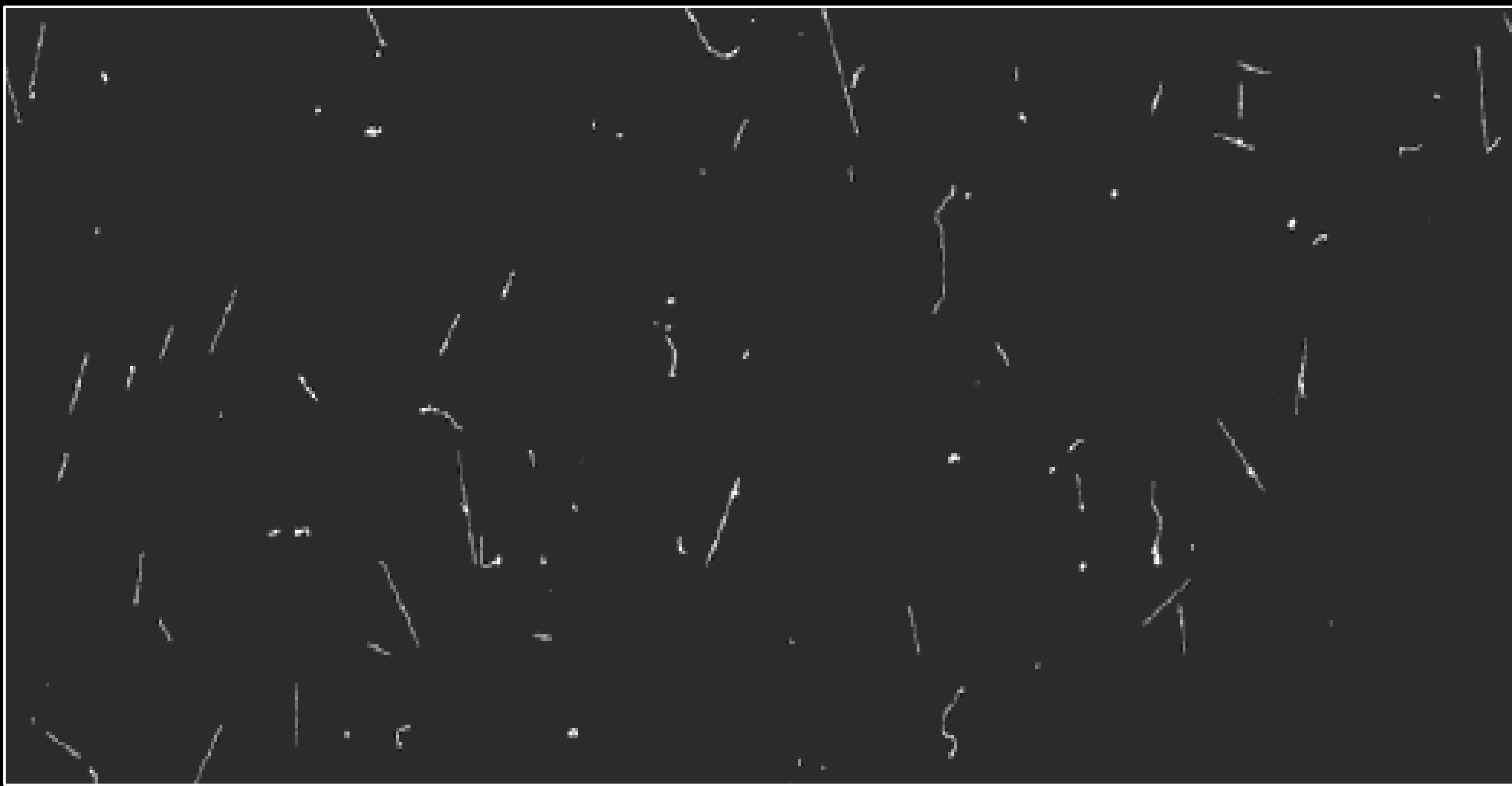
Direct Dark Matter Searches Using CCDs

Natalie Harrison, Fermilab, on behalf of the DAMIC collaboration
(speaking for Juan Estrada)



Technology and Instrumentation in Particle Physics 2011

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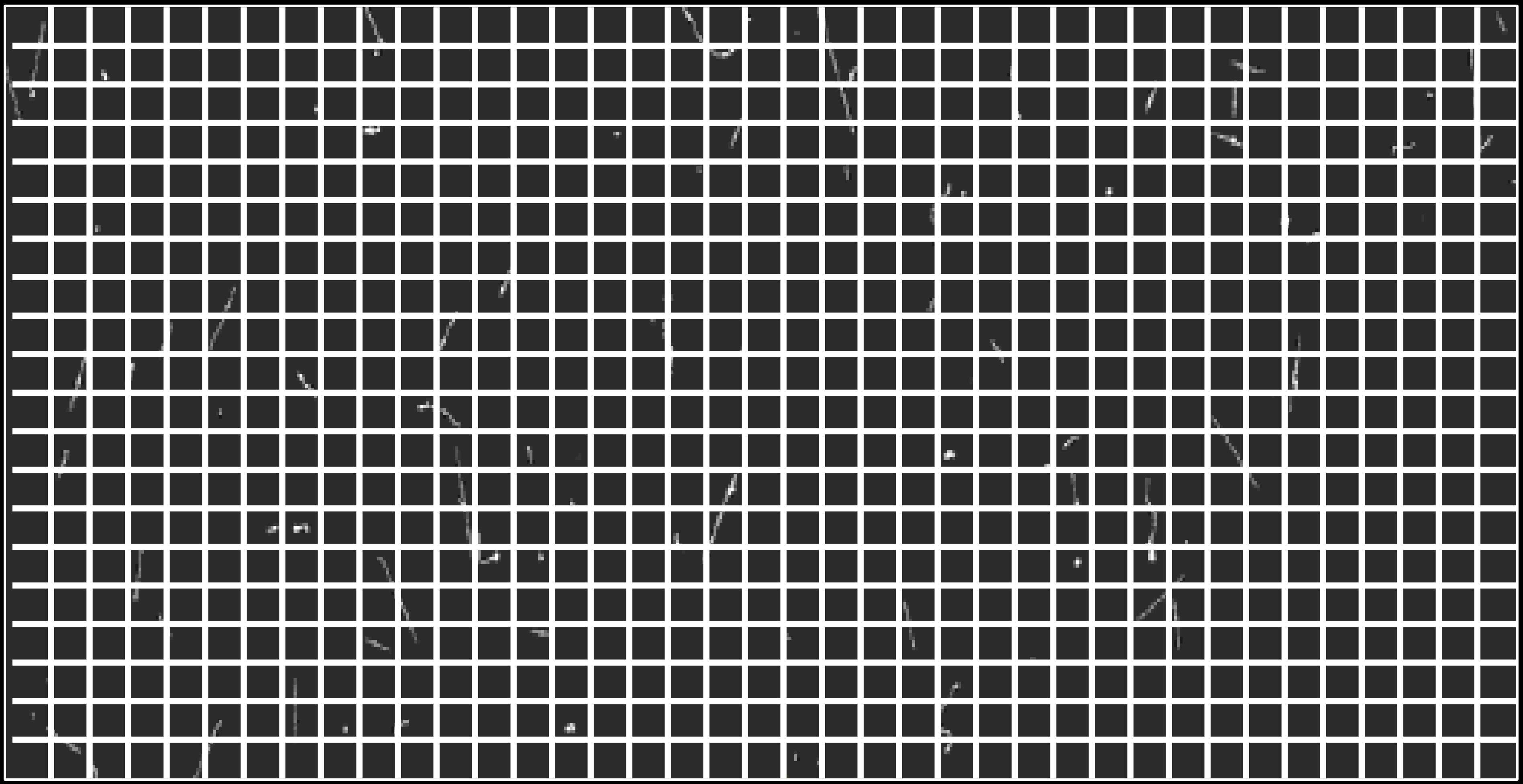
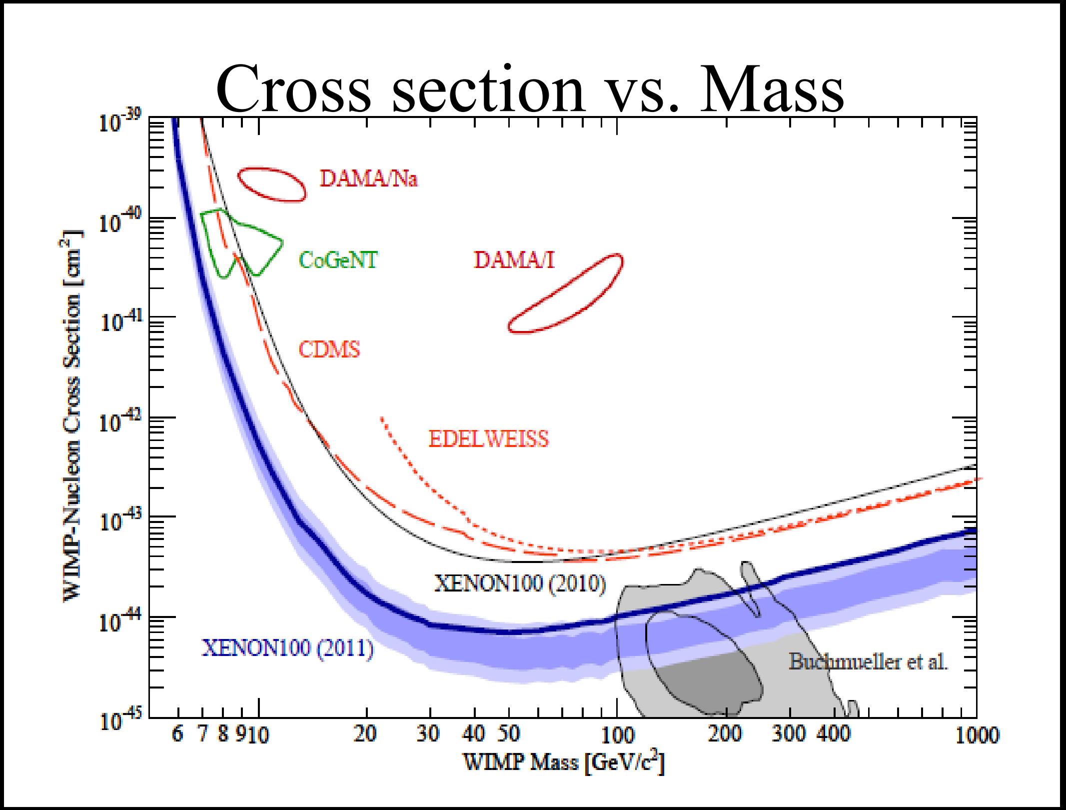
This is an image from a CCD (charged coupling device).



