Dark Matter Search Results from DAMIC at SNOLAB

On behalf of the DAMIC Collaboration

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CERN
DAMIC-M

DM framework for DAMIC

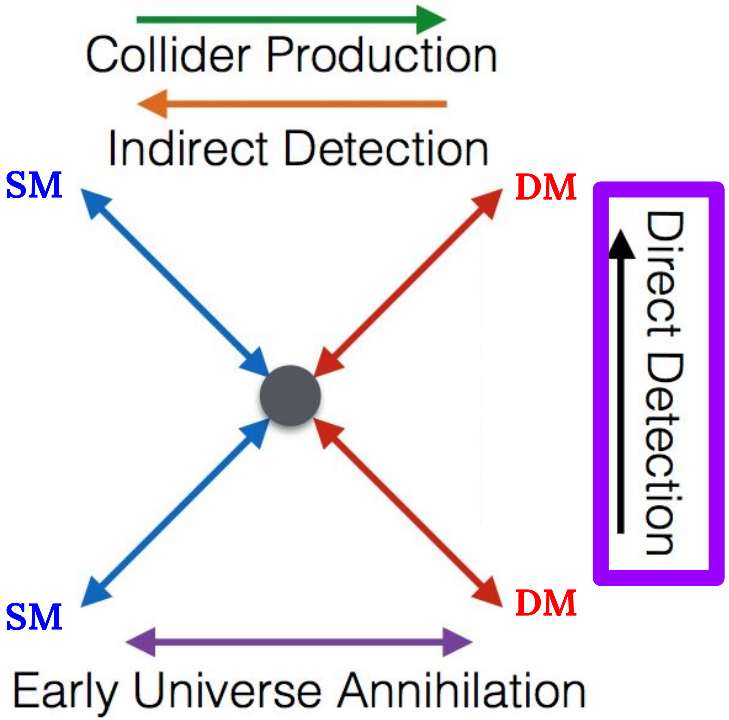
Cosmological evidence of dark matter

- Galaxy rotation curves
- Galaxy formation
- Gravitational lensing
- CMB Power Spectrum

Aim to measure interactions with matter

- **Elastic scattering off nuclei**
  standard WIMP scenario
  1-1000GeV c^{-1}
  0.3-300 keV recoil energy

- **Inelastic scattering off electrons**
  dark sector coupling
  1-1000 MeV c^{-1}
  1-100 eV recoil energy



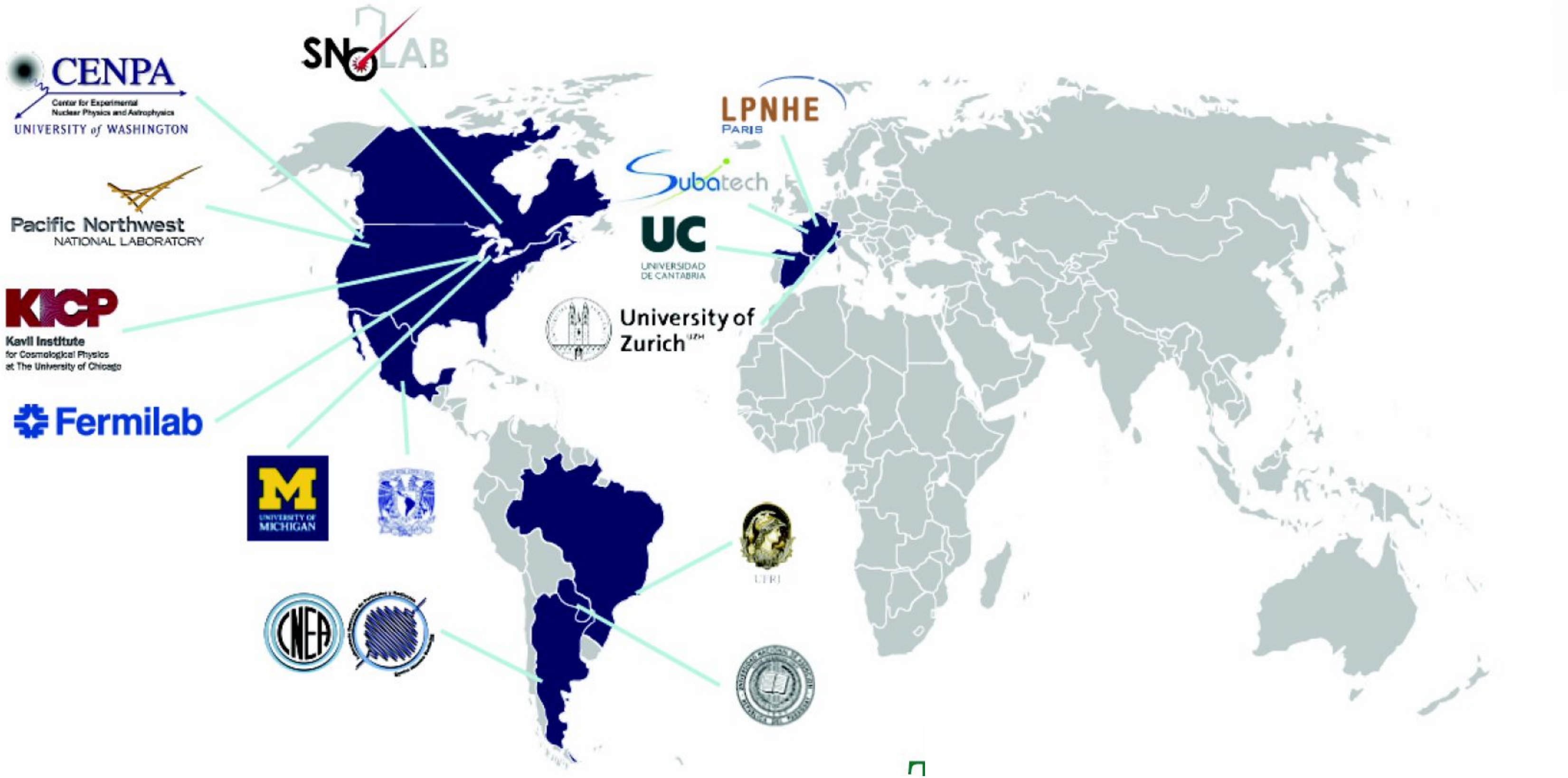
(thermal freeze-out)

