DAMIC: A direct dark matter search with CCDs

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Outline

- Cold dark matter.
- CCDs as particle detectors.
- Calibration of nuclear recoil energy scale.
- SNOLAB installation.
- Exclusion limit with 2015 data.
- Radioactivity measurements.
- DAMIC100 status.
- Toward a kg-scale CCD experiment.
- Other applications: Helioscopes for axions, etc.

It’s great to be back!

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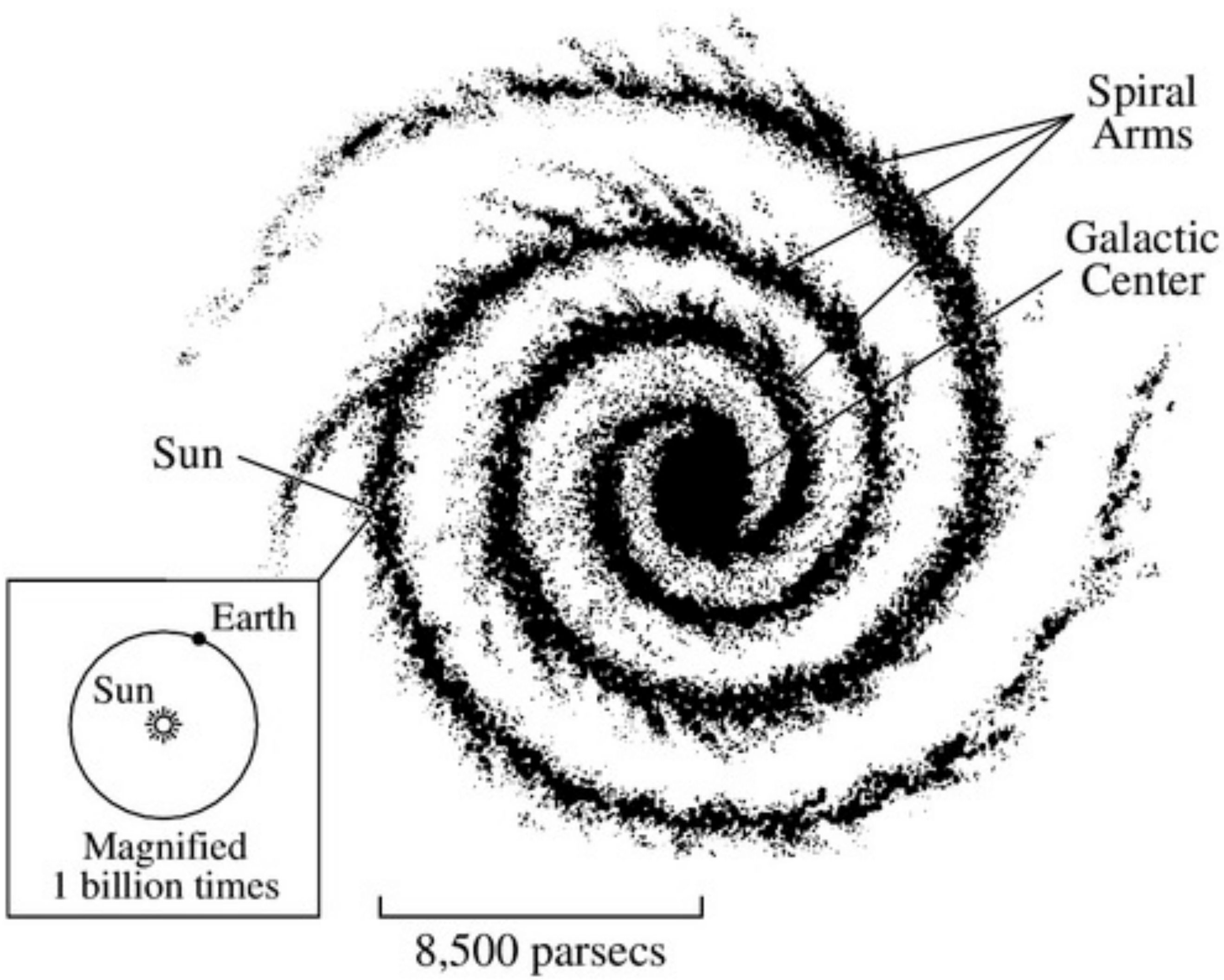
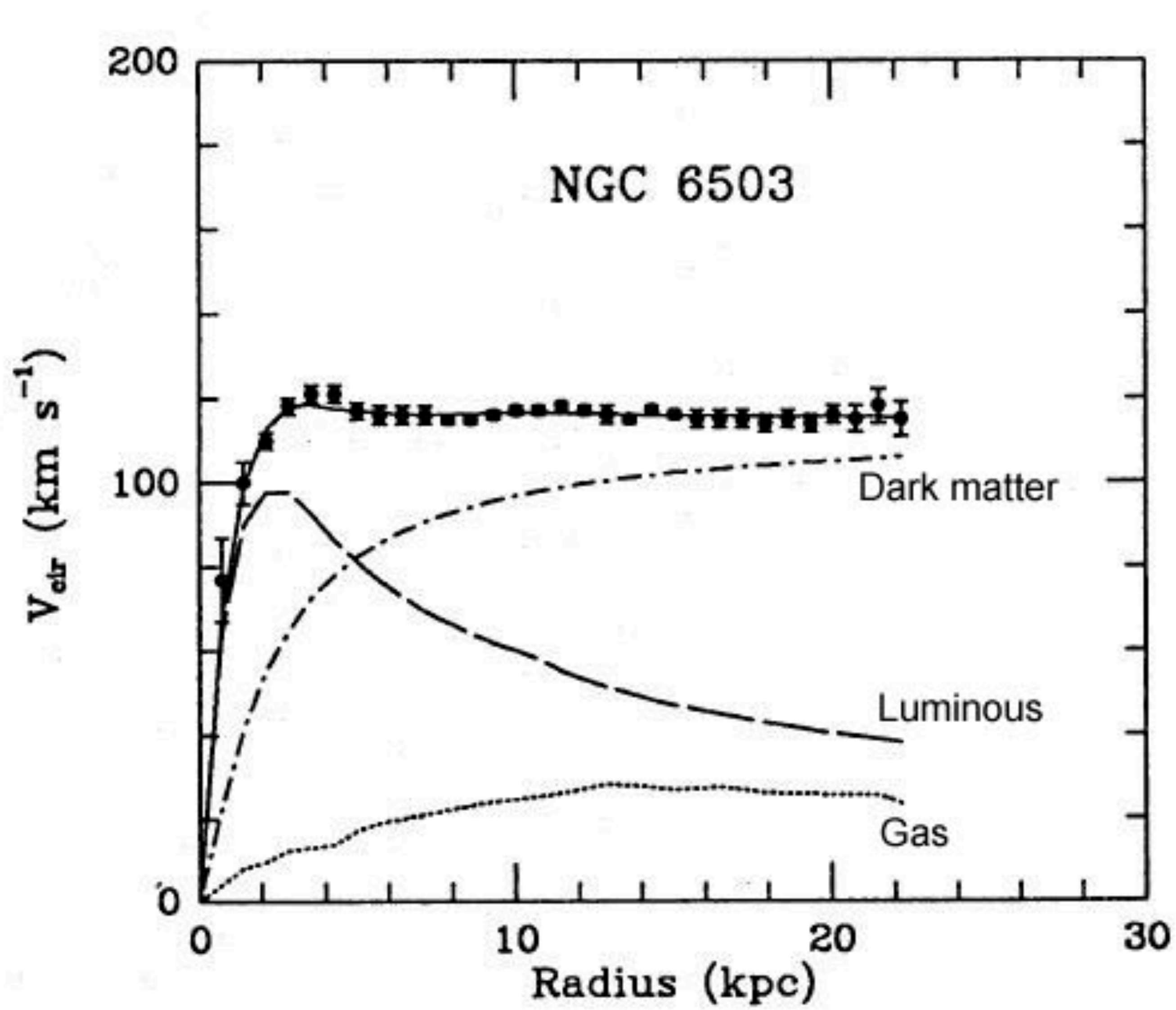
First Evidence of *pep* Solar Neutrinos by Direct Detection in Borexino

G. Bellini,[1] J. Benziger,[2] D. Bick,[3] S. Bonetti,[1] G. Bonfini,[4] D. Bravo,[5] M. Buizza Avanzini,[1] B. Caccianiga,[1] L. Cadonati,[6] F. Calaprice,[7] C. Carraro,[8] P. Cavalcante,[4] A. Chavarria,[7] A. Chepurnov,[9] D. D’Angelo,[1] S. Davini,[8,10] A. Derbin,[11] …

Dark matter





The centripetal force exerted on the "Sun" cannot be explained by stars and gas.

Dark matter

- Cold dark matter is inferred from cosmology...
- ... and formation of galaxies and clusters of galaxies...
- ... and evident from gravitational lensing.
- Overall 5.5 times more dark than baryonic matter.
- Local density ~0.3 GeV cm^{-3}.

This is a **big** problem for particle physics.

The dark matter is all around us.

It could be made of particles...

... that could interact with Standard Model Particles.

Look close enough, we might be able to notice its interactions with baryonic matter on Earth.

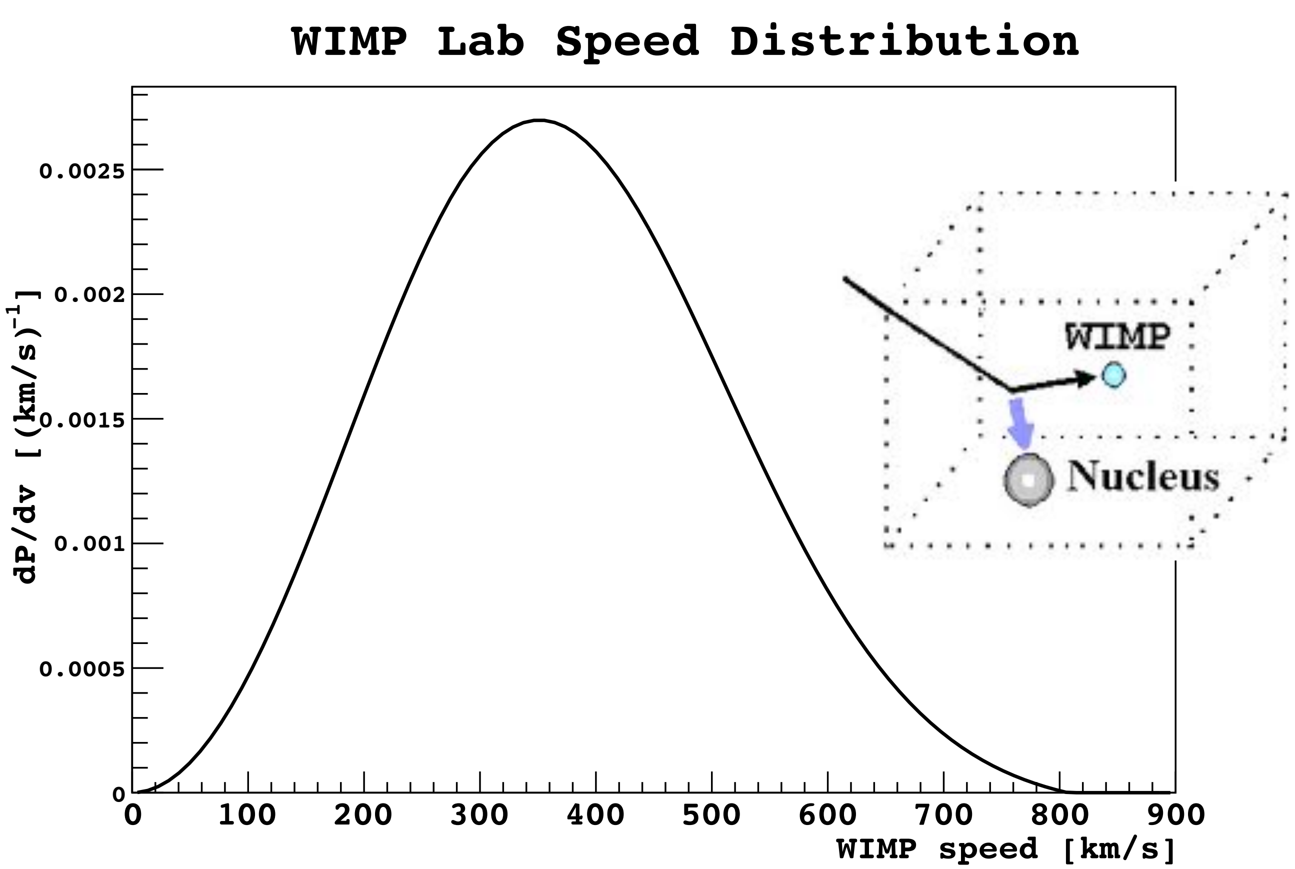
What is the signal?

- We do not know the mass of the dark matter particles.
- We do not know by what mechanism the dark matter abundance in the Universe arose.
- We do not know by what mechanism dark matter interacts with baryonic matter.
- Without a physics model it is not straightforward to compare constraints from different physical processes e.g. production at colliders, annihilation in dwarf galaxies, direct detection experiments.
- Very little guidance from theory and other experiments.

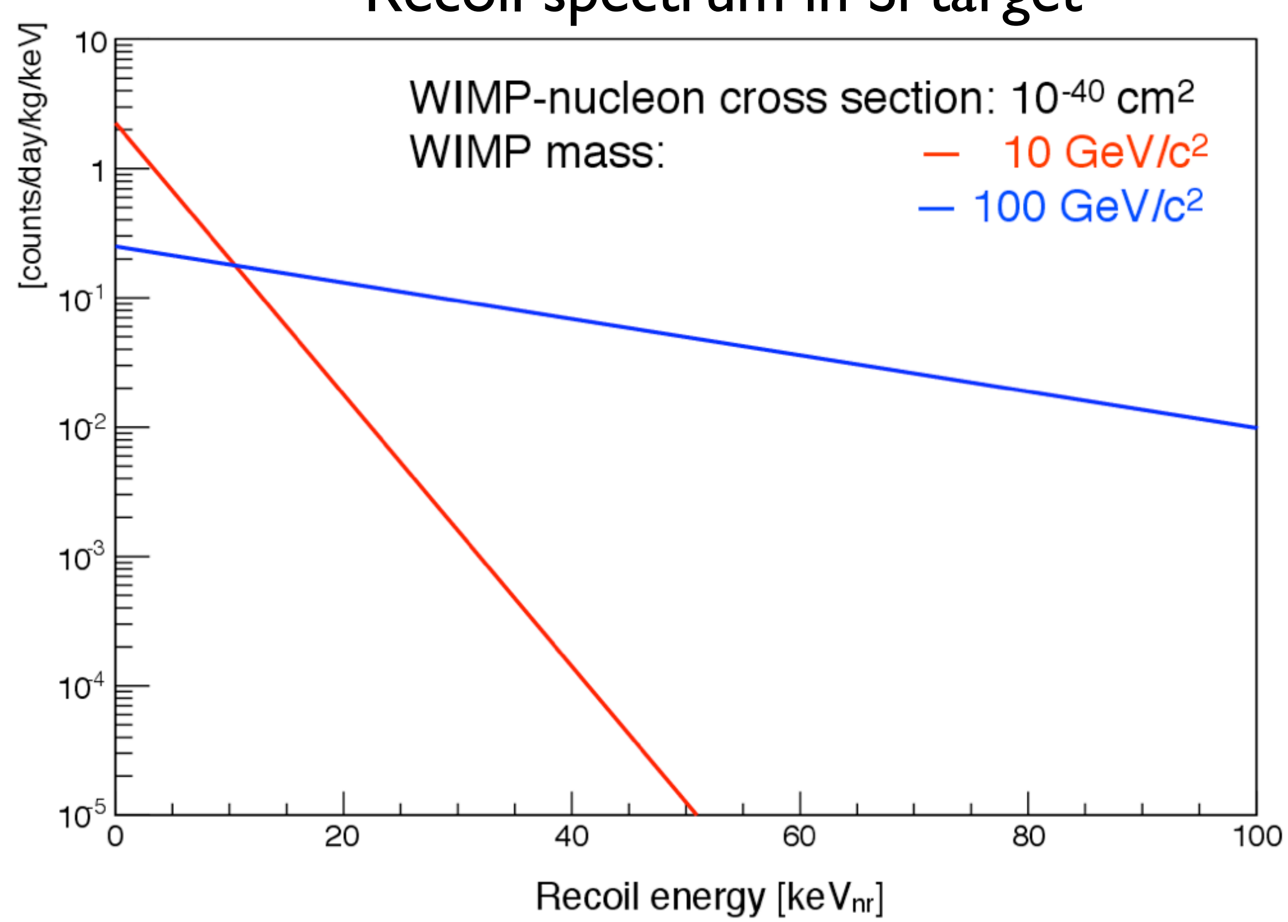
Signal

WIMP: Weakly interacting massive particle is a leading dark matter candidate, $\sigma < 1$ nb (10^{-33} cm^2).

Event rate from 0 to ~10^4 g^{-1} d^{-1}



Recoil spectrum in Si target

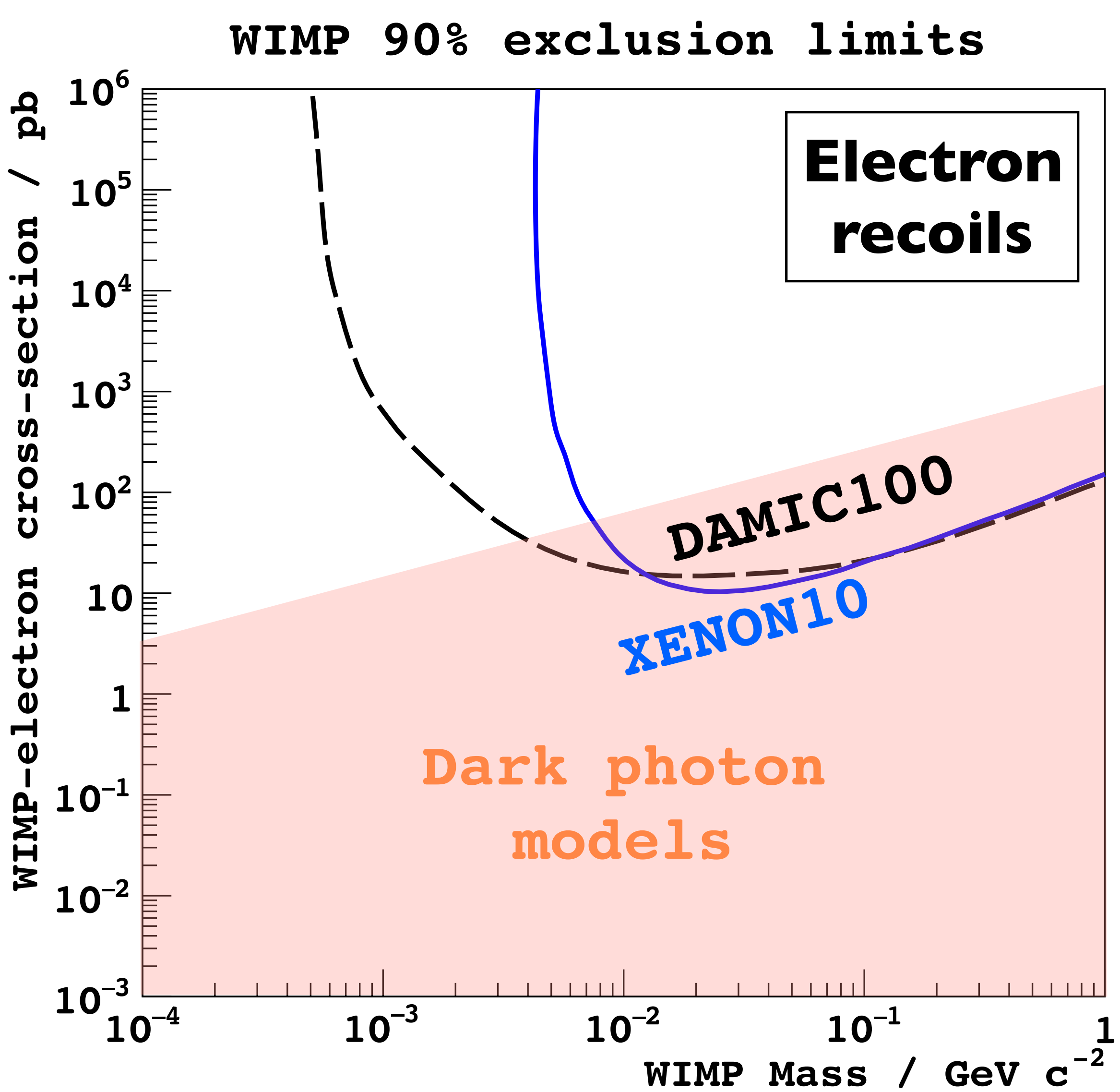


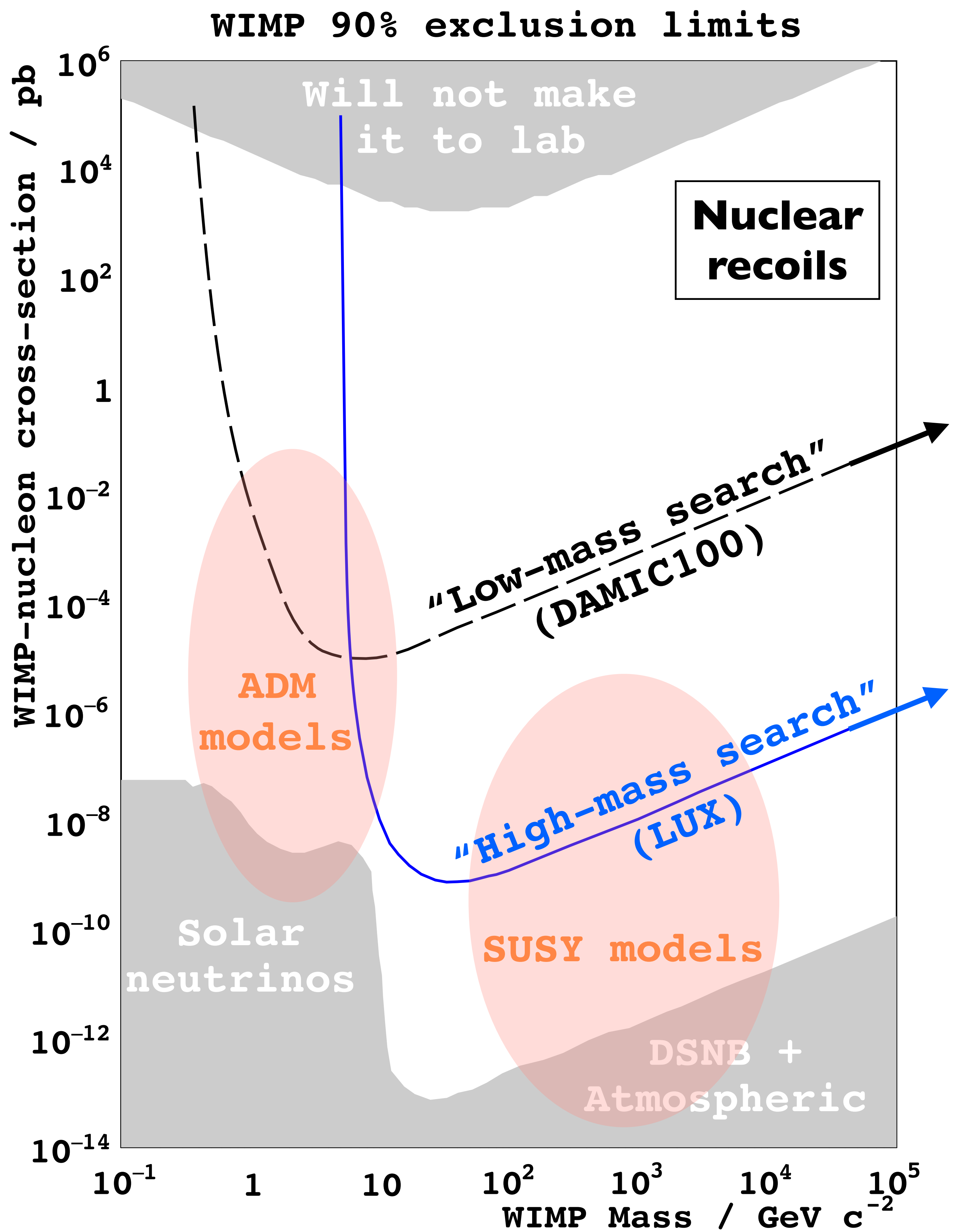
Strategy

- Detector with lowest possible energy threshold (especially in nuclear recoil energies).
- Experiment with large exposure. Up to ton-year.
- Correspondingly low backgrounds from cosmic rays and natural radioactivity. Measured in dru (events keV^{-1} kg^{-1} d^{-1}).
- Multiple targets and technologies to explore more parameter space, avoid unexpected nuclear effects.

