DAMIC : a novel use of CCDs for dark matter searches

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SWAPS
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Naturalness of Dark Matter Mass scale

1. "Wimp miracle" scale : $M_{DM} \sim 100$ GeV
   - SUSY weak cross-sections provide DM density relic Ω_{DM}

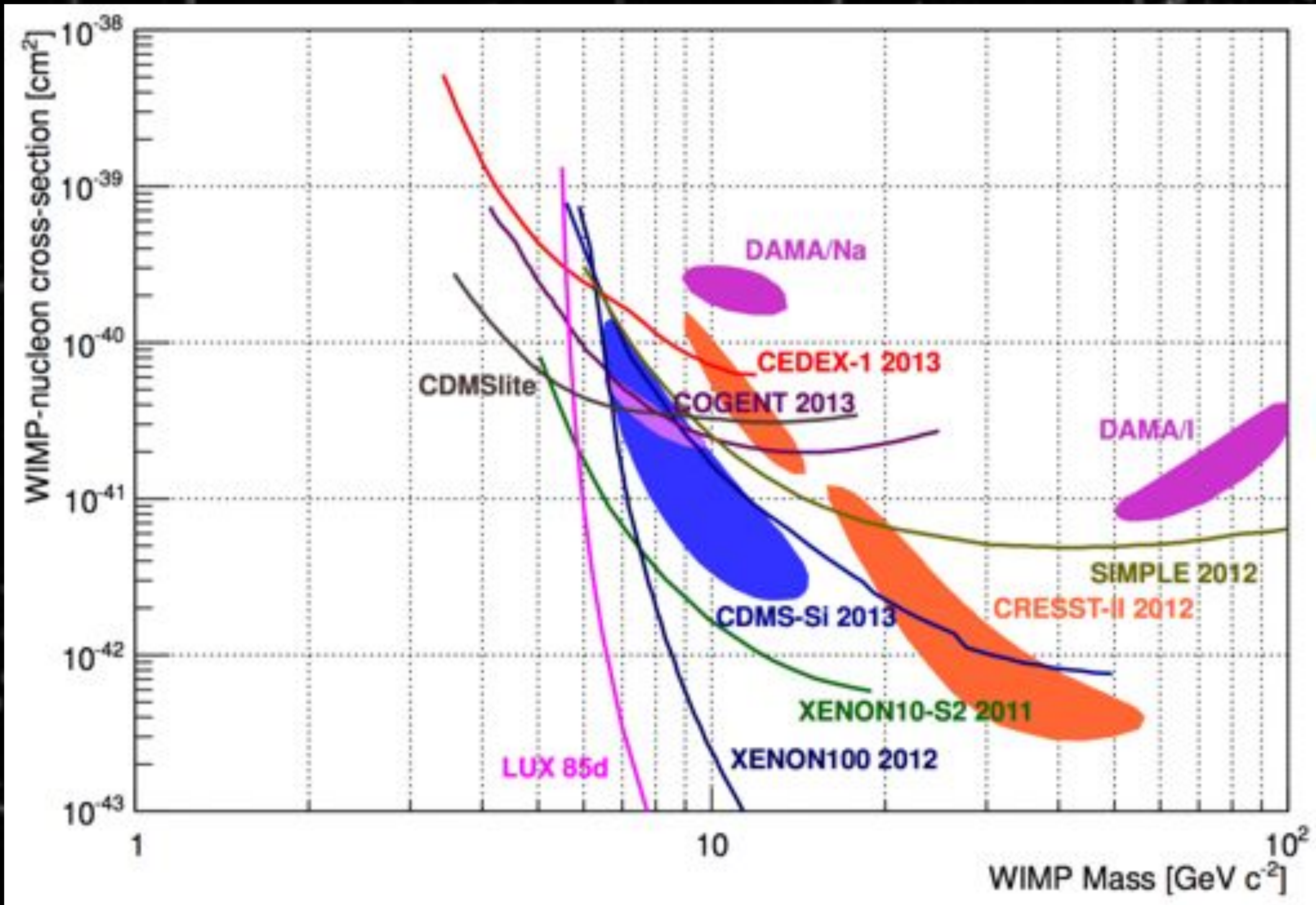
2. "Baryon-DM coincidence" scale : $M_{DM} \sim 5$ GeV
   - $\rho_{DM} \approx 5\ \rho_B$
     - Why is ρ_{DM} similar to ρ_B ?
     - Each is set by independent processes
       - ρ_B is set by CP violating phase
       - ρ_{DM} is set by ie, SUSY mass hierarchy of LSP

   - Assume that at start of universe : $N_{DM} = N_M$
   - Lepton-baryon asymmetry transferred to DM : $N_\ell - N_{\bar{\ell}} = N_{DM} - N_{\overline{DM}}$
   - If $\rho_{DM} \approx 5\ \rho_B$
     → $M_{DM} = 5 * M_{proton}$

Asymmetric DM
hep-ph/1111.0293

Or Intuitively : same number of DM and M particles, but 5 times density
→ DM is 5 times more massive than M

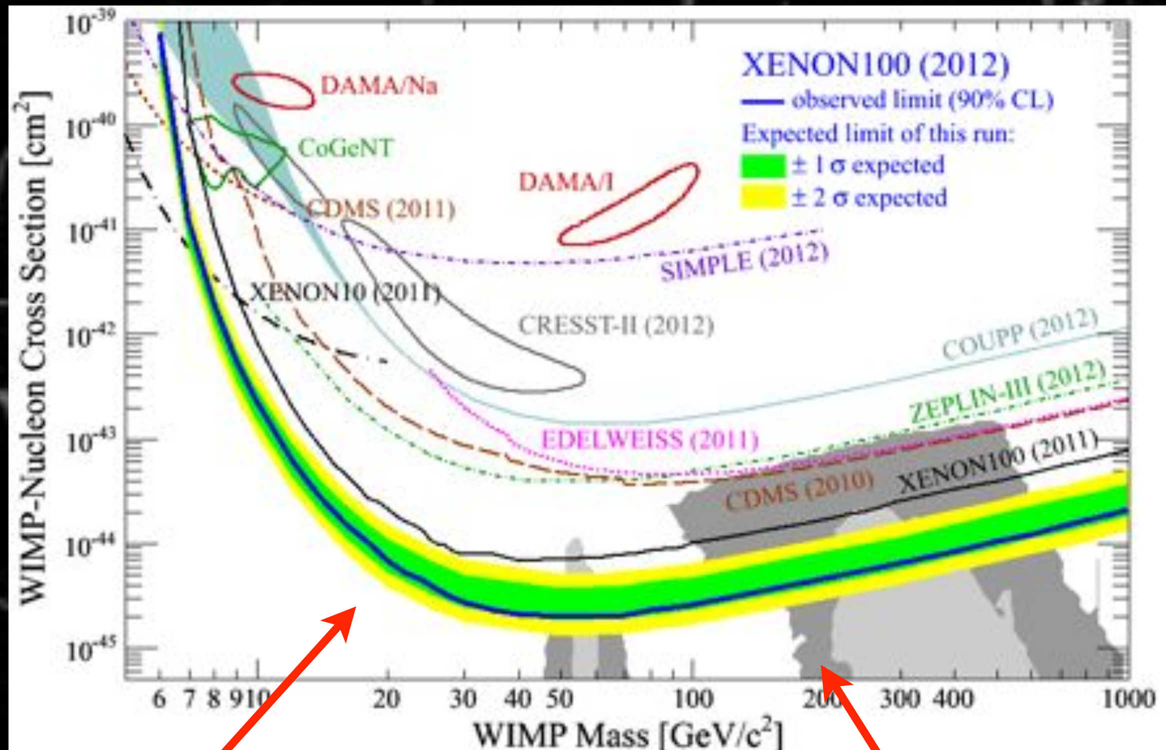
Experimental hints of DM ...



- **... but Xenon100, LUX exclude**

Features of DM searches

Hints of signal at lower masses



CMSSM prefers heavy WIMPs ~200 GeV
But ... increasingly ruled out by LHC & Xenon

Limited by energy threshold
(need lower energy detection)

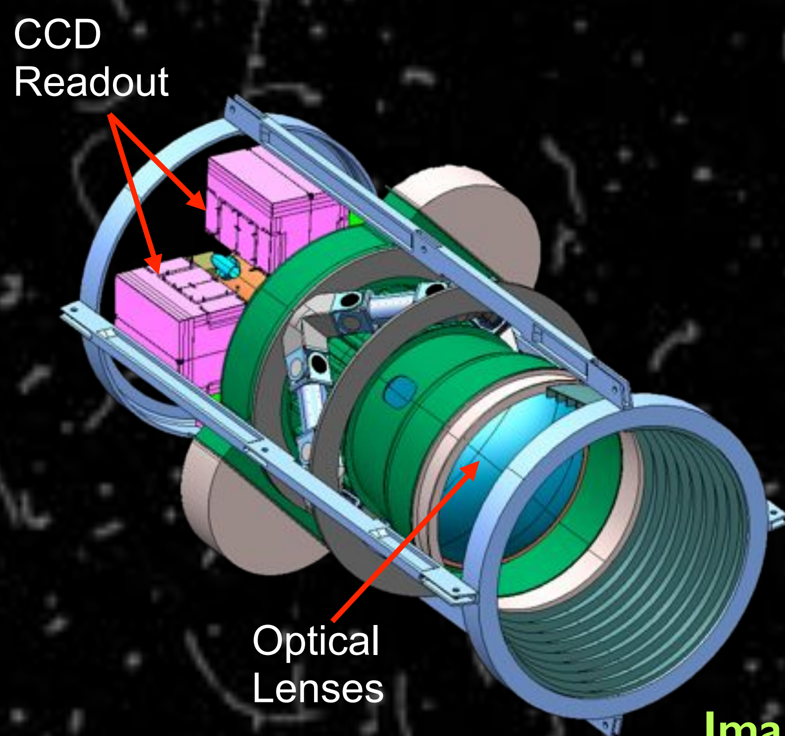
Limited by exposure mass
(need bigger detector)
multi-kg-sized detectors

Low mass (GeV) means low energy thresholds …

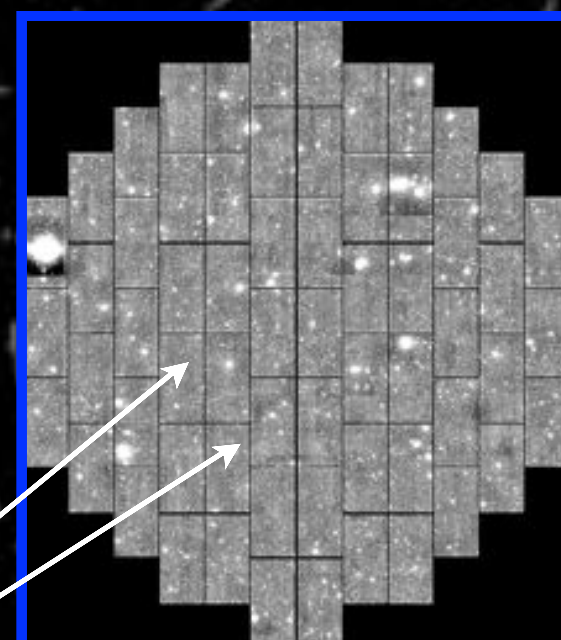
Experiment	Target	Exposure (kg-d)	Threshold	Ref
CDMS-SUF	Ge	65.8	5 keV	[2]
	Si	6.58	5 keV	
CDMS-II	Ge	121.3	10 keV	[3]
	Si	12.1	7 keV	[4]
XENON10	Xe	131	4.5 keV	[5]
CRESST-I	Al_2O_3	1.51	0.6 keV	[16]

Can we get a factor of 10-100 lower than this ?

The Dark Energy Camera (DECam) for Dark Energy Survey (DES)

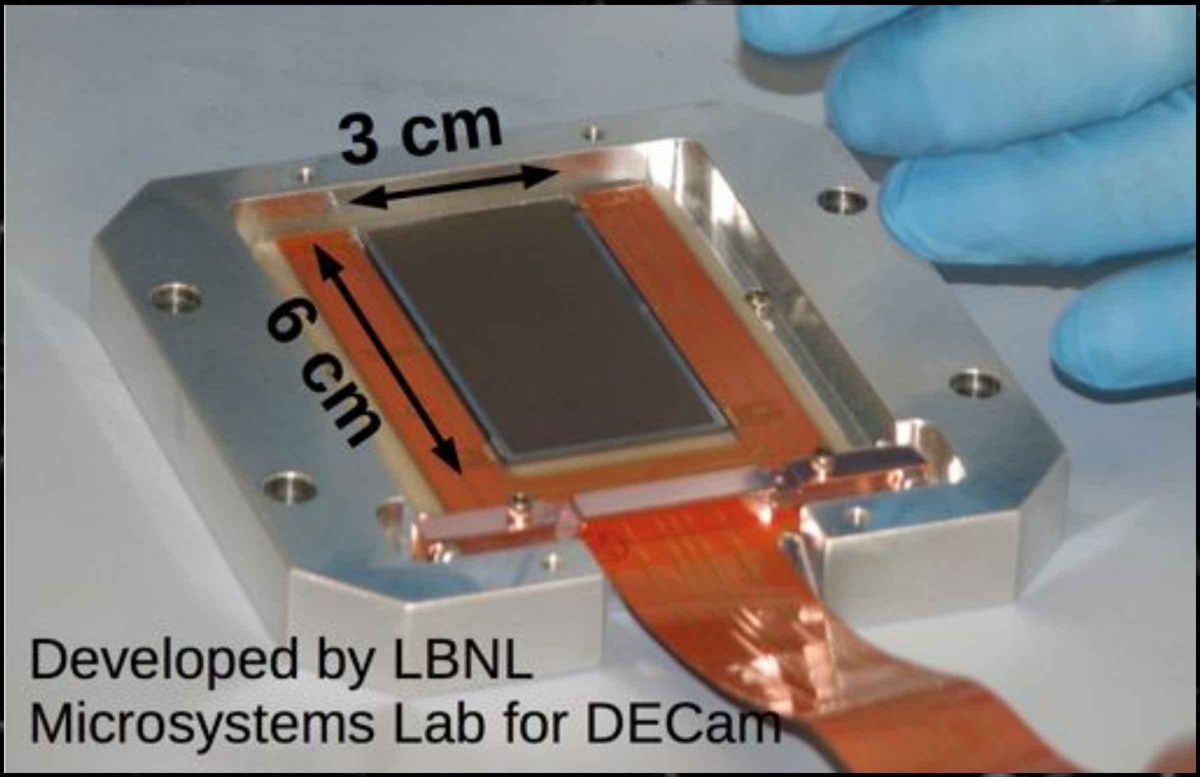


Images collected on ~60 CCDs ~600 Mpix

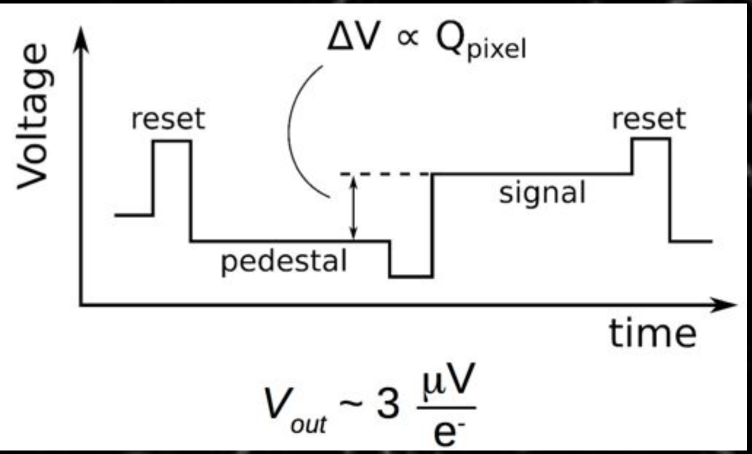


Can we borrow a few CCDs ?

Scientific CCDs

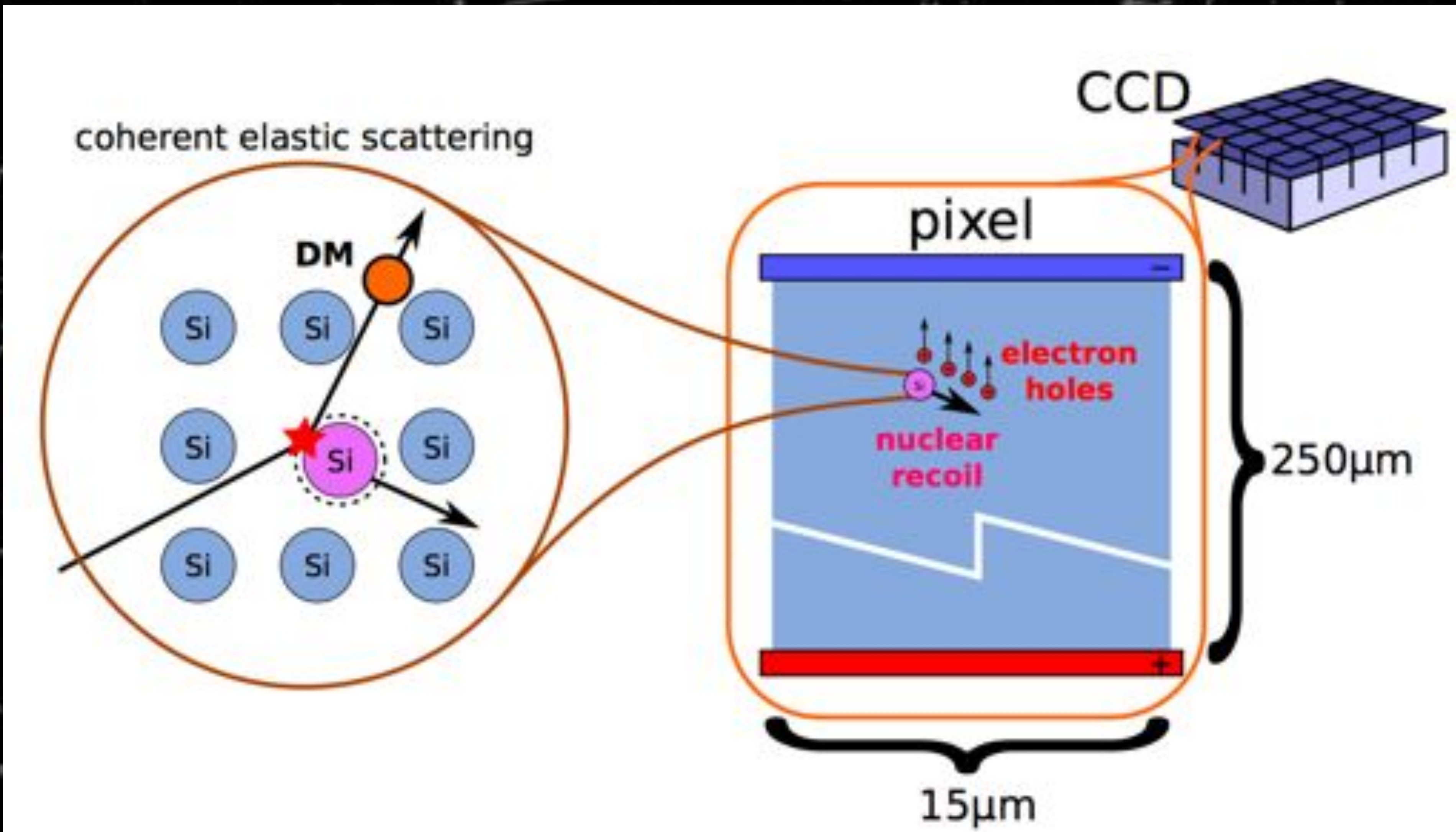


One readout gate - all pixels shifted via phased potential wells and read out



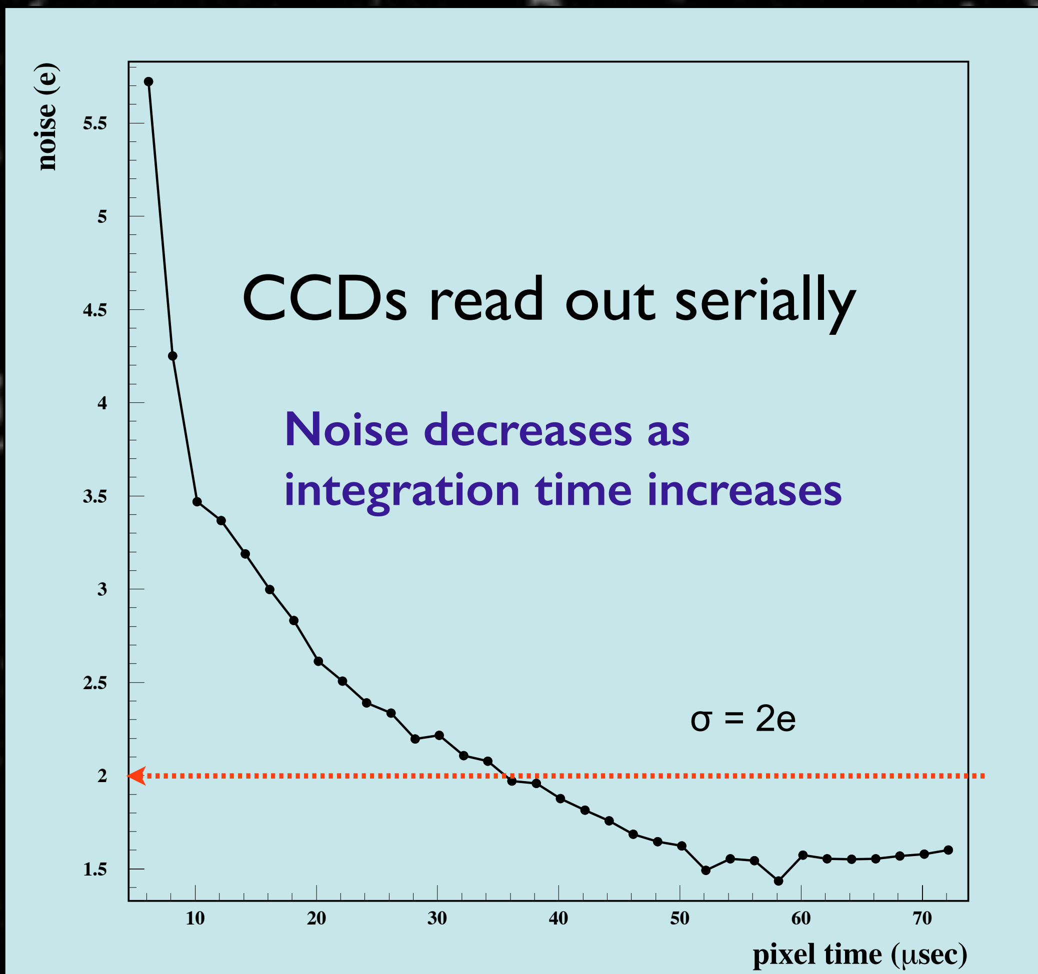
Pixel size:	15 μm x 15 μm
Number of pixels:	2000 x 4000
CCD Thickness:	250 μm
CCD Mass:	1 gram
Operation Temp:	150 K

Scientific CCDs for searching for DM



New opportunities with these CCDs

2. Low readout noise
   - Detectors cooled to operate at -140 C
   - Low threshold energy for detecting recoils



RMS noise of 2 electrons, or 7.2 eV in ionization energy !