Overview

1. Brief introduction on CCDs as Direct Dark Matter detectors
2. DAMIC at SNOLAB Overview
3. Latest result of DAMIC@SNOLAB on WIMPs
4. Future developments

   DAMIC-M the new generation of CCD detectors

DAMIC Collaboration



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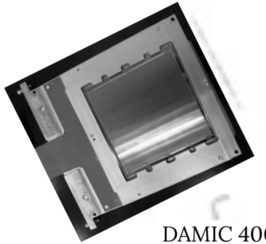
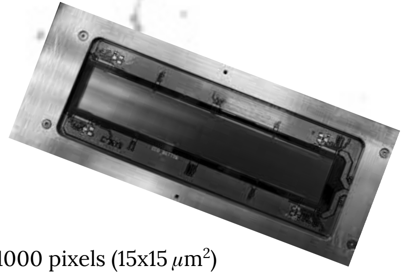
Charge Coupled Devices (CCDs) as PARTICLE DETECTORS



DAMIC 4000x4000 pixels (15x15 μm^2)

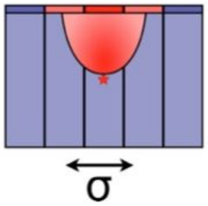


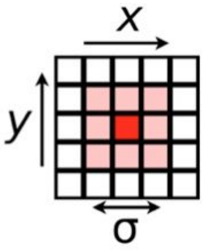
DAMIC 6000x1000 pixels (15x15 μm^2)

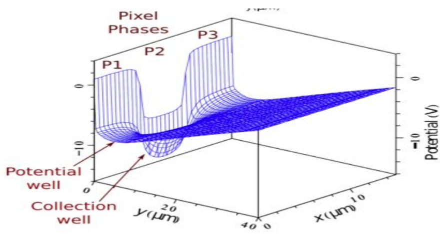
CCDs
as Dark Matter Detectors

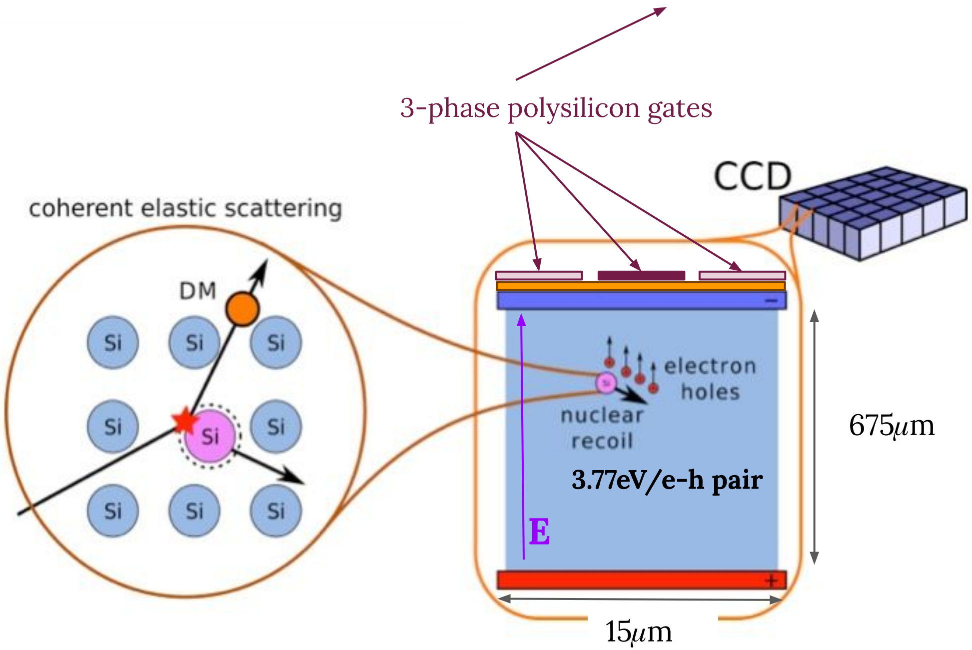
Charge Generation and Collection

- A particle can strike a silicon nucleus in the detector
- This recoiling nucleus/electron may produce some number of e-h pairs in the fully depleted region (~675μm)
- The holes are drifted upwards in an electric field and collected in a pixel array
- The 3-phase structure forms potential wells confining the charge in the pixels for very long periods of time without any loss









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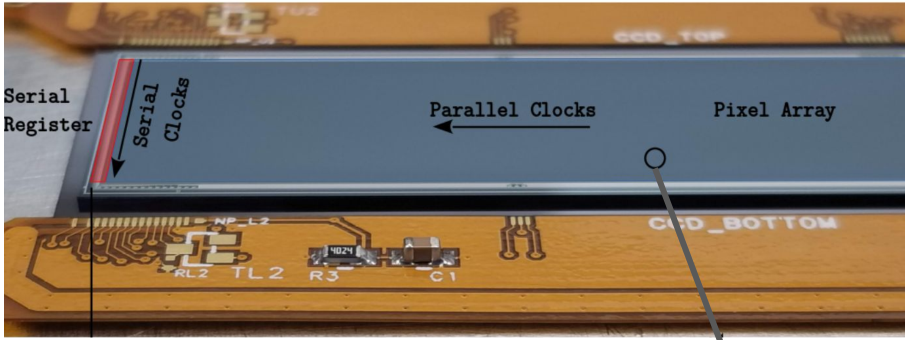
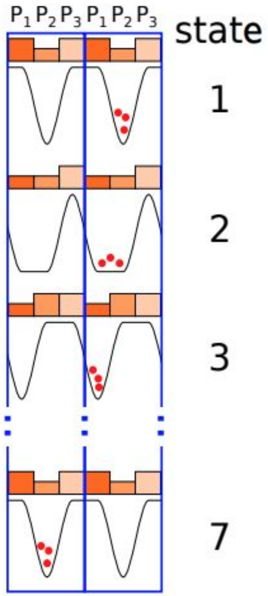
CCDs
as Dark Matter Detectors