Strategy

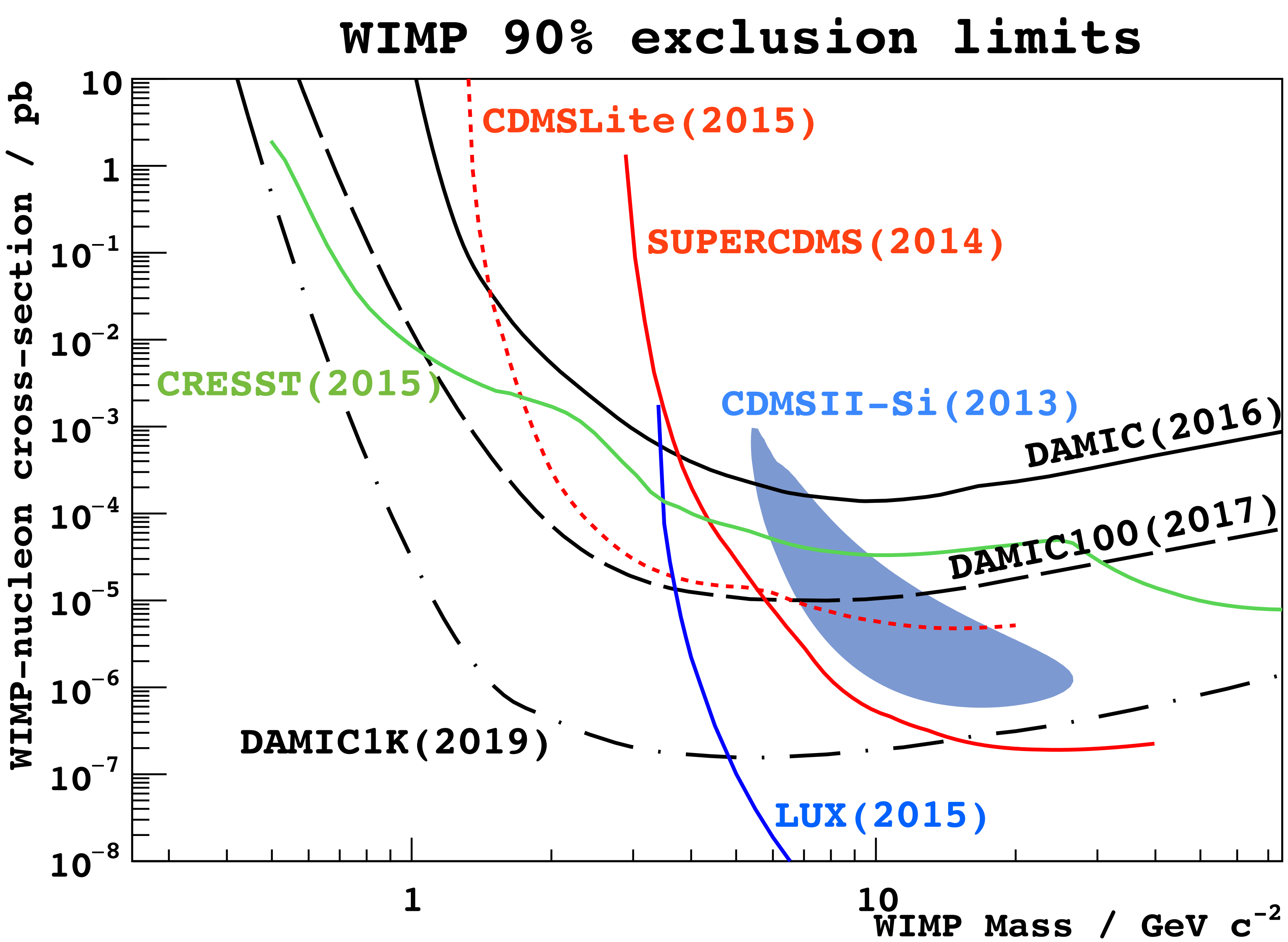
Spin-independent elastic scattering.
There are *many* other possibilities.

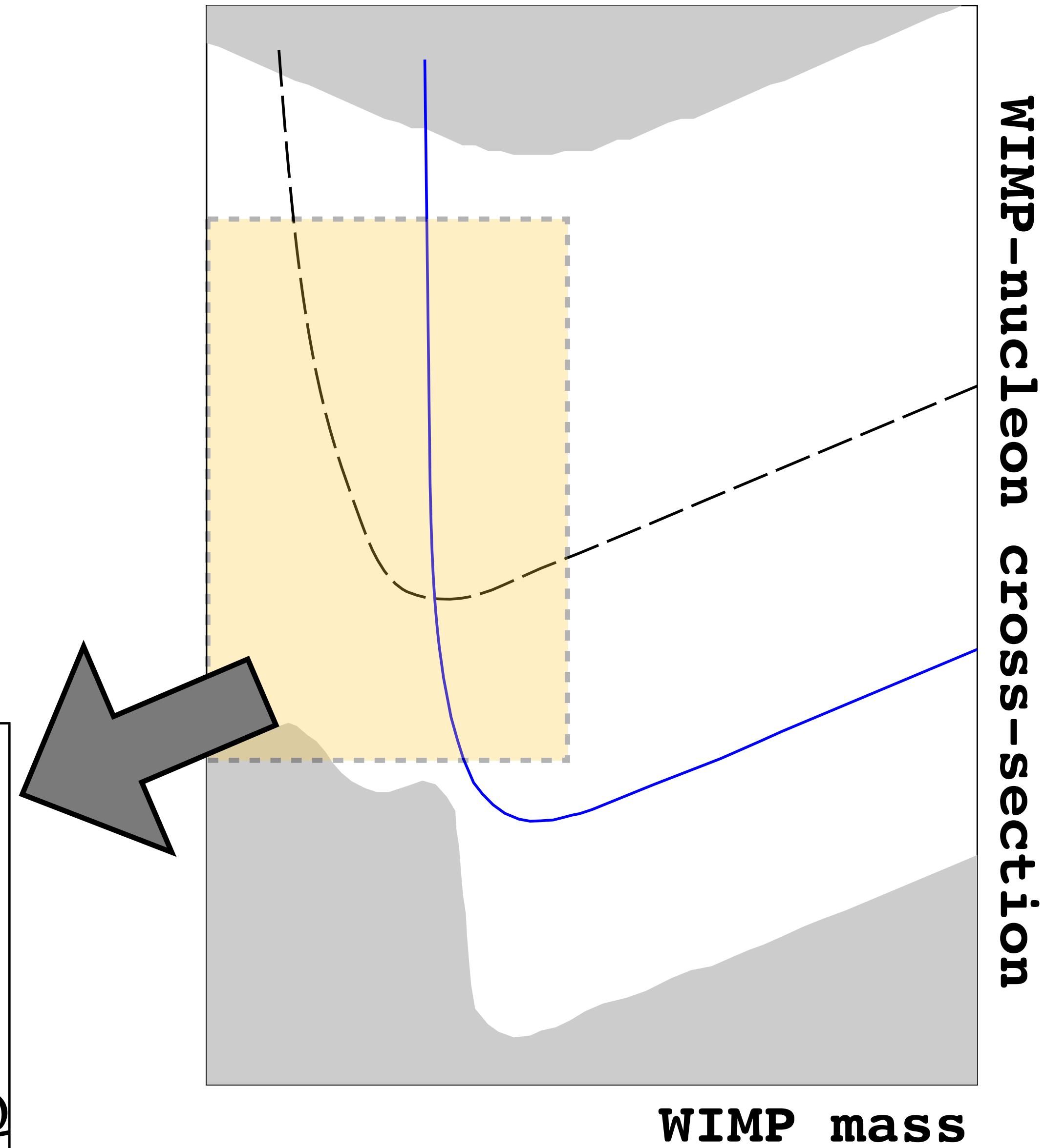




DAMIC

Charge-coupled devices (CCDs) as low threshold, low background particle detectors.

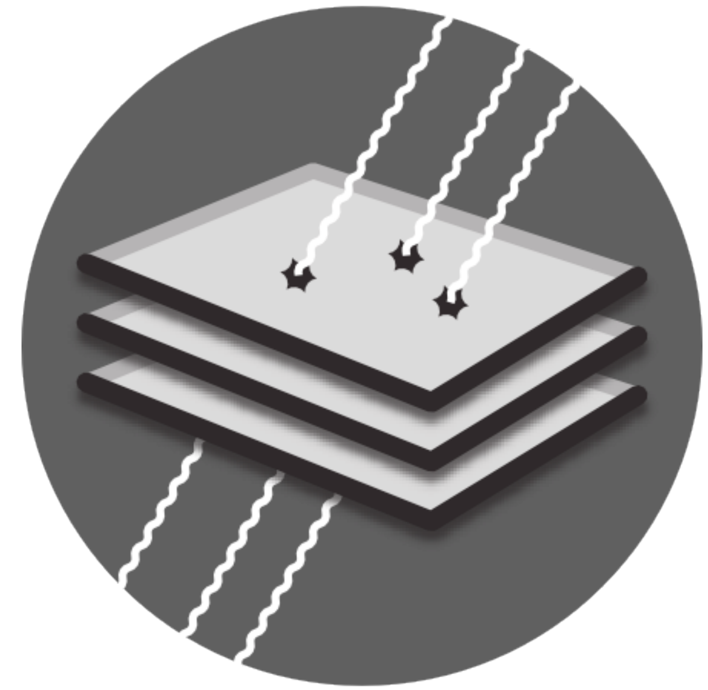




Will directly probe the possible signal in CDMS II-Si.

DAMIC Collaboration

- International collaboration:
  U Chicago, **Fermilab**,
  LPNHE-Paris, SNOLAB,
  U Zurich, Michigan,
  UNAM, FIUNA, CAB, UFRJ.

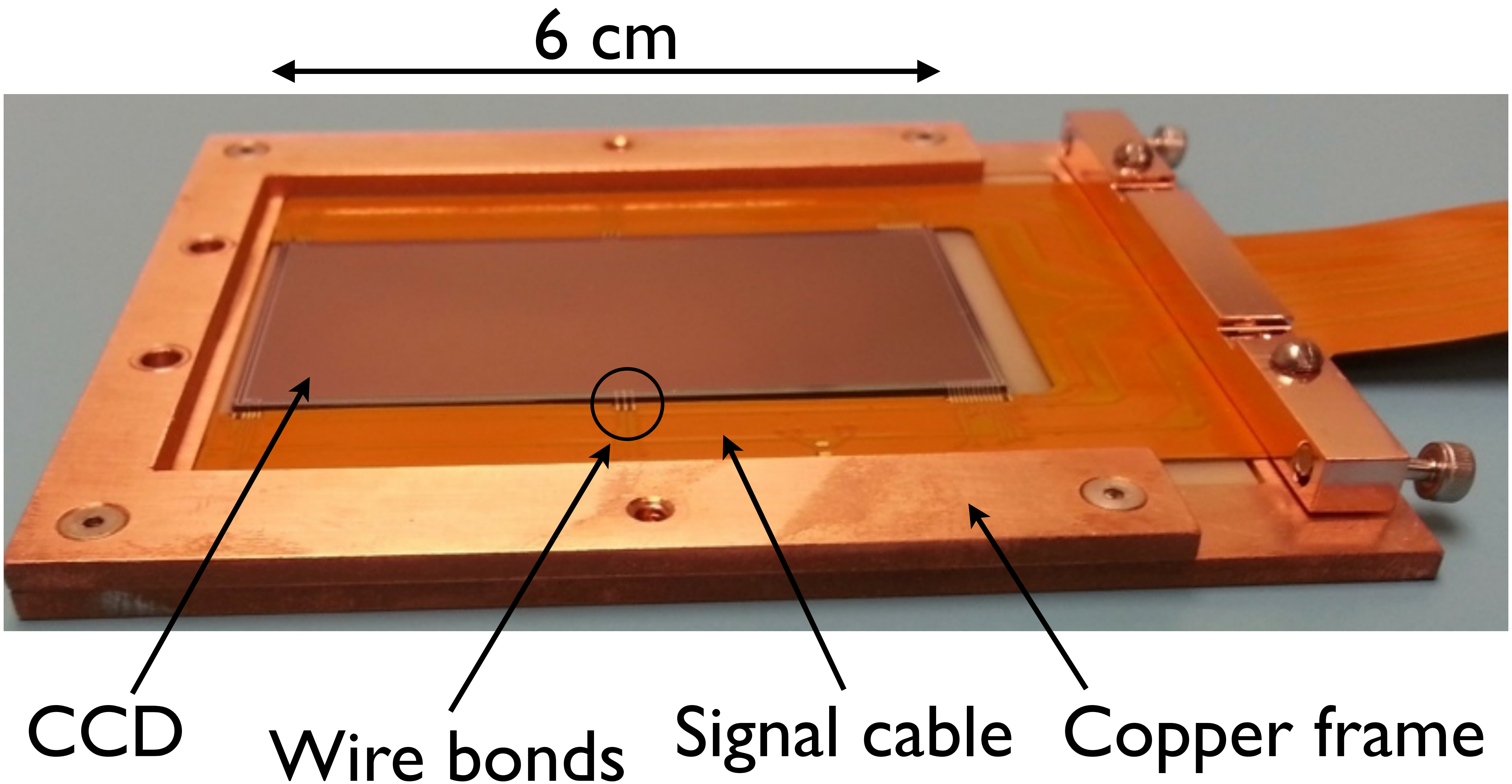


Physicists with experience from low energy particle physics to cosmology (optical astronomy) to colliders to ultra high-energy cosmic rays.

Why CCDs?

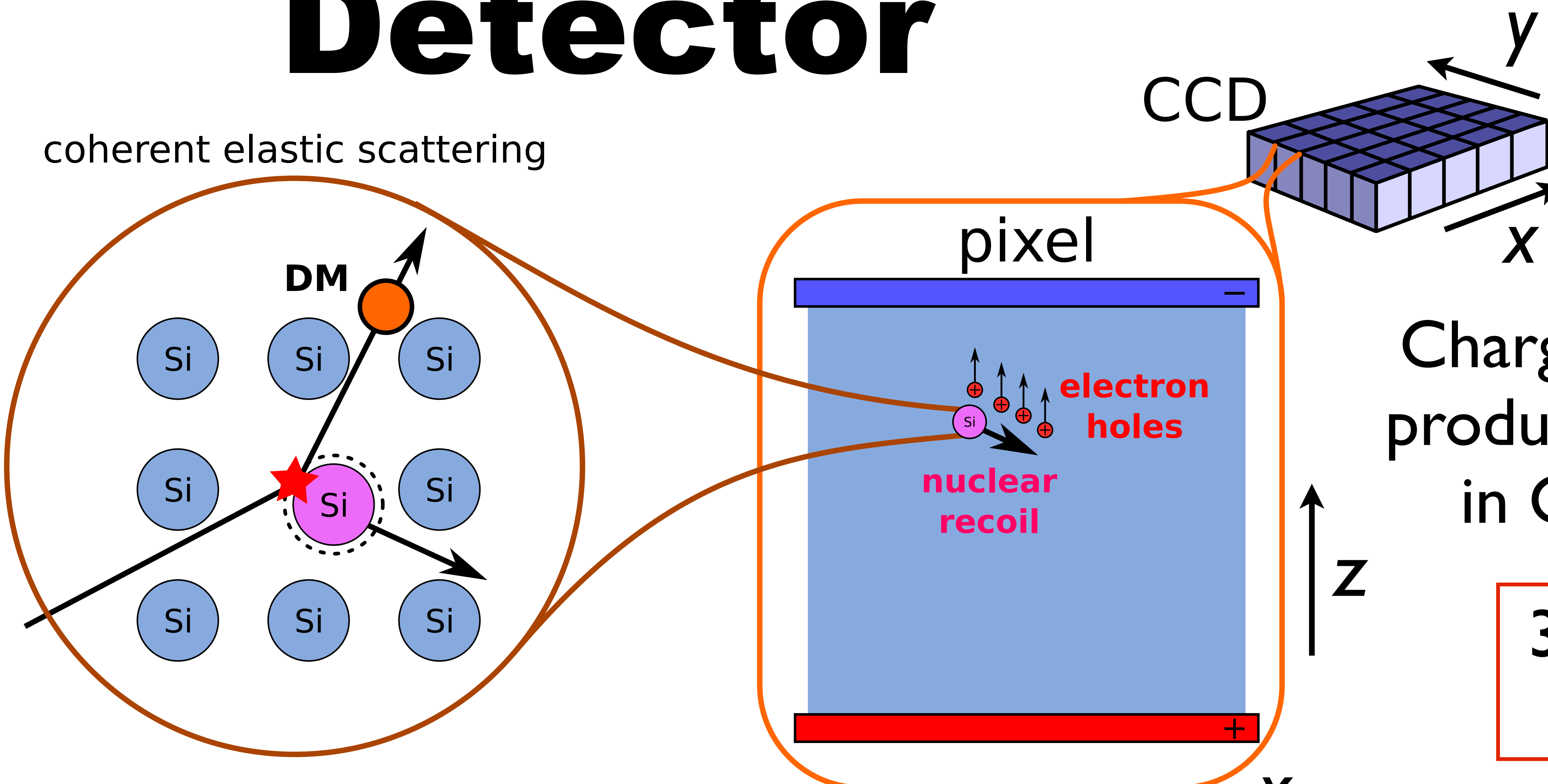
- Lowest threshold ionization detector 50 eV_{ee}.
- Tried-and-true technology (CCDs used extensively in astronomy since the 80s).
- Fully active device, no regions of partial charge/signal collection.
- Scalable: Manufactured at large volumes with standard CMOS technology. Inexpensive (3 k$ per 6 g device). Read-out can be multiplexed.
- Fabricated in highest-resistivity (purity) silicon in semiconductor fab. Expect very low radioactive contamination in device.
- Robust, easy to operate (great performance with commercial electronics), easy cryogenics (130 K).
- Smart investment: Further development of the technology has applications beyond dark matter searches.

Charge-coupled device



CCDs revolutionized astronomy!
2009 Nobel Prize in Physics.

