KICP Colloquium, April 27th, 2016

DAMIC

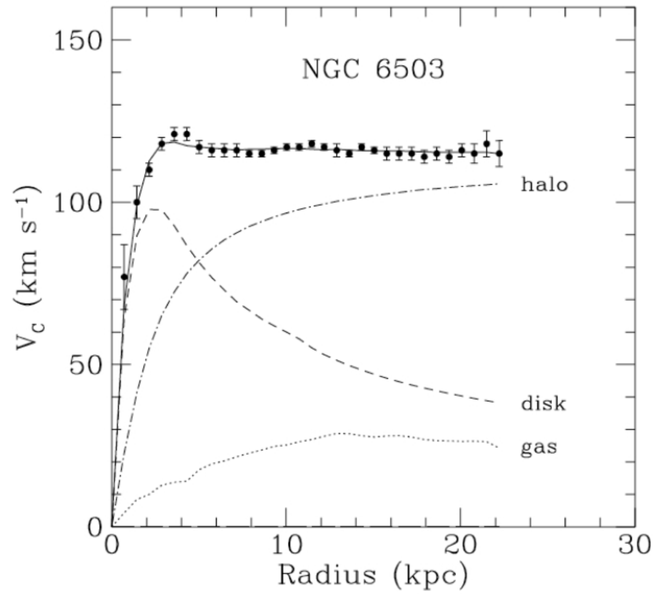
WIMPs taking selfies: the DAMIC experiment at SNOLAB

Paolo Privitera

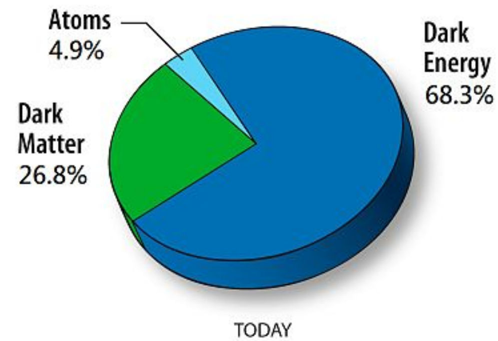
THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES
The Enrico Fermi Institute
KICP

Dark Matter WIMPs 101

1)



Mass and energy in the Universe

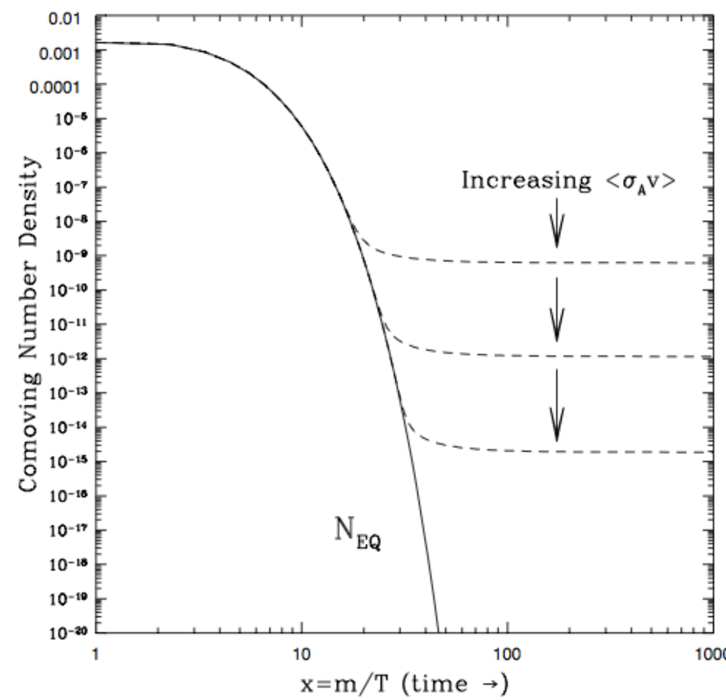


$$\varrho_{DM} \approx 0.3\ \mathrm{GeV/cm^3}$$

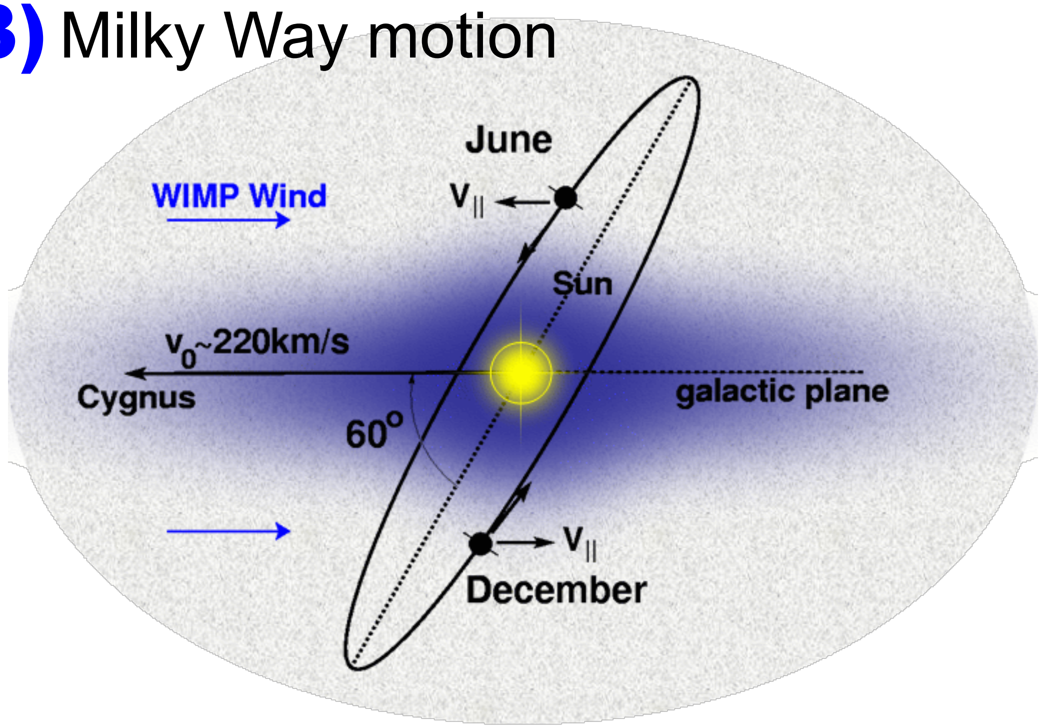
Astrophysical evidence for DM:
Galaxy rotation curve, lensing , CMB

2) Natural candidate: a Weakly Interacting Massive Particle, yet unknown, in equilibrium in the early universe $(\chi\chi \leftrightarrow q\bar{q}, \ell\bar{\ell}, \ldots)$

which “freezes out” according to its cross section (WIMP miracle)



3) Milky Way motion



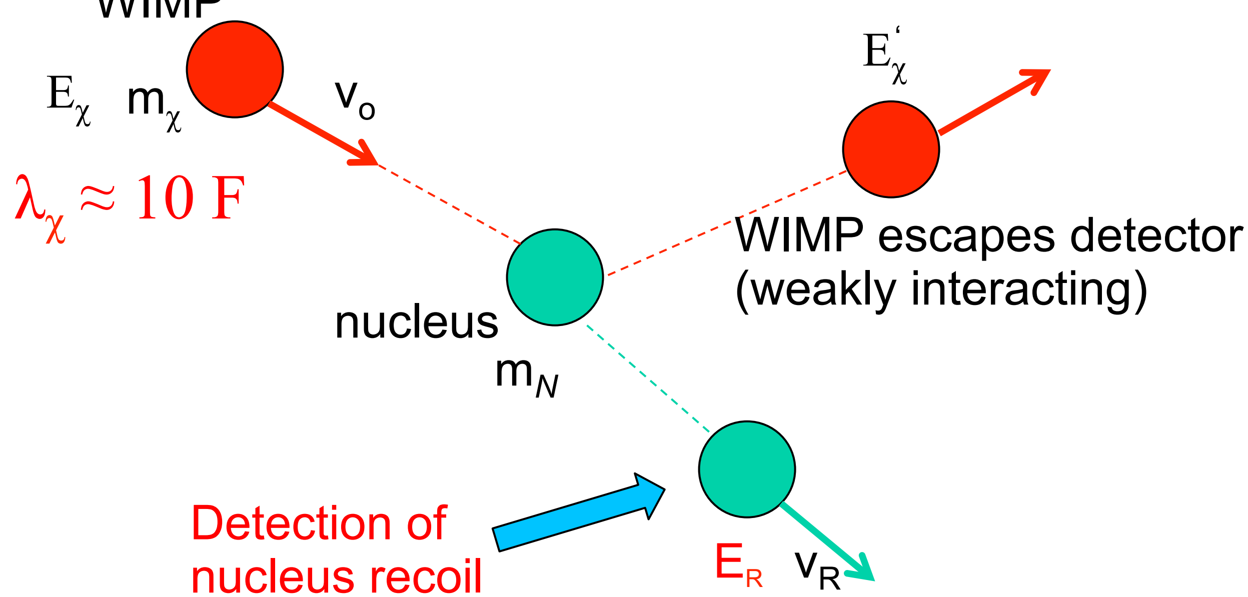
4) WIMP kinetic energy in the Earth (detector) frame

$\frac{1}{2}\, m_\chi\, v_o^2 \approx$ 30 keV

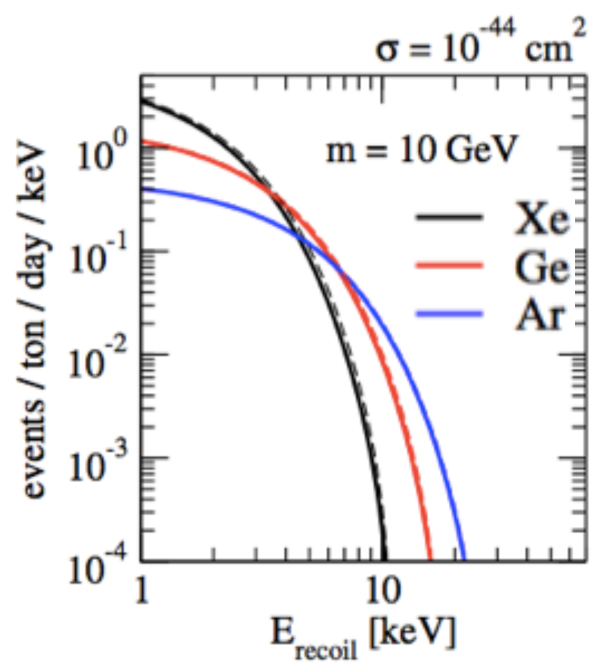
(m_χ = 100 GeV)

Low energy interaction with matter

5) Coherent elastic scattering

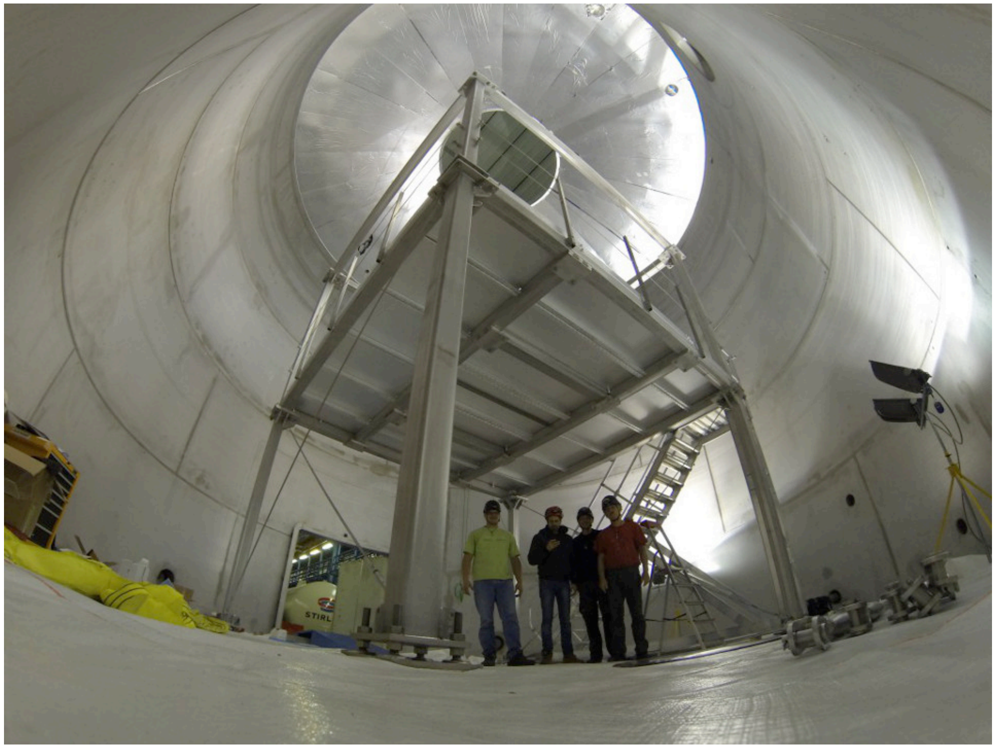


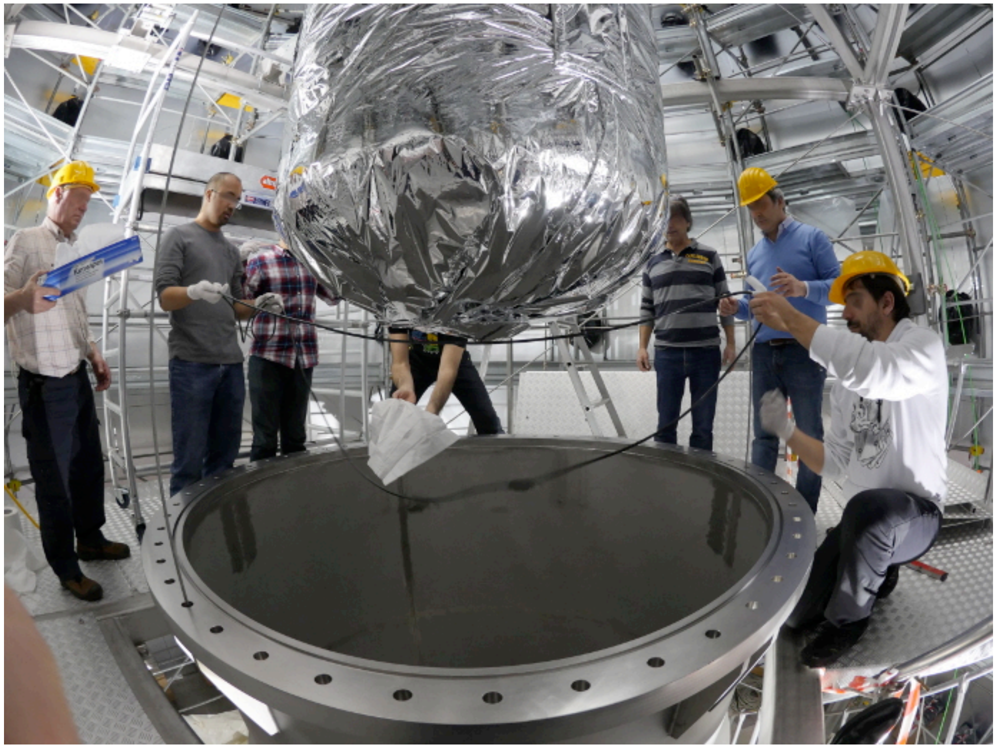
6)



Experimental challenges

- Massive target-detector
- Ultra-pure target (radioactive contaminants)
- Low energy threshold (tens of keV vs MeV in neutrino physics)
- Low background (deep underground; material screening and selection)

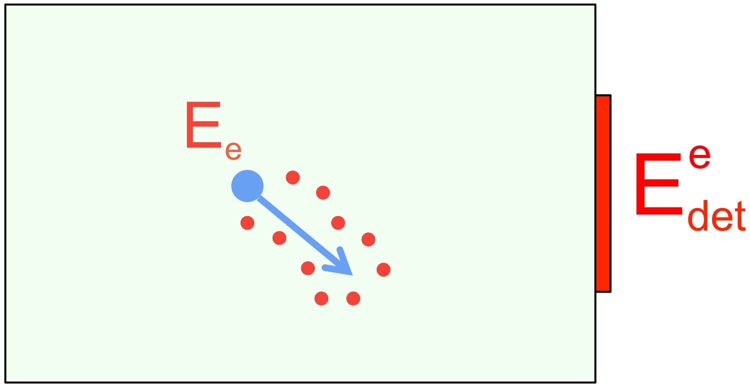




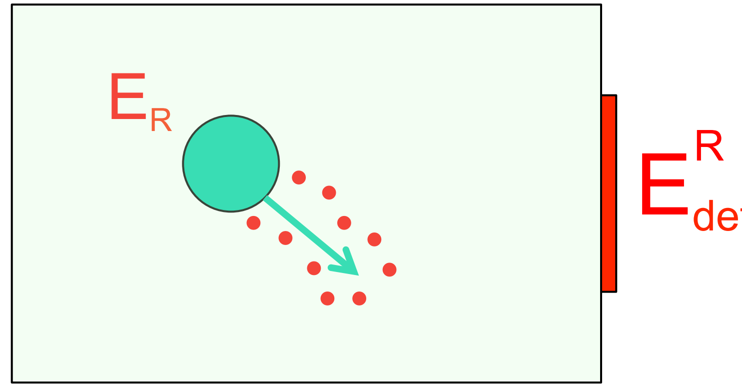
Cryostat support in the Veto water tank **Xenon 1T** Cryostat

7) Nuclear recoil ionization efficiency (quenching factor)

electron

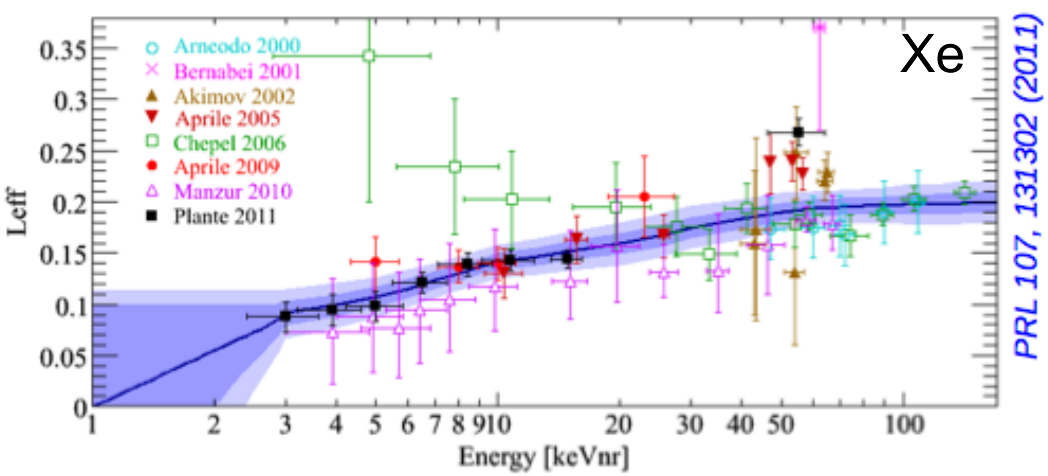


Nucleus recoil



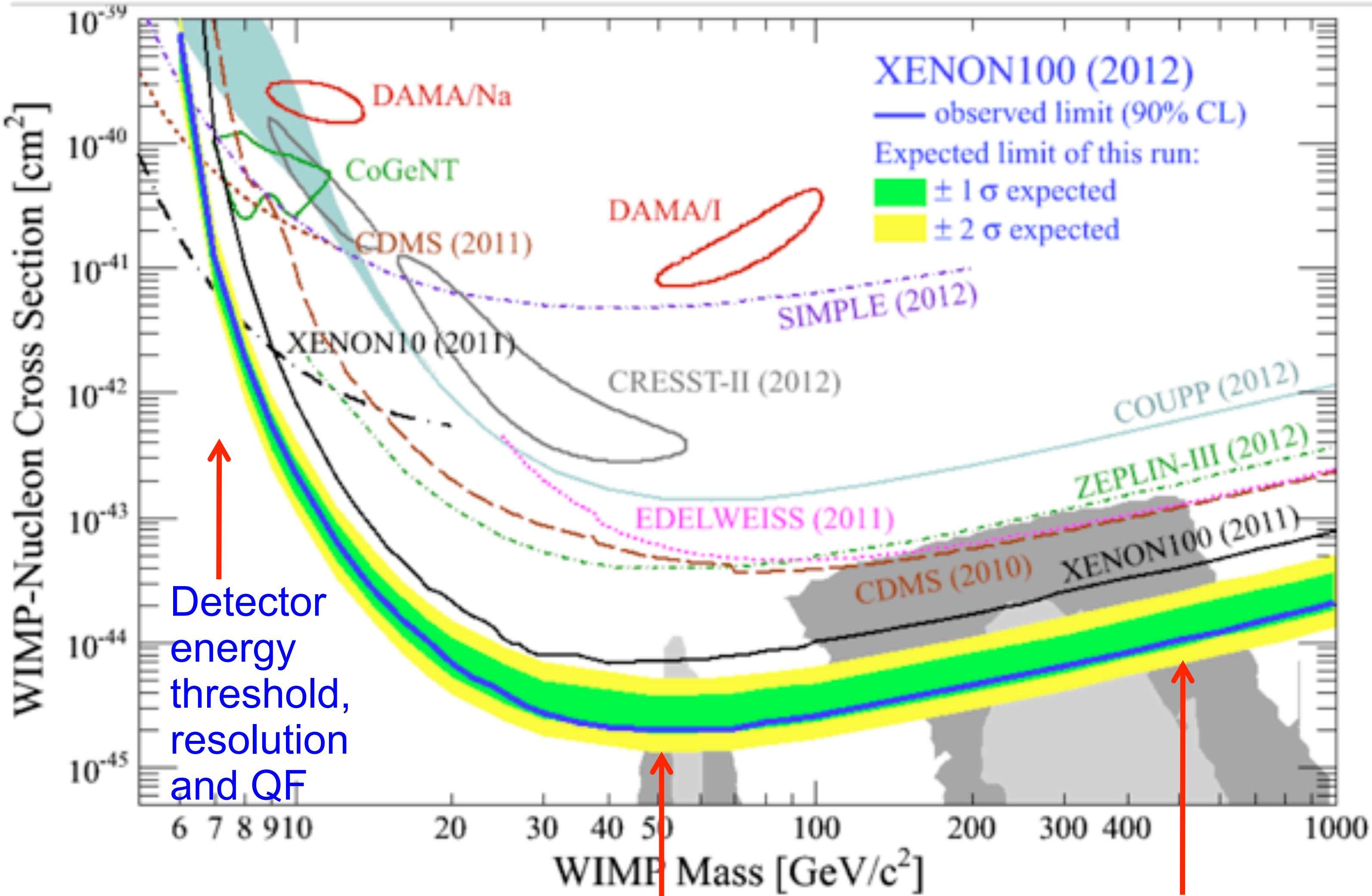
Take a nucleus and an electron of the same energy ($E_R = E_e$).

In general, $E^R_{det} < E^e_{det}$ (the nucleus dissipates its energy through mechanisms other than ionization) "Lindhard theory"



For a given detector ("electron") energy threshold, the nuclear recoil energy threshold depends on the QF. Essential to measure.

WIMP exclusion plot



$n \sim \rho / m_\chi$

$E_R \approx E_\chi \cdot r$ $\quad E_\chi = 0.5\, m_\chi v^2$

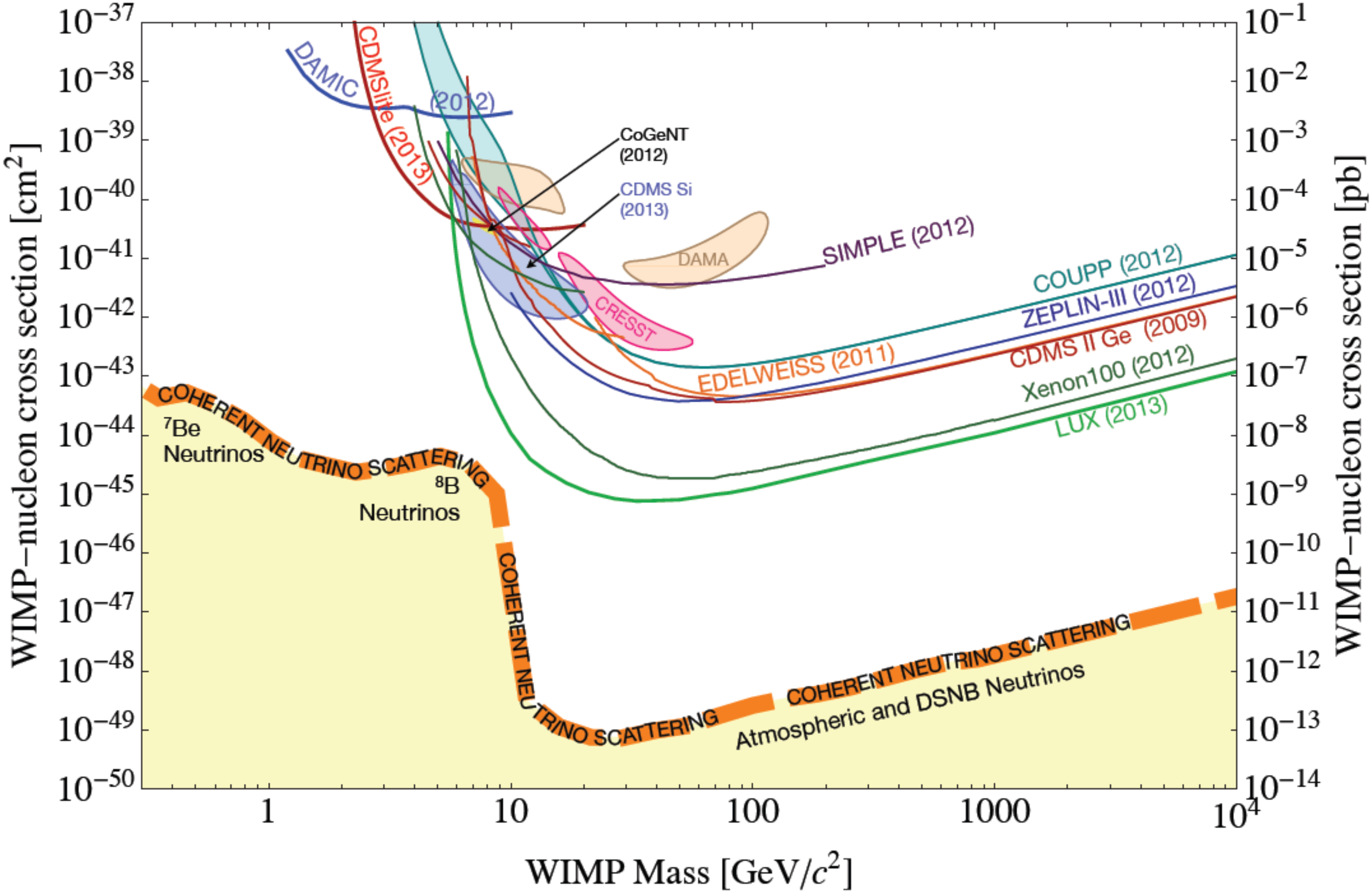
$m_\chi \approx m_N$

$E_R \approx 0.5\, m_N v^2$

$$r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}$$

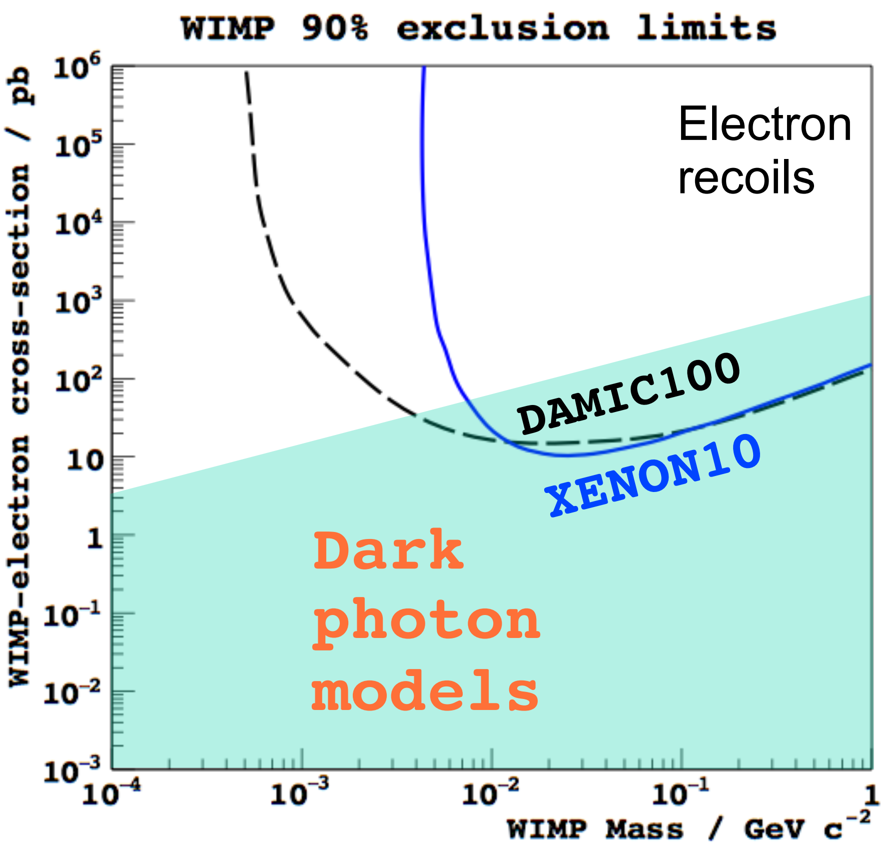
Dark Matter in CCDs

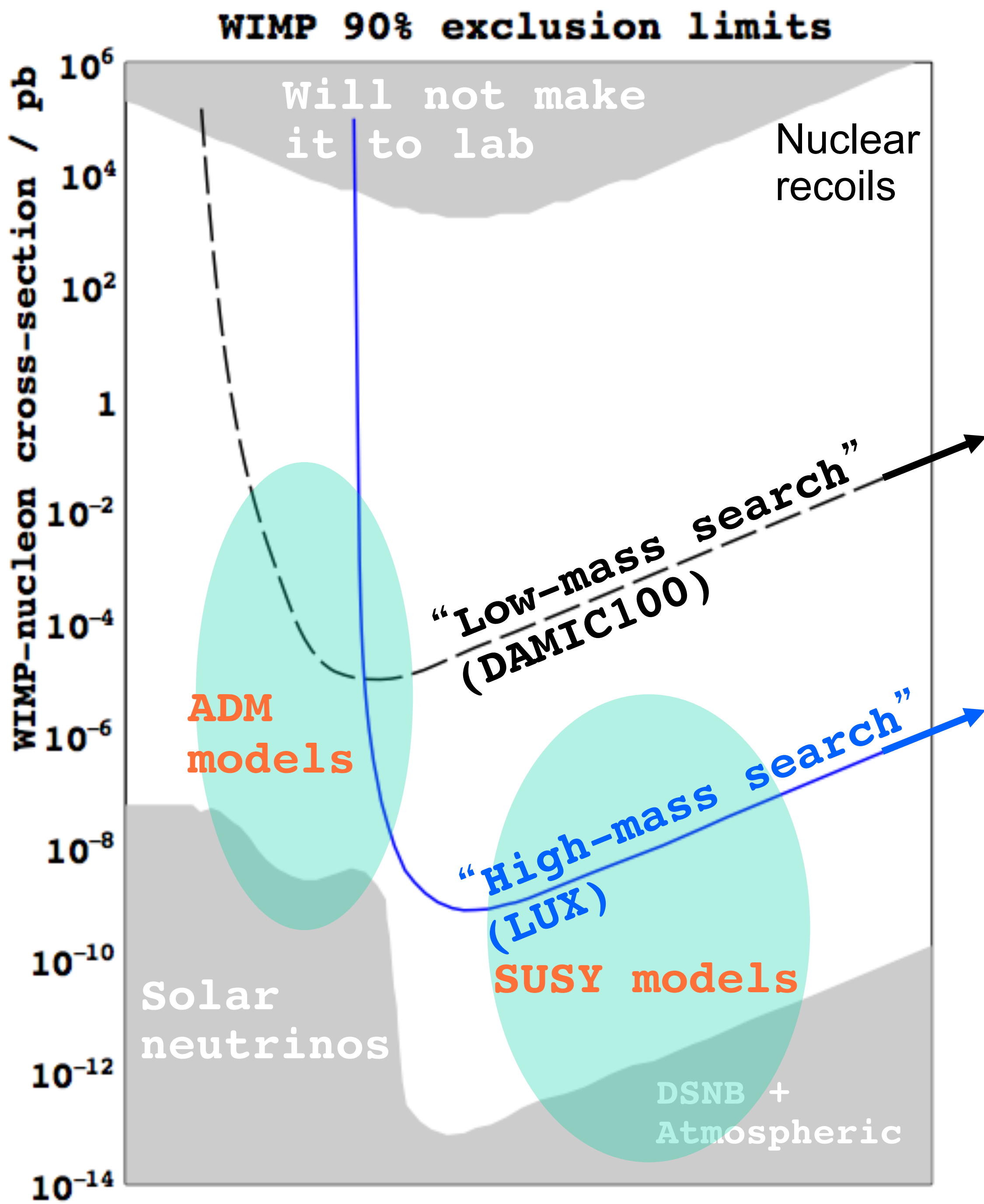
Phys. Lett. B711 (2012) 264-269 from a first test of the concept at Fermilab NuMi hall (350' deep)
J. Estrada, Fermilab