Dark Matter Searches

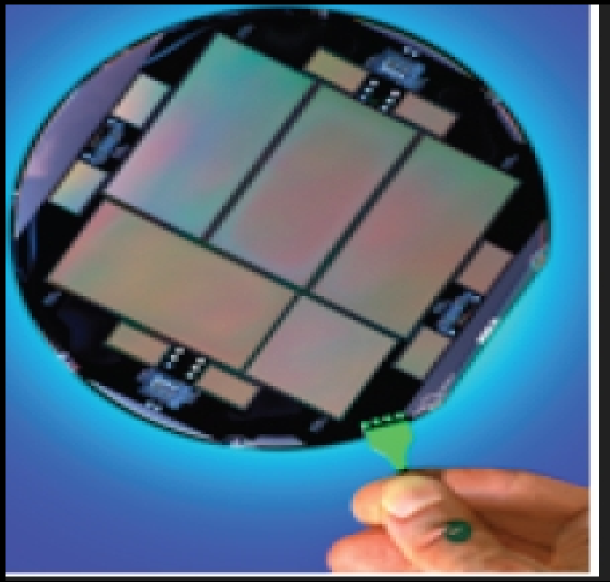
- Many experiments are designed to search for high mass WIMPS because MSSM has a WIMP scale of several hundred GeV
- Many experiments conflict with DAMA/Libra
  - Conflicts can be averted by taking into account channelling of ions in the lattice of the detector, which changes the relationship between the energy detected and the mass of the dark matter

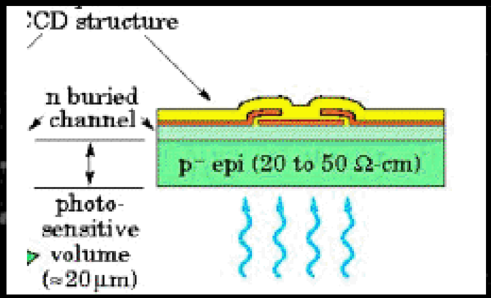


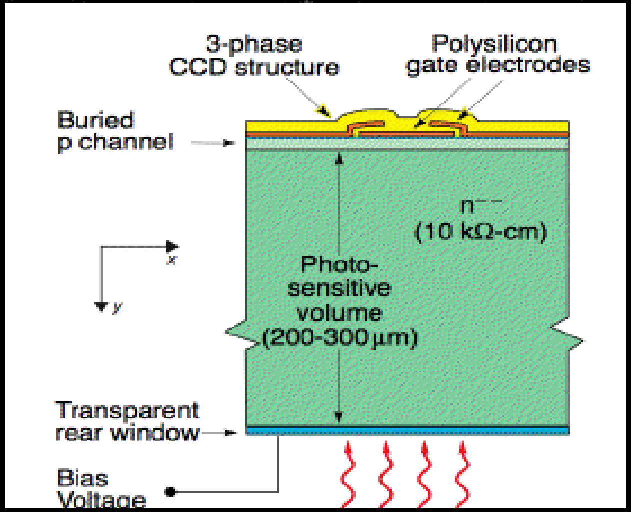
For high mass dark matter → need massive detectors to improve limits

Low mass Dark Matter → detection of low energy recoils → need low detector noise

CCDs



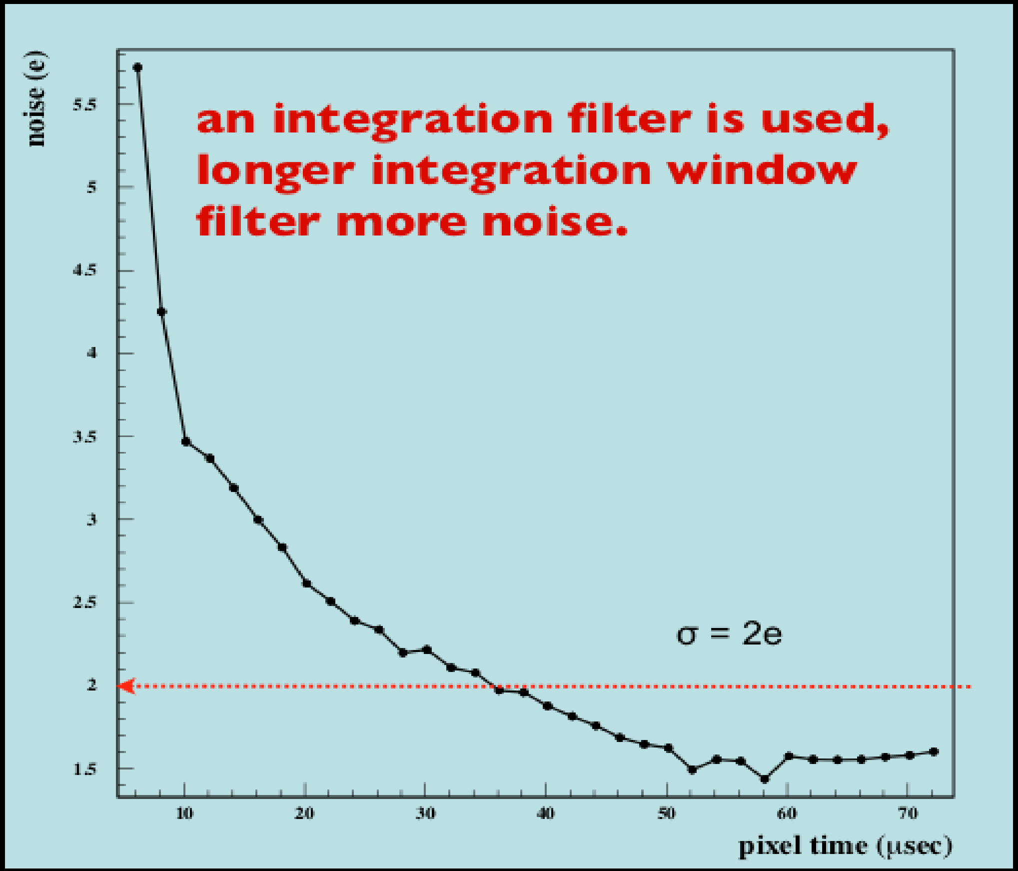




- CCDs are inherently low noise devices
- These CCDs are 10 times thicker than normal CCDs (more massive)
- How they work: When a nuclear recoil occurs, the electrons produced are sent through a bias voltage and collected at one end of the pixel. Charges are then read out serially

