DAMIC : Dark Matter in CCDs

Recent developments towards low threshold

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U.Zürich

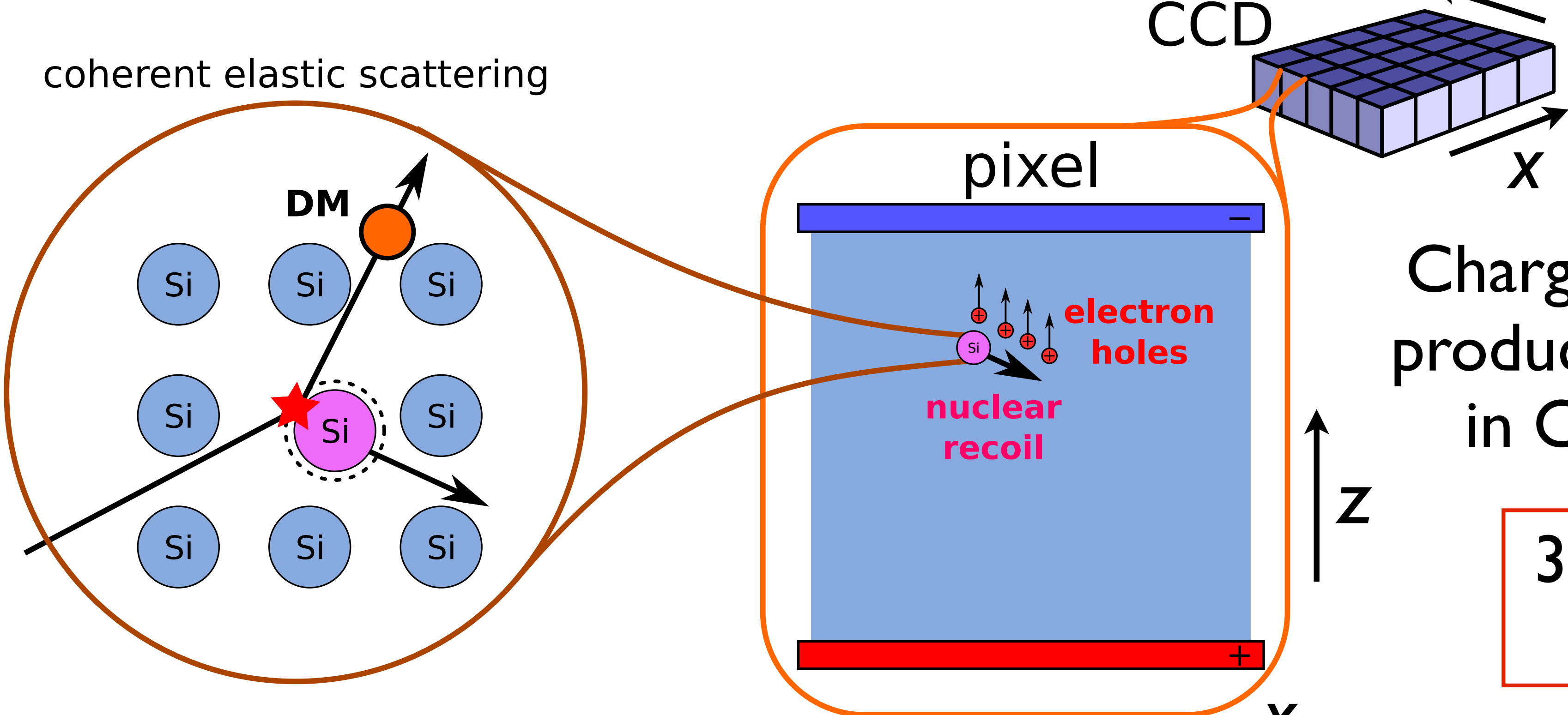
Munich Low mass dark matter conference

December 1, 2015

DAMIC

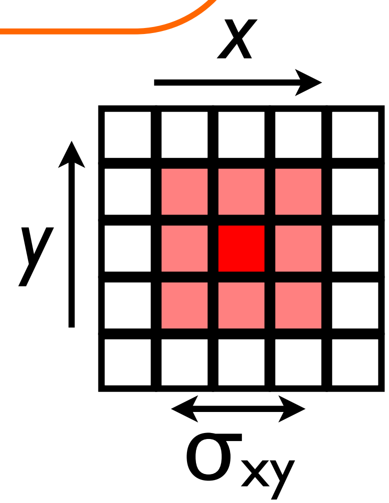
Introduction

Detector



Charged particles produce ionization in CCD bulk.

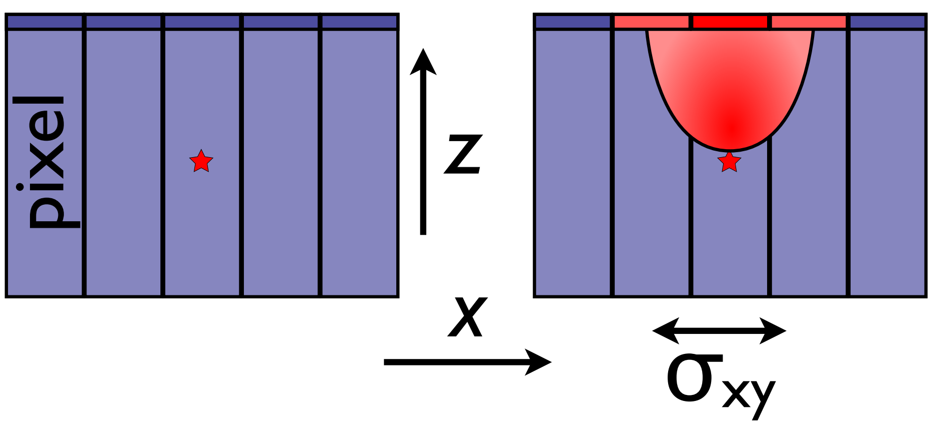
3.62 eV for e-h pair.



Charge collected by each pixel on CCD plane is read out.

~2 e^- RMS read-out noise.

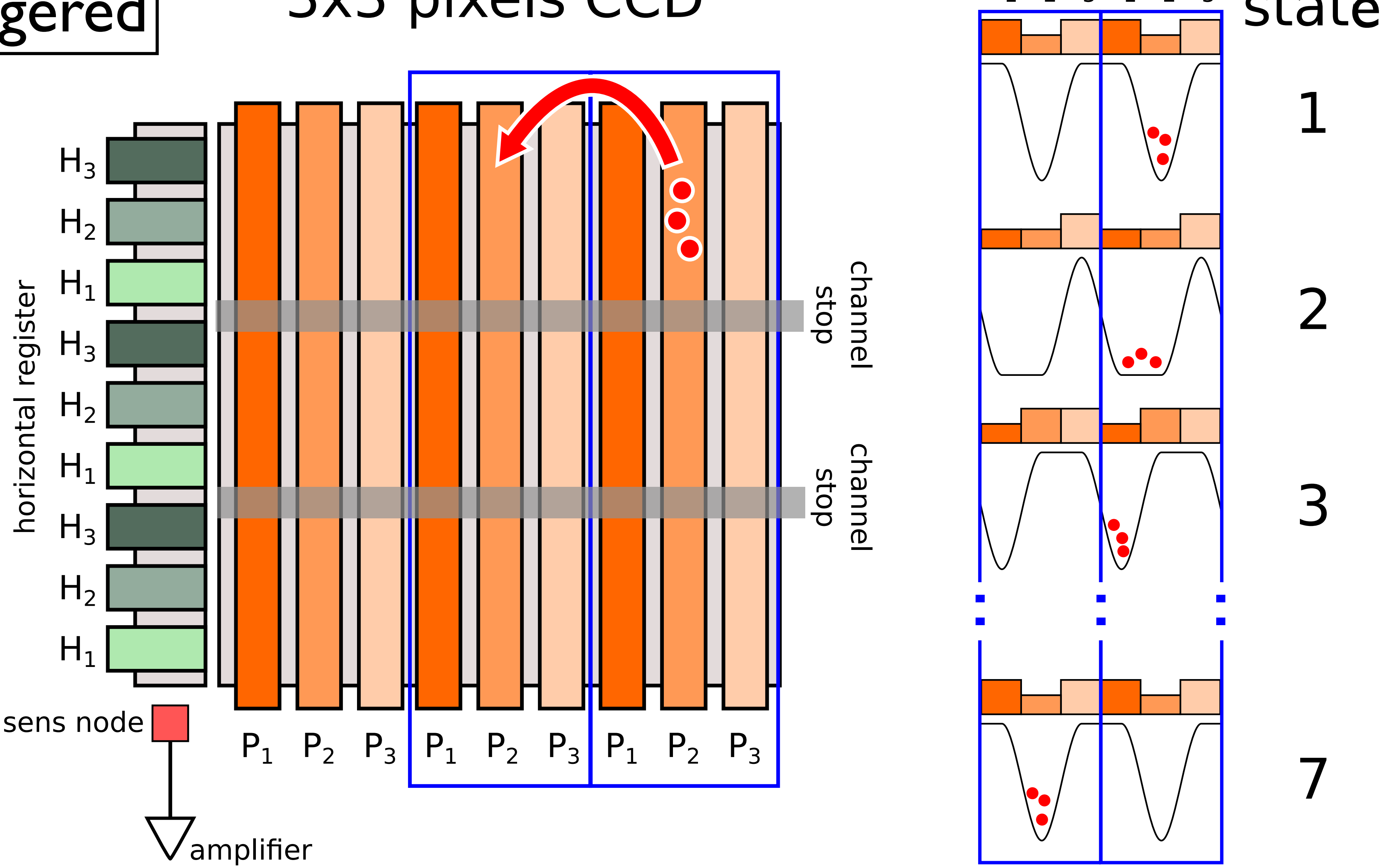
Charge drifted up and held at gates.



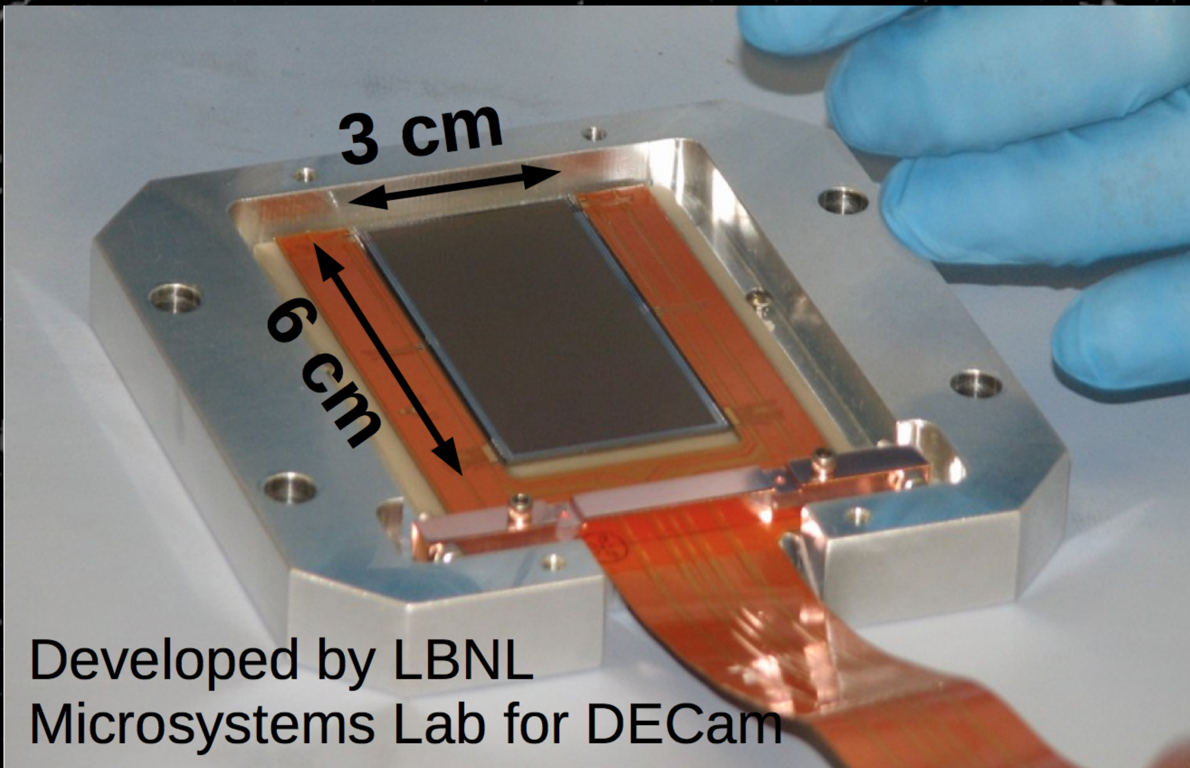
CCD readout

Not triggered

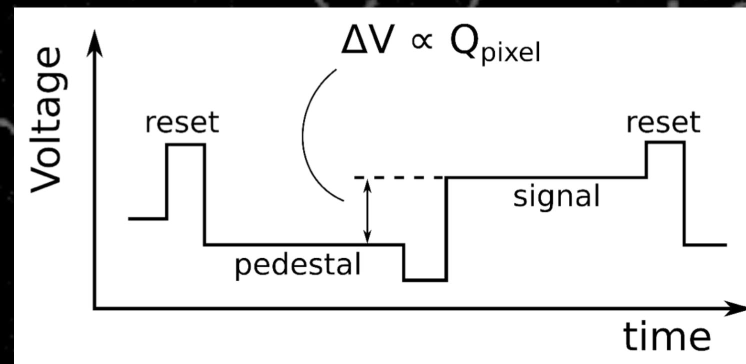
3x3 pixels CCD



Scientific CCDs

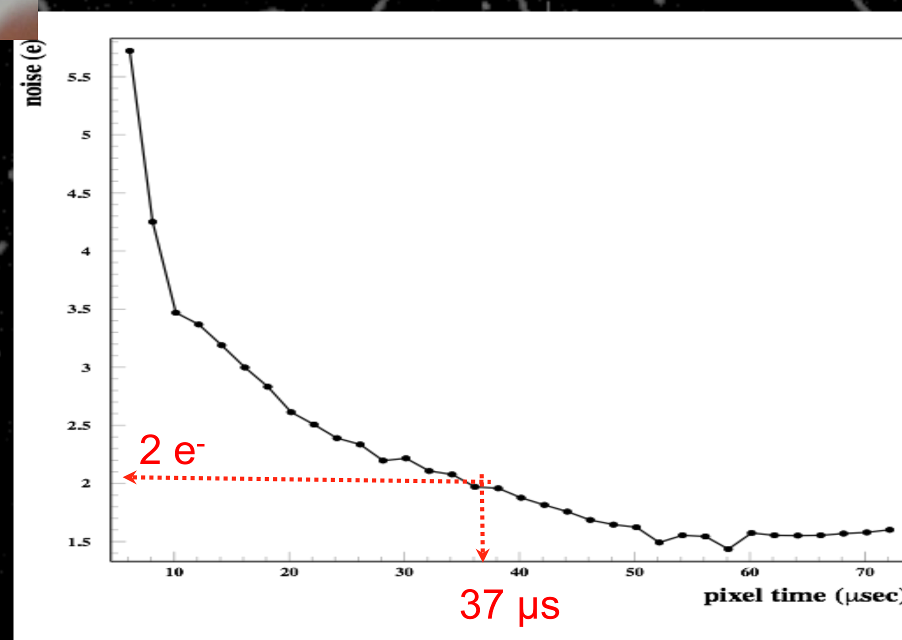


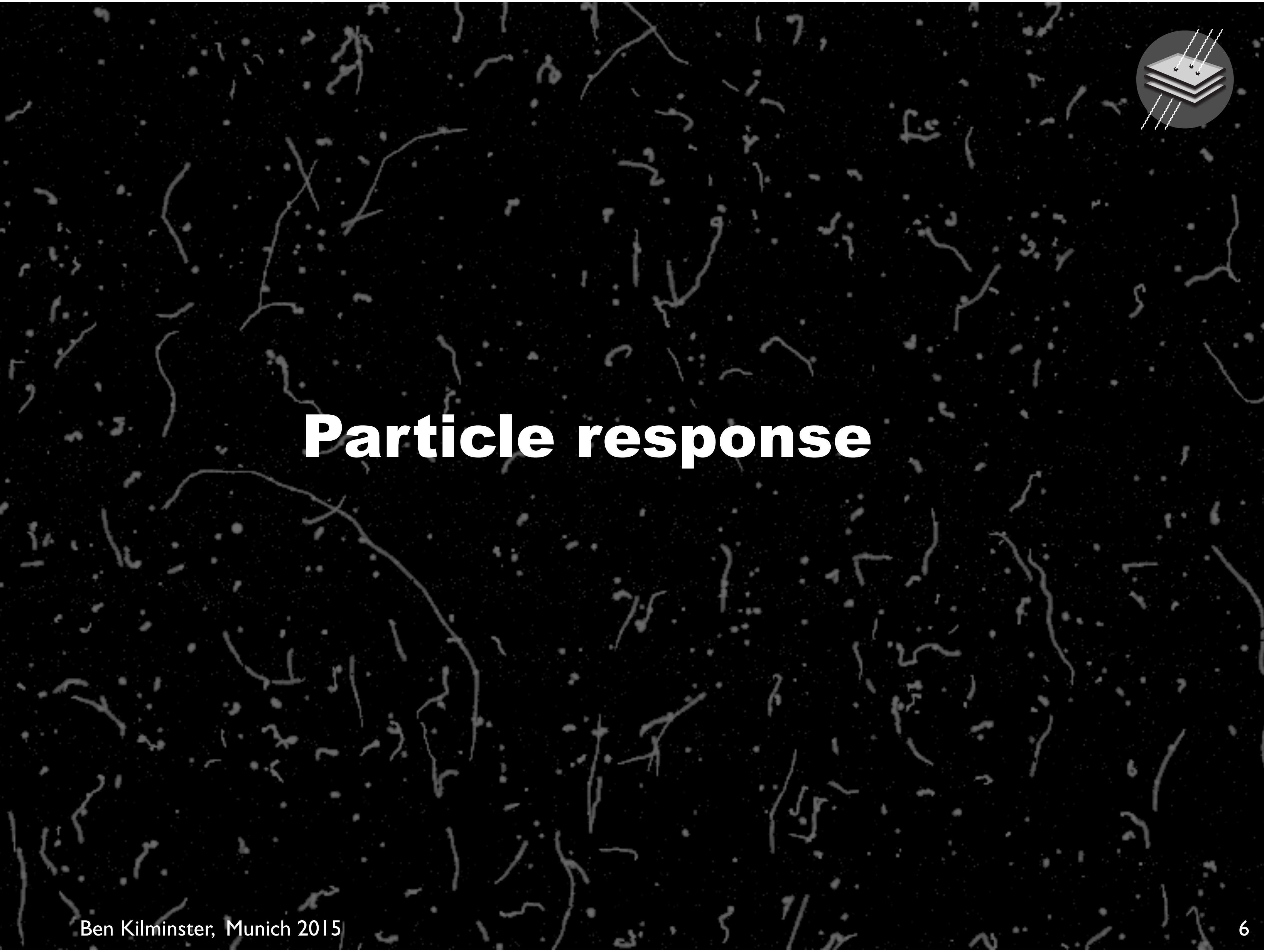
One readout gate - all pixels shifted via phased potential wells and read out



