DAMIC at SNOLAB

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Fermilab, U Chicago, U Zurich, Michigan, UNAM,
FIUNA, CAB, UFRJ.

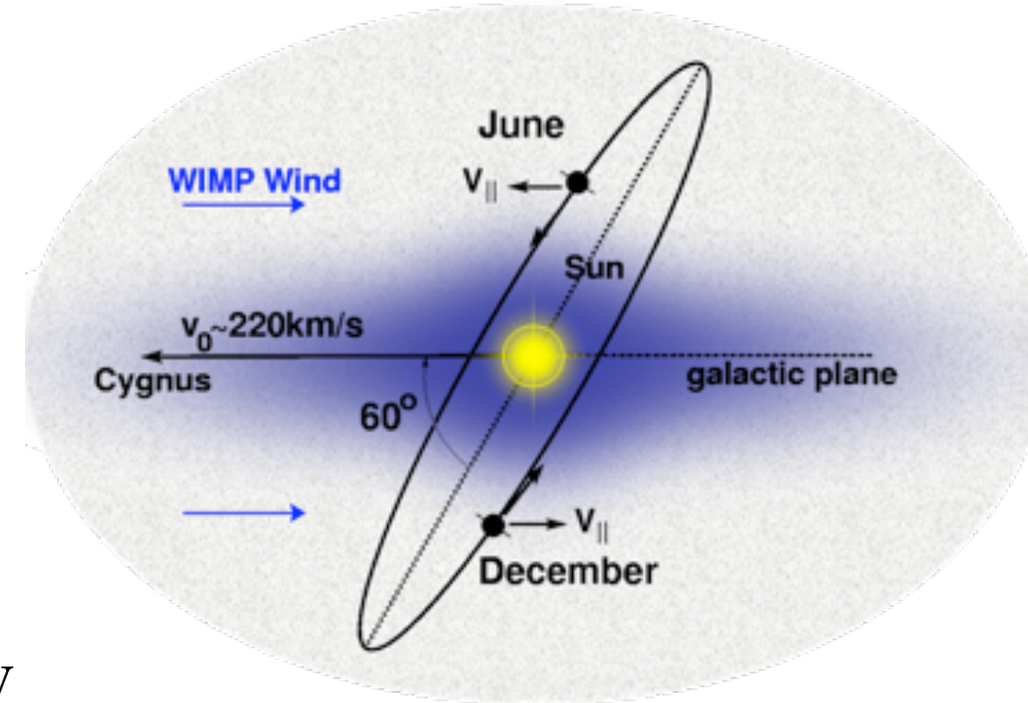
Overview

- Current status of dark matter searches.
- CCDs as particle detectors.
- CCD performance.
- SNOLAB installation.
- Exclusion limit with 0.3 kg day.
- Background measurements.
- DAMIC100 status + improvements.
- Calibration of nuclear recoil energy scale.

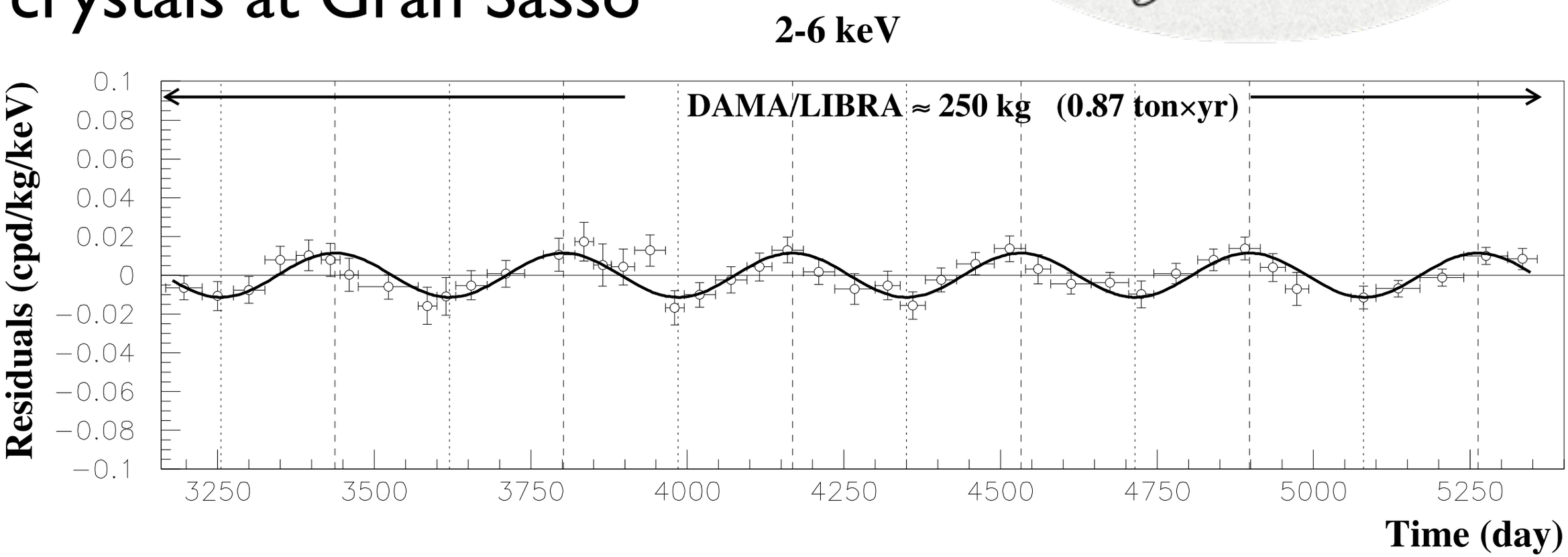
Dark matter

- Cold dark matter is needed for CMB cosmology...
- ... and structure formation.
- ... and to explain galaxy rotation curves.
- ... and evident from gravitational lensing.
- Overall 5.5 times more dark than baryonic matter.
- Local density ~0.3 GeV cm^{-3} with velocities in the Earth's reference frame of 100s of km s^{-1}.
- Could be made of particles...
- ... that could interact with SM particles.
- Numerology: "WIMP Miracle," asymmetric DM, etc.

DAMA/LIBRA



Nal scintillating crystals at Gran Sasso

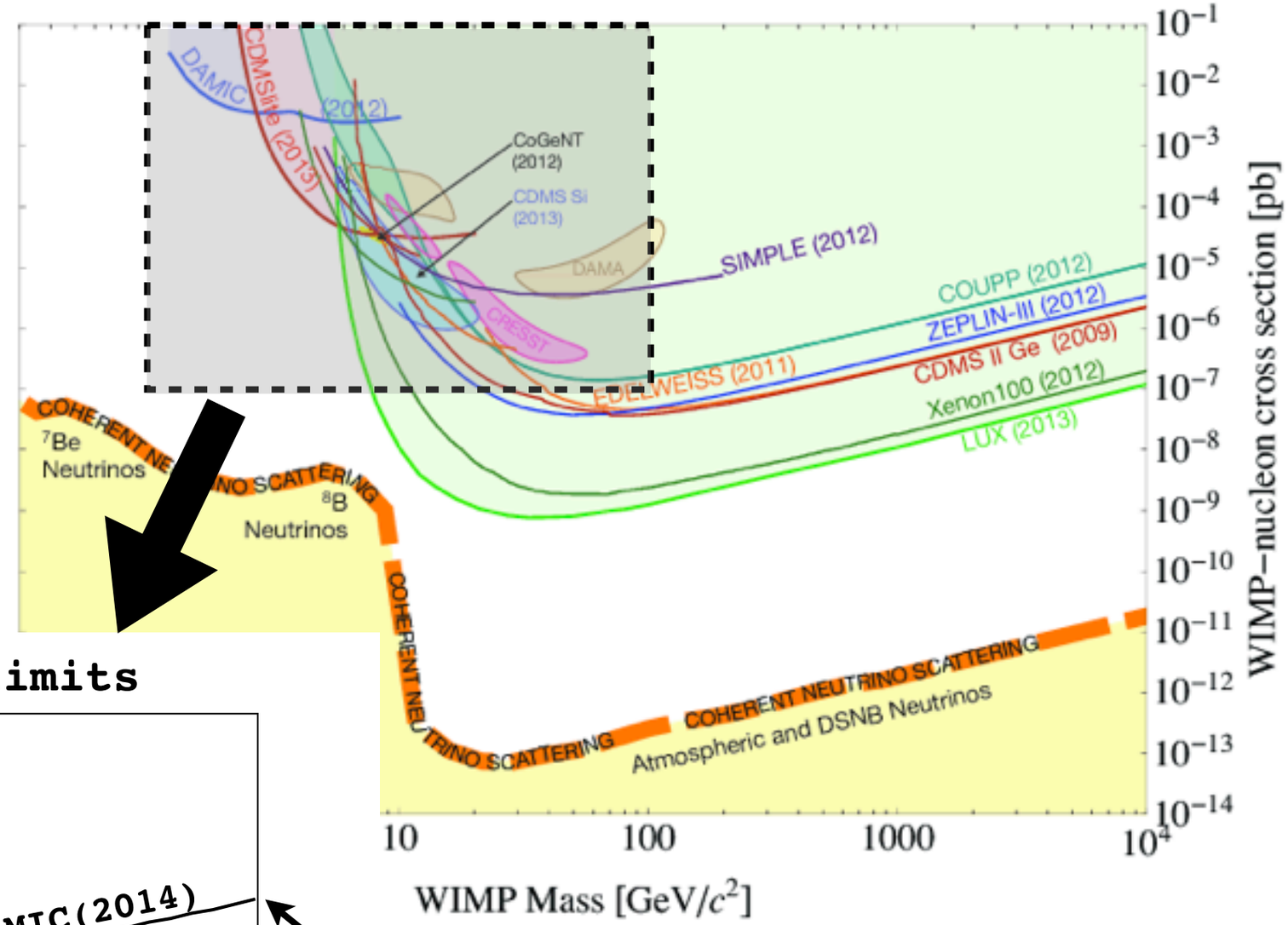


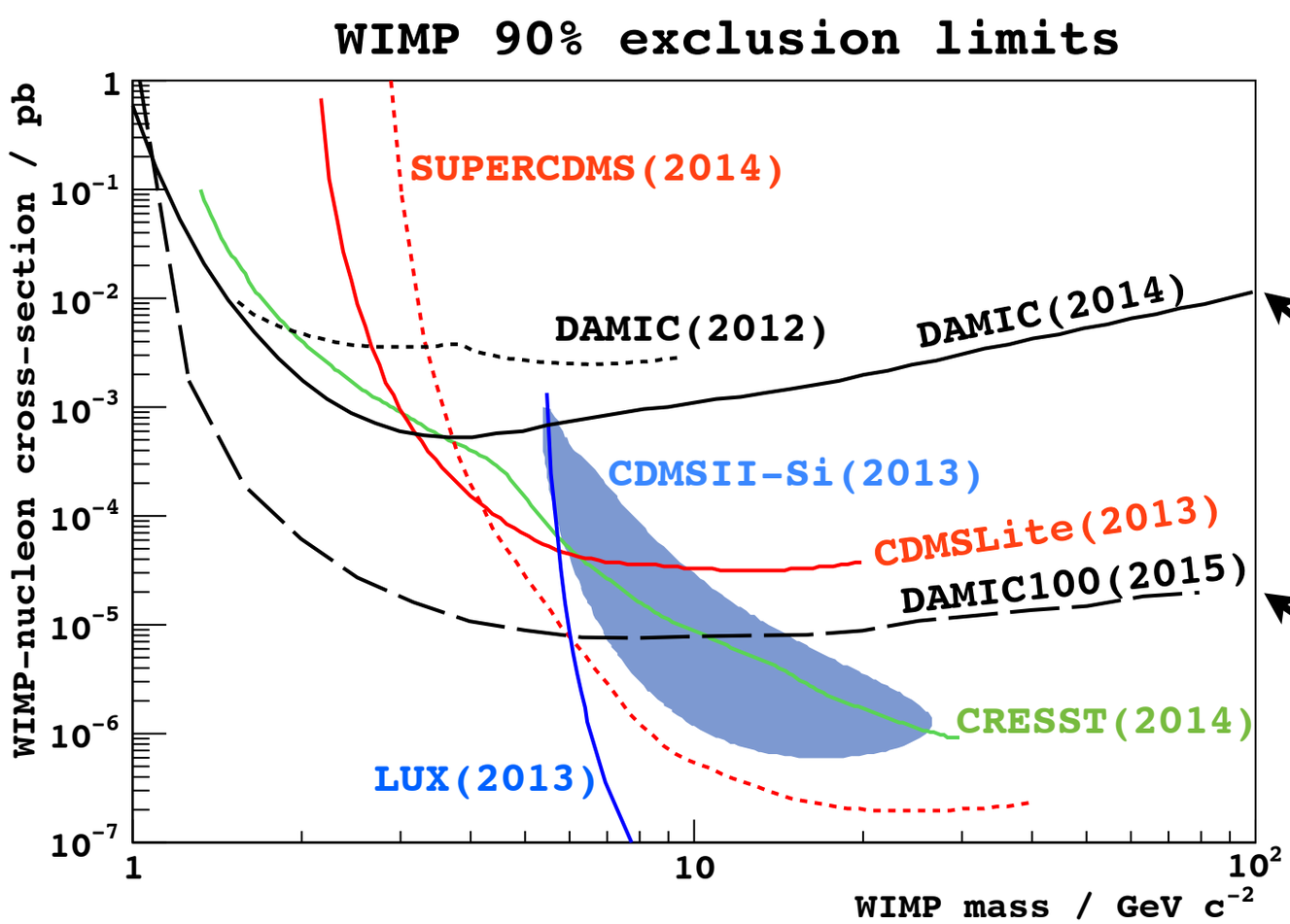
Observe a highly significant (9 σ) annual modulation, consistent with the "model independent DM signal"

T = 0.999 ± 0.002 y and maximum ~ June 2nd ± 7 d

Status

Current results in terms of traditional WIMP-nucleon, spin independent interaction.





I will discuss this recent, preliminary result.

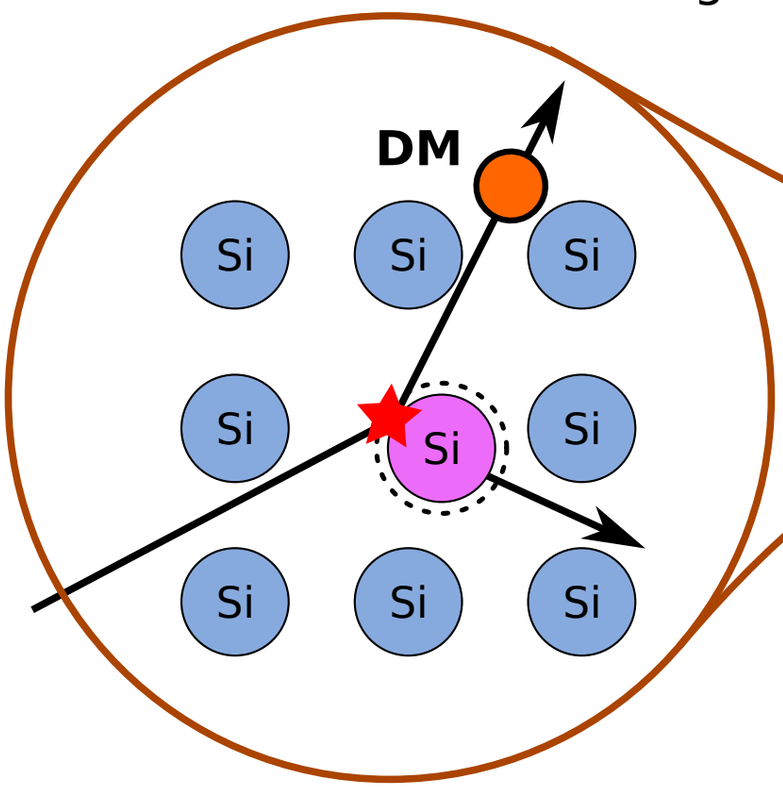
And the progress toward DAMIC100.

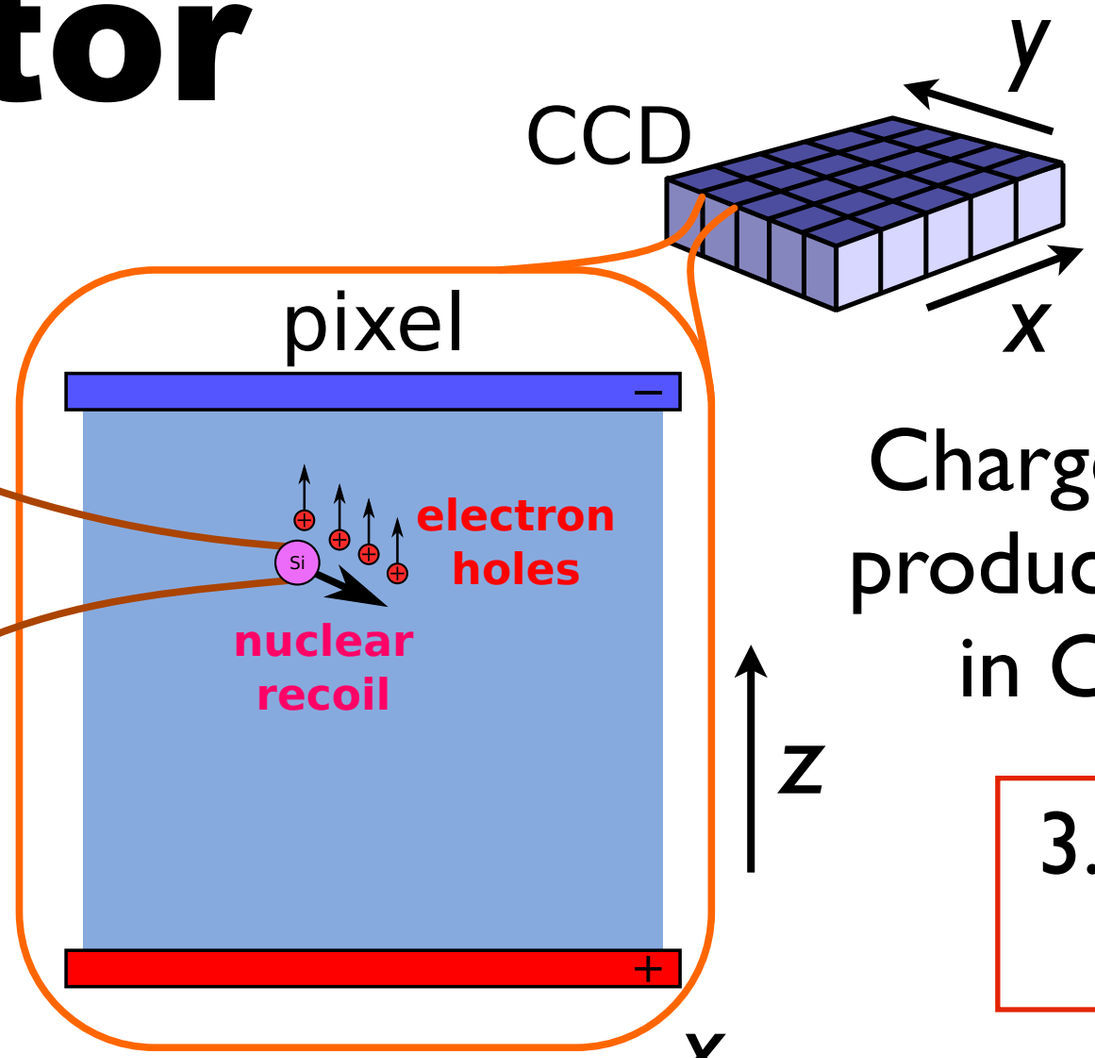
DAMIC Program

- Employ charge-coupled devices (CCDs) as low threshold, low background particle detectors...
- which will allow us to explore new regions of WIMP parameter space (low masses) and other dark matter candidates.
- Low threshold + relatively light target nucleus (Si) generally allows to probe more of the WIMP velocity distribution.

Detector

coherent elastic scattering

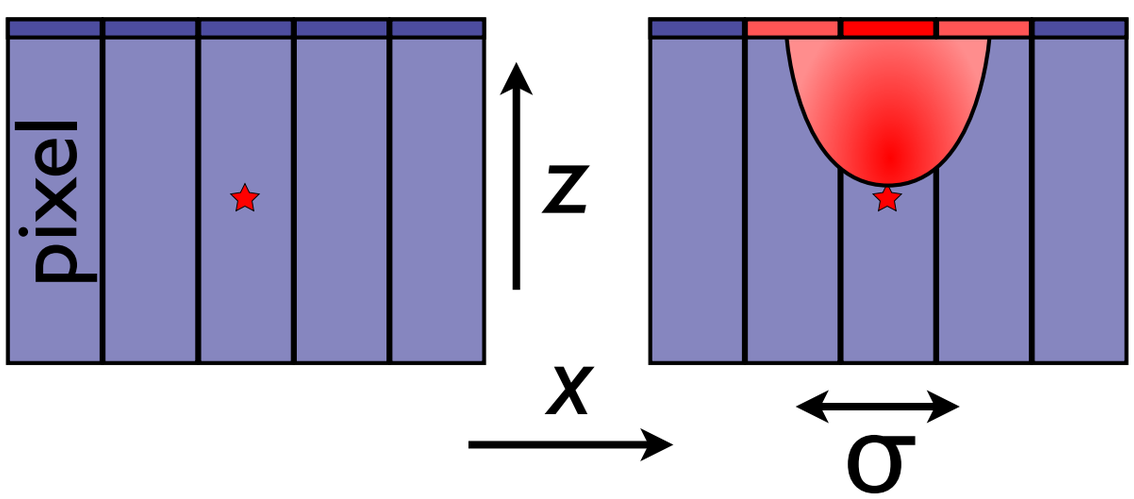


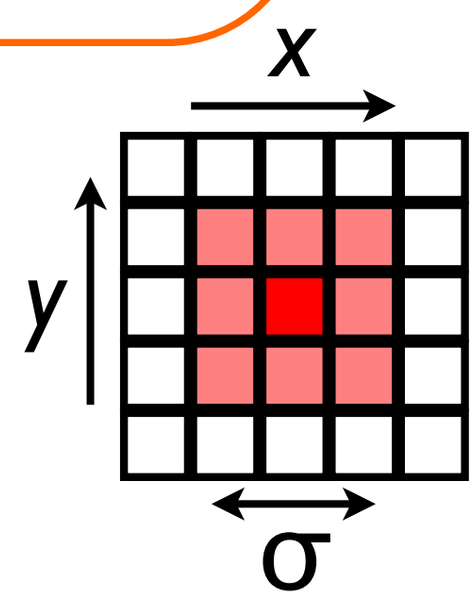


Charged particles produce ionization in CCD bulk

3.62 eV for e-h pair

Charge drifted up and held at gates

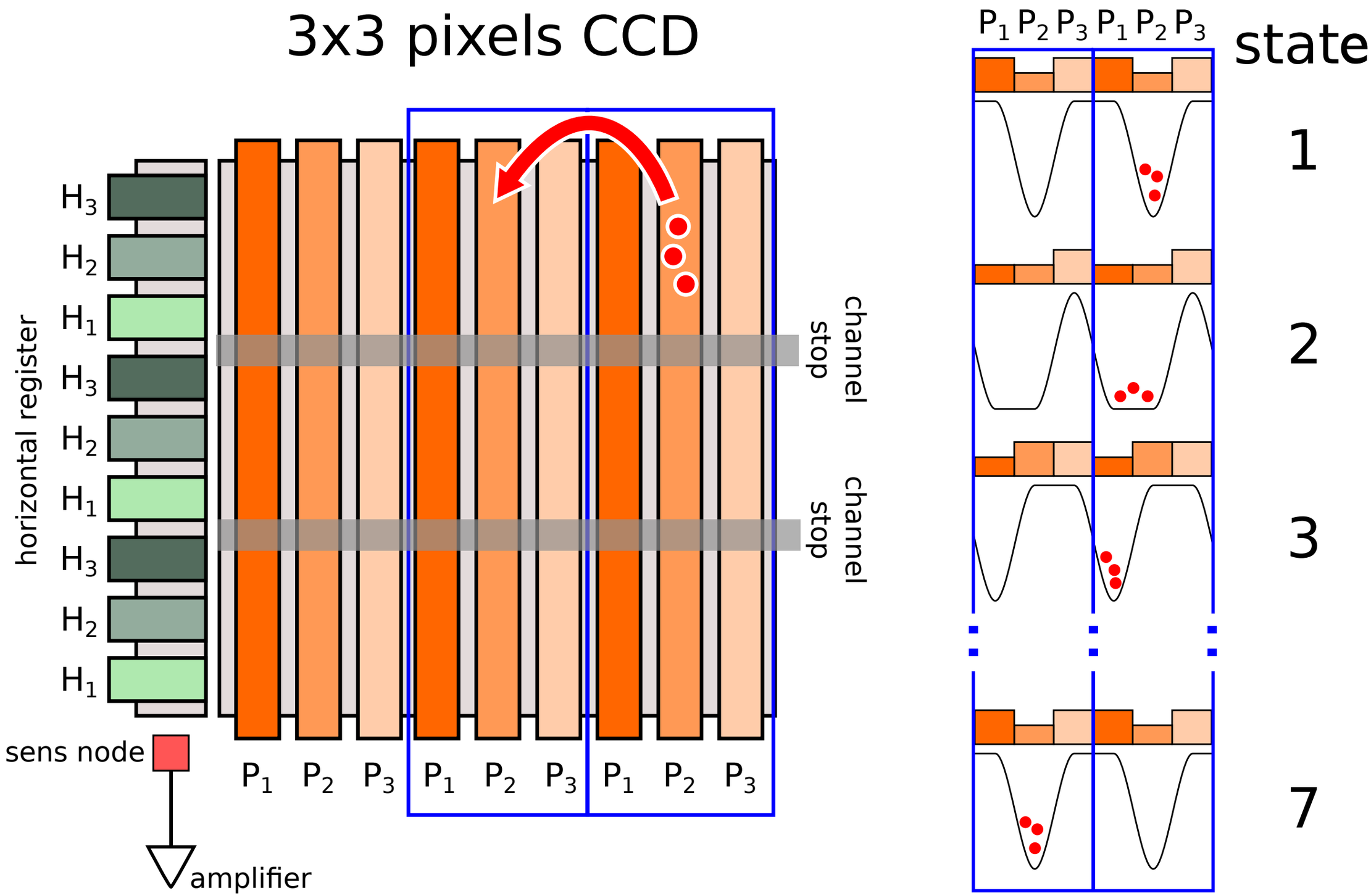




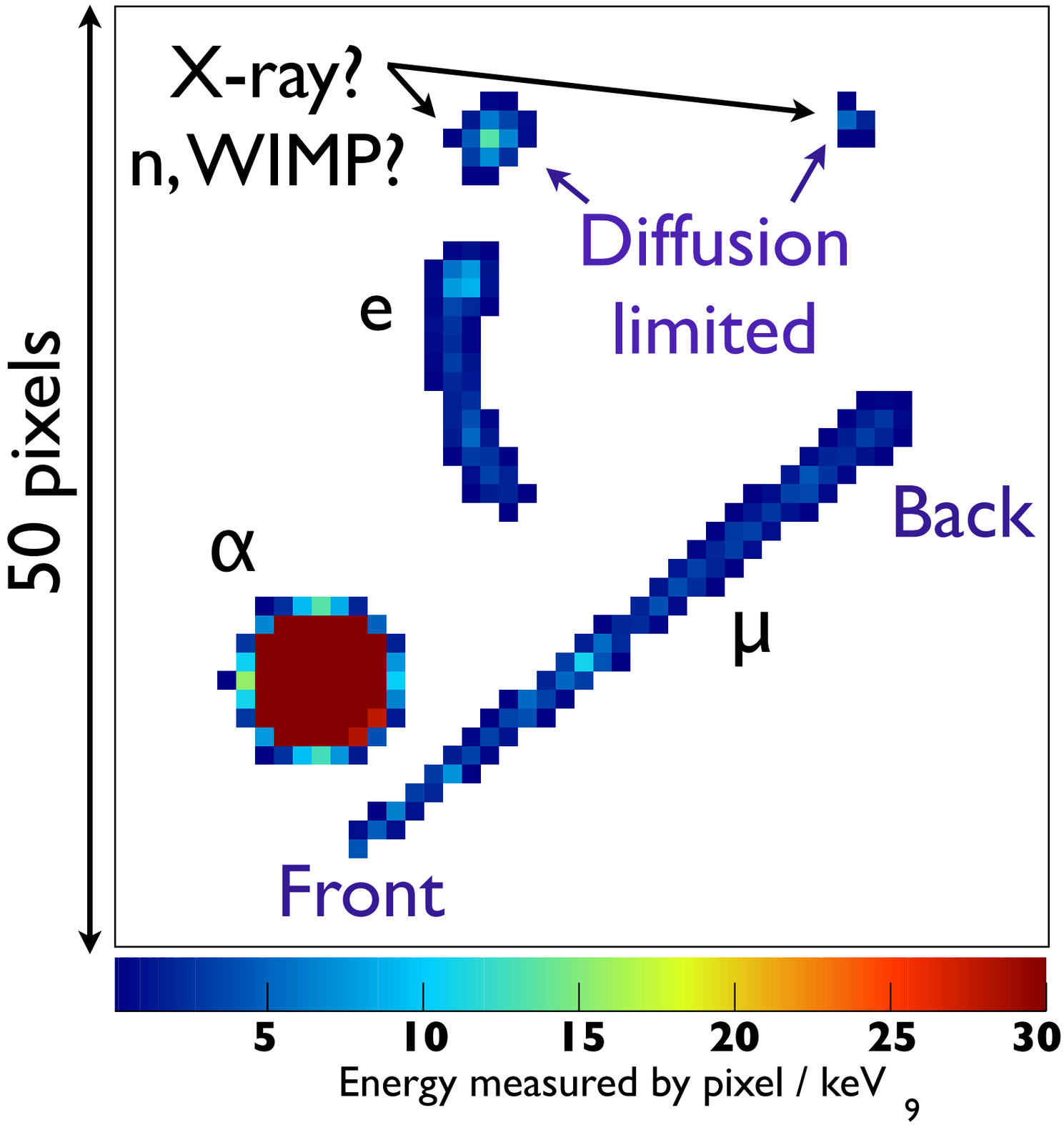
Charge collect by each pixel on CCD plane is read out

~2 e^- RMS read-out noise

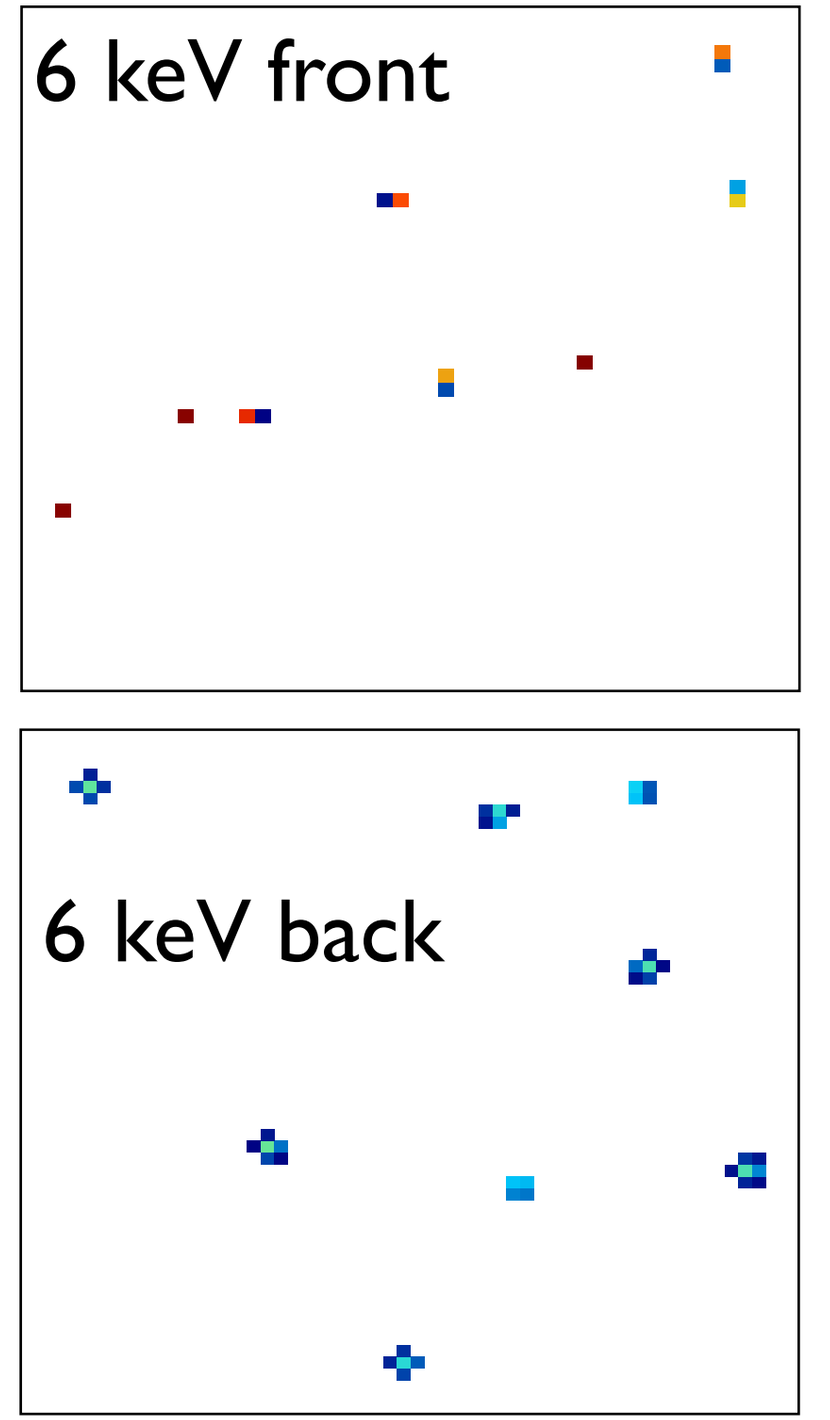
CCD readout


3x3 pixels CCD
horizontal register
H3
H2
H1
H3
H2
H1
H3
H2
H1
channel stop
channel stop
P1 P2 P3 P1 P2 P3 P1 P2 P3
sens node
amplifier
P1 P2 P3 P1 P2 P3
state
1
2
3
7

