DAMIC@SNOLAB

DAMIC
(Dark Matter in CCDs)

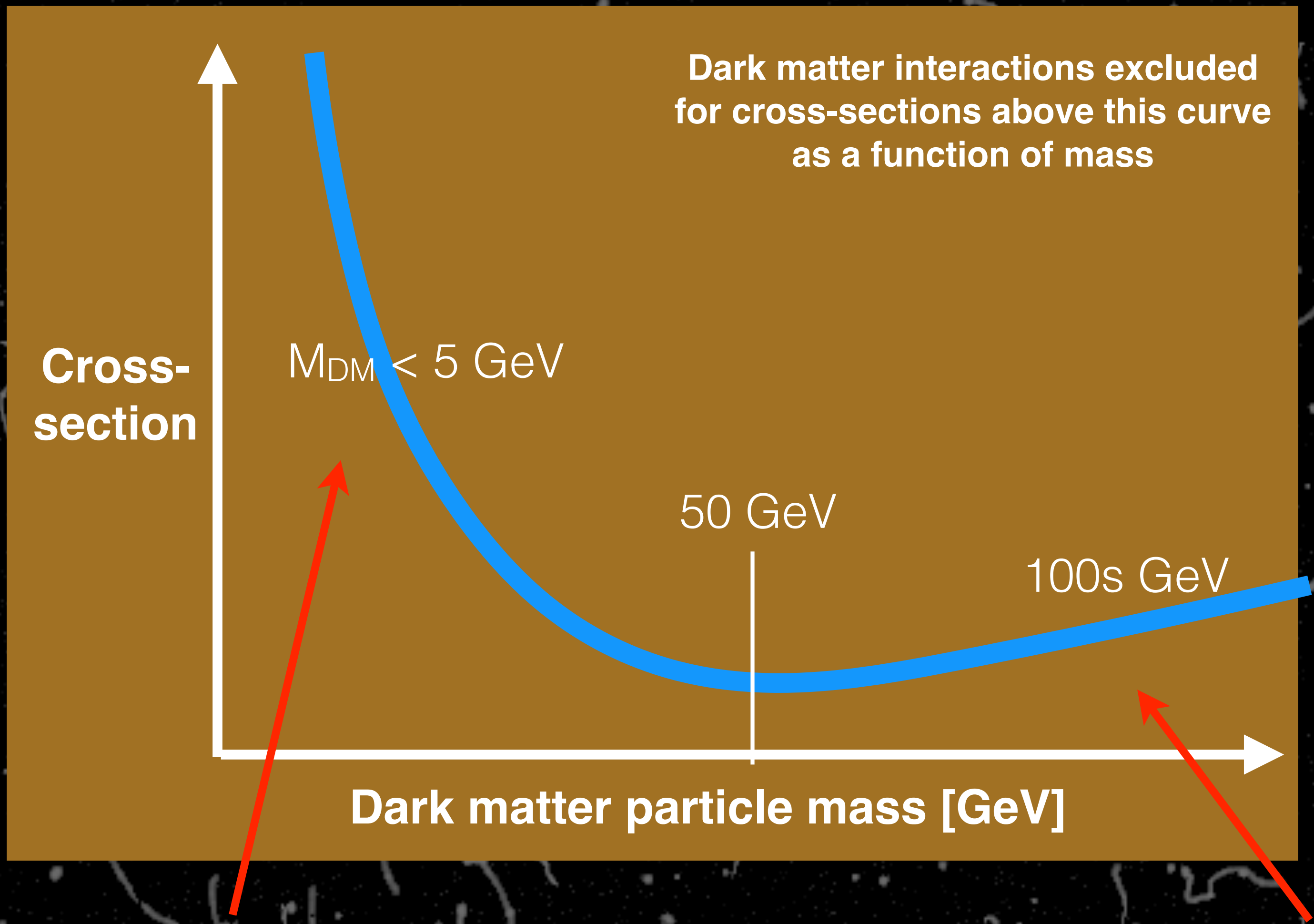
Investigating the low-energy excess

LP2023, July 18th 2023

Ben Kilminster
U. Zürich

PHYSIK INSTITUT
UNIVERSITÄT ZÜRICH
University of Zurich[UZH]

Typical limit plot of DM search



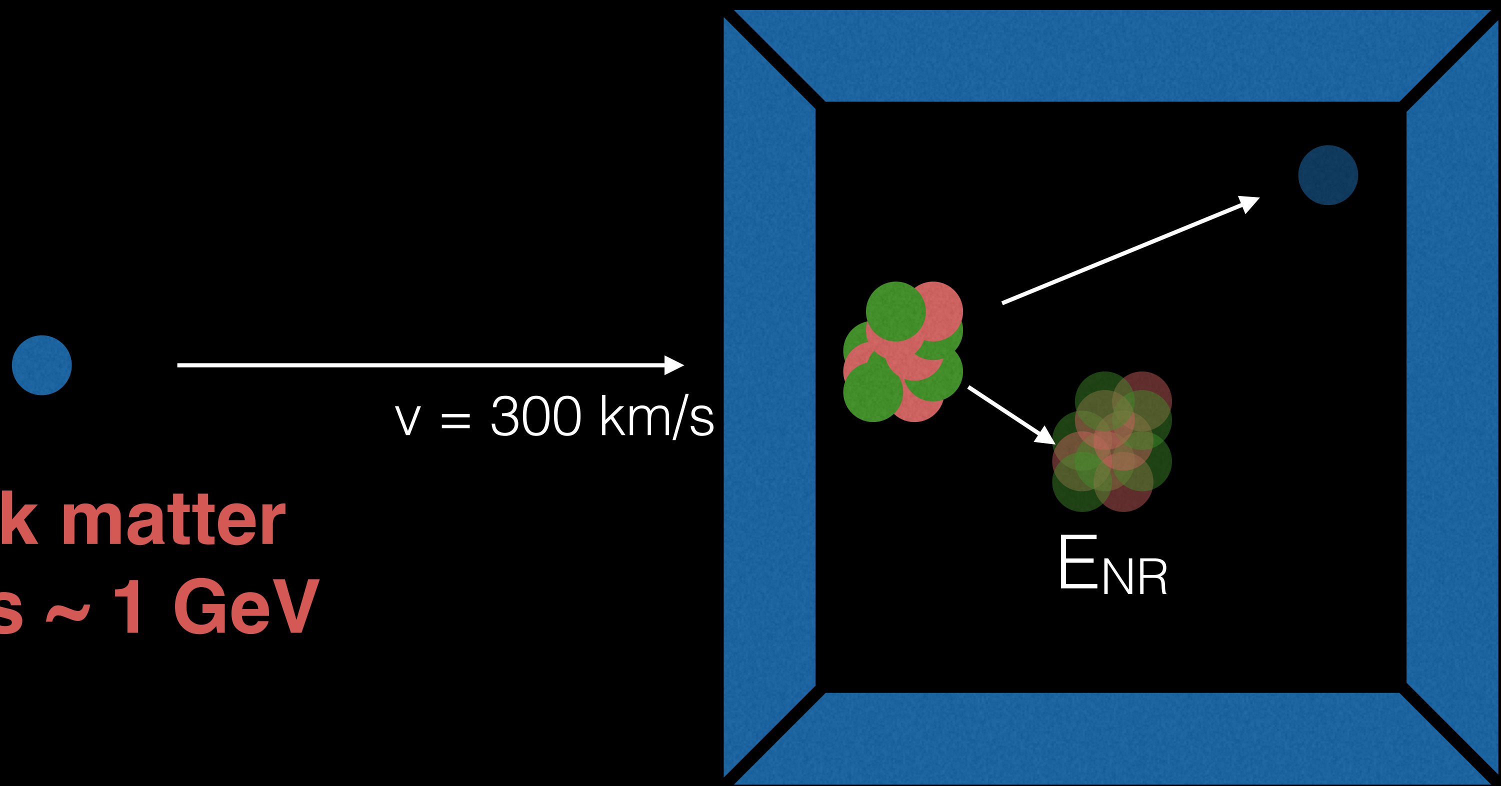
Baryon-DM coincidence:
Limited by energy threshold
(need to detect lower energies)

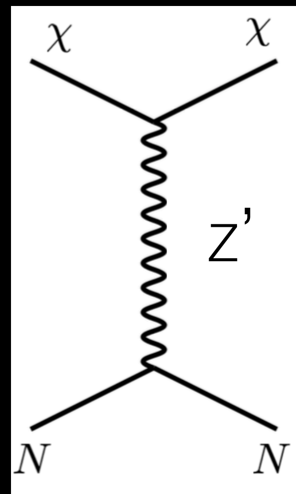
SUSY WIMP:
Limited by exposure mass
(need bigger detector)

Detecting asymmetric DM (m_{DM} ~ GeV)

Elastic scattering of galactic DM

- Dark matter interacts once, coherently with all nucleons in the nucleus





Dark matter
Mass ~ 1 GeV

E_{NR} ~ 500 eV
E_{ioniz} ~ 50 eV

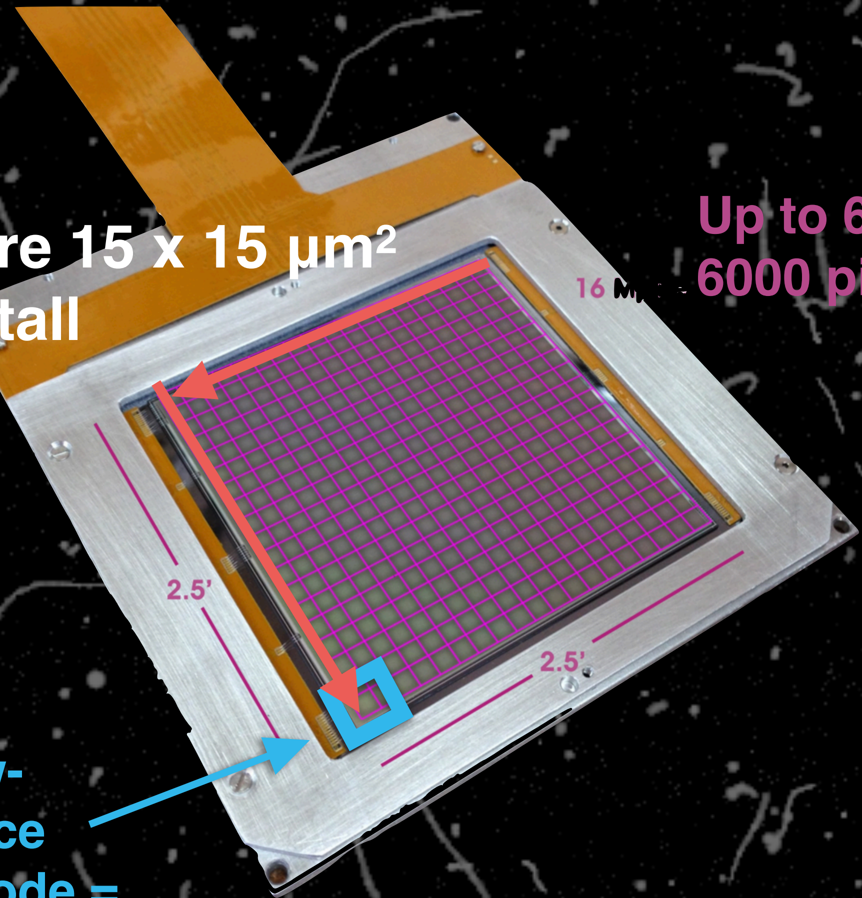
We want to detect ionization energies down to ~ 1eV

We need a low-energy threshold Detector

DAMIC (Dark matter in CCDs)

Pixels are 15 x 15 μm^2
675 μm tall

Up to 6000 x 6000 pixels



Single low-capacitance readout node = low noise = low energy threshold

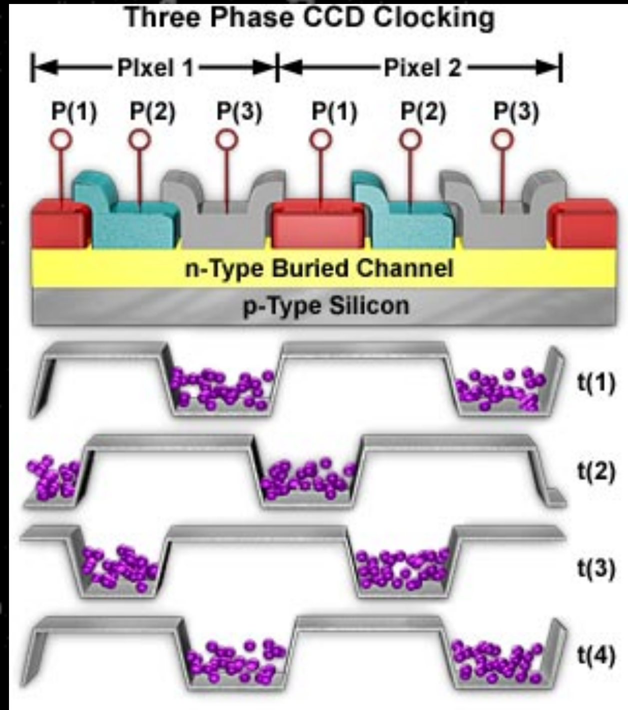


Figure 1

Charge shifted to output readout gate by 3 potential gates per pixel

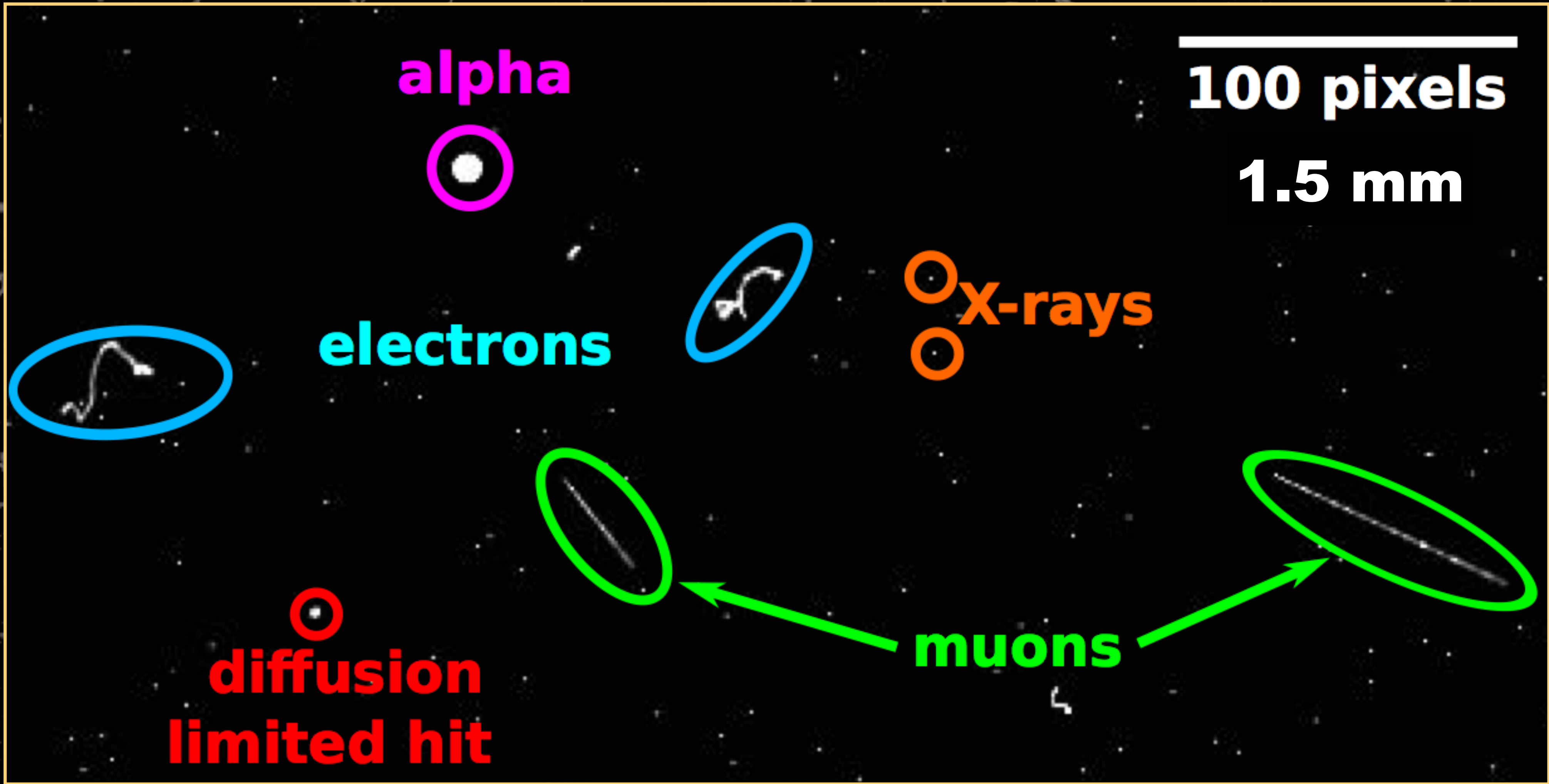
DAMIC-M will use the thickest and biggest CCDs ever made :

Size = 9 cm x 9 cm x 0.675 mm
Mass = 20 g / CCD

(Likely diced into 4 for better yield !)

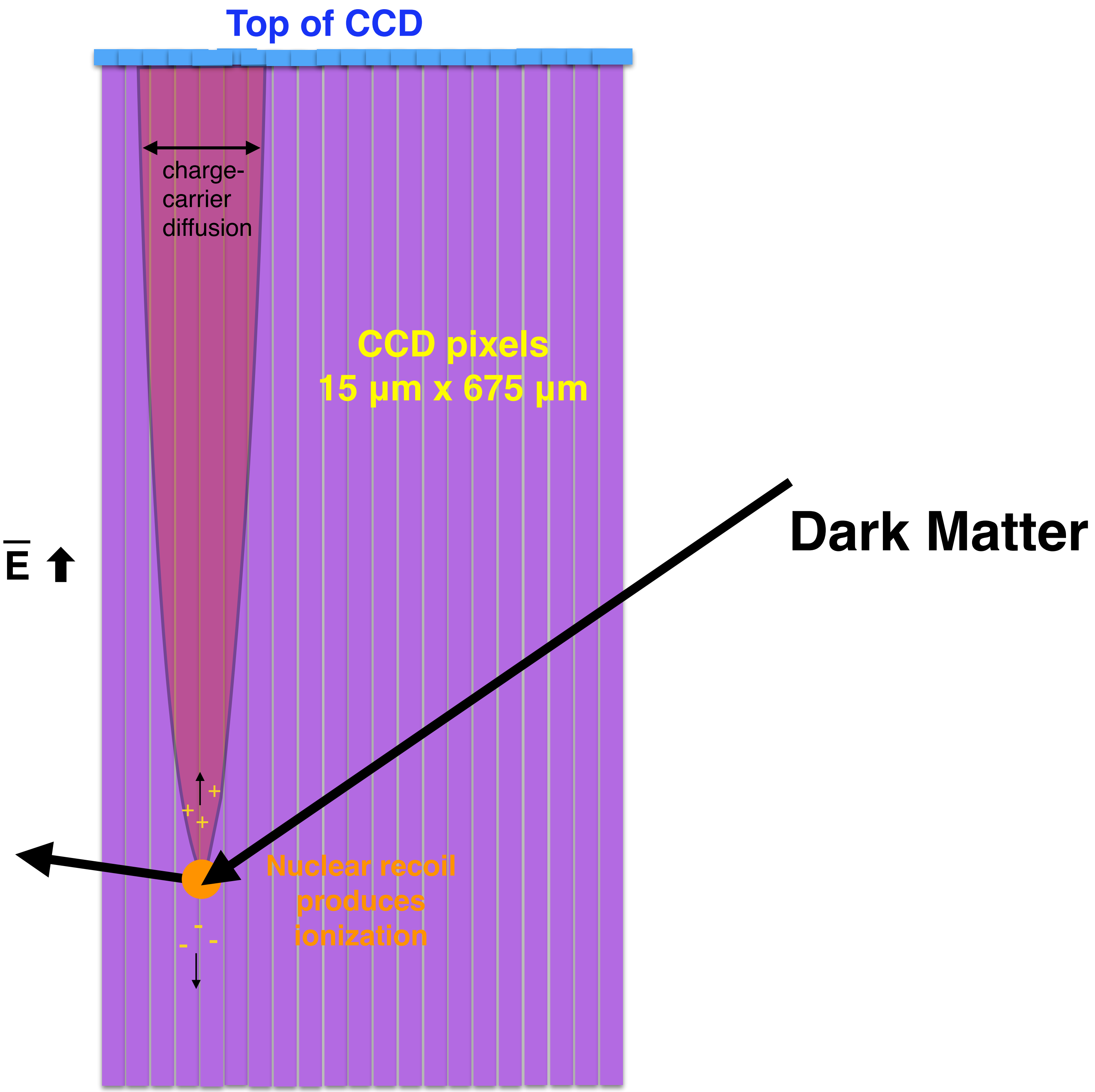
This background is a CCD image

Particle identification in CCD



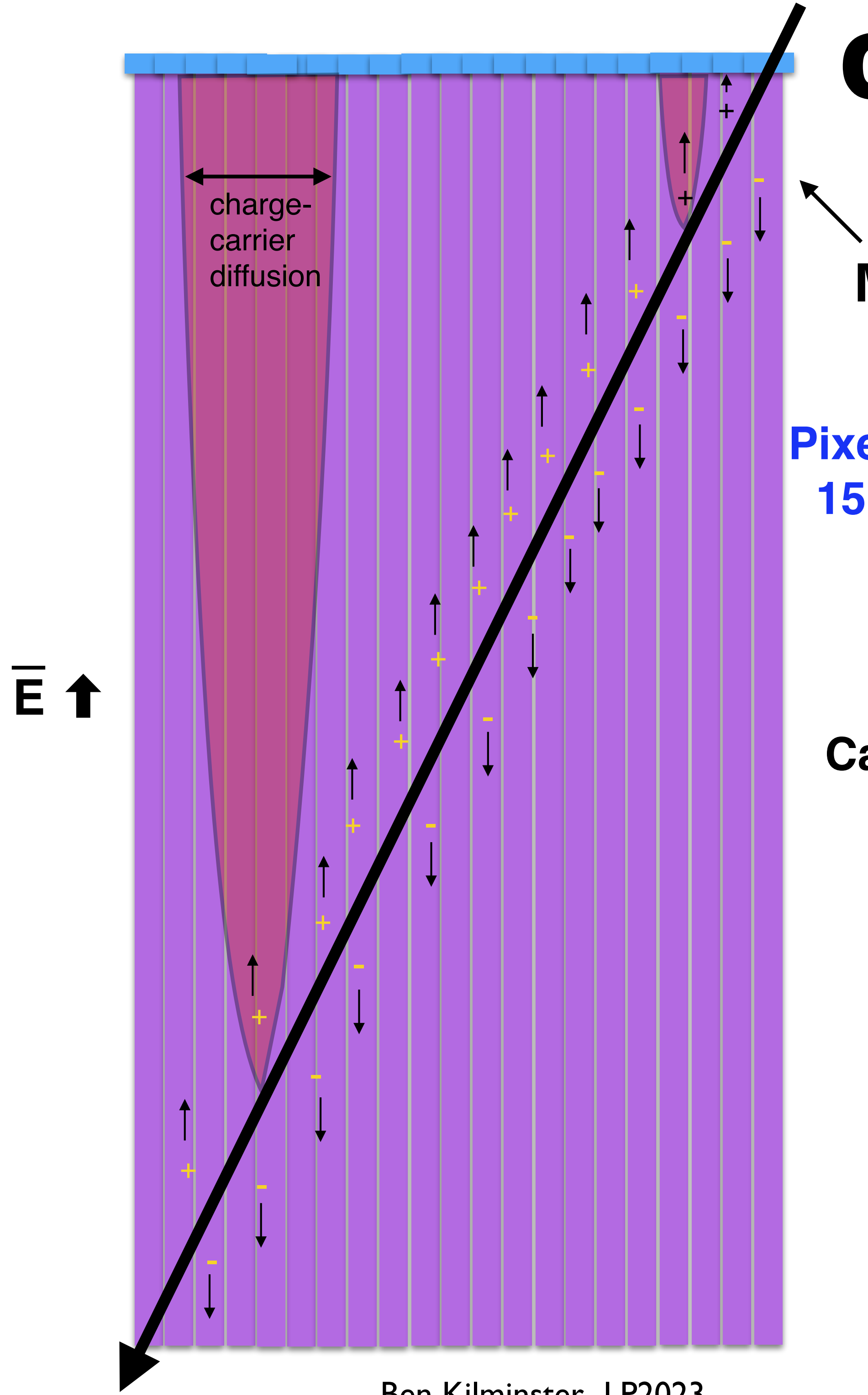
single point resolution ~ 7 um

pixel size : 15 x 15 um²

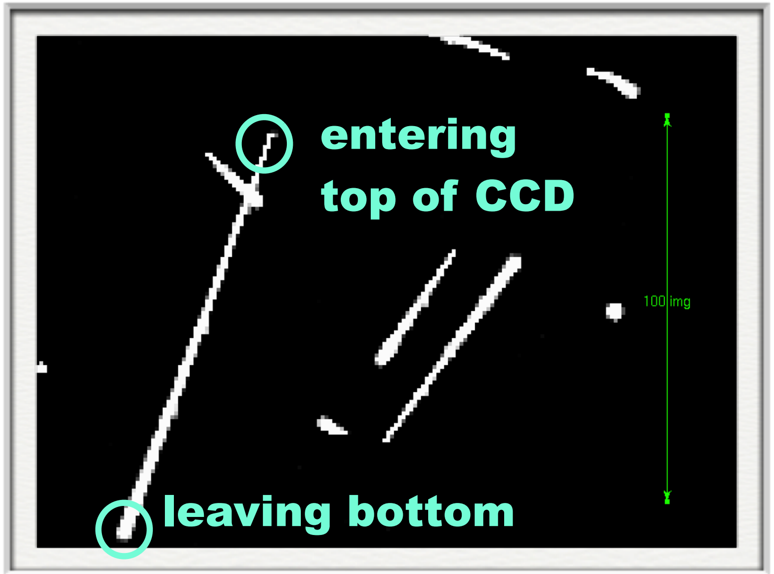


Top of CCD
charge-
carrier
diffusion
CCD pixels
15 µm x 675 µm
Dark Matter
E
+
+
+
Nuclear recoil
produces
ionization
-
-
-