Designed to explore the low-mass WIMP region with very low threshold

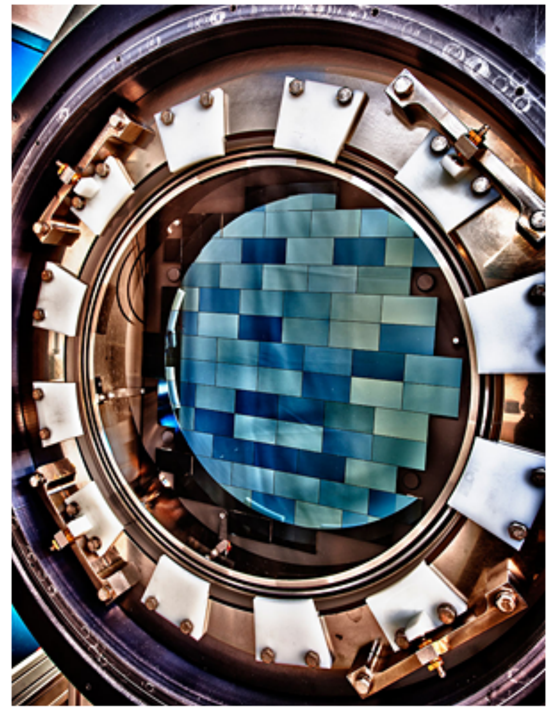
Exploring low-mass Dark Matter



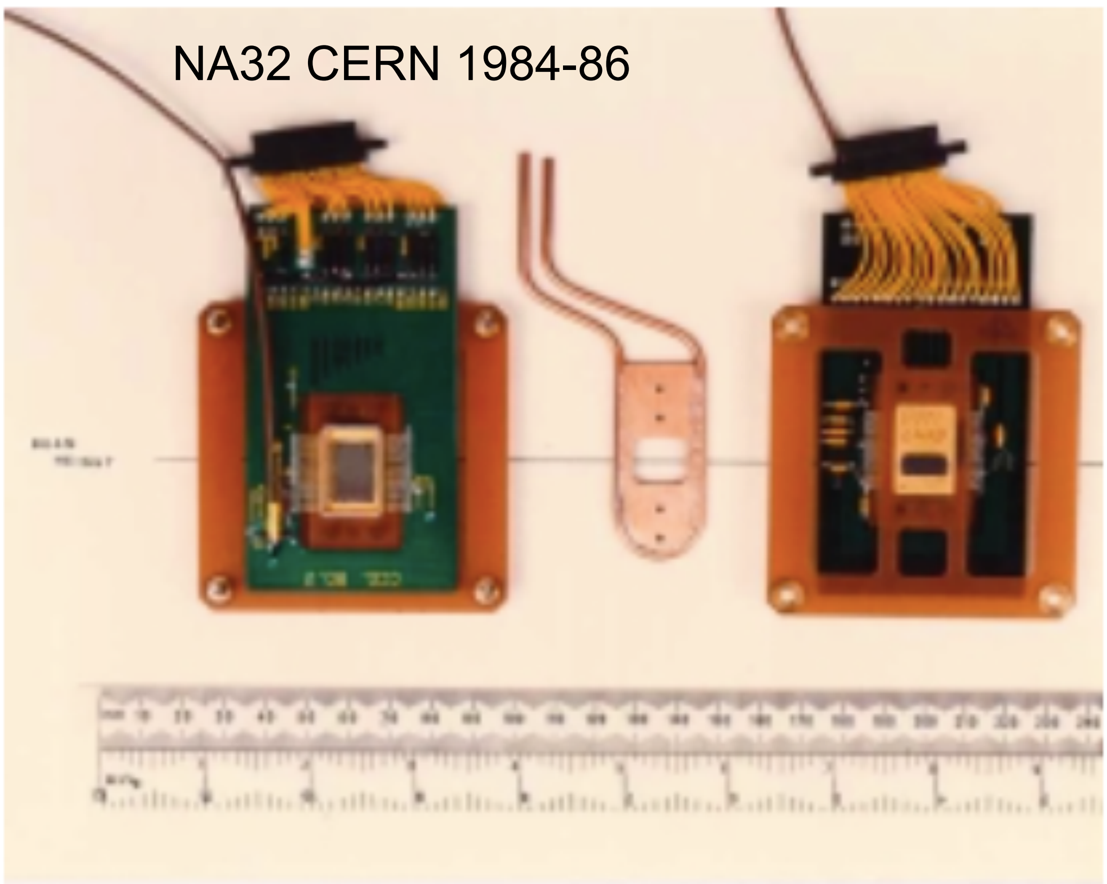


Charge-Coupled-Devices

Dark Energy Survey Camera



250 μm thick CCDs with enhanced IR sensitivity developed at LBNL



NA32 CERN 1984-86

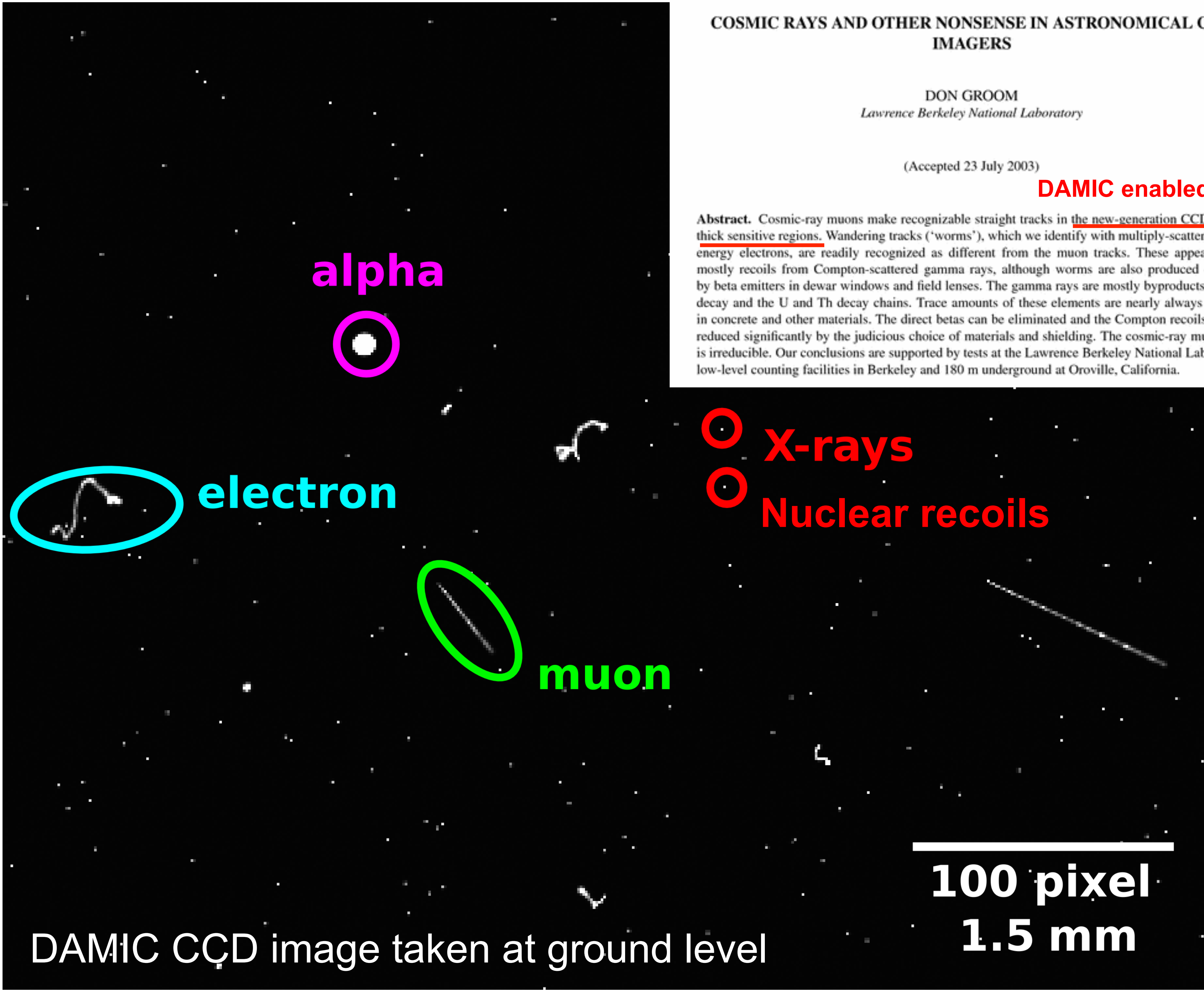
COSMIC RAYS AND OTHER NONSENSE IN ASTRONOMICAL CCD IMAGERS

DON GROOM
Lawrence Berkeley National Laboratory

(Accepted 23 July 2003)

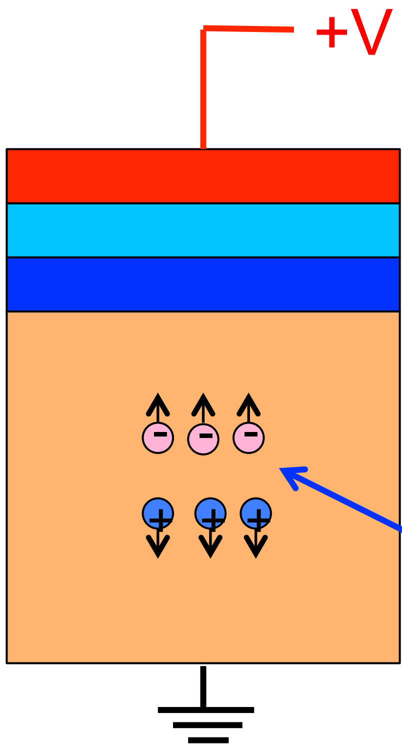
DAMIC enabled by

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.



How a CCD works

Metal-Oxide-Semiconductor capacitor



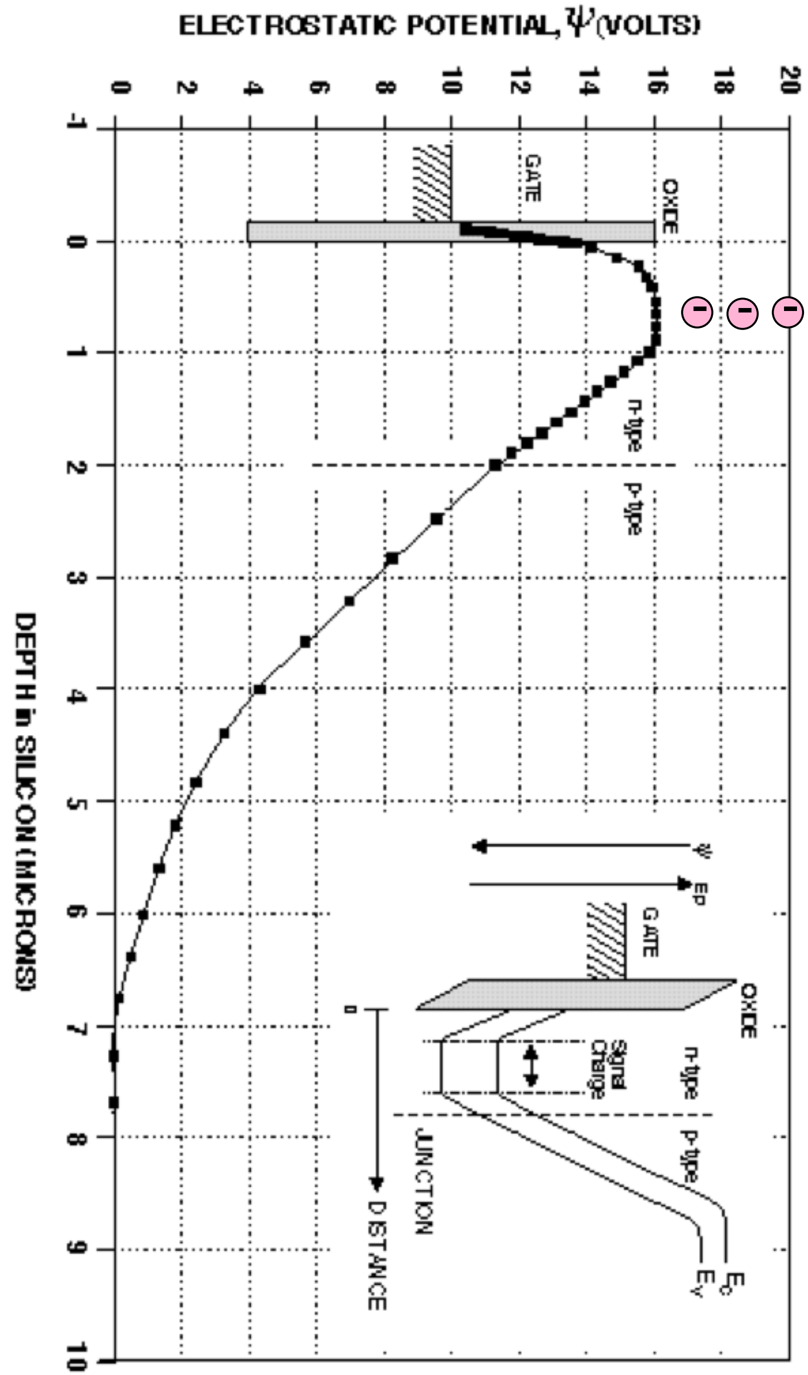
Metal gate

Si oxide (insulator)

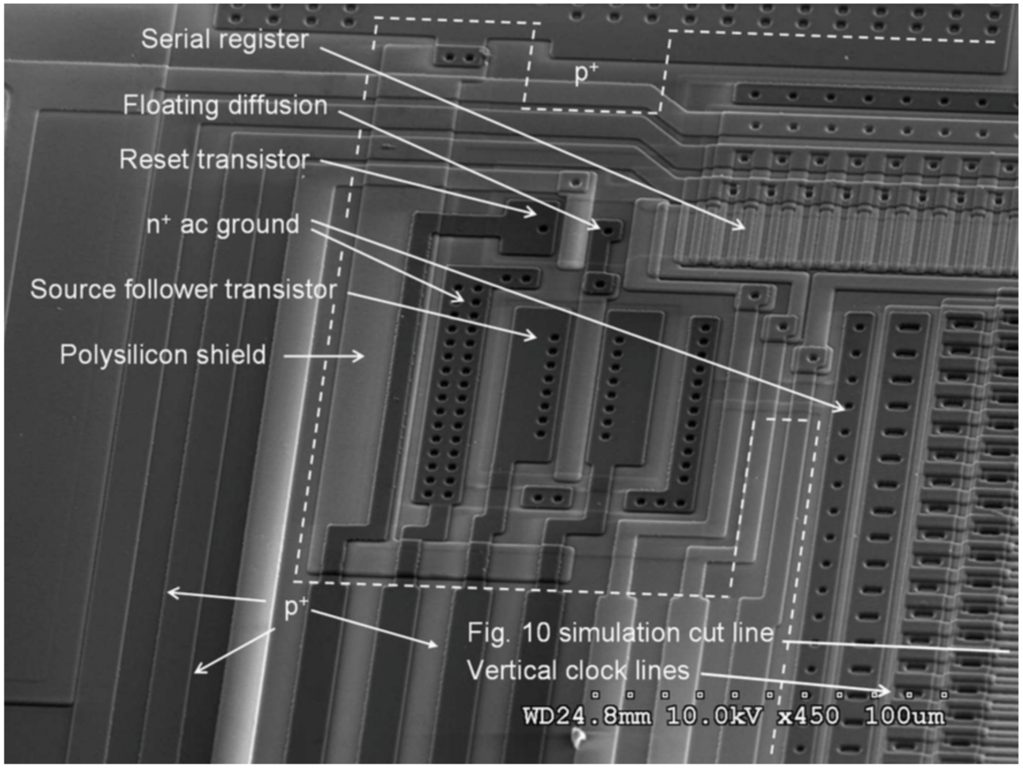
n-type Si (buried channel)

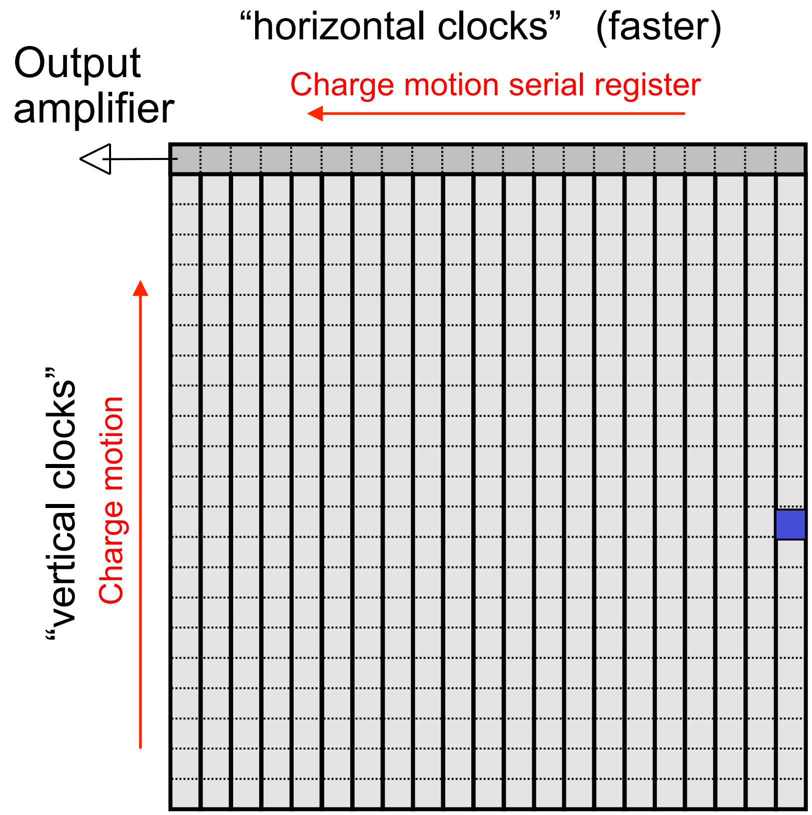
p-type Si

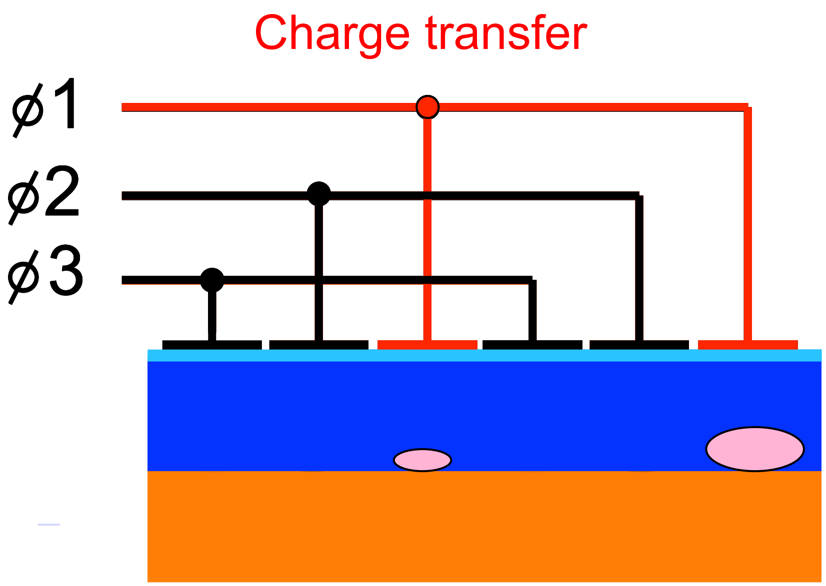
electron-hole pairs
generated by a photon
or ionizing particle
(3.6 eV_{ee} / e-hole pair)



A CCD is an array of MOS capacitors

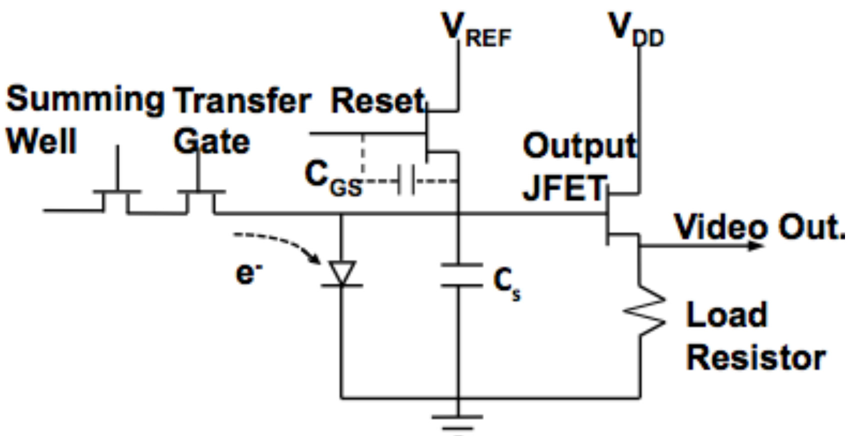


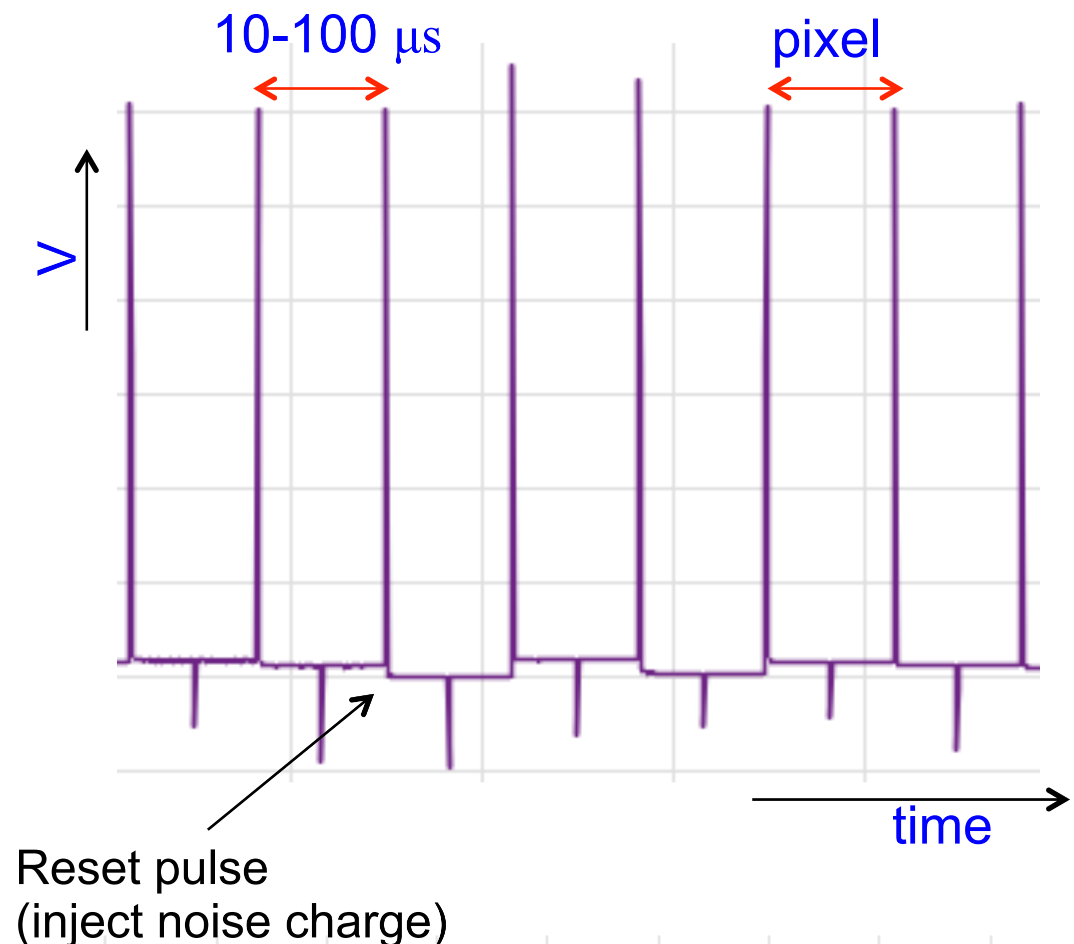




CCD in action

CCD pixel charge readout

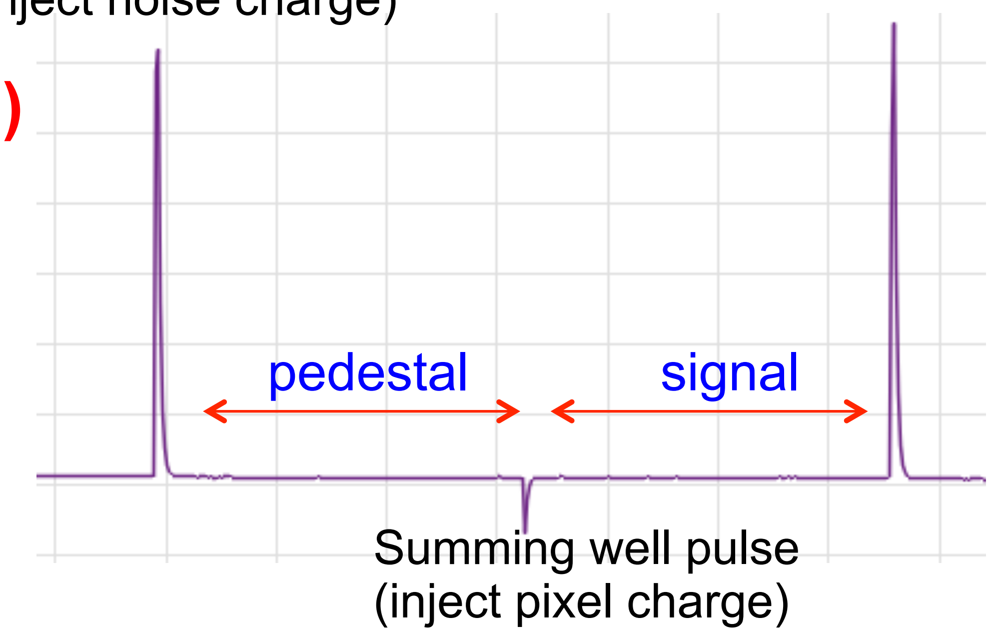




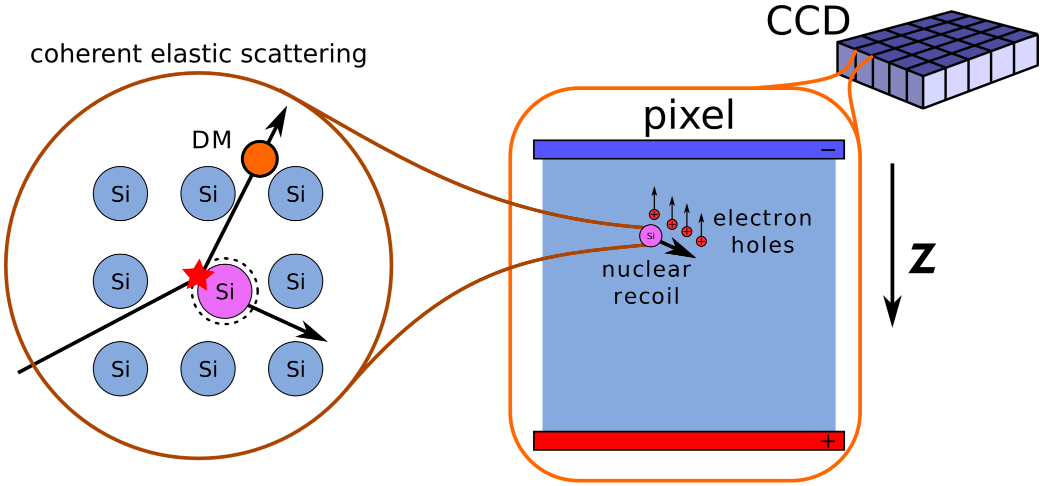
Correlated Double Sampling (CDS)

(signal – pedestal) cancels the reset noise (and also other correlated noise)

Performed <u>analogically</u> in standard CCD readouts

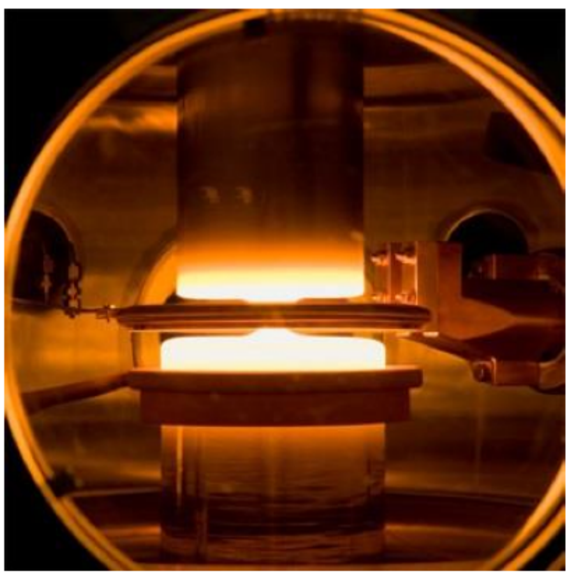


Why Dark Matter in CCDs ?