- Could put threshold as low as 36 eVee

Experiment	Target	Exposure (kg-d)	Threshold	Ref
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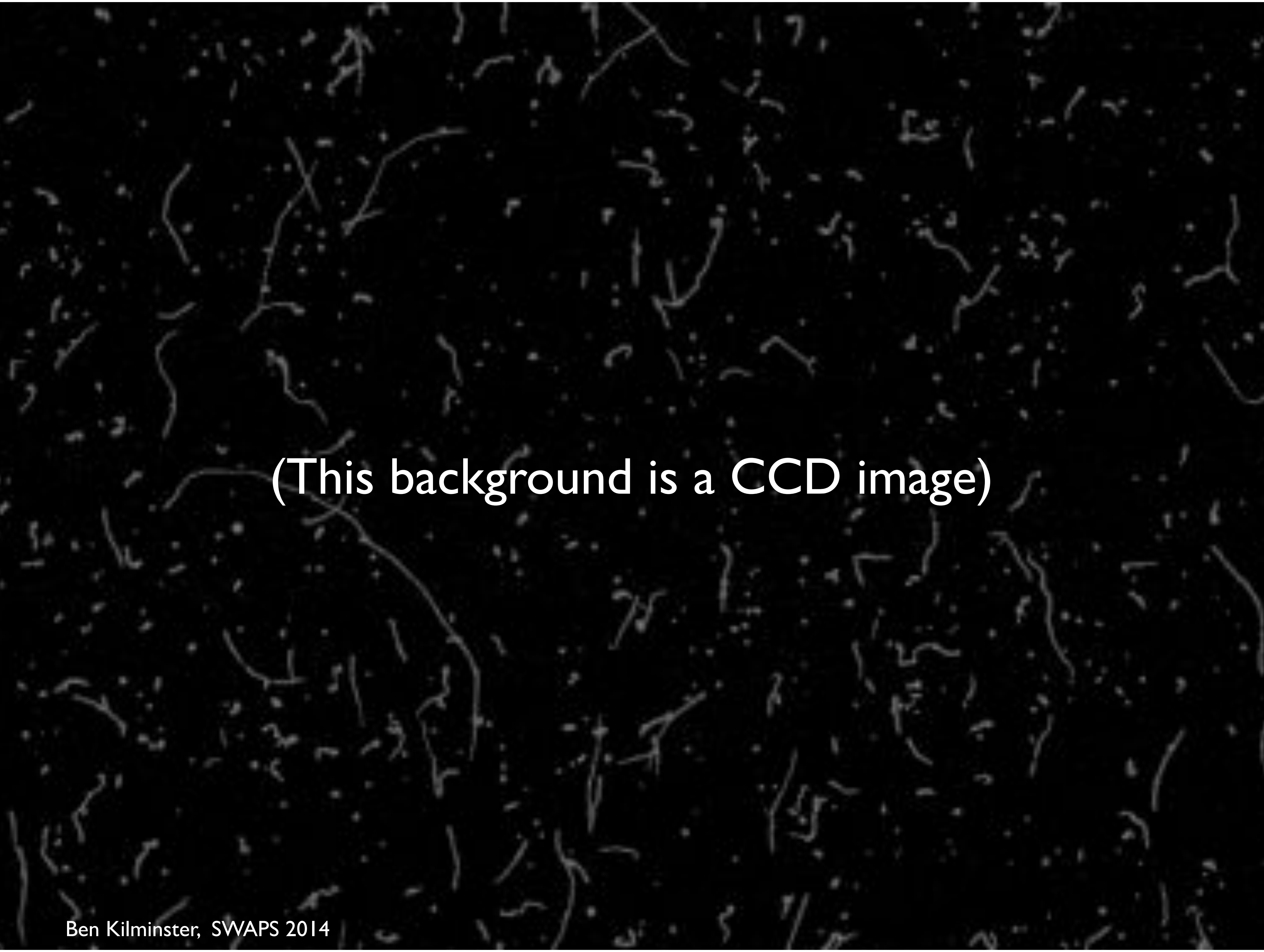
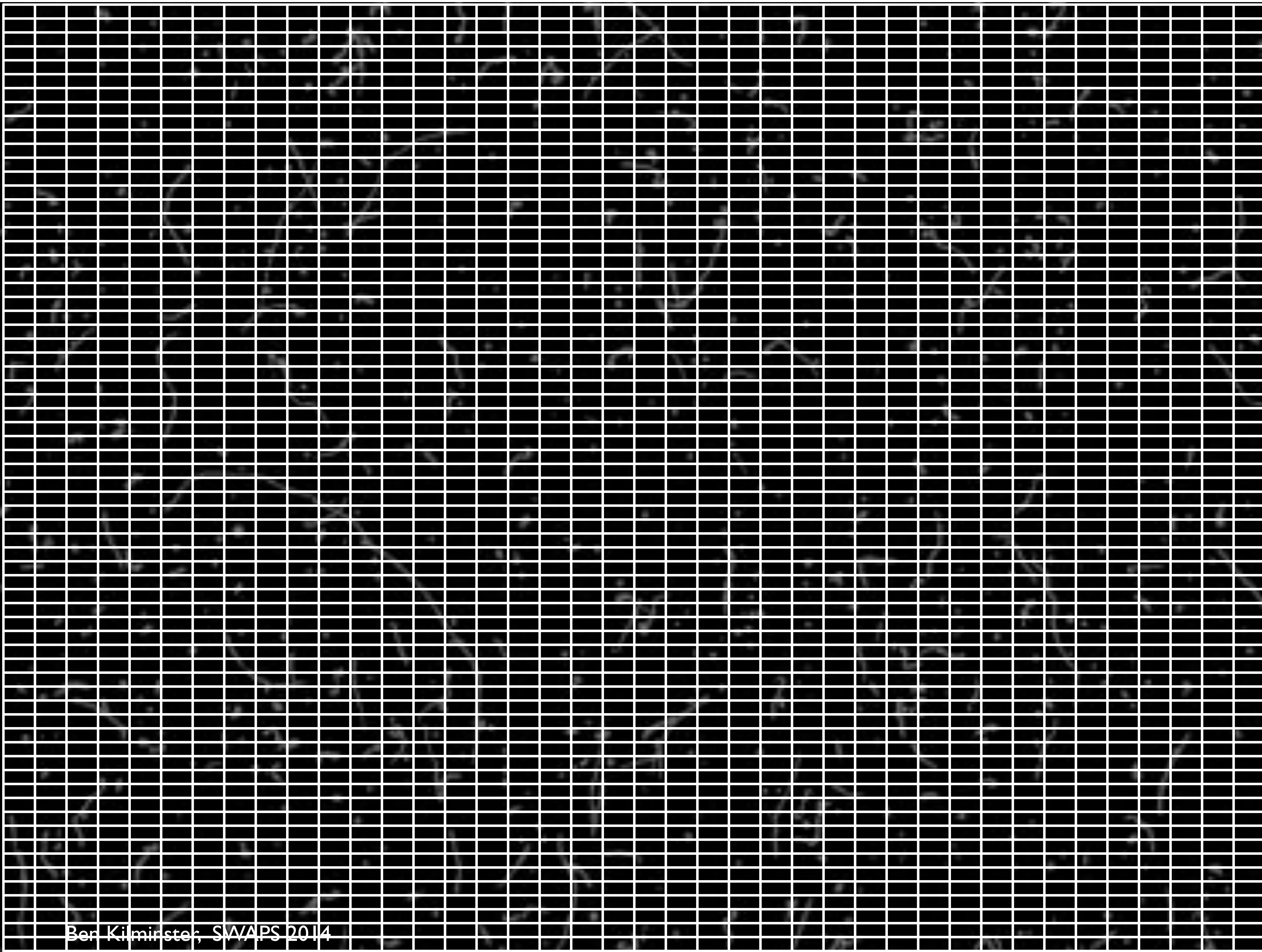
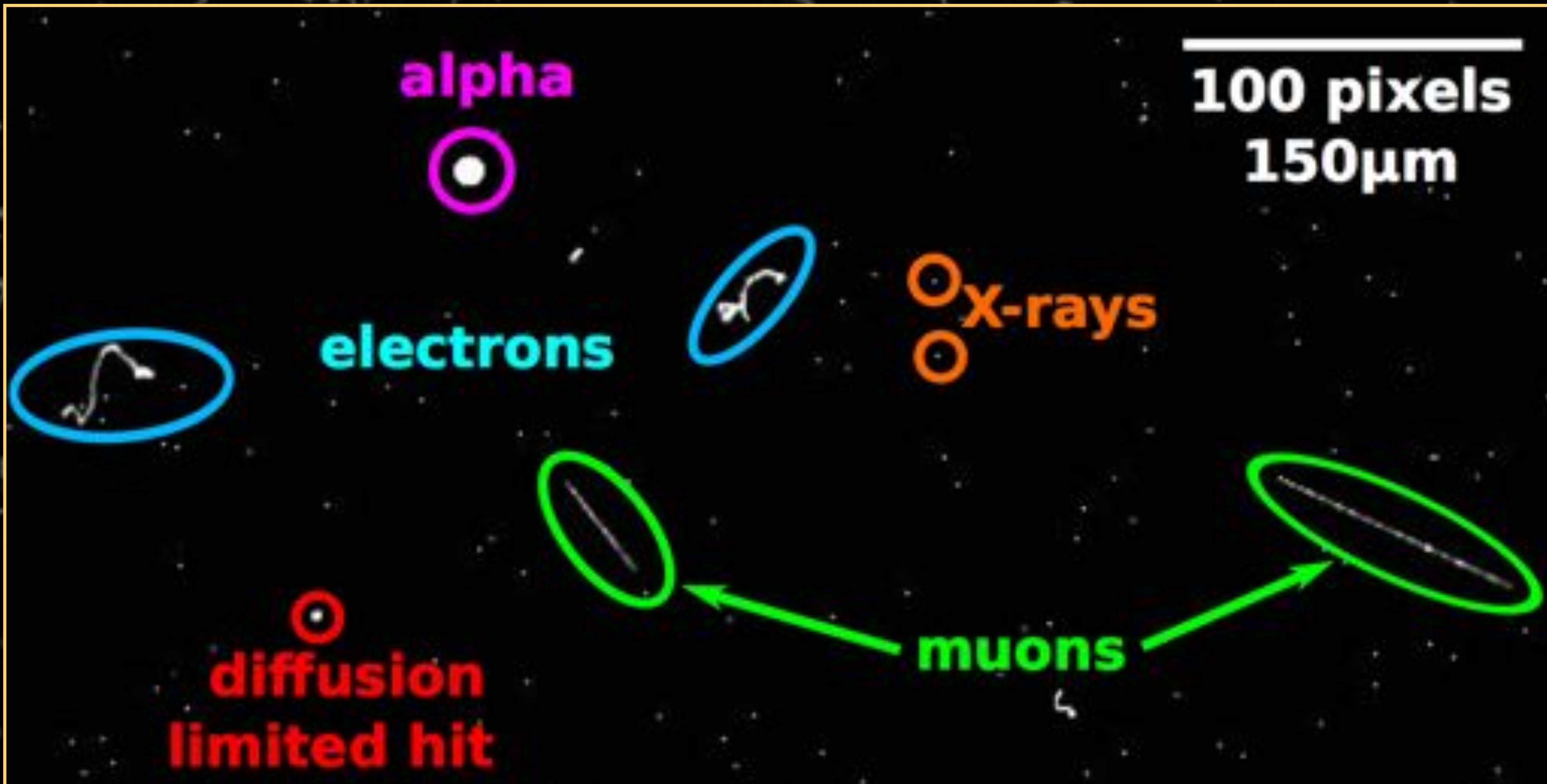


(This background is a CCD image)



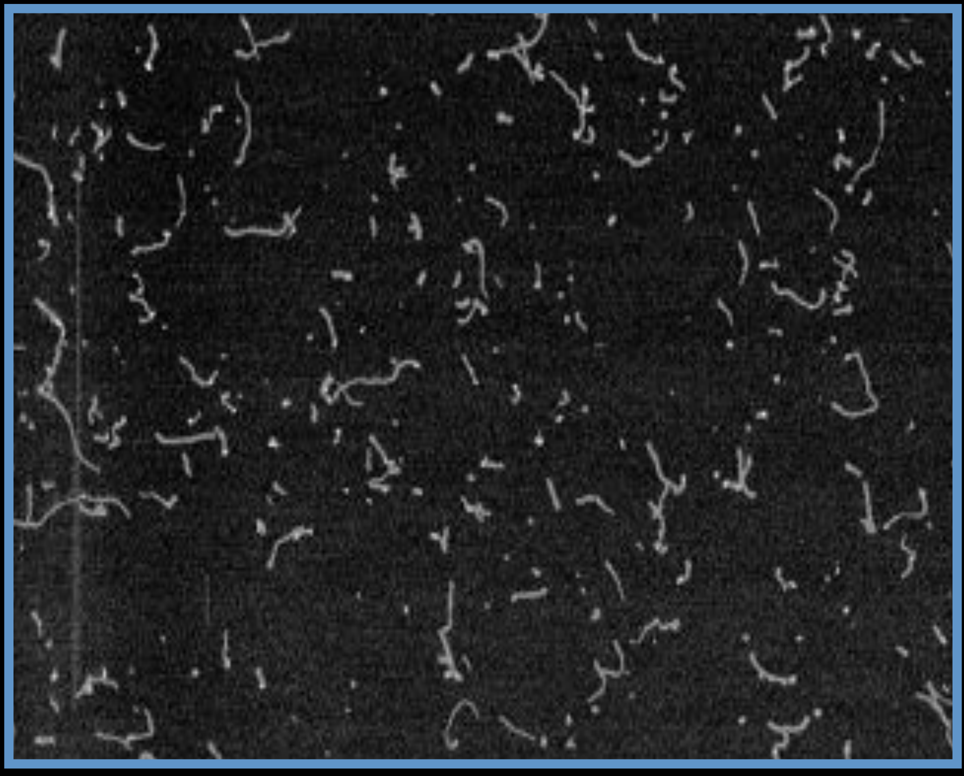
Particle identification in CCD



X-ray ^{55}Fe (5.9 keV)

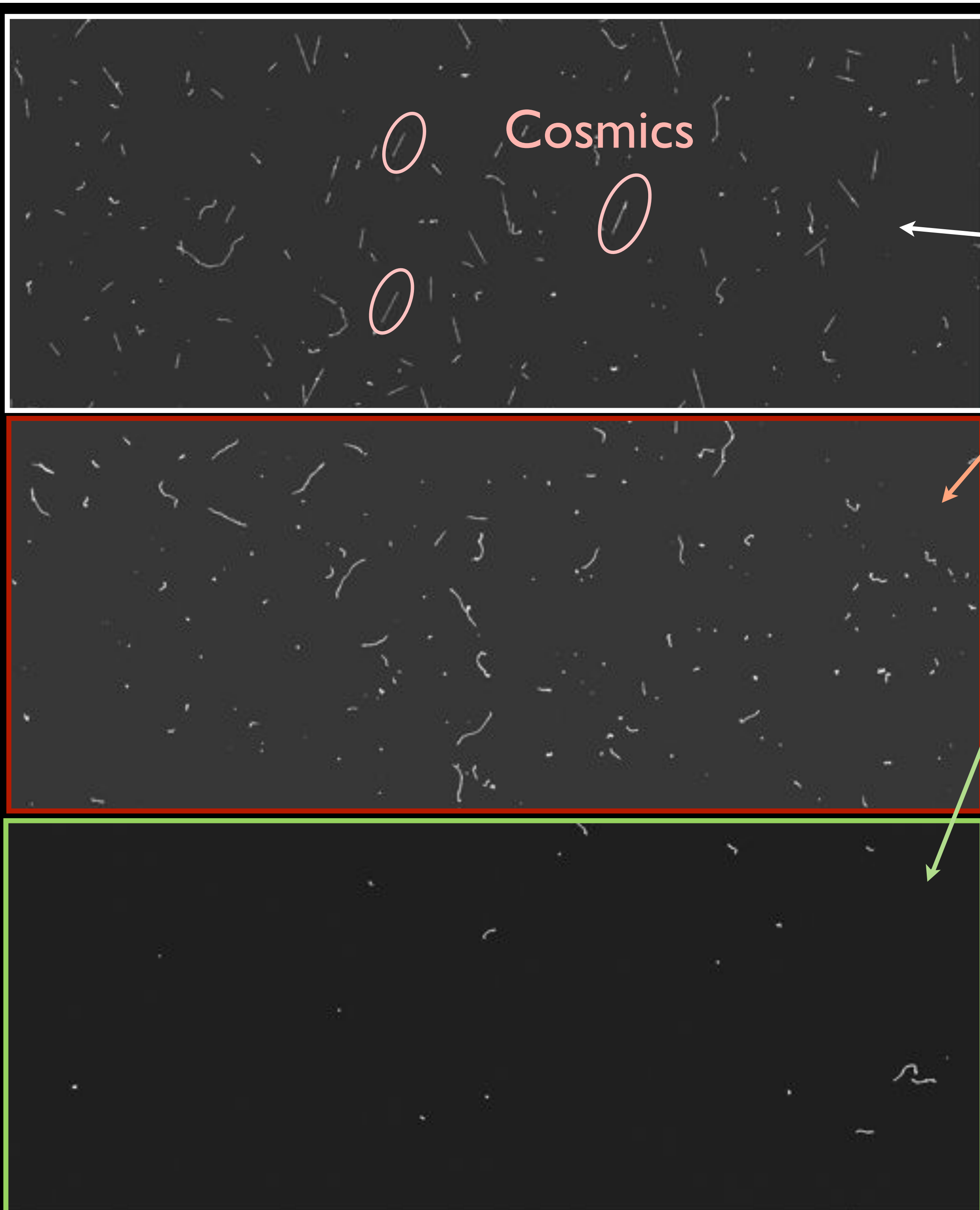
Point like hits
(diffusion limited)

Gammas ^{60}Co (1.33 & 1.77 MeV)



Compton
electrons
(worms) and
point like hits.