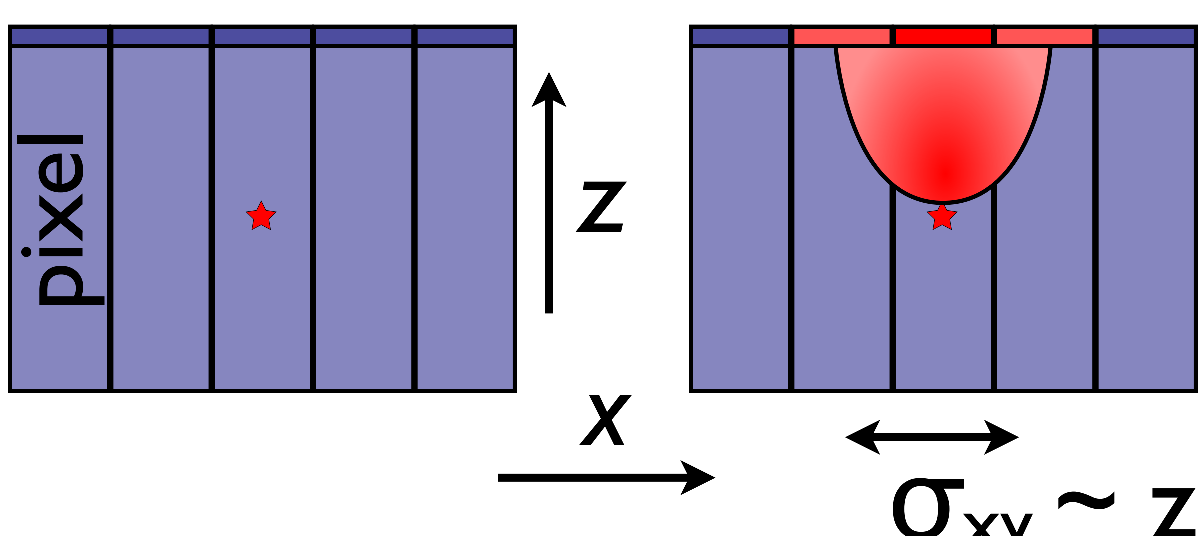
Detector

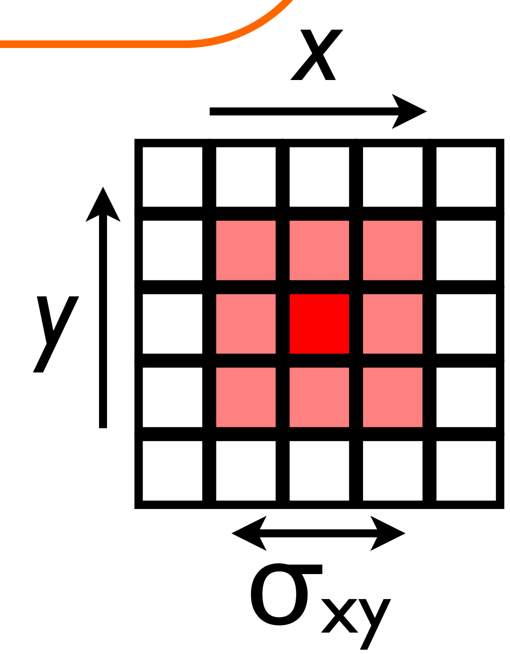


Charged particles produce ionization in CCD bulk.

3.62 eV for e-h pair.

Charge drifted up and held at gates.





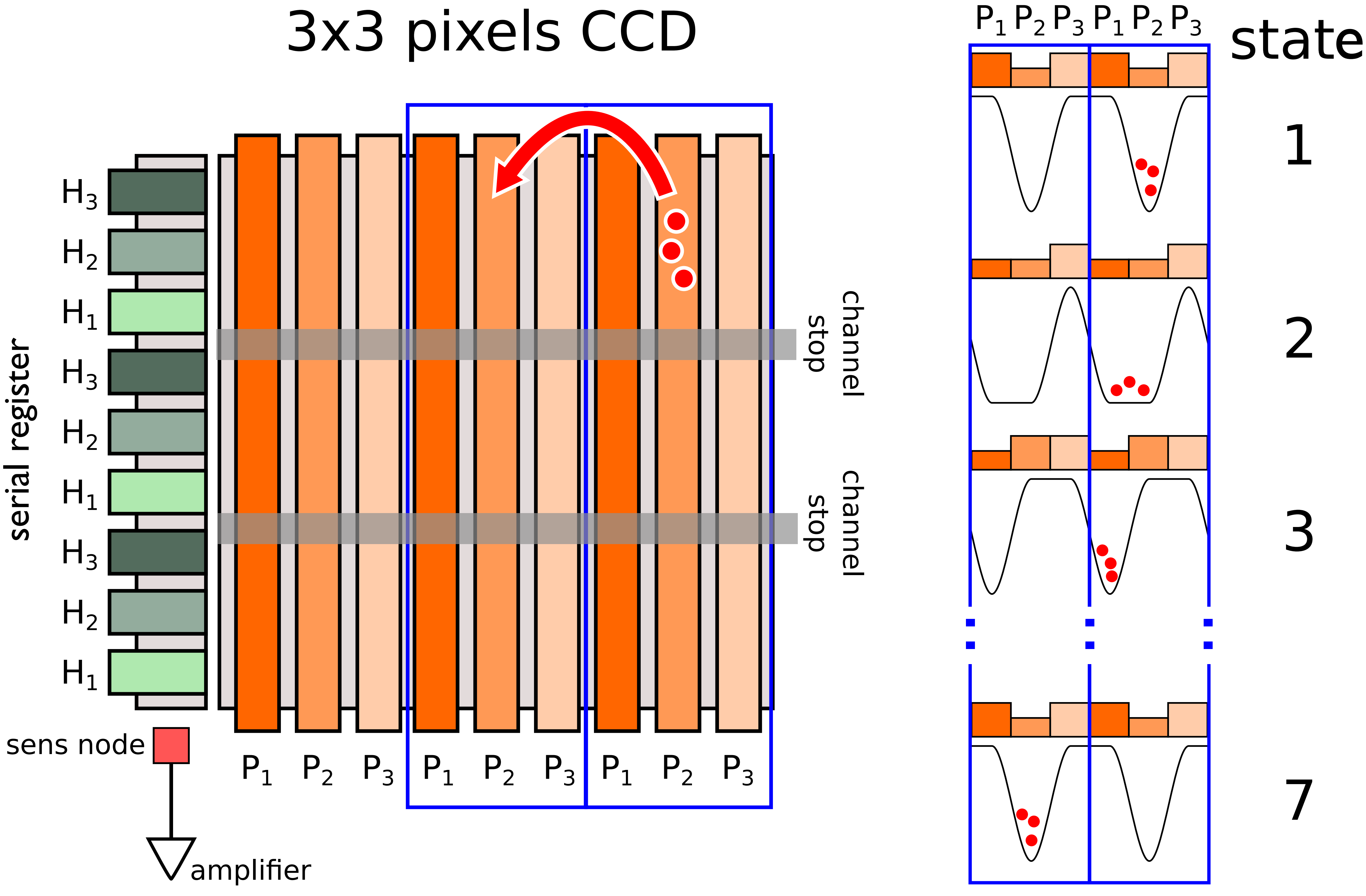
Charge collected by each pixel on CCD plane is read out.

~2 e^- RMS read-out noise.

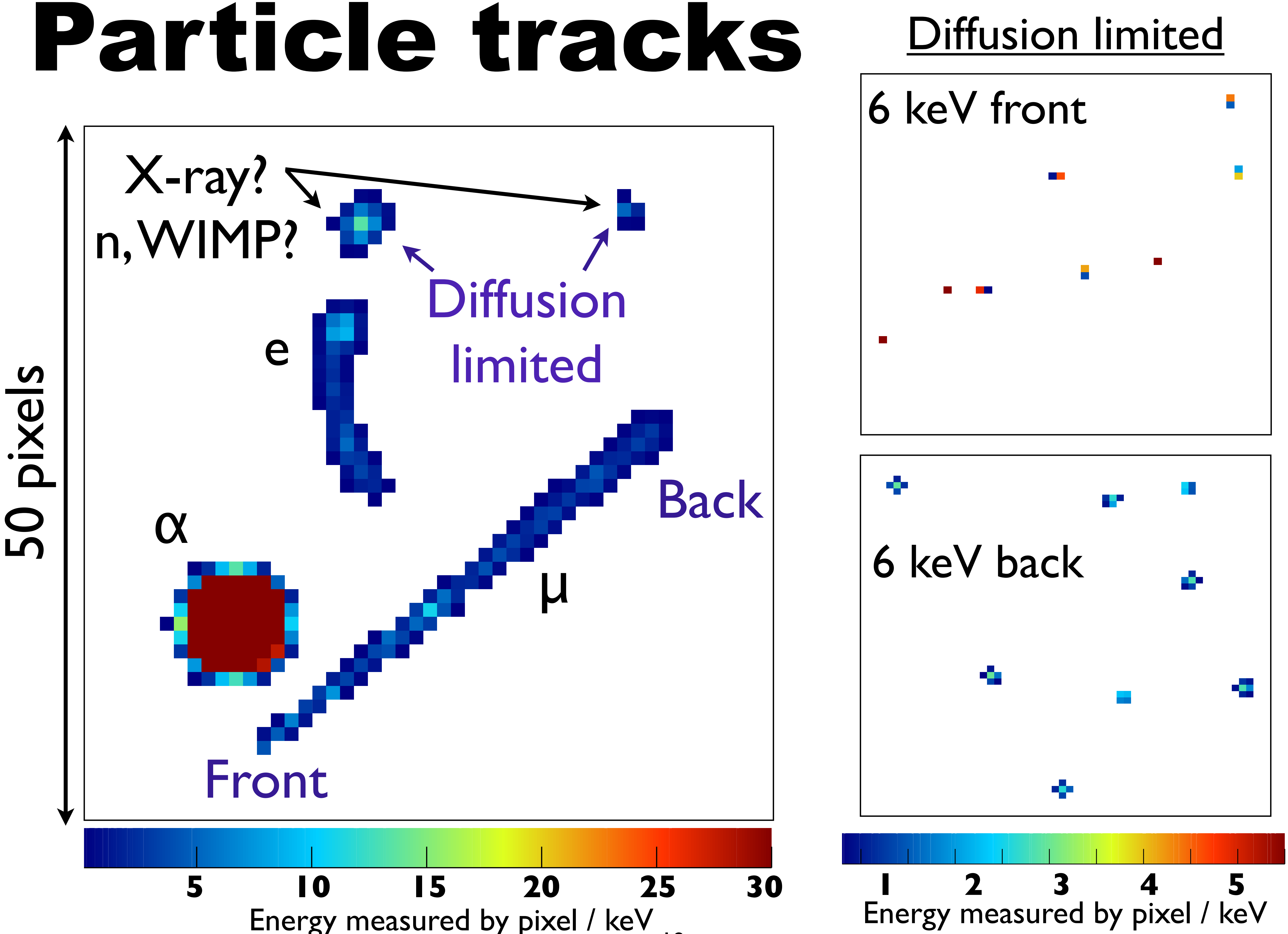
CCDs are not triggered

- The CCD is exposed for a set period of time (usually hours or days).
- *All* charge produced in the silicon bulk is collected on the pixel array.
- There is no ‘hardware’ energy threshold.
- Very weak signals (e.g. single electron ionization) can be integrated for long periods to be detectable above read-out noise.

CCD readout

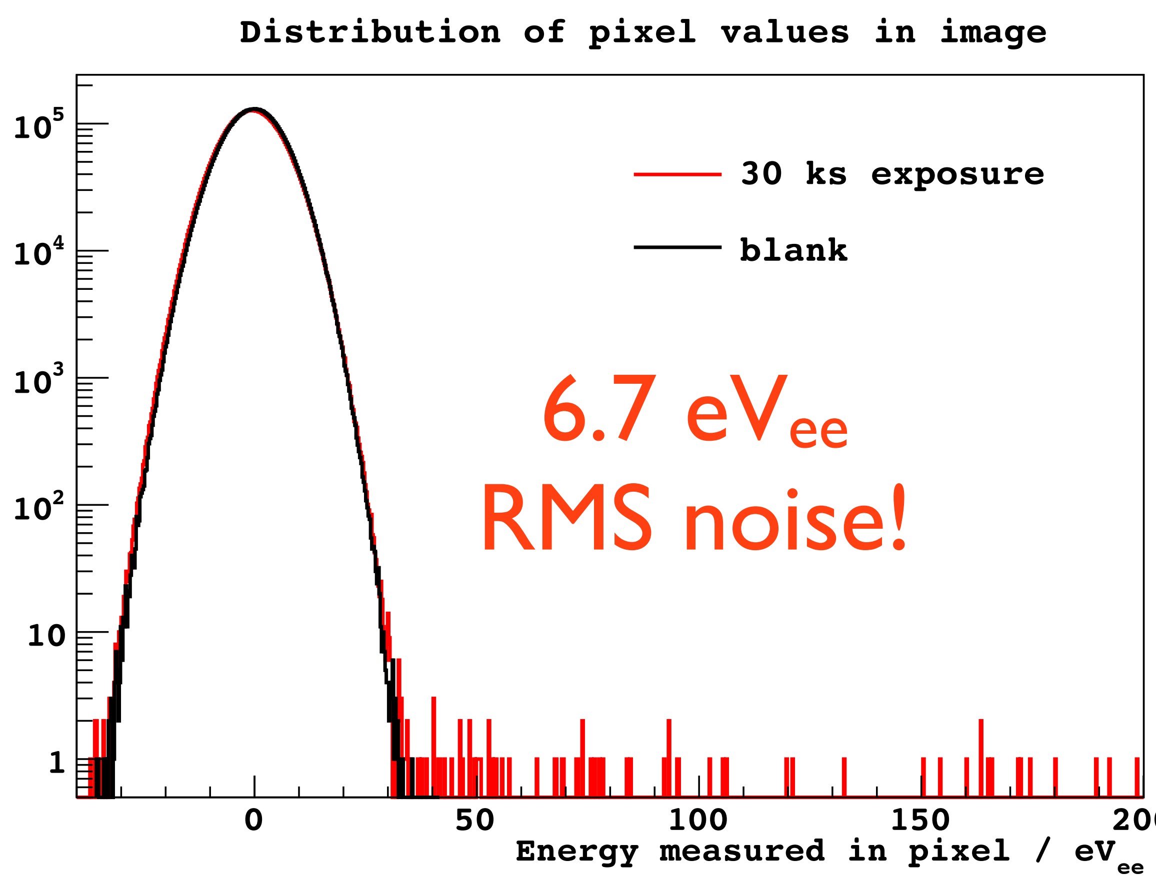

3x3 pixels CCD
serial register
H3
H2
H1
H3
H2
H1
H3
H2
H1
sens node
amplifier
P1 P2 P3 P1 P2 P3 P1 P2 P3
channel stop
channel stop
P1 P2 P3 P1 P2 P3
state
1
2
3
7

Particle tracks

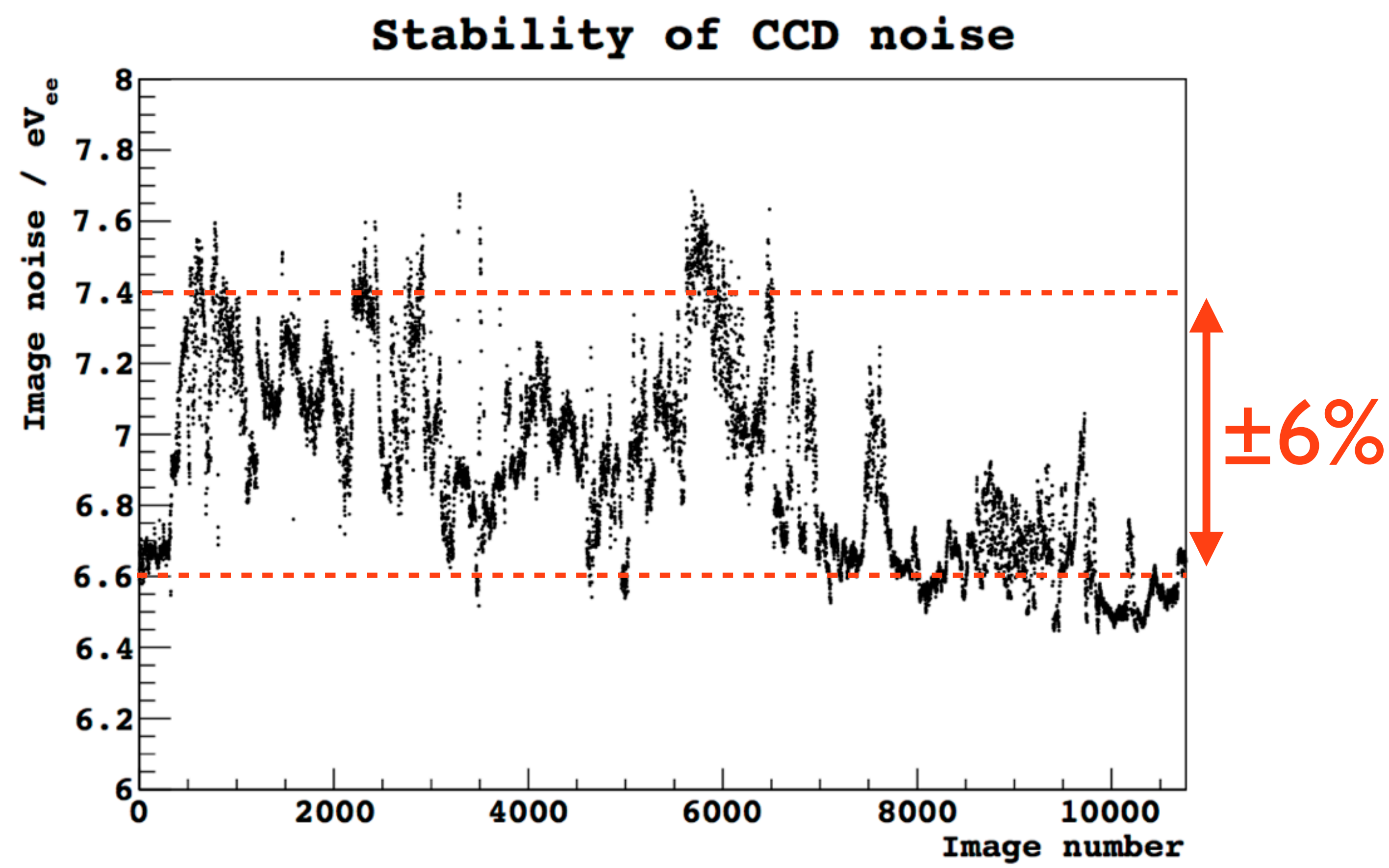


CCD Performance

CCDs are manufactured with very high resistivity silicon:
Low radioactive backgrounds.
Low dark current ($<10^{-3}$ e^{-} / pix / day).
Very few defects in the silicon lattice.

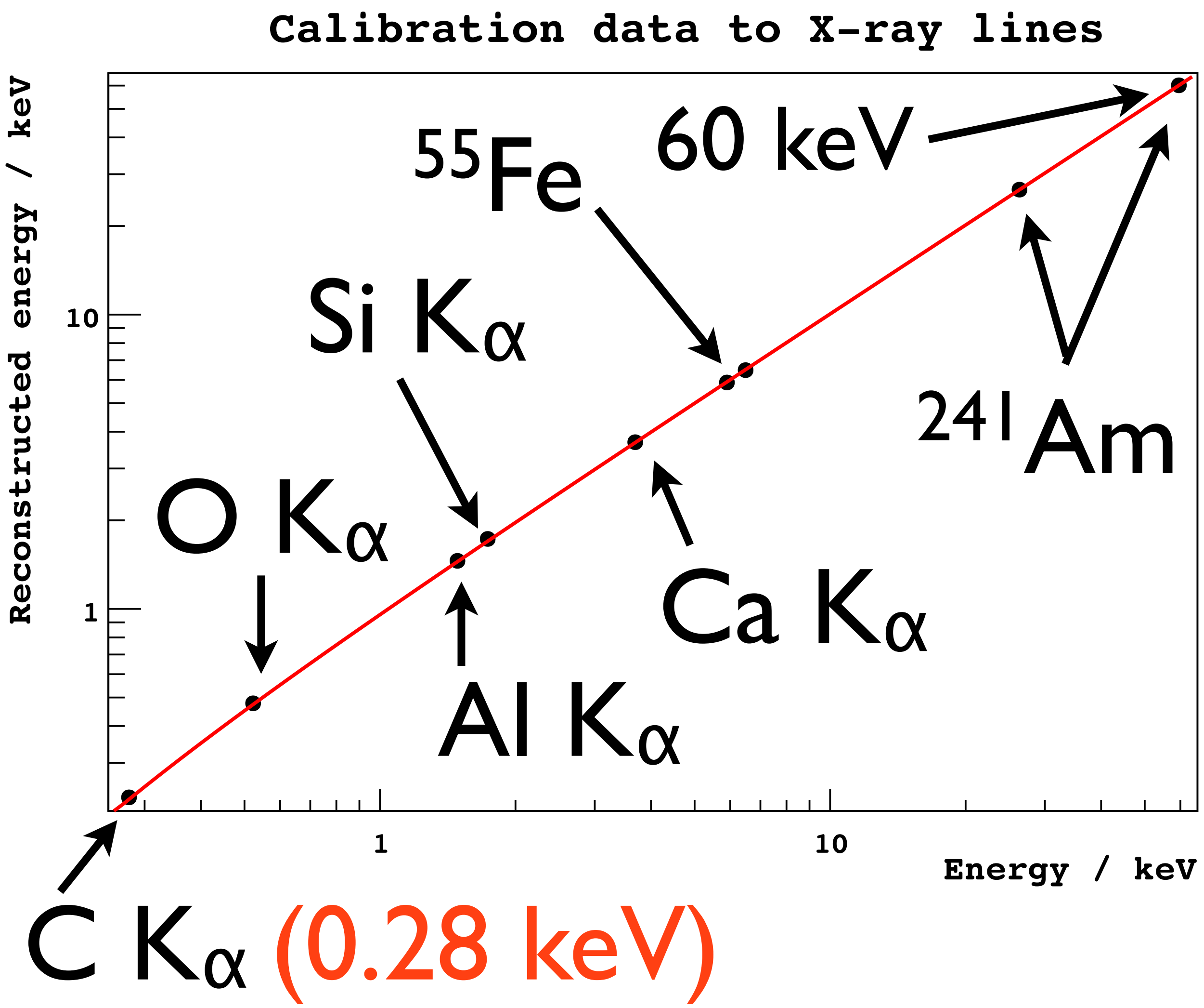


>95% of the image good quality.



