DAMIC

6th Roma International Conference on AstroParticle Physics

RICAP 16

June 23th, 2016

DAMIC at SNOLAB: searching for low-mass WIMPs with CCDs

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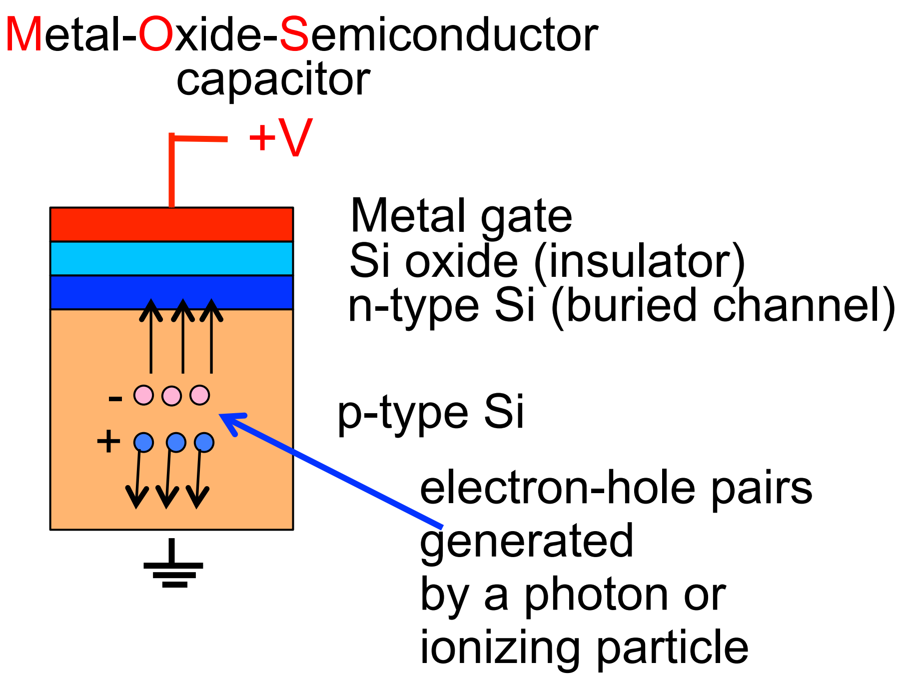
for the DAMIC Collaboration

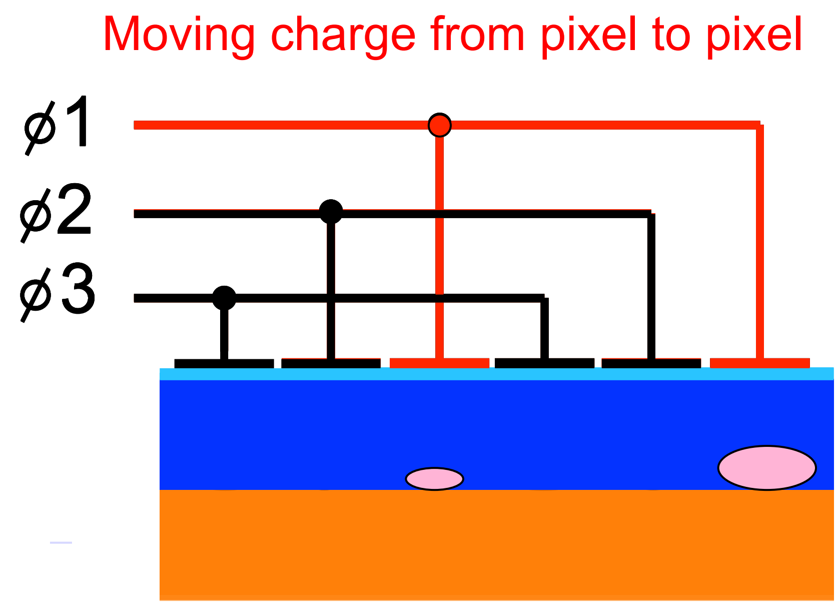
(CAB, FIUNA, Fermilab, LPNHE, SNOLAB, U Chicago, U Michigan, U Zürich, UFRJ, UNAM)

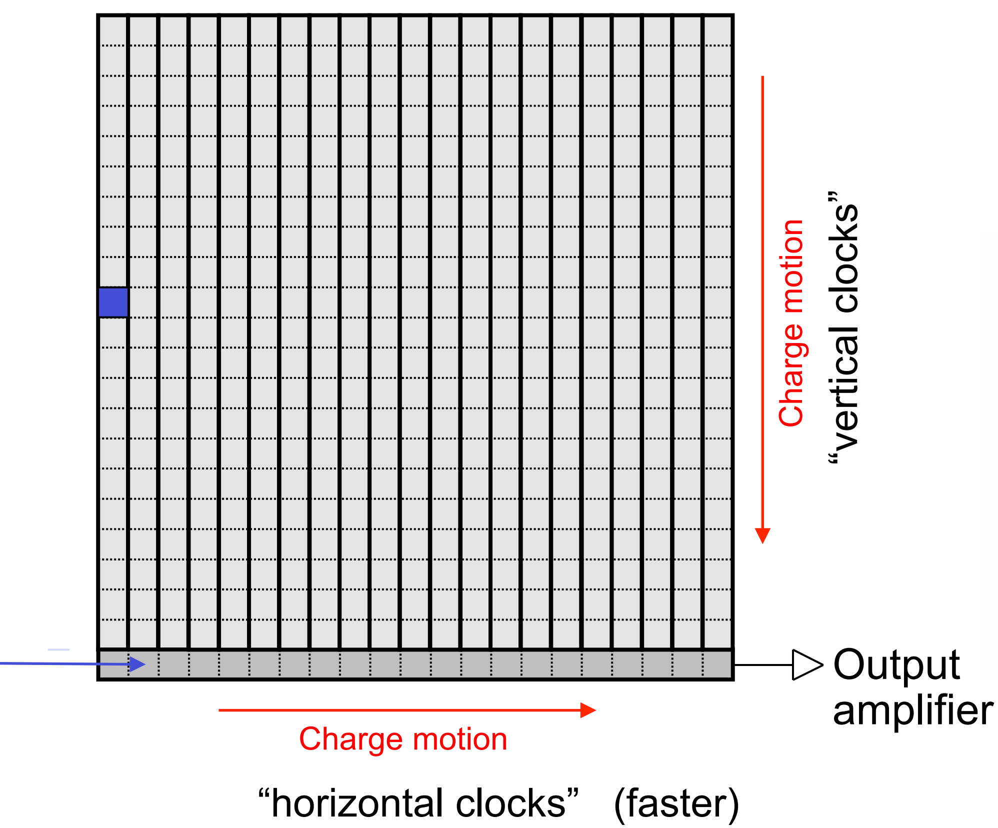
THE UNIVERSITY OF CHICAGO PHYSICAL SCIENCES

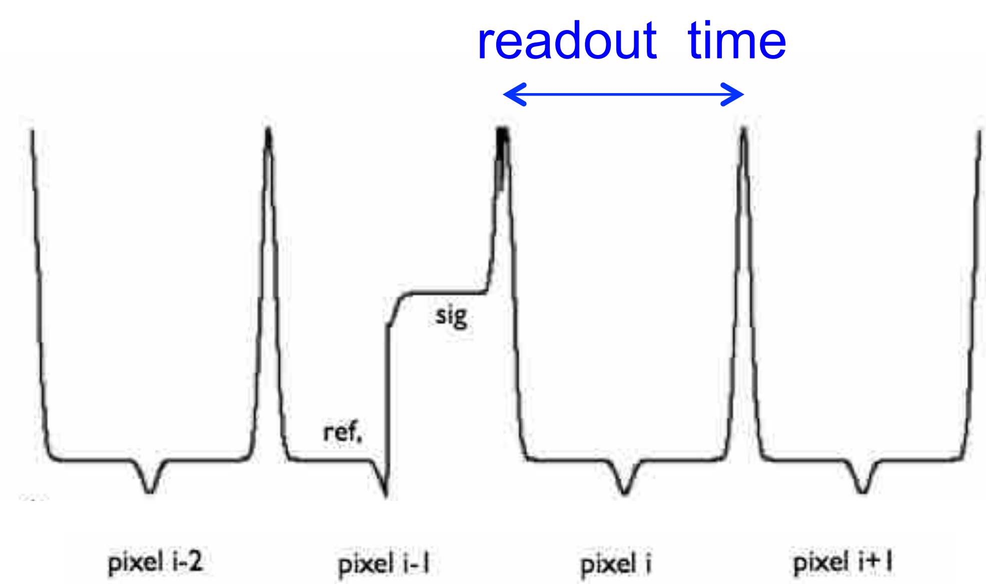
KICP

CCD principle



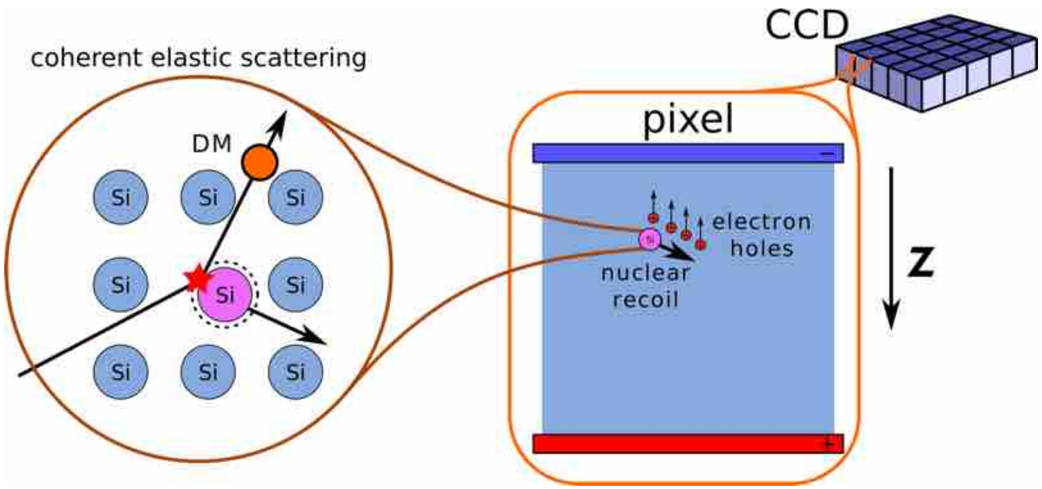






Correlated Double Sampling

Why Dark Matter in CCDs ?



- Detection of point-like energy deposits from nuclear recoils induced by WIMP interactions (10 keV Si ion range 200 A)

1) High-resistivity (10^{11} donors/cm^3) extremely pure silicon

2) Fully-depleted over several 100s μm (typical CCDs few tens of μm)

Float-zone Si

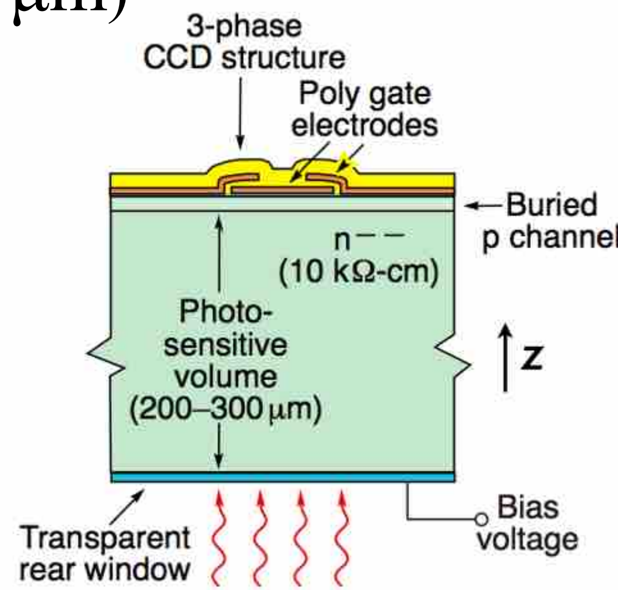
COSMIC RAYS AND OTHER NONSENSE IN ASTRONOMICAL CCD IMAGERS

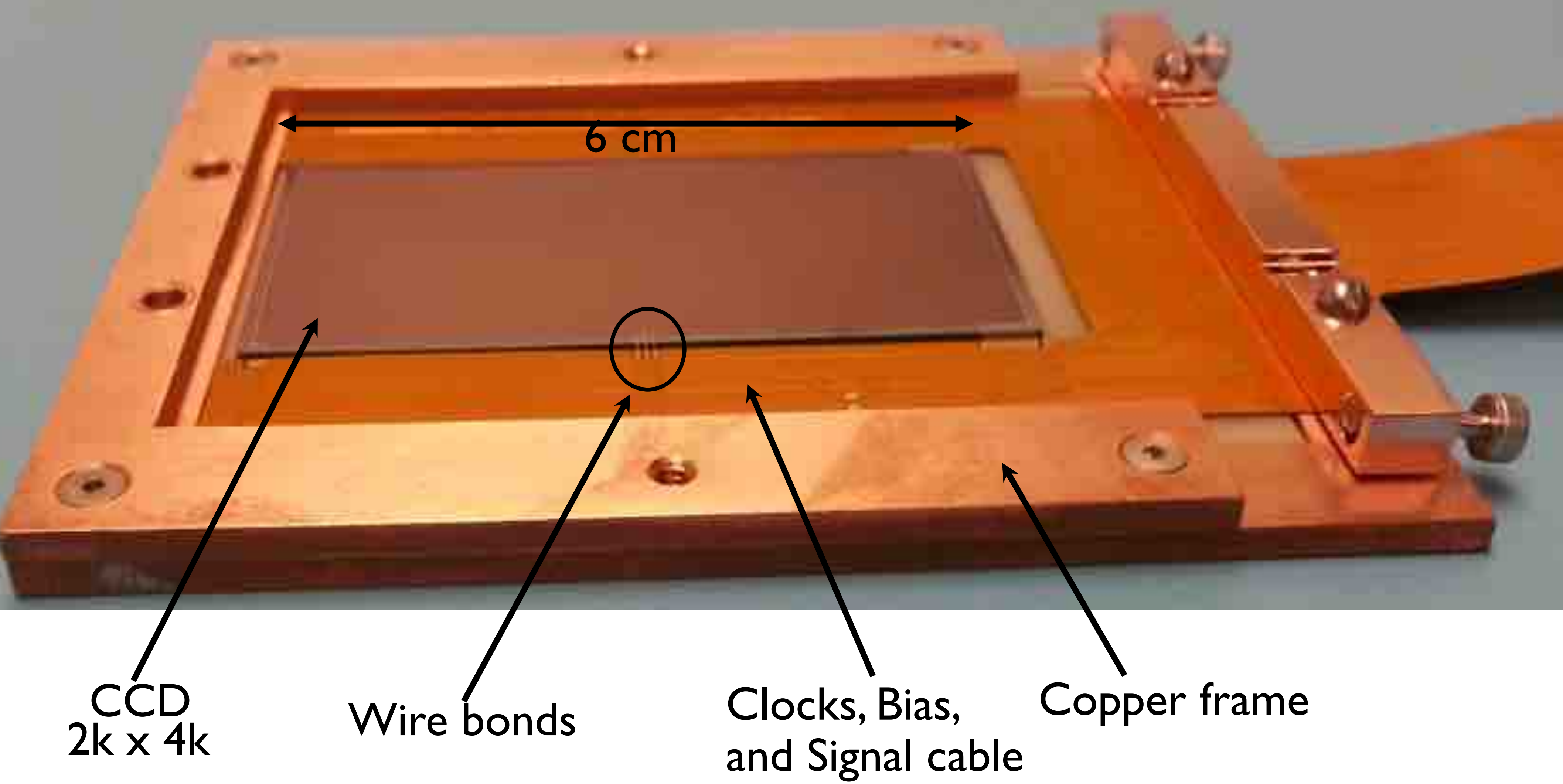
DON GROOM
Lawrence Berkeley National Laboratory

(Accepted 23 July 2003)

DAMIC enabled by

Abstract. Cosmic-ray muons make recognizable straight tracks in the new-generation CCD's with thick sensitive regions. Wandering tracks ('worms'), which we identify with multiply-scattered low-energy electrons, are readily recognized as different from the muon tracks. These appear to be mostly recoils from Compton-scattered gamma rays, although worms are also produced directly by beta emitters in dewar windows and field lenses. The gamma rays are mostly byproducts of ^{40}K decay and the U and Th decay chains. Trace amounts of these elements are nearly always present in concrete and other materials. The direct betas can be eliminated and the Compton recoils can be reduced significantly by the judicious choice of materials and shielding. The cosmic-ray muon rate is irreducible. Our conclusions are supported by tests at the Lawrence Berkeley National Laboratory low-level counting facilities in Berkeley and 180 m underground at Oroville, California.