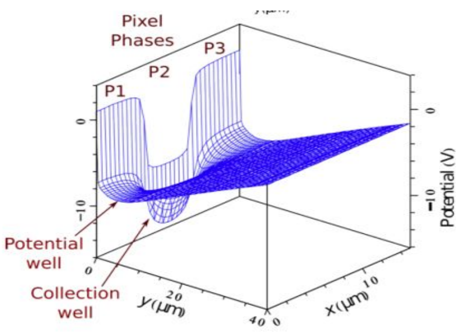
Charge Generation

Charge Transfer

- Shifting up/down these potential wells, charges are **moved pixel to pixel, with very high efficiency,** until they reach the serial register at the end of the CCD, and transferred into the readout **amplifier**







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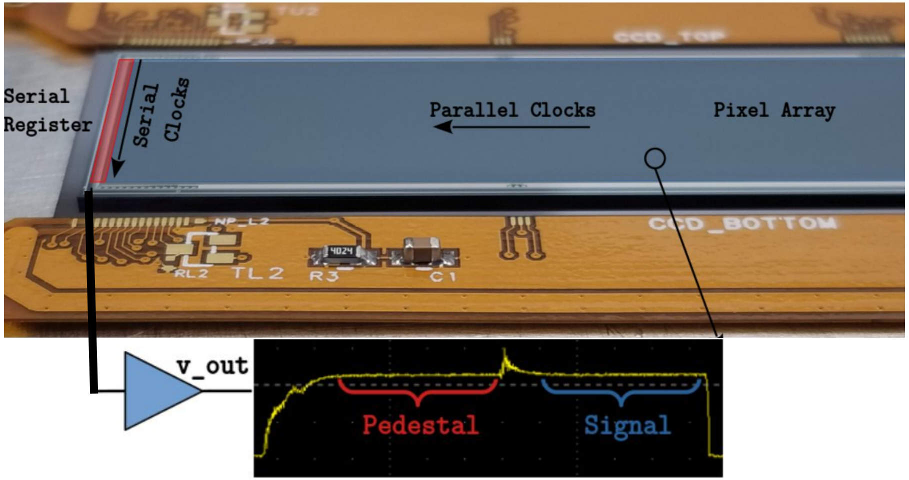
CCDs
as Dark Matter Detectors

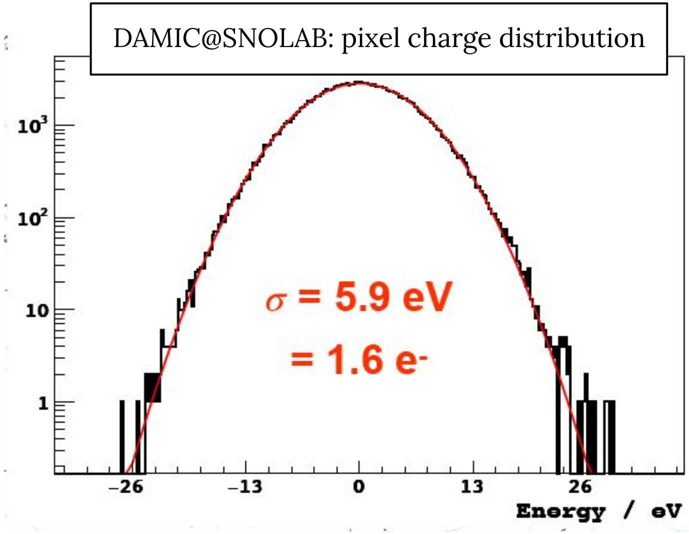
Charge Generation

Charge Collection and Transfer

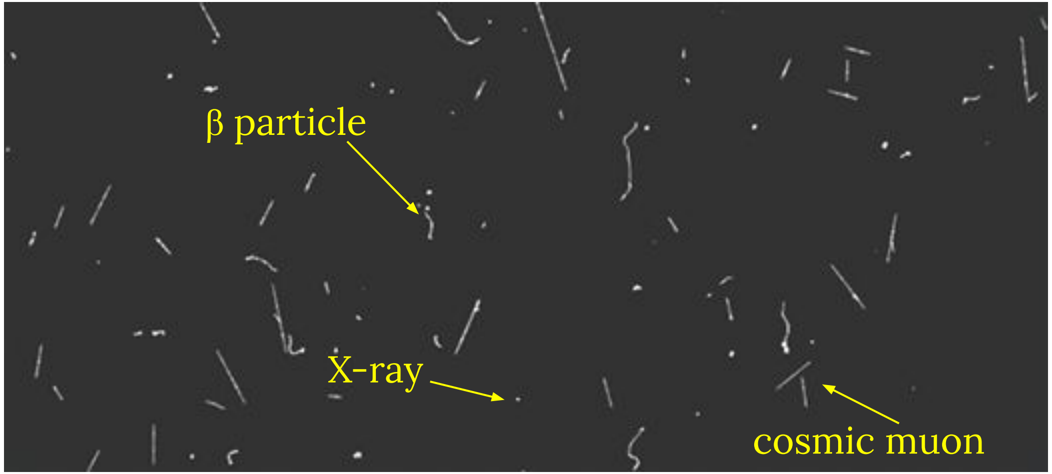
Charge Measurement

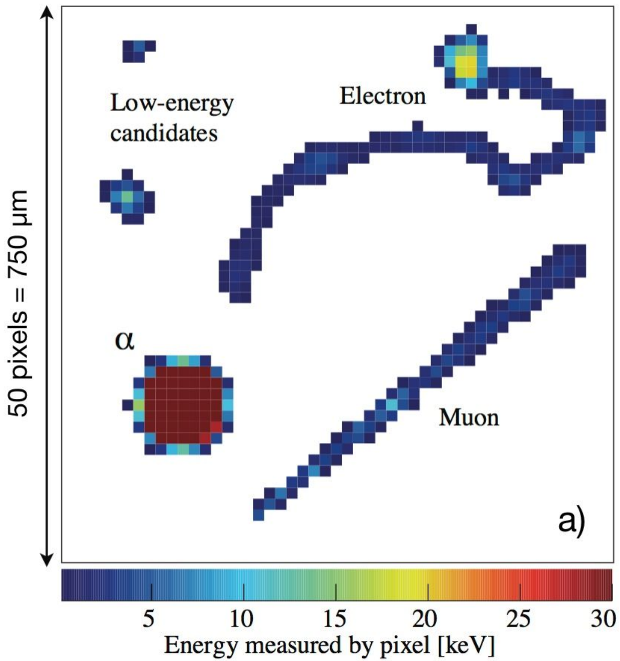
- In standard CCDs, the charge measured is done by **Correlated Double Sampling:** read first the reference voltage (pedestal) and then the signal, the integration time allows us to reduce the high frequency noise, but not the low frequency noise (see skipper at the end of this talk).
- Ultra low leakage/dark current 5×10^{-22} A/cm^2
- Readout can be slow/non-destructive: **low noise** (**few e-**)