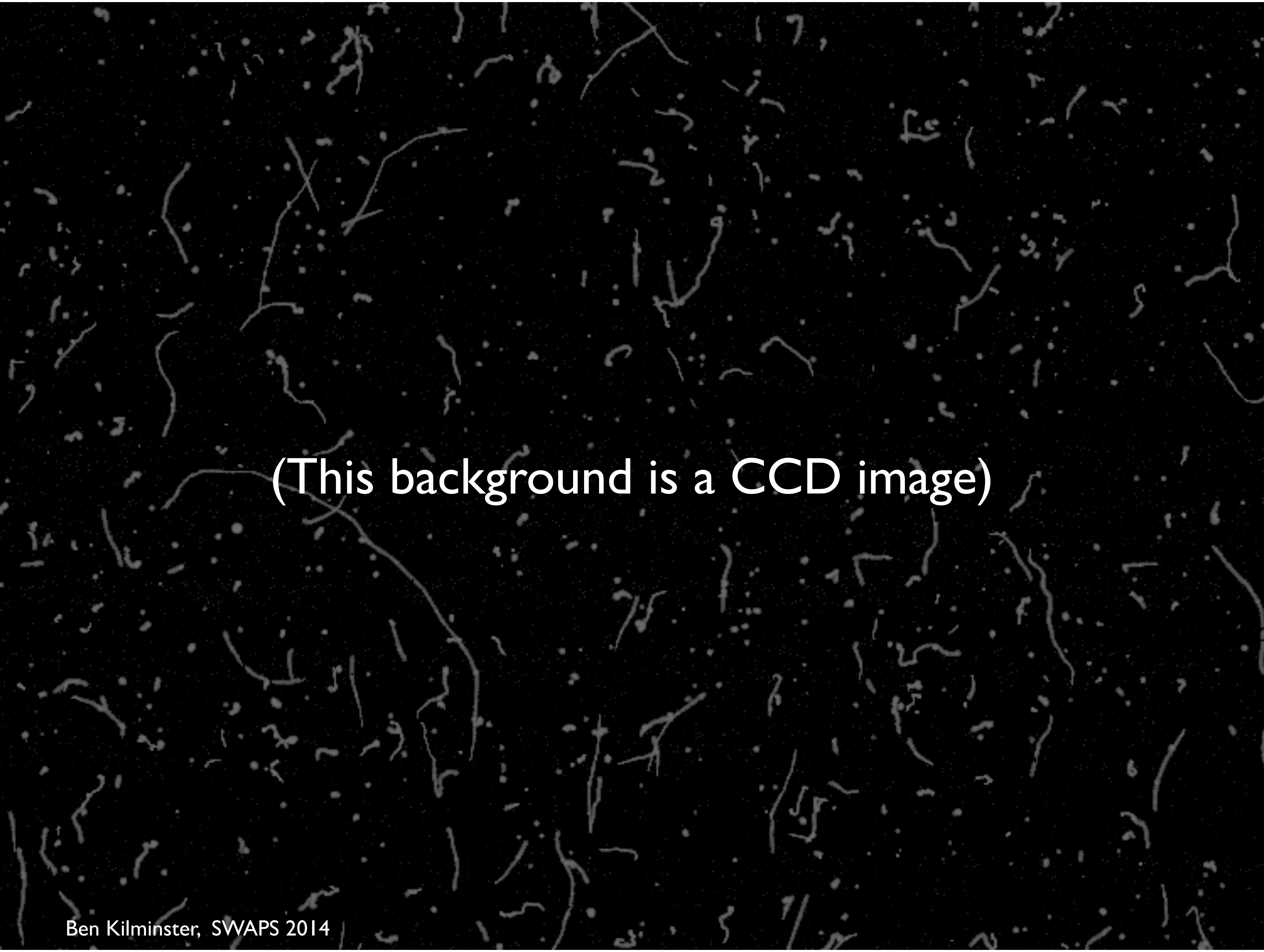
$$V_{out} \sim 3\ \frac{\mu V}{e^-}$$

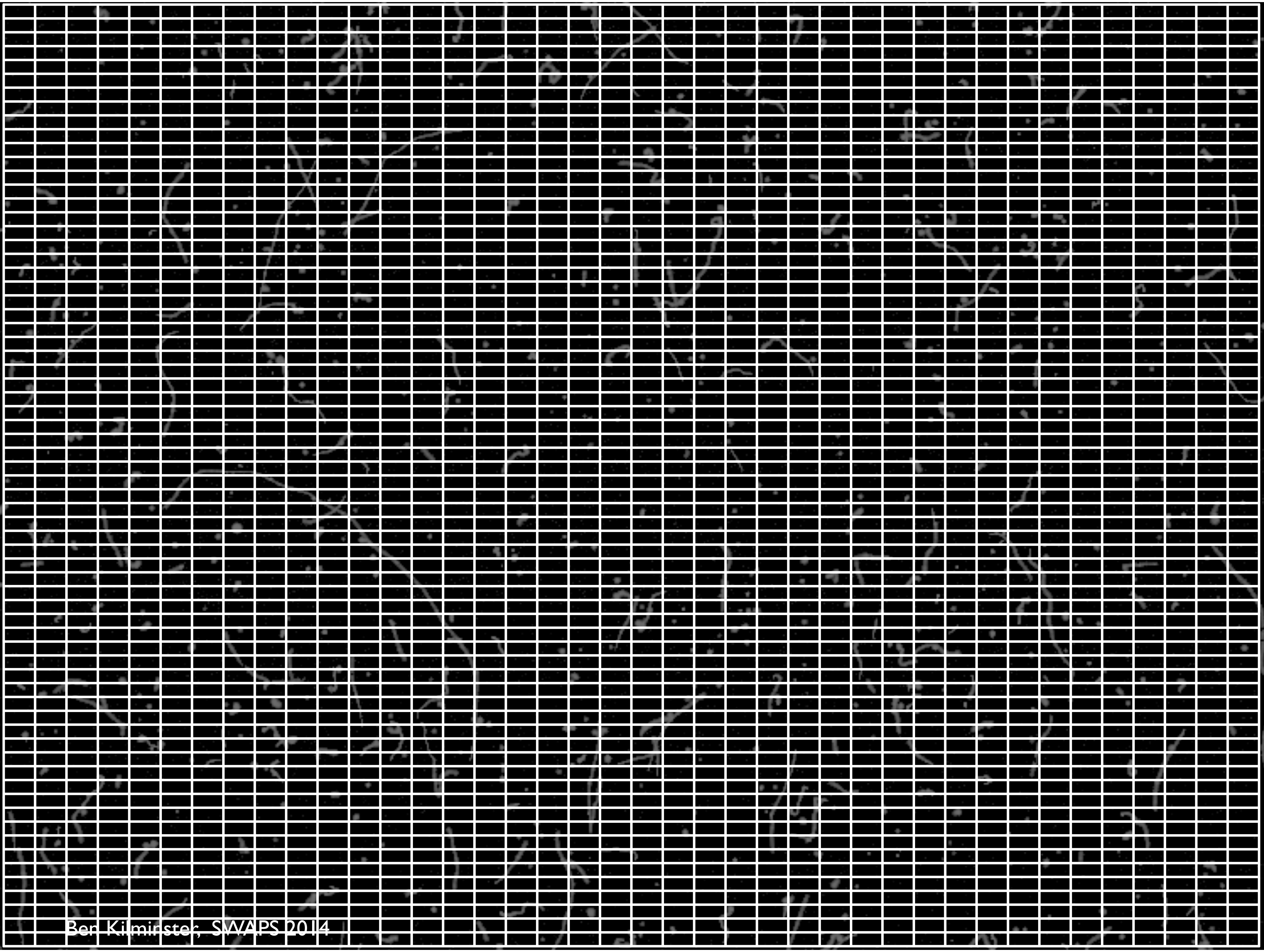
Pixel size:	15 μm x 15 μm
Number of pixels:	2000 x 4000
CCD Thickness:	250 μm (now up to -675 μm)
CCD Mass:	1 gram
Operation Temp:	150 K



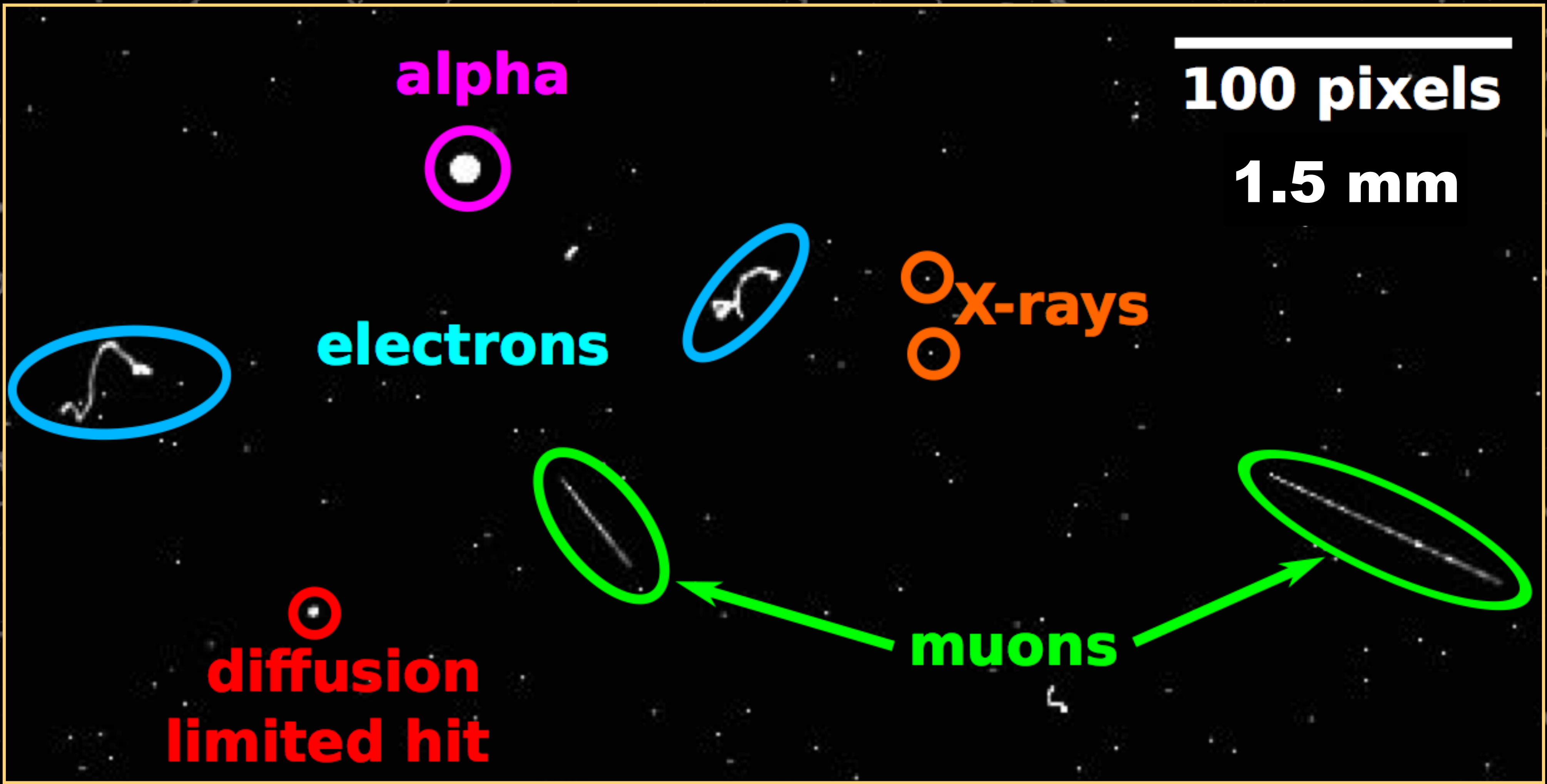


Particle response


(This background is a CCD image)


Ben Kilminster, SWAPS 2014

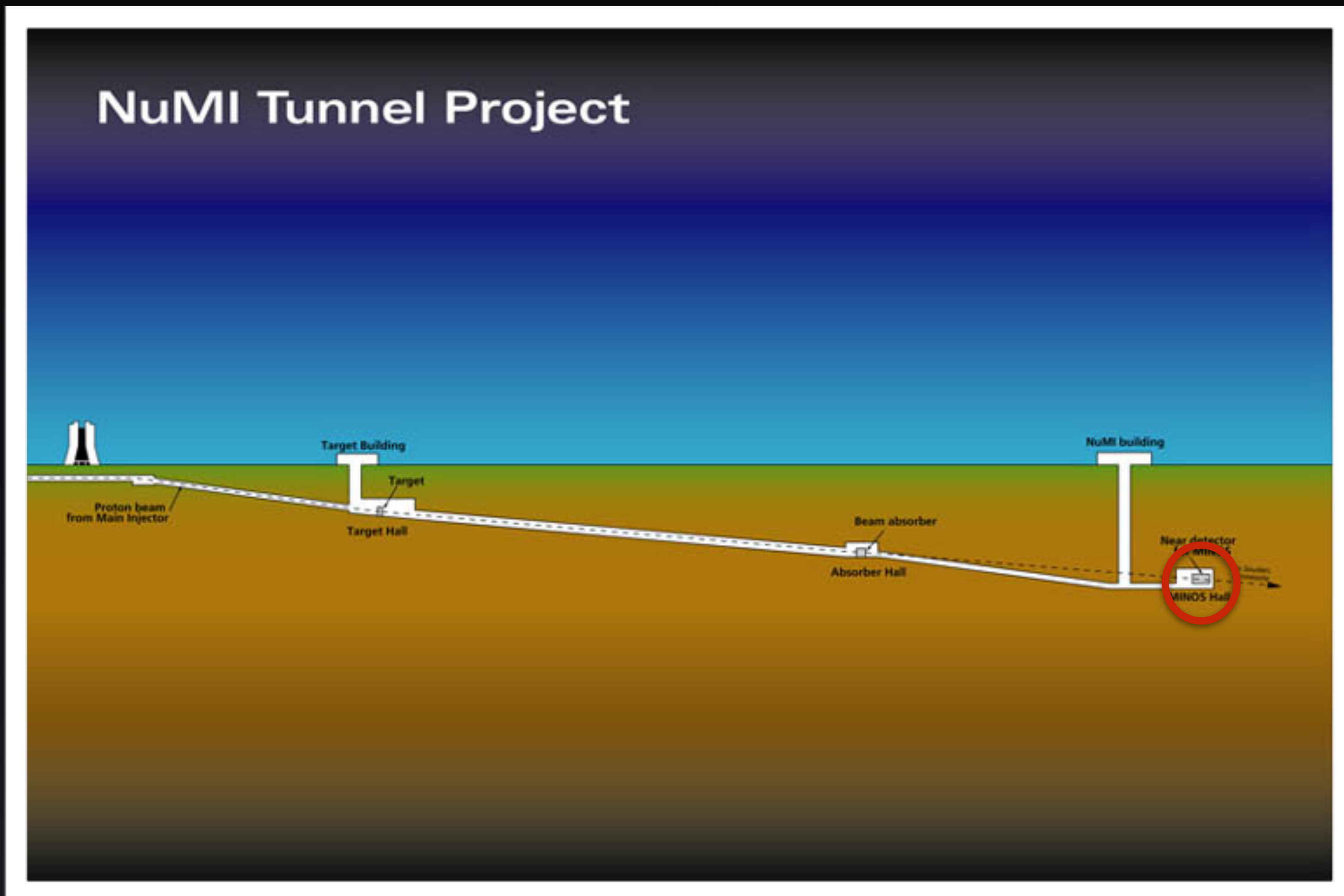
Particle identification in CCD



pixel size : 15 x 15 um^2

DAMIC first run

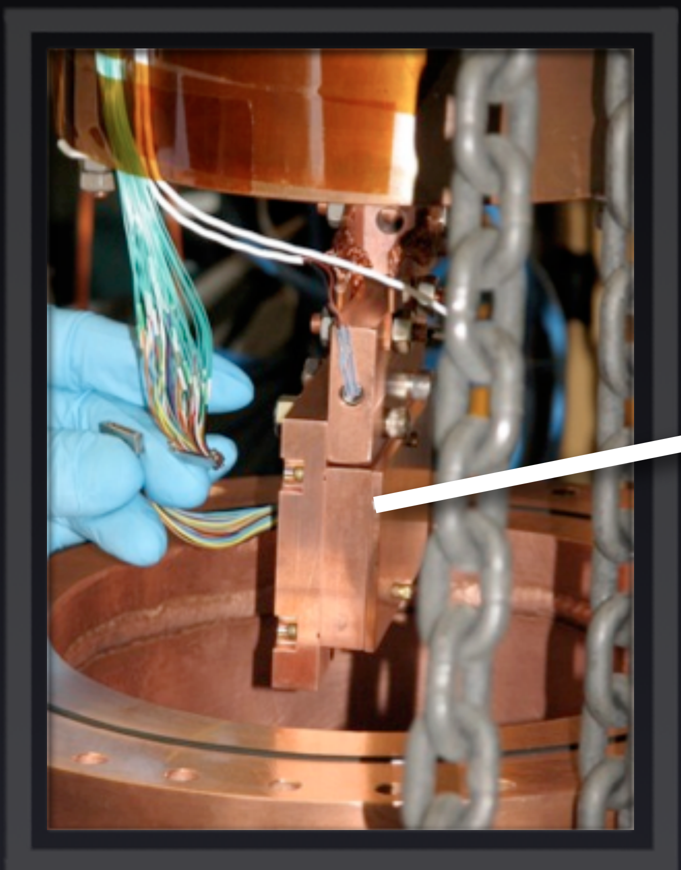
DAMIC 2011



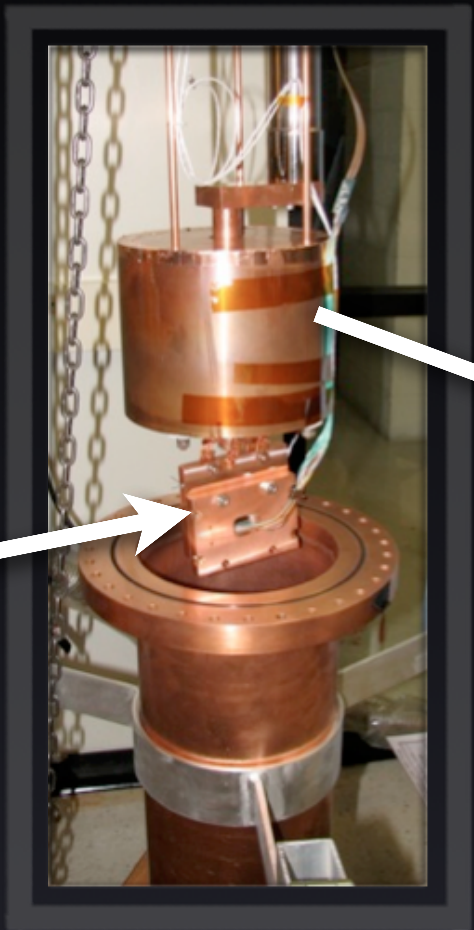
~ 100 meters deep

DAMIC 2011

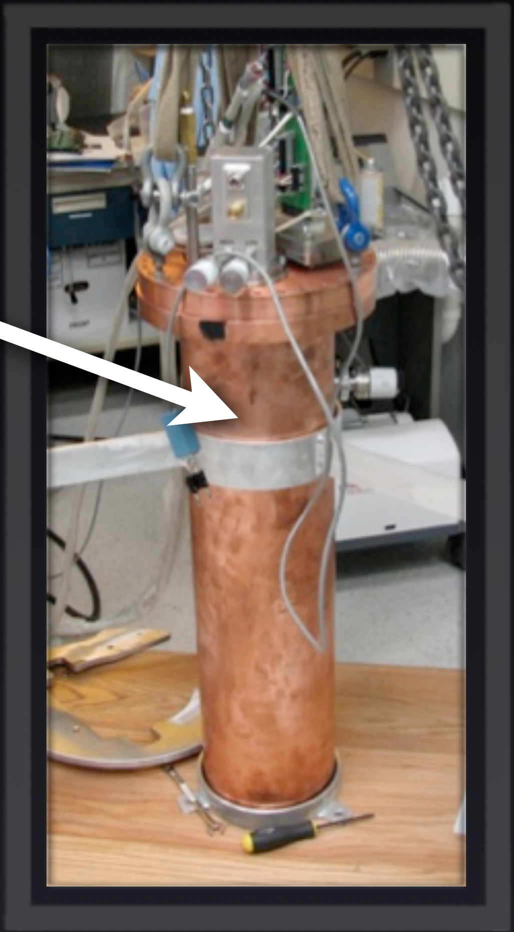
CCD Inside a cold Cu box



Lead Bucket



Cylindrical Cu Dewar

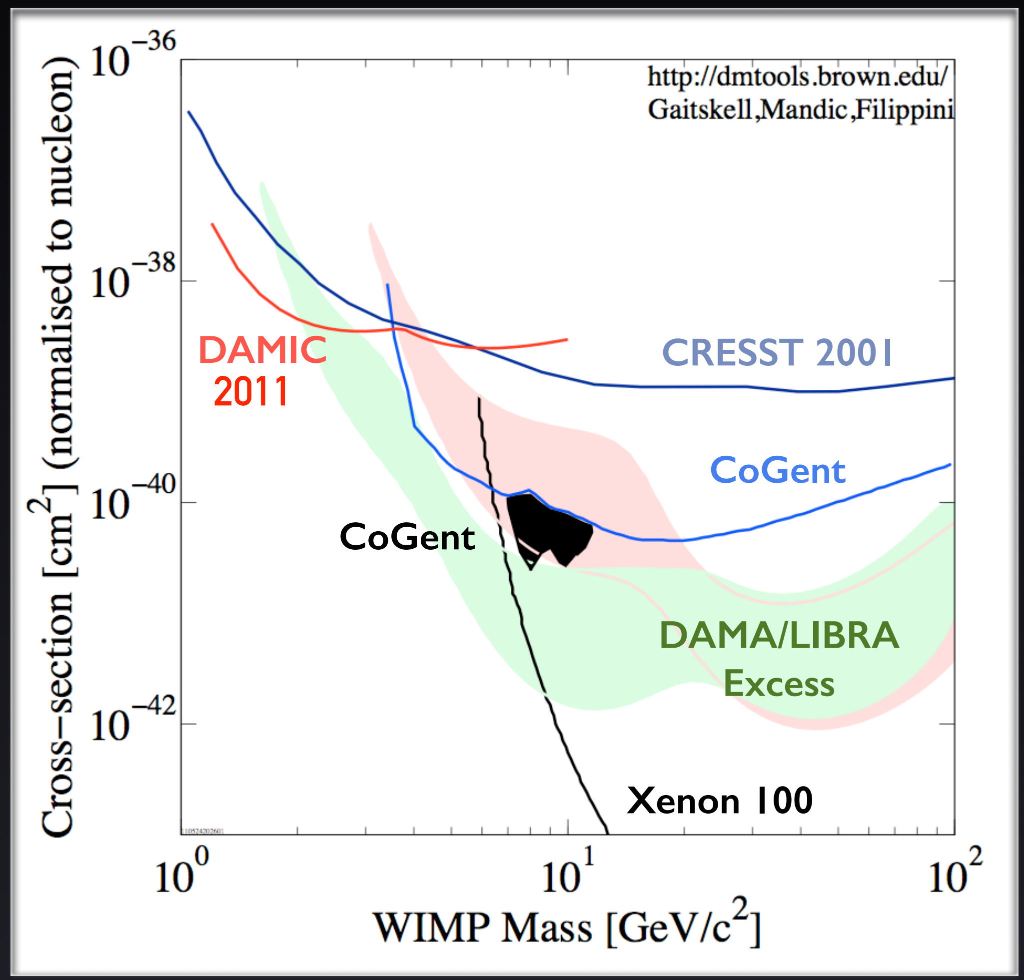


Results from 2011 Run

Assumes Lindhard quenching factor for conservative limits

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

Data : 107 g*days



Results from First Run

Direct Search for Low Mass Dark Matter Particles with CCDs

J. Barreto[1], H. Cease[2], H.T. Diehl[2], J. Estrada[2], B. Flaugher[2], N. Harrison[2] J. Jones[2], B. Kilminster[2], J. Molina[3], J. Smith [2] , T. Schwarz[4] and A. Sonnenschein[2]

[1] *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*

[2] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*

[3] *Facultad de Ingenieria, Universidad Nacional de Asuncion (FIUNA), Asuncion, Paraguay*

[4] *University of California at Davis, USA.*

(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 experiments have been optimized for detecting the elas-

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... ...ology.

