrons include:
  - negative muon capture
  - photo-nuclear reactions in associated EM showers
  - deep-inelastic muon-nucleus scatters
  - hadronic interactions of nucleons, pions and kaons
Tools to Further Reduce Backgrounds

- A combination of high-Z and low-Z materials are employed to diminish the neutron and gamma fluxes.
  - Lead, polyethylene, copper
- Nitrogen purge of shield structures to reduce backgrounds induced by airborne radon decays
- Large water shields
  - Passively reduce environmental radioactivity and muon-induced neutrons
  - Can reduce underground fluxes of gamma and radiogenic fluxes by a factor of $\sim 10^6$ by employing a 1 - 3 m water shield
- Active muon vetos using doped scintillator (ie boron) can be used to identify events related to both cosmogenic and radiogenic neutrons.
Example: LZ Dark Matter Experiment

K. Palladino, TAUP 2017

LXe TPC only
3.8 T fiducial mass

LXe TPC + Skin + OD
5.6 T fiducial mass
The most problematic backgrounds are interactions from neutrons that result from \((\alpha, n)\) and fission reactions from \(^{238}\text{U}\) and \(^{232}\text{Th}\) decays in detector components and in close vicinity of target materials.

**Electron Recoils (ER)**
- Gamma: Most prevalent background
- Beta: on surface or in bulk

**NUCLEAR Recoils (NR)**
- Neutron: NOT distinguishable from WIMP
- Alpha: almost always a surface event
- Recoiling Parent Nucleus: surface event
DETECTOR RESPONSE

**SuperHeated**
COUPP, PICASSO

**Phonons**
- 10 meV/ph
- 100% energy

**Scintillation**
- ~ 1 keV/y
- few % energy

**Ionization**
- ~ 10 eV/e
- 20% energy

**CLEAN**
- DAMA/LIBRA
- DEAP
- NAIAD
- ZEPLIN I
- XMASS
- Xe, Ar, Ne
- Na(Tl)

**CDMS**
- EDELWEISS
- Ge, Si

**CRESST**
- ROSEBUD
- CsWO₄, BGO
- ZnWO₄, Al₂O₃ …

**Xe, Ar, Ne**

**ArDM**
- DarkSide
- LUX
- WArP
- XENON
- ZEPLIN II, III
- Xe, Ar, Ne

**ANNAIS**
- CoGeNT
- COSME
- COUPP
- DM-TPC
- DRIFT
- IGEX
- Ge, Cs₂, CΙ₃F₈

SLAC Summer Institute - 2020 - Jodi Cooley
Simultaneous measurement of energy in two channels allows discrimination of ER from NR.
PARTICLE DEPENDENT RESPONSE

- Simultaneous measurement of energy in two channels allows discrimination of ER from NR

- A bubble chamber is filled with a superheated fluid in a metastable state.
- A particle interaction with energy deposition greater than some energy threshold within a critical radius results in an expanding bubble.
- A smaller or more diffuse energy deposition will result in a bubble that immediately collapses.
- You can “tune” the chamber to make bubbles for nuclear recoils and not for electron interactions.
PARTICLE DEPENDENT RESPONSE

- Simultaneous measurement of energy in two channels allows discrimination of ER from NR

- Cut-and-count analysis methods no longer deliver required sensitivity.
- Profile likelihood and other multivariate analysis techniques that rely on accurate background models are now standard.
➤ Time Dependence - Annual Modulation

➤ Earth’s velocity through galactic halo is maximum in June, minimum in December.

➤ Earth’s orbital speed is much smaller than Sun’s circular speed \( \left( \frac{v_{\text{orb}}}{v_c} \approx 0.07 \right) \). We can Taylor expand.

\[
\frac{dR}{dE_R}(E_R, t) \approx \frac{dR}{dE_R} \left[ 1 + \Delta(E_R) \cos \frac{2\pi(t - t_0)}{T} \right]
\]

Taking \( T = 1 \) year and \( t_0 = 150 \) days, the differential event rate peaks in Dec for small recoil energies and in the summer for large recoil energies.
Directional signal

- WIMP flux in the lab frame is peaked in the motion of the sun.

\[
\frac{dR}{dE_R} \propto \exp \left[ - \frac{[(v_{E orb} + v_c) \cos \gamma - v_{min}]^2}{\sigma_v^2} \right]
\]

where \(v_{E orb} \) = Earth’s velocity parallel to direction solar motion
\( \gamma = \) angle between recoil and direction of solar motion

\[
\sigma_v = \frac{v_{orb}}{v_c} \approx 0.07
\]

Forward-backward asymmetry yield effect \( \mathcal{O}(v_{E orb}/v_c) \approx 1 \)

