The DAMIC Experiment at SNOLAB and beyond

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DAMIC
DARK MATTER IN CCDS

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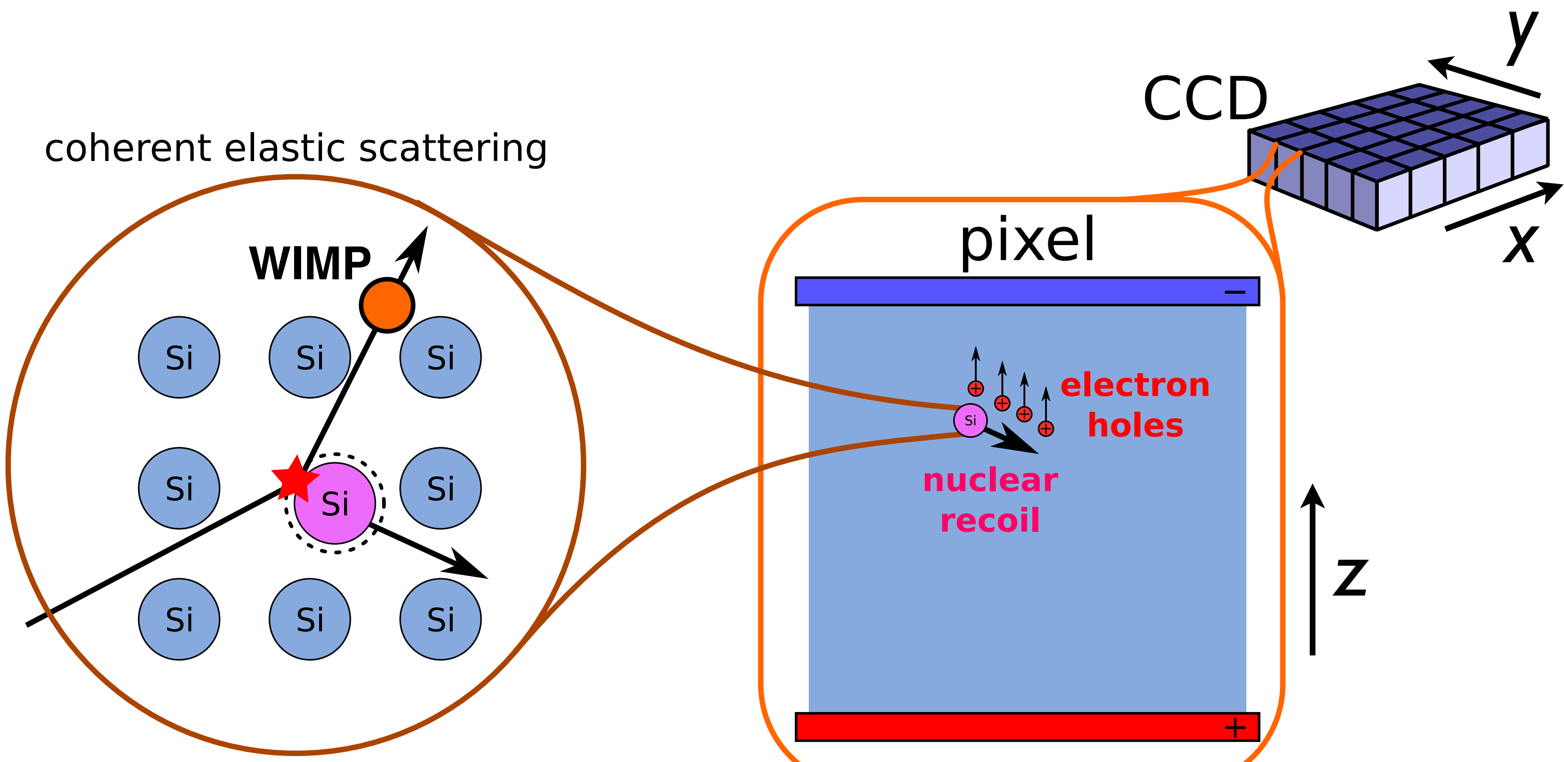
ENRICO FERMI INSTITUTE

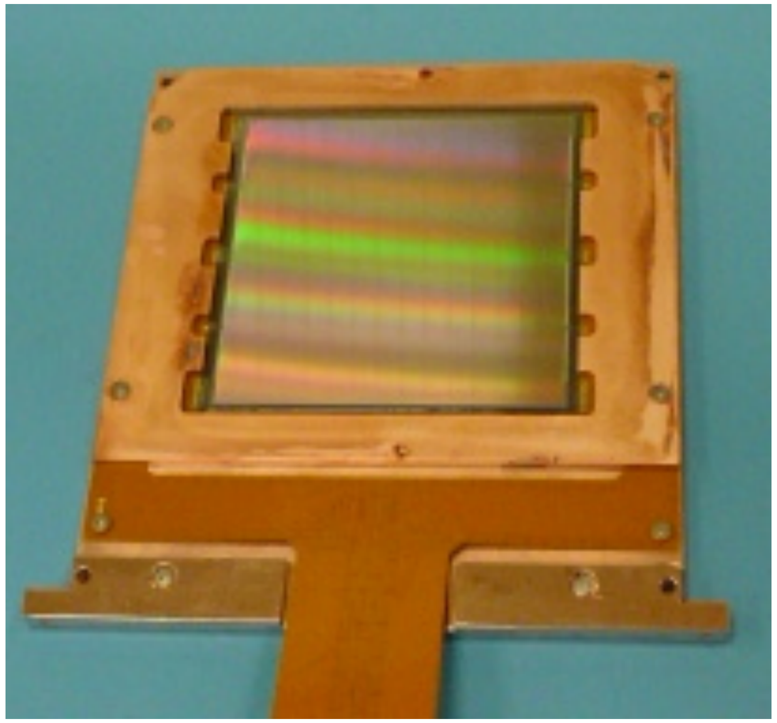
Kavli Institute for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

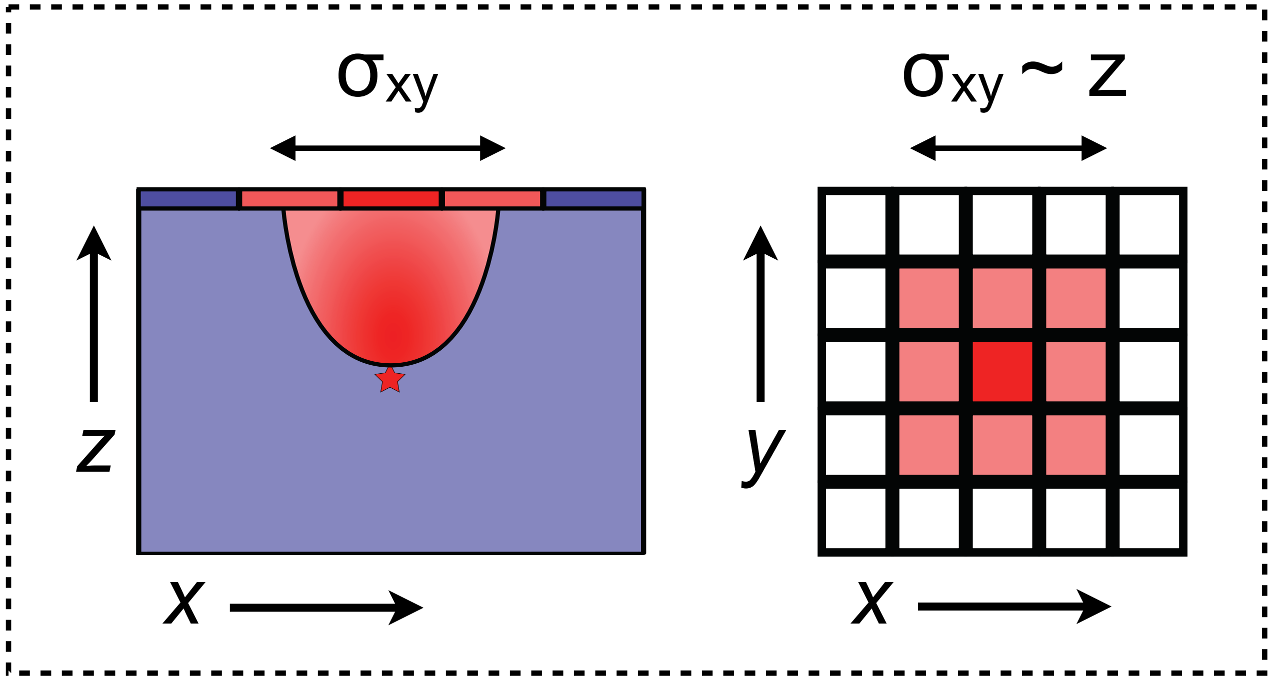
CCD-based dark matter search

- Silicon CCD technology highly advanced thanks to utility in astronomical and satellite-based imaging
- WIMPs scatter coherently off of Si nuclei, which recoil and yield detectable ionization signals
- CCDs are “exposed”, i.e. collect charge, for $\mathcal{O}$(1 day) and images are then read out for analysis



16 Mpix CCD
6 cm x 6 cm
15-μm pixel pitch
675-μm thick



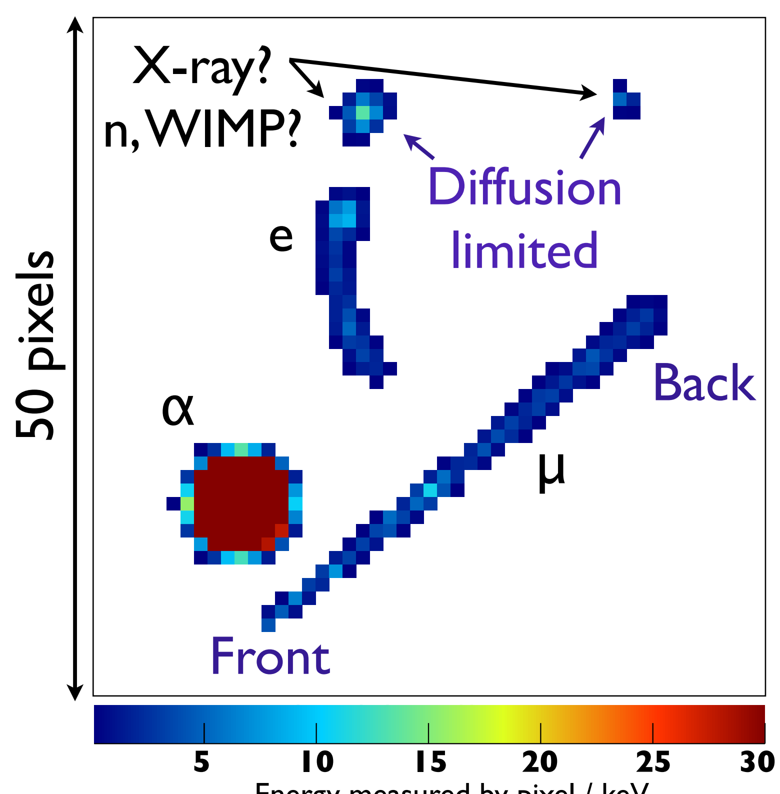


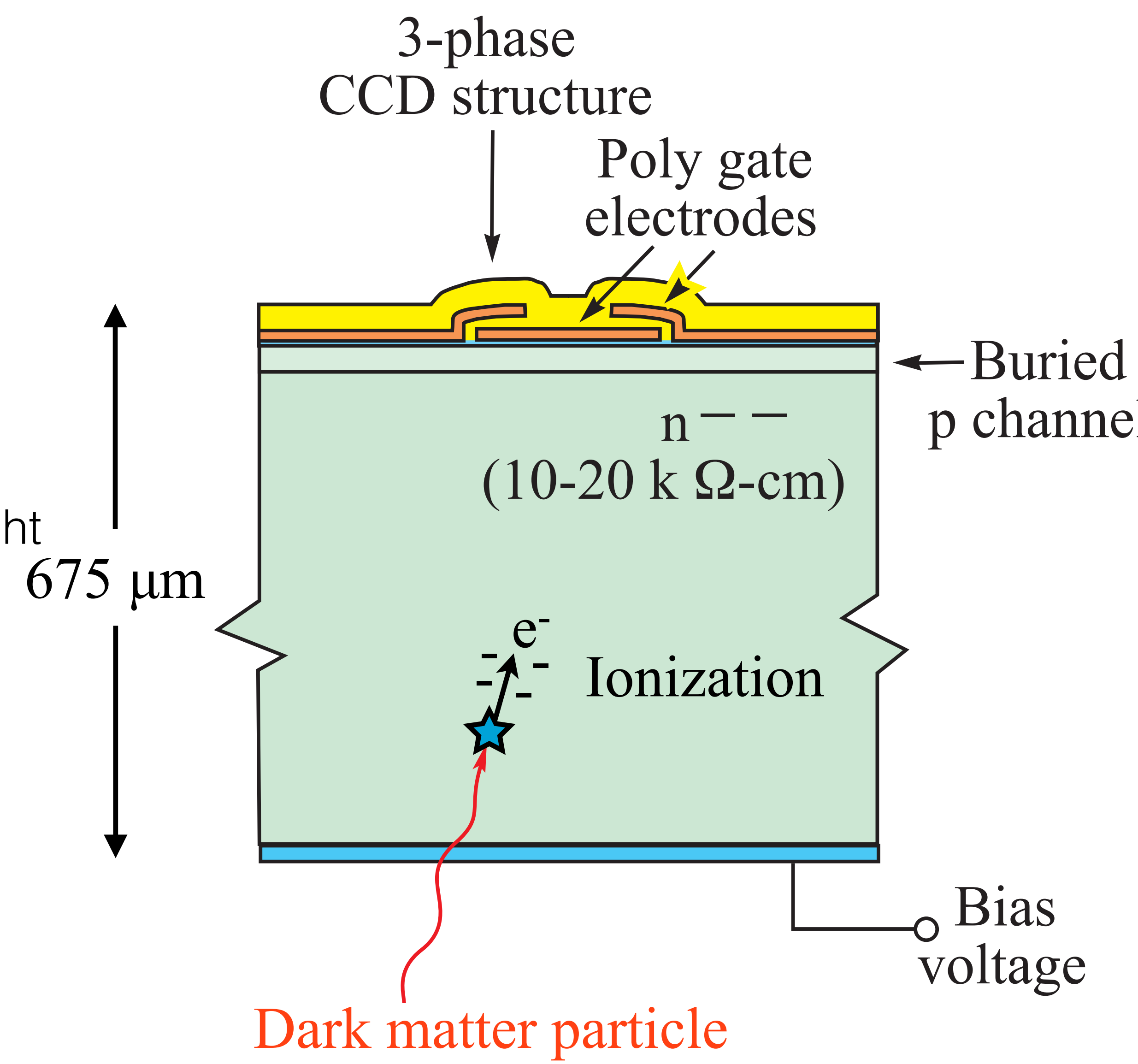
DAMIC DARK MATTER IN CCDS

Top fig. from A. Aguilar-Arevalo *et al.*, arXiv:1506.02562
Lower fig. from A. Aguilar-Arevalo *et al.*, arXiv:1607.07410

CCD characterization

- Detector performance must be understood at very-low energies
  - Calibrate with various gamma-ray sources
- Response to nuclear recoils must be understood
  - Use elastic neutron scattering
- Must be able to reconstruct *z* location of interaction
  - Muons and low-energy sources provide necessary insight