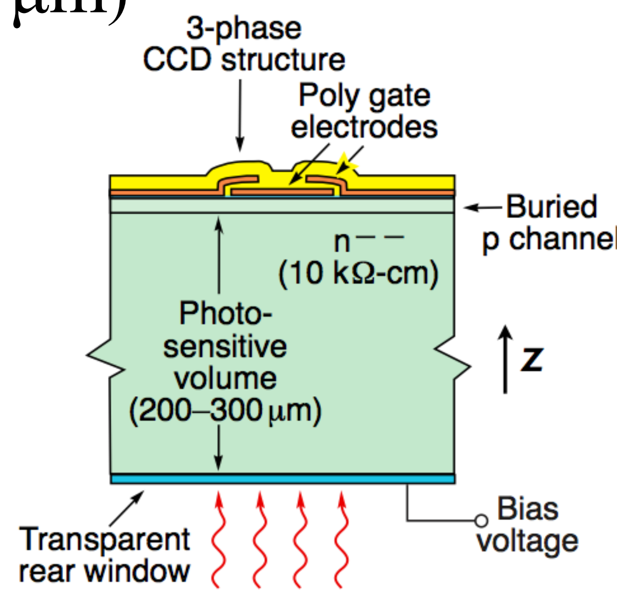
- Detection of point-like energy deposits from nuclear recoils induced by WIMP interactions (10 keV Si ion range 200 A)

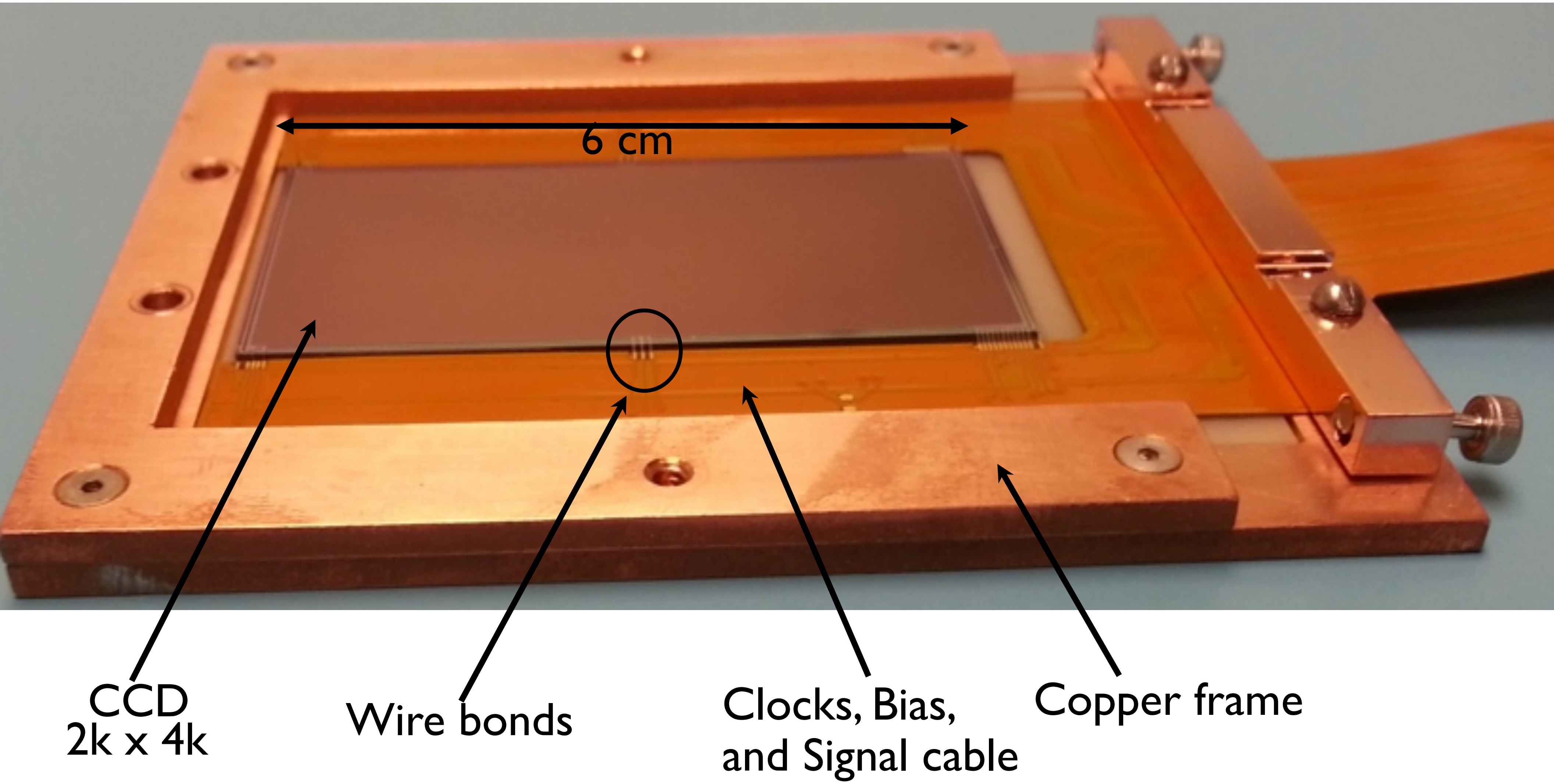
1) High-resistivity (10^{11} donors/cm^3) extremely pure silicon



Float-zone Si

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





3) Sizable mass

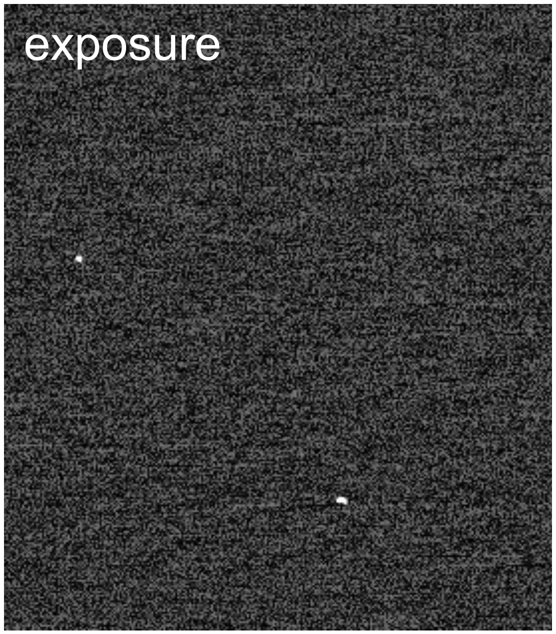
First DAMIC CCDs from DECam!

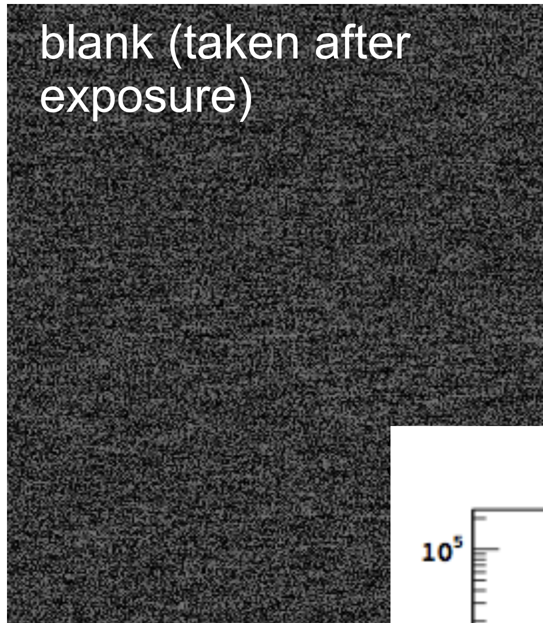
a DAMIC CCD 6 cm x 6 cm, 16 Mpixel (15 μm x 15 μm) has a record thickness of 675 μm and 5.9 g mass

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

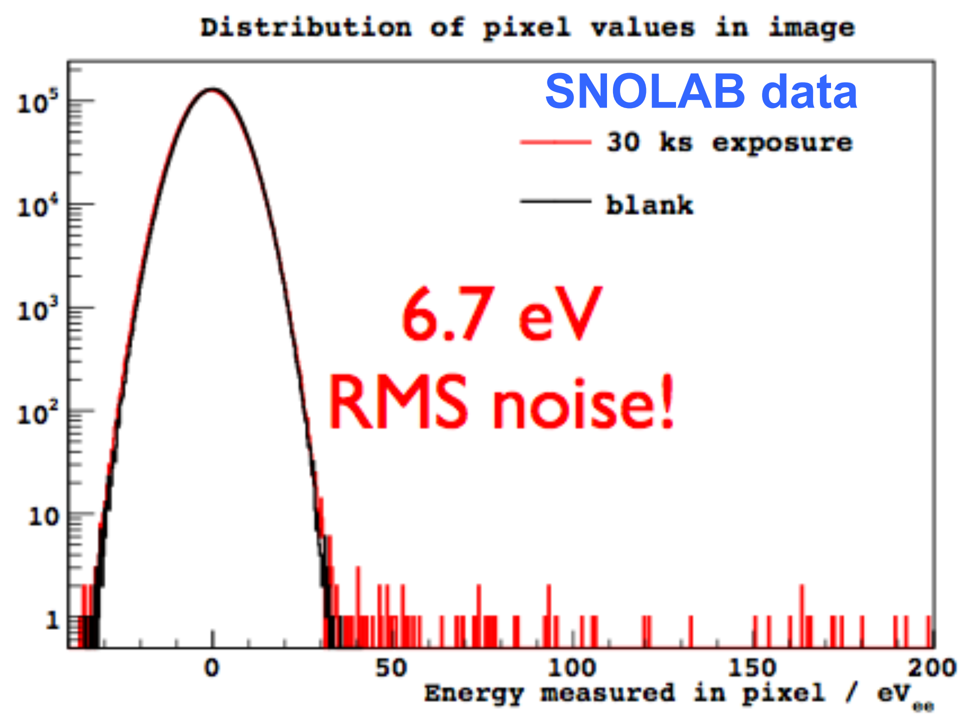
4) Unprecedented low energy threshold

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





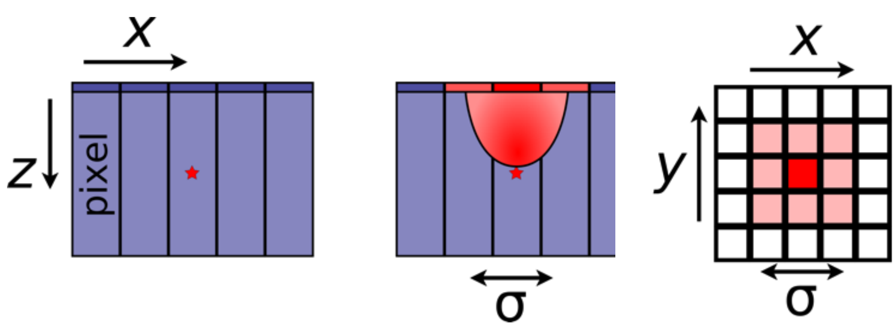
- Slow readout (≈ 5 min / 8 Mpix image) to achieve σ ≈ 2 e- noise



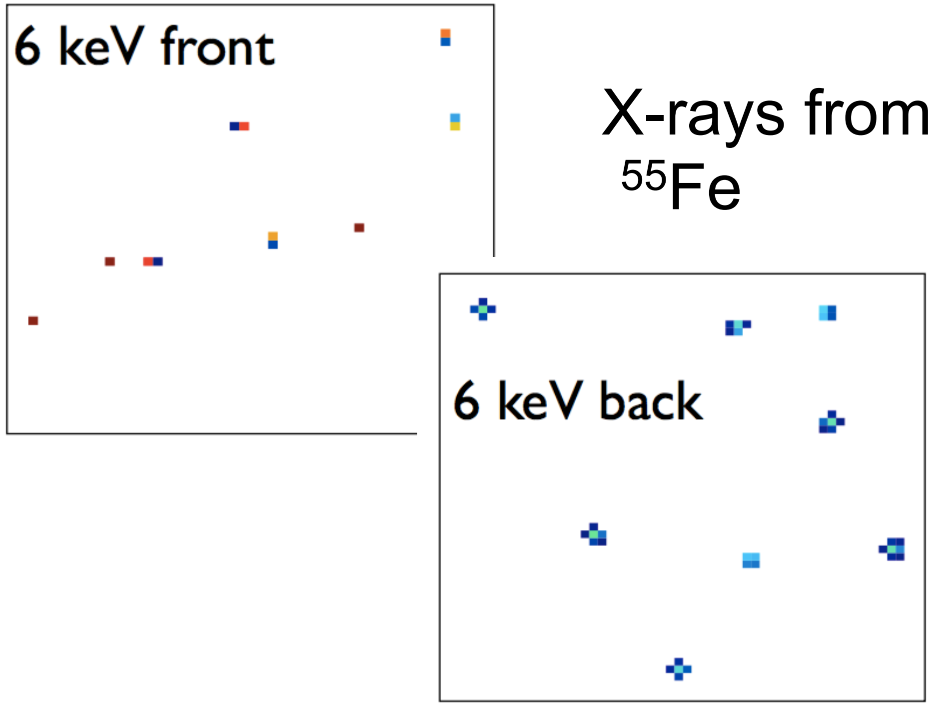
- Very long exposures (8 hours!) to minimize the n. of noise pixels above the energy threshold

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

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

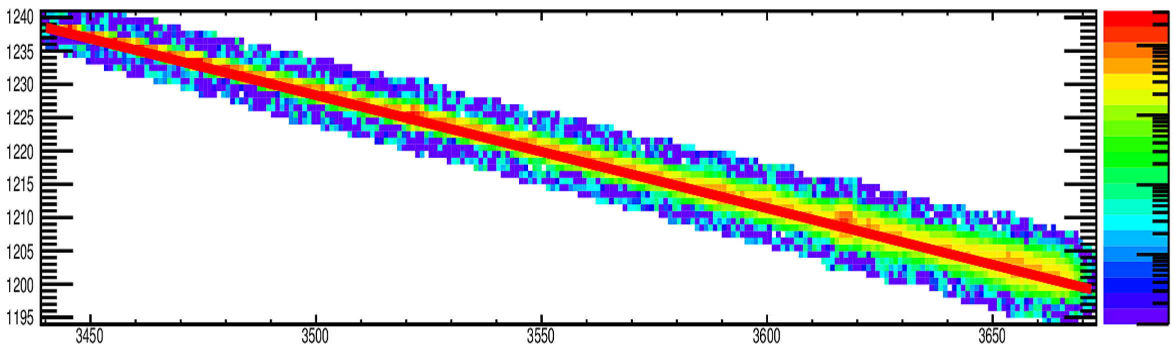


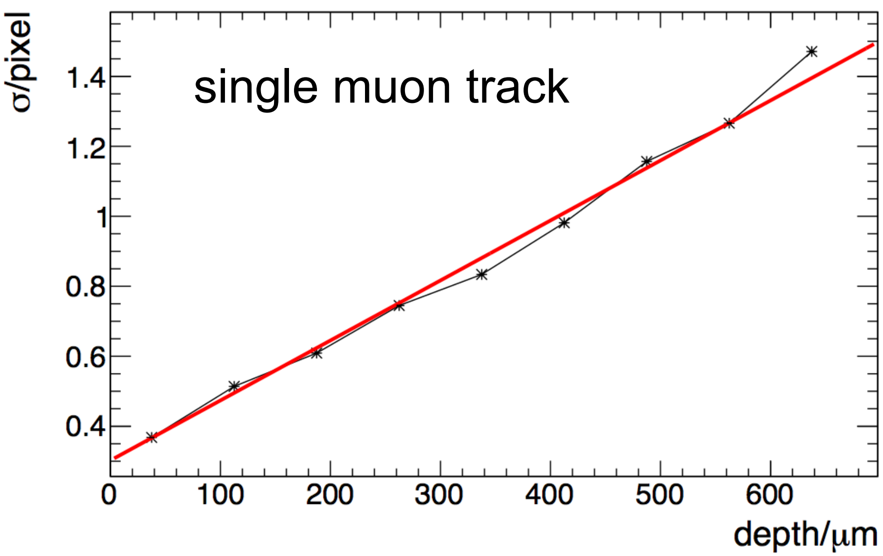
The charge diffuses towards the CCD pixels gates, producing a "diffusion-limited" cluster



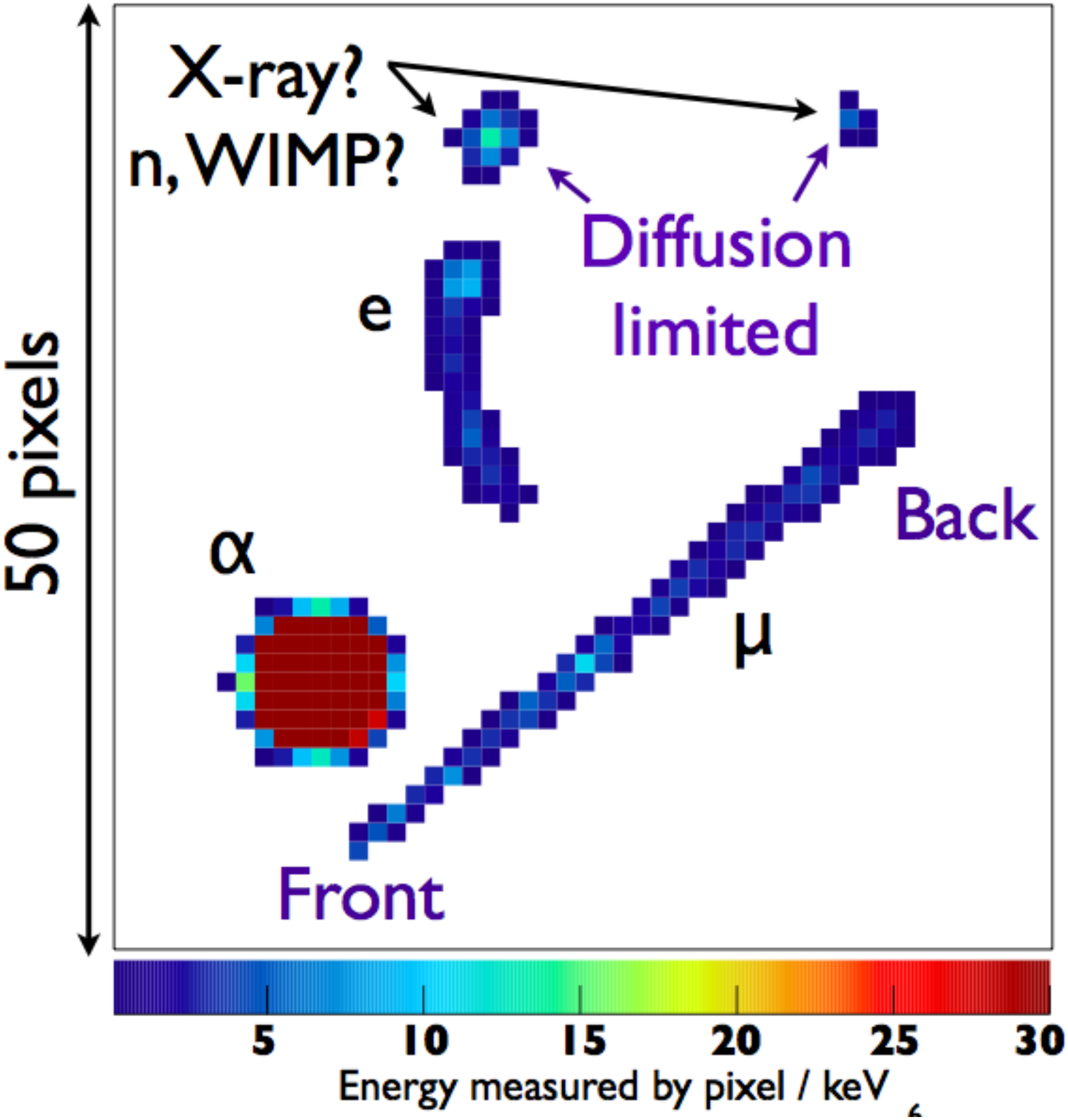
X-rays from ^{55}Fe

a muon piercing a 675 μm thick DAMIC CCD





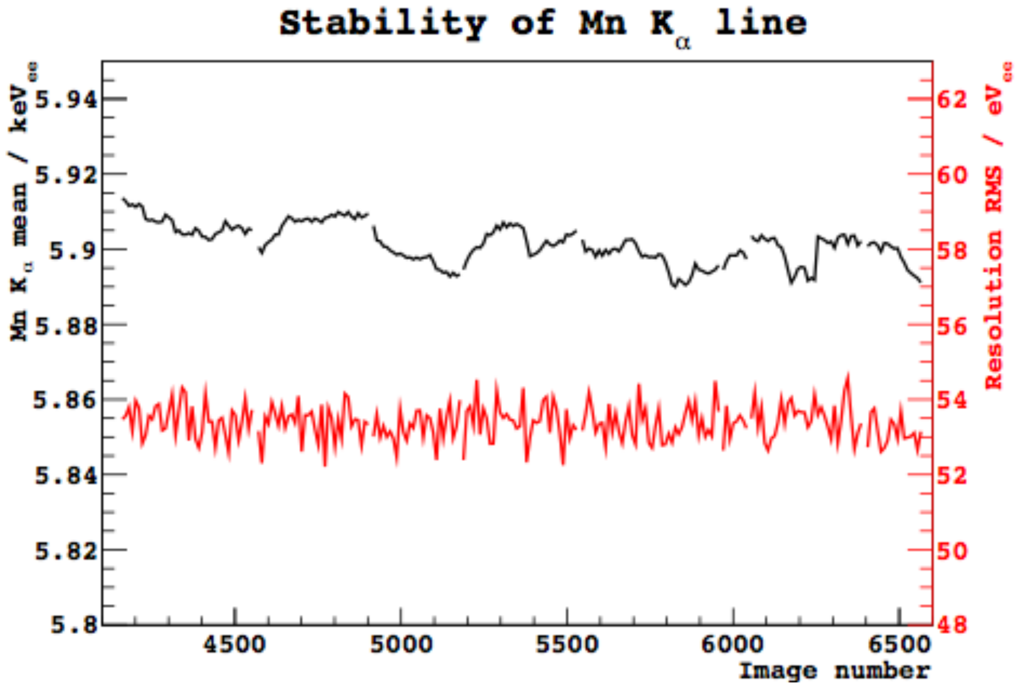
σ ≈ Z : fiducial volume definition and surface event rejection



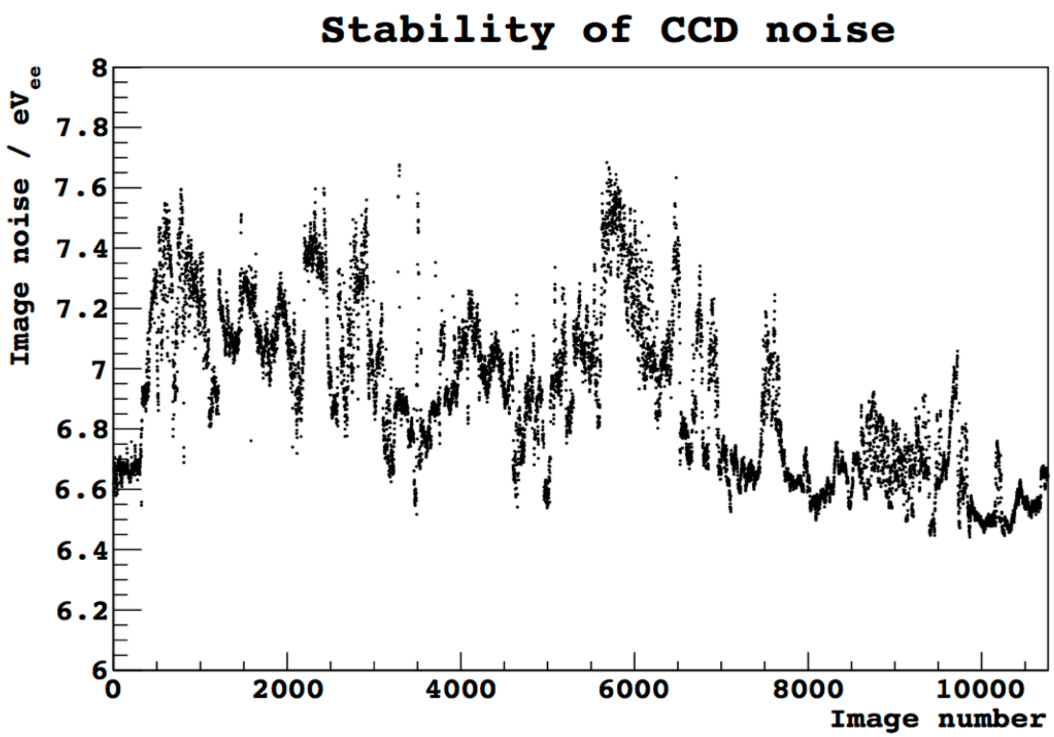
- “Worms” straggling electrons
- Straight tracks: minimum ionizing particles
- MeV charge blobs: alphas
- Diffusion-limited clusters: low-energy X-rays, nuclear recoils

- 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)

SNOLAB

Sudbury, Canada

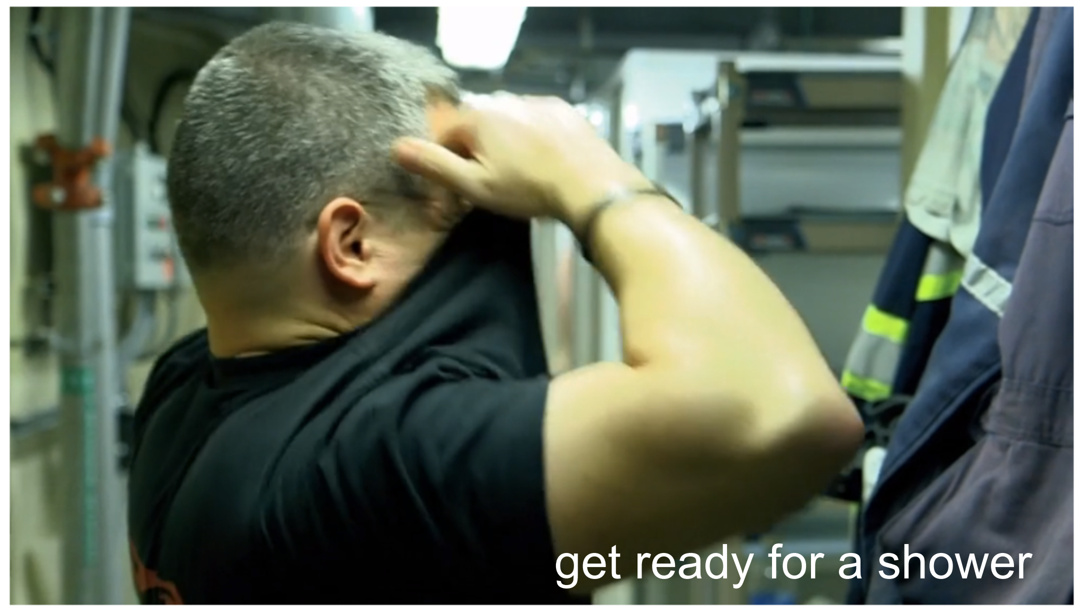
Nickel-Copper active mine

2 km underground

BBC documentary, Dancing in the Dark: the end of Physics


Abandon all hope, ye who enter here
Inferno, Canto III, Dante

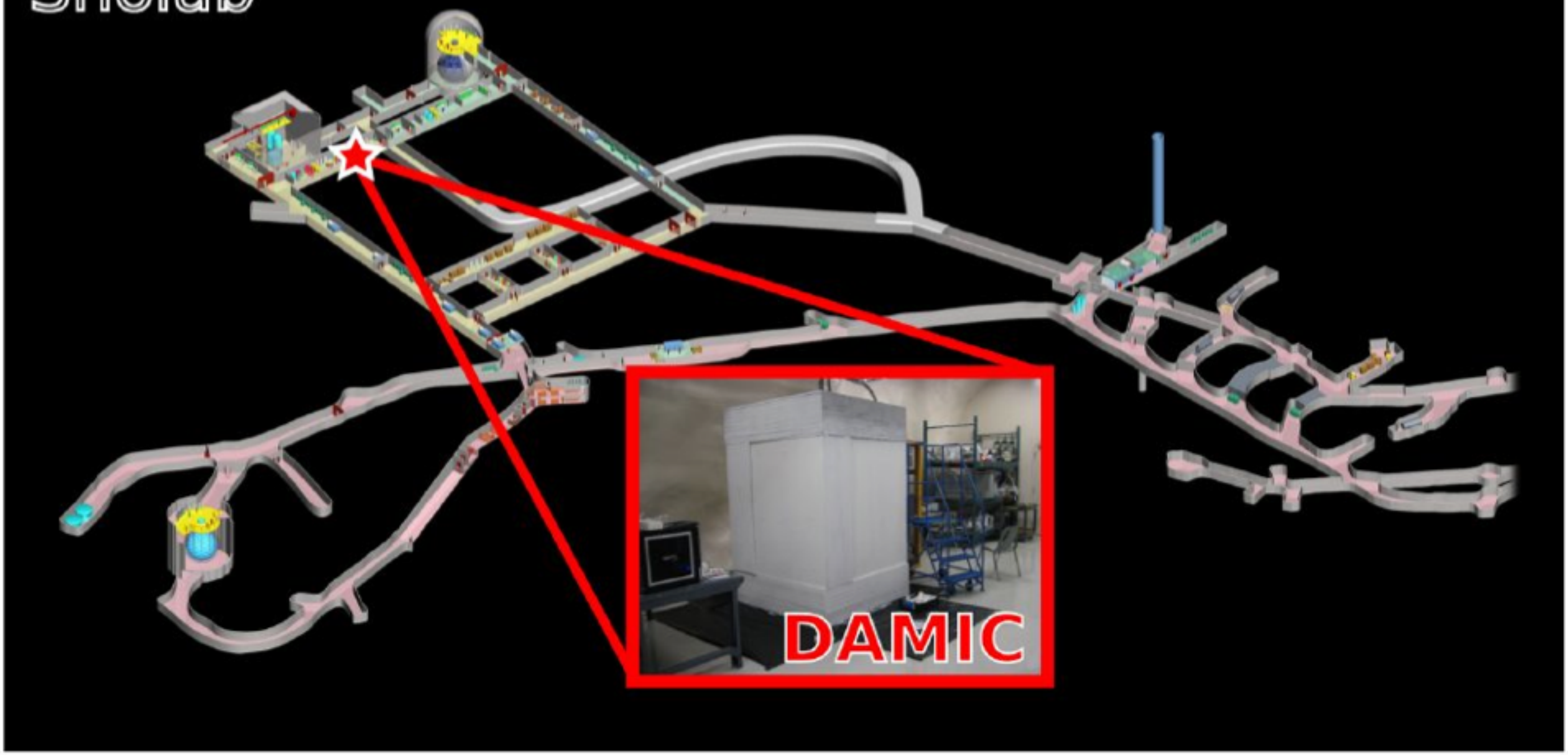
entering the lab


get ready for a shower


nice dress!