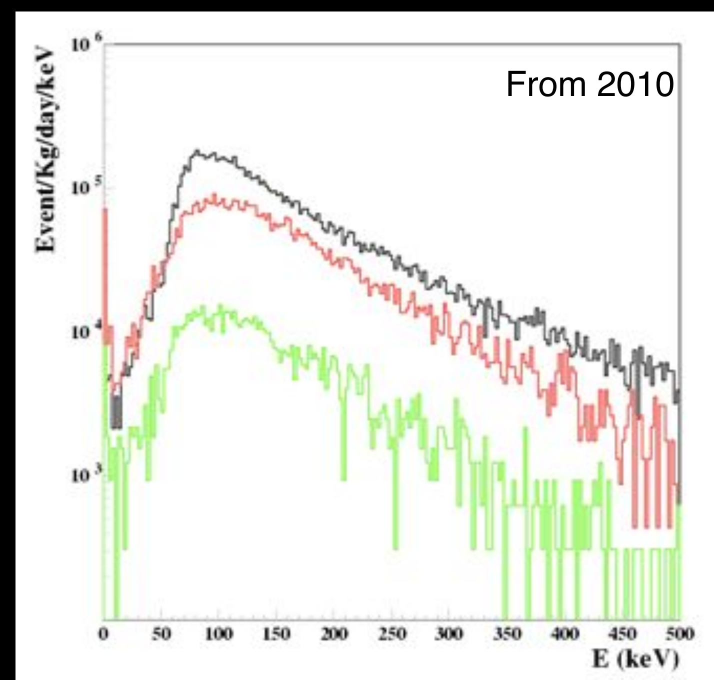
Background reduction



Above ground

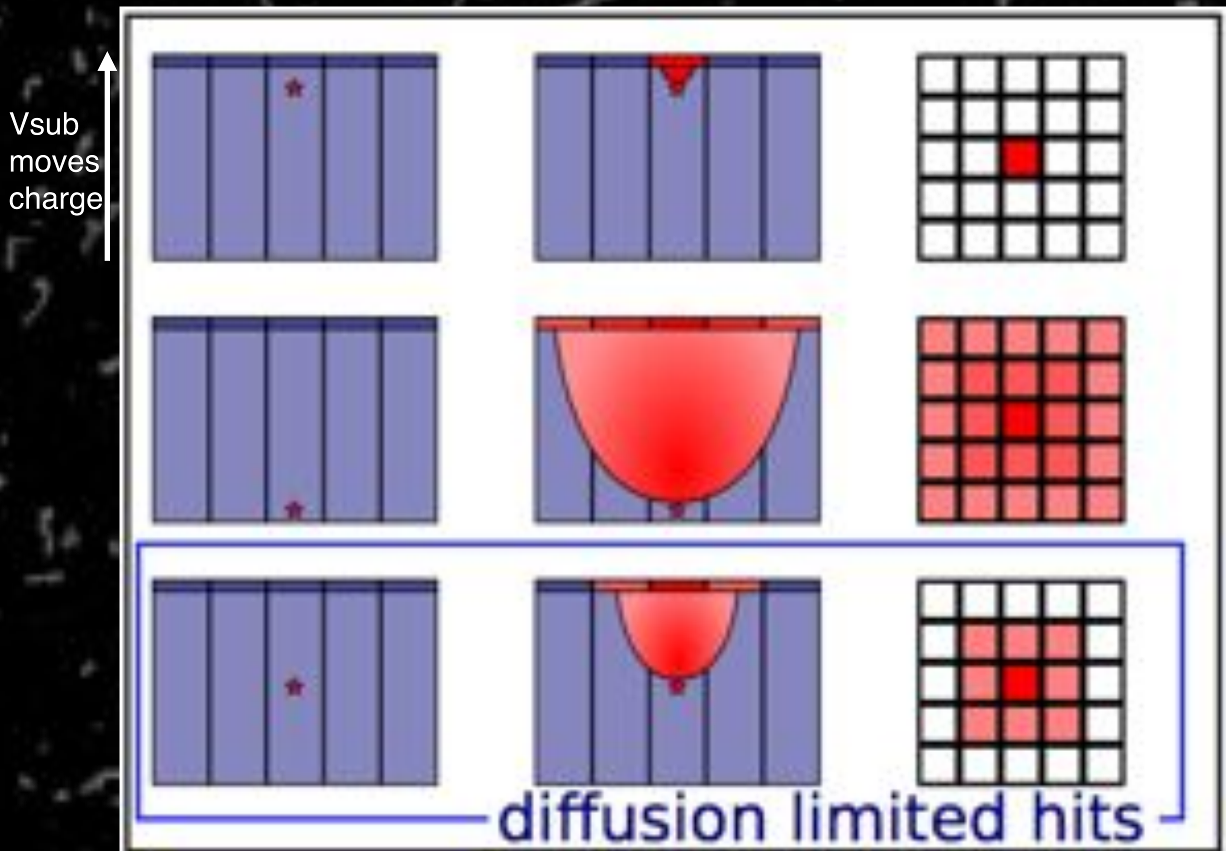
350 ft underground

With lead brick shielding

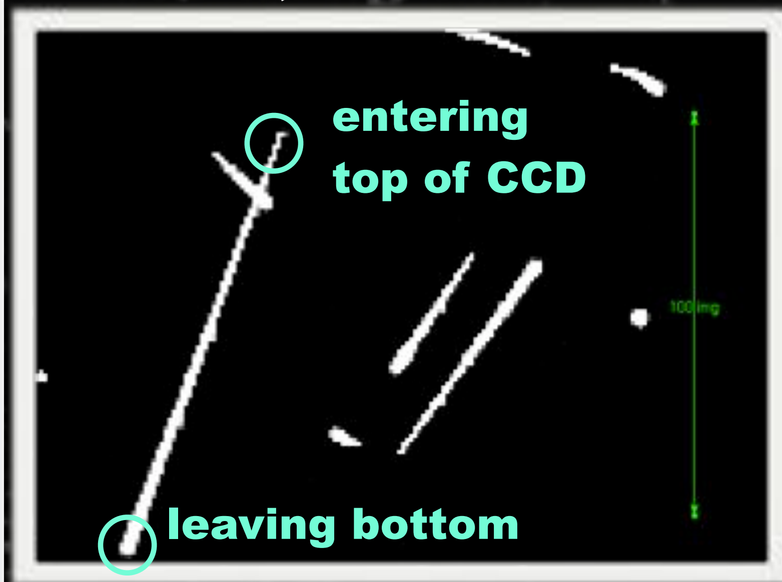


Diffusion of charge

- **Size of hit depends on location within pixel**

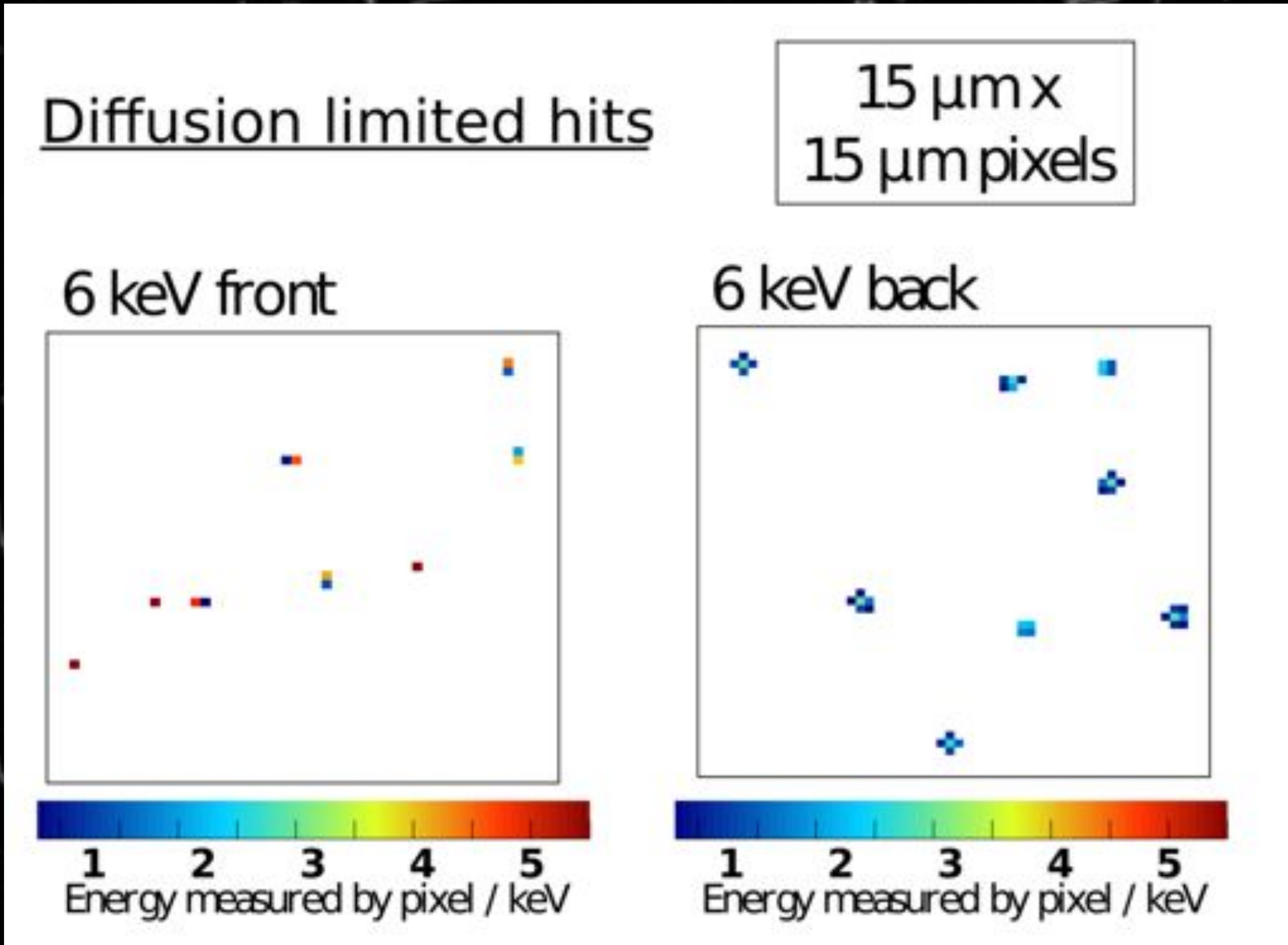


ie, muons



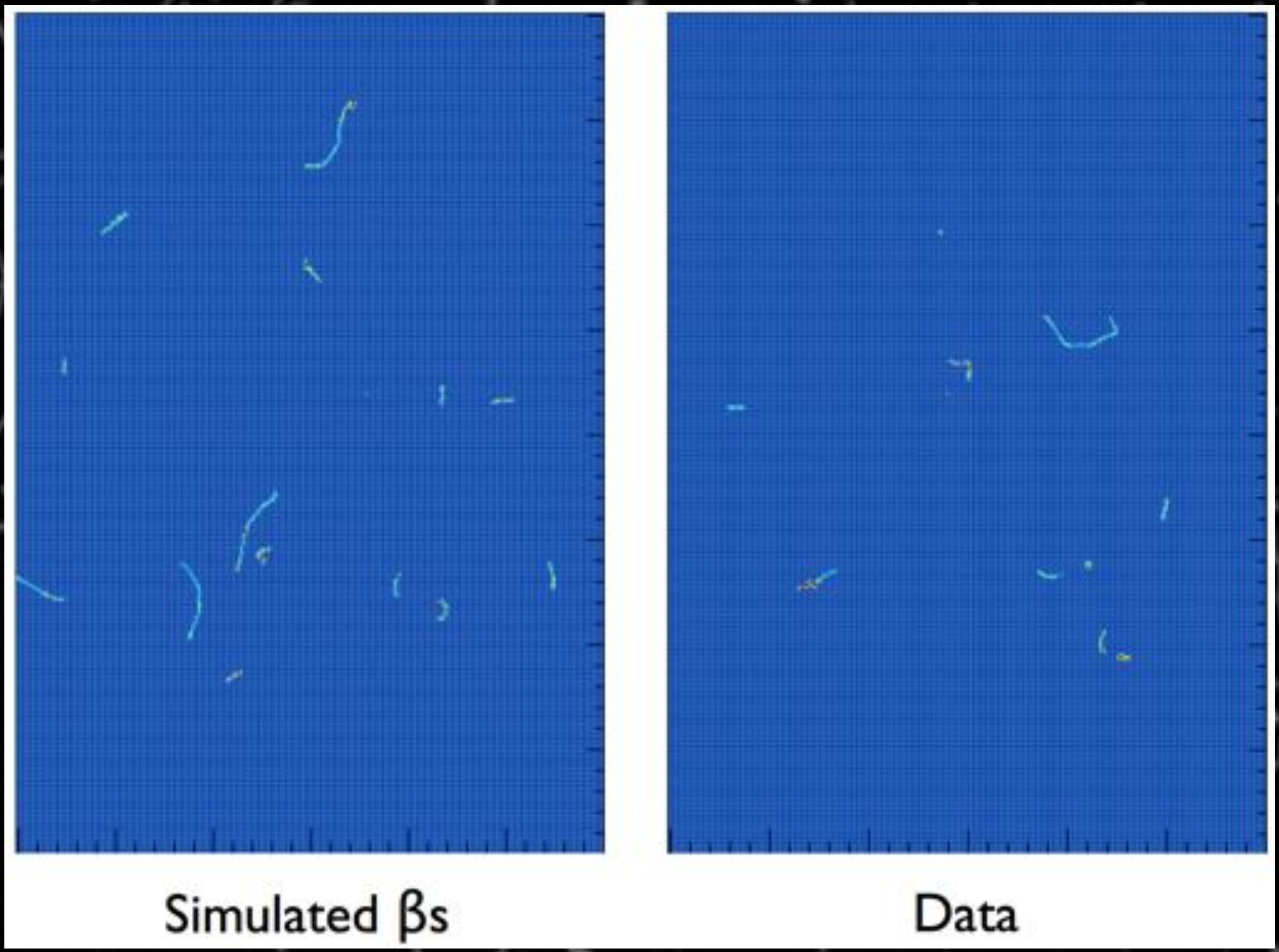
- **Maximal (minimal) diffusion at bottom (top) of CCD**

Charge diffusion can define fiducial selection

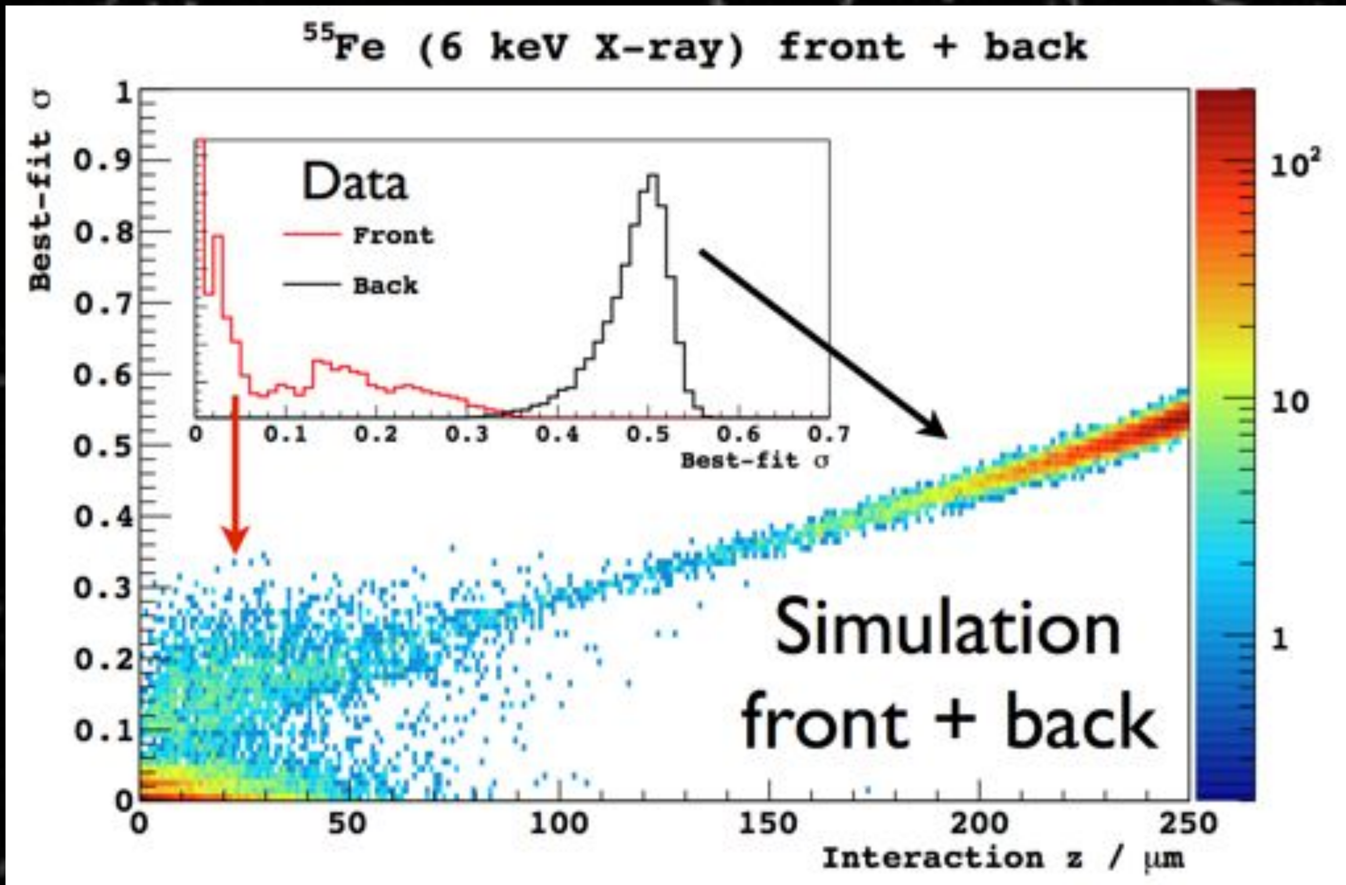


Interactions can be simulated

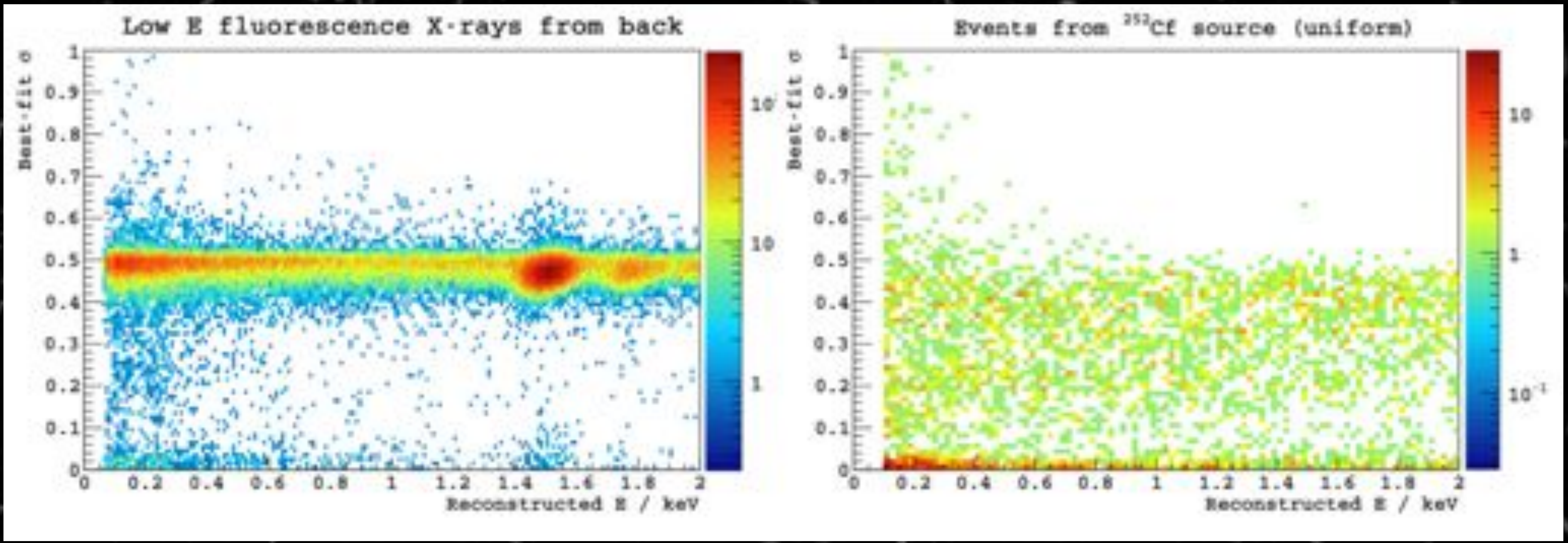
- **MCNPX simulation -> background model**



Simulation of event depth



X-rays vs neutrons



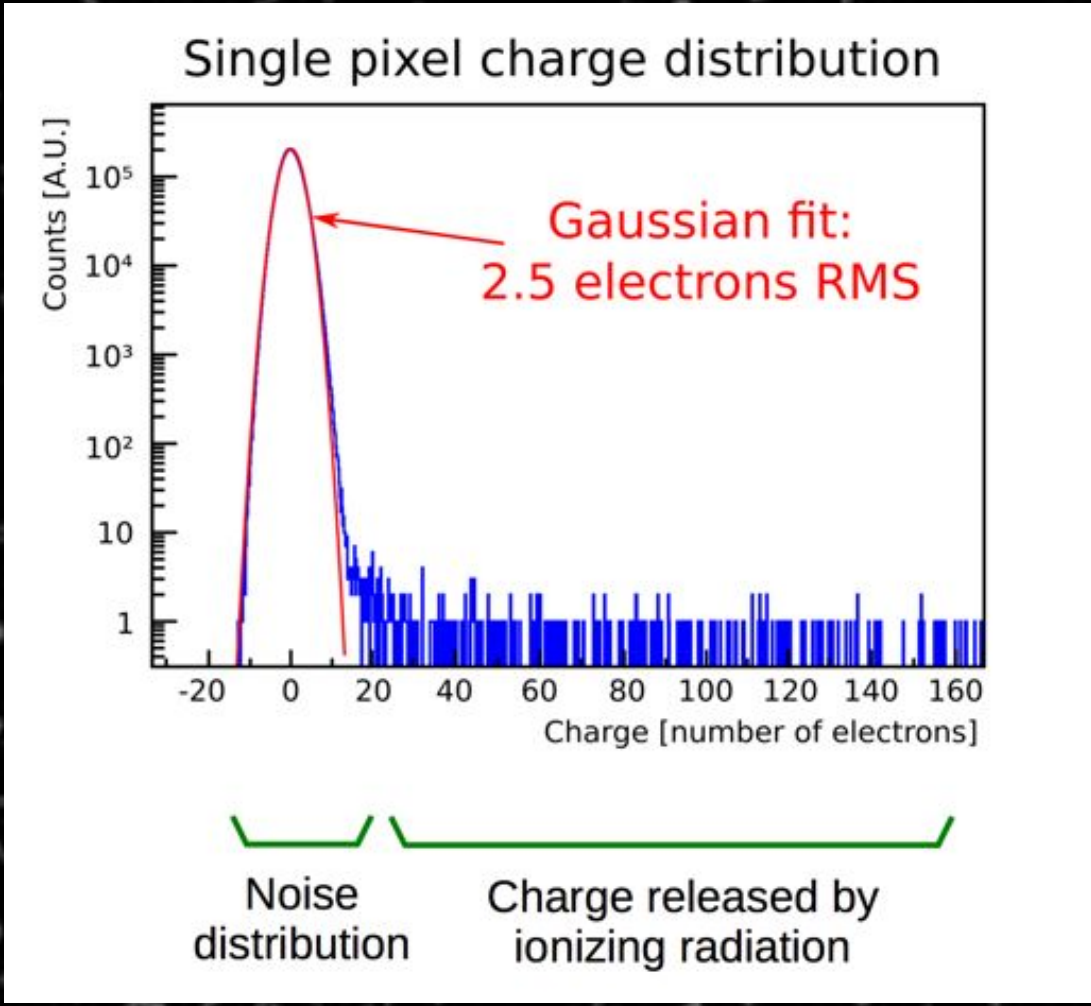
X-rays
bkg-like

Neutrons
"DM-like"