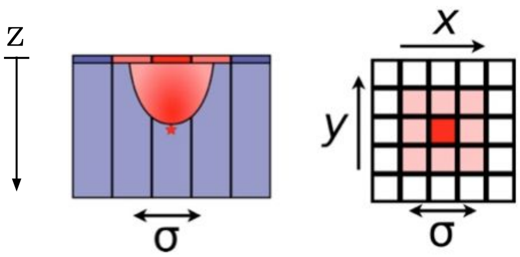




CCDs as Dark Matter Detectors. Charge Diffusion







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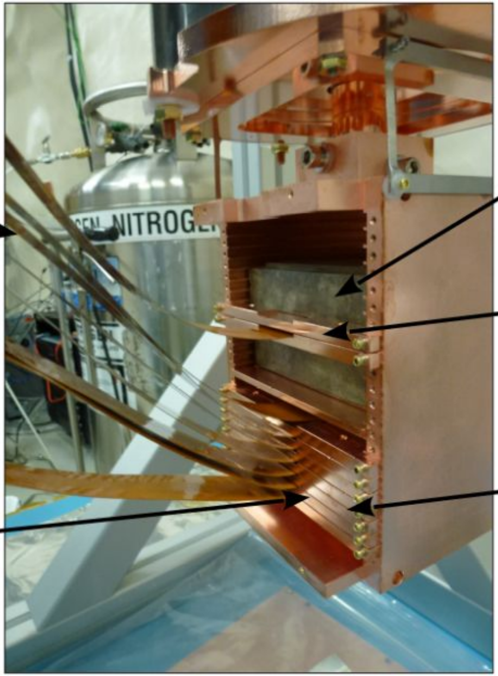
DArk **M**atter **I**n **C**CDs
DAMIC

DAMIC at SNOLAB

- Located at SNOLAB (~6000 M.W.E) in Sudbury, Ontario
- Array of 7 CCDs (6gr, 16 Megapixels) cooled to ~140K
  - Low Noise (<2e-)
  - Extremely low leakage current: 2 10^{-22} Acm^{-2})
- 50 eV_{ee} analysis threshold (10% reconstruction efficiency)
- Total background rate of 10 cts/kg/day/keV_{ee}
- 10.6 kg day exposure of Si target for final WIMP analysis



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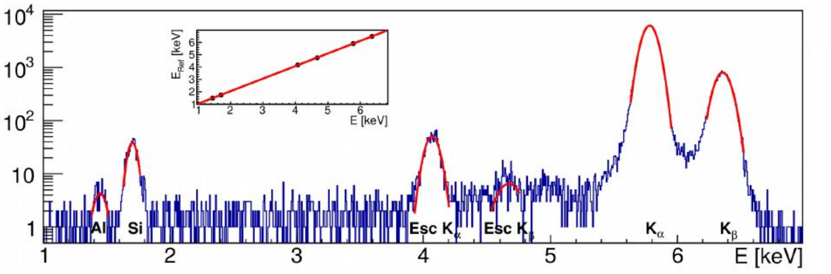
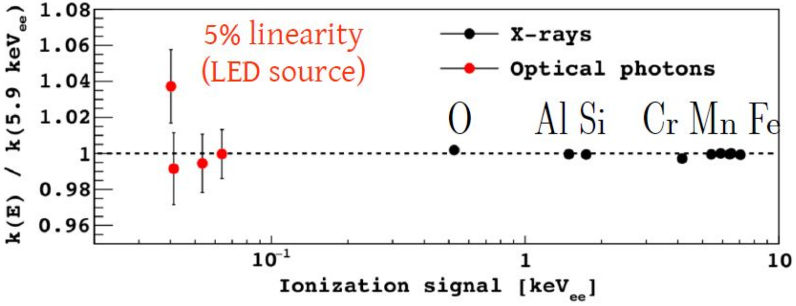
DAMIC. Calibration and Energy Resolution



Energy calibration using O, Alm Si, Cr, Mn, and Fe X-ray lines



CCD linearity down to 40eV$_{ee}$ with optical photons

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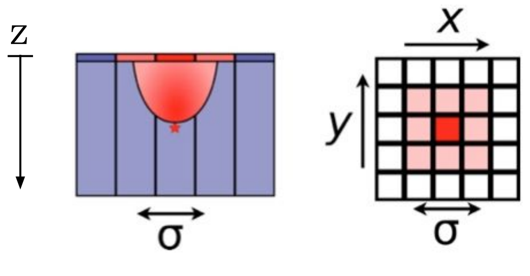
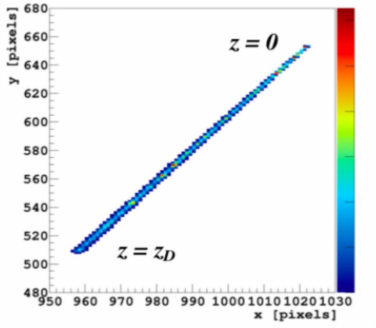
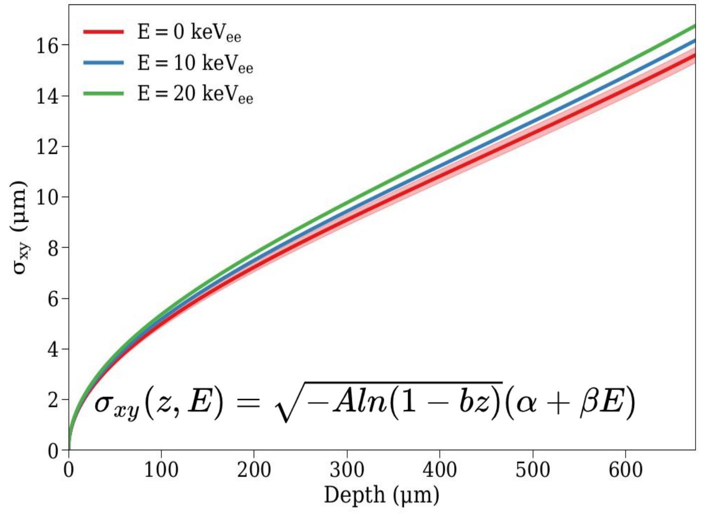
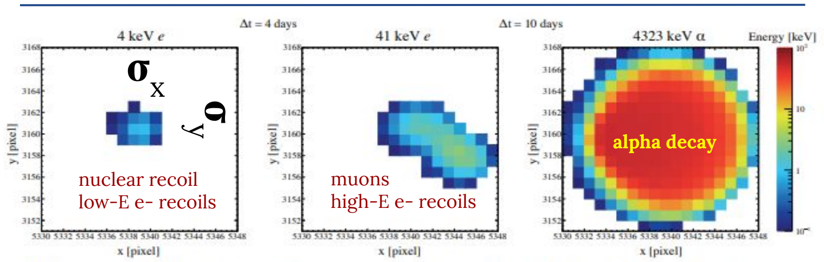
CCDs as Dark Matter Detectors. Charge Diffusion