coffee……

DAMIC at SNOLAB



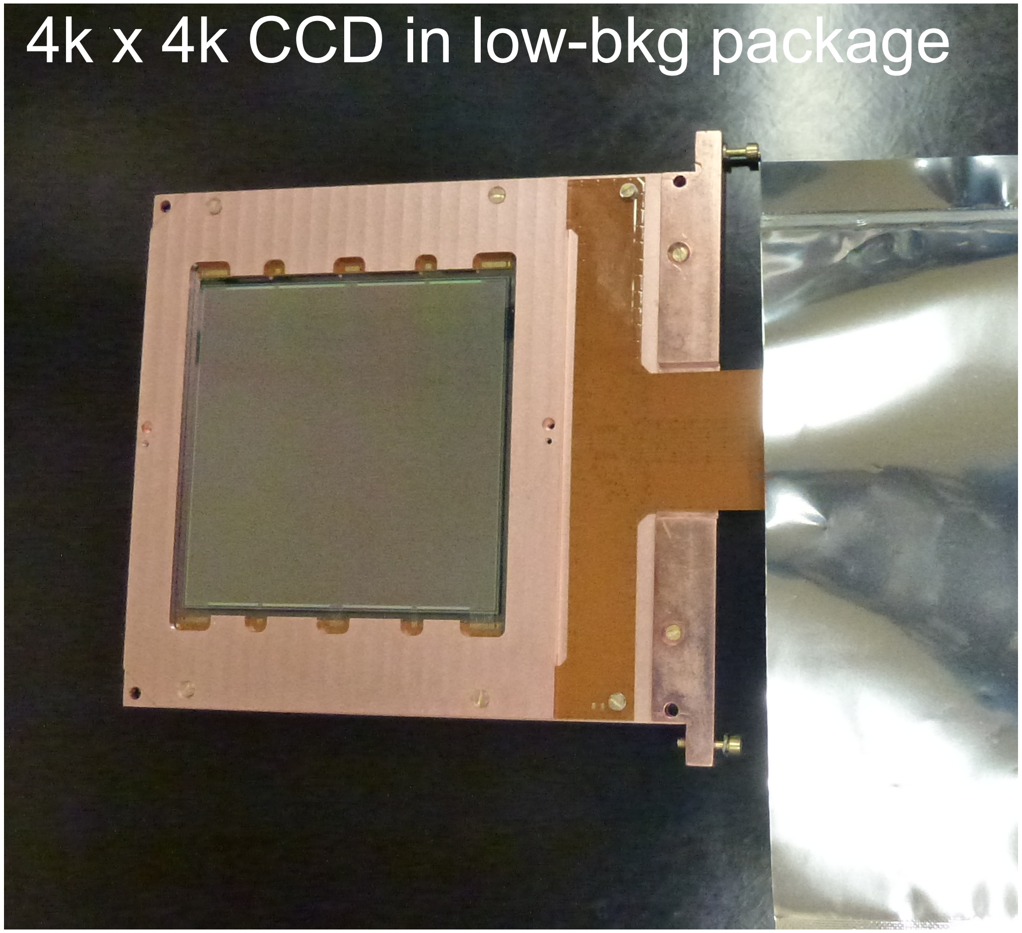
DAMIC R&D program in the J-Drift hall started in early 2013

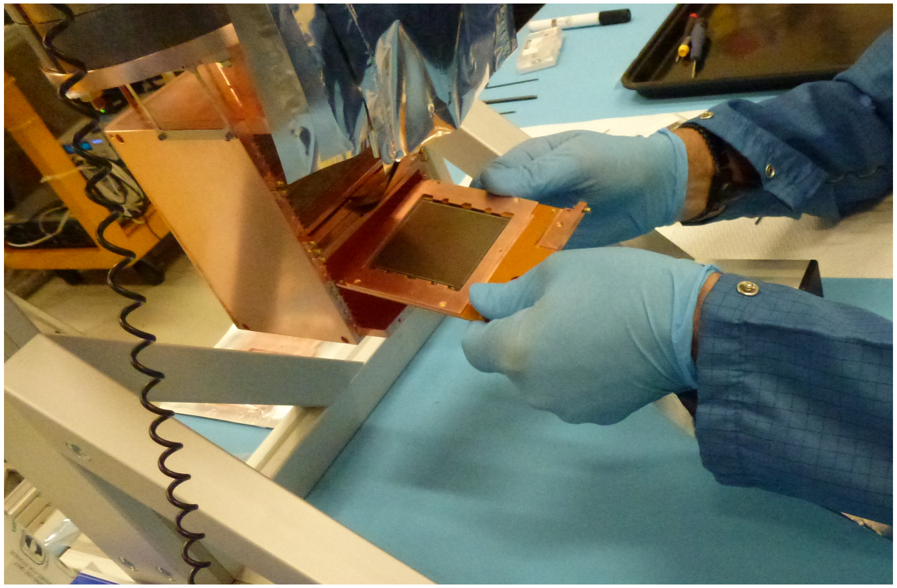
CAB, FIUNA, Fermilab, LPNHE, SNOLAB, U Chicago, U Michigan, U Zürich, UFRJ, UNAM

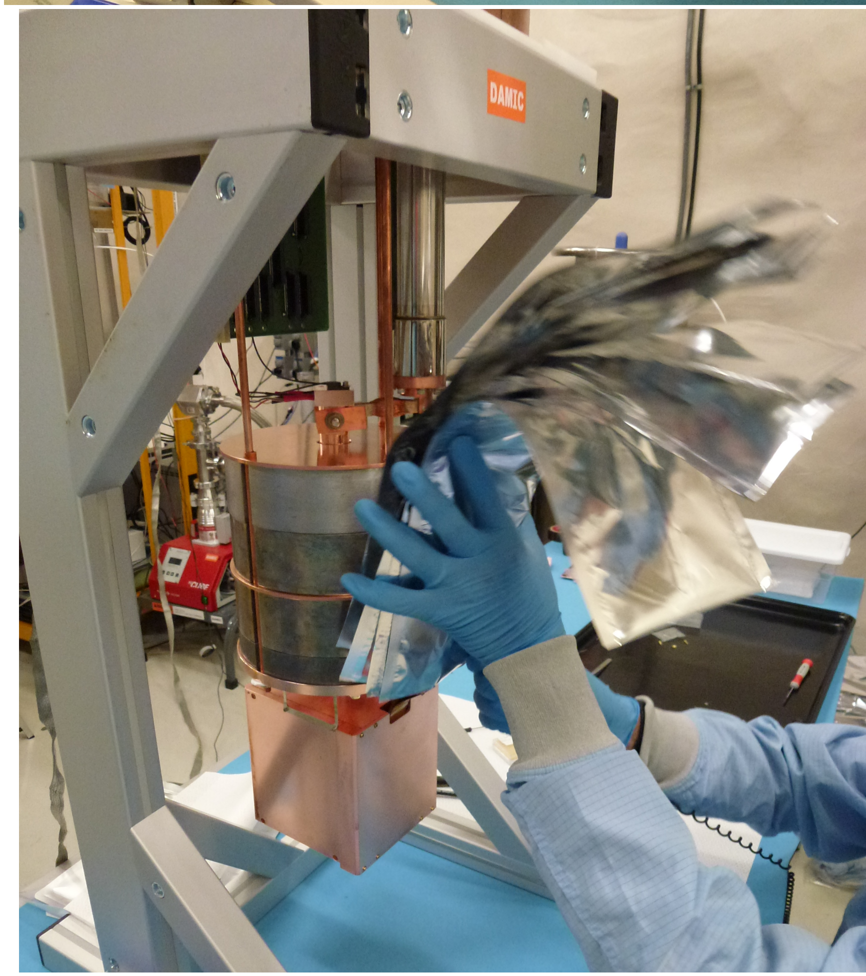
strong collaboration with Fermilab (Estrada, Cancelo, Tiffenberg, Guardincerri)

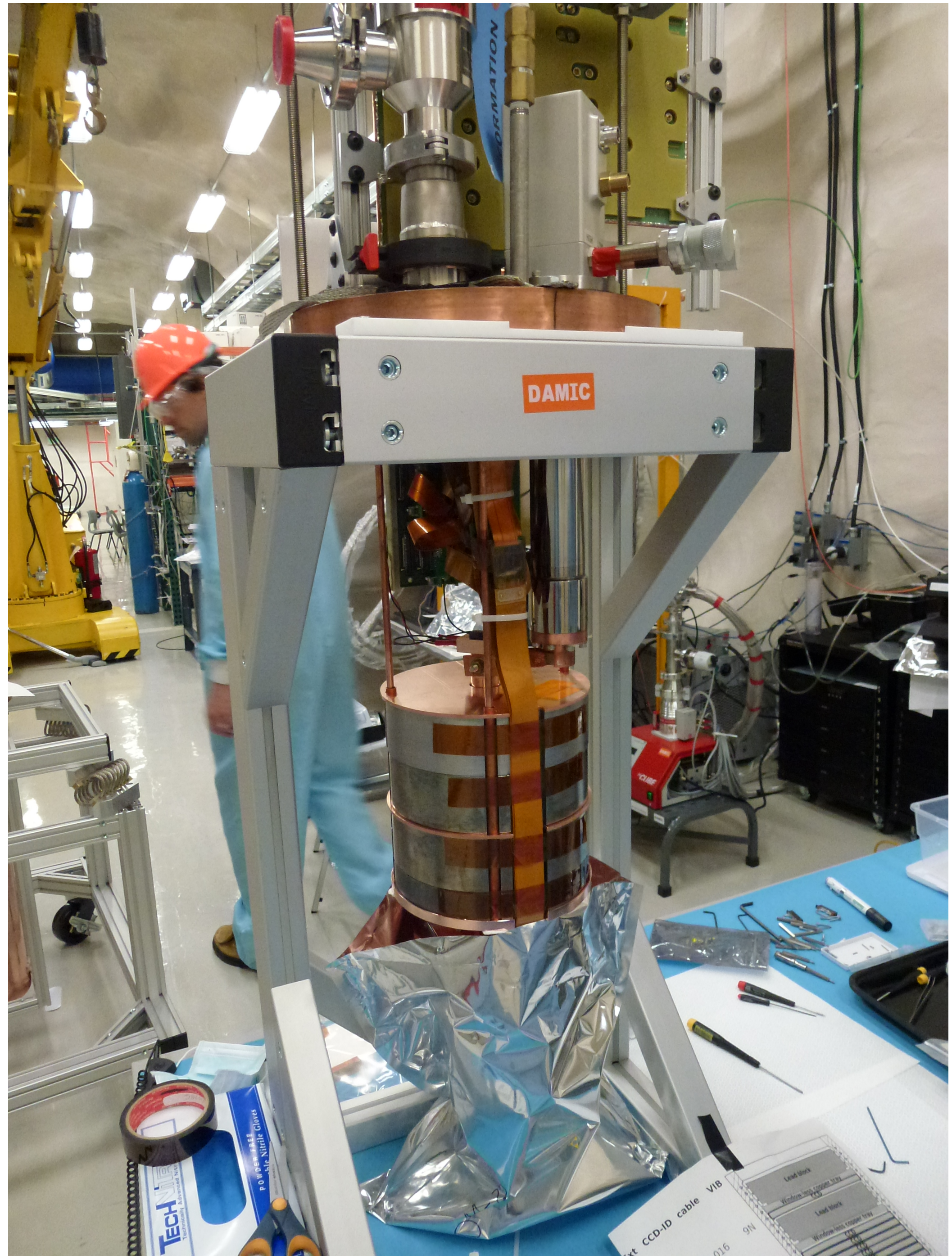
DAMIC100 installation at SNOLAB

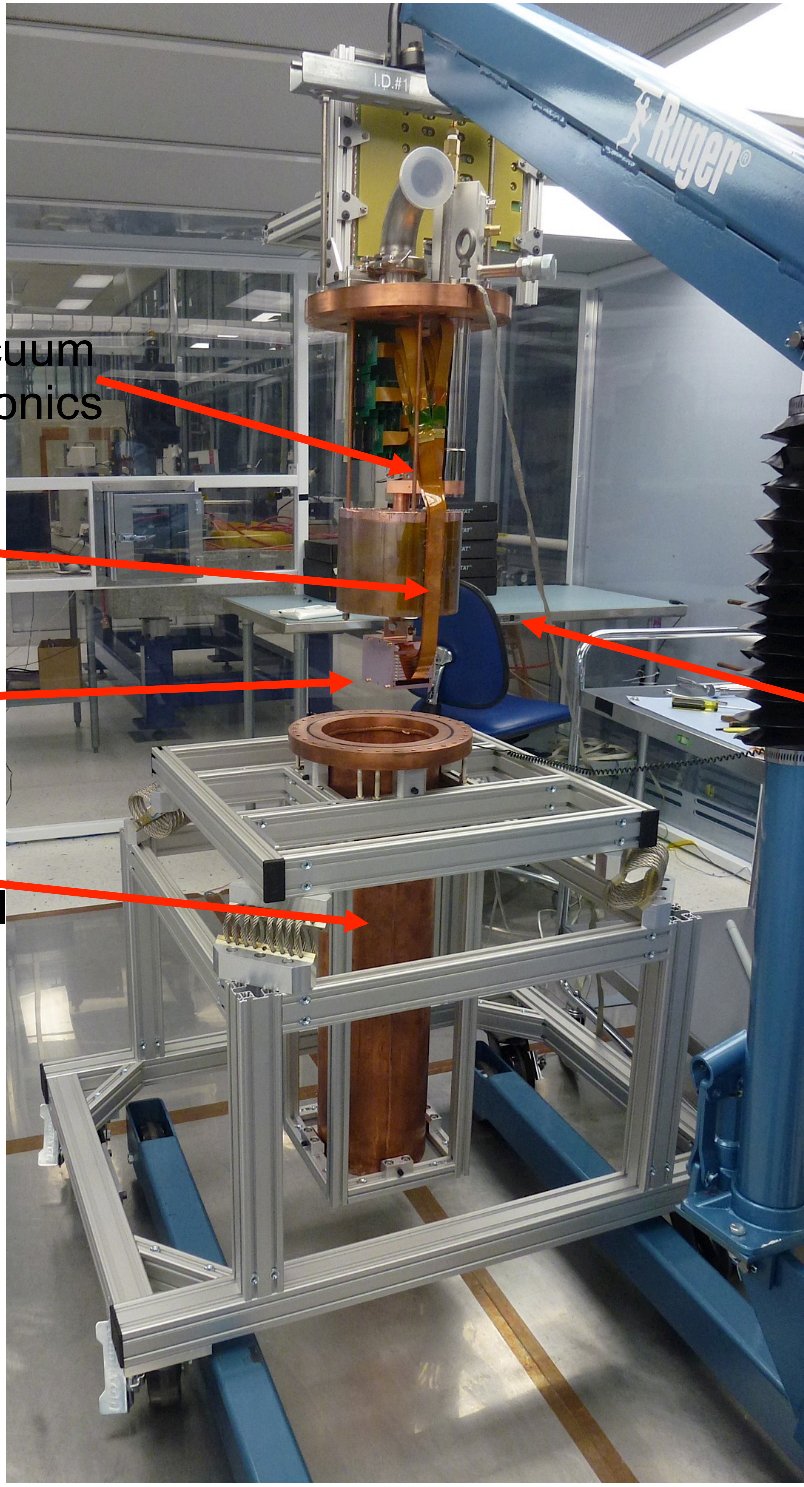
April 2016






DAMIC


DAMIC



in-vacuum electronics

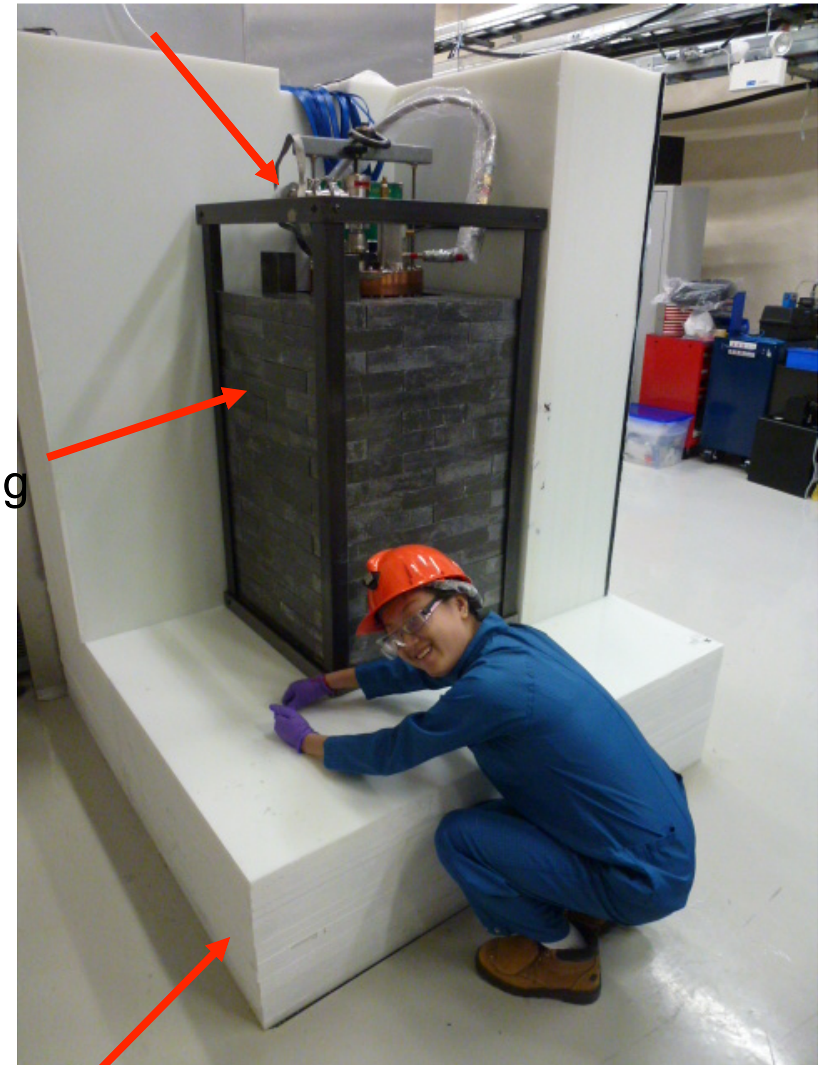
Kapton cables

Cu box

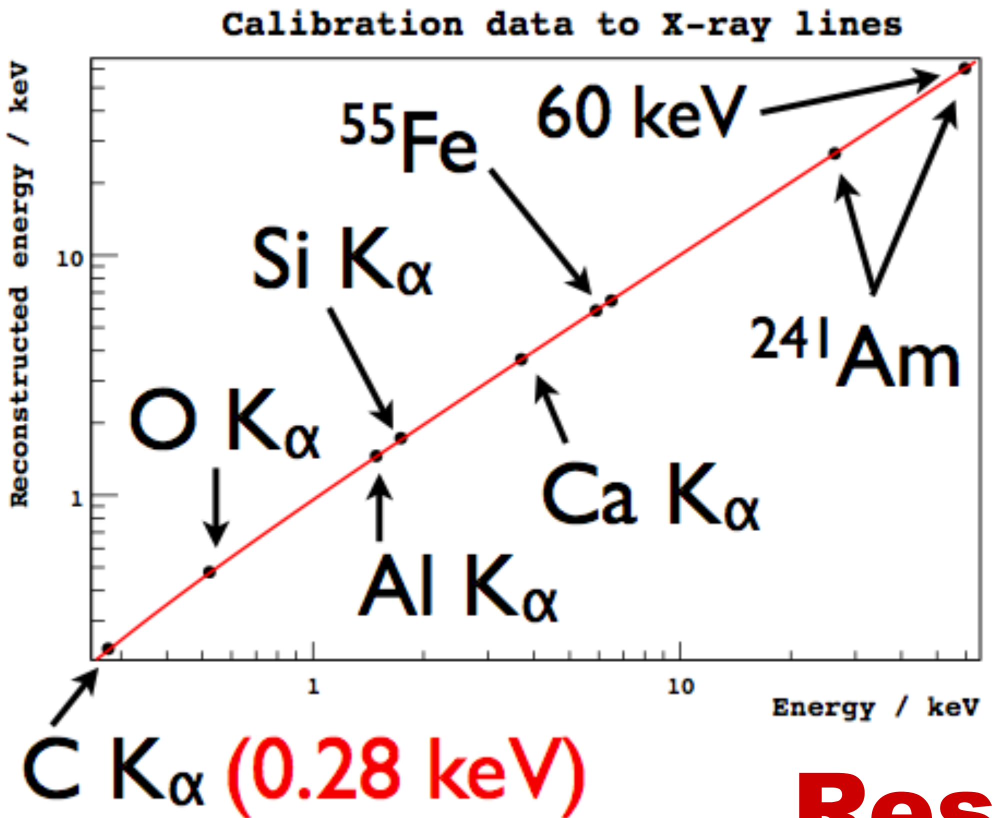
Cu vessel

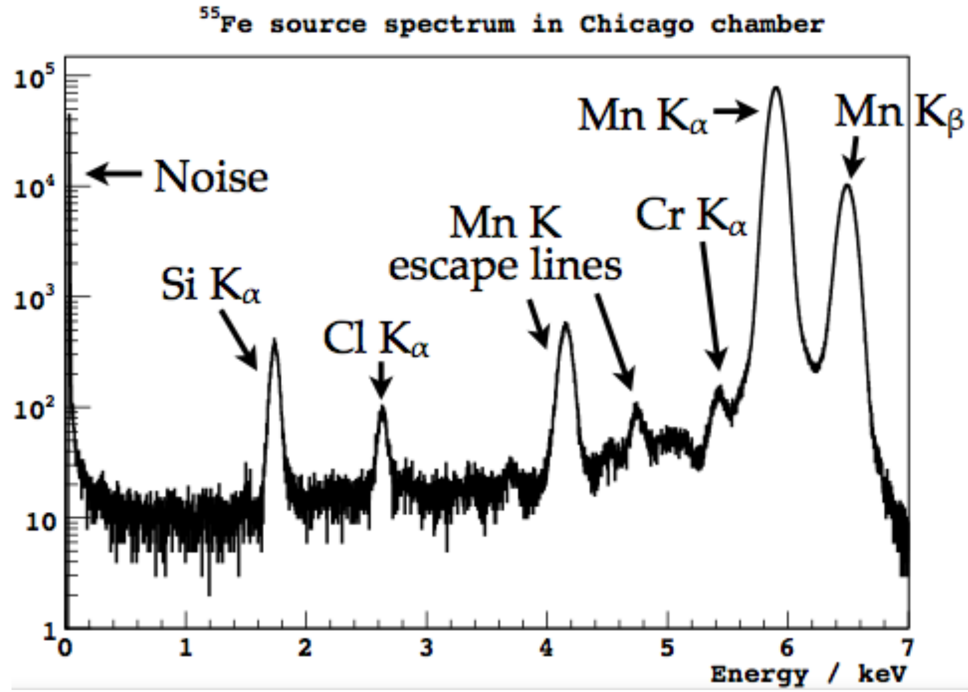
8” lead shielding

vacuum and cryo lines, electronics

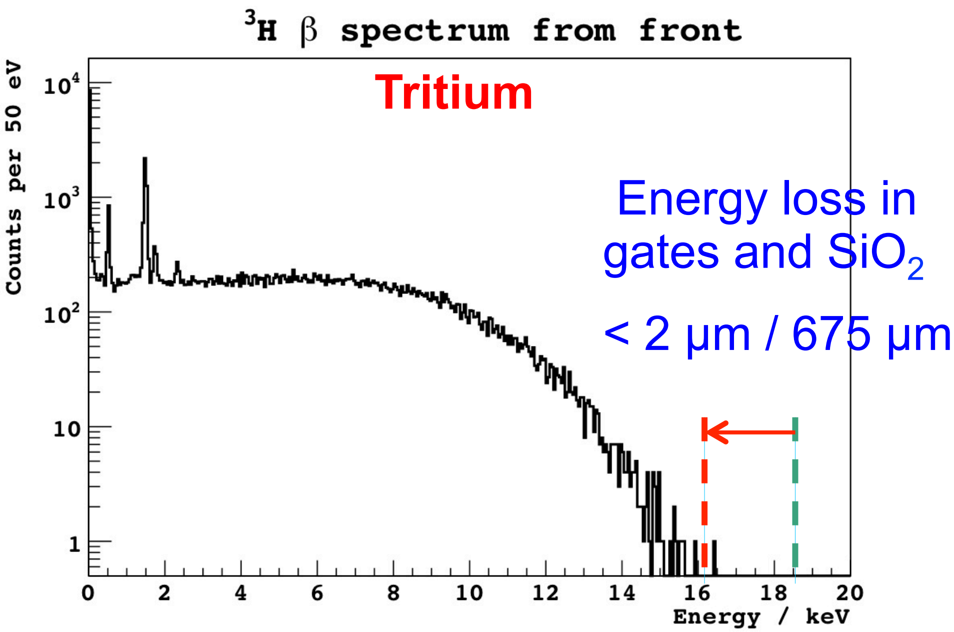


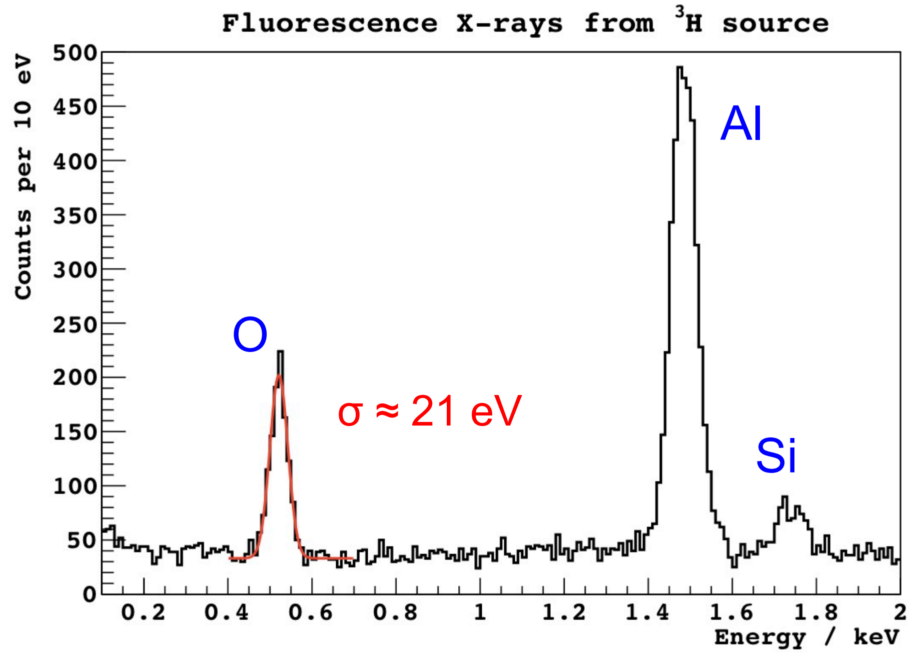
20” thick poly shielding





Response to electrons

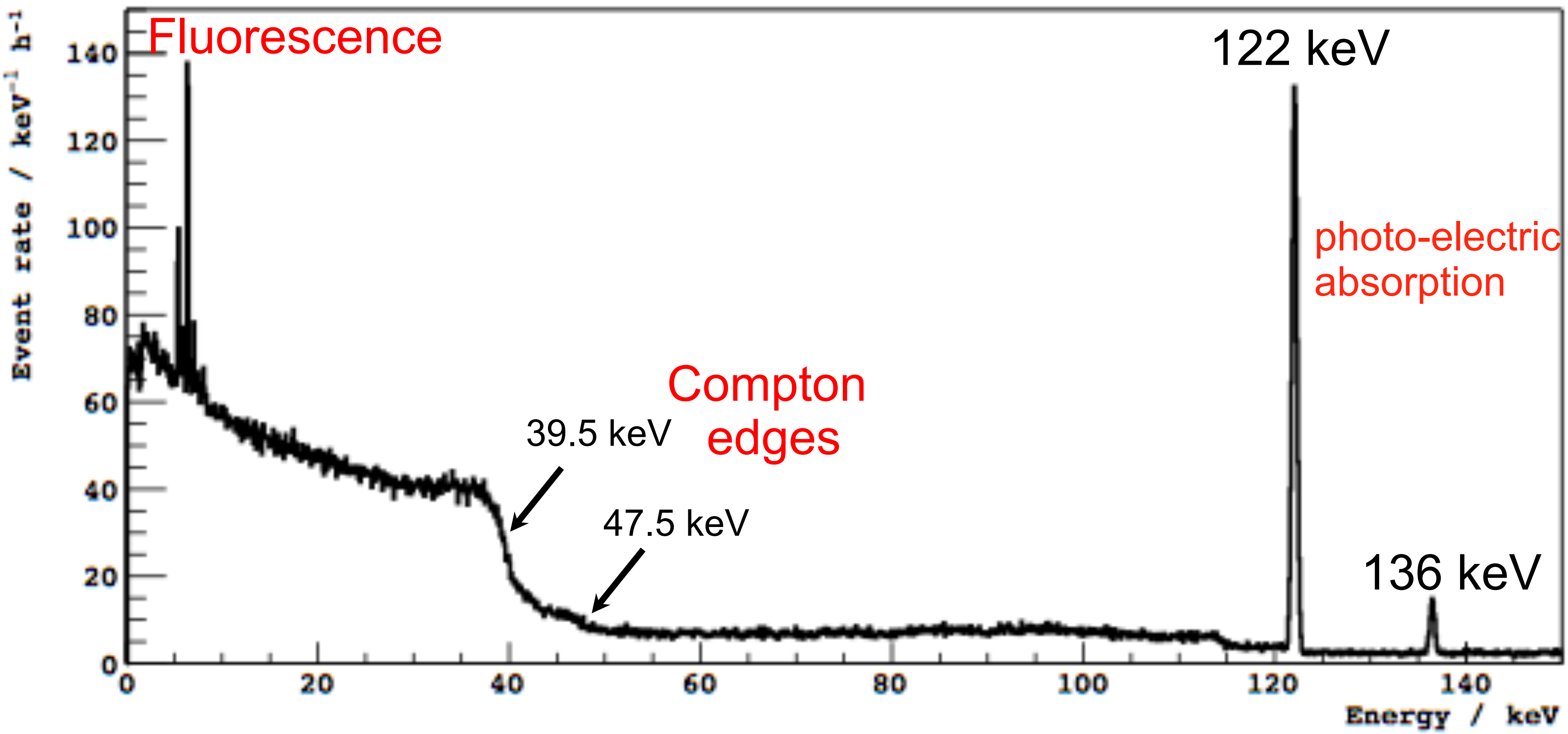




Gamma-rays

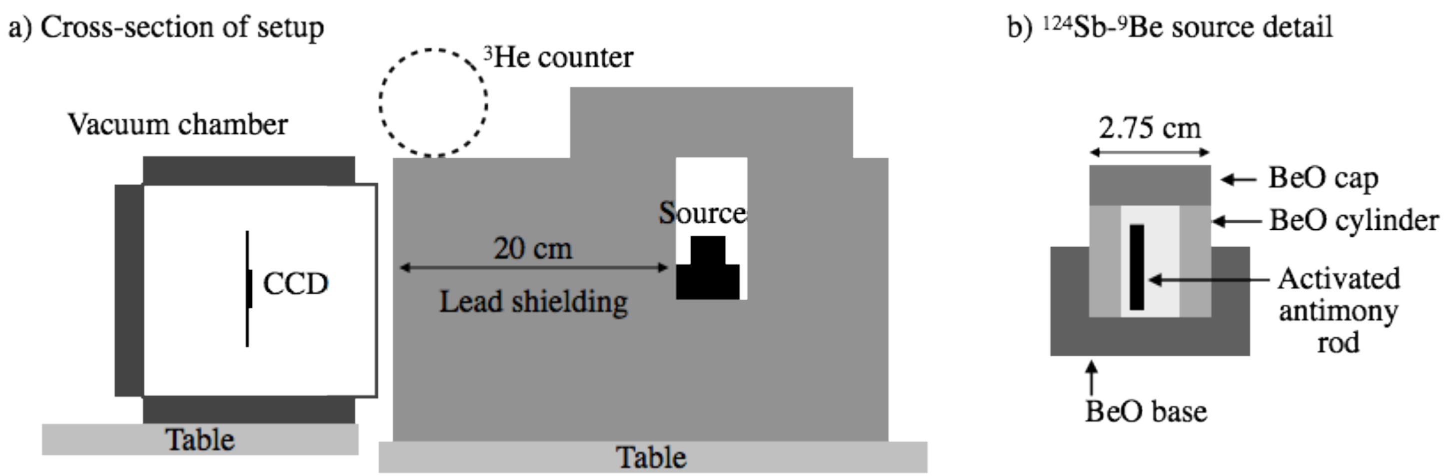
CCD exposed to ^{57}Co source at U Chicago