Particle tracks

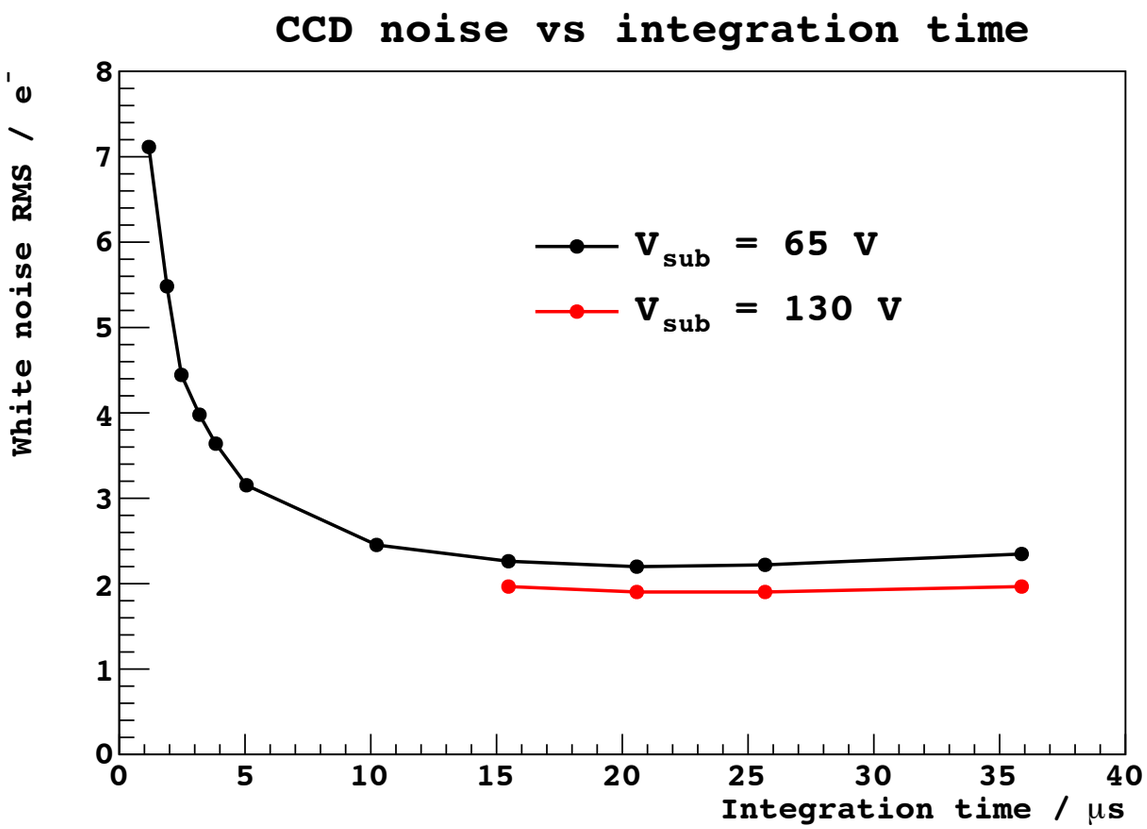


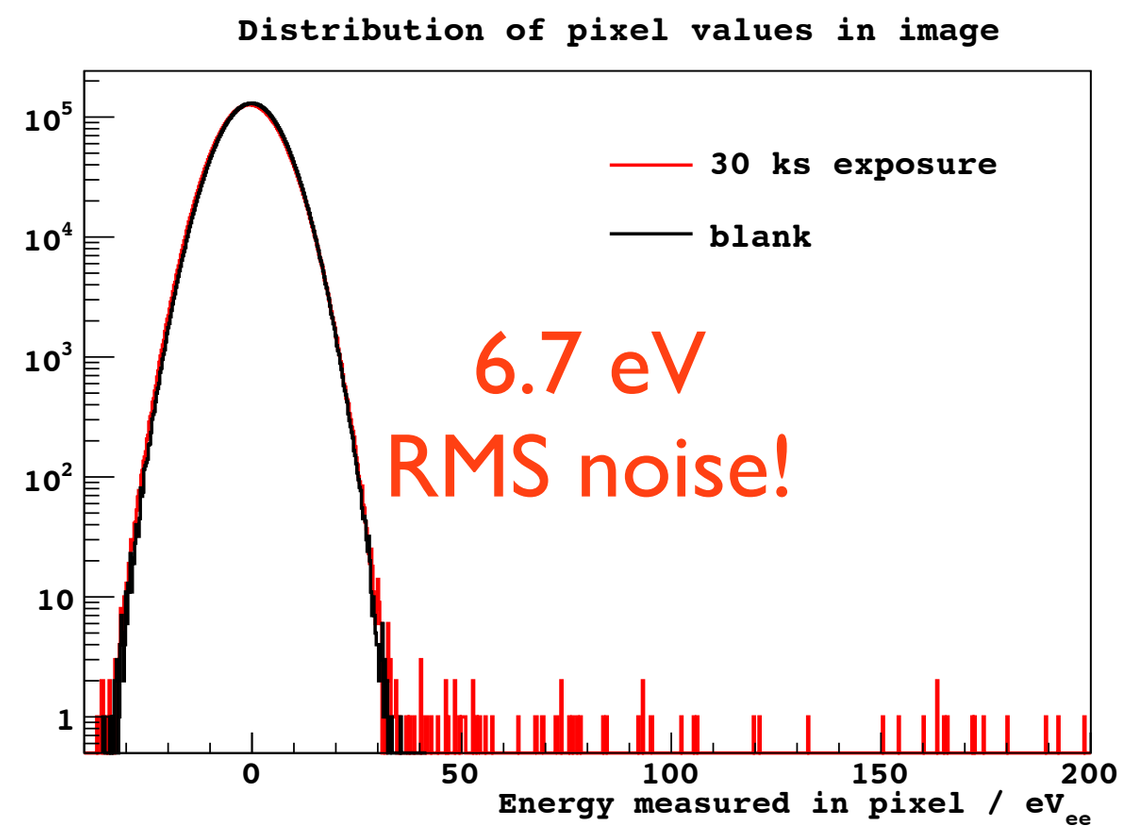
Diffusion limited



CCD Performance

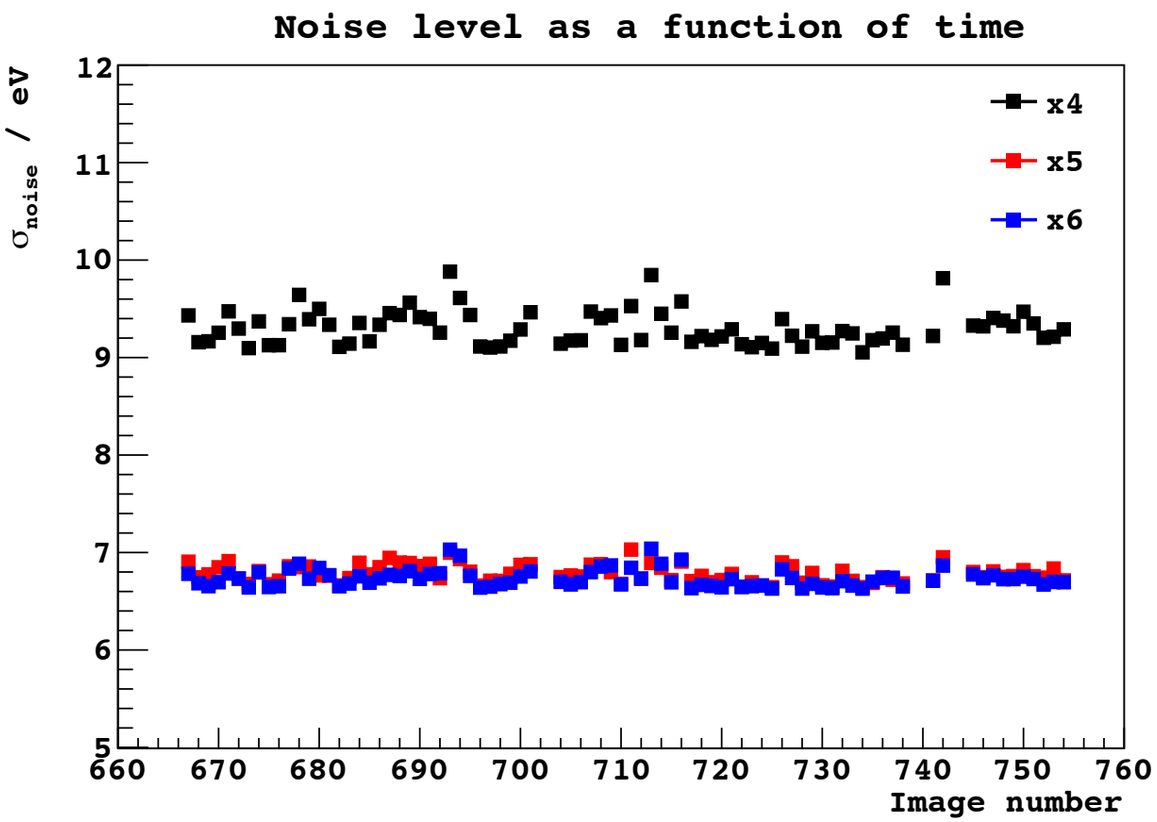
CCDs are manufactured with very high resistivity silicon:
Low radioactive backgrounds.
Low dark current (0.1 e^- / pix / day).
Very few (if any) defects in the silicon lattice.

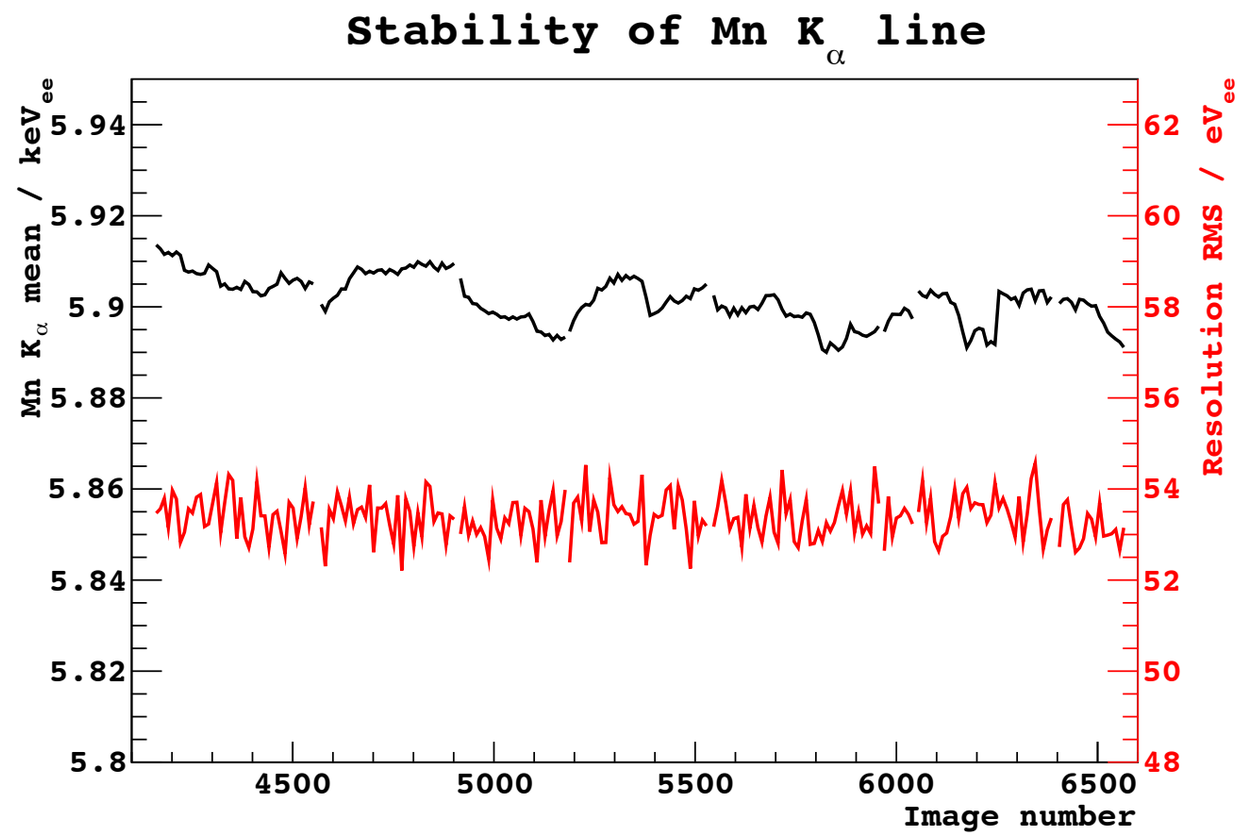




>95% of the image good quality

Noise/Gain stability





30 days of data

at SNOLAB

96% duty cycle

27 days of ^{55}Fe data

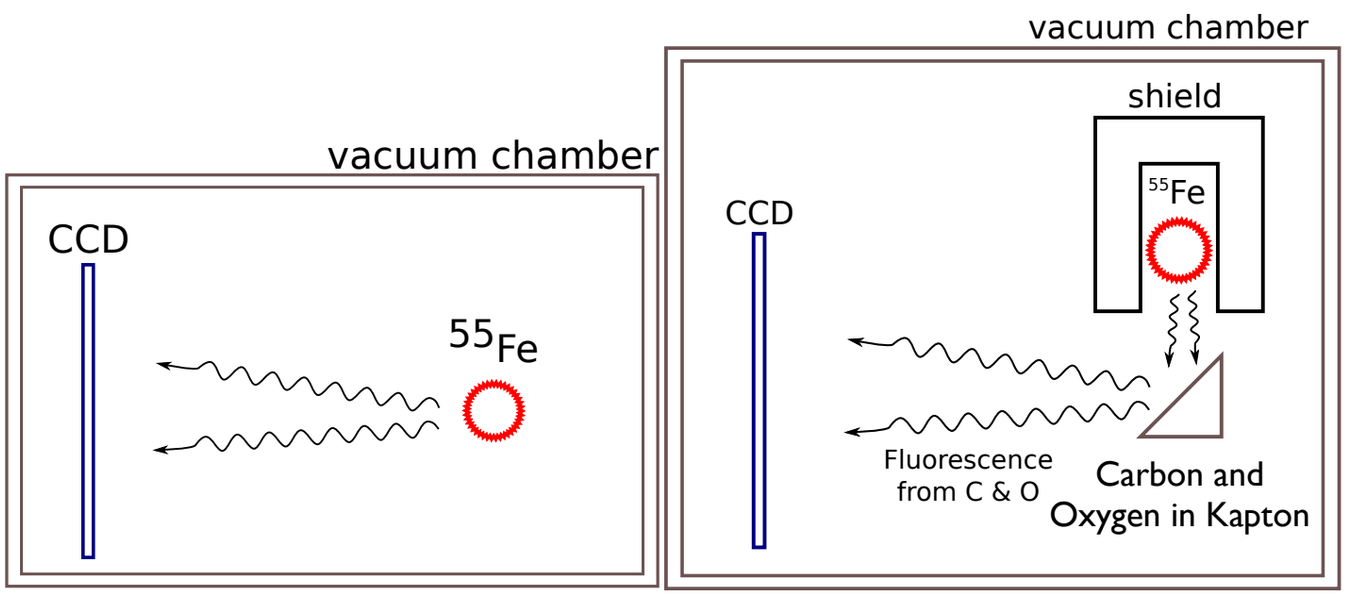
at U Chicago

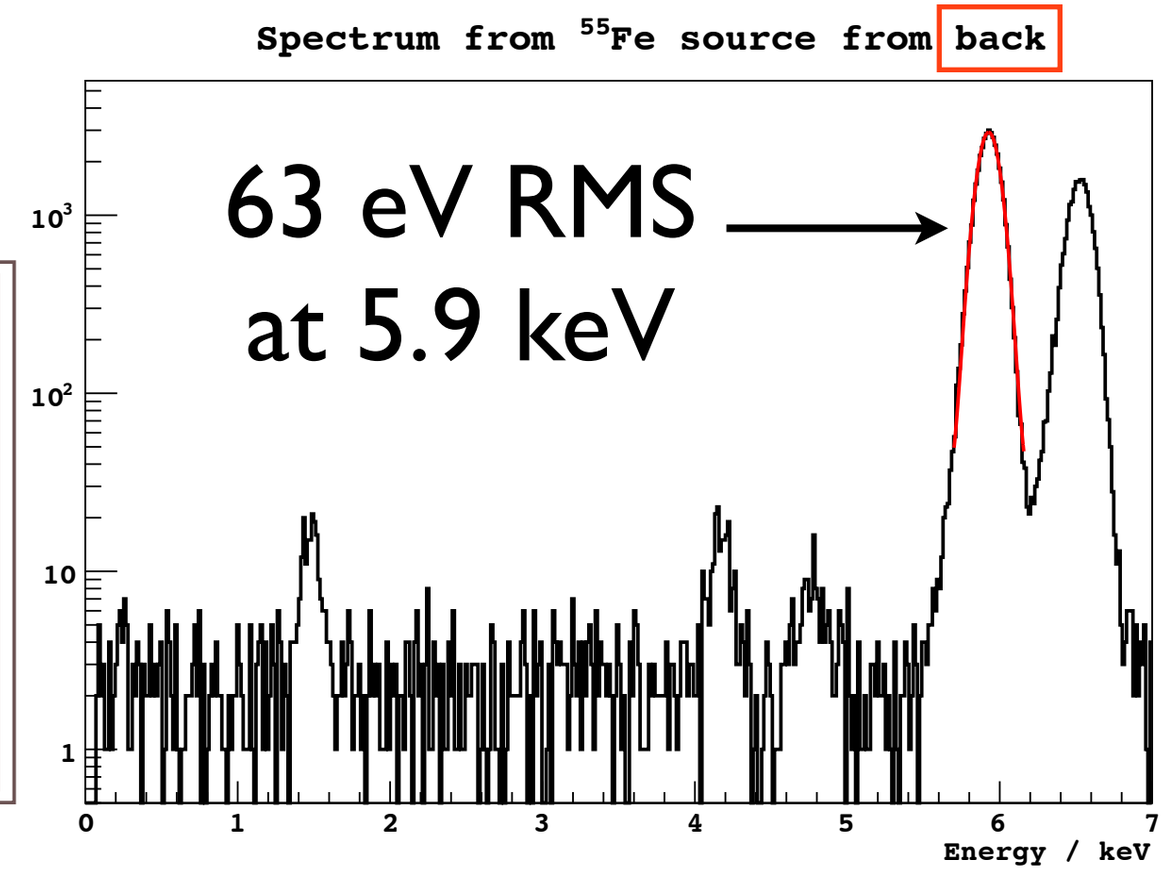
0.1% fluctuations in energy scale

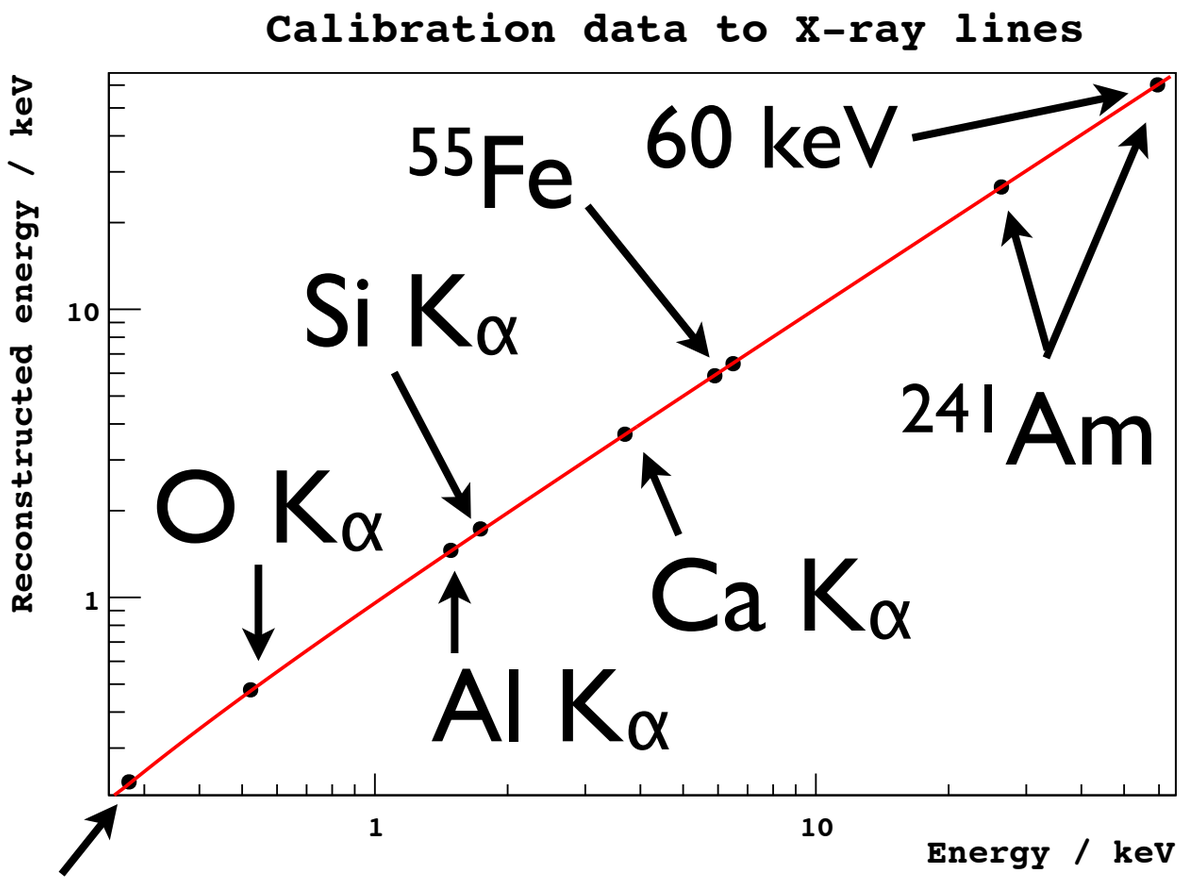
1% fluctuations in resolution

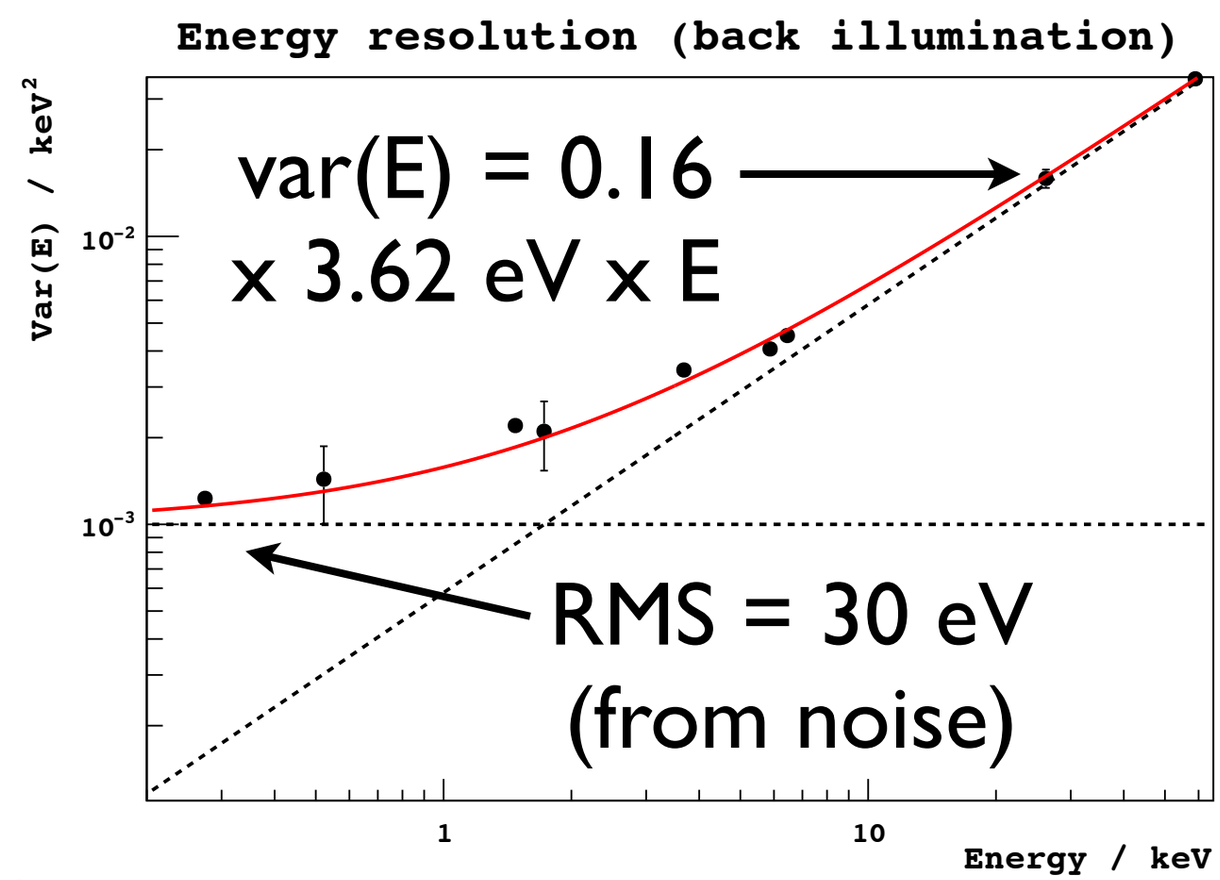
53 eV at 5.9 keV from front!

E response

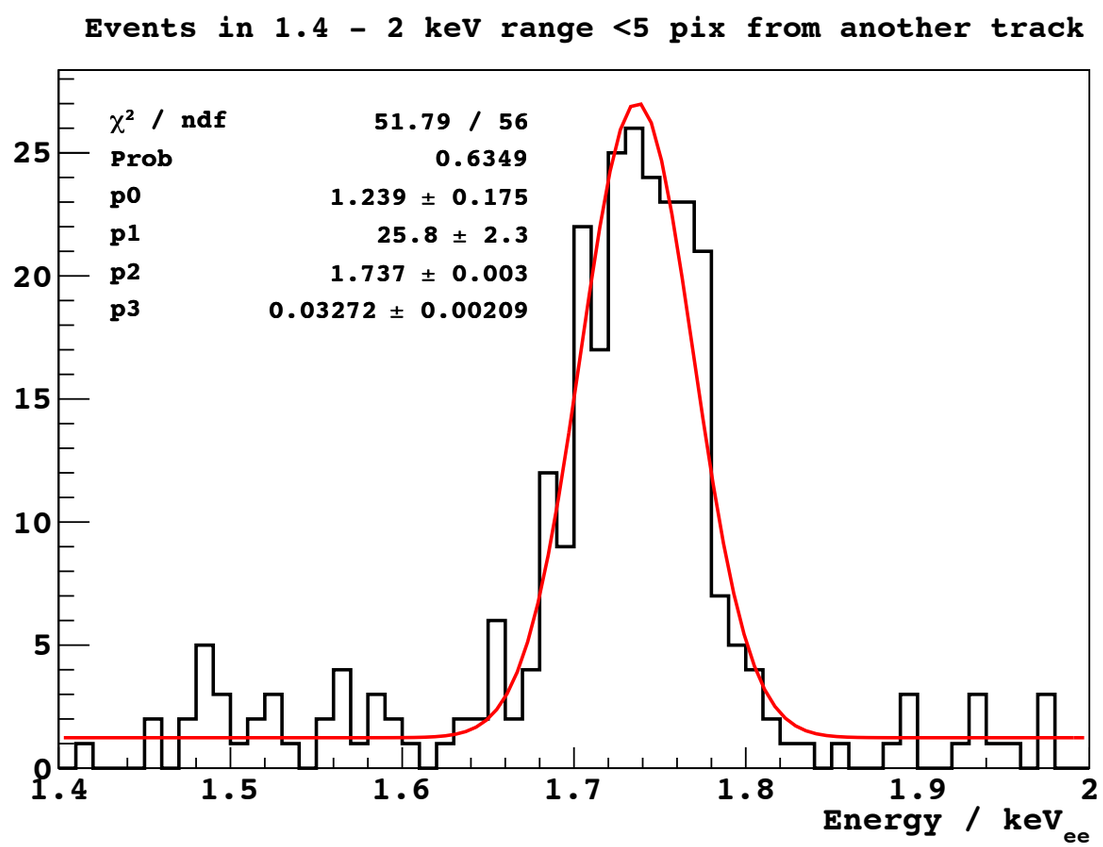

vacuum chamber
CCD
55Fe
vacuum chamber
shield
CCD
55Fe
Fluorescence
from C & O
Carbon and
Oxygen in Kapton


Spectrum from 55Fe source from back
63 eV RMS
at 5.9 keV
Energy / keV

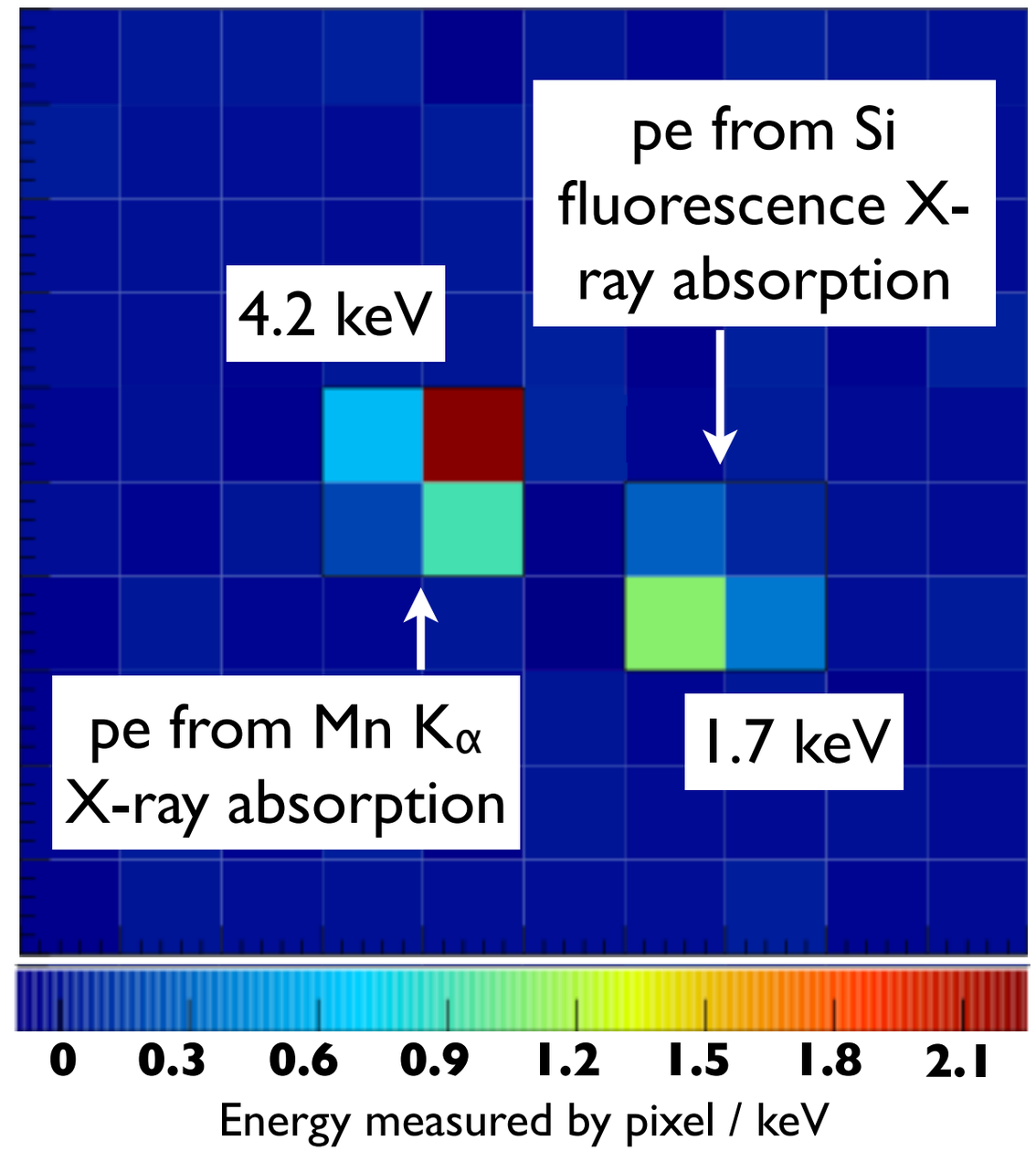

Calibration data to X-ray lines
Reconstructed energy / keV
Energy / keV
55Fe
60 keV
Si Kα
241Am
O Kα
Ca Kα
Al Kα
C Kα (0.28 keV)


Energy resolution (back illumination)
Var(E) / keV²
Energy / keV
var(E) = 0.16
x 3.62 eV x E
RMS = 30 eV
(from noise)