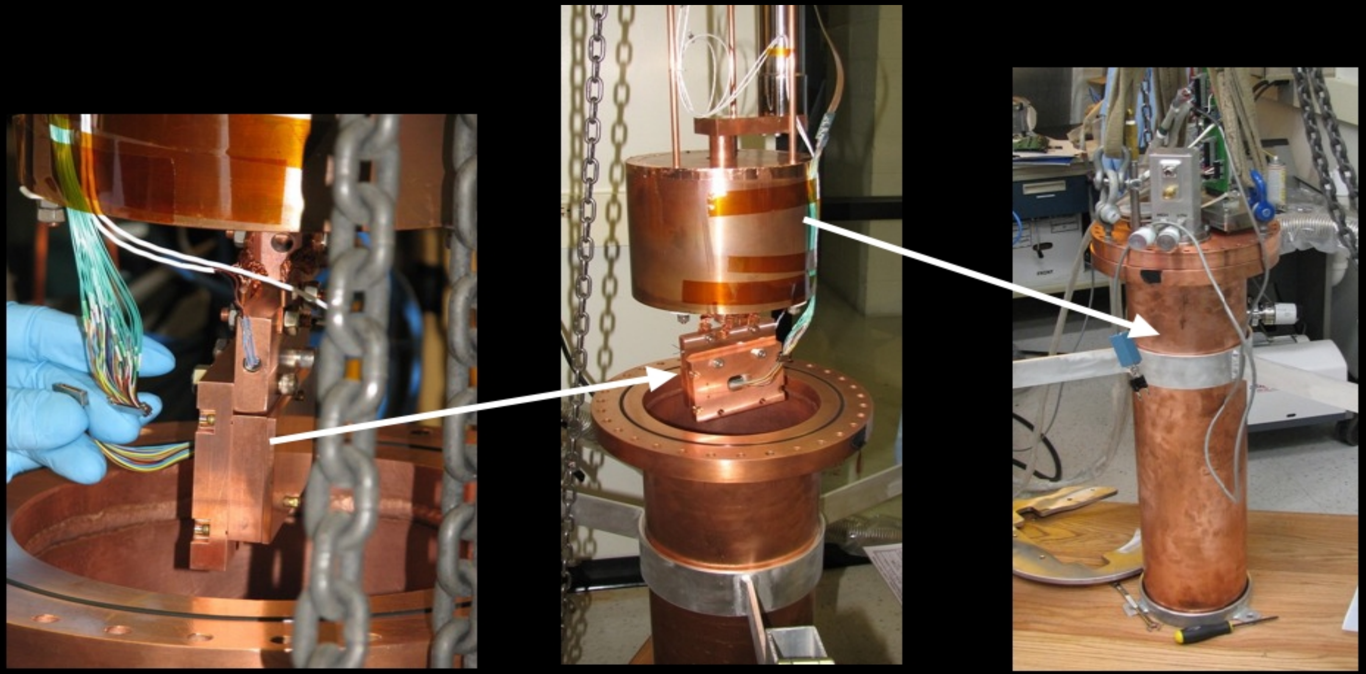
New opportunities with CCDs

- When readout slowly, these detectors have a noise below 2e- (RMS)
- This converts to 7.2 eV in ionization energy (RMS)
- We place threshold at 5σ, 36 eV

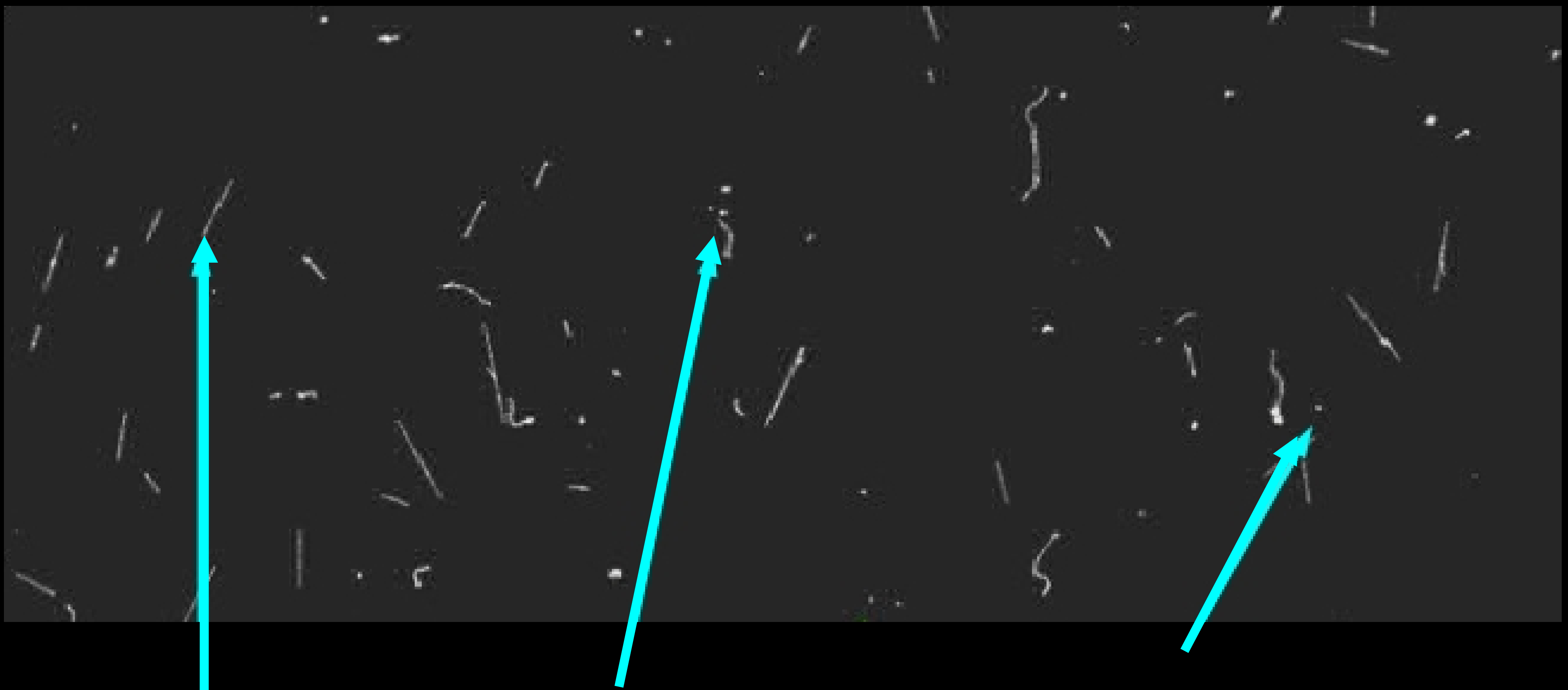


The Detector

- Shallow underground at Fermilab in the MINOS tunnel (350 ft.)
- Shielded with low radioactivity lead to reduce natural radiation backgrounds, CCD is also encased in a copper box.
  - Copper shielding protects detector from X-rays in lead
- Cooled to -140 C to reduce noise and background from radiation and light



Backgrounds



Cosmic Ray Muons

Gamma Rays (compton scattered electrons)

Neutrons, x-rays, possible DM

We can easily remove muons and gamma rays with size-dependent cuts!

Calibration – using X-Rays

- X-rays from ^{55}Fe has a predictable spectrum of X-rays
- We can use the 5.9 keV spectral line to calibrate the energy scale
- We develop selection criteria from these hits