Very large dynamic range

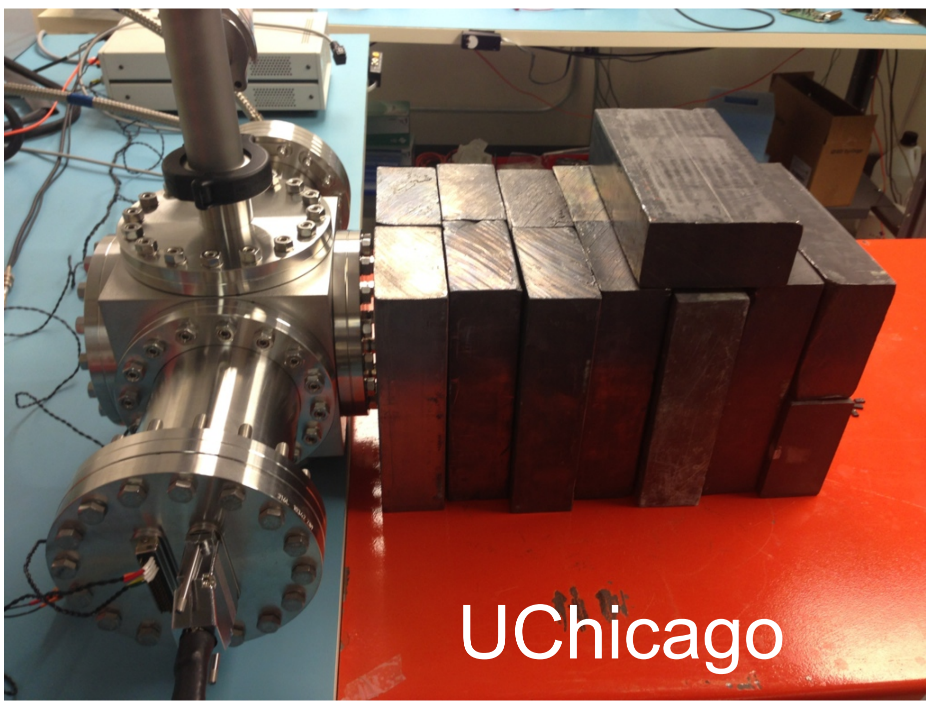


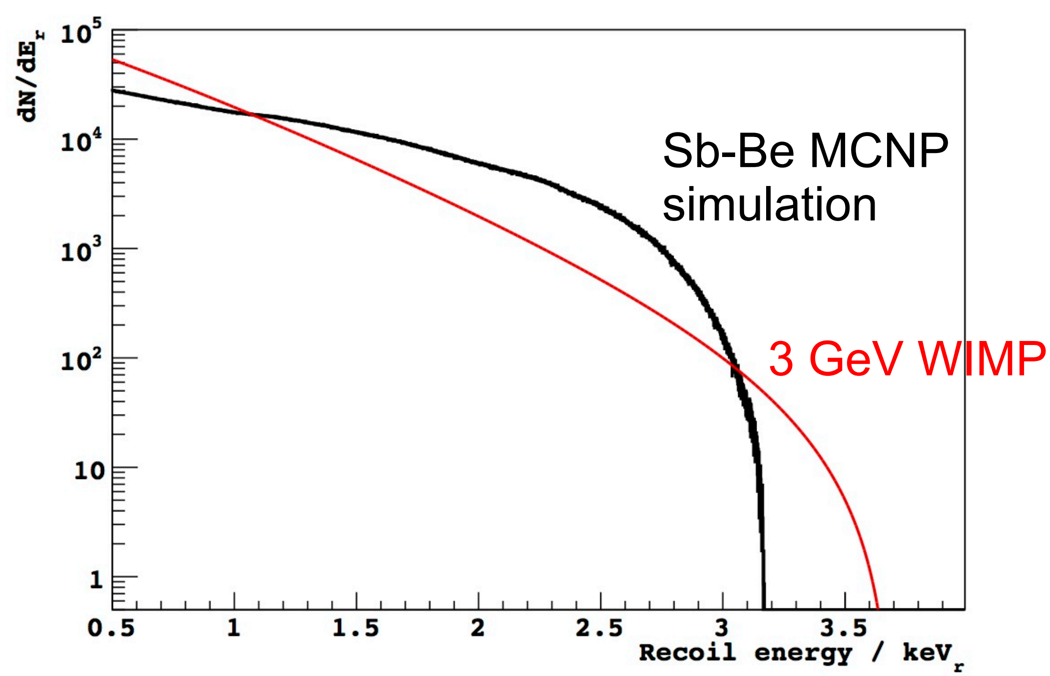
Single-scatter Compton spectrum

Nuclear recoil calibration



24 keV neutrons from ^{9}Be(γ,n) reaction
(J. Collar)





$E_e \approx 0.2\ E_r$ (Lindhard)

Event selection

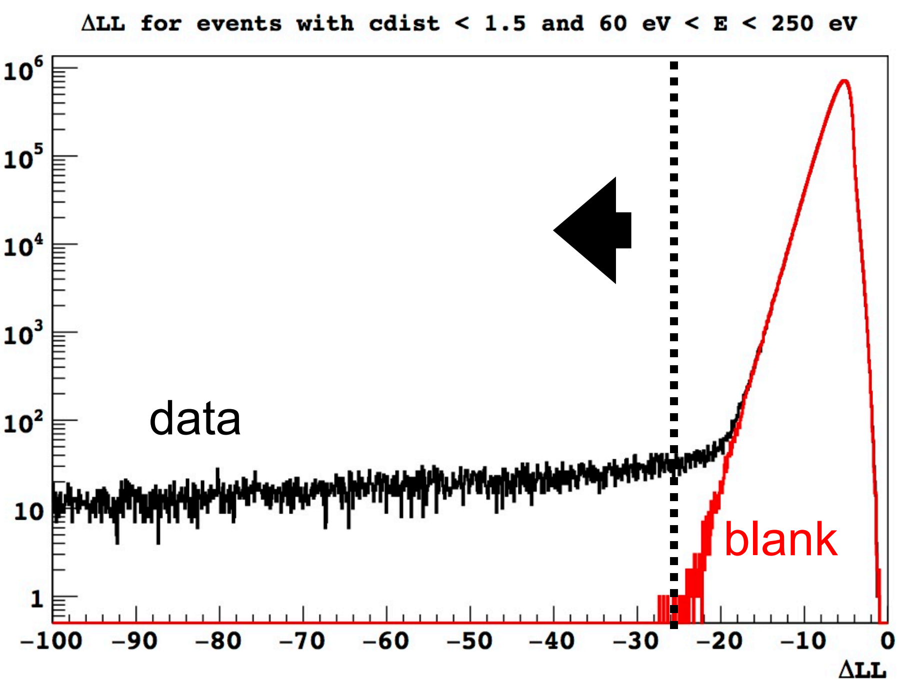
- Fit a 2D gaussian model + background in a sliding 7x7 pixels window. Calculate the corresponding LL and subtract the LL of background only model → ΔLL

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

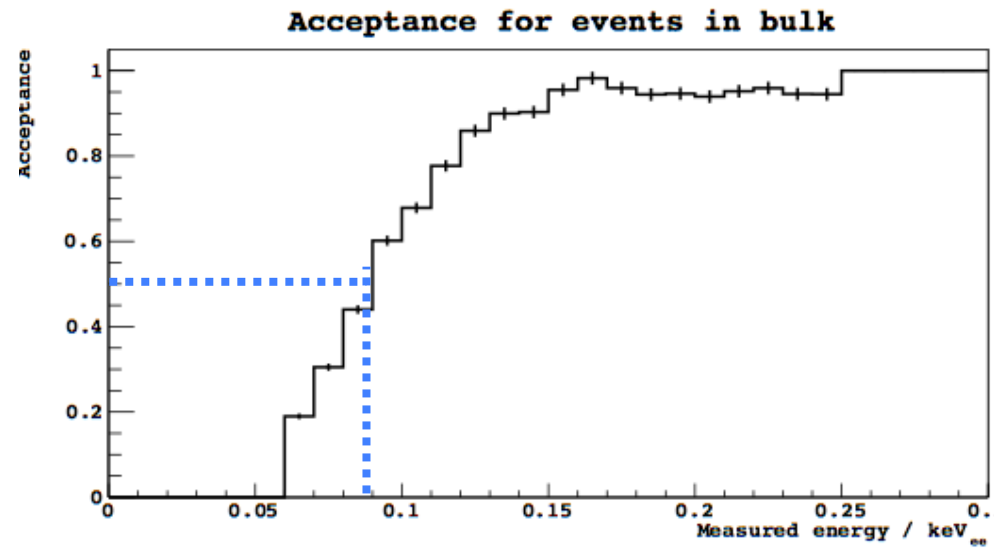
Number of ionized electrons

Best estimate for mean of energy deposition

Lateral spread



< 0.01 events per image from readout noise

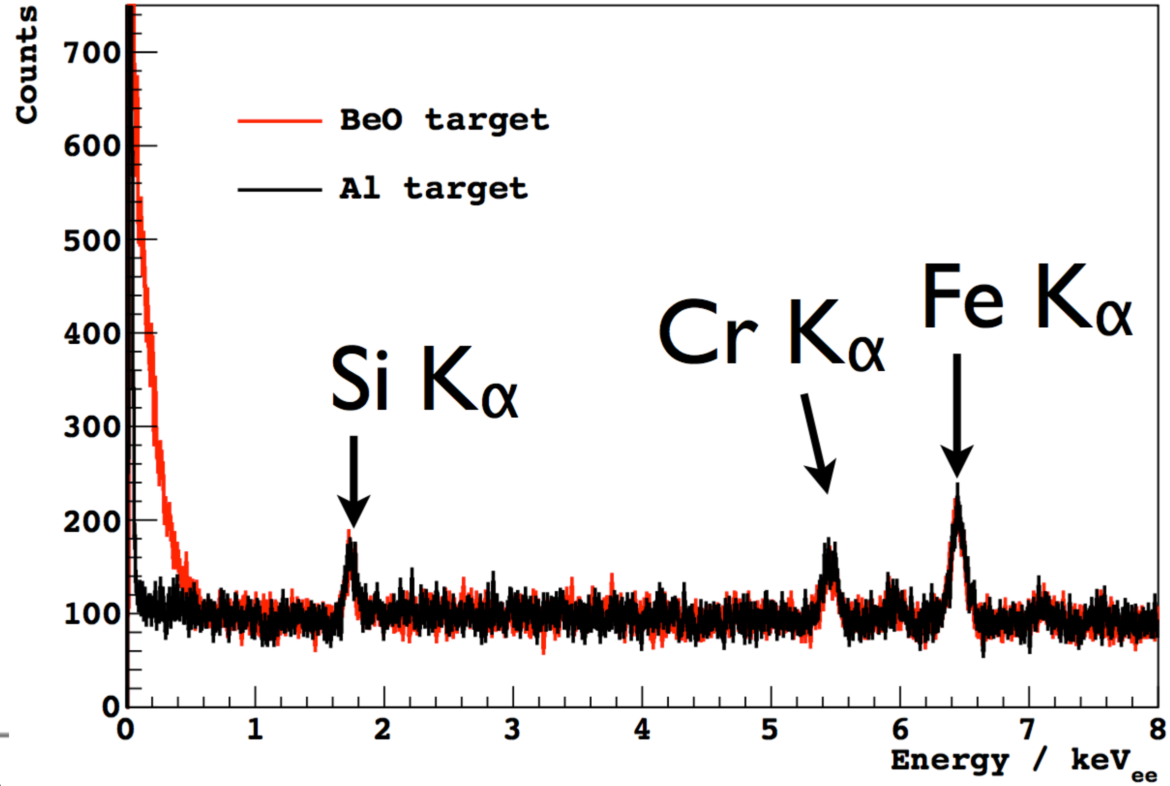


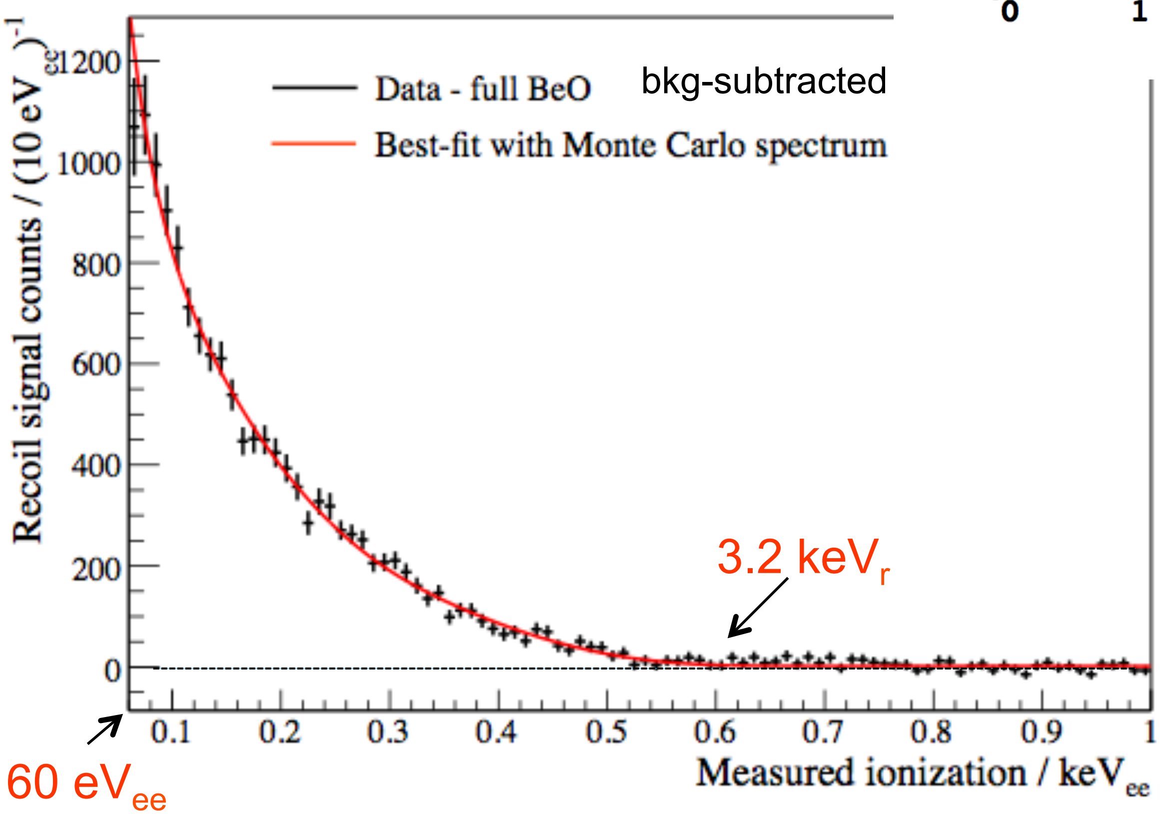
50% at 90 eV$_{ee}$

estimated by injecting simulated events on real images

Nuclear recoil spectrum

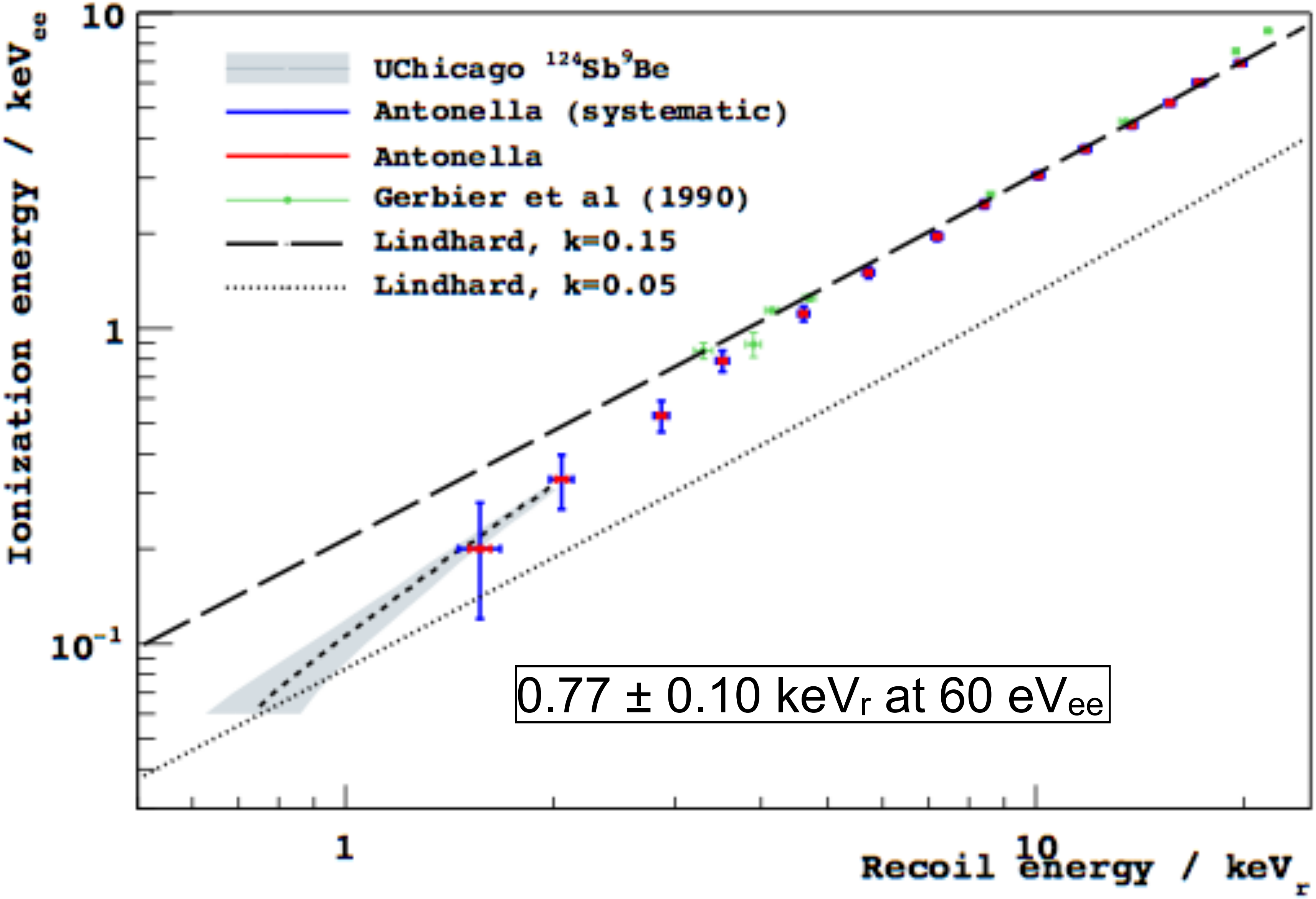
- "Neutron-on" with BeO (n+γ)
  "neutron-off" with Al (only γ)
  Clear signal from neutron-induced nuclear recoils





- Nuclear recoil ionization efficiency from adjusting MC E_r to E_e spectrum
- *single* recoil spectrum
- systematic uncertainties are small, dominated by 9% uncertainty on total predicted rate

Nuclear-recoil ionization efficiency in silicon

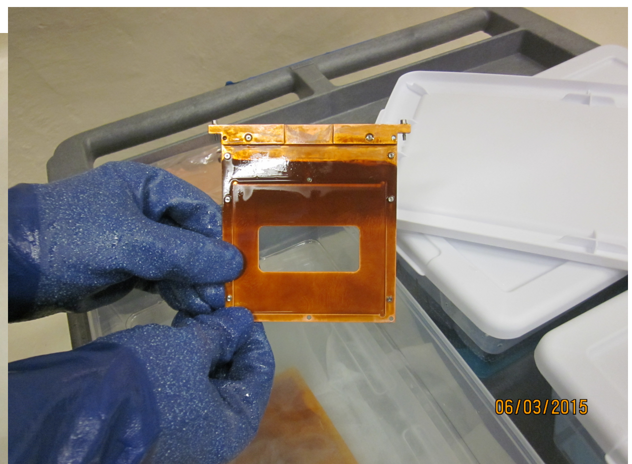


deviation from Lindhard theory observed – crucial for low-mass WIMP searches with silicon detectors

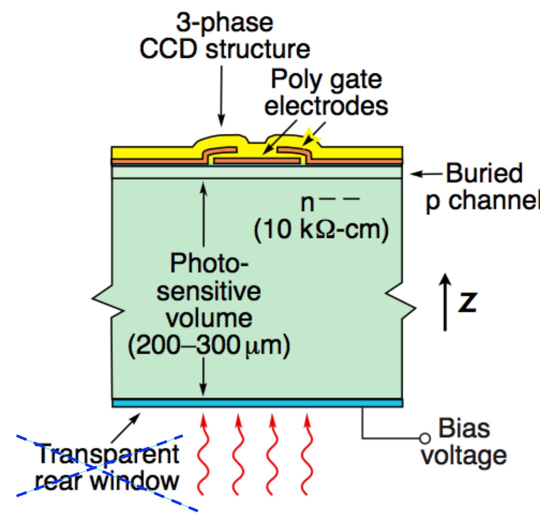
Background, background, background

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

Inner 2” shielding made of ancient lead to avoid bremmstrahlung γs from ^{210}Pb β-decay (22 yrs half-life)

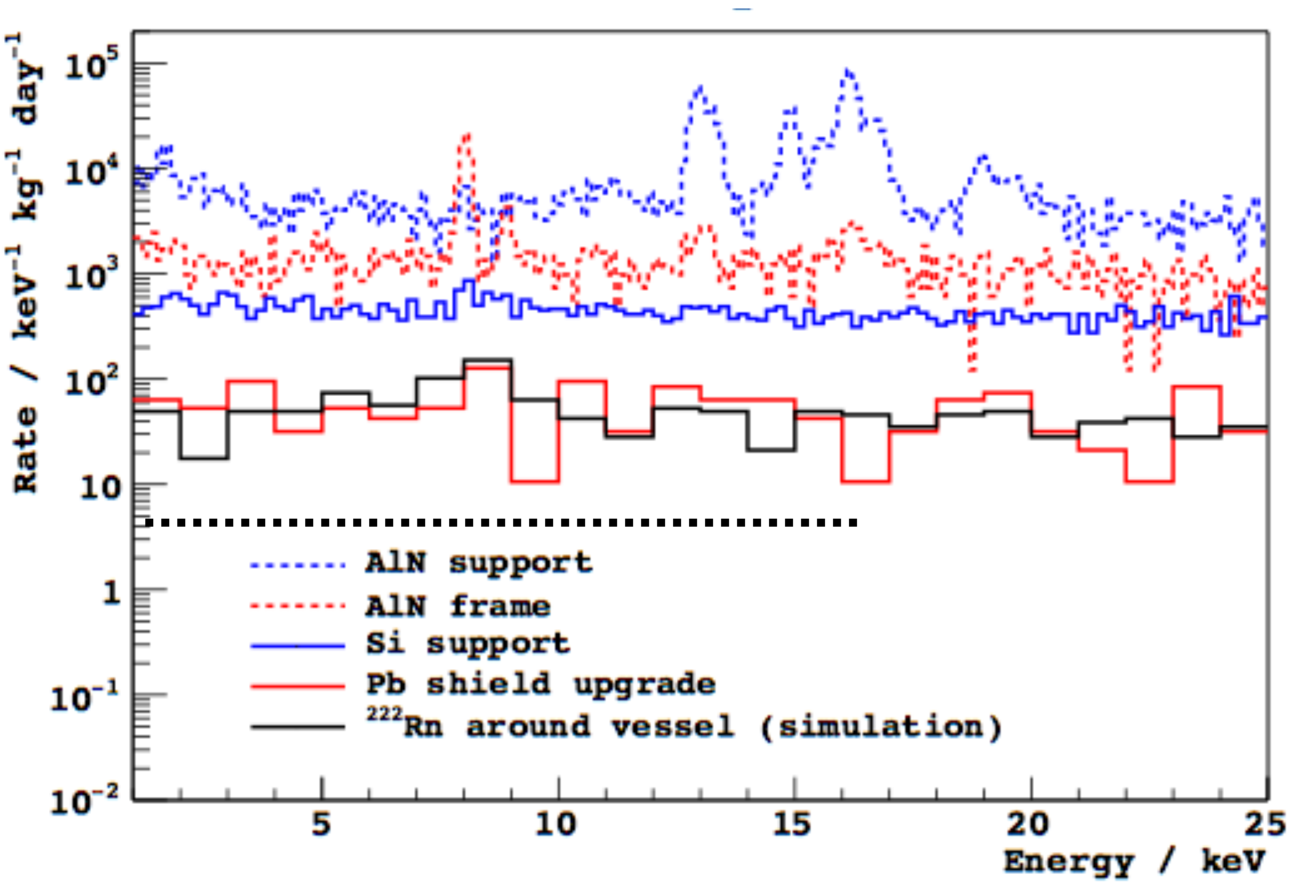


- **Material selection and cleaning:** copper machining, “secret” recipe etching (surface bkg)



Background tour-de-force

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



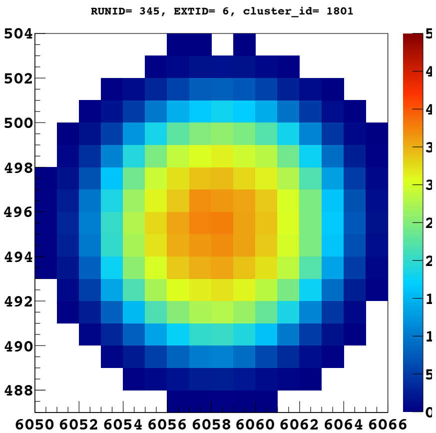
<u>In the last year:</u>

- Seven interventions at SNOLAB.
- Nitrogen purge installation (Radon).
- Improvements in treatment of copper surfaces.
- Suppression of background from thermal neutron captures in copper.
- Mitigation of background from condensation e.g. ^3H.

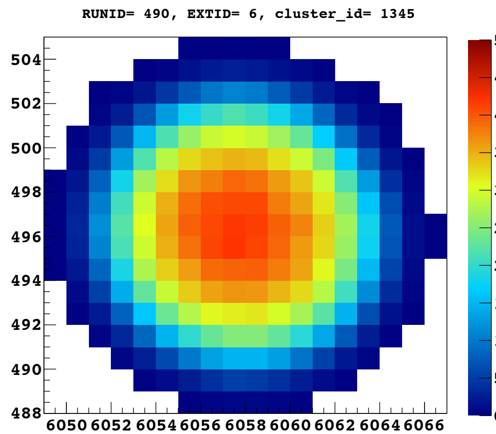
- Background rate may be smaller in DAMIC100: new CCD box and packages, roman lead

DAMIC background characterization

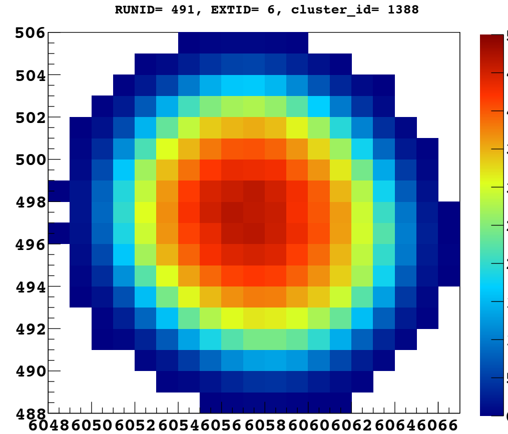
E = 5.4 MeV



E = 6.8 MeV

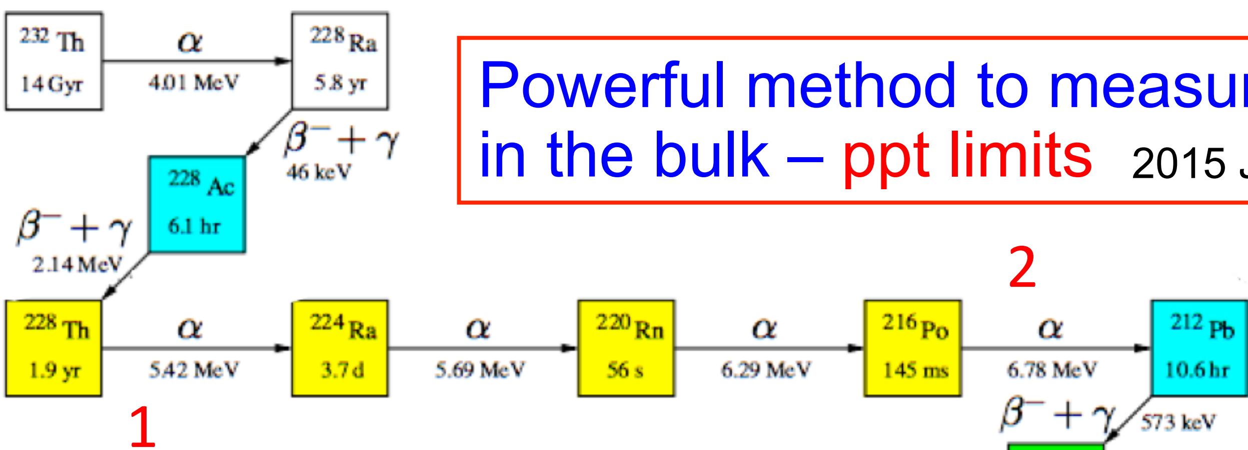


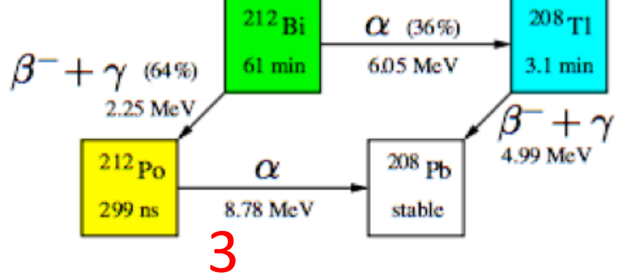
E = 8.8 MeV



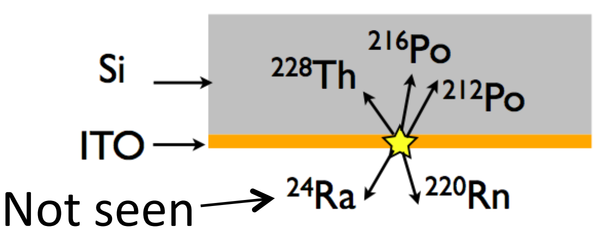
1 Δt = 17.8 d 2 Δt = 5.5 h 3

Three α at the same location!

