# DAMIC
# Dark Matter Search Results

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(on behalf of the DAMIC Collaboration)

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EXCELENCIA MARÍA DE MAEZTU
IFCA
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
UC
UNIVERSIDAD DE CANTABRIA

# Outline

DAMIC Experiment

Charge-Coupled Devices (**CCDs**) as **D**ark **M**atter **Detector**

DAMIC CCD's response to signal and backgrounds

DM-e scattering search (results)

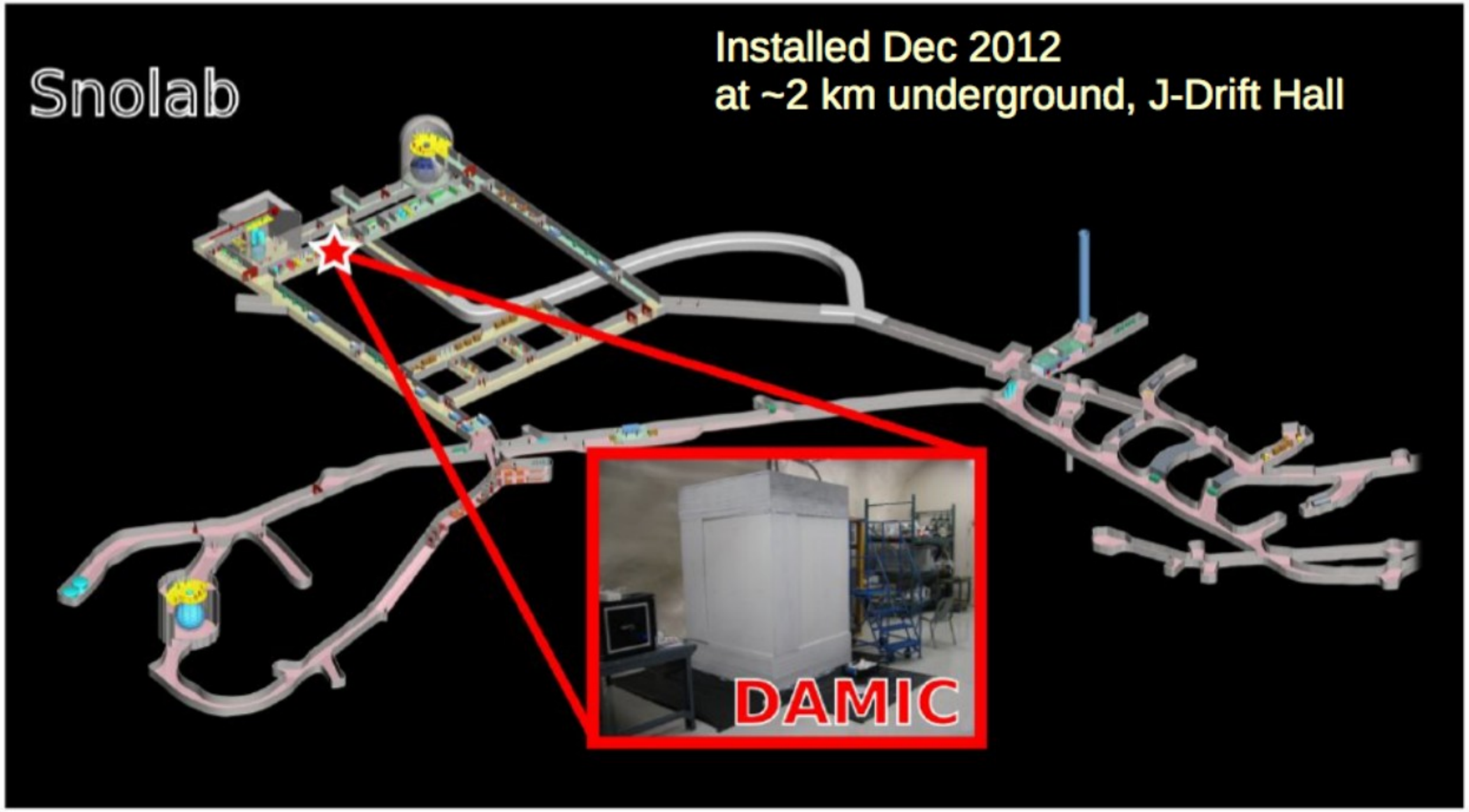
WIMP search (status)

A forward step: DAMIC-M

# DAMIC

## at SNOLAB currently taking data

(Vale Creighton Mine located near Sudbury, Ontario, Canada)



# DAMIC

## DArk Matter In CCDs

In **SNOLAB**, we have set up a DAMIC experiment under 2km of rock (muon flux reduced by ~5 orders of magnitude).

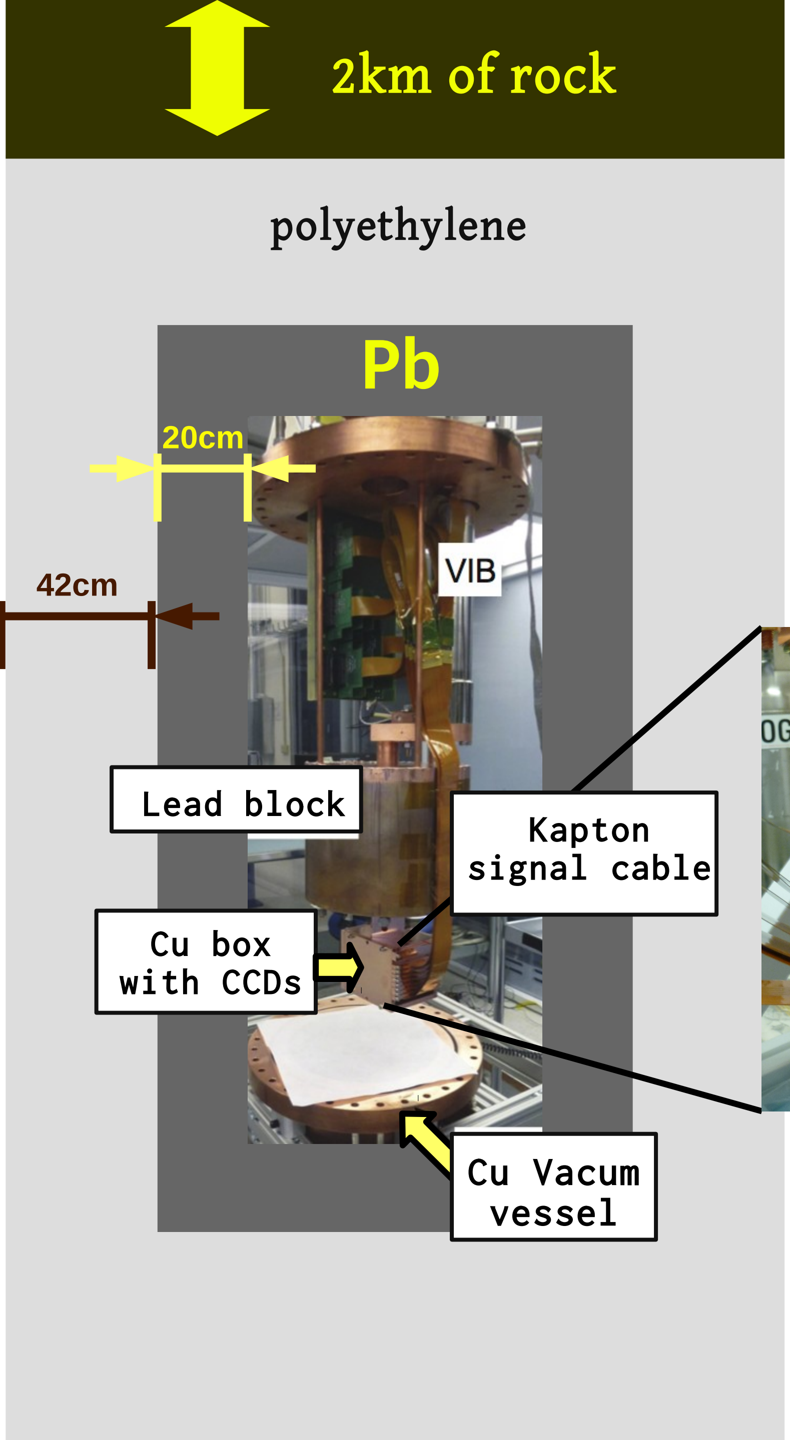
We then **shielded the CCDs** using

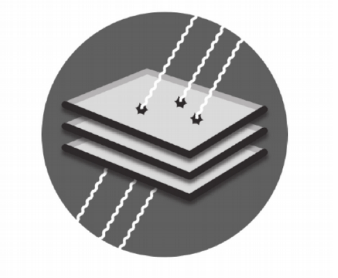
– ancient lead to stop gammas

– **polyethylene layer** (~42cm) **to stop neutrons**

**– a layer of low radioactive lead** (~20cm) **to stop gammas**

We currently have background reading around ~11,8 dru (events/keV/kg/day). Less tan 5 dru when removing surface contaminants.

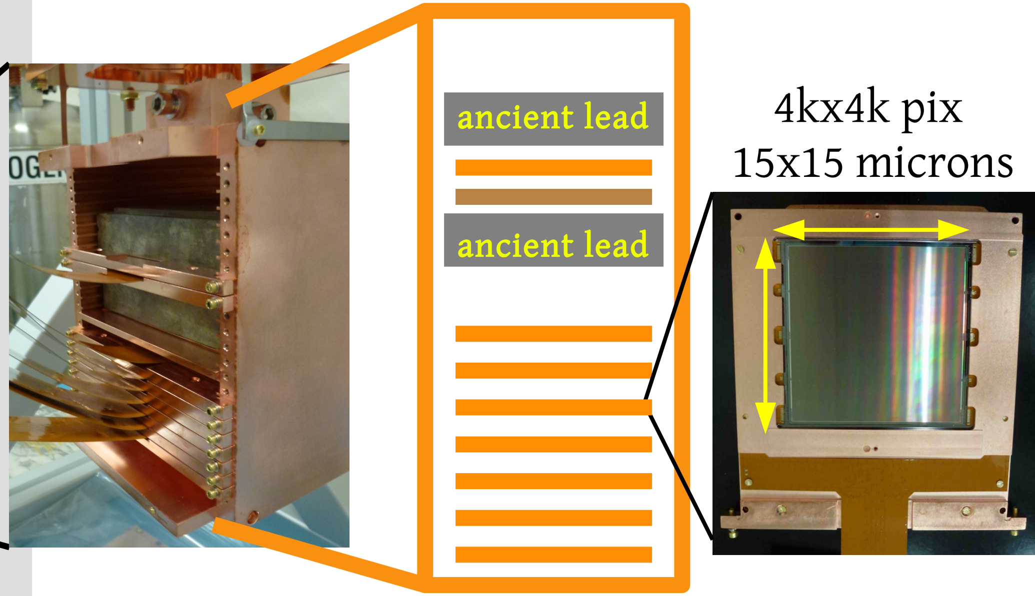


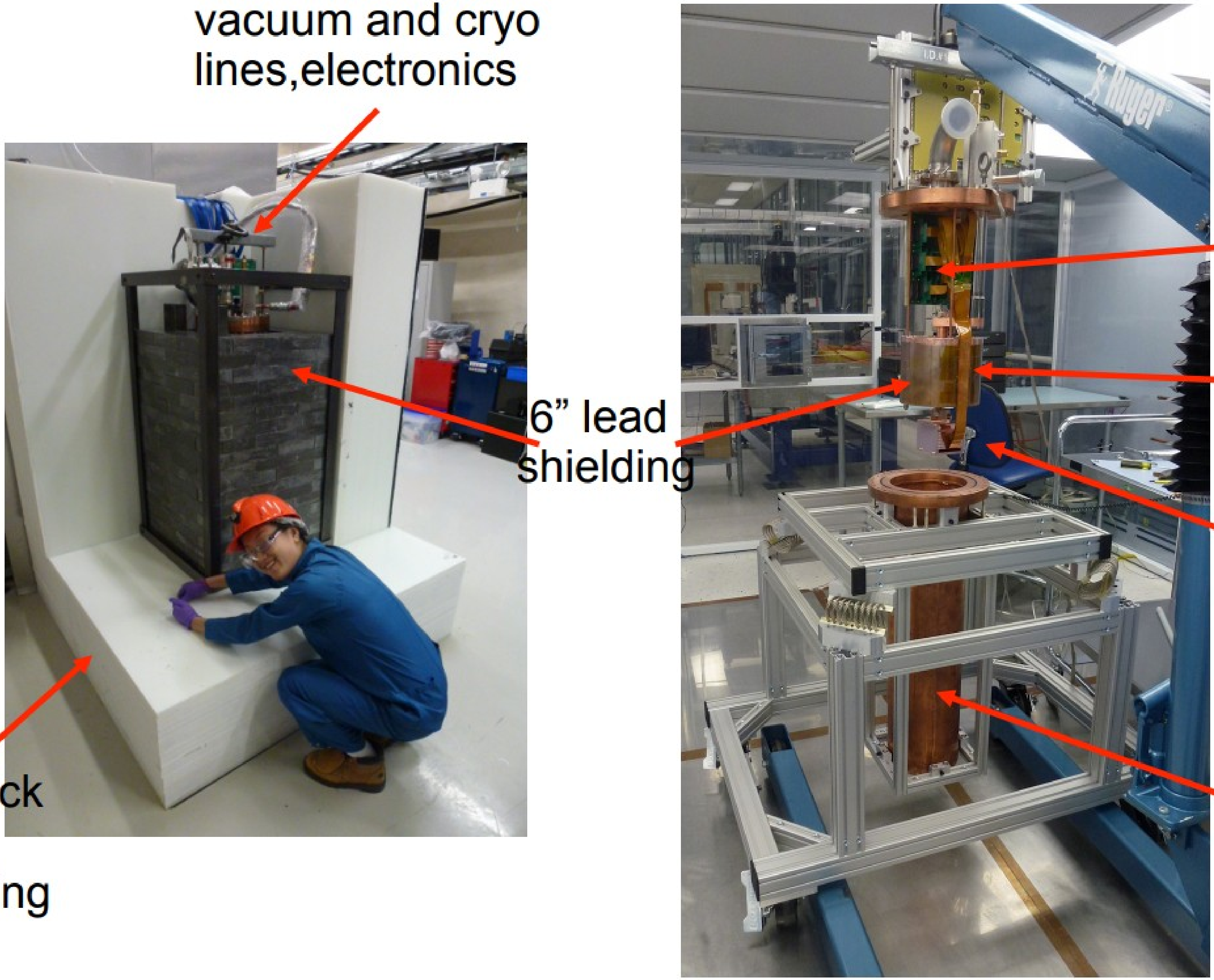
**Current detector configuration:**

7CCDs in stable data tacking since 2017

1 CCD sandwiched in ancient lead



# DAMIC

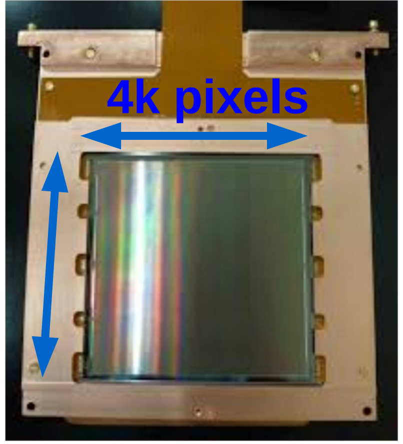

vacuum and cryo lines,electronics
6” lead shielding
20” thick poly shielding
in-vacuum electronics
Kapton cable
Cu box
Cu vessel

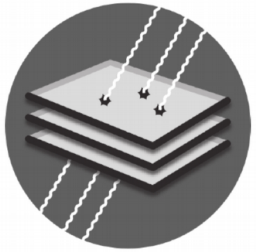
# DAMIC at SNOLAB

## DArk Matter In CCDs

- Conventional 3-phase, triple polysilicon gate CCD, n-type substrate
- 7 CCDs in stable data taking since 2017

  15x15 $\mu m^2$, and 675 $\mu m$ thick (16 Mega pixels)
- 40 g target mass
- Extremely pure silicon ~$10^{11}$ donors/$cm^{-3}$, which leads to fully depleted operation at reasonably low values of the applied bias voltage, ~40V
- Operating temperature of ~140 K (to minimize dark current)