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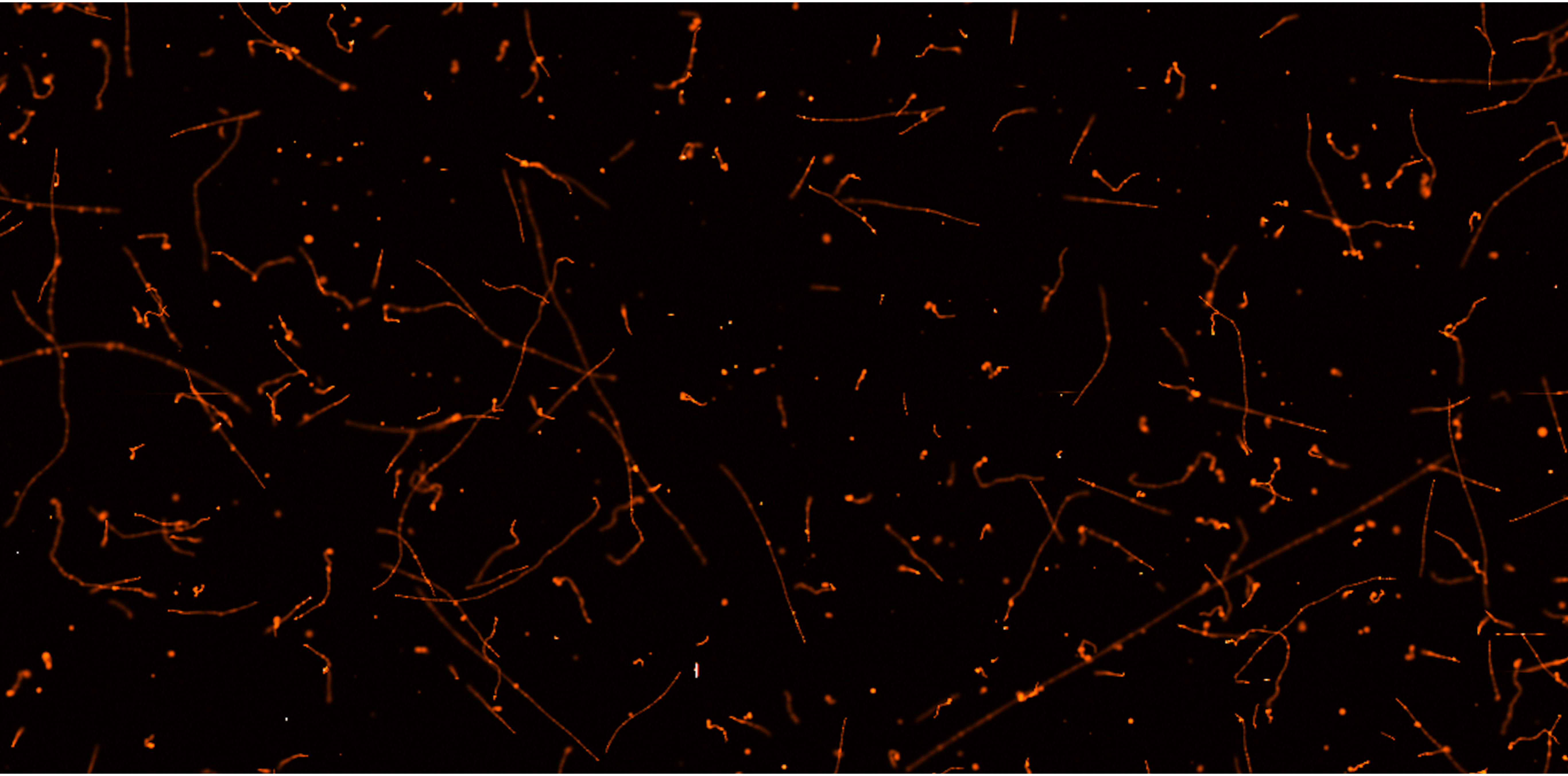
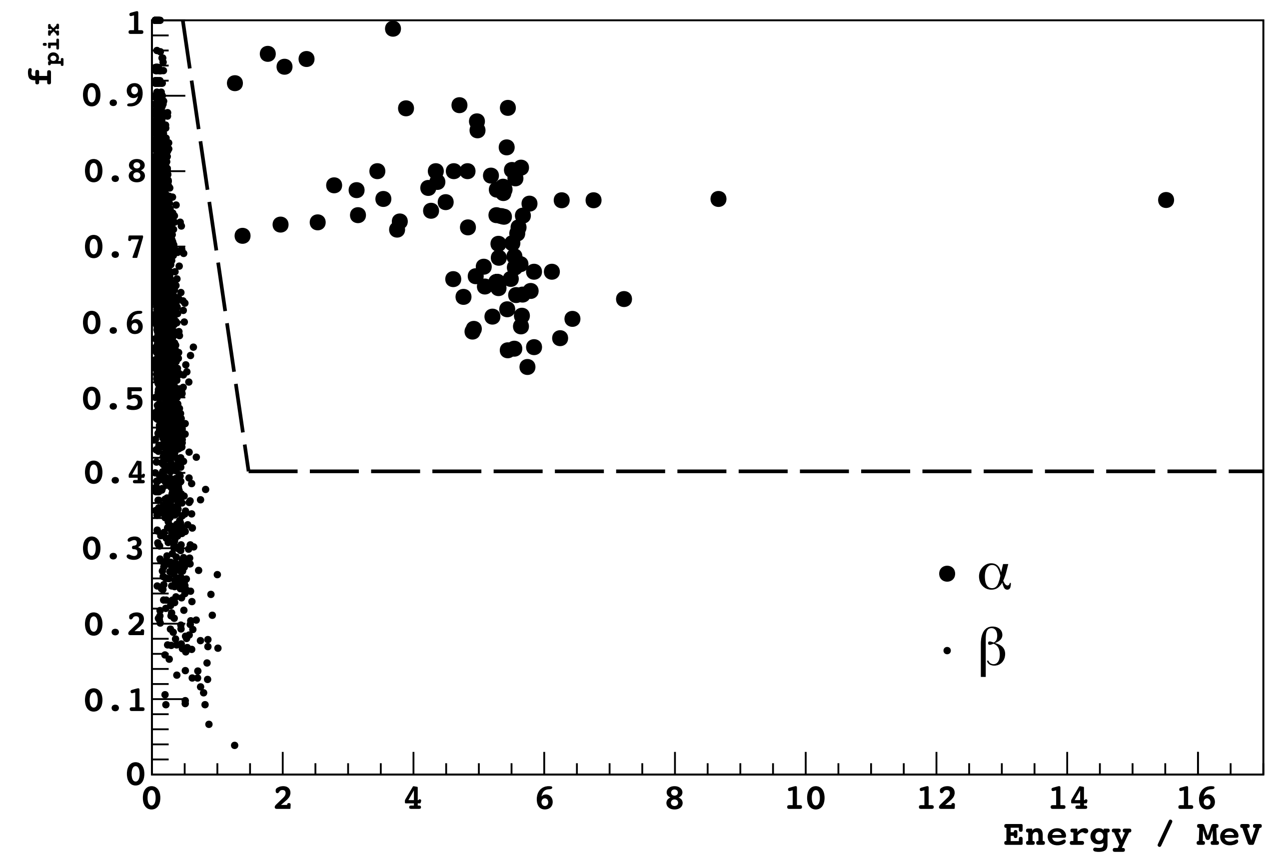
Left fig. from A. Aguilar-Arevalo *et al.*, arXiv:1506.02562
Right fig. adapted by A.E. Chavarria from arXiv:1611.03066

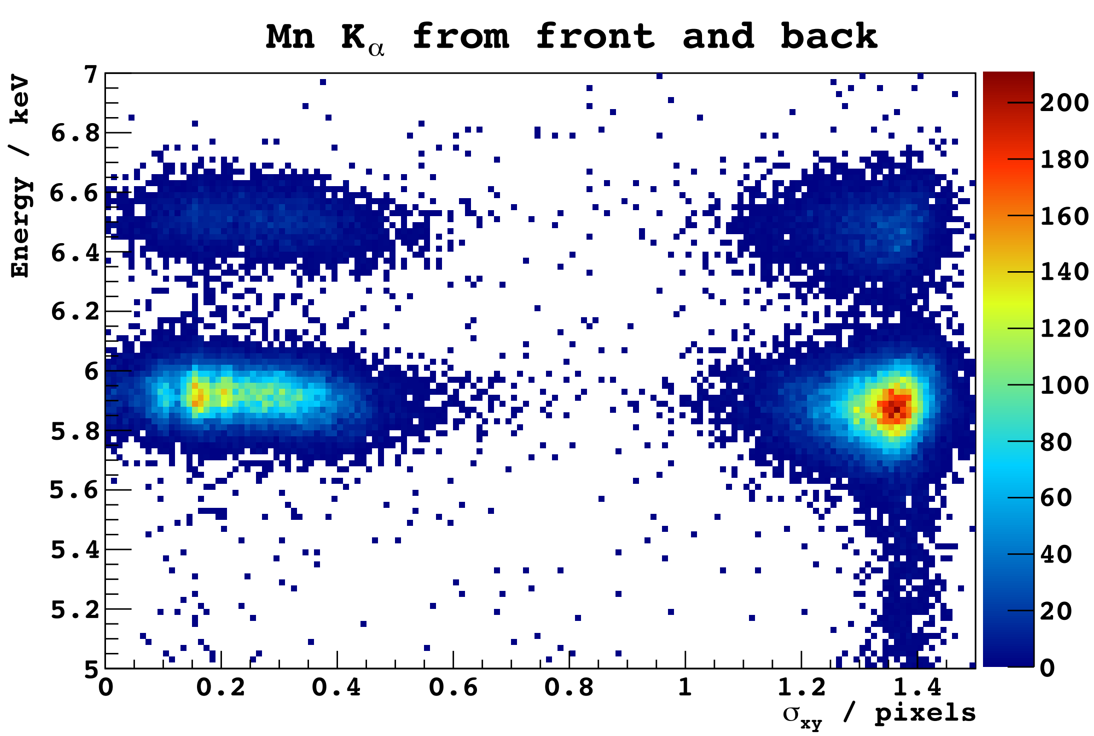
CCD image example with nearby source

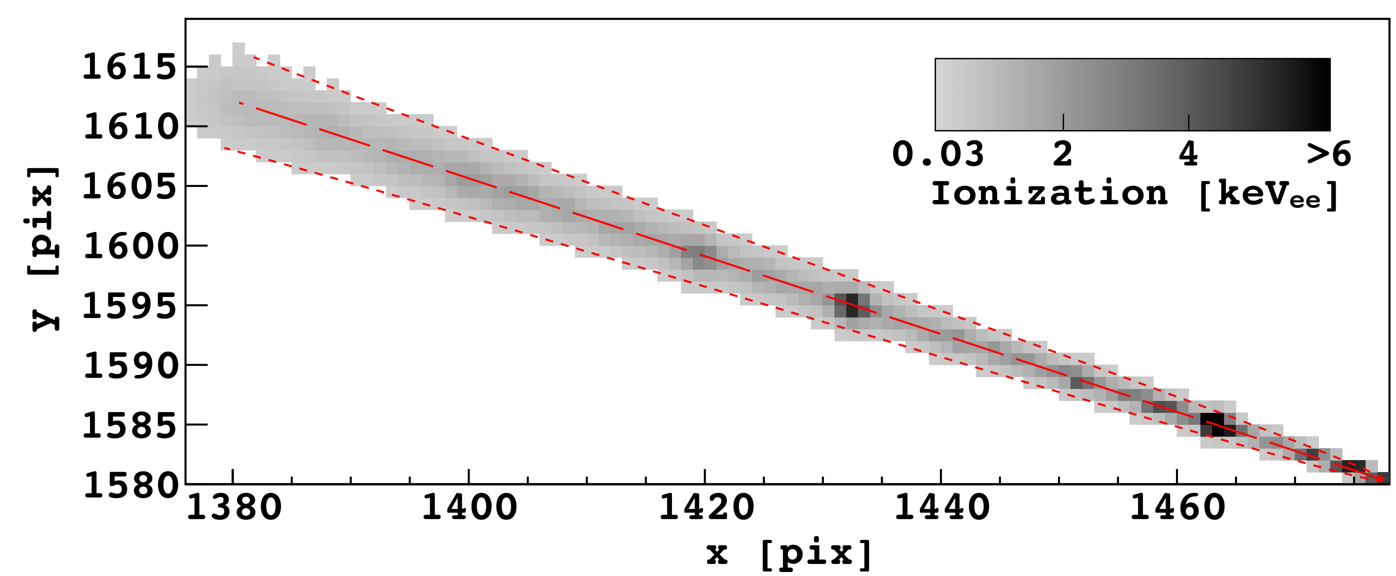


Particle ID and depth determination

- Different stopping power for α vs β results in distinct shapes
- Location in plane of CCD easily reconstructed
- Diffusion through CCD can be exploited to reconstruct z



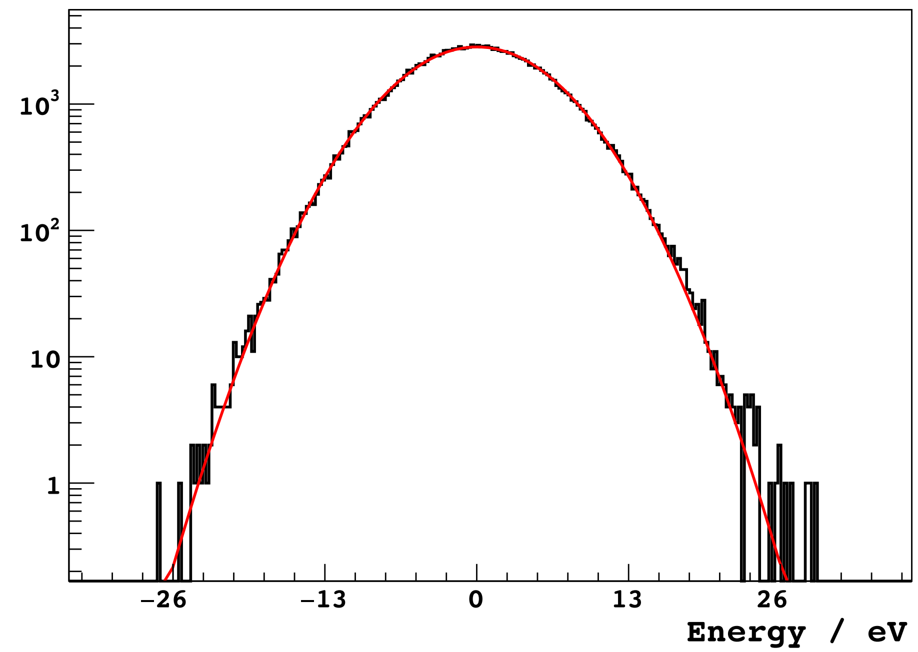


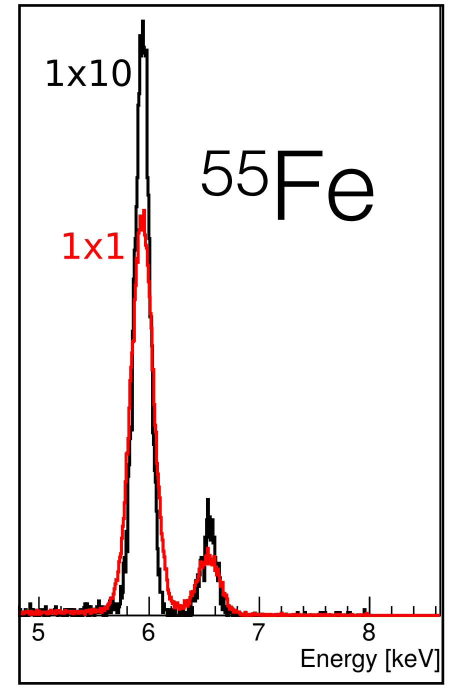


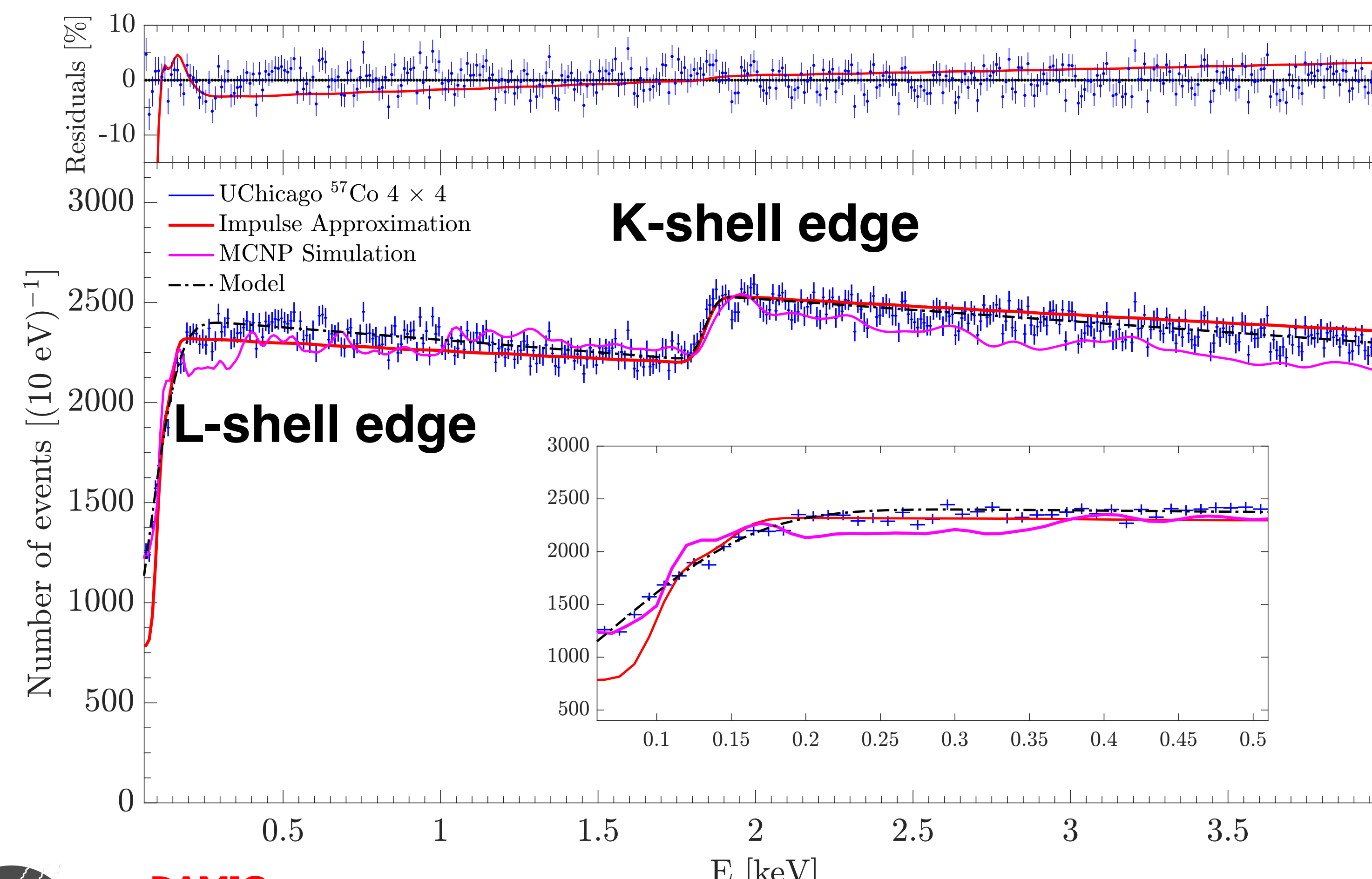
Top fig. from A. Aguilar-Arevalo *et al.*, arXiv:1506.02562
Bottom right fig. from A. Aguilar-Arevalo *et al.*, arXiv:1607:07410

