Trigger Algorithms for the SuperCDMS Dark Matter Search

Xuji Zhao
Advisor: David Toback
Texas A&M University
Masters Defense
Aug 11, 2015
Outline

• Introduction: dark matter and the CDMS experiment

• Triggering during data-taking: Sensitivity of box-car filters, bandpass filters and optimal filters

• Performance Comparison: which is better and why

• What causes the contribution to the resolution?

• What happens if the noise changes during data-taking with the experiment?

• Conclusions
Evidence For Dark Matter

Ordinary Matter
(x-rays)

Galactic Rotation Curves

Cosmic Microwave Background

Dark Matter
(Gravitational Lensing)
The Bullet Cluster suggests that dark matter may be a *particle*.

**Dark Matter Particle Candidate:**
- WIMP (Weakly Interacting Massive Particles)
- Axion
- SuperWIMPs
- Sterile neutrinos
- Neutralinos
- Gravitino
- ....
Hunt for Dark Matter

- Direct Detection
- Indirect Detection
- Production in Collider

AMS, FERMI...

CDMS, XENON, LUX...

Atlas, CMS...
Direct Detection of WIMPs

Elastic Scattering of WIMPs off target ➔ nuclear recoil

background (gamma and beta particles) interact with the atomic electrons ➔ electronic recoil

Requirements for WIMPs detectors:
- Large target mass
- Low energy threshold
- Ultra-low background
- Nuclear and electronic recoil discrimination
CDMS Experiment Idea

1) Make a detector out of a material with which the WIMPs can interact (in CDMS Ge and Si).
   CDMS = Cryogenic Dark Matter Search

2) Determine when the interaction occurs (measure charge and heat)

3) Realize that for every potential WIMP interaction there are \( \geq 1000 \) events from unwanted background sources. (Detector is in deep underground to prevent cosmic background)
   @ Soudan Lab, Minnesota \( \rightarrow \) later: SNOLAB with better readout electronics

Crystals: Ge, Si cooled to few mK - low heat capacity - \( \Delta T \sim \mu K \) (stable)

5 towers * 3 detector each = 15 detectors total

Good discrimination

2341 feet below the surface
Trigger System
(for the new CDMS Experiment being built now to be installed in the SNOLAB mine)

• Trigger will be made of three systems: L1, L2, L3

• New Level 1 triggers allows for digital filtering of information directly out of the detectors

• We are exploring different strategies for our filter design in L1
Why Filter Design is Important?

• 5 - 7 sigma (trigger threshold) range above noise

• Resolution of filter reflects how small of a signal we can pick out from background

• Better filter $\rightarrow$ smaller resolution $\rightarrow$ lower threshold $\rightarrow$ lower mass WIMP sensitivity
What Would the Background and Signal Look Like?

Example Noise of T2Z1

Example Signal

Our motivation:

Distinguish signal from noise in time or frequency domain
What cause the structure in the noise?

- Baseline noise: the TES/SQUID electronics (Johnson Noise)
- Rising Region: low frequency detector vibrations
- Spikes: various sources (phono, detector electronics, or other electronics noise)
Using a Finite Impulse Filter (FIT) (using a box car shape)

Example Noise Event

Example signal event with noise included

\[
\text{Sum (Filter\_weight \times Data)} = \text{Estimated signal amplitude}
\]
Filter Resolution

Example Event Noise-Only Event

Example Event with Signal

Histogram of top plots →

Sigma=5.65
Calculate the Expected Resolution Analytically

- Straightforward to calculate the resolution as a function of frequency
- Gaussian random noise on each frequency
  → the resolution on each frequency = $\sqrt{J}$
- Scale the resolution for each frequency by the filter weight in frequency domain
- Add the uncertainty in quadrature due to the uncertainty propagation

\[
\sigma = \frac{\sqrt{\sum_f \text{fft}(\text{filter\_weight})^2 \cdot J}}{\sum_t \text{filter\_weight} \cdot \text{signal}}
\]
Filter Design Considerations

Consider 3 filter candidates:
1) box-car filters
2) bandpass filters
3) optimal filters

1) Resolution for each filter candidate
   (Start by optimizing and determining the resolution for each assuming the Soudan background noise and signal shapes.)