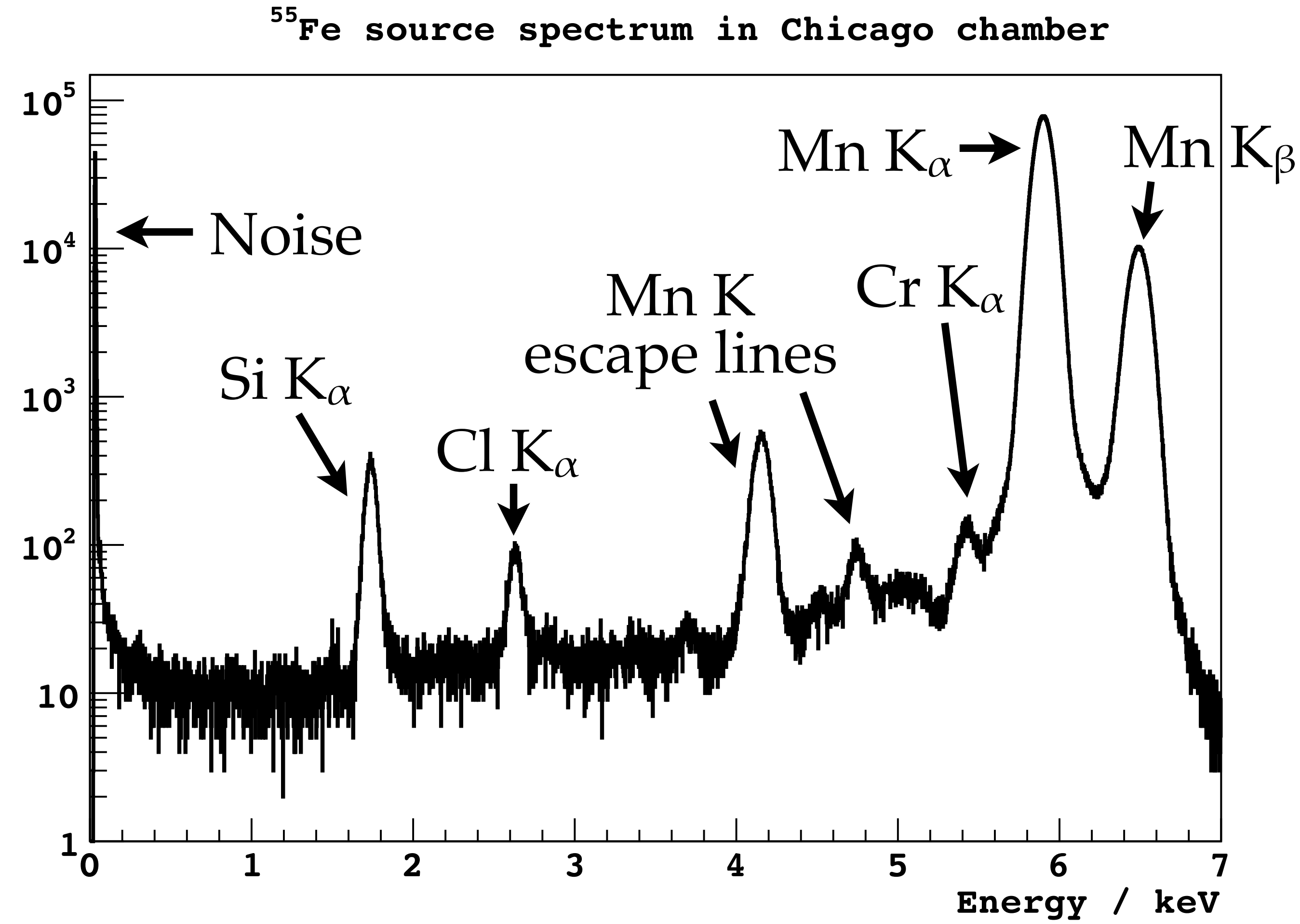
10794 images acquired over 126 days. All good.

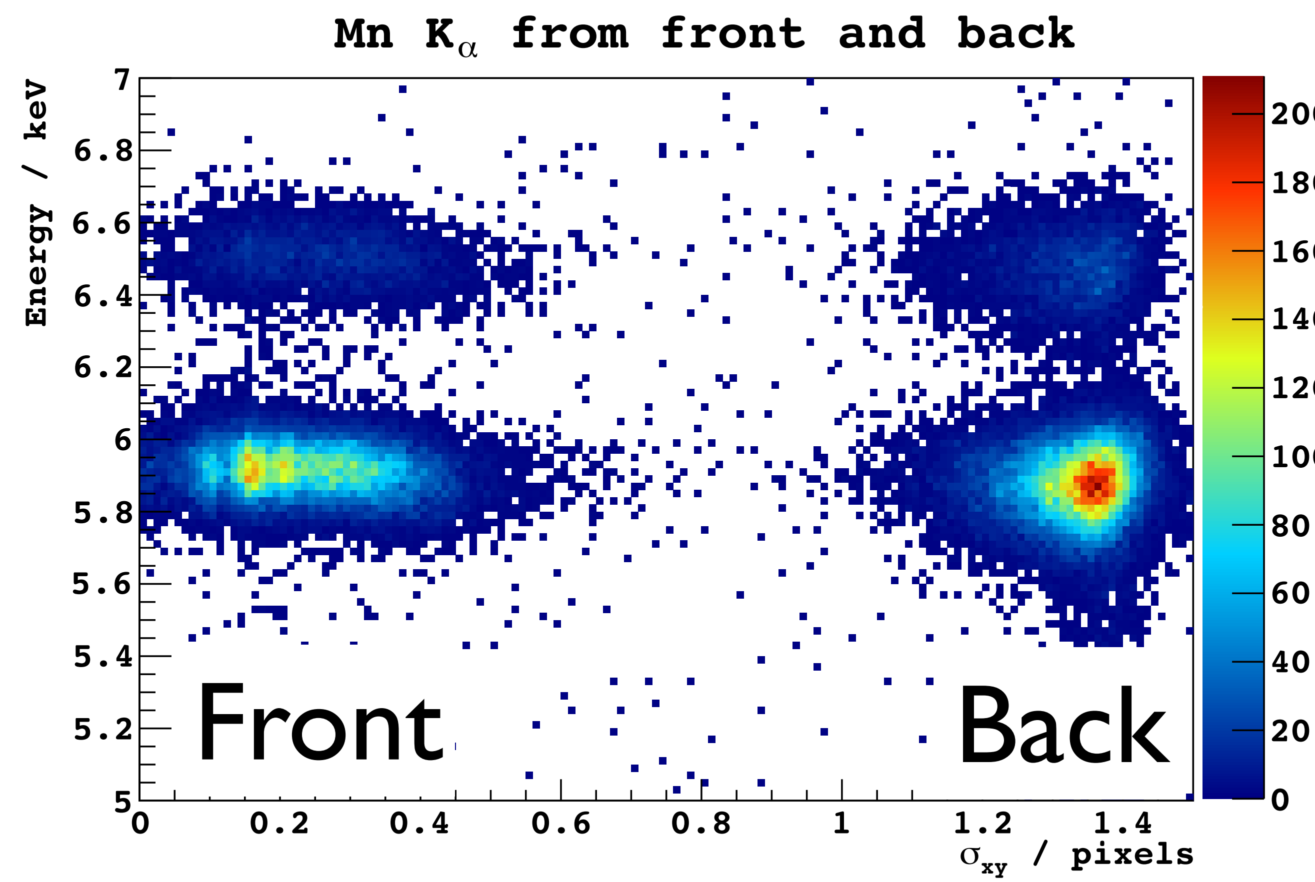
X-rays



E resolution:
53 eV at 5.9 keV from front!
Fano = 0.13.

Depth reconstruction.

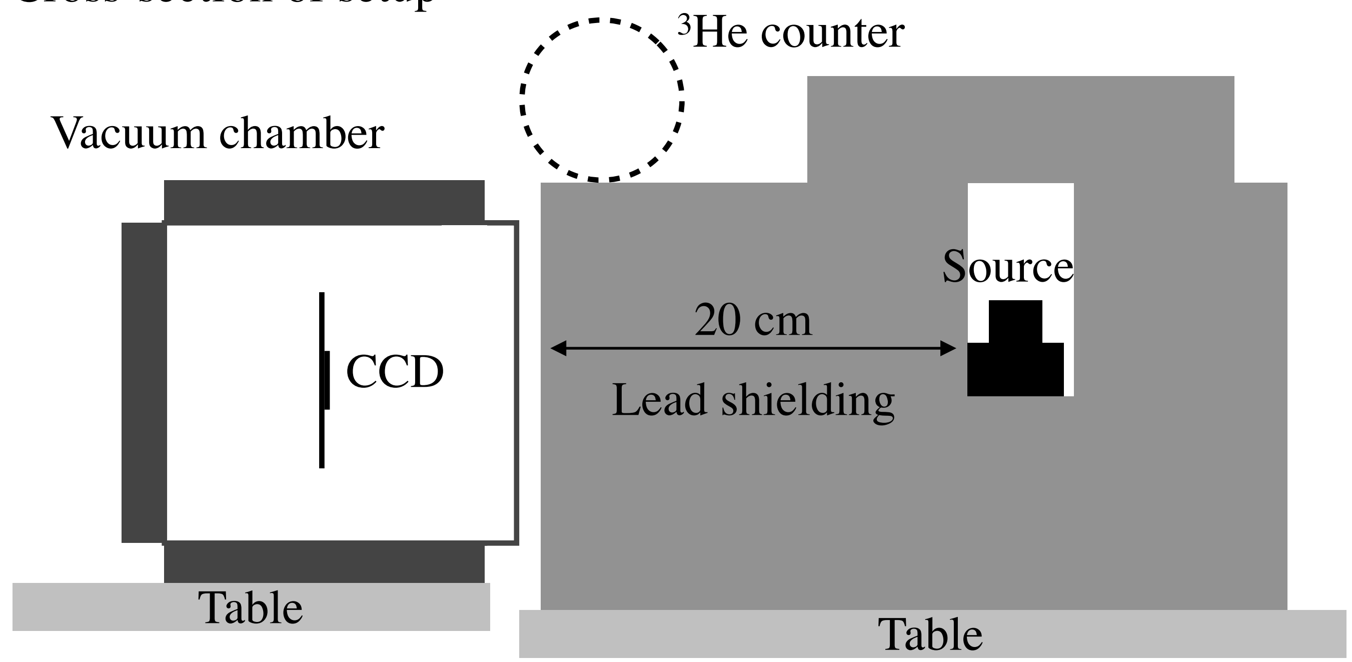




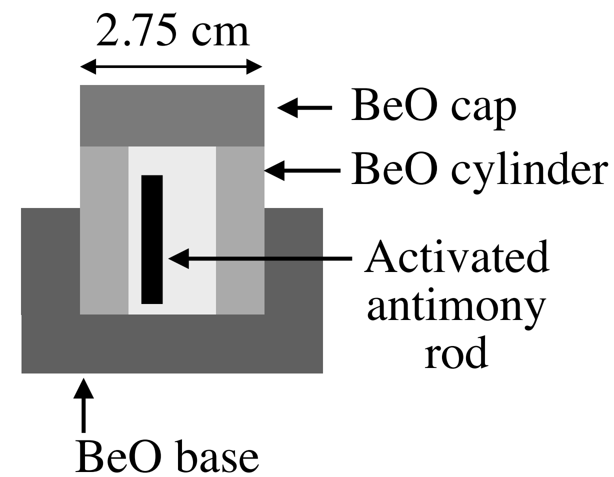
$\sigma_{xy} = 1.4 \longrightarrow z = 675\ \mu m$

Nuclear recoil calibration

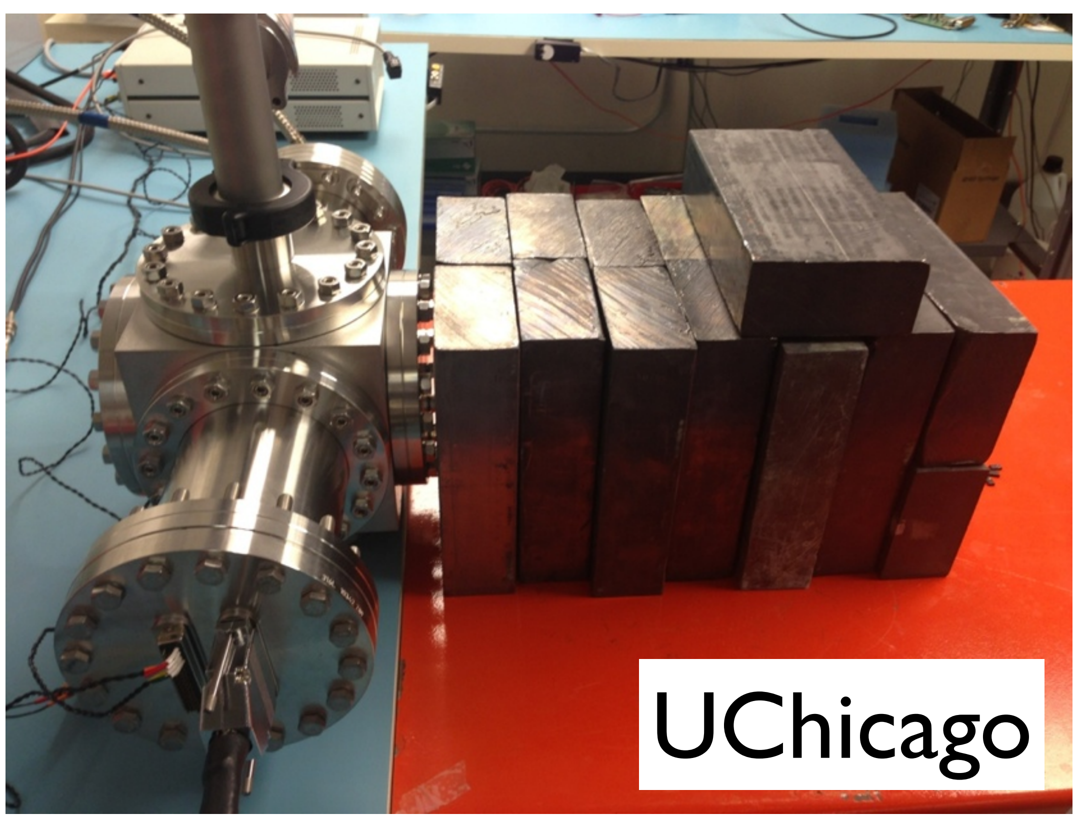
a) Cross-section of setup



b) ^{124}Sb-^{9}Be source detail



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



Use MCNP to simulate neutron production in the source and neutron propagation in the lead.

Simulation has ben validated by rate of ^{3}He counter in 7 positions around lead shield.

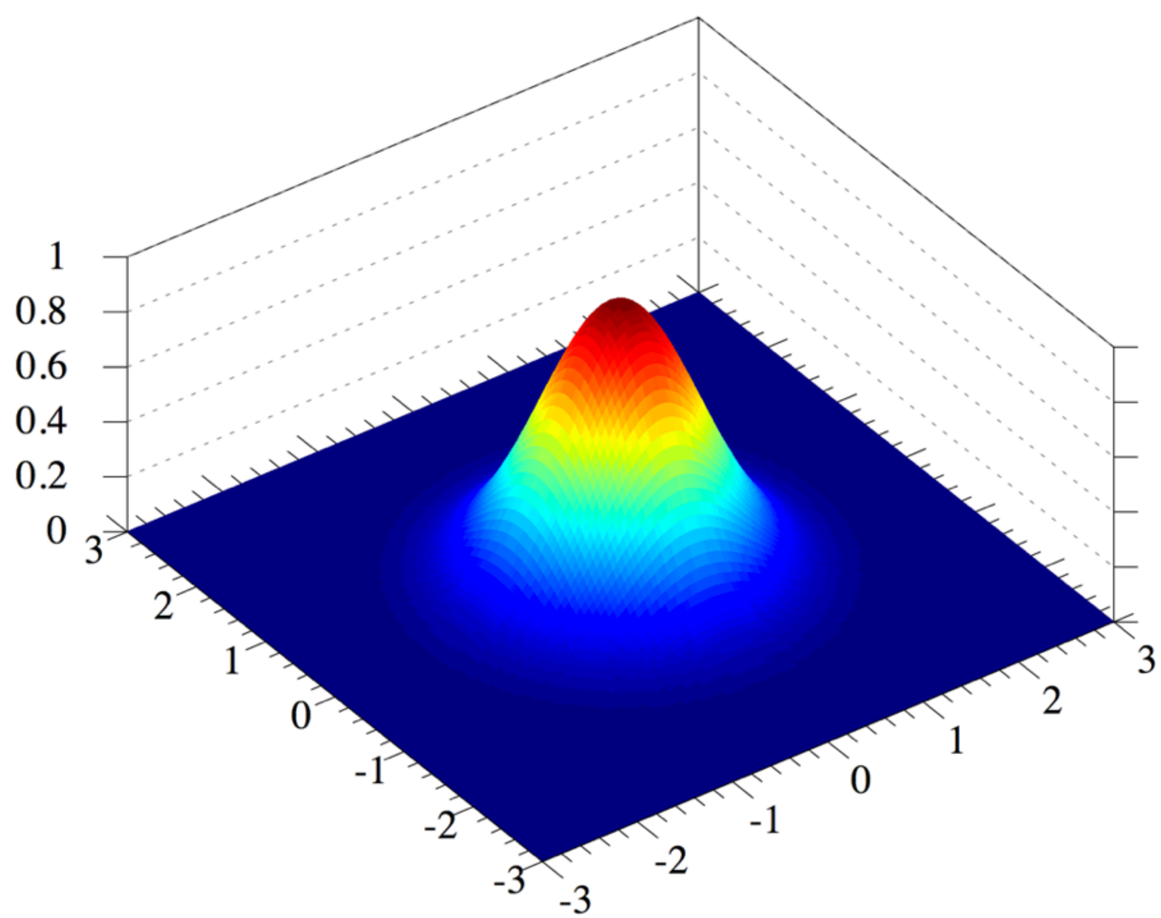
Event identification

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

Number of ionized electrons

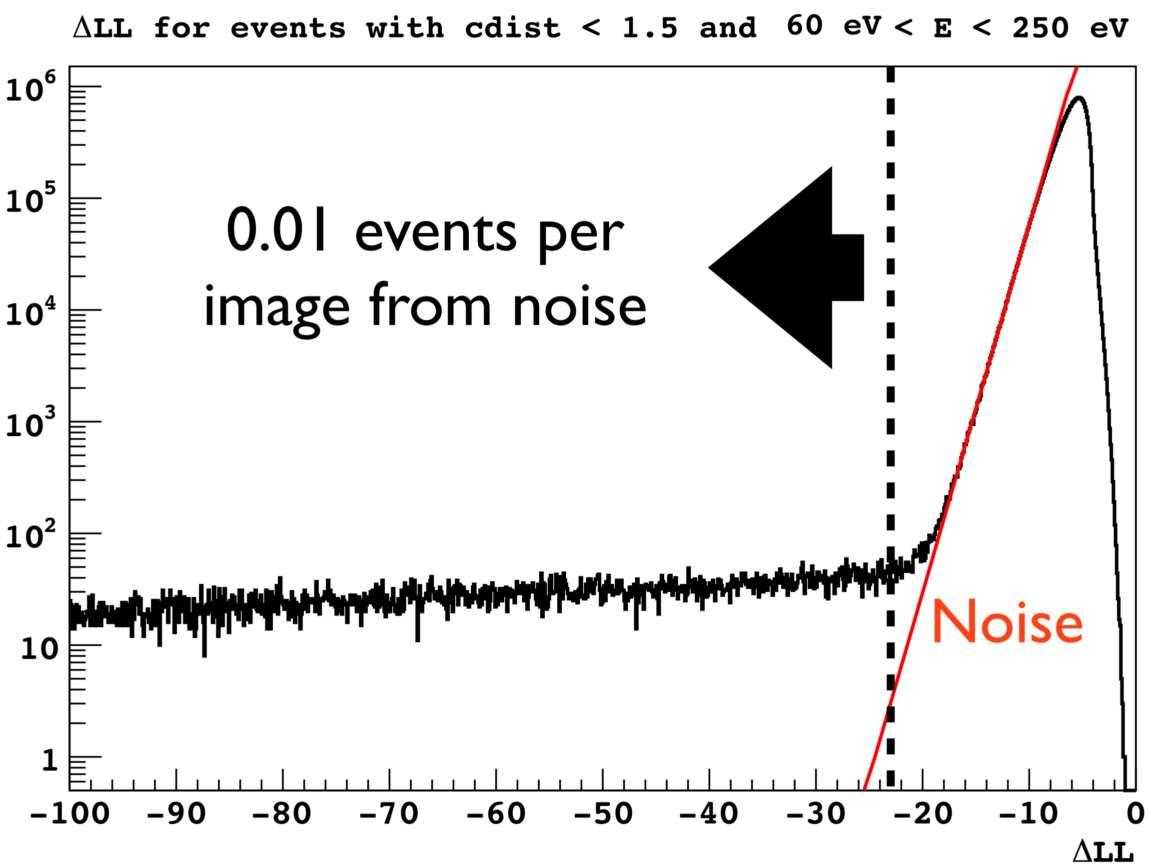
Best estimate for mean of energy deposition