Energy calibration for electron events

- CCDs can accomplish very-low-noise readout
  - Pedestal FWHM < 5 electrons
  - Some improvement can be realized by grouping pixels - same read noise, but more pixels/read
- Gamma interactions are *ultimately* electron events
  - Standard calibration sources can be used to see full-energy peaks in some cases (e.g., ^{55}Fe, top right), but…
- CCDs are thin targets for energetic gammas!
  - Compton scattering response calibrated with ^{57}Co and ^{241}Am, general response model developed [1]
  - Electrons from Compton scattering are expected to be the most significant background in DM search with DAMIC







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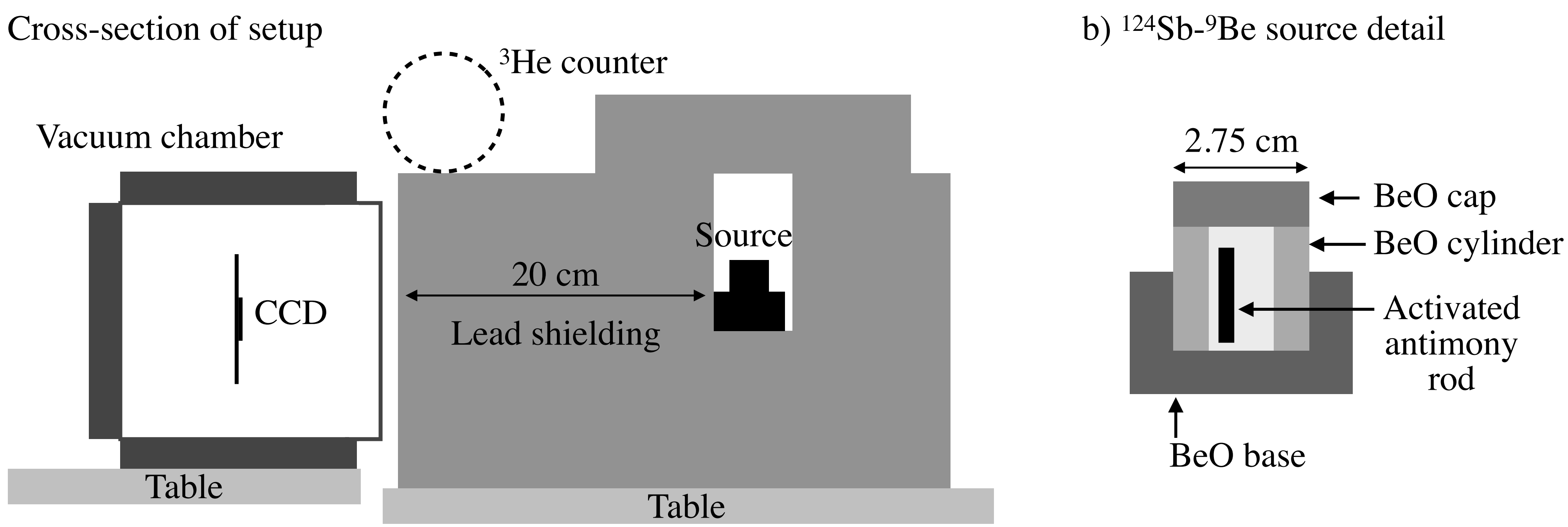
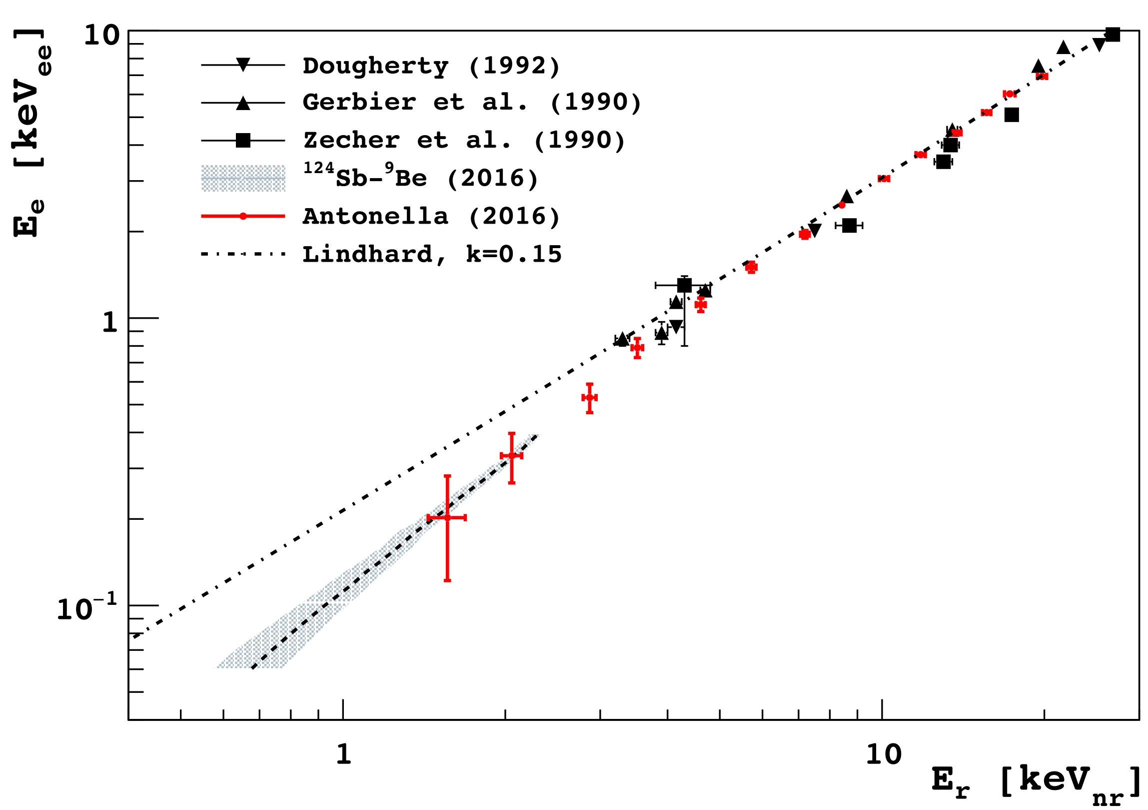
[1] K. Ramanathan *et al.*, arXiv:1706.06053
Bottom fig. from [1]

Response to nuclear recoils: quenching factor





- Elastic scattering of neutrons produces recoiling nuclei, like those produced by WIMP scatters
  - Quenching factor can be extracted from carefully designed neutron-scattering experiments
- 24-keV neutrons produced by photoneutron source used to measure response down to 60 eVee

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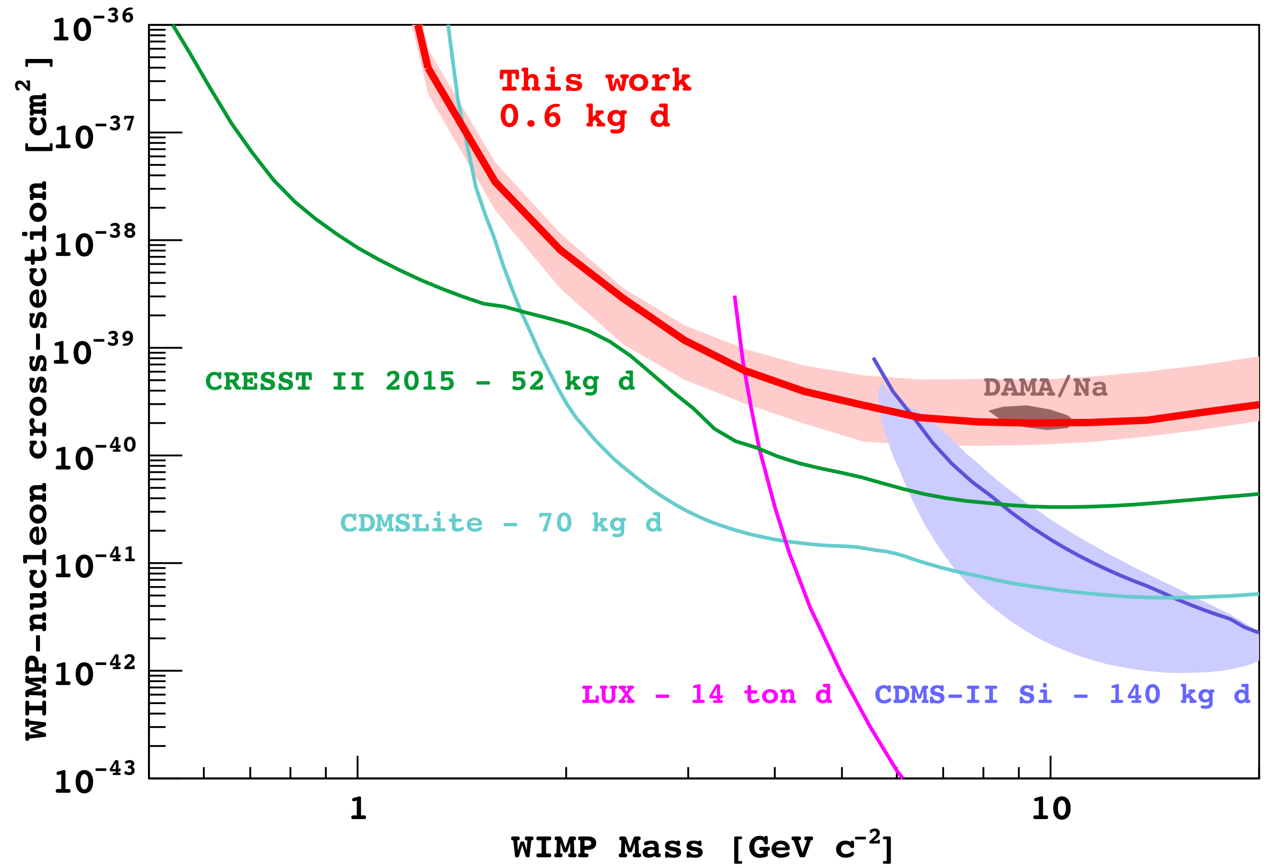
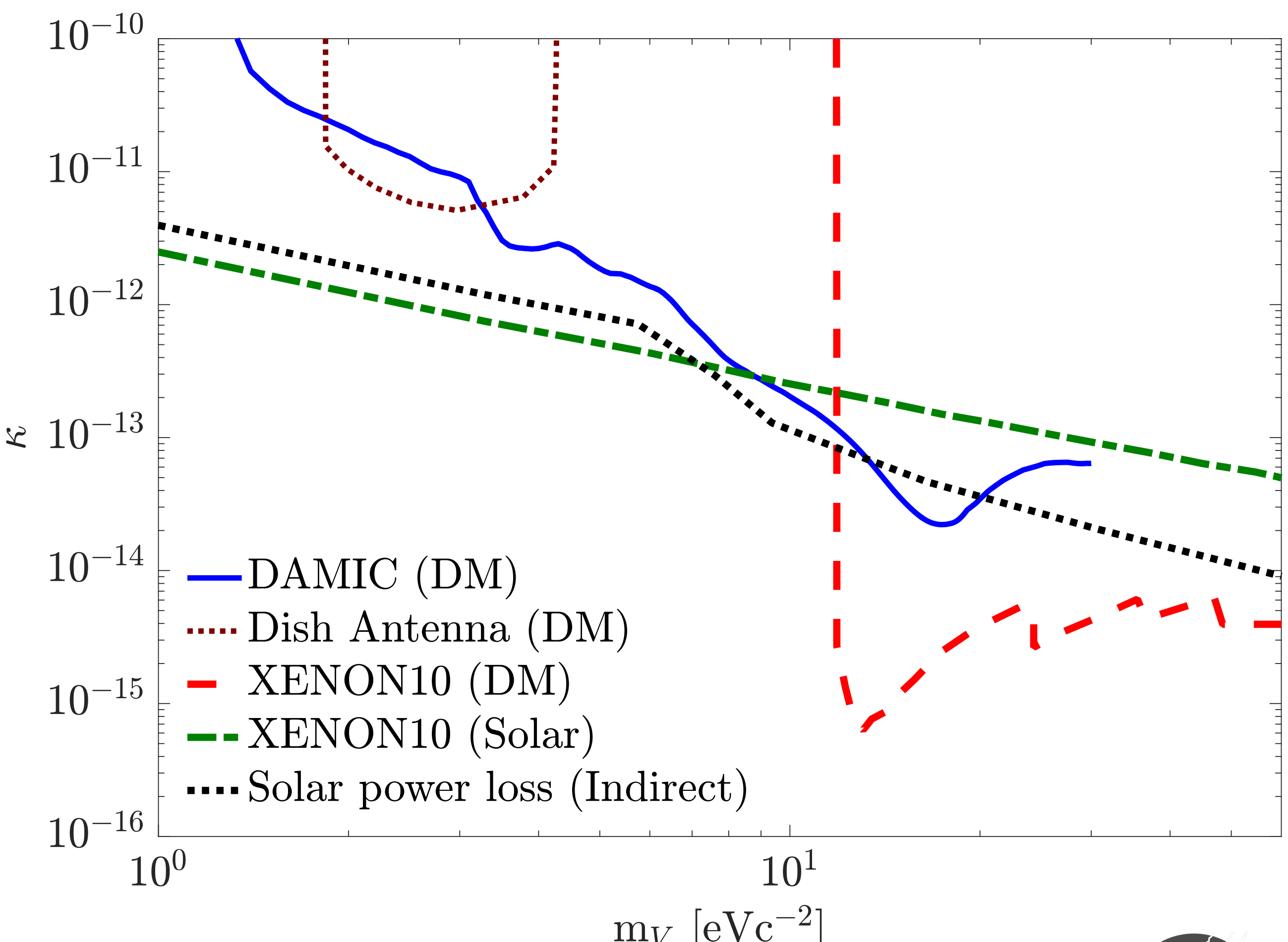
Figures from A.E. Chavarria *et al.*, arXiv:1608.00957

Past science results from DAMIC

WIMP limit from 8 Mpix CCDs at SNOLAB
Aguilar-Arevalo *et al.*, PRD 94, 082006 (2016)
arXiv:1607.07410

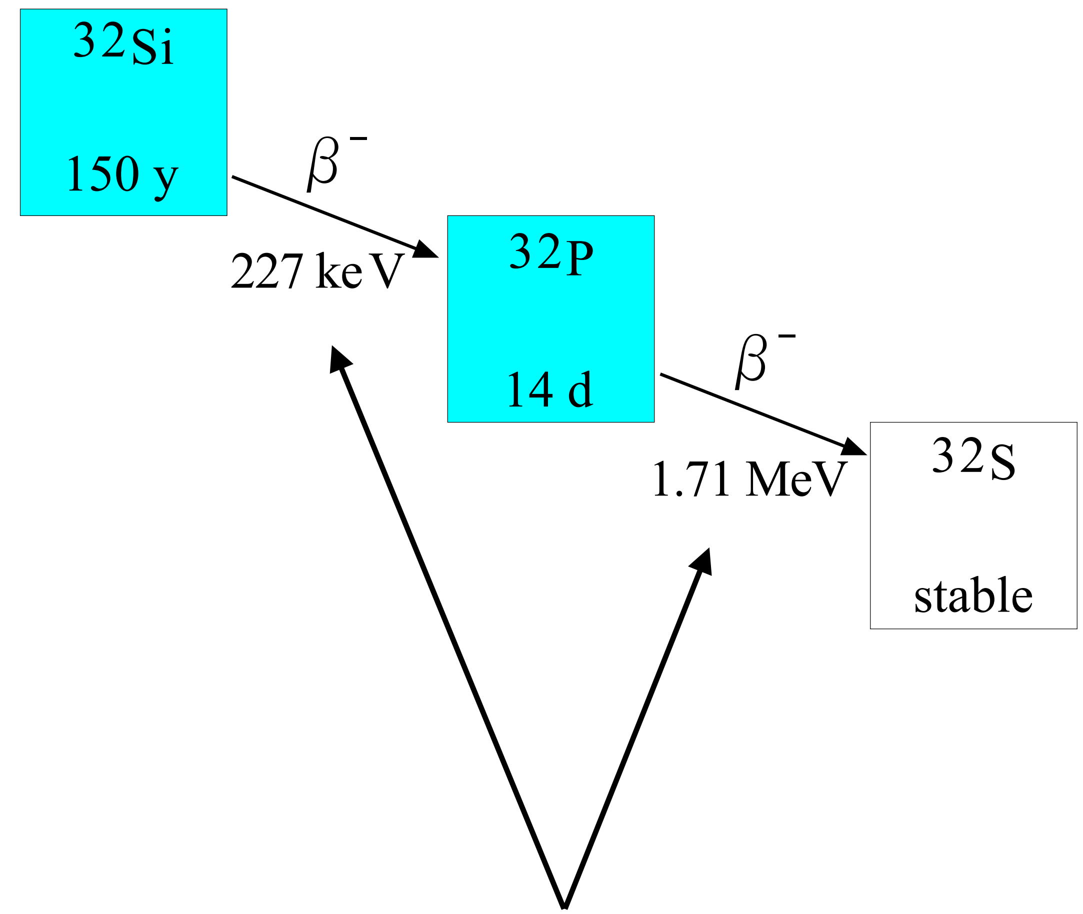




Search for hidden-photon dark matter
Aguilar-Arevalo *et al.*, PRL 118, 141803 (2017)
arXiv:1611.03066