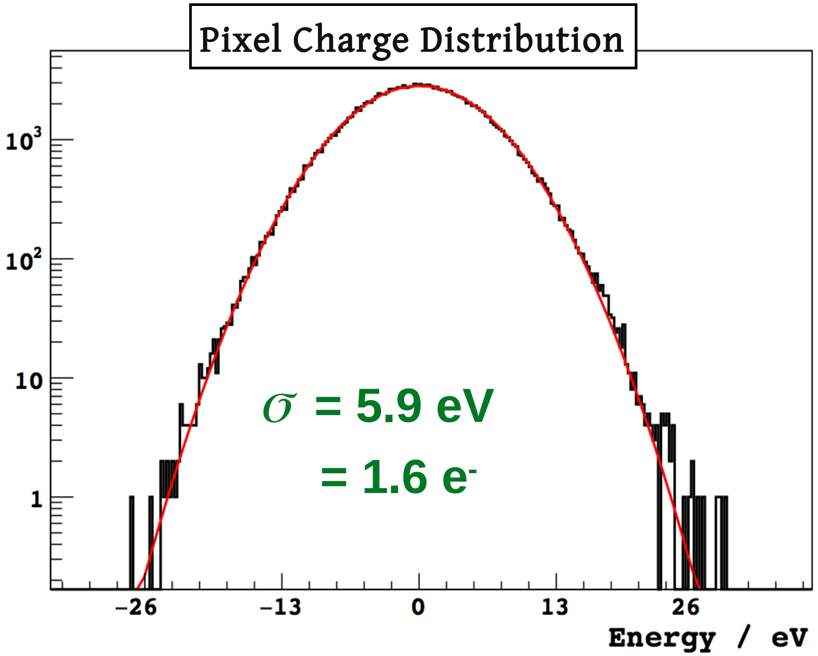
## Performance

**Very low noise and dark current**, DAMIC reached the lowest DC ever measured in Silicon detectors

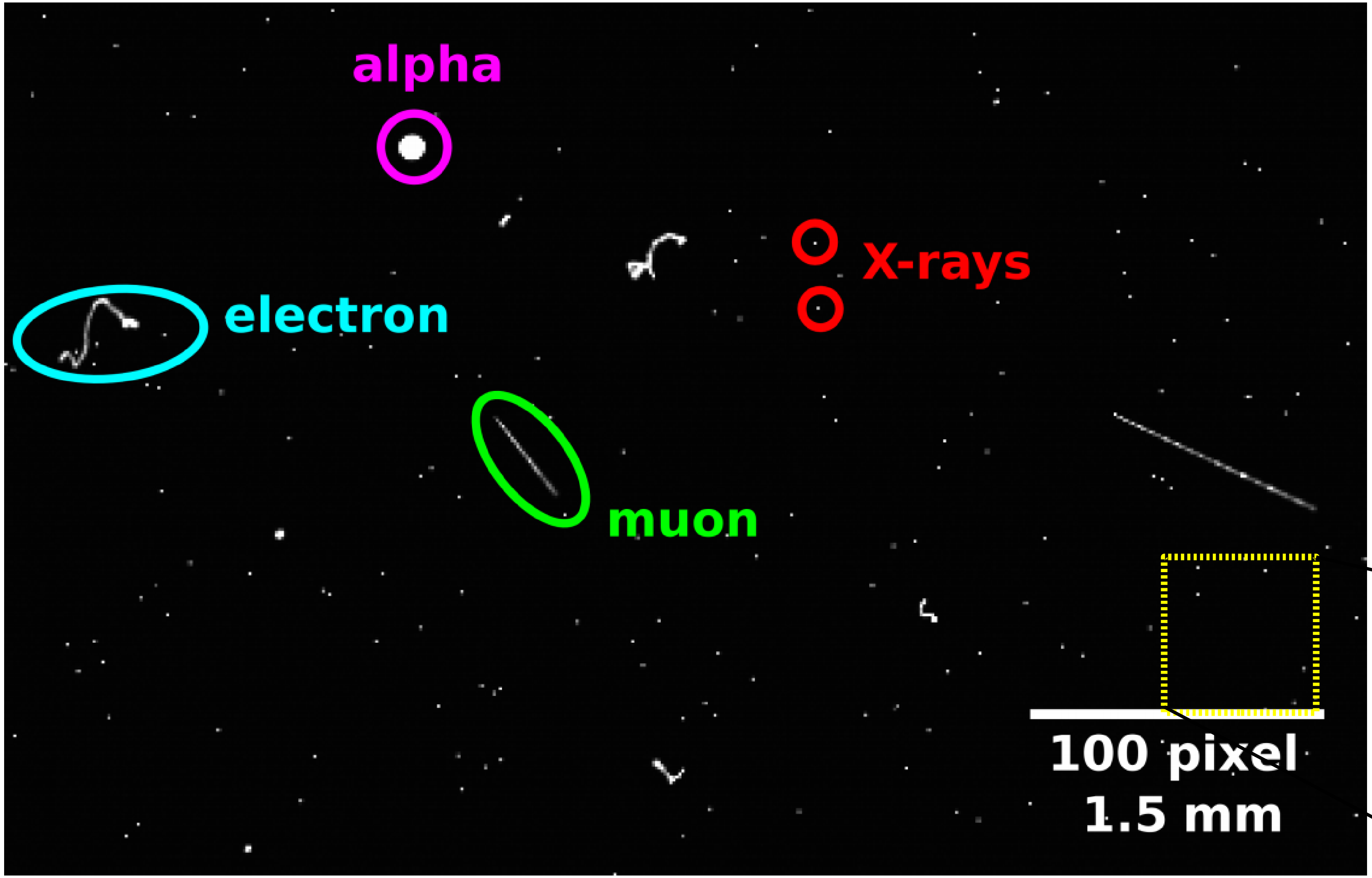
$5 \times 10^{-22}$ A/$cm^2$, <0.001 e/pixel/day (at 140K)

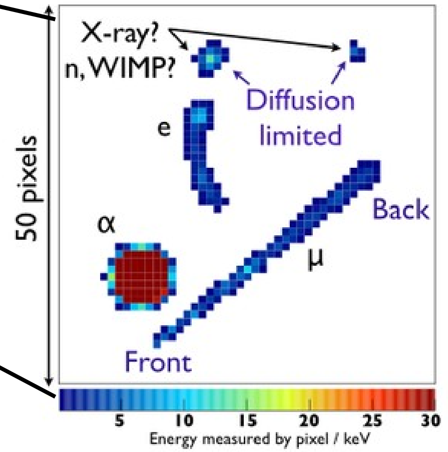
**Resolution of 2e- achieved at SNOLAB**

**Particle identification and background rejection**

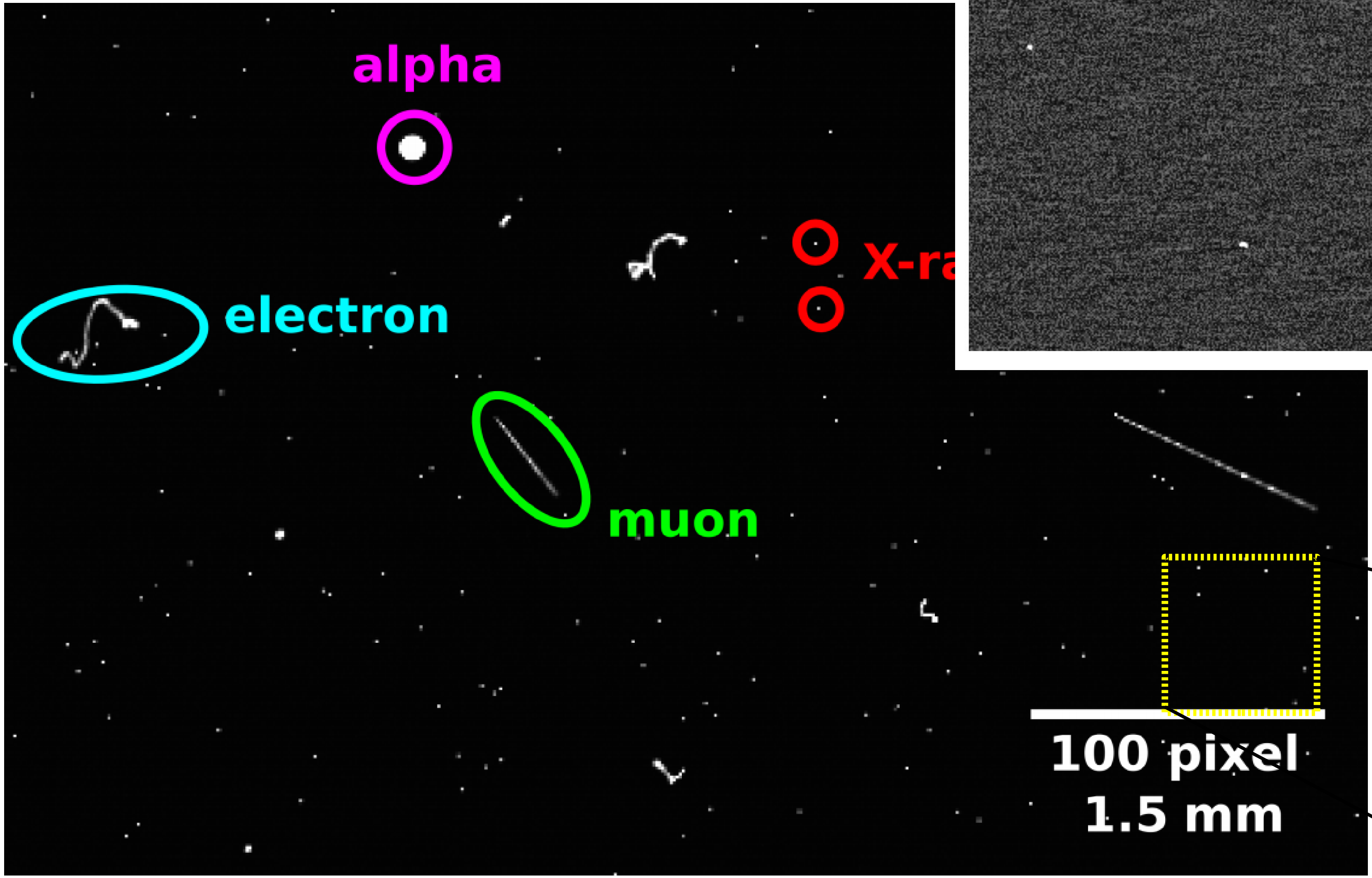


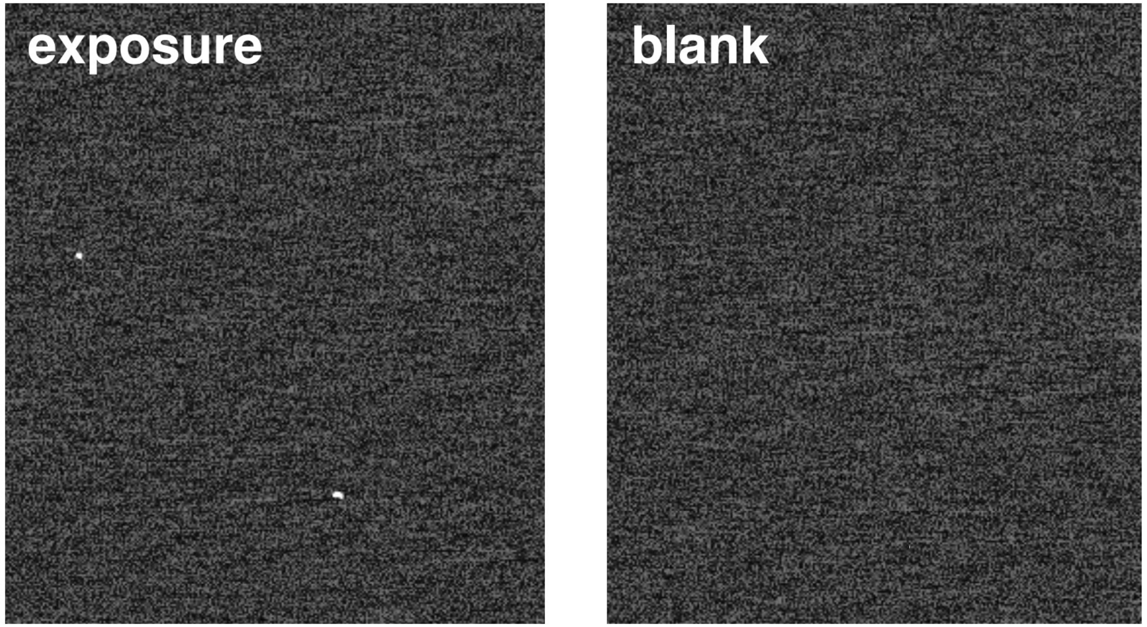
# CCDs as Dark Matter Detectors

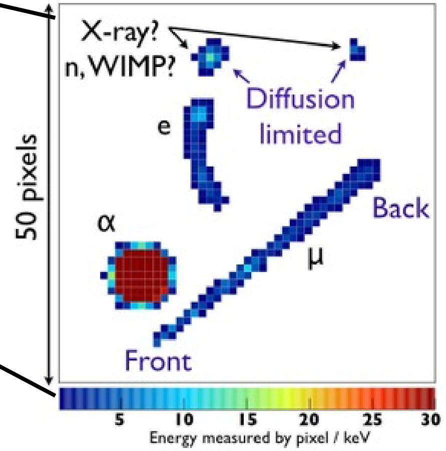


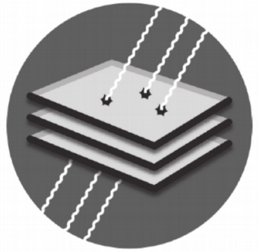
# CCDs as Dark Matter



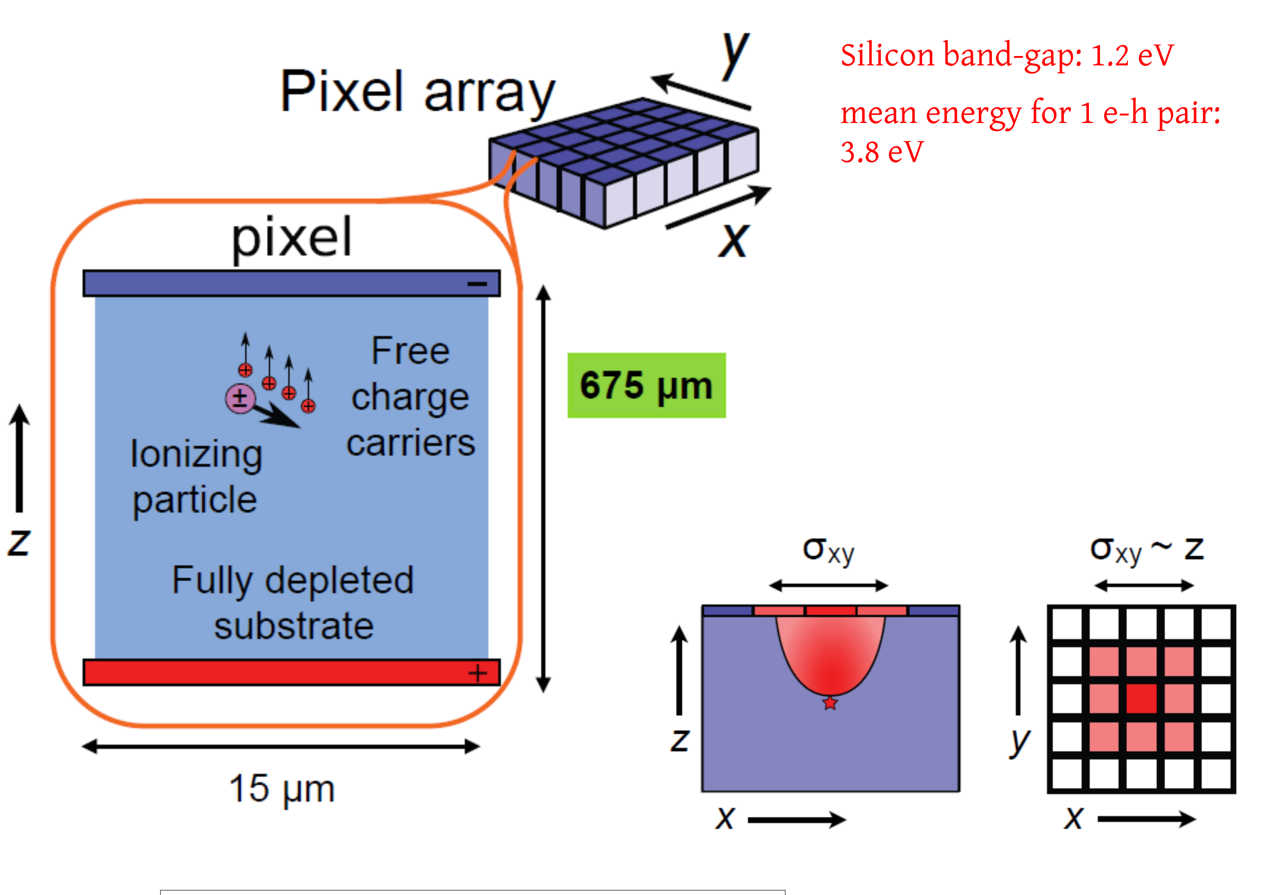



# CCDs as Dark Matter Detectors



The silicon bulk of the CCD is used as **target to interact with dark matter** candidates. From this interaction we expect **charge carriers** to form within the bulk and we collect and count the number of carriers in each pixel. **It is a direct detection apparatus for dark matter.**



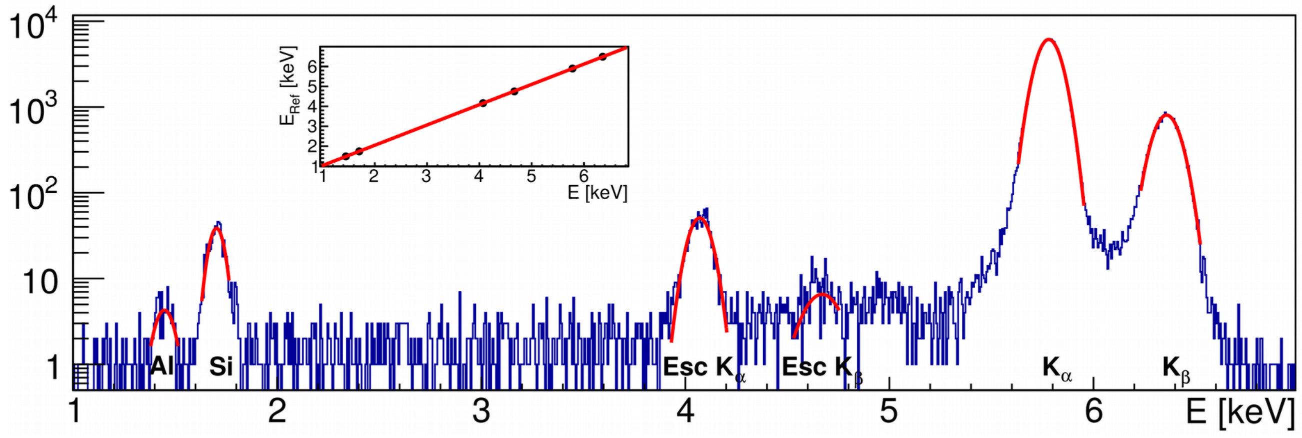

CCD pixel cross-sectional diagram

Interaction with silicon produces free charge carries...