First DAMIC CCDs from DECam!

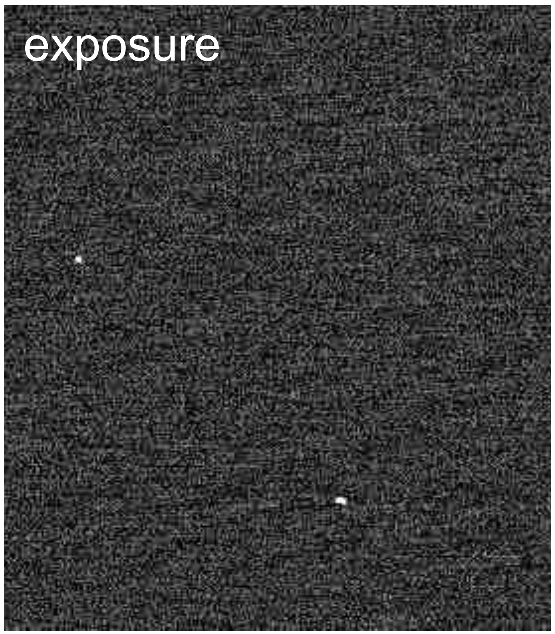
3) Sizable mass

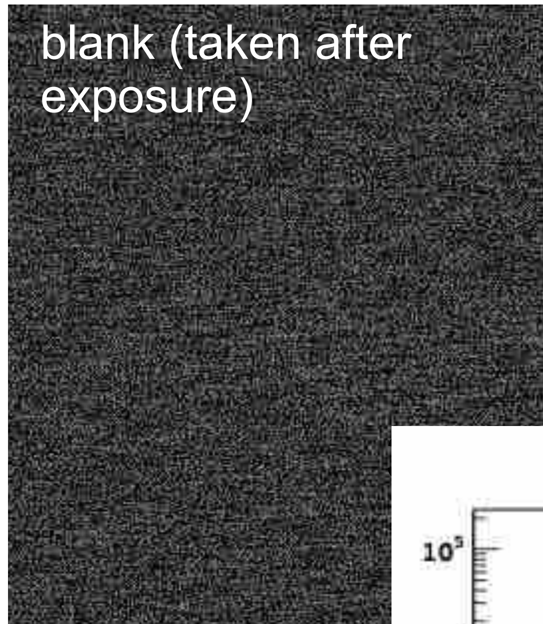
a DAMIC CCD 6 cm x 6 cm, 16 Mpixel (15 μm x 15 μm) has a record thickness of 675 μm and 5.9 g mass

- **DAMIC100**: 100 g detector (18 CCDs) at the SNOLAB underground laboratory, Sudbury, Canada

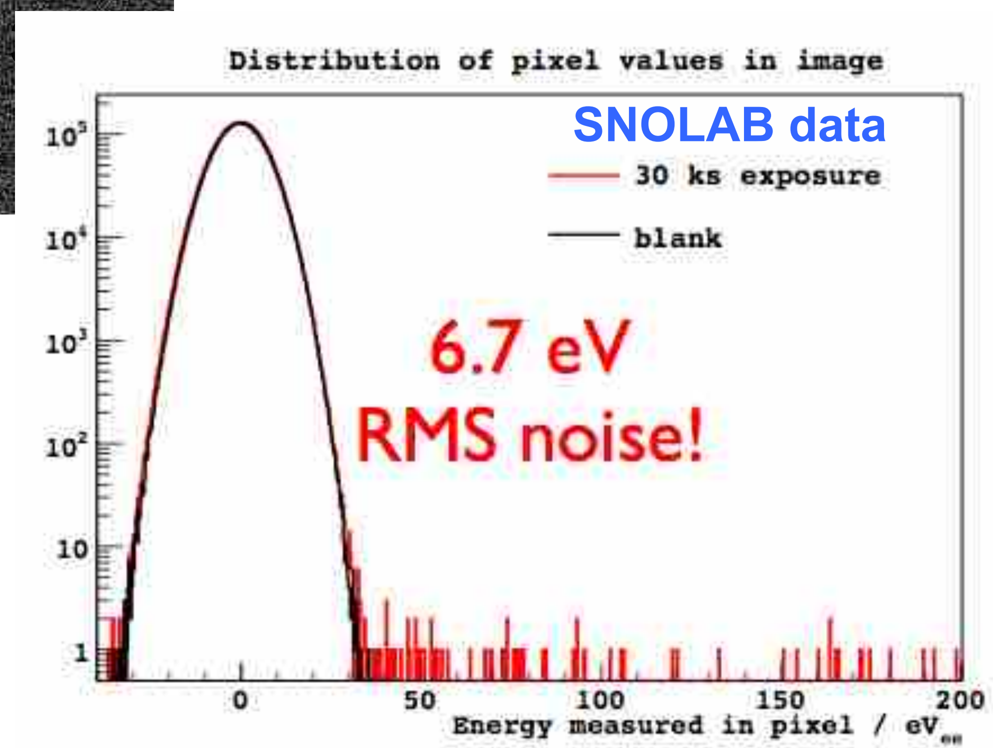
4) Unprecedented low energy threshold

- Negligible dark current < 0.001 e/pixel/day (CCD cooled at 120 K). Readout noise dominant contribution





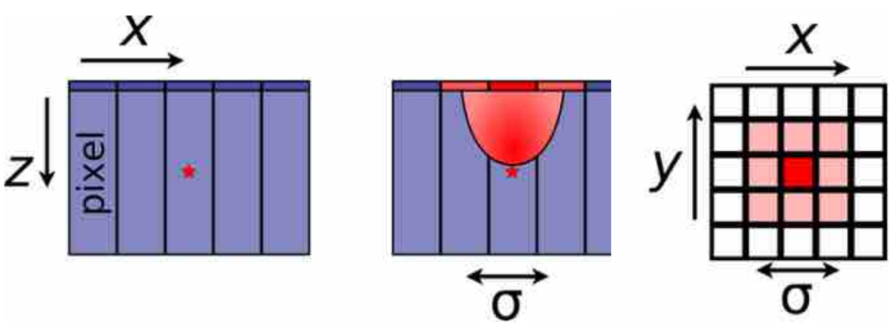
- Slow readout (≈ 5 min / 8 Mpix image) to achieve $\sigma \approx 2$ e- noise

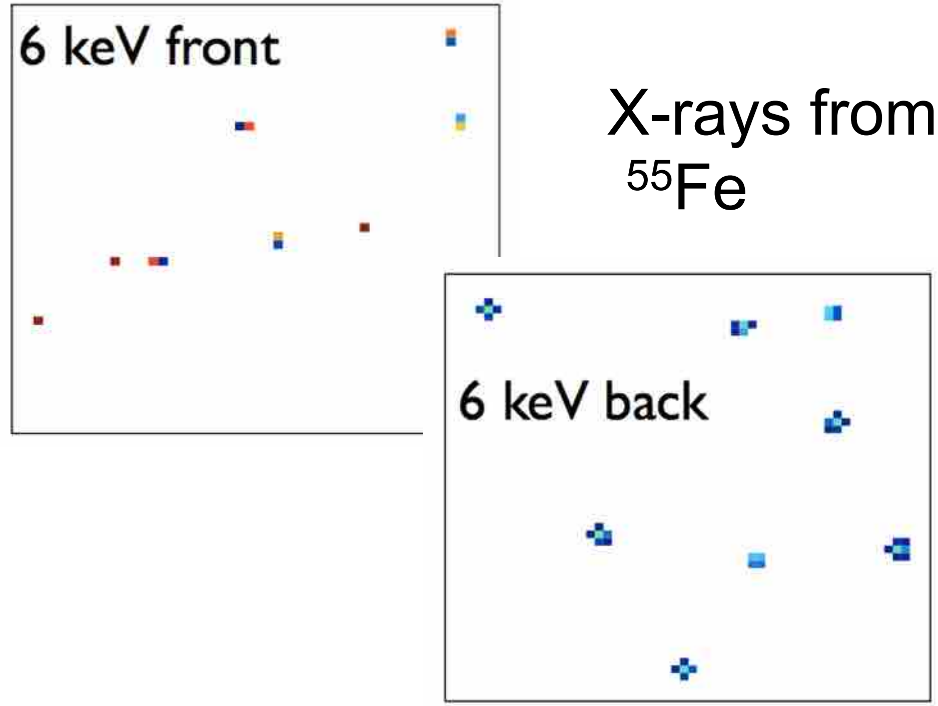


- Very long exposures (8 hours!) to minimize the n. of noise pixels above the energy threshold

Lower threshold, higher WIMP recoil rate (exponential), small mass detector competitive