Si K_α in bulk



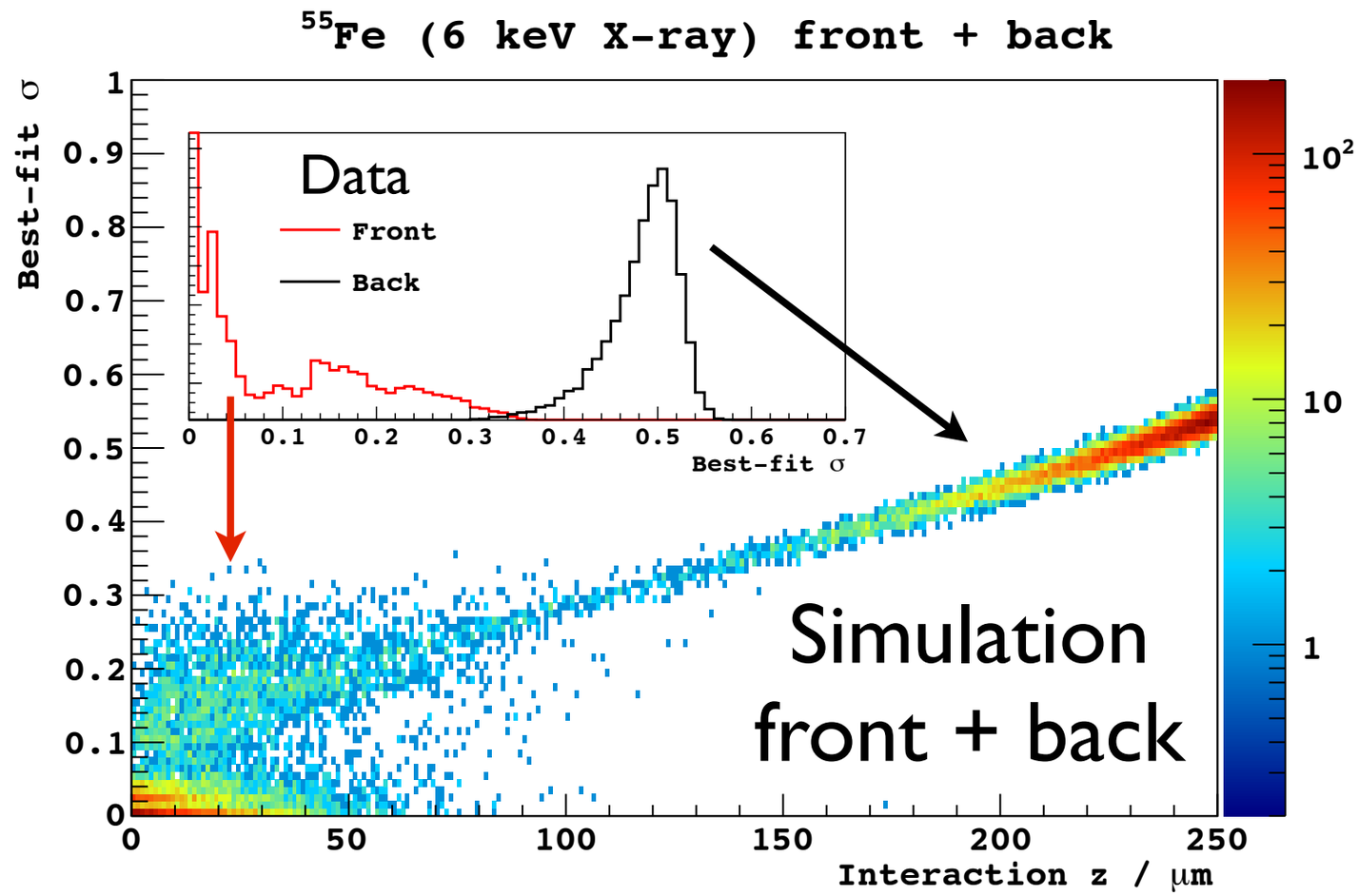
33 eV at 1.7 keV in bulk

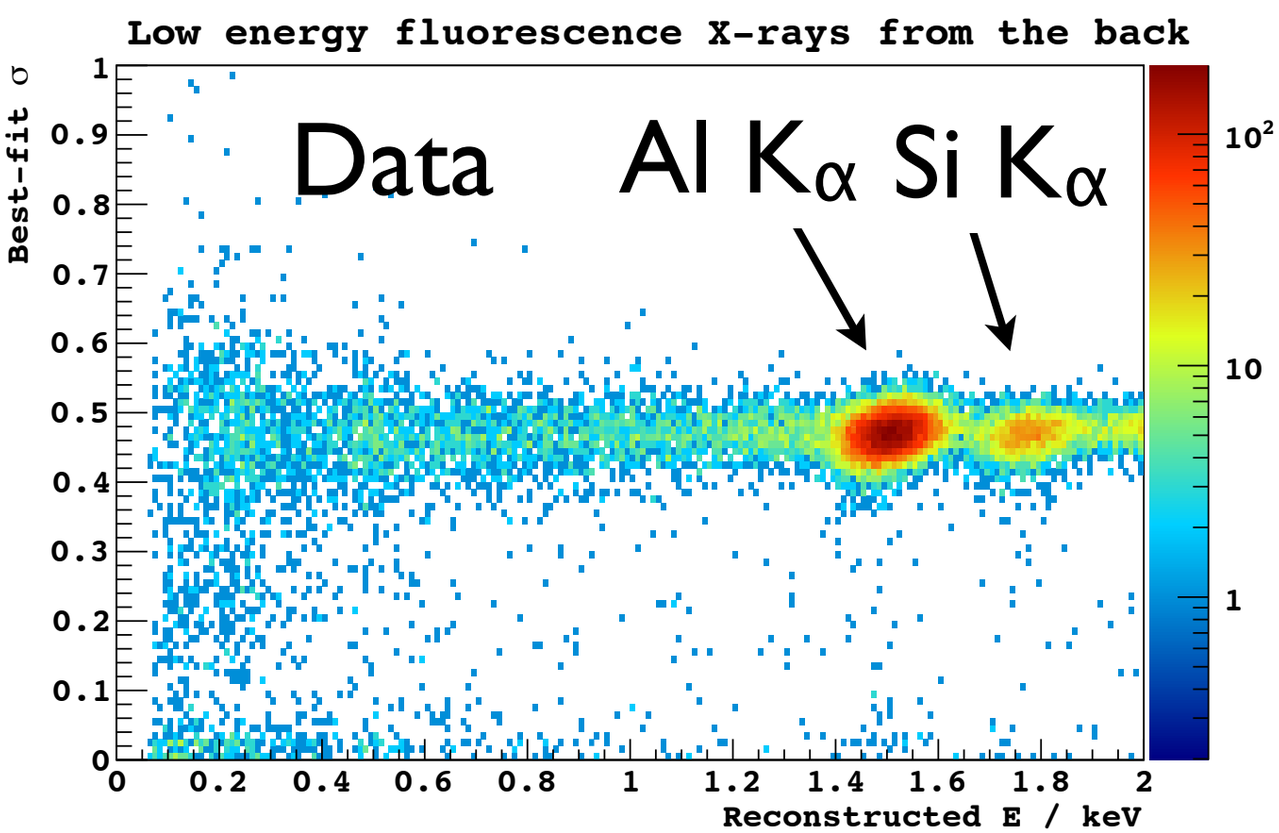


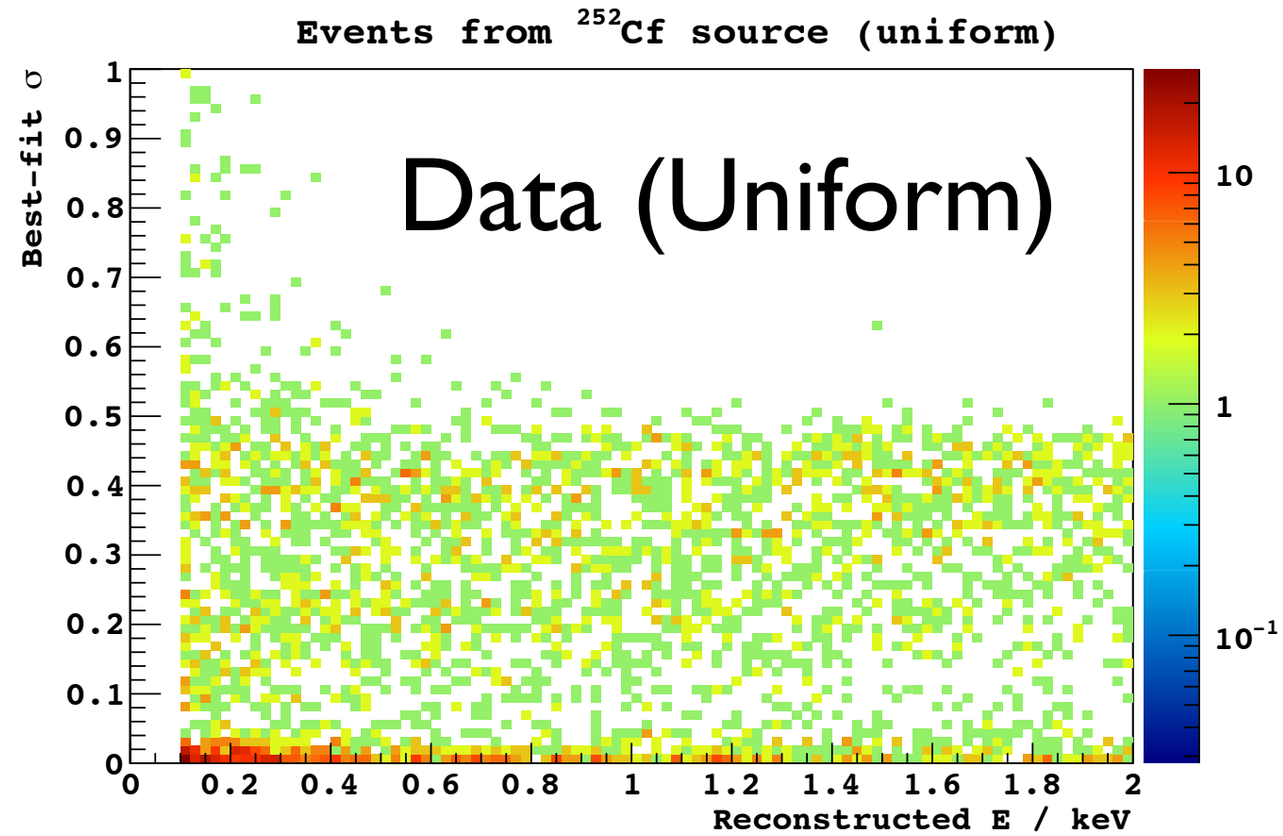
Diffusion

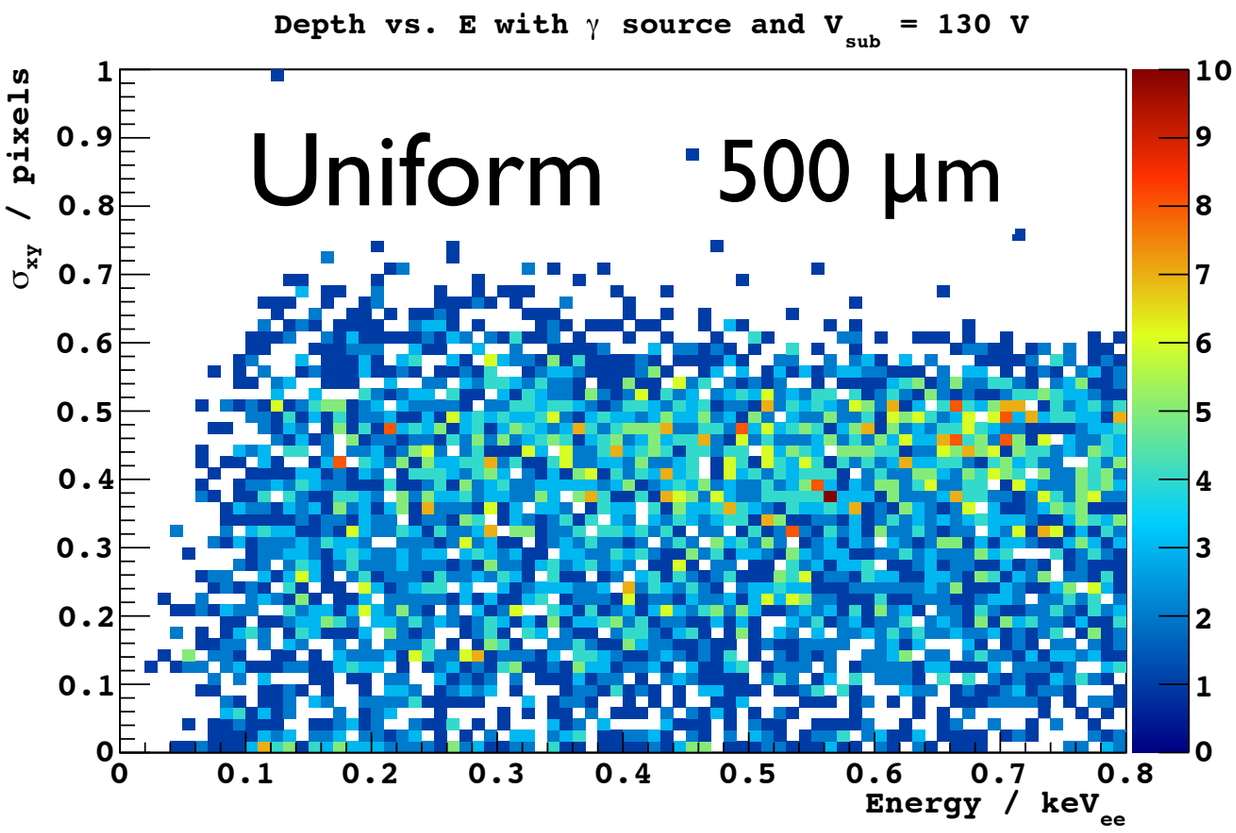
(250 μm)

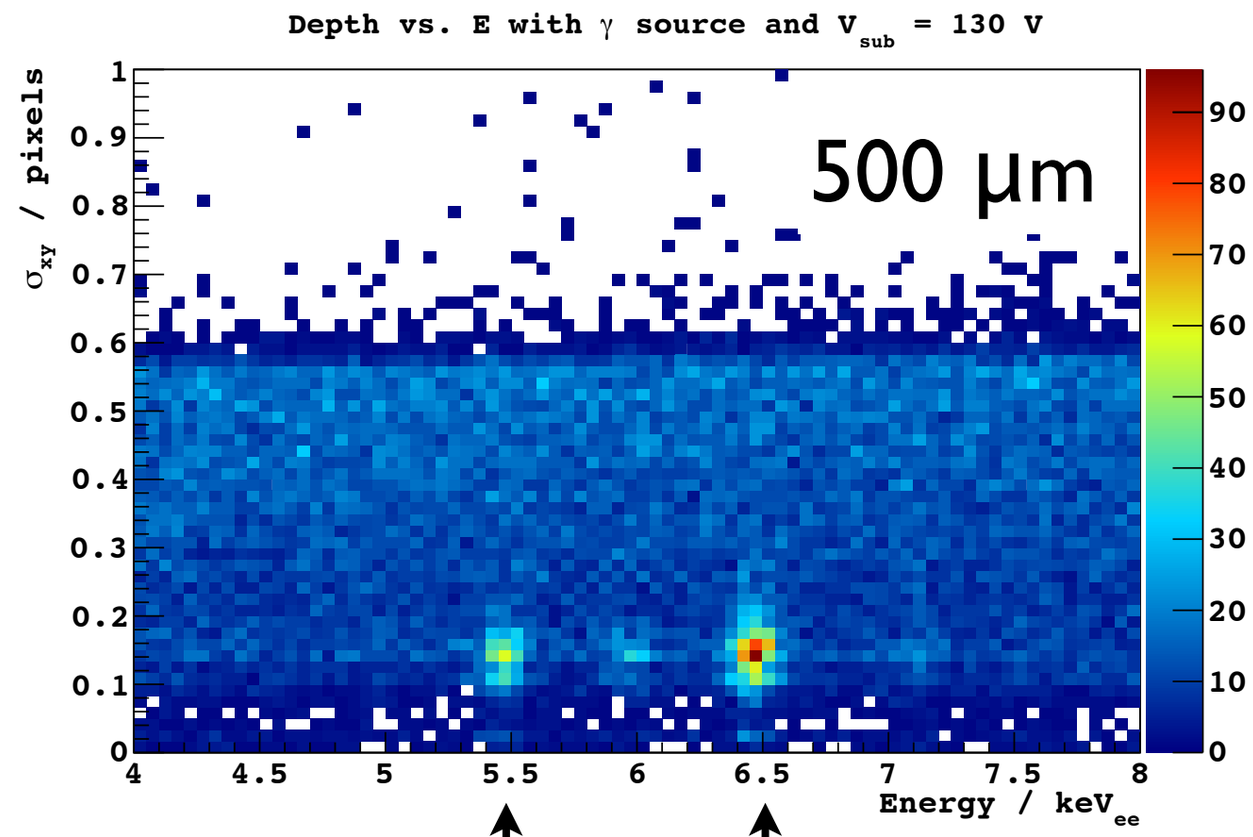
Fit to the radial spread of the cluster allows us to estimate its position in z within the CCD bulk





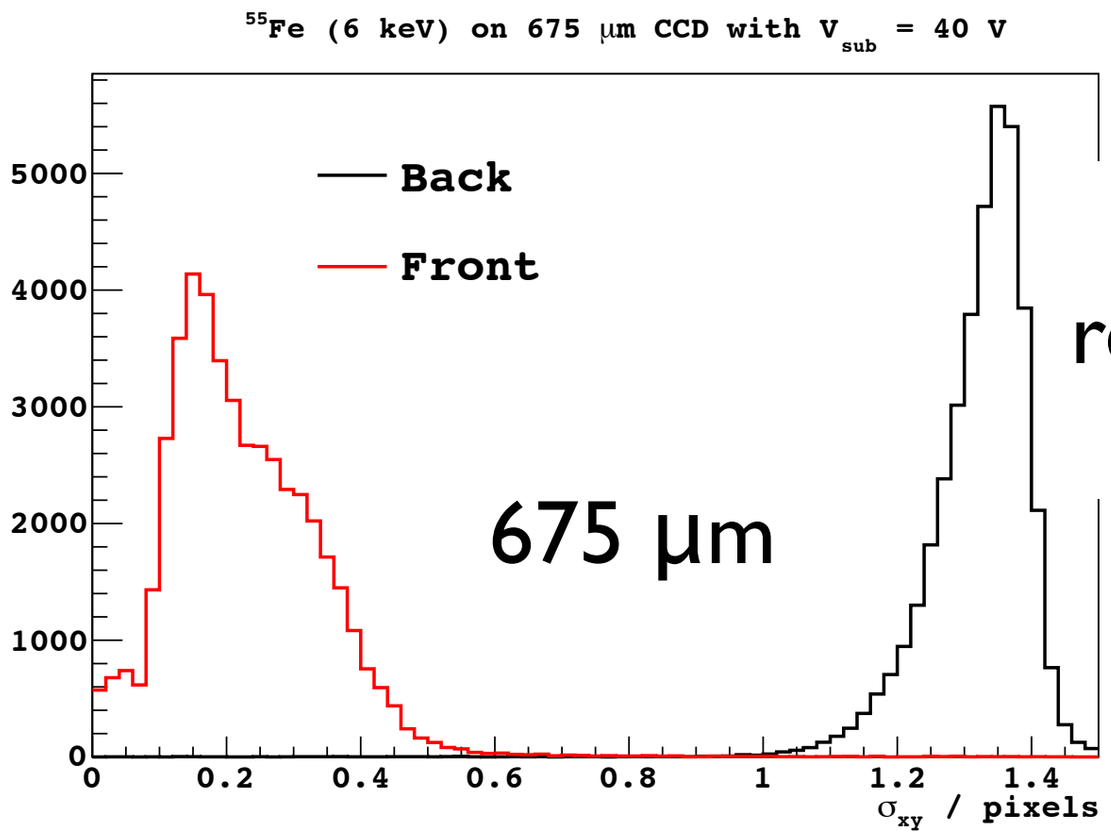






Cr Kα Fe Kα

Fluorescence from front



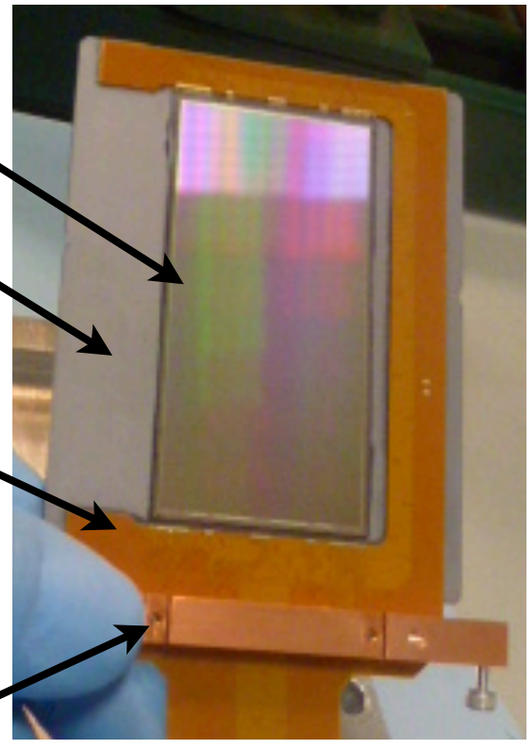
20 µm resolution in back

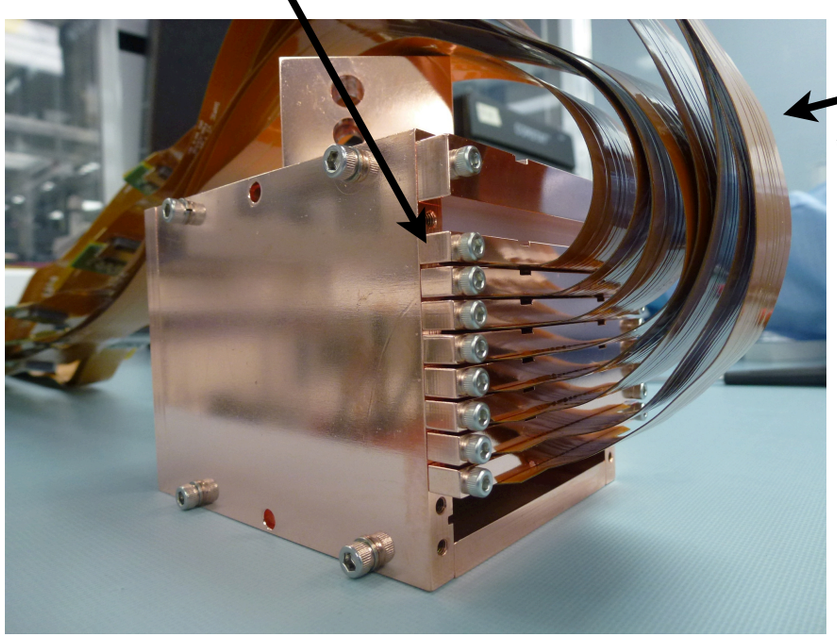
Can operate with low diffusion at 130 V.

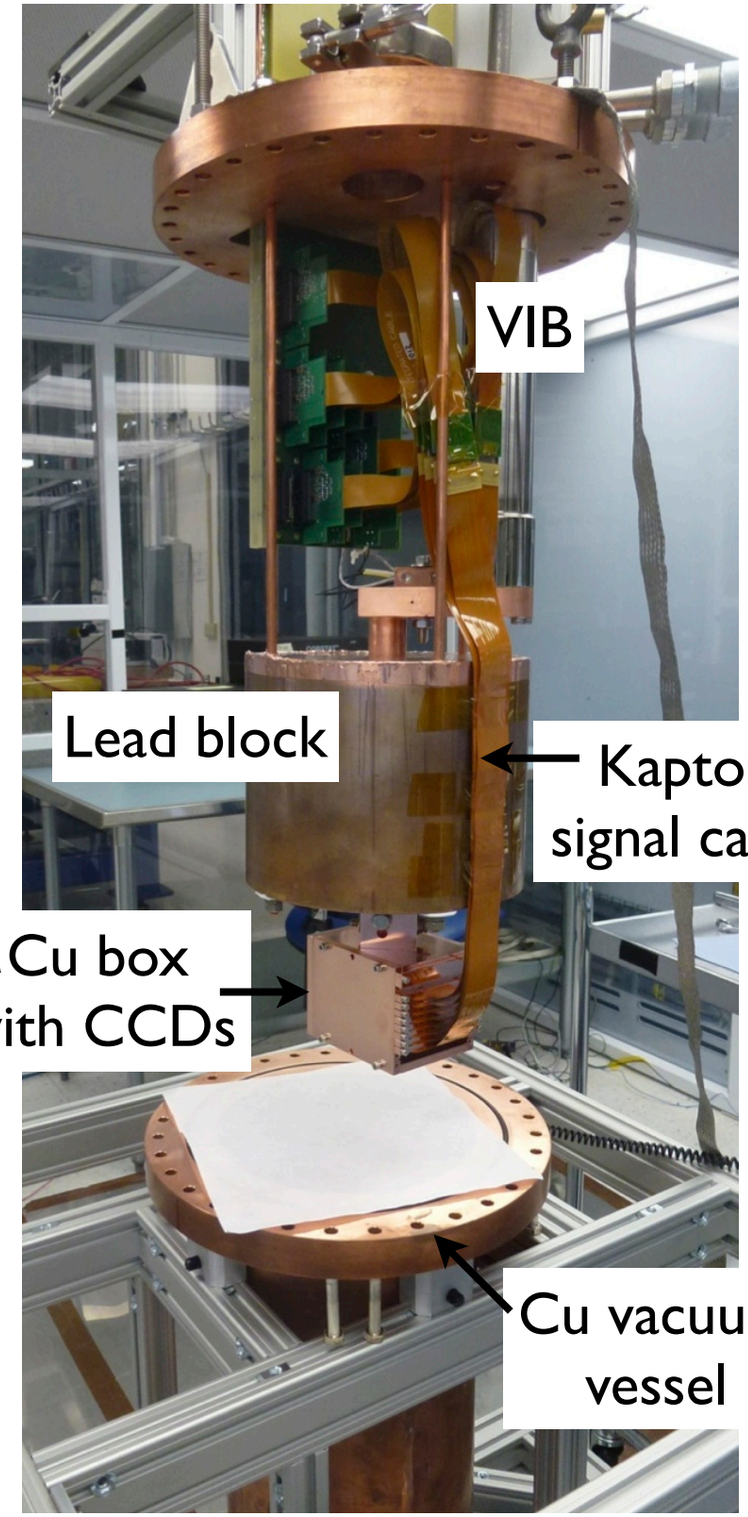
Full depletion and improved depth reconstruction at 40 V.

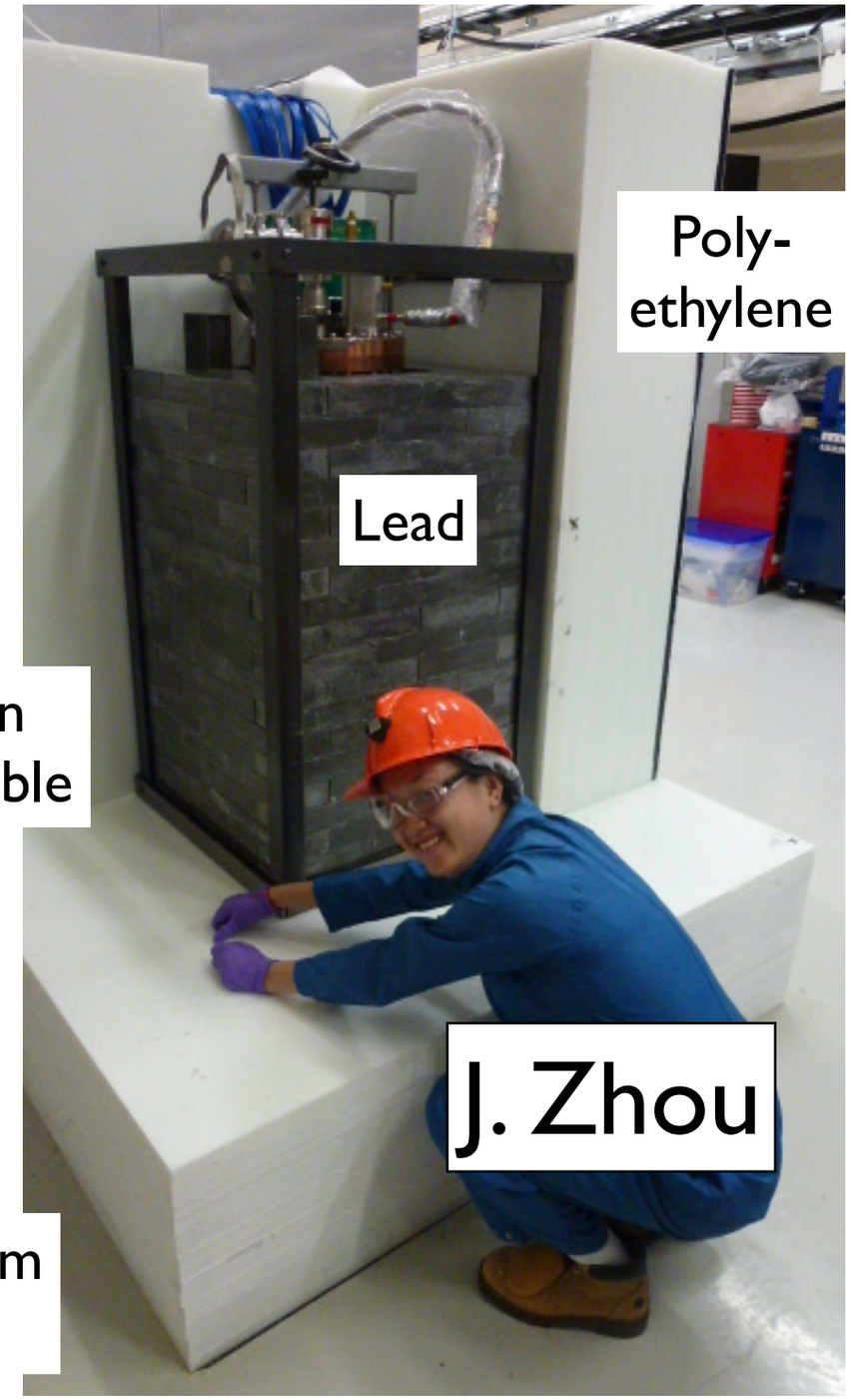
As in SNOLAB

SNOLAB installation





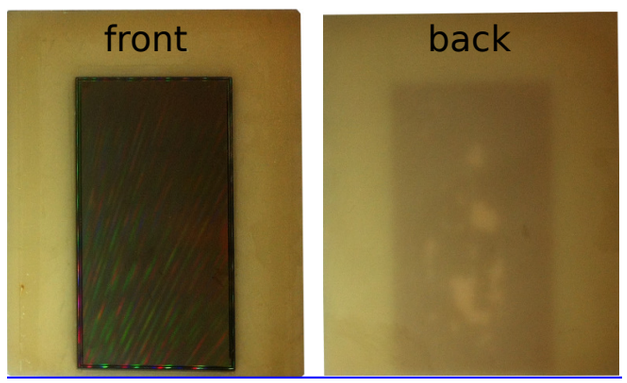




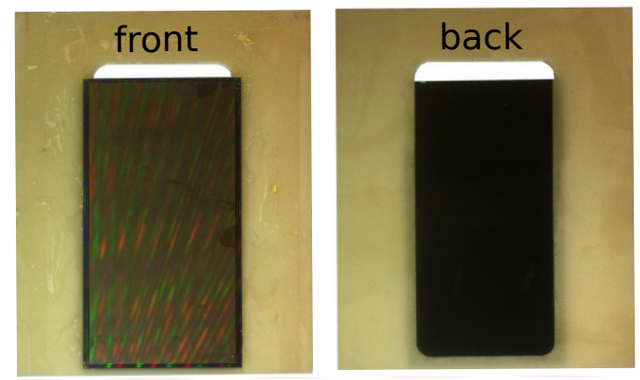
Hardware upgrades

First steps: Remove support piece with 330 ppb of ^{238}U.