2) Robustness to noise variation for each
   (We have 11 detectors and 3 filter options. Run each detector through the different filter options and compare.)
Box-car Filter Parameters

• Box-car filter is defined by two parameters: 
  pre-pulse time and during-pulse time
• Fixed the center position at ~6650, and the area under the curve is zero by construction
• Needs to be optimized detector-by-detector
Box-car Filter Optimization

How does the resolution vary as a function of the two parameters?

- Optimize the boxcar filter by changing pre-pulse time, during pulse time simultaneously
Optimized Box-car Filter

Resolution: \(\sqrt{32.9} = 5.65\)
Option 2: Bandpass Filter

- Bandpass filter is defined by three parameters:
  1) \textit{freqlow} → where the band starts
  2) \textit{freqhigh} → where the band ends
  3) \textit{t0} → related to the phase of filter
Bandpass Filter Optimization

How does the resolution vary as a function of the three parameters?

- Fixed freqlow and frehigh
- Fixed freqlow and t0
- Fixed freqhigh and t0
Option 3: Optimal Filter

- Optimized through calculation
- Signal traces $S(t) = aA(t) + n(t)$
  - $a$ - signal amplitude
  - $A(t)$ - known signal template
  - $n(t)$ - noise realization with noise PSD

Estimate $a$

Optimal technique for amplitude estimation:

- Calculate $\chi^2$ in frequency domain
- Minimize the $\chi^2$
- Obtain optimal value for $a$
- Obtain optimal filter
Optimal Filter Study

Calculate optimal filter by using signal template and noise

Comparison of the filter in time domain and the frequency domain. Similar as expected.
Filter Resolution

- Filter rescaled so the amplitude of signal is the same as the input (e.g: all filters rescaled amplitude and integrated value of 1000 on right plot)
Comparison of the Boxcar, Bandpass and Optimal Filter Resolutions

- Resolution of three optimized filters for T2Z1:
  - bandpass: 8.11
  - boxcar: 6.97
  - optimal: 4.38
Optimize each of the three filters for all 11 detectors from the real Soudan data

Conclusion:
• The optimal filter always has better resolution
• The resolution of optimal filter is between 50% and 85% of the boxcar
Compare all three filter types to each other

**Conclusion:**
- The bandpass filter is better than boxcar for large resolution
- The optimal filter always has better resolution
- The resolution of optimal filter is between 40% and 85% of the bandpass filter
How do the Various Components of Noise Contribute to the Resolution?

No spike in simplified noise!

Two function option: $a/f+b$ and $a/f^2+b$

<table>
<thead>
<tr>
<th>Optimal/Boxcar</th>
<th>Real Noise</th>
<th>$5e8/x+4e6$</th>
<th>$5e8/x^2+4e6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2Z1</td>
<td>4.378 / 5.756</td>
<td>3.314 / 3.907</td>
<td>1.597 / 1.821</td>
</tr>
<tr>
<td>T5Z1</td>
<td>42.76 / 83.35</td>
<td>287.3 / 348.9</td>
<td>36.6 / 37.63</td>
</tr>
</tbody>
</table>

Extra spikes contribute about ~50% of the resolution!
Study the contributions to the resolution by adding spikes to our simplified noise model.

- Optimize a boxcar filter, find the peak in frequency domain.
- Add the spike where the peak is in frequency space.
- Then change the size of the peak.
Choose Seven Different Spike Sizes For T2Z1 Simplified Noise
Reoptimized Filters for Different Spike Sizes of T2Z1 Simplified Noise

- Optimal filter simply pulls out the frequency with spike
- Boxcar filter tries to optimize by pushing the bulk of the weight away from the spike
Resolution of Reoptimized Filters for T2Z1 Simplified Noise

Conclusion:
• Optimal filter doesn’t get much worse and eventually stop getting worse because we just pull that frequency out
• Boxcar filter gets worse until we push it out
How Robust is the Filter to Noise Changes that Might Occur Over Time