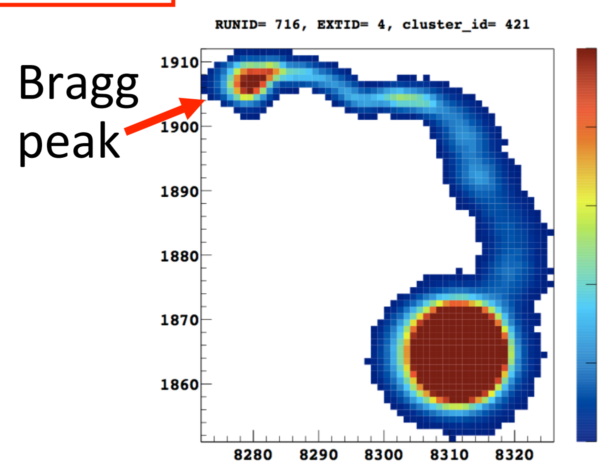




Powerful method to measure U/Th bkg in the bulk – ppt limits 2015 *JINST* **10** P08014



Example of α + β



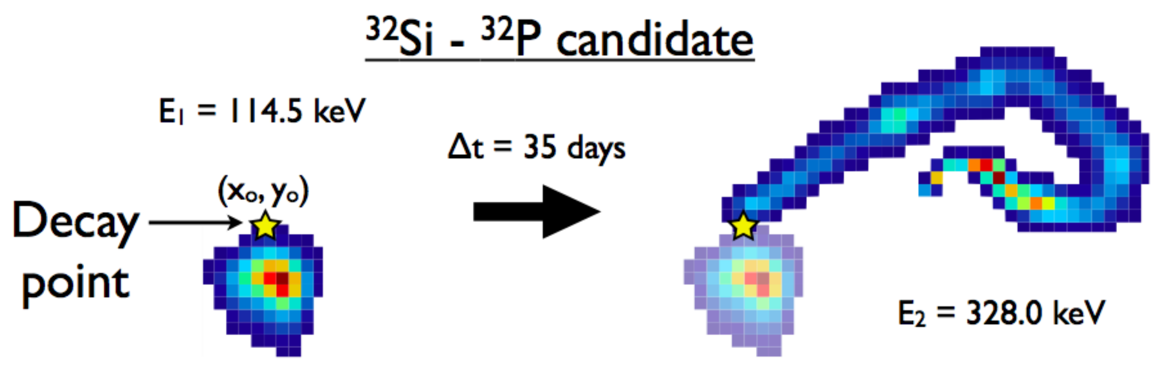
Cosmogenic ^{32}Si

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

$$\tau_{1/2} = 14\ \mathrm{d}$$

- <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



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

2015 *JINST* **10** P08014

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

- Statistically limited, will be measured precisely by DAMIC100.

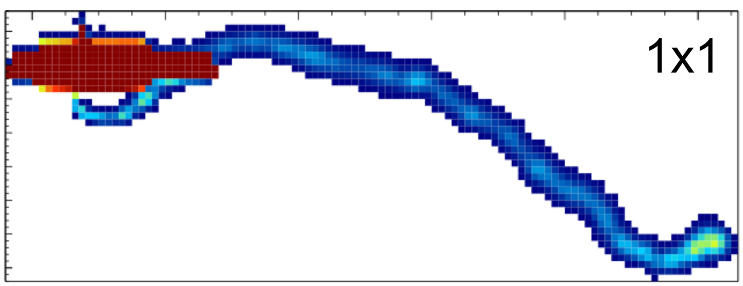
<u>DAMIC unique spatial resolution and excellent duty cycle allows to reject this background</u> (also other β-β sequences e.g. ^{210}Pb)

Dark Matter search with R&D data

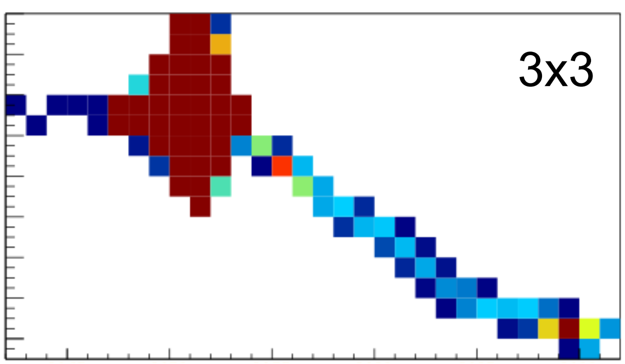
- R&D focused on background reduction and CCD operation.
- We also took a small amount of data to be used for a first limit. Background ≈ 30 dru (now 5 dru!). Exposure ≈ 0.6 kg day.

  Goal: develop search tools and demonstrate CCD science potential

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

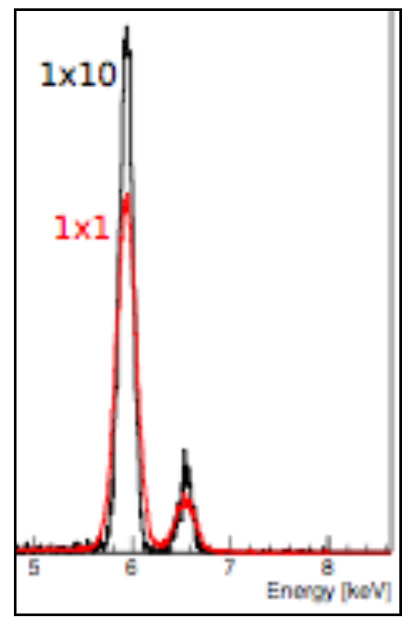


α-β events



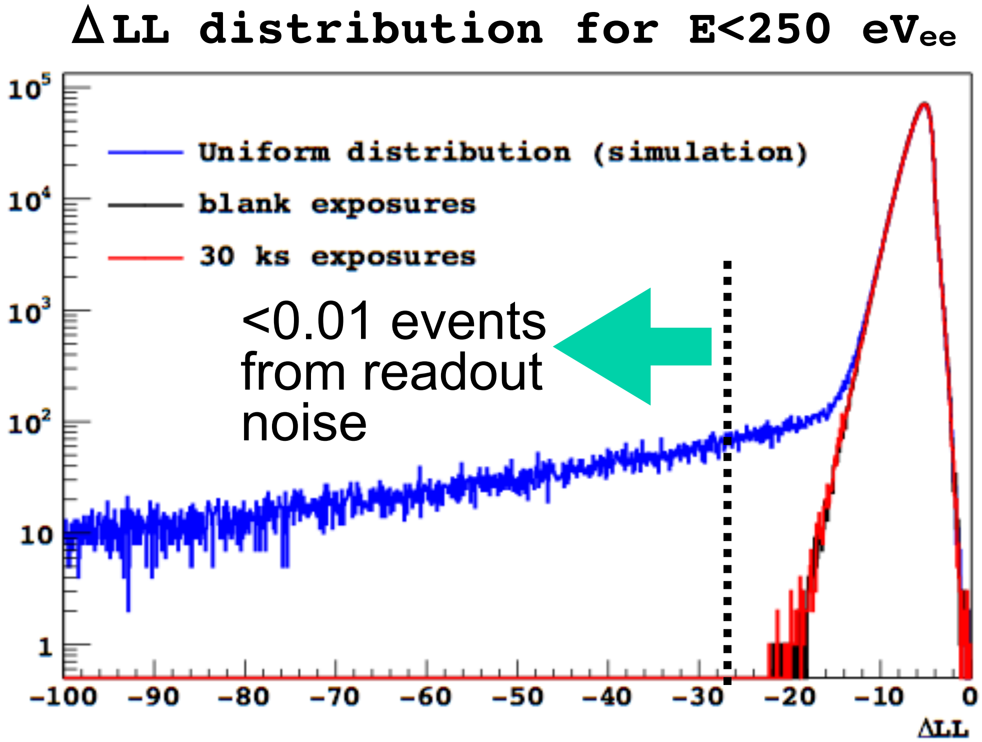
charge of several pixels can be added together before moving it to the readout node

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

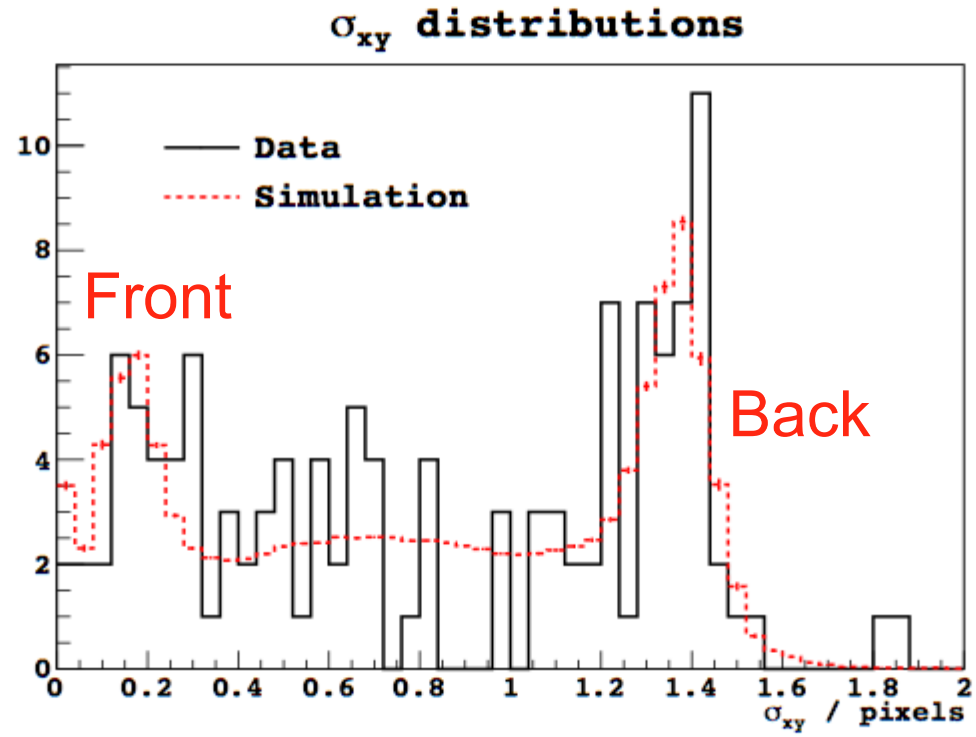


^{55}Fe source: improved energy resolution

Event selection



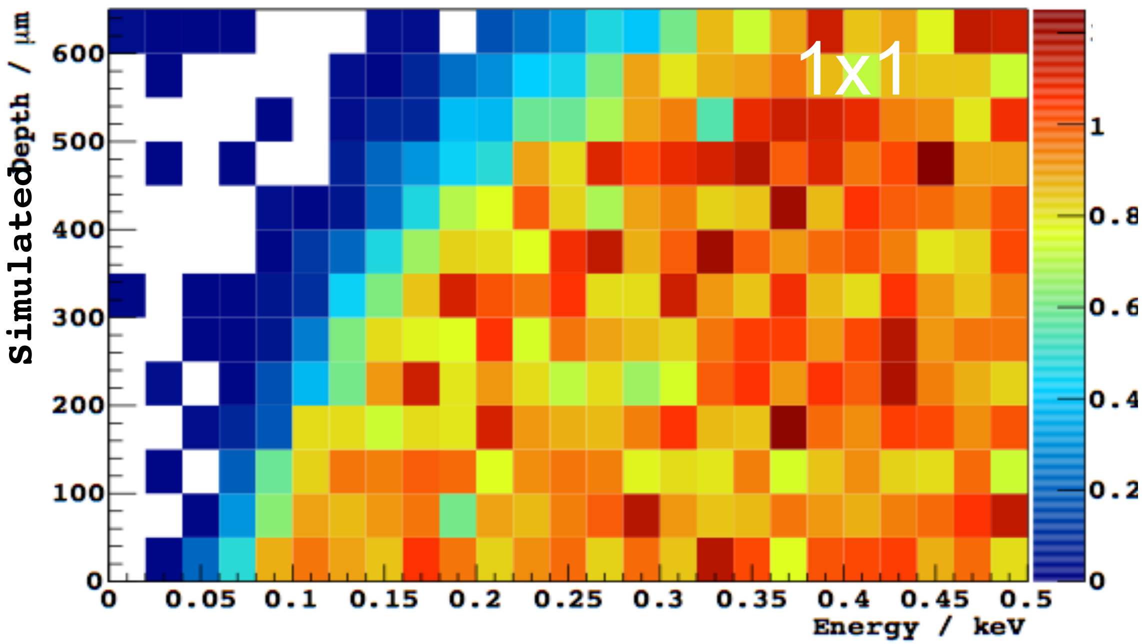
All selected events < 7 keV$_{ee}$

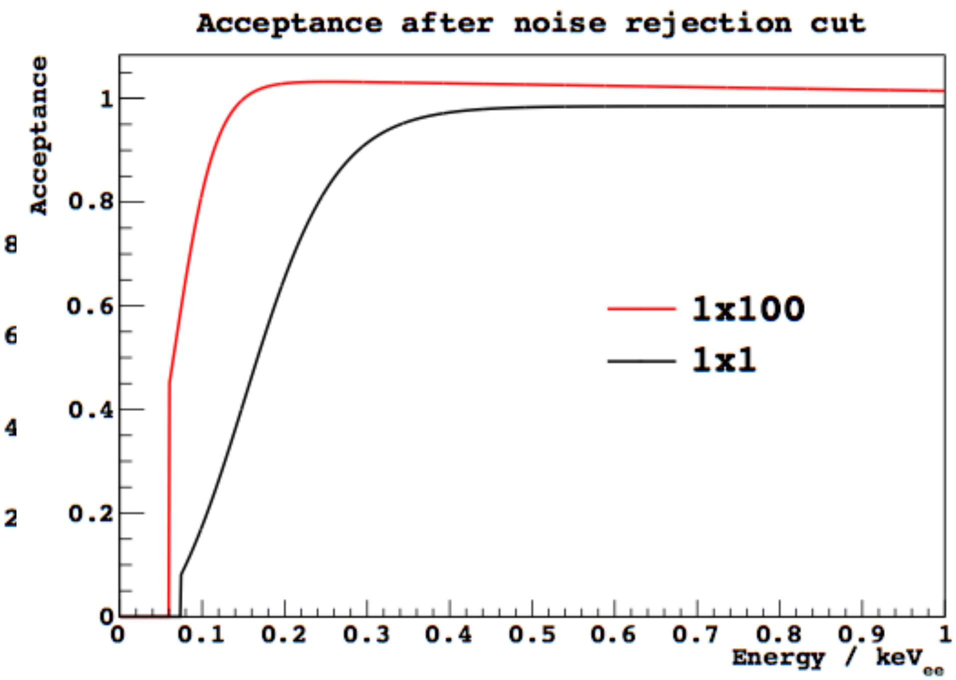


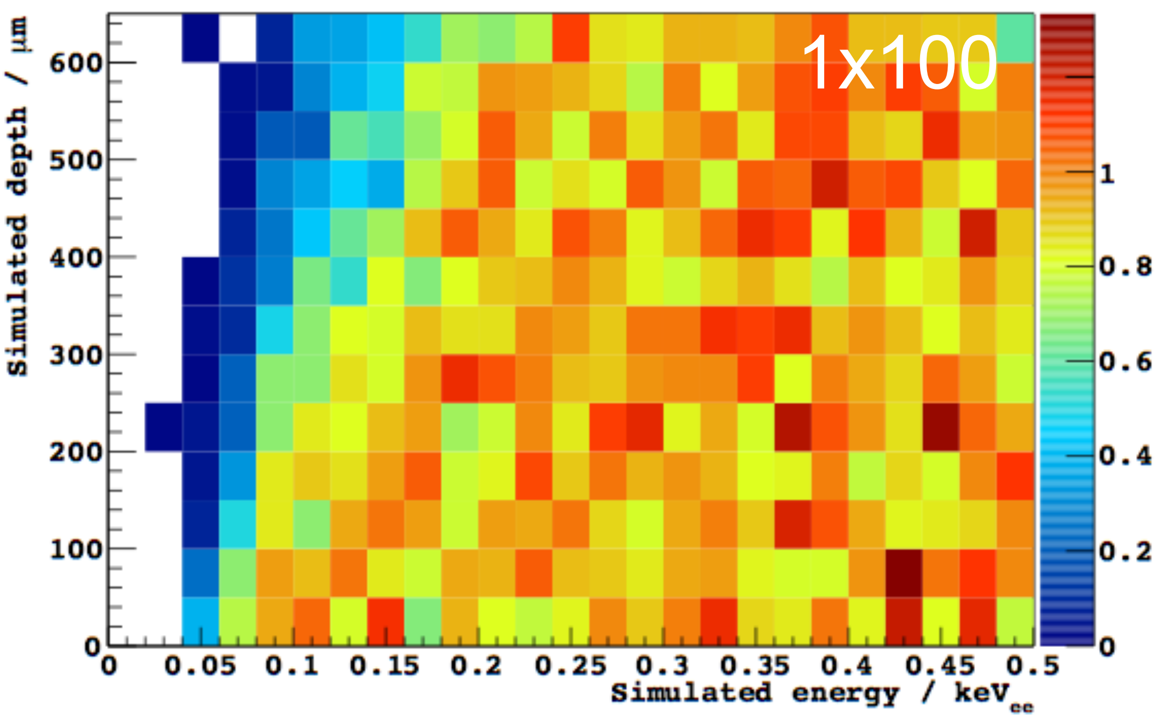
Perform a hard cut on the ΔLL to exclude random fluctuations from noise. Noise leakage <0.01 event in final sample.

Evidence from surface events in data. Include in the signal extraction the likelihood that an event is from bulk or surface.

Detection efficiency

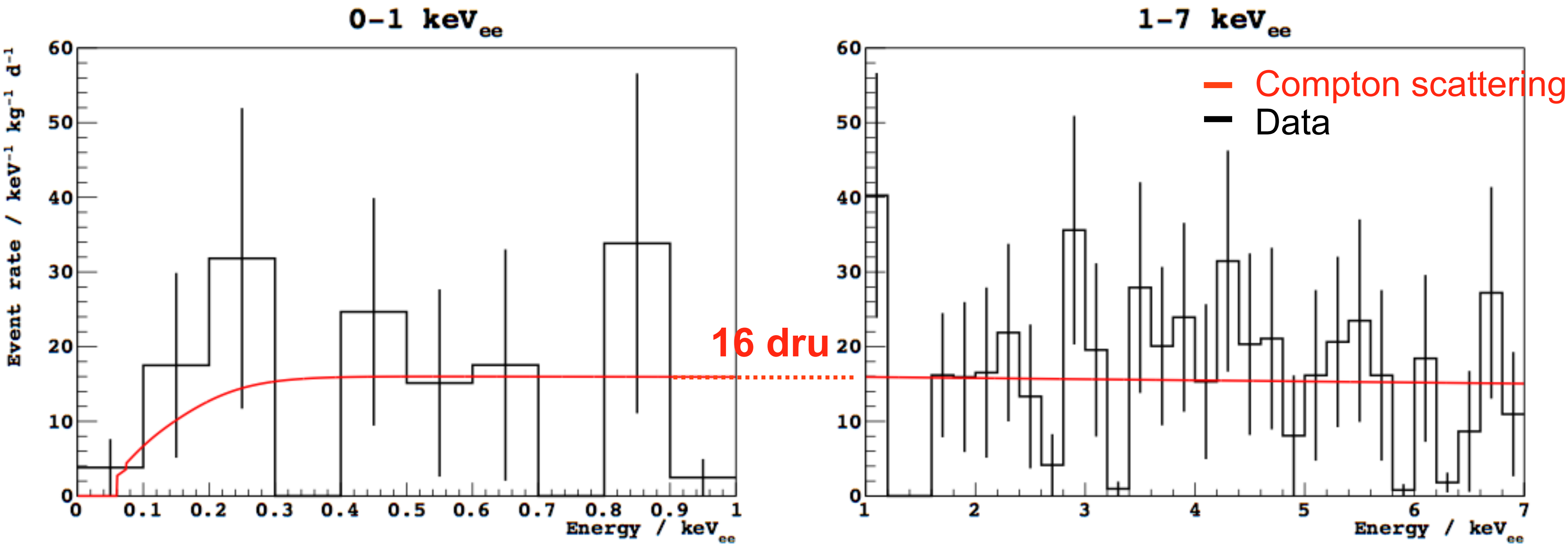






Binning data sensitive to events deeper in the bulk at low energies.

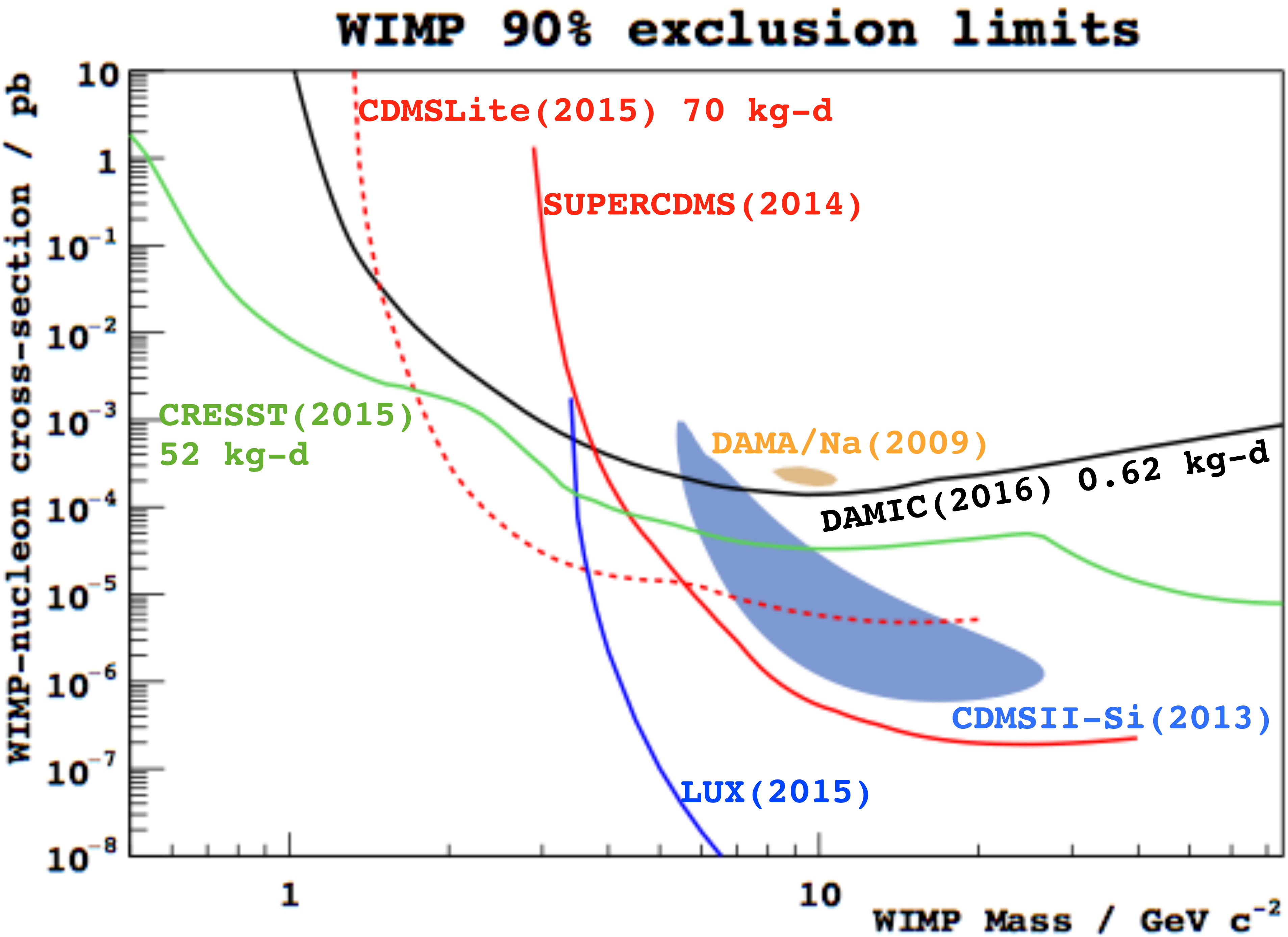
Energy spectrum



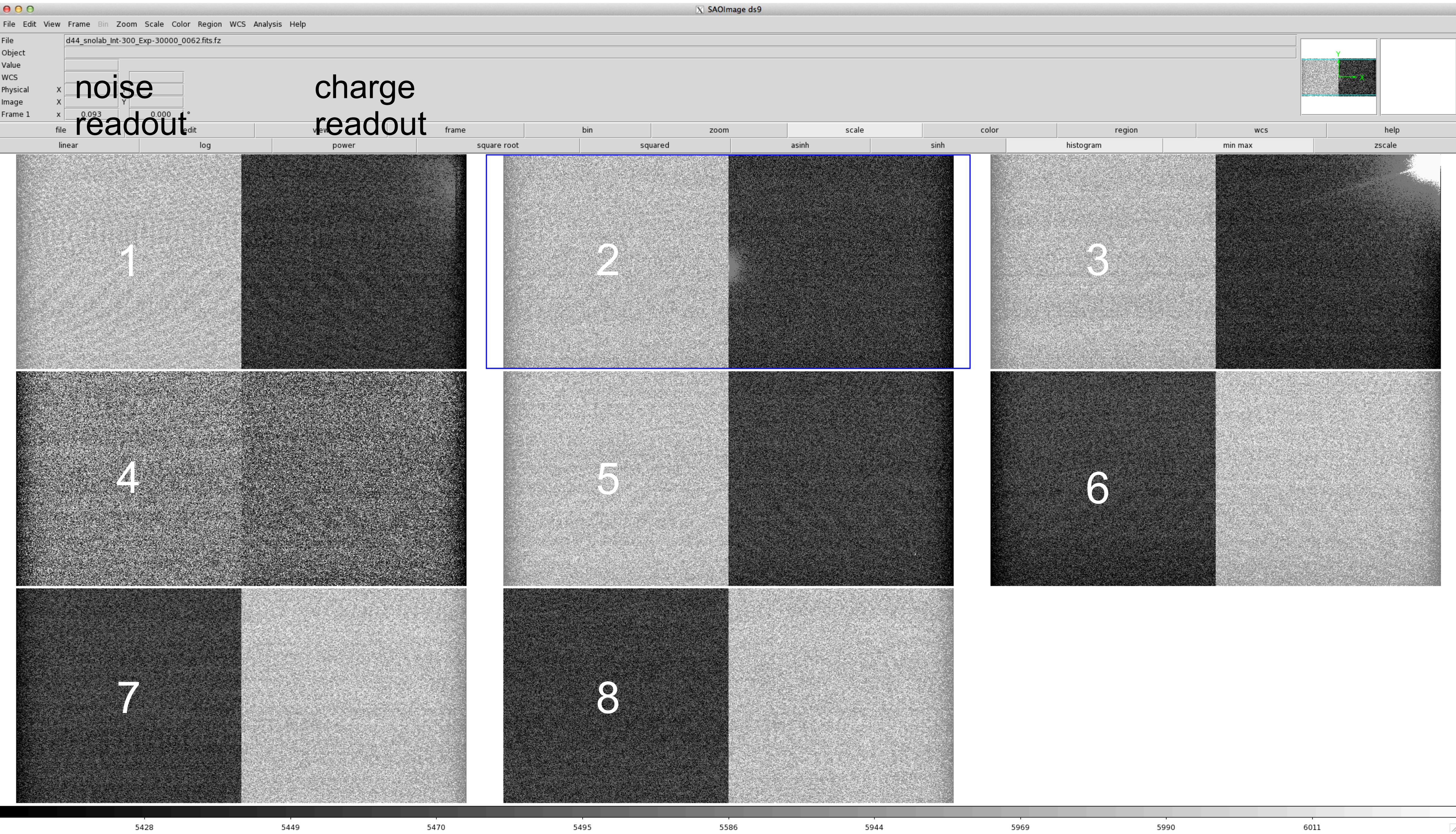
Unbinned likelihood fit to 1x1 and 1x100 data done independently, combined in a single exclusion limit.