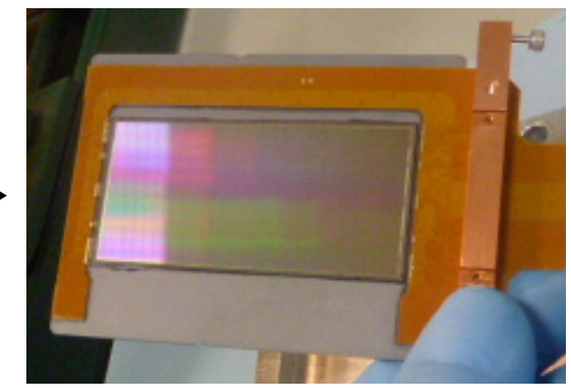
Full AlN



Frame AlN

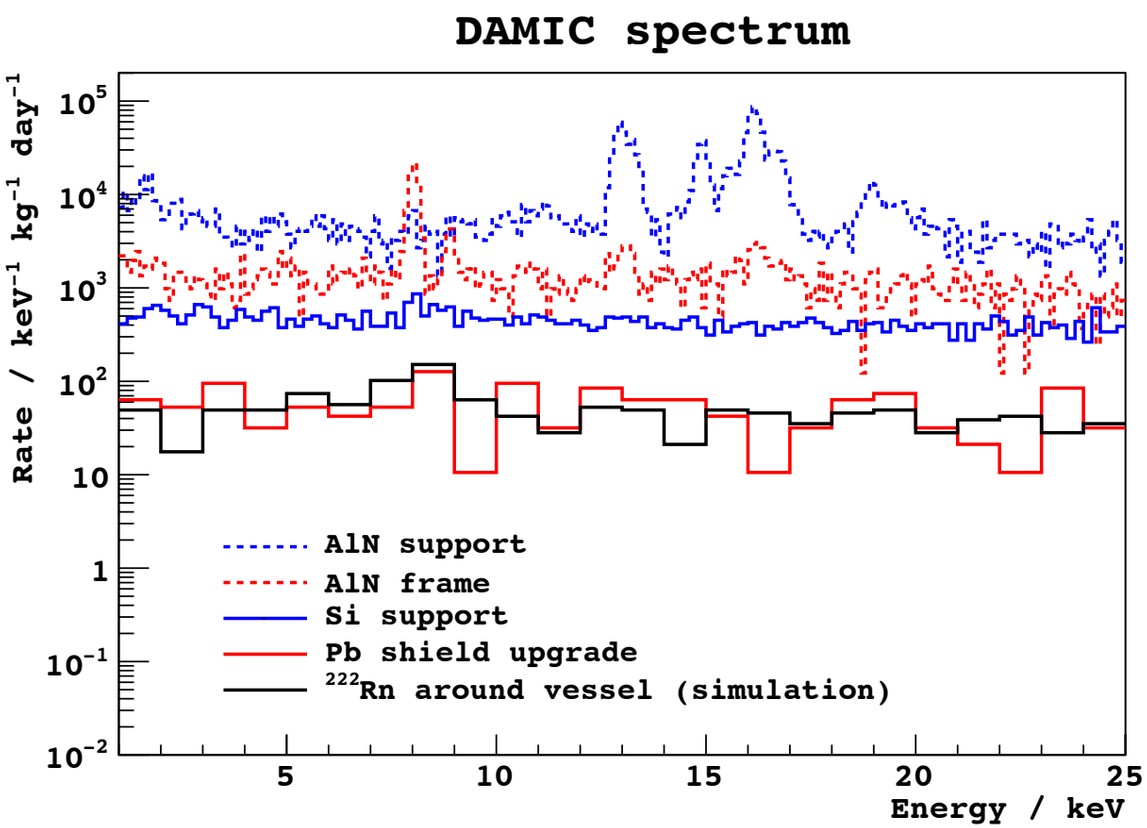


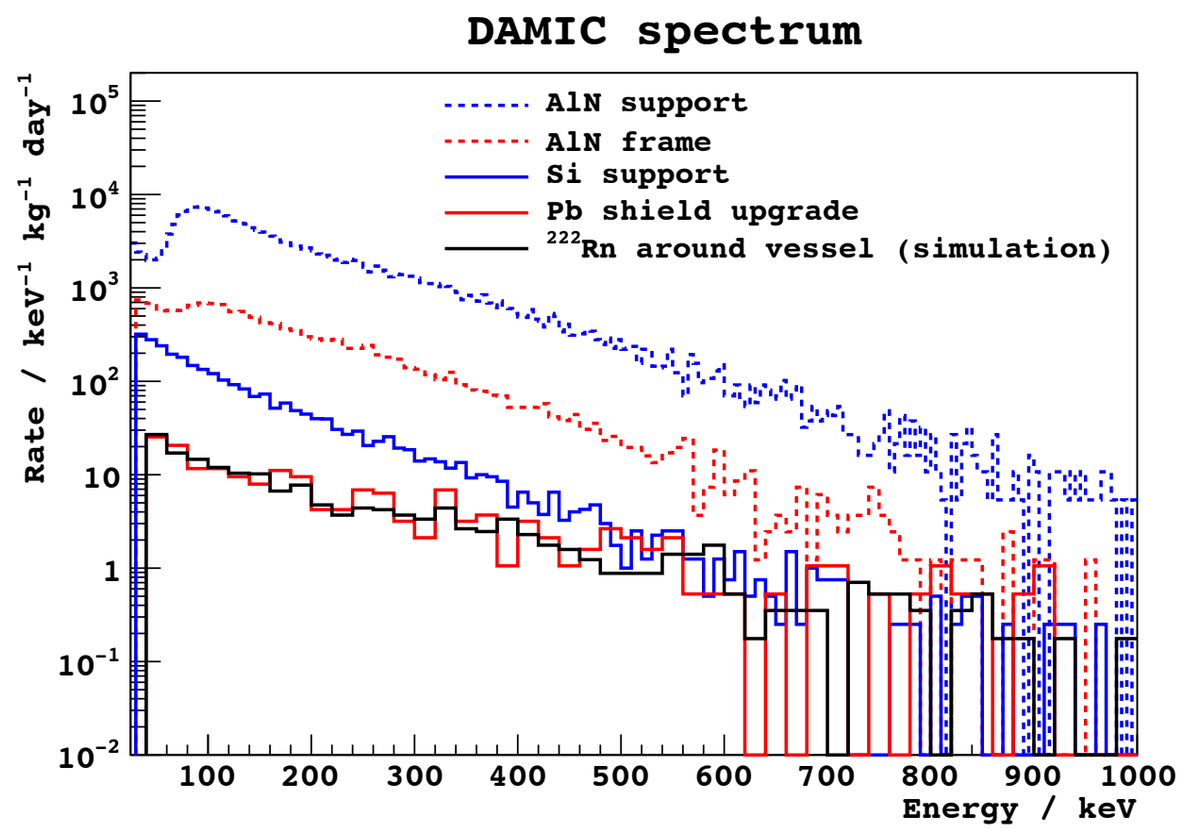
Si Support



Third step:
Upgrade lead shield with ancient lead (<0.02 Bq/kg ^{210}Pb) to stop 50 Bq/kg of ^{210}Pb from outer layers.

Background decrease

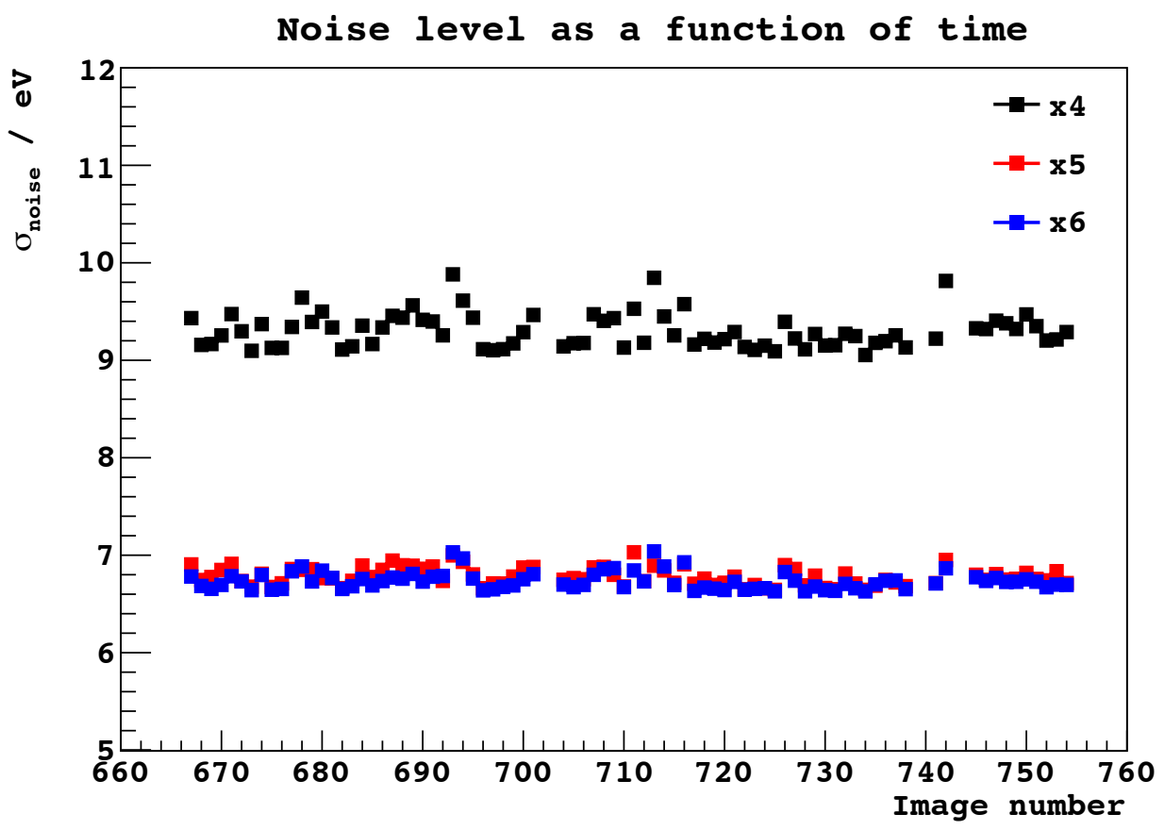




Currently background at low energies is ~50 keV^{-1} kg^{-1} d^{-1} (dru).
Appeared to be consistent with Rn around vessel (130 Bq m^{-3}). Highly uncertain.

Data for WIMP search

- 36 days of data acquired with three CCDs: Two 500 μm (2.2 g) CCDs with ITO on the backside, and one 675 μm (2.9 g) CCD.
- 7 days of data acquired with 675 μm CCD.



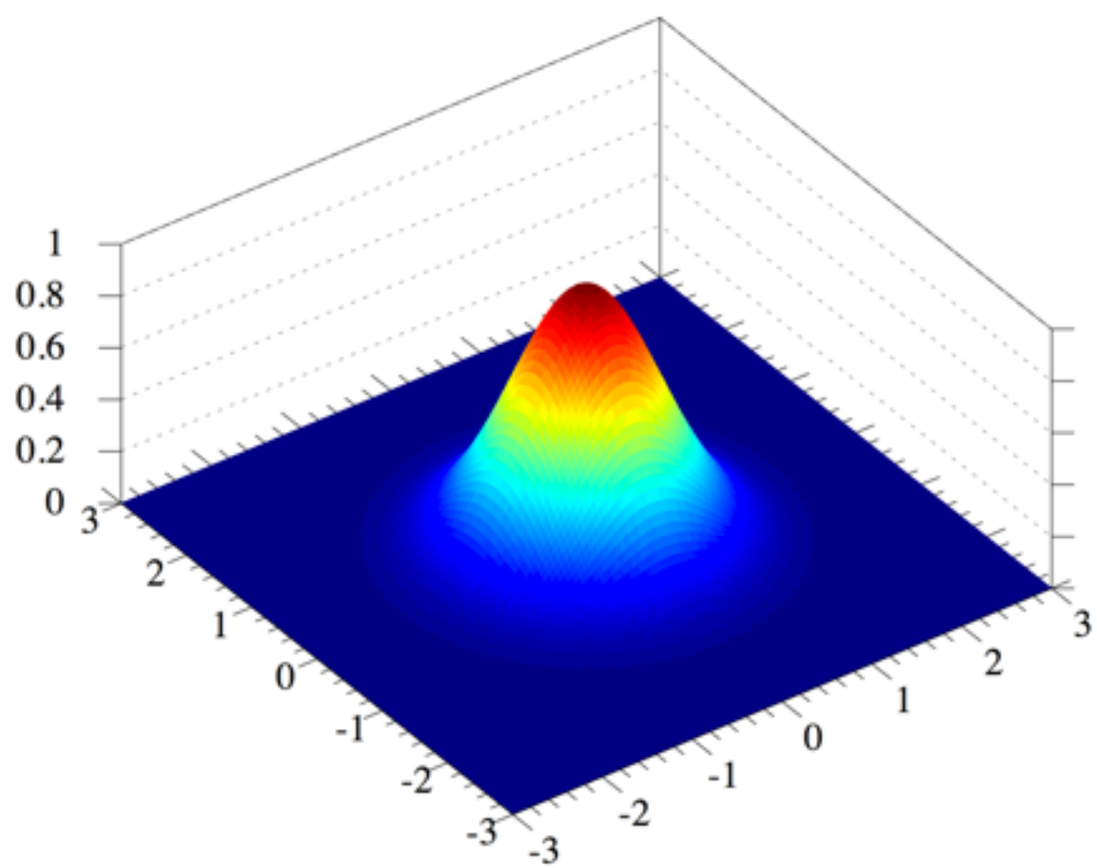
Event identification

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

Number of ionized electrons

Best estimate for mean of energy deposition

Lateral spread

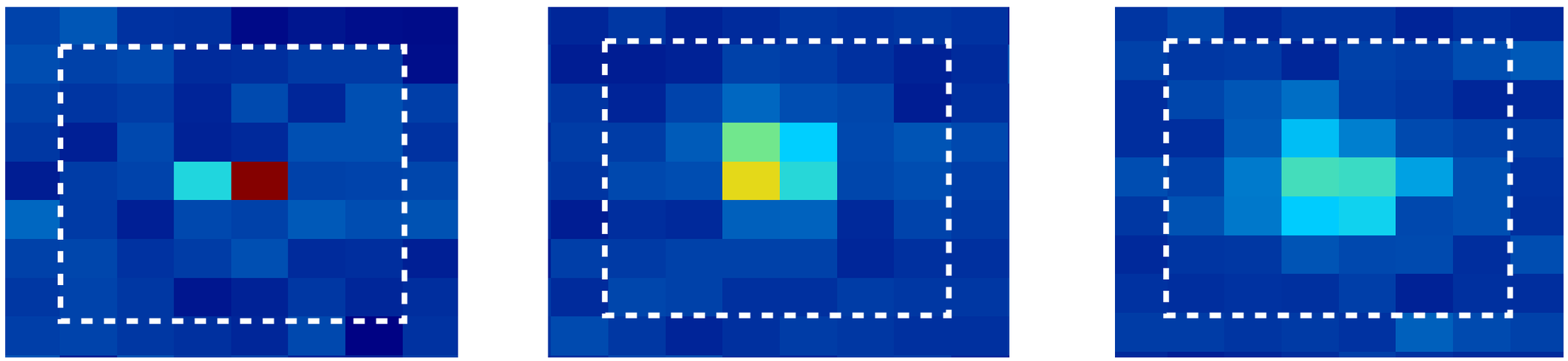


Use 7x7 pixels moving window and fit to a 2D Gaussian distribution. Register LL of best-fit. Compared to LL of constant pixel values. Difference between the two LL (ΔLL) allows us to select for physical events.

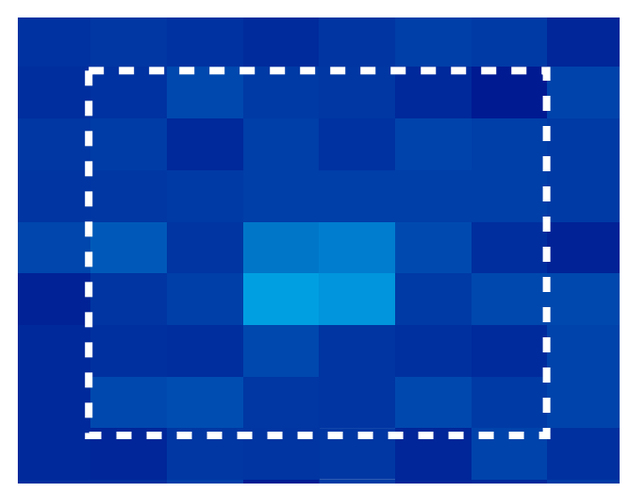
Identified cluster e.g.

Deeper (larger z)

All ~0.7 keV_{ee}

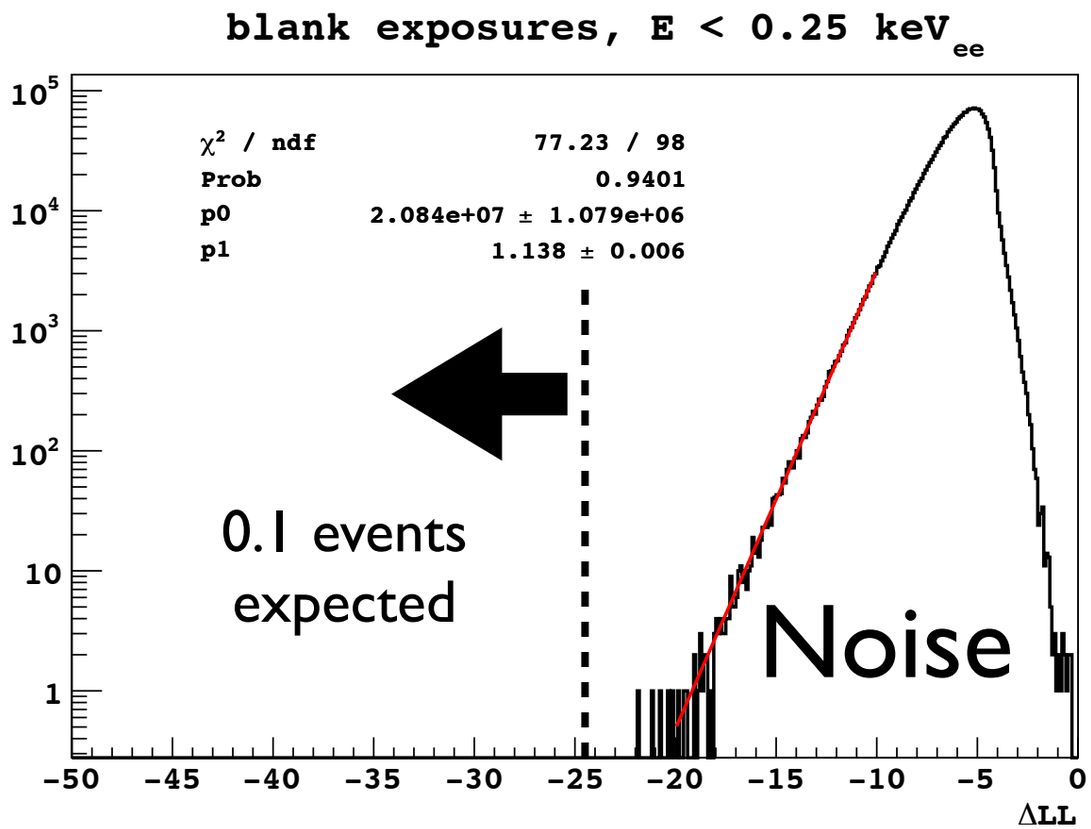


Lowest energy candidate
0.26 keV_{ee}.
$\Delta LL = -60$

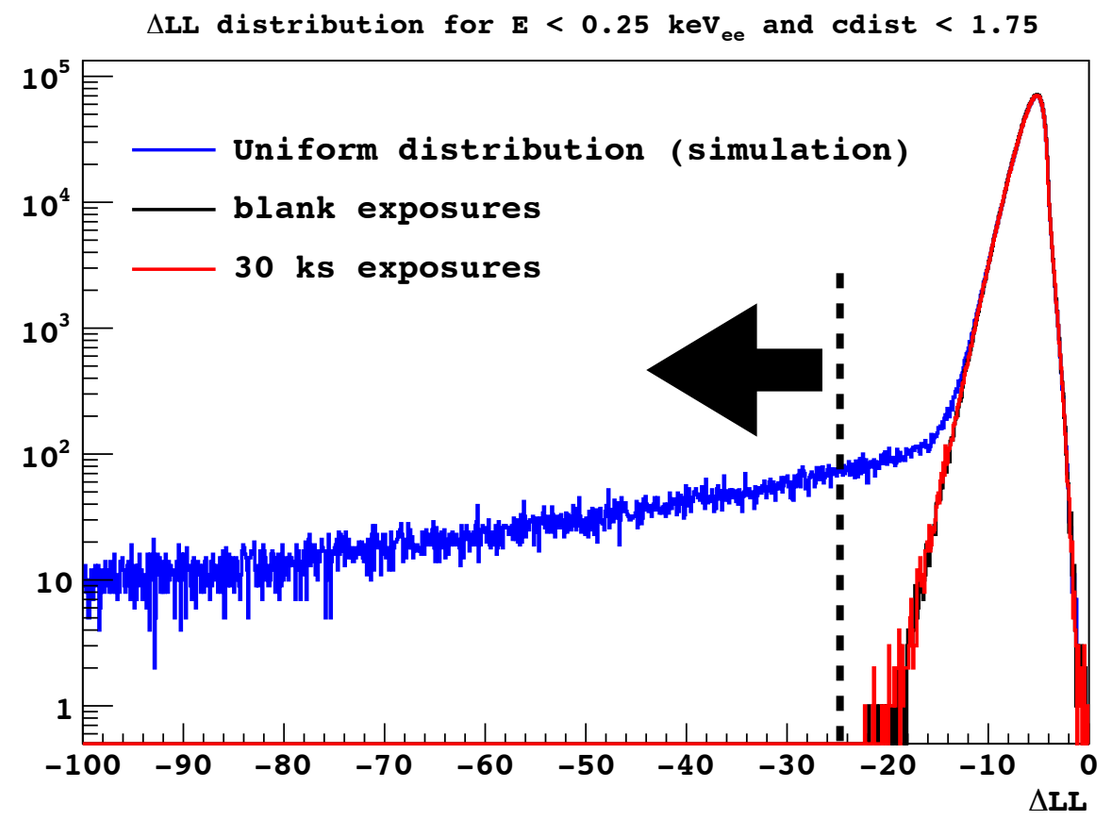


Event selection

Leakage evaluated with **blanks**.



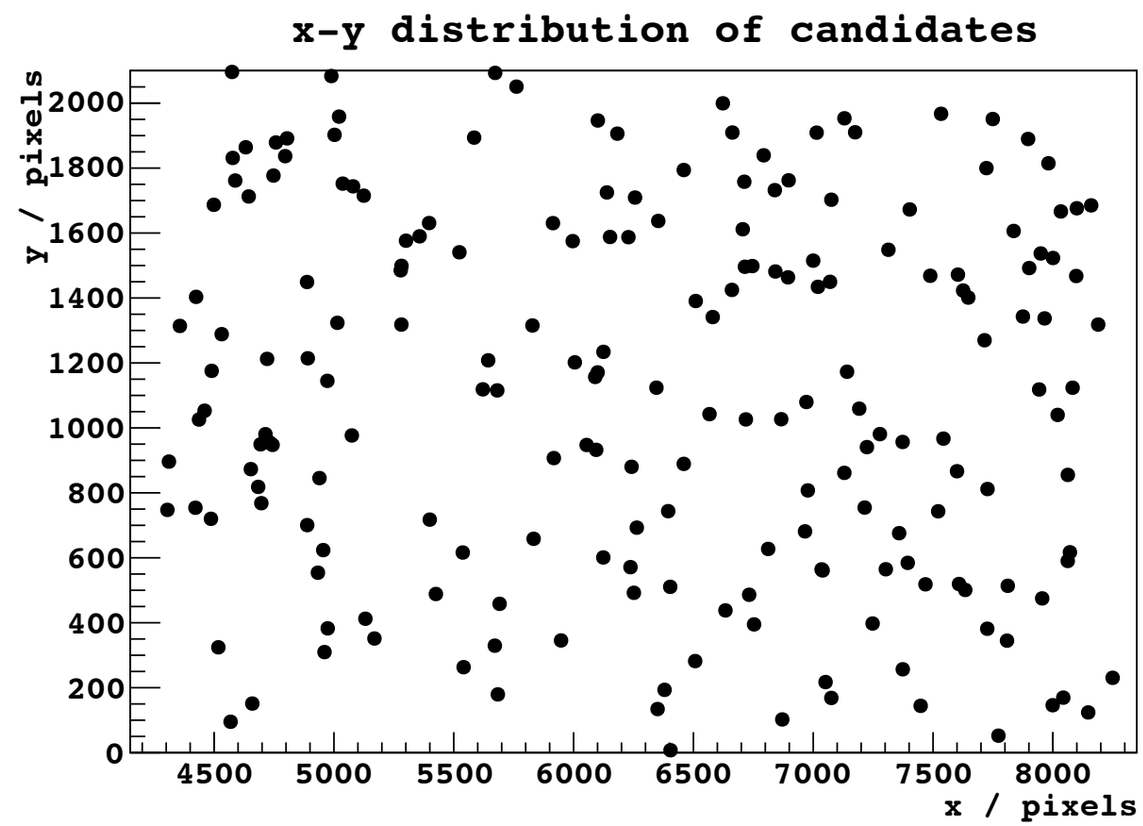
Selection efficiency with **simulation**.



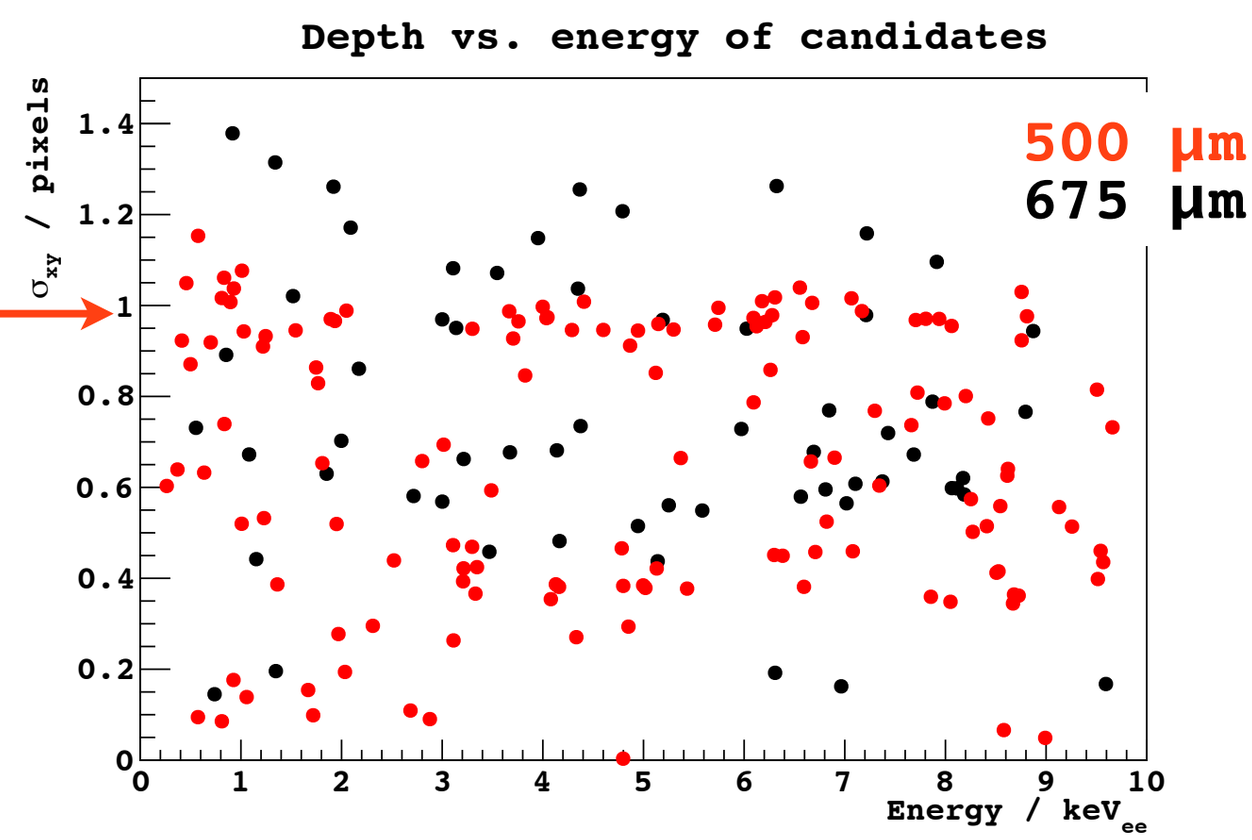
ΔLL is the difference in log-likelihood (LL) between the LL of the null hypothesis (constant pixel values) and the LL of the best-fit 2D Gaussian.

Spatial distribution

Generally uniform in *x*, *y* and *z*. Likely dominated by small angle Compton scatters of external γ-rays.

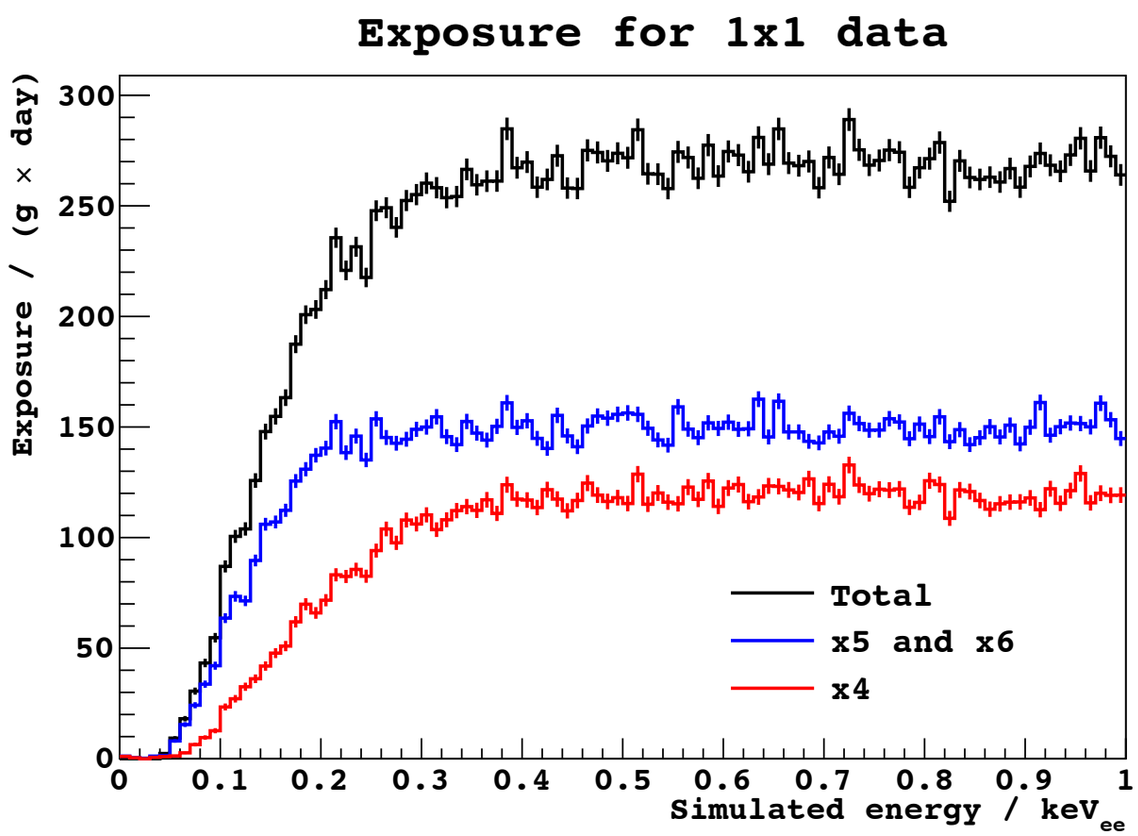


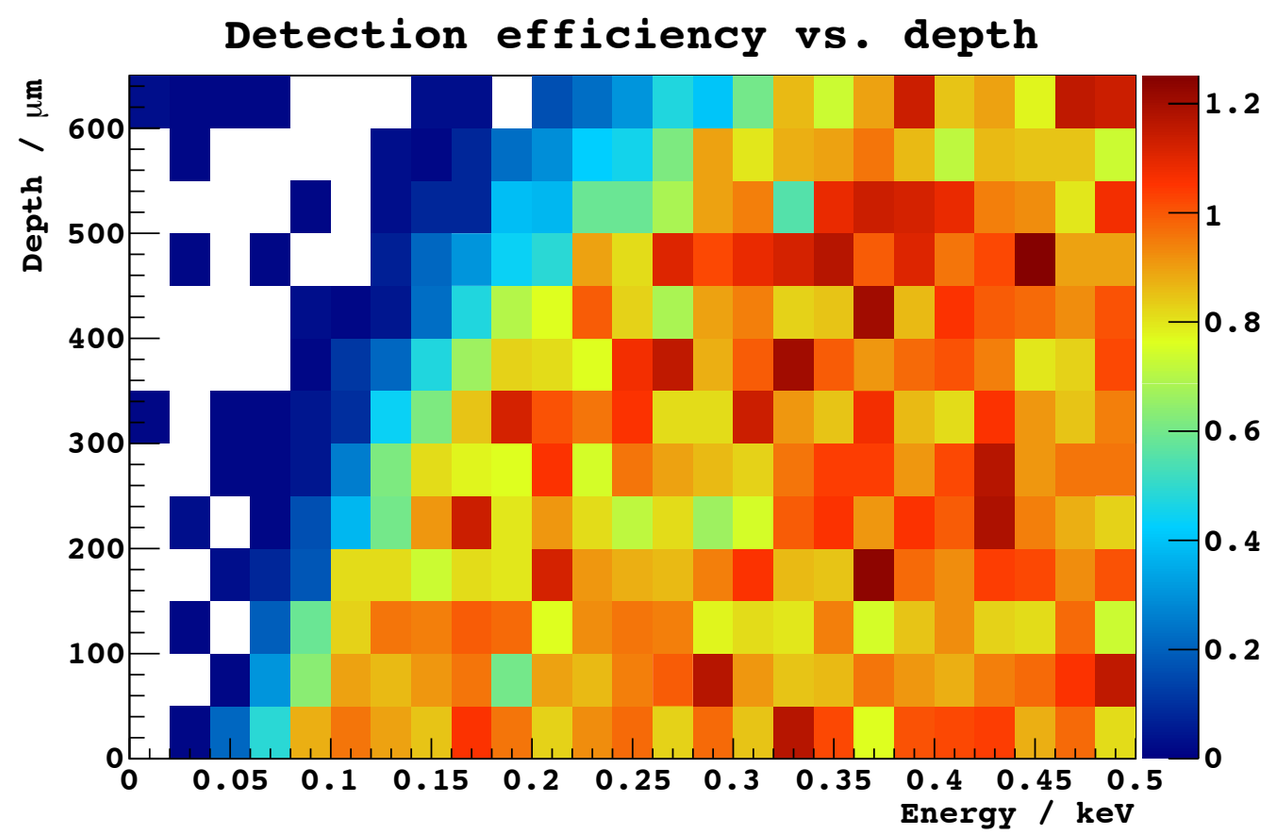
^{115}In on backside



We do not fiducialize in this analysis.