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

Noise 2e- → 0.2 e-
5σ threshold → 4 eV

Calibrations : determine ionization efficiency for low energy nuclear recoils

Stronger collaboration

Deeper to Snolab

DAMIC

Measure limiting impurities in silicon itself

Improve detector materials & shielding radiopurity

More massive CCDs

DAMIC Collaboration

(DArk Matter In CCDs)

International collaboration: 8 institutions from 6 countries

DAMIC

Argentina:	Centro Atómico Bariloche
Brazil:	Universidade Federal do Rio de Janeiro
Canada:	SNOLAB
Mexico:	Universidad Nacional Autónoma de México
Paraguay:	Universidad Nacional de Asunción
Switzerland:	Universität Zürich (UZH)
United States:	Fermilab, U. Chicago, U. Michigan

Performance

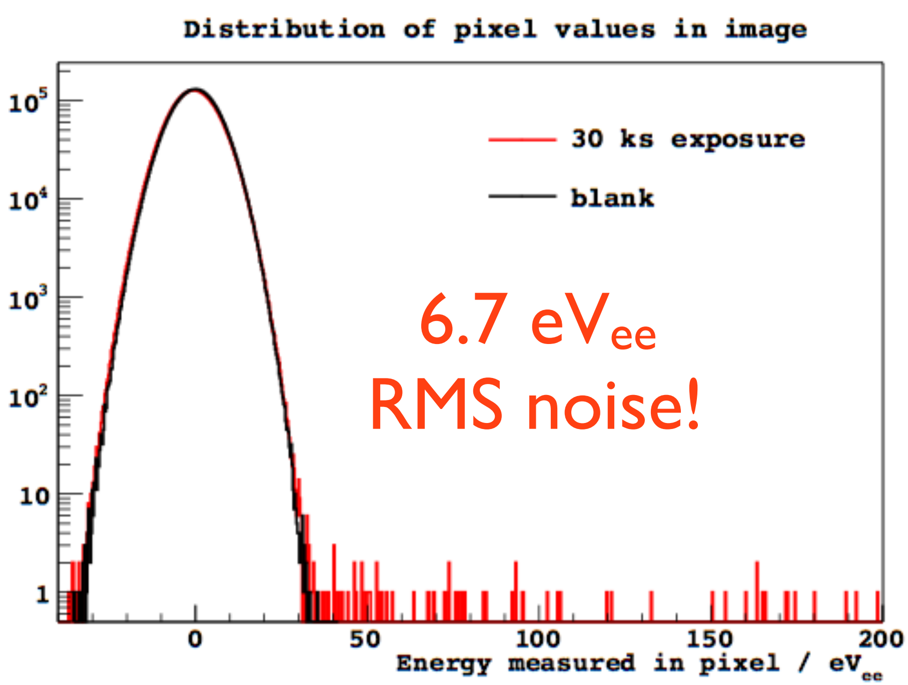
CCD Performance

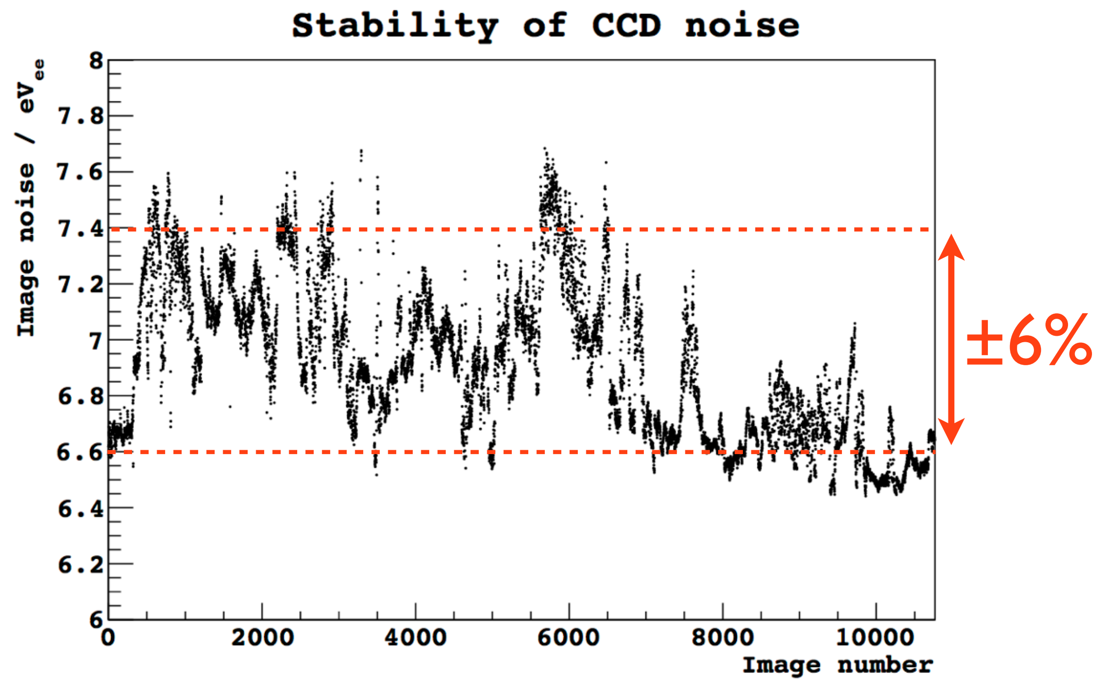
CCDs are manufactured with very high resistivity silicon:

Low radioactive backgrounds.

Low dark current (0.01 e^- / pix / day).

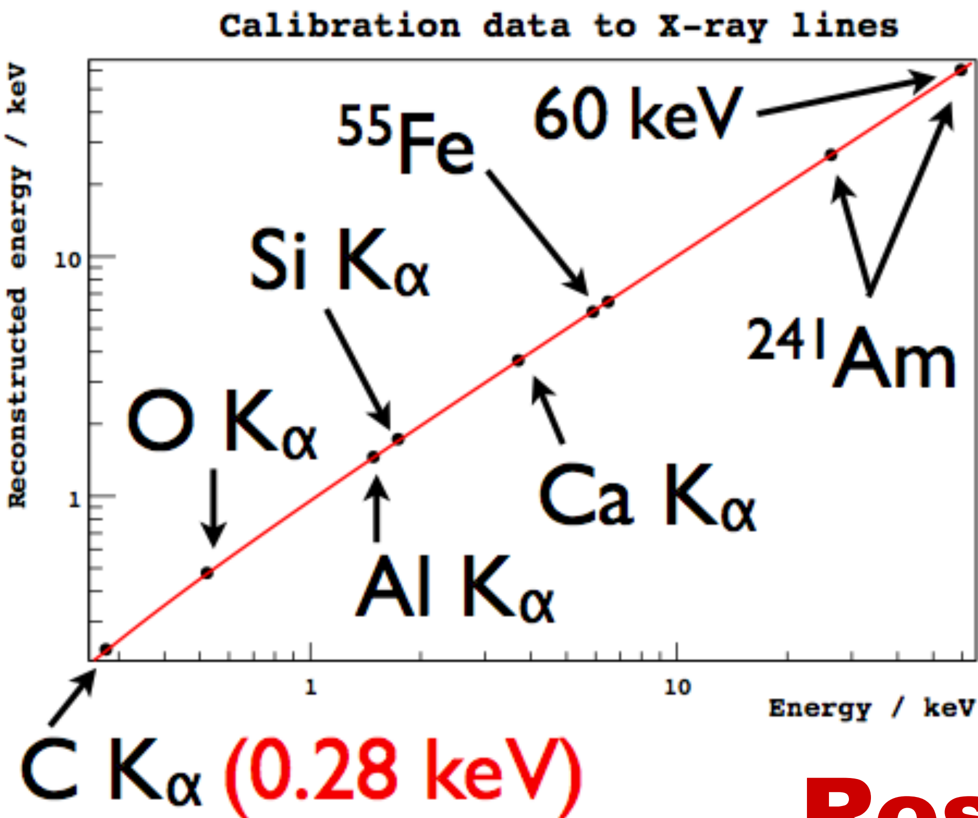
Very few (if any) defects in the silicon lattice.

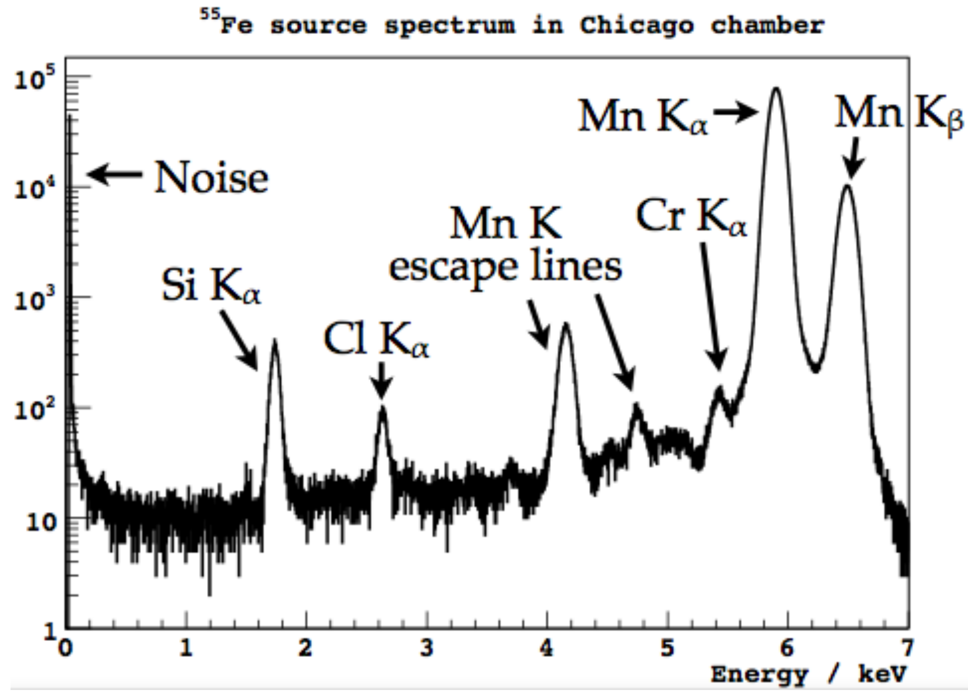




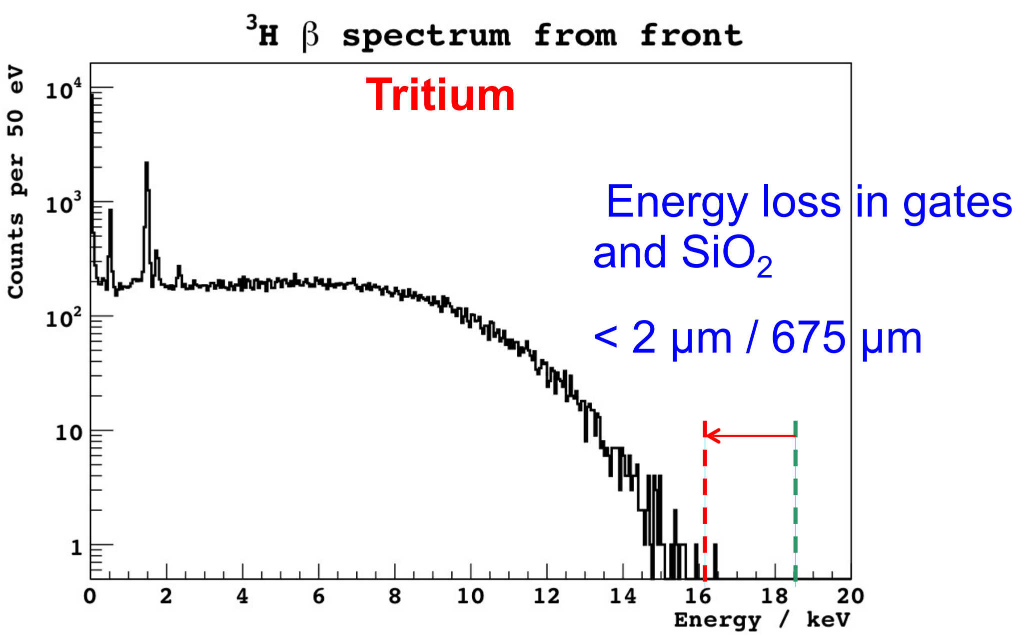
>95% of the image good quality.

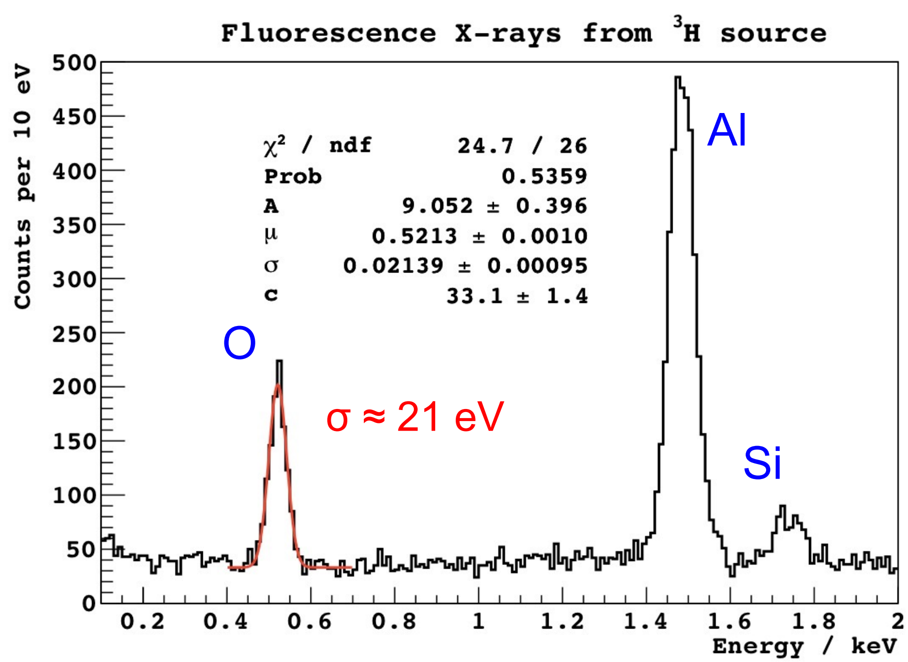
10794 images acquired over 126 days. All good.





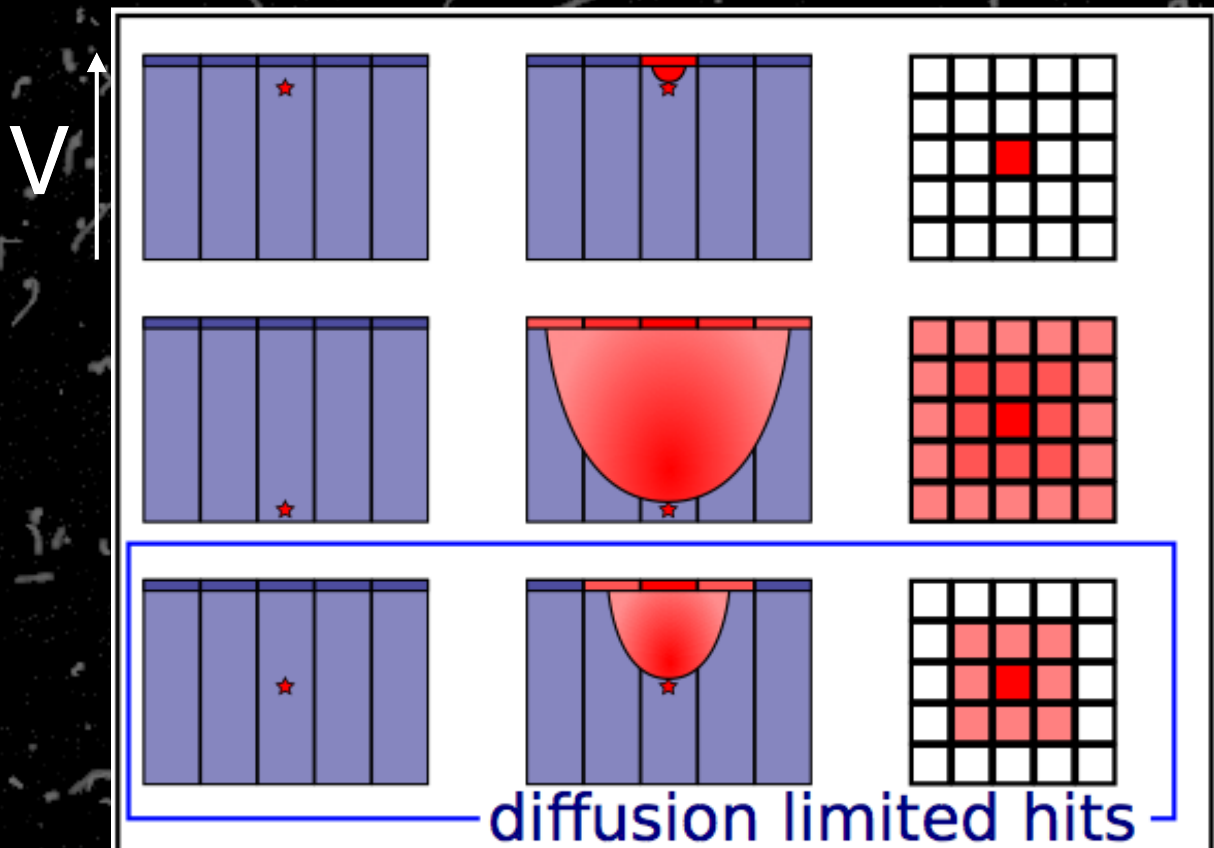
Response to electrons



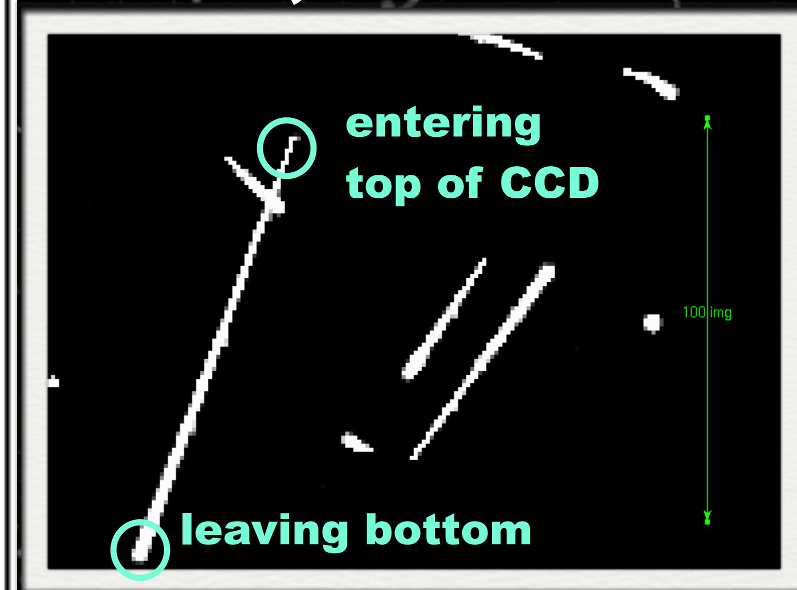


Diffusion of charge

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



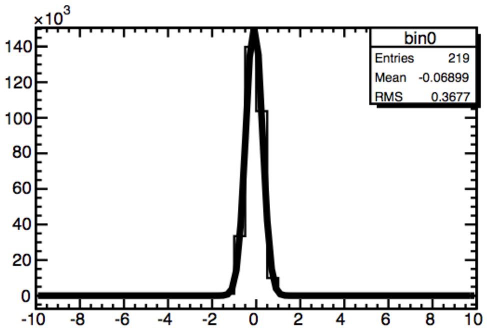
ie, muons



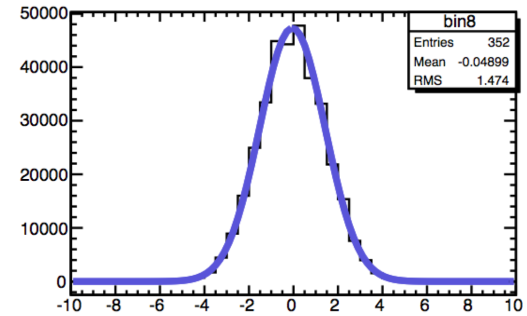
- **Maximal (minimal) diffusion at bottom (top) of CCD**