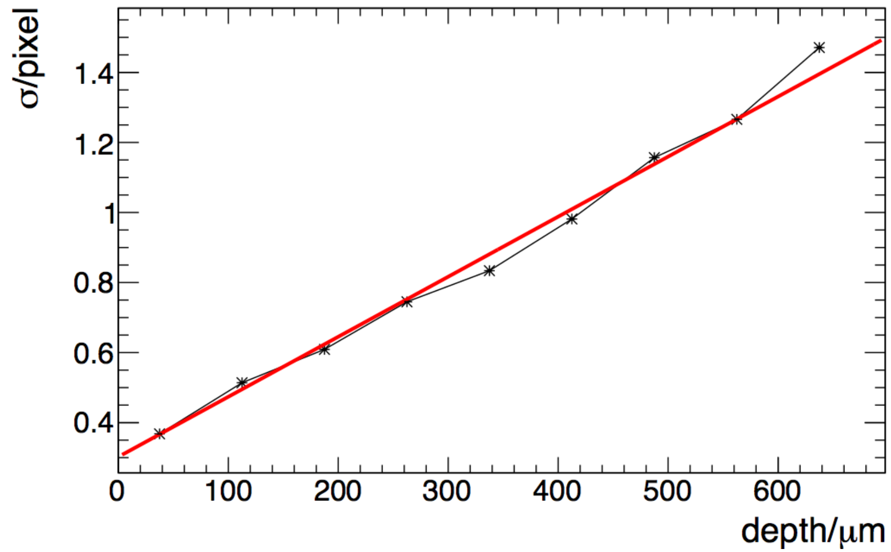
Cluster size vs. depth



Pixels to scale
15 x 675 um



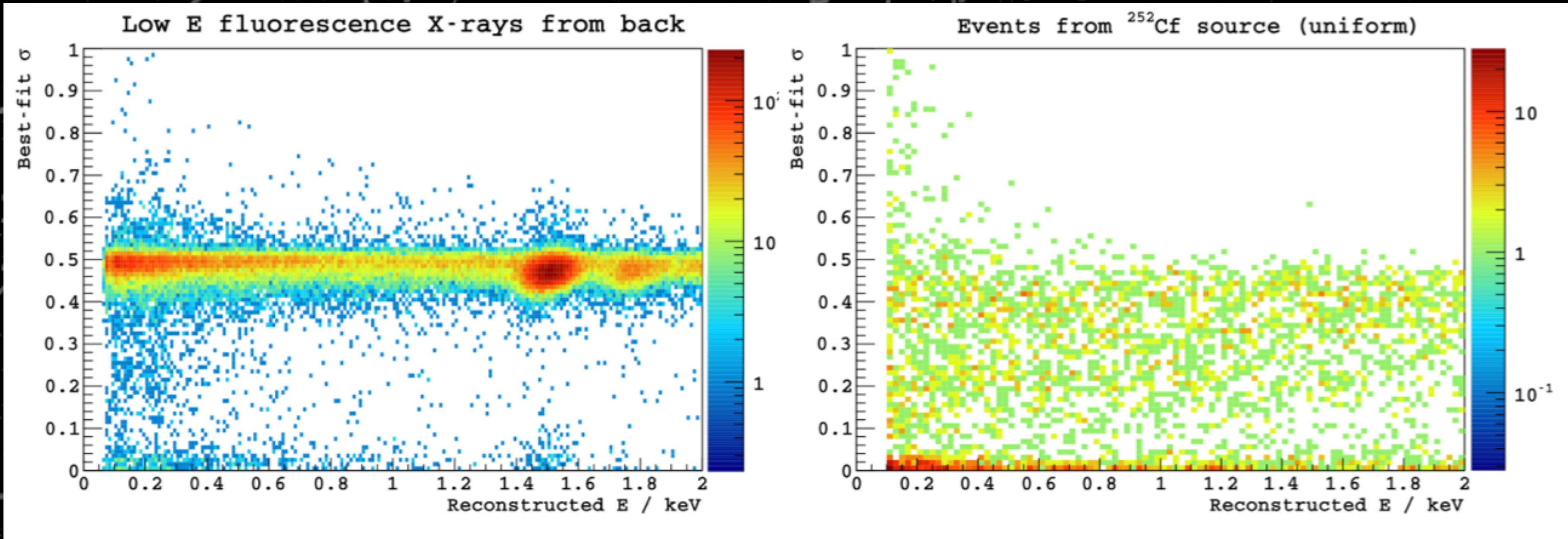
Calibration of cluster size σ vs. interaction depth



Useful for removing surface events

X-rays vs neutrons

Size of pixel clusters vs. Energy



X-rays
bkg-like

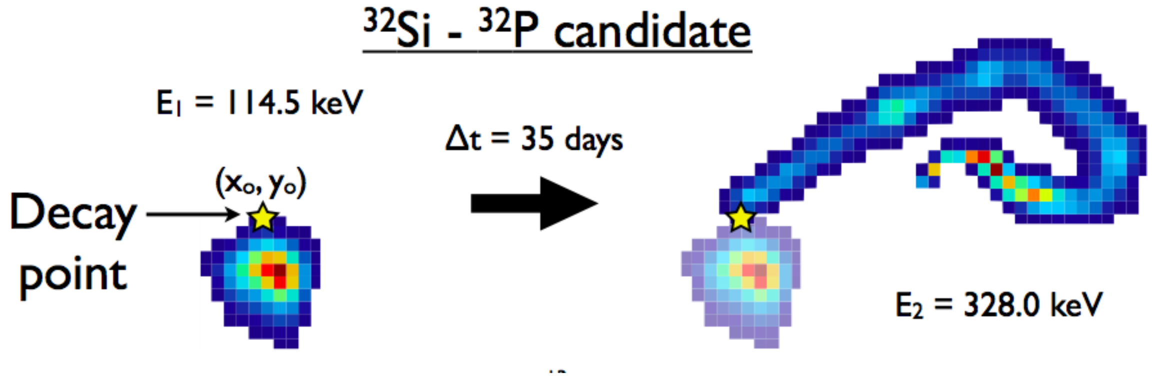
Neutrons
"DM-like"
(No dependence on depth)

Cluster size → Determines depth used to reject backgrounds

Silicon vertex tagging in DAMIC

Intrinsic ^{32}Si rejected by tagging

$^{32}Si \rightarrow {}^{32}P \rightarrow {}^{32}S$ sequence ($\tau_{1/2}$ ~14 days)



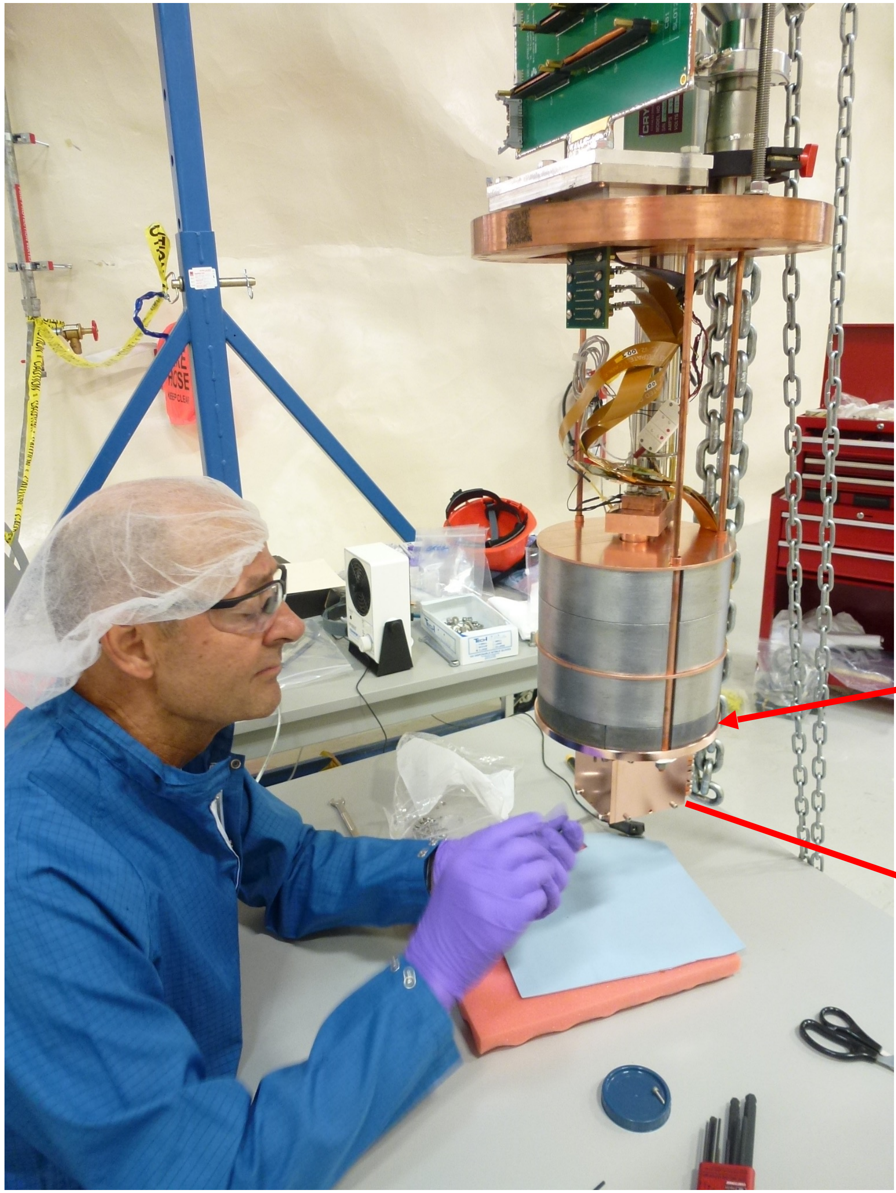
- Search for sequences of βs starting in the same pixel of the CCD in different images

^{32}Si = 140 ± 30 μBq/kg

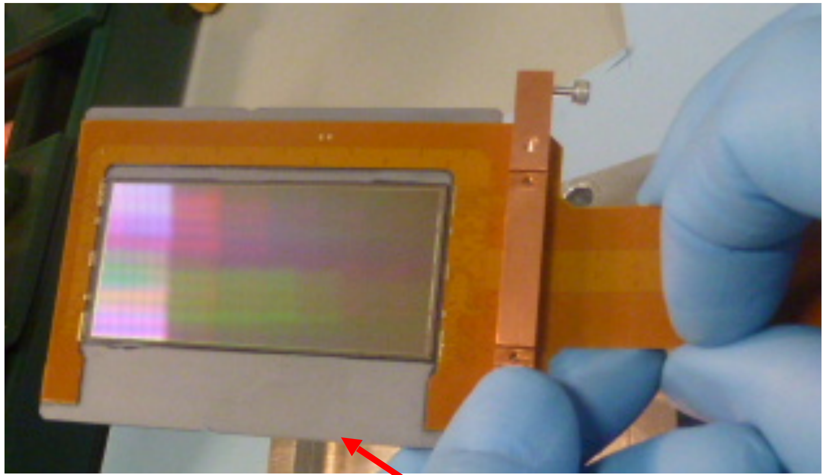
JINST 16 (2021) 06, P06019

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

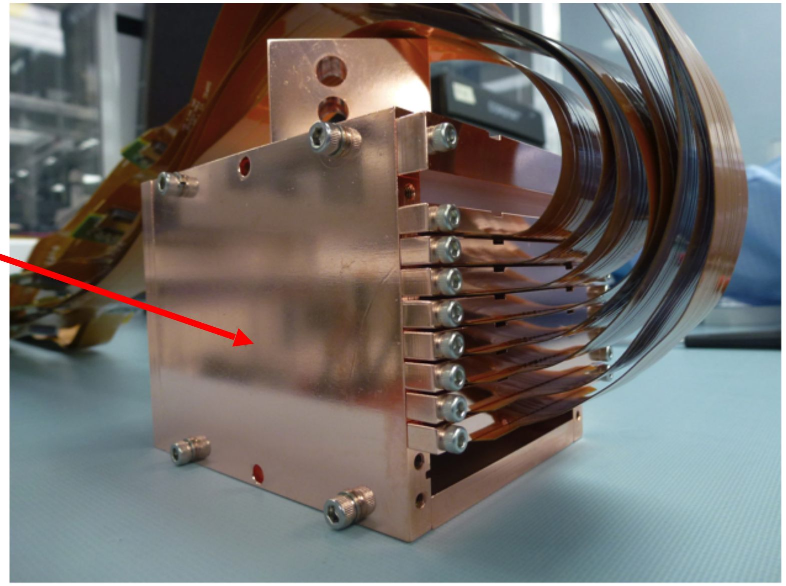
DAMIC @ SNOLAB



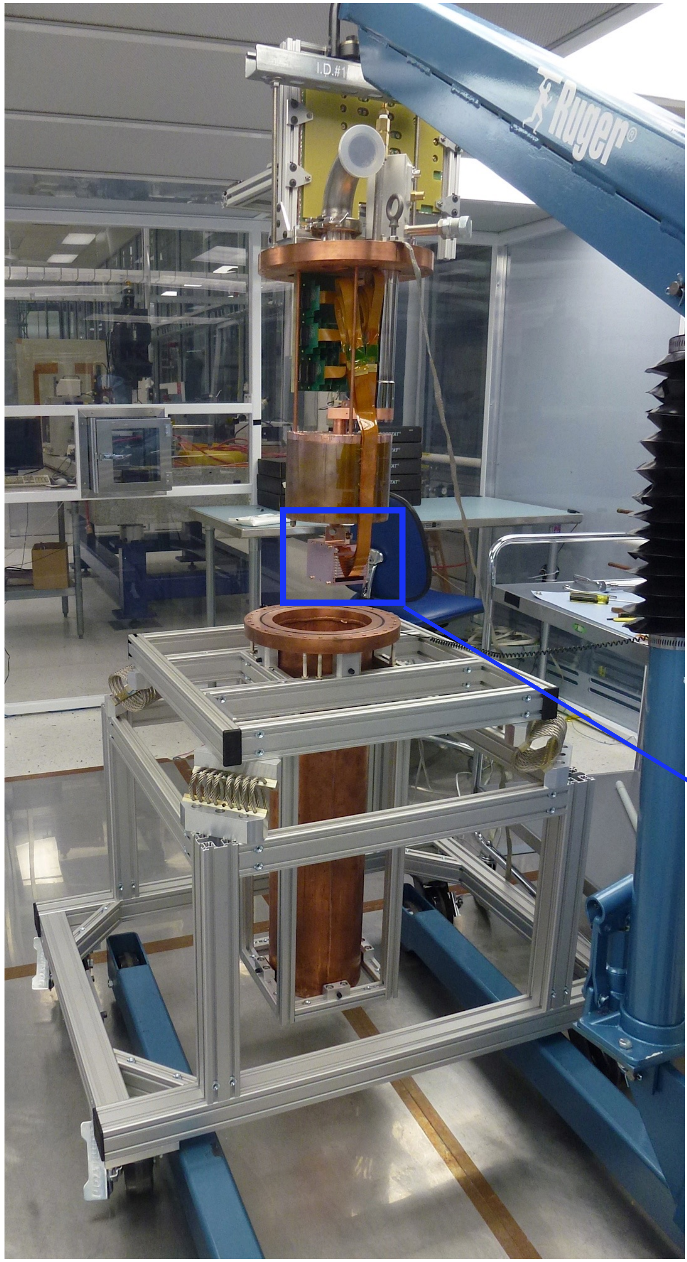
1” Spanish galleon lead

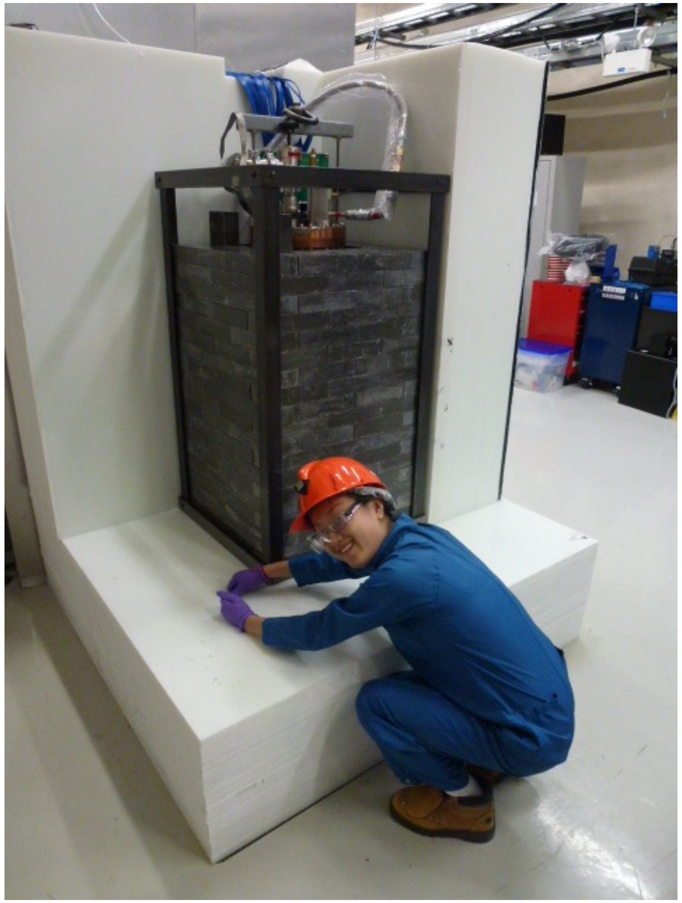


Si support

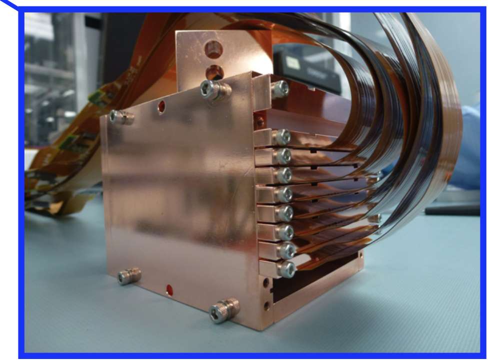


DAMIC @ SNOLAB



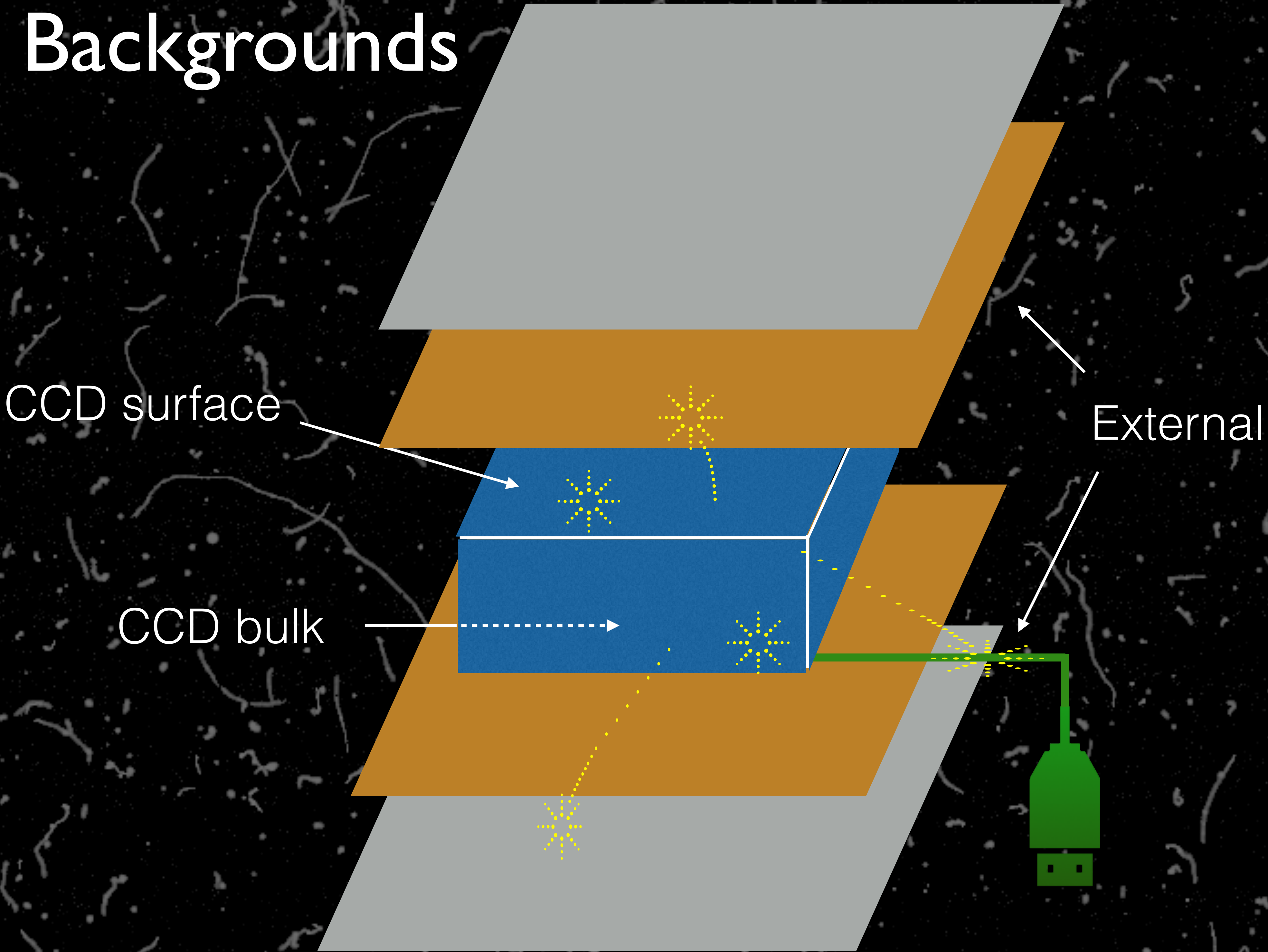


In SNOLAB
6010m water equivalent depth : suppresses cosmics



Operated 7 CCDs = 40 g

Backgrounds



Backgrounds

Copper shielding, cables

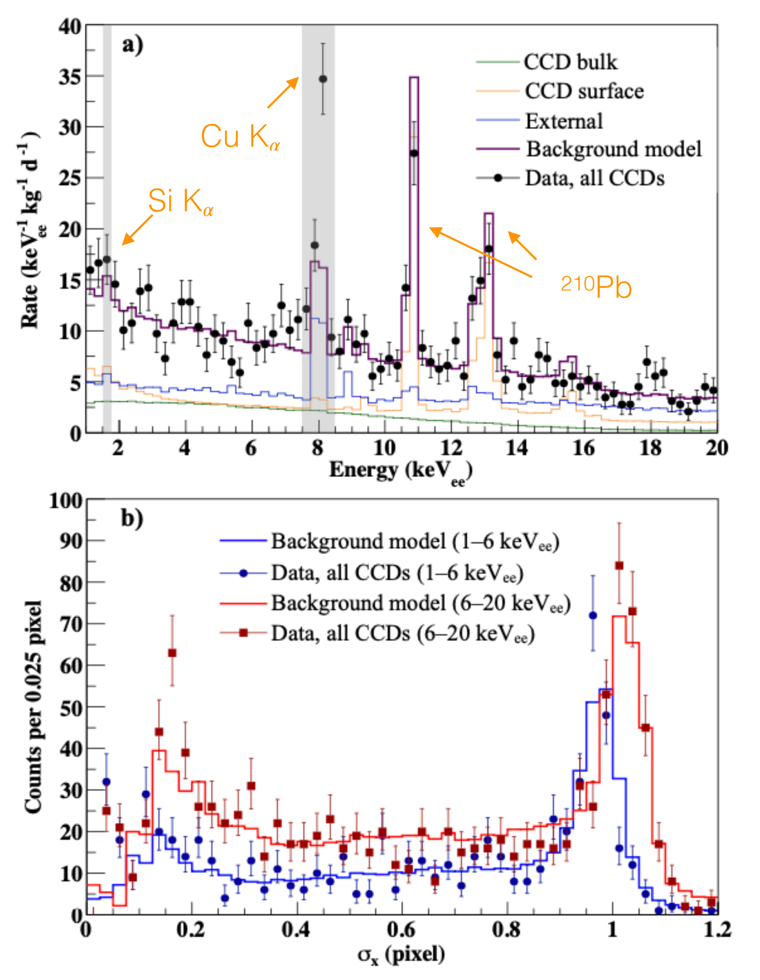
Radon exposure to Silicon surfaces in processing

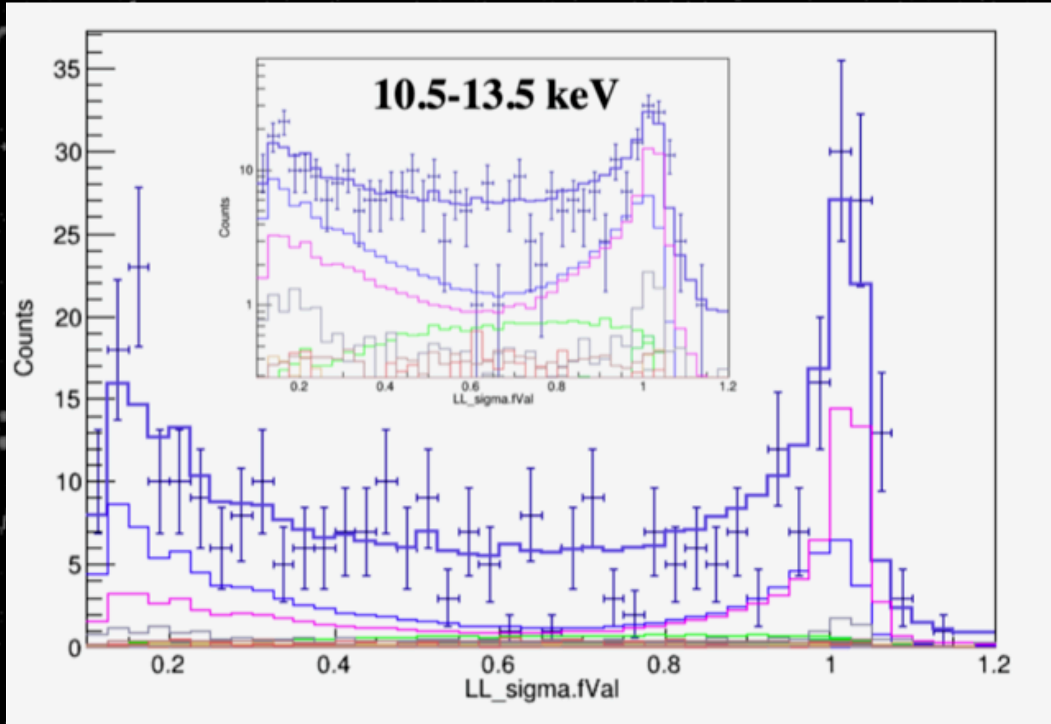
Cosmogenic activation after silicon ingot produced

Cosmogenic spallation of ^{40}Ar in air (intrinsic in surface-gathered silicon)

Dominant Backgrounds	Where ?	Events in CCD ($keV^{-1}kg^{-1}d^{-1}$)
^{60}Co, ^{210}Pb ^{238}U, ^{232}Th	External (Copper, cables)	**4.4 ± 0.5**
^{210}Pb	CCD Surface	**3.8 ± 0.4**
^{3}H & ^{22}Na	CCD Bulk	**2.9 ± 0.7**
^{32}Si & ^{32}P	CCD Bulk	**0.17 ± 0.03**
Noise	Electronics	**< 0.1**