Thermal diffusion causes **charge** to **spread out as it drifts.**
Muons give an excellent **calibration** for the **depth-dependence of sigma**





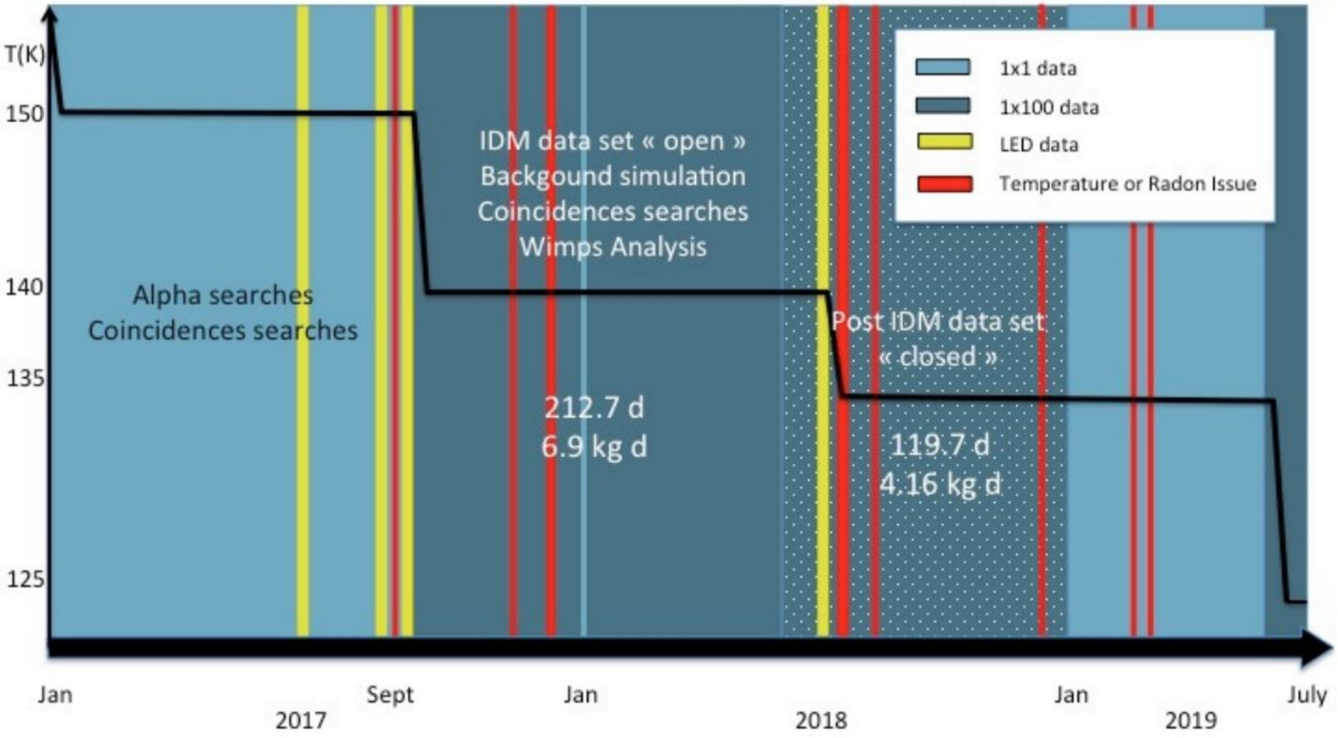




^{210}Pb ($T_{1/2}$= 22.3 y, β) ➔ ^{210}Bi ($T_{1/2}$=5.0 days, β) ➔ ^{210}Po ($T_{1/2}$= 138 days, α)

DAMIC: Main Results

DAMIC at SNOLAB: Data Acquisition



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DAMIC at SNOLAB. Main Results

Calibrations

- Compton Scattering [arXiv:1706.06053]
- Nuclear Recoil Ionization Efficiency [arXiv:1608.00957, arXiv:1702.00873]