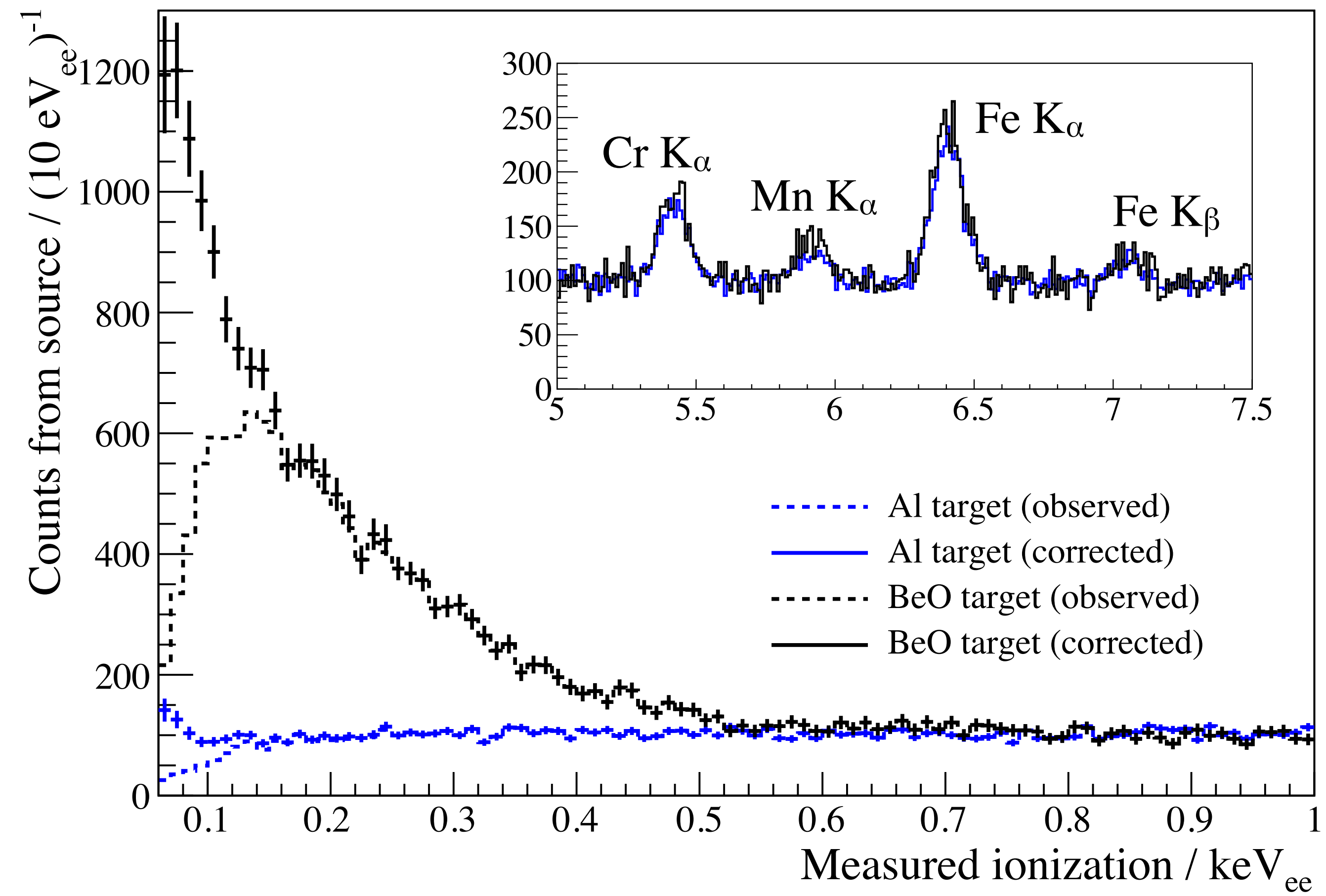
Lateral spread

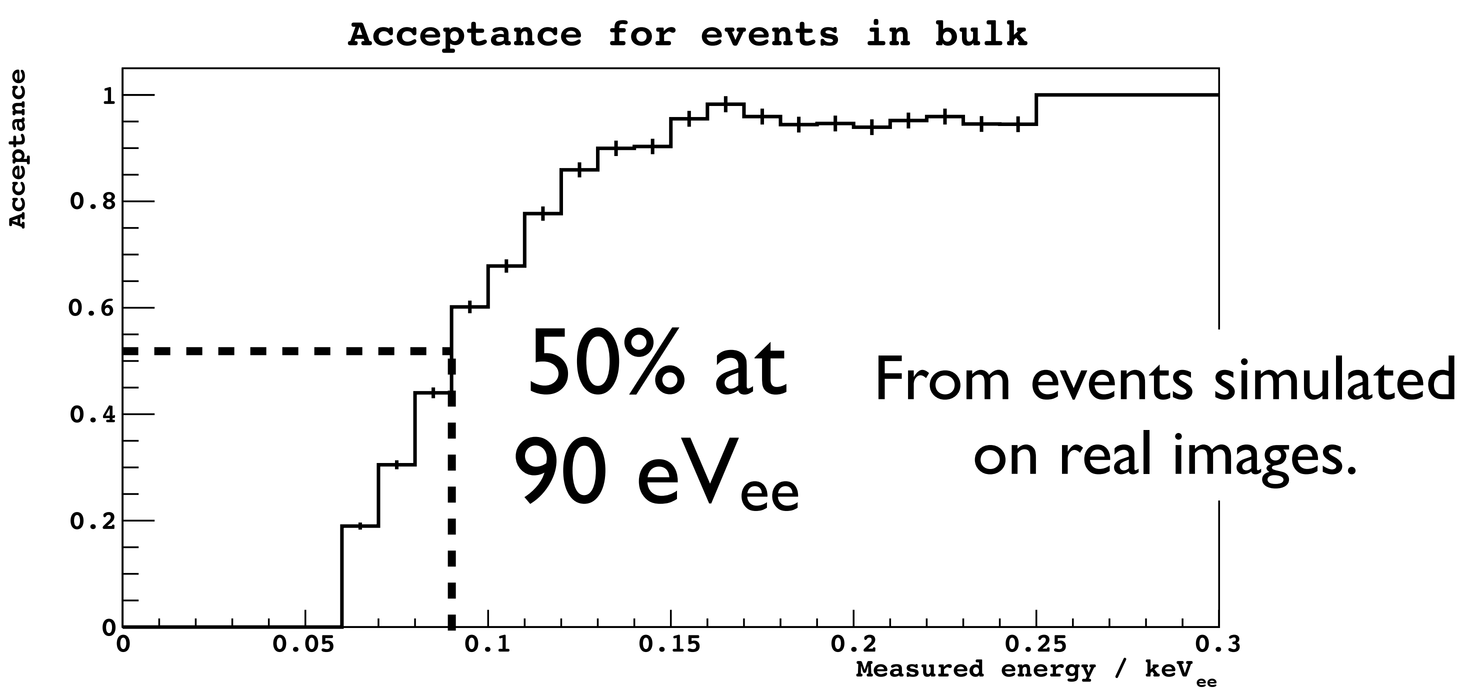


Use 11x11 pixels moving window and fit to a 2D Gaussian distribution. Register LL of best-fit. Compared to LL of constant pixel values. Difference between the two LL (ΔLL) allows us to select physical events.

Data selection

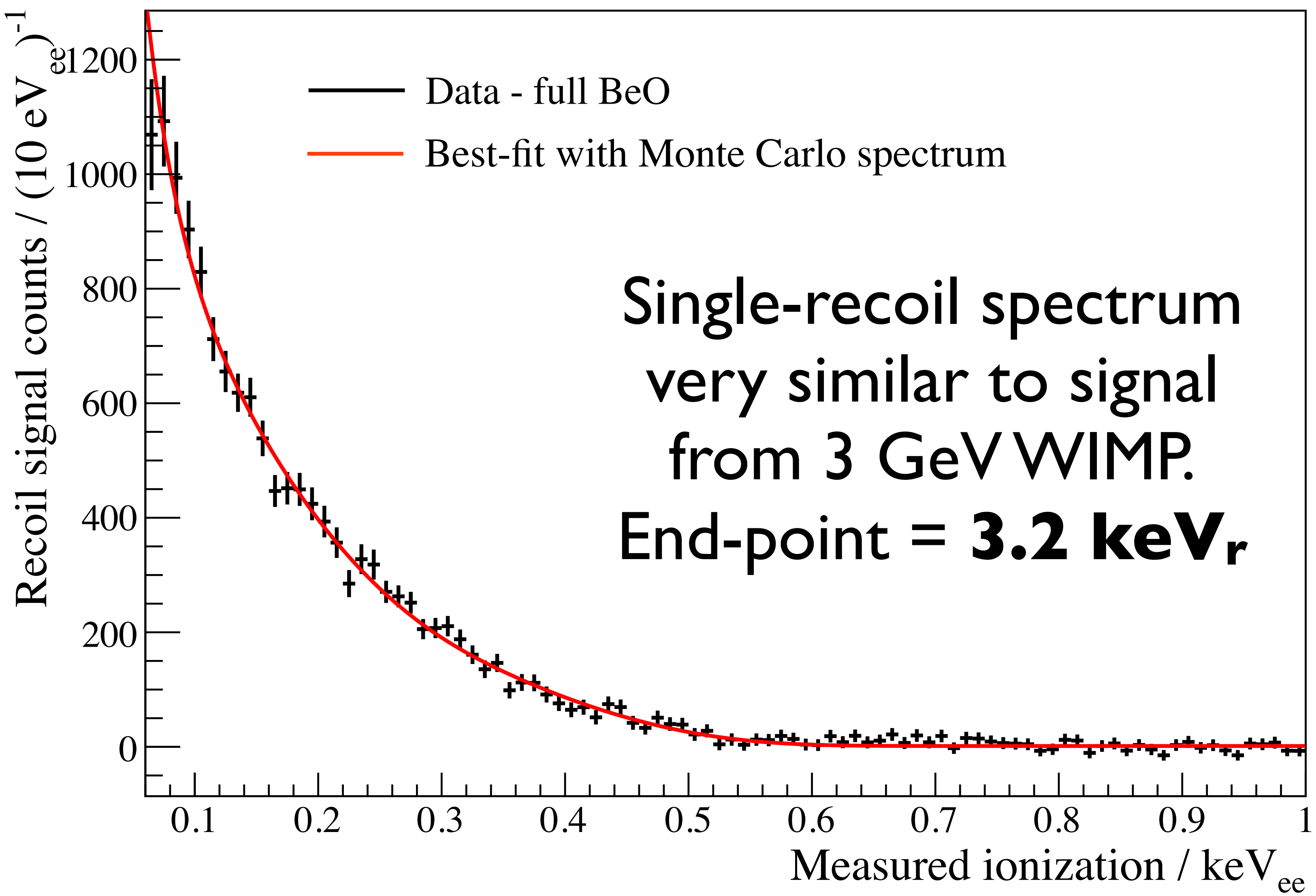






Neutrons-on, **neutrons-off** measurements done by using BeO and Al targets, respectively.

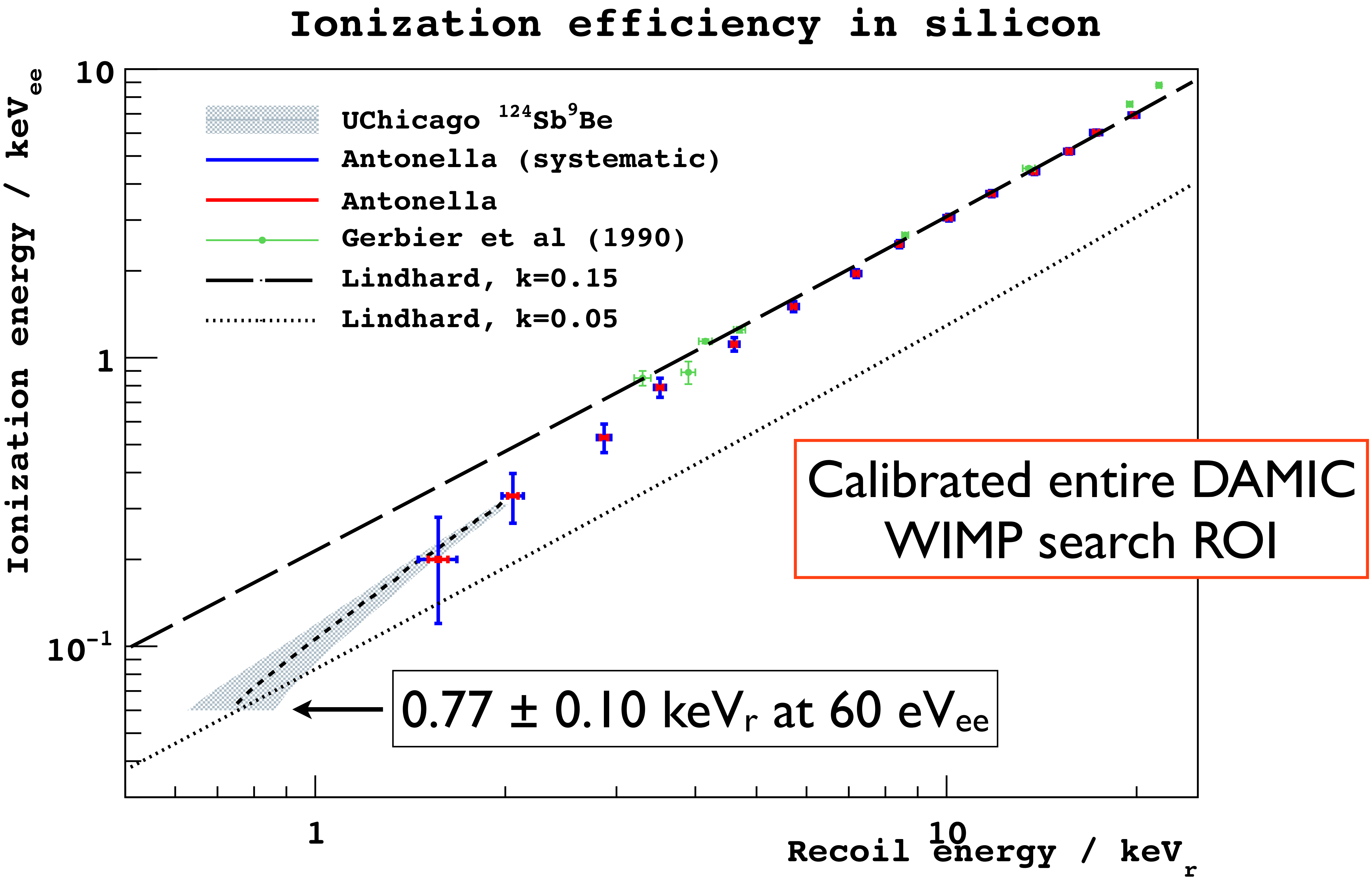
Nuclear recoil spectrum



By comparing simulated and observed *single* recoil spectrum can extract ionization efficiency.

As CCD is fully active and there is no multiple scattering, systematic uncertainties are relatively small. Dominated by 9% uncertainty in total predicted rate.

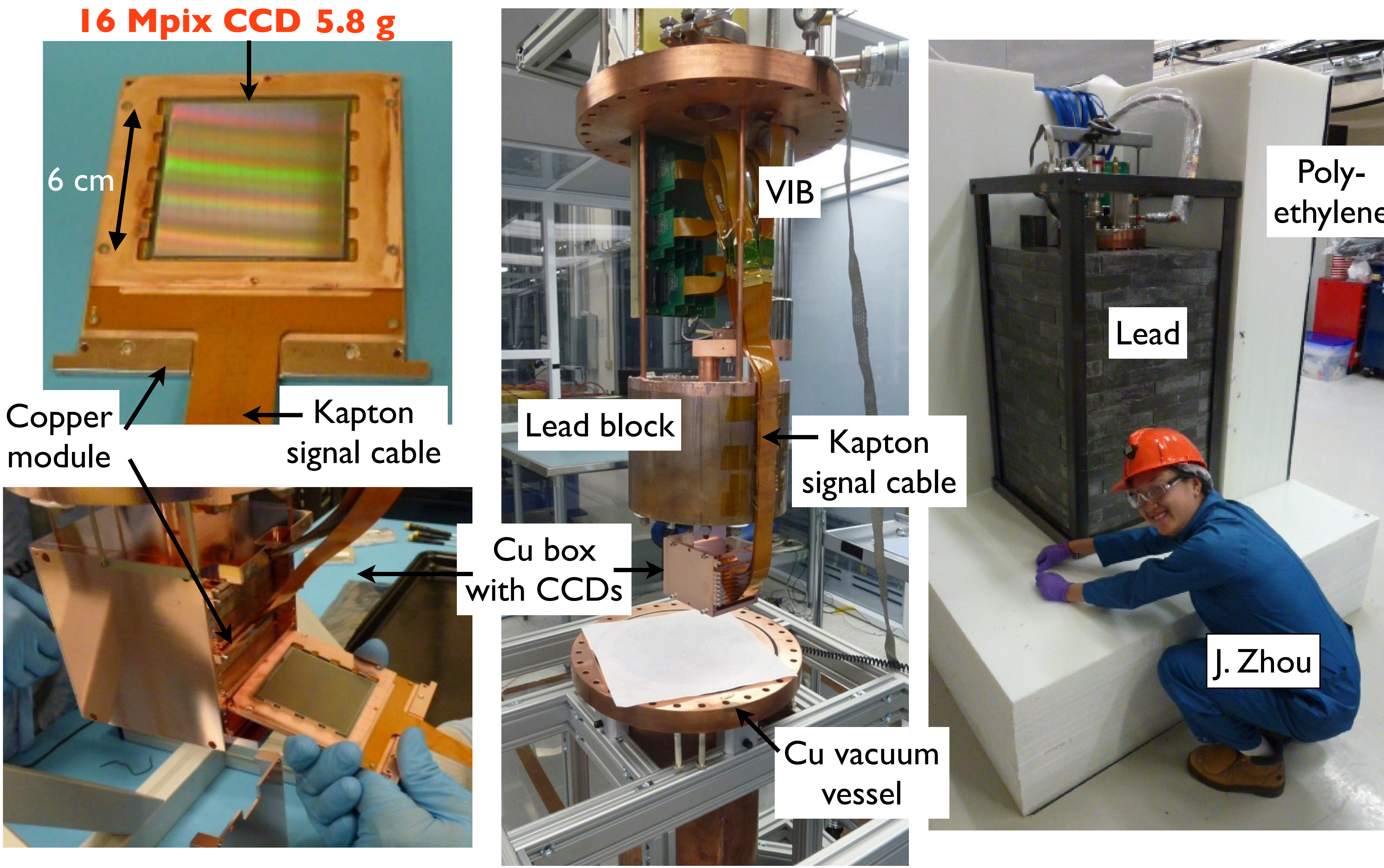
Calibration results



2 km underground

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

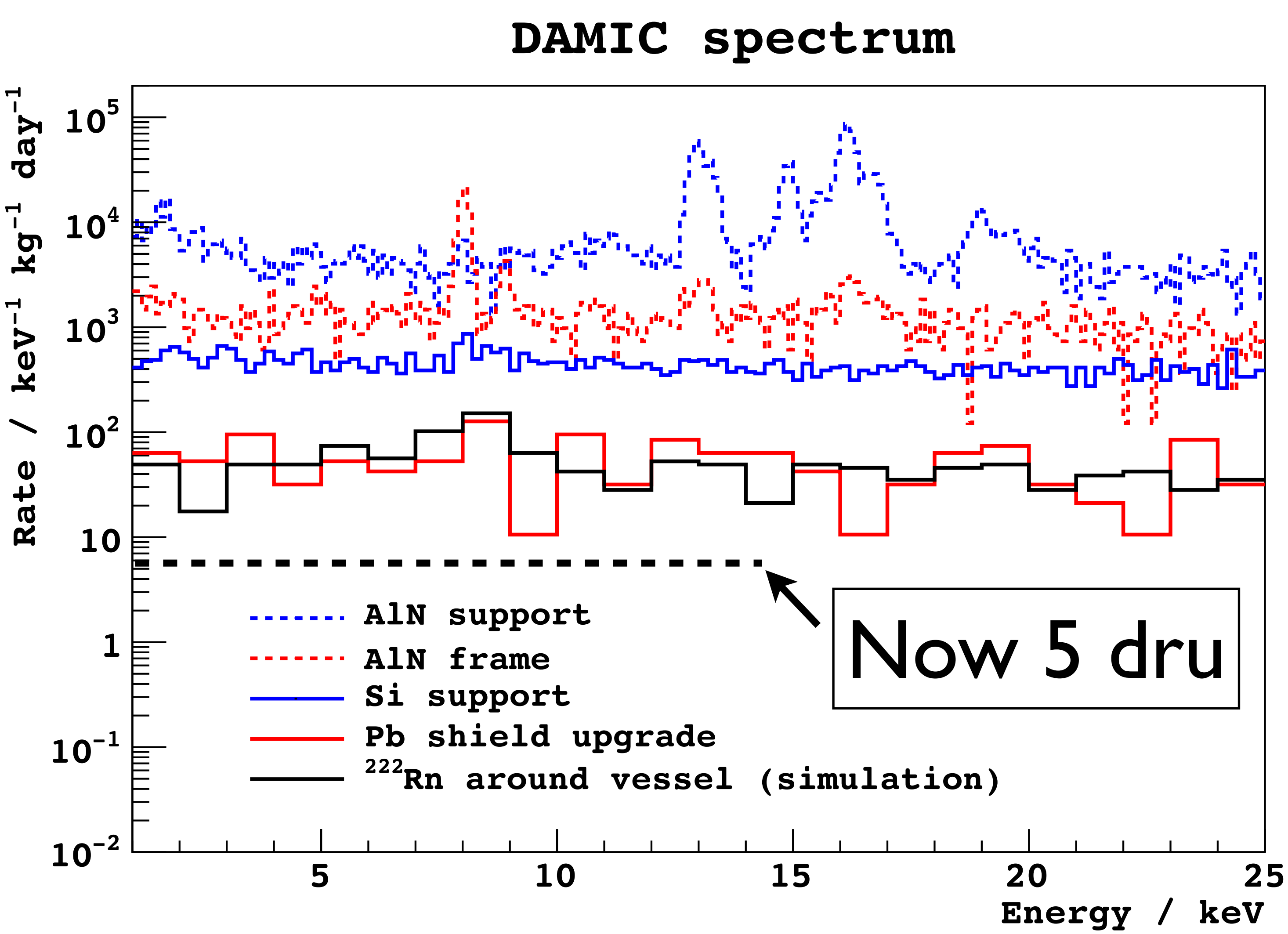
SNOLAB installation



Event rate at SNOLAB

Since 2013 we have decreased the background by >10^3.

About order of magnitude improvement per year.



Not easy!