Background modeling



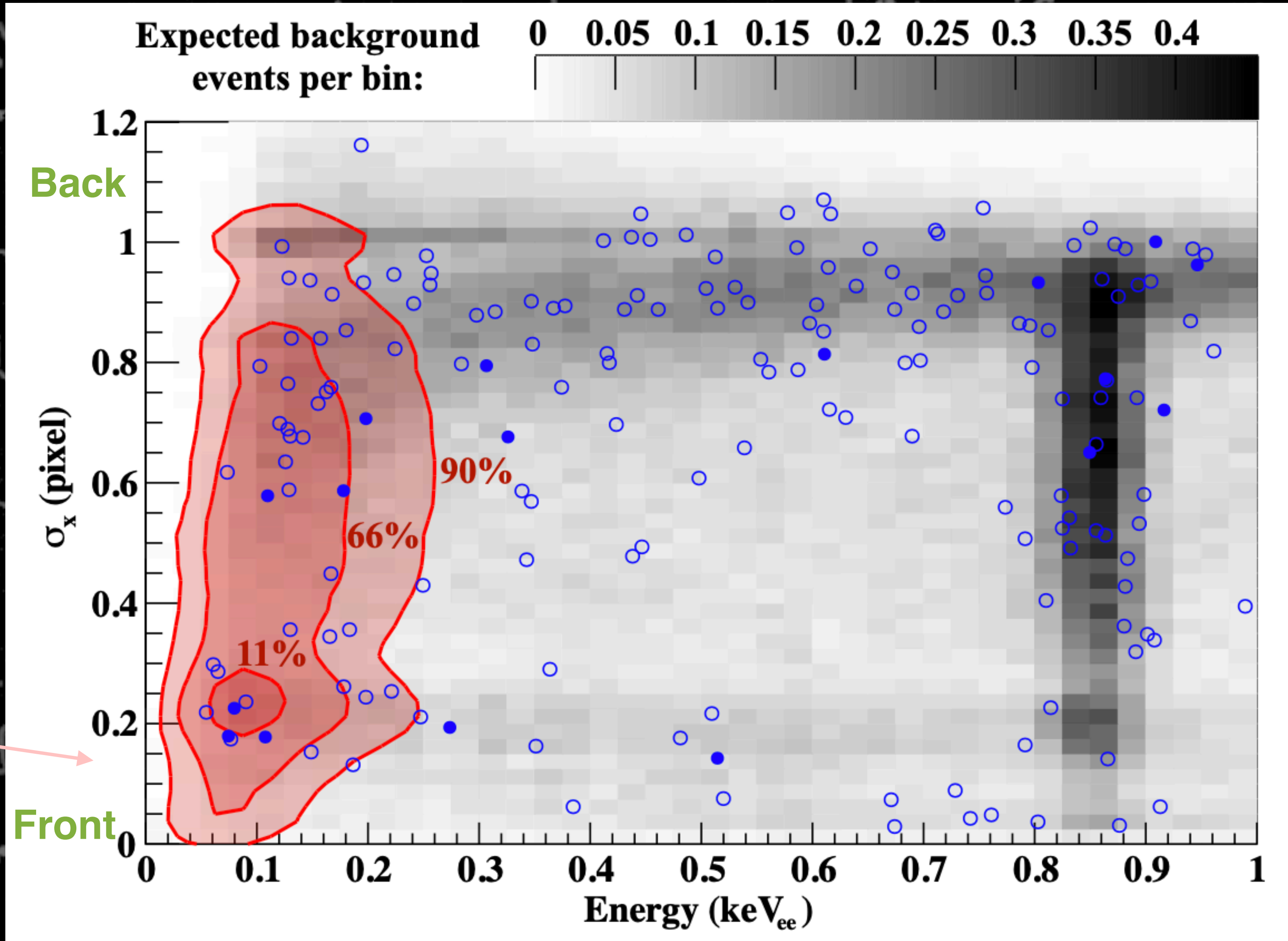


210Pb appears well modeled

Results of background + signal fit

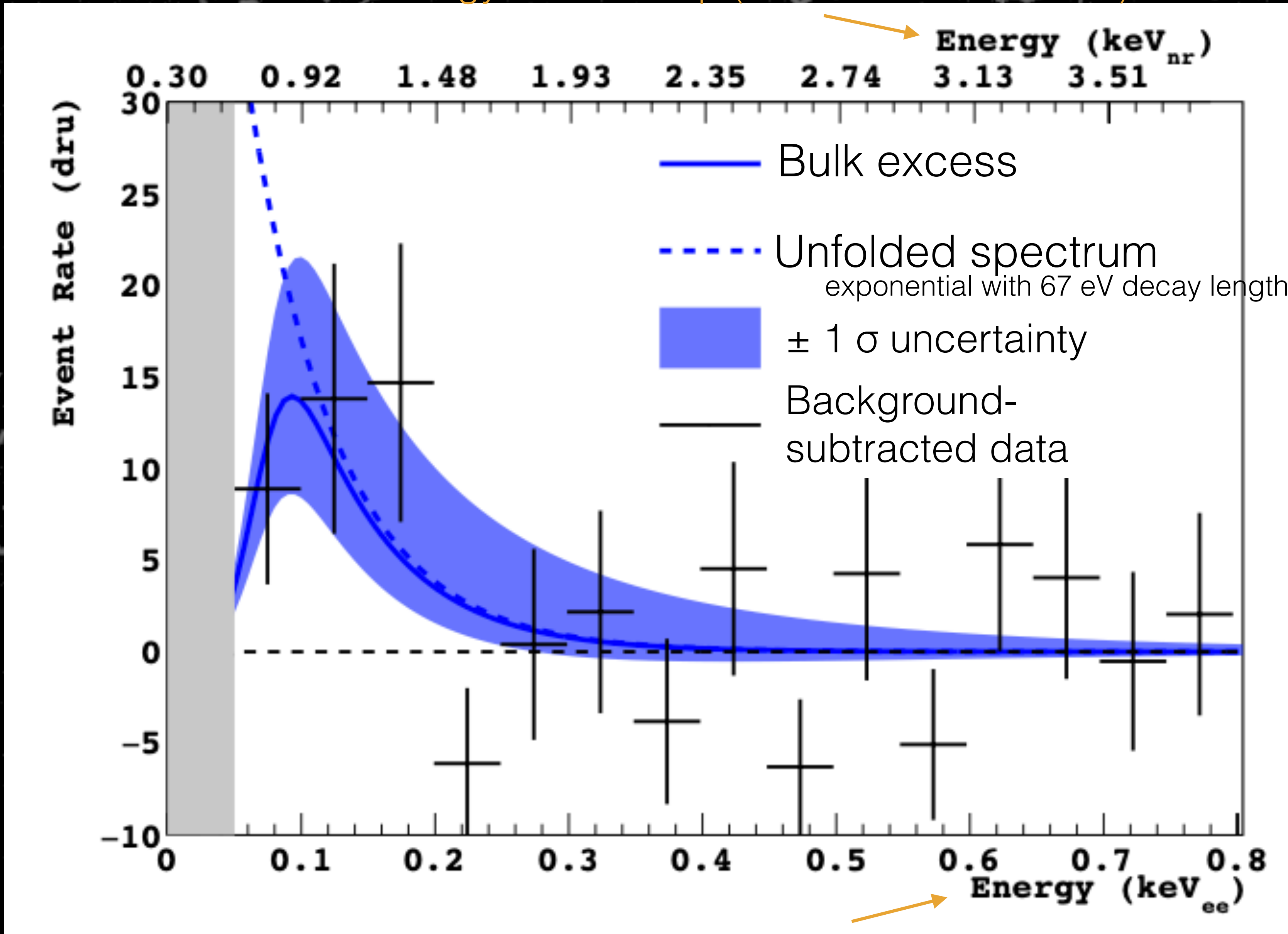
Fit of cluster size vs. energy

3.4 σ excess



Signal excess energy distribution

Nuclear recoil energy scale on top (calibrated to neutrons)



Ionization energy scale (calibrated to X-rays)

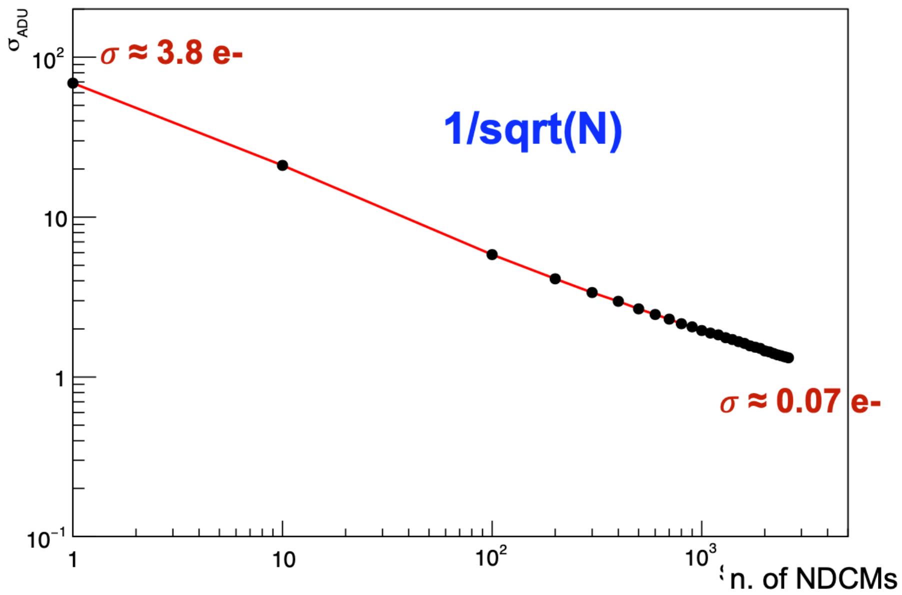
Possible explanations of excess

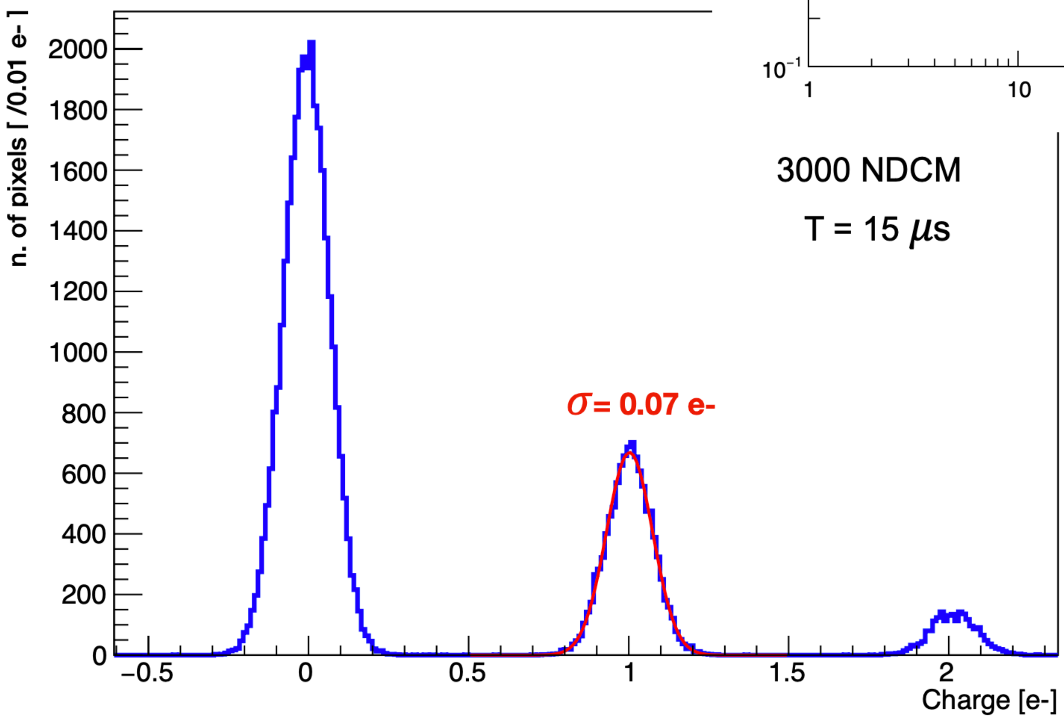
1. Energy threshold effect
2. Under-predicted background component
3. Unknown background component
4. Due to partial charge collection on surface
5. An actual DM signal (WIMP or other)

New WIMP results from DAMIC@SNOLAB

Skipper-CCD energy resolution : 0.07

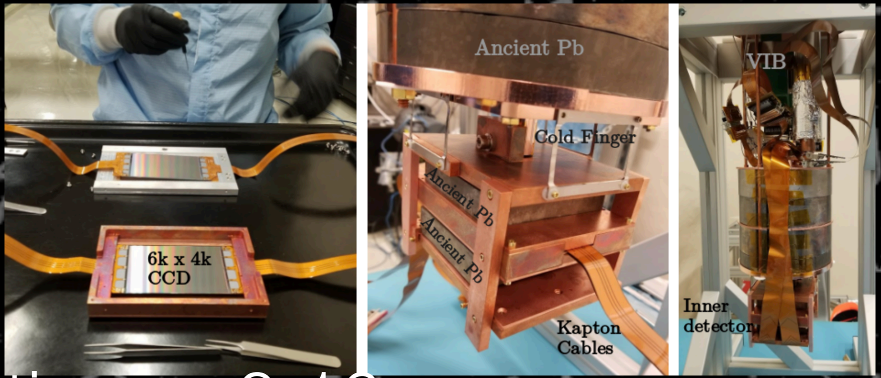
- Reduce noise by √N by repeatedly reading out pixels (skipper CCD)

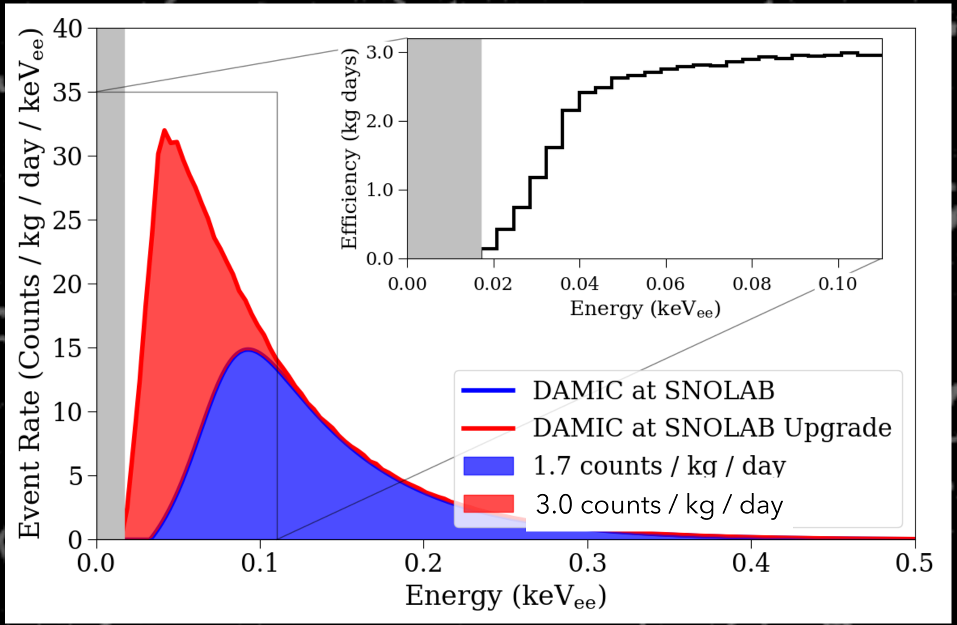




Skipper CCD allows identification of single electrons of produced ionization!

Upgraded DAMIC experiment



- Two 6k x 4k skipper CCDs
- Same bkg contributions
- Same bkg rate : 12 dru
- 10x lower readout noise & resolution : ~0.16 e-
- Science Run March 2022 - Jan 2023
- 4.8 kg*d exposure, 3.1 kg*d after selection
- 

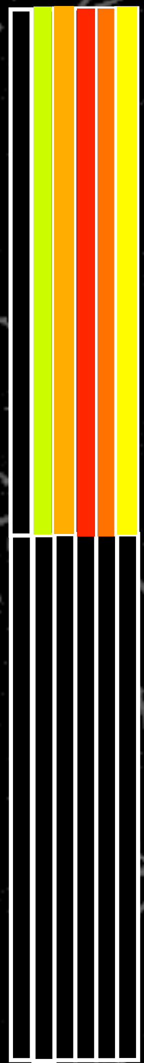
Upgrade provides twice signal efficiency due to increased acceptance at low energy

2021 vs. 2023 experiments

2021

σ_{noise} ~ 1.6 e- per readout

100 pixels grouped before readout



15 x 1500 μm^2

WIMP signal

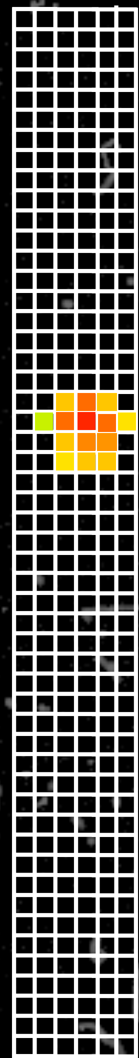
Tradeoff:

- Improved signal/noise
- Poor y-position resolution

2023

σ_{noise} ~ 0.2 e- per readout

Energy cluster



15 x 15 μm^2

DATA SELECTIONS

Likelihood clustering: …and efficiently reject noise accidentals down to 23 eV$_{ee}$

$$\log \mathcal{L}(N, \vec{\mu}, \vec{\sigma}, \lambda, \sigma_r | \vec{q}) = \sum_i \sum_j \left(\sum_k^{\infty} \log \left(\frac{\gamma_{ij}^k \exp(-\gamma_{ij})}{k!} \frac{1}{\sqrt{2\pi\sigma_r^2}} \exp\left(\frac{-(q_{ij}-k)^2}{2\sigma_r^2} \right) \right) \right)$$

$$\gamma_{ij} = \lambda_i + N \int_{i-0.5}^{i+0.5} \int_{j-0.5}^{j+0.5} \text{Gaus}(x, y | \mu_x, \mu_y, \sigma_x, \sigma_y) dx dy$$ **: Noise + Ionization**

$$\Delta LL = -\log \left(\frac{\tilde{\mathcal{L}}_g}{\mathcal{L}_n} \right)$$ discriminates low-energy events from noise accidentals

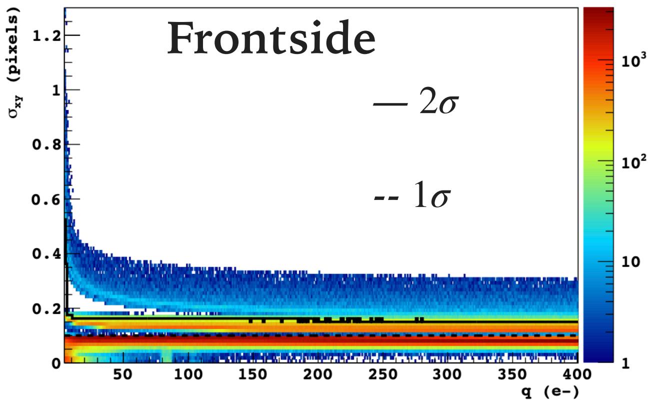
Bulk fiducialization: we also reject CCD surface events, the largest source of systematic uncertainty

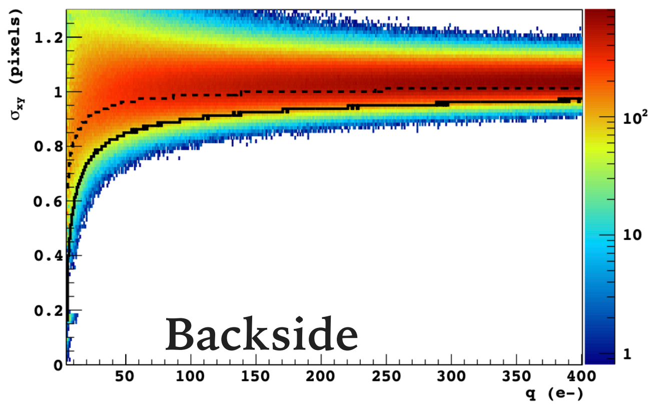
We apply a fiducial selection of bulk events, using the diffusion model:

$$\sigma_{xy}(z, E) = \sqrt{-A \ln(1 - bz)}(\alpha + \beta E)$$

σ_{xy} : cluster spread z : depth E : energy

Model validated in the lab





BKG MODEL VALIDATION

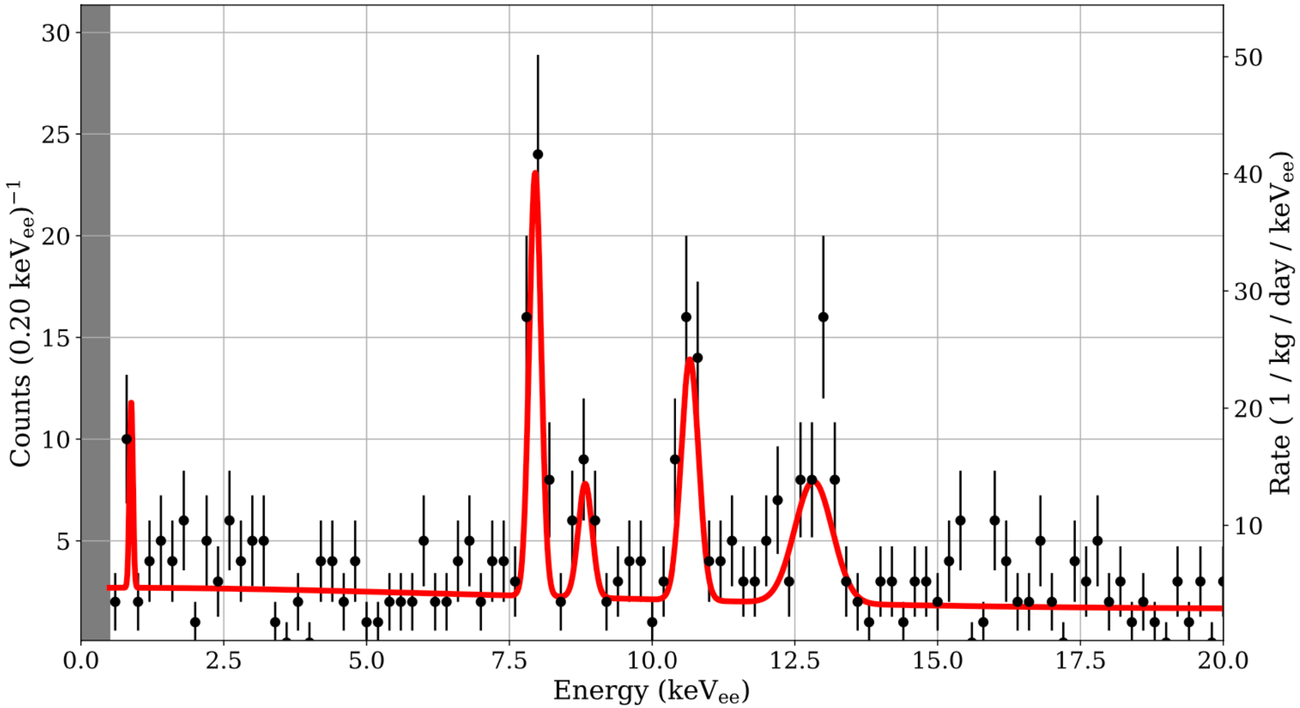
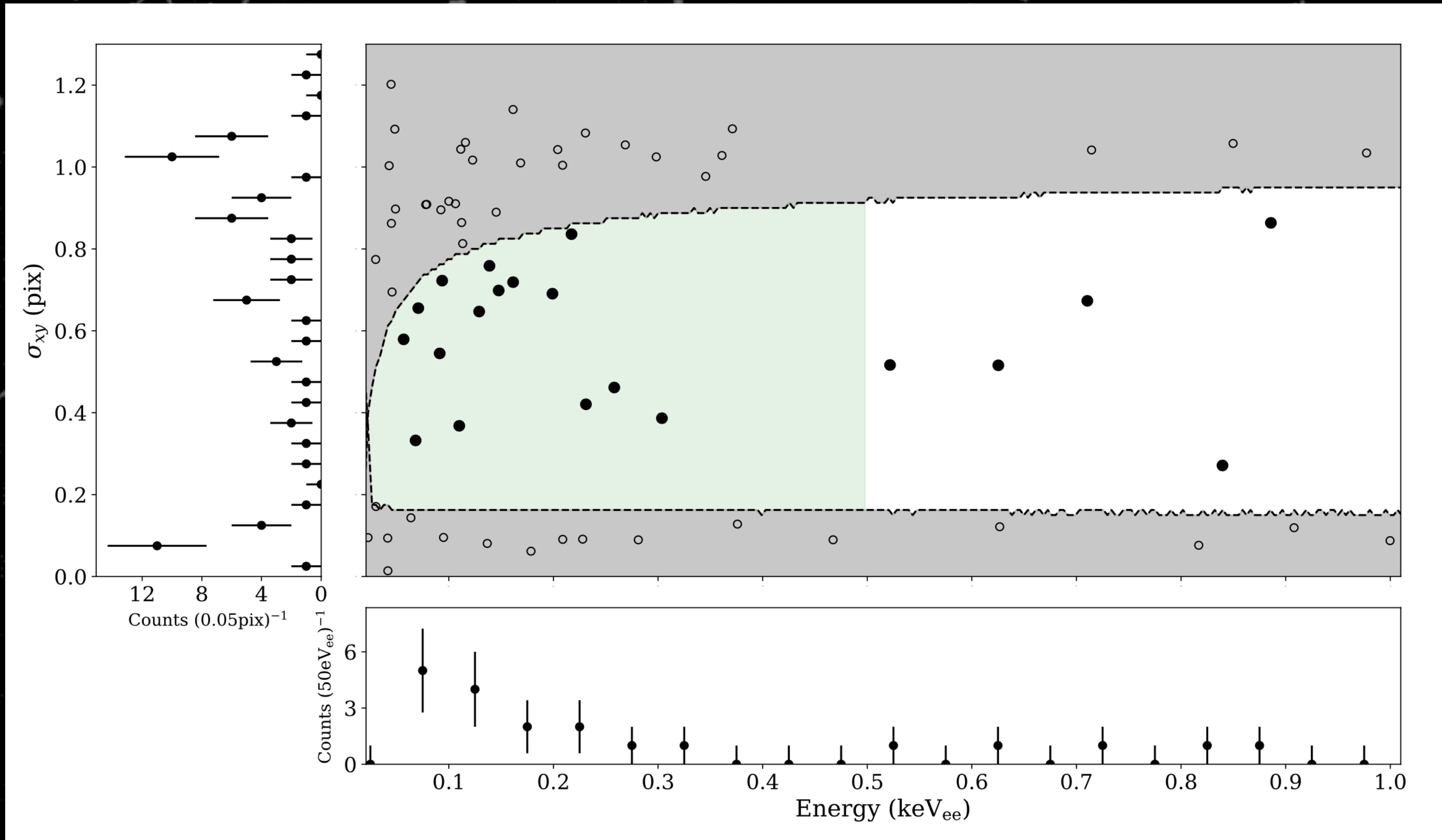


Figure 3.9: The bulk (after σ_y cuts) background rate above 0.5 keV$_{ee}$ for a bulk exposure of ~ 3 kg days.