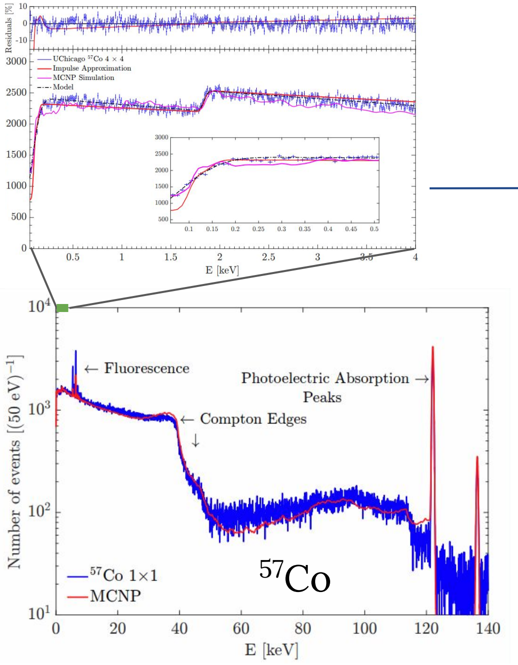


Fig. 1: Compton Scattering

Gammas

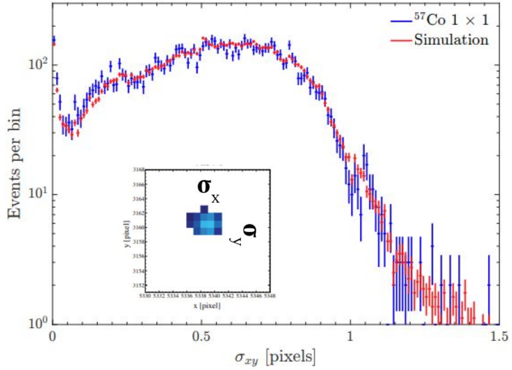
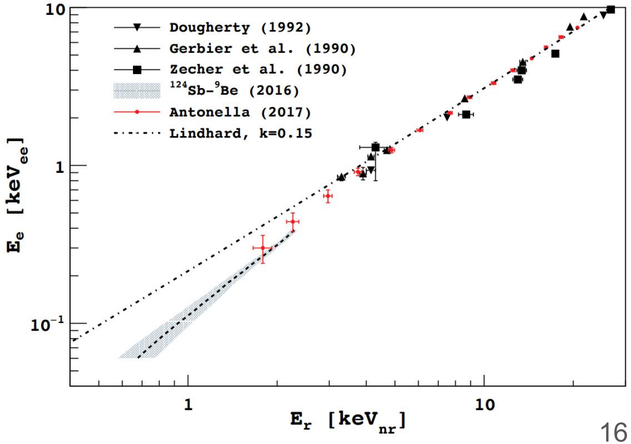


Fig. 2: Ionization Efficiency



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DAMIC. Main Results

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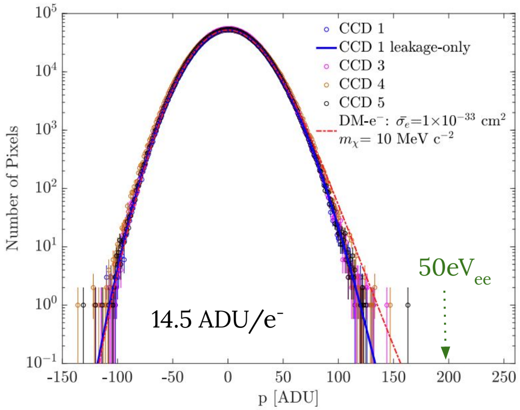
- Compton Scattering [arXiv:1706.06053]
- Nuclear Recoil Ionization Efficiency [arXiv:1608.00957, arXiv:1702.00873]

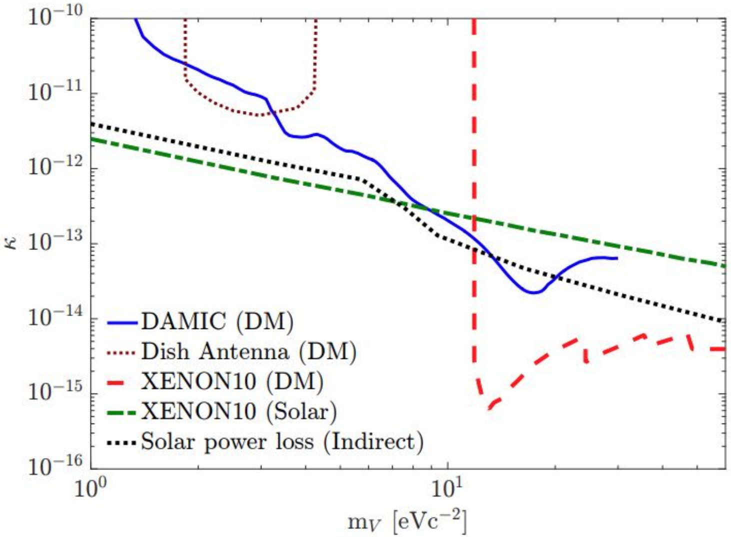
Backgrounds

- Radioactive Backgrounds Study [arXiv:1506.02562]
- Coincidence Analysis [arXiv:2011.12922]
- Full Radioactive Background Model [... in preparation]

Dark Matter Results

- Initial DM-Nucleon Scattering Limits [arXiv:1607.07410]
- **Hidden Photon Limits [arXiv:1611.03066]**
- DM-Electron Scattering Limits [arXiv:1907.12628]
- Full-Exposure DM-Nucleon Scattering Limits [arXiv:2007.15622]





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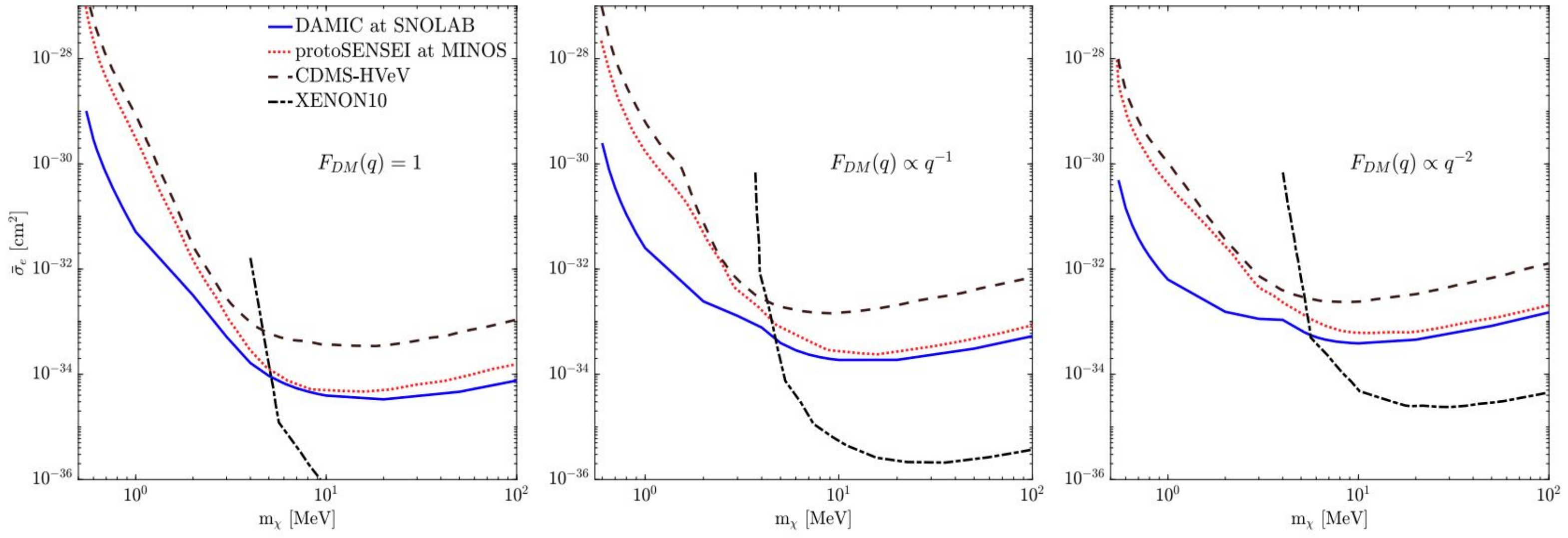
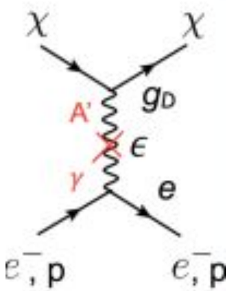
DAMIC. Existing results