Time Dependence - Annual Modulation

- Earth’s velocity through galactic halo is maximum in June, minimum in December.
- Earth’s orbital speed is much smaller than Sun’s circular speed. We can Taylor expand.

\[
\frac{dR}{dE_R}(E_R, t) \approx \frac{dR}{dE_R} \left[ 1 + \Delta(E_R) \cos \frac{2\pi(t - t_0)}{T} \right]
\]

\( T \) = period
\( \Delta(t) \) = phase

\( \Delta(E_R) \) = \( \cos \theta \) where \( \theta \) = angle between recoil and direction of solar motion

~2% seasonal effect - need ~1000 events
In most cases, looking for materials at levels of < 1 ppb.
## How Well Can We Do?

### Augmented Commercial Systems:
Commercially purchased High-Purity Ge detector is placed in a custom designed shield (Pb, copper, neutron moderation and capture materials, active cosmic ray veto, underground location)

### Fully Custom Systems:
In addition to a custom shield, a custom cryostat design with attention to design of and placement of electronics to minimize background sources (U/Th/K).

### HPGe Counting:

<table>
<thead>
<tr>
<th>Isotope/Chain</th>
<th>Standard Size (ppb)</th>
<th>Large Size &amp; Long Count (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{238}U )</td>
<td>(~0.1)</td>
<td>(~1.0)</td>
</tr>
<tr>
<td>( ^{232}Th )</td>
<td>(~0.3)</td>
<td>(~1.5)</td>
</tr>
<tr>
<td>( ^{40}K )</td>
<td>(~700)</td>
<td>(~21)</td>
</tr>
<tr>
<td>( ^{238}U )</td>
<td>(~0.001)</td>
<td>(~0.12)</td>
</tr>
<tr>
<td>( ^{232}Th )</td>
<td>(~0.001)</td>
<td>(~0.004)</td>
</tr>
<tr>
<td>( ^{40}K )</td>
<td>(~1)</td>
<td>(~0.031)</td>
</tr>
</tbody>
</table>
Surface Alpha Screening:

XIA uses pulse shape to reject events not originating from sample tray.

Ultra-pure PNNL Copper

- ~25 nBq/cm² in ²¹⁰Po ROI

indicative of instrument background

Surface Beta Screening:

Expected Sensitivity:

- 0.1 β keV⁻¹ m⁻² day⁻¹
- 0.1 α m⁻² day⁻¹
- (0.1 α nBq/cm²)

BetaCage:
South Dakota Mines, Caltech, PNNL U Alberta
## MANY OTHER OPTIONS

<table>
<thead>
<tr>
<th>Technique</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon Emanation</td>
<td>0.1-10 $\mu$Bq/kg (Ra)</td>
</tr>
<tr>
<td>Immersion Whole Body Counters</td>
<td>$10^{-15}$-$10^{-14}$ g/g (U/Th)</td>
</tr>
<tr>
<td>ICPMS (Inductively Coupled Plasma Mass Spectrometry)</td>
<td>ppt to ppt (U/Th/K)</td>
</tr>
<tr>
<td>SIMS/GDMS (Secondary Ion &amp; Glow Discharge Mass Spectroscopy)</td>
<td>1 ppb (SIMS) 10-100ppt (GDMS)</td>
</tr>
<tr>
<td>AMS (Accelerator Mass Spectroscopy)</td>
<td>&lt; 1 ppt</td>
</tr>
<tr>
<td>Neutron Activation Analysis</td>
<td>100 pg (U), 10 ng (K)</td>
</tr>
</tbody>
</table>
MODELING BACKGROUNDS

➤ Three software frameworks exist to calculate the spectra of neutrons produced by (α-n) interactions.

➤ SOURCES - (EMPIRE2.19 libraries for cross section inputs)

➤ USD WebTool (TENDL 2012 libraries which are validated by TALYS for cross section inputs)

➤ NeuCBOT (TALYS for cross section inputs)

➤ TENDL is a validated library and EMPIRE is recommended by the International Atomic Energy Agency, but neither can properly calculate all resonant behavior that is experimentally observed.

➤ Those spectra can be used in simulation to predict the number of background events from neutrons in an experiment.
Calculated Radiogenic Neutron Spectra

Study found no major systematic differences between the two in terms of input spectra, output spectra and yield.

Both have errors in cross sections and outputs that may require a human eye to catch.
NeuCBOT used by DEAP to predict Neutrons in materials of interest.