Energy vs. depth

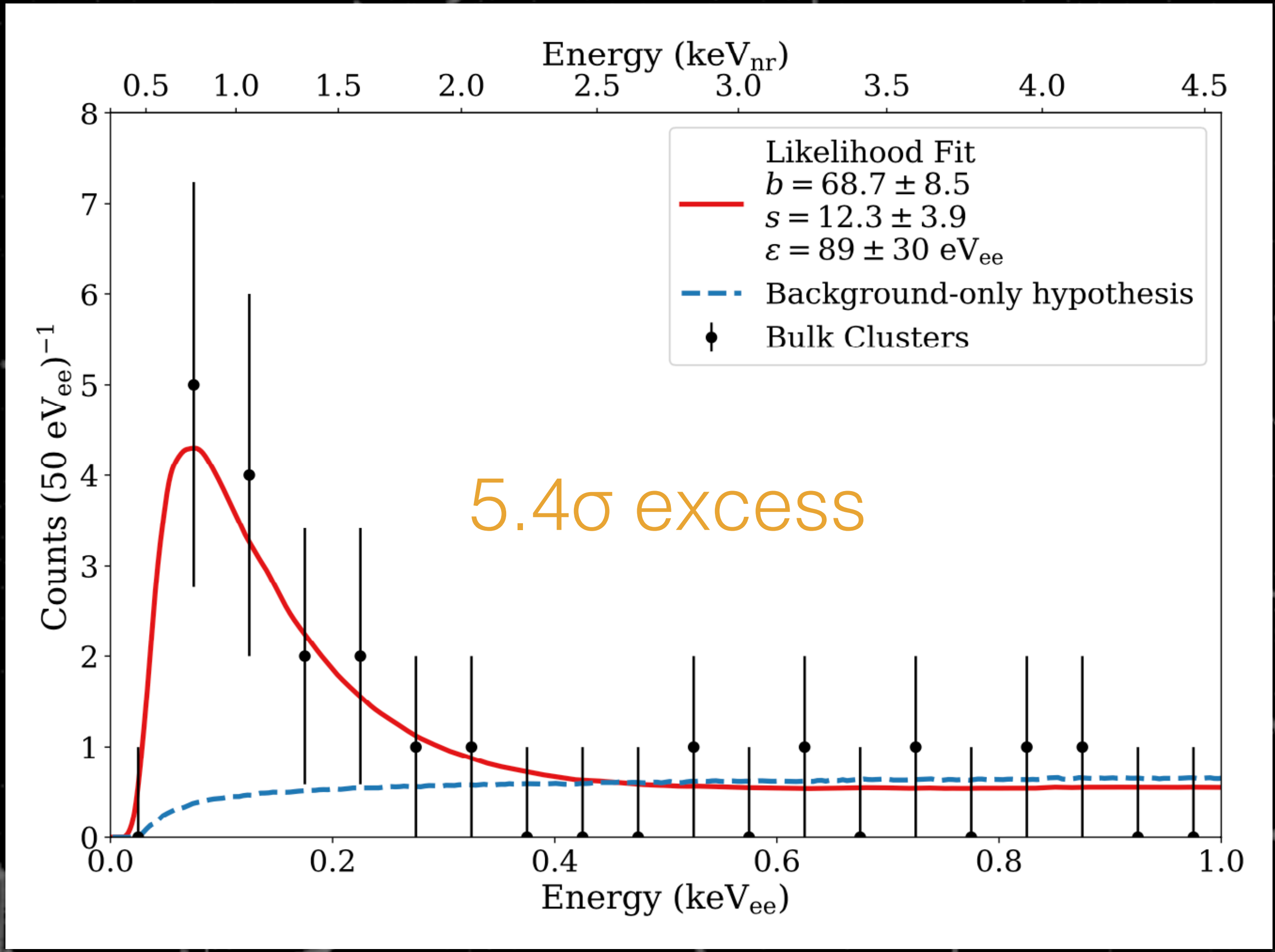


Energy threshold - 23 eV$_{ee}$

Energy spectrum

Best fit cross-section for spin-independent WIMP scattering: M_{DM} = 2.5 GeV @ 3E-40 cm^2

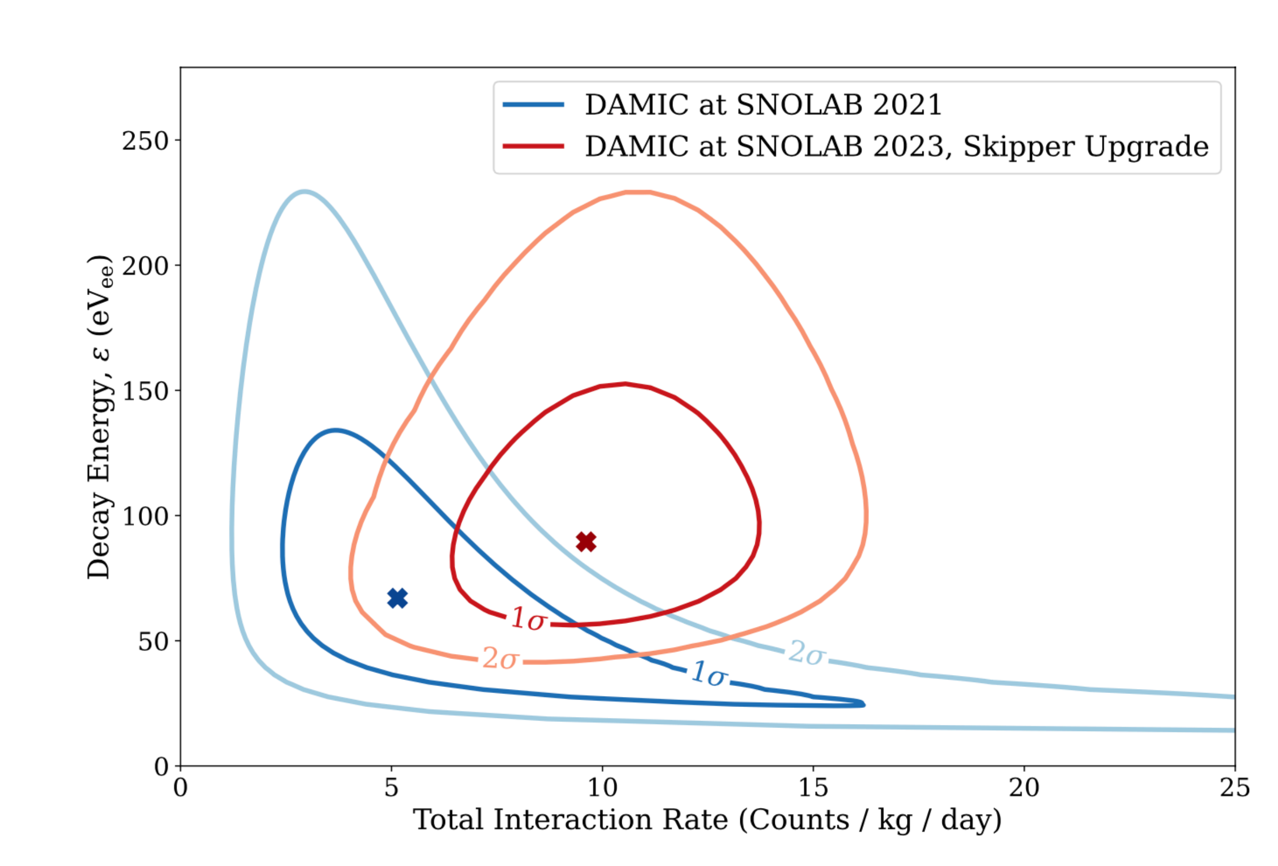
However, this signal interpretation is excluded by other experiments (Darkside-50 [1], CDMSlite [2])



Possibilities : quenching factor calibration, alternate WIMP models ?

1 arXiv:2207.11966
2 arXiv:1808.09098

Consistency with previous result



Possible explanations of excess

1. Energy threshold effect
2. Under-predicted background component
3. Due to partial charge collection
4. Unknown background component
5. An actual DM signal (WIMP or other)

Summary

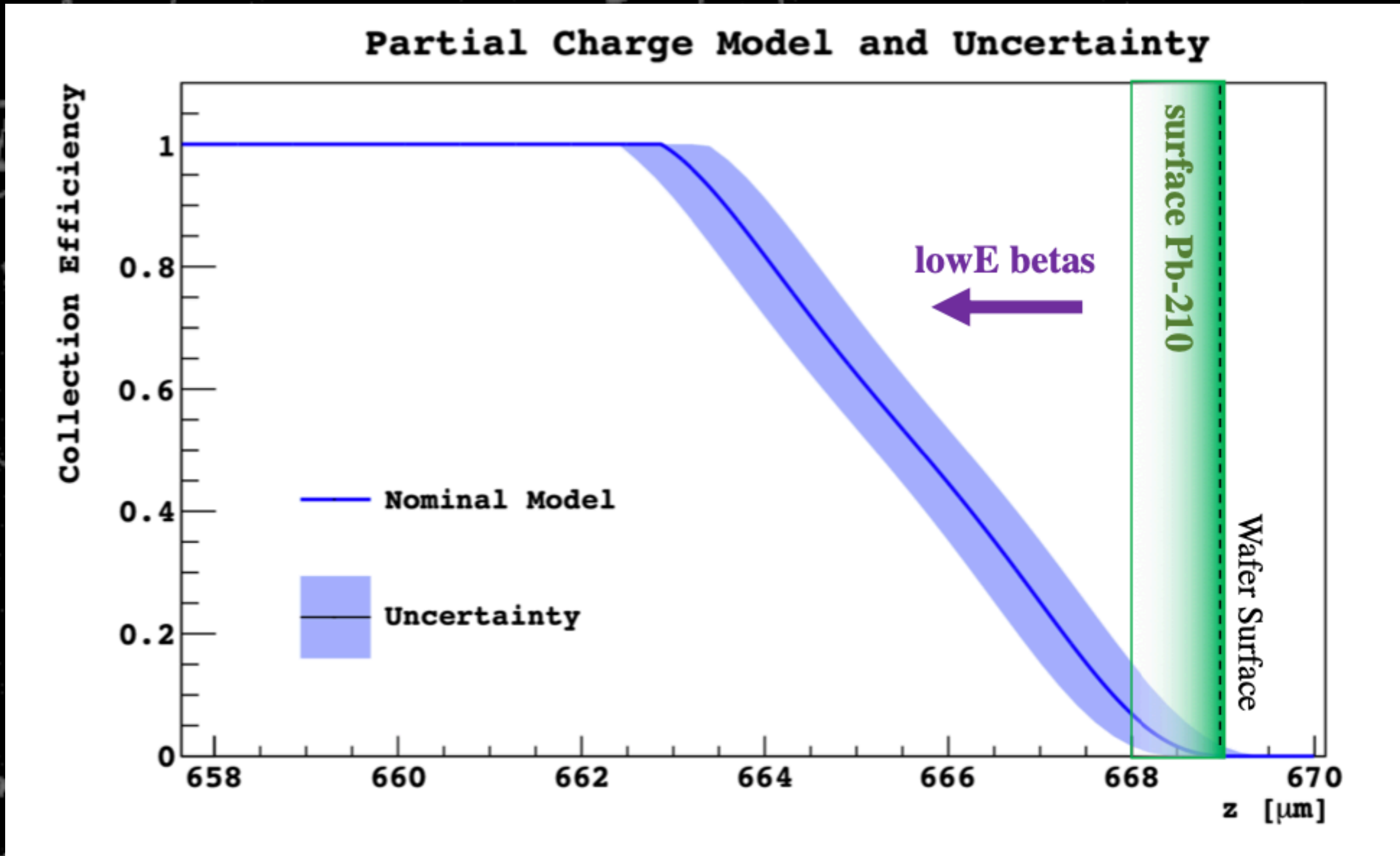
- DAMIC@SNOLAB results
  - Previous WIMP search excess 3.4σ excess
  - New, improved WIMP search with 10* lower noise, 10*better energy resolution → 5.4σ excess

- Future
  - DAMIC-M is a new experiment at Modane (LSM)
    - Same technology as DAMIC@SNOLAB upgrade
    - Lower background rates
    - 200 skipper CCDs
    - To be deployed in 2024
    - Already have some results based on a prototype setup
      - PRL arXiv:2302.02372 sets world's best limits on sub-GeV DM models

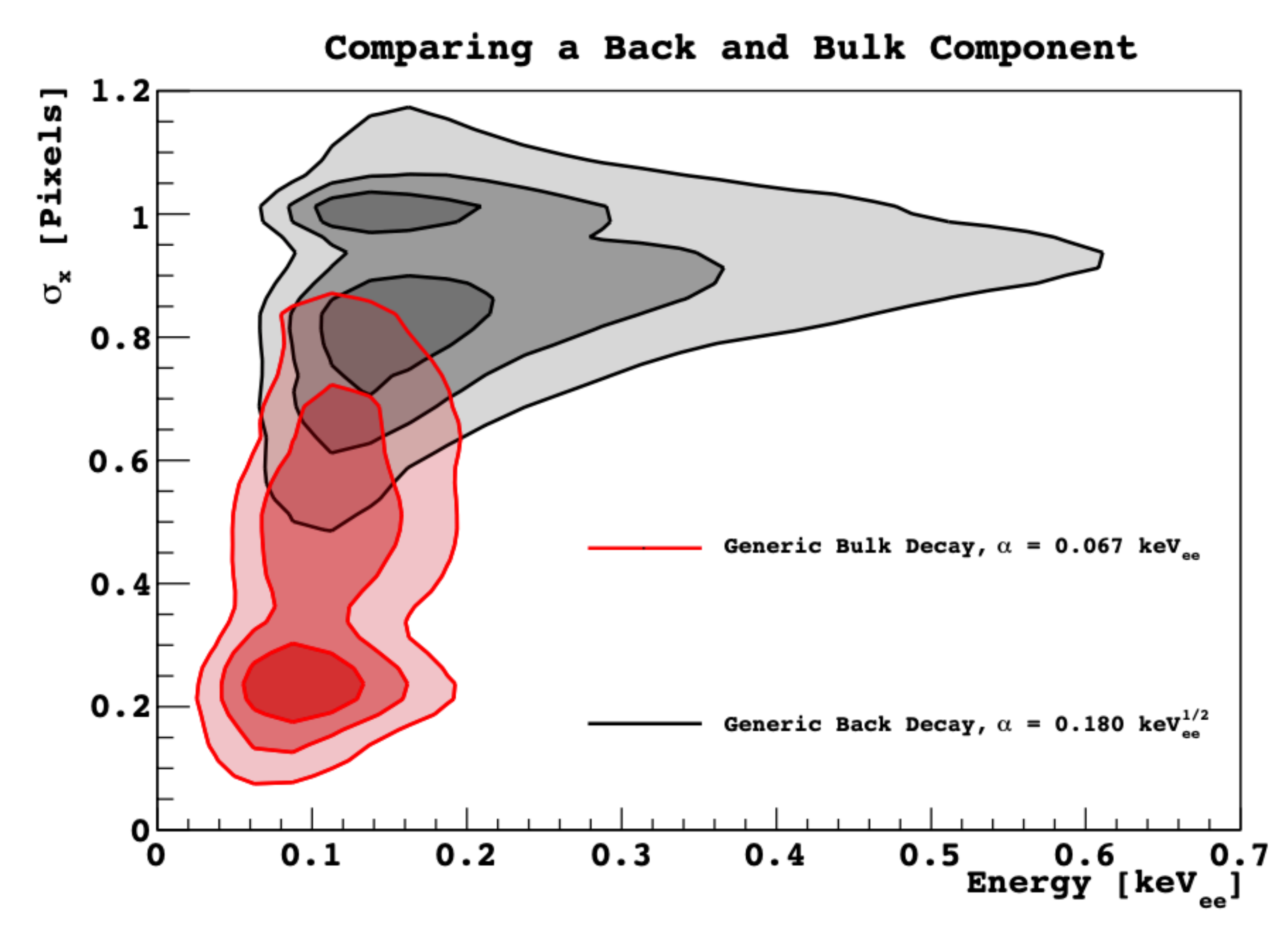
BACKUPS

Backgrounds

Partial charge collection region



Problem with Partial Charge Collection (PCC) model?



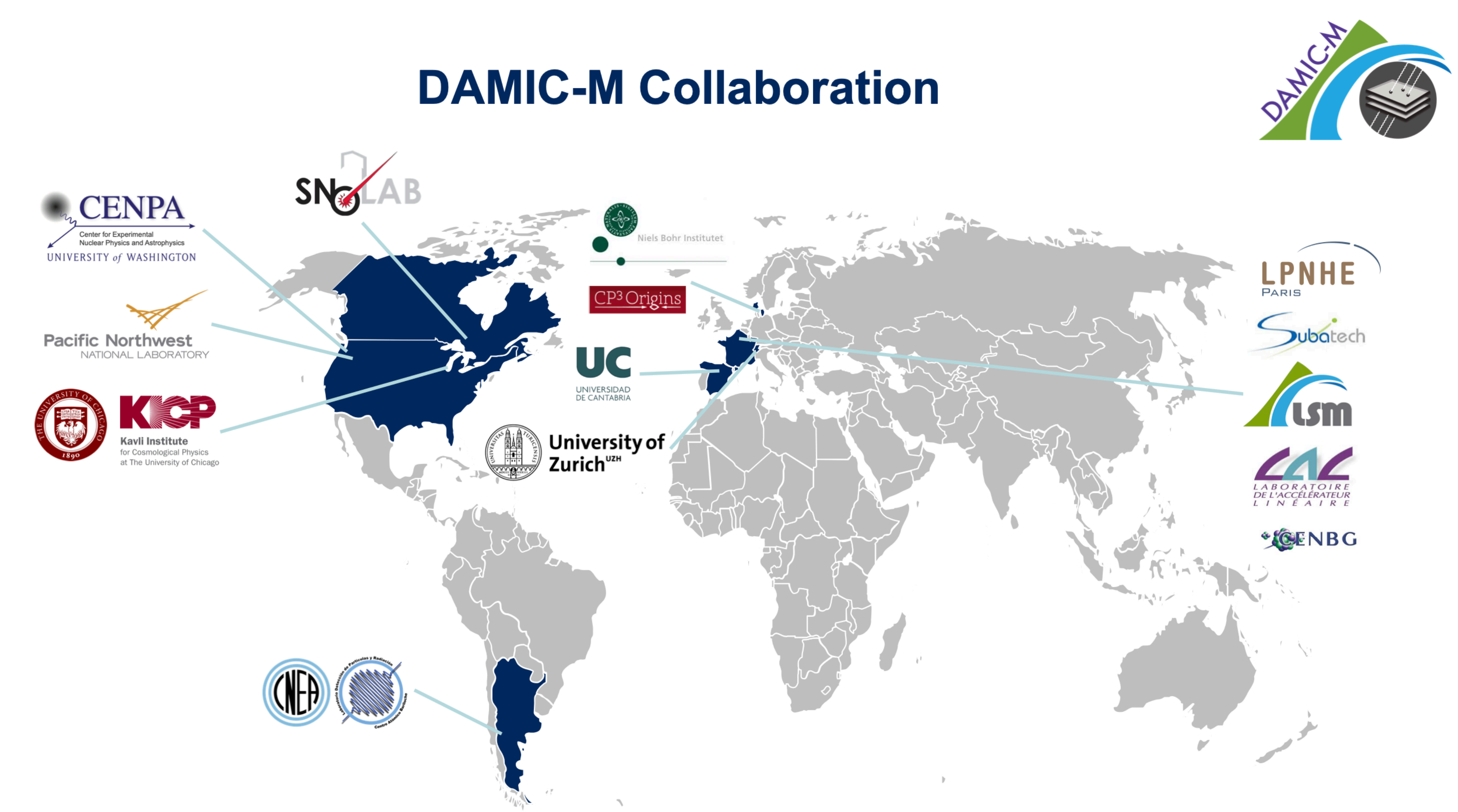
Model of PCC on backside with systematic uncertainties

Cannot explain excess

Achieving a factor of 10 reduction in noise threshold

Goal is to achieve an energy threshold for detecting DM signals as low as ~1 eV

DAMIC-M Collaboration



What's coming soon ? 2021-2022

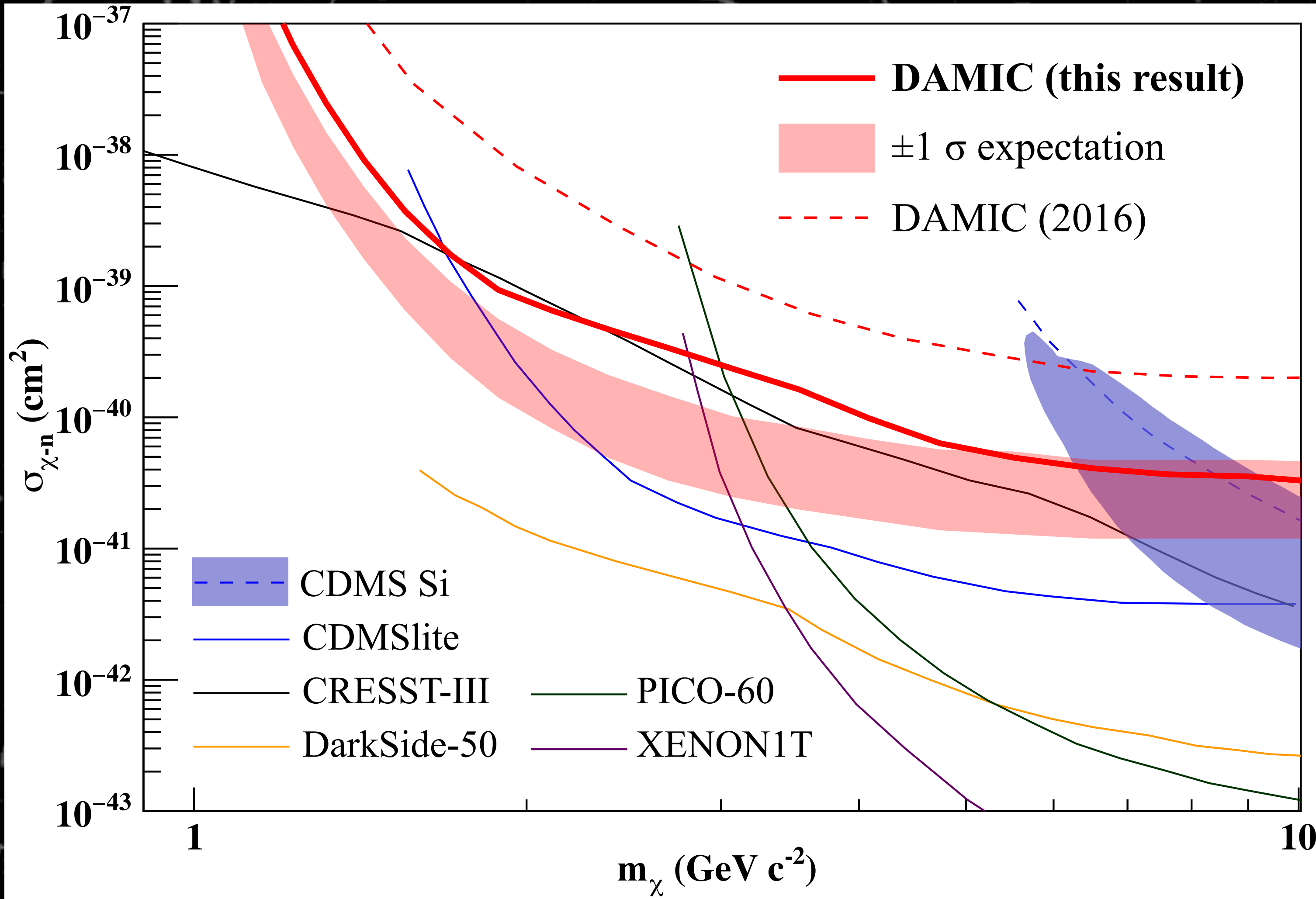
- DAMIC@SNOLAB
  - Upgrading to use skipper CCDs and probe excess
  - Expect to observe 15 events of excess with 6 months of data taking
- LBC
  - First stage of DAMIC-M
  - 5X lower background
  - Test of pre-production skipper CCDs

The next generation : DAMIC-M

- DAMIC-M
  - Factor of 10 improvement in energy threshold and resolution
  - 500 grams (10 times bigger)
  - Redesigned to achieve 50 times reduction in background 5 dru → 0.1 dru
    - Mitigation techniques mentioned previously
  - Moving from SNOLAB to Modane (LSM) in France - 2 hours from Geneva
  - Approved, funded, prototyping underway

- Sensitive to nuclear recoils, electron recoils, γ absorption from A’