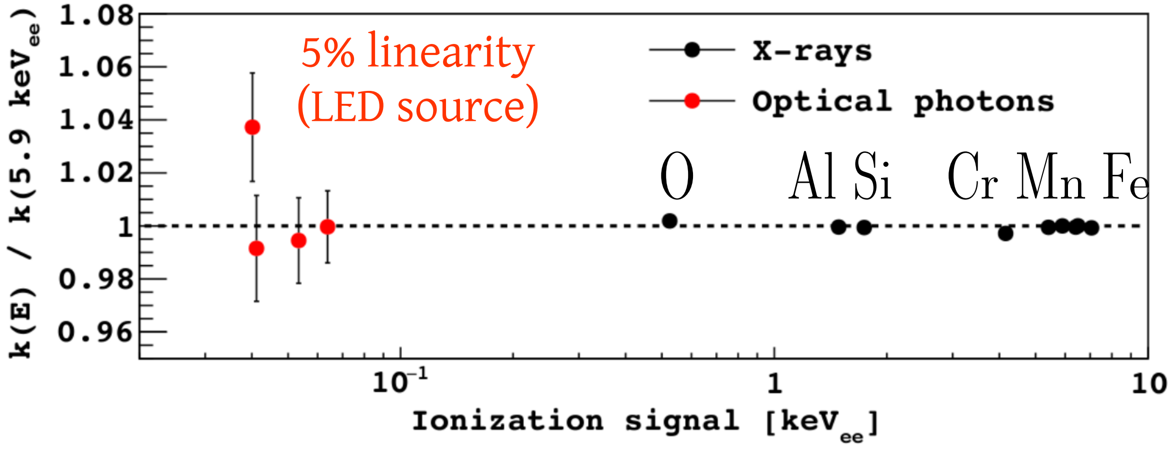
- **drifted across fully-depleted region**
  → *very little loss of charge*
- **collected** in **15 micron square pixels**
  → *exceptional position resolution*
- stored until a user-defined **readout time after many hours**
  → *large exposures*

# Calibration and Energy Resolution

- Energy calibration using a O, Al, Si, Cr, Mn, and Fe x-ray lines

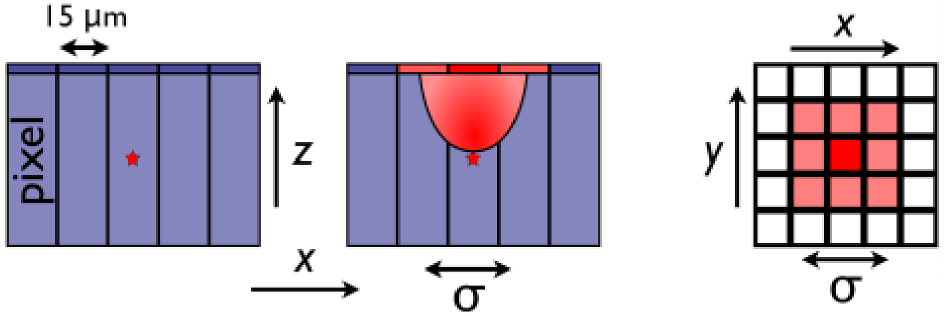



## very nice linearity response of the CCDs down to 40eV

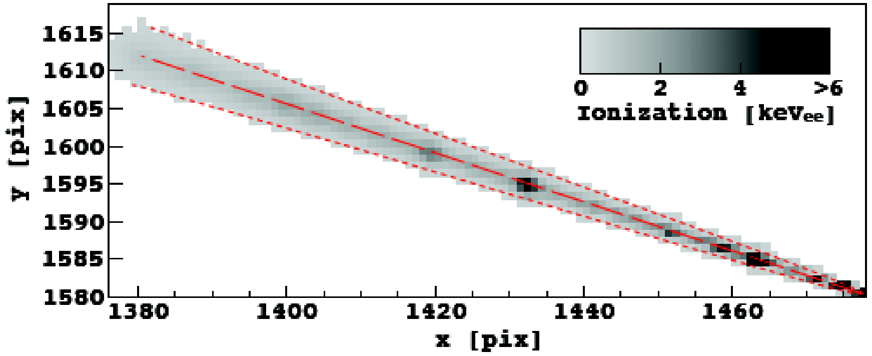


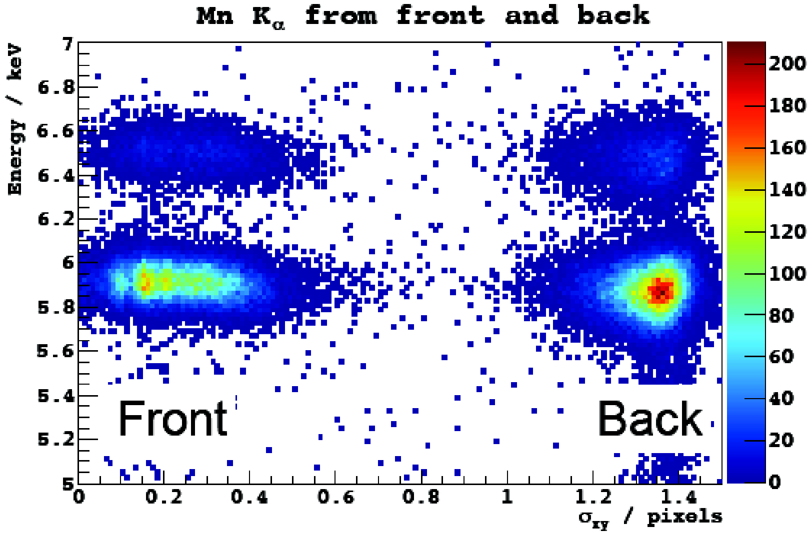

- Amplifiers measure amount of charge in ADU
- Conversion factor $k$ ($ke\ V_{ee}/ADU$) calibrated using X-ray emission lines
- $k$ is constant over the energy range we are interested in

# Depth Reconstruction

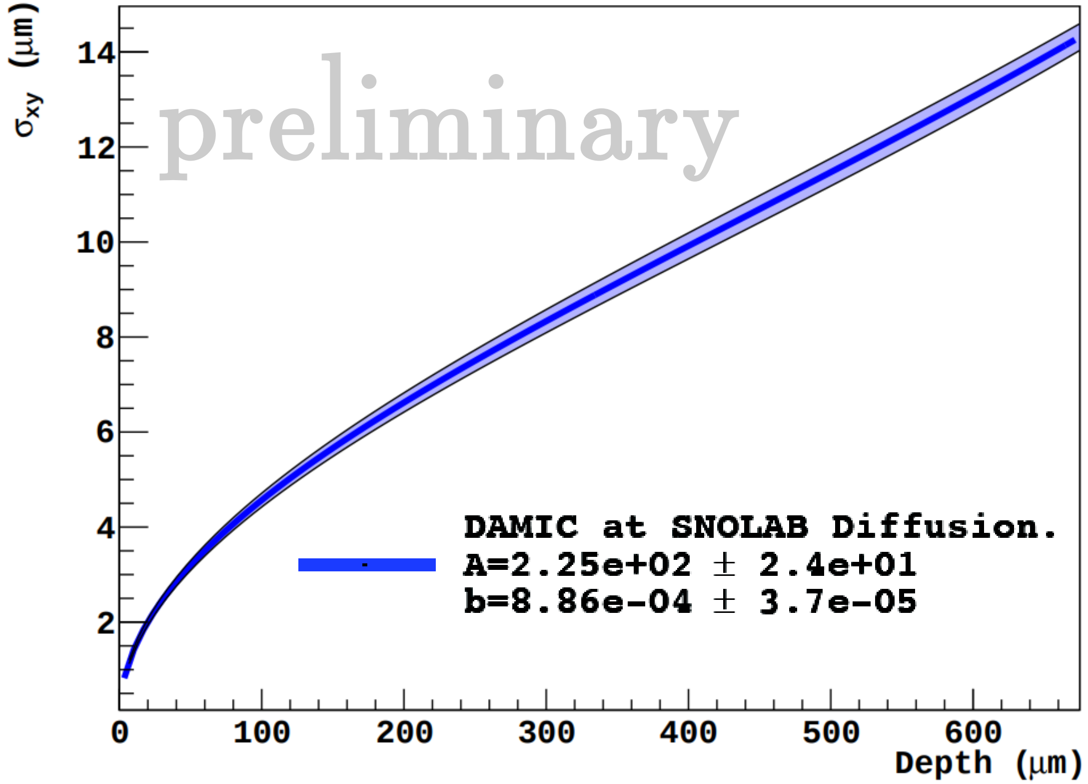



Muons tracks (at ground level) and Event on the back of the CCD are used to model diffusion

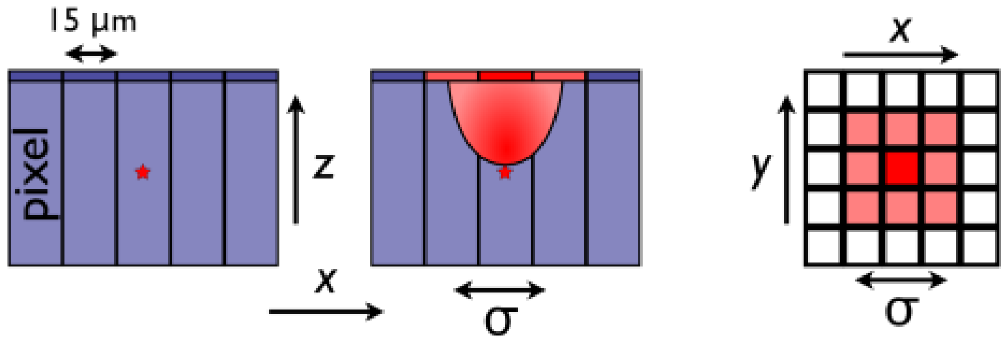


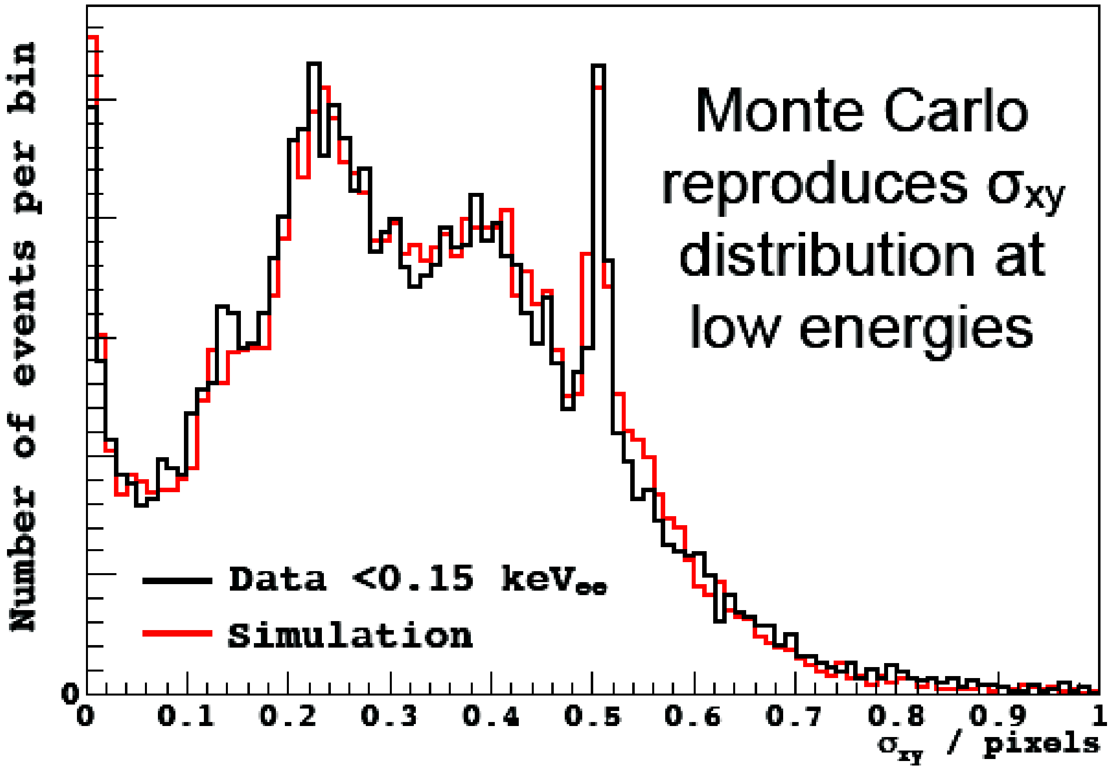




$$\sigma_{xy}^2(z) = -A\ln(1-bz) = Abz + \frac{Ab^2z^2}{2} + \ldots$$

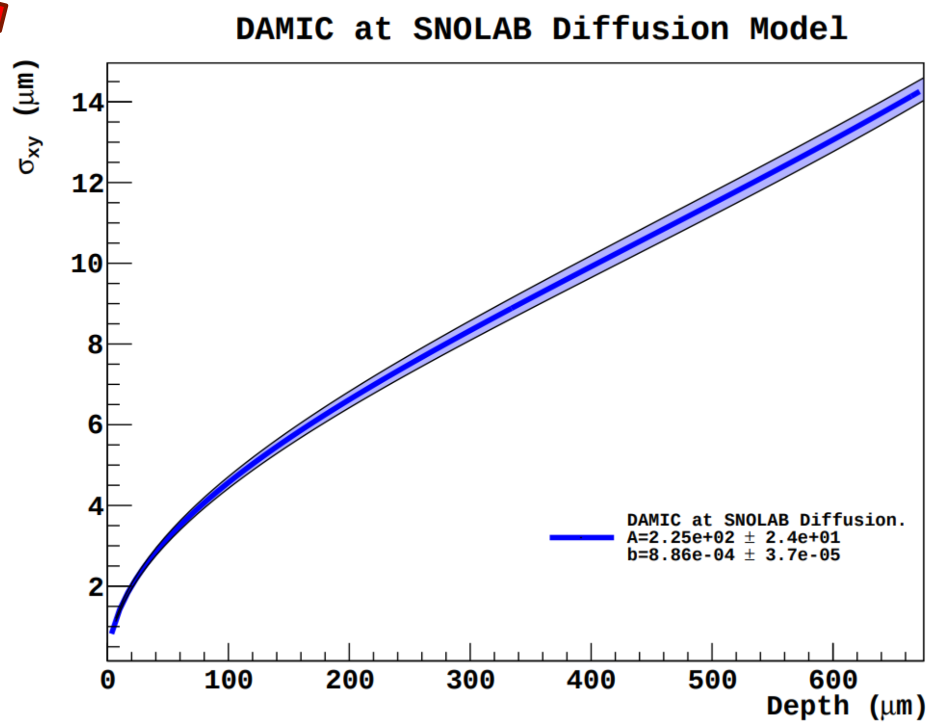


# Depth Reconstruction



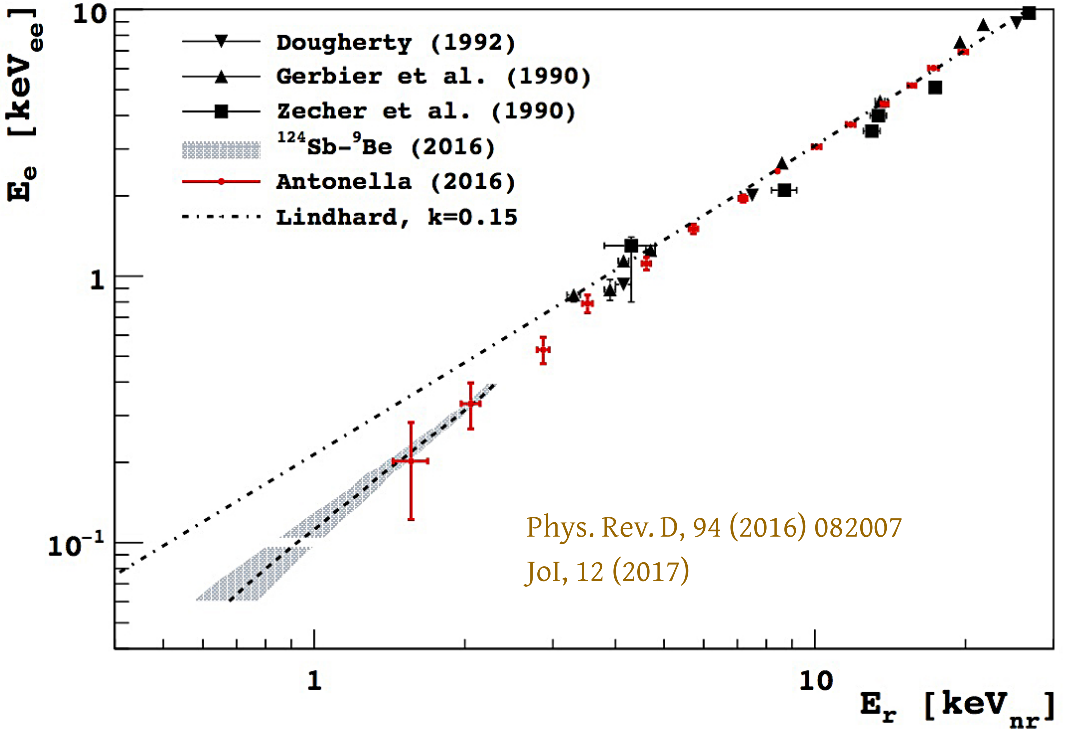

Diffusion model validation at low energies by comparing data with Monte Carlo simulations,



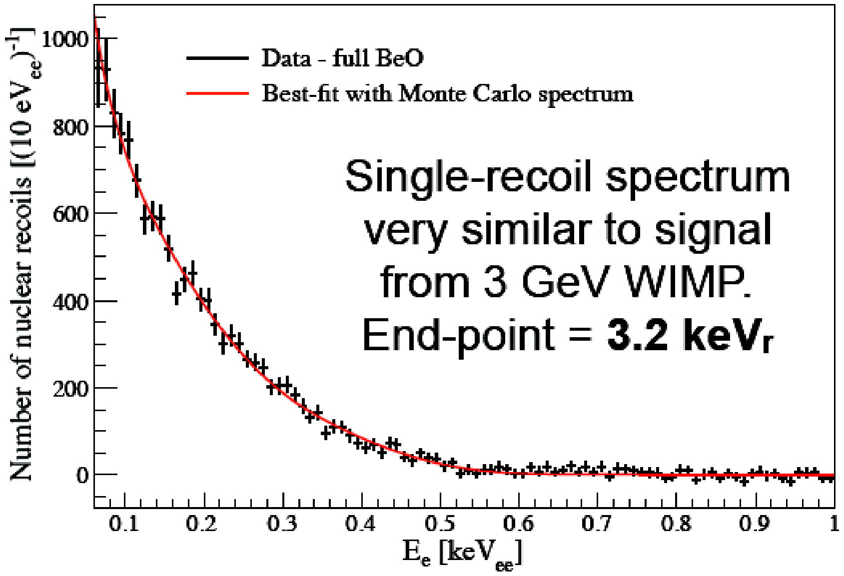
# Nuclear Recoil Efficiency

To characterize a potential DM signal is very important to know the relation between the **energy deposited by the recoiling nucleus in the form of ionization $E_r$** and **the nucleus kinetic energy $E_e$.**

Calibrations down to 60 eV are done with low-E neutrons from a $^{124}Sb$-$^{9}Be$ photoneutron source. Nucleus from the source (monochromatic neutron flux of 24keV) elastically scatter off silicon nuclei; the subsequent nuclear recoils deposit their kinetic energy in the silicon bulk within 10 nm, producing signals that mimic those expected from WIMP interactions.