Depth reconstruction

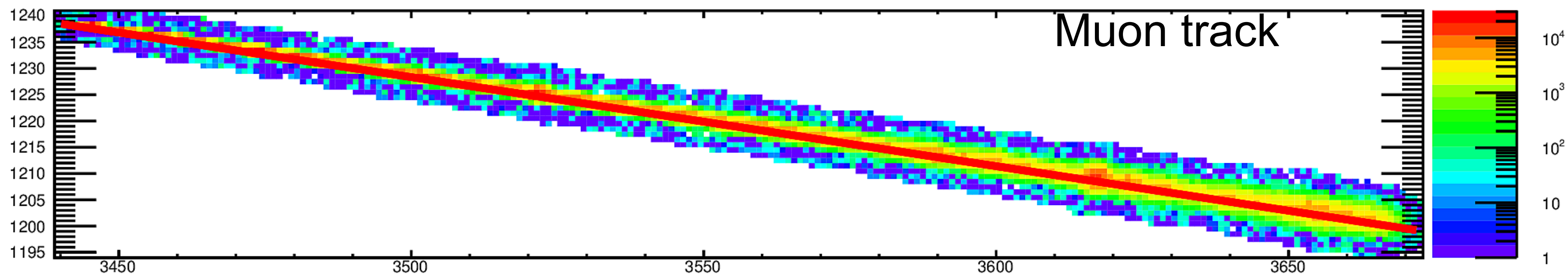
front



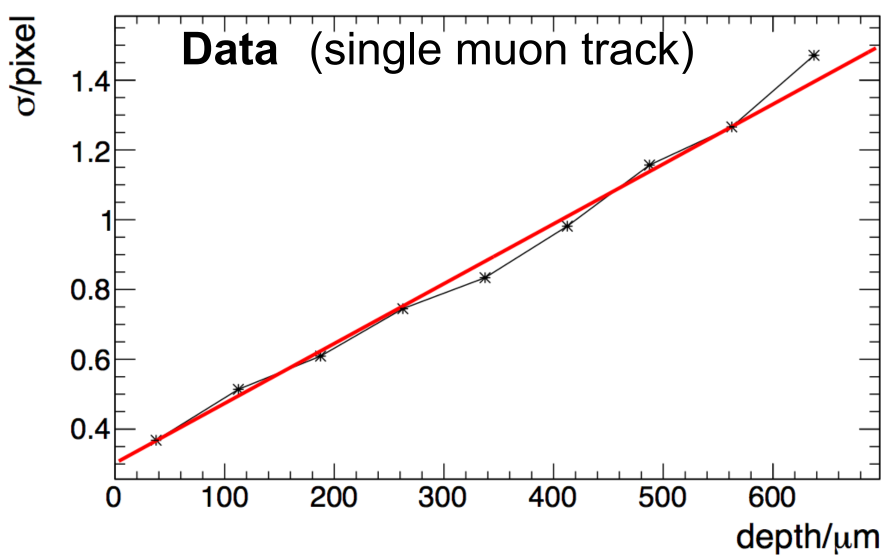
back



- Calibration with muon tracks (at ground level)



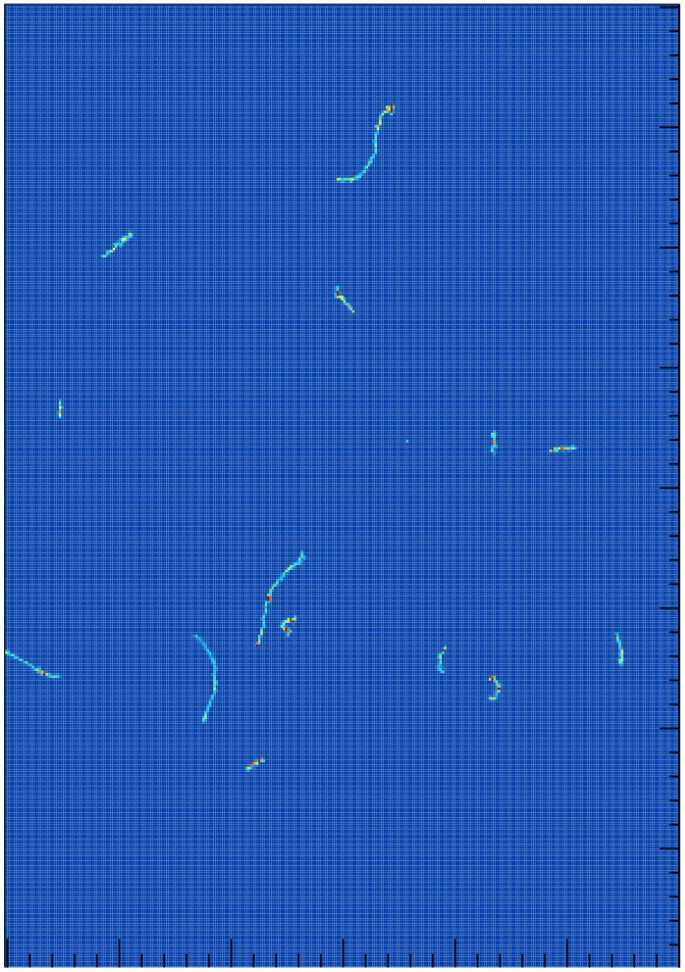
675 µm thick CCD



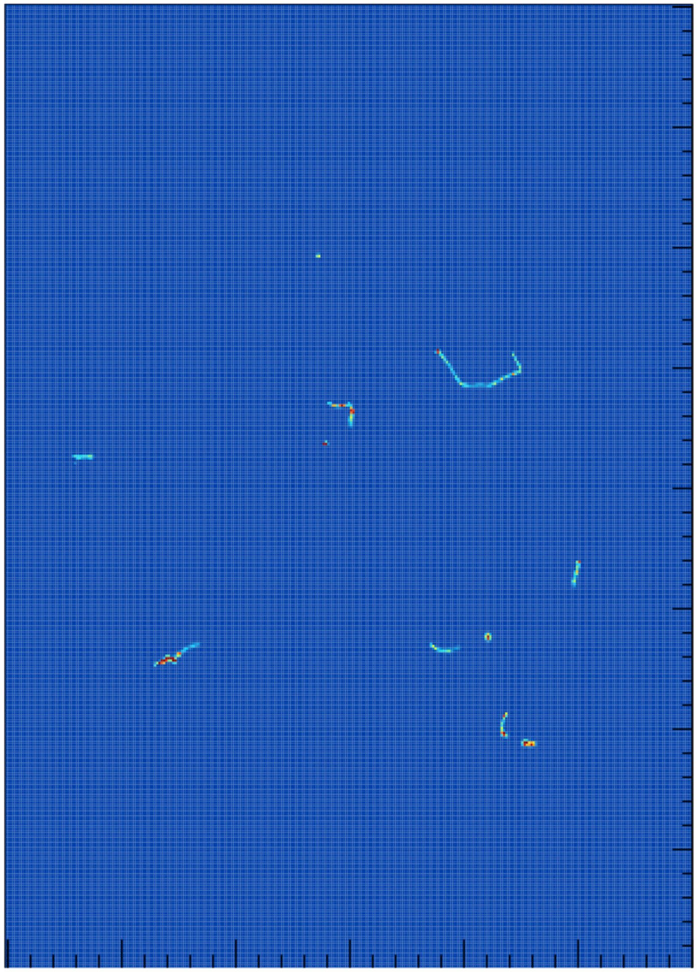
- Diffusion model validated by muon and X-ray data

Interactions can be simulated

- **MCNPX simulation -> background model**



Simulated βs



Data

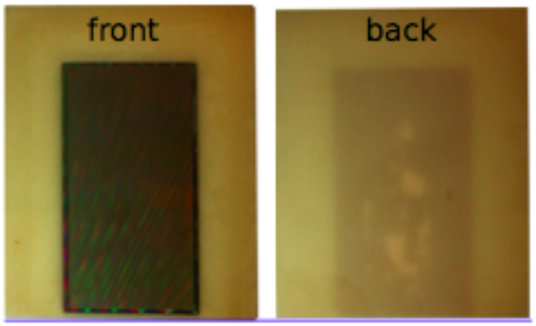
Uses diffusion model determined from muon tracks

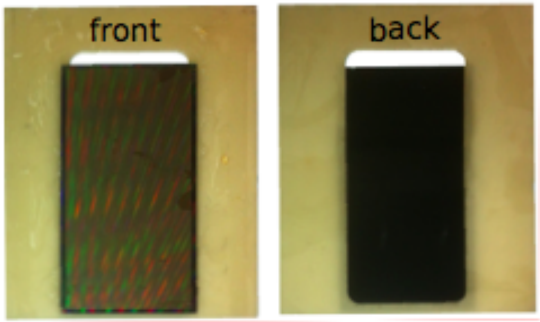
R&D: background reduction

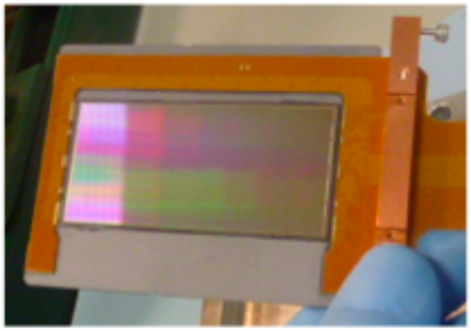
Full AlN

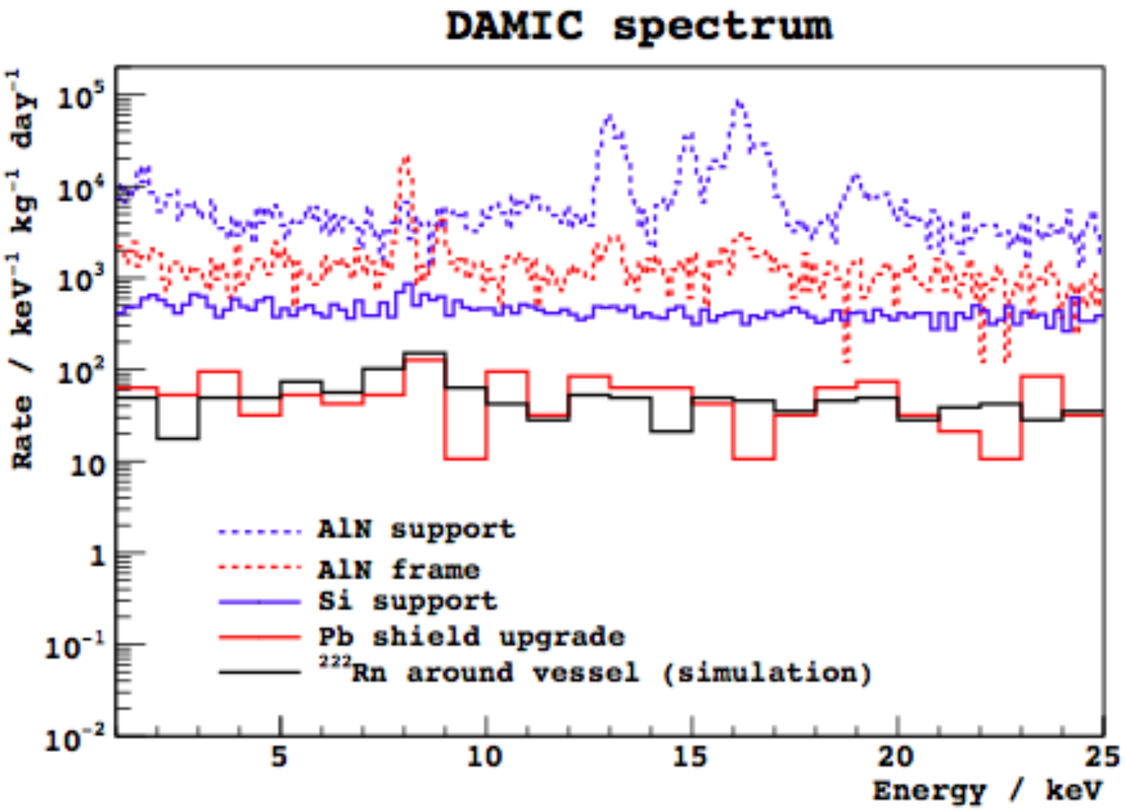
Frame AlN

Si Support





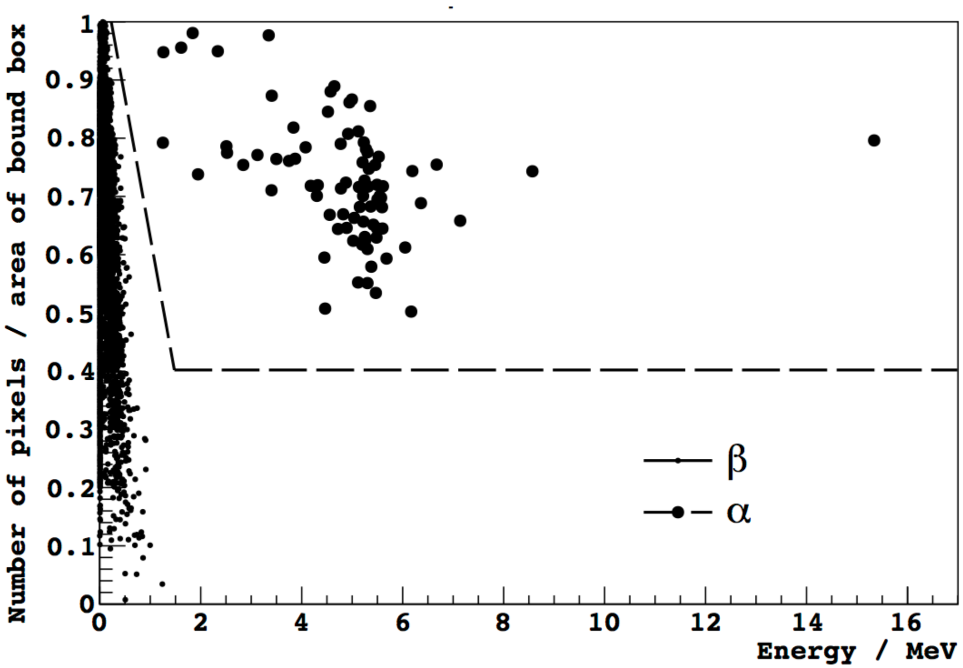




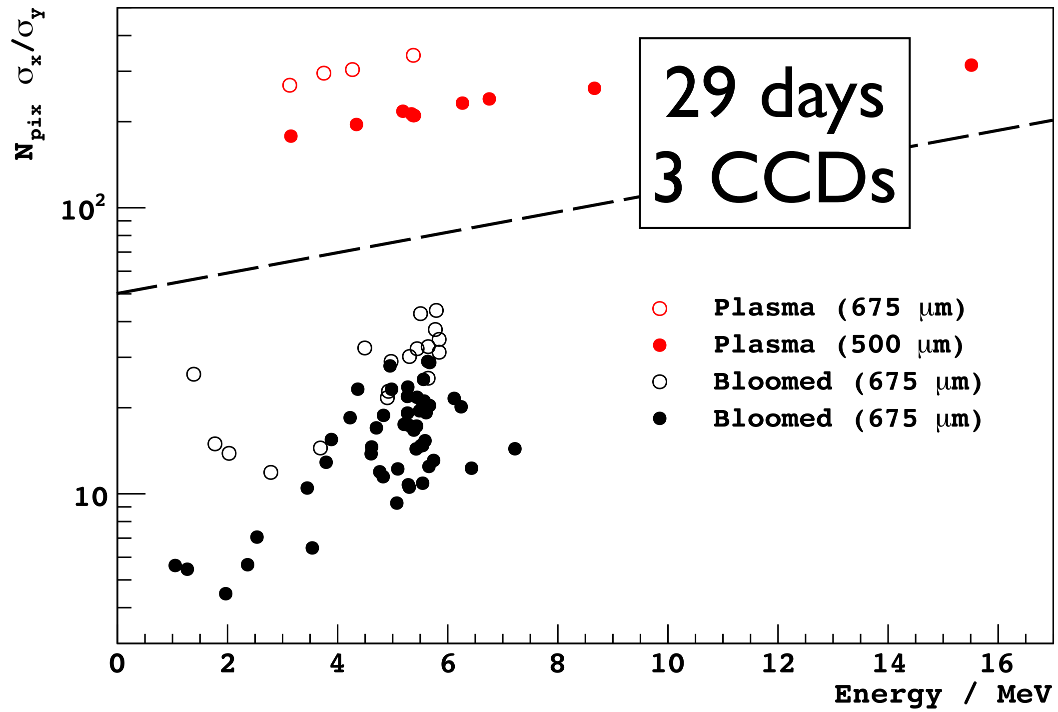
Silicon radioimpurity

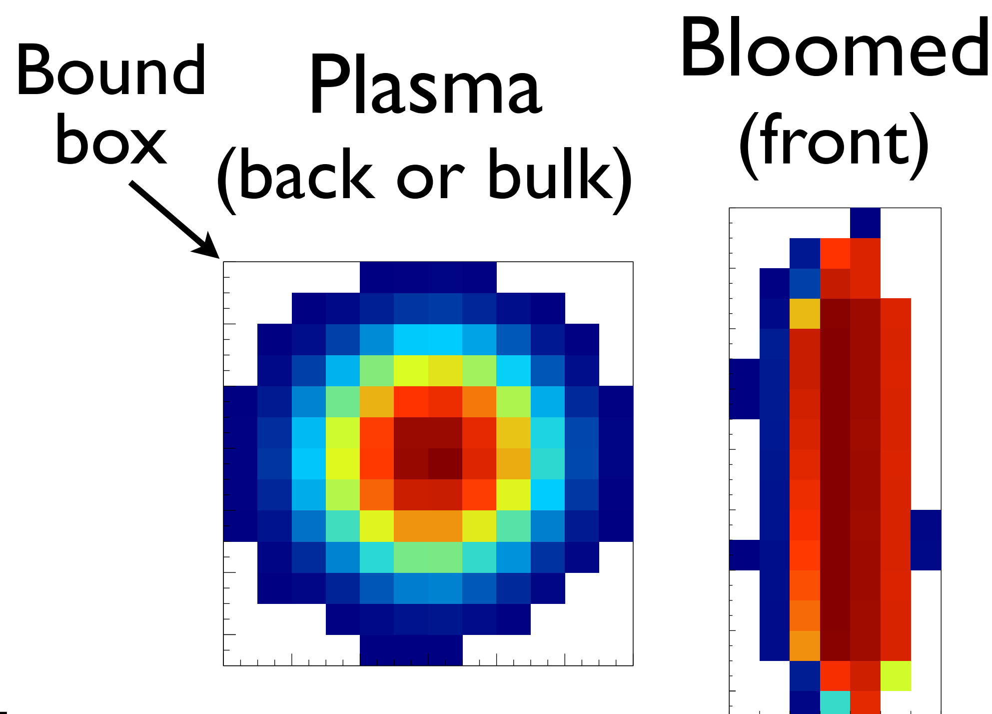
^{32}Si, ^{238}U, ^{232}Th

α particles



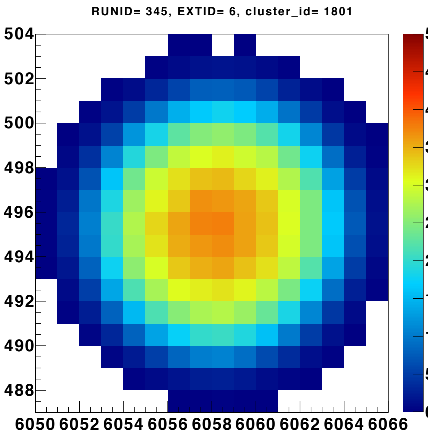
α-β discrimination based on shape of track.



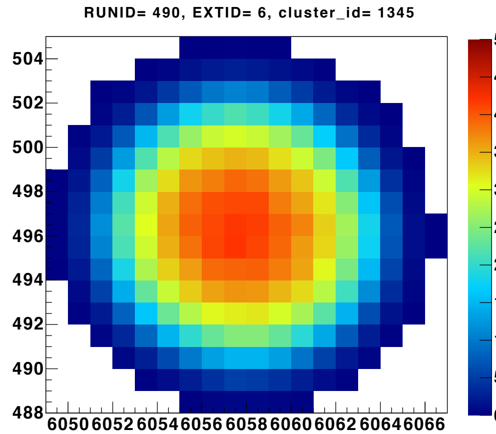


DAMIC unique spatial resolution

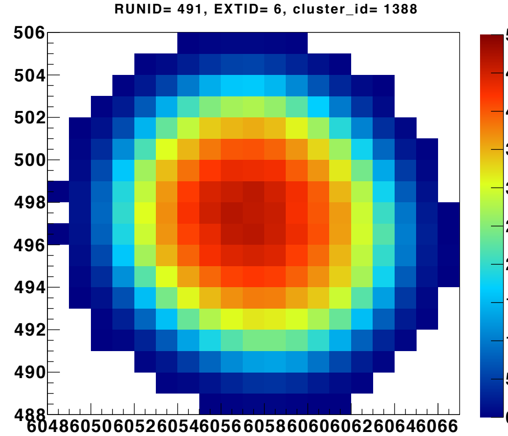
E = 5.4 MeV



E = 6.8 MeV



E = 8.8 MeV



1 $\Delta t = 17.8$ d 2 $\Delta t = 5.5$ h 3

Three α at the same location!