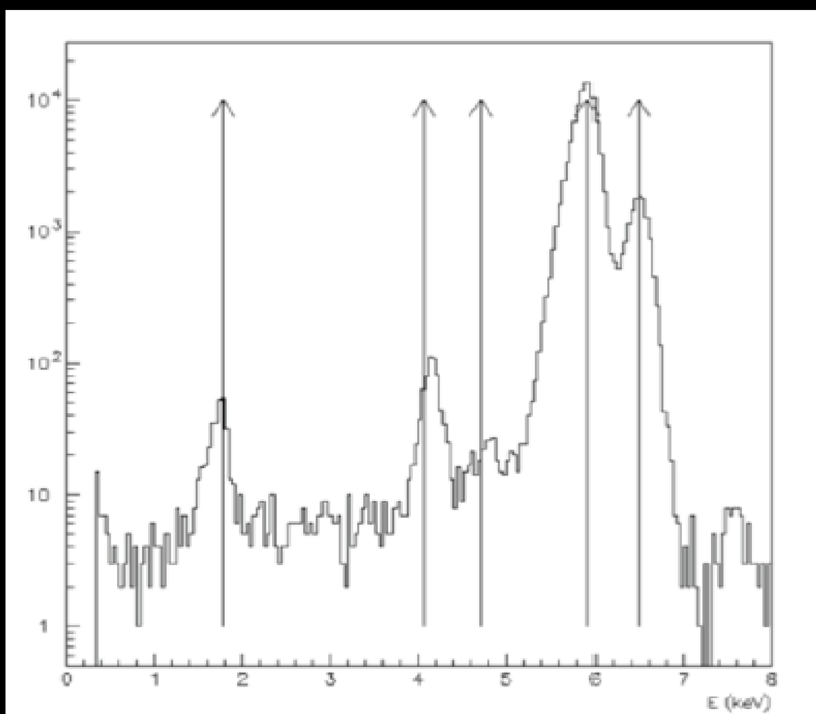
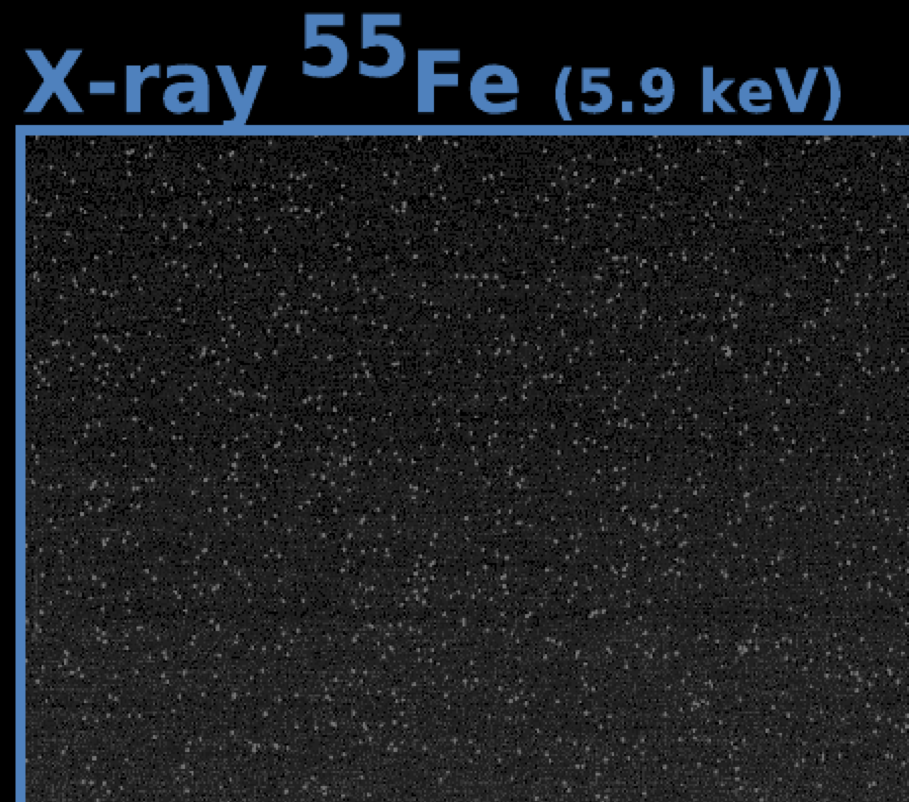
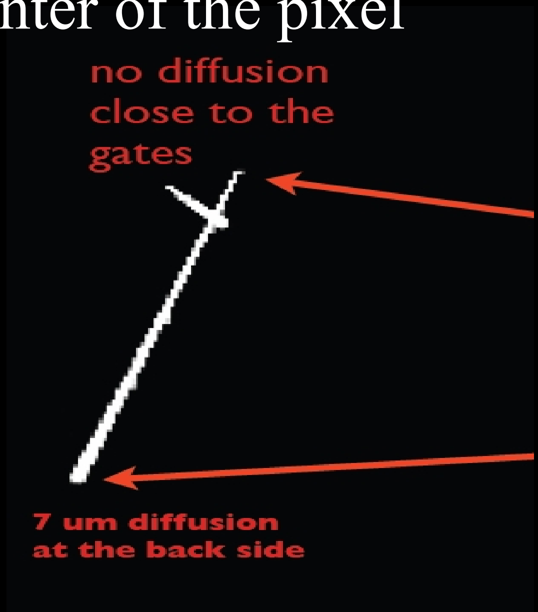


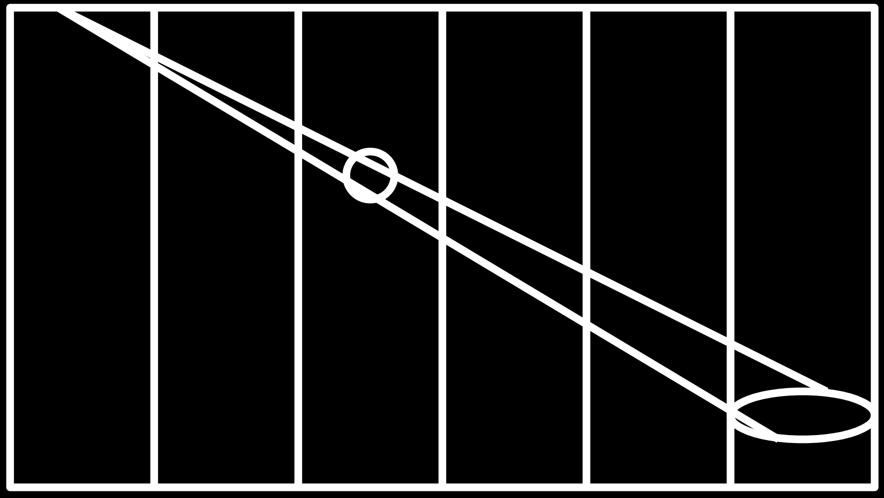
Figure 8. Spectrum obtained for the reconstructed X-ray hits in an ^{55}Fe exposure of a DECam CCD. The arrows are marking the direct X-rays from the source K_α=5.9 keV and K_β=6.5 keV. K_α and K_β escape lines at 4.2 and 4.8 keV, and the Si X-ray at 1.7 keV. The factor of 3.64 eV/e^- is used to covert from charge to ionization energy.



Self Shielding in the Detector

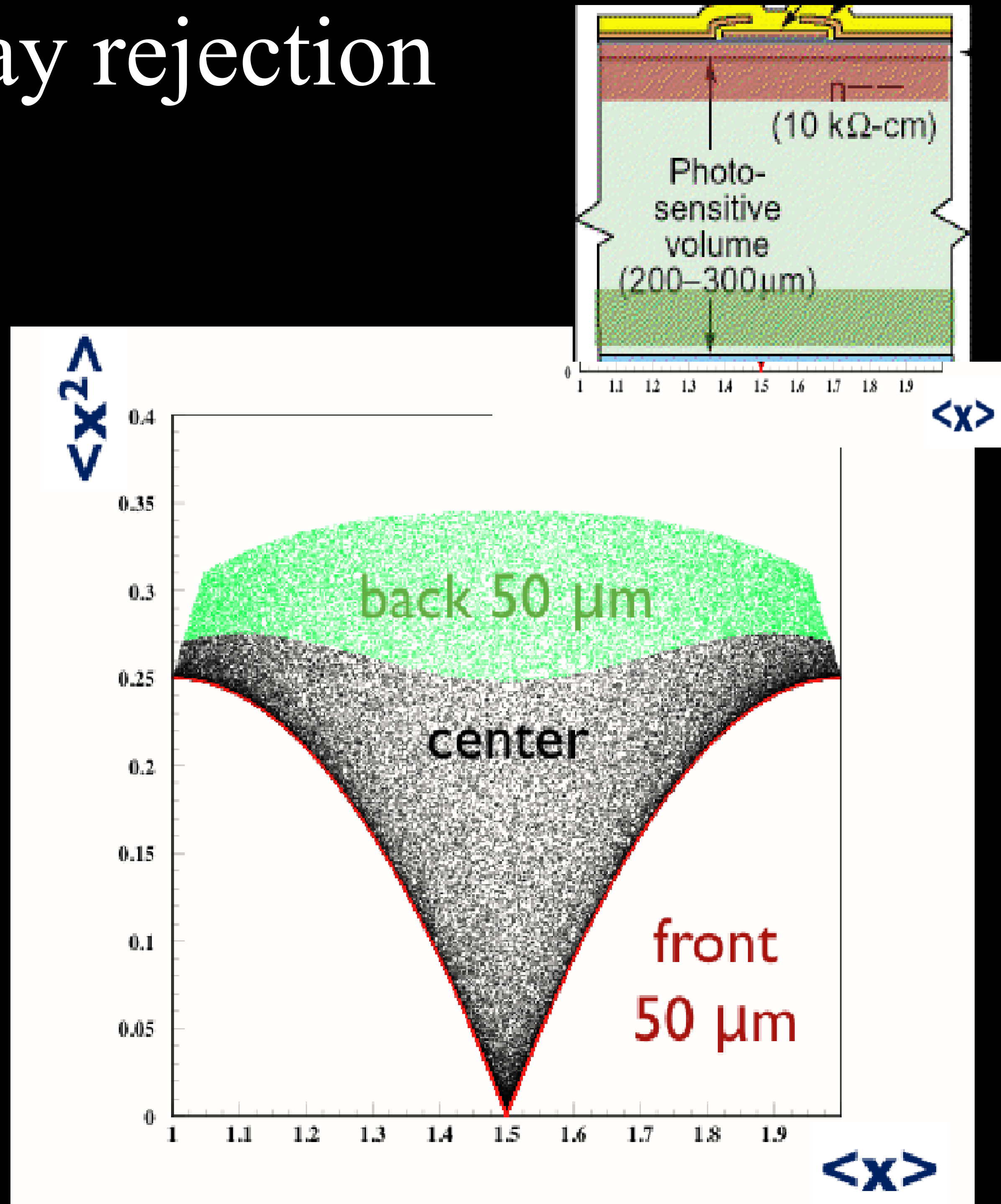
- X-rays are a main background in the detector and they only penetrate the detector a few microns
- Size of hits increase deeper in the detector and no diffusion occurs in the uppermost regions
- We wish to remove any hit on the top or bottom portion of the pixel, we select the hits in the middle region, that have a diffusion consistent with hitting the center of the pixel