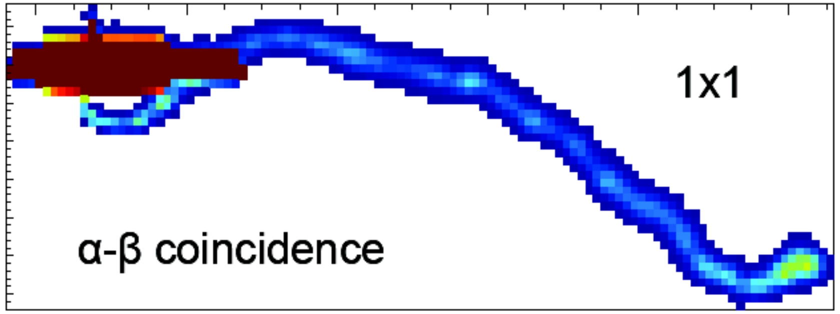

Comparing data with Monte Carlo simulations, ionization efficiency is lower than Lindhard model predictions.

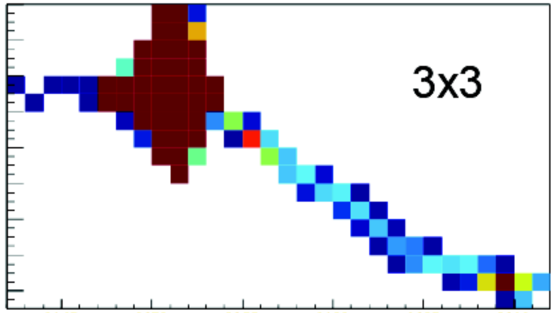


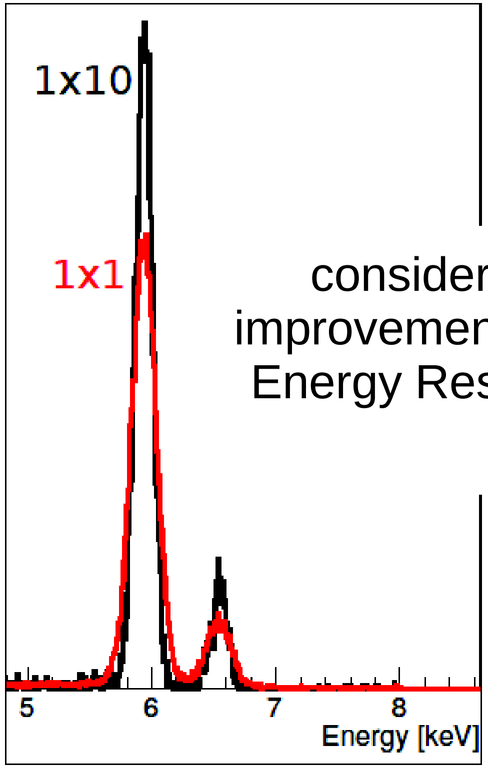
# Readout Flexibility: 1x1 , 1x100

Pixels can be readout in groups (1x100, reading 1 pixel in the x-direction and 100 pixels into the y-coordenate) and the total charge estimated in a single measurement: optimization of the S/N.

This means that we are losing resolution in the y-coordinate (x, z remains the same) but we improve energy resolution



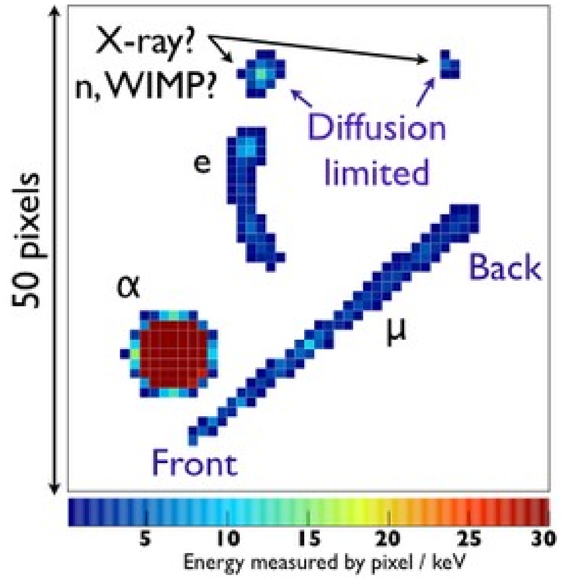

considerable improvement on the Energy Resolution

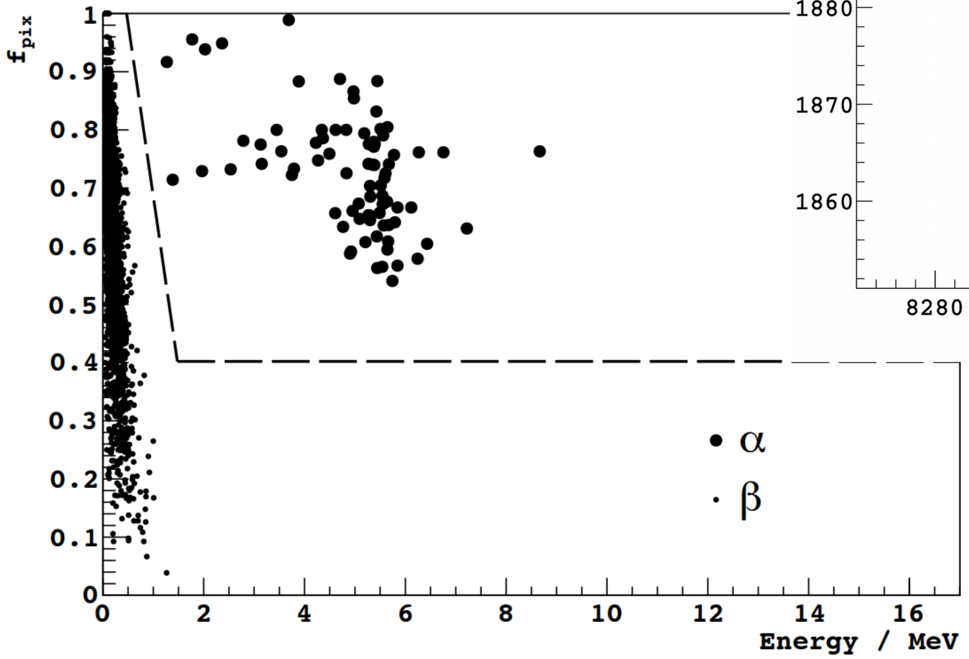
# Background Characterization

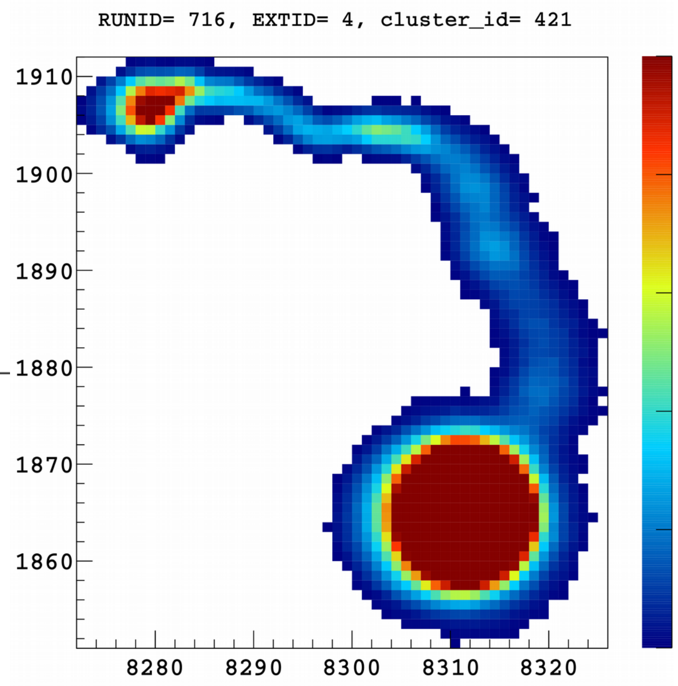
## Particle Identification

As charges drift across the CCD, they experience lateral thermal motion (diffusion) proportional to vertical distance traveled (depth)

Above 1keV, the event profile can identify the progenitor ...



# Background Characterization

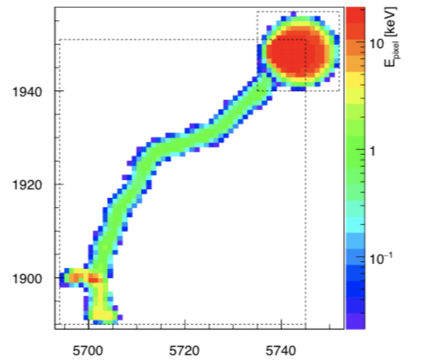
## Background Characterization and Rejection

**$^{210}$Pb (from radon) and $^{32}$Si (cosmogenic)** are backgrounds that are very hard to estimate and must be demonstrated **to be low** (or able to be rejected) **for** any proposed **dark matter search** (Si-based for $^{32}$Si) without electron rejection.

$$^{210}\text{Pb} \xrightarrow[\text{64keV}]{} {}^{210}\text{Bi (5d)} \xrightarrow[\text{1.2MeV}]{} {}^{210}\text{Po(138d)} \xrightarrow[\text{5.3MeV}]{} {}^{206}\text{Pb}$$

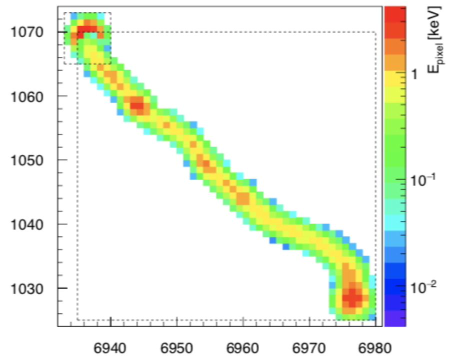
$$^{32}\text{Si} \xrightarrow[\text{0.22MeV}]{} {}^{32}\text{P (14d)} \xrightarrow[\text{1.7MeV}]{} {}^{32}\text{S}$$

### $^{210}$Pb $\beta_1$-$\alpha$



- $E_{\beta 1}$ = 717 keV
- $E_{\alpha}$ = 3.62 MeV
- $\Delta t$ = 32.3 d

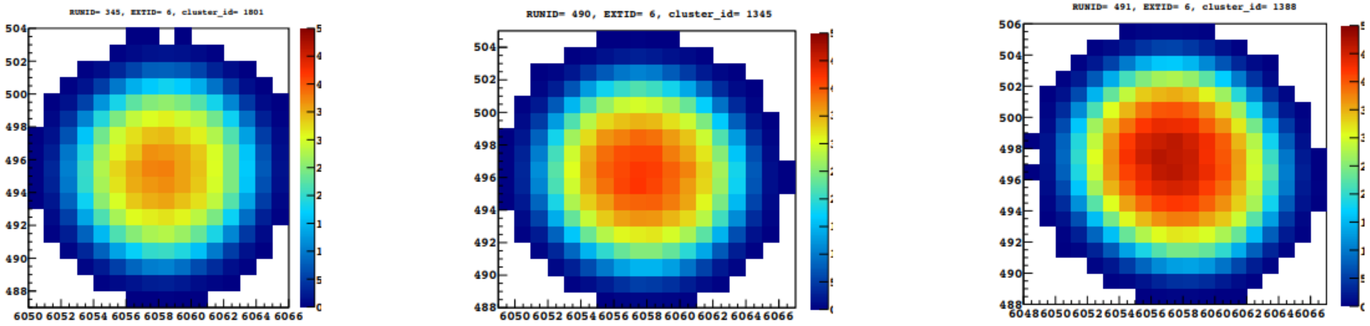
### $^{32}$Si $\beta_1$-$\beta_2$



- $E_{\beta 1}$ = 110 keV
- $E_{\beta 2}$ = 361 keV
- $\Delta t$ = 11.7 d

3 alphas at the same location consistent with a sequence from $^{232}$Th

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



1 $\Delta t$ = 17.8 d 2 $\Delta t$ = 5.5 h 3

# Leakage Current Analysis

| | |
|---|---|
| N | total number of pixels; |
| $n_c$ | charges from DM; |
| $n_l$ | charges from readout shot noise |
| $\Omega$ | e- to ADCu |
| $\mu_o, \lambda_d, \sigma_{pix}$ | noise parameters |

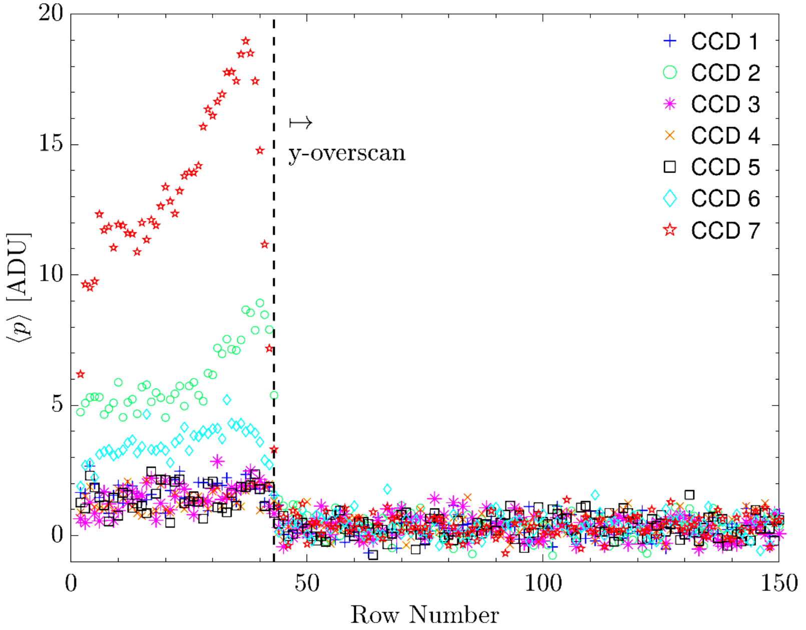
Select CCDs with constant leakage current from 200 g-d of data in 100 ks exposures

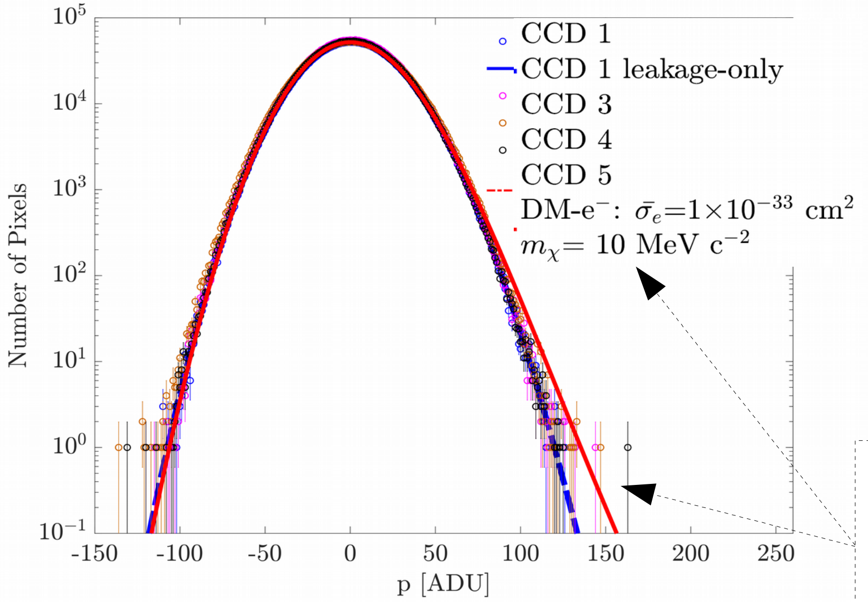
Model pixel charge distribution to $\Pi$(p) with and without the hypothesis of DM-e signal (S)

$$\Pi(p) = N \sum_{n_c=0}^{\infty}\sum_{n_l=0}^{\infty}\left(\left[\sum_{j=0}^{n_c} \overbrace{S(j\mid\bar{\sigma}_e, m_\chi)}^{\text{DM-e Signal}}\, \overbrace{\mathrm{Pois}(n_c-j\mid\lambda)}^{\text{Leakage Current}}\right] \overbrace{\mathrm{Pois}(n_l\mid\lambda_d)\,\mathrm{Gaus}(p\mid\Omega\left[(n_c+n_l)+\mu_0\right], \Omega\sigma_{\mathrm{pix}})}^{\text{pixel readout noise (blank+overscan)}}\right)$$

e bound && crystalline band structure
→ QEDark

arXiv:1907.12628 (accepted by PRL)