- **Maximal diffusion ~ 7μm (0.5 pixel) RMS**
- **Can be used to reject surface events**

Calibrations

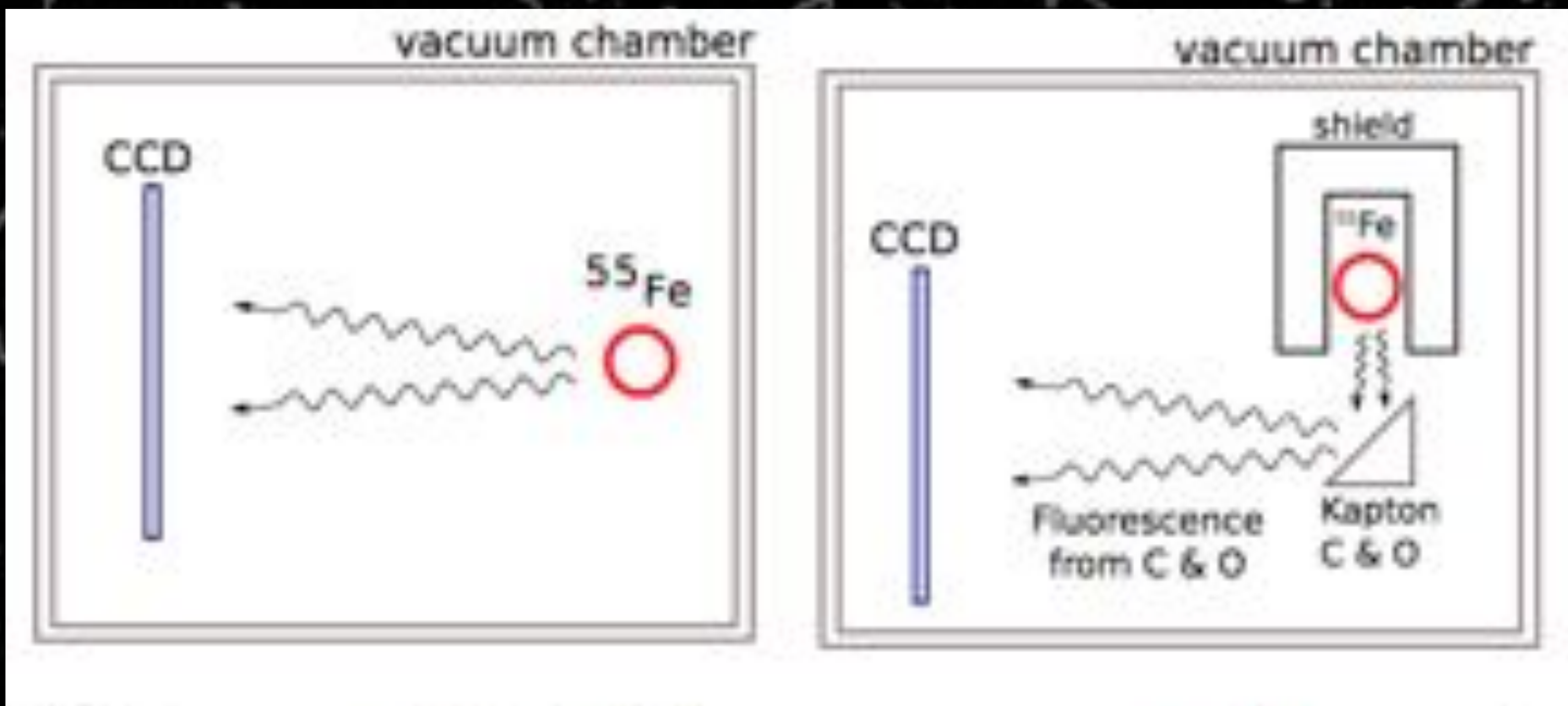
Noise measurement



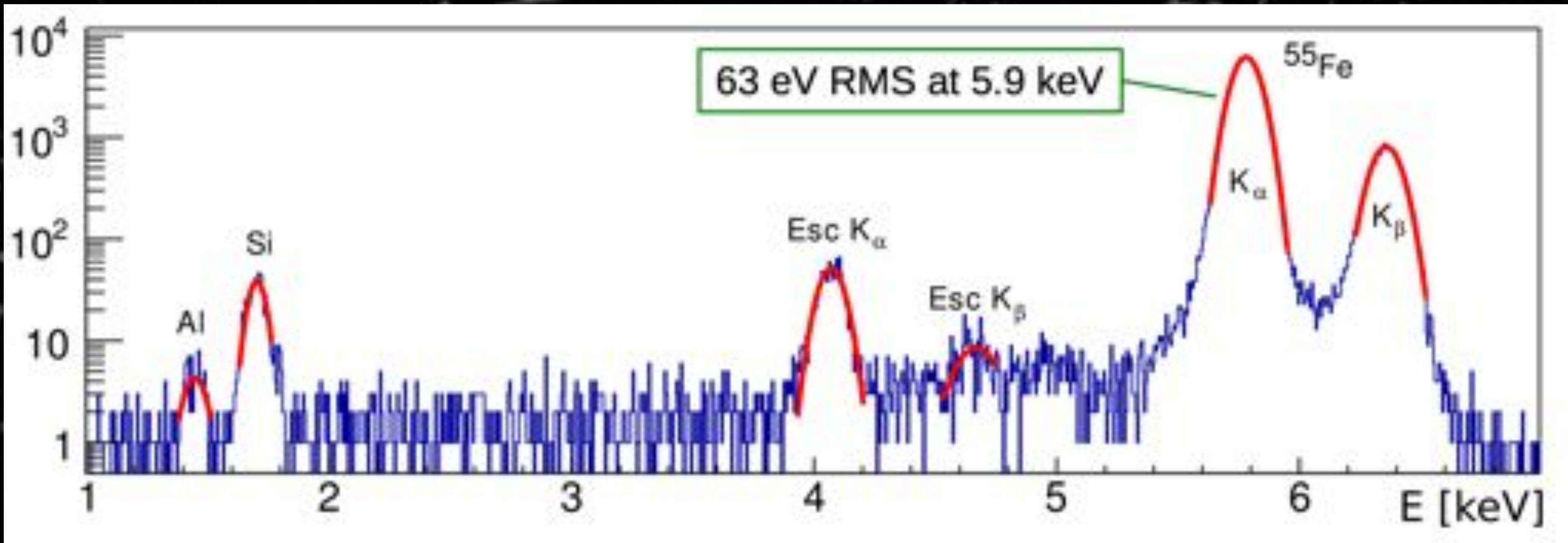
- **Allows lowest energy threshold of current dark matter experiments ~ 50 eV (32 eV recently)**

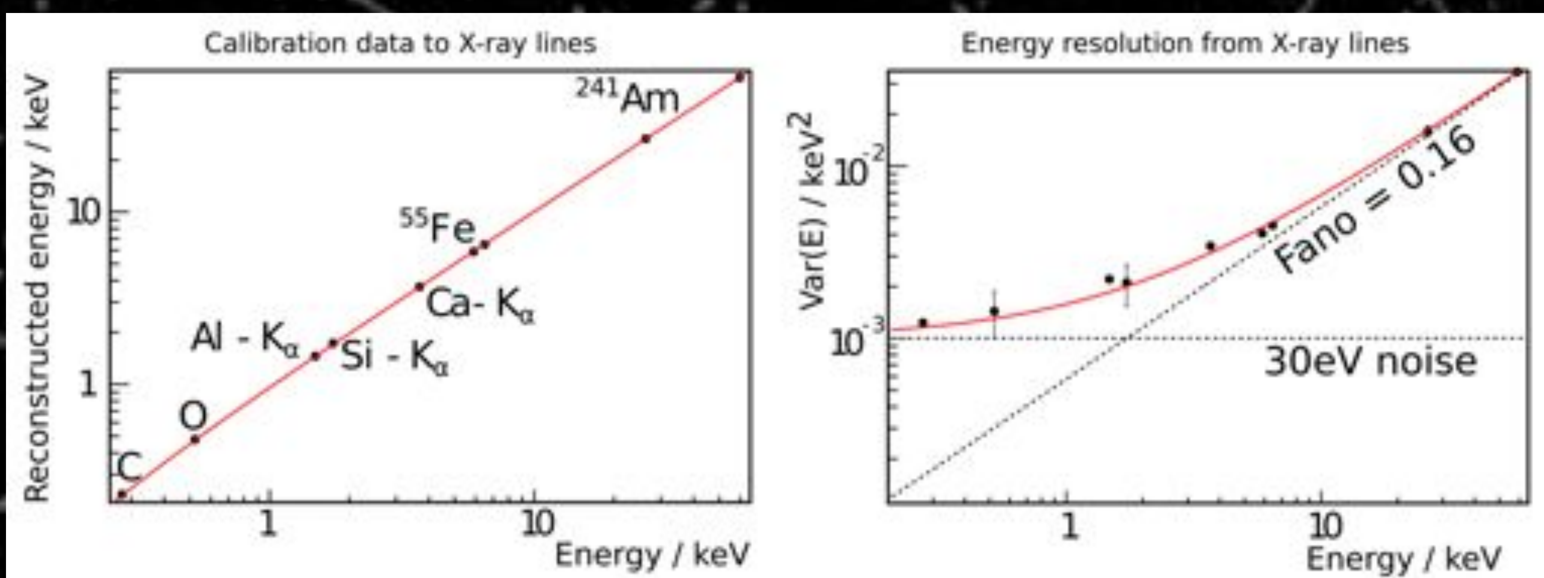
Energy calibration

- **X-rays and fluorescence X-rays**

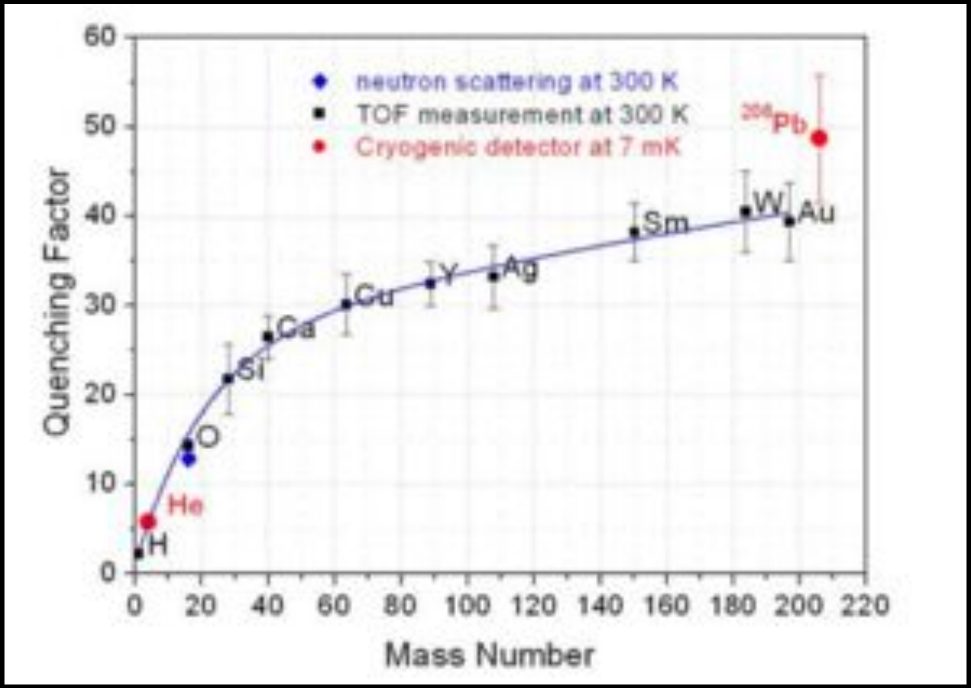


Calibrations with X-rays

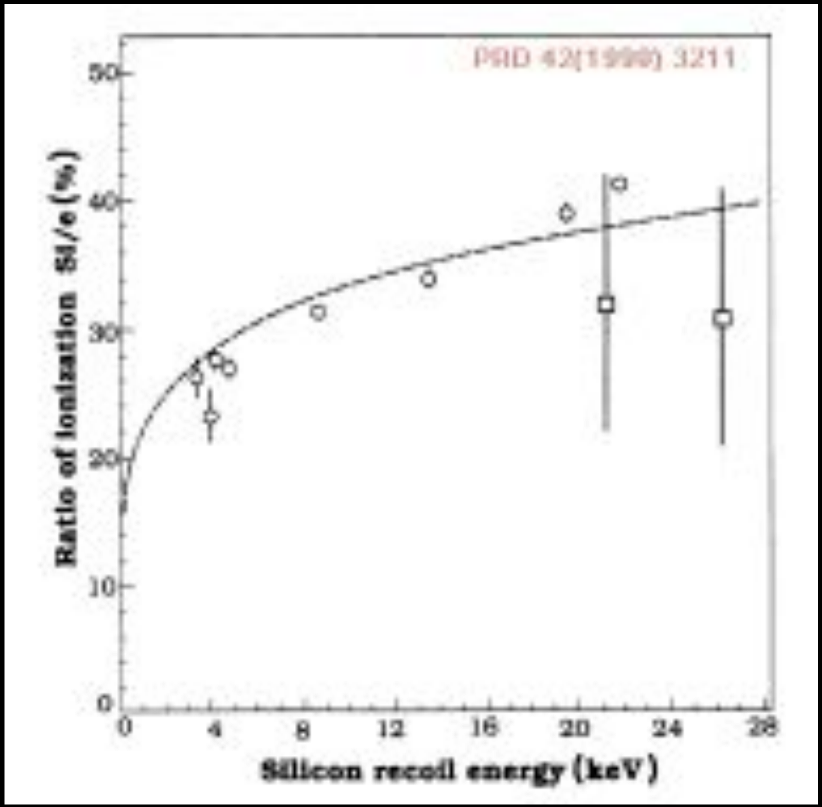




Nuclear recoils from DM are different



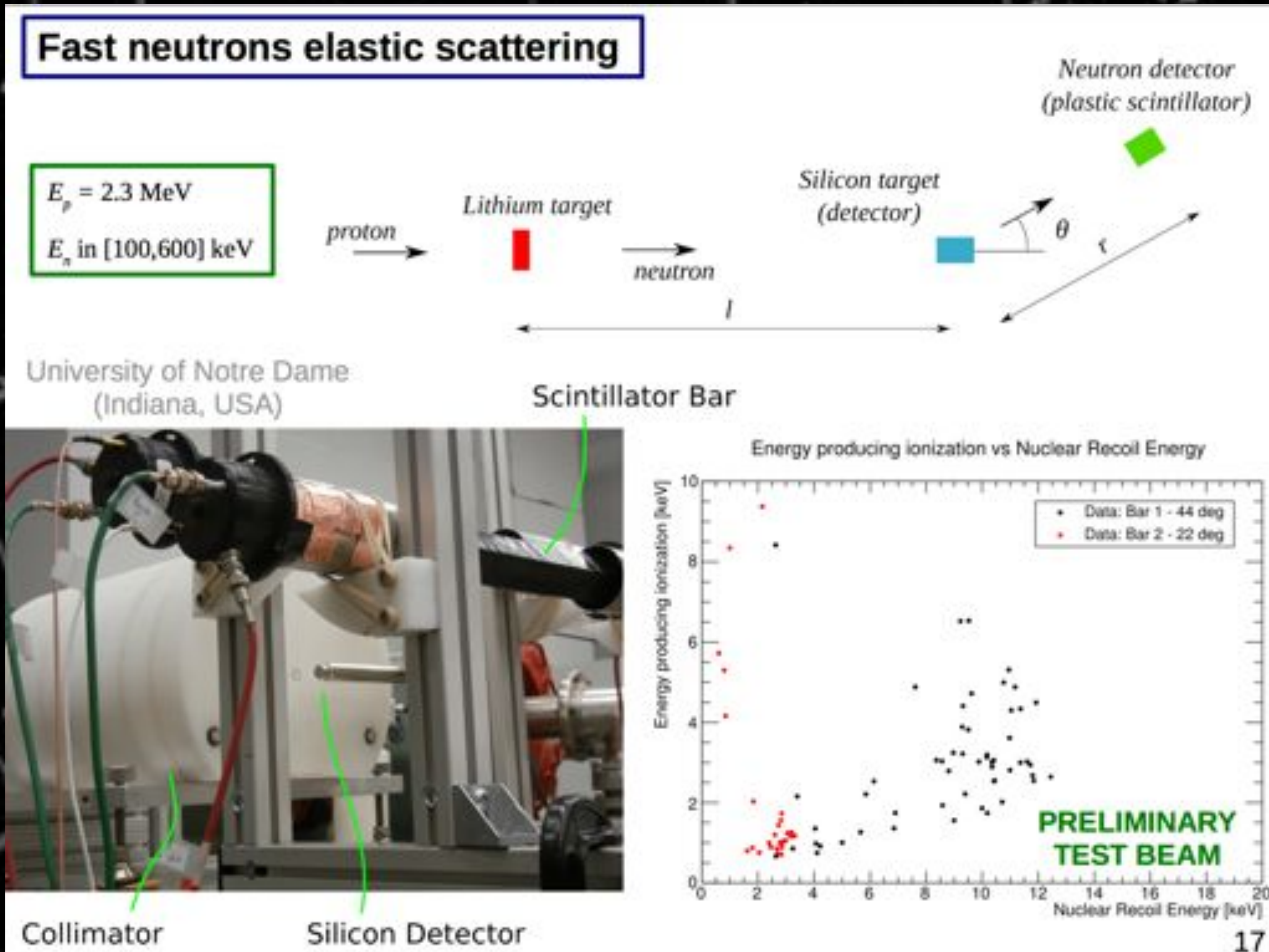
Fraction of observed energy :
"Quenching factor" depends on
Mass Number ...



... but also on recoil energy :

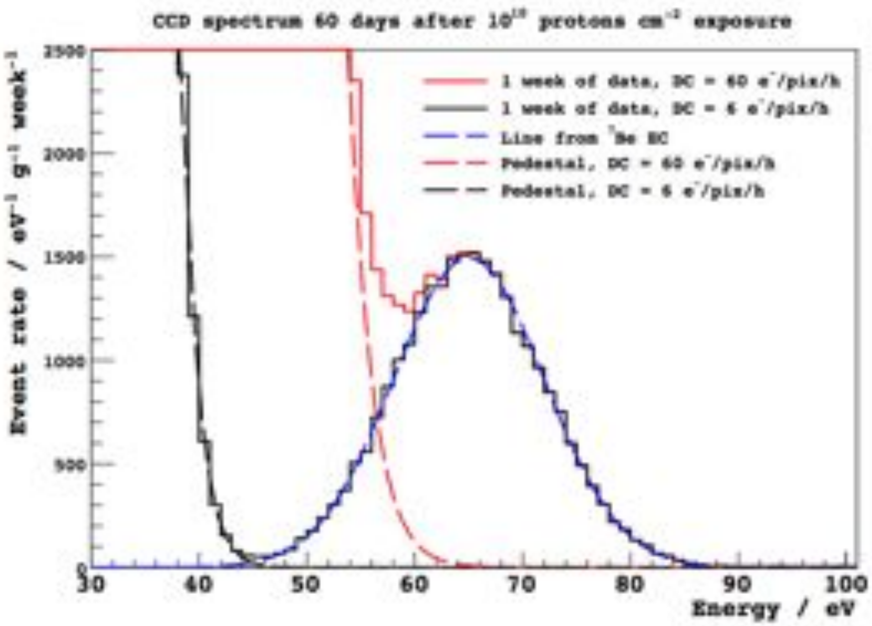
Note lack of data below 4 KeV

1 KeV range nuclear recoils



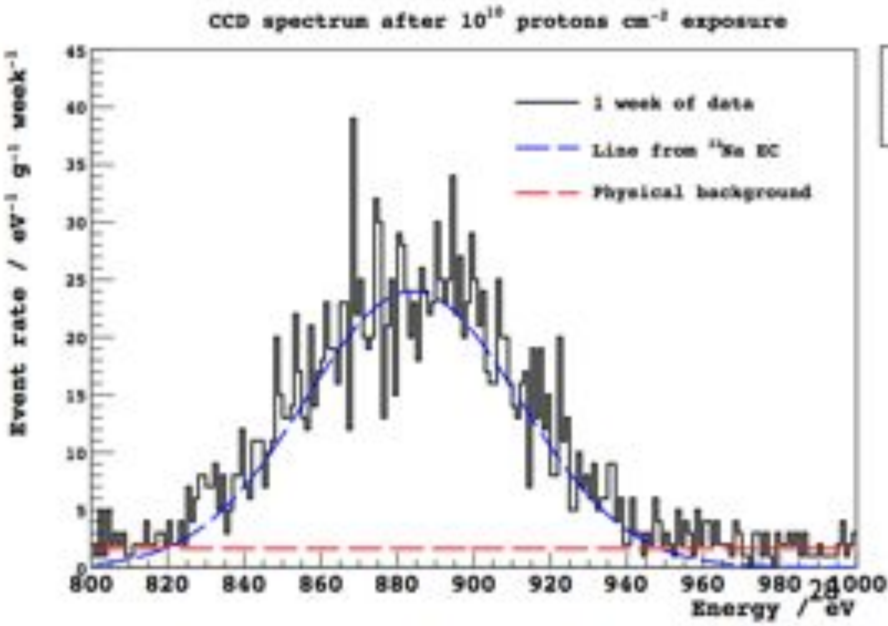
Getting to lower energies

- Irradiate CCD with protons (2E10 @ 230 MeV)
- Activates ^{7}Be and ^{22}Na uniformly in CCD
- These decay by electron capture
  - Nominally emits 54 eVee & 849 eVee photons
  - But small energy shift due to nuclear recoil
- Precisely measure photons
  - Shift tells you nuclear recoil calibration
  - Momentum conservation !