5) Unique spatial resolution: 3D position reconstruction and particle ID

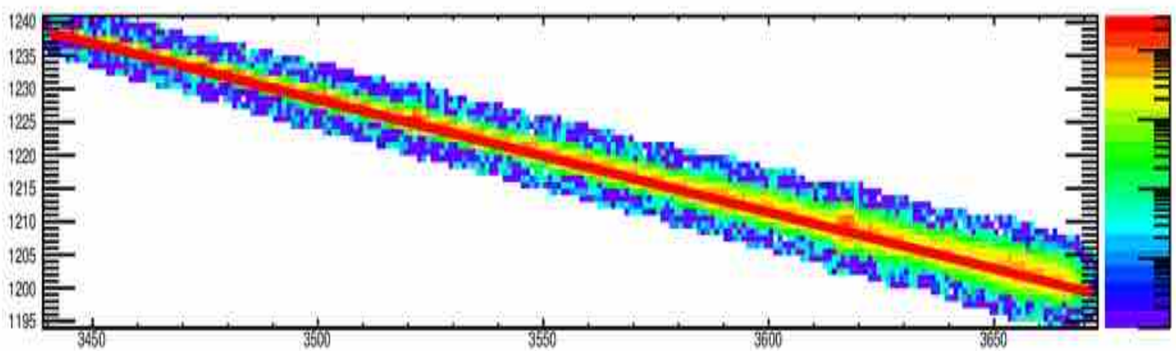


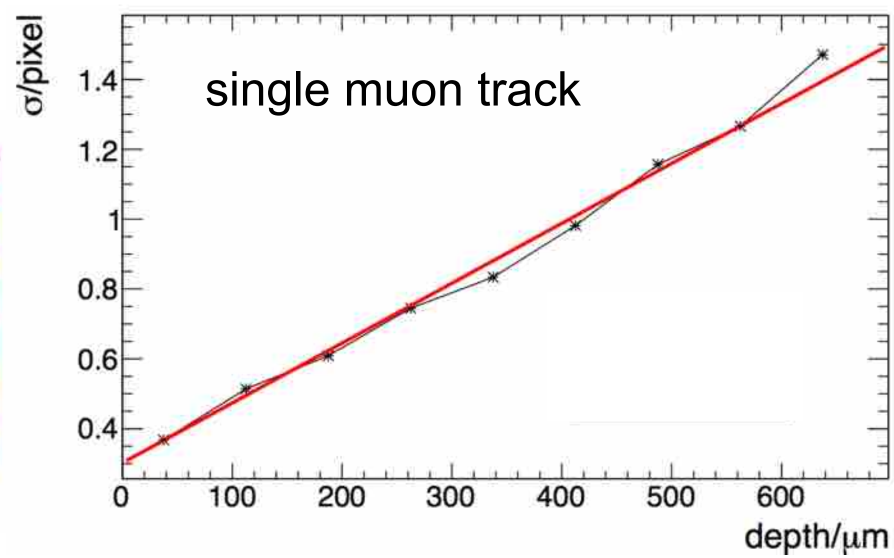


X-rays from ^{55}Fe

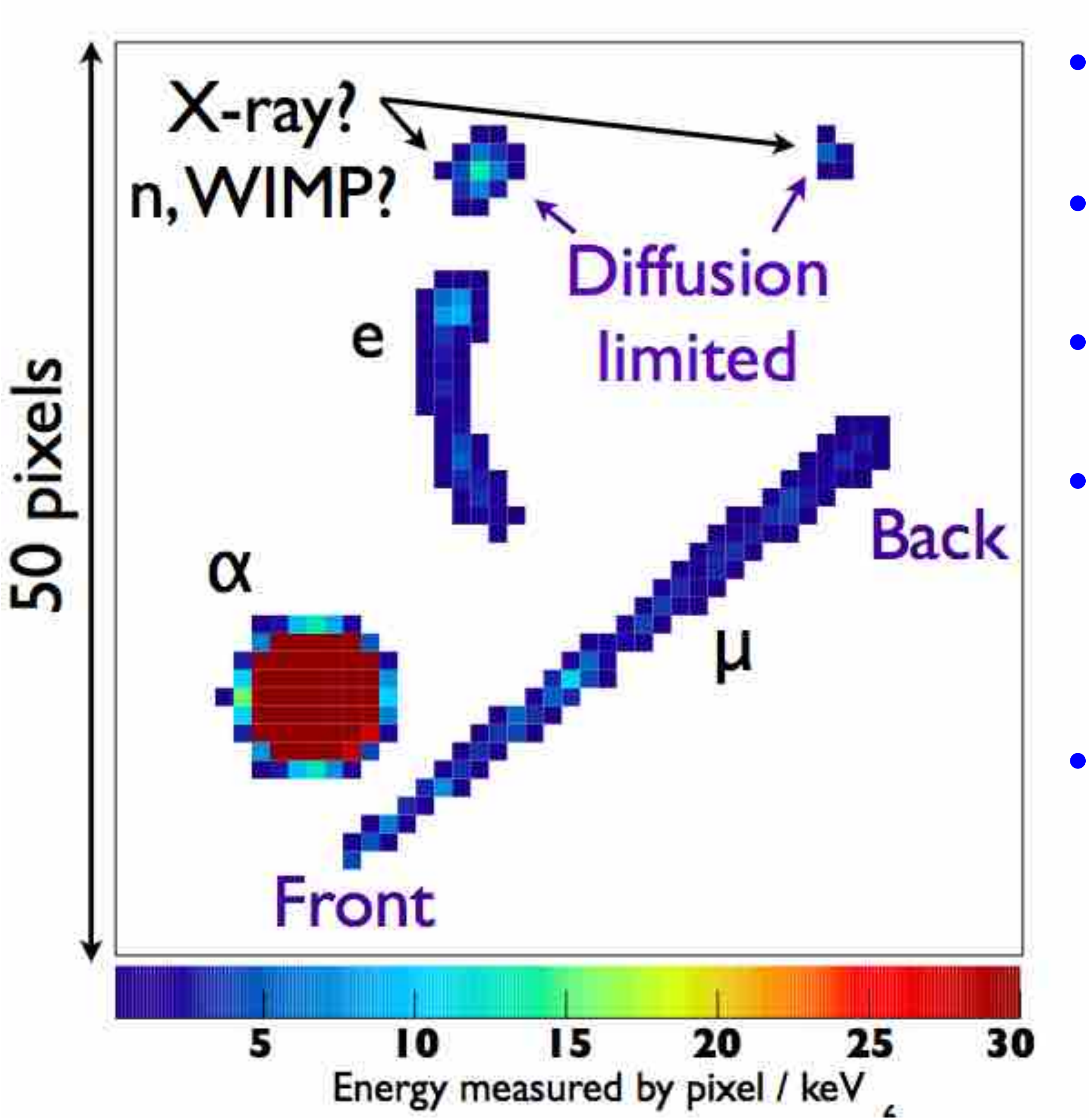
The charge diffuses towards the CCD pixels gates, producing a "diffusion-limited" cluster

a muon piercing a 675 μm thick DAMIC CCD





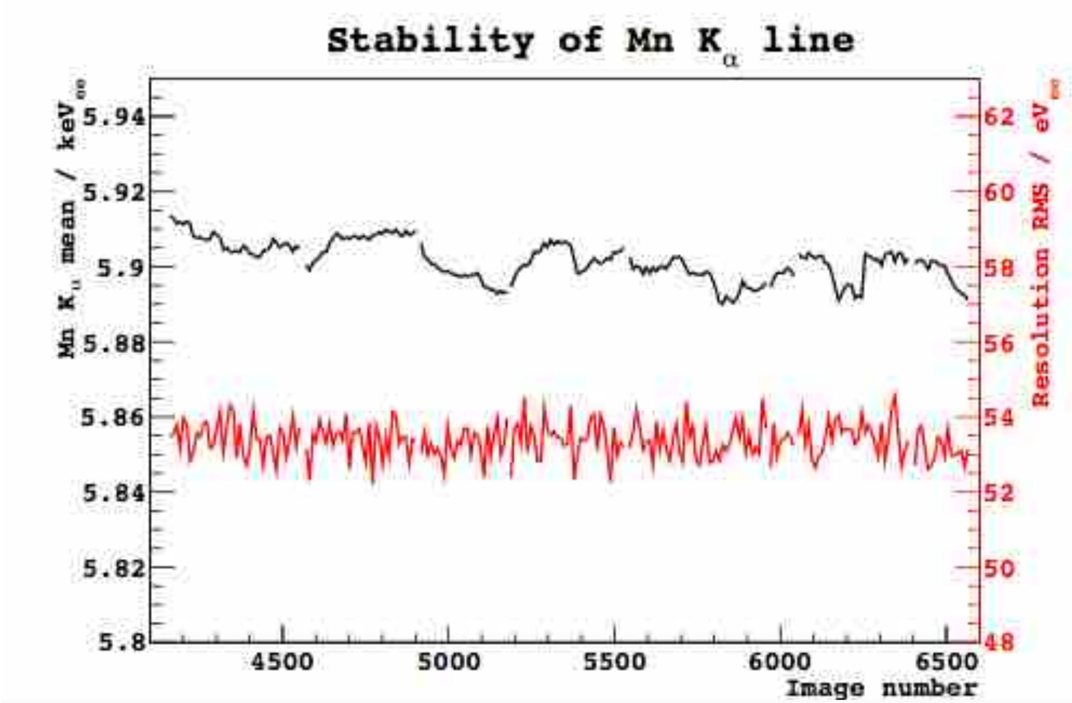
σ ≈ Z : fiducial volume definition and surface event rejection



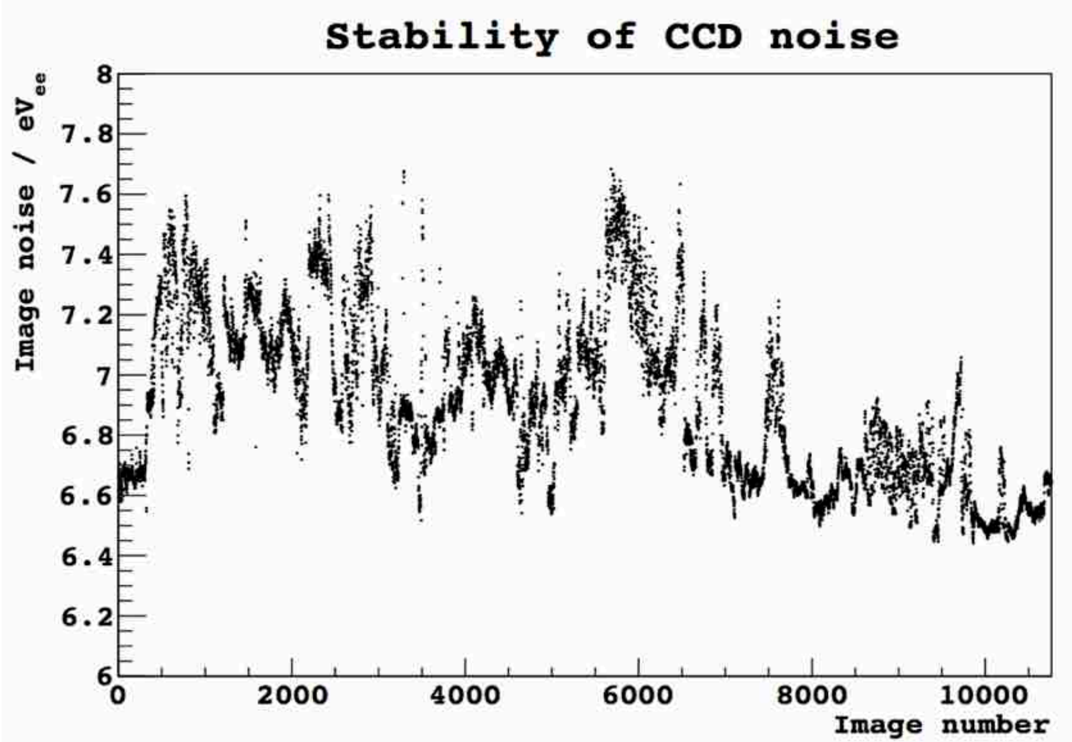
- "Worms" straggling electrons
- Straight tracks: minimum ionizing particles
- MeV charge blobs: alphas
- Diffusion-limited clusters: low-energy X-rays, nuclear recoils

- CCD spatial resolution provides a unique handle to the understanding of the background

6) Stable and reliable detectors



Energy scale stable to < 1%

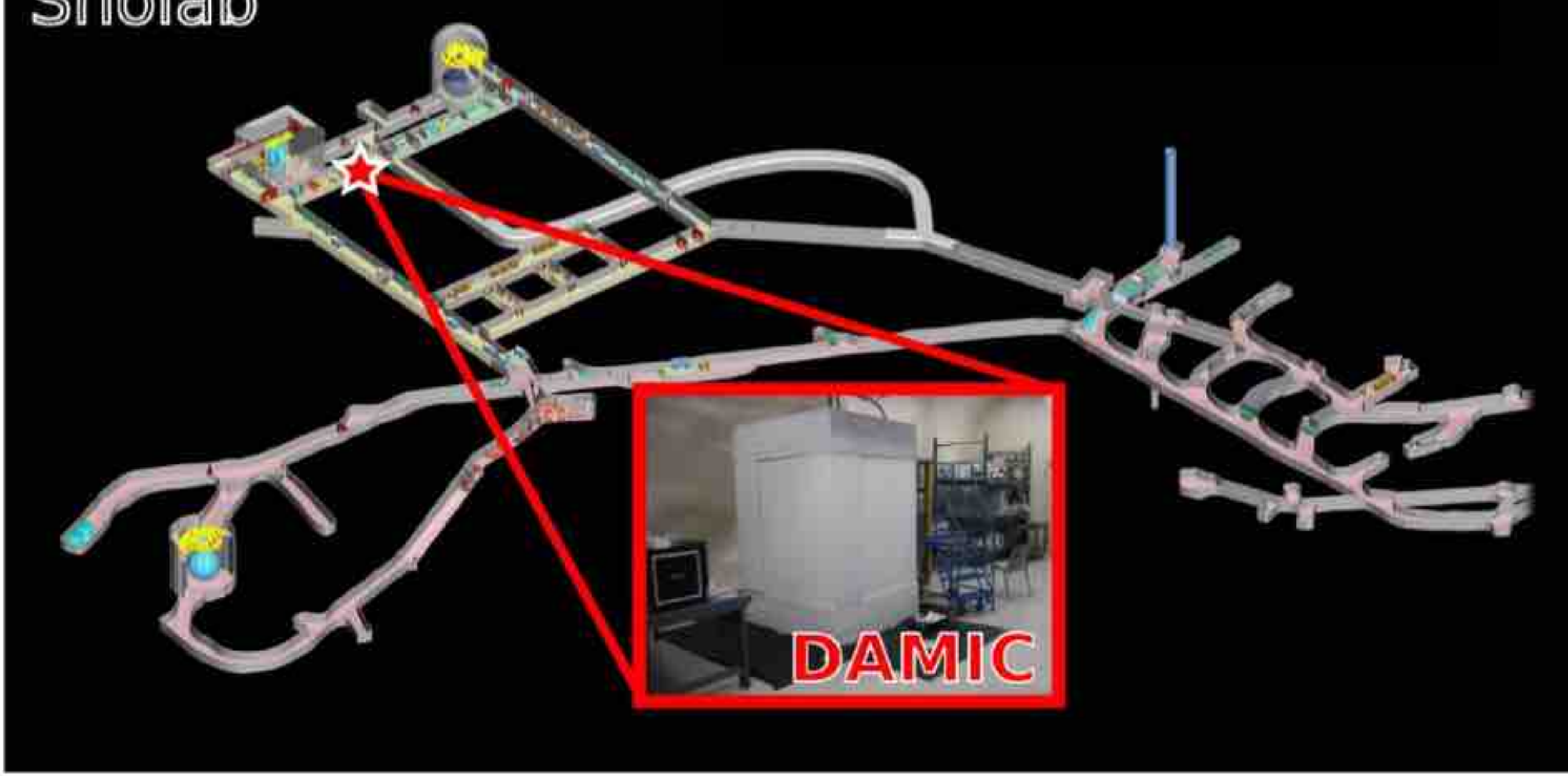


Noise stable to 6% over 126 days.

Duty cycle close to 100%

(cf. superconducting detectors)

DAMIC at SNOLAB

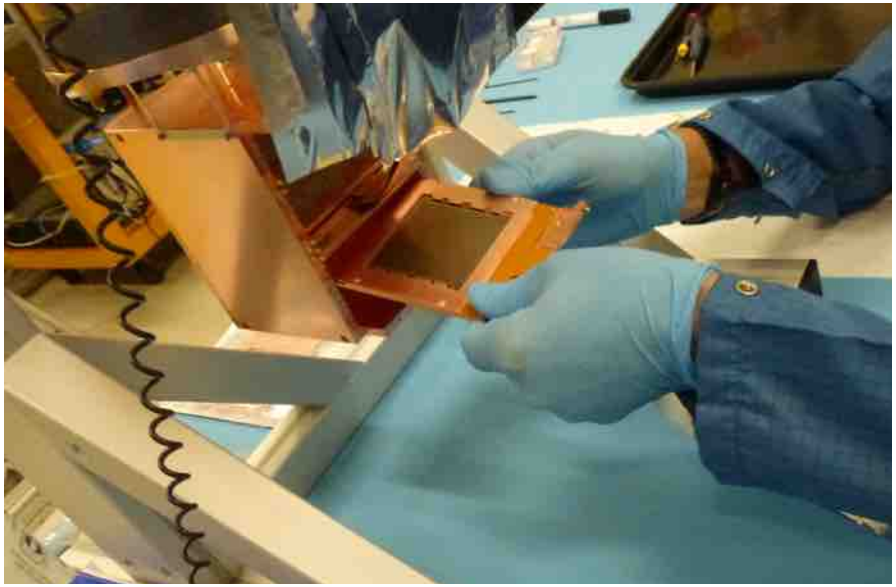


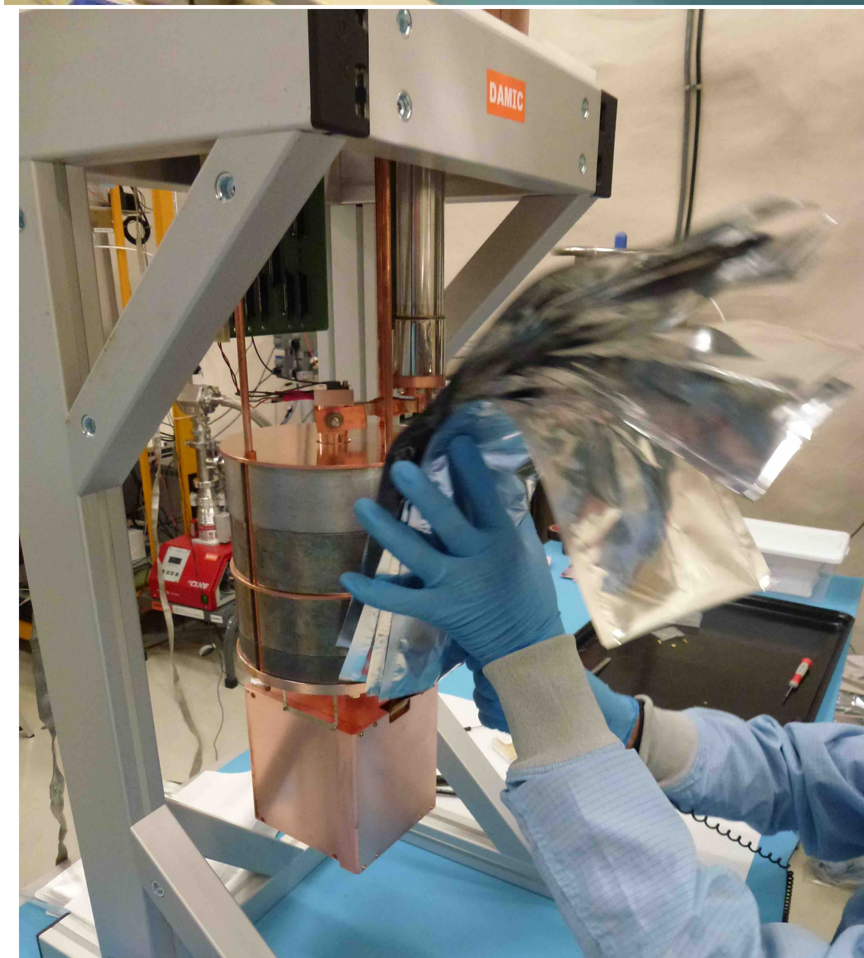
DAMIC R&D program in the J-Drift hall started in early 2013