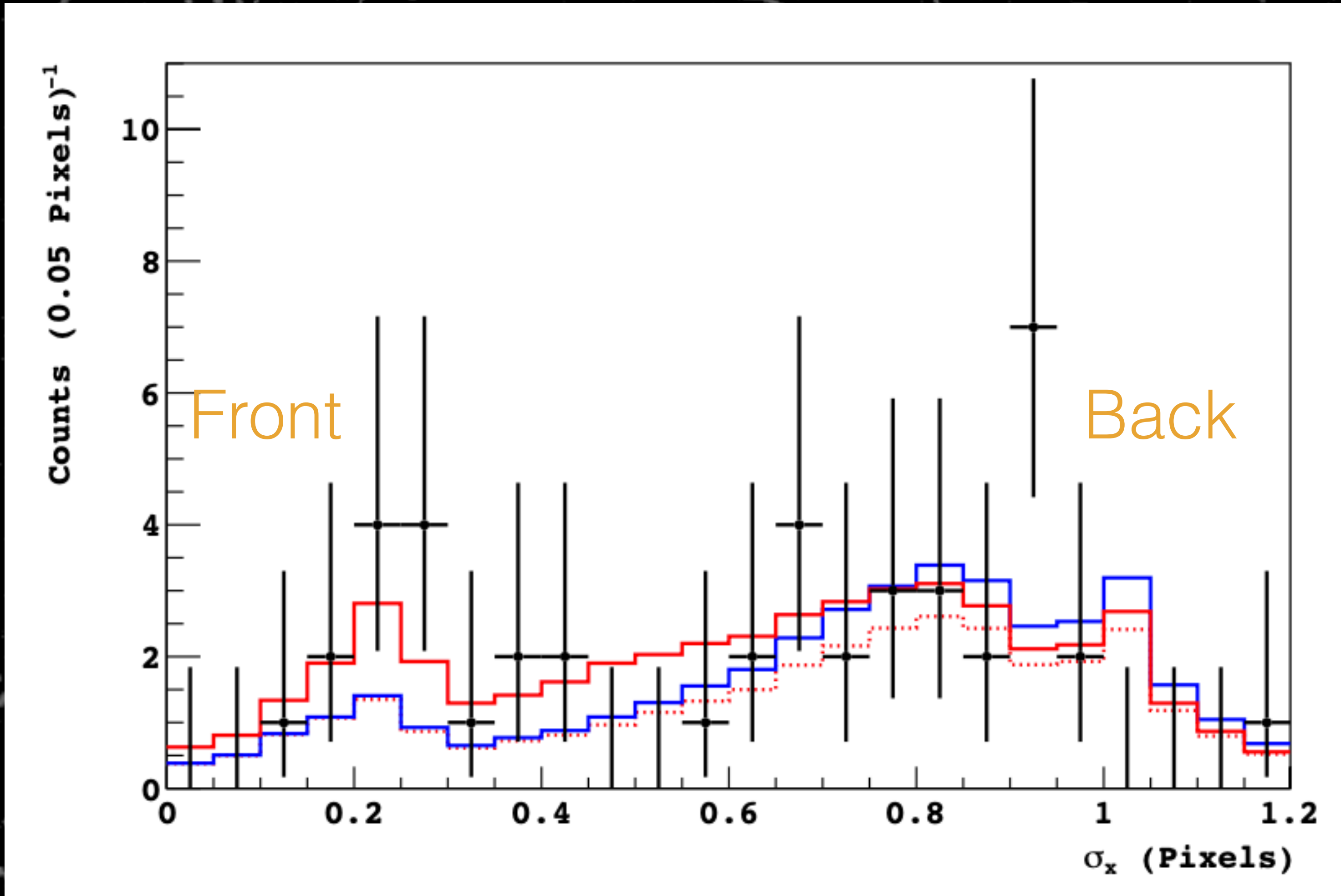
DAMIC 2020 limits



Observed limit is, of course, worse than expected

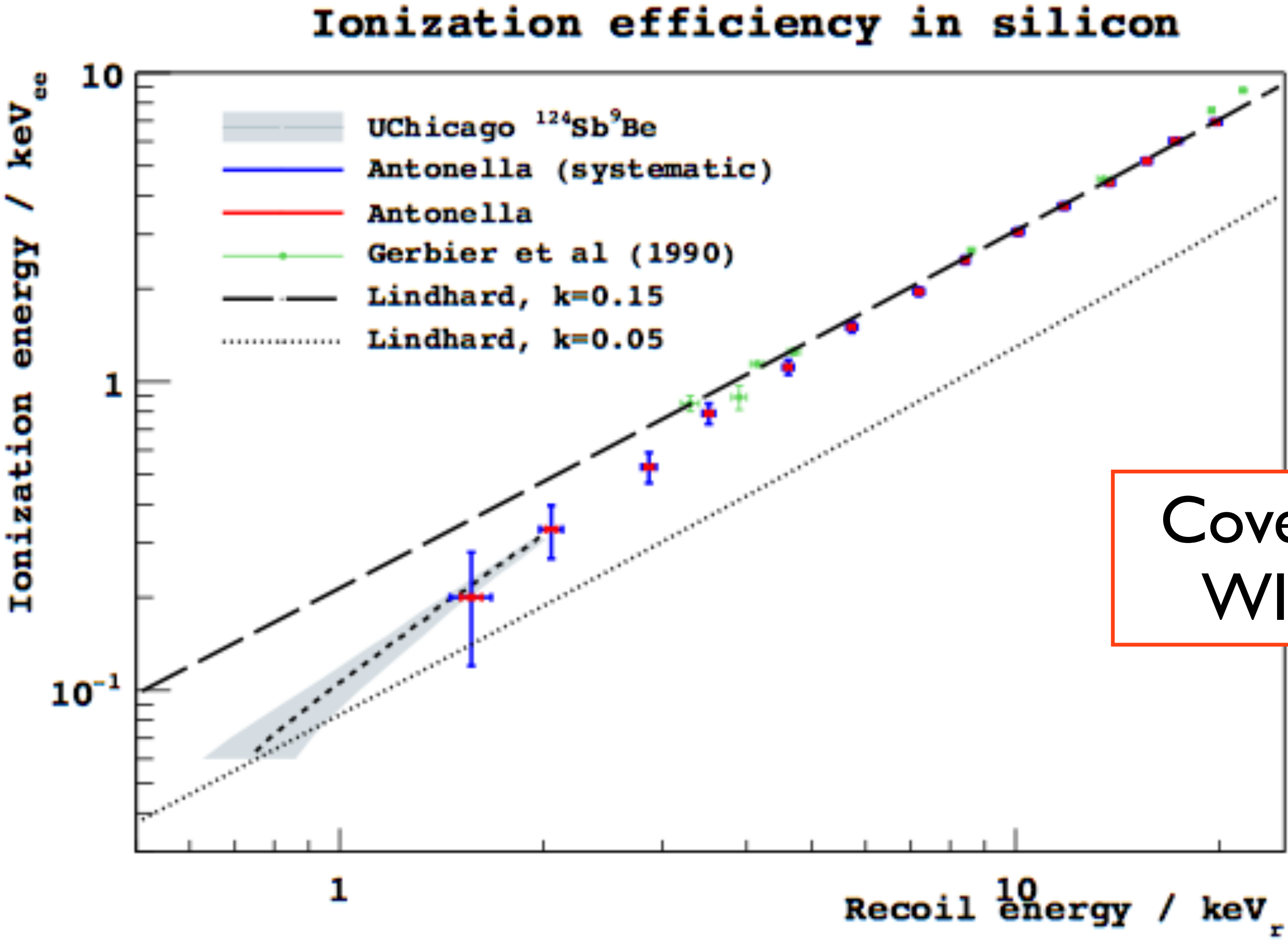
Cluster size projection

for 50 < E < 250 eV



Excess is spread out - not just one part of CCD

Nuclear recoil calibrations



Antonella : 1702.00873
U.Chicago : 1608.00957

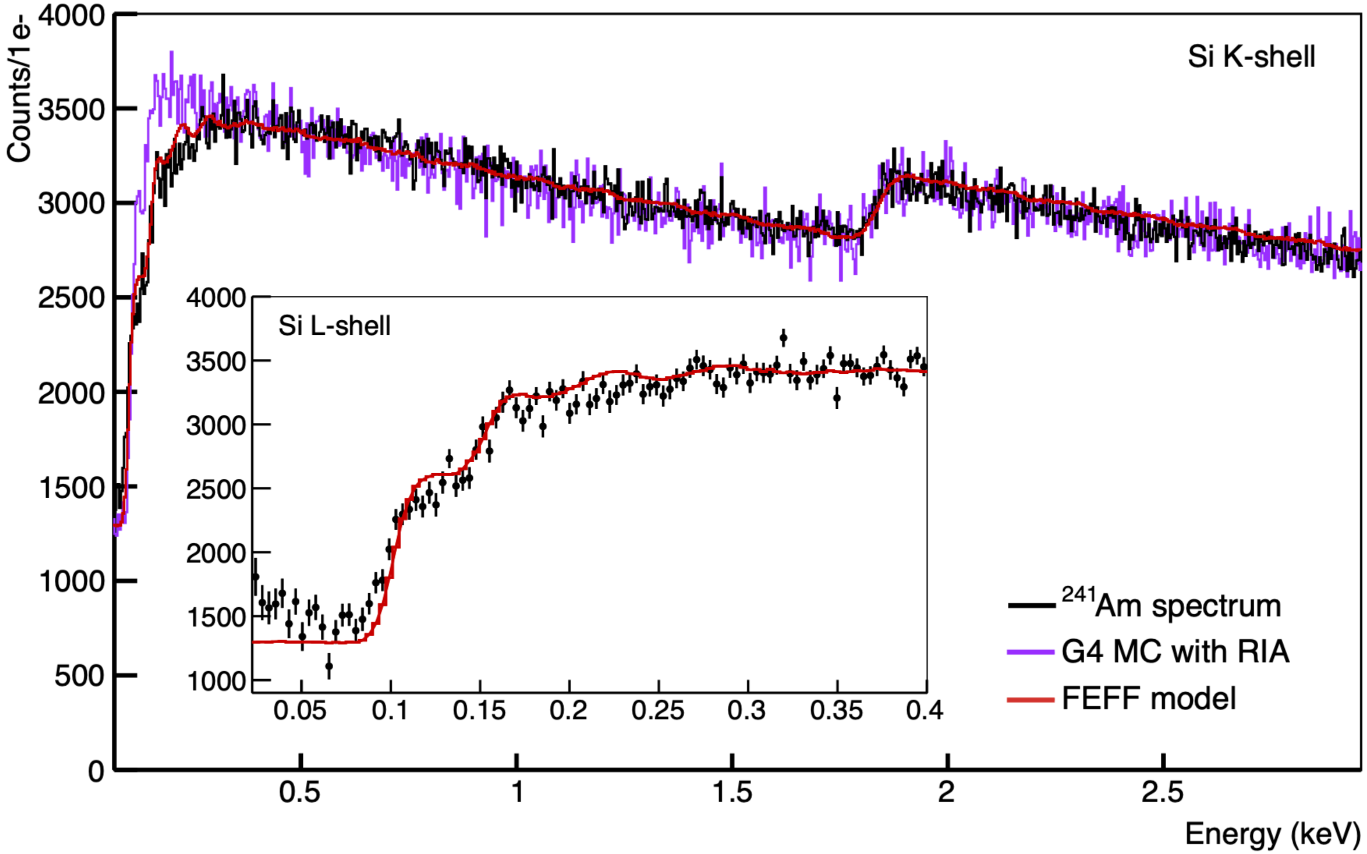
Cover entire DAMIC WIMP search ROI

- **Two independent experiments using different techniques**
- **Greatly improved statistical uncertainties at low energies**
- **Both find departure from Lindhard calculation**
  - **Ionization energy yield lower than expected**

Related publications

- DAMIC @ SNOLAB
  - 2023, submitted 2306.01717 : confirmation of excess
  - 2020, PRL 2007.15622 : excess in WIMP search observed
  - 2021, PRD 2110.13133 : description of backgrounds
  - 2020, JINST 2011.12922 : measure of radioactivity in CCD
  - 2019, PRL 1907.12628 : DM-e scattering / hidden DM
  - 2017, PRL 1611.03066 : First eV-mass-scale DM search

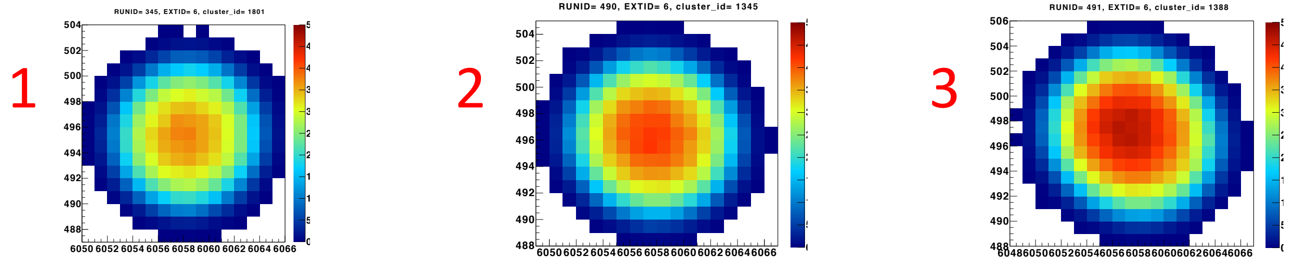
MAIN BACKGROUNDS: COMPTON



CCDs have unique spatial resolution

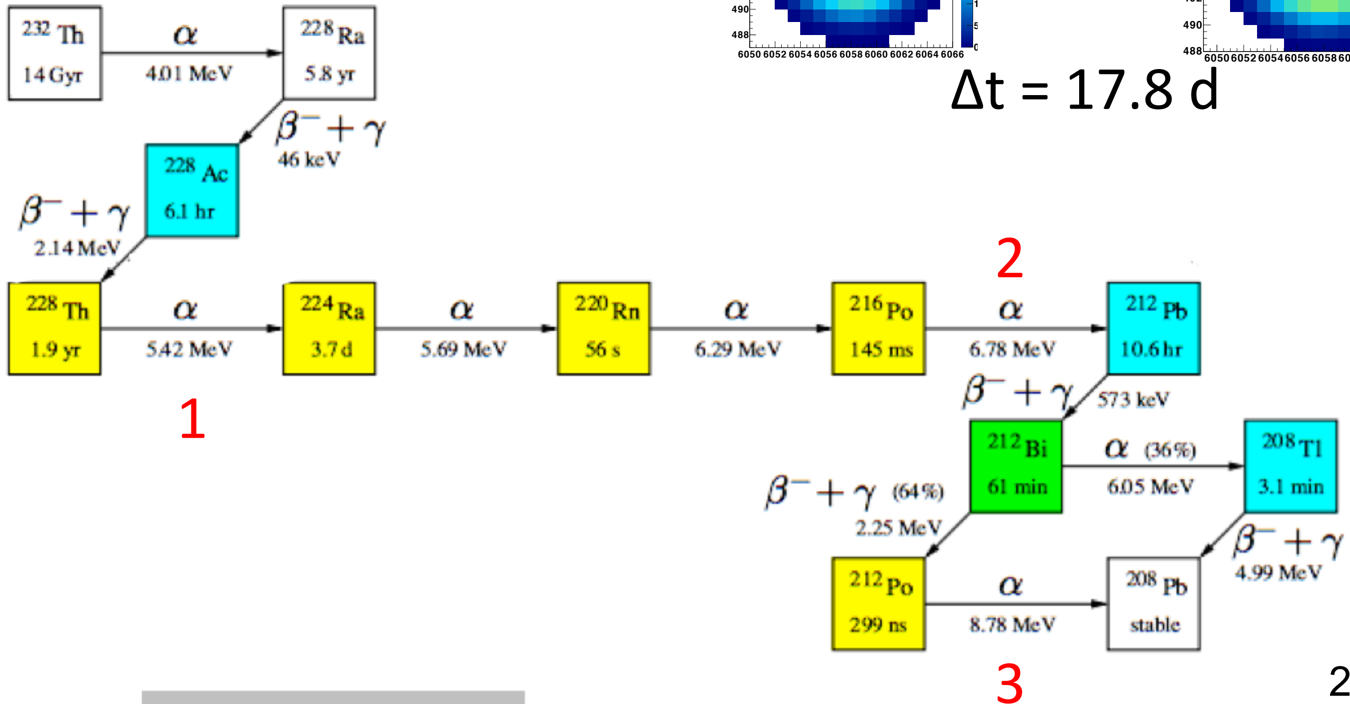
Three α at the same pixel location!

E = 5.4 MeV E = 6.8 MeV E = 8.8 MeV



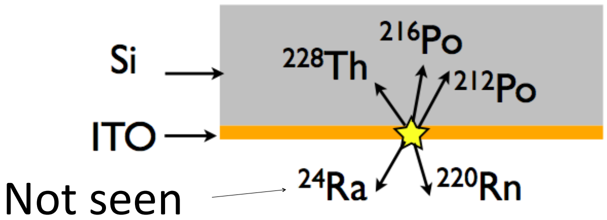
Δt = 17.8 d Δt = 5.5 h

Corresponds to decay chain of Thorium



arXiv:1506.02562

2015 *JINST* **10** P08014



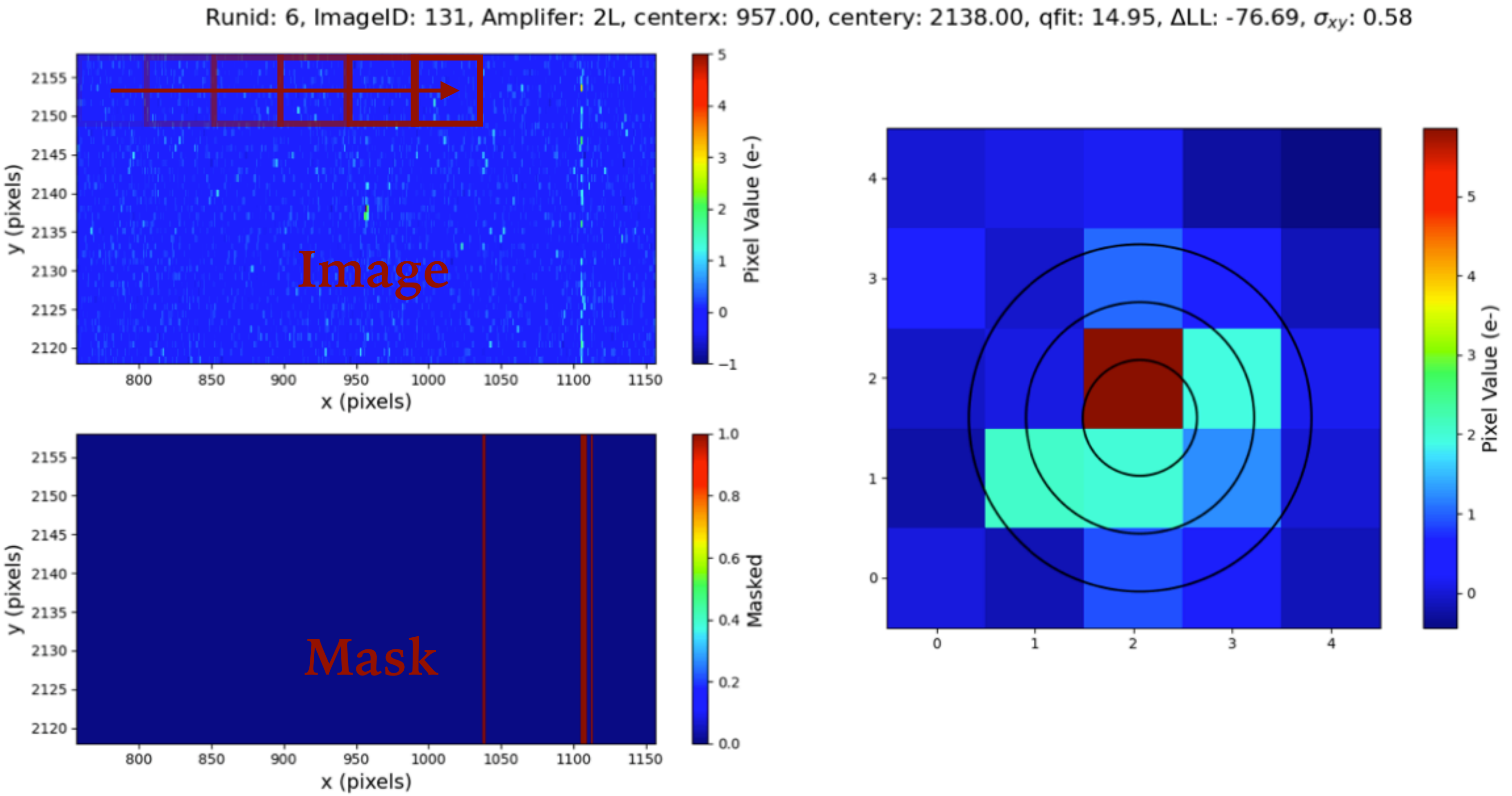
We set in situ limits on contamination:
^{238}U < 5 kg^{-1} d^{-1} = 4 ppt
^{232}Th < 15 kg^{-1} d^{-1} = 43 ppt

DAMIC experiment generations

- 2010-2011 : DAMIC first run at Fermilab
  - Best DM limits for WIMPs below 4 GeV
- 2015- now : DAMIC @ SNOLAB
  - Hidden photon DM search
    - 2017 : First eV-scale results
    - 2019 : Result reported today
  - WIMP search
    - 2016 : First result
    - 2020 : Low-energy excess observed
    - 2023 : Today: low-energy excess confirmed with skipper CCD
- 2023 : DAMIC-M @Modane
  - Single e-h pair resolution (achieved)
  - Test of prototype CCDs in 2021 (LBC)

LOW-ENERGY CLUSTERS

<u>Likelihood clustering</u>: find low-energy clusters by computing likelihood of ionization event inside moving window…



DATA SELECTIONS

Likelihood clustering: …and efficiently reject noise accidentals down to $23\ \mathrm{eV}_{ee}$

$$\log \mathcal{L}(N, \vec{\mu}, \vec{\sigma}, \lambda, \sigma_r|\vec{q}) = \sum_i \sum_j \left(\sum_k^{\infty} \log \left(\frac{\gamma_{ij}^k \exp(-\gamma_{ij})}{k!} \frac{1}{\sqrt{2\pi\sigma_r^2}} \exp \left(\frac{-(q_{ij}-k)^2}{2\sigma_r^2} \right) \right) \right)$$

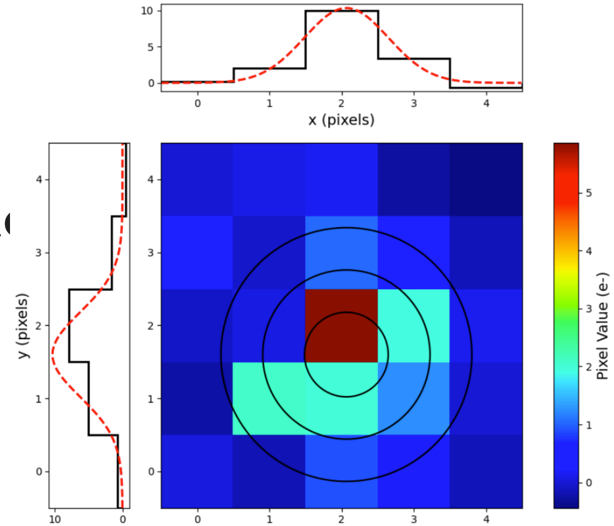
$$\gamma_{ij} = \lambda_i + N \int_{i-0.5}^{i+0.5} \int_{j-0.5}^{j+0.5} \mathrm{Gaus}(x, y|\mu_x, \mu_y, \sigma_x, \sigma_y)dxdy$$ **: Noise + Ionizati**

$\downarrow$

$\Delta LL = -\log \left(\frac{\tilde{\mathcal{L}}_g}{\mathcal{L}_n} \right)$ discriminates low-energy events from noise accidentals

$\mathcal{L}_g$: global likelihood under hypothesis of ionization

$\mathcal{L}_n$: local likelihood under noise-only hypothesis



Naturalness of Dark Matter Mass scale

Standard WIMP :

1. "WIMP miracle" scale : $M_{DM} \sim 100$ GeV

   - Coincidence that SUSY weak cross-sections provide DM density relic Ω_{DM}

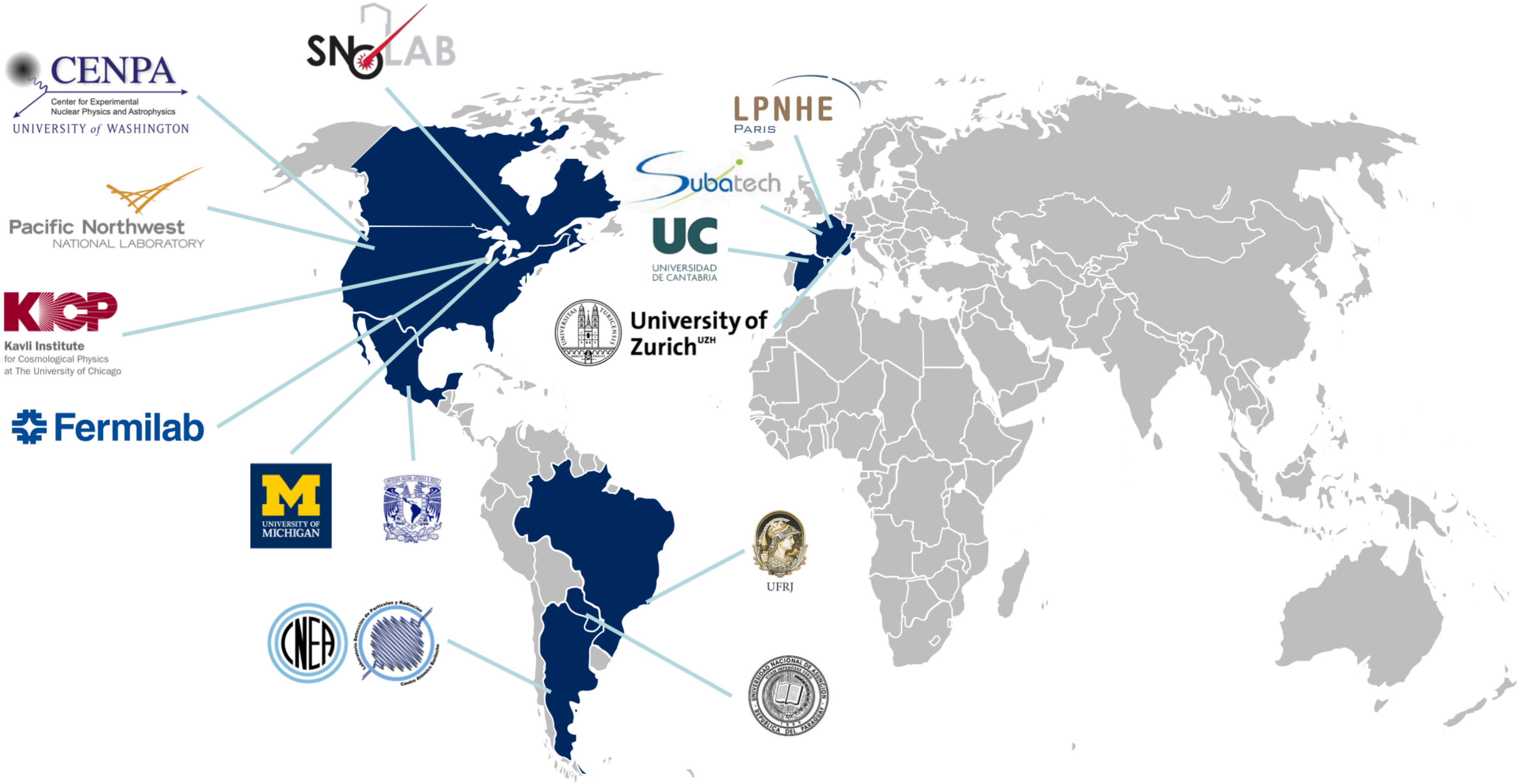
Light WIMP :