^{7}Be EC

55 eV shifted to 65 eV for Q ~ 10%

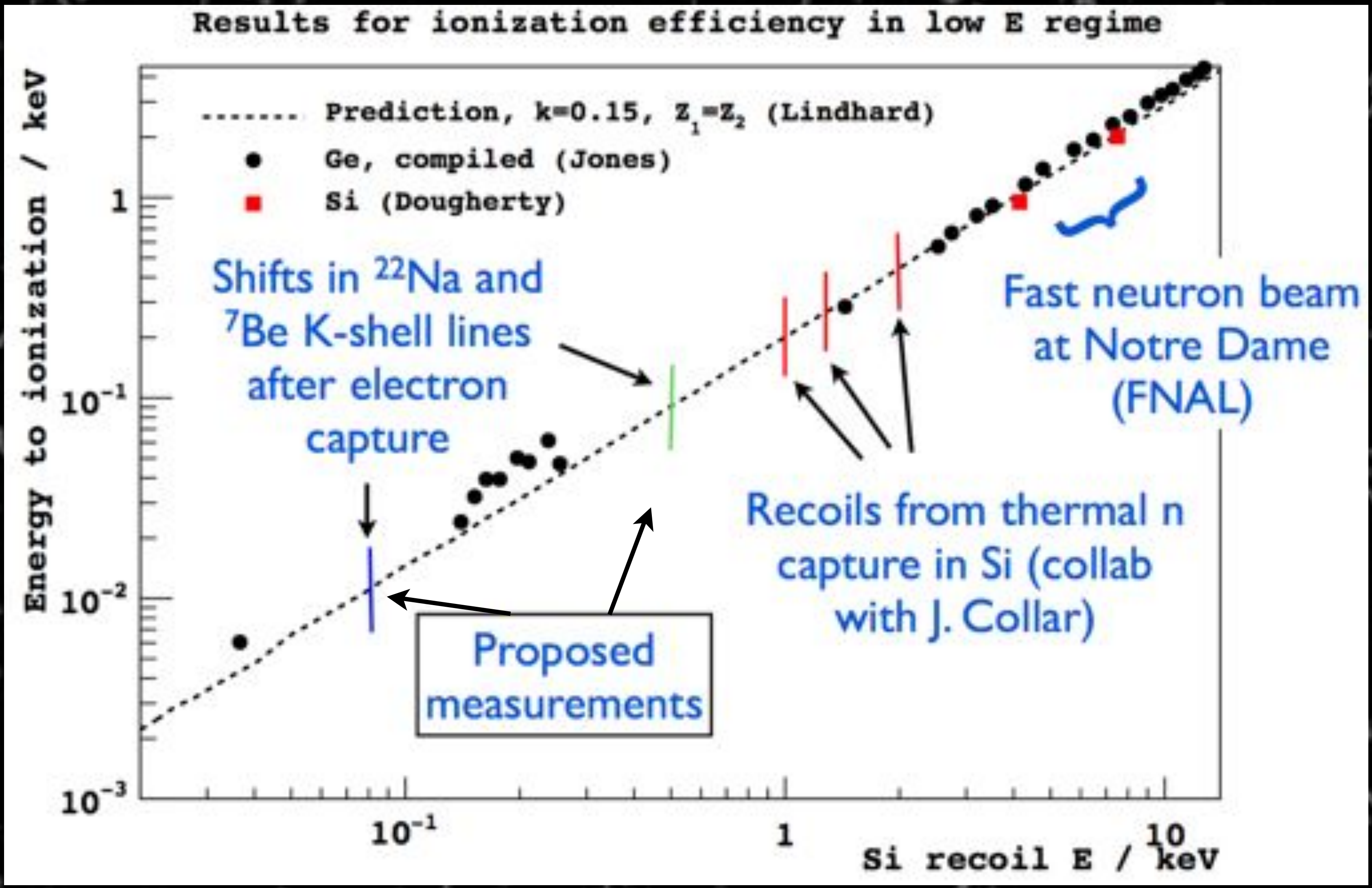


^{22}Na EC

870 eV shifted to 884 eV for Q ~ 10%

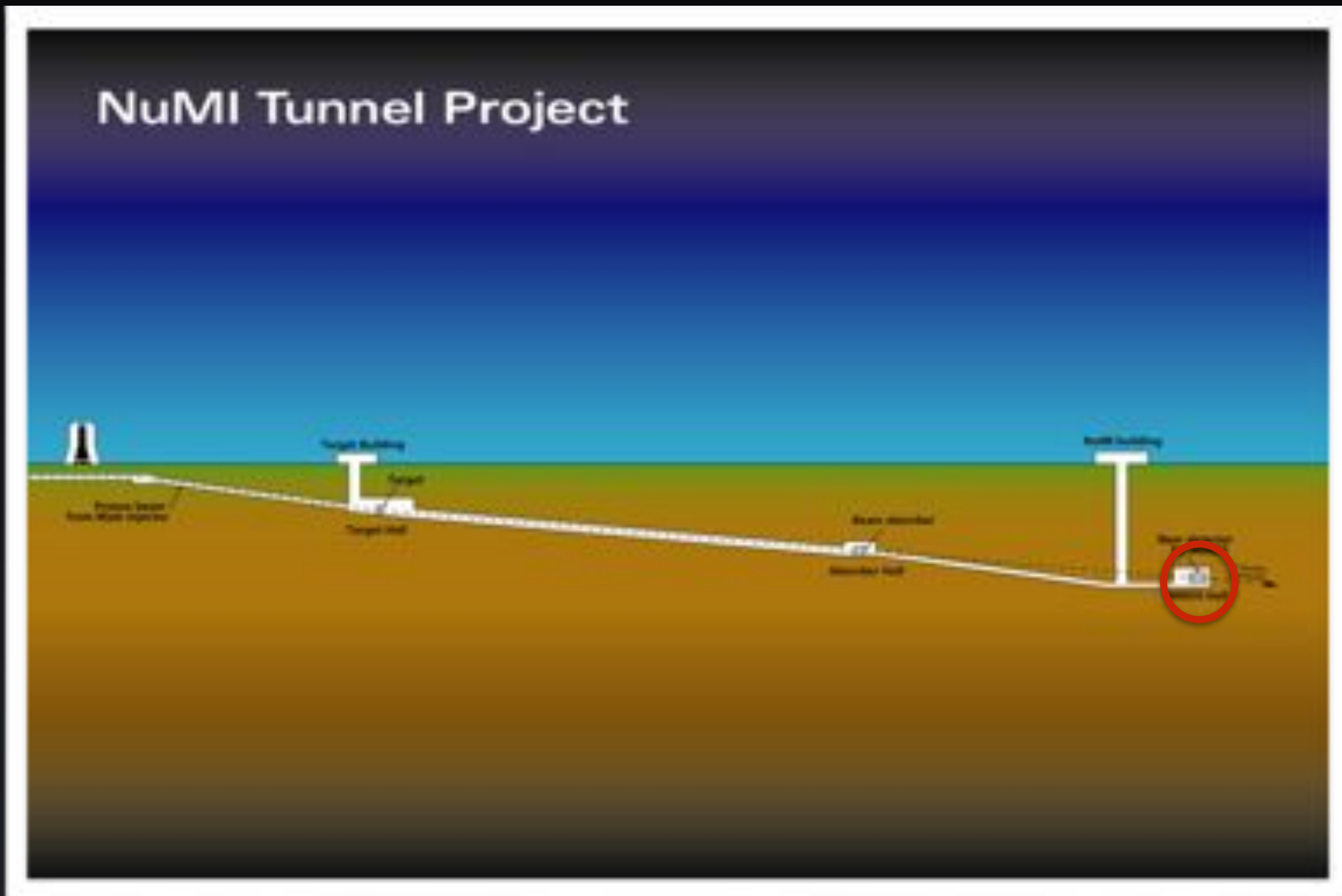
Ionization efficiency for nuclear recoils

- **Challenge is to provide dependable calibration down to 50 eV energy threshold**



DAMIC experiment

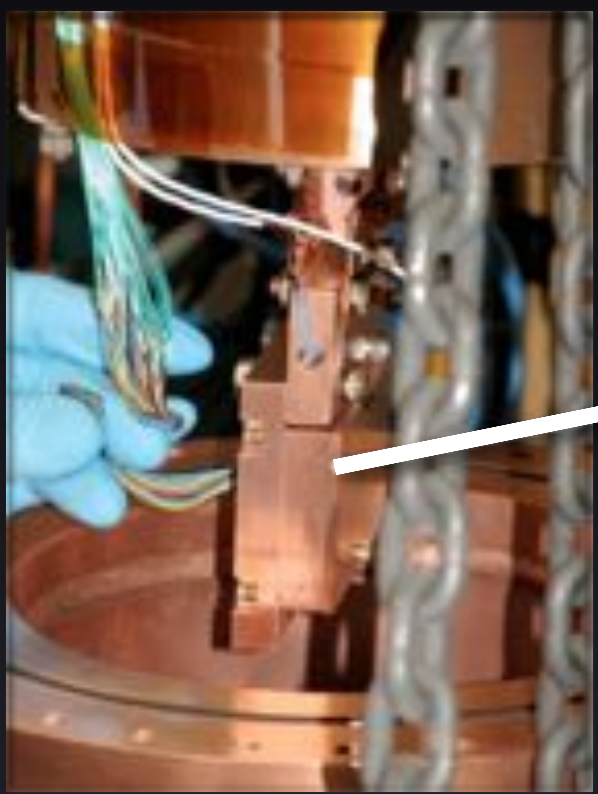
DAMIC 2011



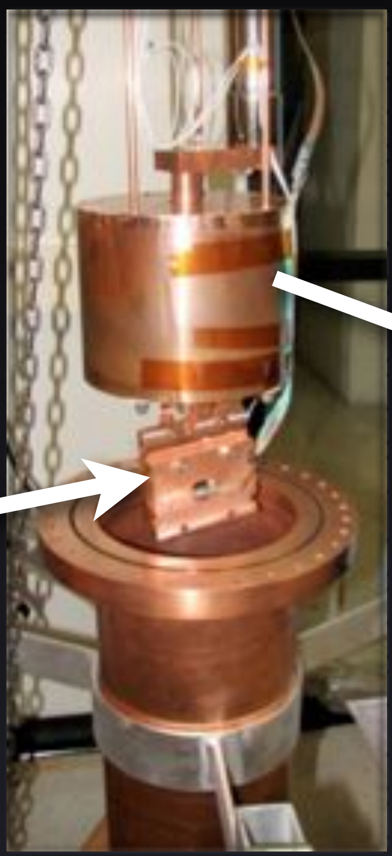
~ 100 meters deep

DAMIC 2011

CCD Inside a cold Cu box



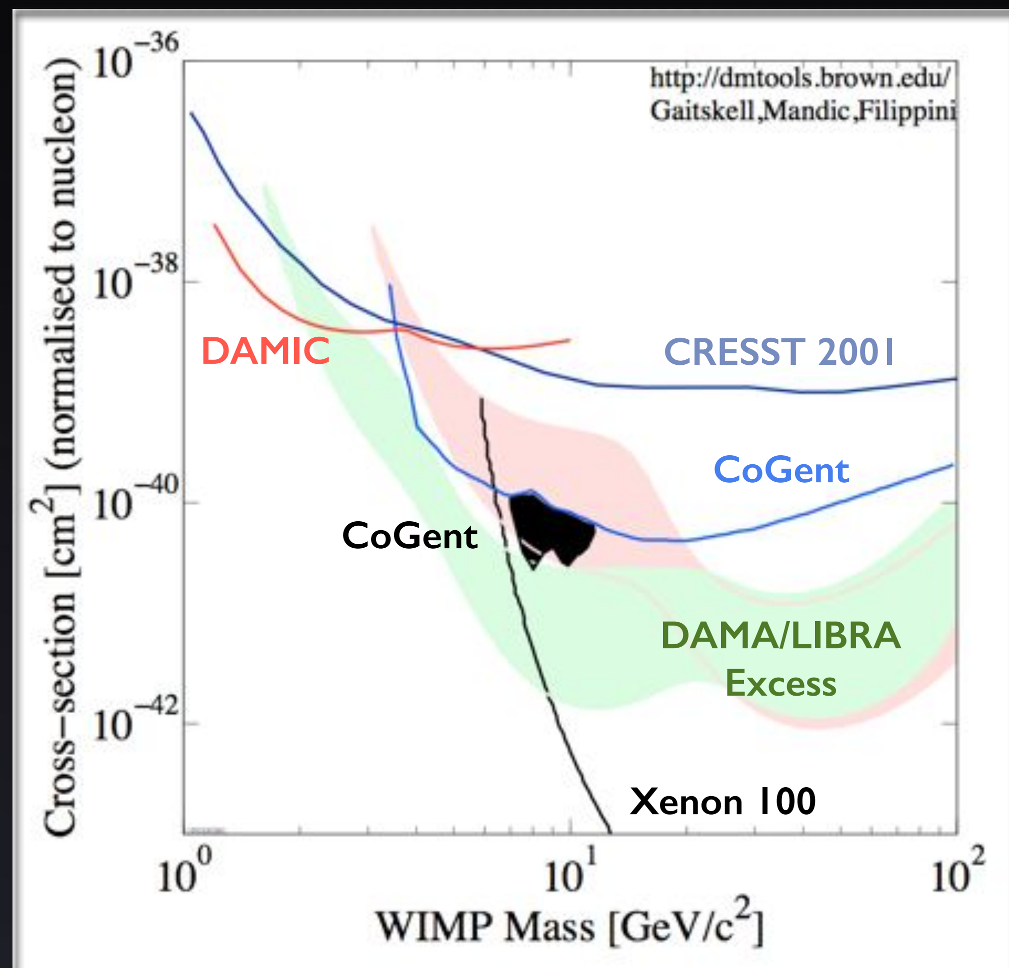
Lead Bucket



Cylindrical Cu Dewar

Results from 2011 Run

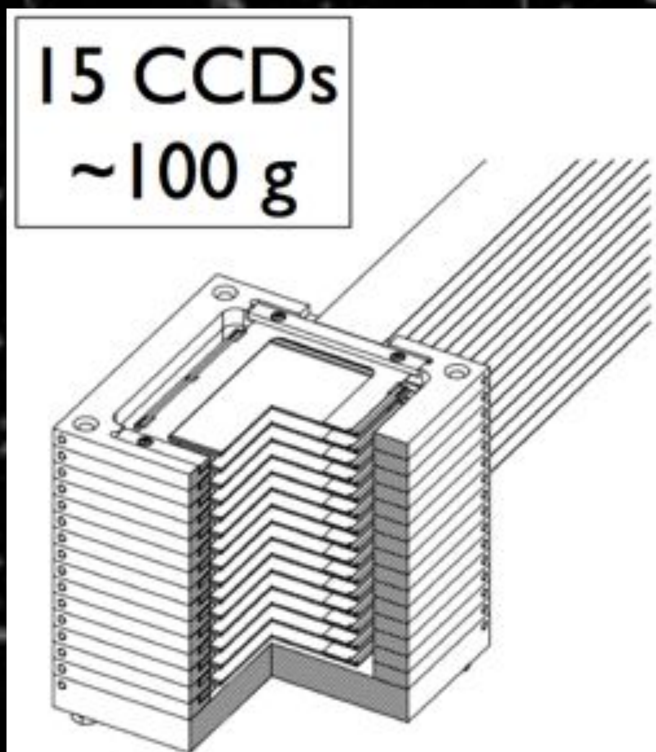
- **Wimp density → 0.3 GeV/cm**
- **V_{earth} = 244 km/s**
- **V_{escape} = 650 km/s**



Assumes Lindhard quenching factor for conservative limits

Upgrading DAMIC

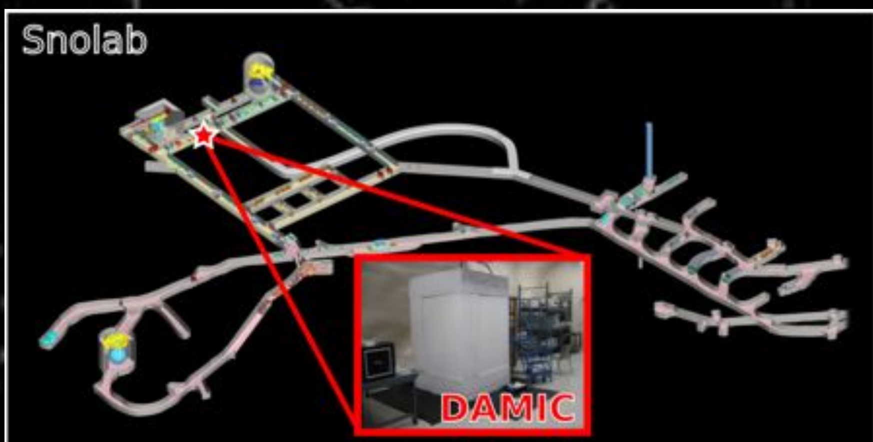
- **LBNL CCD group has produced thicker, fully depleted high resistivity CCDs (650 μm)**
  - **DAMIC 2011 used 250 μm (normal CCD ~ 25 μm)**
  - **Can now reach 100 g of detector mass**

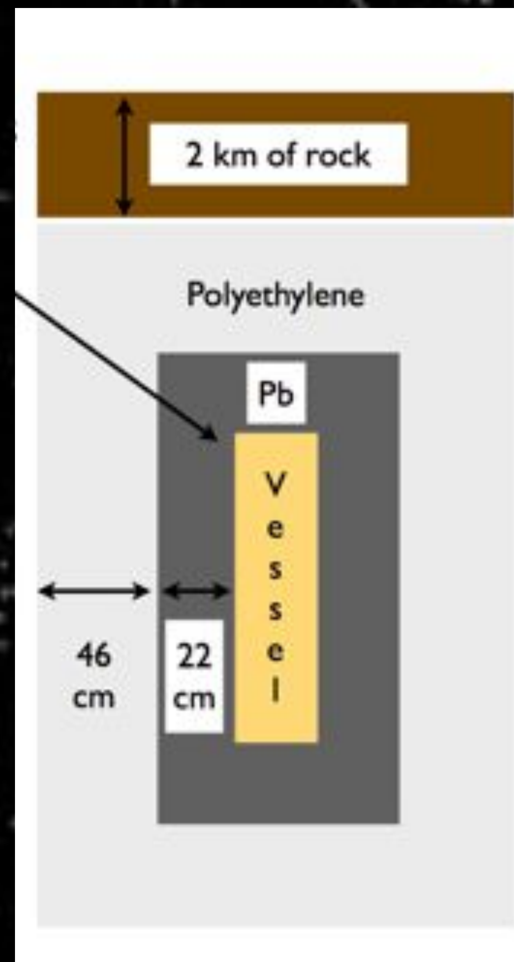


And going lower

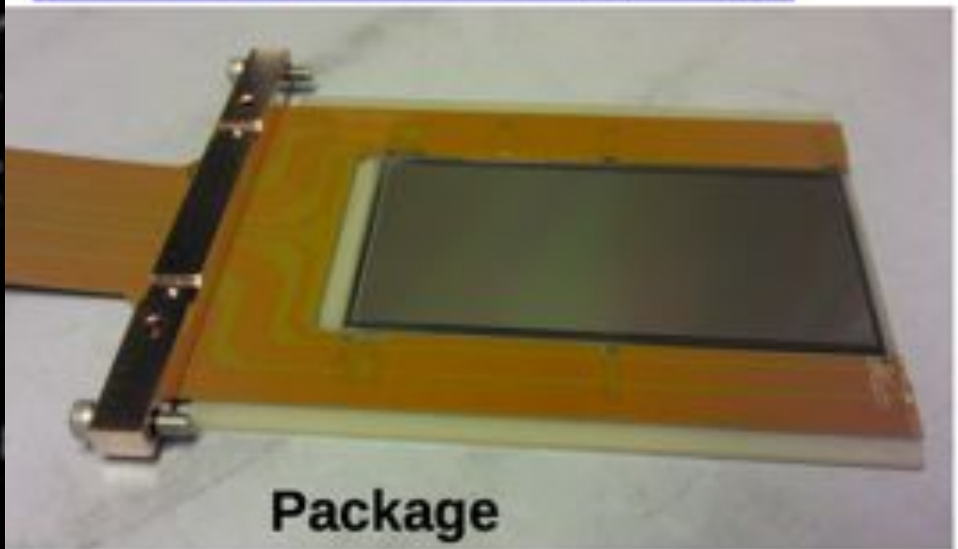
Improved shielding ...