X-ray rejection

- We can measure the x position within the pixel and the RMS of the hits
- Simulation of a CCD with 9 pixels (3x3). The hit occurs in the central pixel at different depths and places in the detector (x-z axis)

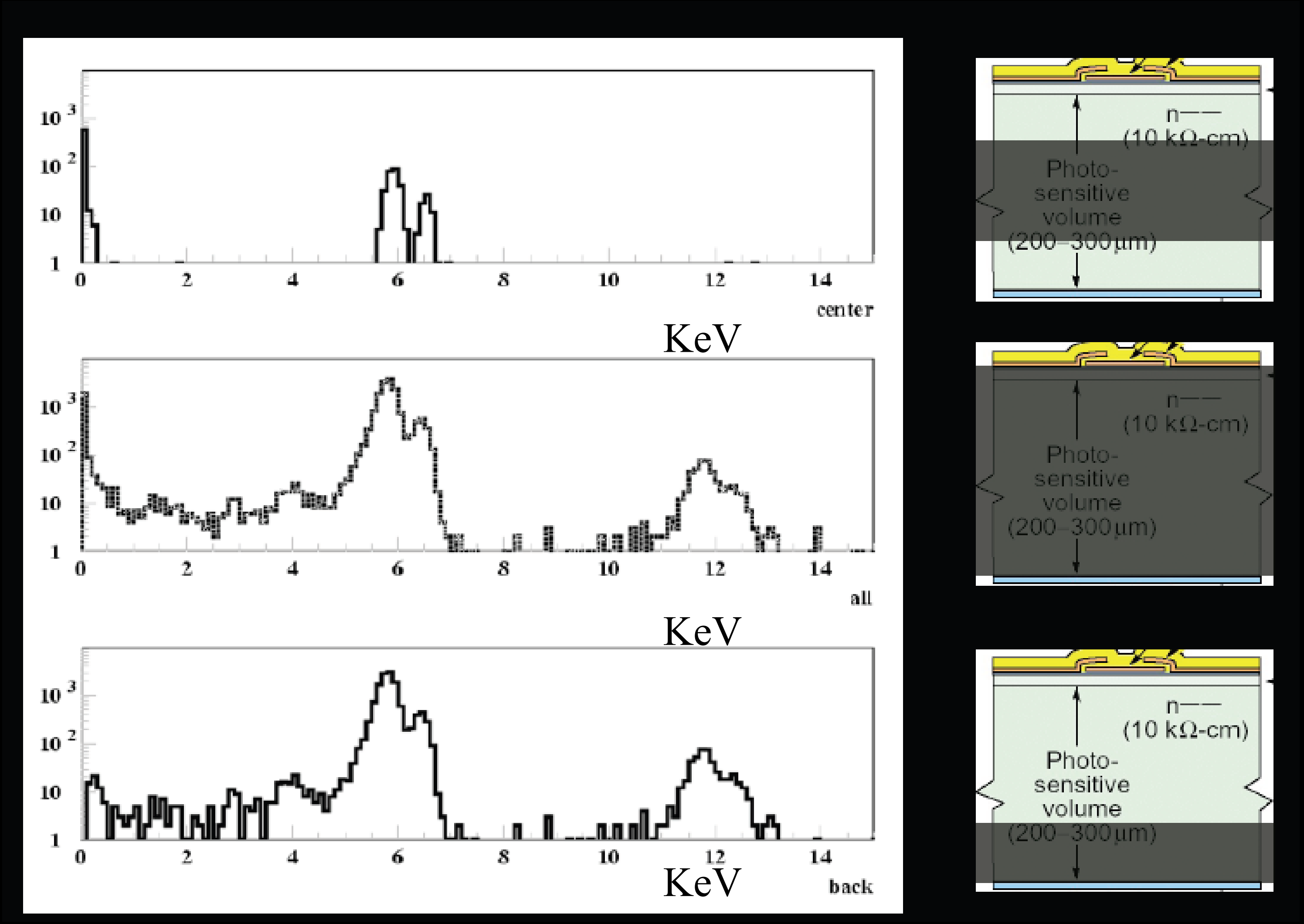


This X-ray calibration data is from above ground

Bulk of the Pixel →

Entire Pixel →

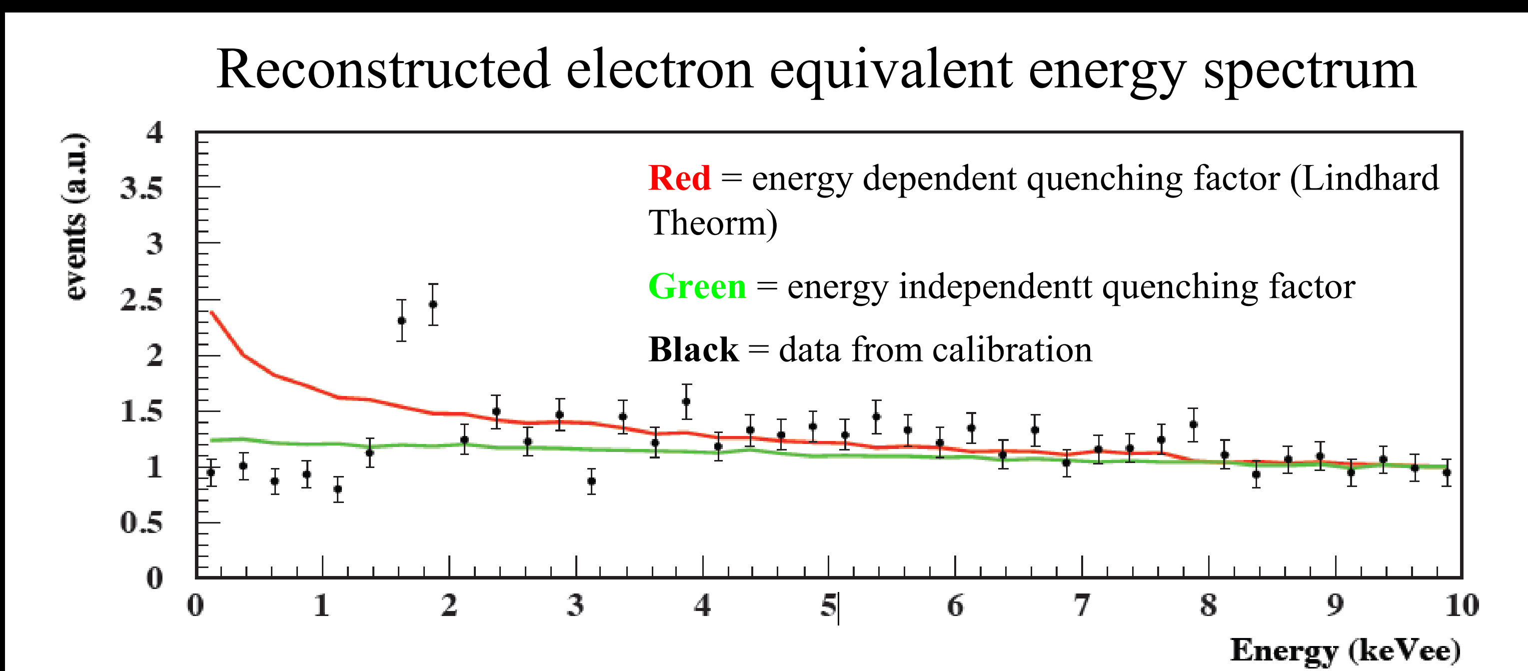
Bottom Portion of the Pixel →



- We get a huge background rejection of X-rays from this cut, the "Bikini Cut," which rejects high and low diffusion hits