Measurement of ^{32}Si contamination

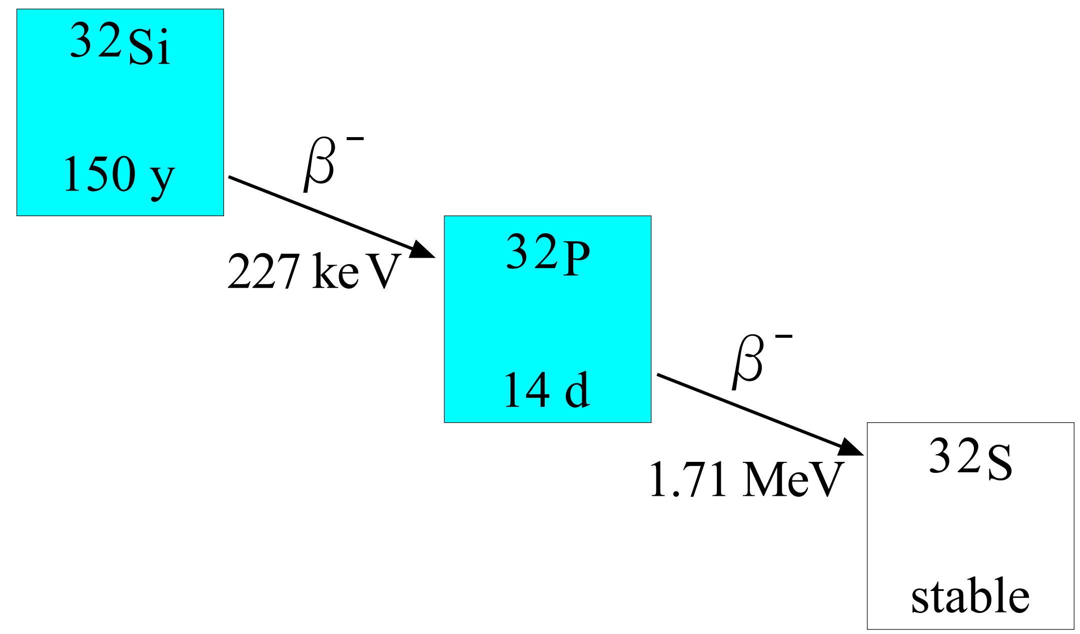
- ^{32}Si is produced in cosmic ray interactions with ^{40}Ar in the atmosphere; falls to earth in precipitation
  - Chemical processes can't separate silicon isotopes
  - ^{32}Si will be a problem for any silicon-based rare event search (e.g., SuperCDMS)
- Decay sequence from ^{32}Si can be exploited with CCDs to search for decays
- Understanding efficiency of our search, we can back out an abundance for ^{32}Si

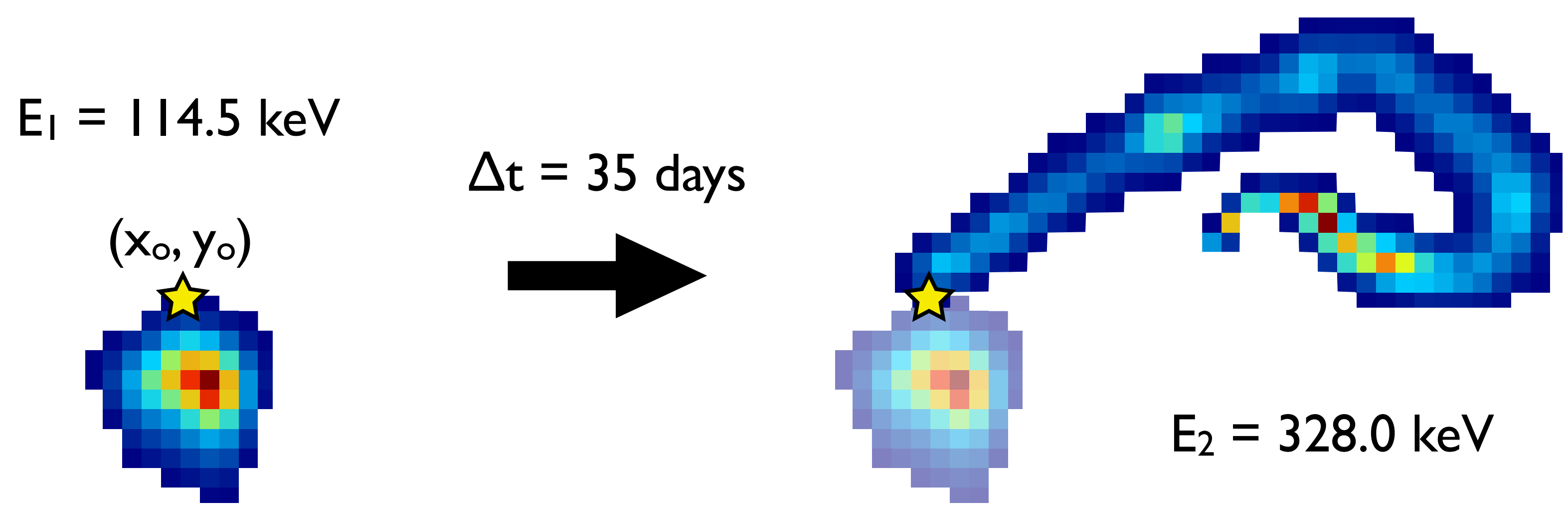


Expect spatially coincident e^- pair in separate images

Measurement of ^{32}Si contamination

- Earlier study found rate of 80 (+110, -65) /kg/day [1]
- Updated study with larger data set nearing completion
- Variability of abundance?
  - Sample size is limited now, must be careful before generalizing understanding for SuperCDMS





DAMIC DARK MATTER IN CCDS
[1] A. Aguilar-Arevalo *et al.*, J. Inst 10 (2015) arXiv:1506.02562

^{238}U and ^{232}Th decay chains

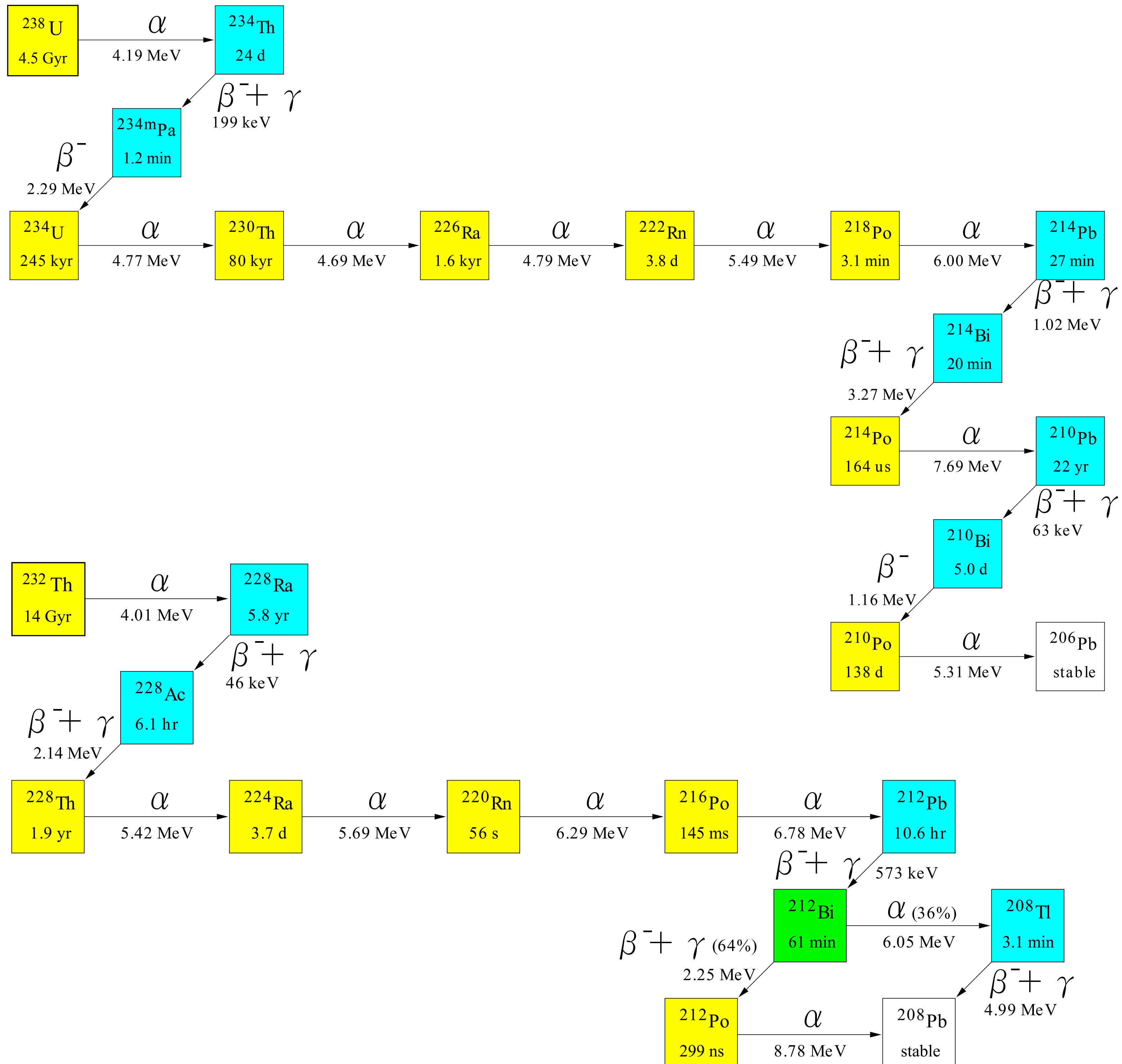
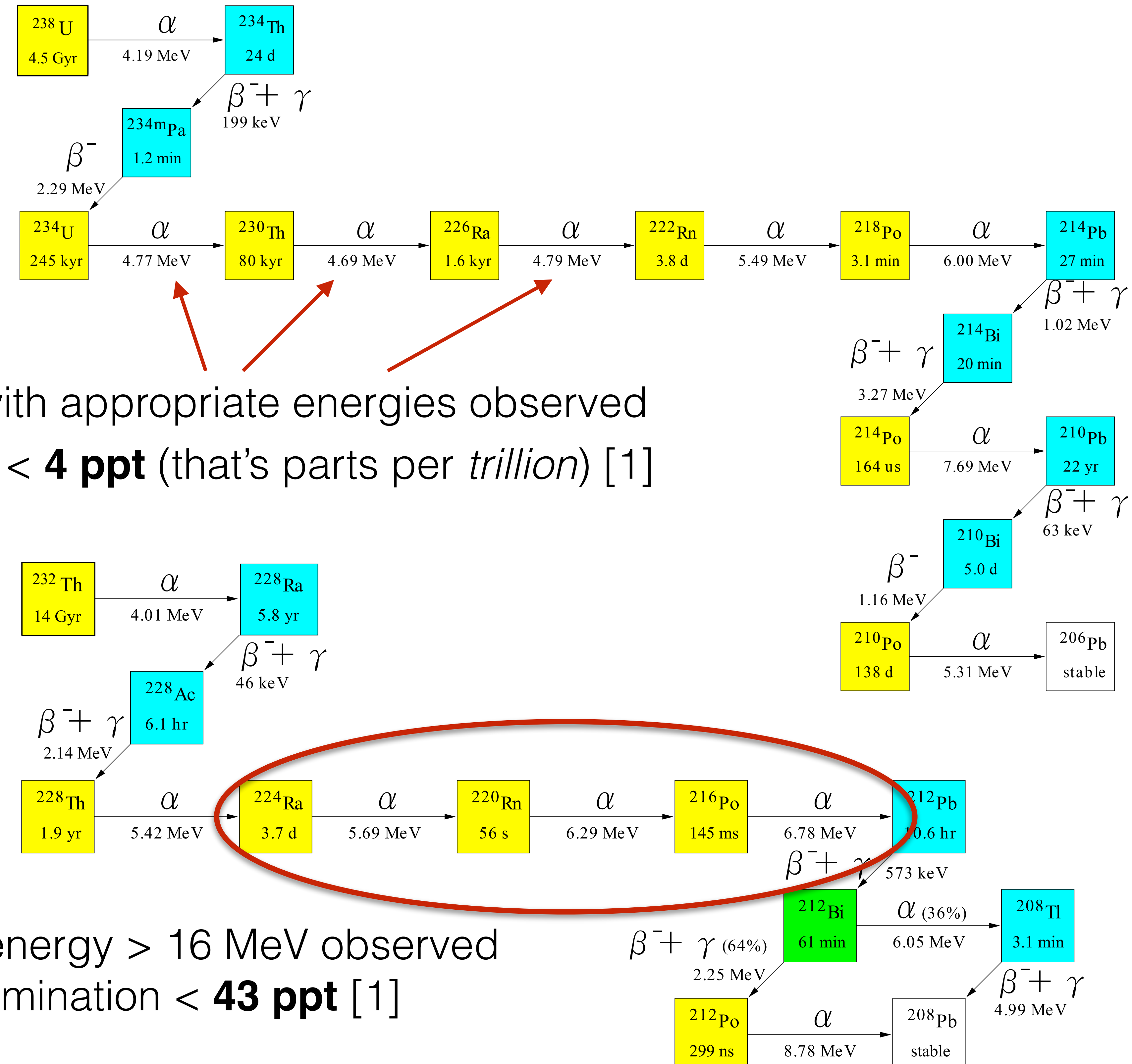


Fig. adapted from A. Aguilar-Arevalo *et al.*, J. Inst 10 (2015) arXiv:1506.02562

^{238}U and ^{232}Th limits in bulk Si



No bulk α events with appropriate energies observed

^{238}U contamination < **4 ppt** (that's parts per *trillion*) [1]

No events with energy > 16 MeV observed

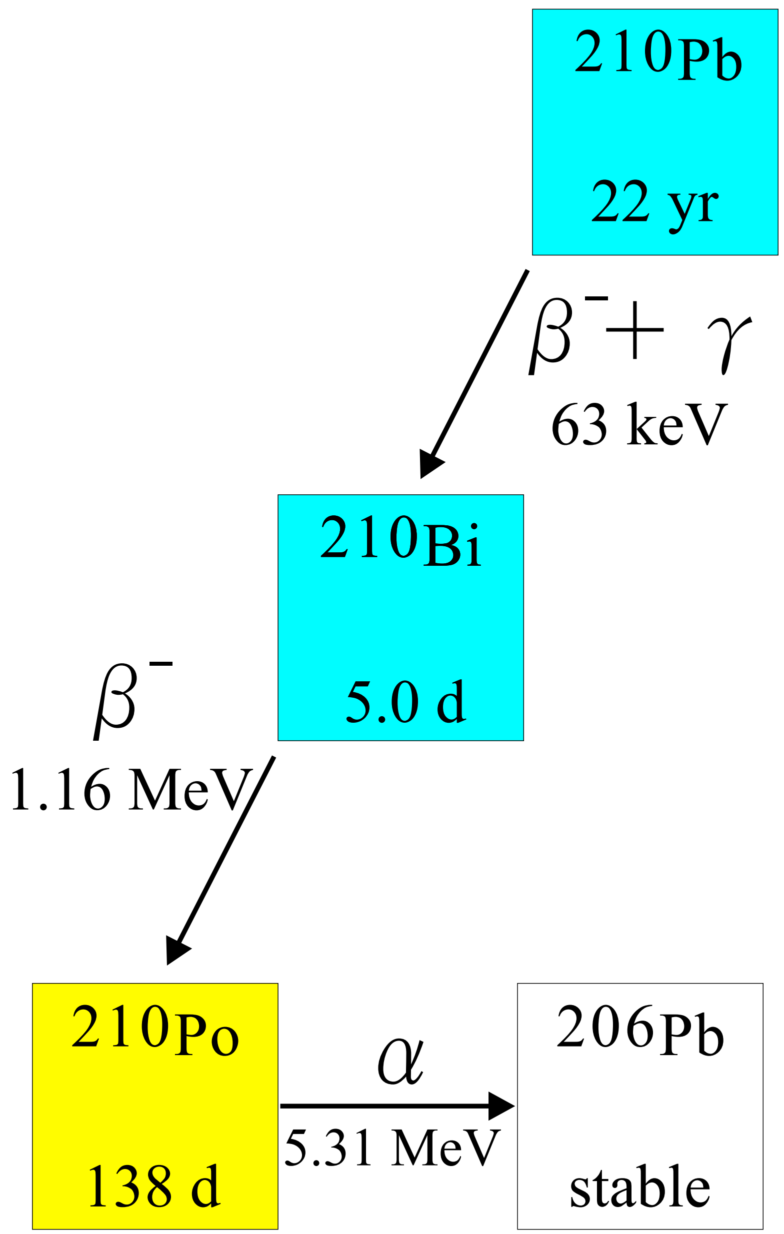
^{232}Th contamination < **43 ppt** [1]