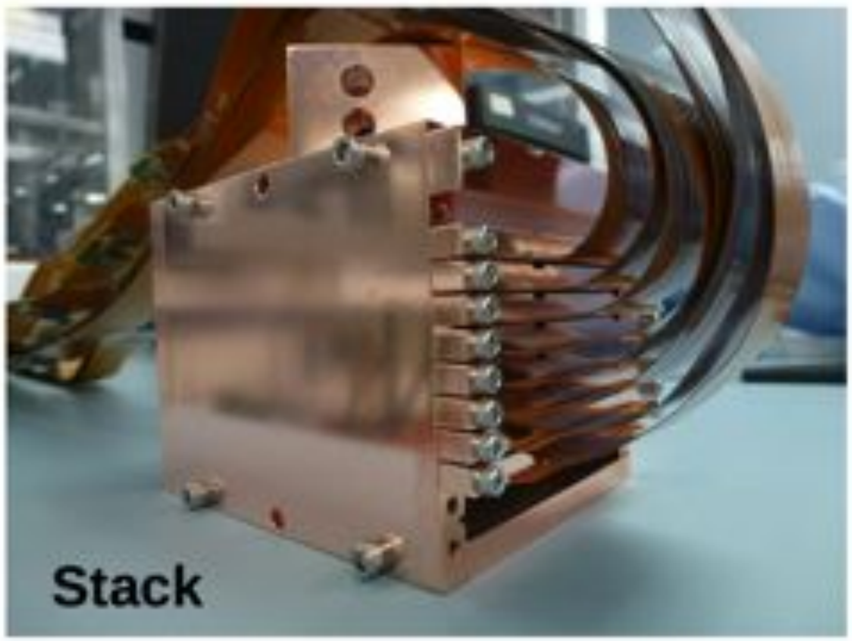
- **DAMIC prototype in operation at SNOlab**





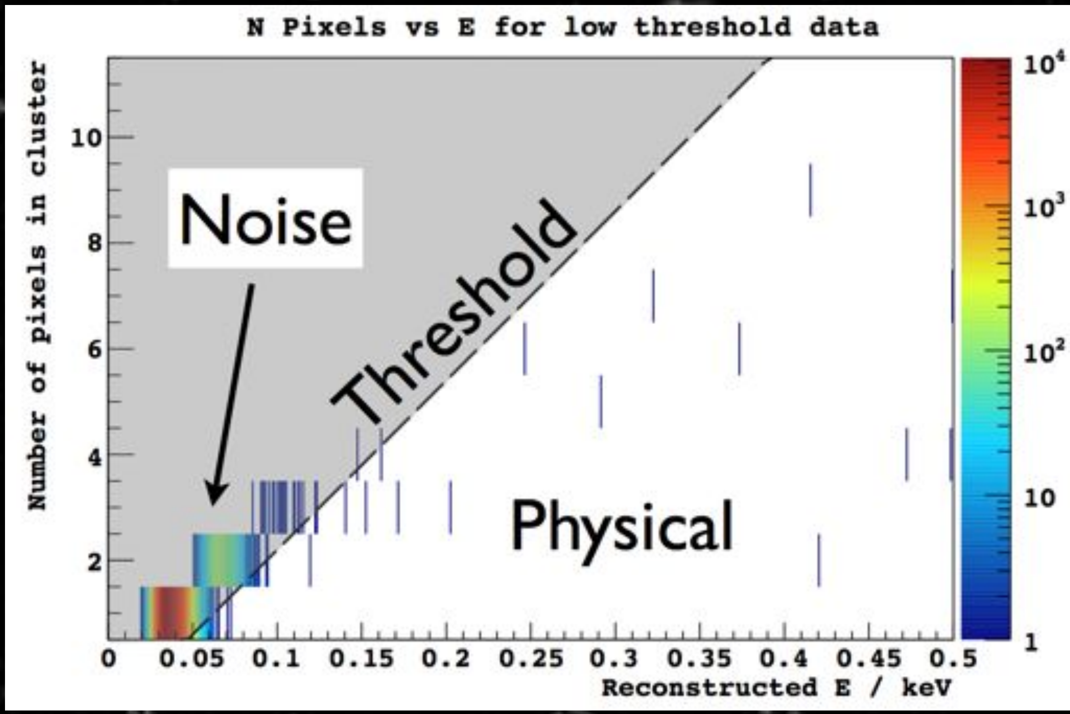
DAMIC: at SNOLAB (2013)

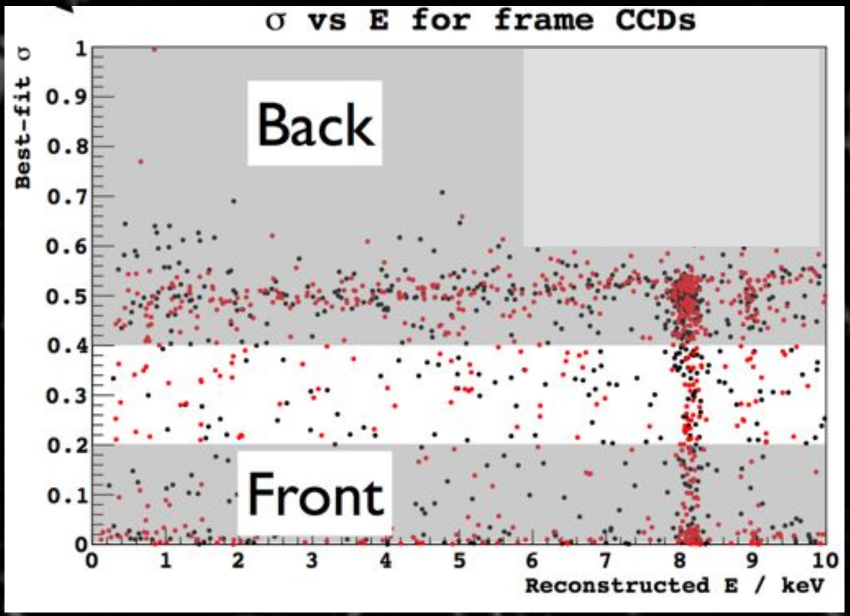


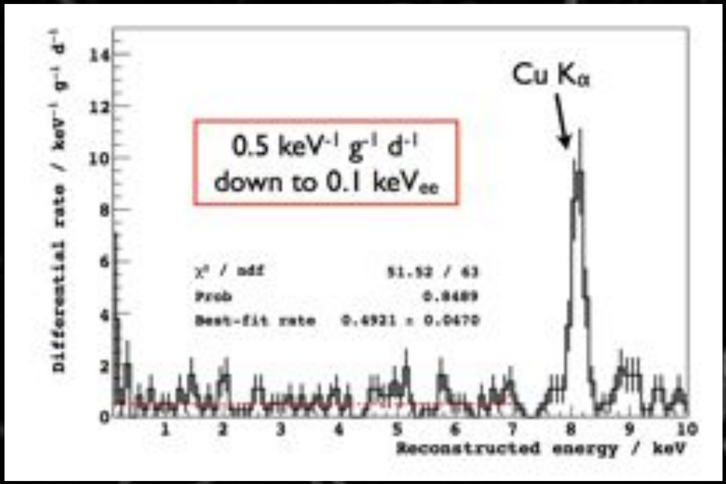


DAMIC: at SNOLAB (2013)

First DAMIC data @ Snolab

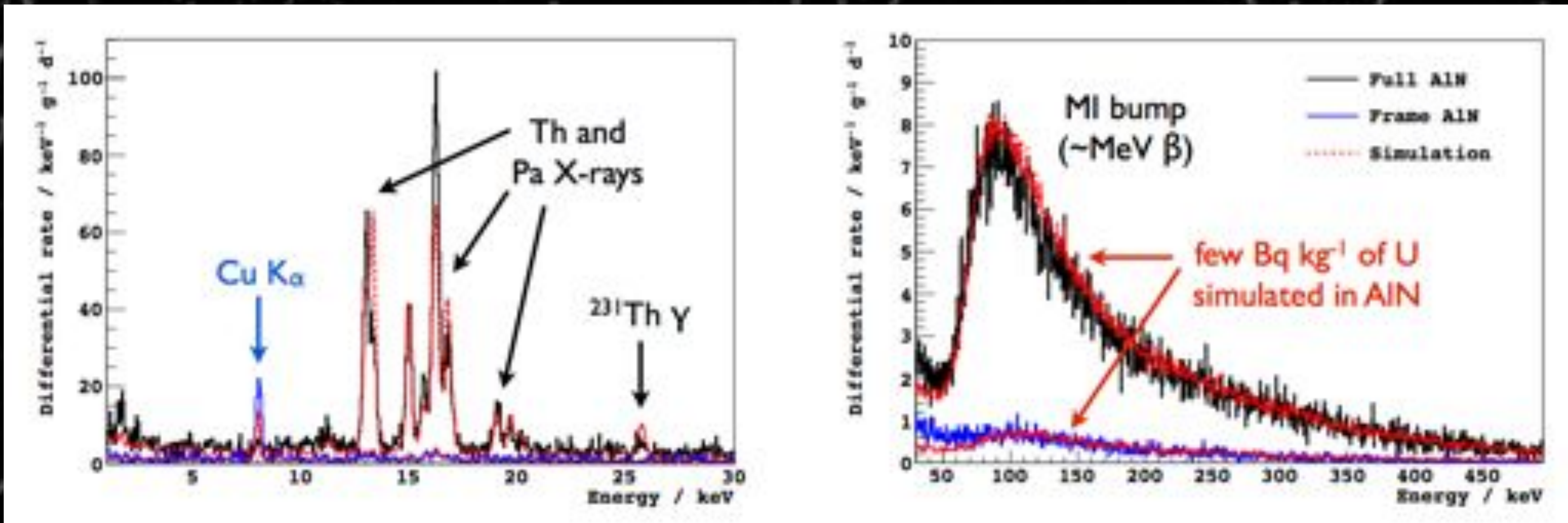






Simulation of backgrounds

Contamination of Uranium 238 decay chain in CCD frame



Red is simulation

New frame design solves this background …

DAMIC 100 - begins in ~3 months

Collaboration :
Fermilab
U. Chicago
U. Zürich
U. Michigan
UNAM
FIUNA
CAB

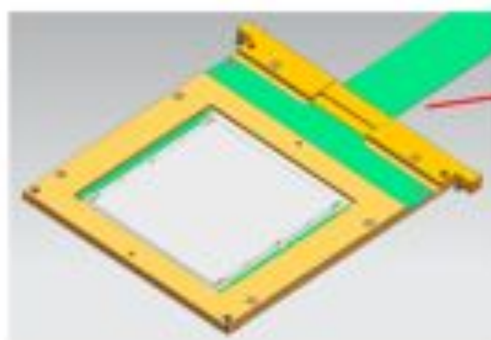
DAMIC100 Under construction now

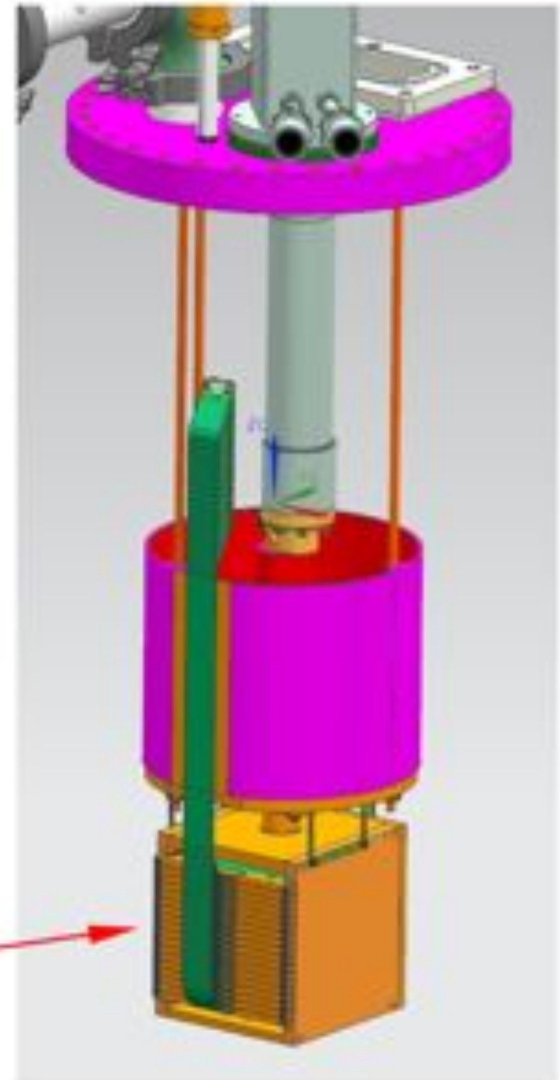
- 100 g of Silicon active mass
- 18 CCDs
  - 5.5 g
  - 6 cm x 6 cm
  - 650 μm thick
- Fits in existing Dewar and Shield
- Background

Current: 100 events/(kg day keV$_{ee}$)

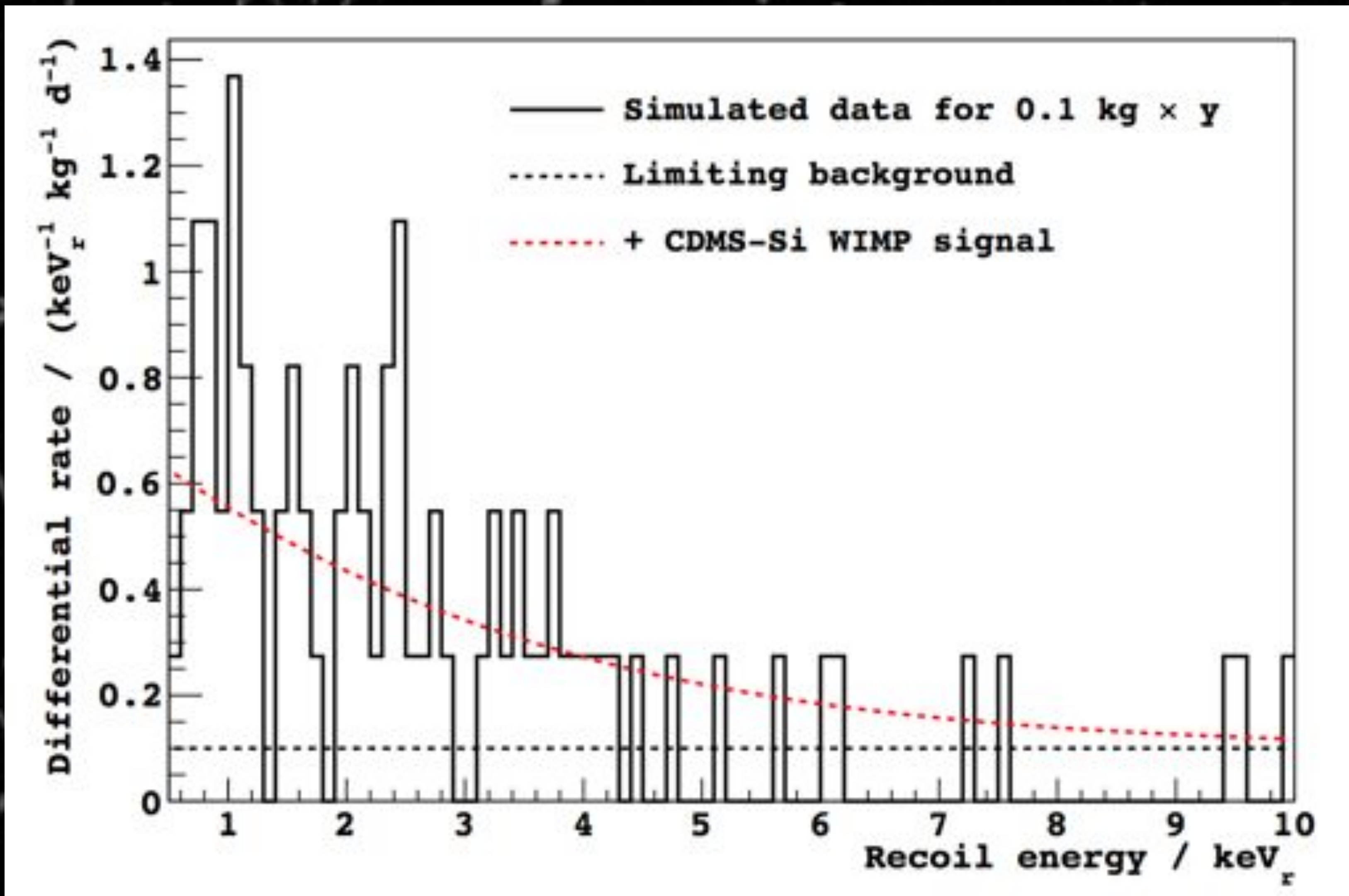
DAMIC100: few events/(kg day keV$_{ee}$)

- Lead upgrade:
  low Pb-210 + ancient
- CCD package
  high resistivity silicon



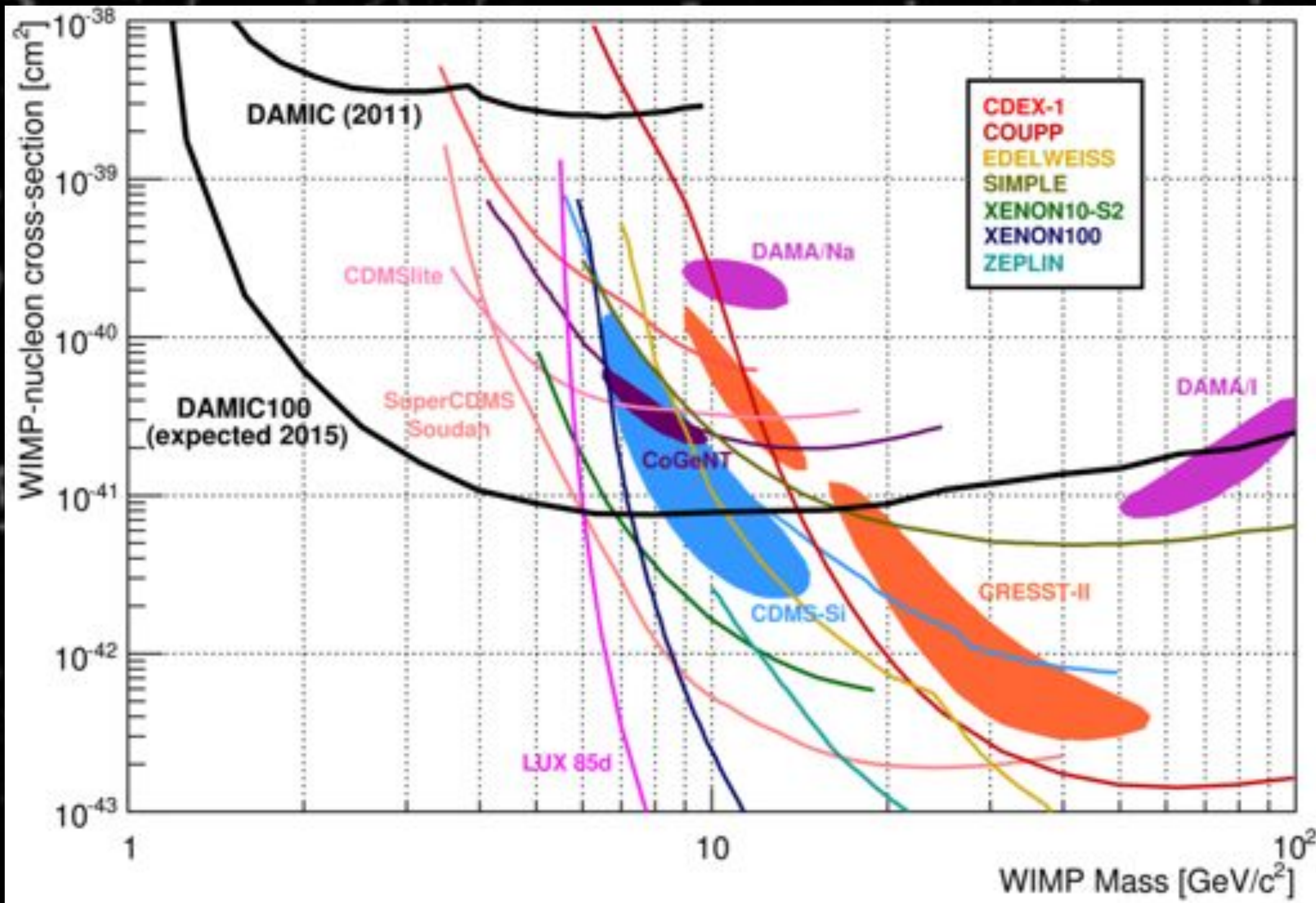


Simulation of DAMIC 100



Sensitivity

- **Projected DAMIC 100 with 1 year of data**



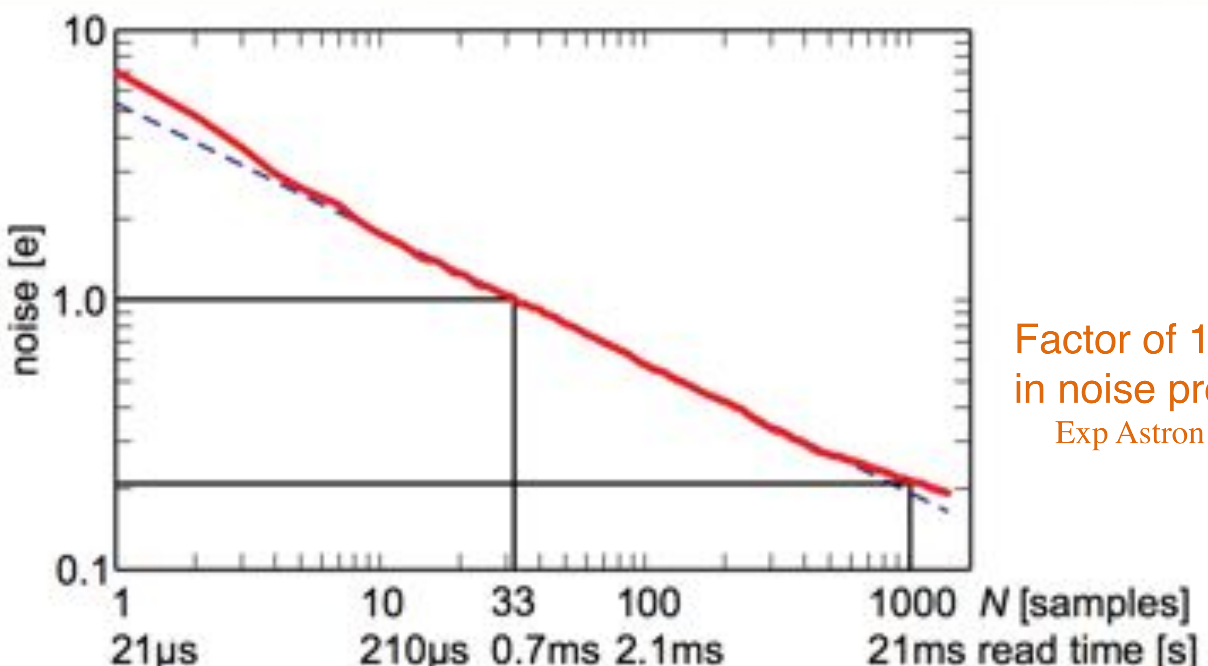
2011 DAMIC limit 107 g-days
with 0.04 keV energy threshold
Phys.Lett. B711 (2012) 264-269

- **Will test much of low mass interesting region**

Future

Lowering the noise: Skipper CCD

- Main difference: the CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$



Factor of 10 reduction in noise proven
Exp Astron (2012) 34:43–64

0.2 e- noise !