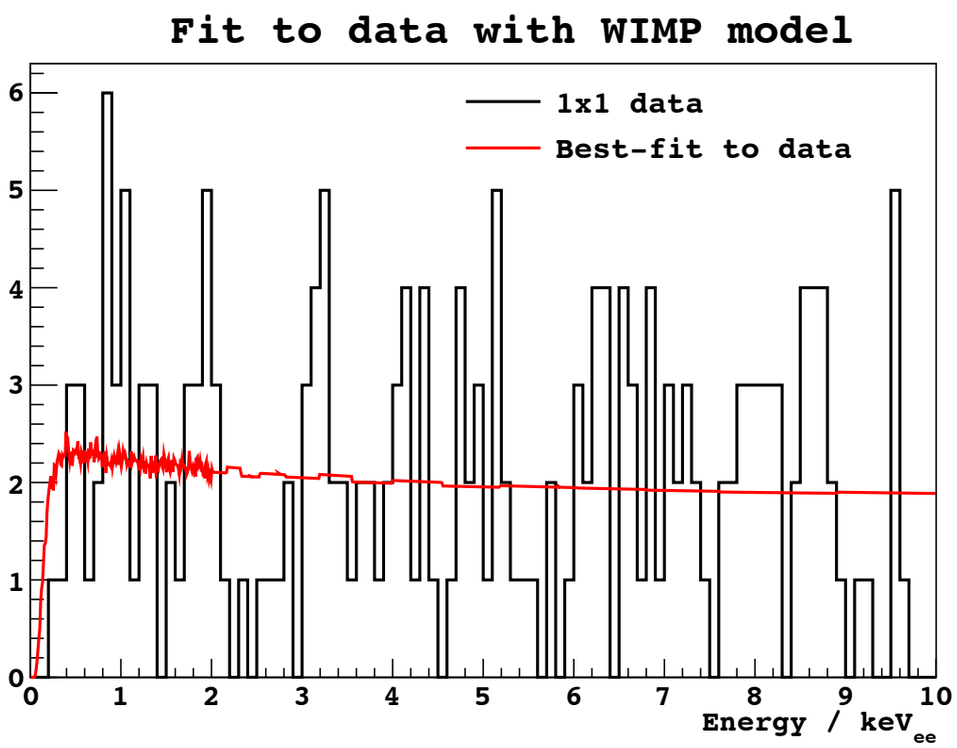
Selection efficiency

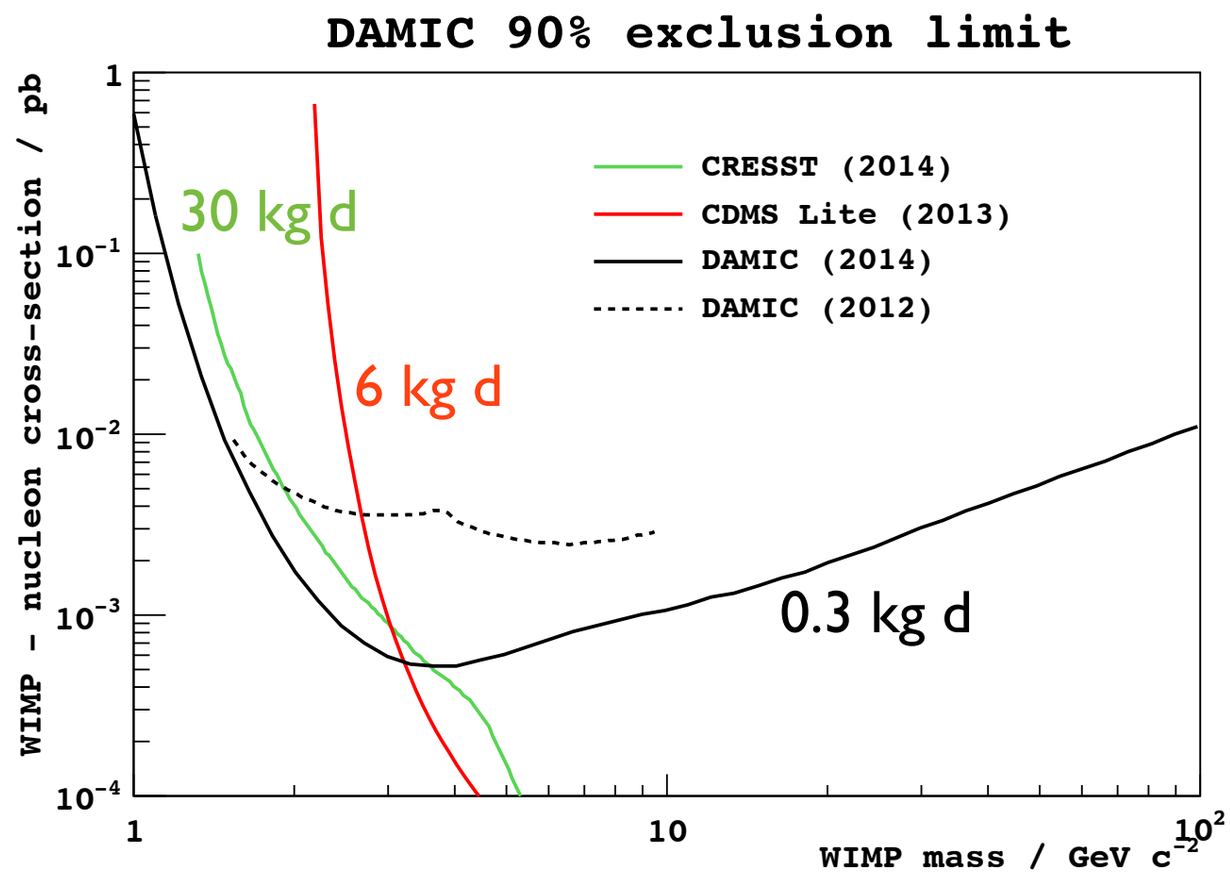




Sensitive to events down to pixel threshold but only for interactions occurring close to the gates.
Loss of efficiency as lateral spread increases. Note: running with largest lateral spread possible to study backgrounds.

Unbinned likelihood fit



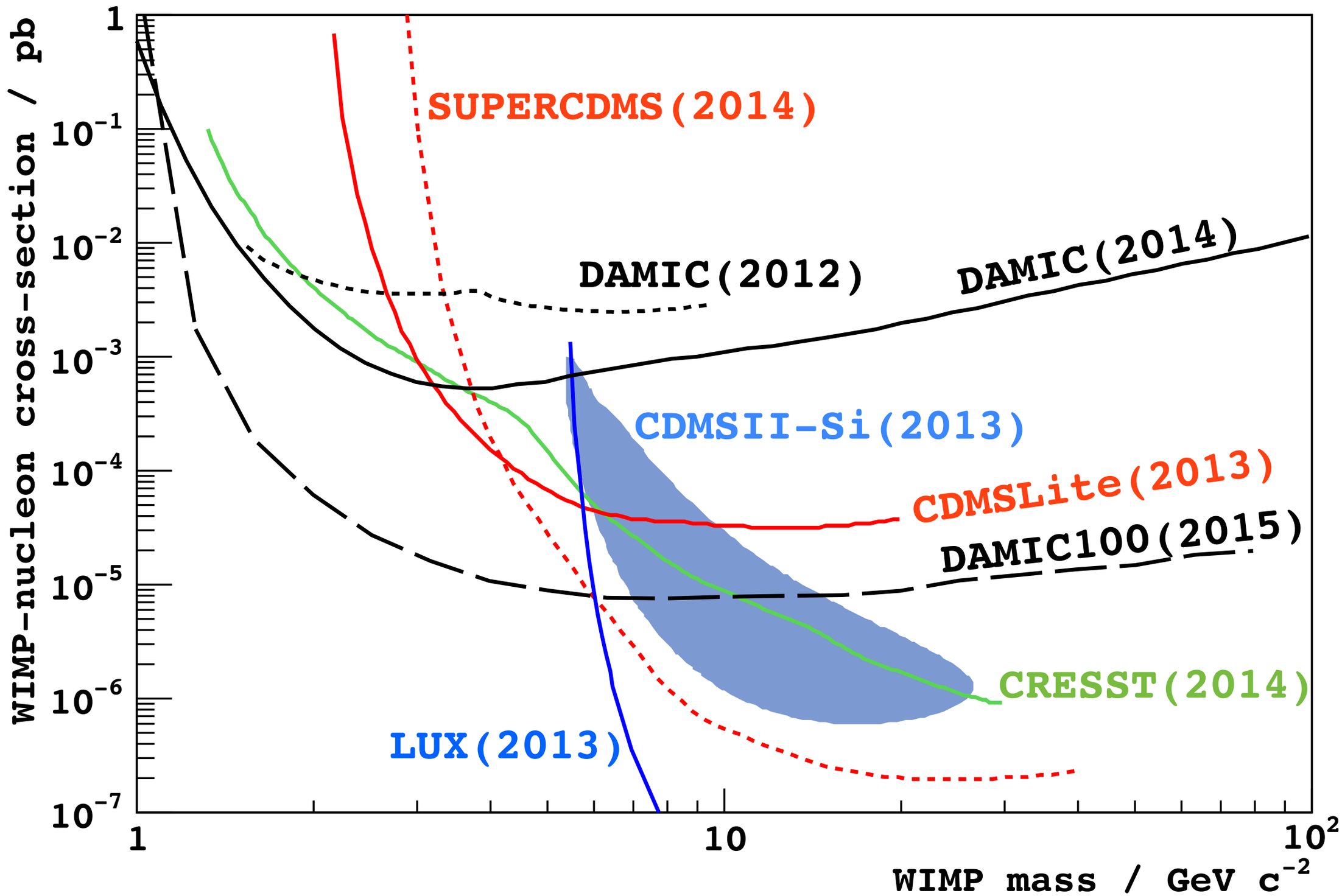


Best fit mass: 26 ± 46 GeV/c^2
Best fit xs: (7 ± 16) x 10^{-4} pb
Best fit c: 67 ± 13 dru
Minimum -ll: -396.5

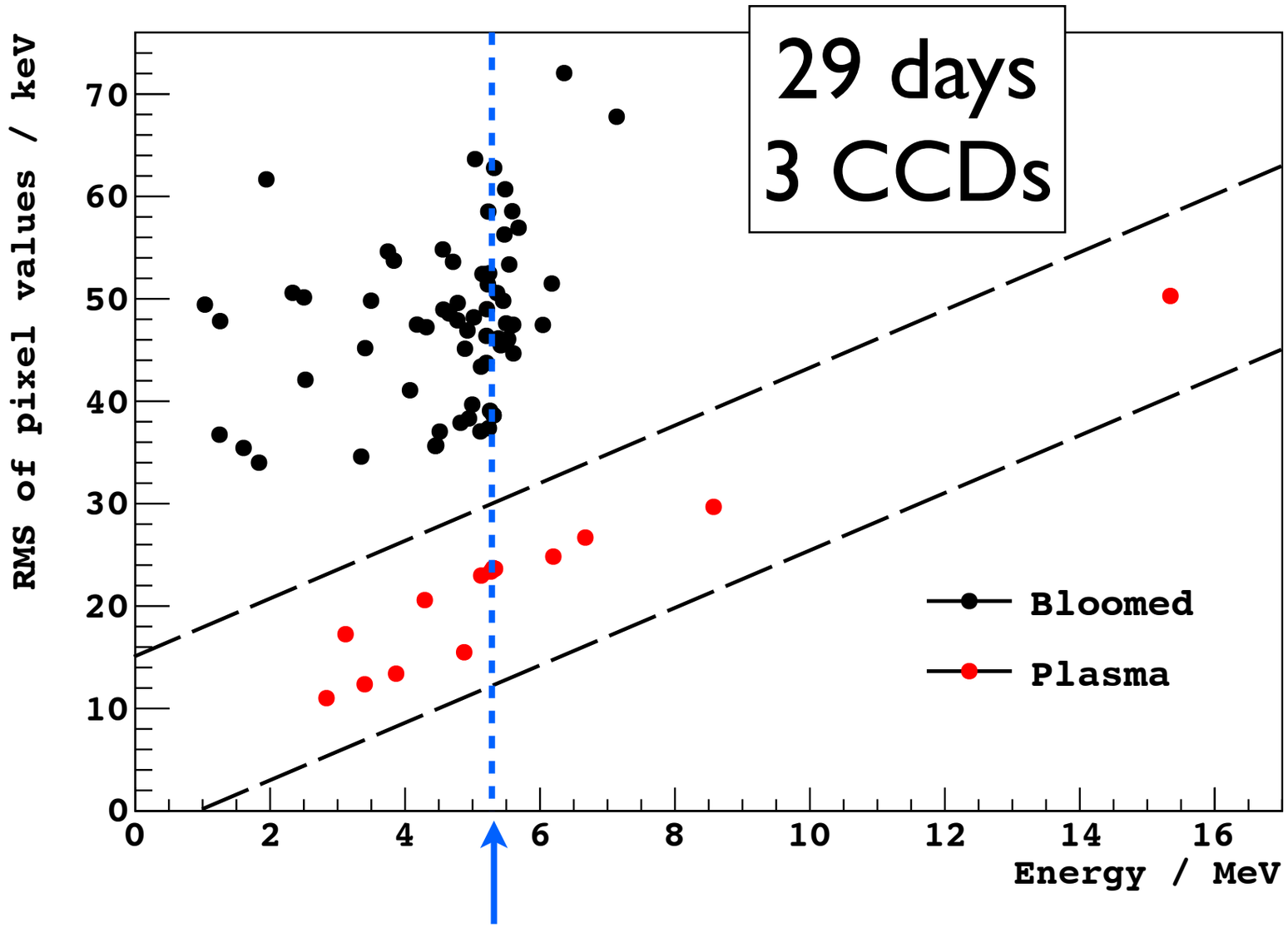
Null hypothesis c: 74 ± 5 dru
Minimum -ll: -396.1

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}

WIMP 90% exclusion limits

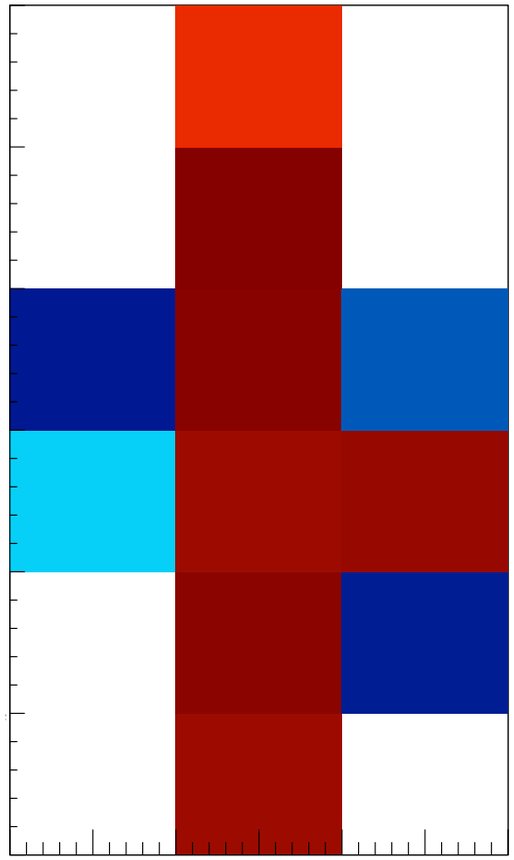


α particles

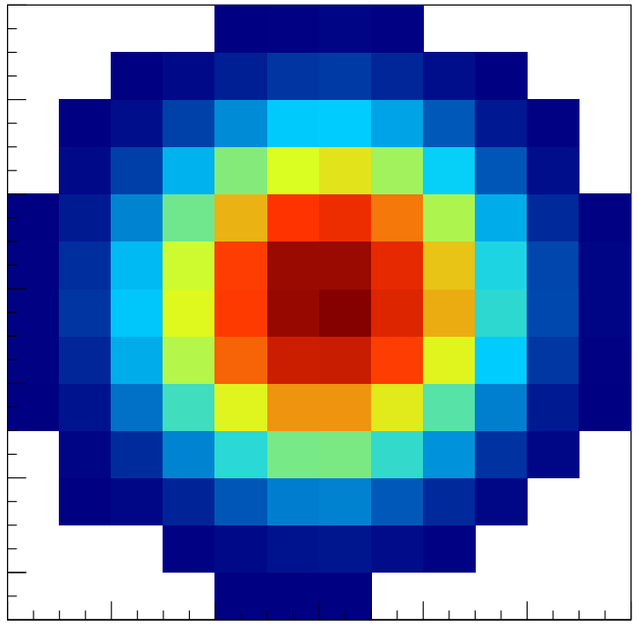


^{210}Po
(surface contamination)

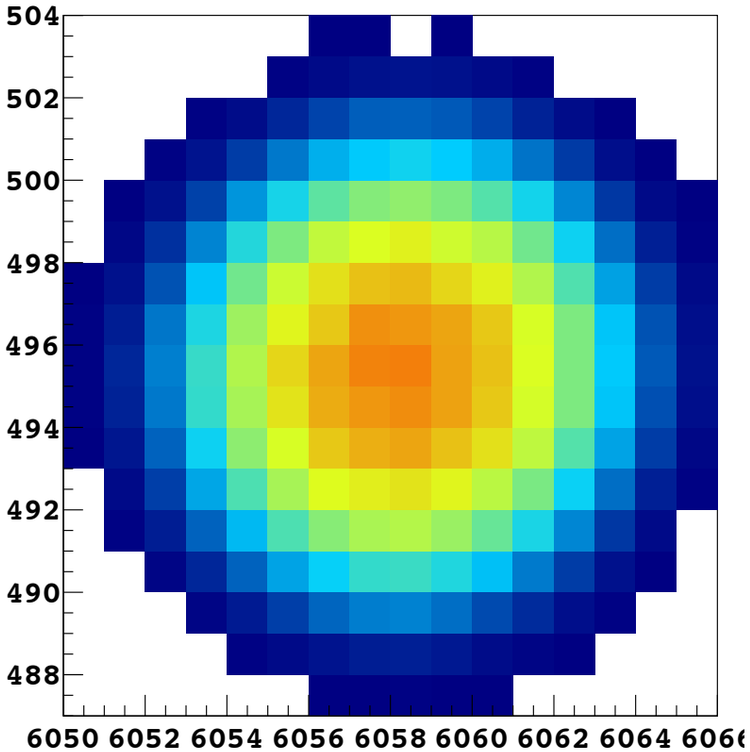
Bloomed (front)



Plasma (back)



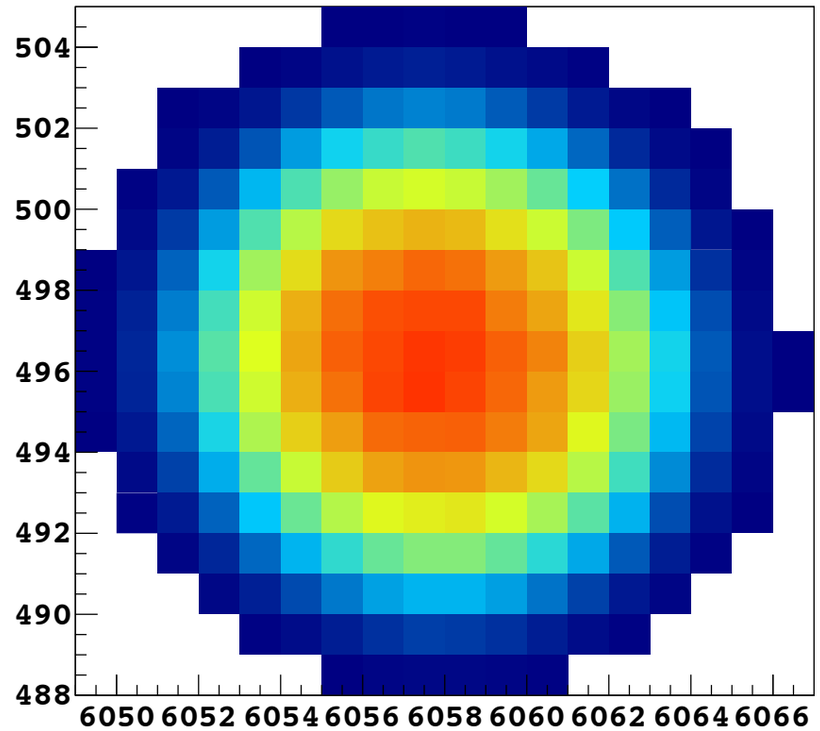
E = 5.39 MeV



Δt = 17.8 d

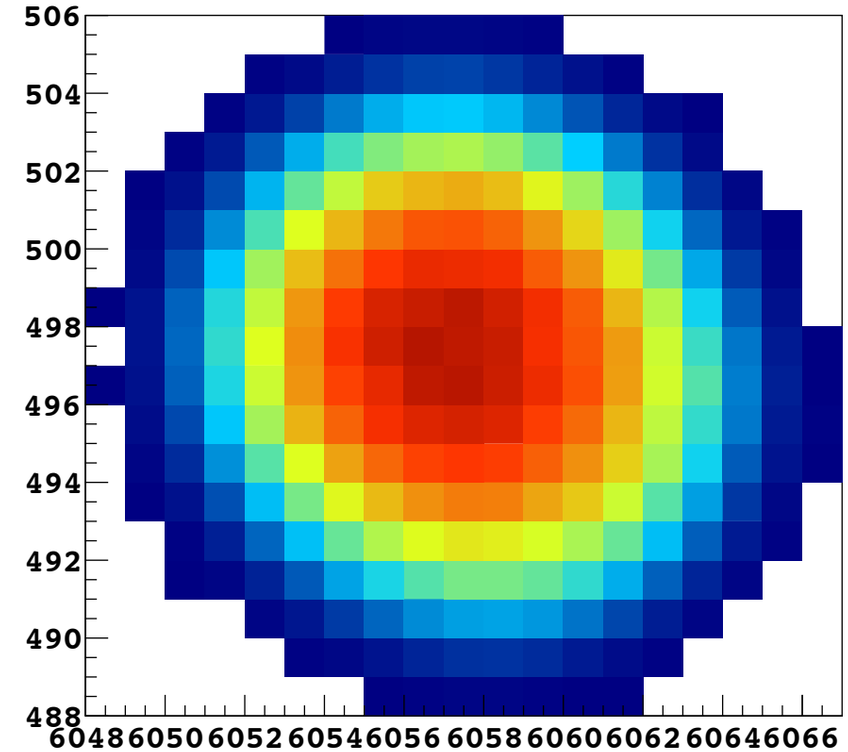
^{228}Th

E = 6.75 MeV



^{216}Po

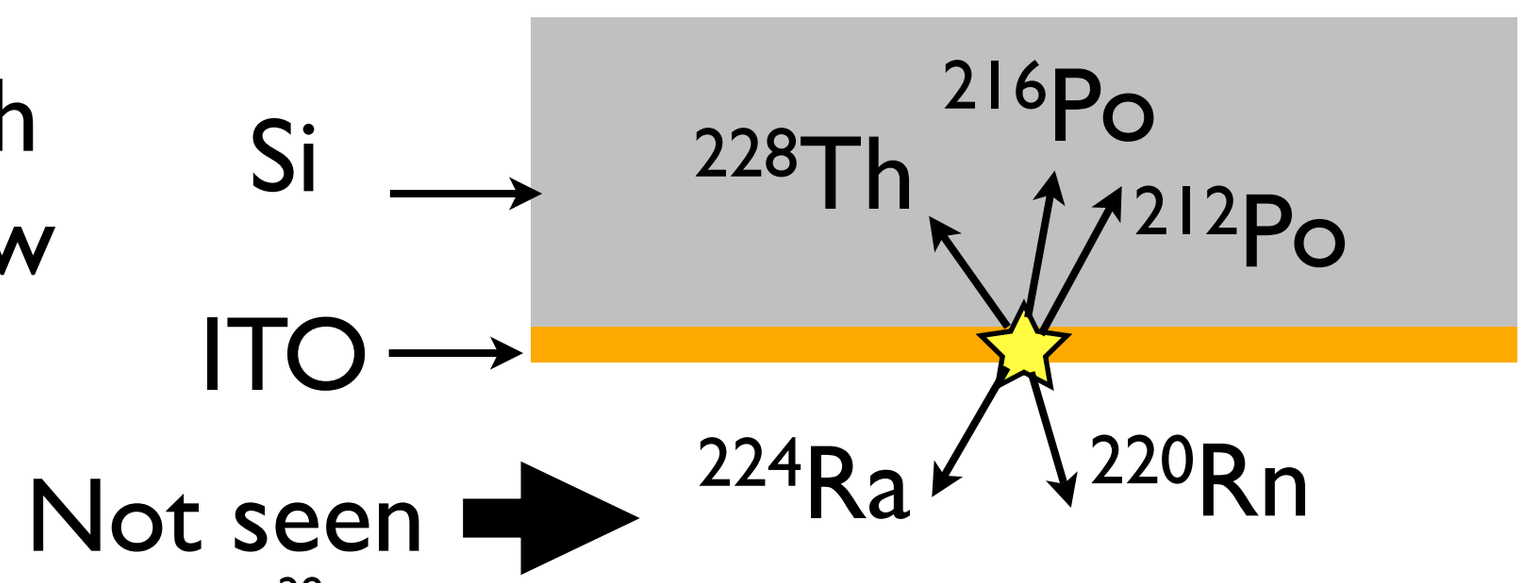
E = 8.66 MeV



Δt < 5.5 h

^{212}Po

Identification of ^{228}Th decay sequence below CCD (ITO?)



Limits from αs

From α search in 4.5 - 5 MeV energy region

^{238}U uncorrelated daughters ^{234}U (4.77 MeV), ^{230}Th (4.69 MeV), ^{226}Ra (4.79 MeV) place limit

$< 8\ kg^{-1}\ day^{-1} = 0.08\ mBq\ kg^{-1} = 7$ ppt (95% C.L.)

From α search of 18.8 MeV pile-up α from fast sequence

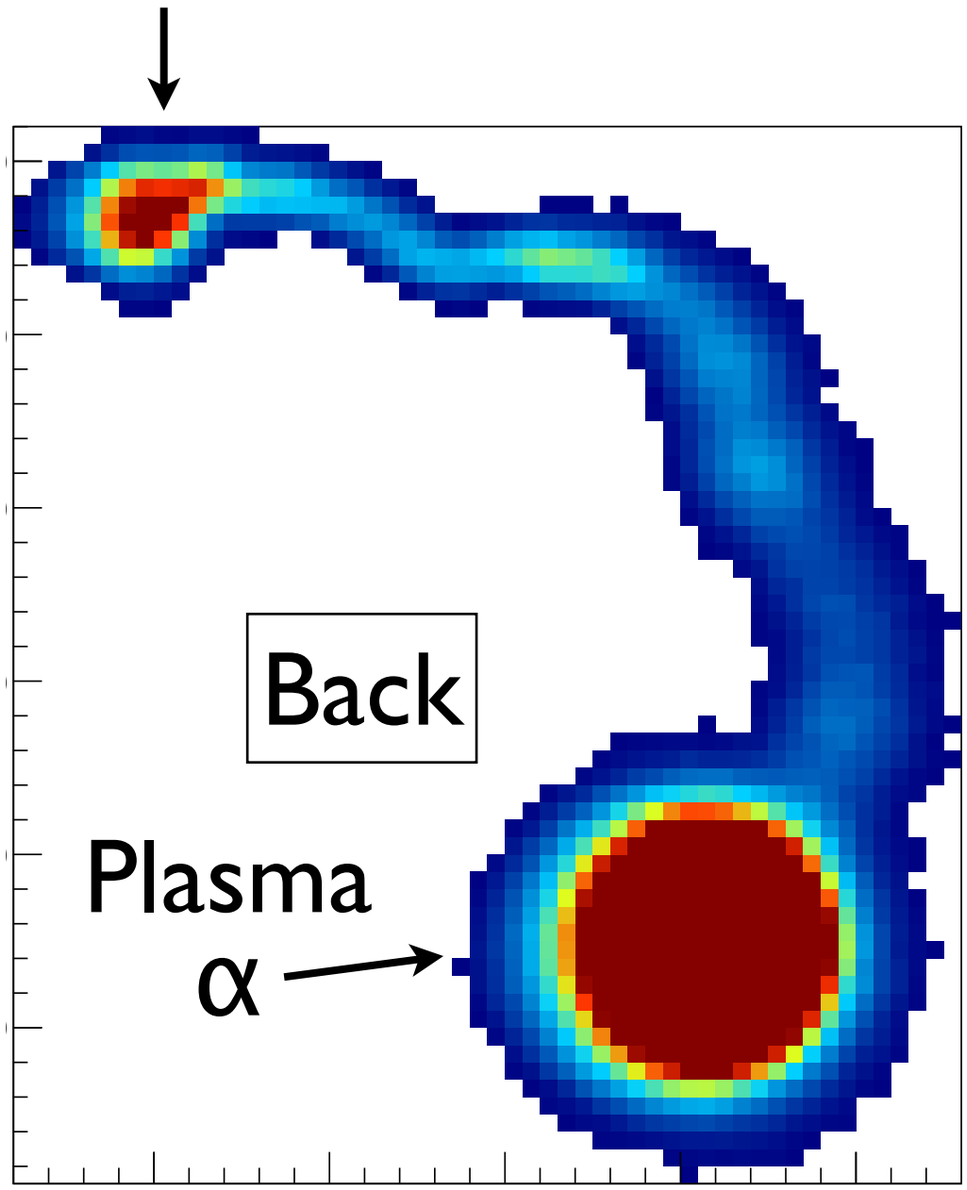
^{224}Ra (5.69 MeV) → ^{220}Rn (6.29 MeV) → ^{216}Po (6.78 MeV)

^{232}Th:

$< 15\ kg^{-1}\ d^{-1} = 0.17\ mBq\ kg^{-1} = 43$ ppt (95% C.L.)

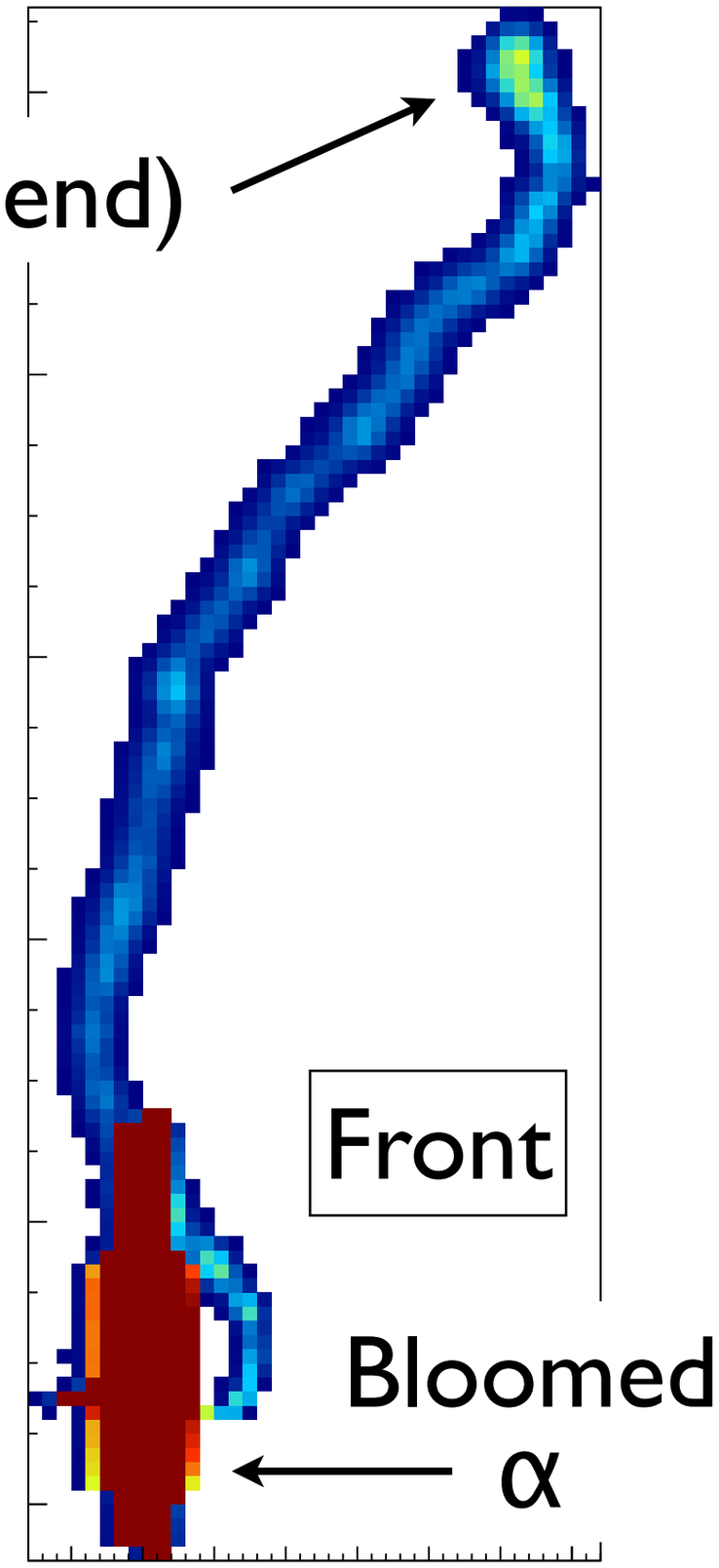
α-β coincidences

β Bragg peak (end)



β emerges from decay point under α

β Bragg peak (end)



β-β coincidences

$$^{210}Pb \xrightarrow{64\ keV} {}^{210}Bi \xrightarrow{1.2\ MeV} {}^{210}Po$$

$\tau_{1/2} = 5$ d

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

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

Sequence of βs starting in the same pixel of the CCD in different images

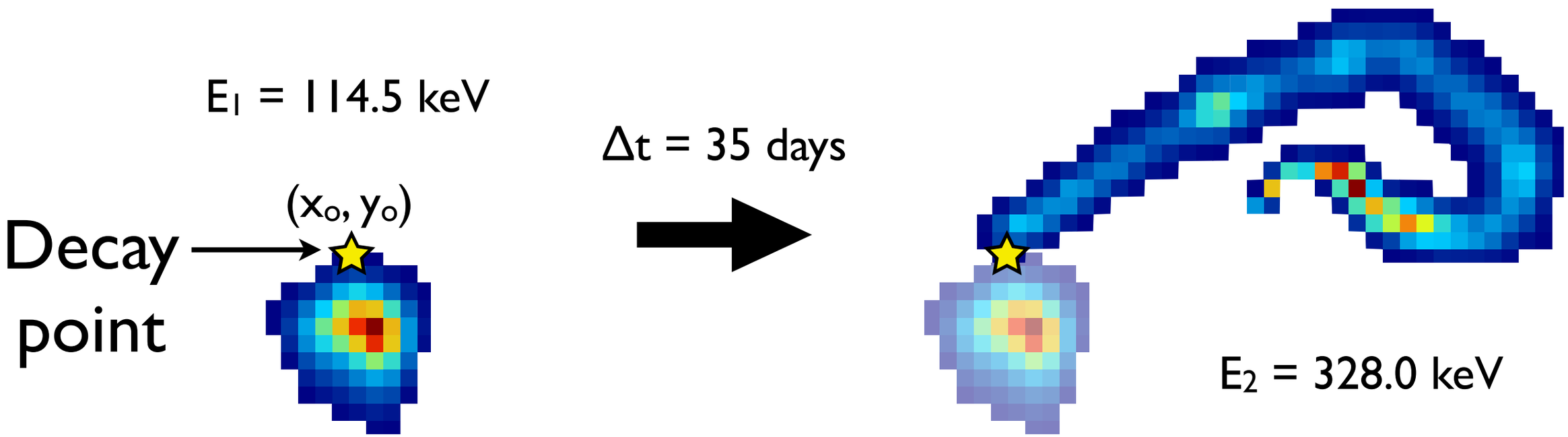
These are backgrounds that are very hard to estimate and **must be demonstrated** to be low for any proposed dark matter search in Si without electron rejection.