DAMIC DARK MATTER IN CCDS

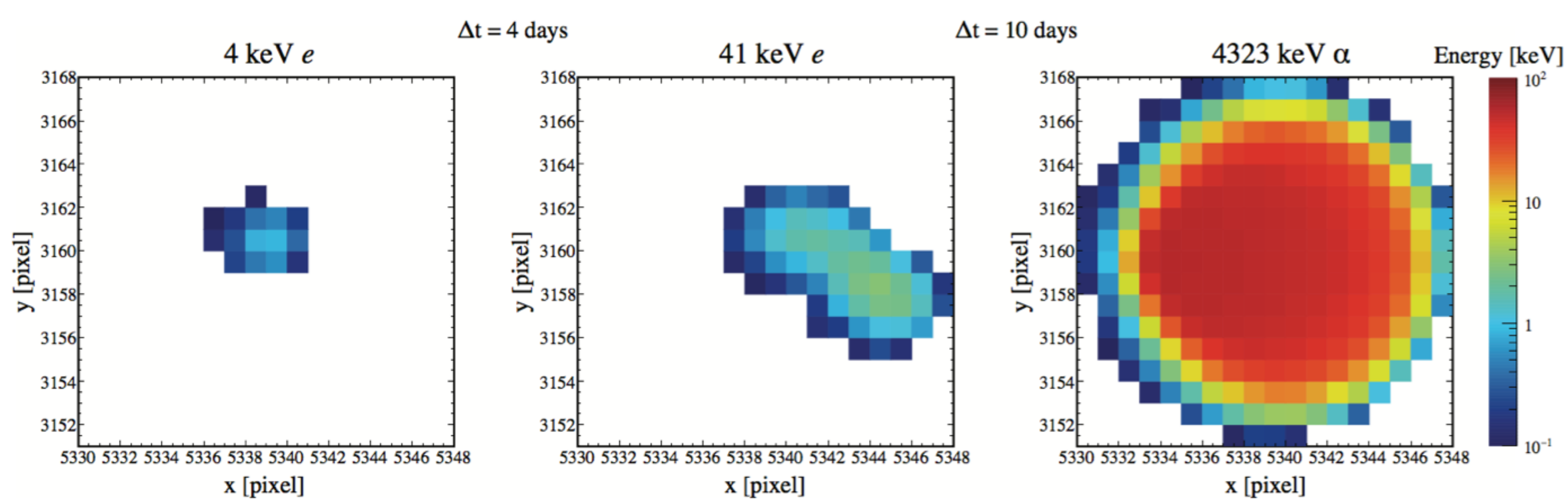
[1] A. Aguilar-Arevalo *et al.*, J. Inst 10 (2015) arXiv:1506.02562

Fig. adapted from [1]

^{210}Pb contamination measurements



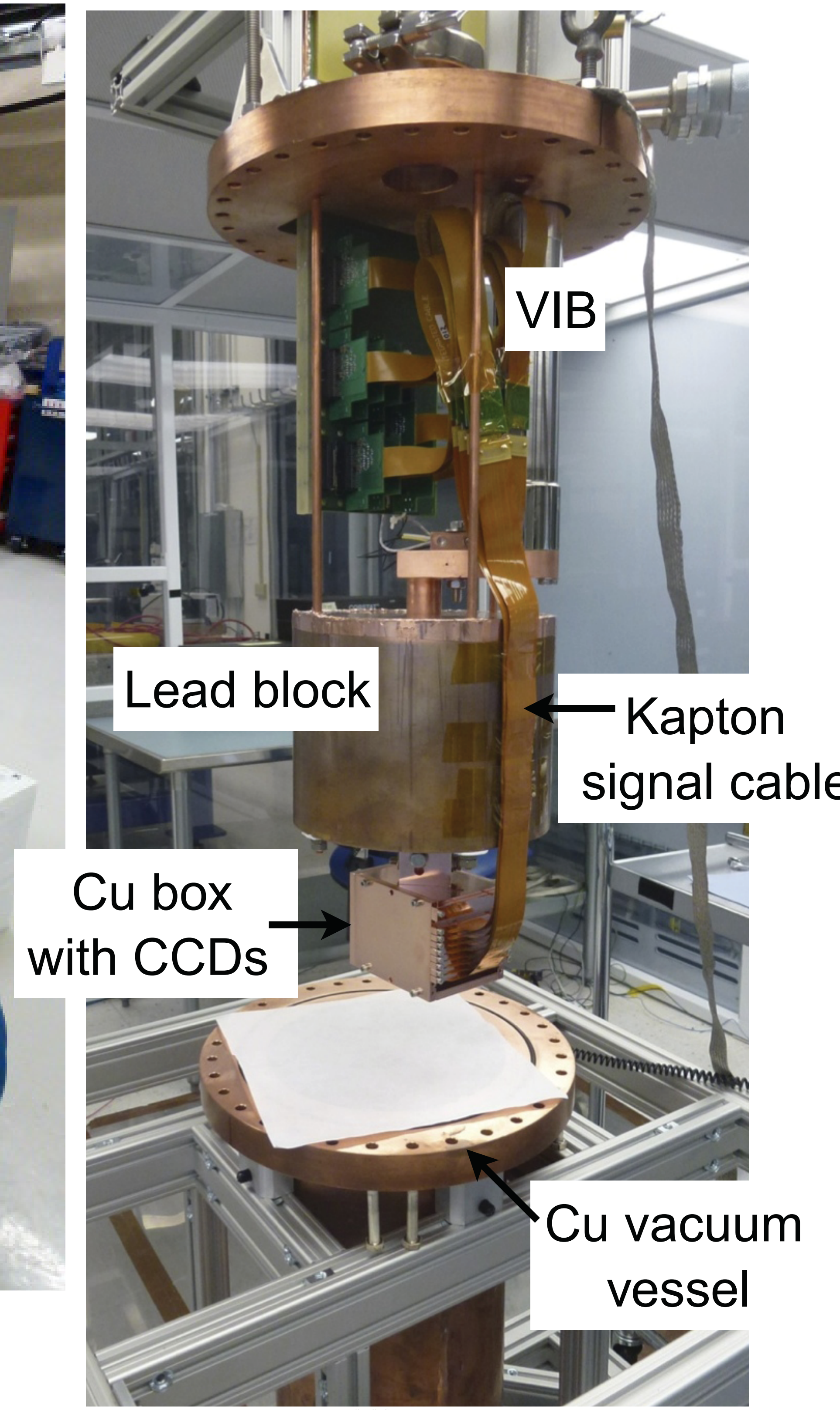
- ^{210}Pb is a daughter of ^{222}Rn (part of ^{238}U chain)
  - May reasonably expect it to be a surface contaminant
- As with ^{32}Si, can search for spatially correlated series of events
  - Should observe some combination of the two β and the α
- Previously determined rates (/ cm^2 / day) [1]
  - 0.012 ± 0.004 (back)
  - 0.078 ± 0.010 (front)

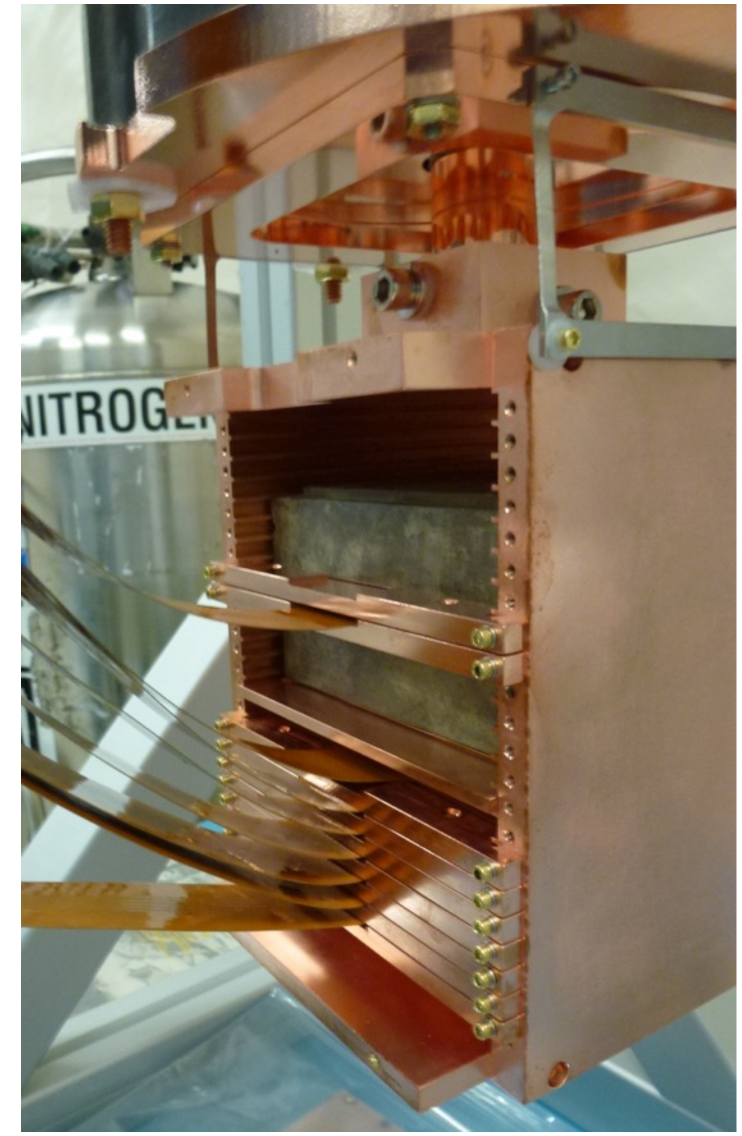


DAMIC DARK MATTER IN CCDS

[1] A. Aguilar-Arevalo *et al.*, J. Inst 10 (2015) arXiv:1506.02562

DAMIC @ SNOLAB





- 40-g target mass (7 CCDs) taking data at 140 K since 2017
- 7.6 kg d “background” data with 1x1 readout
- Pixels grouped (1x100) to reduce noise for science data

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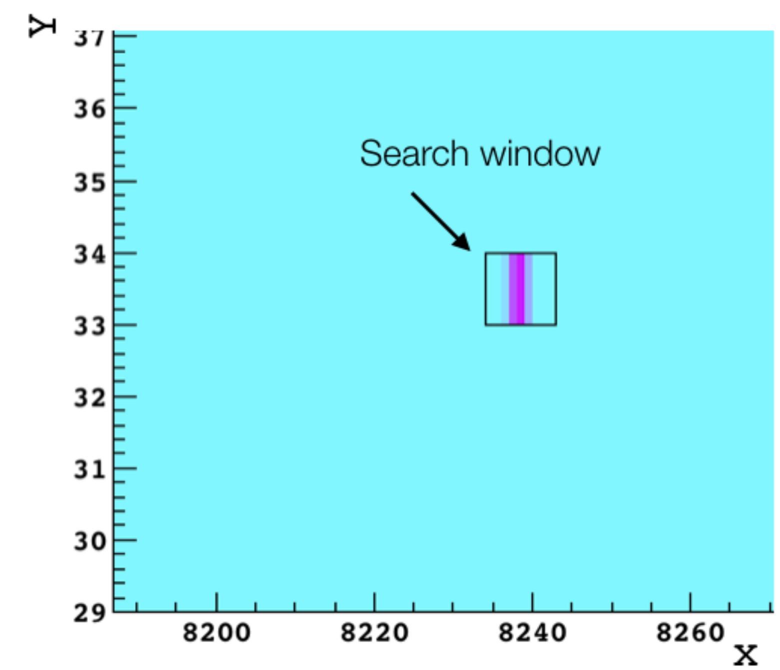
IN CCDS

Event search strategy

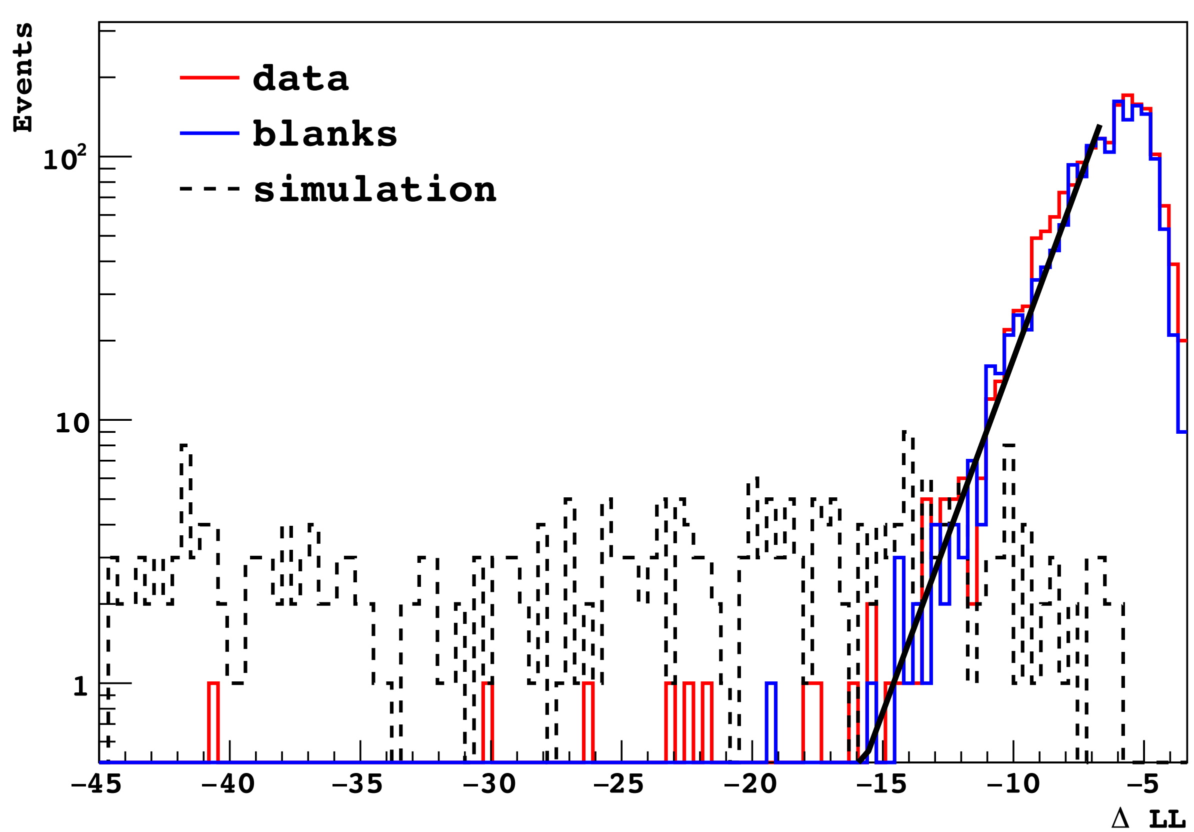
- "Hot" pixels identified and rejected from analysis
- Pedestal and correlated noise subtraction
- Moving window scans through image, likelihood comparison between signal and no-signal models provides threshold