2. "Baryon-DM coincidence" scale : $M_{DM} \sim 5$ GeV

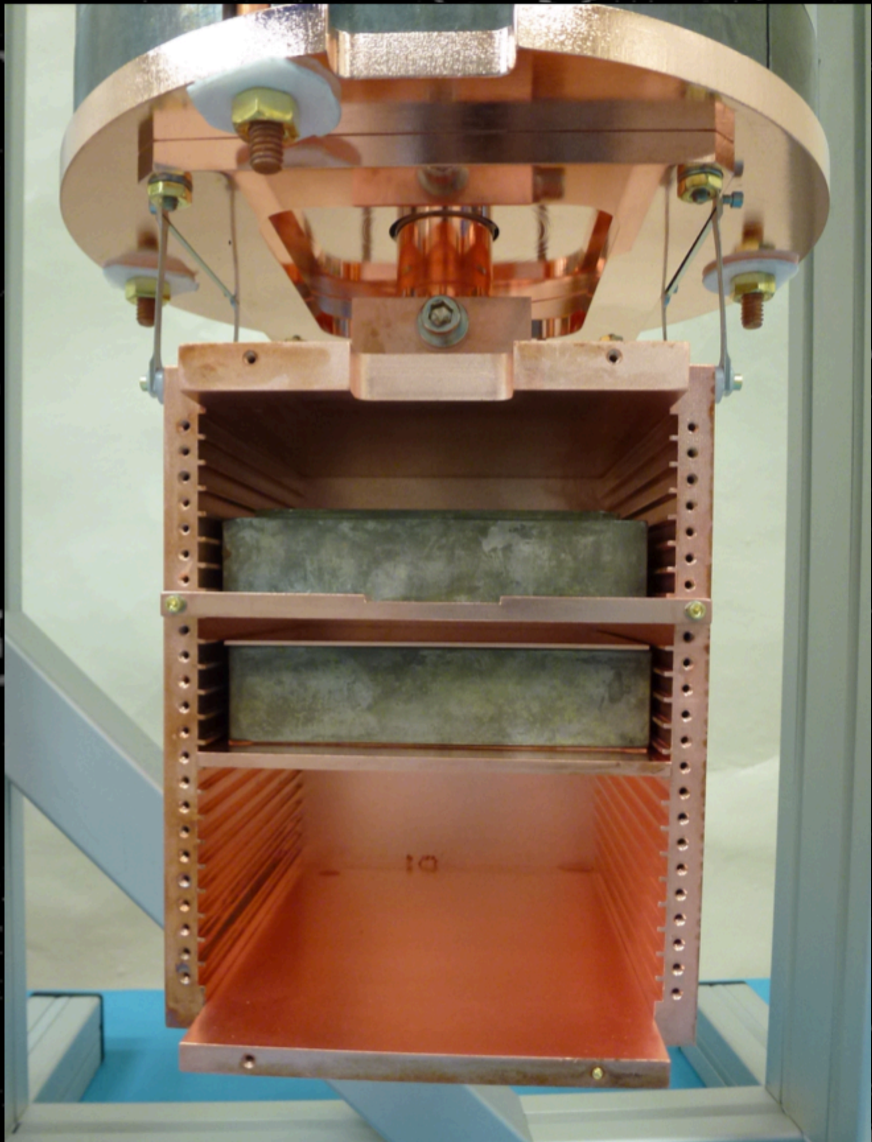
   - $\rho_{DM} \approx 5\ \rho_B$
     - ρ_B is set by CP violating phase
     - ρ_{DM} is set by mass of dark matter
   - If we consider the two related :
     $\rightarrow$ $M_{DM} = 5 * M_{proton}$

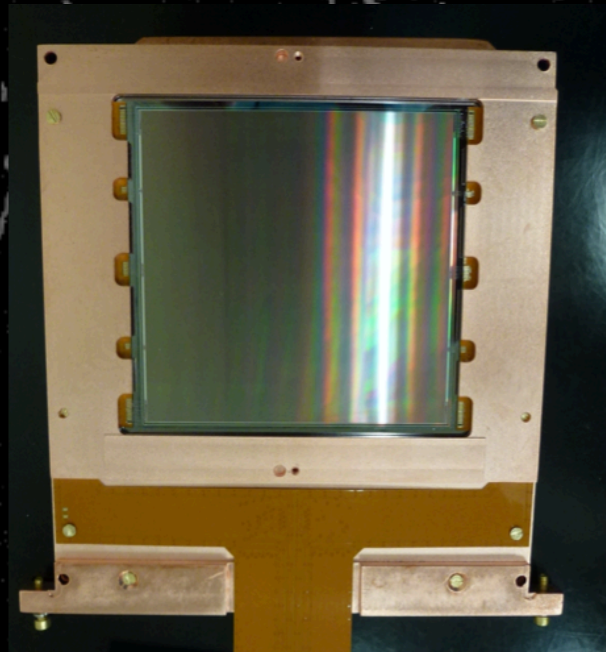
Asymmetric DM
hep-ph/1111.0293

DAMIC@SNOLAB Collaboration



Backgrounds





- GEANT4 simulation of detector with 23 isotopes decaying
  - Most isotopes constrained by radioactive screening of materials
  - Some constrained using in situ measurements

Reducing backgrounds for DAMIC-M

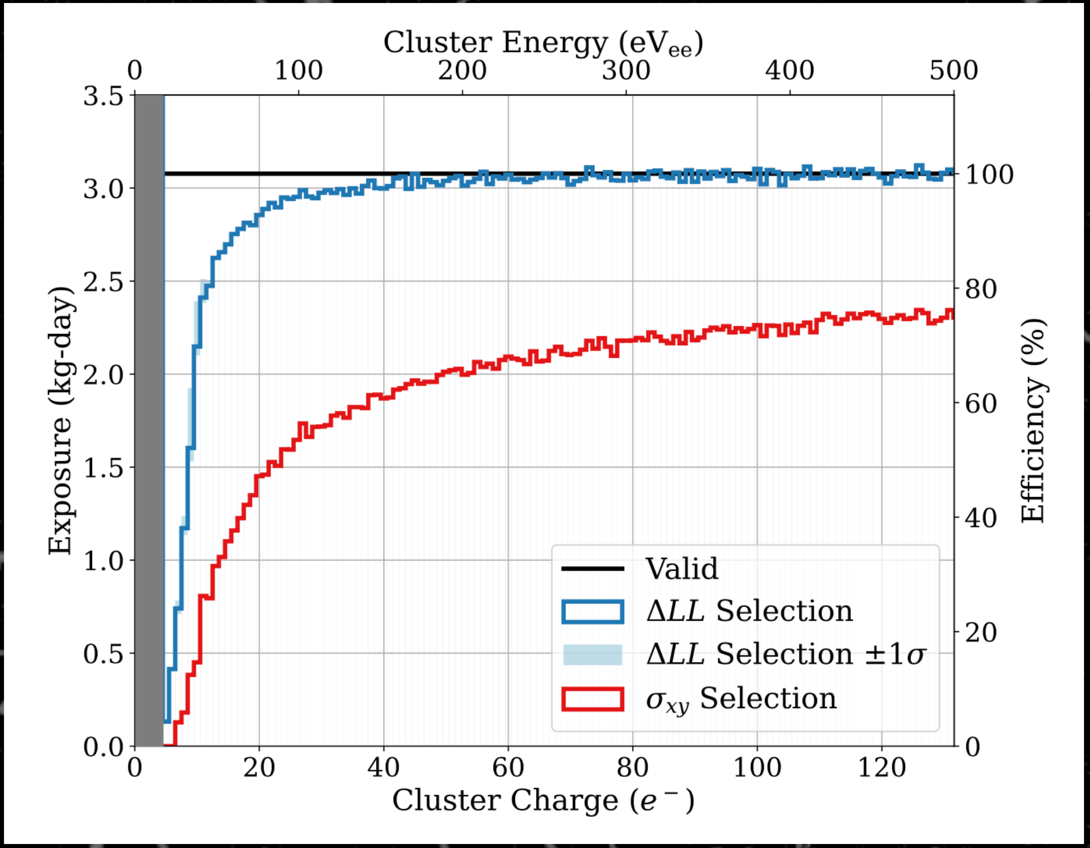
Dominant Backgrounds	**How to reduce**
^{60}Co, ^{210}Pb ^{238}U, ^{232}Th	Electro-forming copper underground
^{210}Pb	Cleaner CCD processing/ fabrication
^{3}H & ^{22}Na	Shielding silicon Underground storage & processing
^{32}Si & ^{32}P	**Silicon vertex tagging***

* Not what you expect !

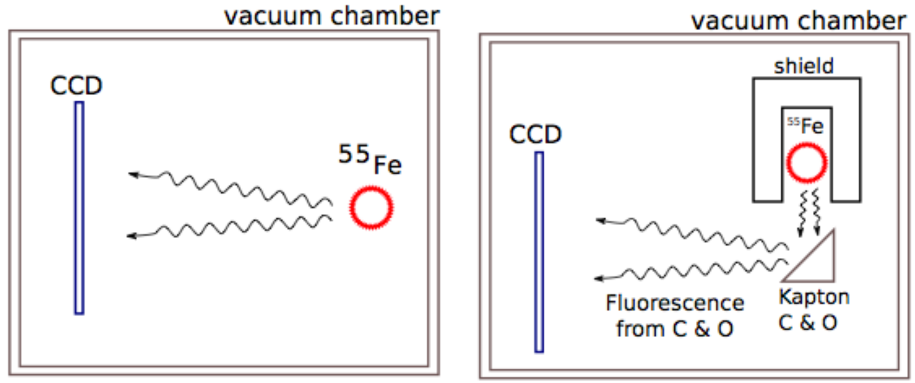
BACKUPS

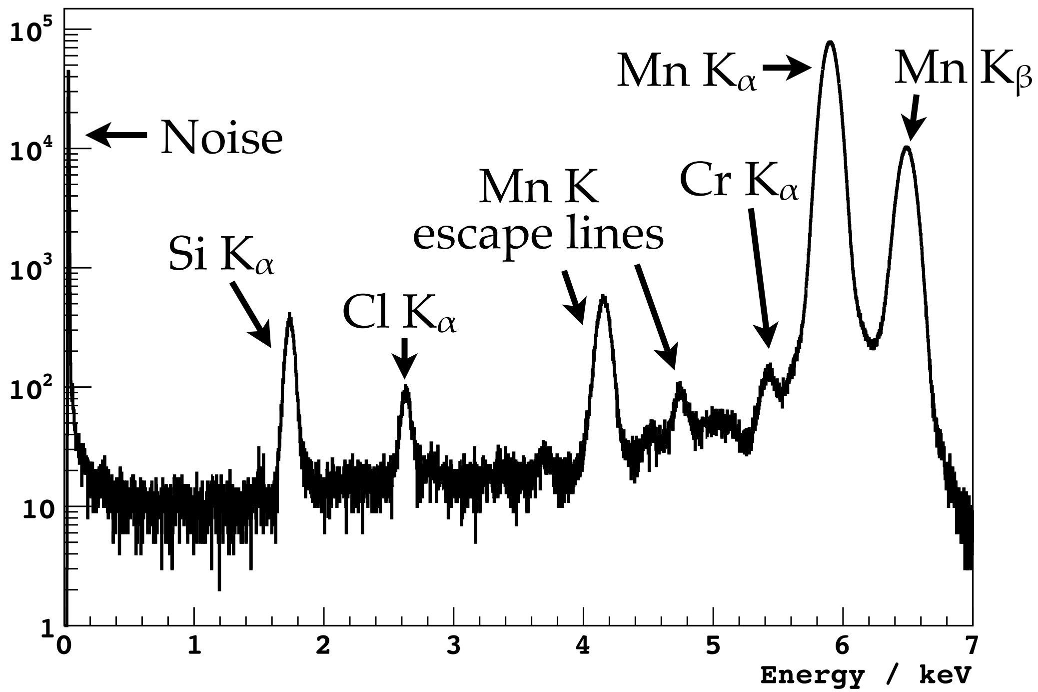
General

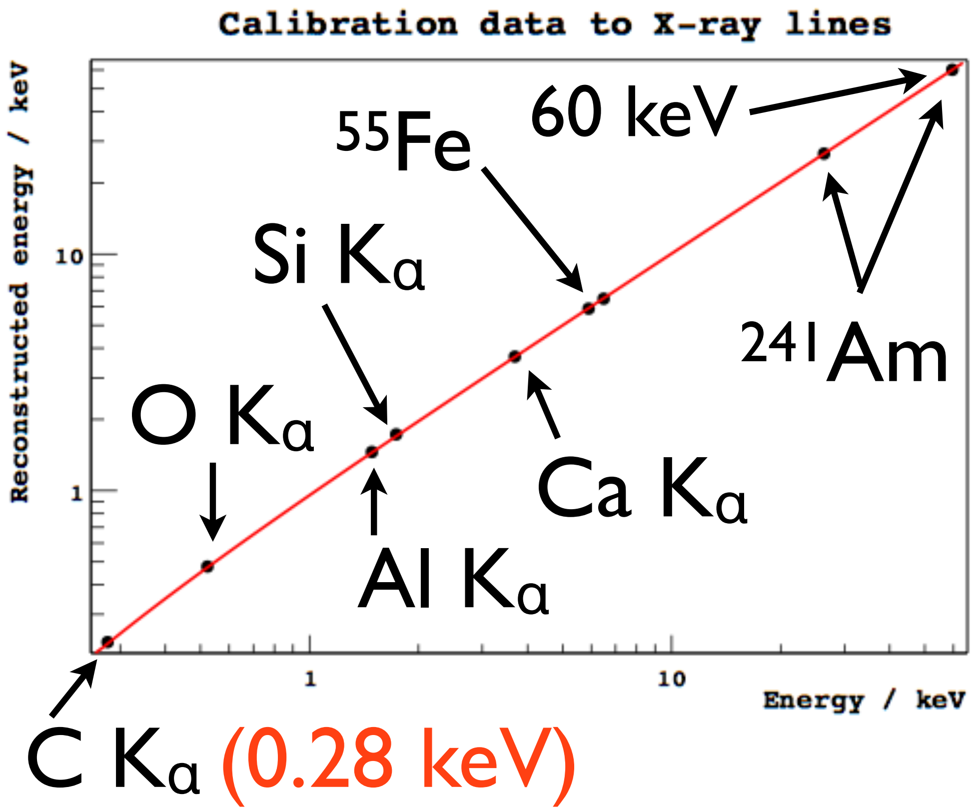
Improvement in 2023 experiment



X-ray calibration of CCDs







E resolution 53 eV at 5.9 keV

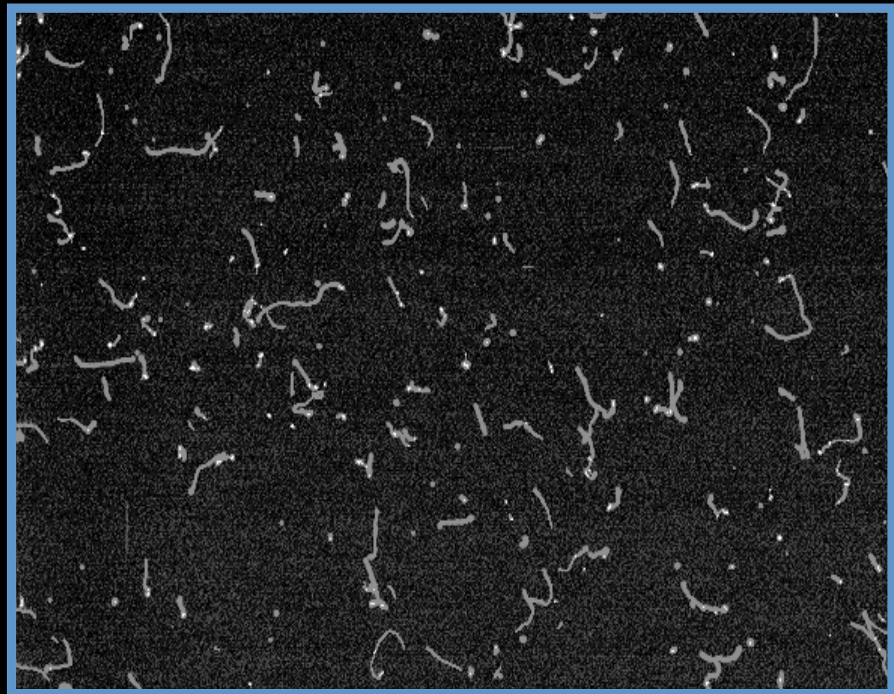
Linear response, good resolution

We can calibrate with various sources

X-ray ^{55}Fe (5.9 keV)

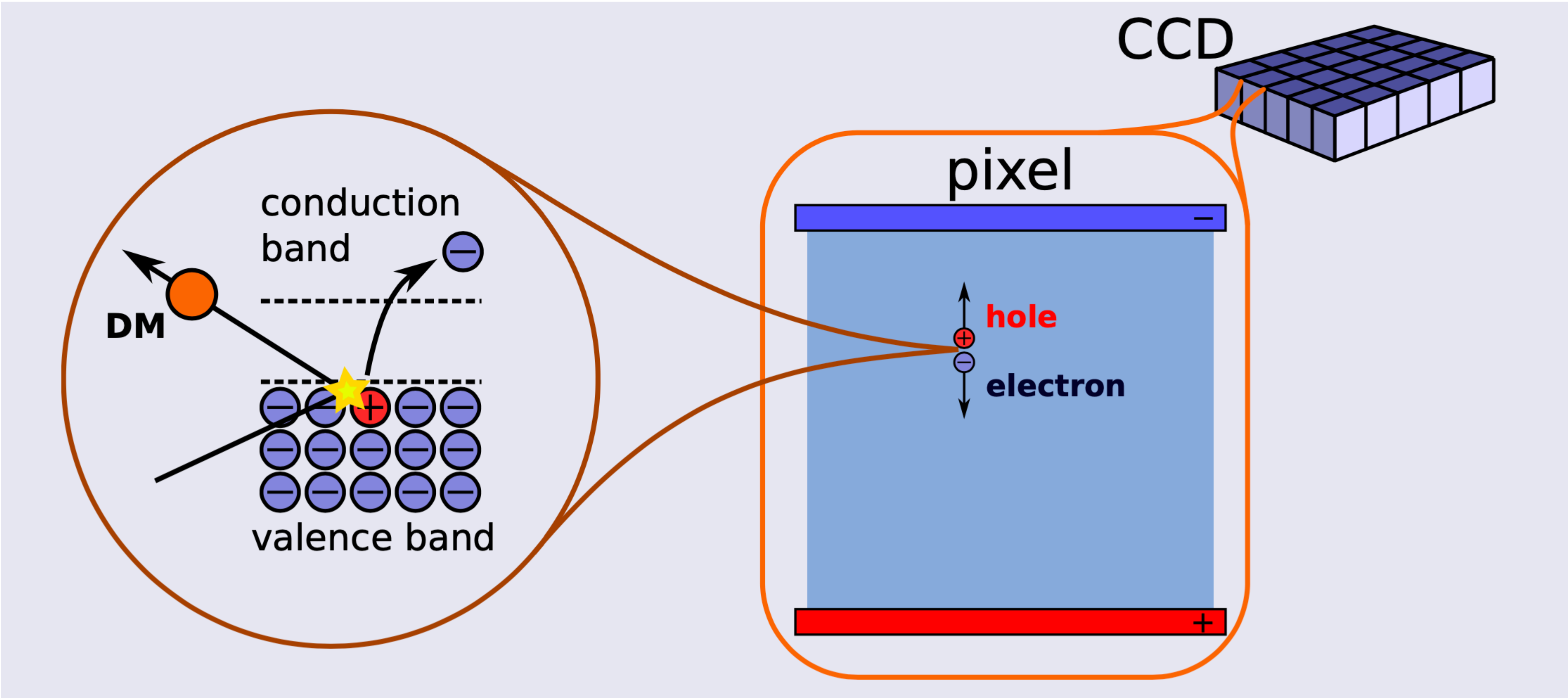
Point like hits
(diffusion limited)

Gammas ^{60}Co (1.33 & 1.77 MeV)



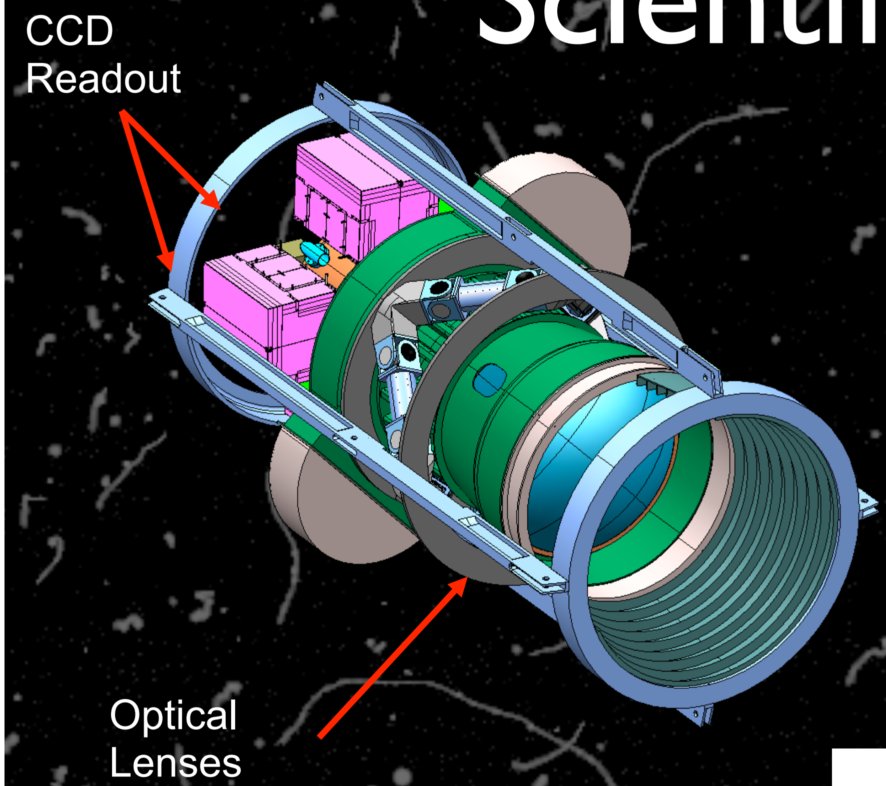
Compton electrons (worms) and point-like hits.

Detecting DM in a CCD

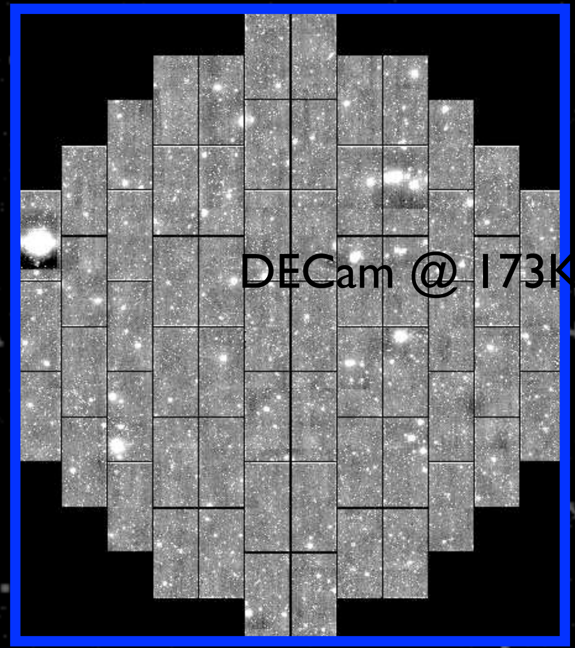


Minimum energy ~ 1 eV to move charge from valence to conduction band

Scientific CCDs



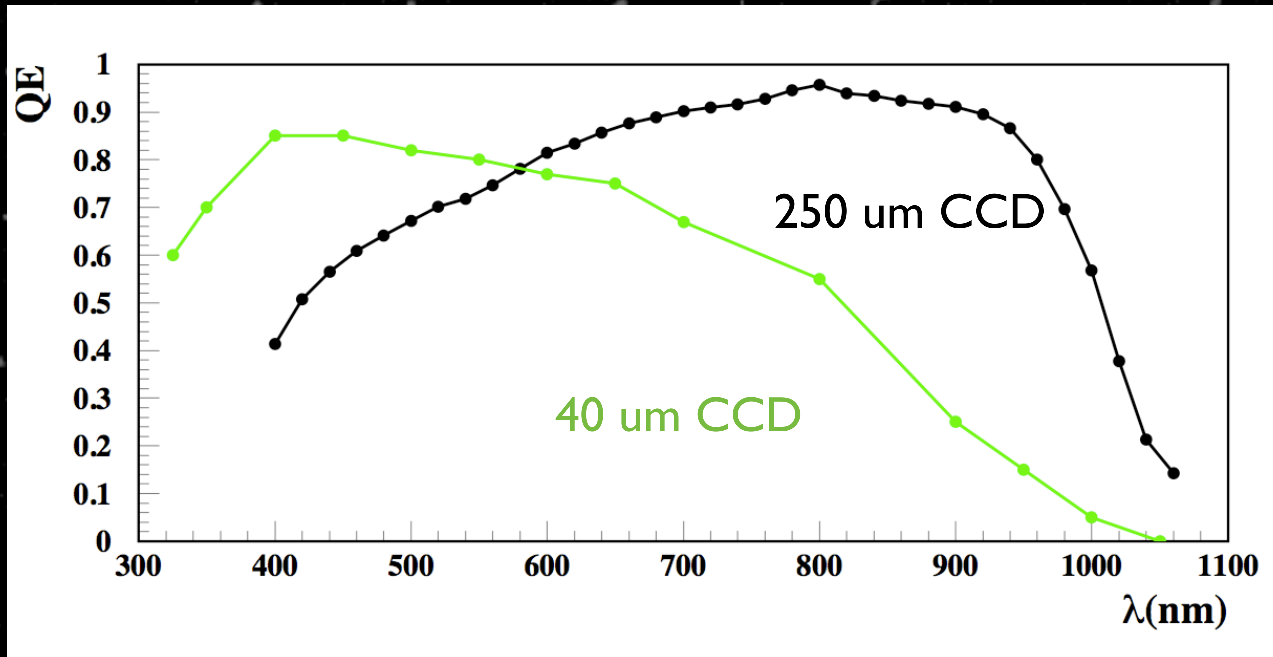
Images collected on ~60 CCDs ~600 Mpix



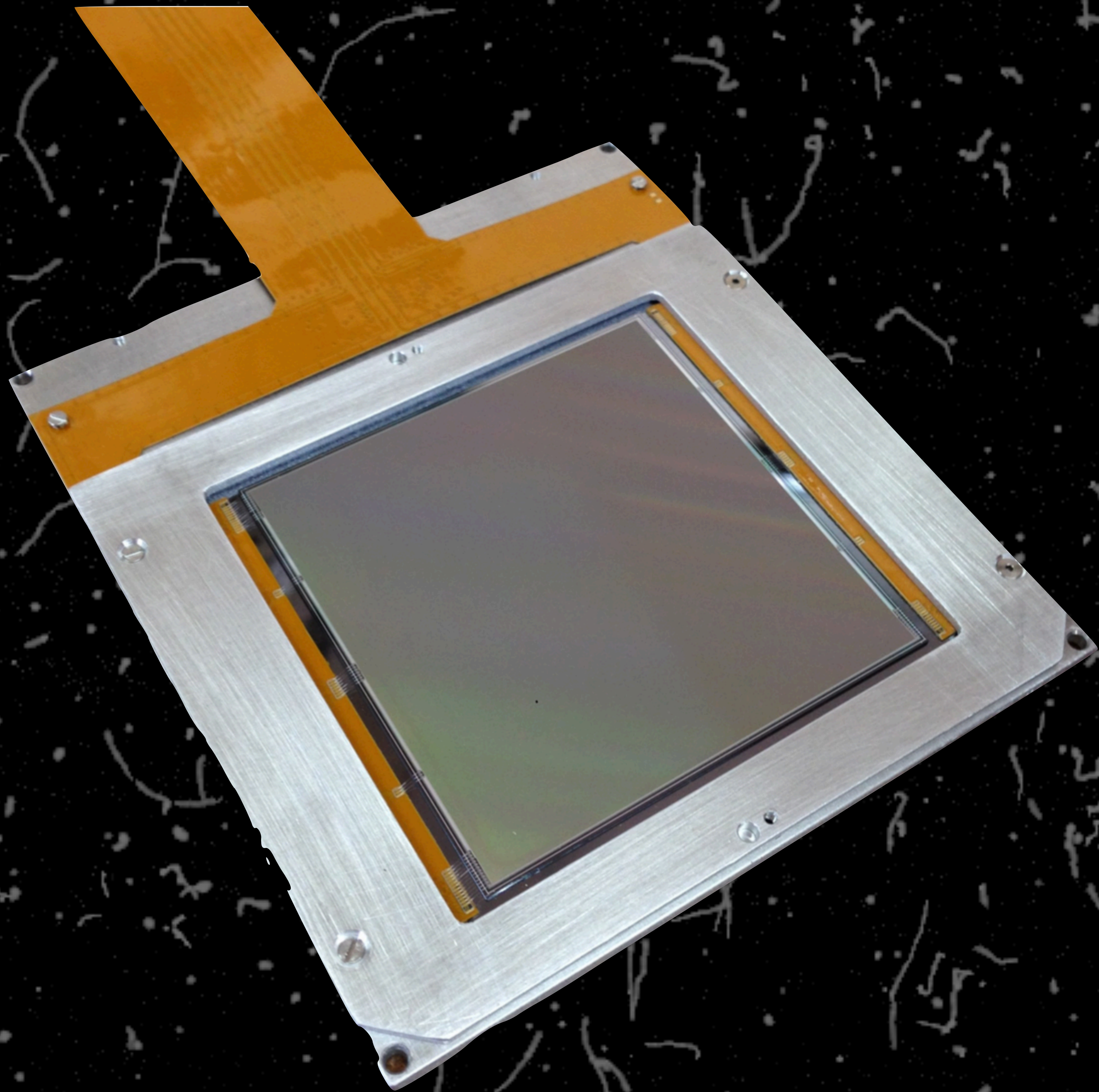
CCDs originally created for DES (DECam) by LBNL

Thick to be sensitive to infrared

= massive !