300 kg^{-1} d^{-1} of ^{32}Si + ^{32}P correspond to ~2 dru at low energies.

β-β coincidences

We have performed a search for ^{32}Si and ^{210}Pb in 57 days of data.

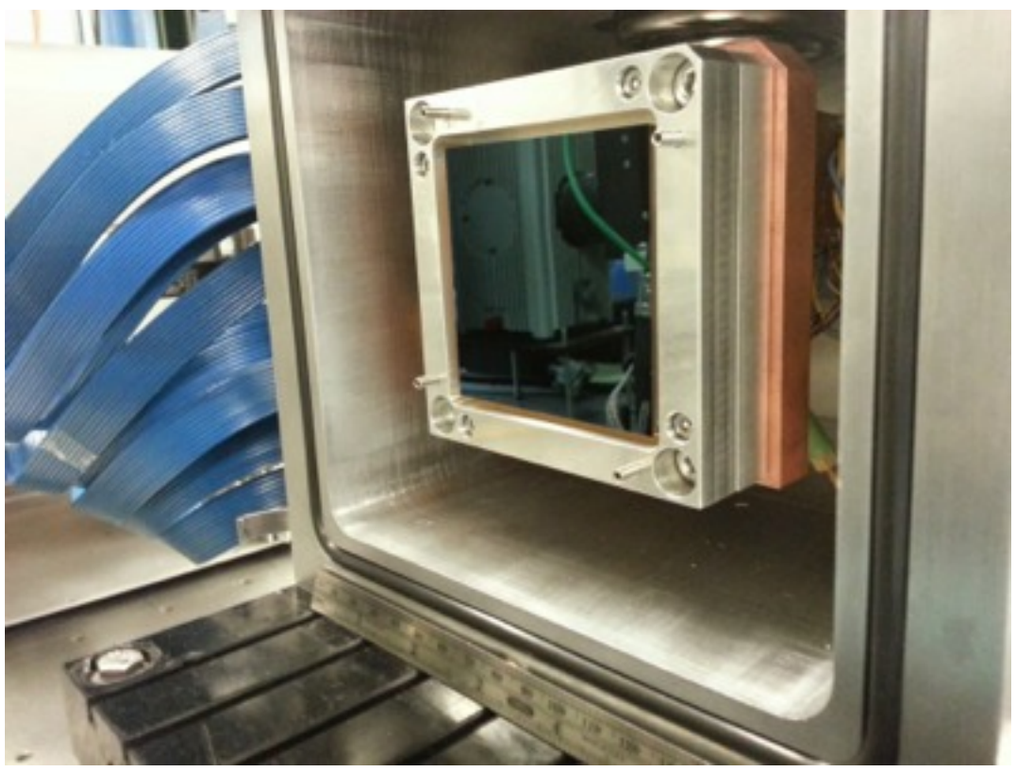
^{32}Si - ^{32}P candidate from data:



Same method serves to veto ^{32}Si decays if present.

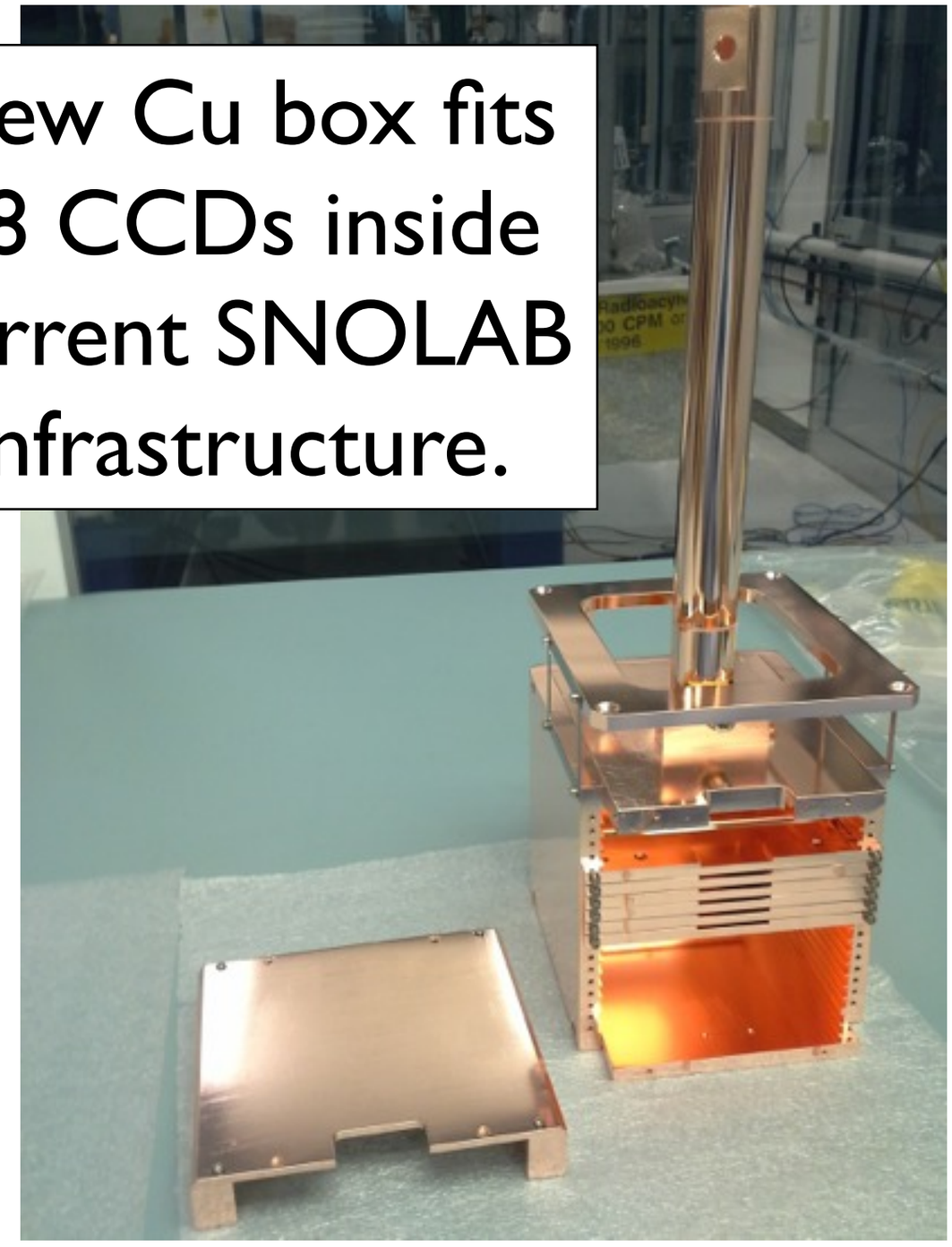
DAMIC100

We have 24, 16 Mpixel, 675 μm CCDs. Each is 5.5 g.

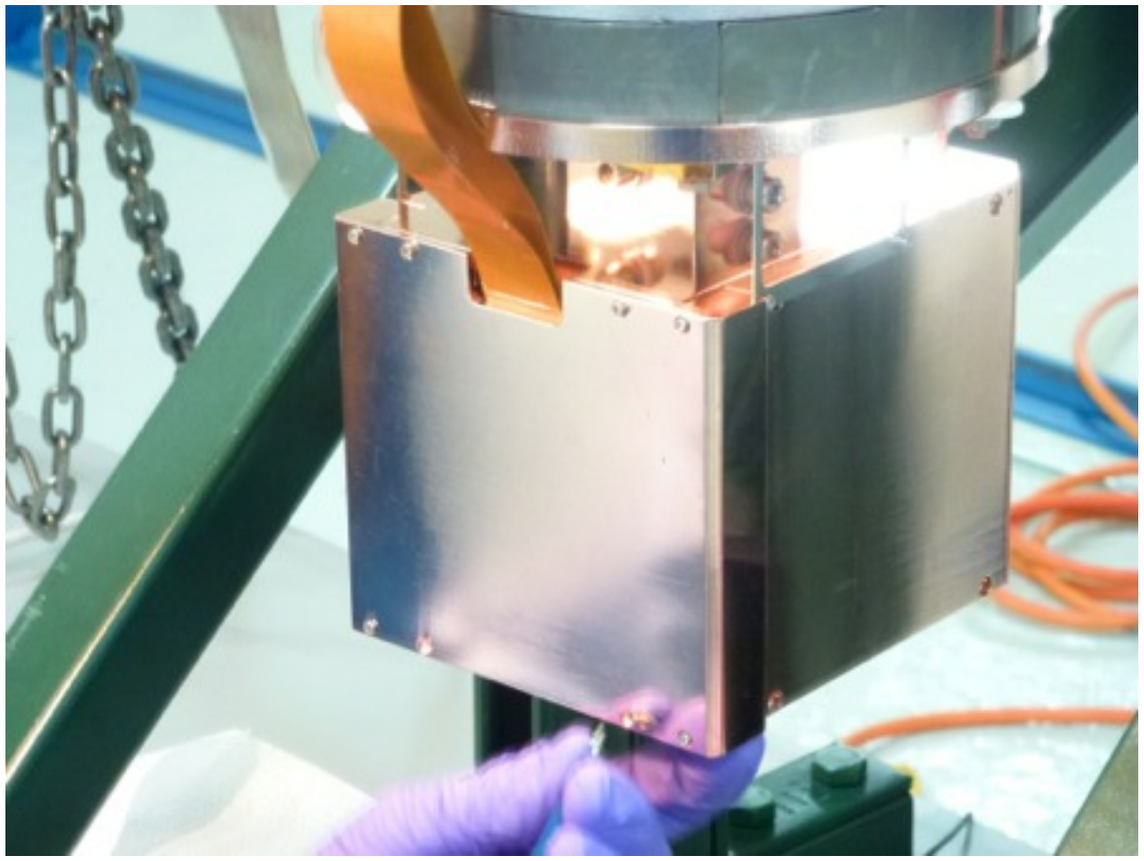


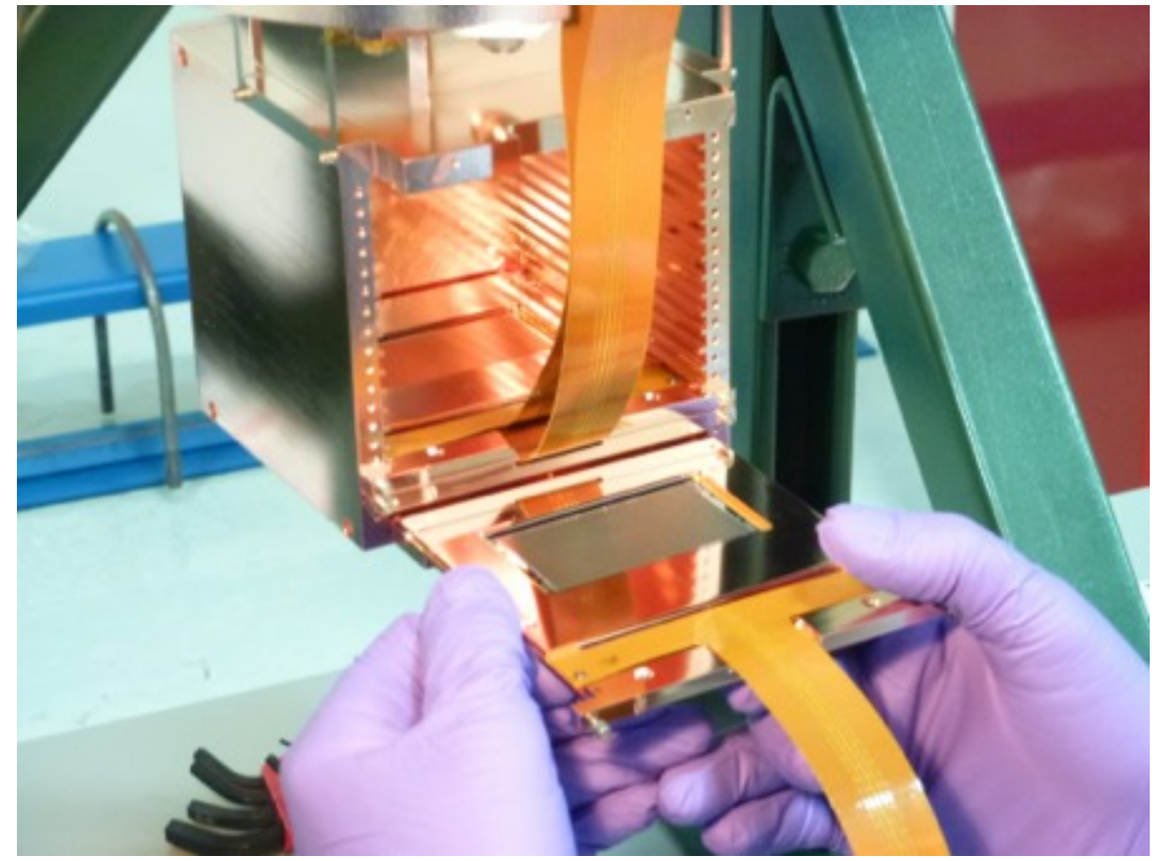
Example in DESI package.

New Cu box fits 18 CCDs inside current SNOLAB infrastructure.



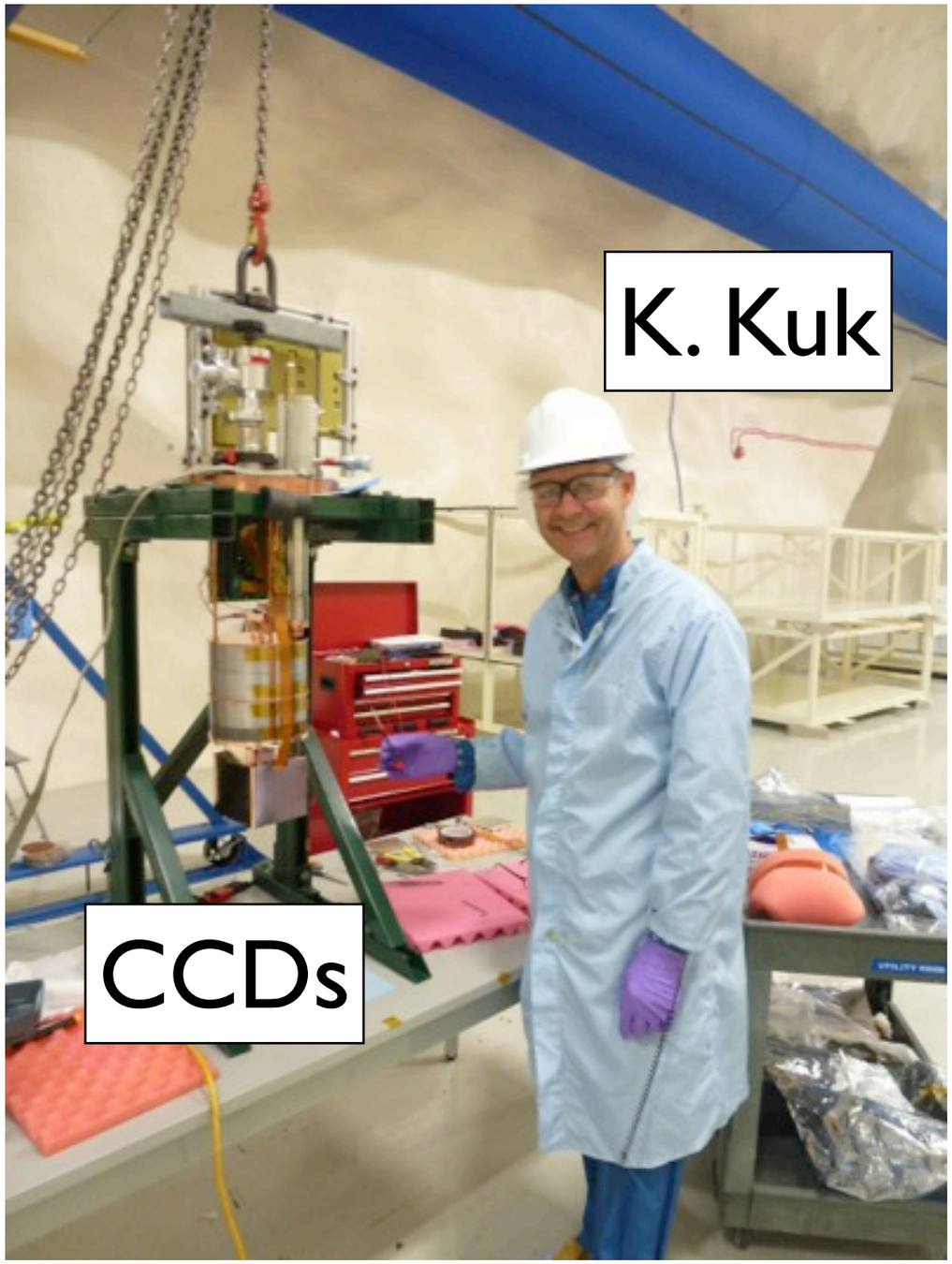
Box at SNOLAB

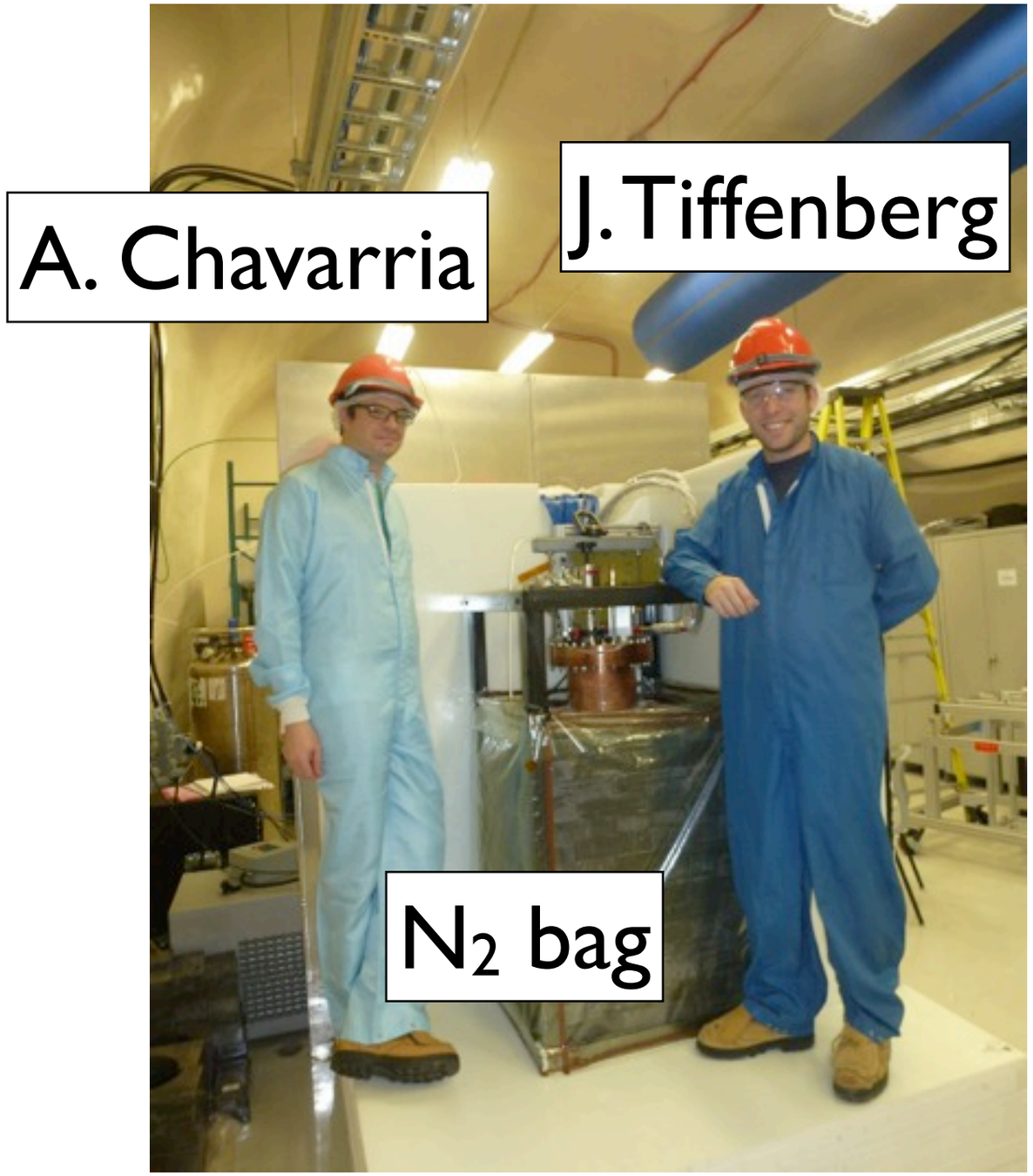




In December, 2014 we installed DAMIC100 copper box with three 8 MPixel, 675 μm thick CCDs at SNOLAB to study backgrounds.

December 2014





	^{210}Pb Bq/kg	^{238}U mBq/kg	^{226}Ra mBq/kg	^{232}Th mBq/kg	^{40}K mBq/kg
Si support	–	<11.2	–	<3.6	$<8\times10^{-4}$
Flex cable	–	<460	<16	<14	118±88
Epoxy	–	<12	<6.8	1.12±0.07	13.3±3.5
Outer lead	58±18	<35	<0.2	<0.7	<0.35
Inner lead	<0.02	<0.1	–	<0.03	<0.006
VIB	–	–	9.1±1.2 Bq	17.3±2.9 Bq	8±1 Bq

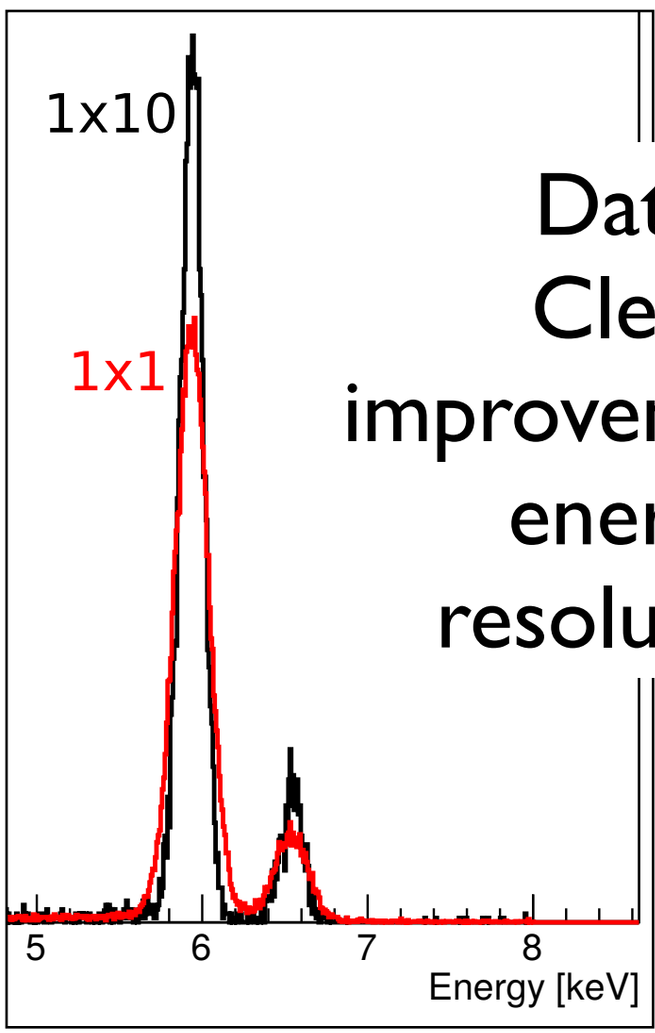
All these contribute to ~0.5 d.r.u.

Cobalt activation in copper at 1mBq/kg ~4 dru

Improving performance

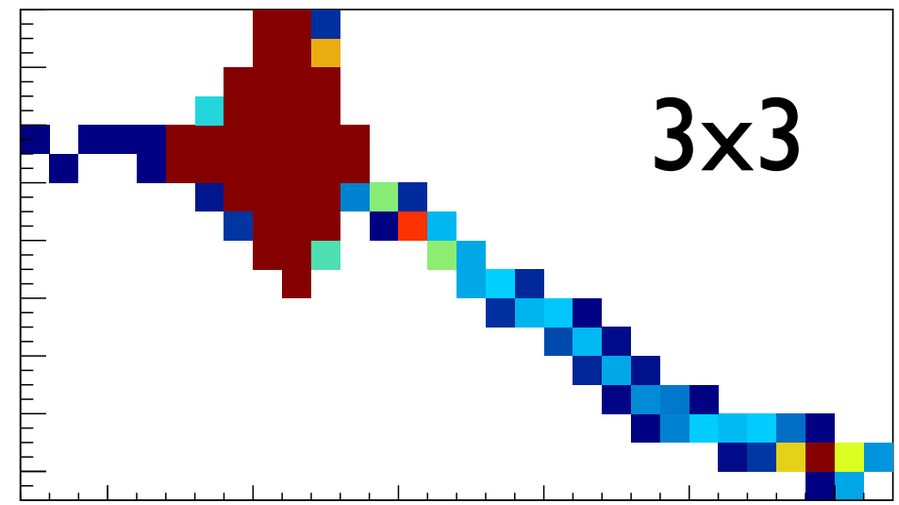
In a CCD we can "hardware bin," i.e. put the charge from many pixels into the output node before measuring.

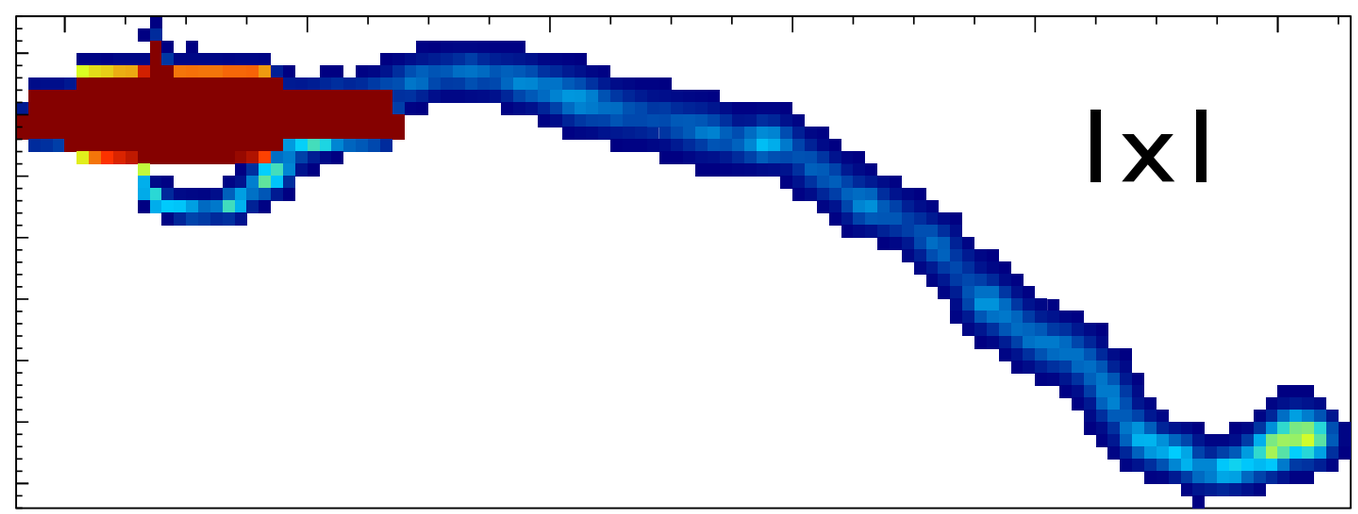
Less pixels but same pixel noise!



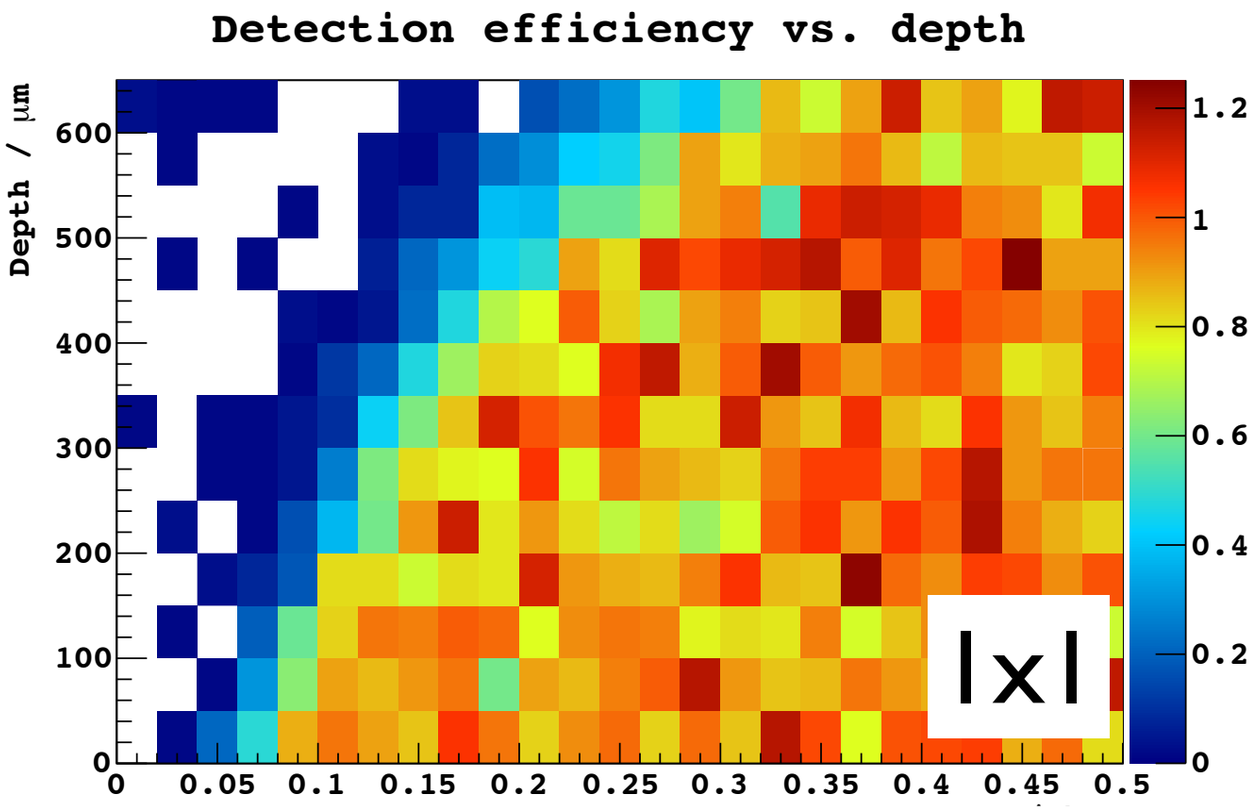
Data: Clear improvement in energy resolution.