Summary

- Low mass dark matter
  - Experimental hints ?
  - Theoretically motivated
  - But low energy threshold difficult

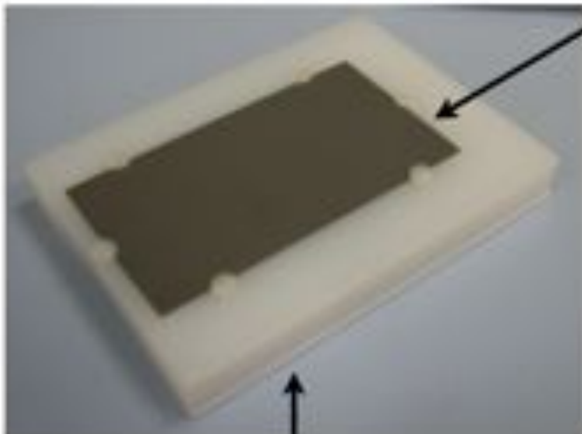
- CCDs
  - Achieves very low energy threshold
    - Can do factor of ten better
  - Requires strong calibration effort & bkg understanding

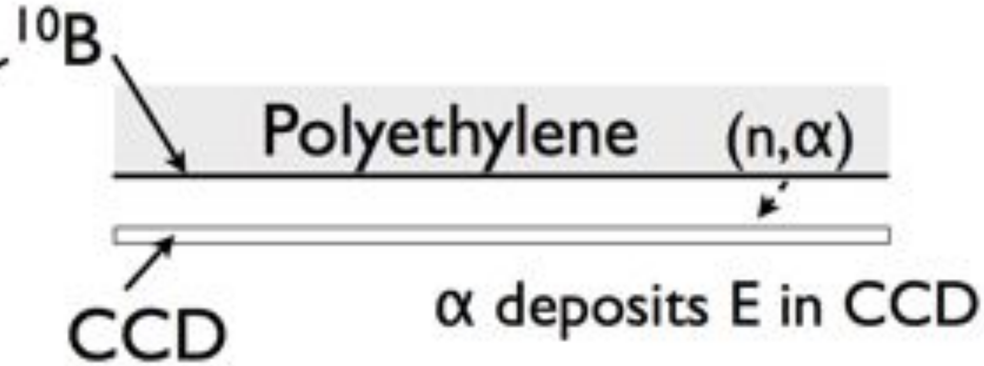
- DAMIC 100 begins this summer
  - Will provide strong constraints for low mass dark matter in ~ 1 year

An event

BACKUPS

In-situ neutron background estimate

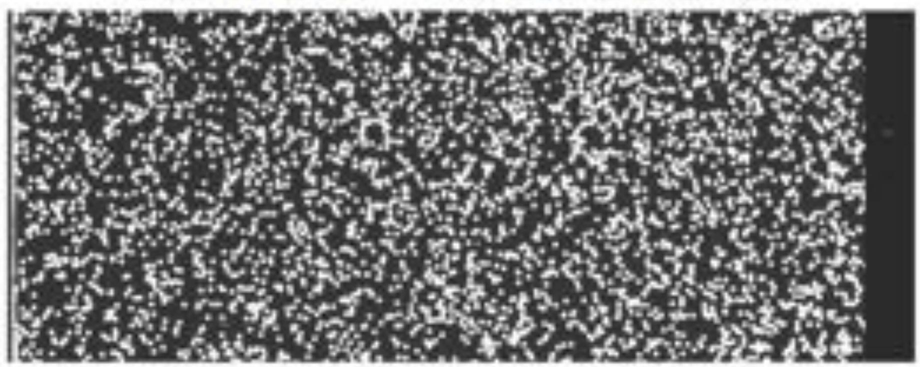




Slides into Cu box at SNOLAB

Test performed at FNAL this summer

αs from ^{241}Am source



Nucl.Instrum.Meth. A665 (2011) 90-93

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CCD activation at a proton beam

Isotope	Half-life days	Si(p,x) mb	Activation $\mathrm{Bq\,g^{-1}\,(10^{10}\ p\ cm^{-2})^{-1}}$	EC prob.	E_γ keV	E_K eV	σ_K eV	E_R eV	δ_E eV
^{7}Be	53.12	3.2	0.103	1.000	477.6	55	7	$57+0$	10
^{22}Na	950.3	15.8	0.029	0.097	1275	870	28	$60+40$	14

Long lived EC isotopes

Activation of a fraction of a Bq (^{7}Be and ^{22}Na)

γ-ray may be used to precisely measure activation

K-shell line near threshold

Shift in line due to A recoil

For 230 MeV *p* beam

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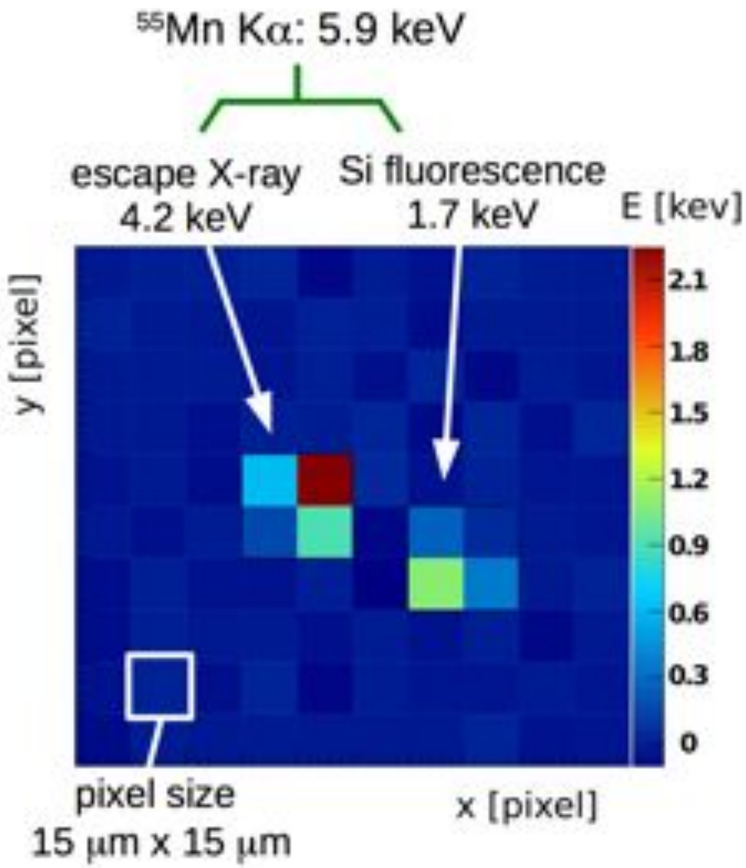
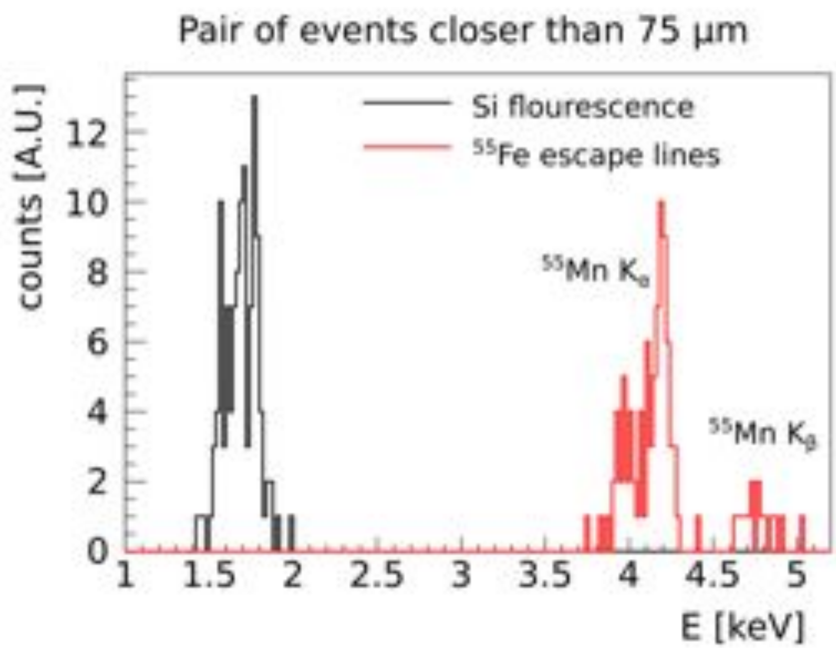
Event reconstruction





EC capture

10.2. Activated EC isotopes in the CCD

In September, 2013 we irradiated a DAMIC CCD with a flux of 2×10^{10} 230 MeV protons/cm^2 at the Warrenville proton beam facility. The instrumental performance is as expected from previous radiation tolerance measurements [16]. The aim of this irradiation was to produce uniformly distributed ^{7}Be and ^{22}Na within the CCD bulk. These isotopes decay by electron-capture (EC) and, as the νs and γ-rays escape the CCD, the only energy deposited is that from the refilling of the K-shell vacancy, leading to mono-energetic deposits of nominally 54 eV$_{ee}$ and 849 eV$_{ee}$. A small energy shift due to the energy deposited by the recoiling nucleus following ν and γ-ray emission is also expected. Furthermore, the total activation of these isotopes can be measured precisely from the emitted γ-rays with a Ge detector. These lines will allow us to further characterize the detector for sub-keV$_{ee}$ energy deposits in the bulk, and to demonstrate the detection efficiency of the CCD for low energy events near our threshold.

Thermal neutron calibration

10.3. Nuclear recoil energy calibration with a thermal neutron source

We are pursuing the calibration of the ionization efficiency of nuclear recoils in Si at $\sim$1 keV$_r$, crucial in understanding the energy spectrum of a potential WIMP signal in DAMIC100. The strategy is to expose a Si detector to a flux of thermal neutrons and rely on the reaction [17]:

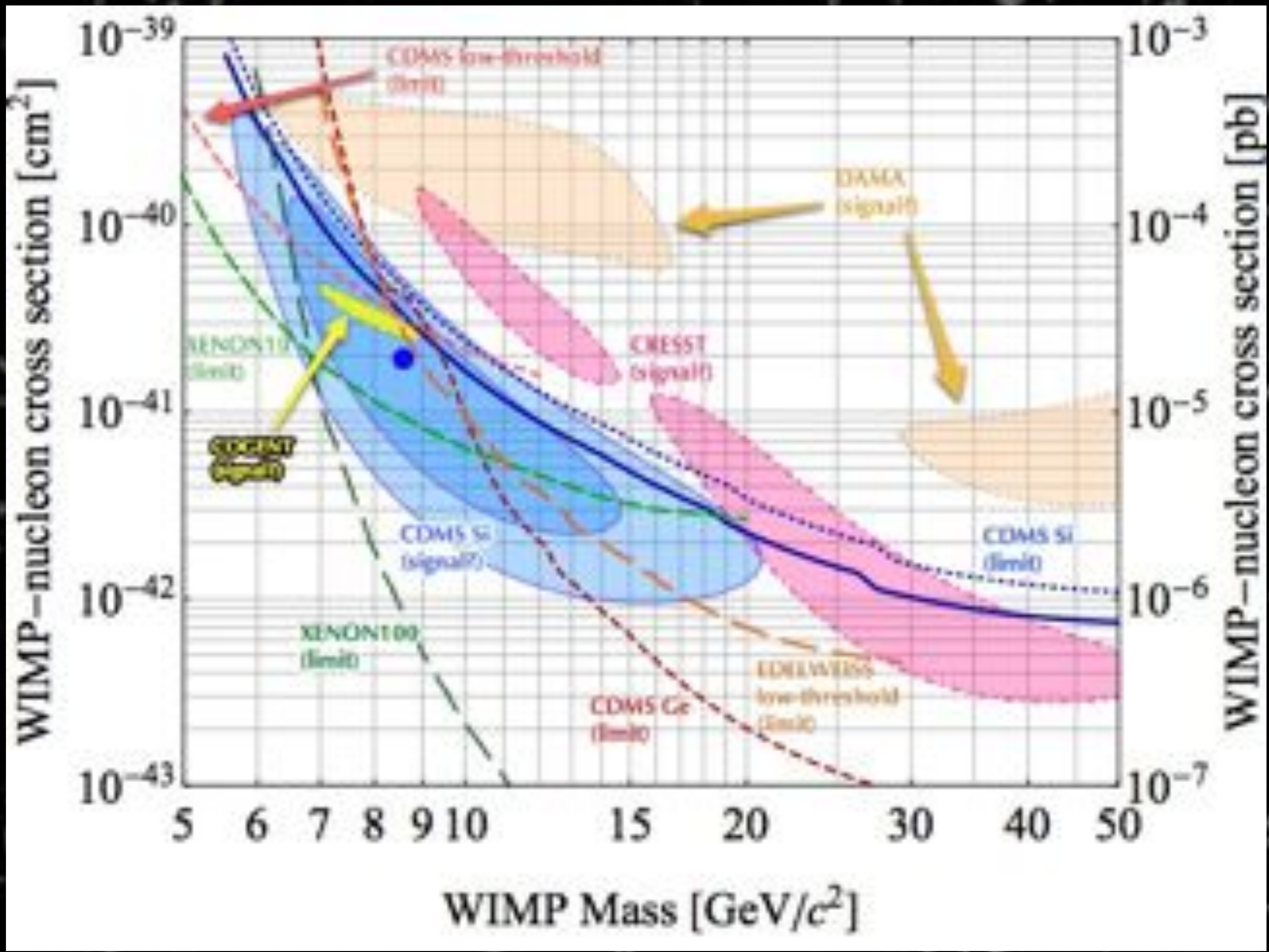
$$^{A}\mathrm{Si} + n \longrightarrow {}^{A+1}\mathrm{Si} + \gamma\mathrm{s} \tag{1}$$

where the $^{A+1}$Si nucleus recoils from the γ-ray emission due to momentum conservation. If only one γ-ray is emitted, or the lifetime of nuclear states in the γ-ray cascade is much greater than the stopping time of the recoils, then the total nuclear energy deposit is mono-energetic. Considering the maximum γ-ray energy of $\sim$10 MeV, these recoil lines have energies $<$2 keV$_r$. If a Si detector is exposed to a thermal neutron beam, and the coinciding γ-rays from the interaction are detected in a secondary detector, then the nuclear recoils can be effectively tagged by a time coincidence. As the recoil energy is known from the kinematics of the reaction, the nuclear recoil ionization efficiency can be measured.

As good time resolution is required to observe the coincidence, a CCD cannot be used for this calibration. We have already attempted this measurement by exposing a LAAPD [18] to a thermal neutron beam in the LENS facility at Indiana University and in a research reactor at Ohio State University, with negative results in both cases. The instrumental integrity of the LAAPD could not withstand the large neutron flux and associated backgrounds. We plan to attempt this measurement in the near future with a Si-Li detector.

Where there may be signals

- Now large collection of low mass dark matter signals (or underestimated backgrounds)
- Though mostly excluded by Xenon10 & Xenono100



- Low mass dark matter (~ < 10 GeV) search region interesting
- Key is detection of low energy nuclear recoils

Ramping Up!

Better Background Predictions

- In-situ measurement of neutr
- Layer of Boron-10 on polyethy
- Poly slows down neutrons - B
(2 protons & 2 neutrons) from
- Alphas have a distinct signatu

Plasma effect in Silicon Charge Coupled Devices (CCDs)

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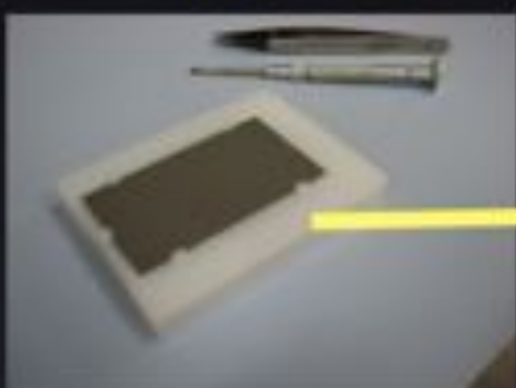
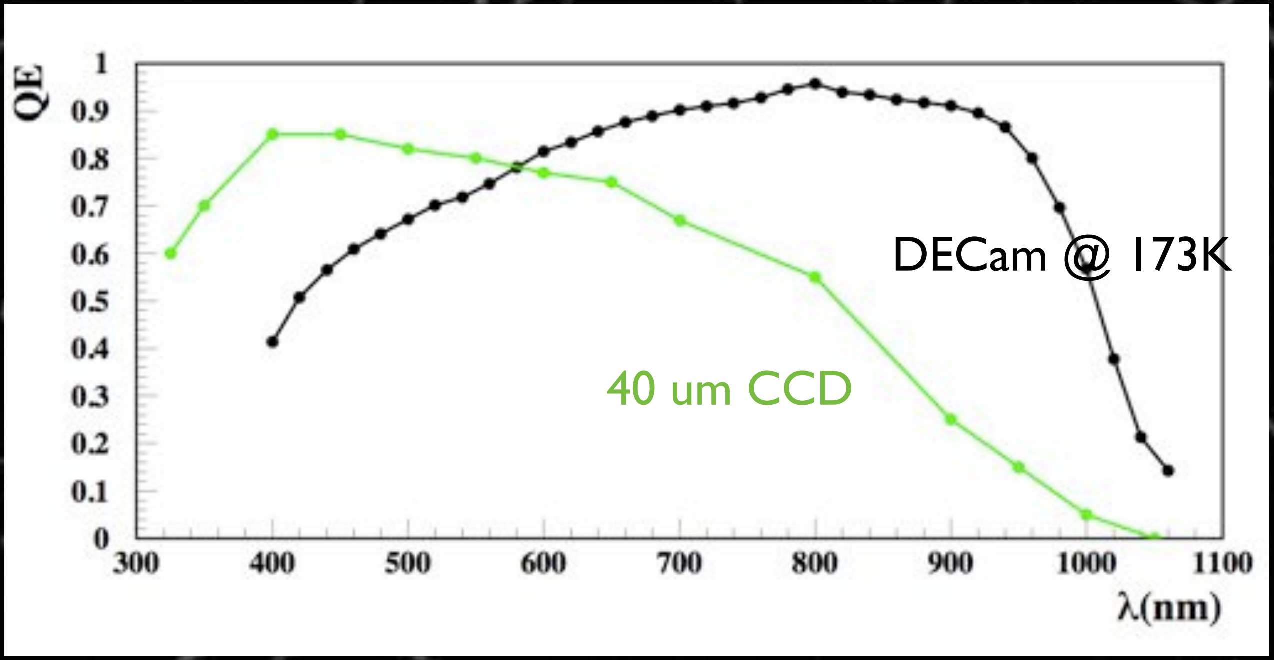
[4]Universidad Nacional del Sur, Bahía Blanca, Argentina

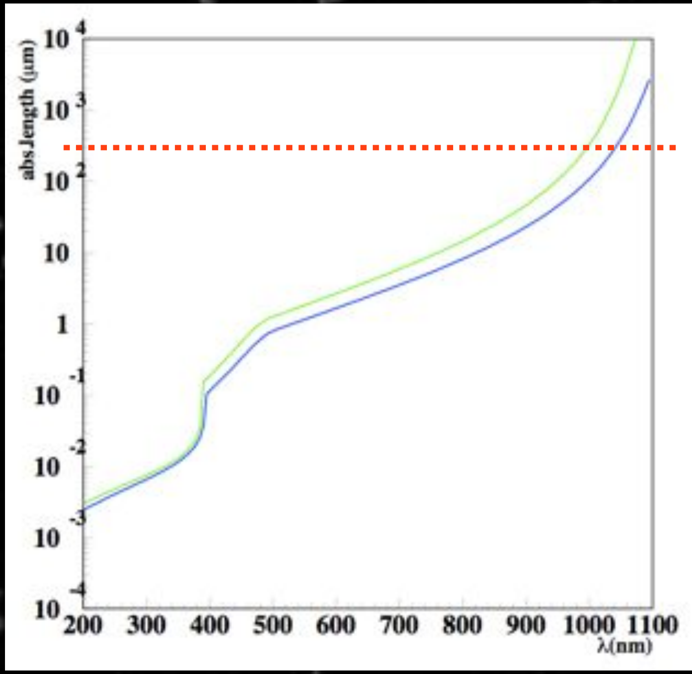
(Dated: May 31, 2011)