CAB, FIUNA, Fermilab, LPNHE, SNOLAB, U Chicago, U Michigan, U Zürich, UFRJ, UNAM

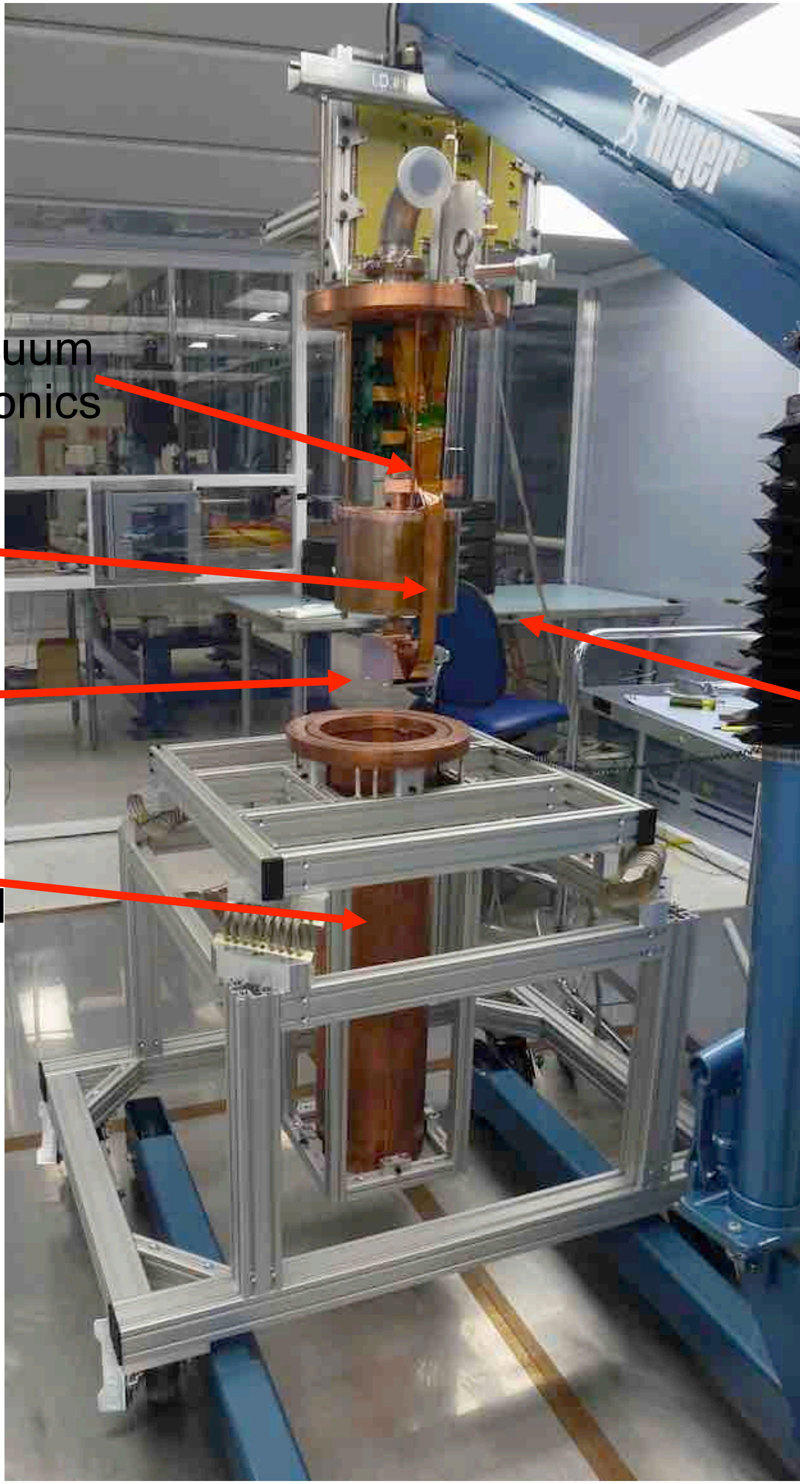
DAMIC100 installation at SNOLAB

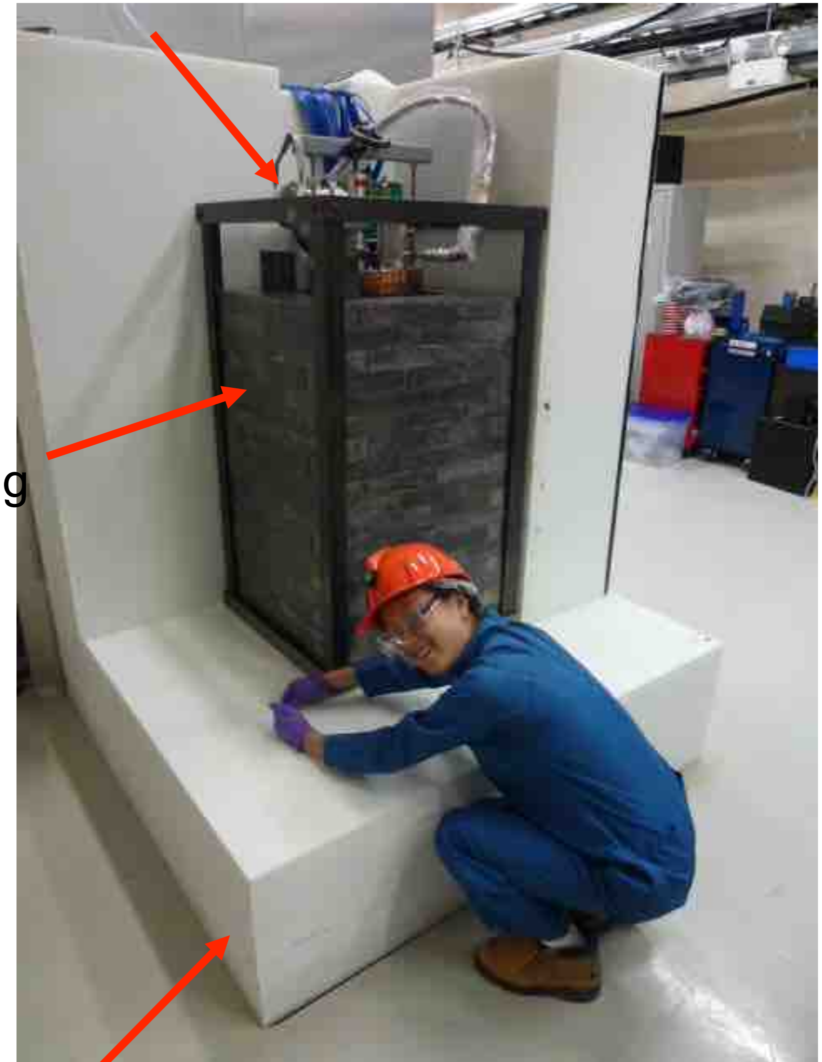
April 2016



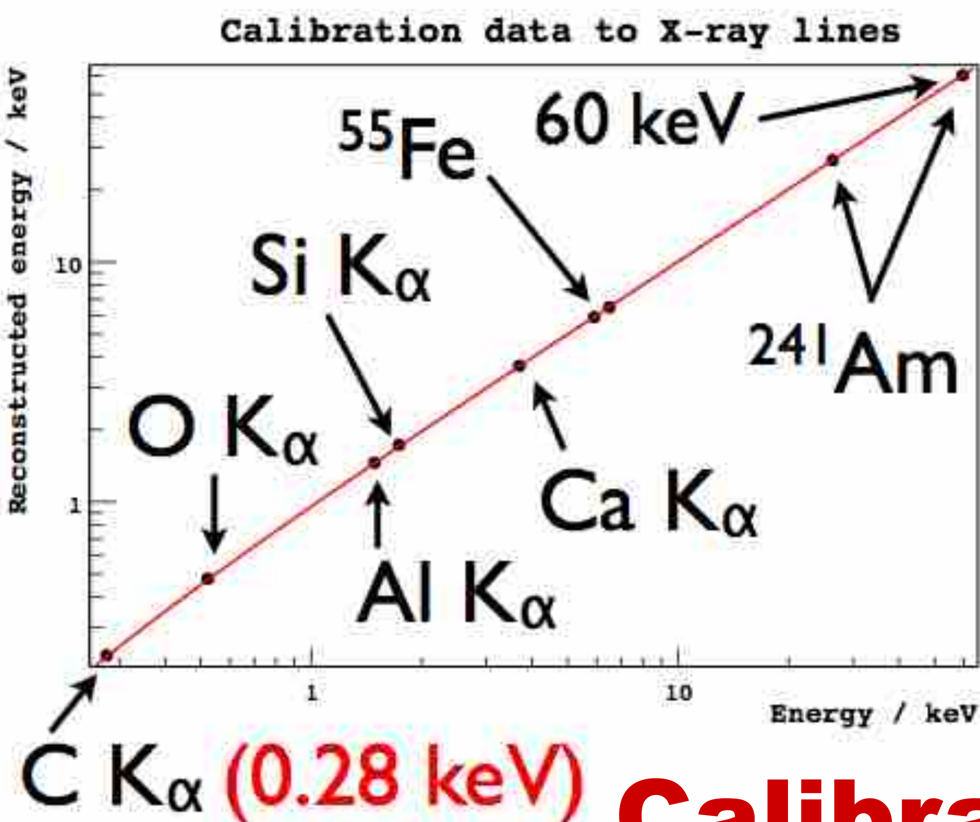

DAMIC

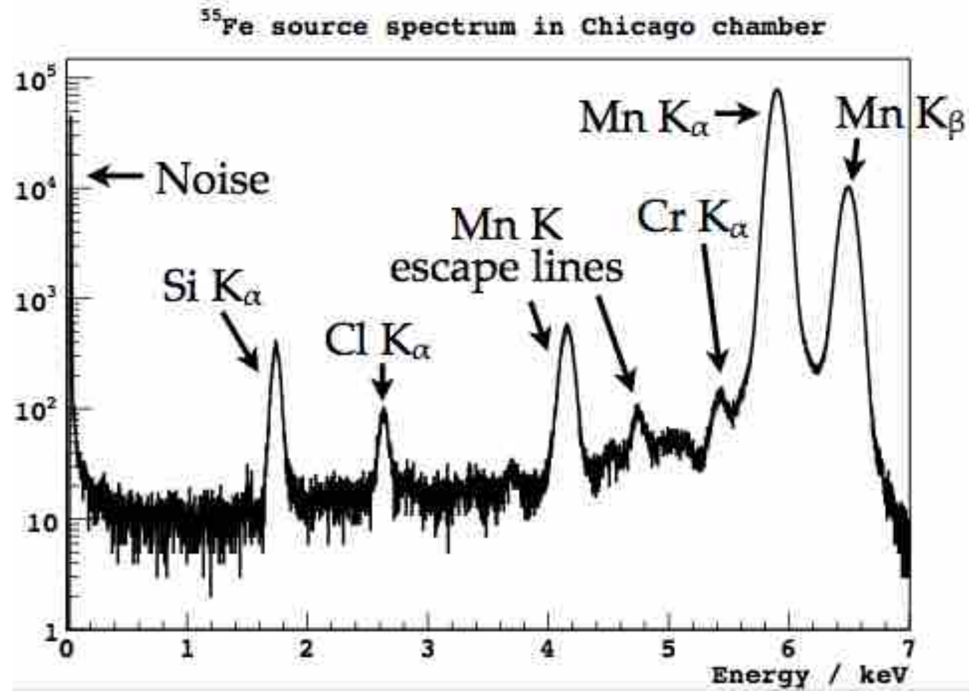

DAMIC

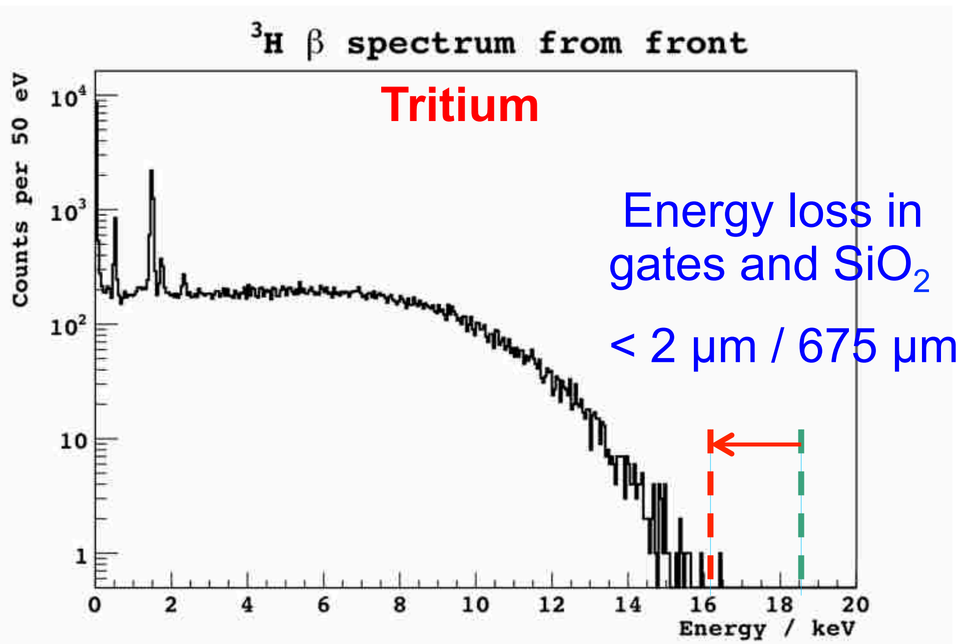

in-vacuum electronics
Kapton cables
Cu box
Cu vessel

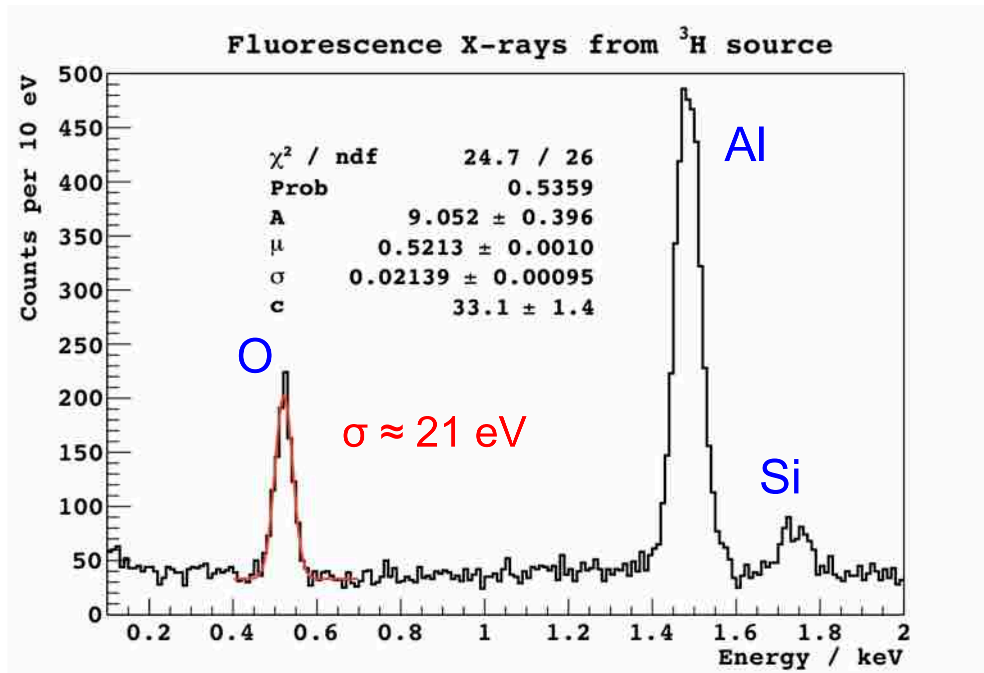

vacuum and cryo lines, electronics
8” lead shielding
20” thick poly shielding

Calibration with electrons