Neutron Calibration

- We simulate the neutron energy spectrum through a GEANT detector and convolute this with the measured energy distribution (collected using ^{252}Cf) to determine the energy dependent quenching factor
- Quenching Factor = Energy calibration used to calculate incoming dark matter energy (the green line represents Q = 0.3)

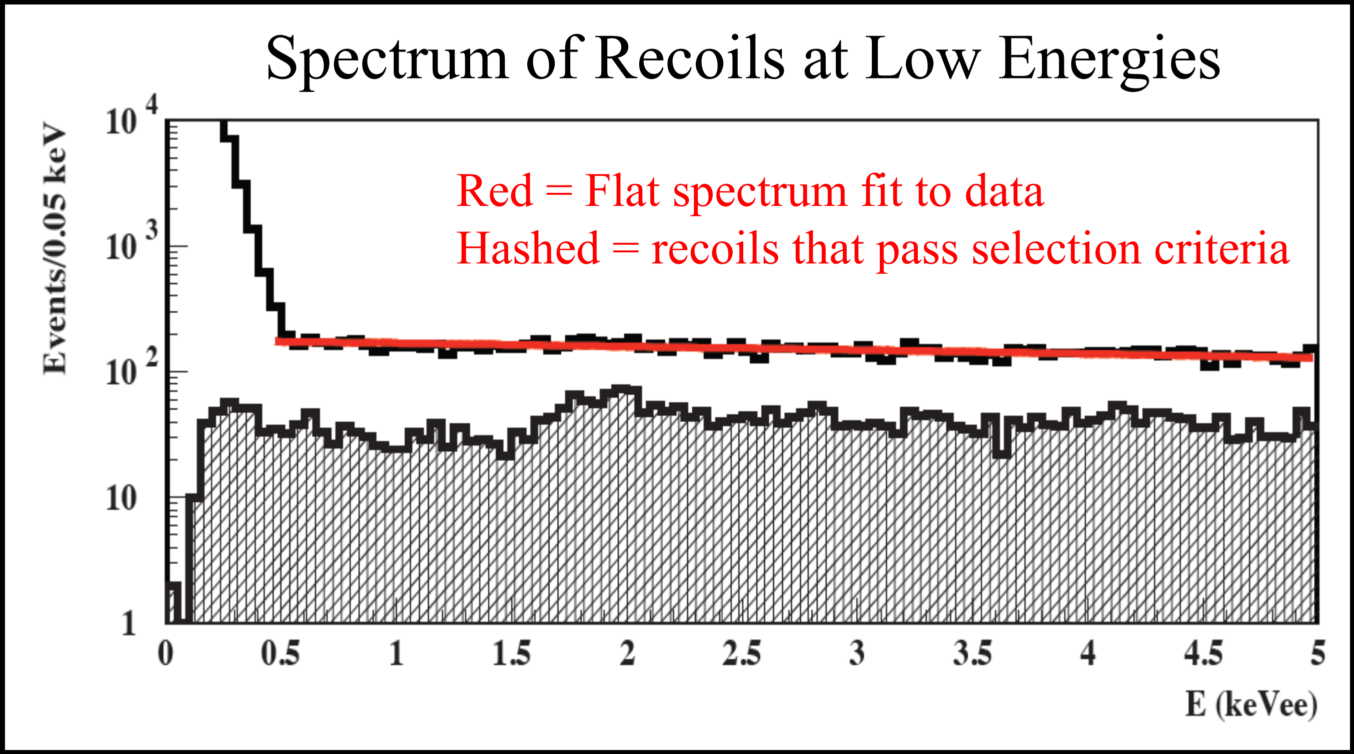


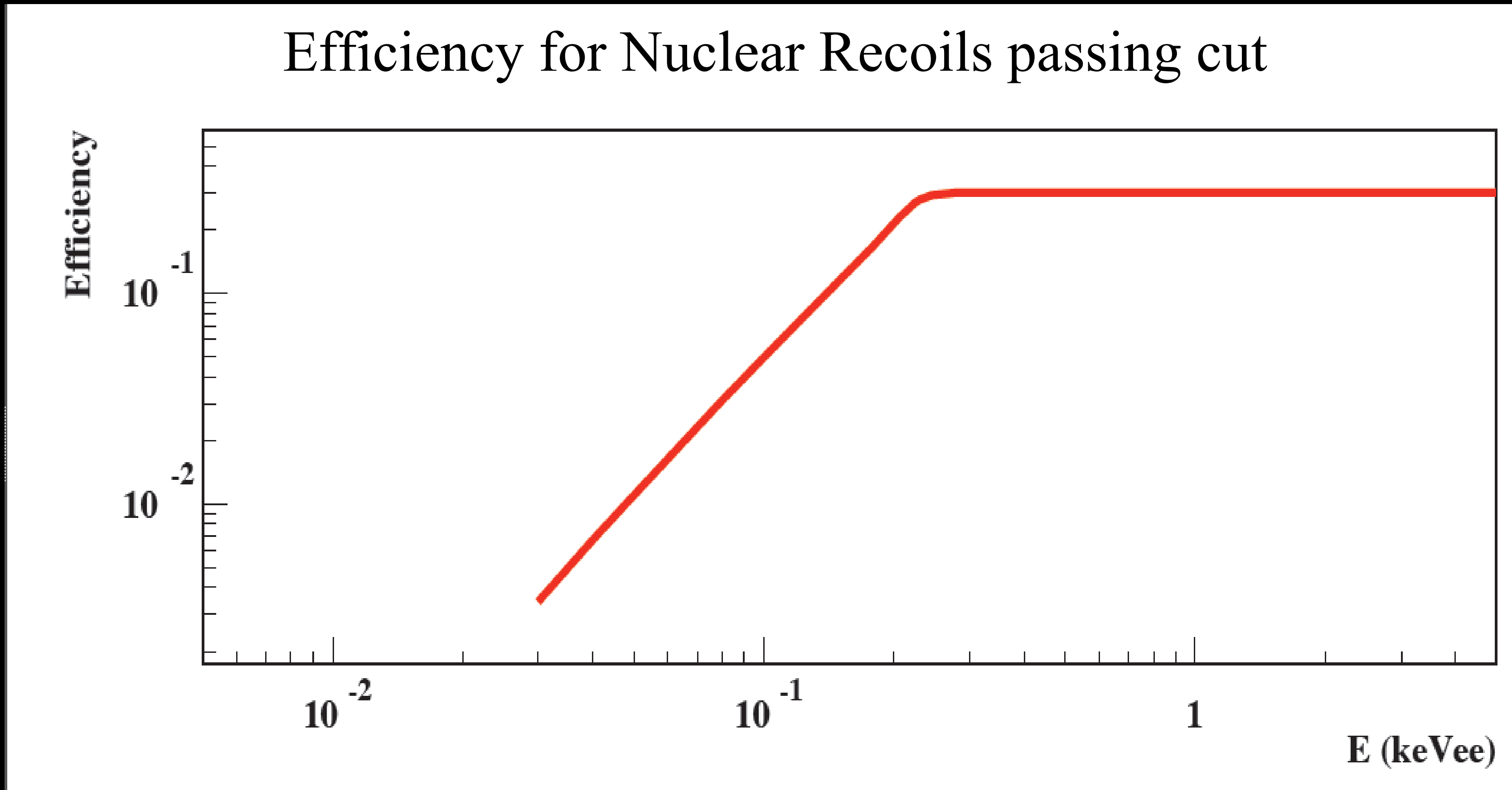
The peak at 1.7 keV is consistent with silicon excitations

Data deviates from Linhard theory below 1.5 keV

Spectrum and Efficiency

- We reconstruct the spectrum of nuclear recoils from Californium with and without size selection.
- The recoils are expected to produce a flat spectrum at low energies
- The raw spectrum (no size selection) is contaminated by low energy photons and electrons.