Plasma effect is observed in CCDs exposed to heavy ionizing α-particles with energies in th
0.5 - 5.5 MeV. The results obtained for the size of the charge clusters reconstructed on th
pixels agrees with pervious measurements in the high energy region (≥ 3.5 MeV). The measur
were extended to lower energies using α-particles produced by (n,α) reactions of neutrons in
target. The effective linear charge density for the plasma column is measured as a func
energy. The results demonstrate the potential for high position resolution in the reconstruc
alpha particles, which opens an interesting possibility for using these detectors in neutron in

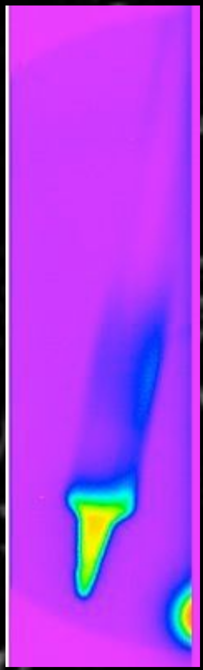


Thickness was to get IR sensitivity





250 μm thick fully depleted produces a higher efficiency in the near-IR



Soldering iron IR imaging with DECam CCD. 20 seconds exposure with a narrow (10nm) filter centered at 810nm. (picture by K.Kuk)

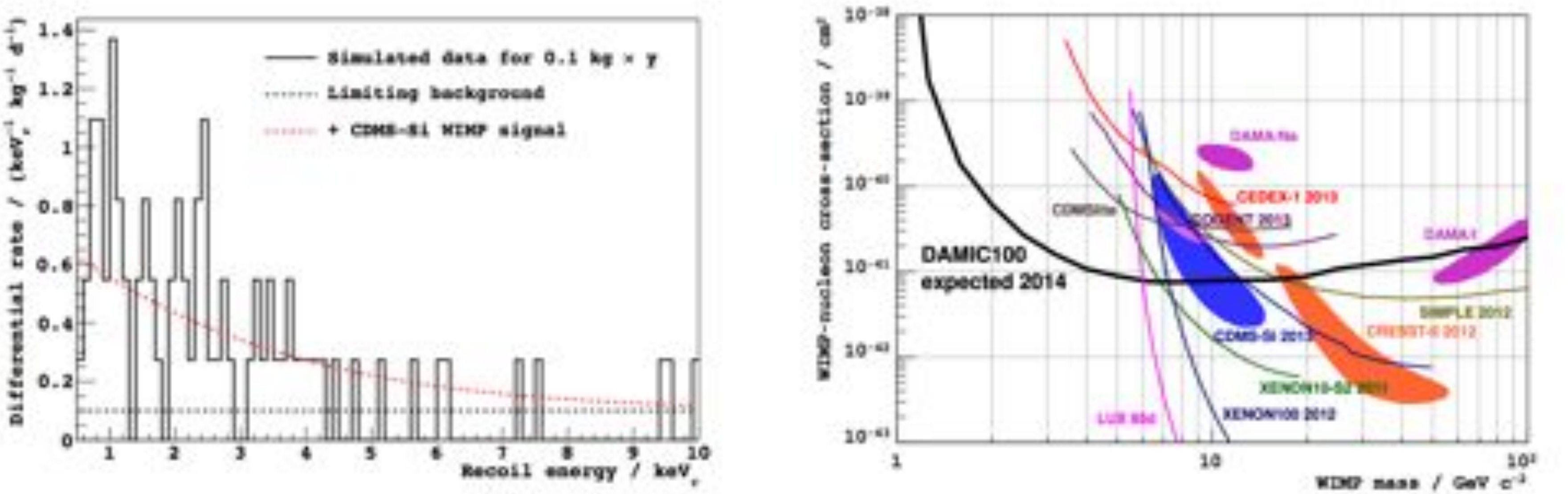
Ongoing R & D

- Neutron energy response at low energy
  - Electron Capture from irradiated silicon (calibration at ~ 100 eV) : could be done at PSI
  - Lower energy calibrations still needed
- Improved readout - multiple sampling (skipper) of CCD data can yield sub-eV noise
- CCD limitation is long exposure time : 1000s of seconds - no timing to reject triggerable backgrounds
  - Other types of silicon detectors with fast readout and low background noise can be investigated

Conclusions

- CCDs are a viable particle detector for low mass dark matter
  - Can provide useful constraints on an exciting mass range for dark matter
  - Relatively cheap (DAMIC 100 ~ 400 kCHF)
- Detector R&D advancing with thick, high resistivity, low noise scientific CCDs
- U. Zürich is playing a leading role in this experiment
  - Building a CCD lab for testing and calibrations

DAMIC 2011 BACKUPS

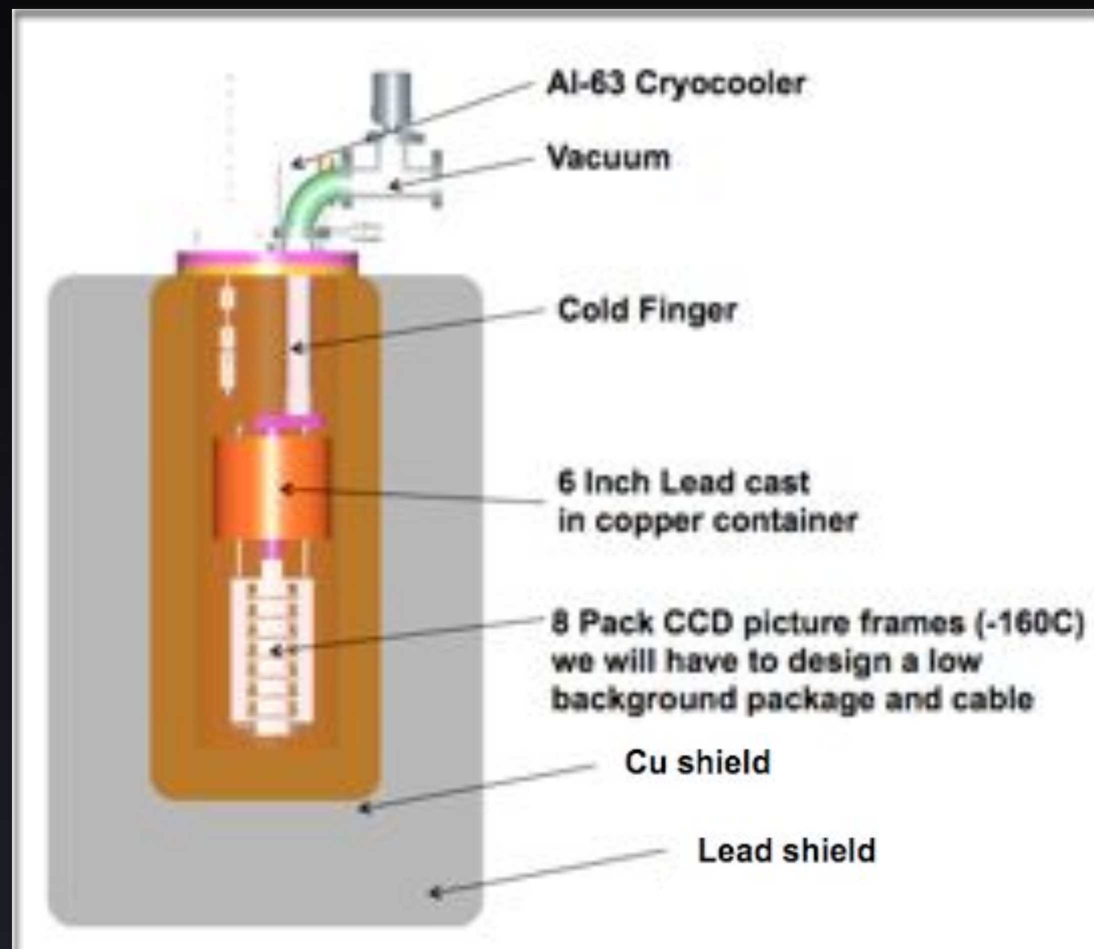


(a) Spectrum after 1 y of DAMIC100

(b) Exclusion plot after 1 y of DAMIC100

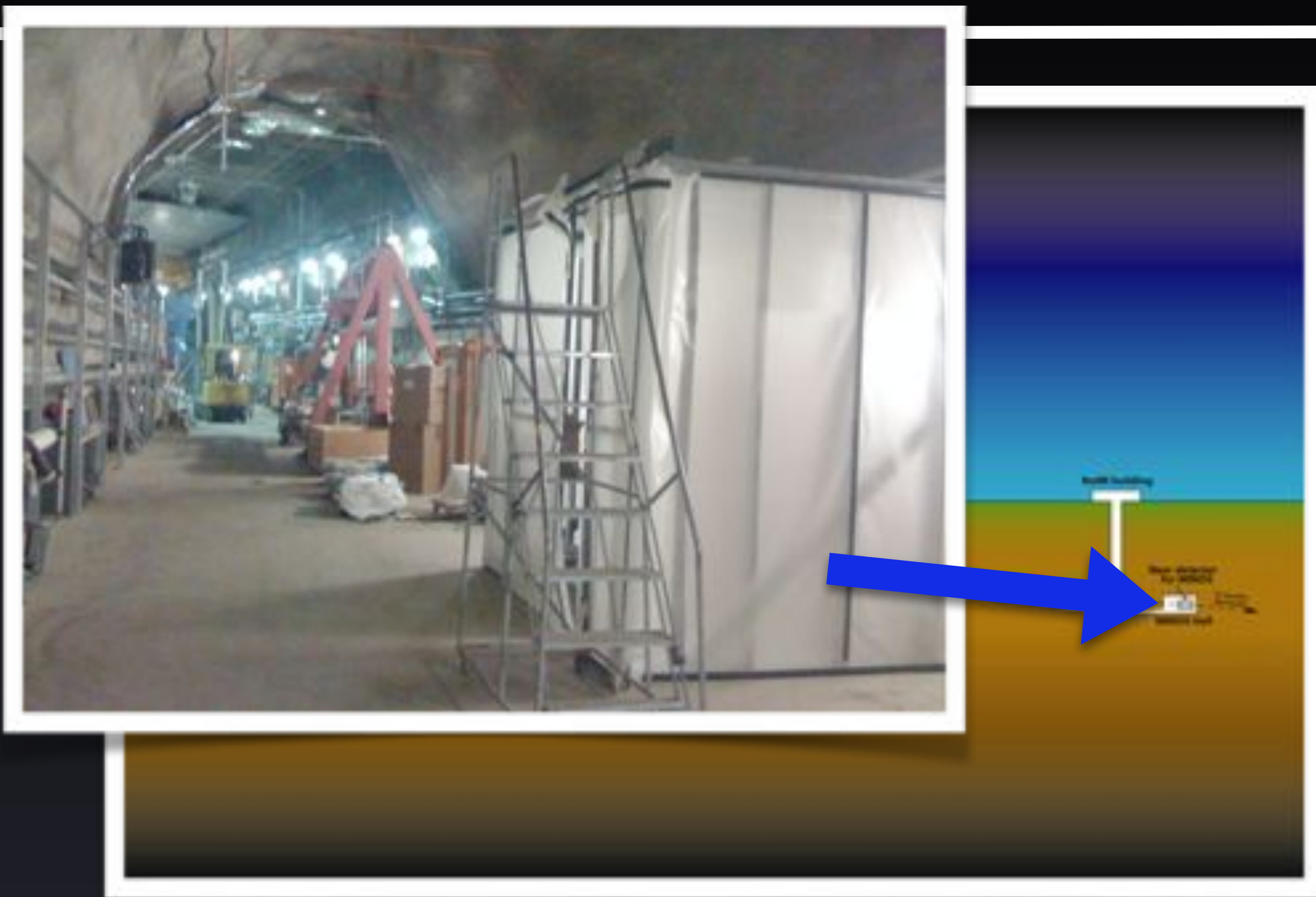
Fig. 12. a) Simulated spectrum of DAMIC100, considering a WIMP with the mass and interaction cross-section of the best-fit to the CDMS-Si signal (M_χ=8.6 GeV/c^2 and $\sigma_{\chi N}$=1.9×10^{-41} cm^2) [4], standard halo parameters (ρ_χ=0.3 GeV/c^2/cm^3, v_0=220 m/s, v_E=232 m/s, v_{esc}=544 m/s) and a 0.1 kg·y exposure. For this illustration, the ionization efficiency of nuclear recoils is assumed to be 0.2 and energy independent. Thus, the expected limiting background of 0.5 events/(keV$_{ee}$·kg·d) corresponds to 0.1 events/(keV$_r$·kg·d). The exponential increase at low energies, starting below 5 keV$_r$ (~1 keV$_{ee}$), is evident. b) Under these assumptions we present a 90% exclusion plot for spin-independent interactions by performing a χ^2 test on simulated spectra with the flat background spectrum and the simulated WIMP signal for different values of M_χ and $\sigma_{\chi N}$. DAMIC100 will place the best limits on spin-independent WIMP-nucleon elastic scattering for M_χ<6 GeV/c^2.

DAMIC 2011

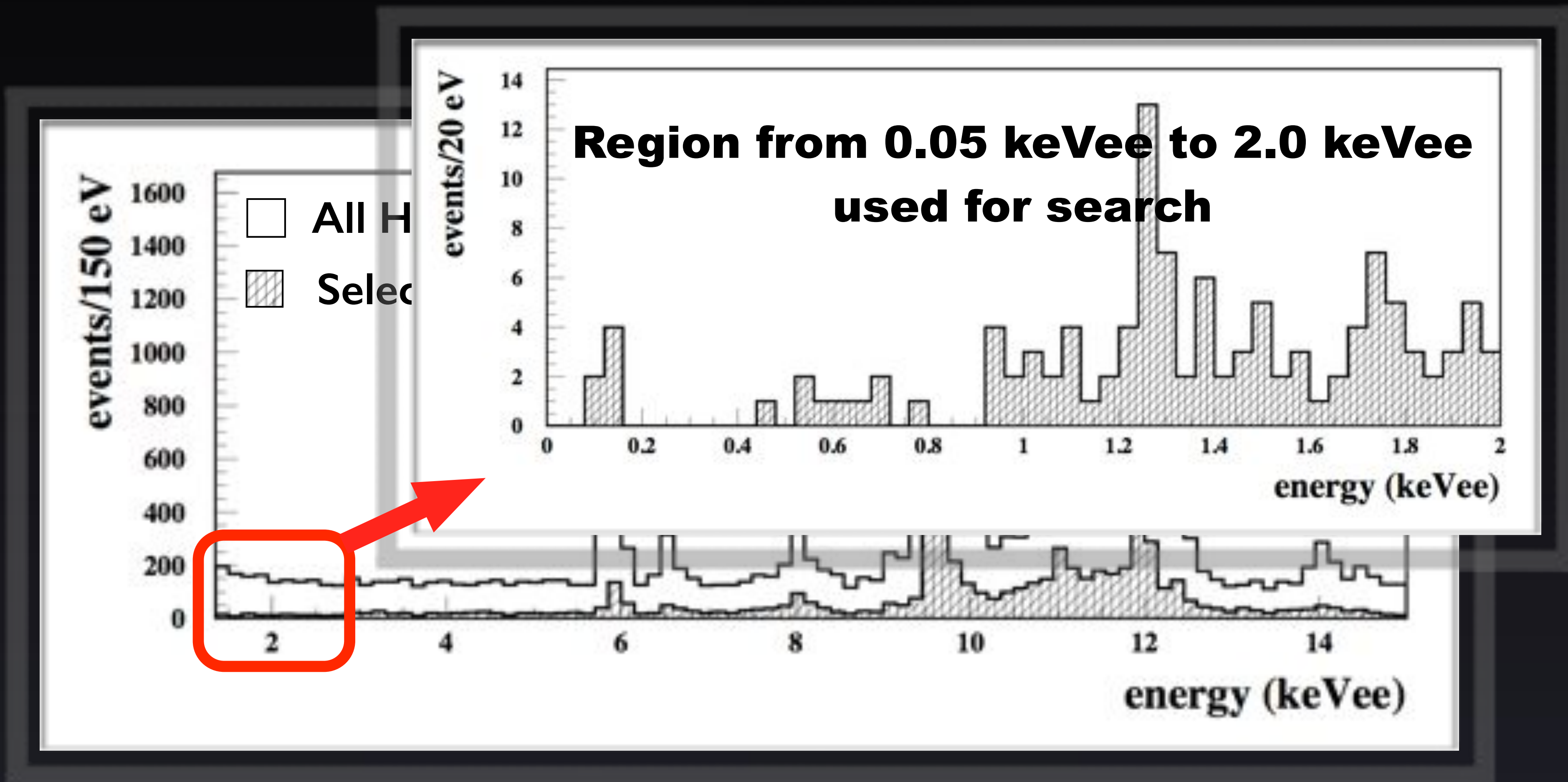


Al-63 Cryocooler
Vacuum
Cold Finger
6 Inch Lead cast
in copper container
8 Pack CCD picture frames (-160C)
we will have to design a low
background package and cable
Cu shield
Lead shield

DAMIC 2011



Energy Spectrum



Results from First Run

Direct Search for Low Mass Dark Matter Particles with CCDs

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(Dated: August 17, 2011)

A direct dark matter search is performed using fully-depleted high-resistivity CCD detectors. Due to their low electronic readout noise (RMS~7 eV) these devices operate with a very low detection threshold of 40 eV, making the search for dark matter particles with low masses (~ 5 GeV) possible. The results of an engineering run performed in a shallow underground site are presented, demonstrating the potential of this technology in the low mass region.

PACS numbers: 93.35.+d, 95.55.Aq

I. INTRODUCTION

There have been several direct-detection experiments searching for dark matter (DM) performed in recent years, and several more in development.[1]. Most of these

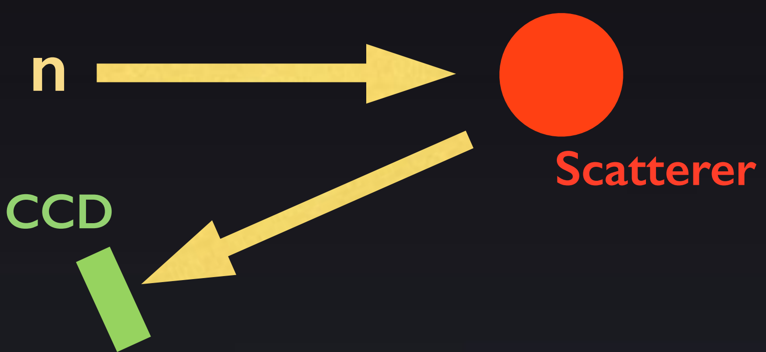
of their very low fiducial mass. The re... of thick, fully-depleted CCDs ... than conventional CCDs ... on. The Dark Matter in C... ment is the first DM sear... ogy.

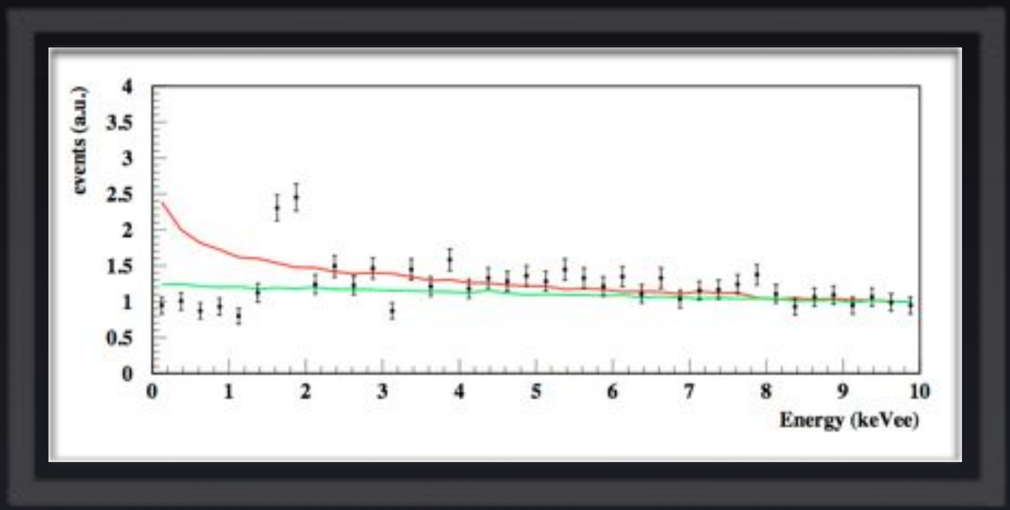
Phys. Lett. B 711 (2012) 264-269

Ramping Up!

Calibrating to Lower Energy

- **Using a mono-energetic beam of neutrons to calibrate quenching factor to very low energies**





Naturalness of Dark Matter Mass scale

1. **"Wimp miracle" scale :**
   - **Why do SUSY cross-sections provide correct relic DM density ?**

     $M_{DM} \sim 100$ GeV

2. **"Baryon-DM coincidence" scale :**
   - **Why is the DM abundance so close to matter ?**

     $\rho_{DM} \sim 5 \cdot \rho_{M}$
   - **What if dark matter is more baryon-like ?**
   - **Assume $N_{DM} \sim N_{baryon}$ in early universe**

     $M_{DM} \sim 5$ GeV

Asymmetric DM hep-ph/1111.0293