<table>
<thead>
<tr>
<th>NeuCBOT Material</th>
<th>n/s/Bq U238 upper</th>
<th>n/s/Bq U238 lower</th>
<th>n/s/Bq U235</th>
<th>n/s/Bq Th232</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borosilicate Glass</td>
<td>3.93E-06</td>
<td>1.76E-05</td>
<td>2.56E-05</td>
<td>2.43E-05</td>
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<tr>
<td>Acrylic</td>
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<td>9.72E-07</td>
<td>1.42E-06</td>
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<tr>
<td>Invar</td>
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<tr>
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</tr>
<tr>
<td>Argon</td>
<td>8.82E-08</td>
<td>1.41E-05</td>
<td>1.72E-05</td>
<td>2.64E-05</td>
</tr>
</tbody>
</table>
NeuCBOT used by DEAP to predict Neutrons in materials of interest.

<table>
<thead>
<tr>
<th>Material</th>
<th>Neutrons/year from PMT glass</th>
<th>Neutrons/year from PMT ceramic</th>
<th>Neutrons/year from polystyrene filler foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borosilicate Glass</td>
<td>3.93E-06</td>
<td>1.76E-05</td>
<td>2.56E-05</td>
</tr>
<tr>
<td>Acrylic</td>
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<td>5.21E-08</td>
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<tr>
<td>Invar</td>
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<td>3.31E-08</td>
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<tr>
<td>TPB</td>
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<td>8.82E-08</td>
<td>9.12E-07</td>
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<tr>
<td>Polyethylene</td>
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<td>Stainless Steel</td>
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<td>Polyurethane</td>
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<td>8.82E-08</td>
<td>1.41E-05</td>
<td>1.72E-05</td>
</tr>
</tbody>
</table>

**NeuCBOT:**
- 15 n/year from PMT glass
- 1 n/year from PMT ceramic
- 3 n/year from polystyrene filler foam

** SOURCES-4C:**
- 13 n/year from PMT glass
- 2 n/year from PMT ceramic
- 2 n/year from polystyrene filler foam
SIMULATION TOOLS

➤ Geant4 simulations of backgrounds based on assay information

SuperCDMS Geometry in Geant4
SIMULATION TOOLS

- Geant4 simulations of backgrounds based on assay information
- Produce anticipated background spectra

SuperCDMS anticipated background spectra (Ge iZIPS)

- SuperCDMS Geometry in Geant4

Raw Singles Event Rate
Includes yield model and energy resolution

Events after Cuts
Adds ionization yield and fiducial cuts
BACKGROUND INVENTORY

➤ Background inventories of components and their required purity can be made.
➤ Provides a tool that can be used for material and vendor selection.
IF YOU CAN’T FIND IT – BUILD IT

Electroformed copper at PNNL
Th decay chain (ave) $\leq 0.1 \, \mu$Bq/kg
U decay chain (ave) $\leq 0.1 \, \mu$Bq/kg

XENON1T Gas Purification System and Distillation Column

➤ Commercial Xe: 1 ppm - 10 ppb of Kr
➤ XENON1T sensitivity demands: 0.2 ppt
➤ 5.5 m distillation column, 6.5 kg/h throughput

DarkSide Cryogenic distillation column for purification of $^{39}$Ar

Aprile, UCLA 2018
NEUTRINO BACKGROUNDS

- Solar pp-neutrinos
  - low energies, high fluxes
  - contribute to the ER background via $\nu$-e scattering at a level of 10 - 25 event per (ton x year) at low energies
- Neutrino-induced NR can not be distinguished from WIMP signals (8B solar neutrinos)
  - $\sim 10^3$ events per (ton x year) for heavy targets
- Atmospheric Neutrinos and Diffuse Supernovae Neutrinos
  - $\sim 1-5$ events per (100 ton x year)
DIRECT DETECTION NEEDS

➤ Ability to see low energy WIMP induced recoils (>10 keV - 10s keV)
  ➤ Radiogenically pure
  ➤ Low threshold

➤ Ability to distinguish nuclear recoils
  ➤ Difference between electronic recoils & nuclear recoils
  ➤ Difference between alphas and nuclear recoils

➤ Radiogenic and cosmogenic backgrounds mitigation
  ➤ Passive and/or Active shielding from these backgrounds
  ➤ Position reconstruction and fiducialization
  ➤ Characterization of these backgrounds

➤ Long exposures with long term stability
  ➤ Especially for annual and diurnal modulation
THE SEARCH SPACE

- Asymmetric DM
- NMSSM
- J. Cao +
- M. Cahill-Rowley++
THE SEARCH SPACE

[Graph showing the search space for WIMP–nucleon cross section vs. WIMP mass in GeV/c². The graph includes data from various experiments and theoretical models, such as CDMS, SUPERCOSM, DAMIC, CRESST-III, XENON1T, LUX, and pMSSM. The region of interest is marked with constraints from different experiments and models, indicating the possible parameter space for WIMPs.]