Limits on contamination:

^{238}U < 5 kg^{-1} d^{-1} = 4 ppt

^{232}Th < 15 kg^{-1} d^{-1} = 43 ppt

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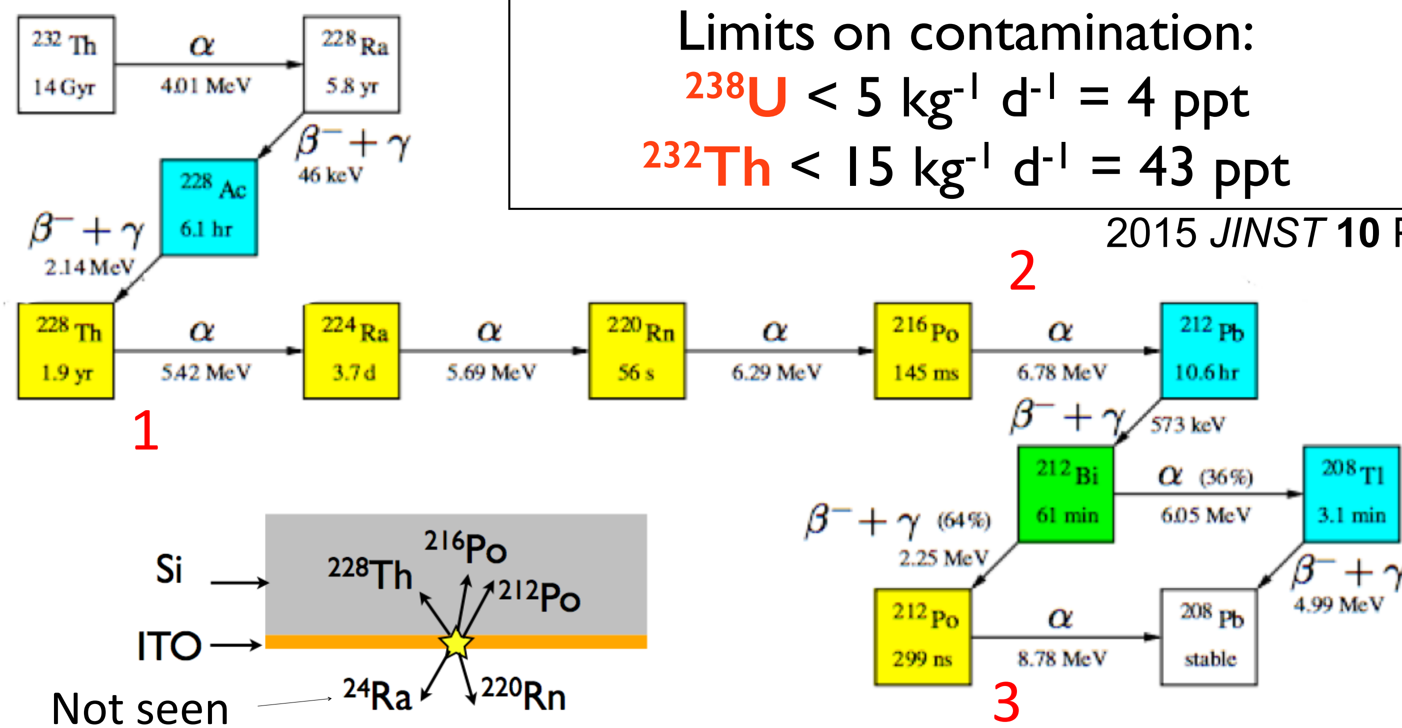
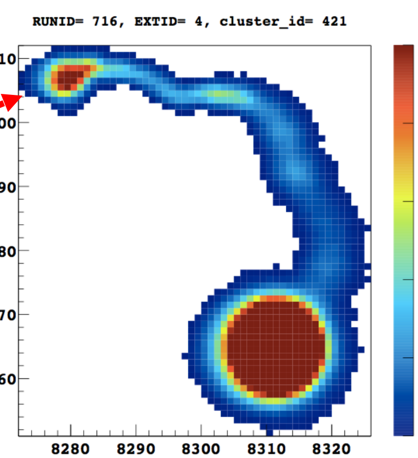


Example of α + β

Bragg peak



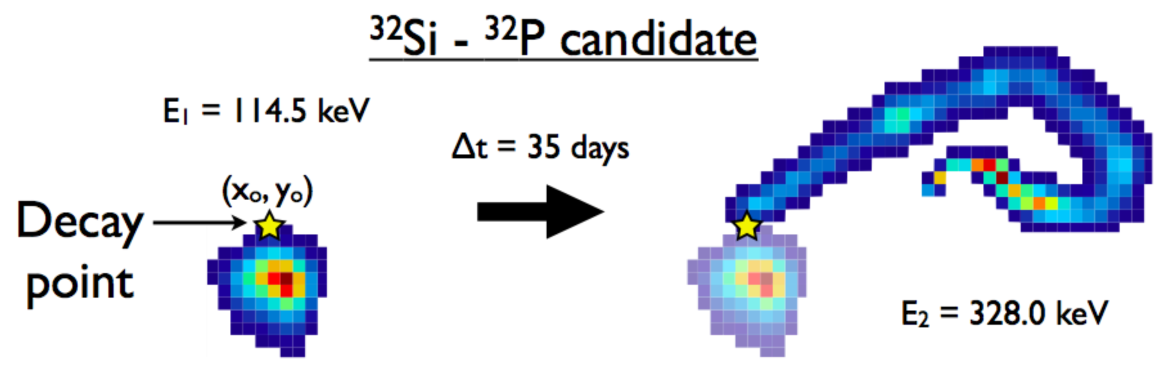
Cosmogenic ^{32}Si

$$^{32}Si \xrightarrow{0.22\ \mathrm{MeV}} {}^{32}P \xrightarrow{1.7\ \mathrm{MeV}} {}^{32}S$$

$T_{1/2} = 14$ d

- <u>Must be demonstrated to be low for any Dark Matter search in silicon without electron rejection</u>

- Search for sequences of βs starting in the same pixel of the CCD in different images



$$^{32}Si = 80^{+110}_{-65}\ \mathrm{kg}^{-1}\,\mathrm{d}^{-1}\ (95\%\ \mathrm{CI})$$

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≈ 100 kg^{-1} day^{-1} corresponds to ≈1 dru at low energy!

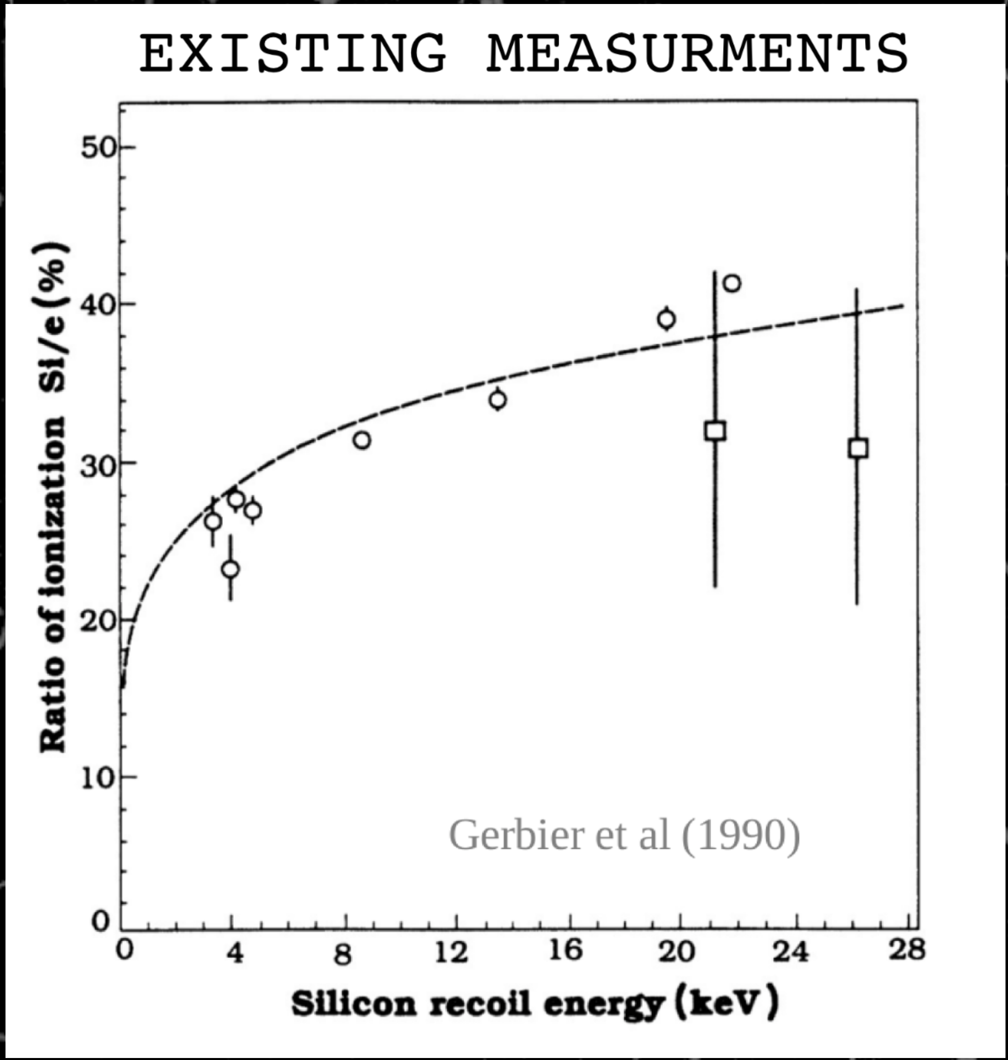
- Statistically limited, will be measured precisely by DAMIC100.

<u>DAMIC unique spatial resolution and excellent duty cycle allows to reject this background</u> (also other β-β sequences e.g. ^{210}Pb)

Low energy quenching factor

Quenching factor

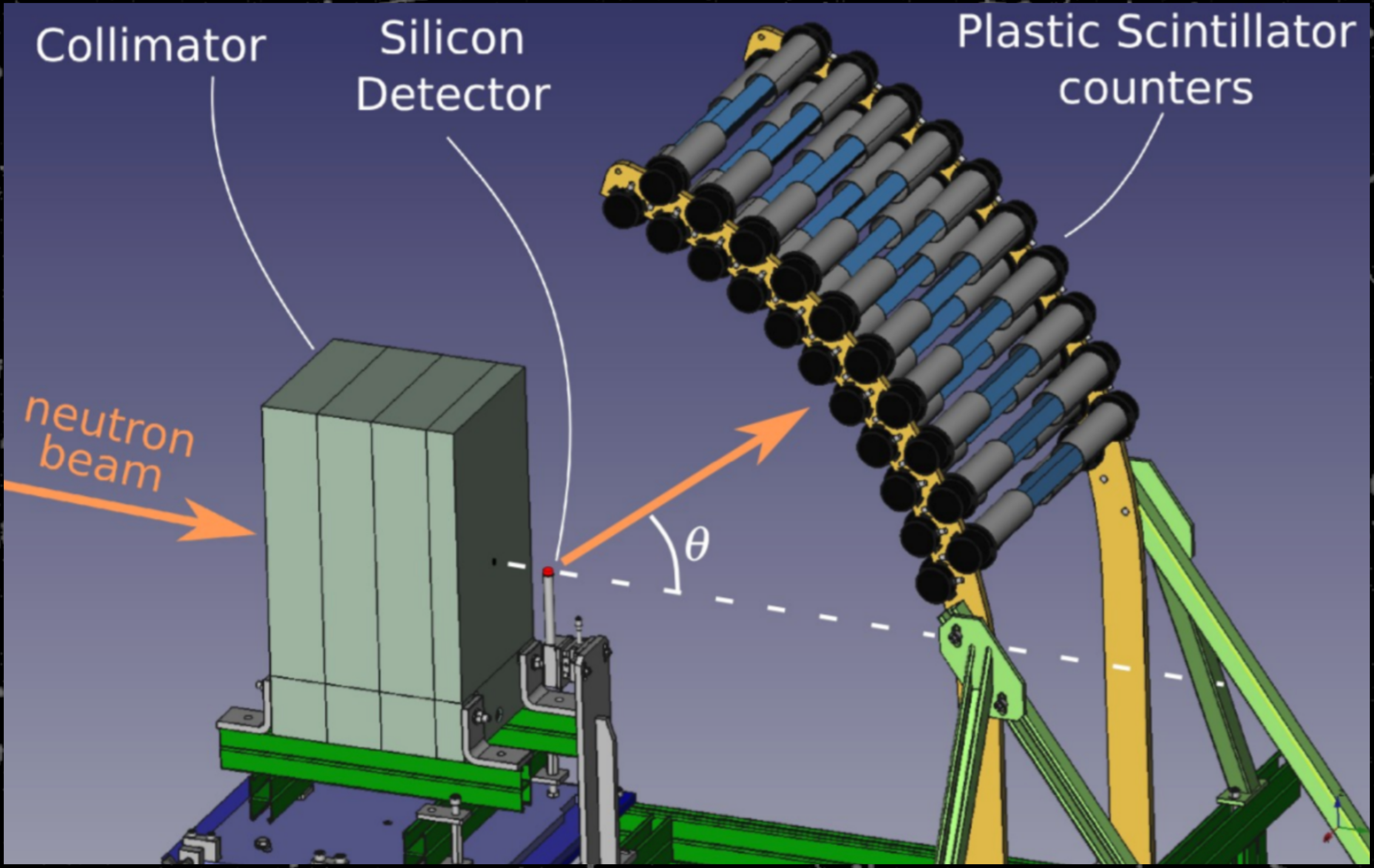
- Existing data points only go down to 4 KeV
- Line shows Lindhard theory used by experiments



Low energy neutron calibrations

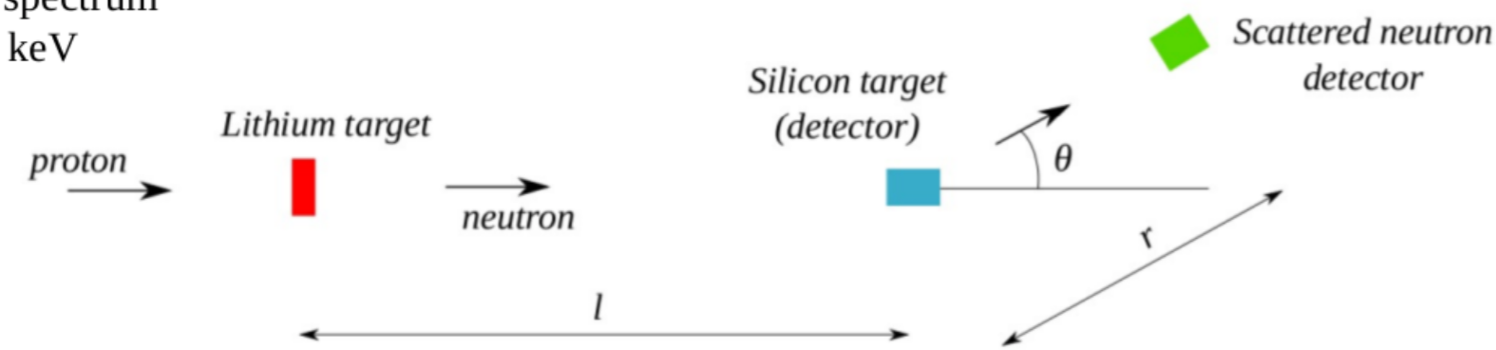
- DAMIC collaborators have done two experiments to test Lindhard theorem below 4 KeV down to threshold
  - Antonella: Neutron scattering experiment
  - Photoneutron calibration

Antonella



Collimator
Silicon Detector
Plastic Scintillator counters
neutron beam
θ

Broad neutron spectrum
E_n in [50, 600] keV



$$E_n = \frac{m}{2(\Delta t)^2}\left[l + r\,\frac{(A+1)}{\cos\theta + \sqrt{A^2 - \sin^2\theta}}\right]^2 \qquad (1)$$

Δt = neutron total Time-of-flight

$$E_{NR} = E_n\,\frac{2}{(A+1)^2}\left[A + \sin^2\theta - \cos\theta\sqrt{A^2 - \sin^2\theta}\right] \qquad (2)$$

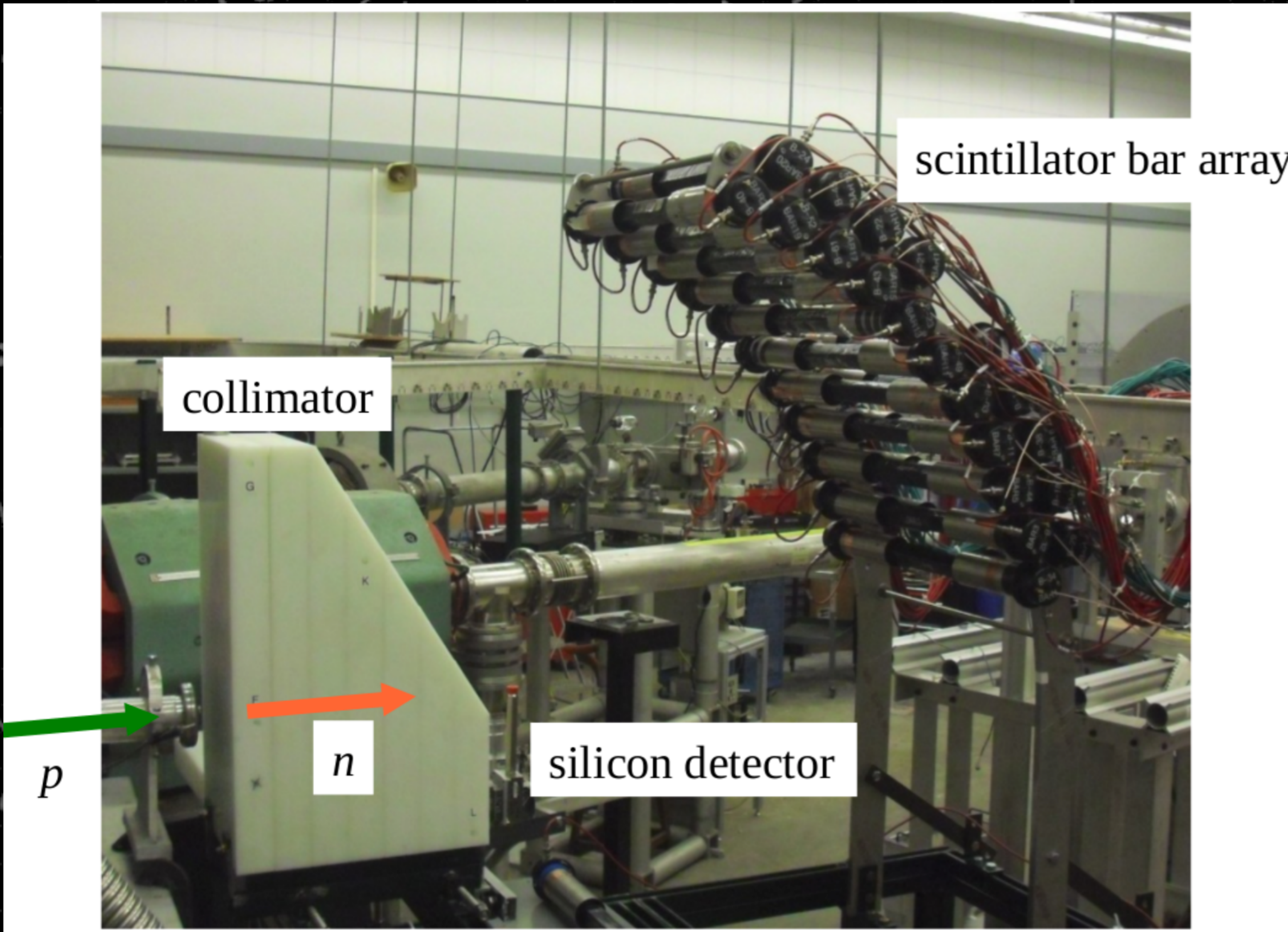
Program:

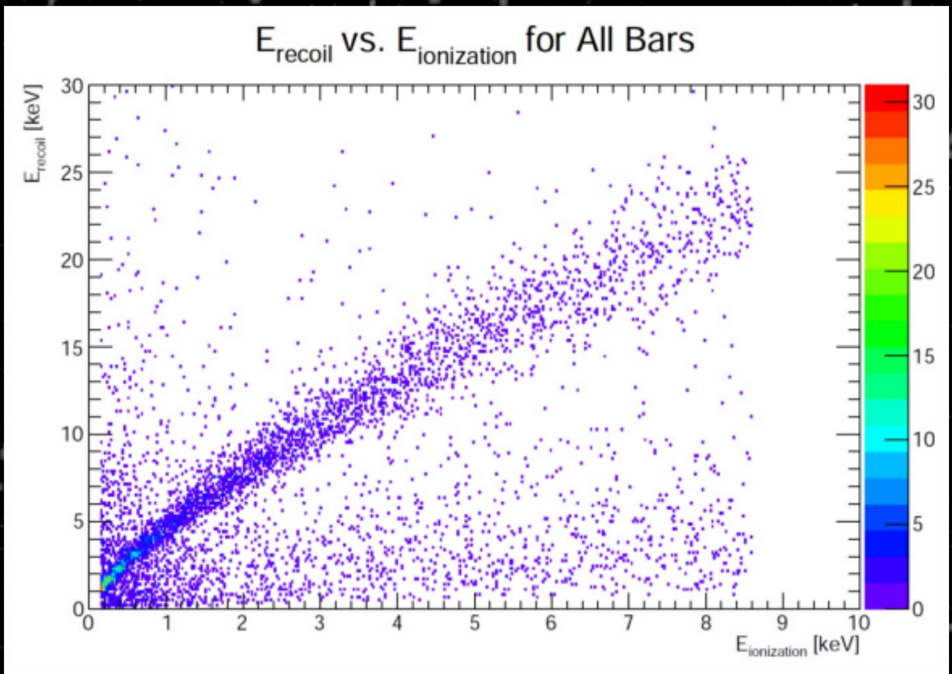
1. Measure neutron energy by time-of-flight (1)
2. Detect a scattered neutrons in a neutron detector
3. Measure charge produced by ionization
4. Calculate the nuclear recoil energy with kinematics (2)

$$Ion_{Eff} = \frac{E_{ionization}}{E_{NR}}$$

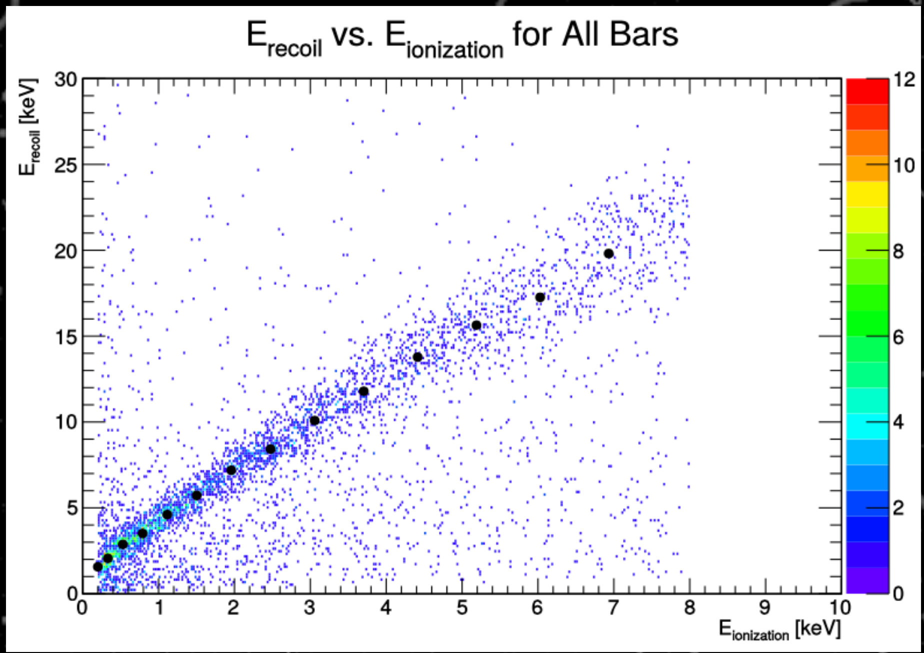
$(dE/dx)_{LiF}$ = 26 keV/μm

Target thickness = 18 μm ⟶ Maximize the neutron yield


scintillator bar array
collimator
n
p
silicon detector

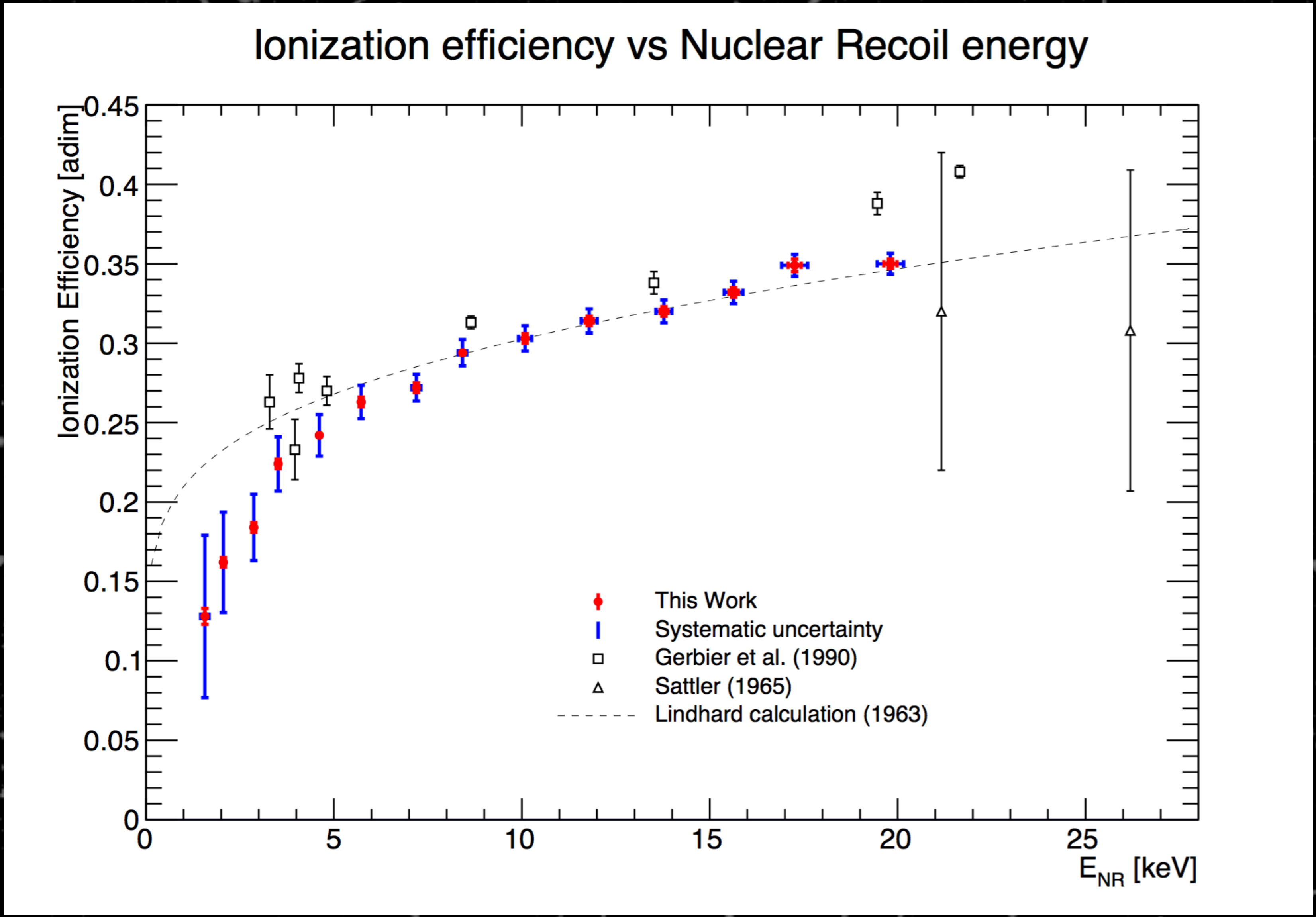


GEANT simulation



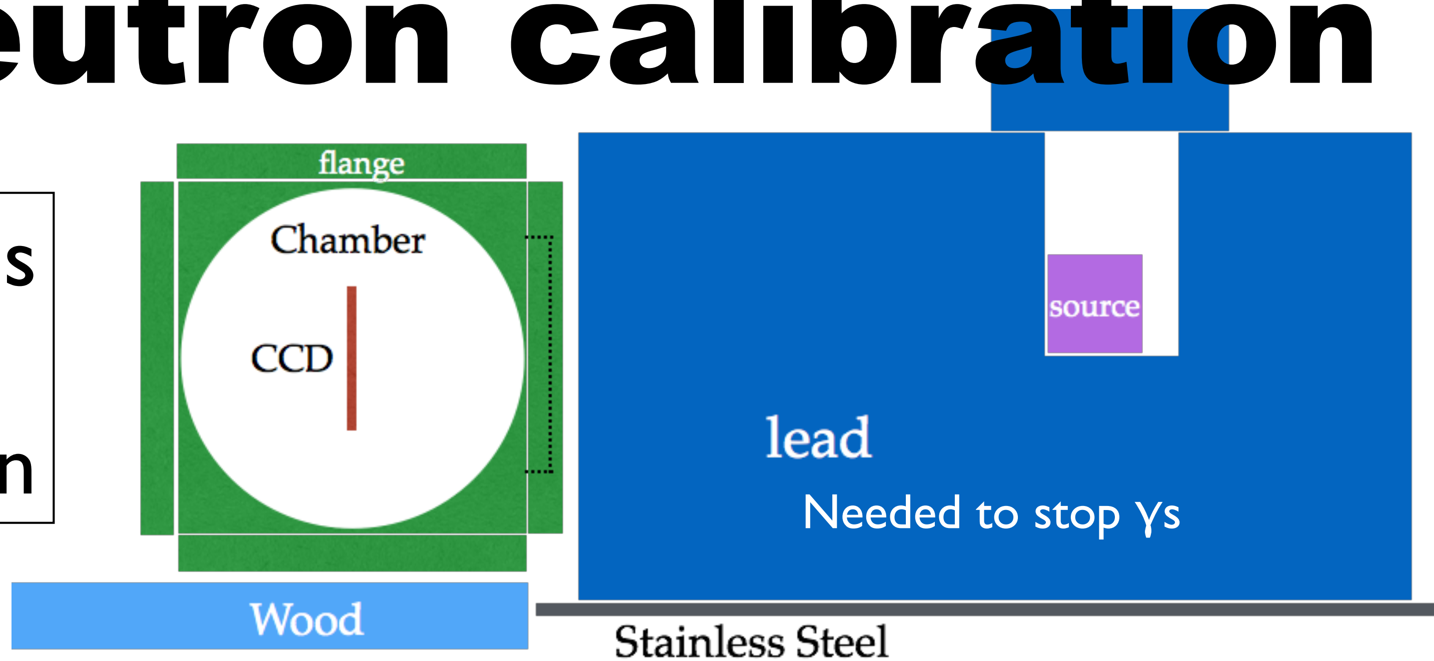
Data

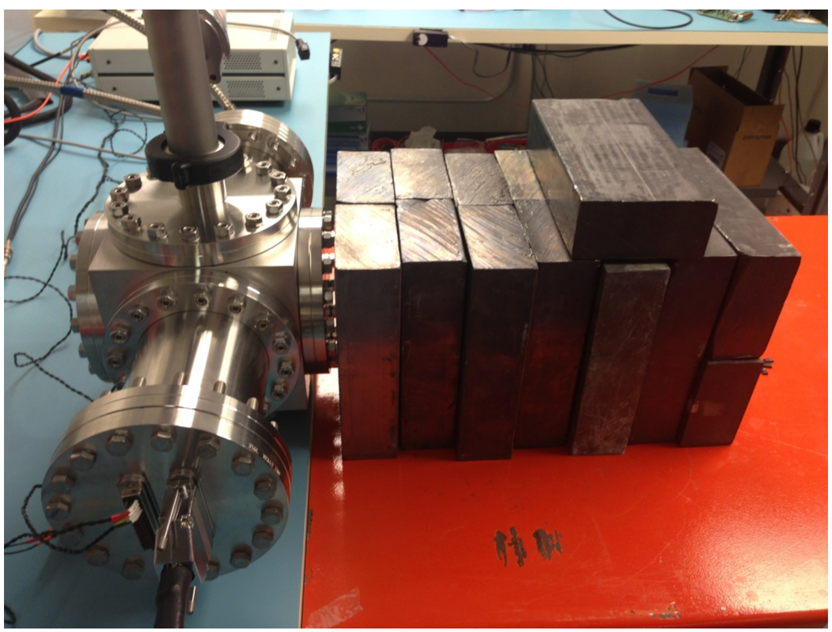
Antonella results

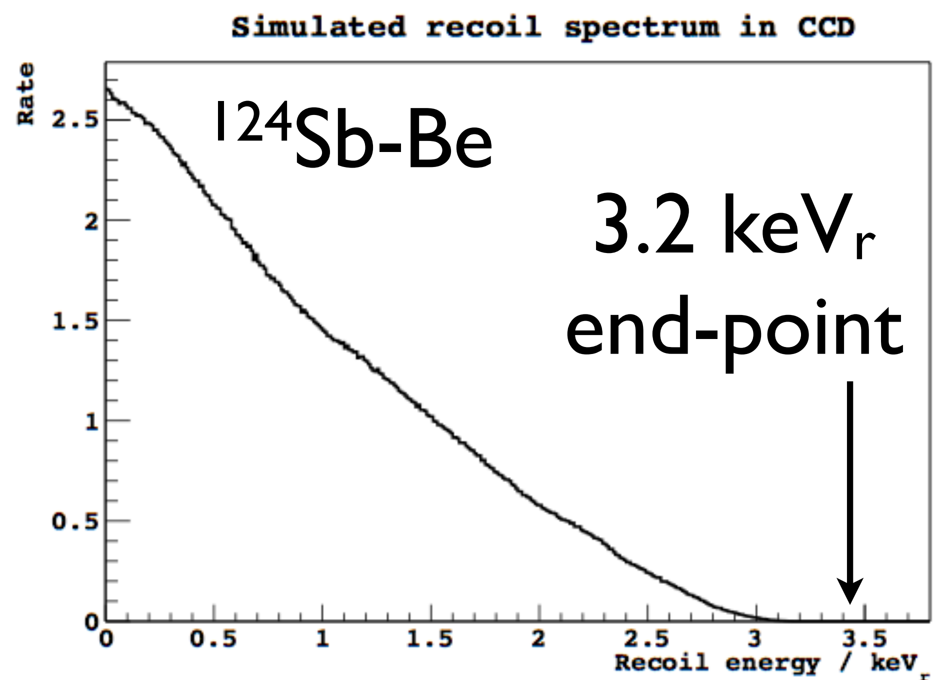


Photoneutron calibration

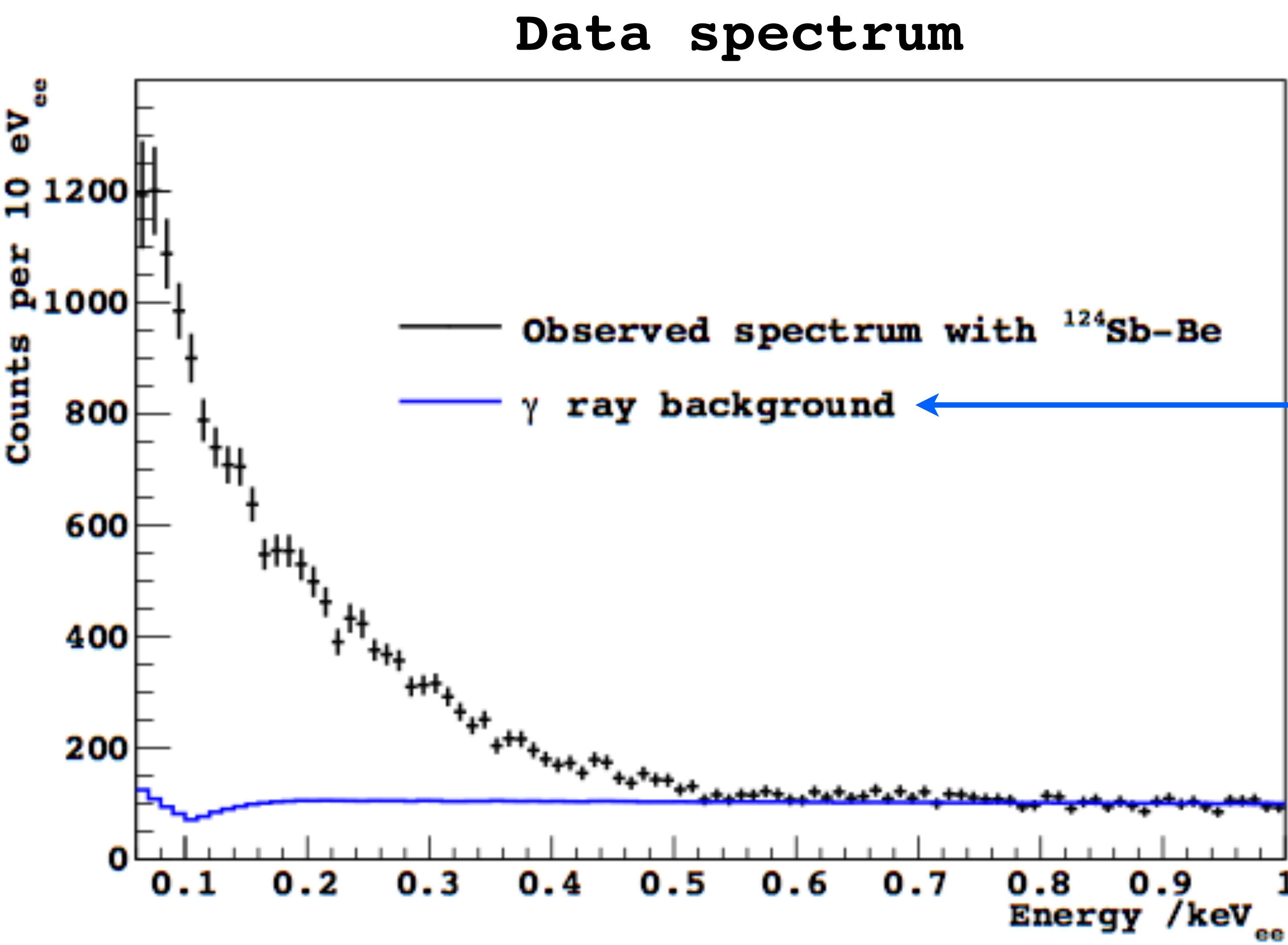
24 keV neutrons from $^{9}Be(\gamma,n)$ reaction







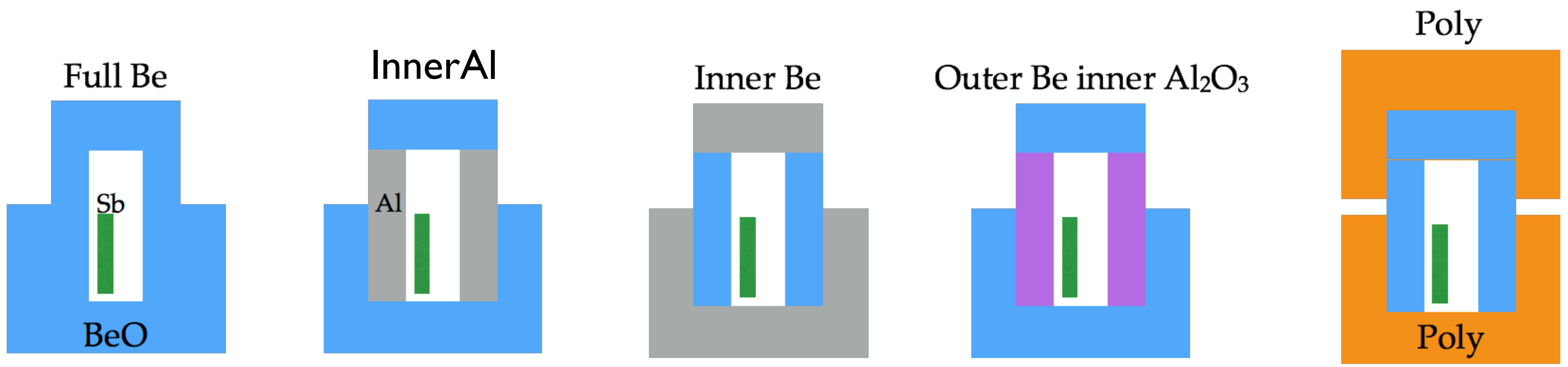
Observed spectrum

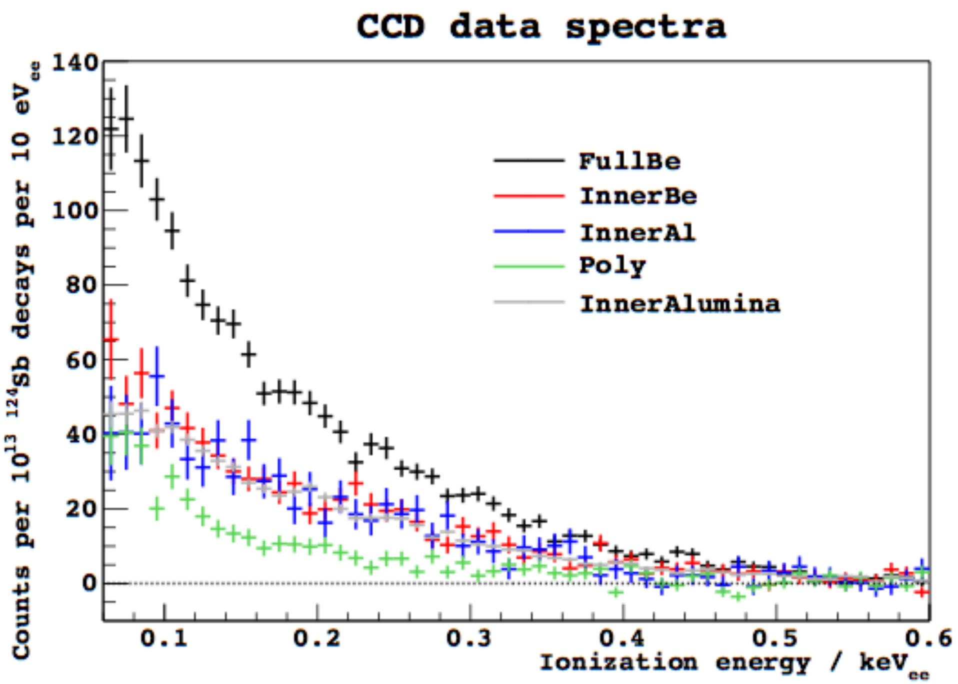


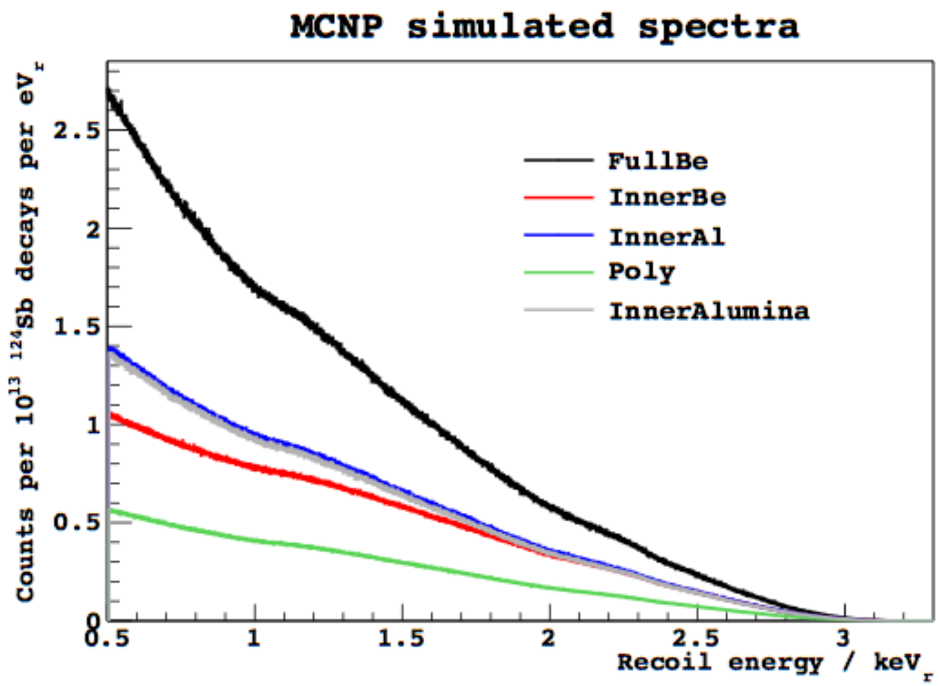
Normalized to count rate 2-5 keV$_{ee.}$

Uncertainty propagated in analysis.