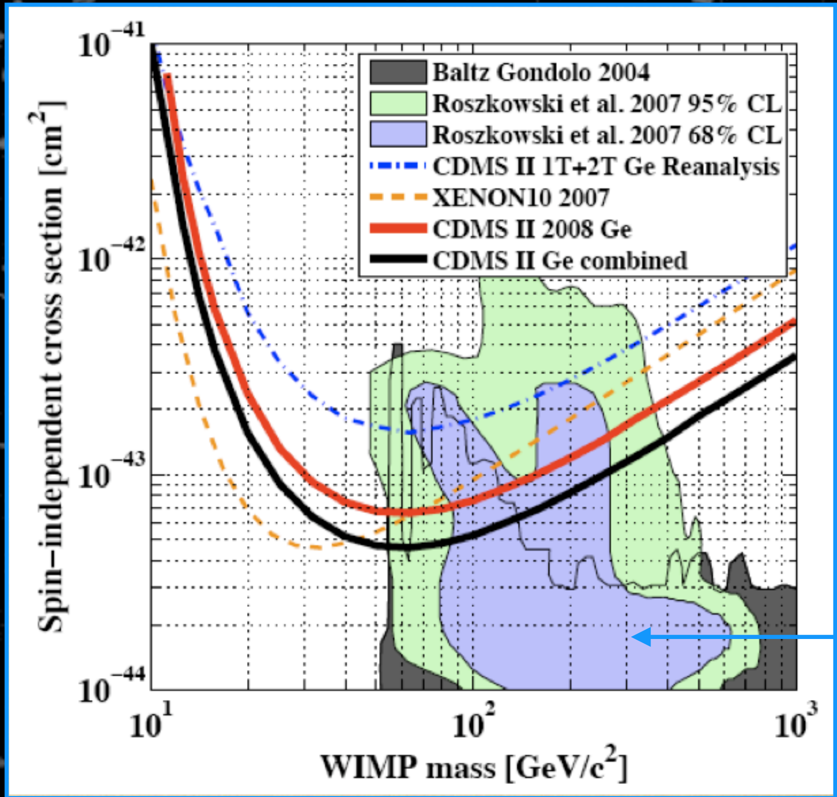


Scientific CCDs



2007 : Prospects for SUSY dark matter

Cross-section



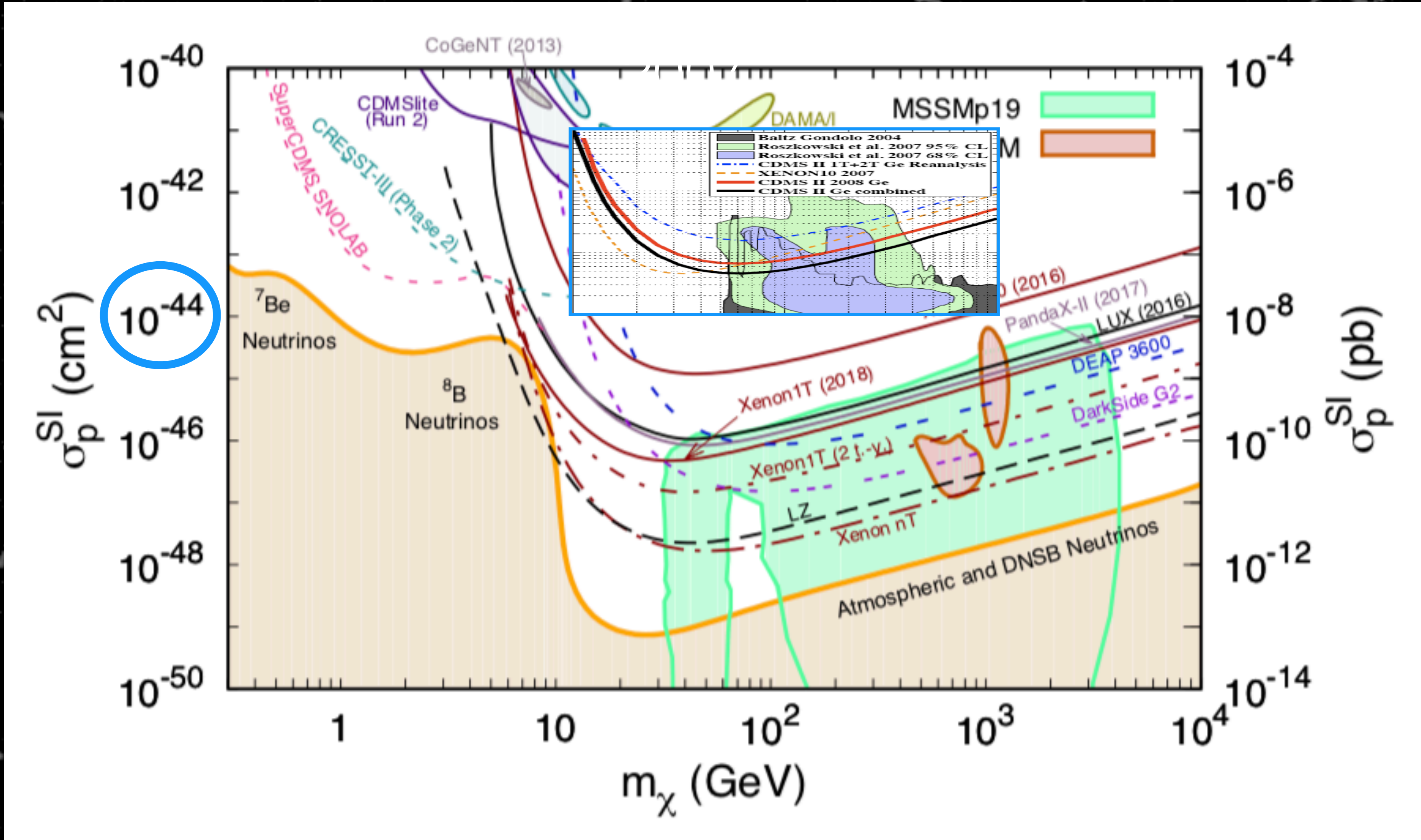
10^{-44} cm^2

Mass of WIMP dark matter

Experimental searches

SUSY favored region

~Today



SUSY is a moving target

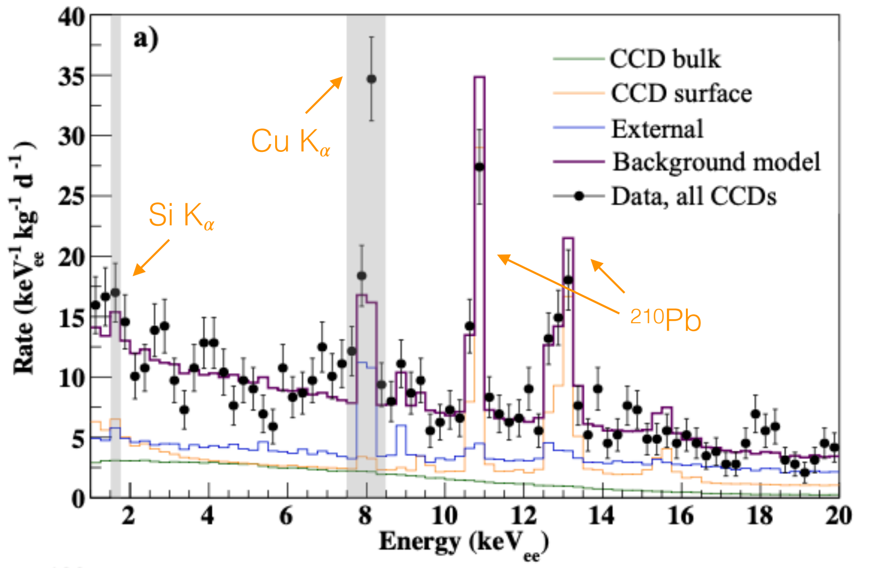
BACKUPS

DAMIC@SNOLAB

Simulation of backgrounds

Backgrounds grouped :

- External : detector materials
- In CCD bulk
- On CCD surfaces



Some energy regions excluded in fits due to poor modeling

Model :

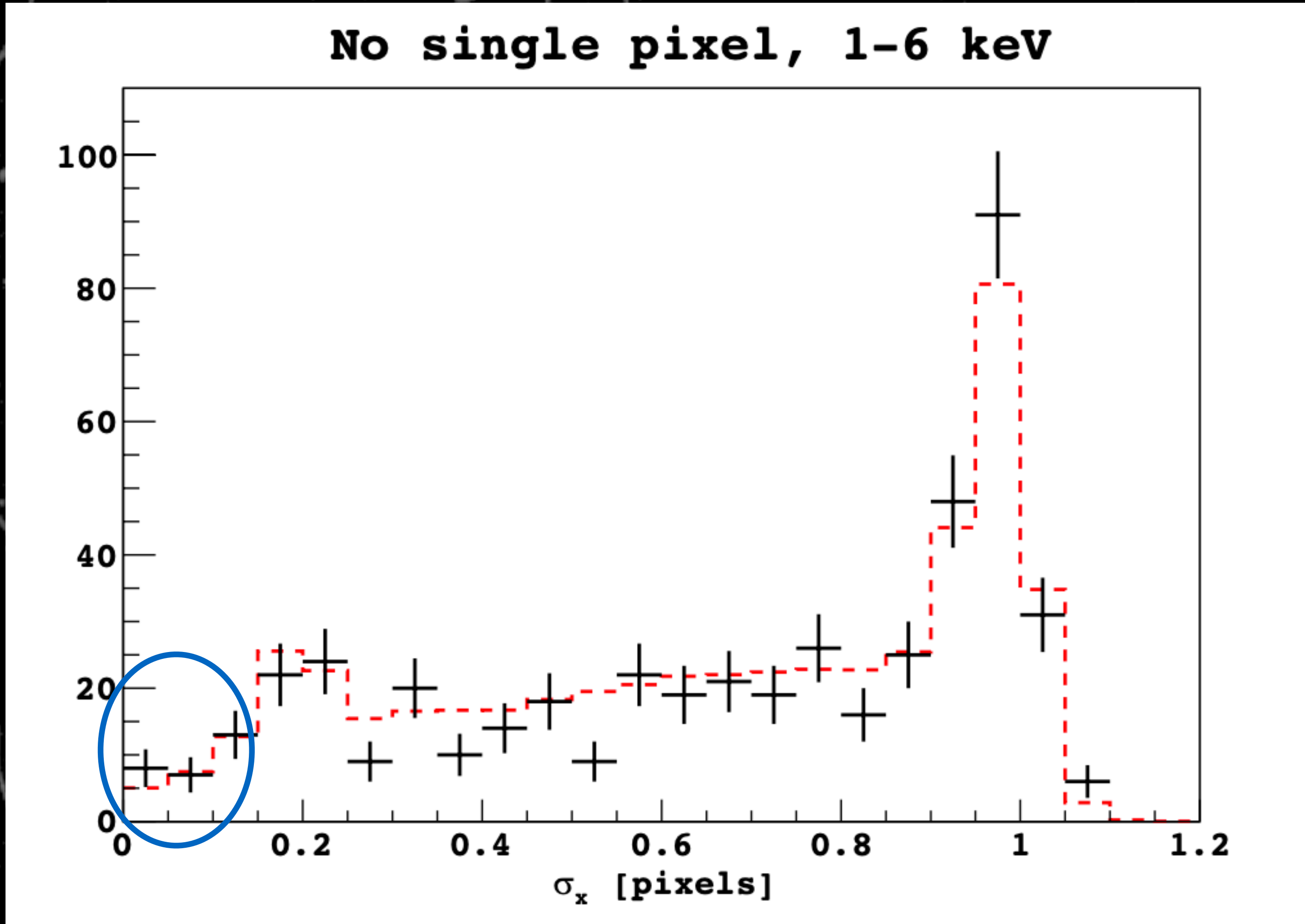
- GEANT simulation compared to data
- 2D model : energy vs. cluster size

  Cluster size constrains depth

A priori uses fast clustering algorithm - not perfect

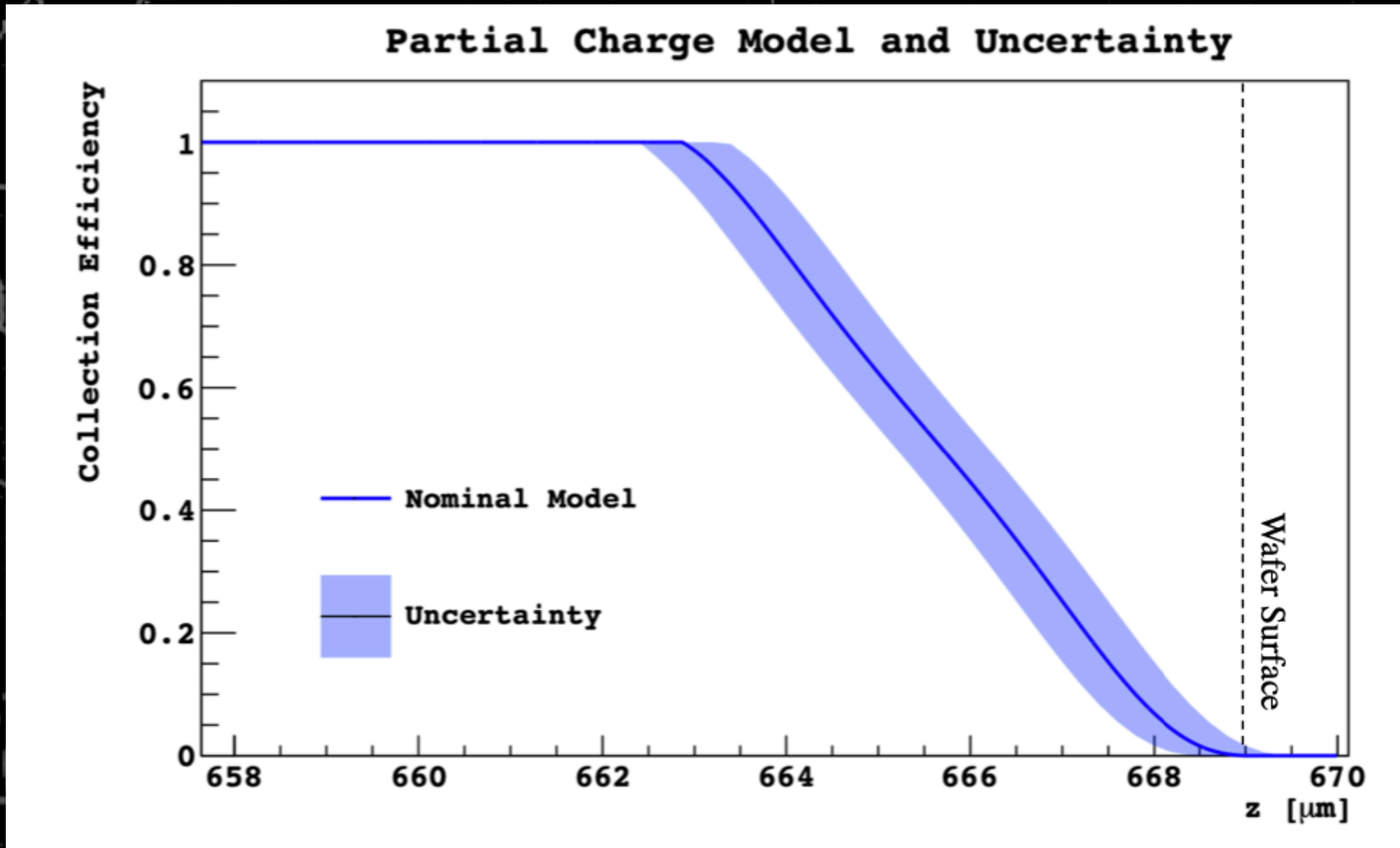
Using log-likelihood clustering

Clustering used in analysis



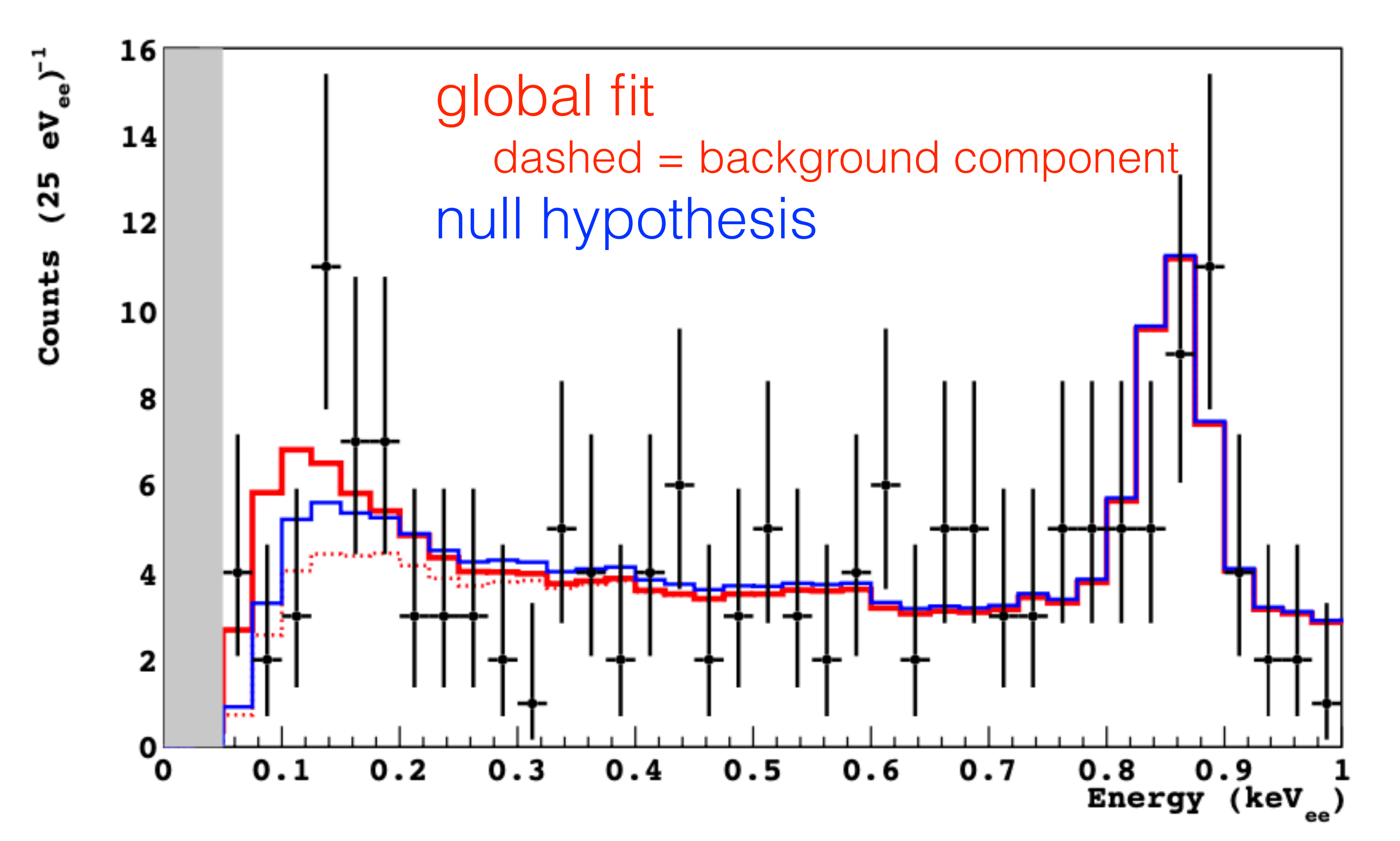
Good agreement at low σ_x

Partial charge collection region



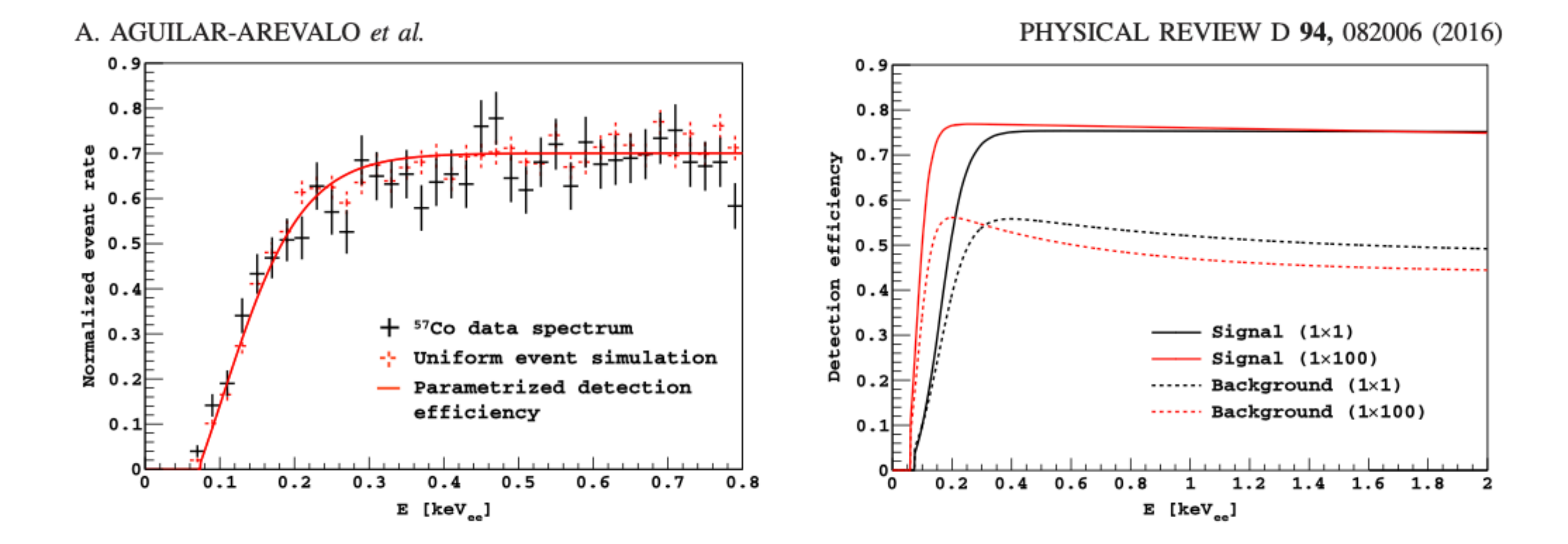
Energy projection

summed over all σ_x



Does not appear to be energy-threshold effect

Efficiency



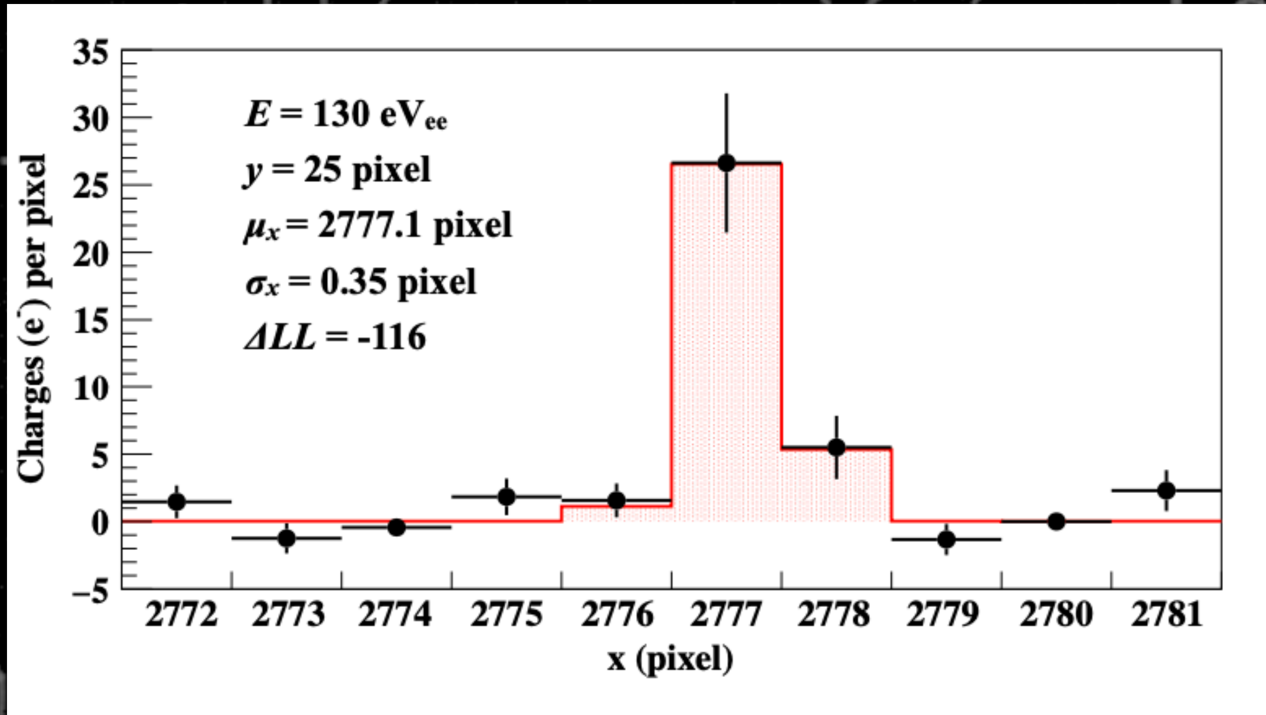
- Efficiency model validated with data
- Reading out 100 pixels improves detection efficiency (by reducing noise)

arXiv:1607.07410

Cluster finding

Log likelihood algorithm scans across CCD
→ Fits position, energy, RMS size of cluster