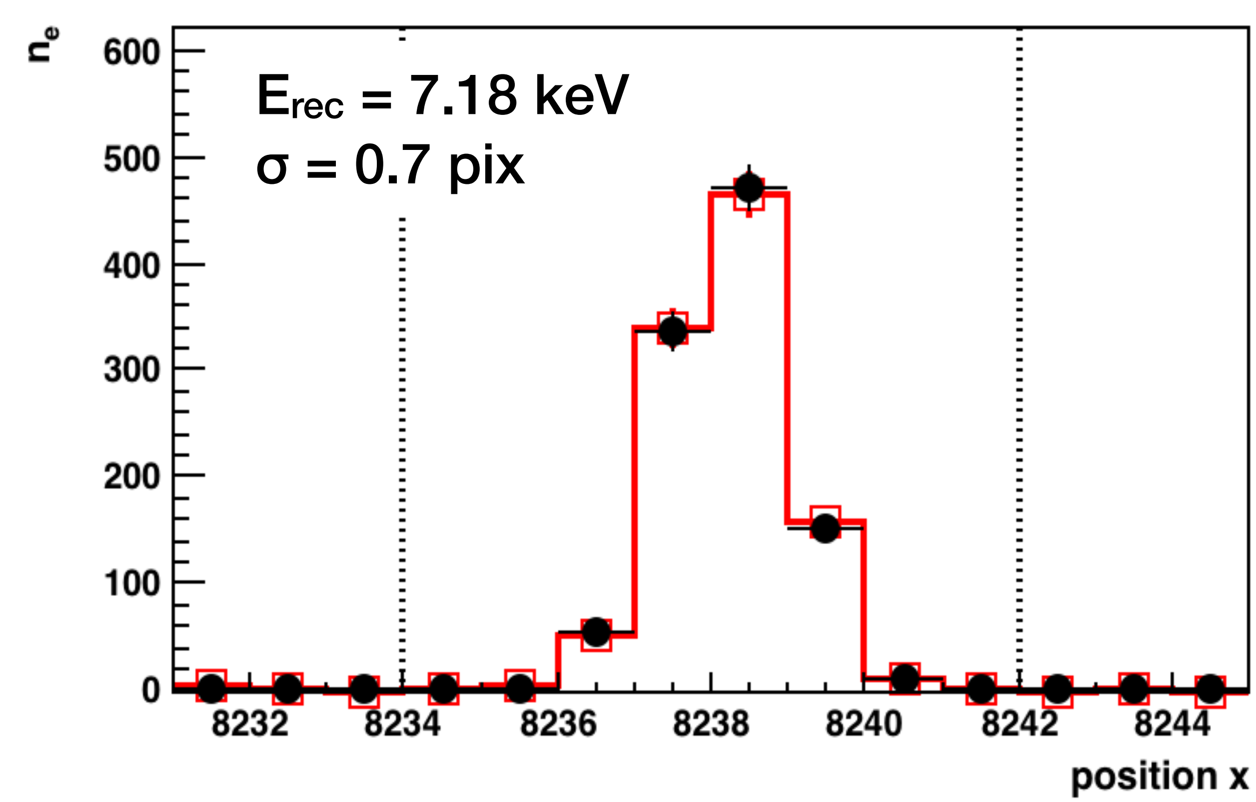


$$\Delta LL = \mathscr{L}_{noise} - \mathscr{L}_{sig}$$

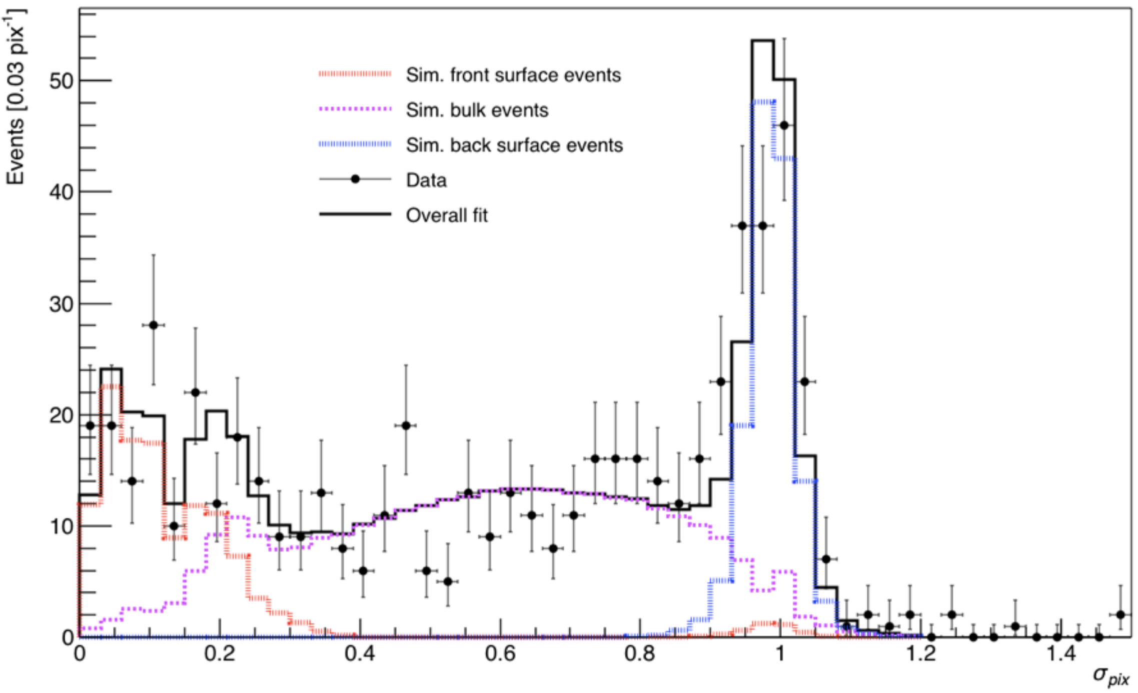
Flat background

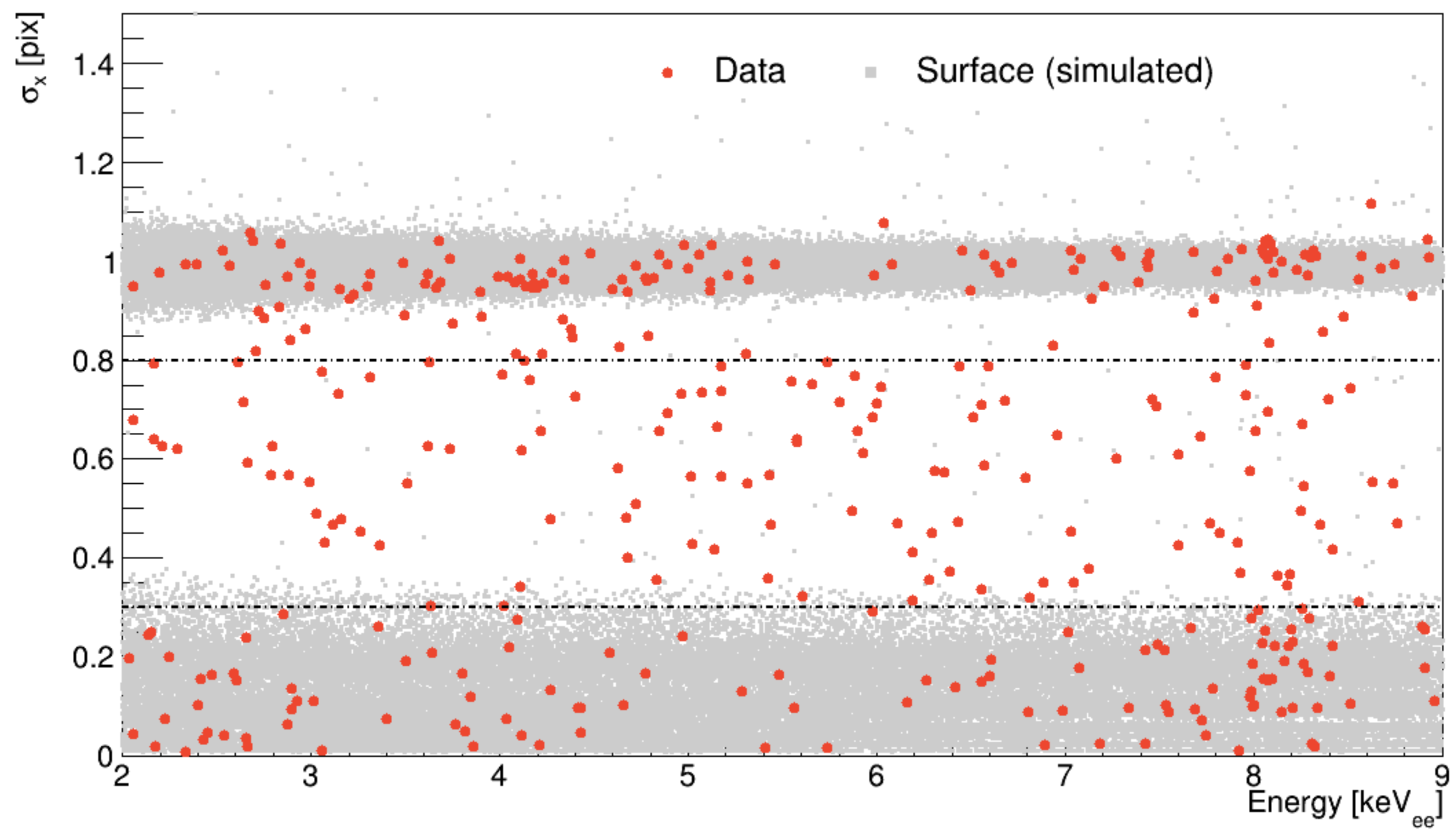
Flat background + gaussian signal



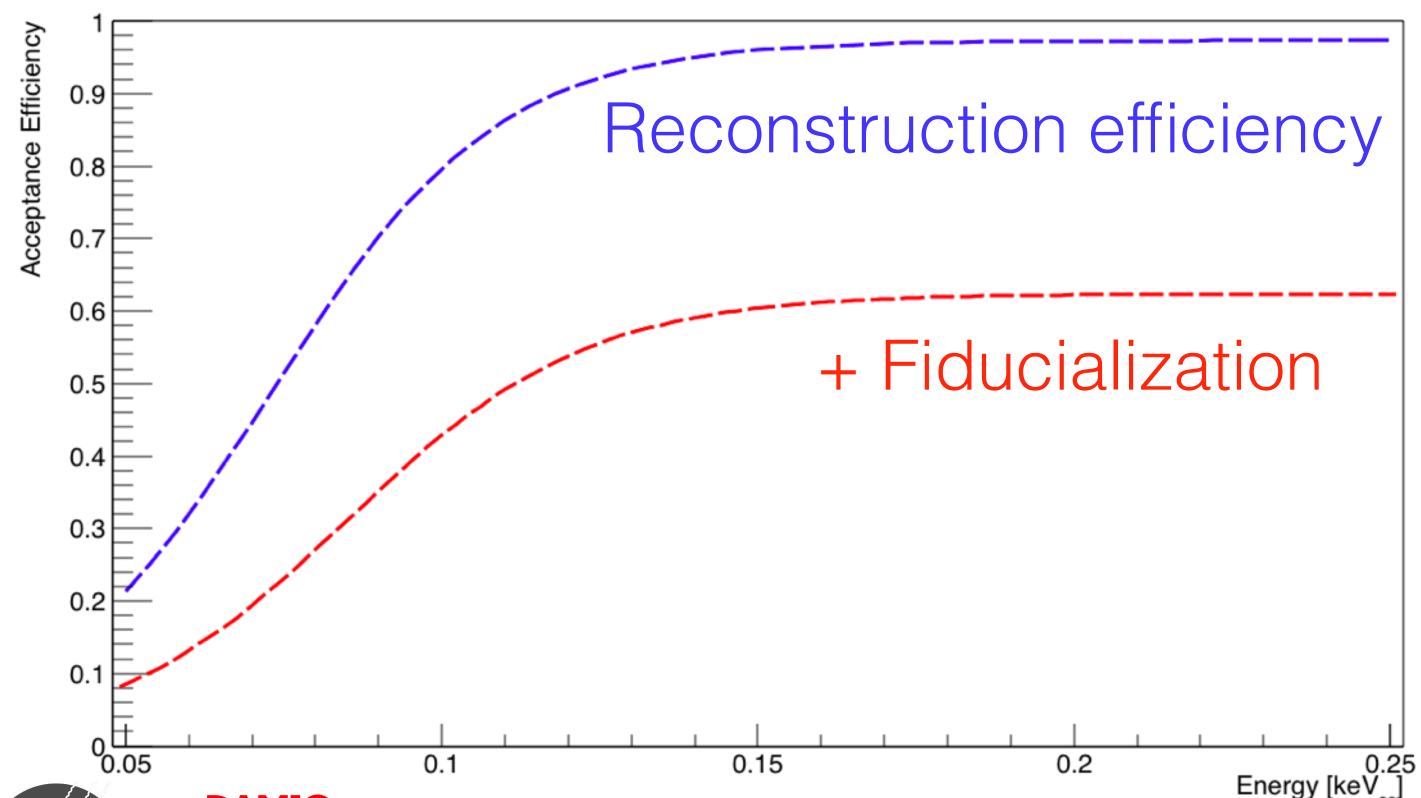


Fiducialization and rejection of surface events



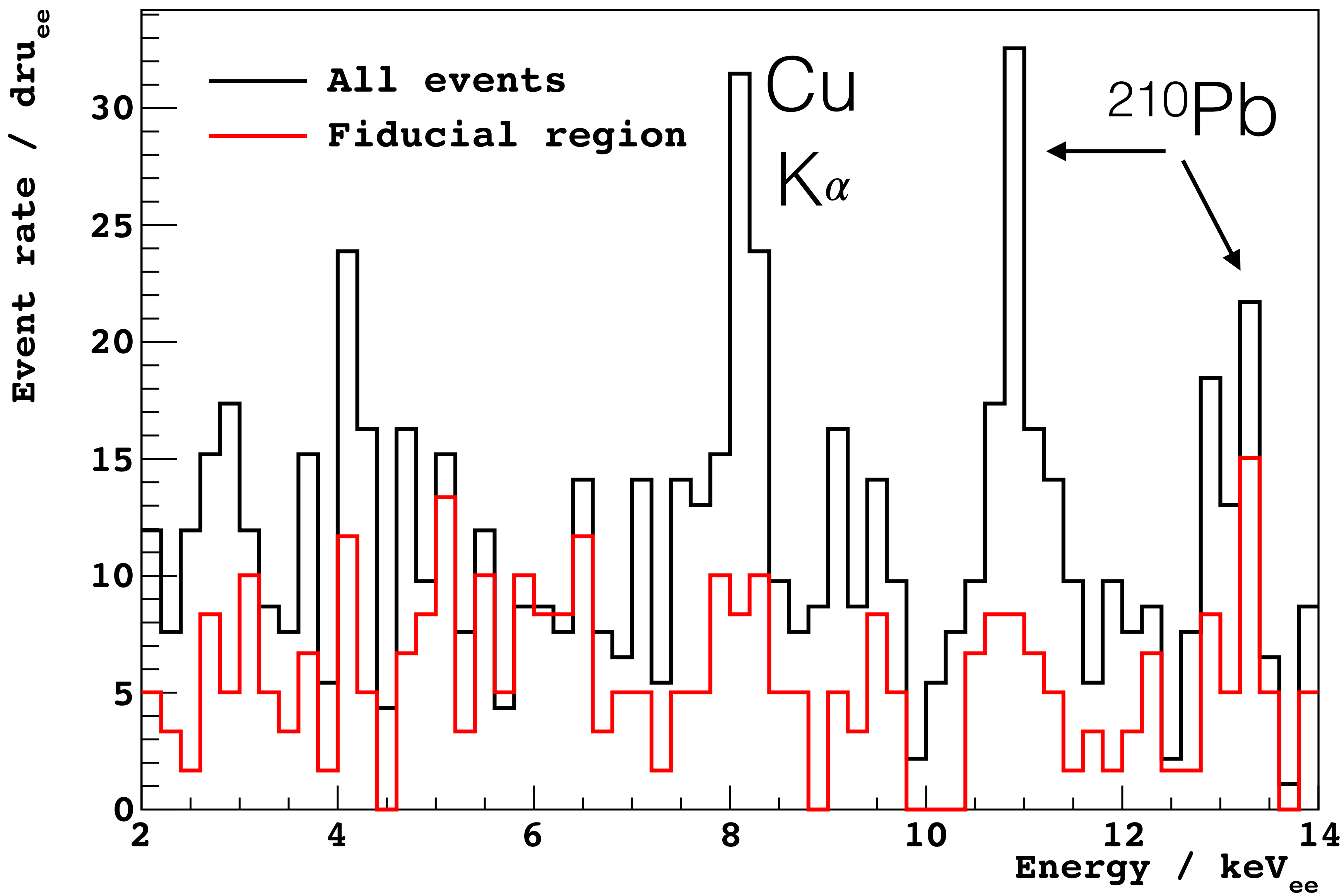


- MC simulations compared with σ distribution of data
  - Determination of front/back/bulk ratios
  - Confirm diffusion model works reasonably well
- Simulations used to determine event reconstruction efficiency and efficiency of fiducial cut
  - Plot at right shows acceptance of simulated bulk events

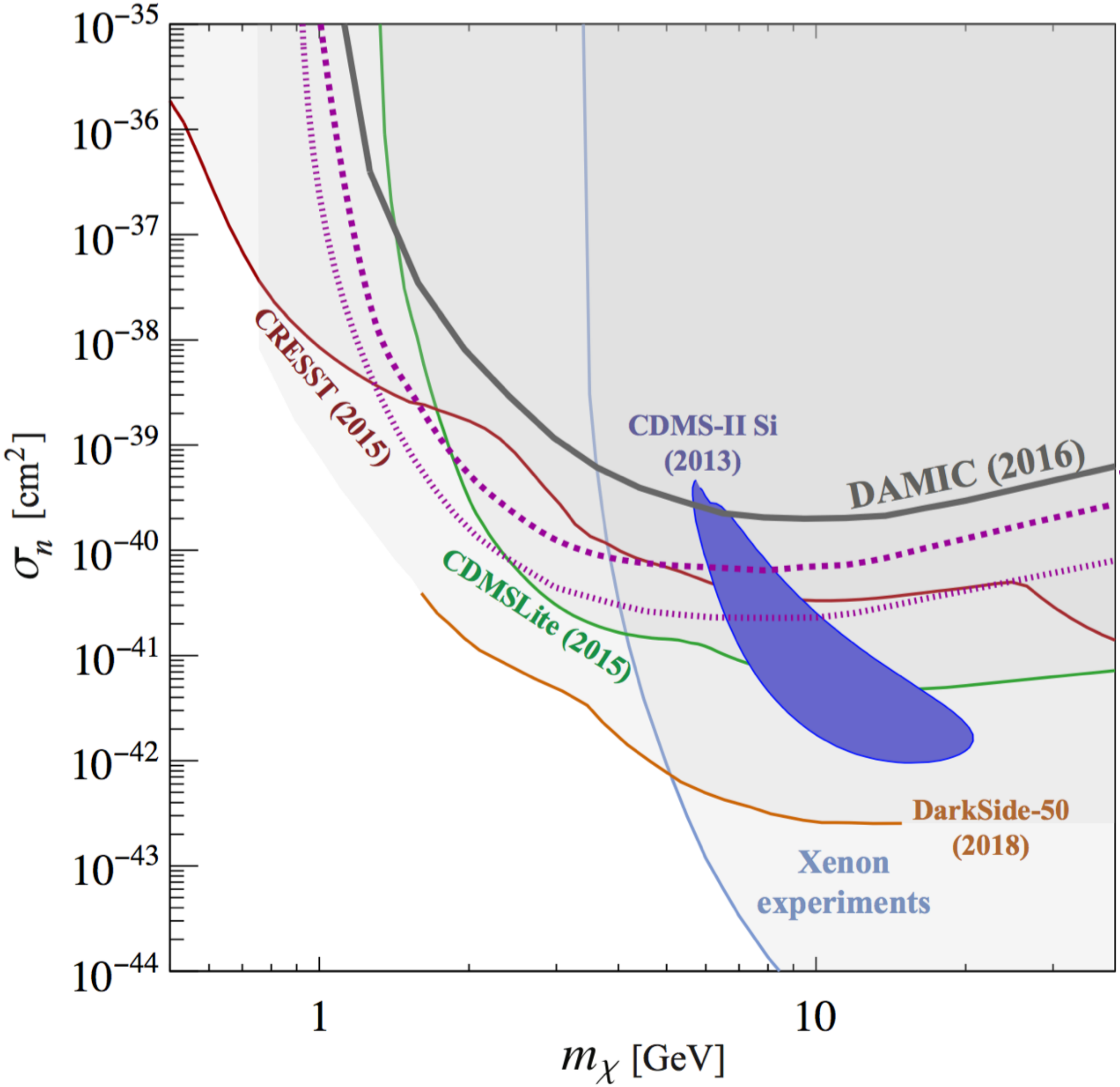


Energy spectrum from current SNOLAB data

- Background index ~5 ckkd
  - ckkd: counts / keV / kg / day, aka dru (differential rate unit)
  - Substantial improvement over previous DAMIC backgrounds (factor of ~3-4 reduction)
- Continuing to refine background model before analysis at lower energies
  - Realizable threshold: ~50 eVee