Given Noise \rightarrow \text{calculate} \rightarrow \text{Filter} \rightarrow \text{apply} \rightarrow \text{Different Noise}

Compare resolution
Examine the performance of each filter if the noise for a detector changes

We have 11 detectors and 3 filter options. Run each detector noise through the different filter options and compare.
Apply the Optimal Filter and the Optimized Box Car Filter on the “wrong noise” simulated by using a different detector

The plot only shows the results for low values of the noise, will show high values in next slide

Conclusion:
• Optimal filter works better than boxcar filter in most cases
• Boxcar filter works better than optimal filter in some special cases

What about when there is large noise?

†Data 01140523_1642
Most data below red line!
Large Noise Results

When the noise changes a small amount, the optimal filter is still better than the boxcar filter, this stops being true for large noise.

Conclusion:
• For "good" detectors, the optimal filter is more robust than the boxcar filter, but for "bad" detectors, the two seem "equally bad".

Question: What causes the cases where the boxcar starts working better than the optimal filter?
Add a spike in simplified noise of T2Z1

- Add the spike at where the optimal filter weight is smaller than the boxcar filter weight.

Why add spike here?
- To see how the weight difference affects the resolution as more noise is added there.
Resolution of Non-reoptimized Filters for T2Z1 Simplified Noise with Spikes

- Both optimal and boxcar get worse when the size of spike increases, but optimal filter is **ALWAYS** better than boxcar filter
• The optimal filter without reoptimization works much worse when the spike is large enough (e.g. > 5e+10)
Add a spike at 0.9kHz in simplified noise of T2Z1 Simplified Noise

Why add spike here?
- To see how the weight affects the resolution as more noise is added there

Add the spike at where the boxcar filter weight is smaller than the optimal filter weight.

Why add spike here?

Add the spike at where the boxcar filter weight is smaller than the optimal filter weight.
Resolution of Non-reoptimized Filters for T2Z1 Simplified Noise with spike at 0.9kHz

- If we don’t reoptimize the filters, the optimal filter works better than boxcar filter for noise with small spike size, while boxcar filter works better for noise with large spike size.
Conclusions

• We are searching for dark matter with the CDMS experiment, and upgrading the experiment for use at the SNOLAB mine. The sensitivity of the filter choice in Level 1 is the key to the CDMS’s ability to discover dark matter.

• We have studied the use of an optimal filter, an optimized boxcar filter and bandpass filter, and found that the Optimal Filter always works better by approximately 15% to 50%.

• We recommend to use optimal filter in triggering in our future experiment in SNOLAB, hopefully it will help us discover dark matter.
Back-up slides
Add a spike in simplified noise of T5Z1

- Add the spike at where the optimal filter weight is smaller than the boxcar filter weight

Why add spike here?
- To see how the weight affects the resolution as more noise is added there
Resolution of Non-reoptimized Filters for T5Z1 Simplified Noise

- If we don’t reoptimize the filters, optimal filter works best for VERY small spikes, then as the spike gets bigger the boxcar filter works better than optimal filter, while optimal filter works better for noise with large spike size.
How to Calculate Optimal Filter?

- Estimate the amplitude of a signal of known shape $A(t)$ amidst a background of gaussian random noise of known power spectral density (PSD) $J(f)$
- Signal traces $S(t) = aA(t) + n(t)$
  - $A(t)$ - known template
  - $n(t)$ - noise realization with $J(f) = \langle n(f) \rangle$

Optimal technique for amplitude estimation: perform a frequency-domain ChiSquare:

$$
\chi^2(a) = \sum_n \frac{|\tilde{S}_n - a\tilde{A}_n|^2}{J_n}.
$$

Minimize it $\Rightarrow$ 

$$
\hat{a} = \frac{\sum_n \frac{\tilde{A}_n^* \tilde{S}_n}{J_n}}{\sum_n \frac{|\tilde{A}_n|^2}{J_n}}.
$$

Estimate $a$

The estimate of $a$