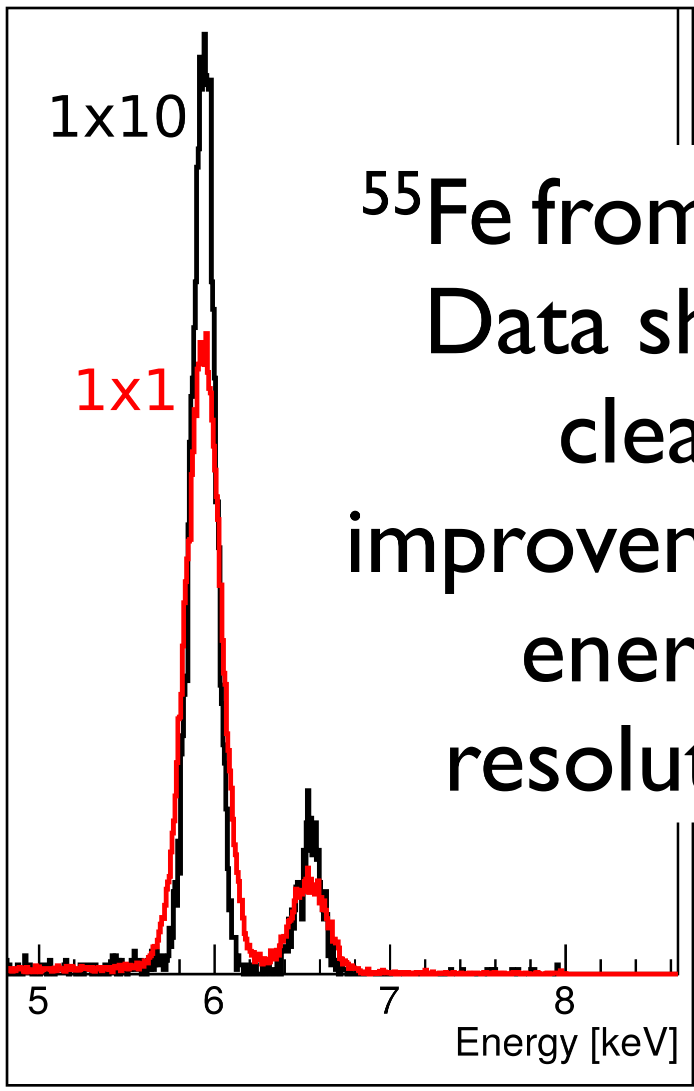
<u>In the last year:</u>

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

Hardware binning

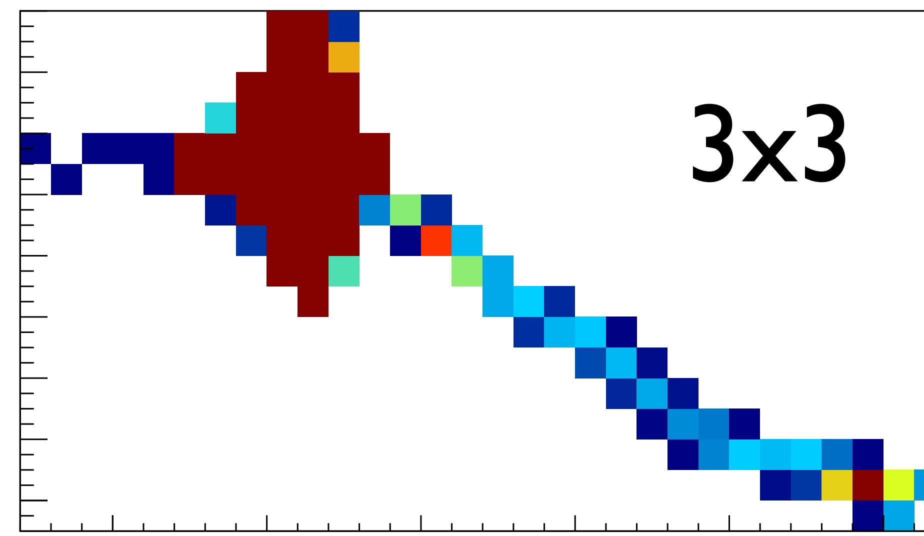
In a CCD we can "hardware bin," i.e. put the charge from many pixels into the output node before measuring.

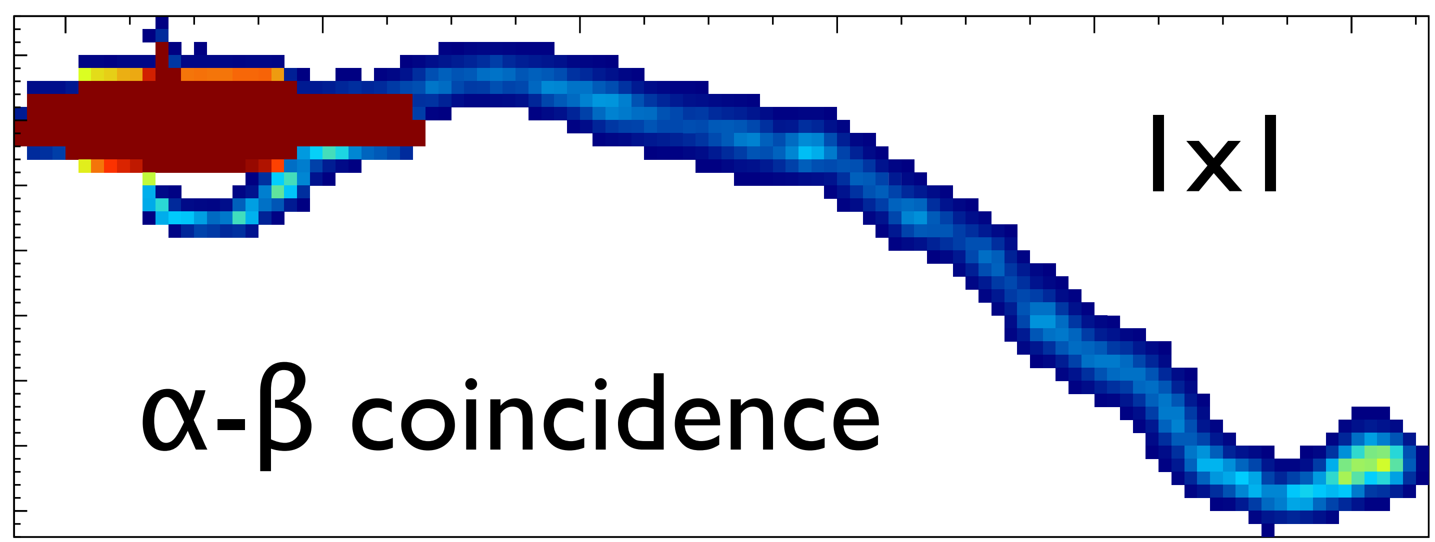
Less pixels but same pixel noise!



^{55}Fe from back: Data shows clear improvement in energy resolution.

Loss of x, y and z information

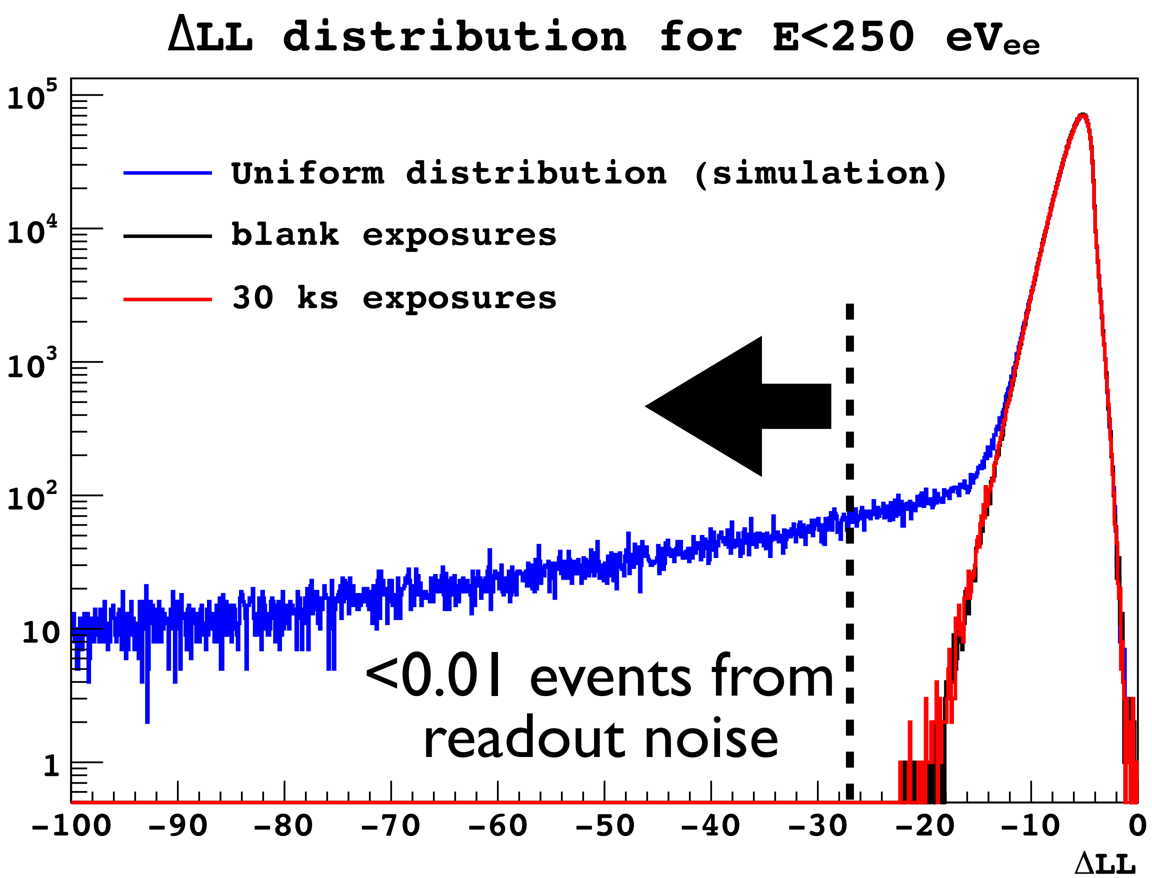


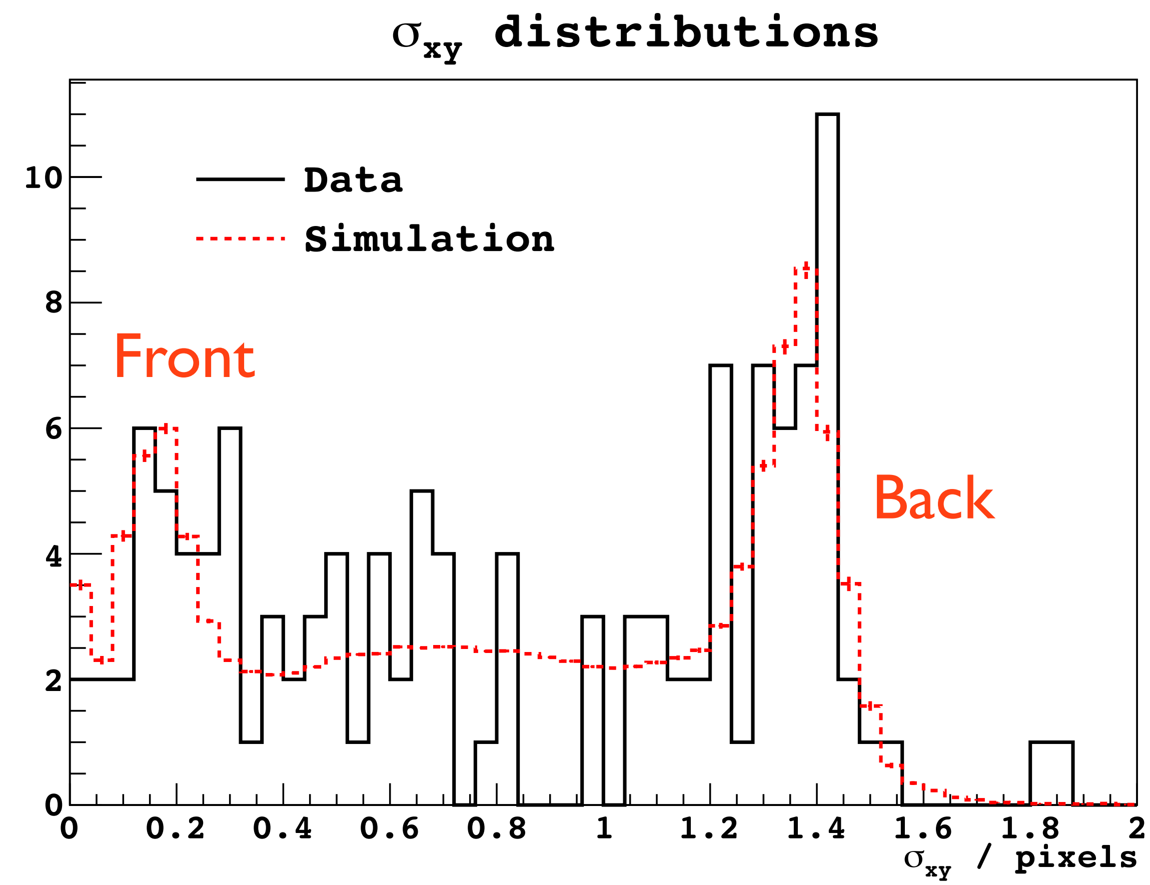


Dark matter search

- Last year (2015) was mostly devoted to decreasing radioactive backgrounds at SNOLAB.
- However, we took some small amount of DM search data.
- **0.385 kg d** of 1x1 data and **0.234 kg d** of 1x100 data.
- Total radioactive background rate **~30 dru** (now **5 dru!**).
- Exclusion limits presented at UCLA Dark Matter Conference in February 2016.

Event selection

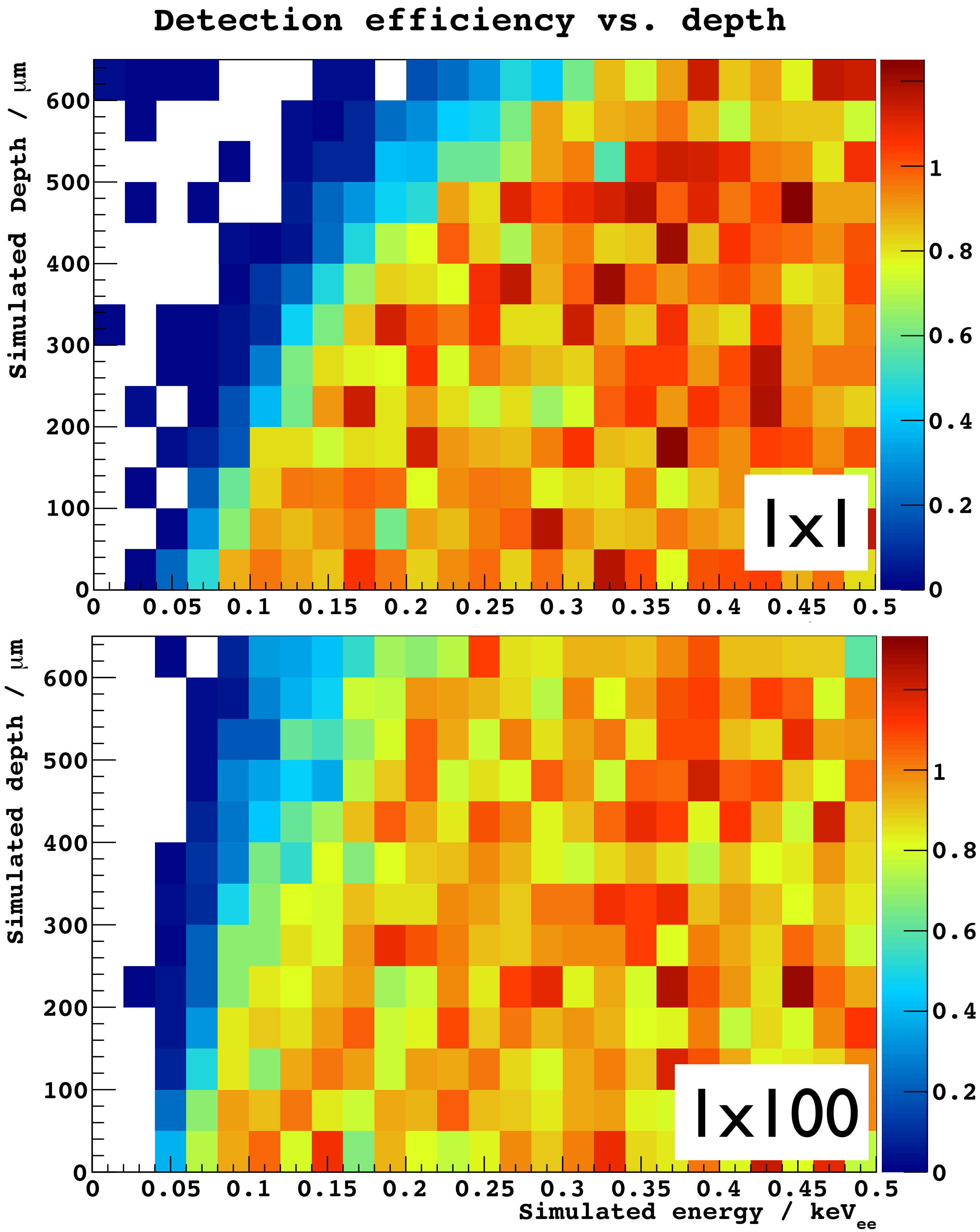


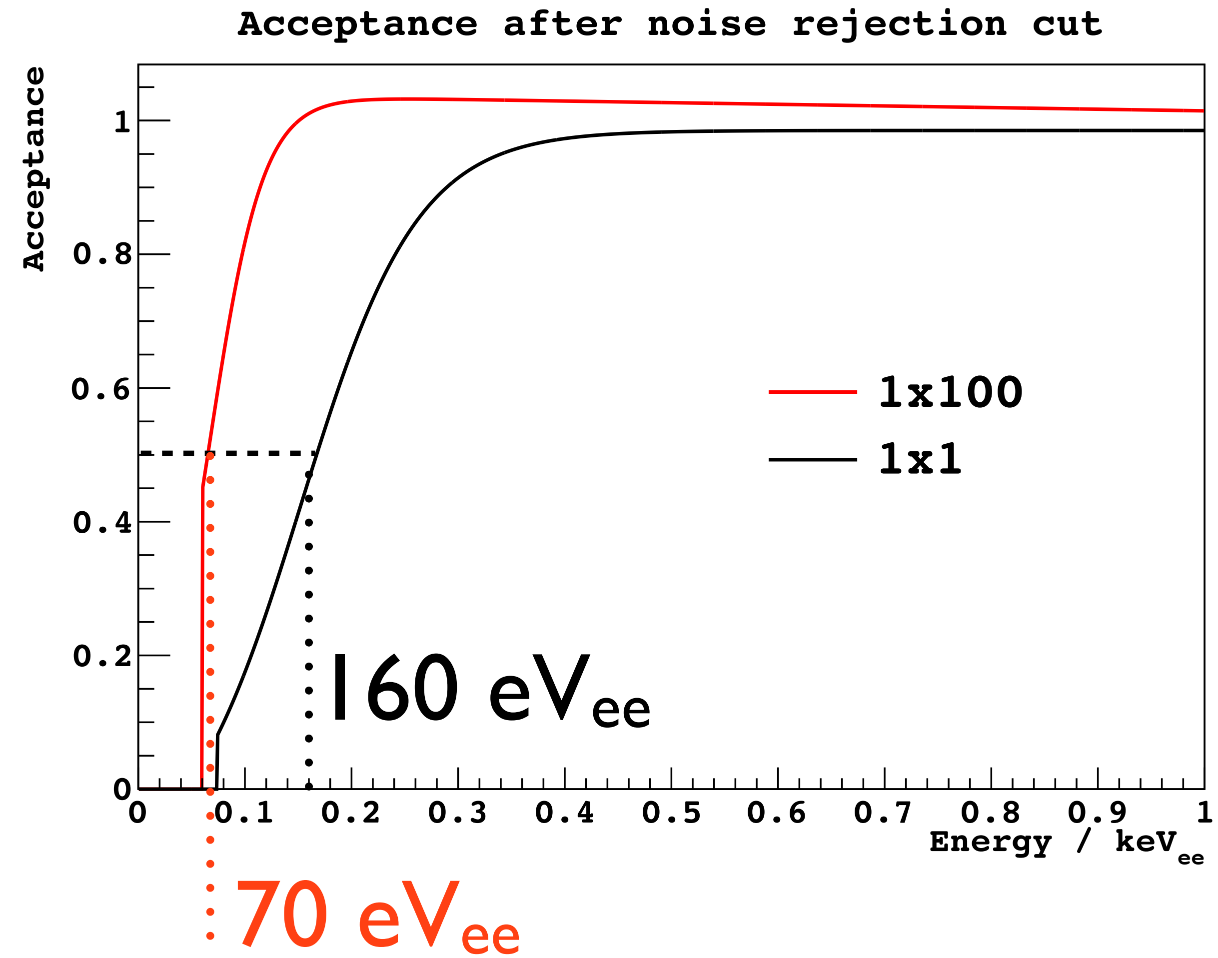


Perform a hard cut on the ΔLL to exclude random fluctuations from noise. Noise leakage <0.01 event in final sample.

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

Detection efficiency

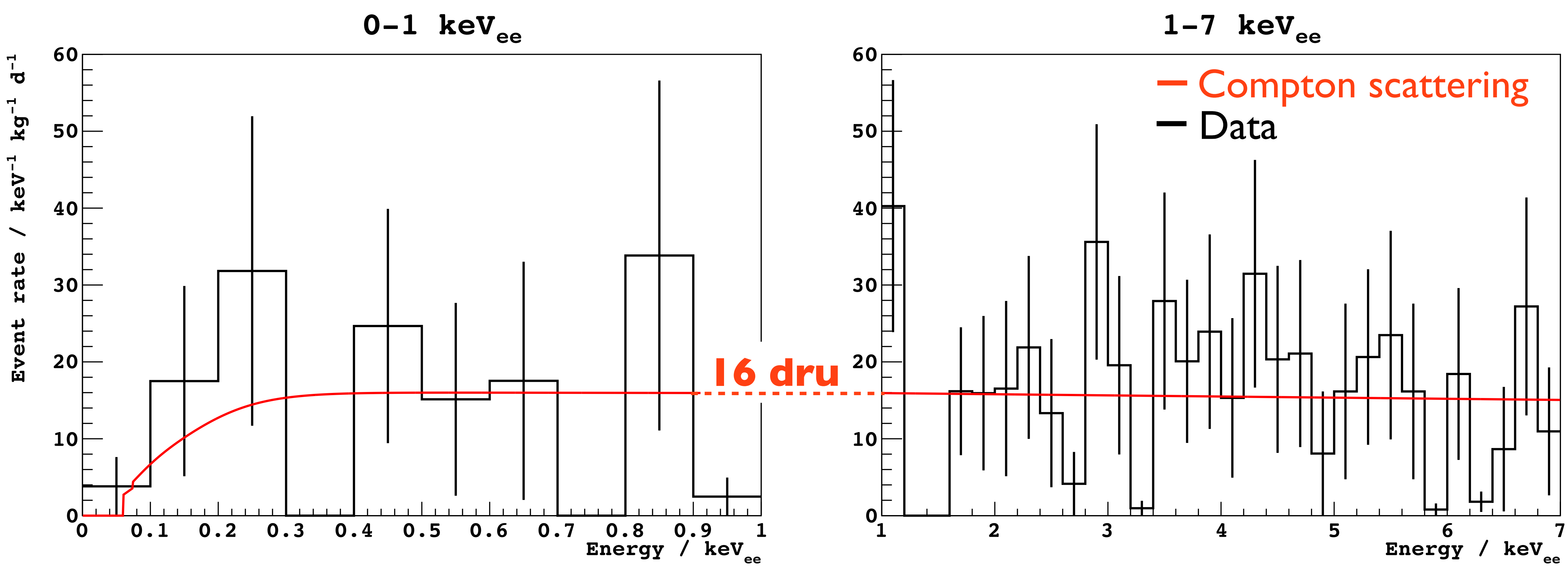




Sensitive to events deeper in the bulk at low energies.