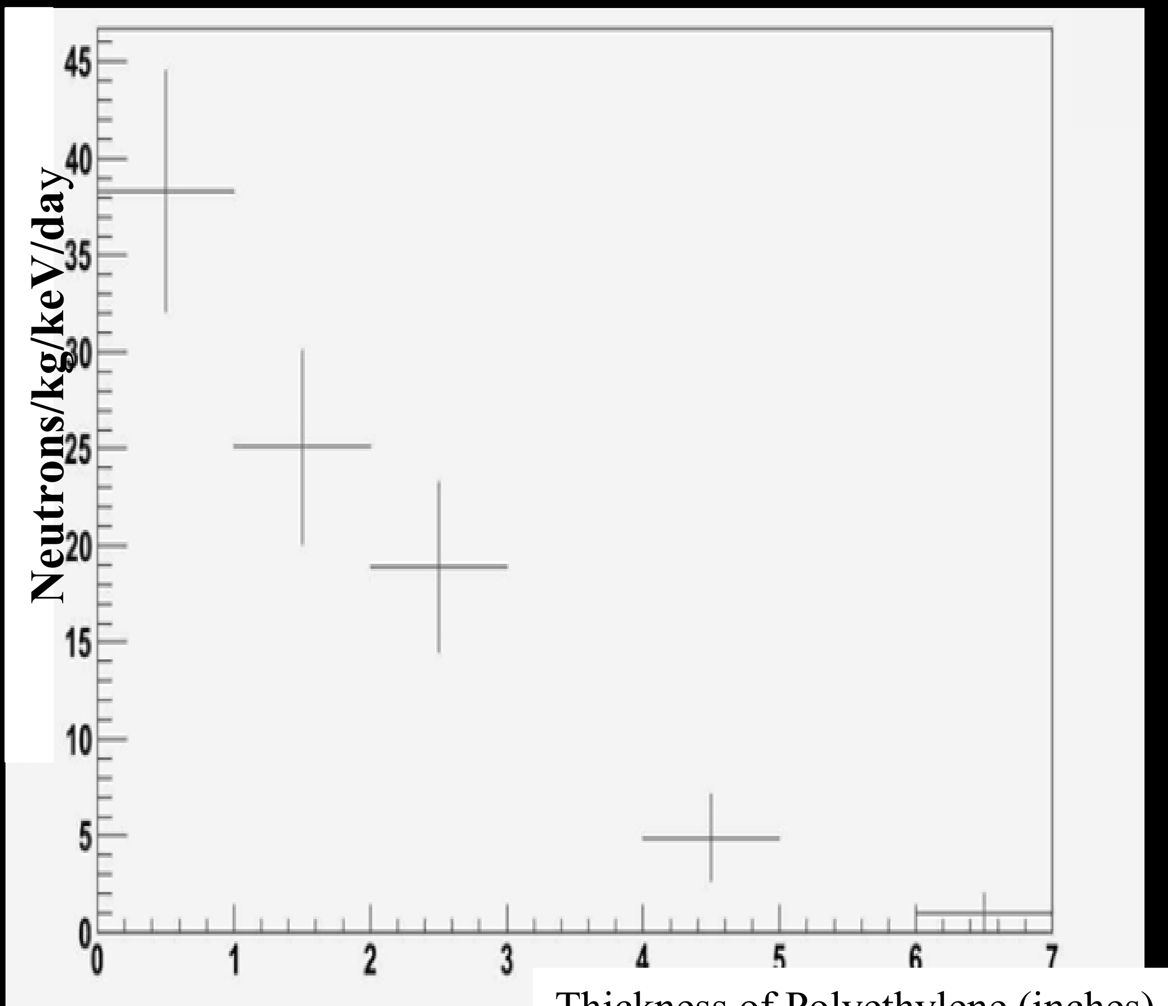


From this we calculate the efficiency for nuclear recoils passing the charge diffusion selection criteria. The ratio between the spectrum of selected hits and the linear fit to the raw spectrum defines the efficiency.

Remaining Backgrounds

- Removed
  - Electronics Noise – place a threshold at 36 eV
  - Muons and Gamma Rays – we remove these with size cuts
  - X-rays – remove by selecting limited range of diffusion hits
- Remaining
  - Natural radioactivity
  - Neutrons produced by NuMi beam (in MINOS tunnel)
  - Comsogenic muons interact with shielding and produce neutrons

Polyethylene Shielding



- We are studying the effect of adding polyethylene shielding
- Polyethylene thermalizes neutrons, reducing their energy – this should reduce the number of neutrons
- Measured number of neutrons from MINOS tunnel is significantly reduced when 6 inches of polyethylene is used

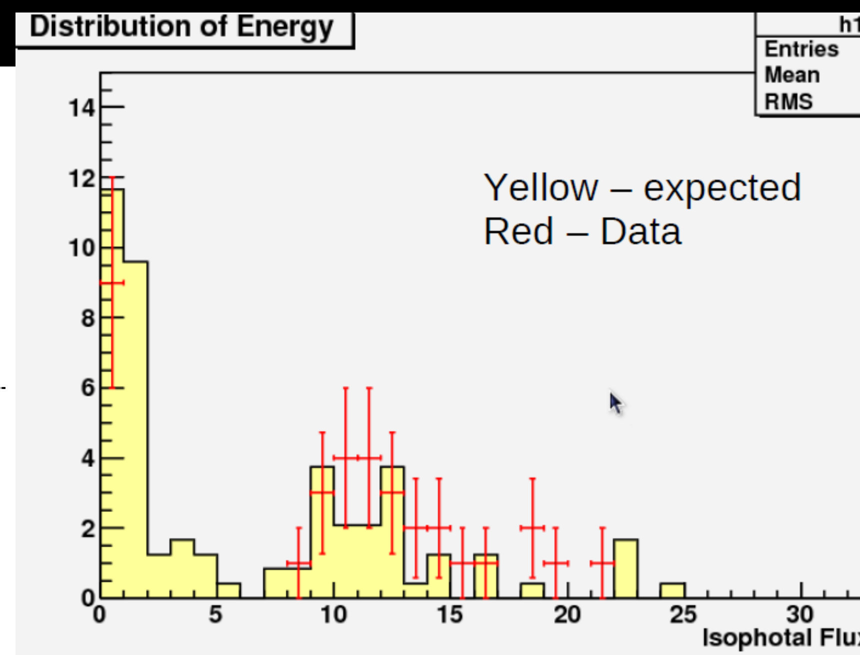
Data Quality

- Goal is to run for extended period of time to check for modulation
- Need some sort of quality assurance
- Look at rates of interactions at certain energies and temperatures

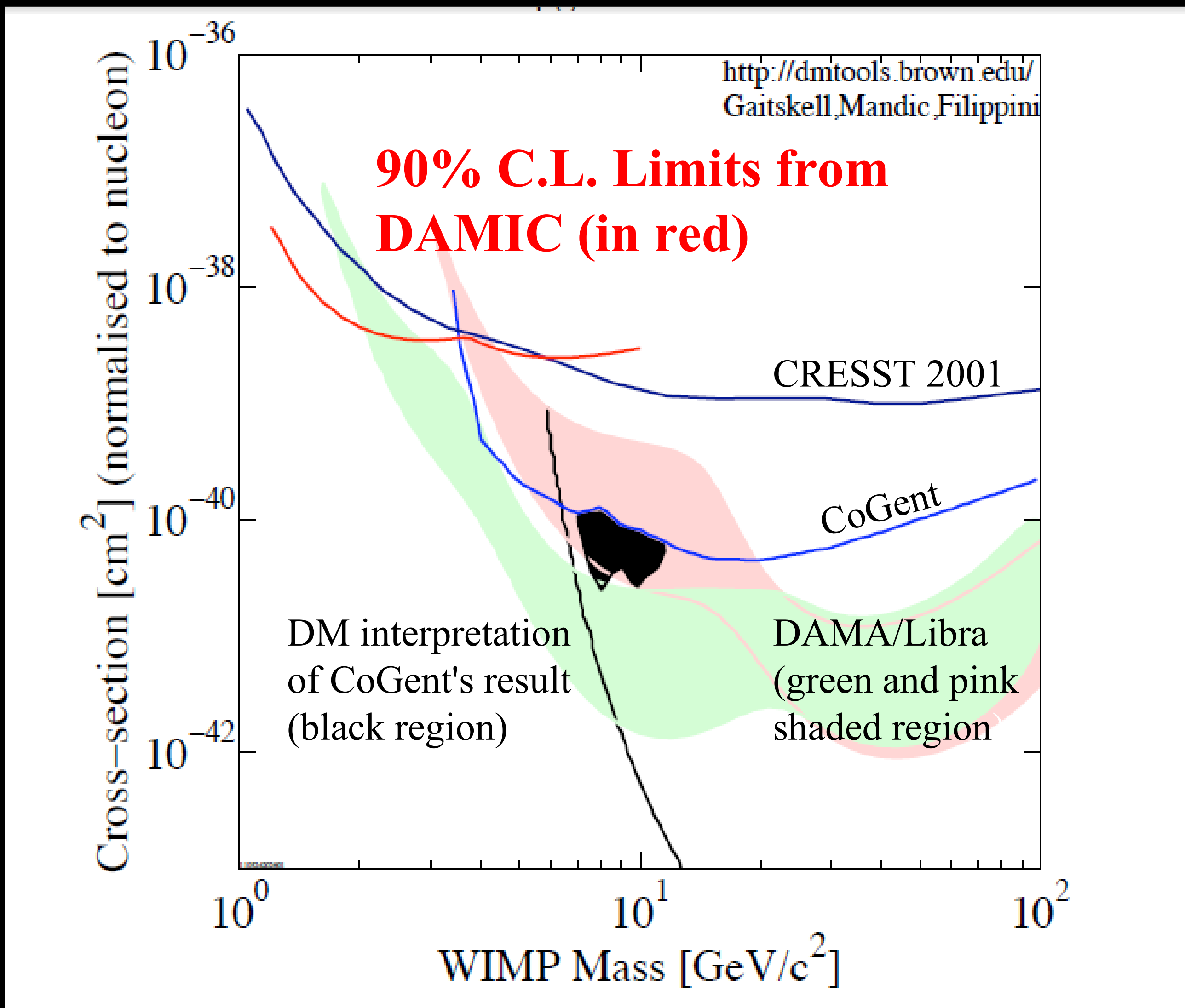
We used 96,000 seconds of data to formulate means and standard deviations for all the energy bins as well as the diffusion limited hits