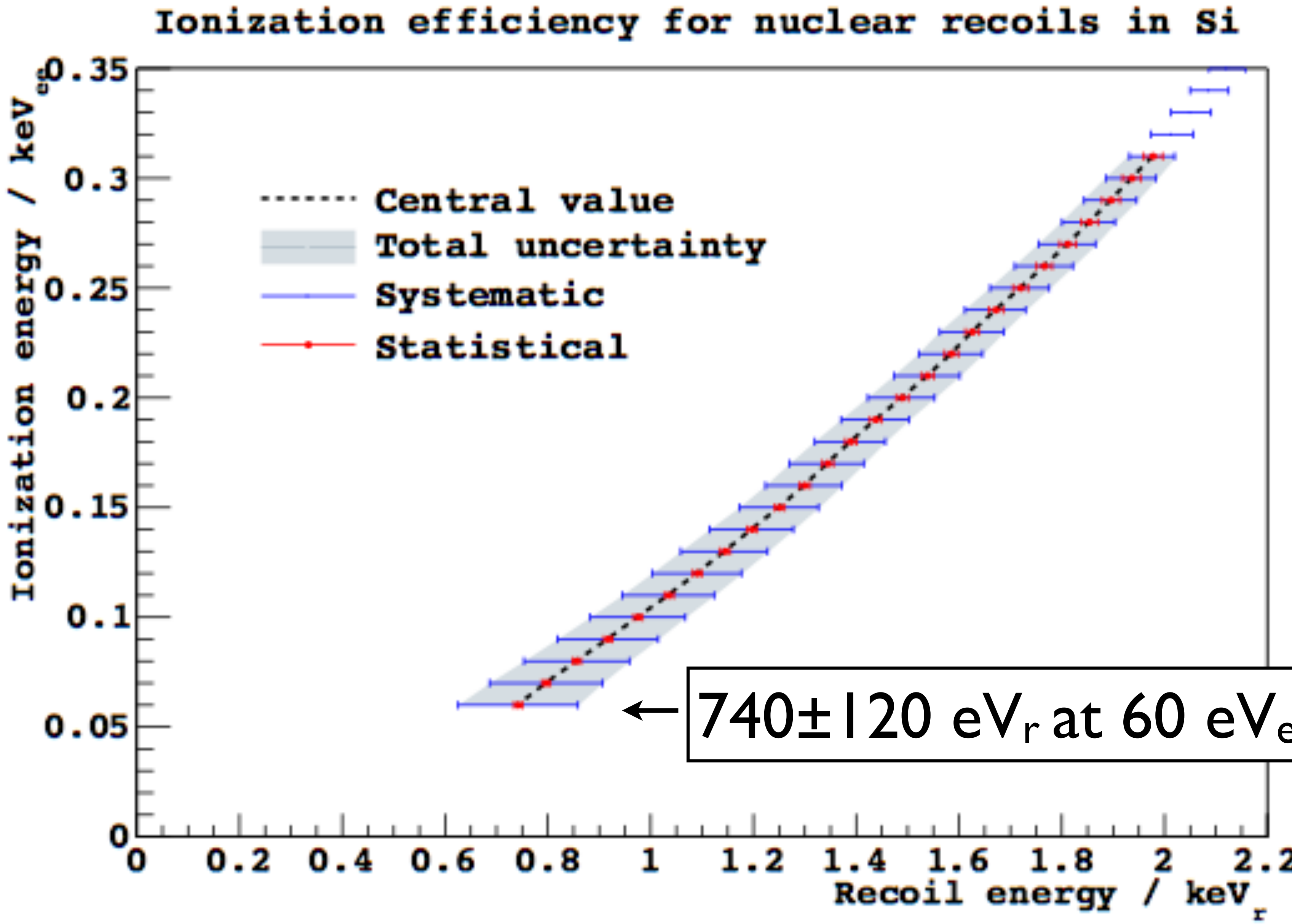
Source configuration





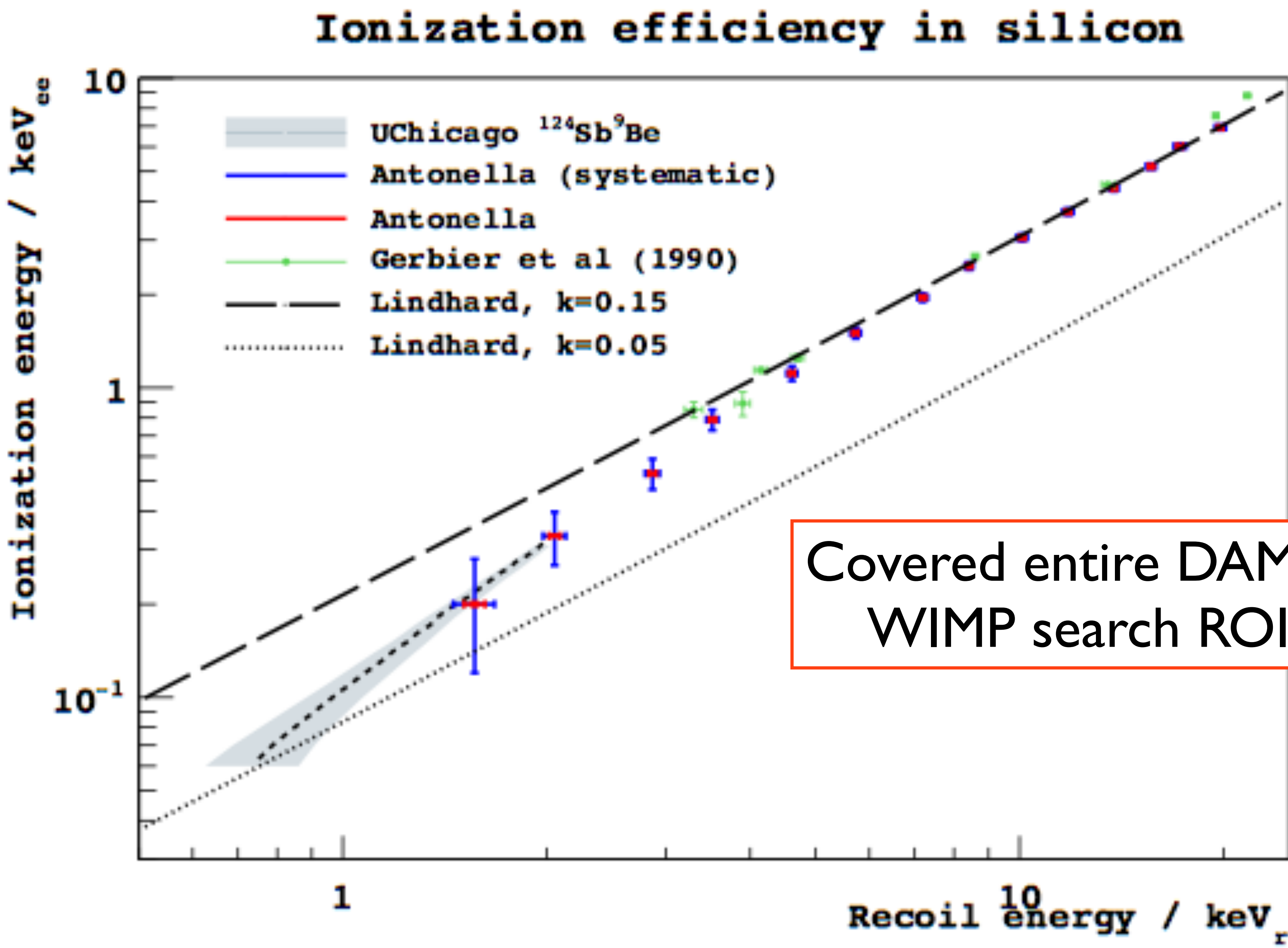


Results



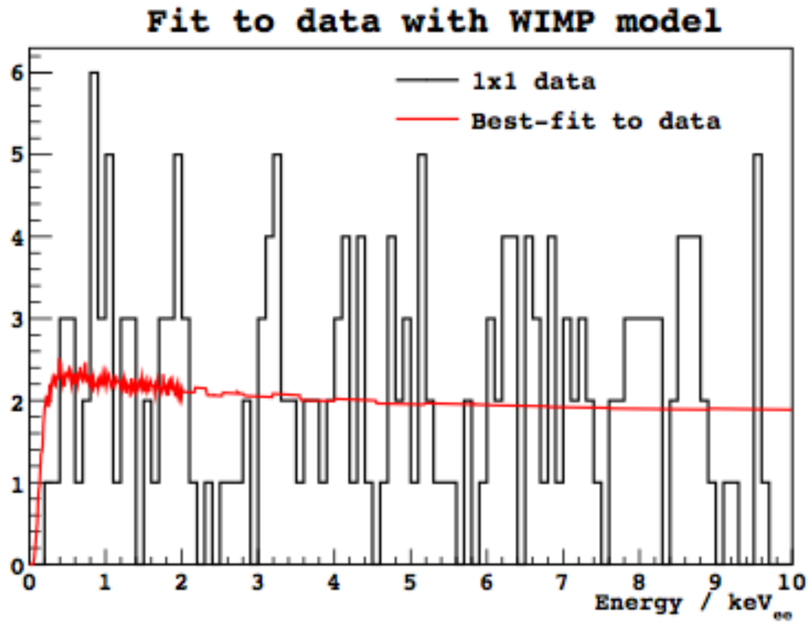
← 740±120 eV$_r$ at 60 eV$_{ee}$

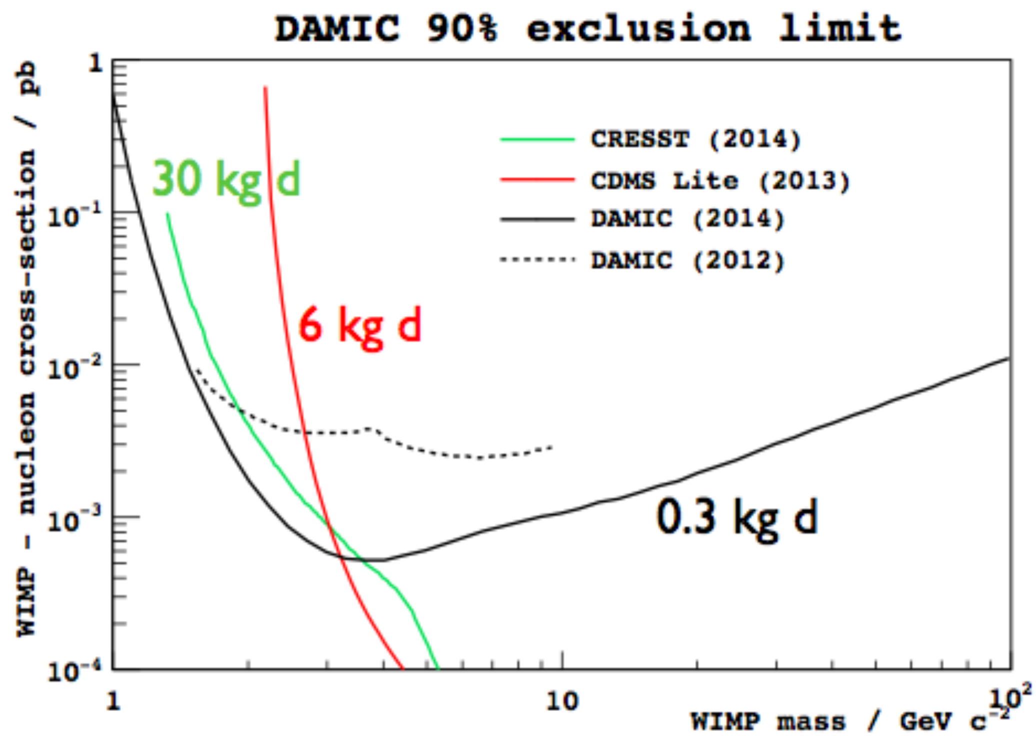
Two DAMIC calibrations



Covered entire DAMIC WIMP search ROI

DAMIC 2014: R&D data





Best fit mass: 26 ± 46 GeV/c^2

Best fit xs: (7 ± 16) x 10^{-4} pb

Best fit c: 67 ± 13 dru

Minimum -ll: -396.5

Null hypothesis c: 74 ± 5 dru

Minimum -ll: -396.1

Ionization efficiency: Lindhard, k=0.15

v_0 = 220 km s^{-1}

v_E = 232 km s^{-1}

v_{esc} = 544 km s^{-1}

ρ = 0.3 GeV c^{-2} cm^{-3}

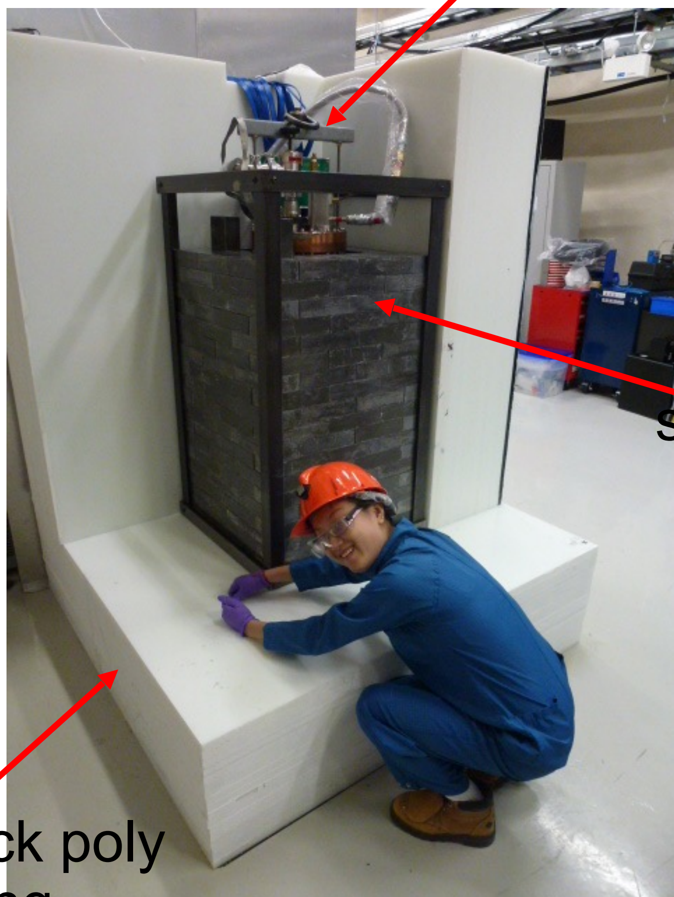
25

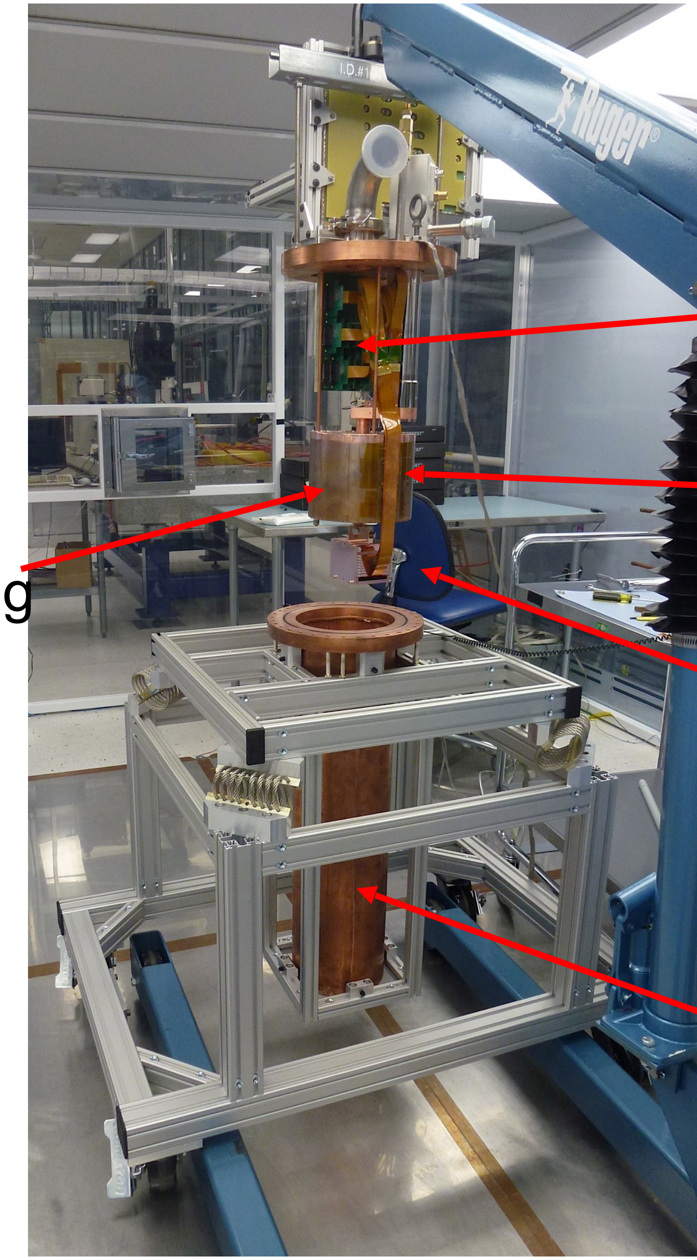
DAMIC100

- 100 g detector, 18 CCD 4k x 4k 675 μm
- Minimal changes in SNOLAB setup: Cu box, CCD support and cable

  expected bkg ≈ 1 event keV^{-1} kg^{-1} day^{-1}
- Detectors designed by Lawrence Berkeley Lab and fabricated by DALSA, all in hand, packaging started, high yield
- In the first half of 2015, installation of CCD box and background improvements:
  - installation of N_2 purge for radon
  - etching of vacuum vessel to remove surface bkg
  - several CCDs (2k x 4k) 675 μm packaged and installed to study bkg