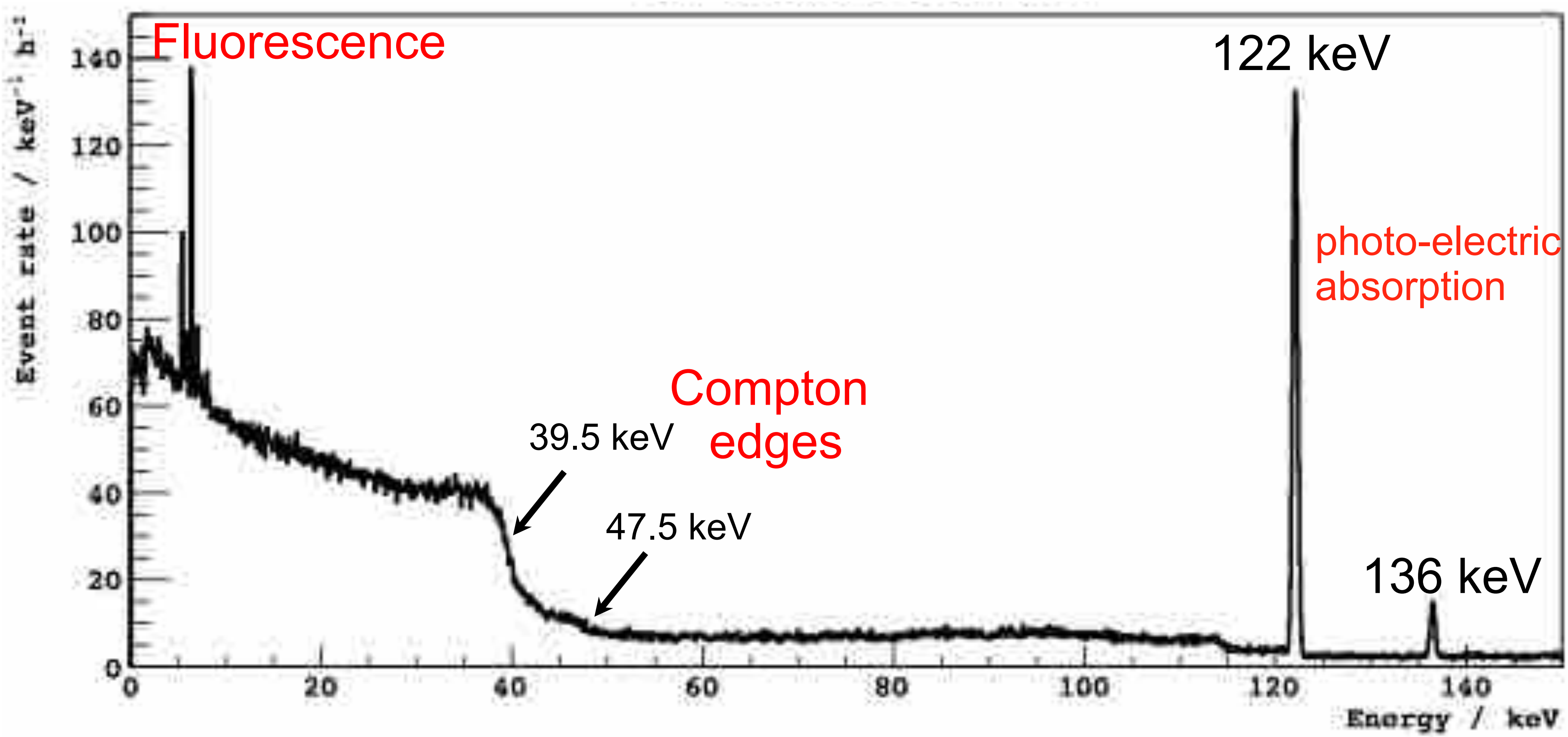


Gamma-rays

Main bkg. In DM searches

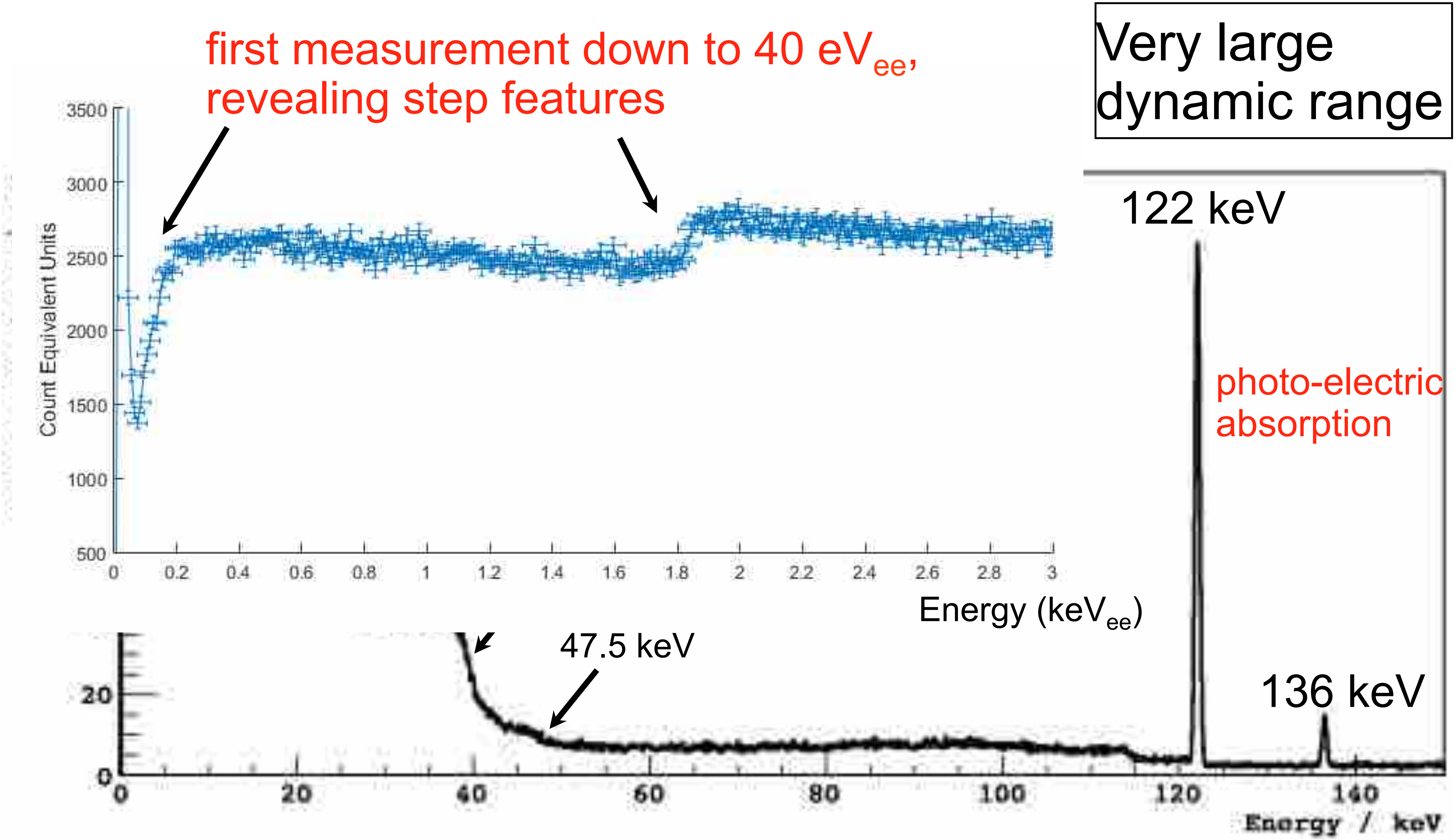
Very large dynamic range

CCD exposed to ^{57}Co source at U Chicago



Single-scatter Compton spectrum

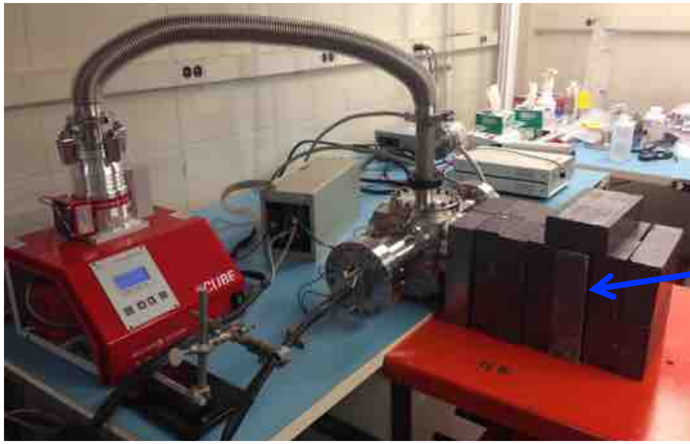
Gamma-rays

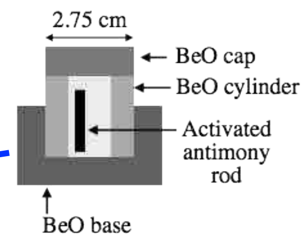


Single-scatter Compton spectrum

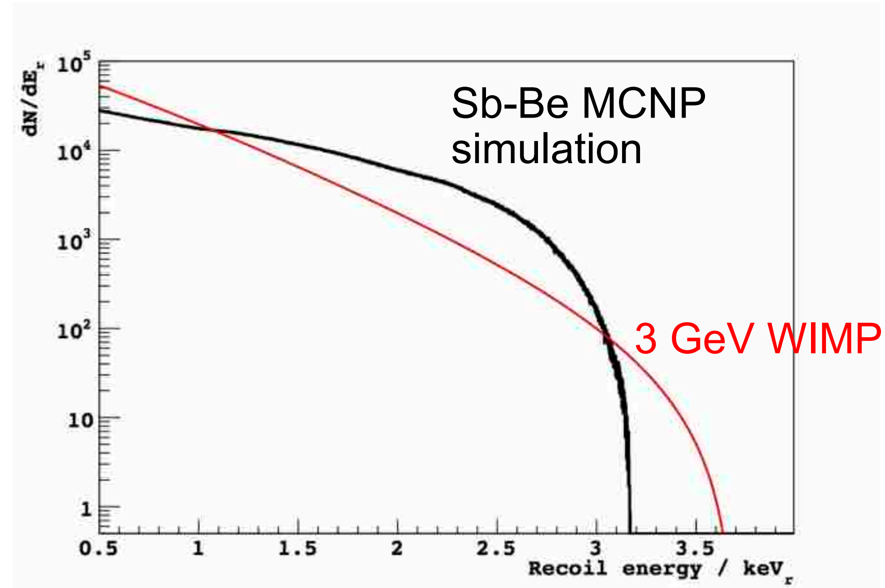
DAMIC nuclear-recoil calibration

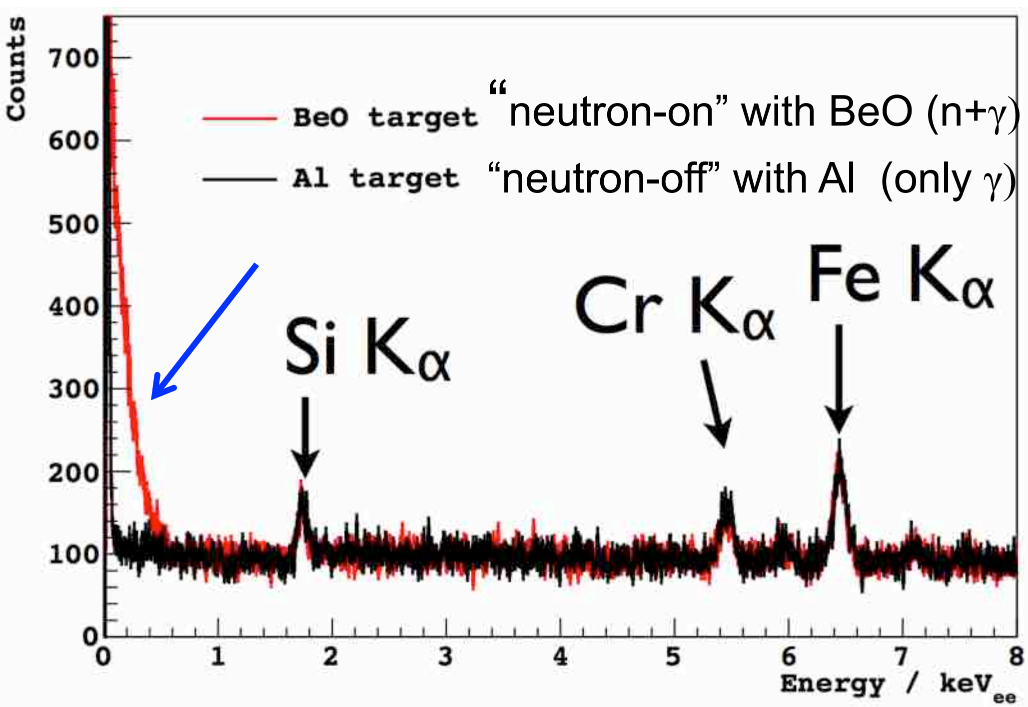
Previous measurements of nuclear recoil ionization efficiency in Si limited to >3 keV_{nr}!