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

Exclusion limit

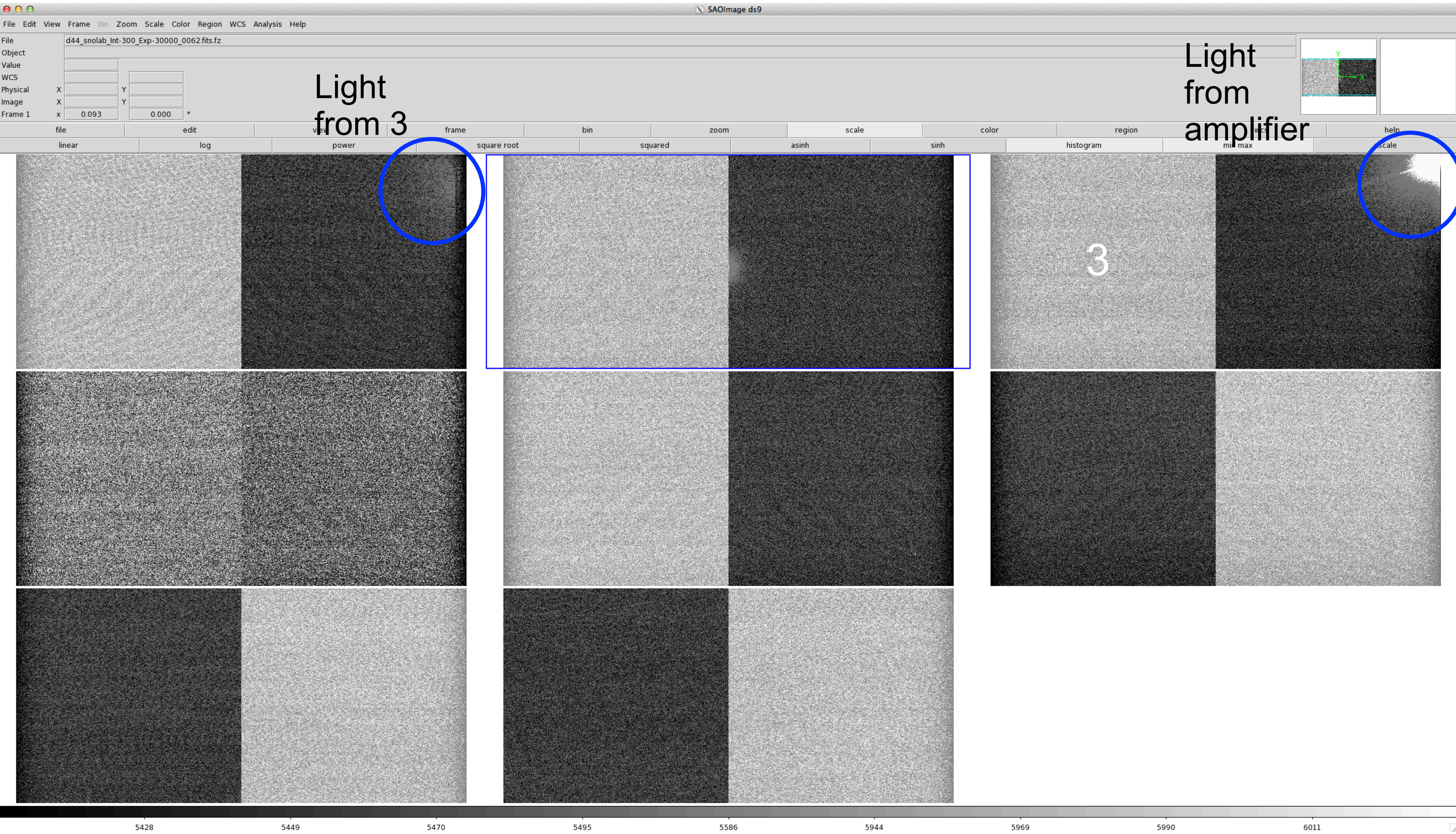


DAMIC100 first "light"

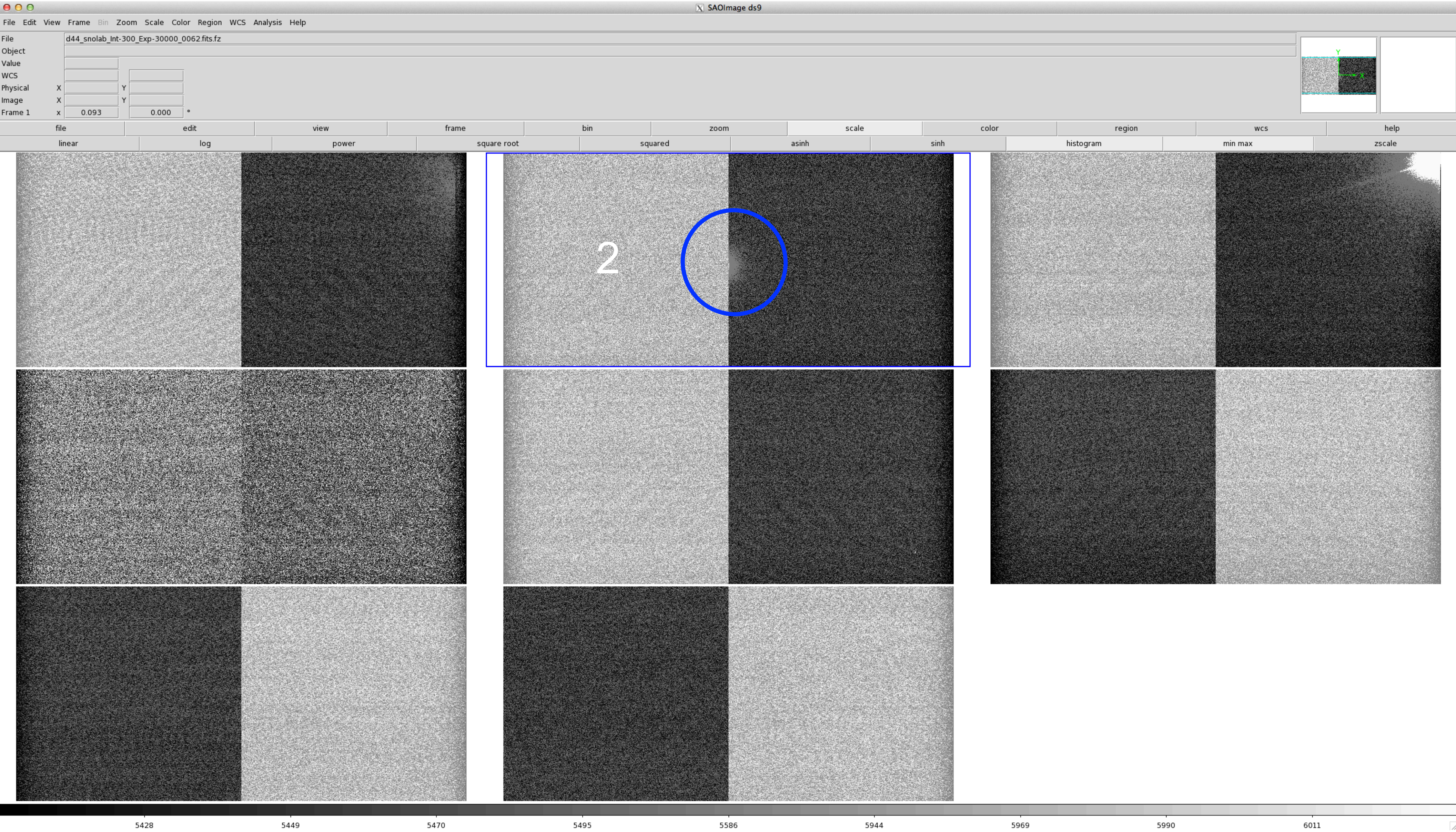


eight 4k x 4k CCDs (≈ 50 g) installed this month

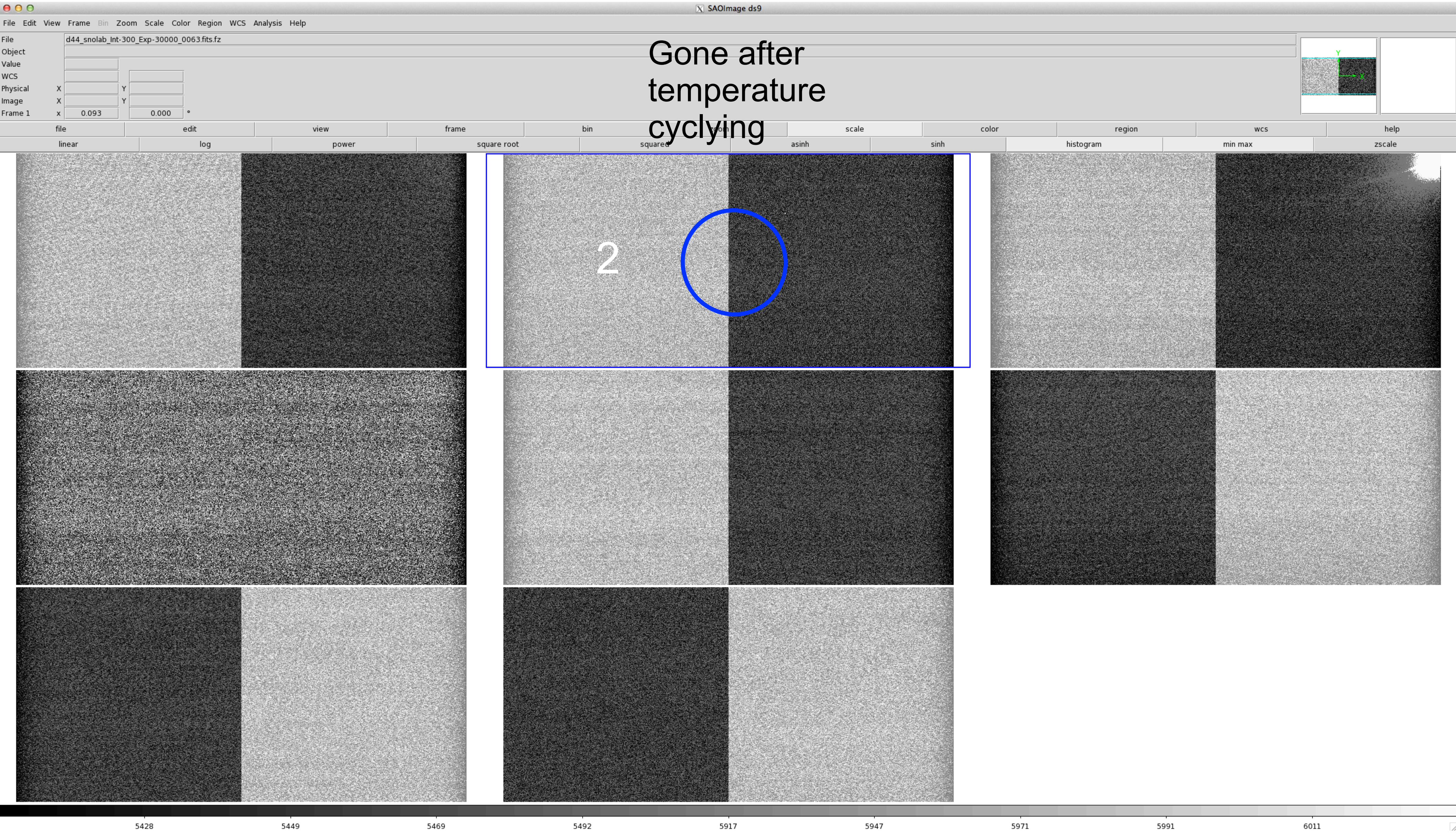
DAMIC100 commissioning



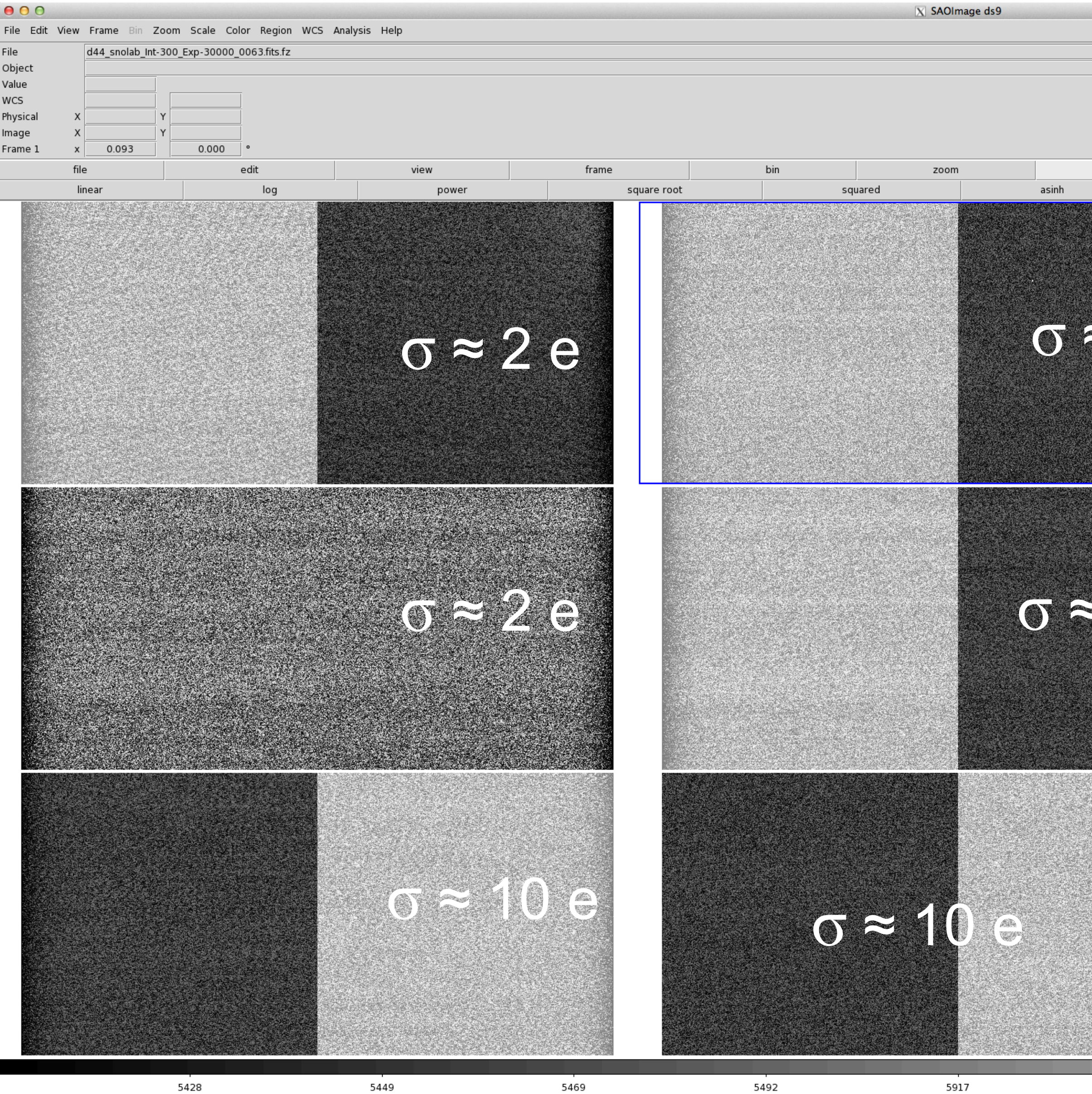
DAMIC100 commissioning

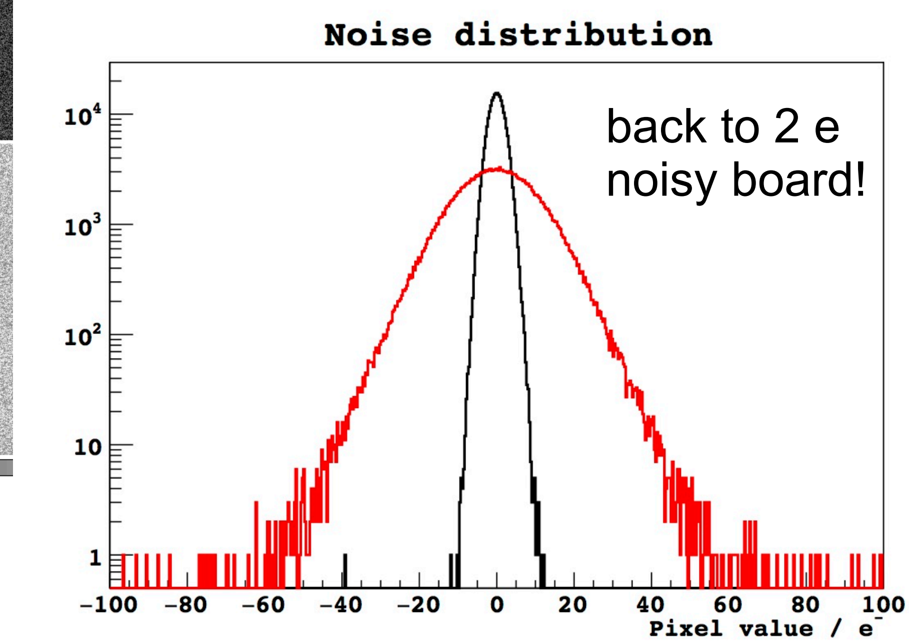


DAMIC100 commissioning



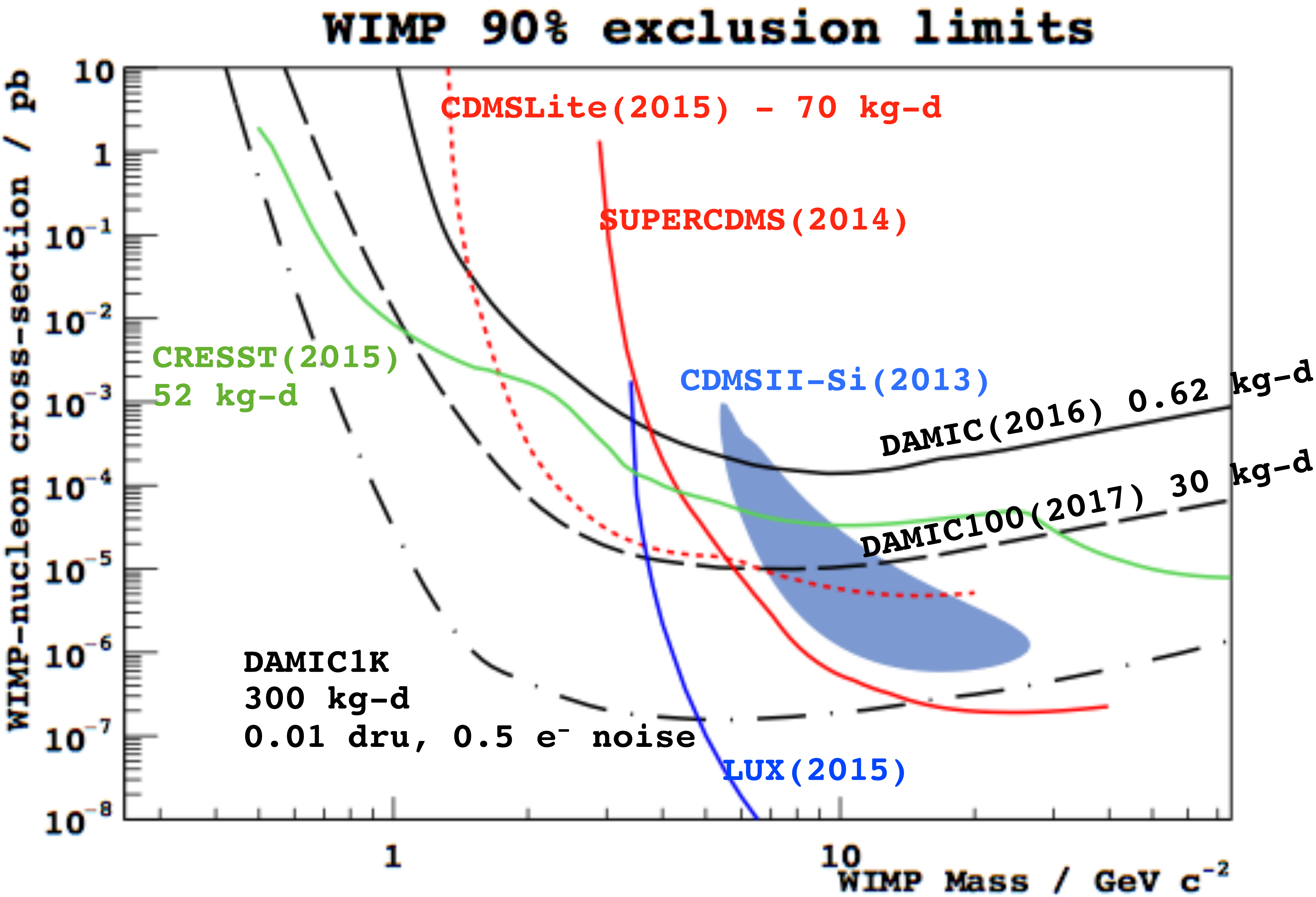
DAMIC100 commissioning



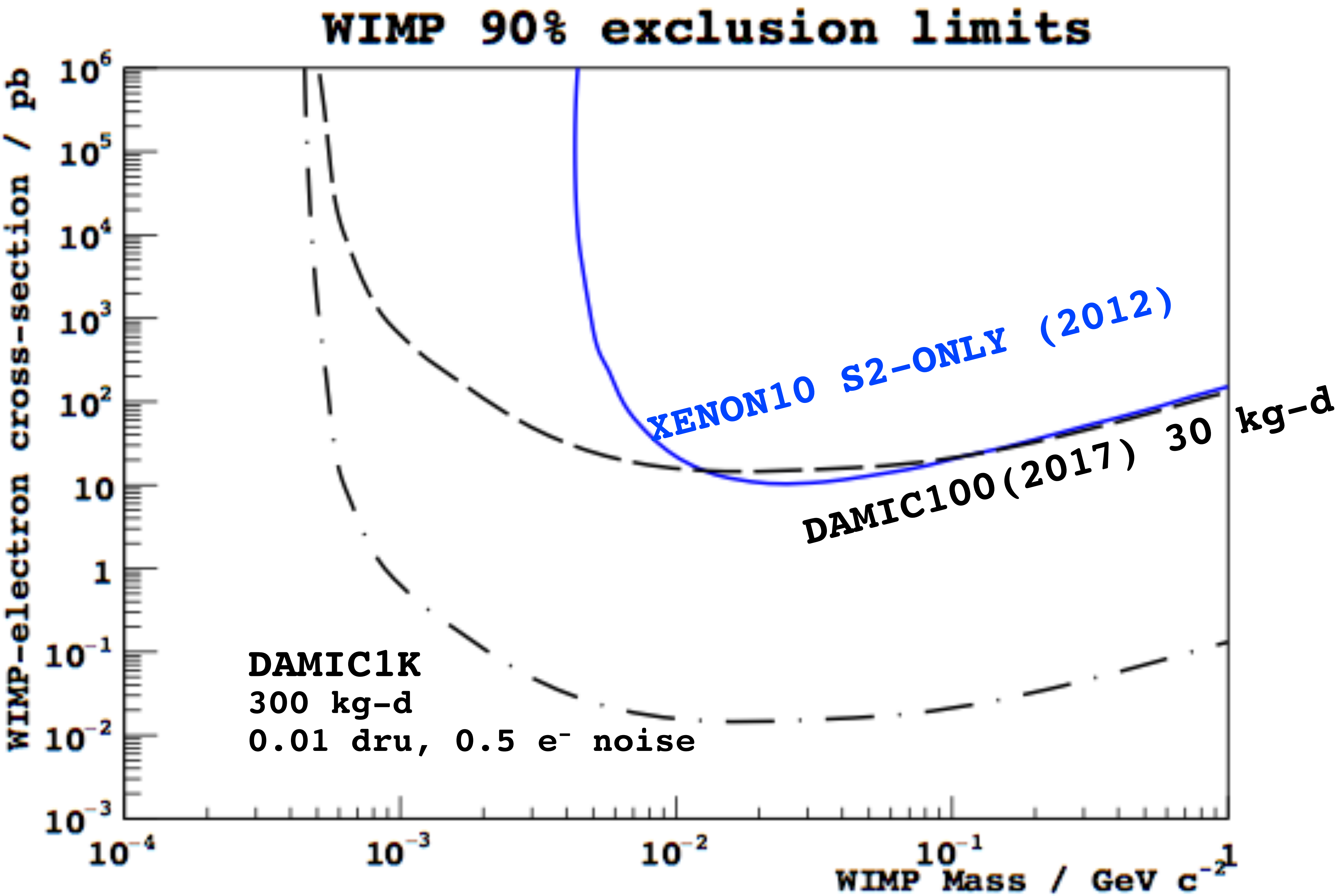


also, too early for a background measurement, but no bad surprises….

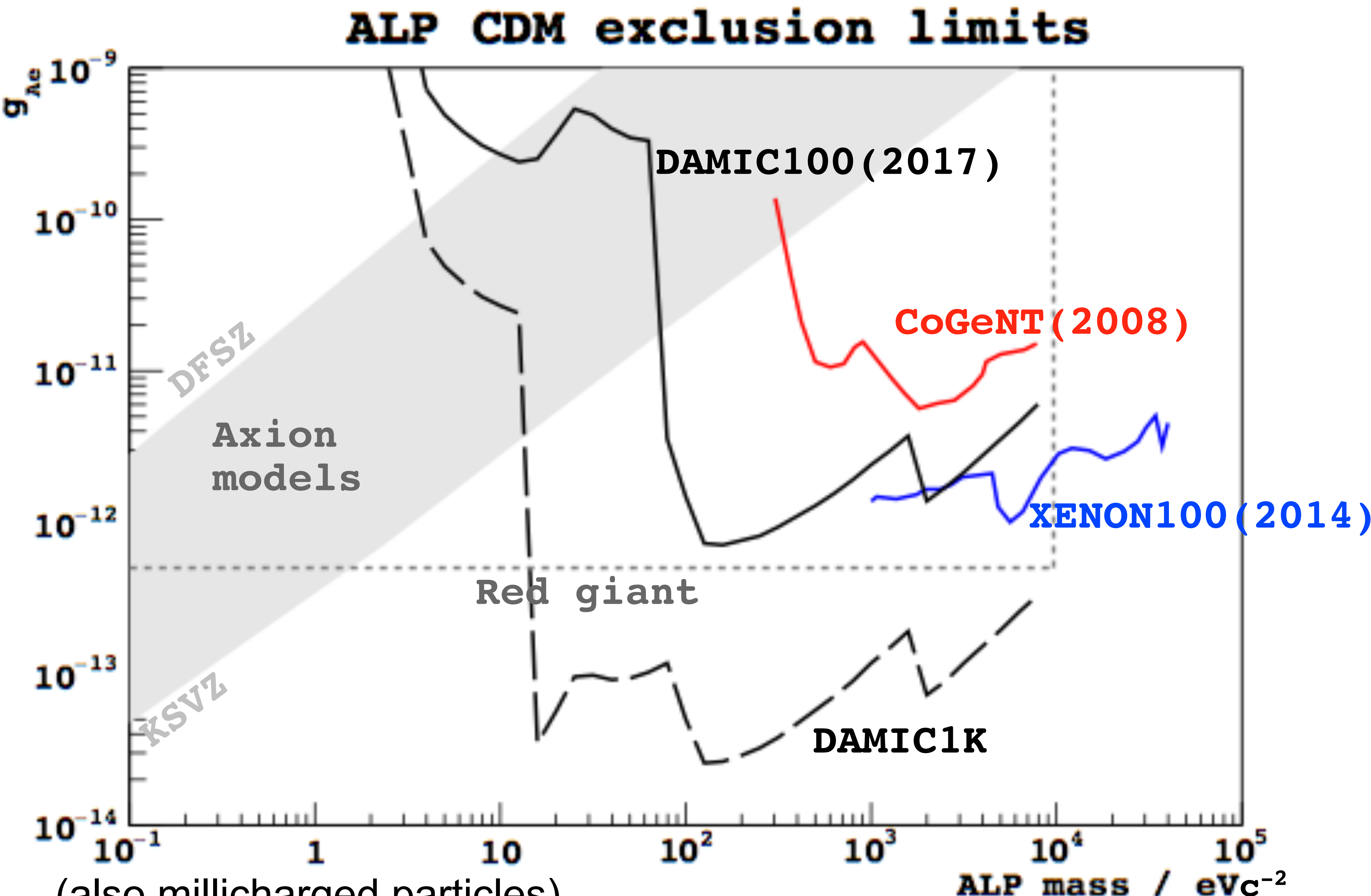
Expected sensitivity



Electron recoils



Axion-like particles

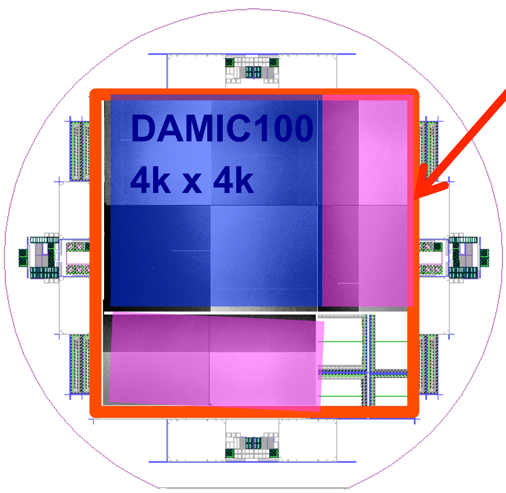


(also millicharged particles)

Prospects for a kg-size DAMIC

- A kg-size DAMIC can be built <u>with the existing technology</u> in a short time

Silicon wafer



6k x 6k pixels, 1 mm thick

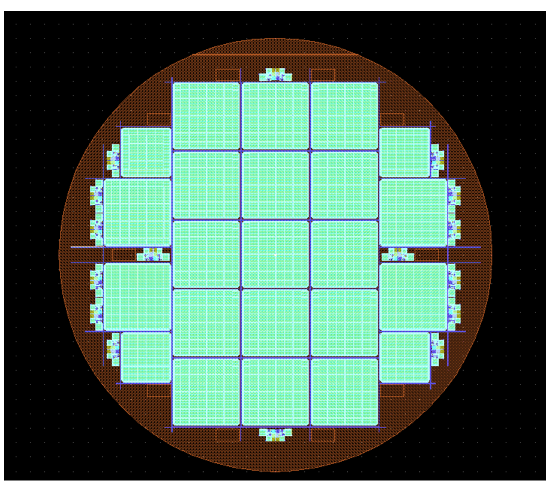
≈ 20 g / CCD

≈ 50 CCDs / 1 Kg

DAMIC100: one batch (24 wafers)

DAMIC1K: three batches

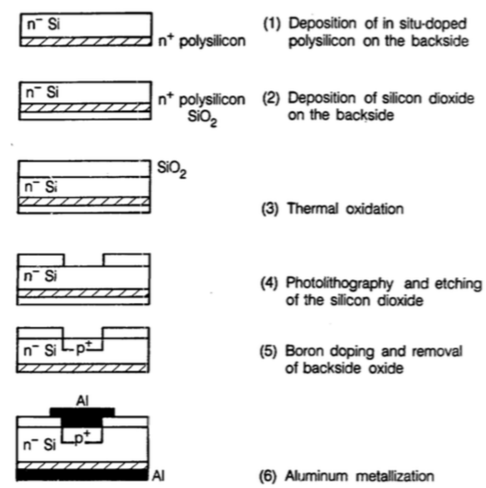
- Thicker CCDs development at the Pritzker Nanofabrication facility



- up to 1” thickness (1 mm max at DALSA or LBNL)

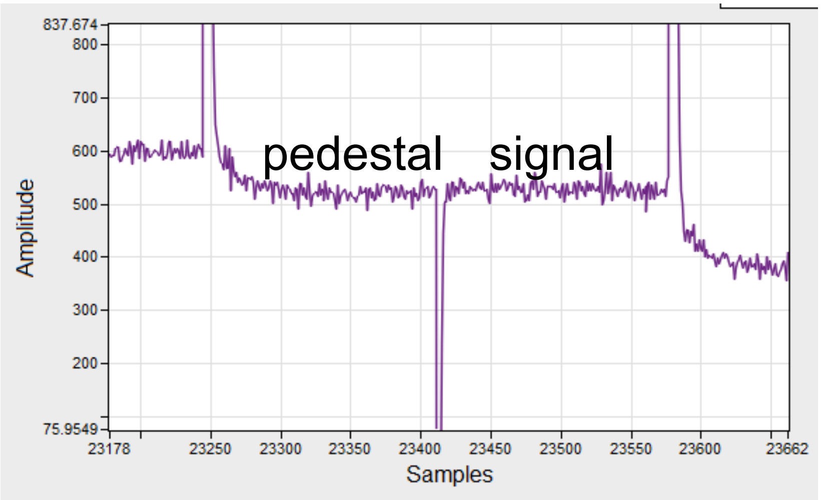
- Process flow for fabrication ok

- Start with photodiode array (LBNL, S. Holland)