DAMIC light WIMP sensitivity



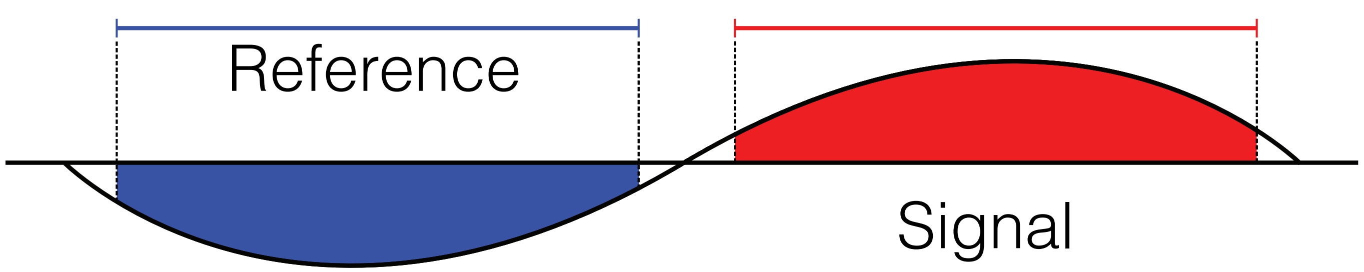
DAMIC (4.6 kg d)
DAMIC (13 kg d)

- Projected sensitivities assume currently realized background index of 5 ckkd
- 4.6 kg d exposure obtained by March 2018
- 13 kg d exposure by end of 2018

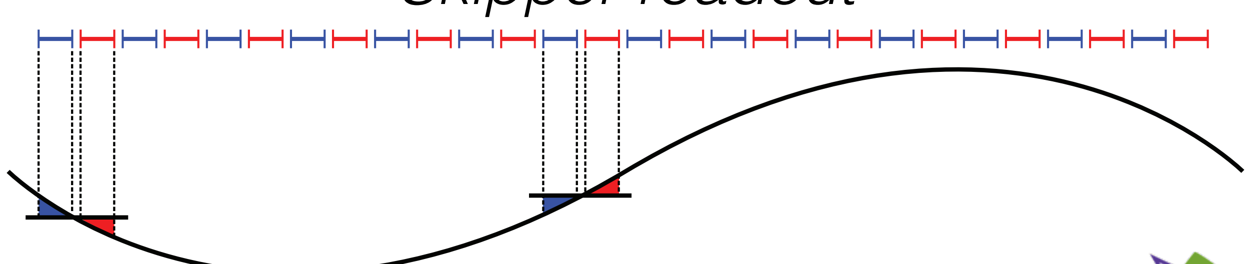
DAMIC-M @ Laboratoire Souterrain de Modane

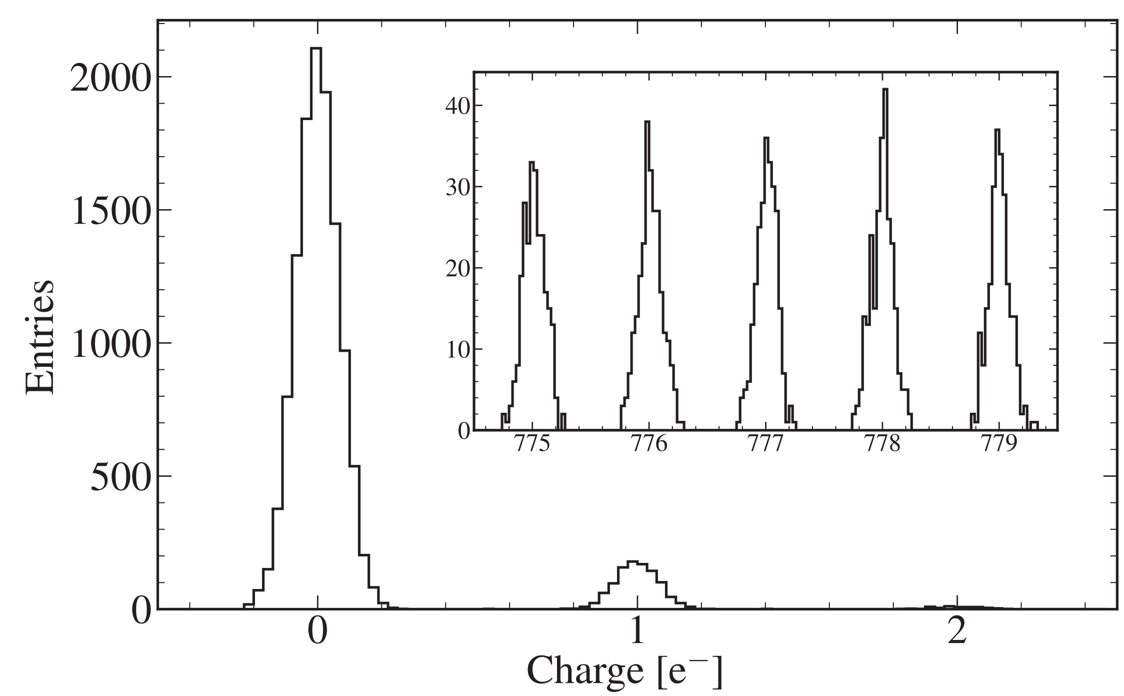
- Next stage of DAMIC to take place at Modane using 1 kg of large (20 g) DAMIC CCDs with *skipper*-style readout
    - Skipper readout allows for single-electron resolution, demonstrated by SENSEI [1]
- Characterization of large skipper CCDs to begin this summer
- Realizable dark-current level should be < 0.005 e^-/pix/day

Conventional readout



Skipper readout





[1] J. Tiffenberg *et al.*, arXiv:1706.00028
Lower right fig. from [1]

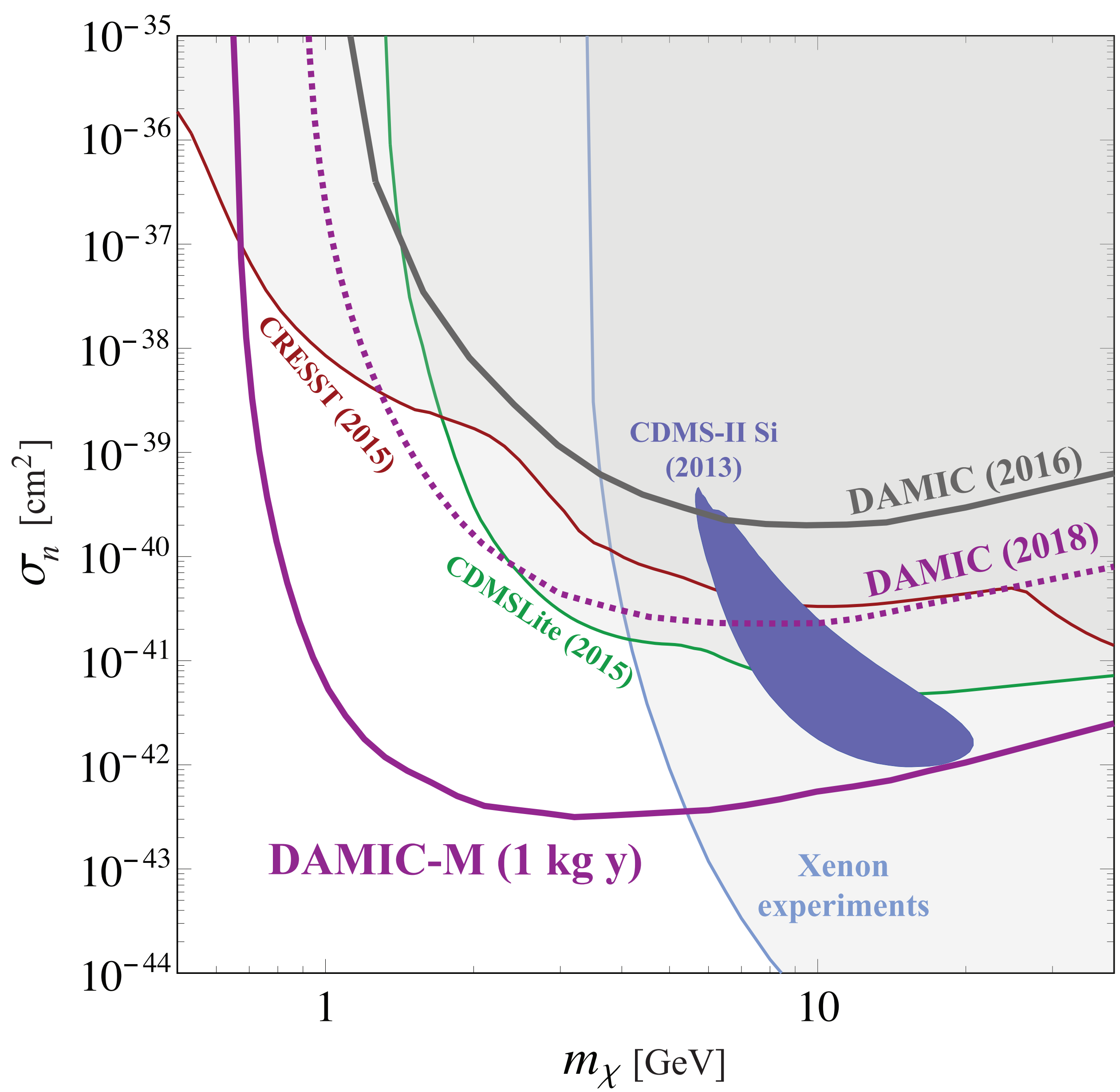
DAMIC-M @ Laboratoire Souterrain de Modane

- Skipper-readout DAMIC CCDs will be complemented by careful, proven background-reduction methods
  - Goal is background index of 0.1 ckkd, successfully realized in MJD and C4
- Expect dominant contribution from cosmogenic ^{3}H in bulk silicon
  - Ongoing measurement campaign at LANSCE to mimic cosmic activation with high-energy proton beam
- Material procurement and handling will benefit from experience rare-event search community
  - Key pieces will be made with PNNL electroformed copper (top photo)
  - Packaging of CCDs and detector assembly to take place in radon-free cleanroom at LSM
  - Silicon will be stored underground / in purpose-built shielding containers to minimize activation (GERDA container seen in bottom photo)

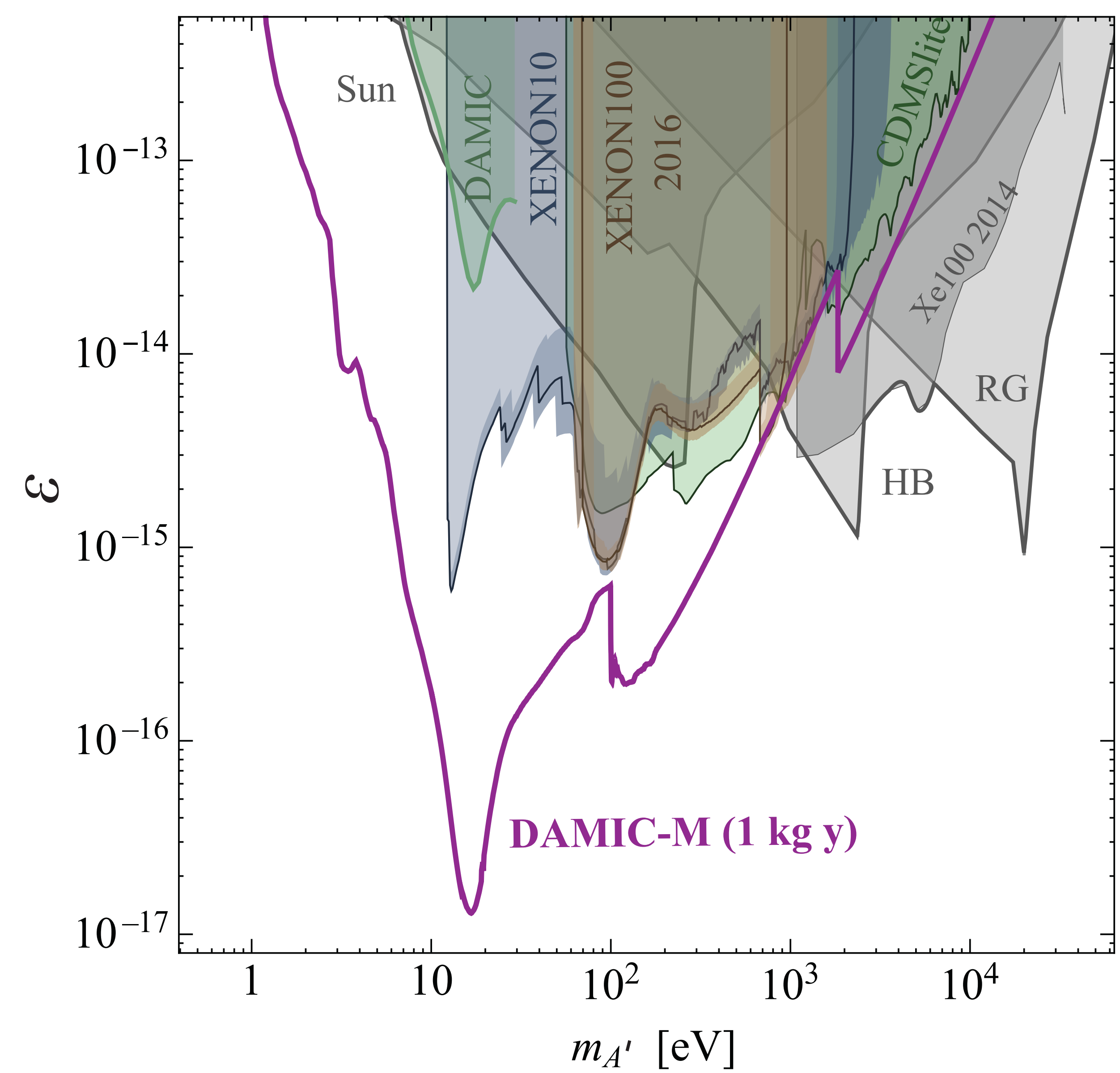
Bottom photo from M. Hult *et al.*, JRC Sci. Tech. Rep., JRC43108 (2008)