- **DM-Electron Scattering Limits [arXiv:1907.12628]**

$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2}\, \eta(m_\chi, q, E_e)|F_{DM}(q)|^2|f_c(q, E_e)|^2$$

DAMIC. The latest results on WIMP Search

Results on low-mass weakly interacting massive particles from a 11 kg d target exposure of DAMIC at SNOLAB

A. Aguilar-Arevalo,[1] D. Amidei,[2] D. Baxter,[3] G. Cancelo,[4] B.A. Cervantes Vergara,[1] A.E. Chavarria,[5] J.C. D'Olivo,[1] J. Estrada,[4] F. Favela-Perez,[1] R. Gaïor,[6] Y. Guardincerri,[4,*] E.W. Hoppe,[7] T.W. Hossbach,[7] B. Kilminster,[8] I. Lawson,[9] S.J. Lee,[8] A. Letessier-Selvon,[6] A. Matalon,[3,6] P. Mitra,[5] C.T. Overman,[7] A. Piers,[5] P. Privitera,[3,6] K. Ramanathan,[3] J. Da Rocha,[6] Y. Sarkis,[1] M. Settimo,[10] R. Smida,[3] R. Thomas,[3] J. Tiffenberg,[4] M. Traina,[6] R. Vilar,[11] and A.L. Virto[11]
(DAMIC Collaboration)

2020 PhRvL 125x1803A

DAMIC. Existing results

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- Nuclear Recoil Ionization Efficiency [arXiv:1608.0095

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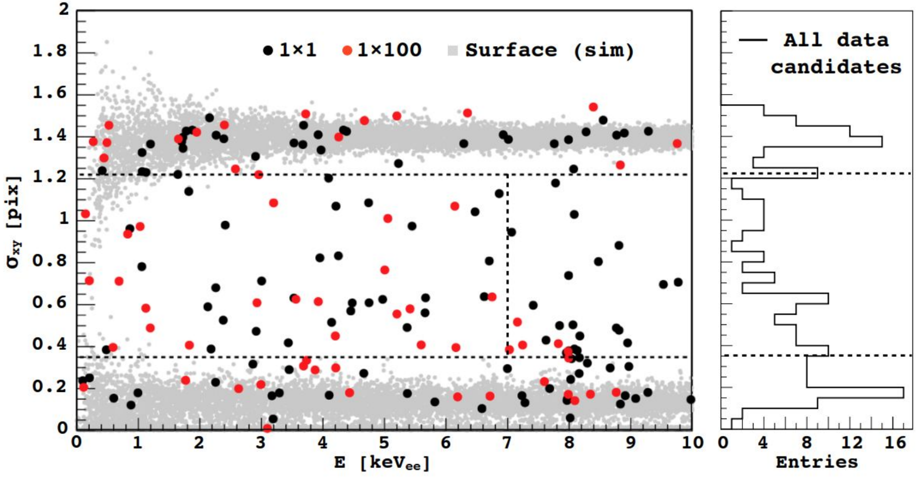
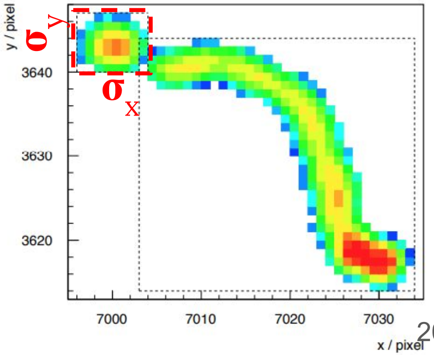
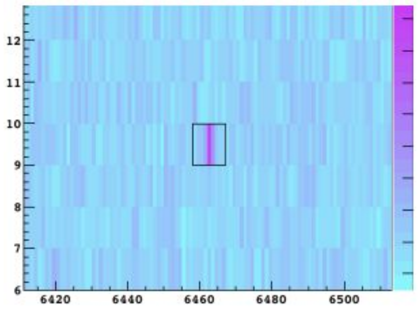


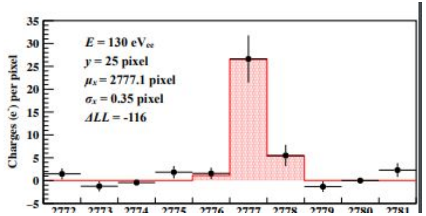
Lateral spread sigma

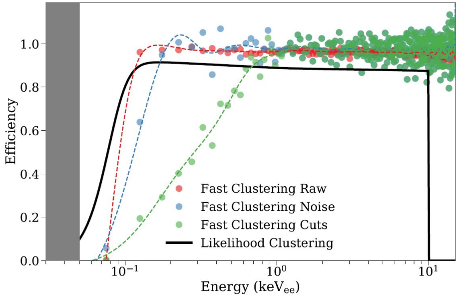


DAMIC. WIMP Search Methodology

1. 7 CCDs (40 g target mass) collected 11 kg-day of data over > 1 year
2. We **build a background model**
3. We compare the observed spectrum events with our modeled background
4. **THE EXCESS.** We measured an excess of 17.1±7.6 events above background model