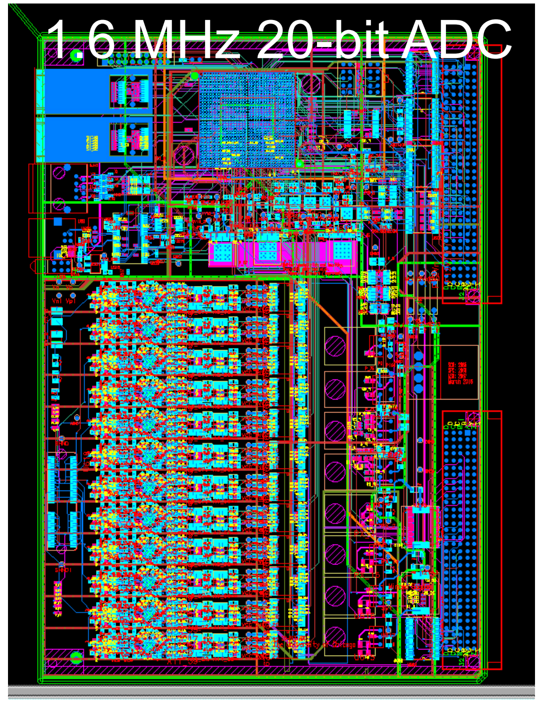


Strategic Initiative UChicago-Fermilab

- Noise reduction to < 1 e
  - Digital CDS: digital filtering



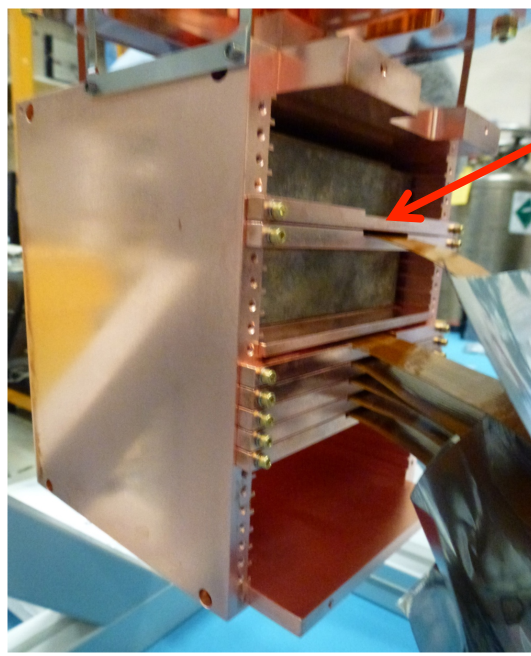
to be installed in DAMIC100



- Improve the CCD amplifier (3 μV /e) currently optimized for dynamic range of astronomy
- Skipper CCD: multiple non-destructive charge readout,< 0.5 e noise (Fermilab)

- Background reduction

Electroformed copper



one module being tested in DAMIC100

Realistic goal: 0.01 dru (dominated by ^{32}Si after coincidence rejection)

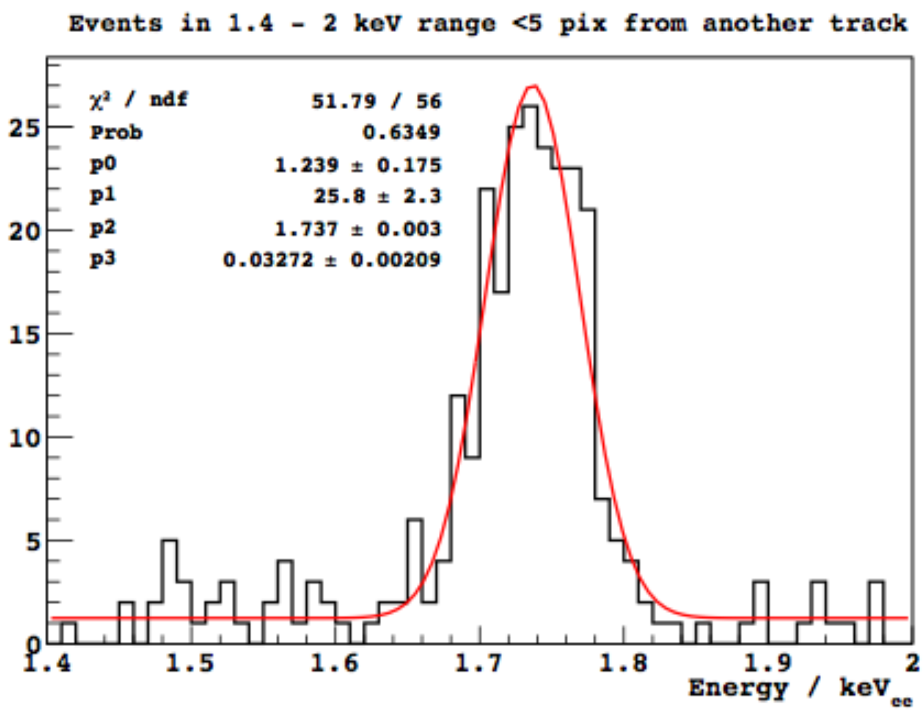
(“underground” silicon for ultimate bkg; SuperCDMS)

Conclusions and outlook

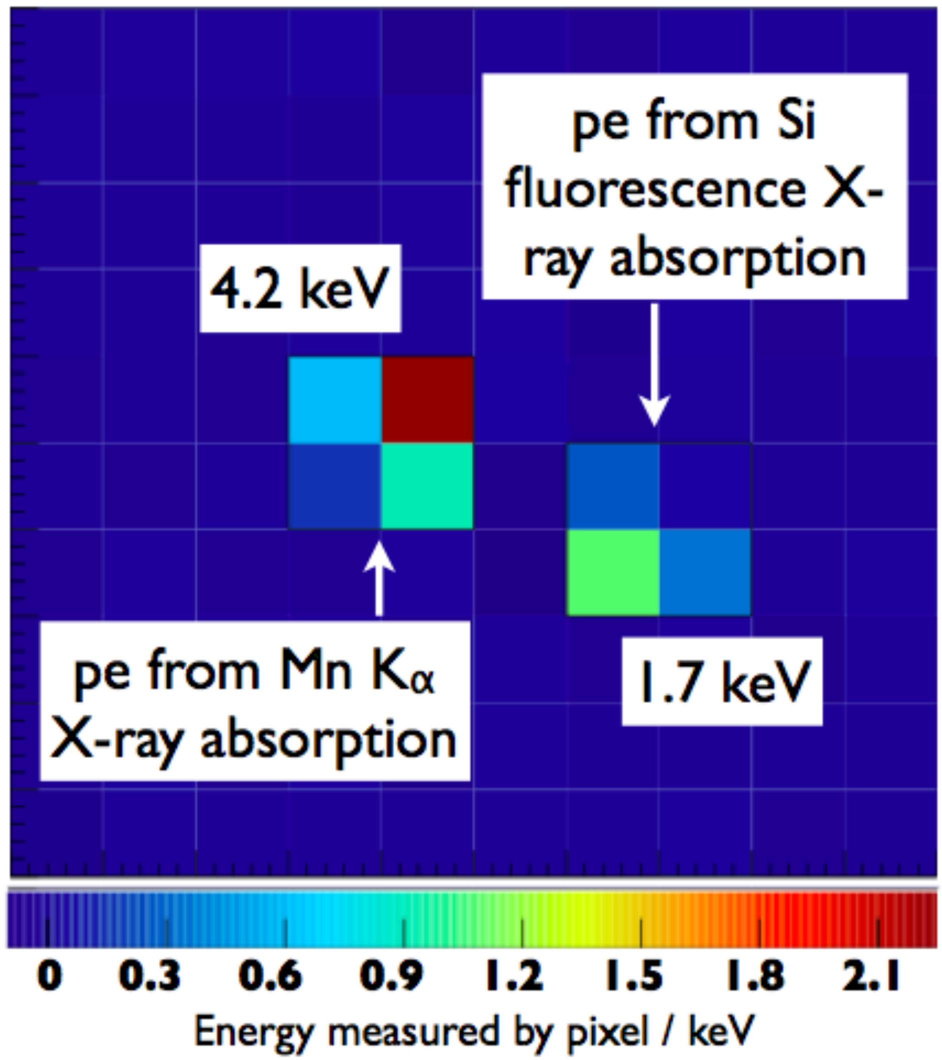
- DAMIC has successfully completed its R&D phase demonstrating the potential of CCDs as DM detectors:
  - stable, low noise, low background operation of large size, thick fully depleted CCDs at SNOLAB
  - unique spatial granularity to study backgrounds with unprecedented precision
  - nuclear-recoil 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 this summer. DAMIC100 will be a major player in the field in the next few years.
- A 1kg CCD detector can be built at low cost and fast. We will push for it….
- Other applications: nuclear forensics (PNNL), soft error (IBM)

A. Chavarria, J. Zhou, K. Ramanathan, R. Thomas, S. Dixon, J. Pena, C. Sengul GRAZIE!

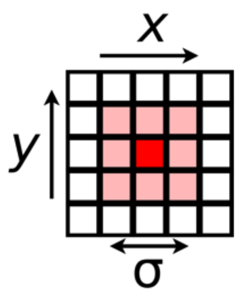
Example of spatial resolution: Si K_α

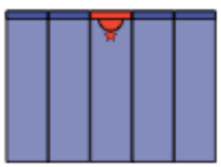


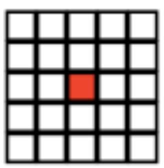
33 eV at 1.7 keV in bulk



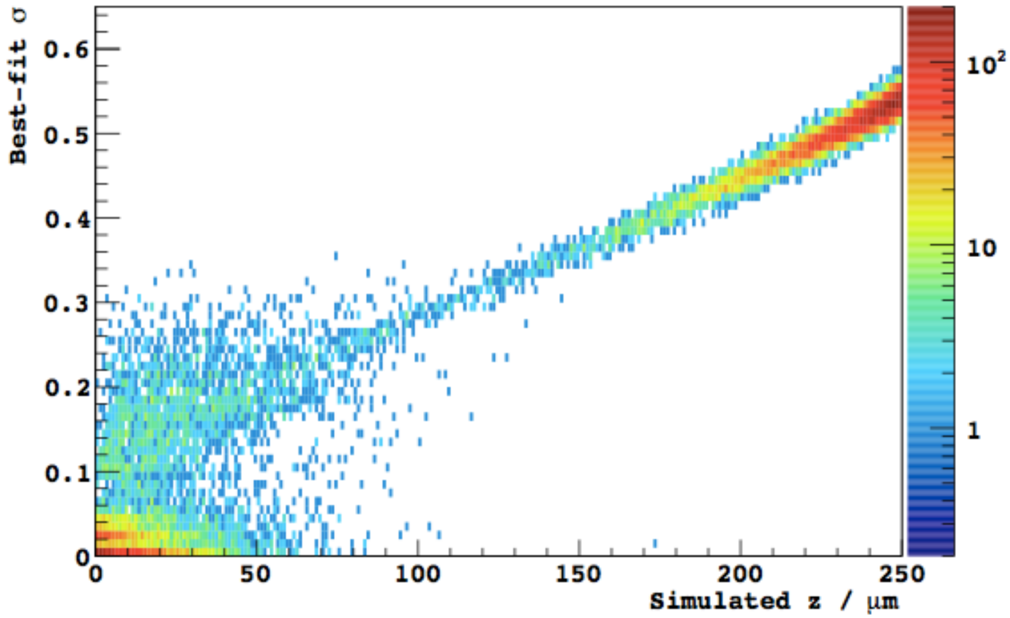
Diffusion and 3-D reconstruction

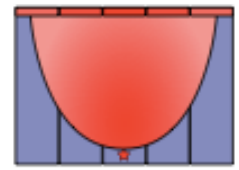


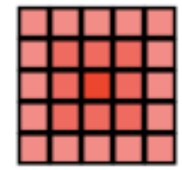




^{55}Fe source 6 keV X ray (front and back)

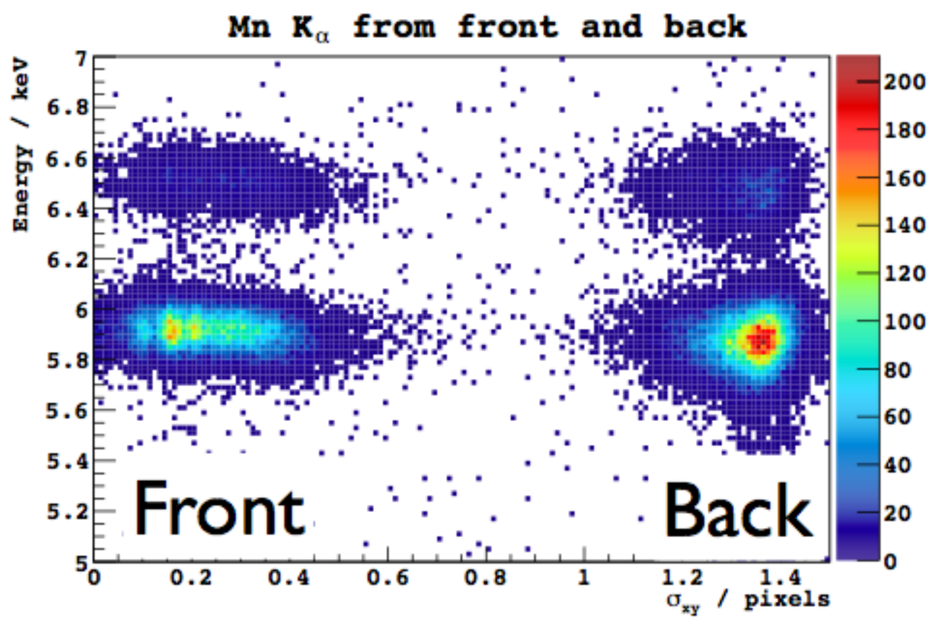






Simulation

250 μm thick CCD

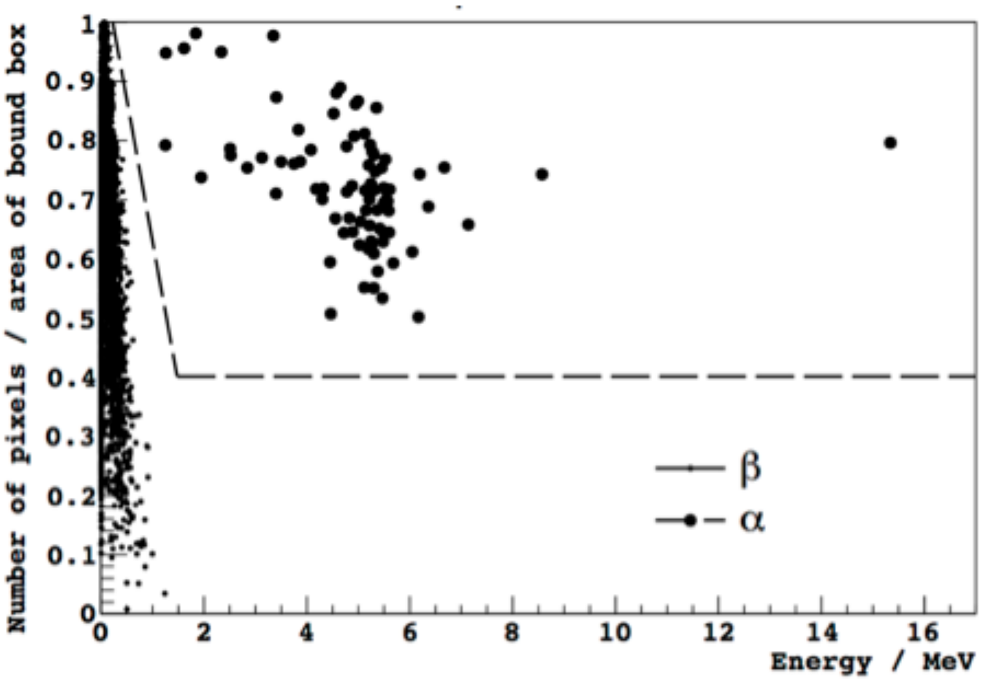


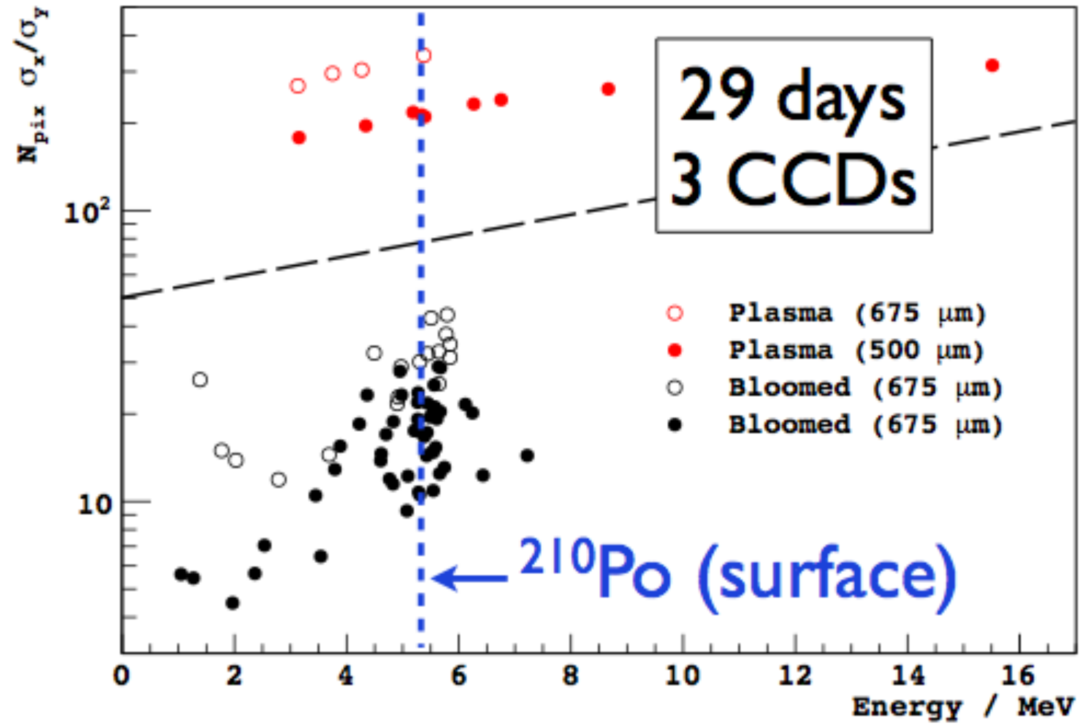
Data

675 μm thick CCD

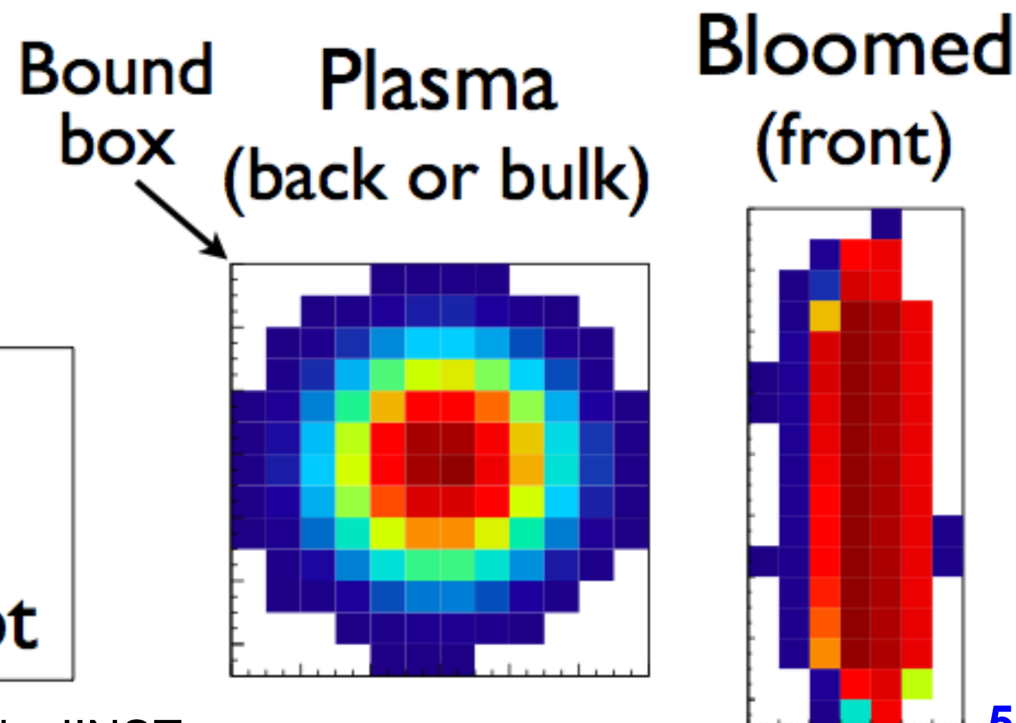
8 $\sigma_{xy} = 1.4 \rightarrow z = 675\ \mu m$

α particles





α-β discrimination based on shape of track.



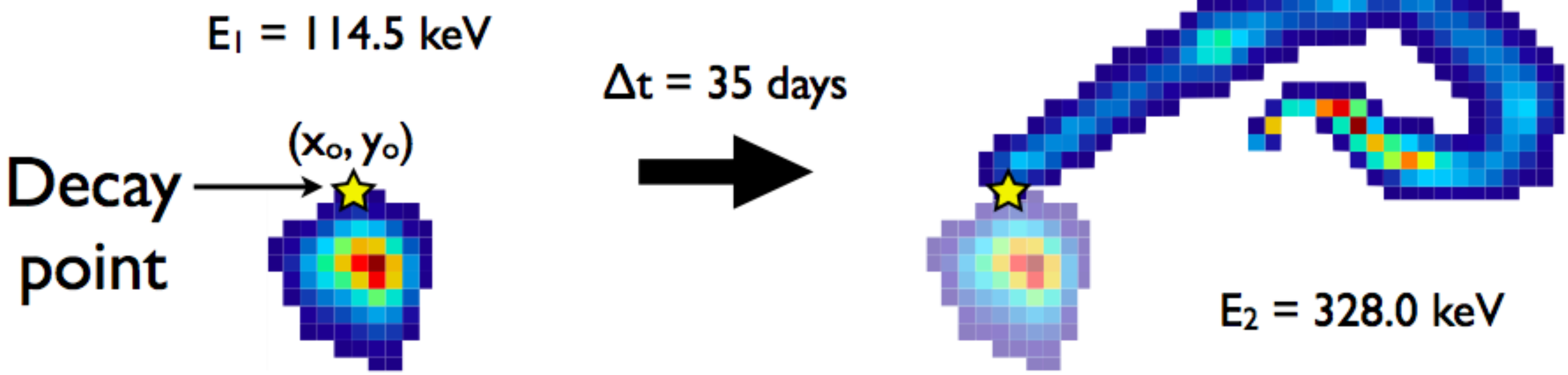
Limits on contamination:

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

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

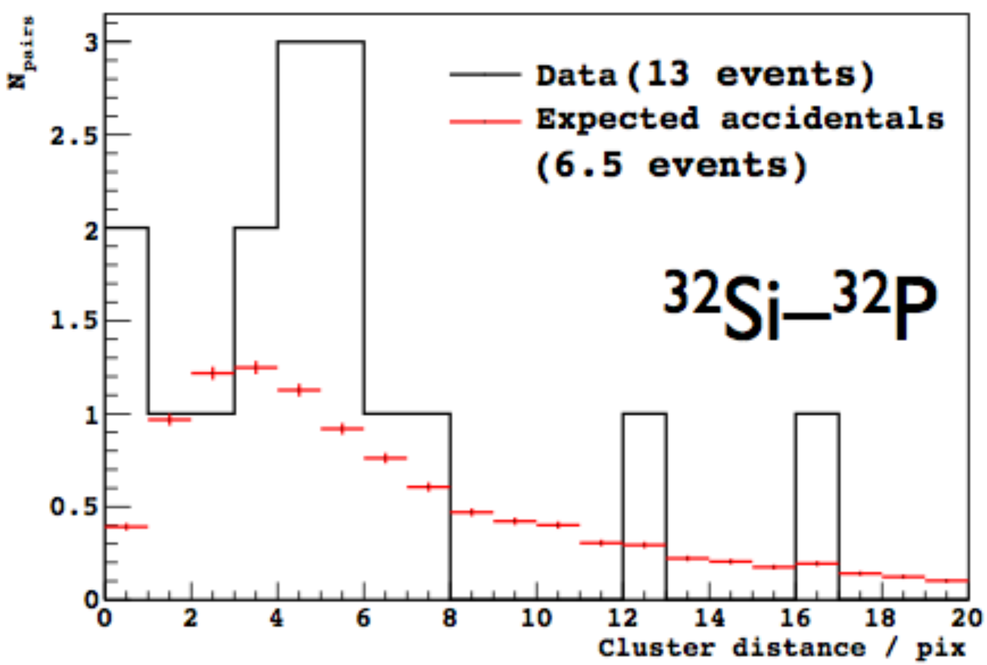
arXiv:1506.02562 to appear in JINST

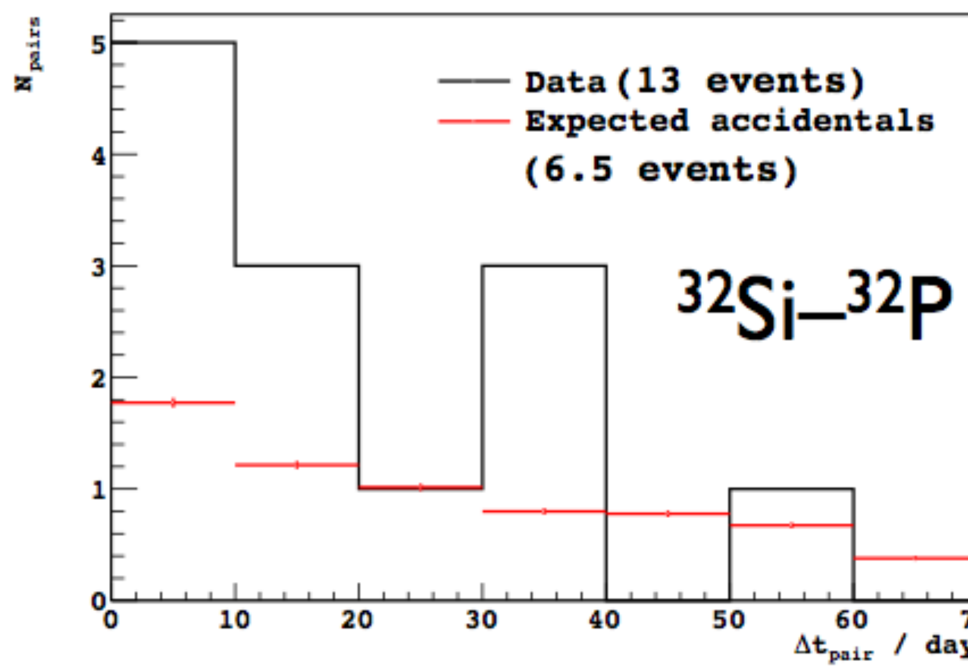
^{32}Si - ^{32}P candidate



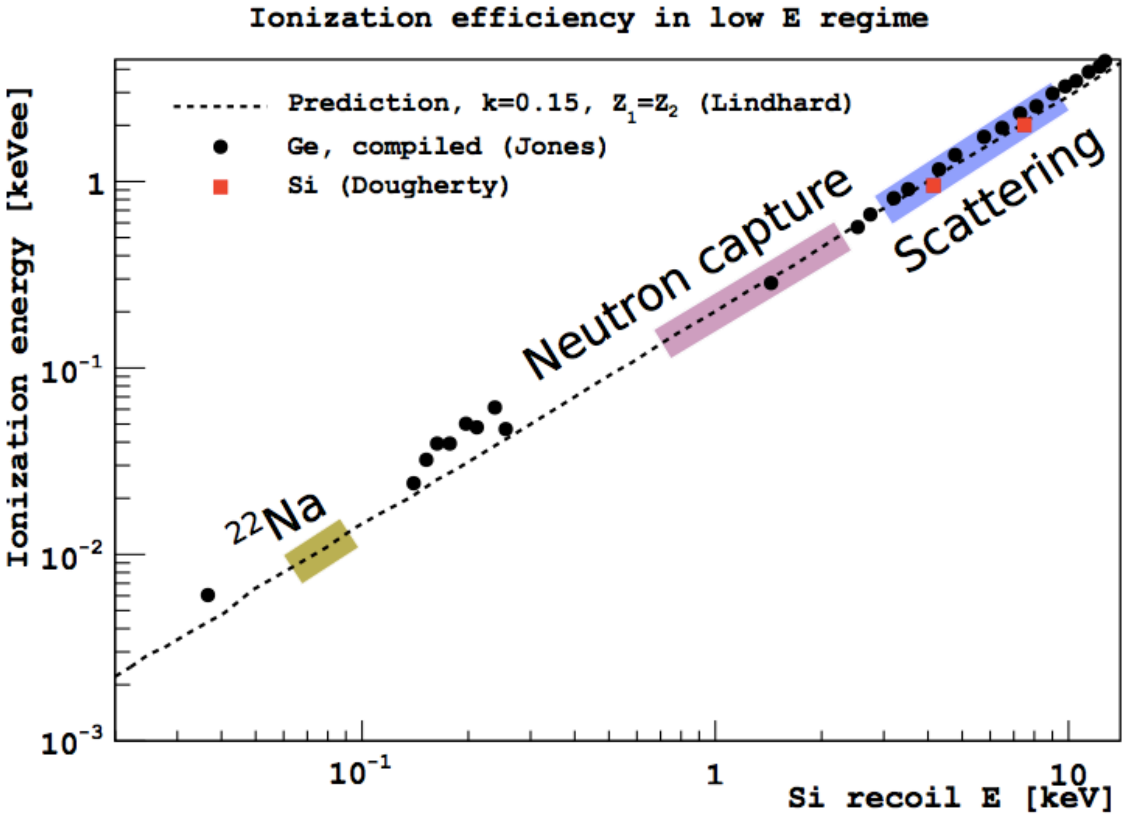
$$^{32}\mathrm{Si} = 80^{+110}_{-65}\,\mathrm{kg}^{-1}\,\mathrm{d}^{-1}\ (95\%\ \mathrm{CI})$$

arXiv:1506.02562
to appear in JINST

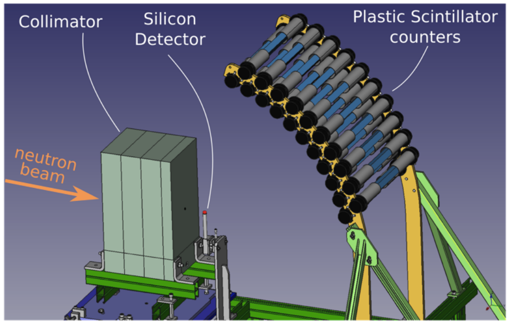




DAMIC calibration (keV_{nr})



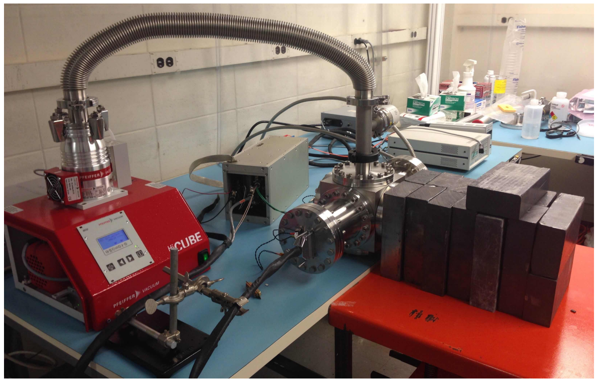
University of Notre Dame



eg. $^{28}Si + n \longrightarrow {}^{29}Si + \gamma$

Argonauta reactor (UFRJ, Rio de Janeiro)

340 Watt, thermal neutron flux few $10^5/cm^2/s$



Sb/Be “monochromatic” neutron source (24 keV), U. Chicago

CCD activation with proton beam (CDH proton center, Illinois) Nuclear recoil from EC of ^{22}Na