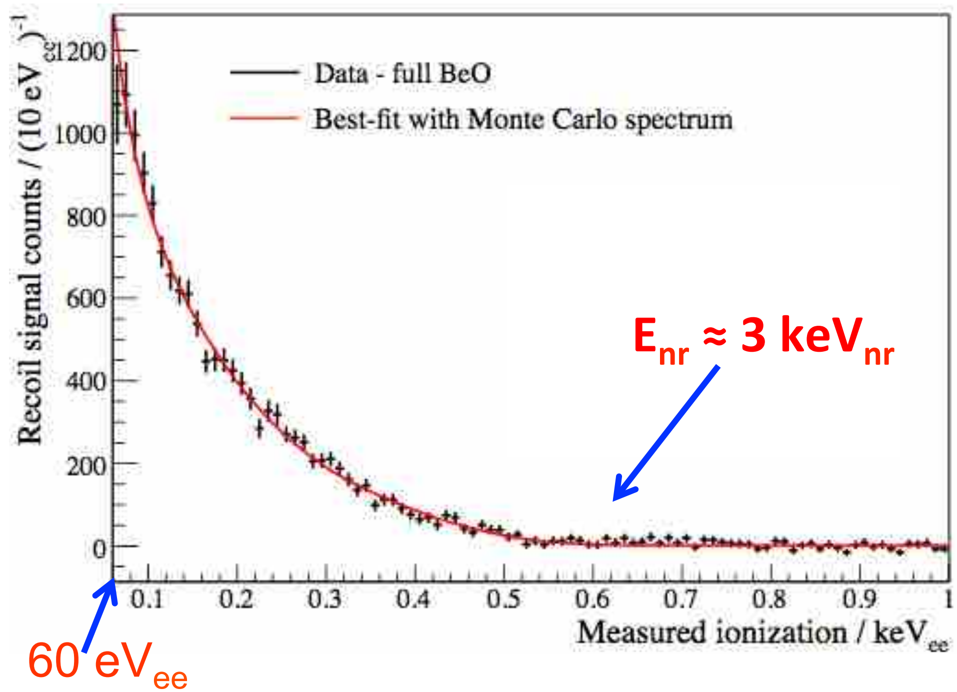




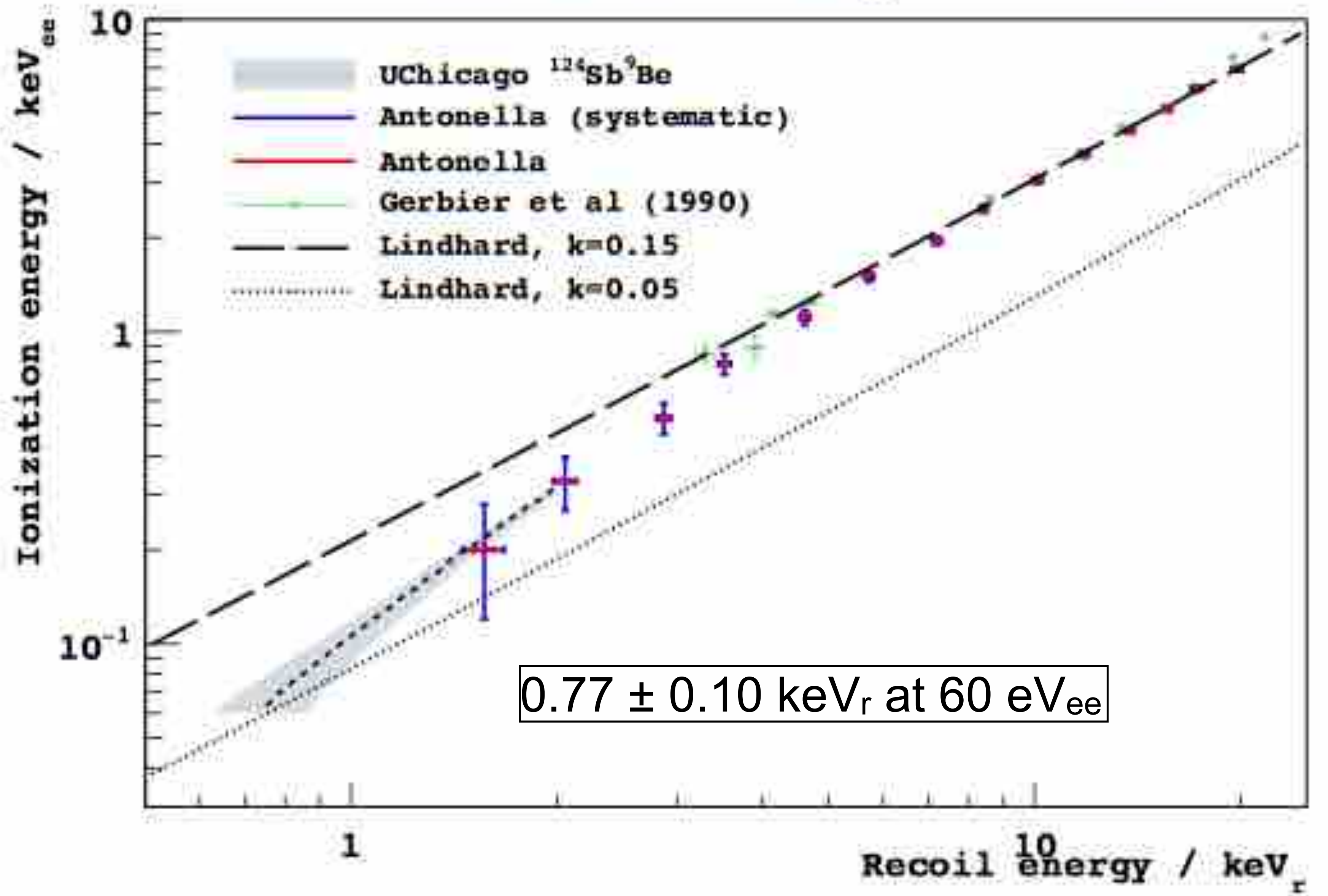
Sb-Be "monochromatic" neutron source (24 keV)







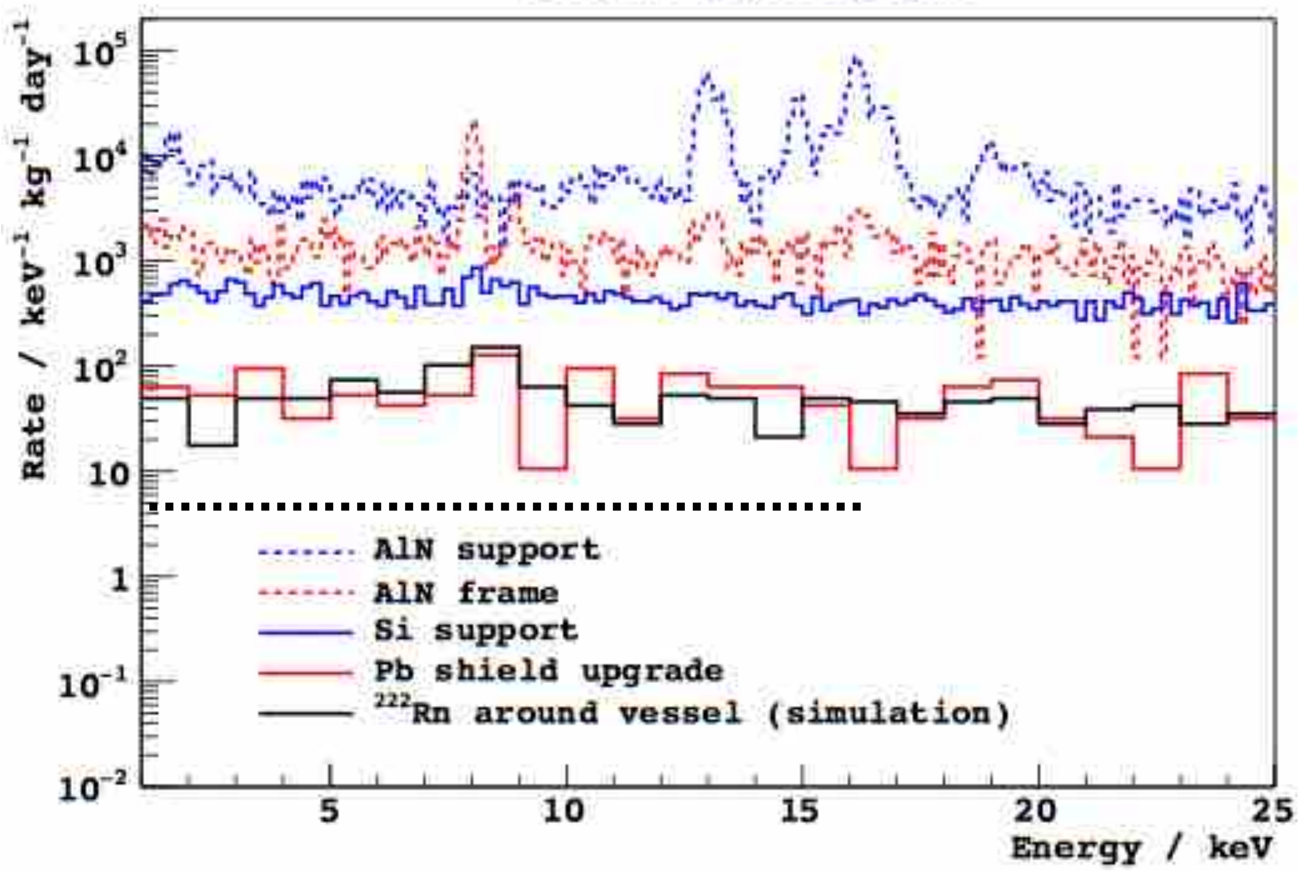
Nuclear-recoil ionization efficiency in silicon



0.77 ± 0.10 keV_r at 60 eV_{ee}

deviation from Lindhard theory observed – crucial for low-mass WIMP searches with silicon detectors

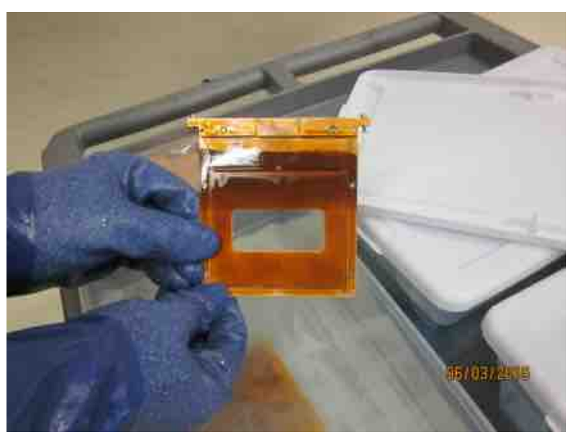
- Since 2013 background reduced by $>10^3$
- ≈ 5 dru achieved before DAMIC100 installation (similar to competitors)



Background tour-de-force

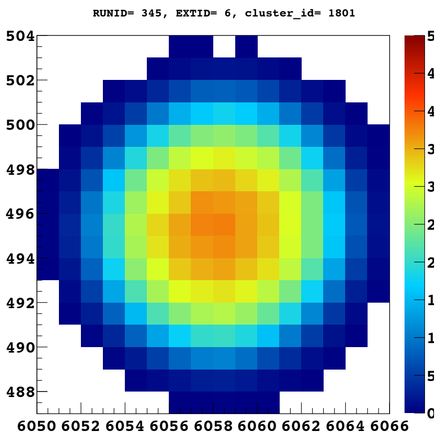
- **Lead shielding** to stop environmental γ rays

- **Material selection and cleaning:** copper machining, etching (surface bkg)