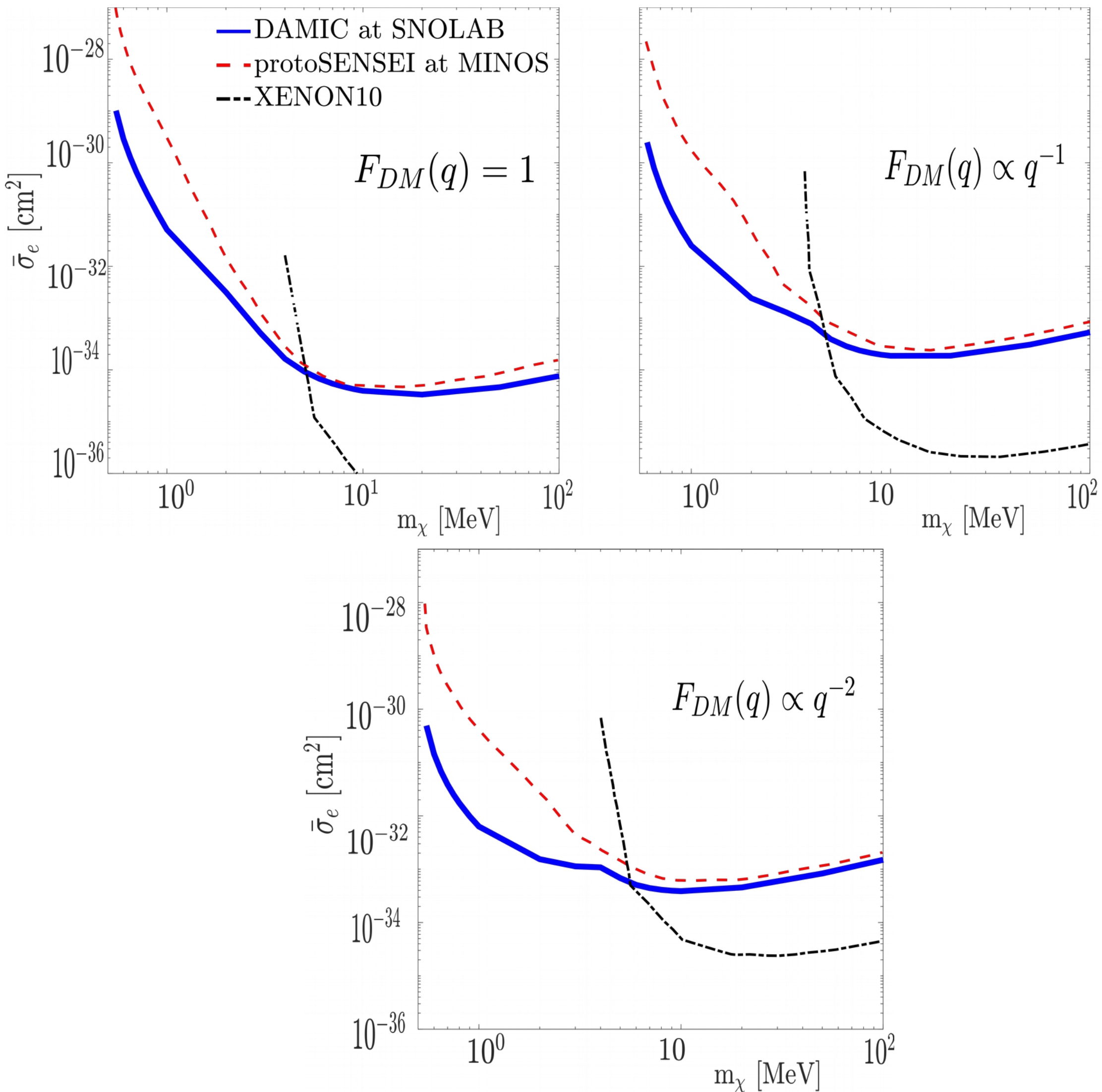

| CCD n. | $\lambda = \lambda_{tot} - \lambda_d$ [e⁻ mm⁻² d⁻¹] |
|---|---|
| 1 | 2.8(2) |
| 3 | 1.7(2) |
| 4 | 1.0(2) |
| 5 | 2.0(2) |

fit suggests non-zero DM mass, mostly due to the right tail which is also present in blank images, probably has a noise origin

arXiv:1907.12628 (accepted by PRL)

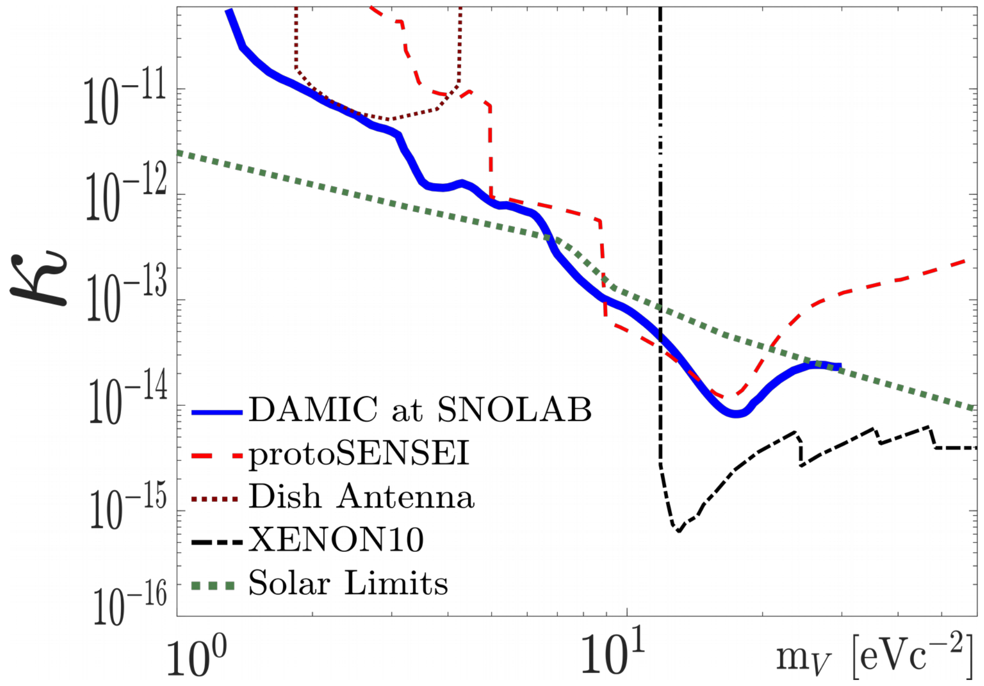
# Leakage Current Analysis: DM-e limits

Best exclusions limit for the **scattering of dark matter** particles within masses **<5MeV/c²**

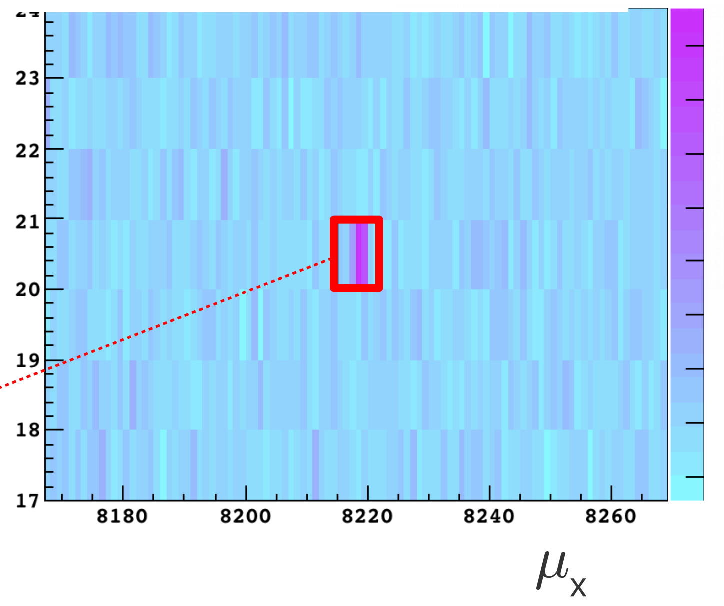



*arXiv:1907.12628 (PRL)*

Best exclusions limit for the **absorption of hidden photons** with masses **1–10 eV/c²**



# WIMP Analysis




- Remove pedestal and subtract correlated noise
- Mask any cluster with energy >10keV$_{ee}$
- Mask defects: repeating patterns in images
- Select images with expected noise profile

## Likelihood Cluster Search

- Perform a log-likelihood fit for a signal in a moving window across the image.

$$\Delta LL = -\ln\left(\frac{Max(L_G)}{L_n}\right)$$

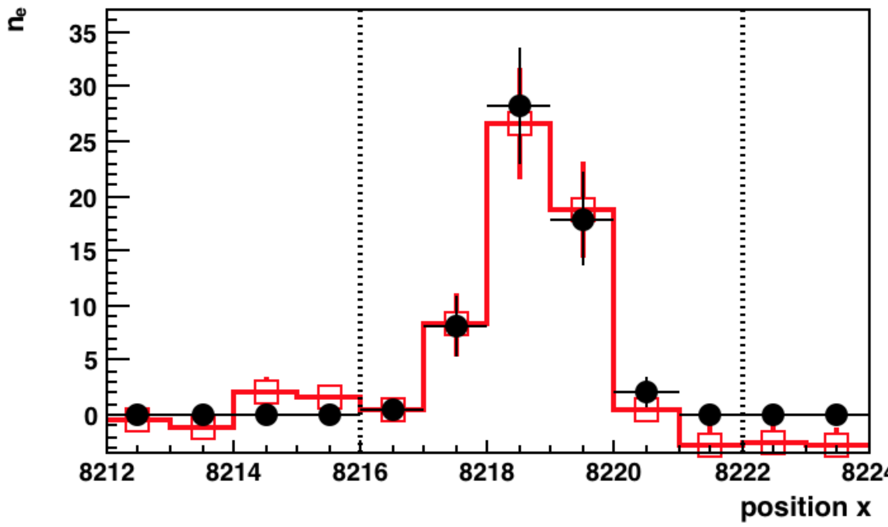
$L_G$: described by 1D Gaussian on top of the white noise $kN_e G(x,\mu_x,\sigma_x)$

$L_n$: described by white noise

So, each event has

- its statistical significance $\Delta$LL above noise (likelihood of a cluster to be signal as opposed t noise)
- its amplitude (E,energy)
- its spread ($\sigma_{xy}$ proportional to z)

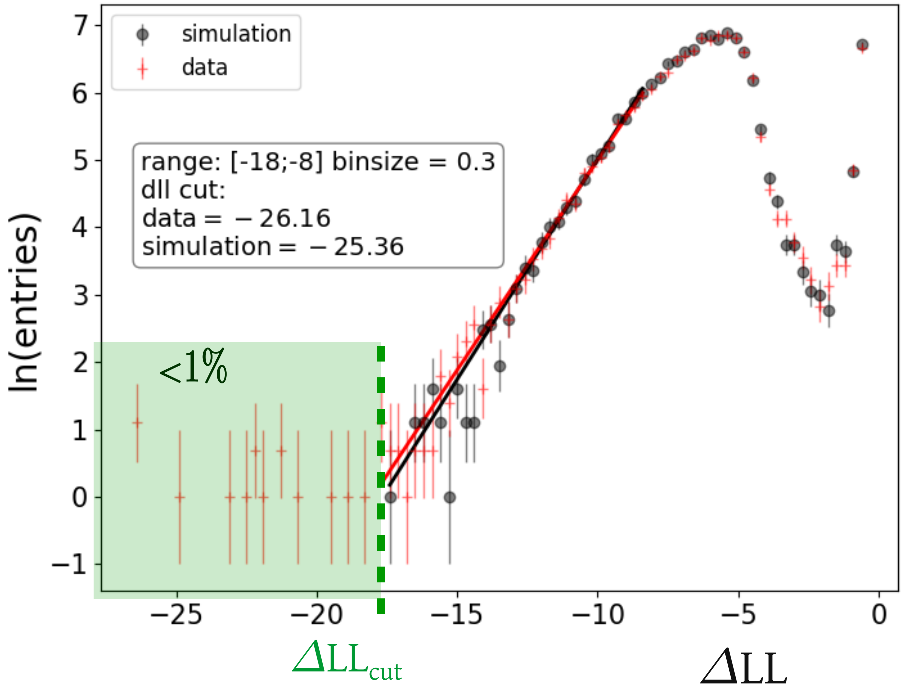
**E=0.20keV, $\sigma_x$= 0.5pix, $\Delta$LL=-128**

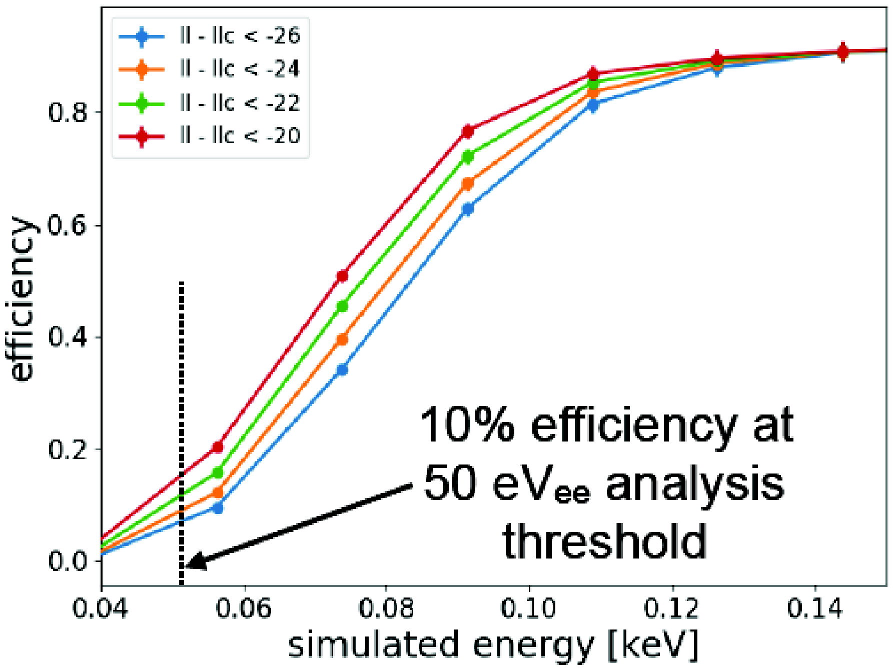


# WIMP Analysis

## Ionization Event Selection

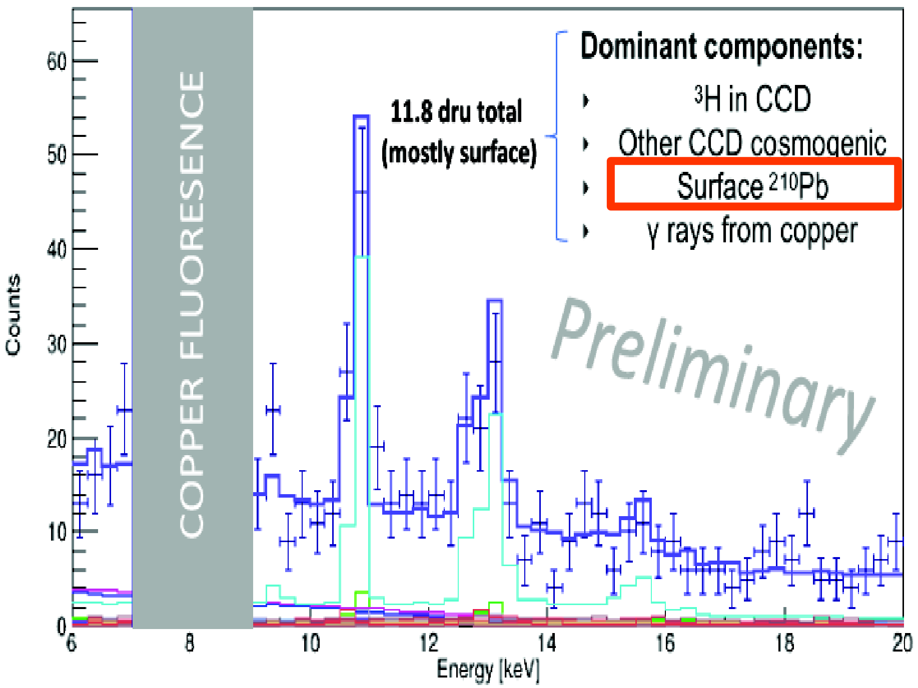
- Basic quality cuts (cluster reconstruction quality)
- Due to **high leakage current in some of the runs**, the **$\Delta$LL profile** for “noise” is given by
  - simulating a leakage current (Poison) on top of the blank images
  - and extract the event cluster $\Delta$LL from the previous images (“blank+leakage”)
- Define a $\Delta LL_{cut}$ (by fitting an exponential to simulation) which allows less than 1% of contamination from electronics and leakage current noise
- Calculate the **event selection efficiency:** by comparing the # of clusters reconstructed over the simulated one as a function of the simulated energy



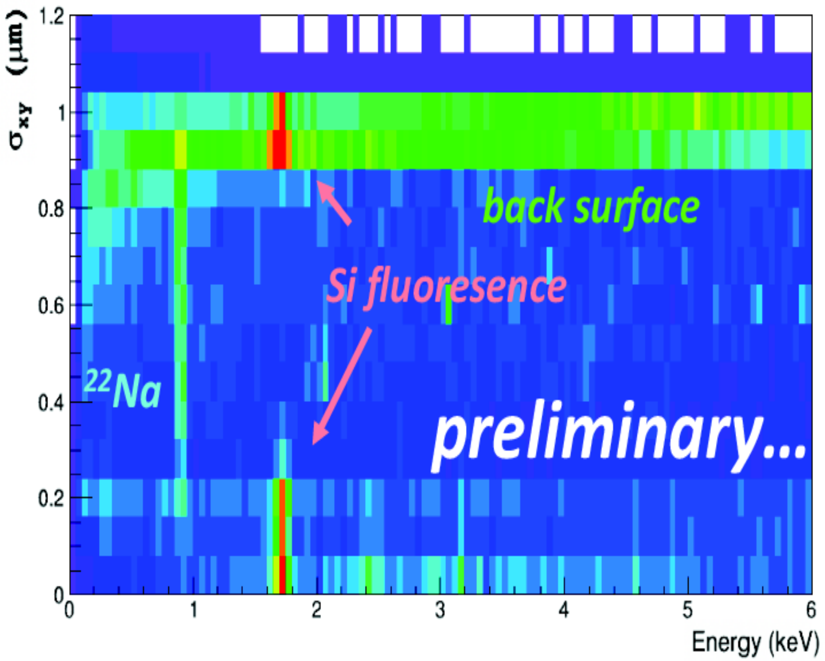



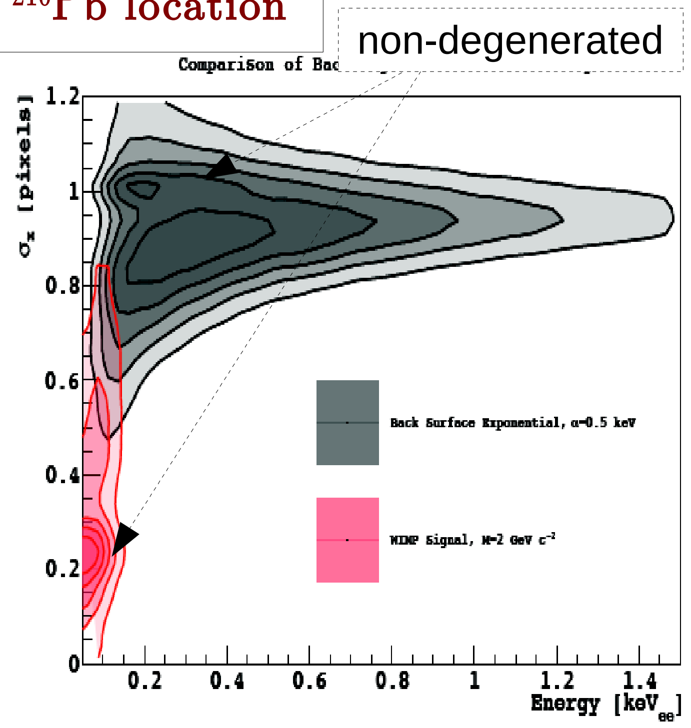
# WIMP Analysis: Background Modeling

- Assay each part of the detector to determine its **activity in counts/kg/day**
- Each **contaminant** (set of isotopes) on every part of the detector (GEANT4)
  - → **50 templates in Energy – $\sigma_x$ for each detector part and decay chain**
- **2D (E,$\sigma_x$) fit to data above 6keV**
  - Assuming no DM signal above 6 keV (DM mass > 10GeV)
  - Each component is allowed to float within the uncertainty of the respective assay (or float freely down to zero if is an upper limit)
- The fit above 6keV gives a background model for our ROI (below 6keV)