Expected1	33.708	4.667	1.125	1.542	1.458	0.5
Std. Dev.	Not Applicable	2.461	2.071	0.721	1.444	0.833

Filename	Total Events	Diffusion Limited	Lowest Energy	Midlow Energy	Midhigh Energy	Highest Energy		
16Jun2010_4ks0065.dat.root	27.0	4.0+/-2.000	0.0	1.0	3.0	0.0		
16Jun2010_4ks0064.dat.root	30.0	3.0+/-1.732	0.0	1.0	2.0	0.0		
16Jun2010_4ks0063.dat.root	29.0	7.0+/-2.646	1.0	2.0	4.0	0.0		
16Jun2010_4ks0062.dat.root	34.0	7.0+/-2.646	5.0	2.0	0.0	0.0		
16Jun2010_4ks0061.dat.root	34.0	2.0+/-1.414	0.0	1.0	1.0	0.0		
16Jun2010_4ks0060.dat.root	37.0	2.0+/-1.414	0.0	1.0	1.0	0.0	1.1135	-1.084



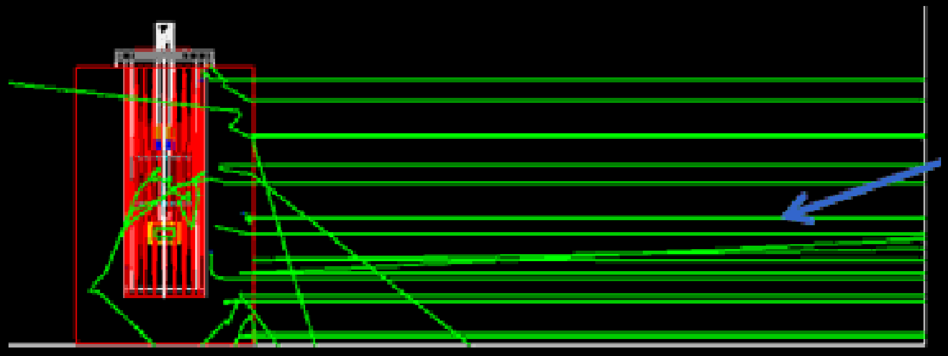
Results from DAMIC



- Linhard model used to obtain the recoil energies
- The Optimal Interval method was used for determining the upper cross section limits
- DAMIC has the best limit for dark matter particles of masses below 4 GeV

Simulation (using GEANT 4)

- Since we're not very deep underground, we expect cosmogenic muon background
- To understand the composition of this background, we do a simulation of muons that interact and produces neutrons from the MINOS tunnel (from floor, walls, muon flux, etc.)

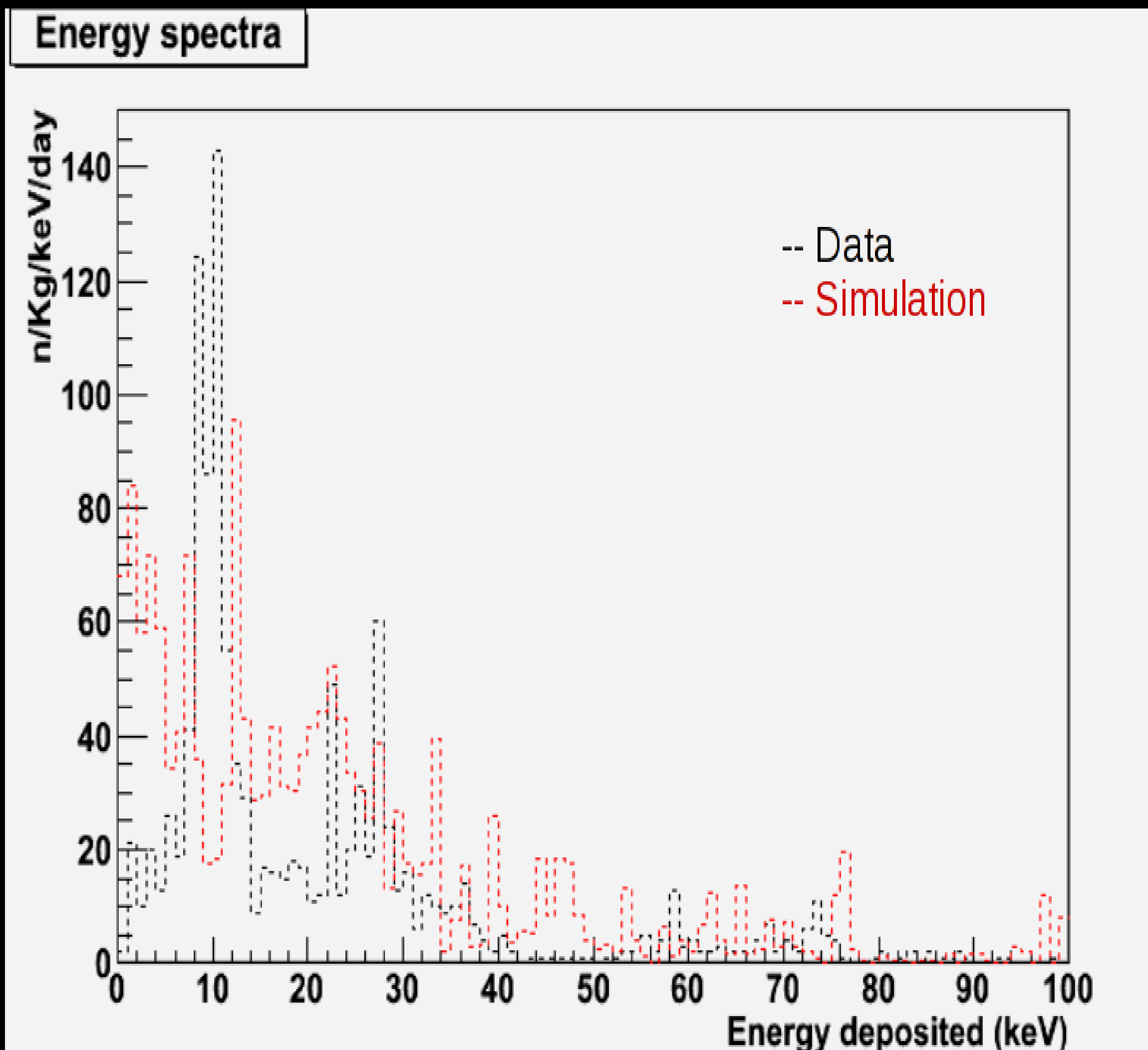


Perform simulation for our detector without polyethylene shielding

Data used: July-August, 2010

We compare the resulting energy spectrum to the data

Simulation Comparison



- Rate from cosmogenic muons are comparable to data
- Going deeper underground would reduce most of our background rate
- The excess of events can be explained by the neutrons coming from the rock of the MINOS tunnel

Conclusions

- We have preliminary limits competitive with other experiments for low mass Dark Matter
- Simulation Studies suggest deeper underground location would reduce most of the backgrounds
- Still investigating
  - Improved electronics readout for lower noise
  - Optimum polyethylene shielding for neutron rejection
  - Low energy neutron calibrations

Future

- DAMIC expects to further improve its sensitivity to low mass dark matter.
  - Moving deeper underground: it is possible that DAMIC may move to SnoLab
  - We expect to implement new CCDs in our next detector that have an RMS of 0.2 electrons (or 0.72 eV of ionization energy). These CCDs use the same high resisitivity silicon technology being used in our current CCDs.
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Thank you!

If you want to read more on DAMIC and CCD technology:

- arXiv number: 1106.1839v1

  Achieving subelectron readout noise in Skipper CCDs

- arXiv number: 1105.5191v1

  Direct Search for Low Mass Dark Matter Particles in CCDs