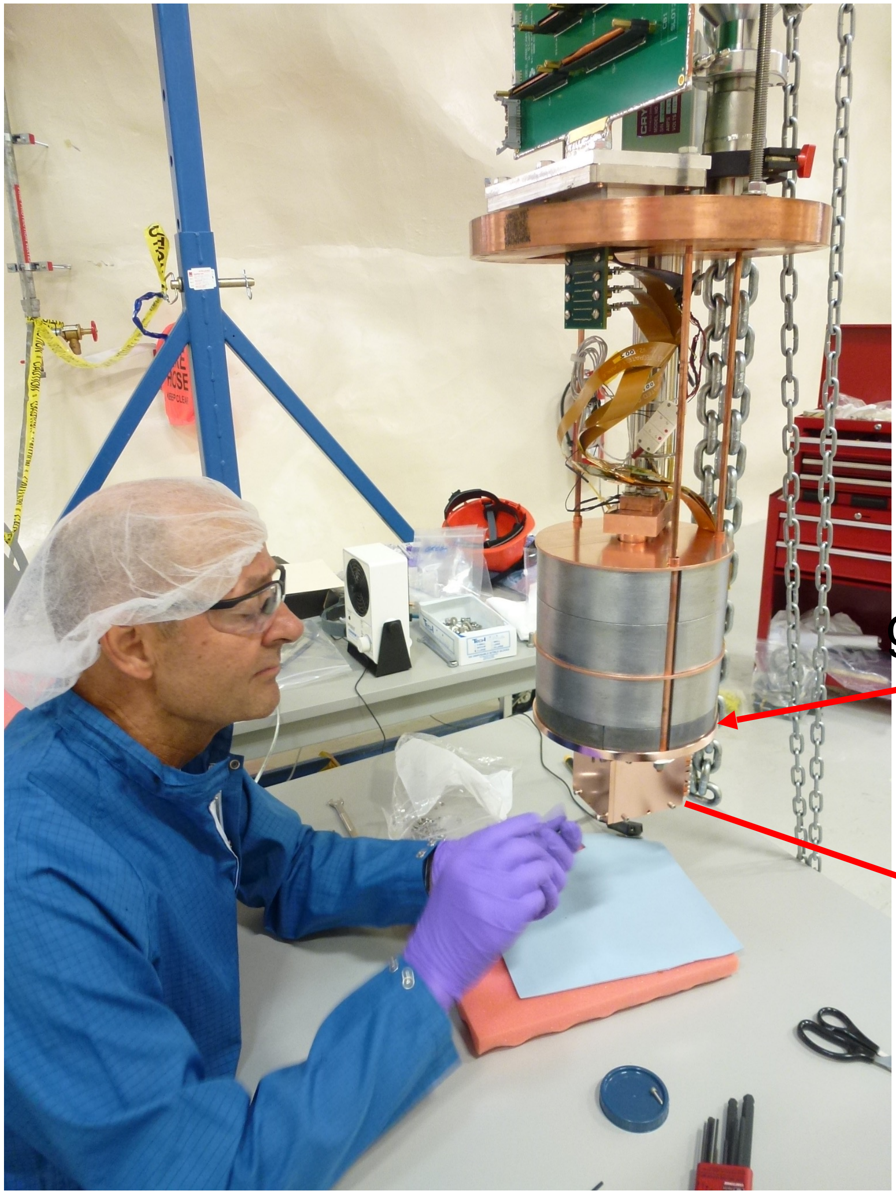
Dark Matter in CCDs at SNOLAB



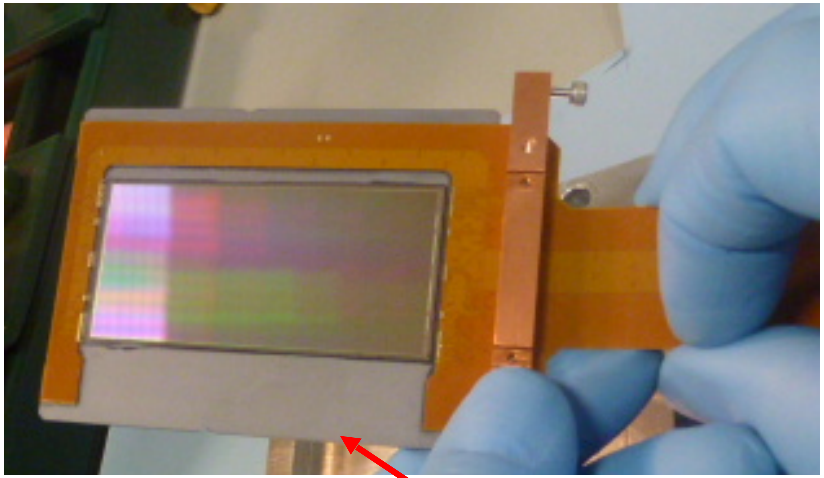


Intense R&D program started in 2013 with the goal of a 100 g detector

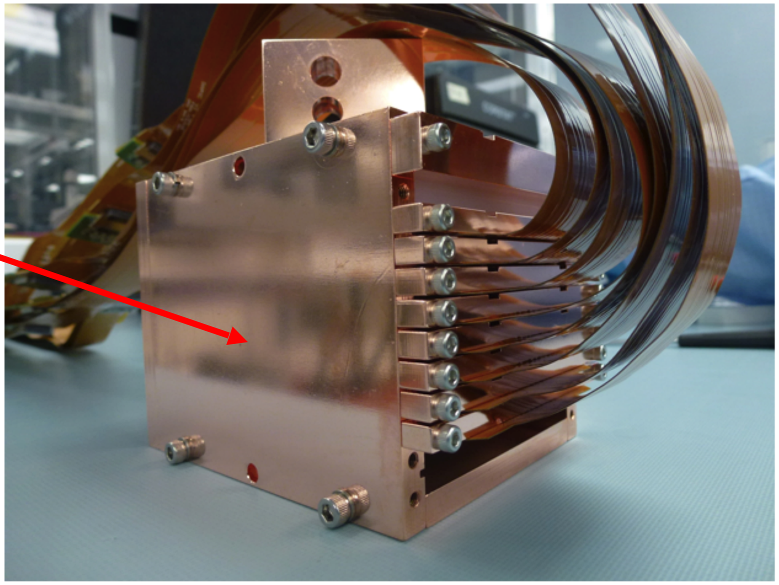
DAMIC setup at SNOLAB



1” Spanish galleon lead

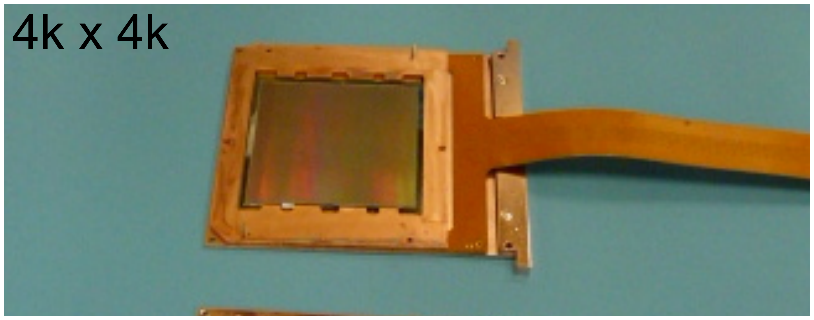


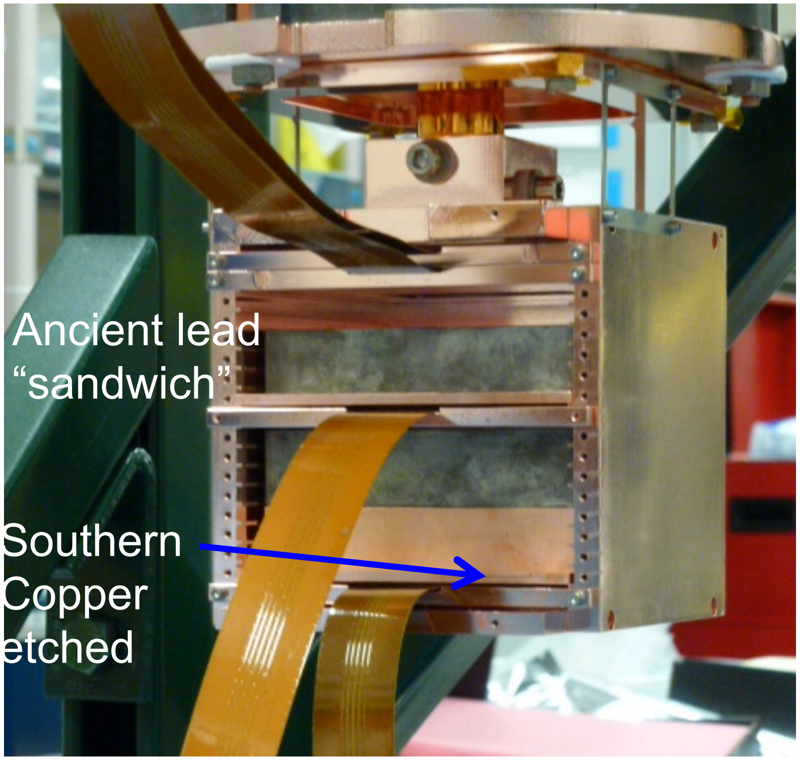
Si support



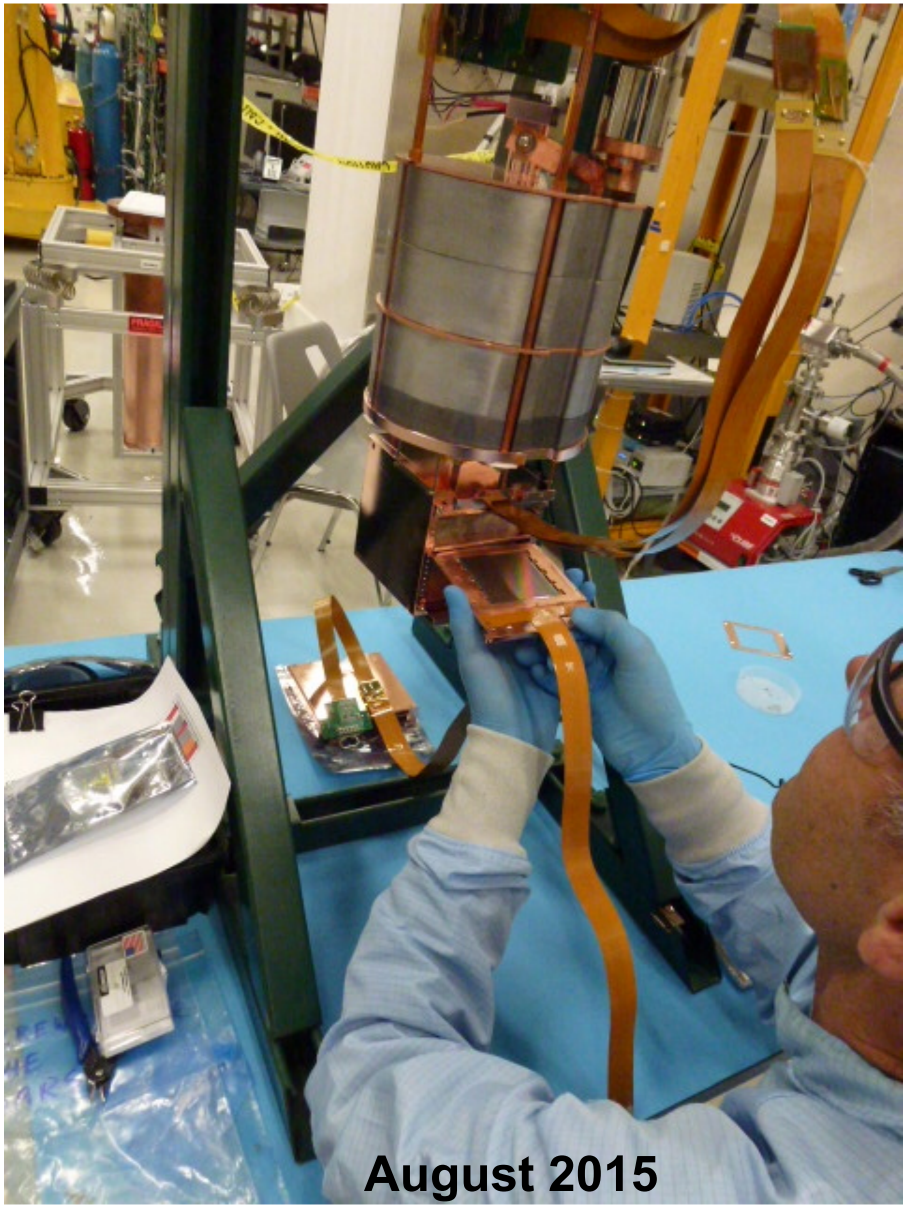
DAMIC100 recent progress

First 4k x 4k CCD with final packaging installed few weeks ago

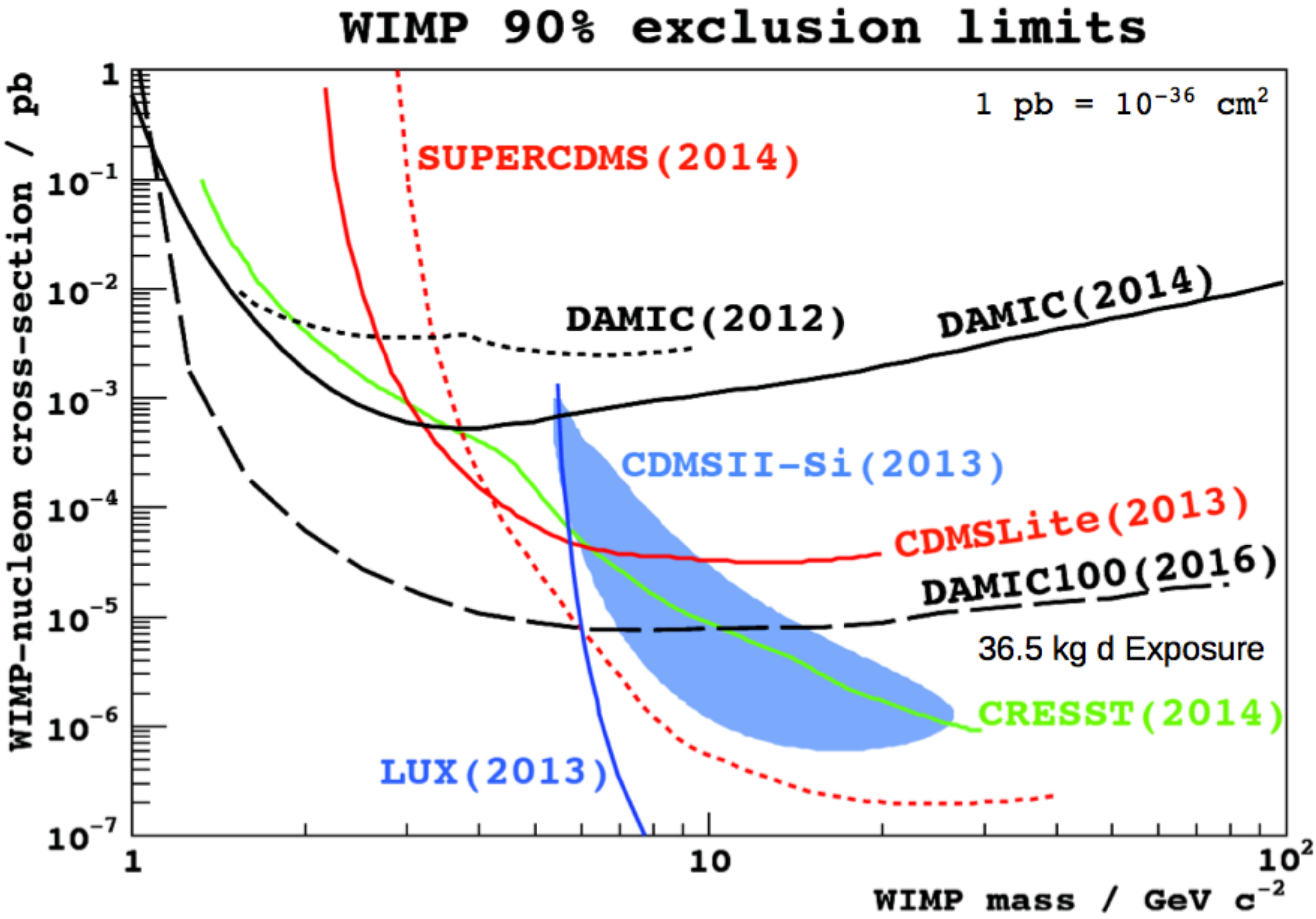




Special setup to validate bkg
before full scale installation



DAMIC sensitivity

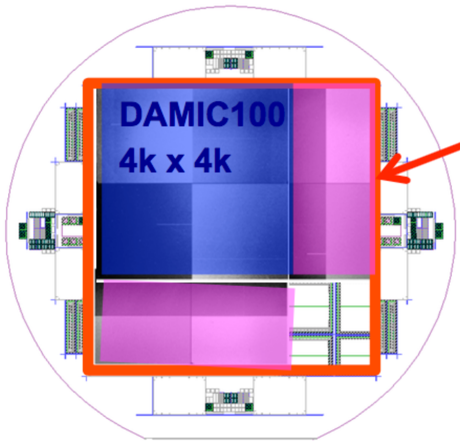


Beyond DAMIC 100

Strategy for DAMIC 1kg

- Scaling mass

Silicon wafer



6k x 6k pixels, 1 mm thick

≈20 g / CCD

≈ 50 CCDs / 1 Kg

One batch of 24 wafers production for DAMIC100

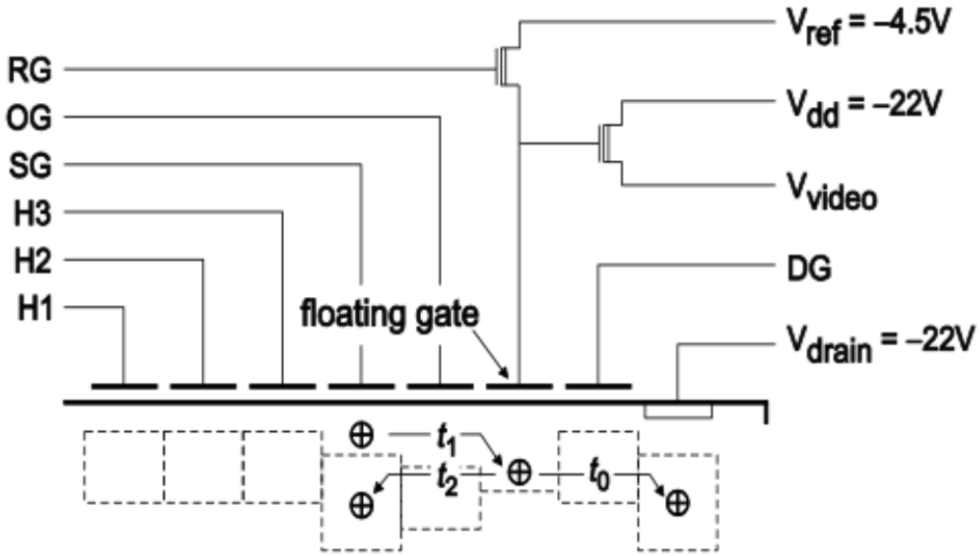
Three batches sufficient for DAMIC 1kg

Cost does not scale with mass

O(50) CCDs ok even with existing design of electronics (e.g. DECam 62 CCDs)

0.1 e- noise

- Readout noise ≈ 1/10 e^- with skipper CCDs



R&D at Fermilab demonstrated 0.2 e^- noise

http://arxiv.org/abs/1106.1839

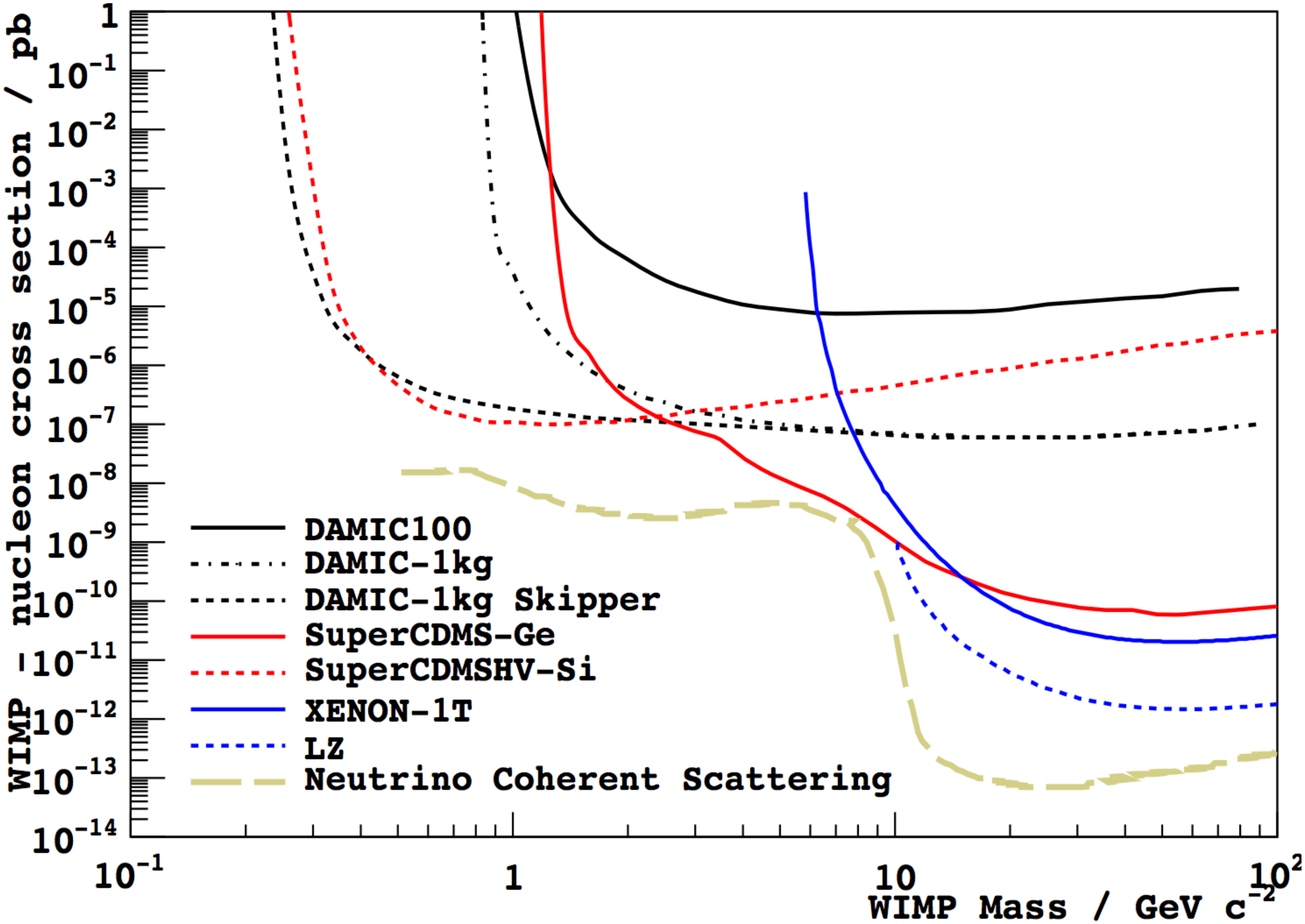
Special design of the readout node, with a floating gate output that allows for multiple readouts of the charge in each pixel

- Pixel charge is measured N times, with integration time short to keep 1/f noise negligible
- Noise improves by 1/sqrt(N)

Technology known since long time – the challenge is in the implementation on a large number of CCDs

DAMIC 1 kg

Potential of a 1 kg Si detector



Conclusions

- DAMIC 100 has made good progress
- DAMIC 2014 result improves upon 2011
- CCD performance understood
- Intrinsic Si^{32} background determined
- Quenching factor
  - Two separate measurements
  - Nuclear recoil ionization efficiency understood down to energy threshold
  - Show consistent discrepancy with Lindhard
- DAMIC 1kg could get close to neutrino floor around 1 GeV