Systematic uncertainty of the $^{210}$Pb location



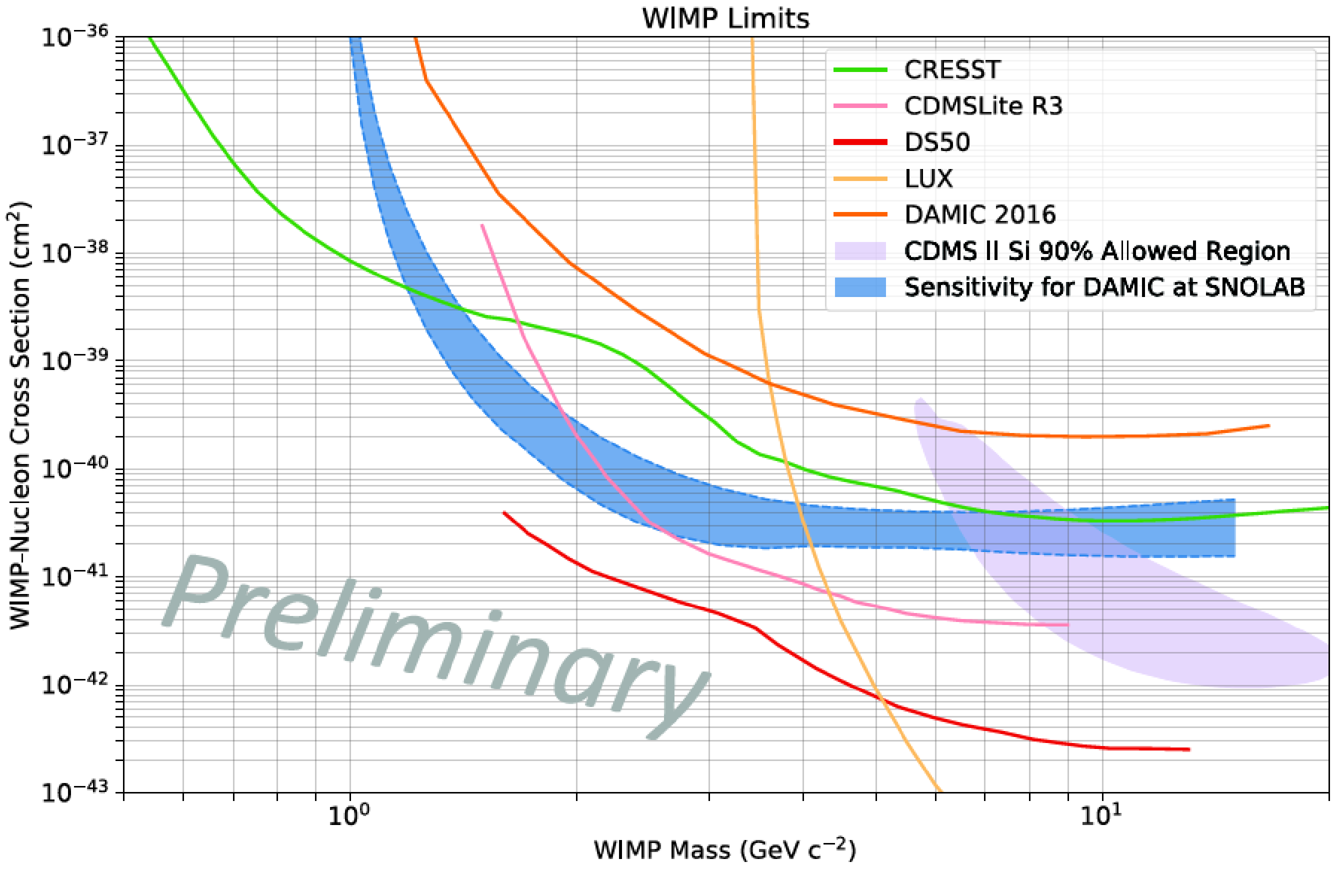
# WIMP Analysis: Expected Sensitivity

- We randomly sample this background model many times
- And see what limit we would get with the fake data (containing no WIMP signal)
- To determine what the sensitivity of DAMIC at SNOLAB will be

Analysis in its final stages … results coming soon!

Potential for discovery of WIMPs with masses 1–2 GeV/$c^2$

Result can exclude significant fraction of CDMS II-Si



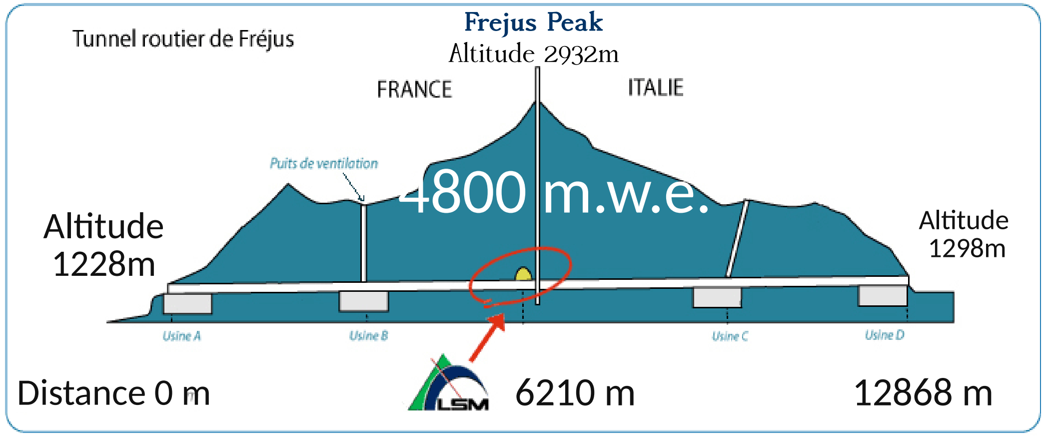
# DAMIC-M

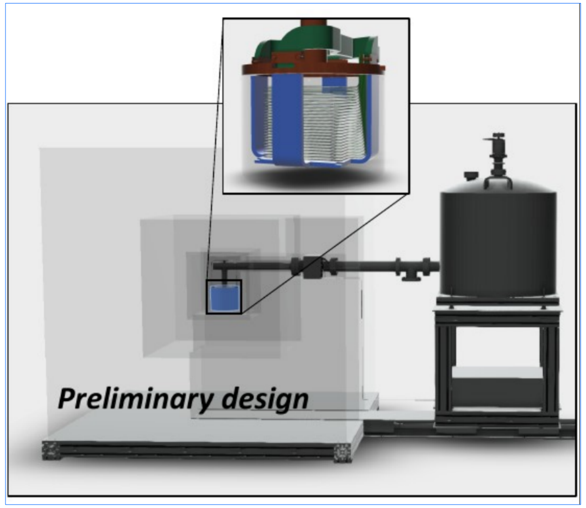
- 50 CCDs (**kg-size target mass**)
  Most massive CCDs ever built (>10 g each): 15x15x675 $\mu m^3$
- **Single electron resolution** with skipper readout
- **A fraction of dru** (0.1 events/kg/keV/day) background

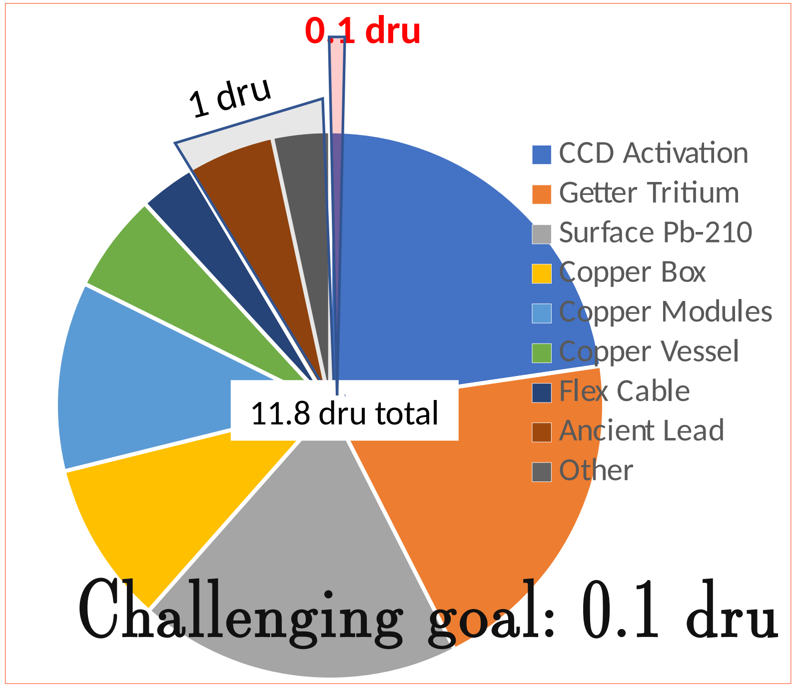
- Classical design (Ge detectors and DAMIC at SNOLAB)

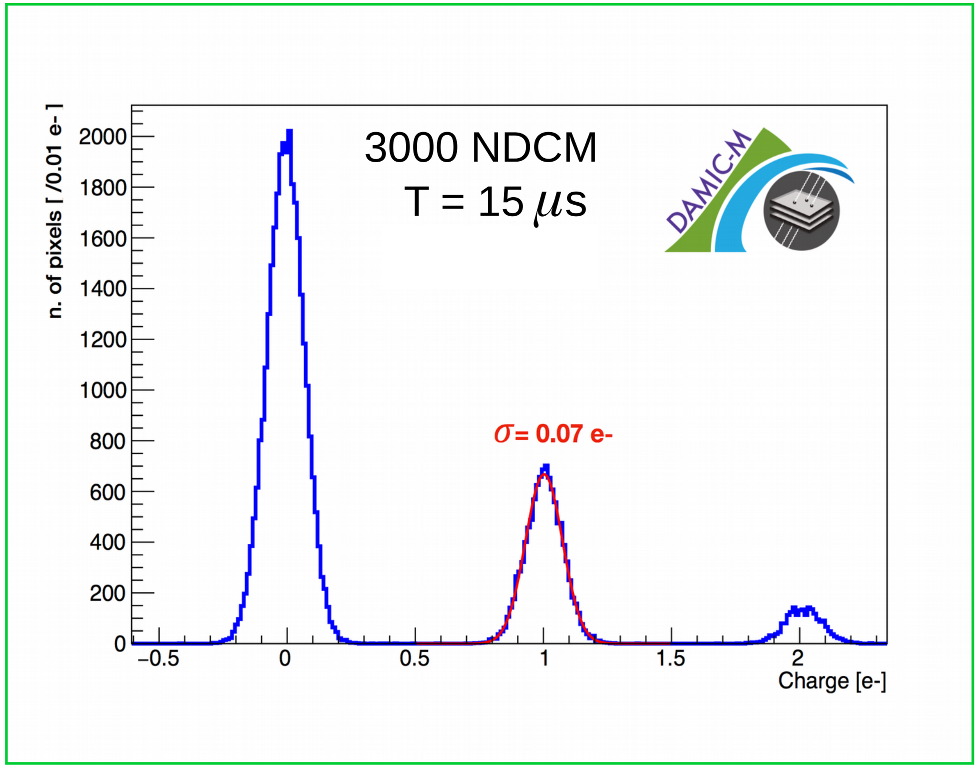
- R&D and design up to 2021
- Construction 2022
- Installation in 2023