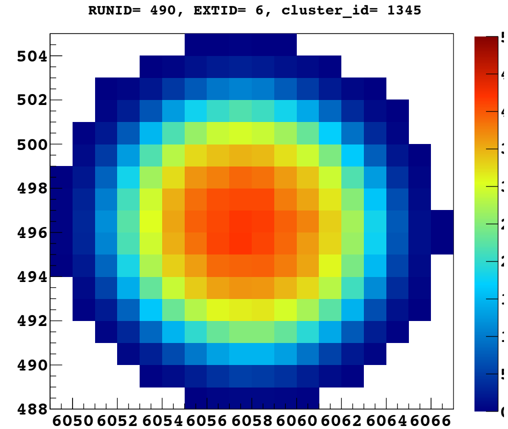


DAMIC unique spatial resolution

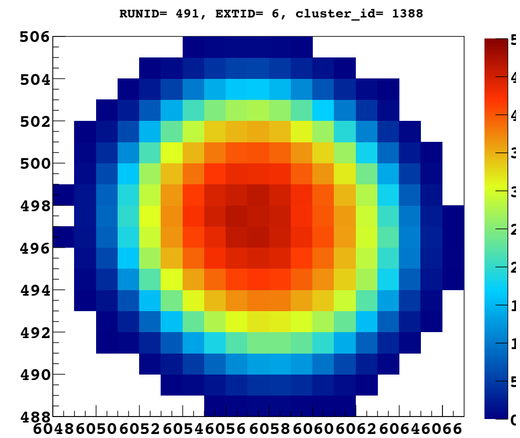
E = 5.4 MeV



E = 6.8 MeV

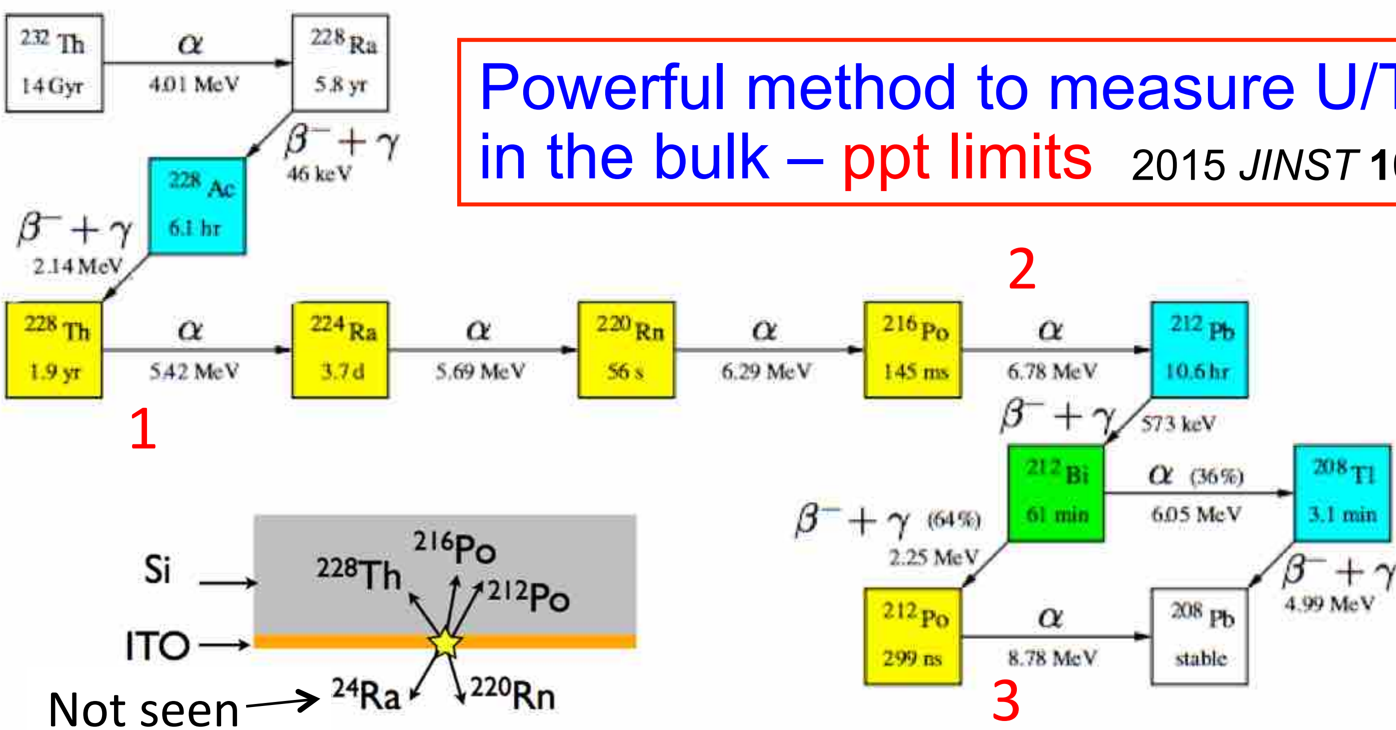


E = 8.8 MeV



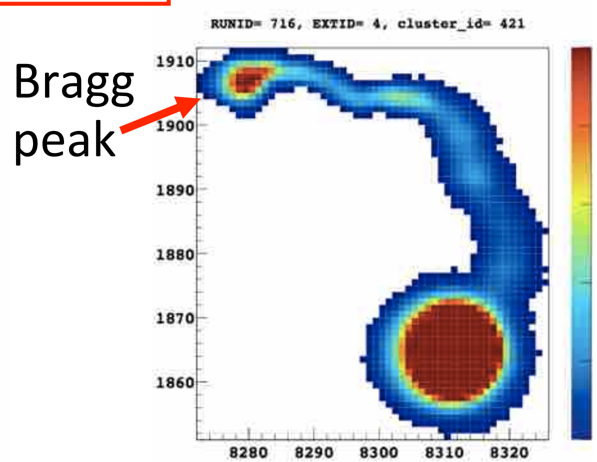
1 $\Delta t = 17.8$ d 2 $\Delta t = 5.5$ h 3

Three α at the same location!

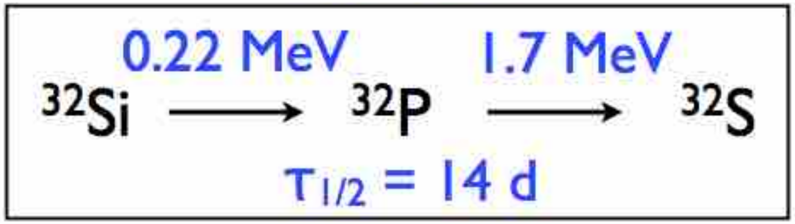


Powerful method to measure U/Th bkg in the bulk – ppt limits 2015 *JINST* **10** P08014

Example of α + β

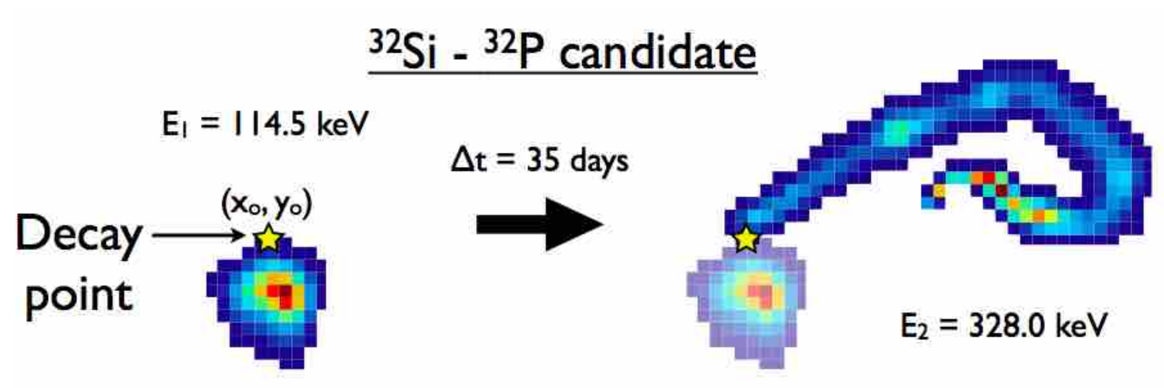


Cosmogenic ^{32}Si



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

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



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

2015 *JINST* **10** P08014

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

- Statistically limited, will be measured precisely by DAMIC100.

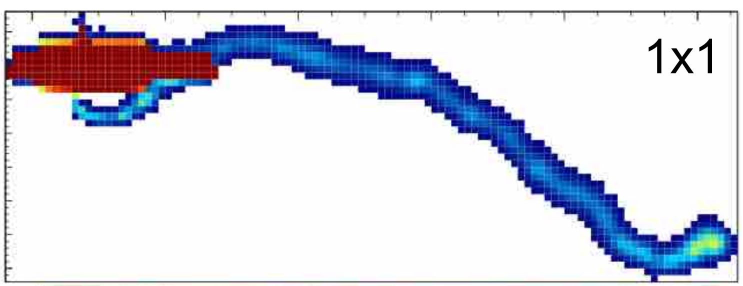
DAMIC unique spatial resolution and excellent duty cycle allows to reject this background (also other β-β sequences e.g. ^{210}Pb)

Dark Matter search with R&D data

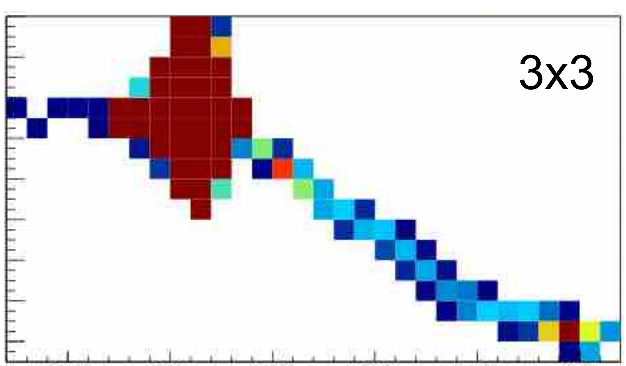
- R&D focused on background reduction and CCD operation.
- We also took a small amount of data to be used for a first limit. Background ≈ 30 dru (now 5 dru!). Exposure ≈ 0.6 kg day.

  Goal: develop search tools and demonstrate CCD science potential

- Part of exposure (0.23 kg day) taken with *hardware binning*

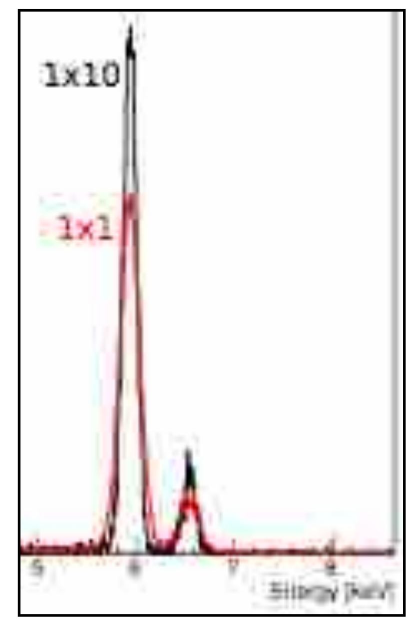


α-β events



charge of several pixels can be added together before moving it to the readout node

some loss of spatial resolution but improved signal to noise (same readout noise but more charge in a binned pixel)



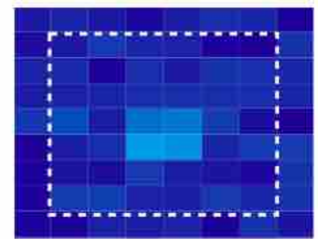
^{55}Fe source: improved energy resolution

Dark Matter search with R&D data

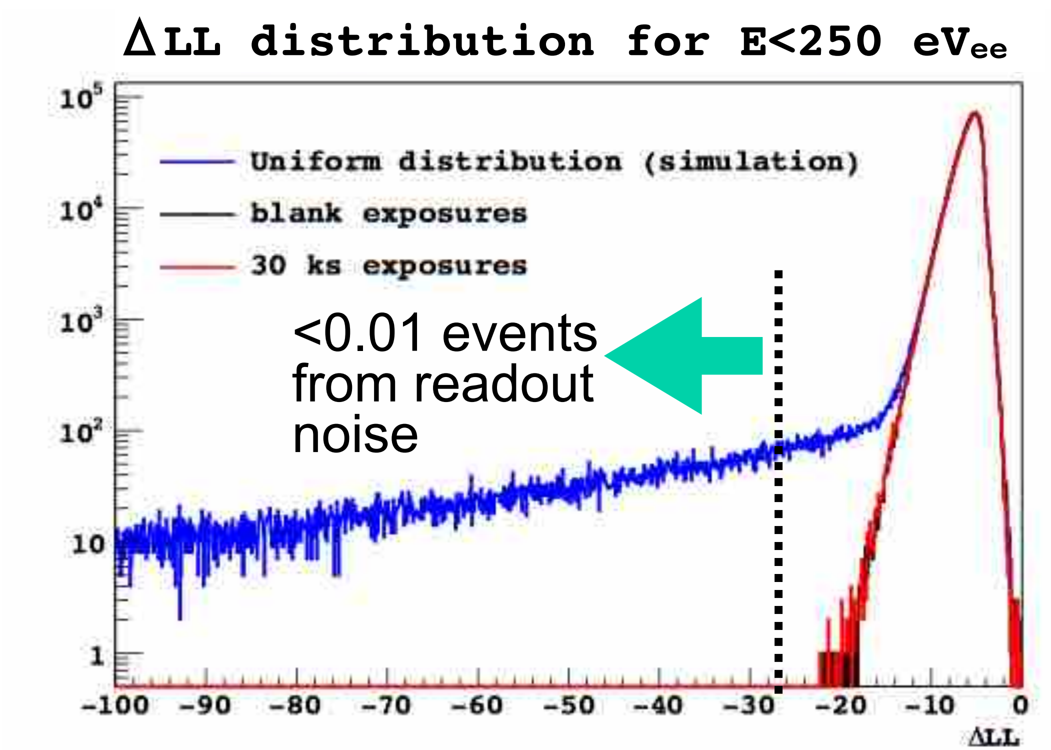
- Fit a 2D gaussian model + background in a sliding 7x7 pixels window. Calculate the corresponding LL and subtract the LL of background only model ⟶ ΔLL

$$N_e(E) \times \mathrm{Gaus}(x, y, \mu_x, \mu_y, \sigma(z))$$

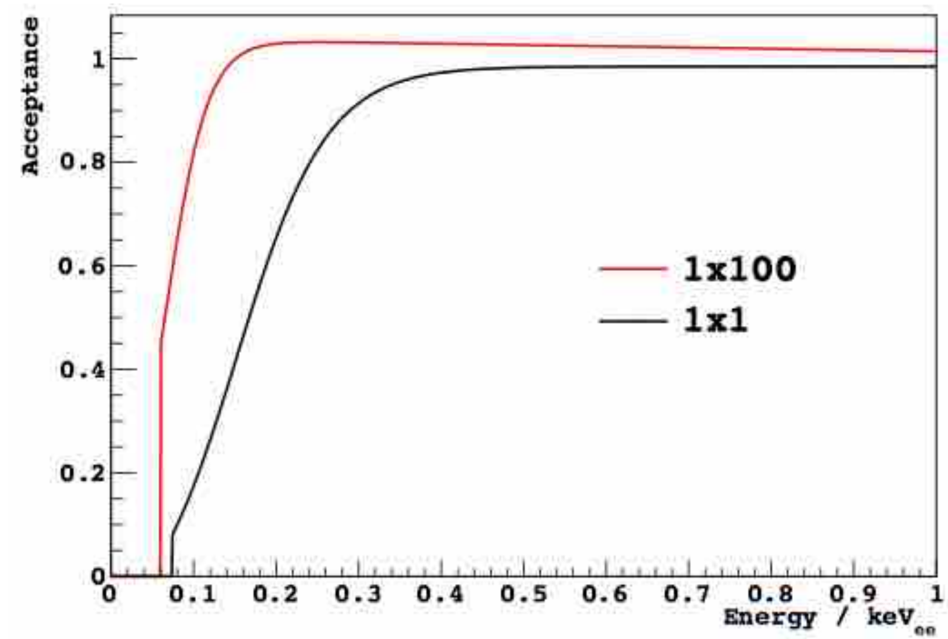
Number of ionized electrons ($N_e(E)$); Best estimate for mean of energy deposition (μ_x, μ_y); Lateral spread ($\sigma(z)$)