DAMIC-M anticipated sensitivities

WIMP nuclear-recoil search

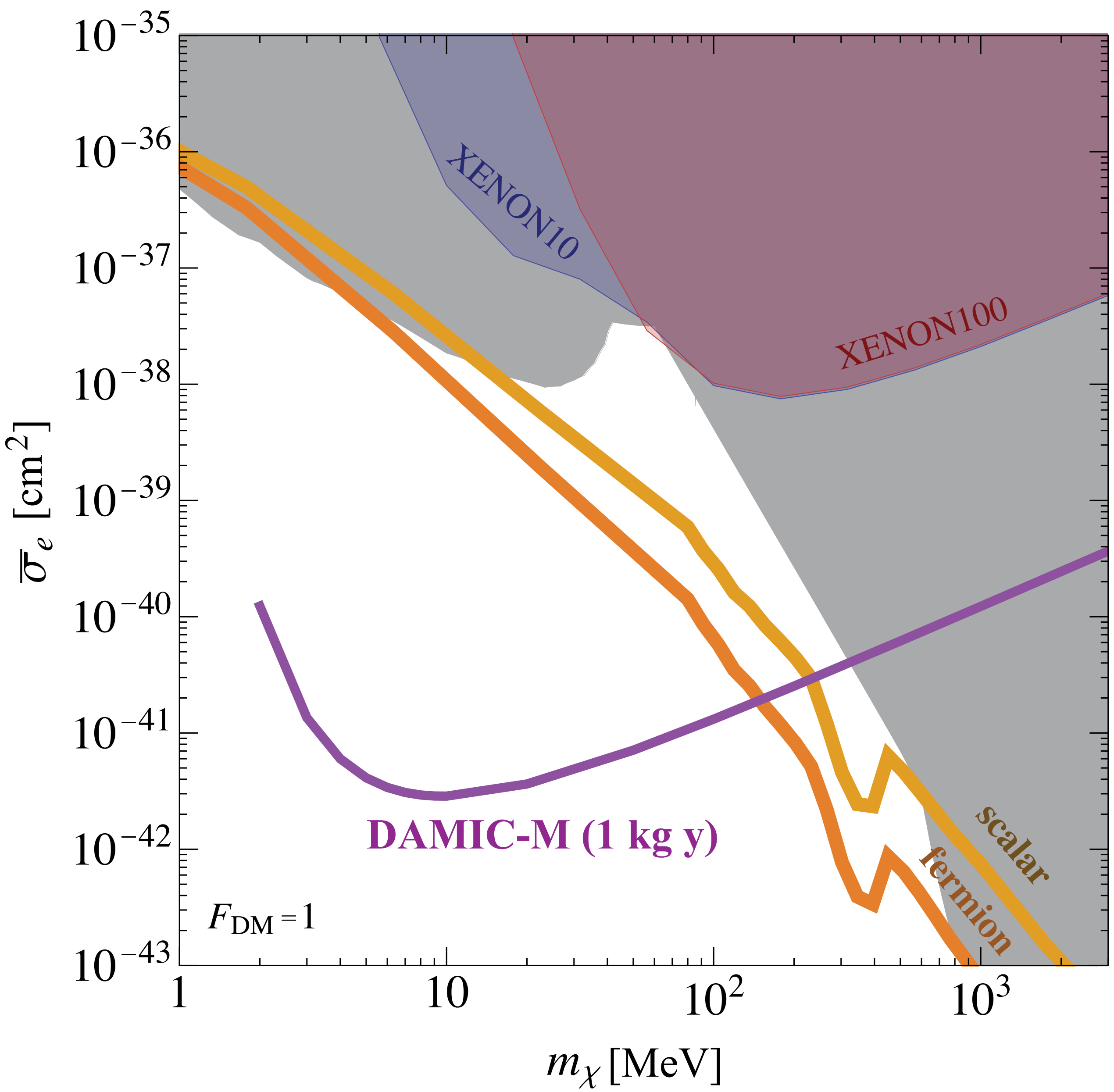


Hidden-photon search

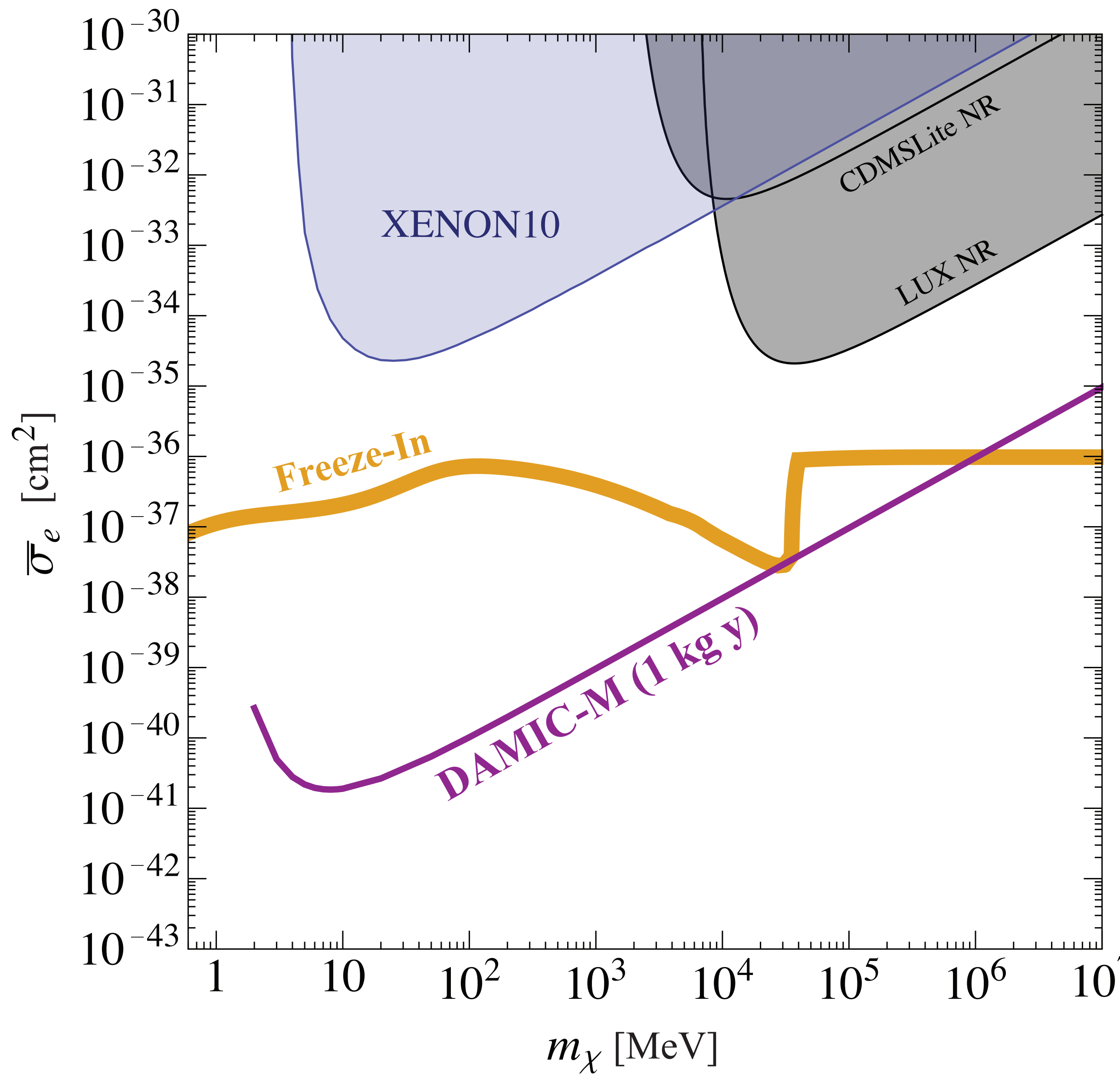


DAMIC-M sensitivity to DM-electron scattering

Heavy mediator



Light mediator



Summary and outlook

- DAMIC continues to collect data with 40-g array at SNOLAB, ~50 eVee threshold, expecting ~13 kg d integrated exposure by end of 2018
- Spatial resolution of CCDs allows awesome feats of background rejection using “coincidences” with time scales on the order of months
    - Background increasingly well understood, essential for WIMP analysis and useful as input for SuperCDMS, e.g., ^{32}Si abundance
    - Studies underway to refine knowledge of cosmogenic ^{3}H production in silicon
- CCDs provide information-rich datasets that we can continue to explore for additional cross checks or handles on backgrounds
- Next stage is DAMIC at Modane (DAMIC-M), now funded by ERC
    - 1-kg array of large DAMIC CCDs with skipper readout
    - First large skippers to be evaluated this summer, other work also beginning in earnest

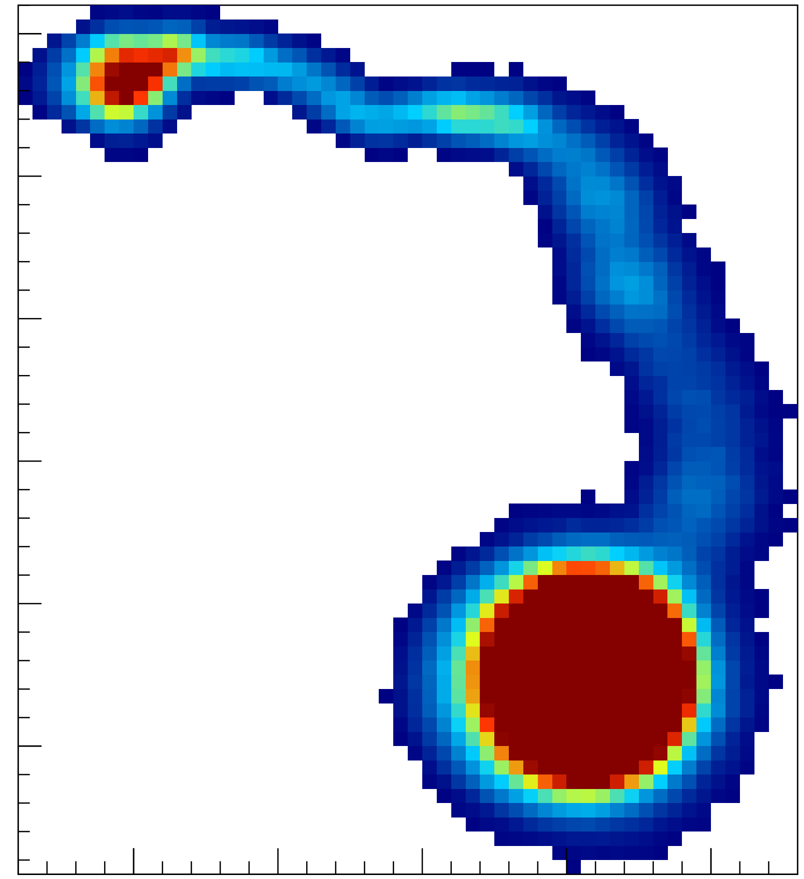
Backup

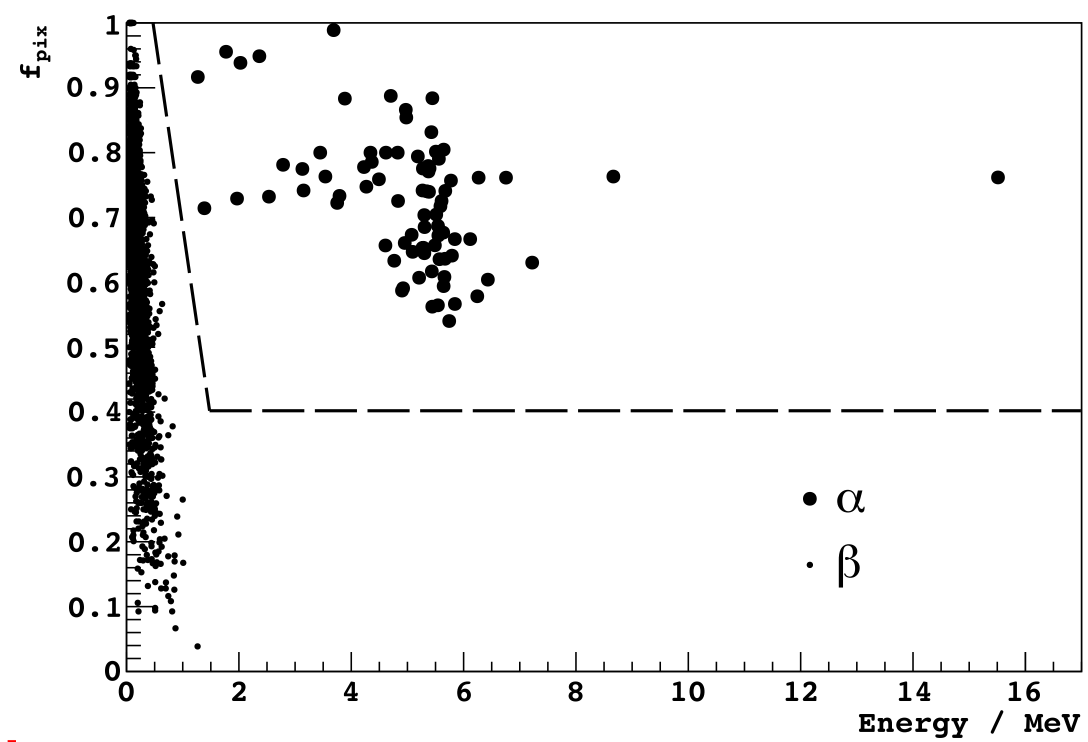
α/β selection

- Alphas and betas show very different track characteristics in the CCD [1]

- Metric “fpix” can be used to discriminate with reasonable effectiveness

    - Size of smallest box that fully contains event





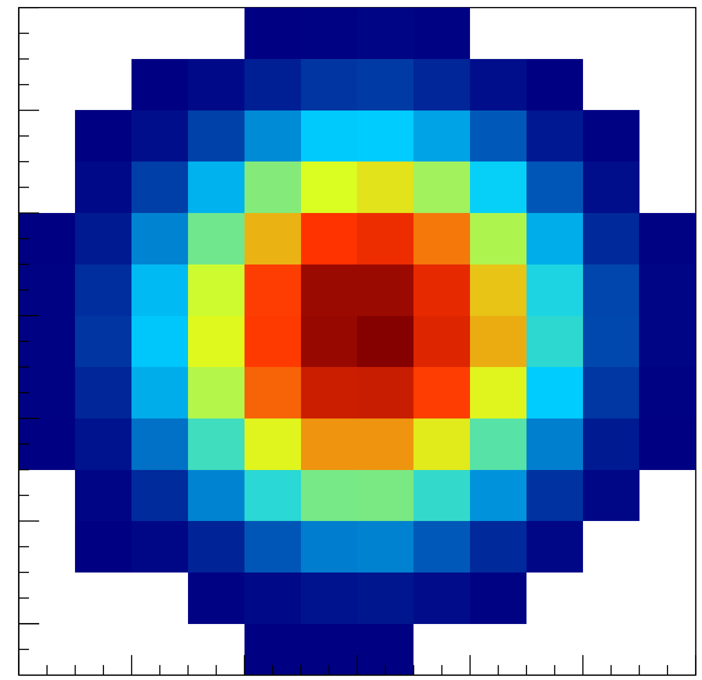
DAMIC DARK MATTER IN CCDS

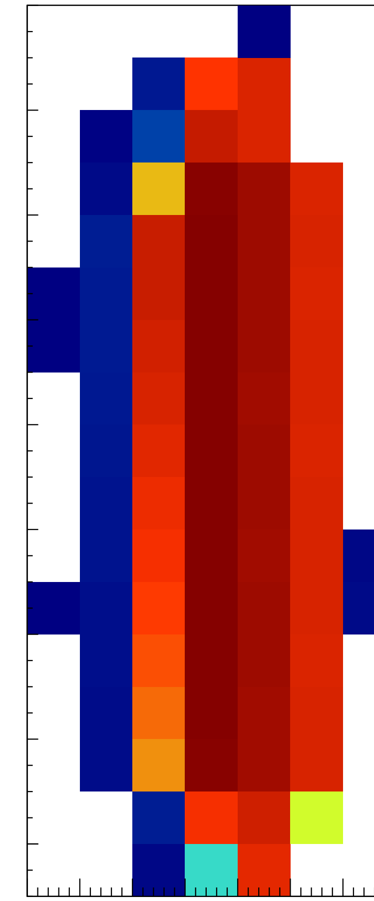
[1] A. Aguilar-Arevalo *et al.*, J. Inst 10 (2015) arXiv:1506.02562

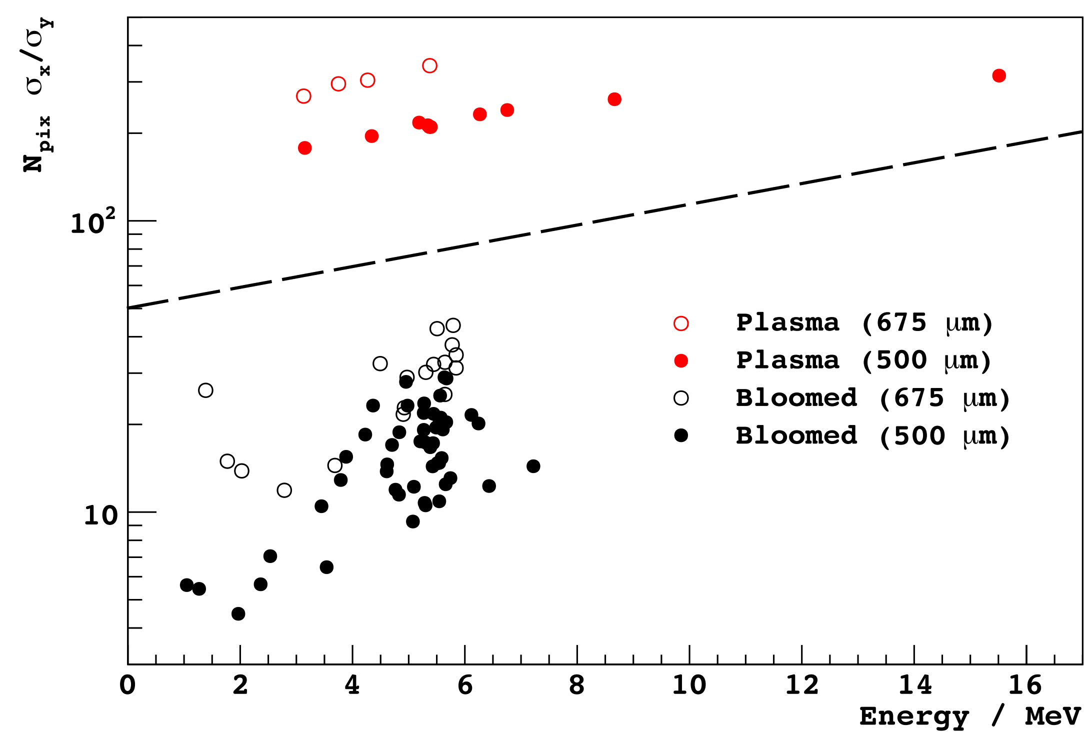
Figures from [1]

Alpha event characteristics

- Beyond discriminating betas from alphas, can further subdivide alpha events
- Possible to separate those occurring on front vs back surfaces
  - Plasma alphas (L) originate in bulk or on back surface of CCD
  - “Bloomed” events (R) originate on front surface
- Front vs back events have *slightly* different efficiencies
- Can divide population and determine front vs back rate as done in [1]







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[1] A. Aguilar-Arevalo *et al.*, J. Inst 10 (2015) arXiv:1506.02562