Laboratoire Souterrain de Modane



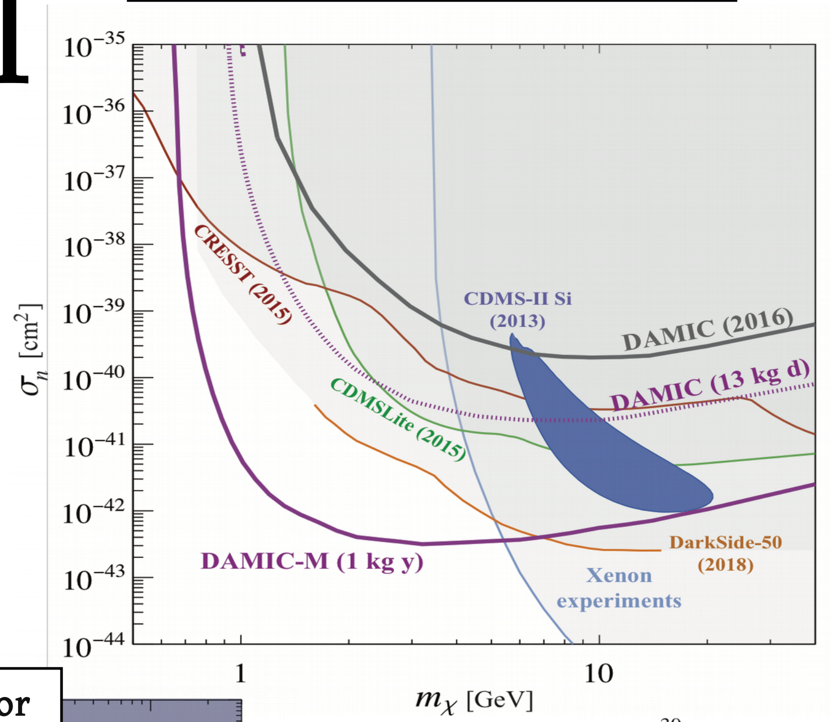



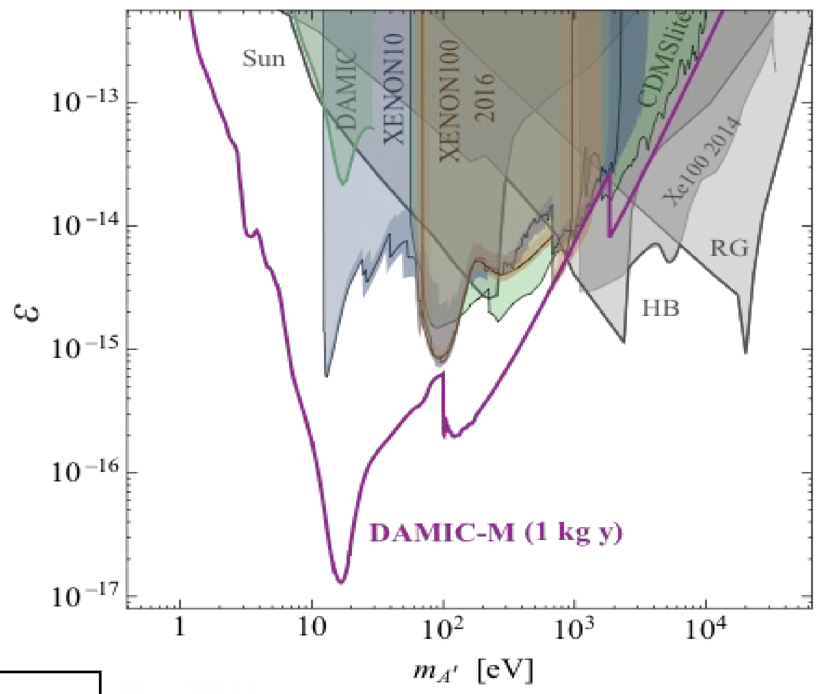



# DAMIC-M

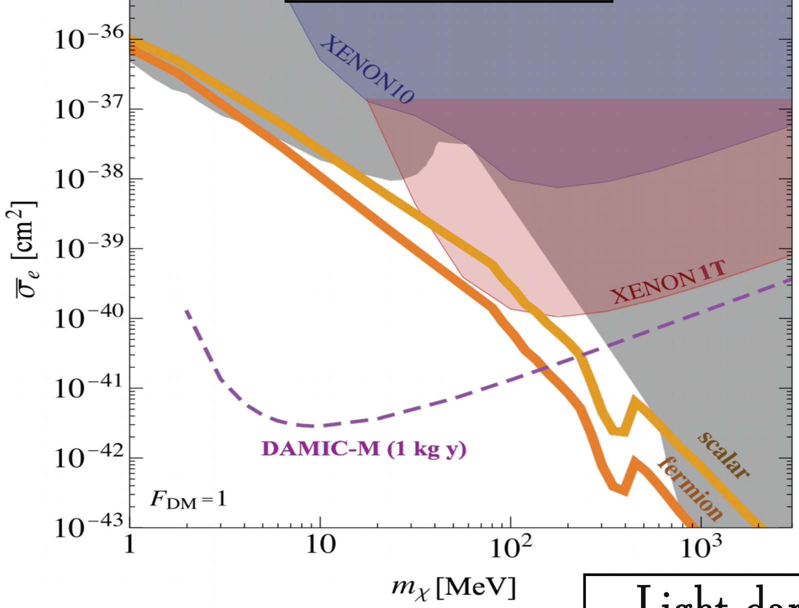
WIMP – nuclear recoil search

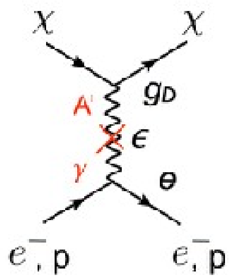



Hidden photon search

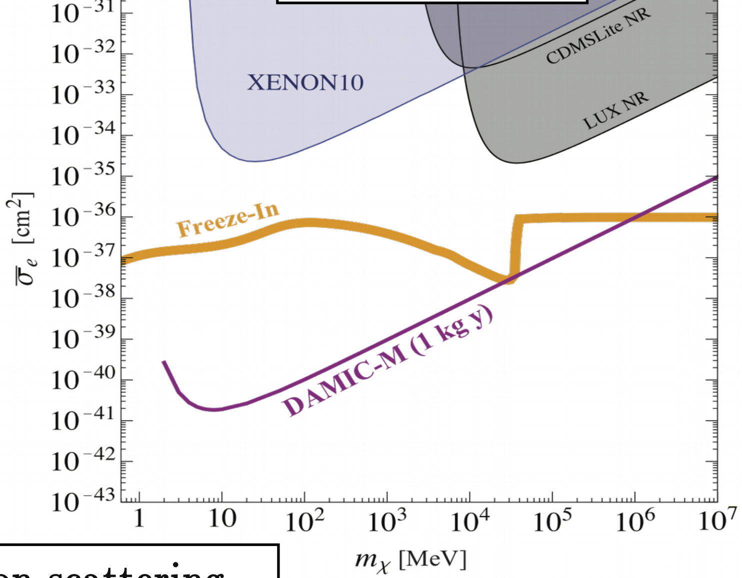



Heavy mediator




Light mediator



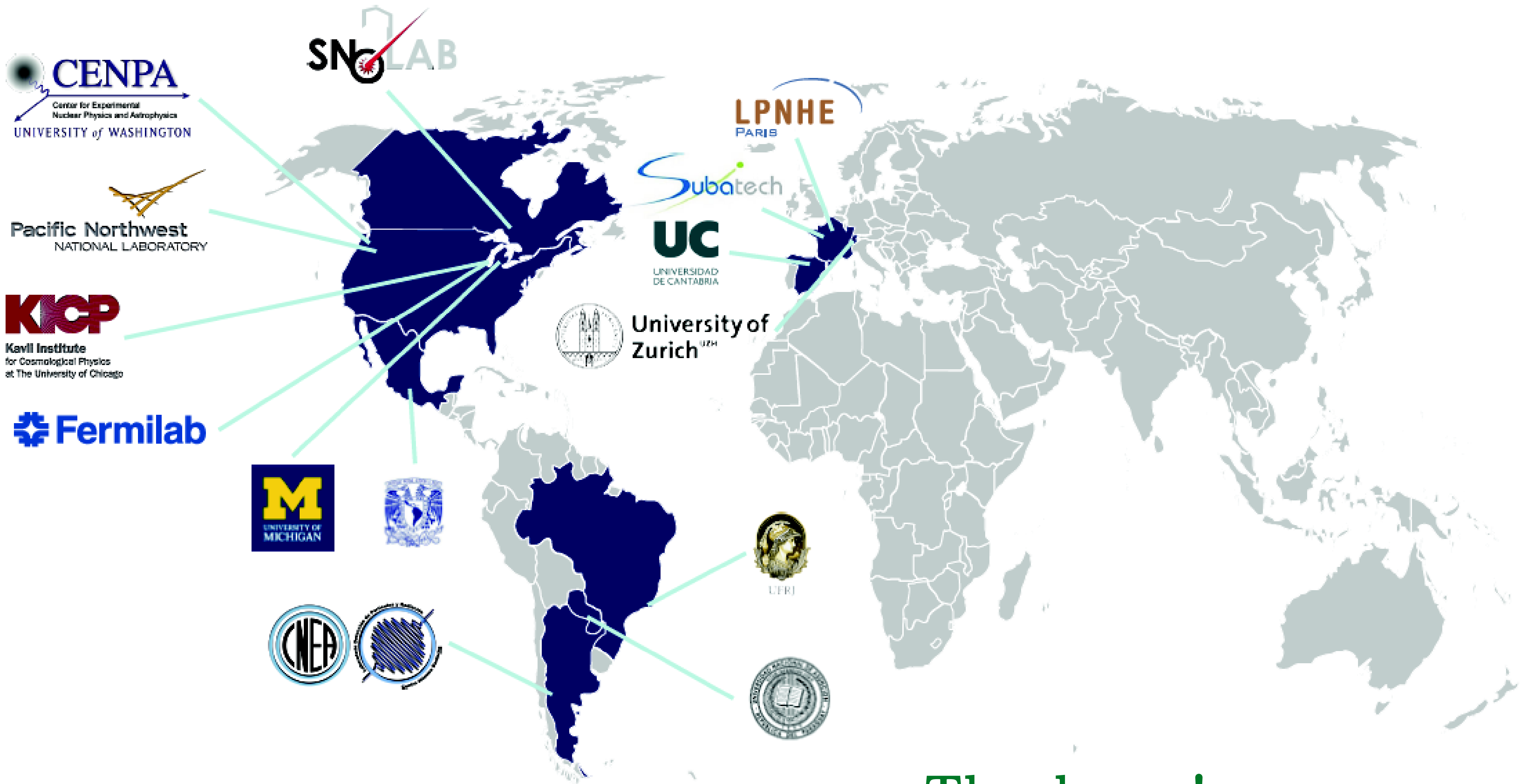

Light dark matter – electron scattering

# Outlook

- DAMIC at SNOLAB has demonstrated **CCDs** as an **excellent** technology **for dark matter direct detection**.
- Extensive understanding of CCD response and backgrounds for an experiment with potential for discovery
- Best results for DM scattering with masses <5 MeV/$c^2$
- WIMP search data campaign complete. Exposure of 13 kg-d under analysis. Expected results very soon!
- Particularly good sensitivity for WIMPs with 1–2 GeV/$c^2$
- DAMIC-M will improve on this by orders of magnitude due to low backgrounds, single electron resolution, and much larger exposure

European Research Council
Established by the European Commission

# DAMIC Collaboration

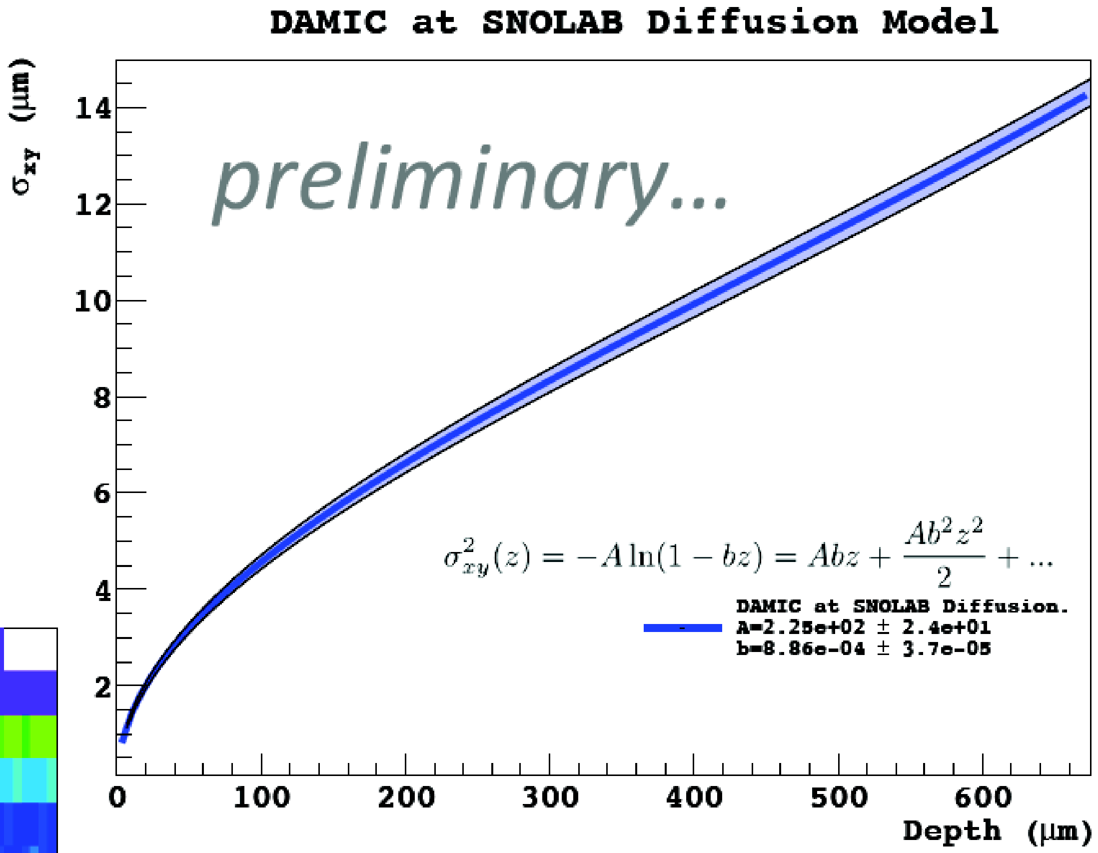


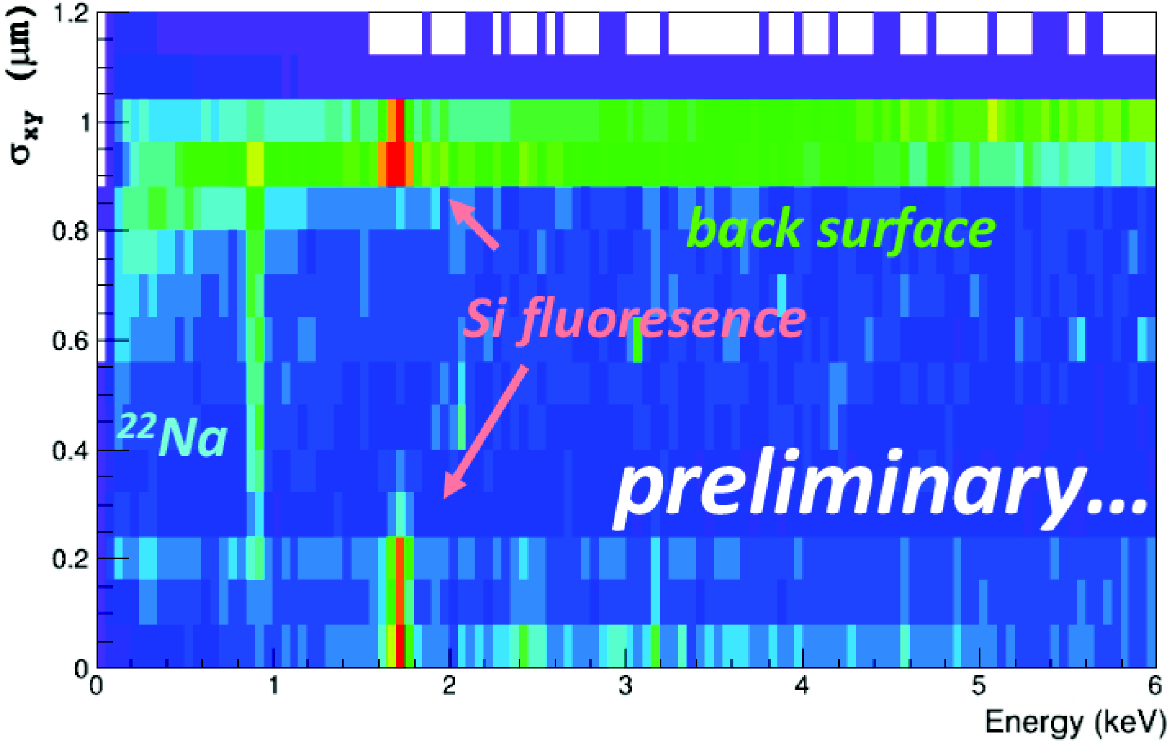

Thank you!

# Extra Slides

# Modeling Diffusion

- We calibrate depth (diffusion) using events at the back of the CCD and muons passing through




- We randomly sample our background model (in E-z)...
- ...apply our diffusion model to fake events...
- ...paste onto blank images to account for read-out noise...
- ...and output a background model in observed variables energy-sigma

# Fitting to Data

- Perform a 2D template **likelihood** fit in energy-sigma space
- Assume the probability of measuring $\boldsymbol{k}$ events given an expectation $\boldsymbol{\nu}$ from the $\boldsymbol{i}$ th energy bin and $\boldsymbol{j}$ th sigma bin is described by a Poisson distribution:

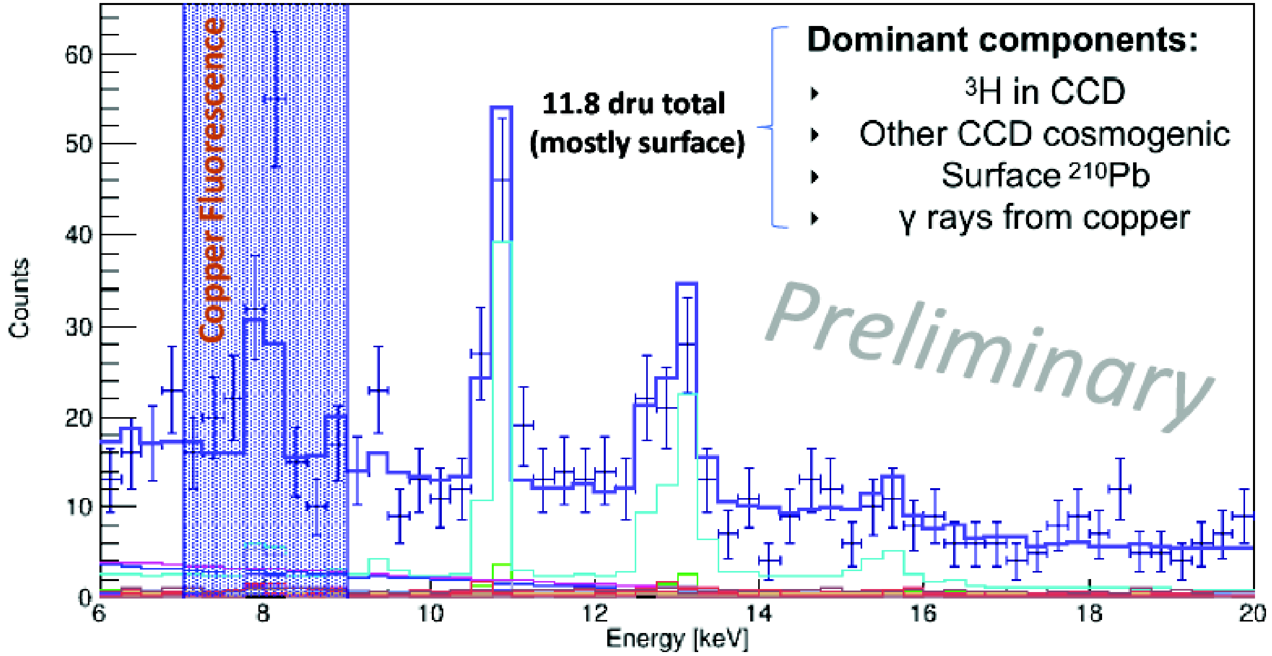
$$P(k_{ij}|\nu_{ij}) = \frac{e^{-\nu_{ij}}\nu_{ij}^{k_{ij}}}{k_{ij}!} \qquad \nu_{ij} = \sum_l C_l \nu_{ijl}$$

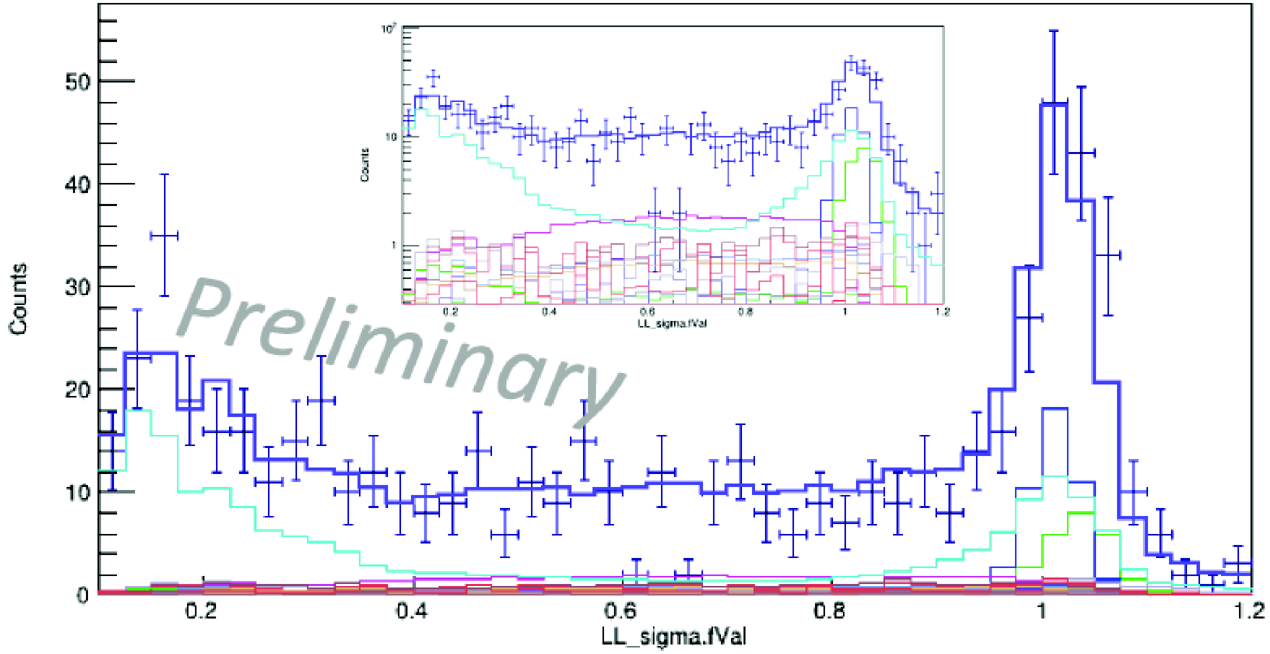
- Assign each template $\boldsymbol{l}$ a fit parameter $\boldsymbol{C_l}$ that scales it up or down and constrain these fit parameters according to material assays using a Gaussian constraint for each $\boldsymbol{n}$ measured activity constraint

$$LL = \sum_i \sum_j \left(k_{ij}\log(\nu_{ij}) - \nu_{ij} - \log(k_{ij}!)\right) - \sum_n \left(\frac{(N_n^o - N_n)^2}{2\sigma_n^2}\right)$$