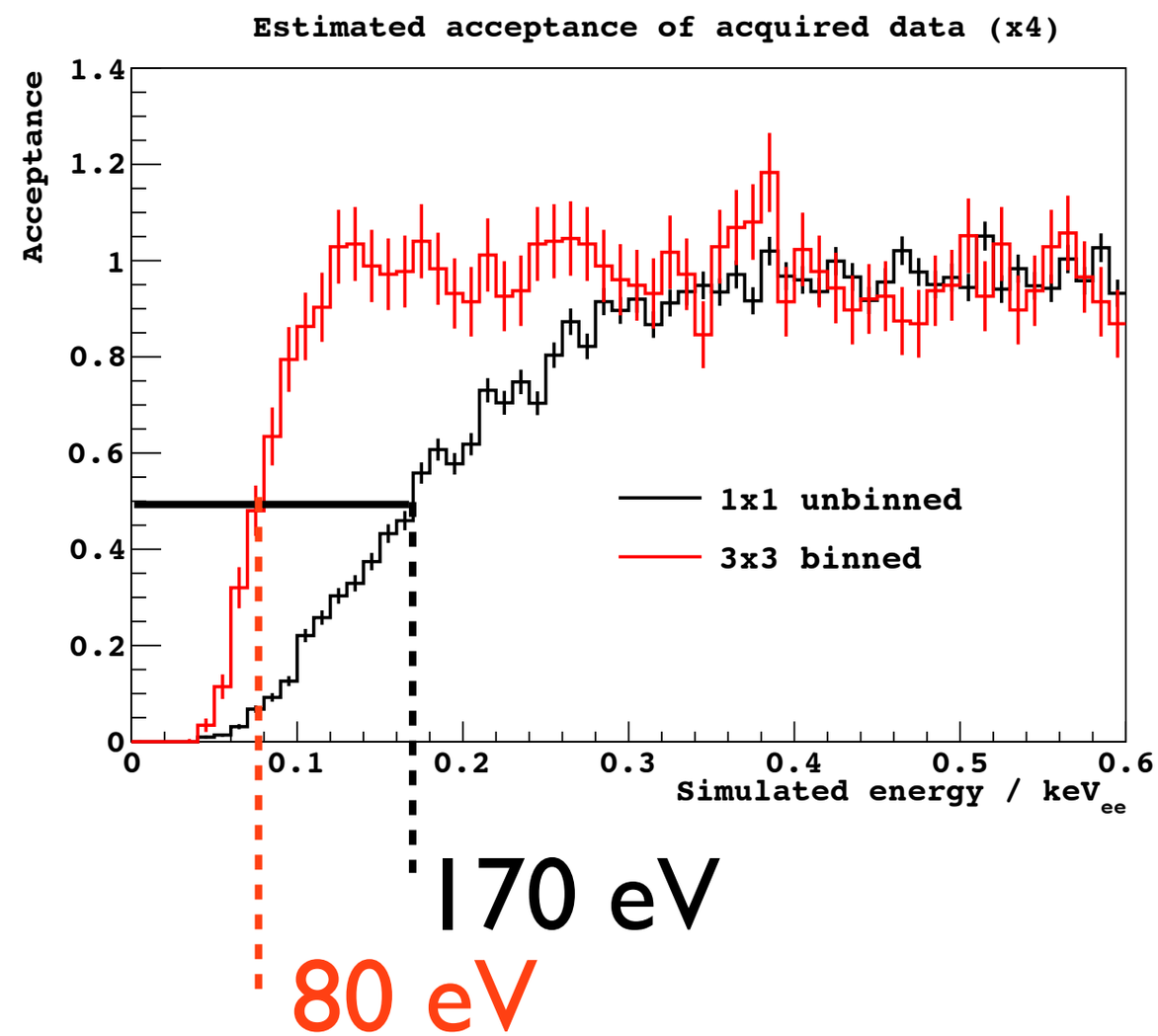
Loss of x, y and z information

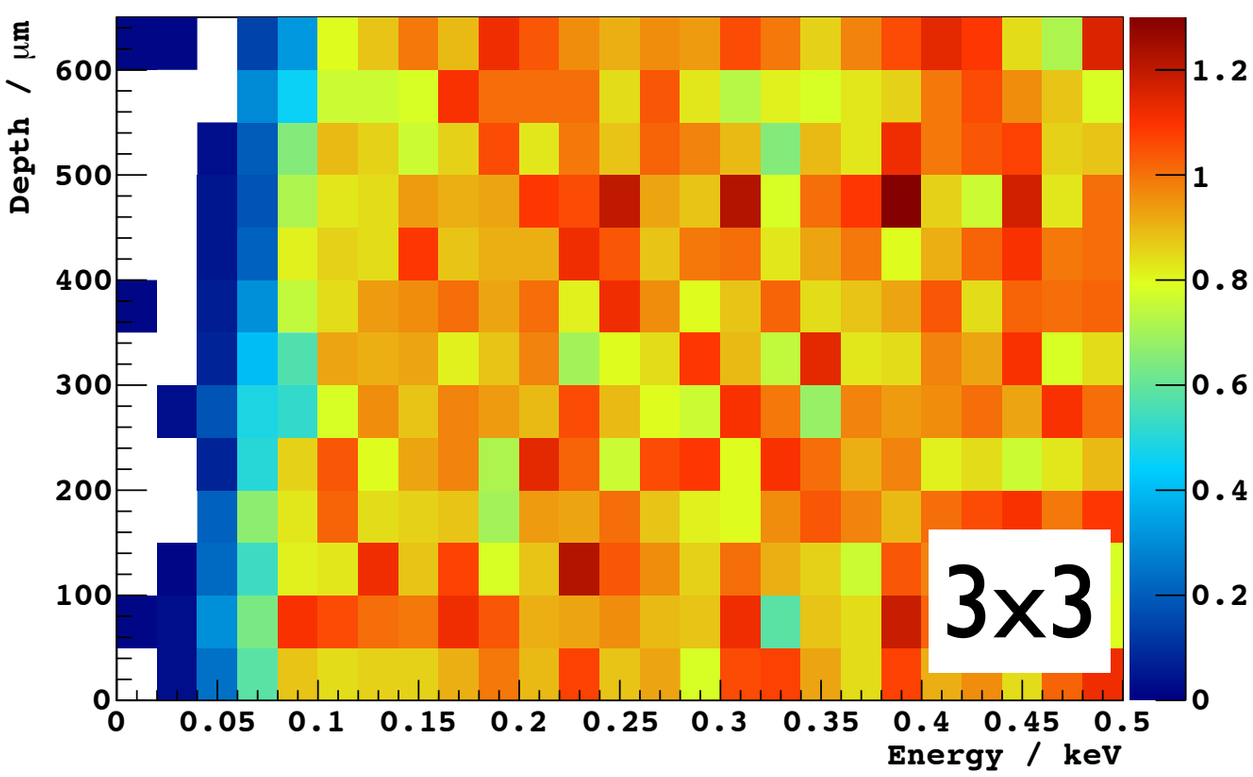




Detection efficiency







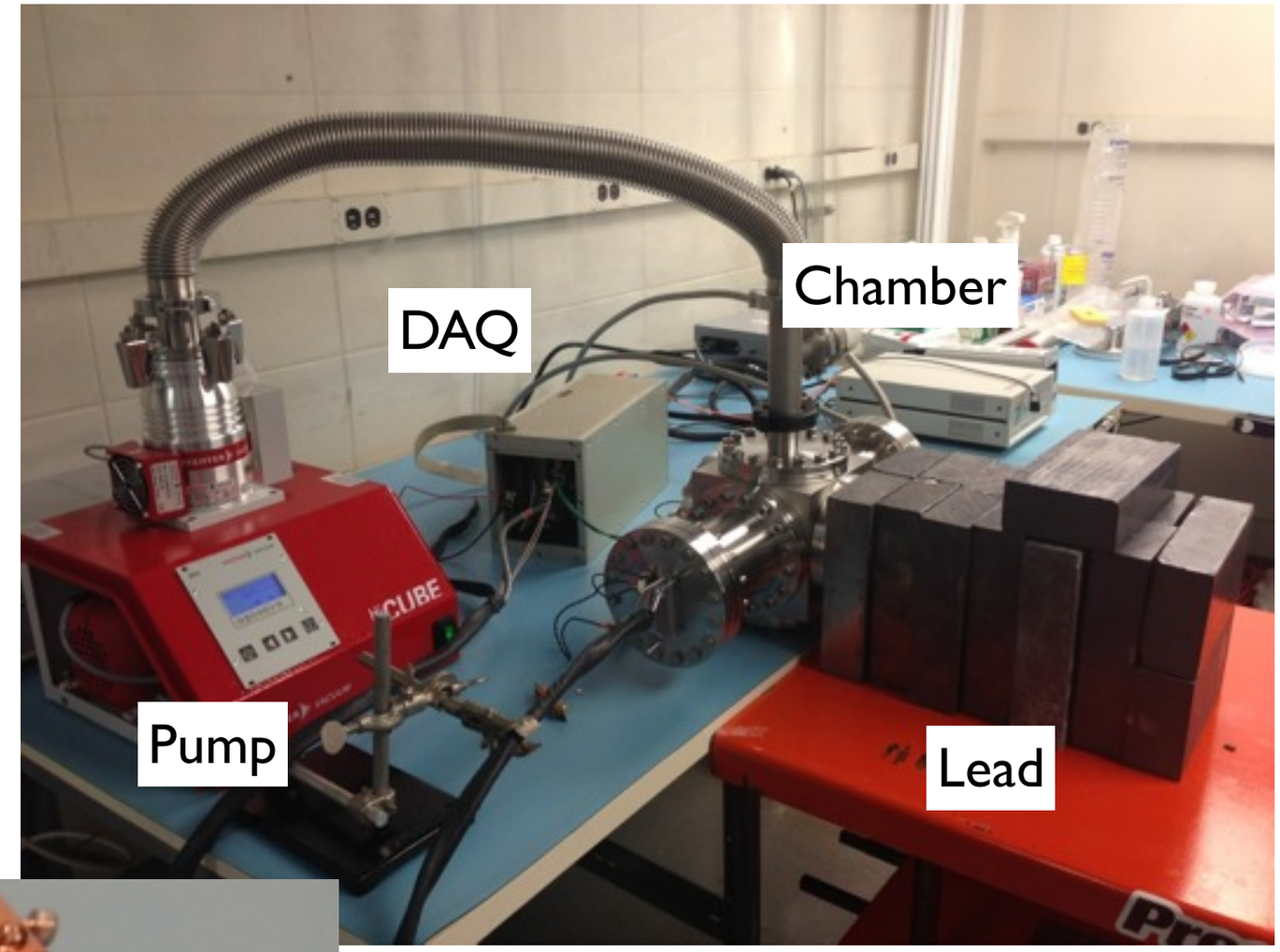
Significant improvement in threshold!

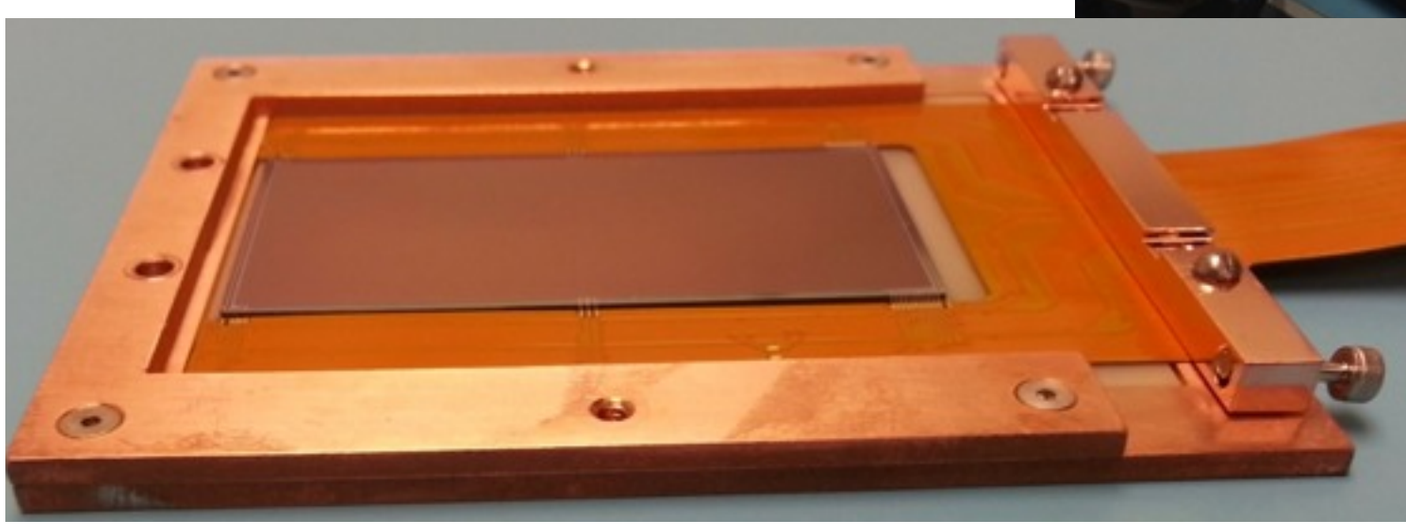
Already acquired some data in SNOLAB.

Recoil energy calibration

Neutron calibration with $^{9}Be(\gamma,n)$ reaction using 5 mCi ^{124}Sb source.

At U Chicago.

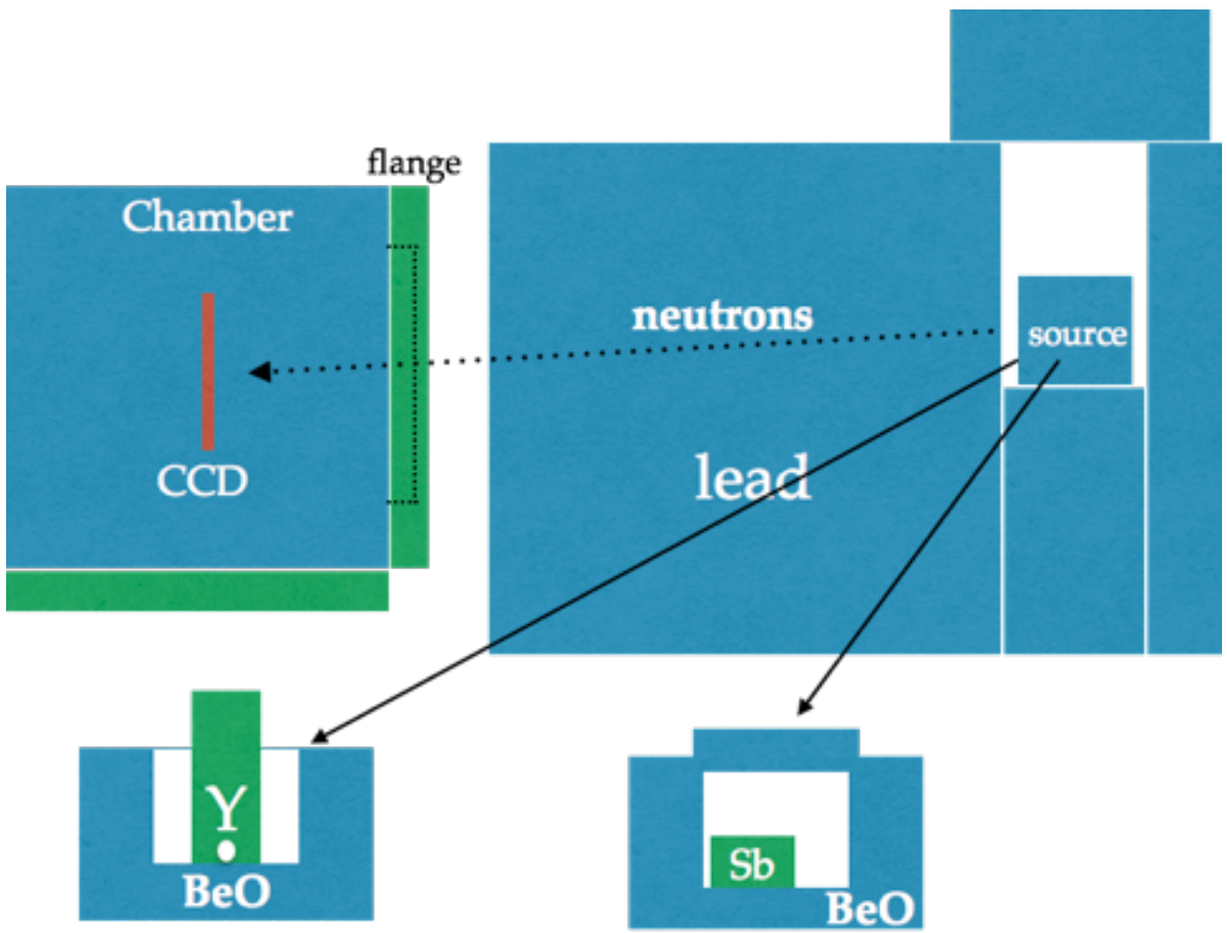


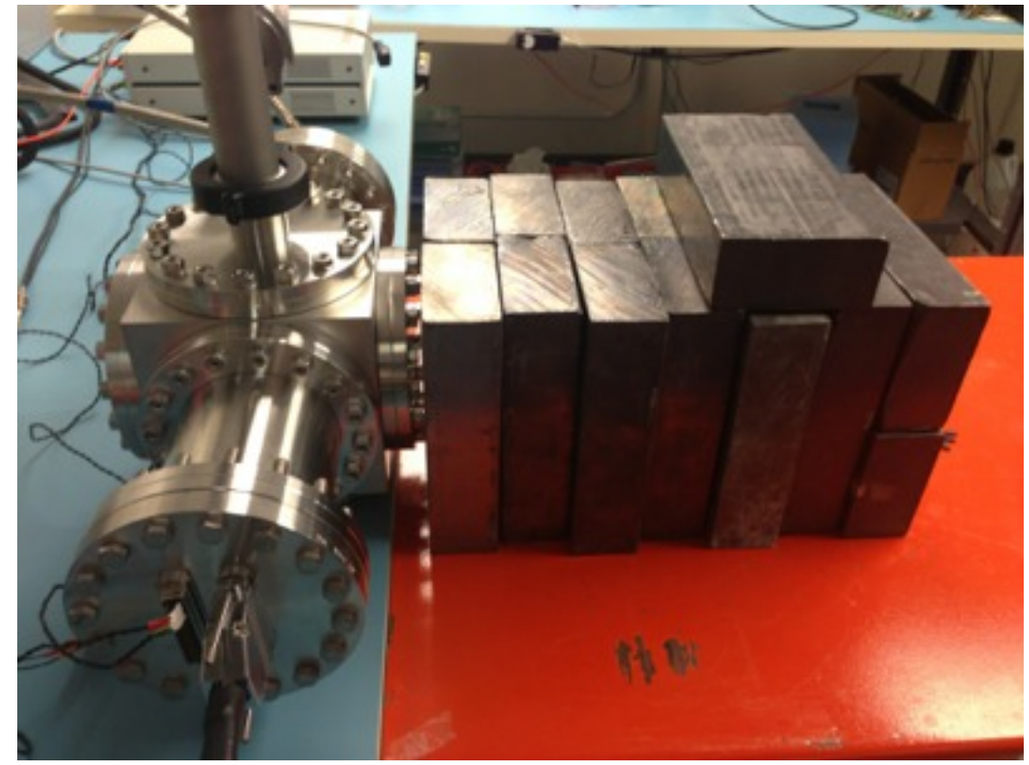


500 μm CCD

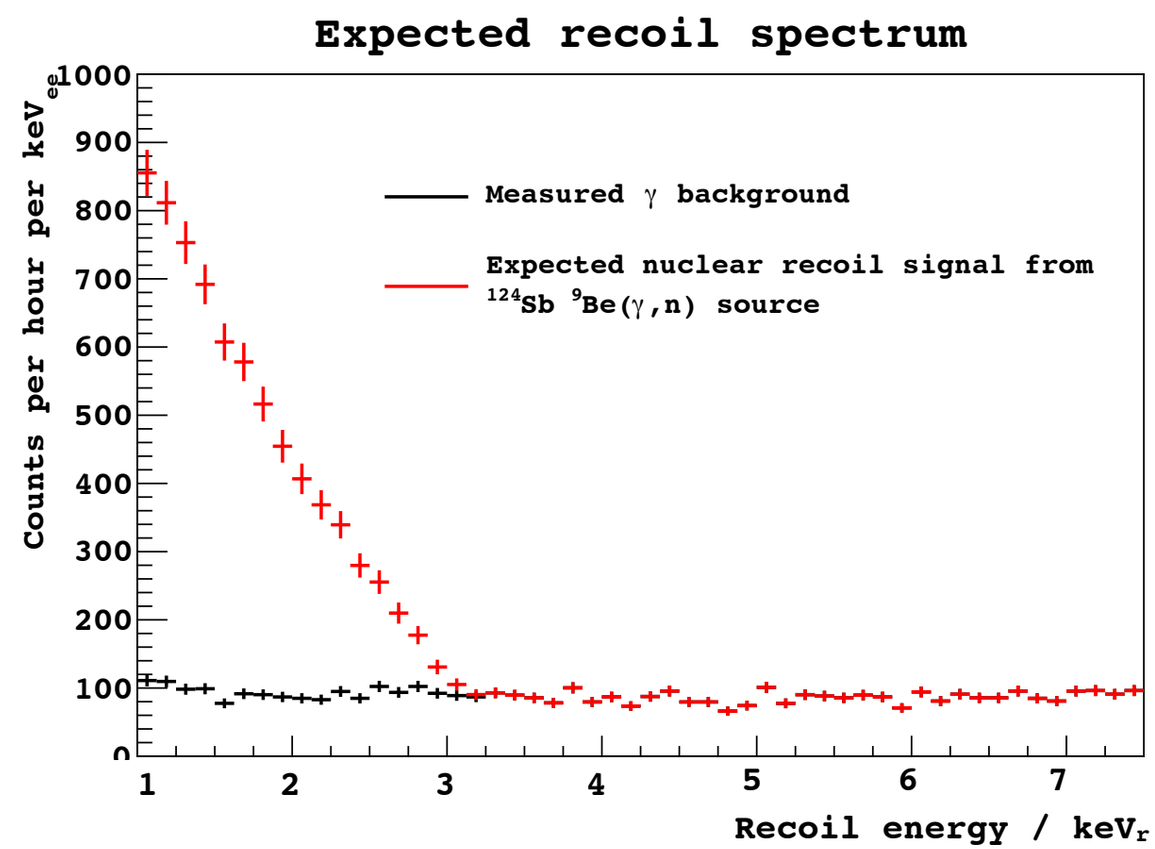
Installed with help from Javier

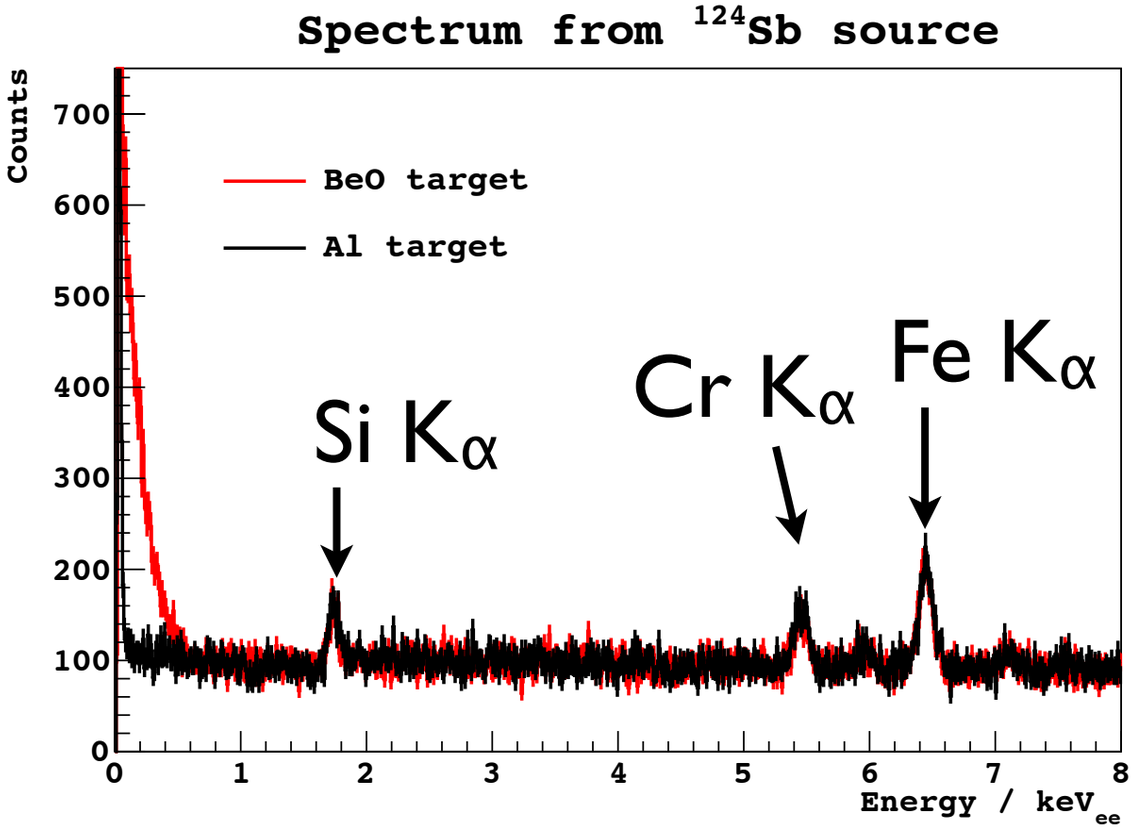
^{124}Sb + BeO target

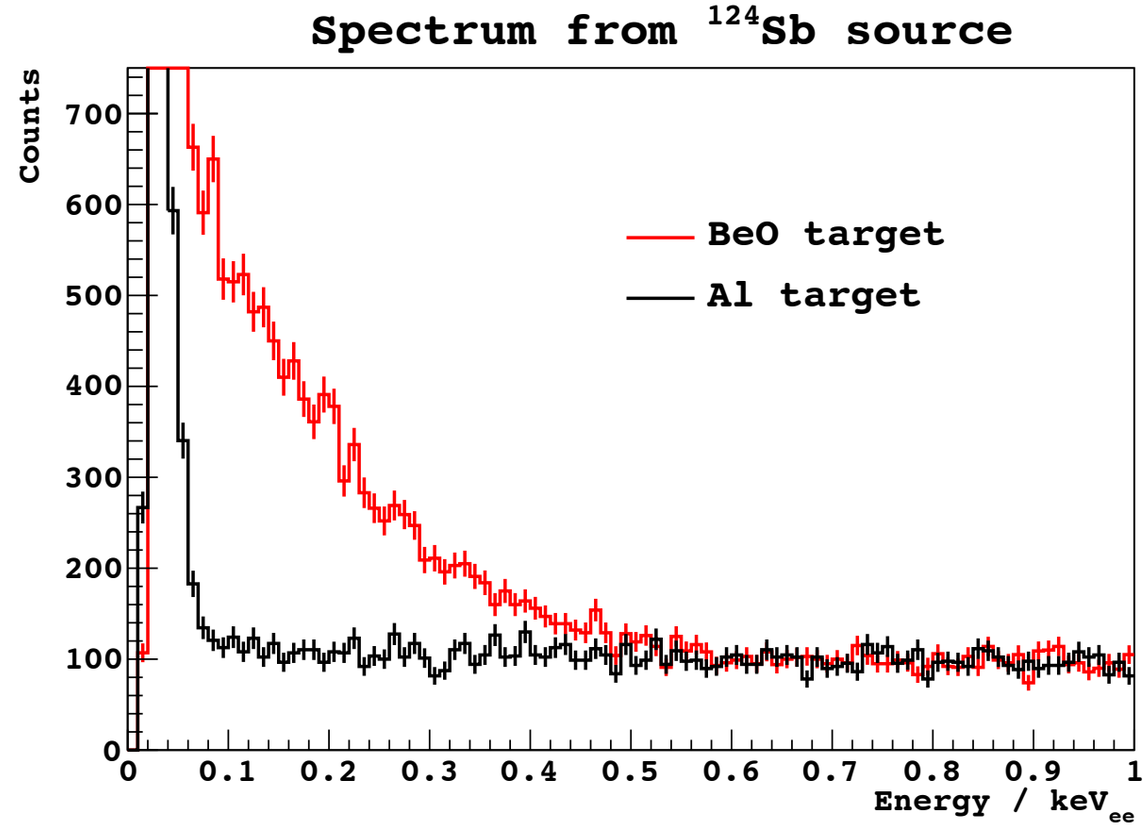


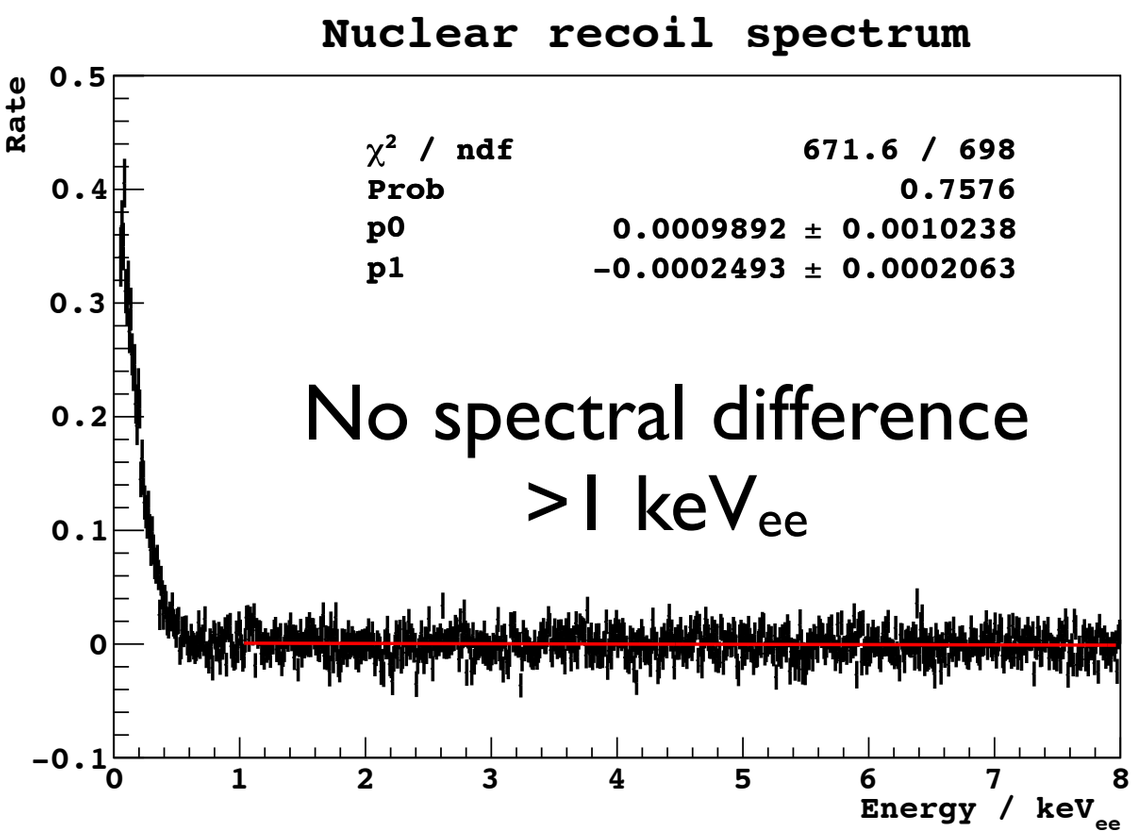


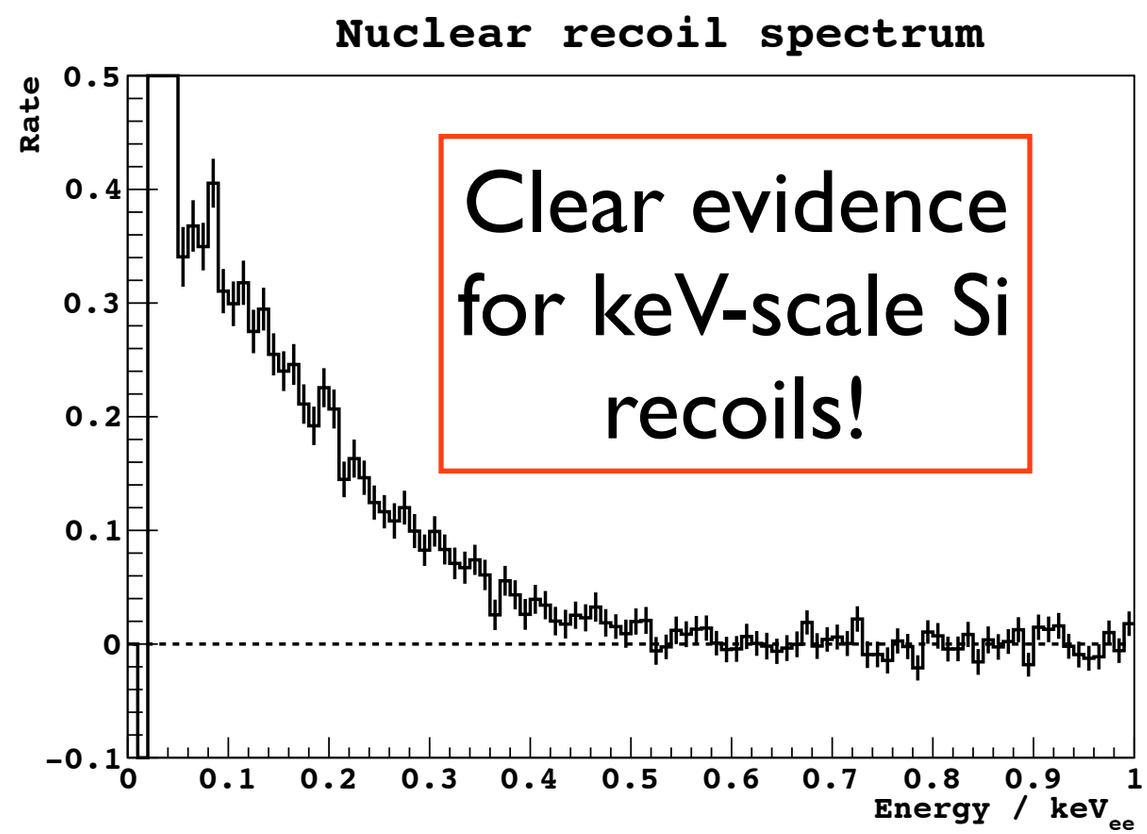
Emitted neutrons
26 keV



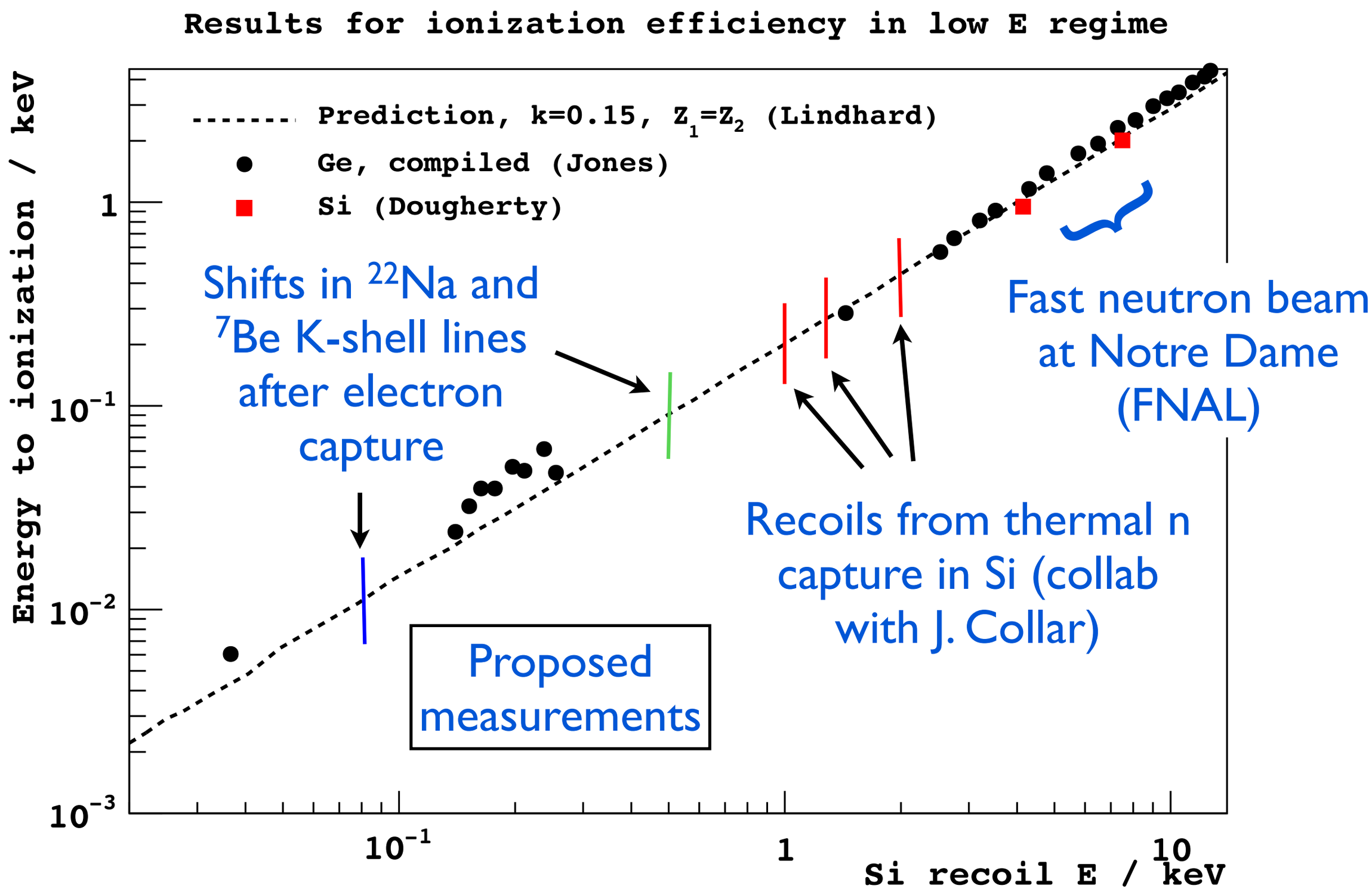

Spectrum from ^{124}Sb source
Counts
BeO target
Al target
Si Kα
Cr Kα
Fe Kα
Energy / keV$_{ee}$