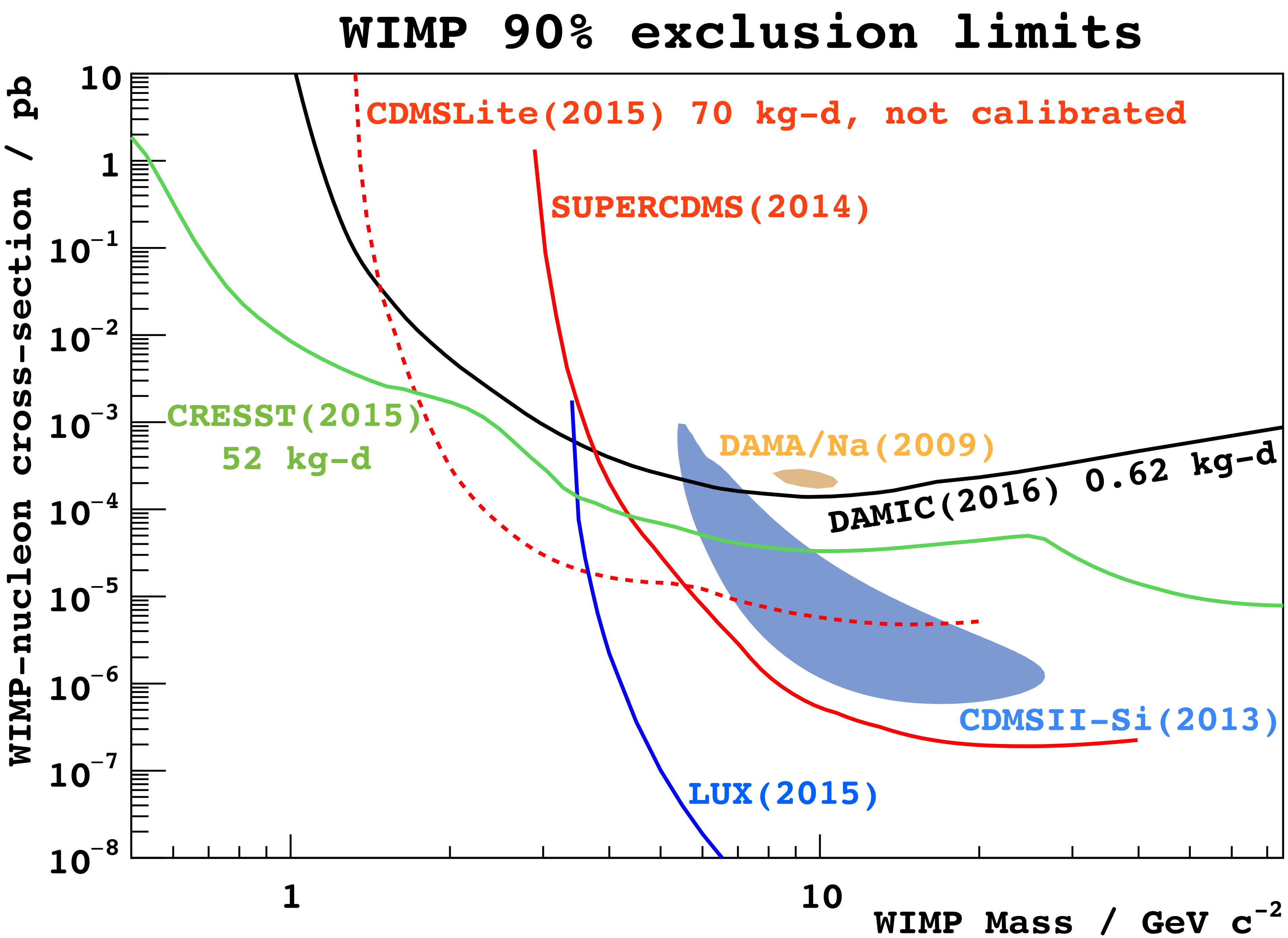
Less pixels read out: Less background from readout noise.

Bulk spectra



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.

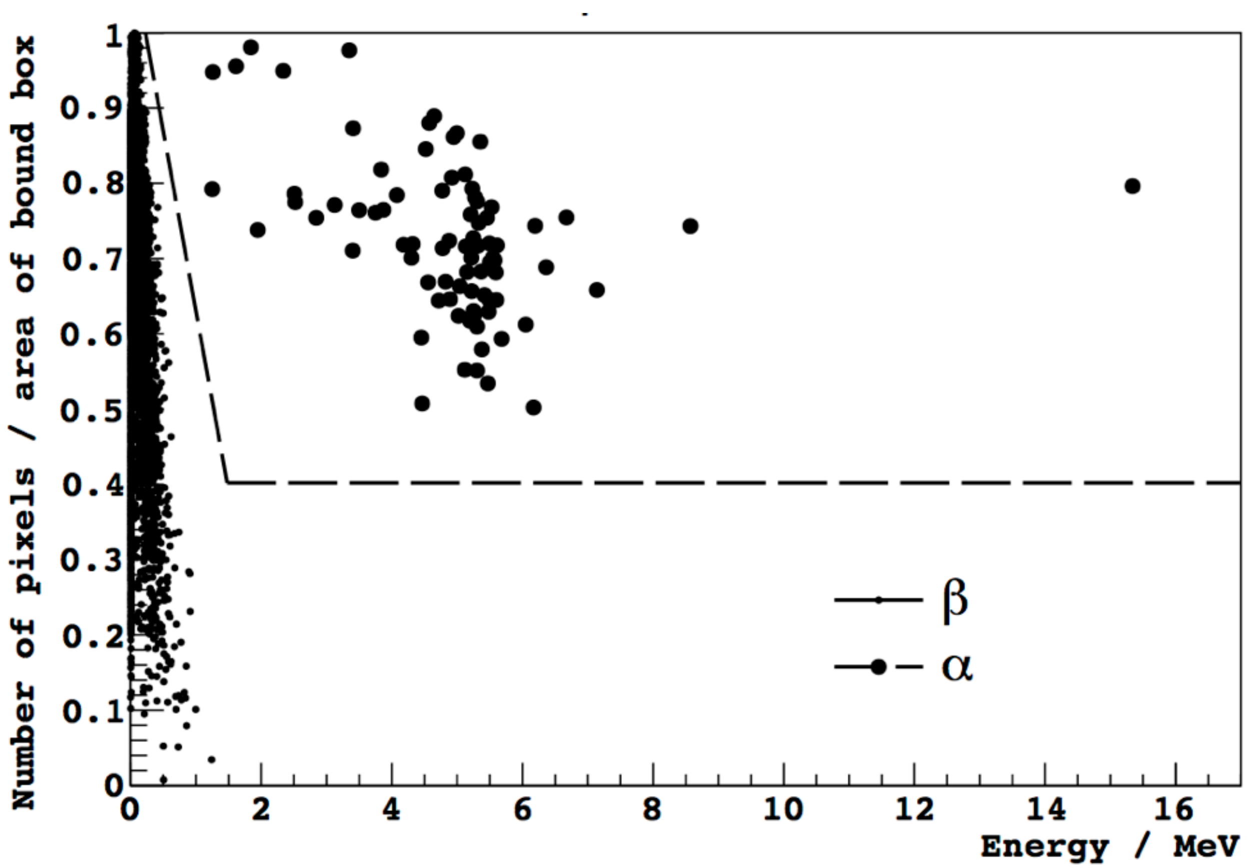
Exclusion limits

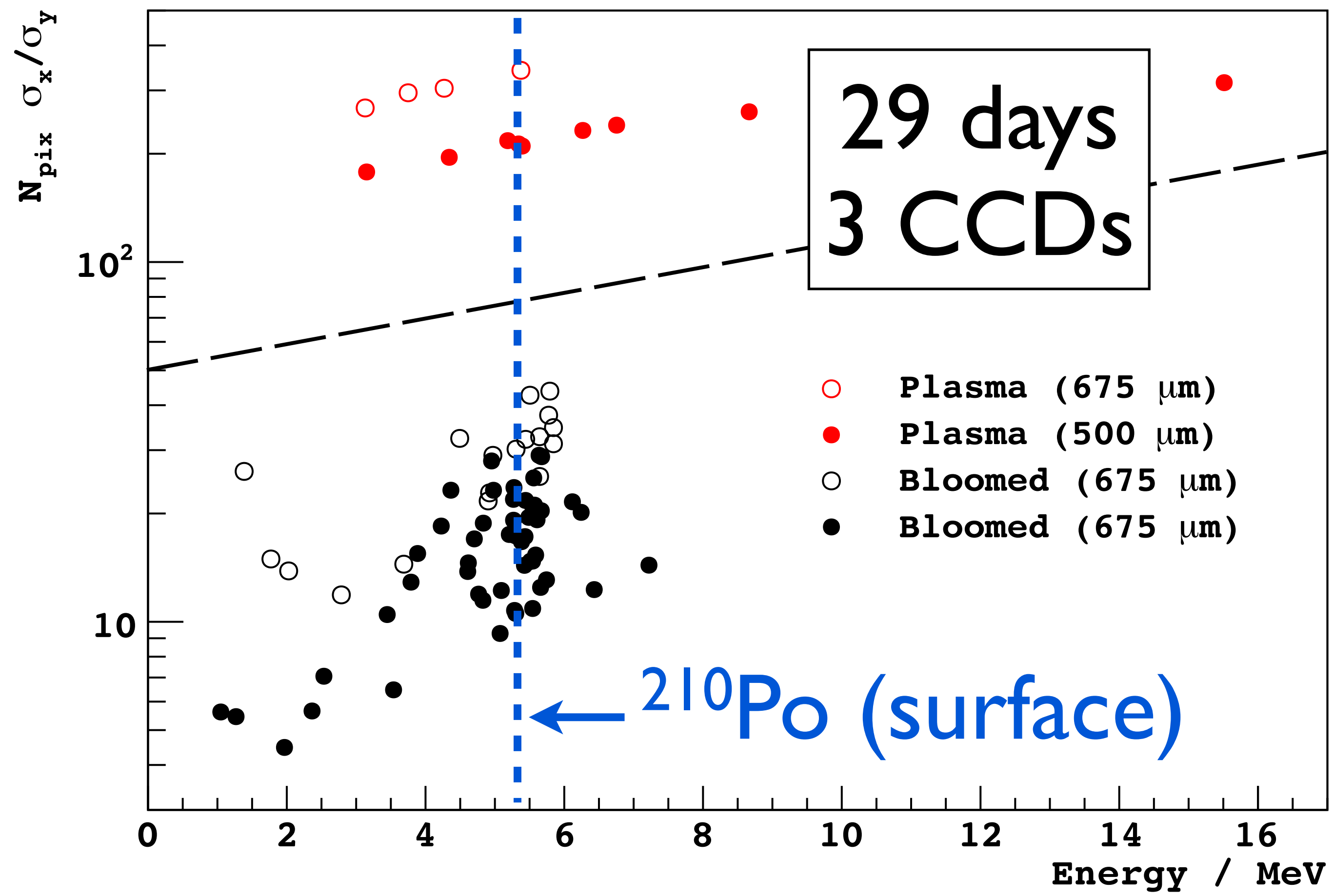


Radioactive contamination in CCD

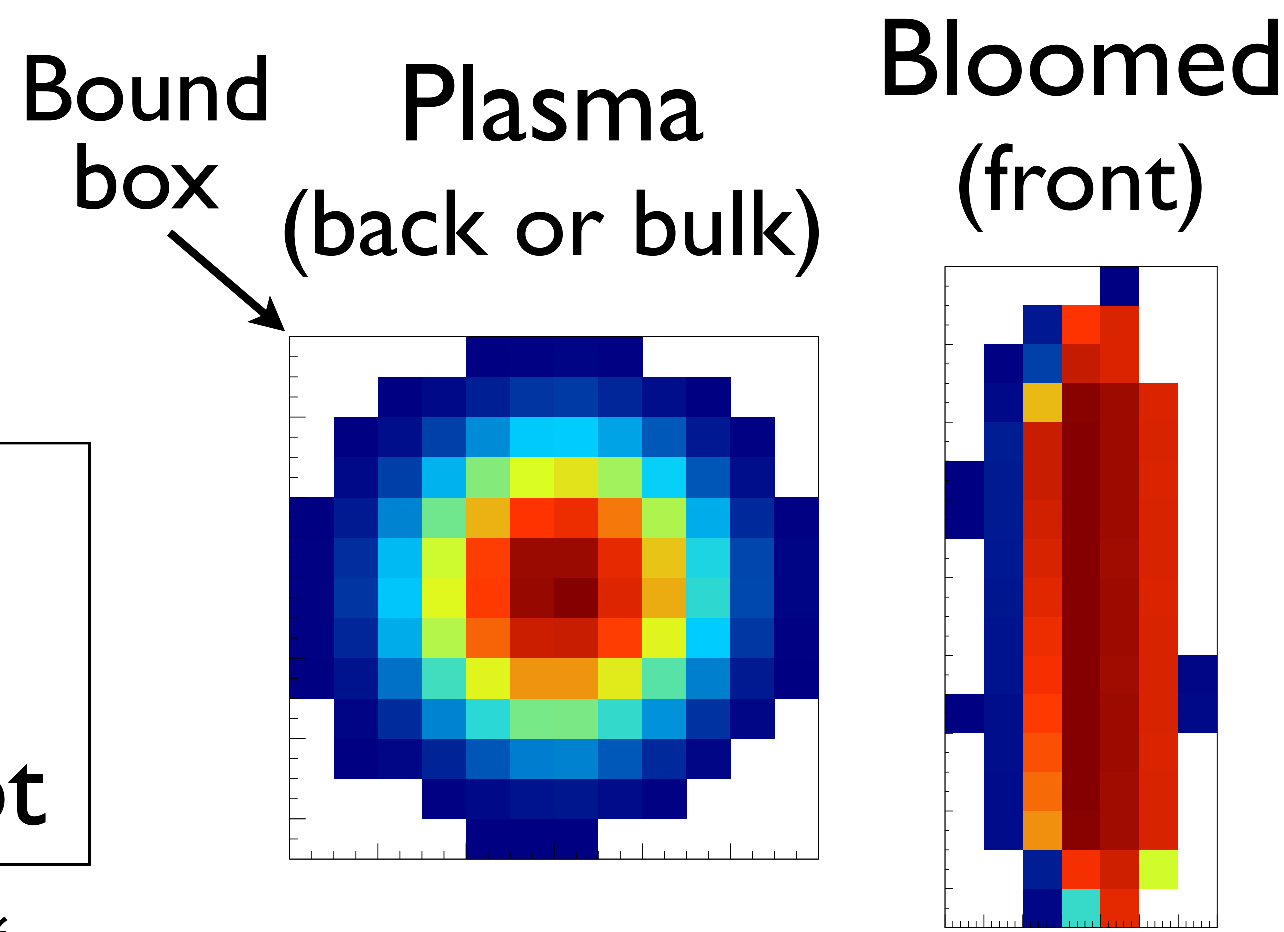
- The ultimate sensitivity of CCD dark matter search will be determined by the intrinsic radioactivity of the devices.
- We have placed strong limits on the radioactive contamination of detector-grade silicon.
- Strategies include α spectroscopy and spatial coincidence searches. Could have applications beyond dark matter searches.

α particles





α-β discrimination based on shape of track.

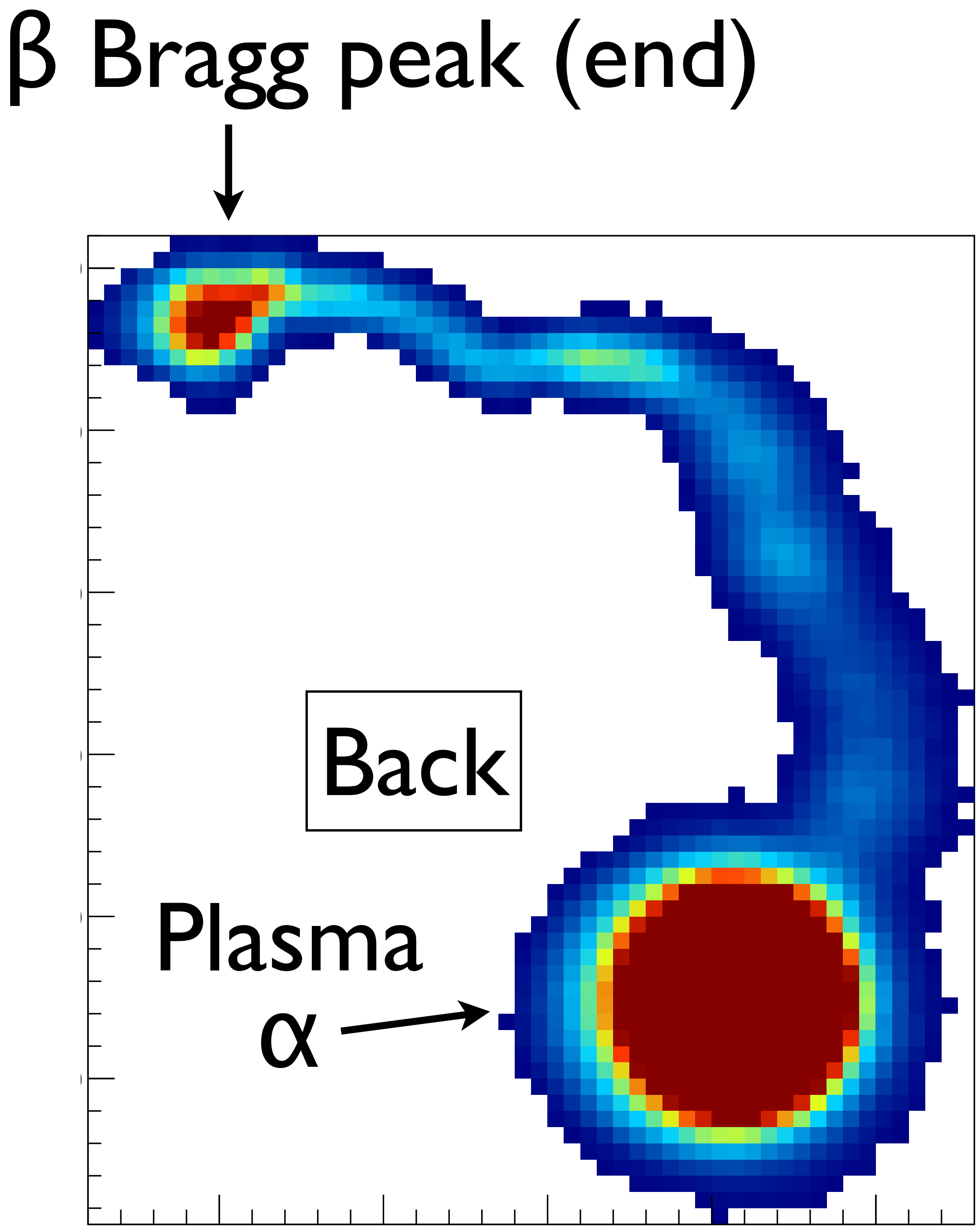


Limits on contamination:

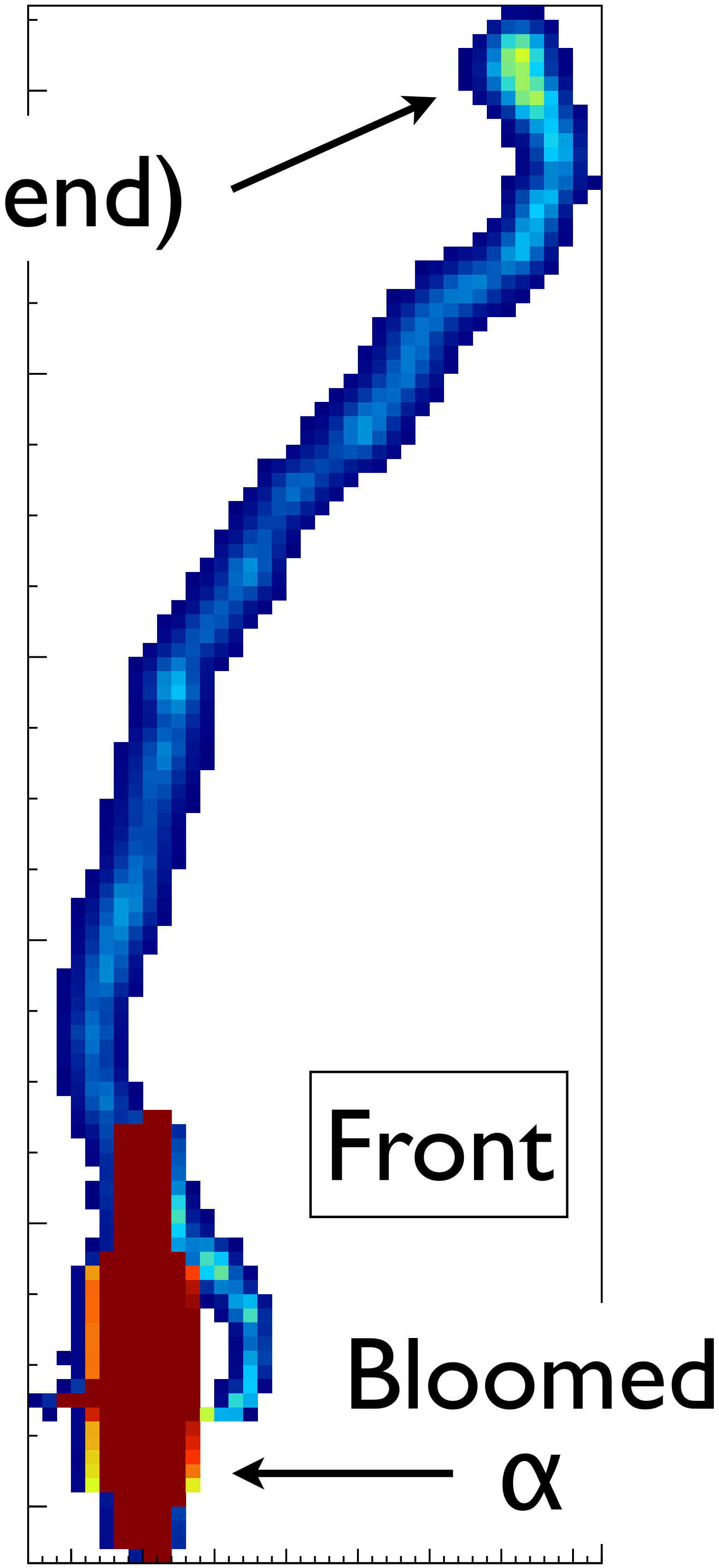
^{238}**U** < 5 kg^{-1} d^{-1} = 4 ppt

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

α-β coincidences



β emerges from decay point under α.