# Fit Results

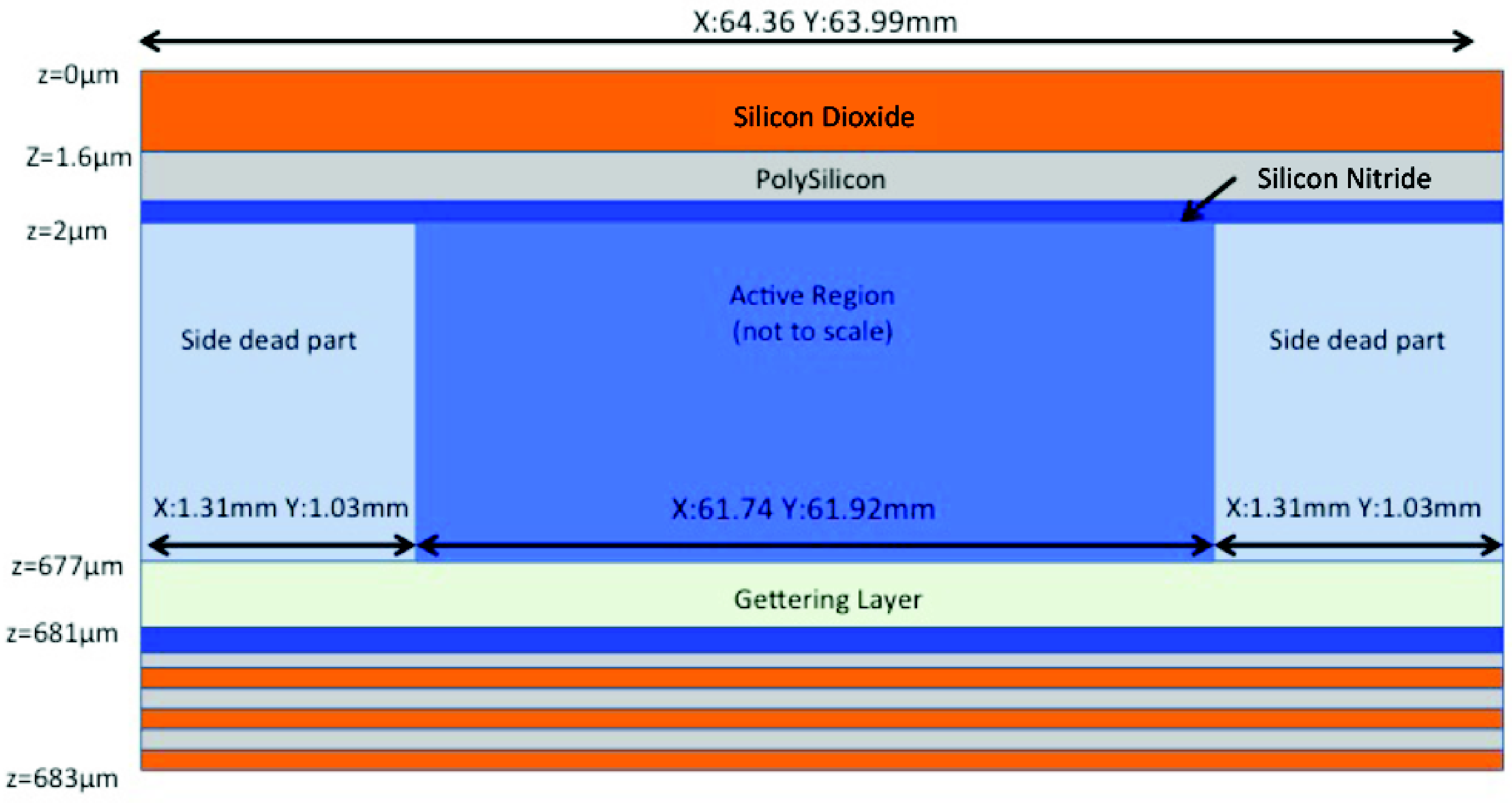
- This gives us 53 templates in energy-sigma for each detector part and decay chain
- …which we fit against the data above 6 keV
  - This implicitly assumes that we have no DM signal above 6 keV (DM mass > 10 GeV)
  - Each component is allowed to float within the uncertainty of the respective assay (or float freely down to zero if constrained by an upper bound)
- We use the fit above 6 keV to give us a background model for our WIMP ROI (0.5-6 keV)…



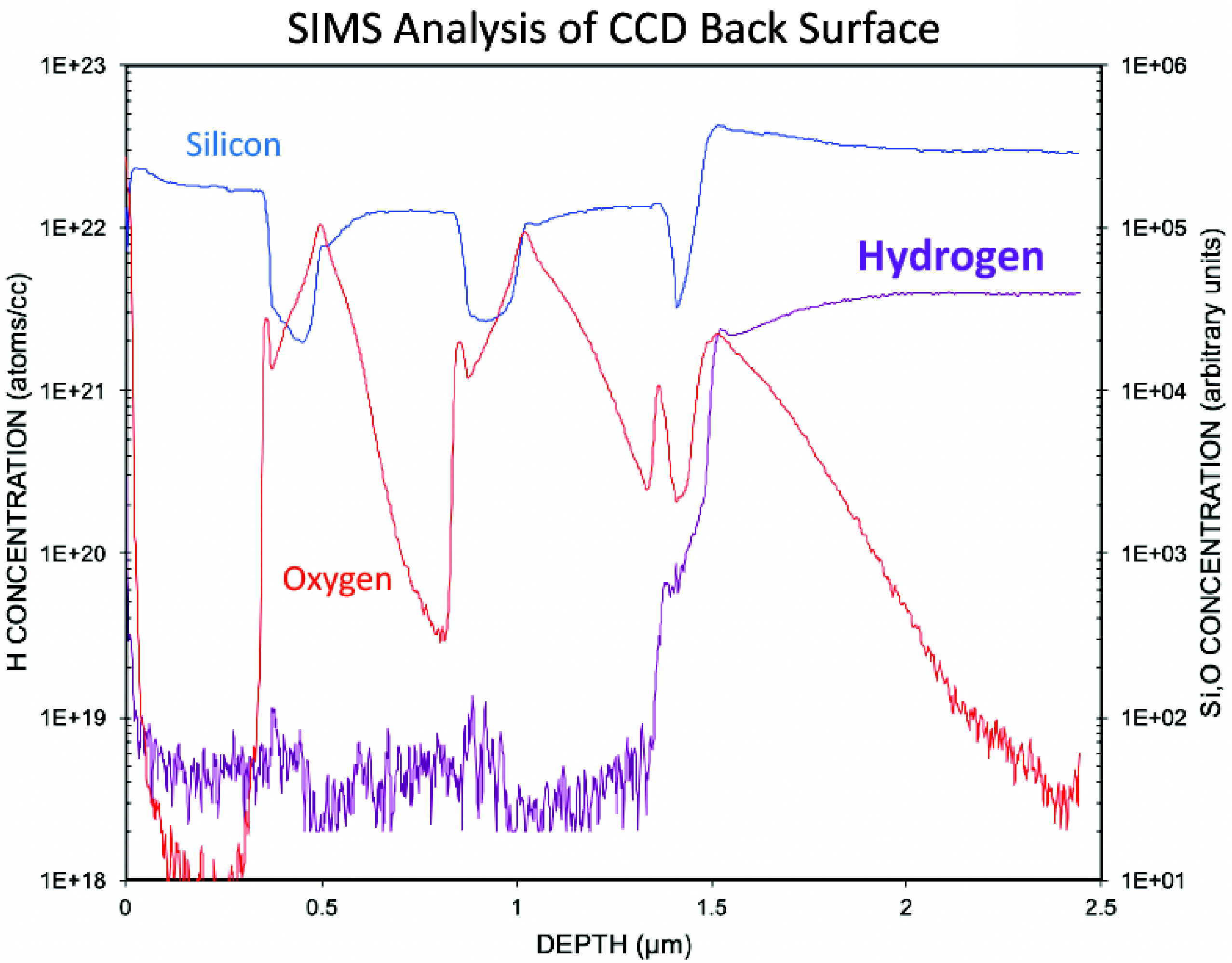
# Checking the Result: Tritium

| | |
|---|---|
| **In-situ doped polysilicon** | ~4 µm |
| **Silicon nitride** | 0.1 µm |
| **P-doped polysilicon** | 0.4 µm |
| **Silicon dioxide** | 0.3 µm |
| **P-doped polysilicon** | 0.4 µm |
| **Silicon dioxide** | 0.3 µm |
| **P-doped polysilicon** | 0.4 µm |
| **Silicon dioxide** | ★ 0.3 µm |
| **TOTAL** | **~6 µm** |




★ Layer removed on the next slide

# Checking the Result: Tritium

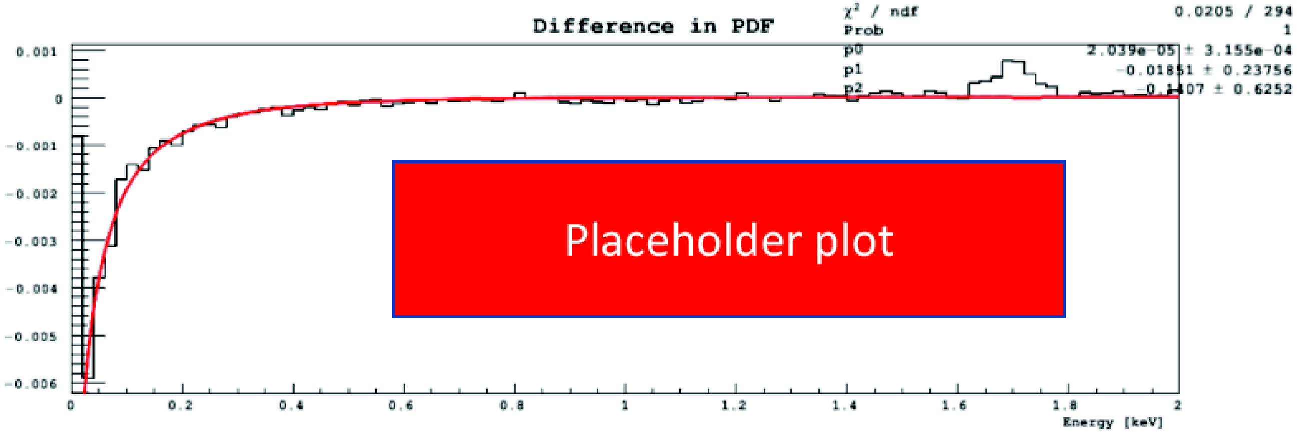



- **We find 4 x$10^{21}$ H/$cm^3$ in the backside getter layer!**
- If we assume tritium fraction in water (1 x$10^{-18}$ $^3$H/H)…
- …we calculate
  - **3 x$10^5$ decays/kg/day**
- The DAMIC@SNOLAB analysis gives
  - **1.3 ± 0.3 x$10^5$ decays/kg/day** ***(preliminary)***
- **Completely independent measurement!**

# Systematic Uncertainty: Pb-210

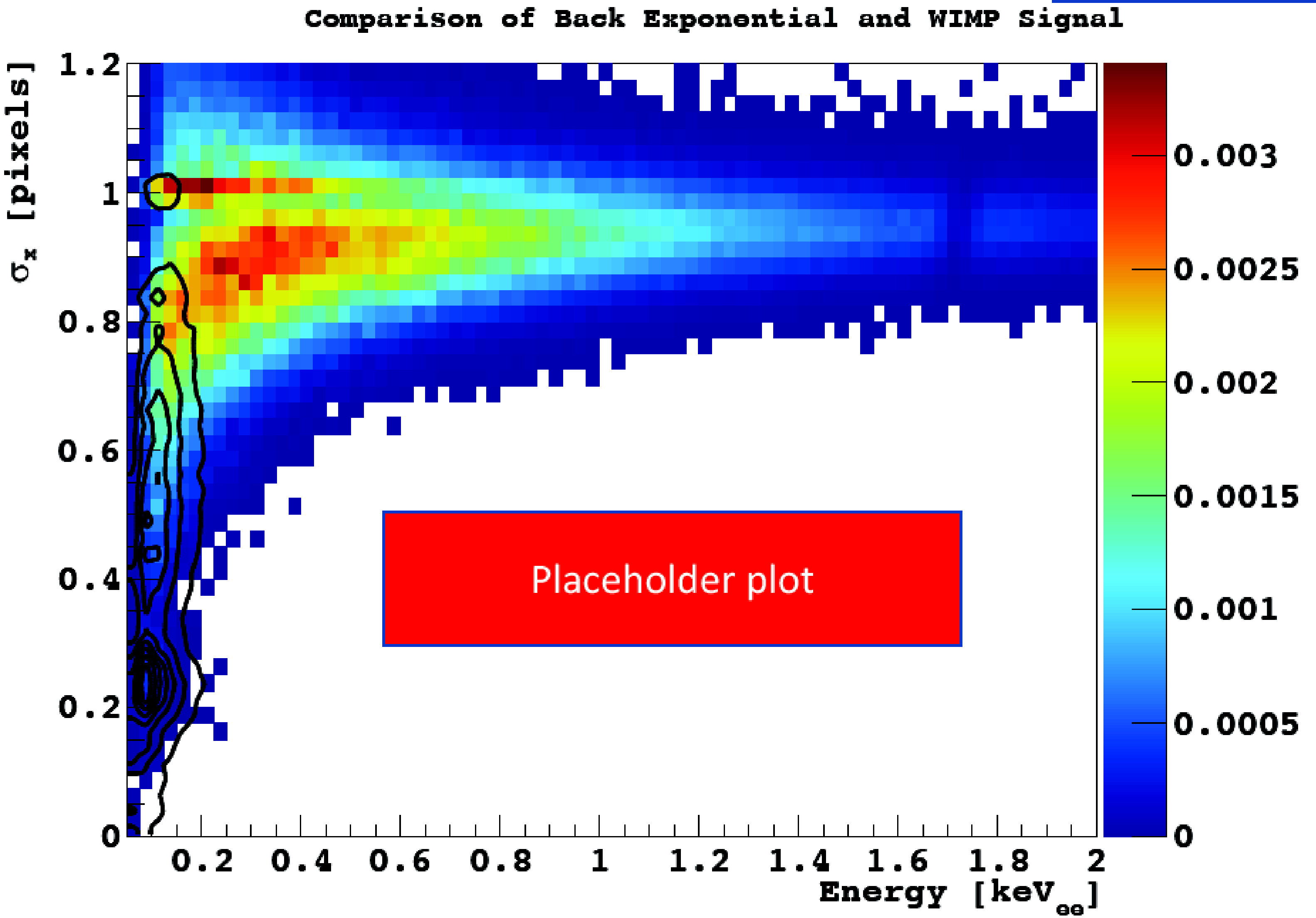
- We know there is a significant surface Pb-210 component to our background…
- **…but we don't know which surface.**
- The fit prefers to put Pb-210 on the back of the active region
    - This corresponds to the back of what was the silicon wafer

| Location | Bulk | Front | Back | Wafer | External |
|---|---|---|---|---|---|
| Preferred? | No | No | No | Yes | Yes |

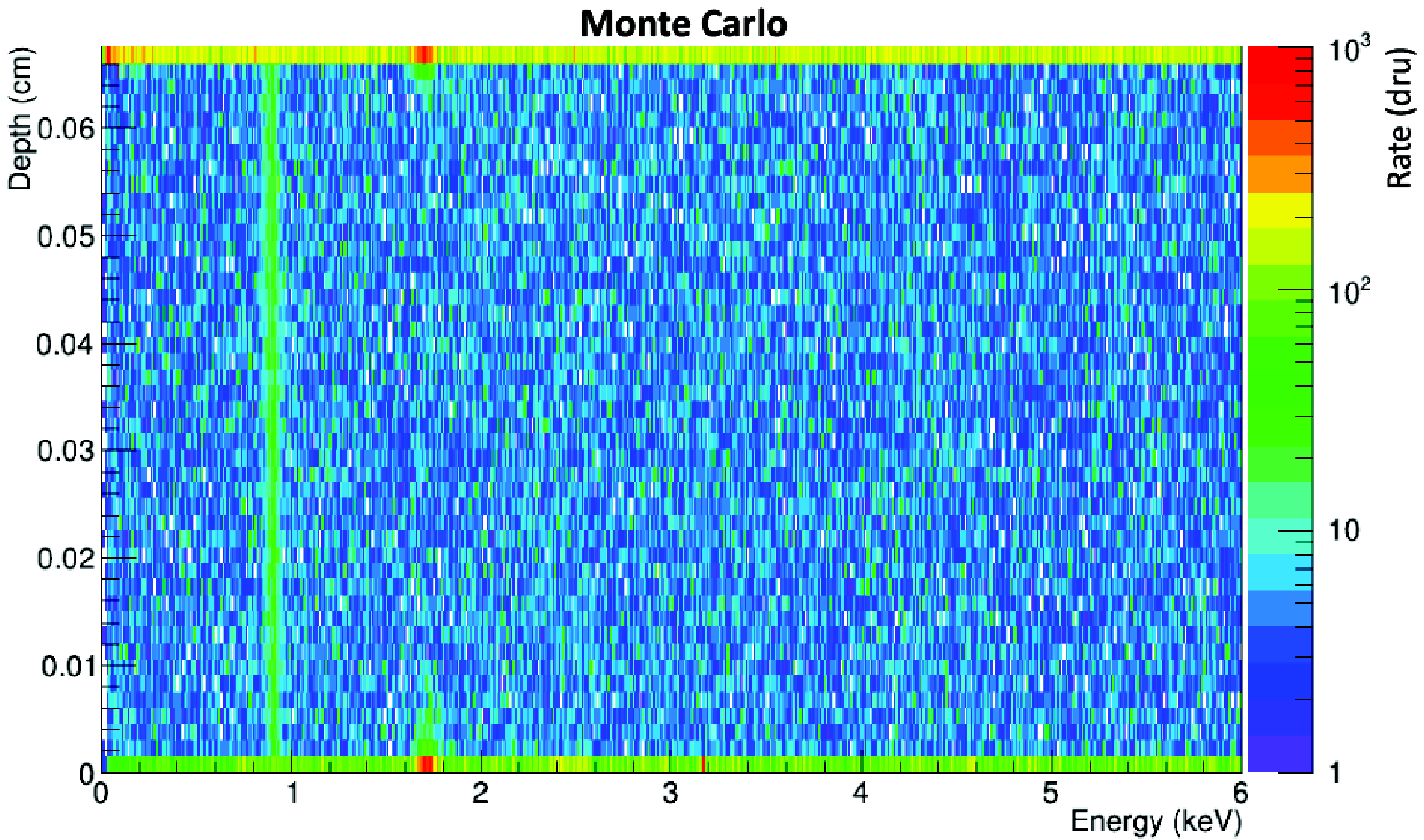


# Systematic Uncertainty: Pb-210

- A back-side exponential rise is non-degenerate with a WIMP signal
  - <u>Solution</u>: Consider this a free parameter in the WIMP analysis to account for the systematic uncertainty of the $^{210}$Pb location
- For DAMIC-M, this component must be removed…
  - <u>Criteria</u>: < 0.5 nBq/cm$^2$ on the wafer



# DAMIC at SNOLAB Background Model




- We randomly sample our background model (in E-z)…
- …apply our diffusion model to fake events…
- …paste onto blank images to account for read-out noise…
- …run the same clustering algorithm that is used on the data to account for efficiencies…
- …and output a background model in observed variables energy-sigma

# DAMIC at SNOLAB Background Model