Spectrum from ^{124}Sb source
Counts
BeO target
Al target
Energy / keV$_{ee}$


Nuclear recoil spectrum
Rate
χ^2 / ndf 671.6 / 698
Prob 0.7576
p0 0.0009892 ± 0.0010238
p1 -0.0002493 ± 0.0002063
No spectral difference
>1 keV$_{ee}$
Energy / keV$_{ee}$


Nuclear recoil spectrum
Rate
Clear evidence
for keV-scale Si
recoils!
Energy / keV$_{ee}$

Calibration of E_r scale

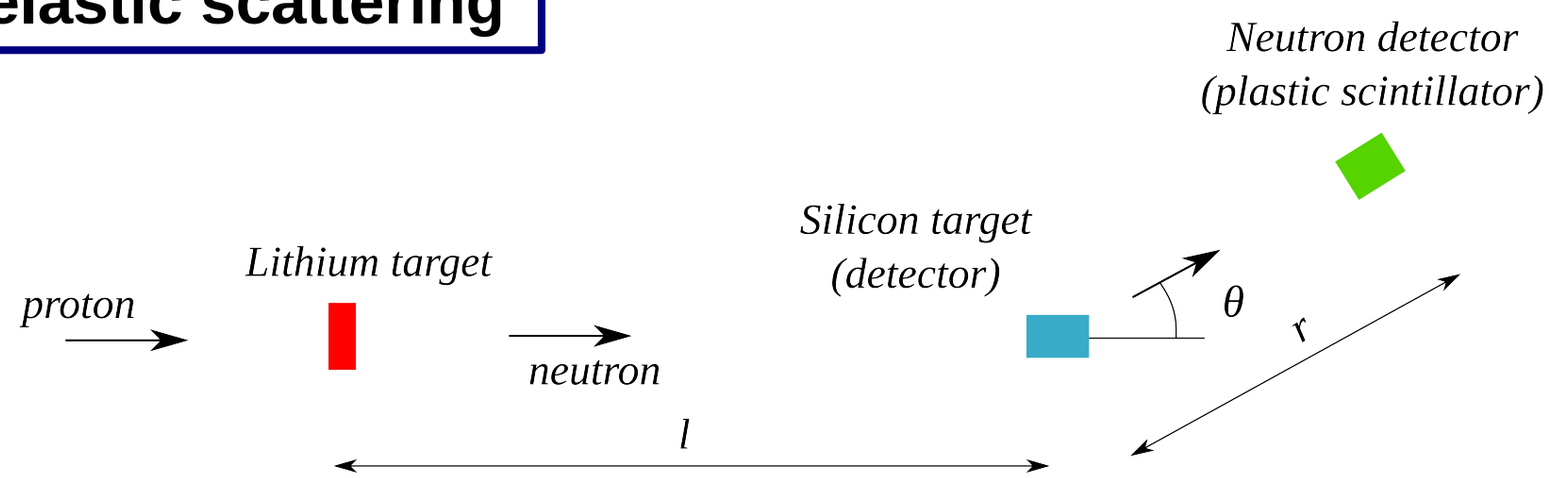


Antonella

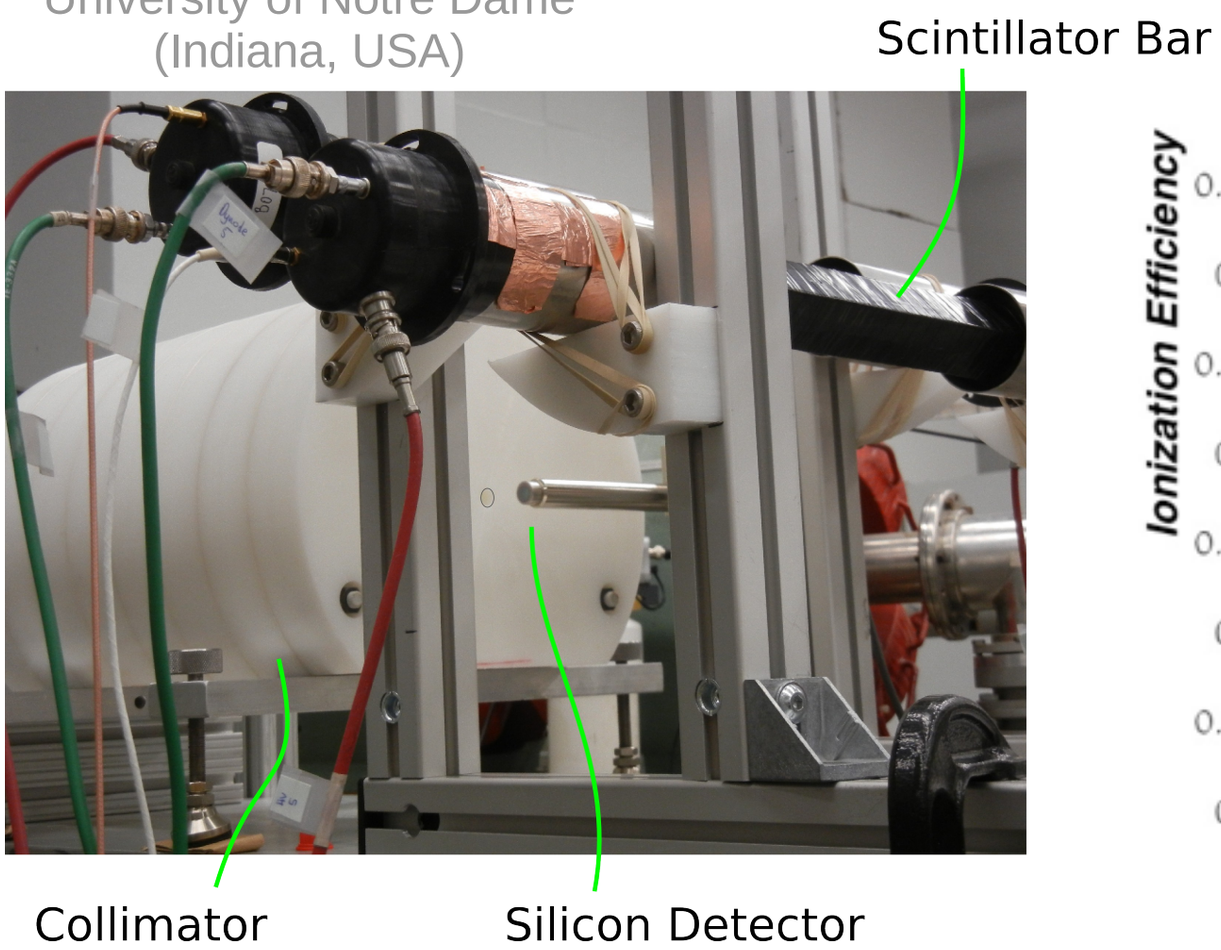
Fast neutrons elastic scattering

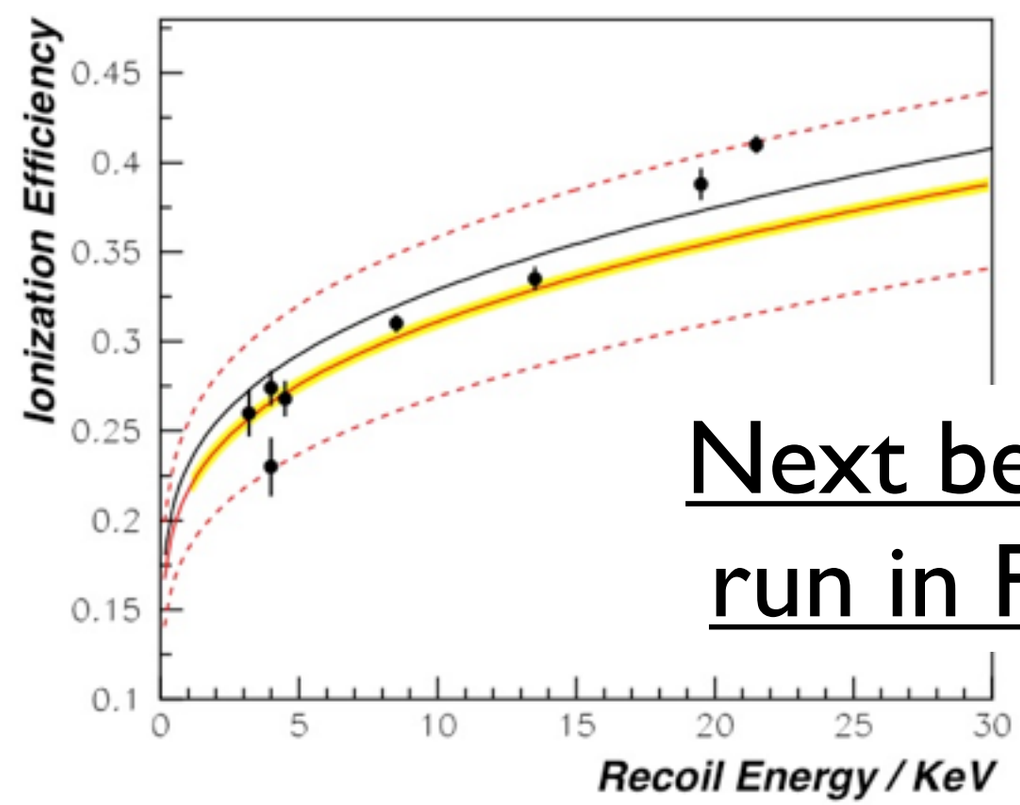
E_p = 2.3 MeV

E_n in [100,600] keV



University of Notre Dame
(Indiana, USA)



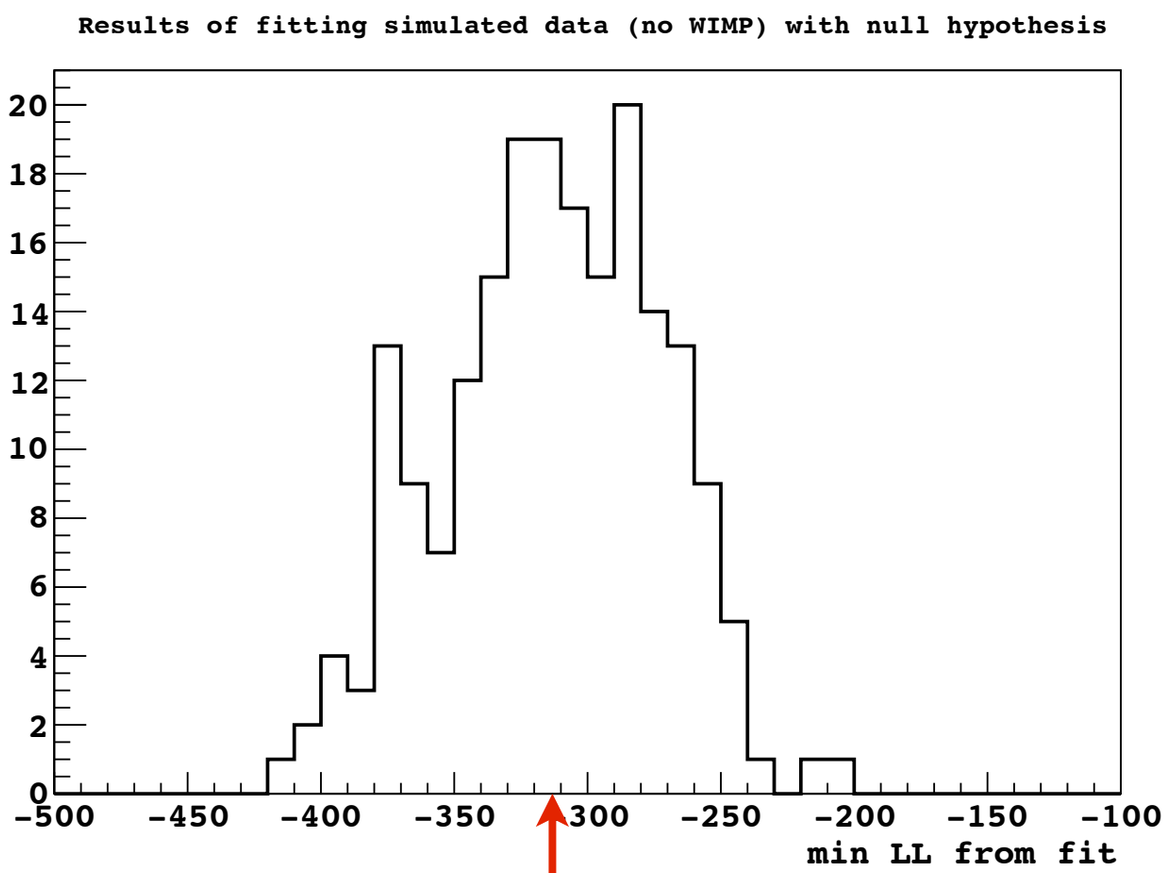


Next beam run in Feb

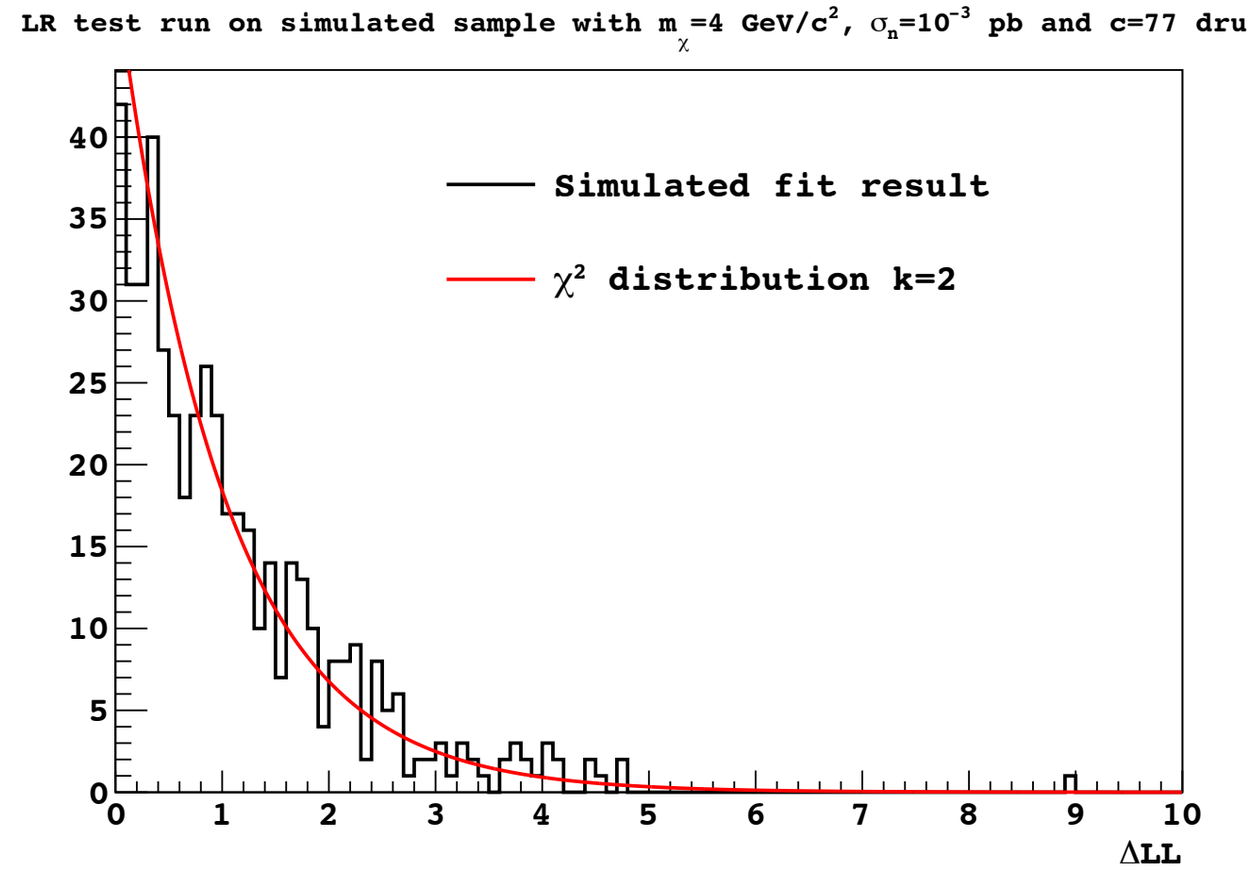
Conclusions

- CCDs perform well as particle detectors: superb energy threshold and spatial resolution.
- Modest DAMIC exposure (0.3 kg d) can already probe new regions of WIMP parameter space.
- CCDs are well suited to identify and suppress radioactive backgrounds.
- DAMIC100 on its way and should be up and running in the next few months.
- DAMIC100 will probe new regions of parameter space and test CDMSII-Si possible signal.

Backup Slides

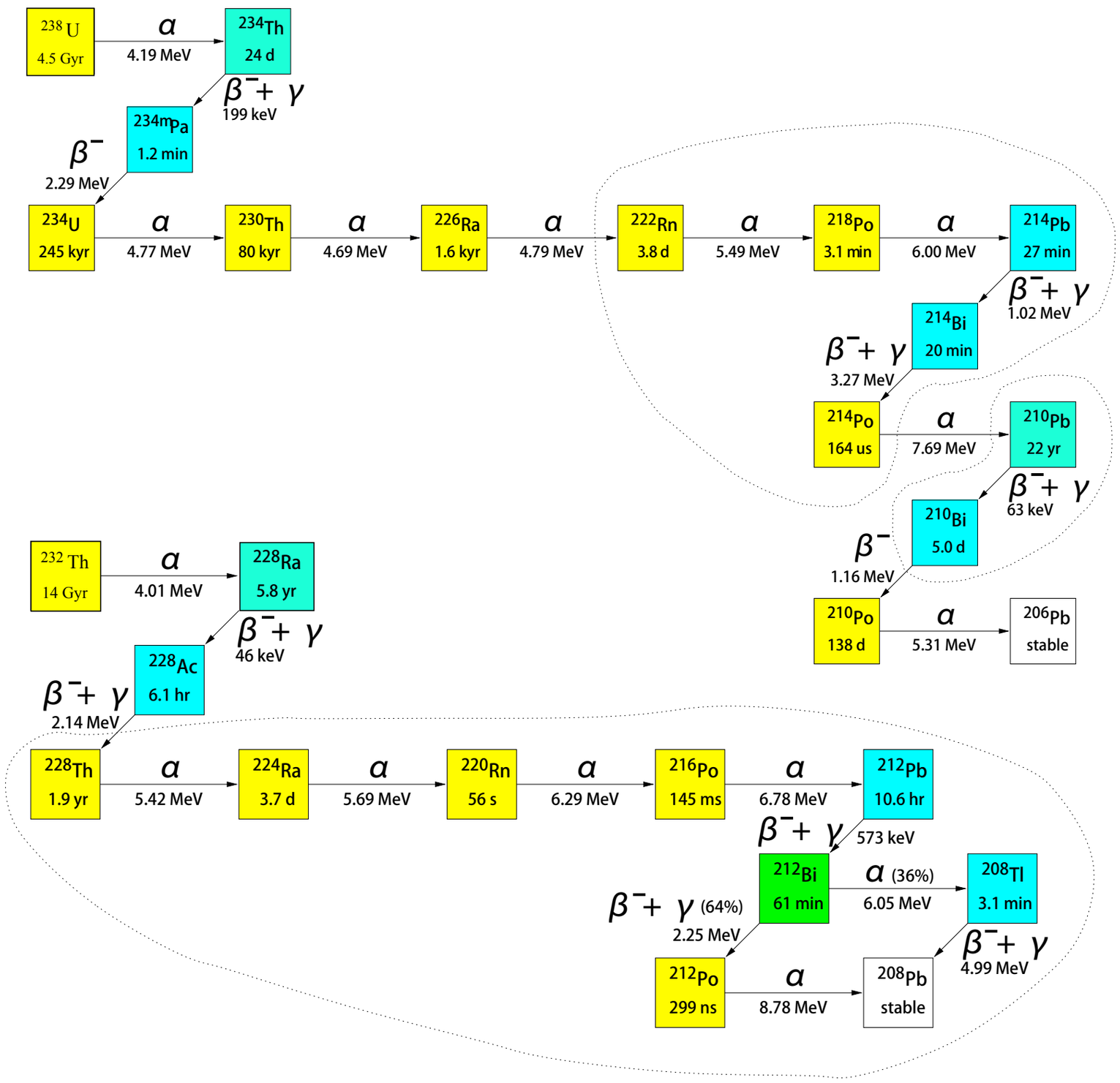


min LL for fit to data is -312. Fit is "good" and is fully consistent with null hypothesis.



ΔLL distribution follows expected χ^2 distribution. Validates method used to obtain limit.

U/Th decay chains



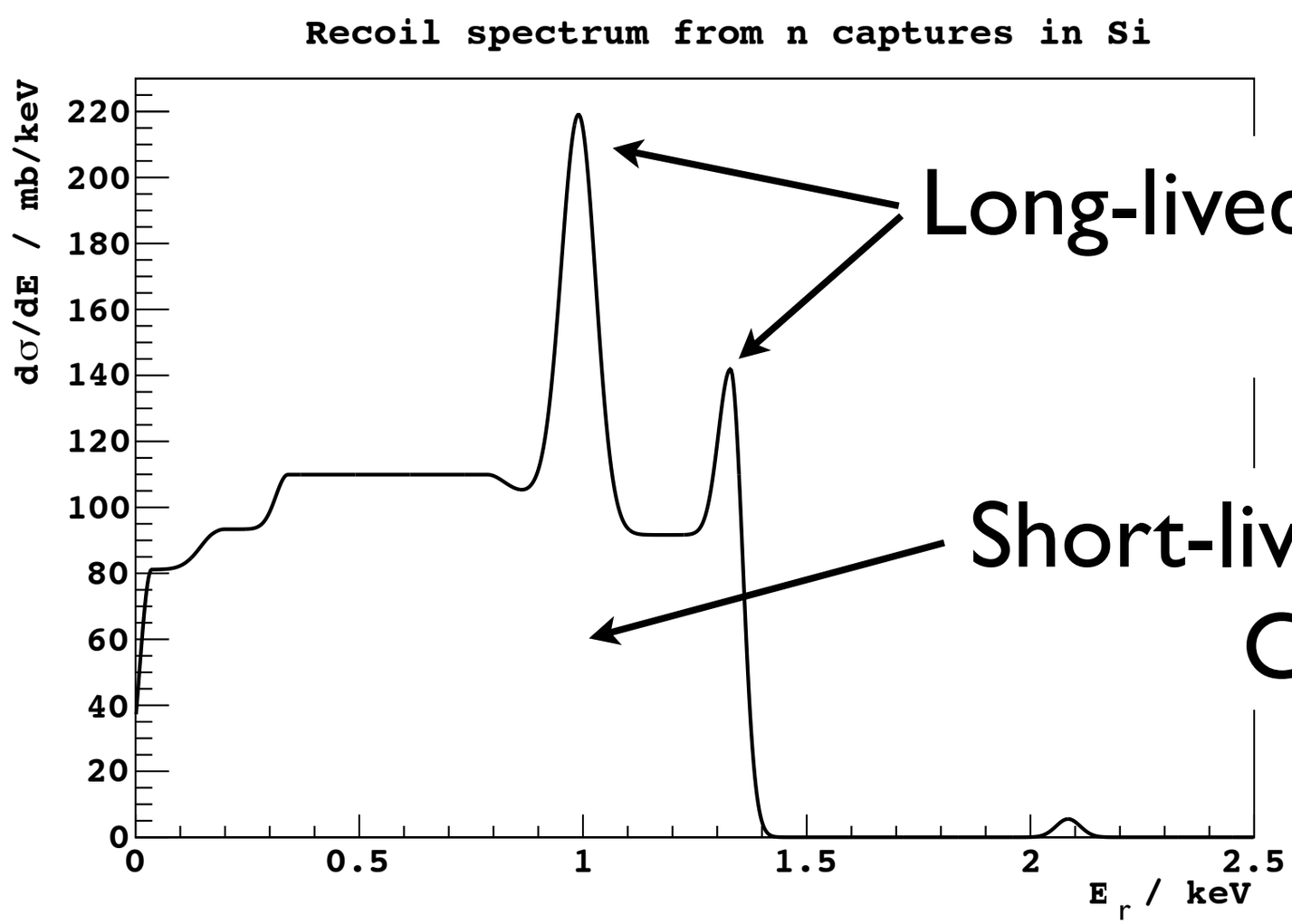
Thermal neutron capture

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

Cascade in coincidence

~MeV

Nucleus recoils ~keV



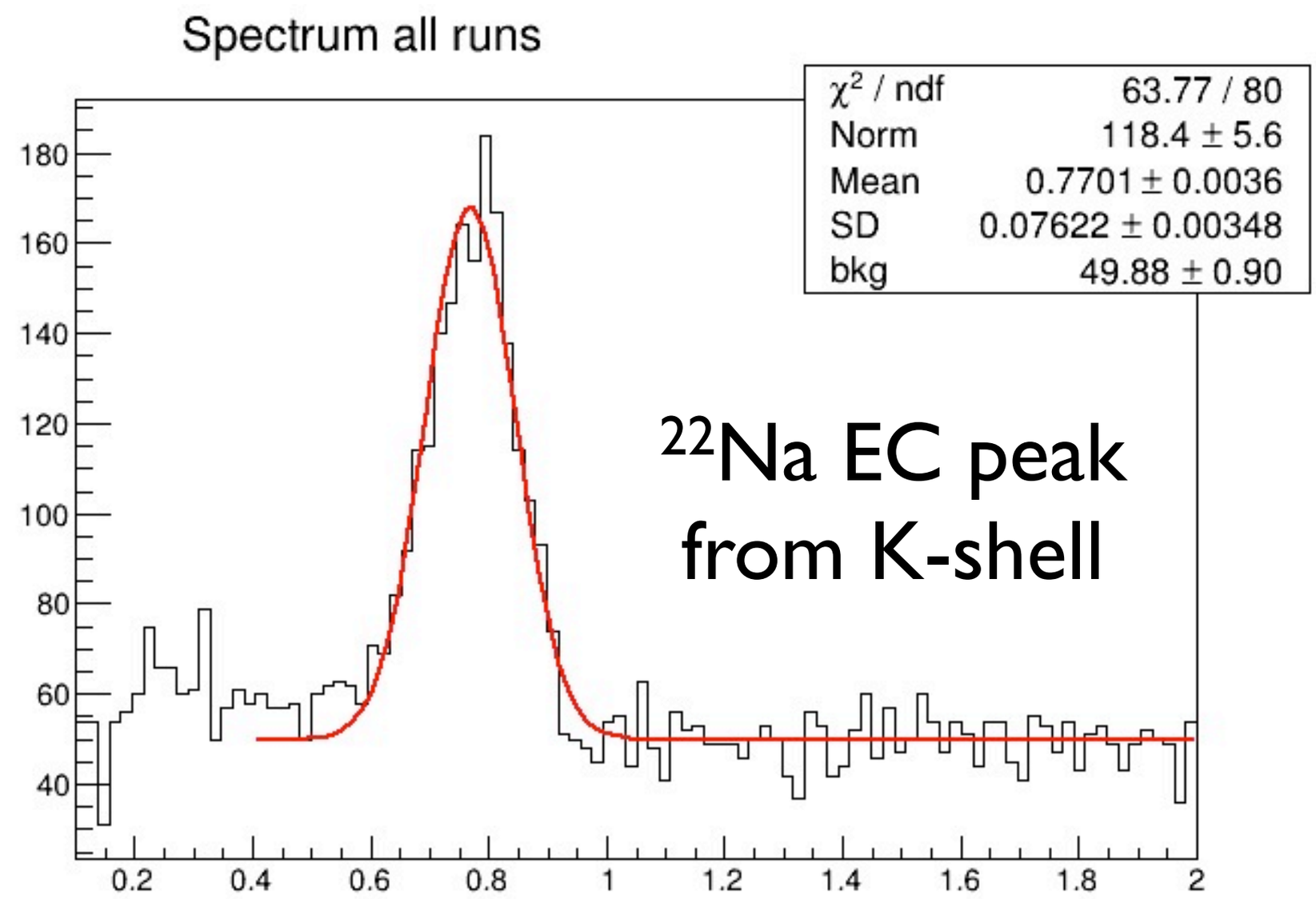
Long-lived nuclear states
Peaks

Short-lived nuclear states
Continuum

Activated CCD

CCD activated with proton beam: 2×10^{10} protons cm^{-2}

Look for shift from recoiling ^{22}Ne nucleus



n backgrounds

Source	Collisions in 5 g x 1000 days	Ref
μ in Shield	<0.1	BX ZEPLIN
Norite rock	<0.001	COUPP
(α,n) in shield	<0.1	ZEPLIN

COUPP-4 was "dirty" (4 kg of borosilicate glass with ppm of U, piezoelectric transducers next to active volume) and it saw ~0.25 bubbles $kg^{-1}d^{-1}$.
Even that level not a problem for us.