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

57 days of data in 1 CCD:

^{210}Pb $< 37\ kg^{-1}d^{-1}$
(95% C.L.)

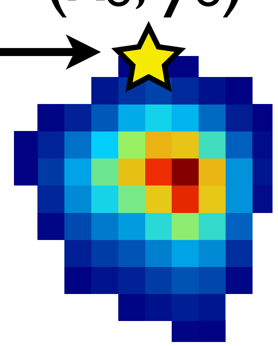
^{32}Si $= 80^{+110}_{-65}\ kg^{-1}d^{-1}$
(95% C.L.)

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

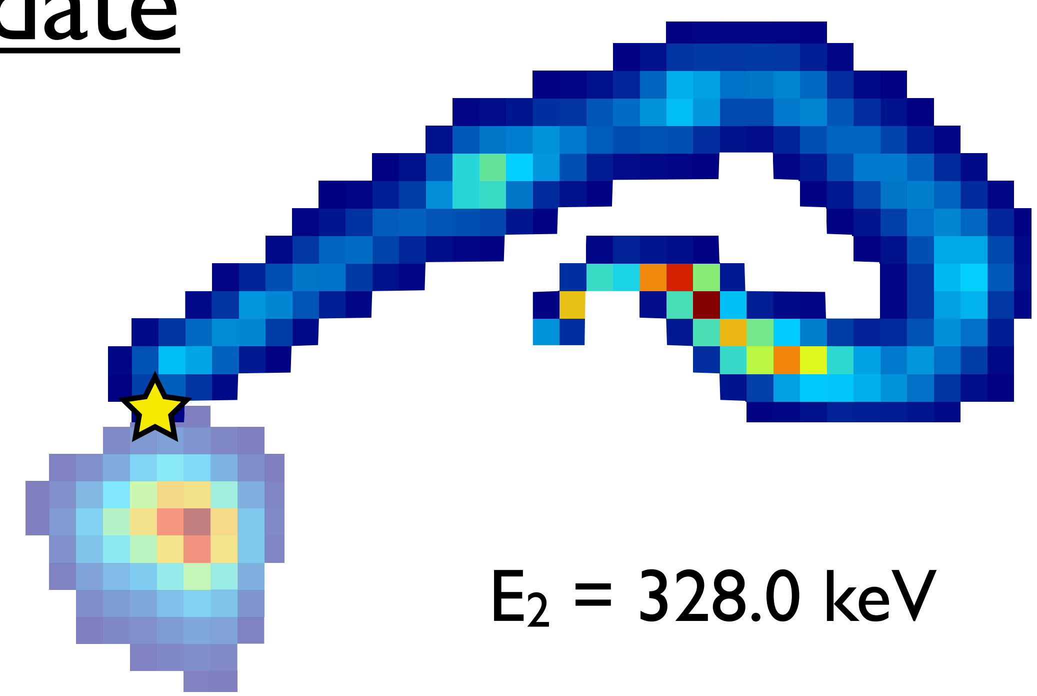
$E_1 = 114.5$ keV

Decay point

(x_o, y_o)



$\Delta t = 35$ days

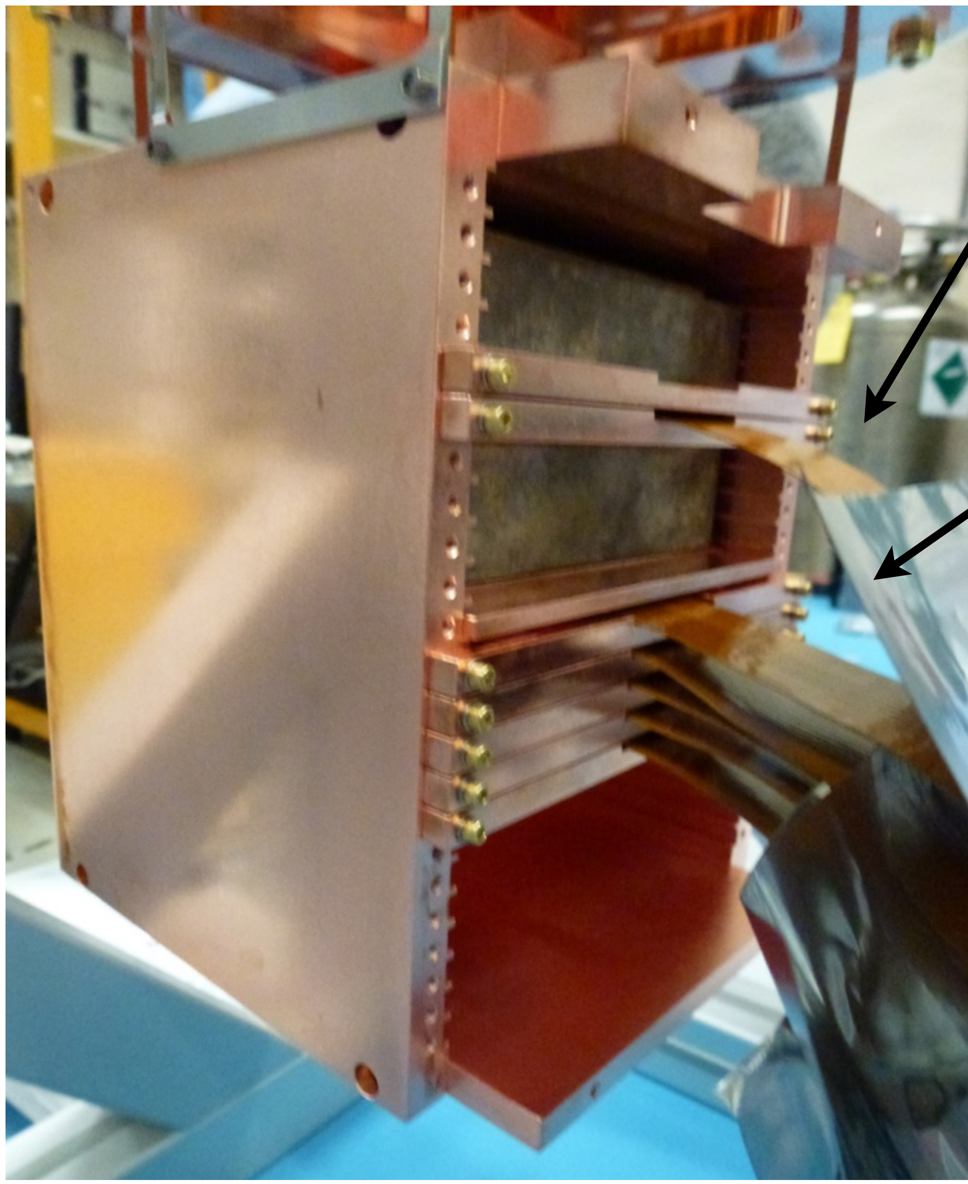


$E_2 = 328.0$ keV

DAMIC100

- Already achieved radioactive background and low-noise performance for 100 g detector.
- Stack of 18, 16 Mpix CCDs in current SNOLAB vacuum vessel and shielding.
- Currently packaging CCDs.
- Installed 8 modules (48 g) last week. Installation of remaining 10 modules in ~1 month.
- First results by the end of this year.

DAMIC100 Installation



CCD in module with electroformed copper by PNNL.

Seven (five shown) CCDs in "commercial copper" modules. Carefully machined and cleaned.

Now inner 5 cm of ancient lead shielding.

DAMIC1K

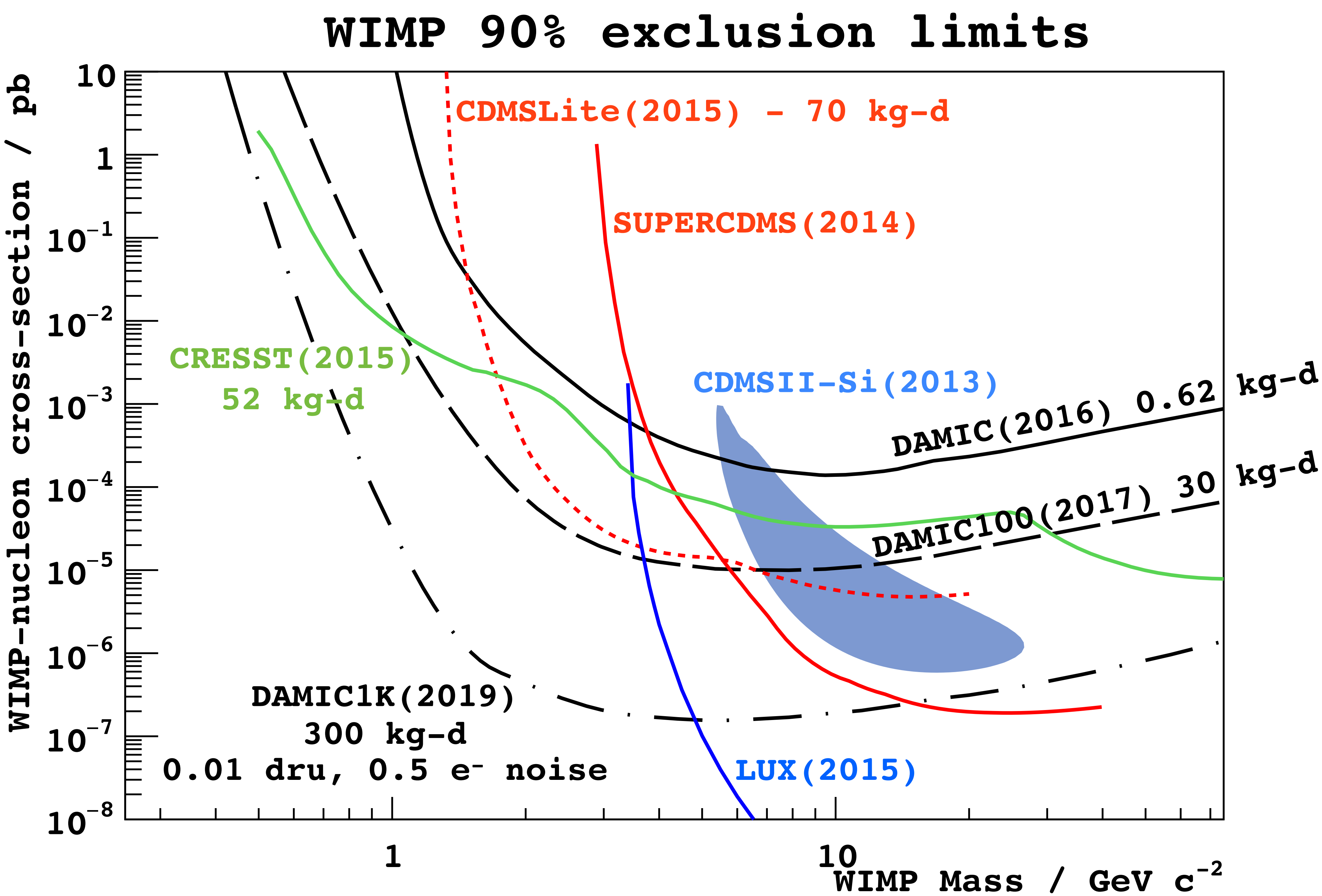
- Fifty 20 g CCDs.
- Current CMOS manufacturing technology.
- Goal to be limited by ^{32}Si background after coincidence veto at 0.01 dru.
- 0.5 e^- noise with new on-chip amplifiers and digital filtering.
- New vacuum vessel in current shield.
- Aim for results before 2020.

Electroformed copper by PNNL for DAMIC testing.

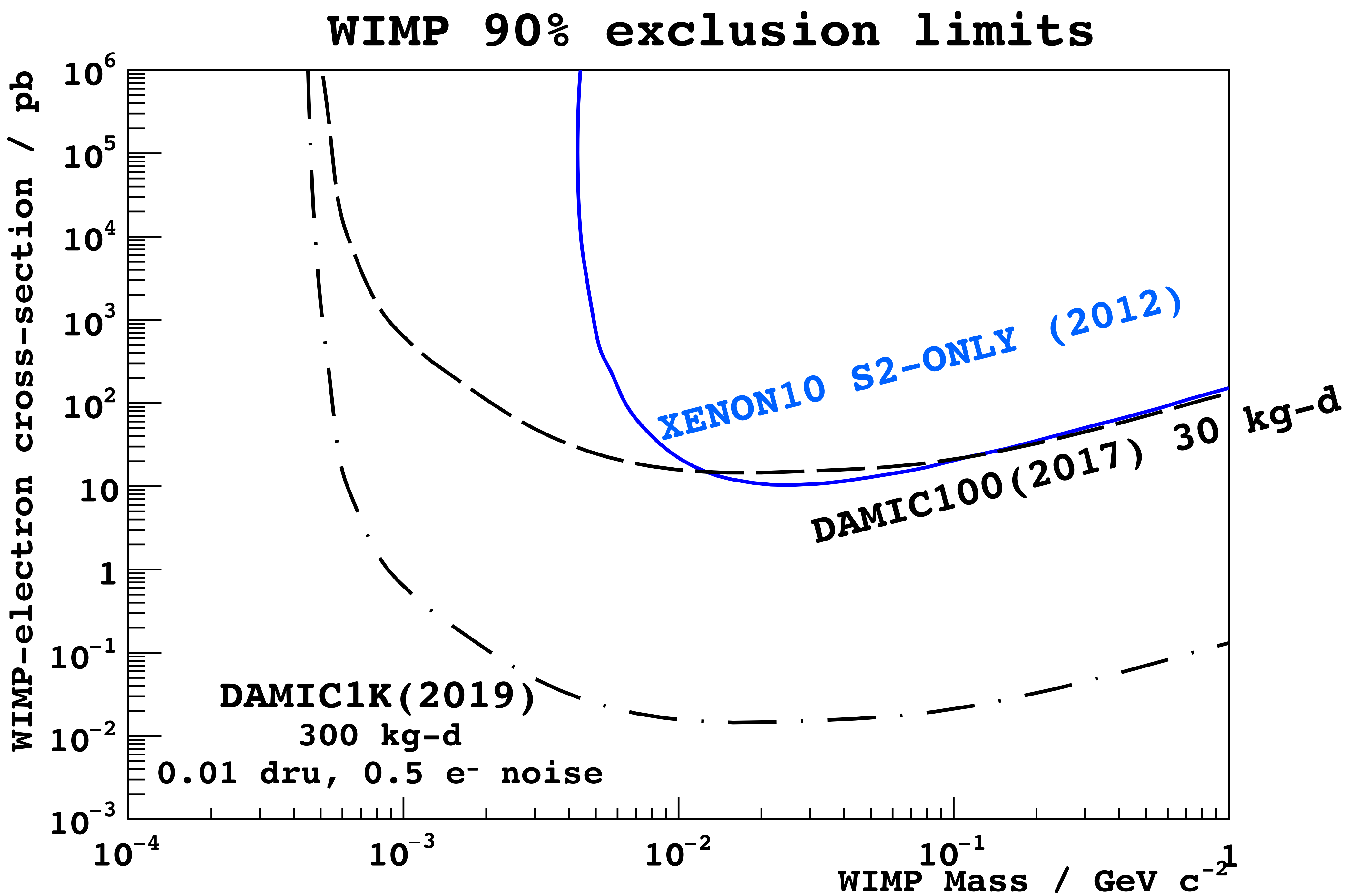
Beyond

- Development of CMOS manufacturing technology on thicker wafers.
- Selection of sources of raw silica with low ^{32}Si content.
- Design of read-out circuits optimized for different applications. E.g. Skipper CCD for lower noise, lower energy threshold detectors. Goal: single electron/ photon detection.
- **Great opportunities for collaboration with industry!**

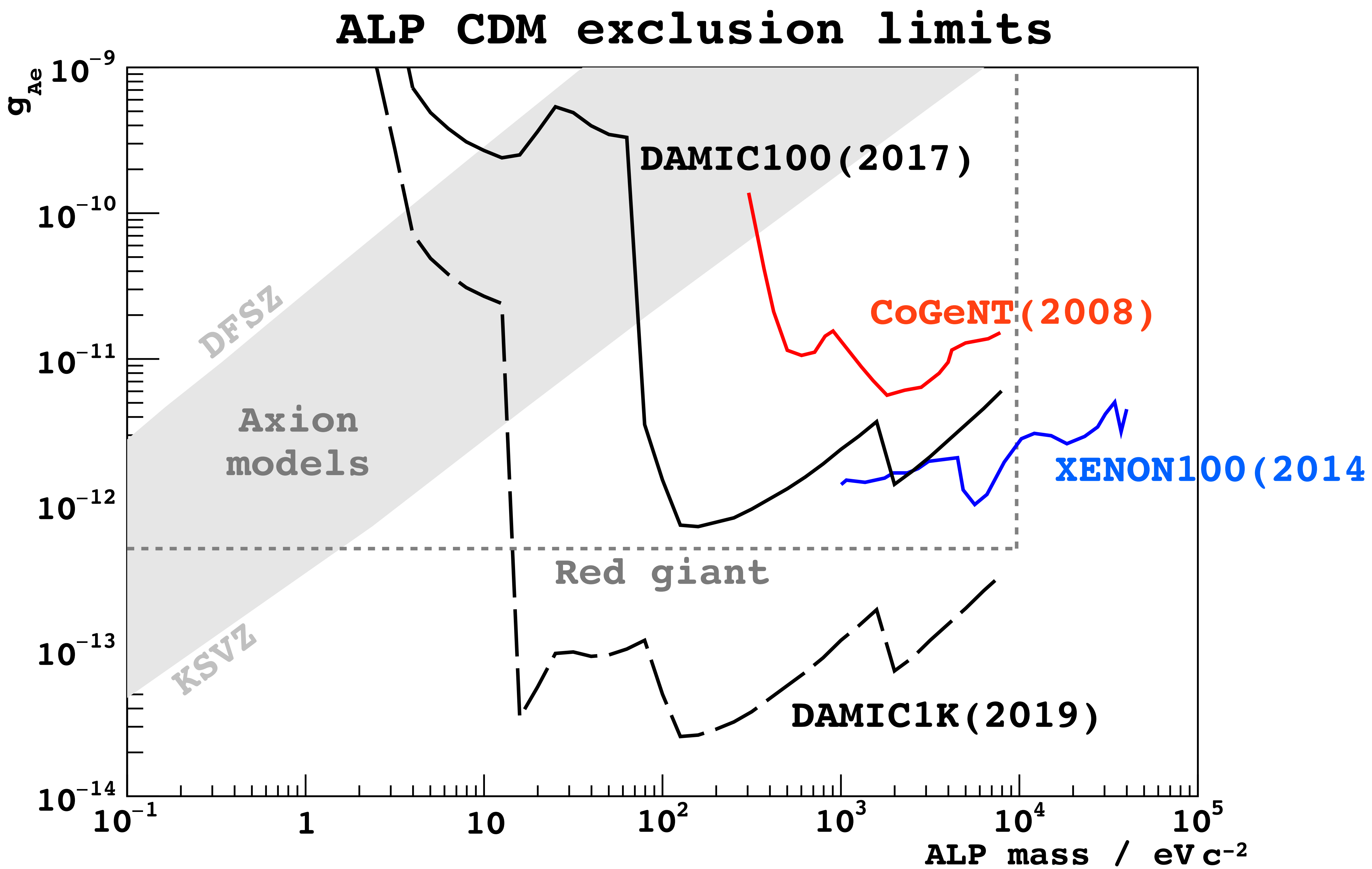
Nuclear recoils



Electron recoils



Axion-like particles



Other Applications

- A single photon detector CCD with higher quantum efficiency in the infrared will have *transformative* applications in astronomy.
- Precise spatial localization and identification of radioactive particulates: Non-destructive nuclear forensics + low radioactivity physics. On-going collaboration with PNNL.
- Lowest background X-ray detectors for next generation axion helioscopes (e.g. IAXO).
- Detection of ν-nucleus coherent scattering from nuclear reactors.
- Trackers to search for fractionally charged particles ($q \sim 0.01\ e^-$) from particle colliders.

Conclusions

- CCDs are very low radioactivity, low threshold particle detectors whose response to ionizing radiation has been thoroughly characterized.
- Different particles can be identified, localized and tracked. Very useful for signal identification and background rejection.
- DAMIC100 will start taking dark matter search data in the next month. Results by end of 2016.
- DAMIC1K to be developed in the next three years. Expect to lead the "Low-mass" WIMP field in both nuclear and electron recoil channels.