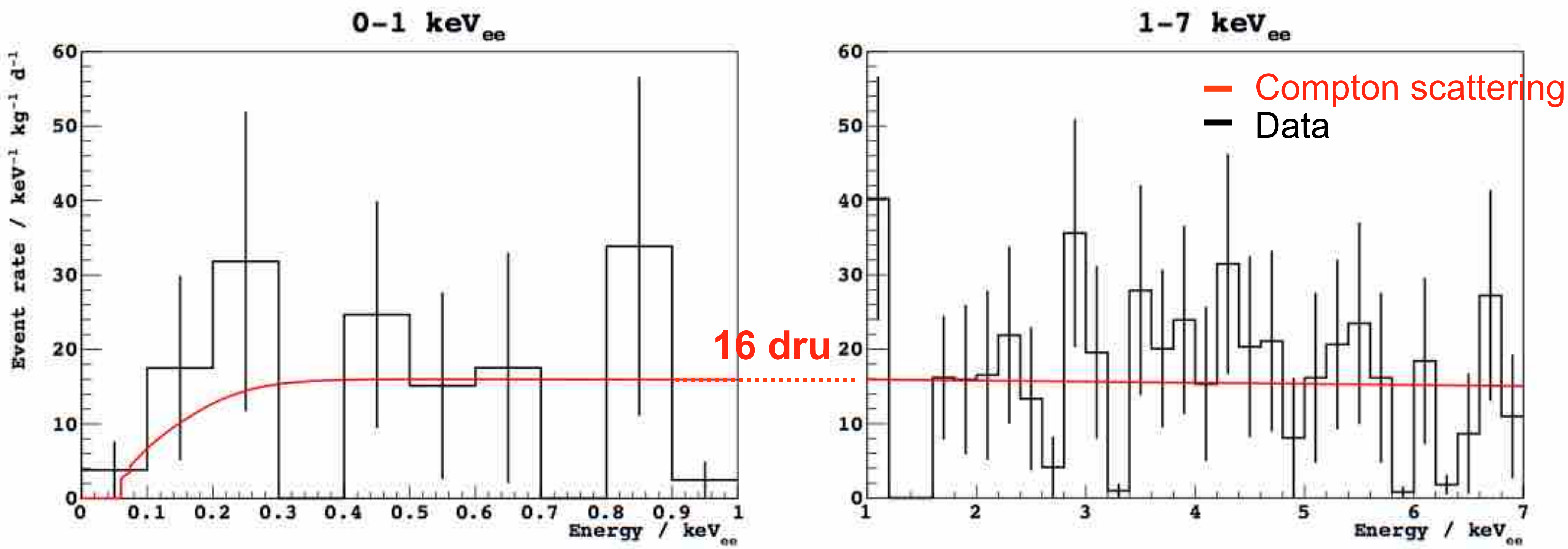
260 eV
ΔLL=-60



- Simulations used to evaluate the selection efficiency



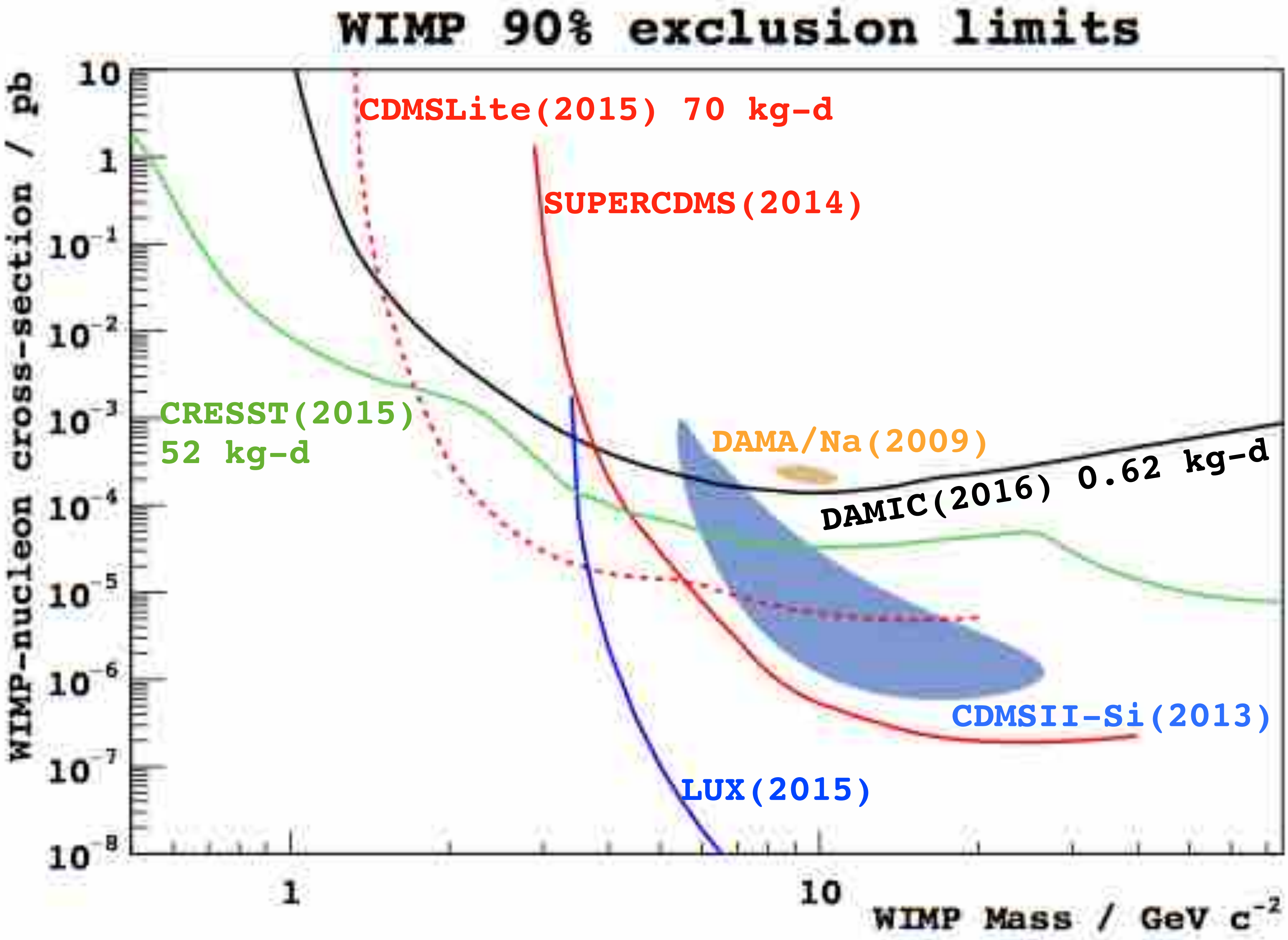
Energy spectrum



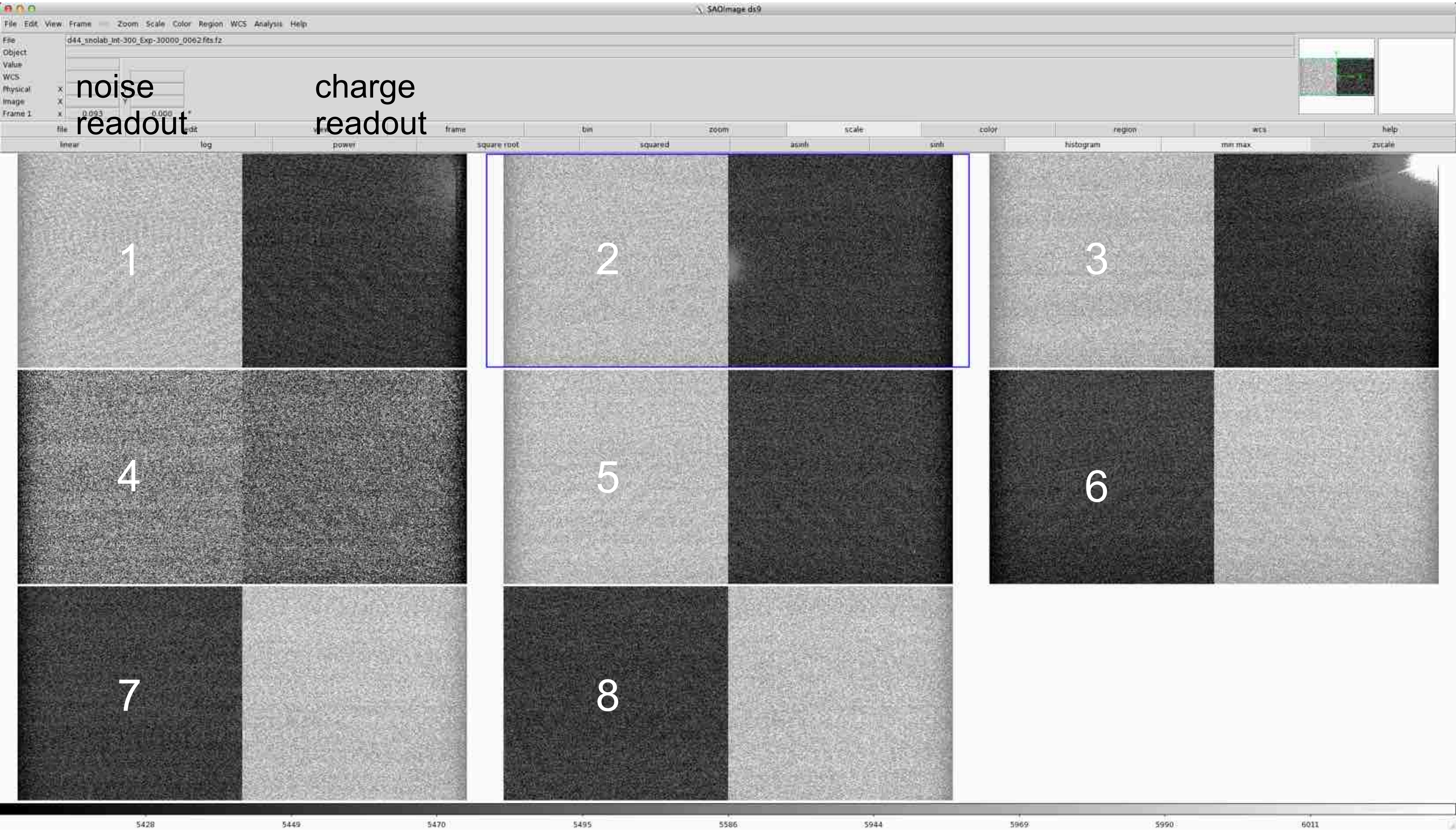
Unbinned likelihood fit to 1x1 and 1x100 data done independently, combined in a single exclusion limit.

Null (background-only) hypothesis consistent with both data sets.

Exclusion limit

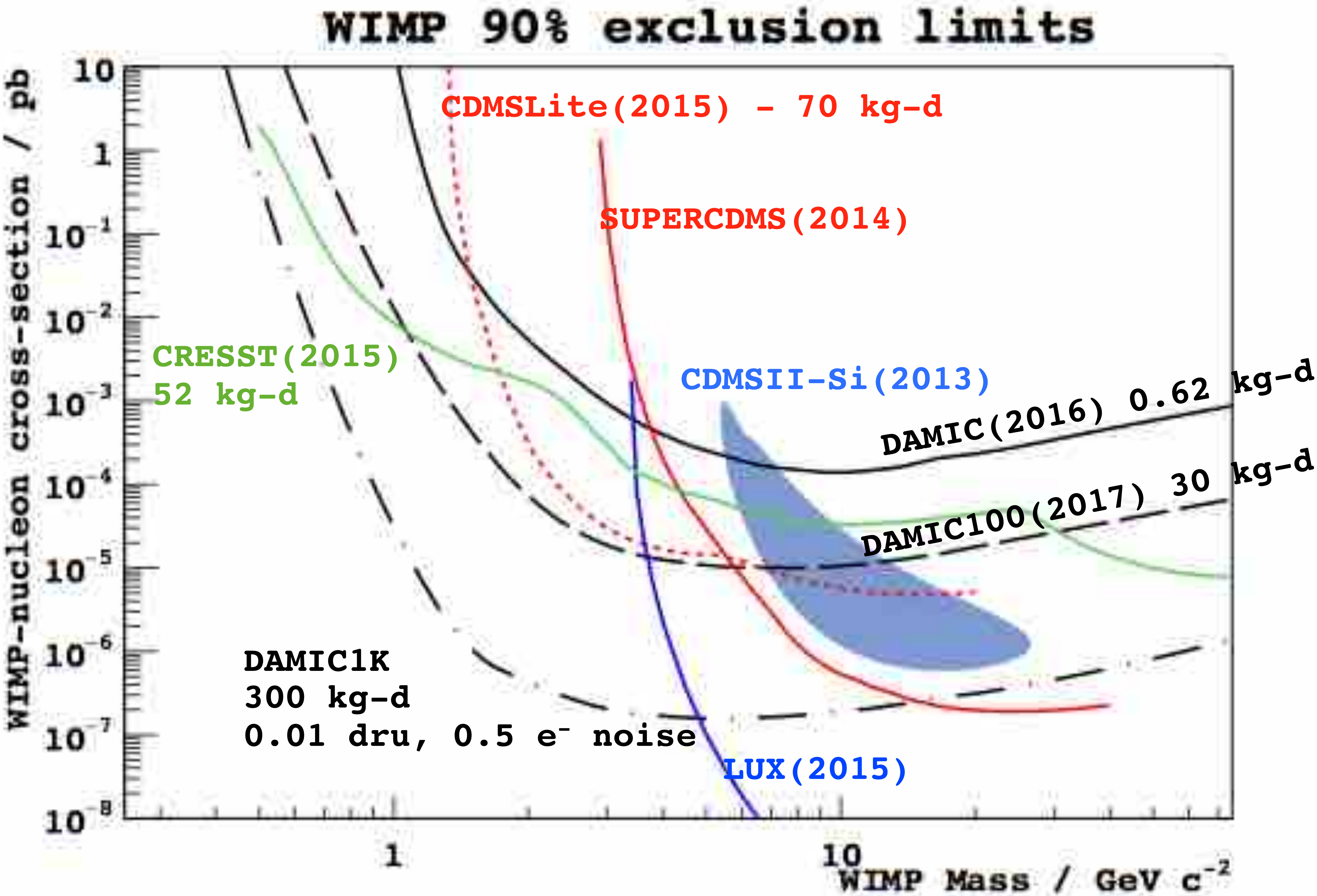


DAMIC100 first "light"



eight 4k x 4k CCDs (≈ 50 g) just installed; undergoing commissioning

Expected sensitivity



Conclusions and outlook

- DAMIC has successfully completed its R&D phase demonstrating the potential of CCDs as DM detectors:
  - stable, low noise, low background operation of large size, thick fully depleted CCDs at SNOLAB
  - unique spatial granularity to study backgrounds with unprecedented precision
  - nuclear-recoil ionization efficiency measured down to 60 eV_{ee} threshold
  - low mass WIMP sensitivity with R&D data

- DAMIC100 installation and commissioning has started, 100 g detector ready for science data taking by the end of 2016. DAMIC100 will be a major player in the field in the next few years.

- Future: a 1kg CCD detector

DAMIC