Example of cluster



Size of cluster σ_x → Determines depth of interaction, z

$$\sigma_x^2 = -A \ln|1 - bz|$$

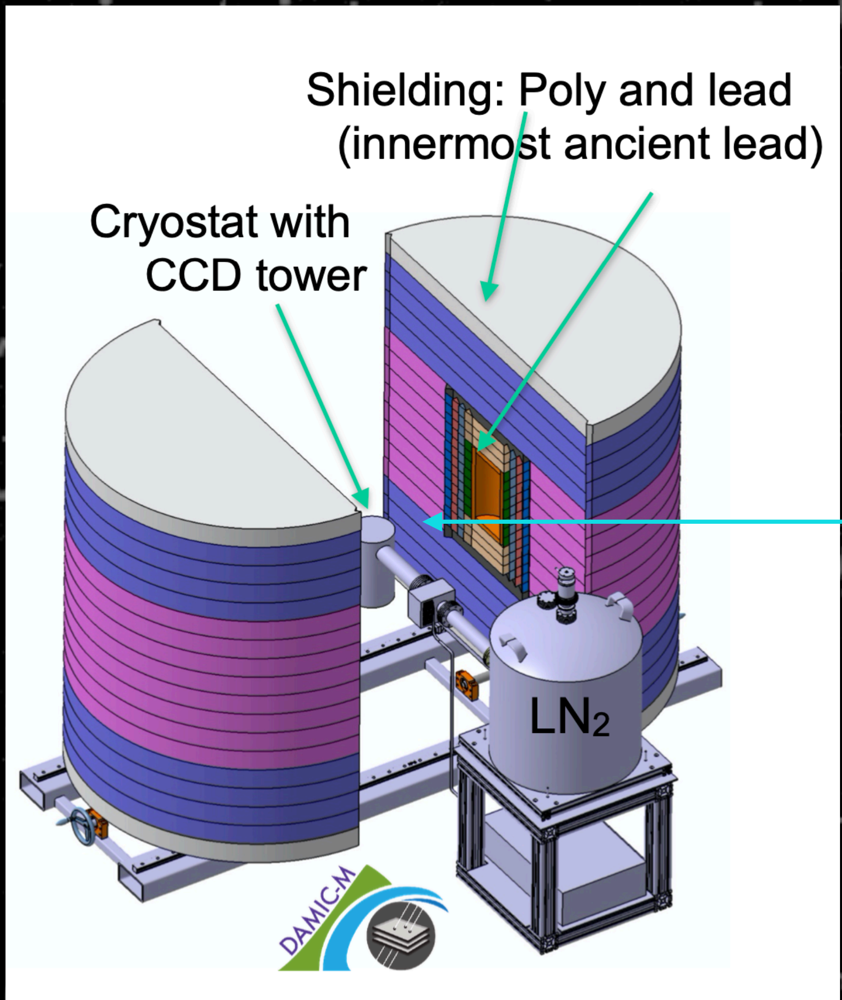
A, b : from cosmic ray tracks

BACKUPS

DAMIC-M

DAMIC-M

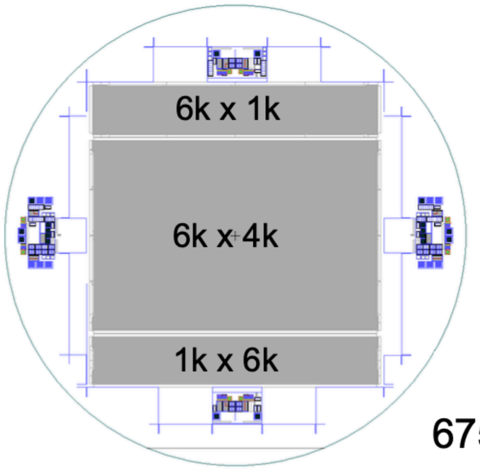
- R&D and prototyping ongoing



Electro-formed copper at PNNL

DAMIC-M CCDs

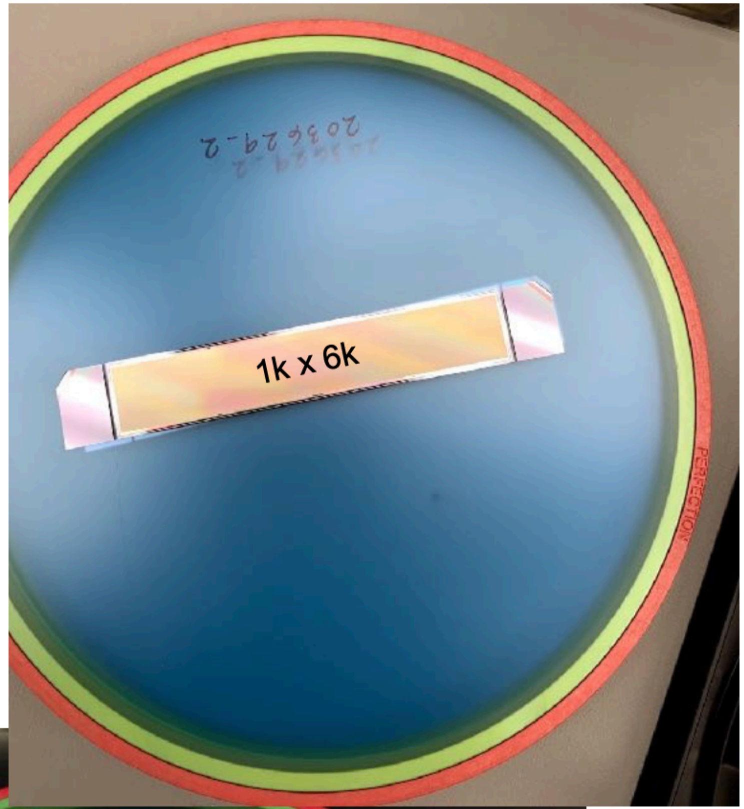
design by S. Holland (LBNL), fabricated by Teledyne/DALSA

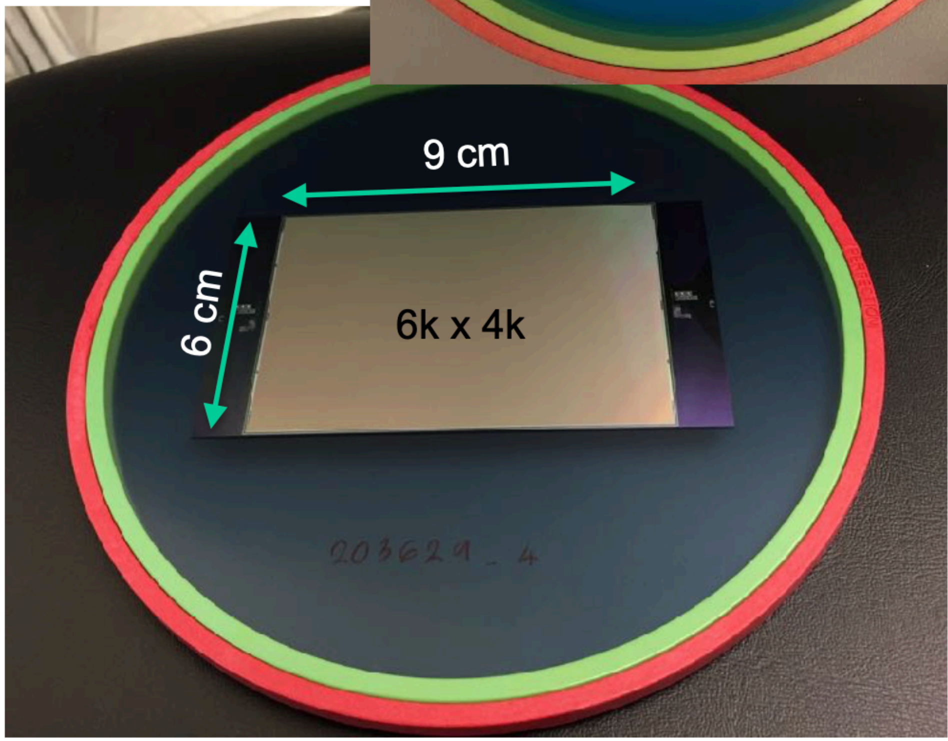


DAMIC-M prototype skipper CCDs

Three CCDs per wafer to test different skipper readout amplifier design.

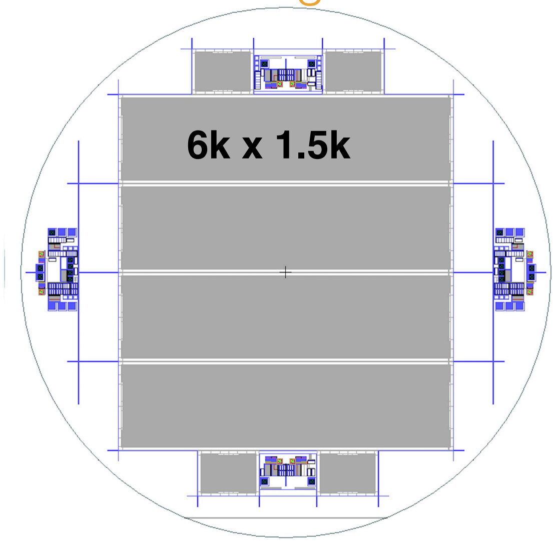
675 μm thick





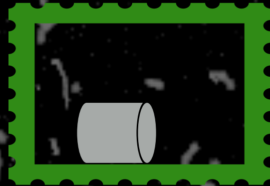
DAMIC-M production skipper CCD design

Yield better dividing CCD in 4



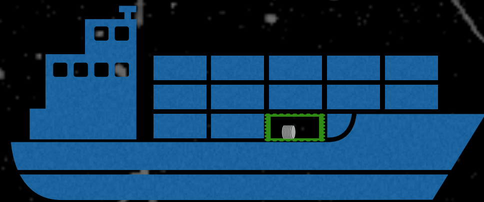
Recent progress with DAMIC-M CCDs

1) Silicon crystal produced (Denmark)

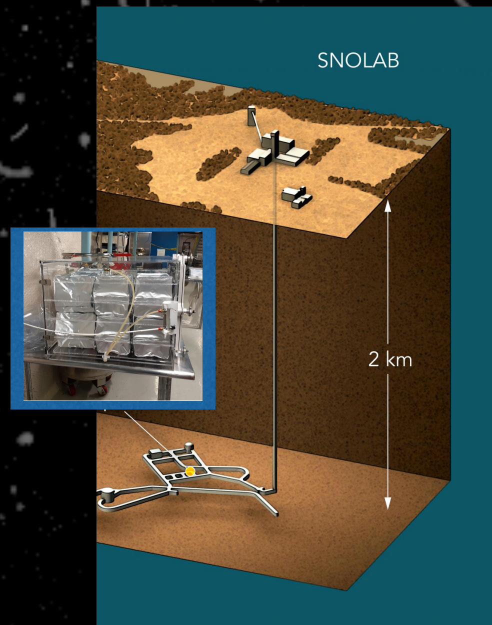


2) Wafers cut (U.K.)

3) Wafers shipped across ocean



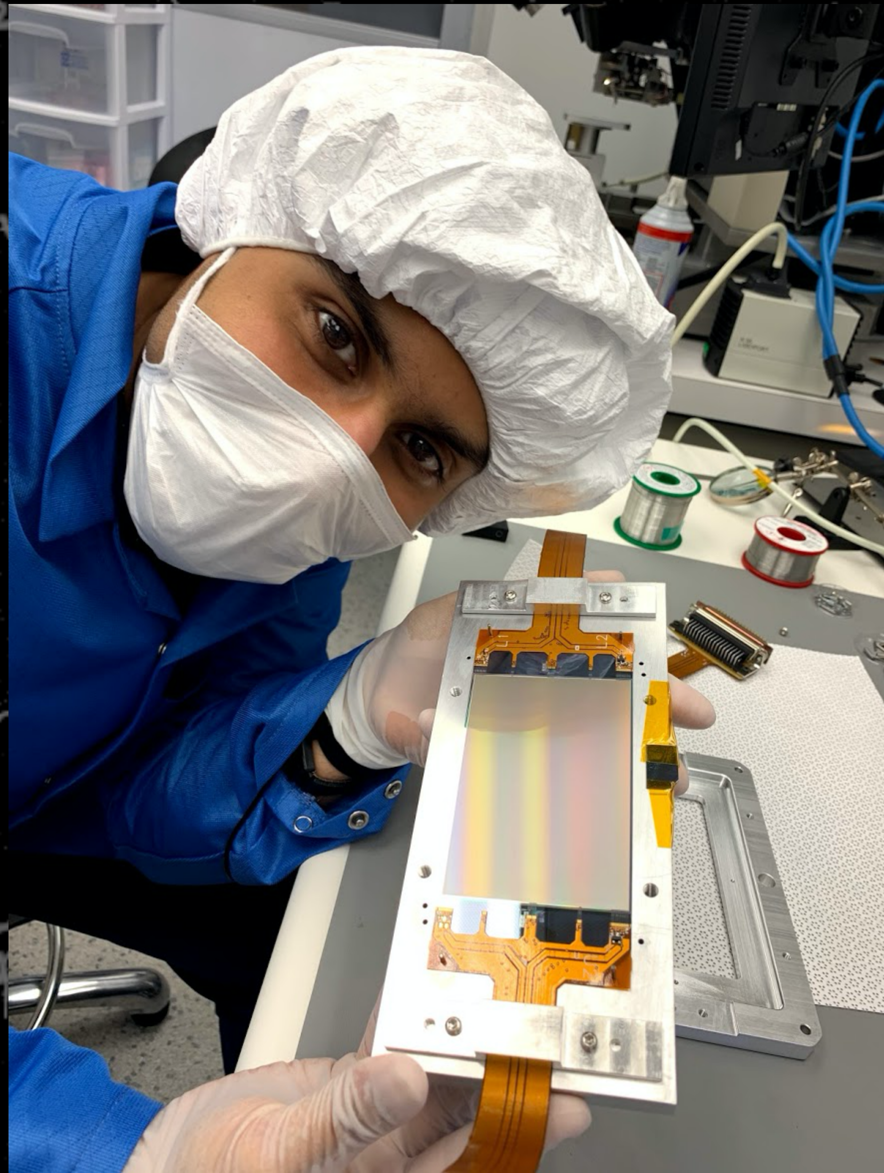
4) Wafers stored (Canada)



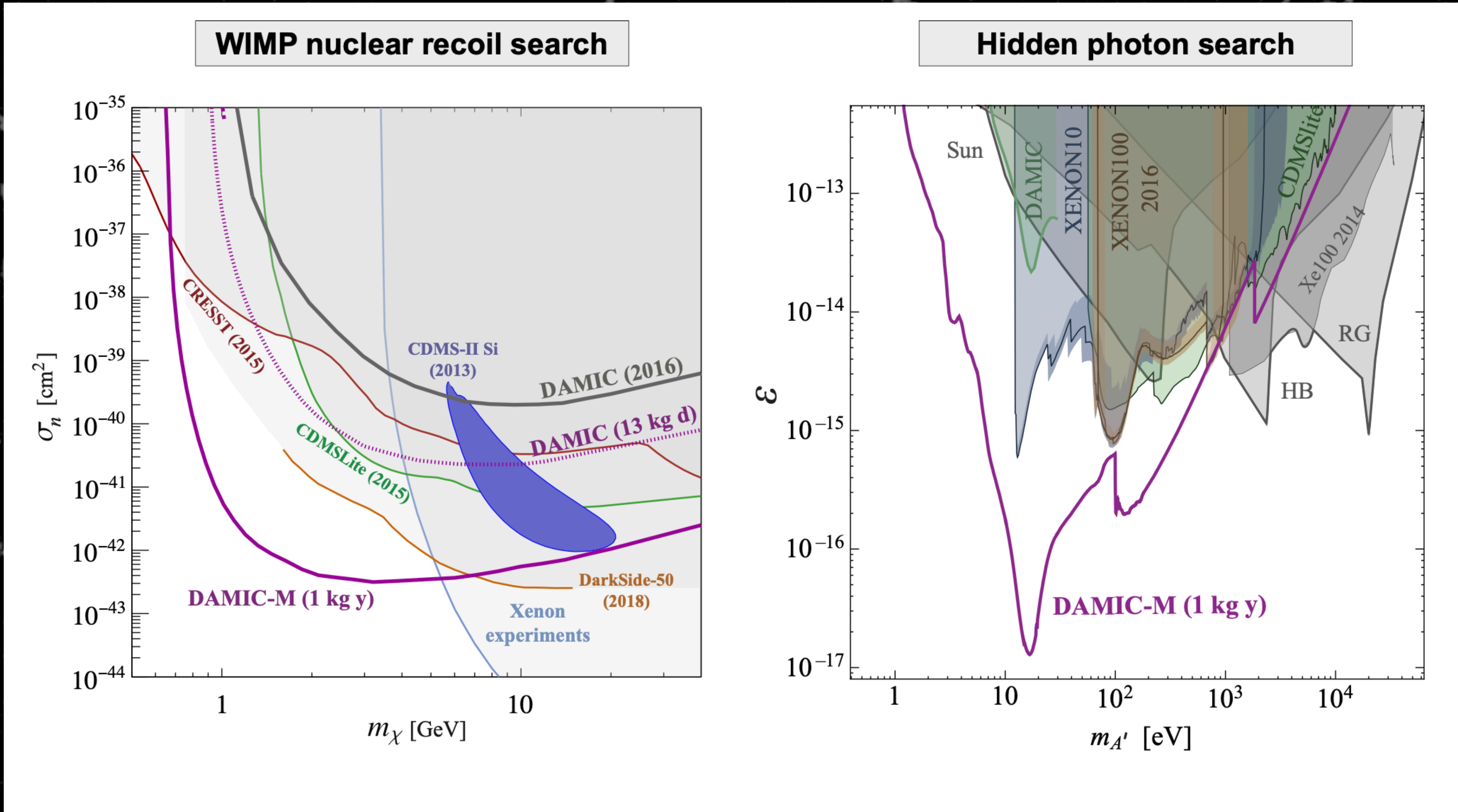
Total equivalent surface exposure
14.3 days !
Cosmogenic activation minimized !

CCD packaging

Progress packaging different size CCDs



DAMIC-M reach



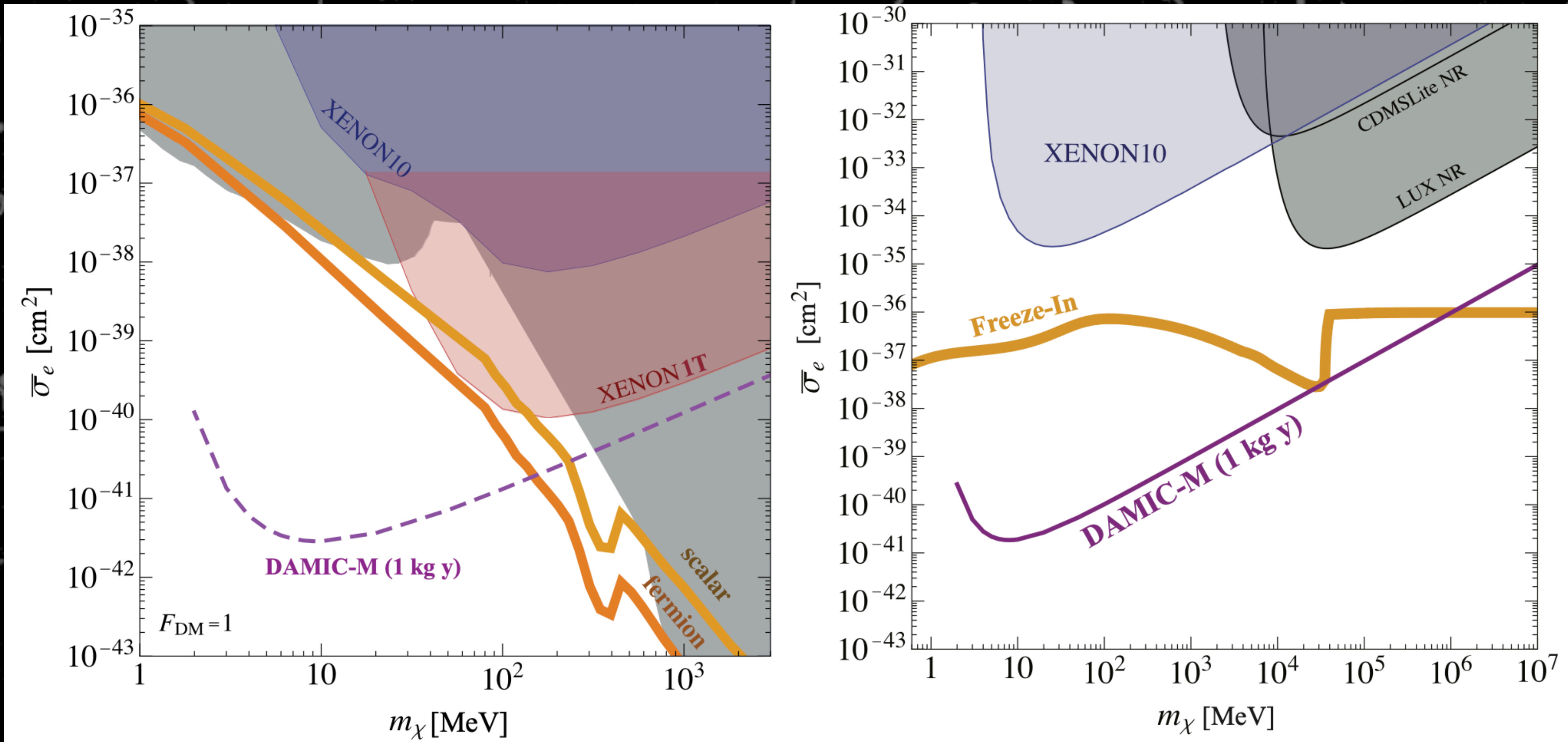
DAMIC-M reach for nuclear recoils of WIMP

As a function of kinetic mixing parameter (A' with γ) assuming A' constitutes all dark matter

DAMIC-M reach

DM-electron cross-sections

(heavy mediator >> keV) (light mediator << keV)

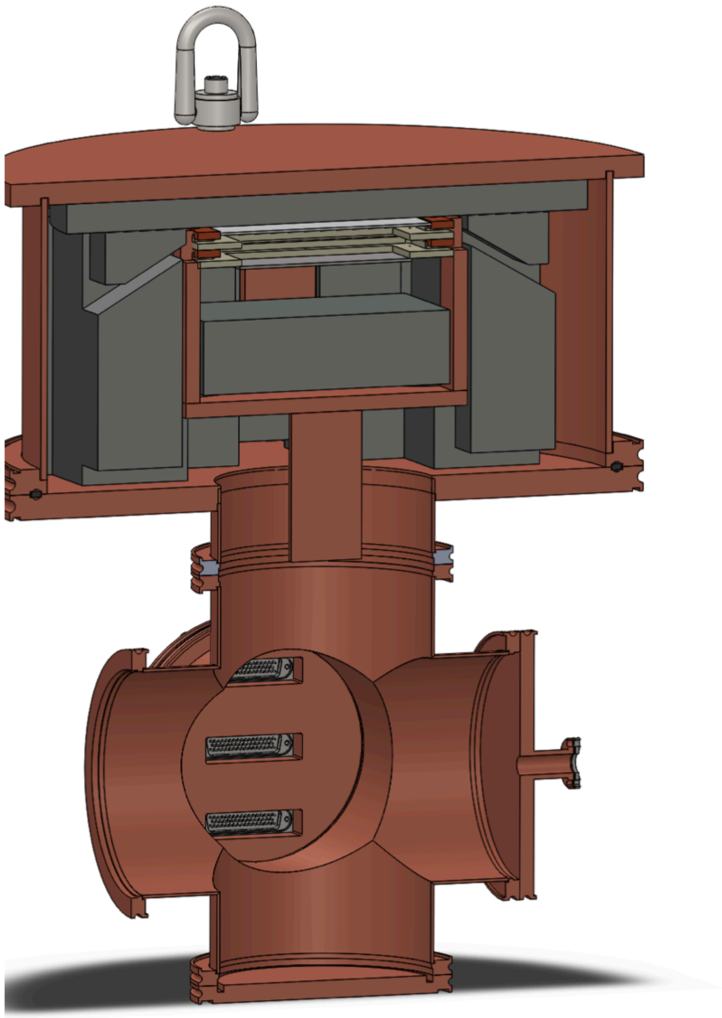


Weakly-coupled χ does not reach thermal equilibrium, and "freezes in"

Orange are theoretical predictions

Now: First phase of DAMIC-M

Low Background Chamber



- A low-background chamber (background level ≈ dru) is in preparation
- Main objectives:
  - characterization of DAMIC-M CCDs in low-bkg environment: dark current; ^{32}Si rate; ^{210}Pb surface bkg; CCD packaging
  - first science results with a few CCDs
- **Installation in 2021**

Timeline

2018 | 2021 | 2022 | 2023 | 2024

DAMIC@ SNOLAB

DAMIC@ SNOLAB

Upgrade w/ skipper CCDs

Goals: test excess with same background, better energy resolution, lower energy threshold

DAMIC-M

R&D / Prototyping

LBC w/ skipper CCDs

CCD testing

Assembly

Data!

Goals: test pre-production CCDs, operate CCD experiment in Modane w/ lower background

DAMIC experiment generations

- 2010-2011 : DAMIC first run at Fermilab
  - 4 grams of detector mass
  - 2e- noise → Energy threshold 35 eV
  - Best DM limits for WIMPs below 4 GeV
- 2015- now : DAMIC @ SNOLAB
  - 40 grams
  - Background 5 events / keV / kg / day
  - Hidden photon DM search
    - 2017 : First eV-scale results
    - 2019 : Result reported today
  - WIMP search
    - 2016 : First result
    - 2020 : New result today
- 2023 : DAMIC @ Modane (LSM)
  - 500 grams
  - 0.2e- noise → Energy threshold 3 eV
  - Background 0.1 events / keV / kg / day
  - Test of prototype CCDs in 2021 (LBC)