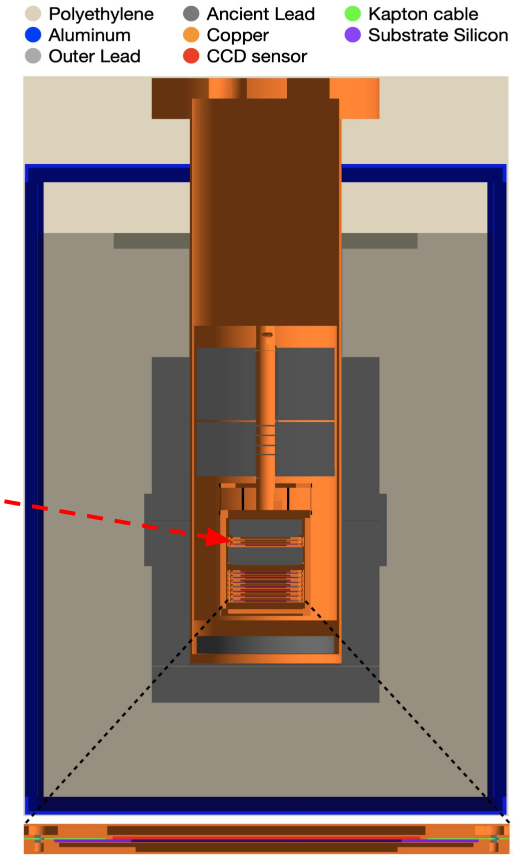






DAMIC. Background Model Methodology

1. Categorize detector backgrounds (ER: γ/β)
   - Assumption: neutron, muon, alpha → induced backgrounds are subdominant
2. Simulate full detector
   - Assumption: GEANT4 accurately simulates relevant decays down to threshold
3. Choose an energy region of interest (0.05-6keV$_{ee}$)
   - Threshold: below 0.05 keV$_{ee}$ our reconstruction efficiency is <10%
   - Maximum: above 6keV$_{ee}$ mostly sensitive to heavier DM (Mχ>10GeV)
4. Set aside some amount of data as a check (Ext 1)
   - Ext1 is sandwiched between two ancient lead bricks and has ½ the background
5. Perform a fit against data (assuming Poisson stats)
   - Assumption: no DM sensitivity in this mass range
   - Maximum endpoint ~20keV$_{ee}$ to include full tritium spectrum
6. Assemble weighted templated and extrapolate down to low energy to use in WIMP search



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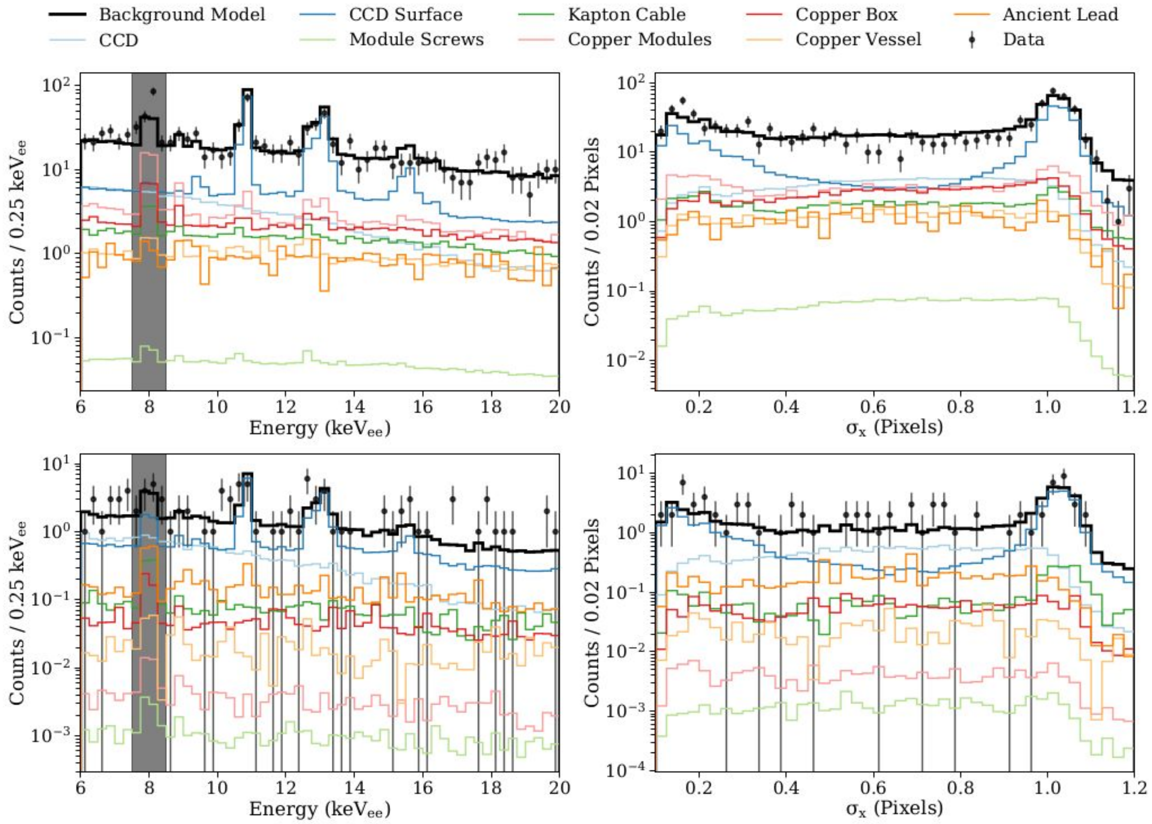
DAMIC. Background Model - Fit Results

CCD 2-7
2D template fit in E-σ_x space



CCD 1. Not a fit!
Based on CCD 2-7 result

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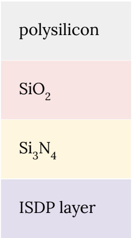
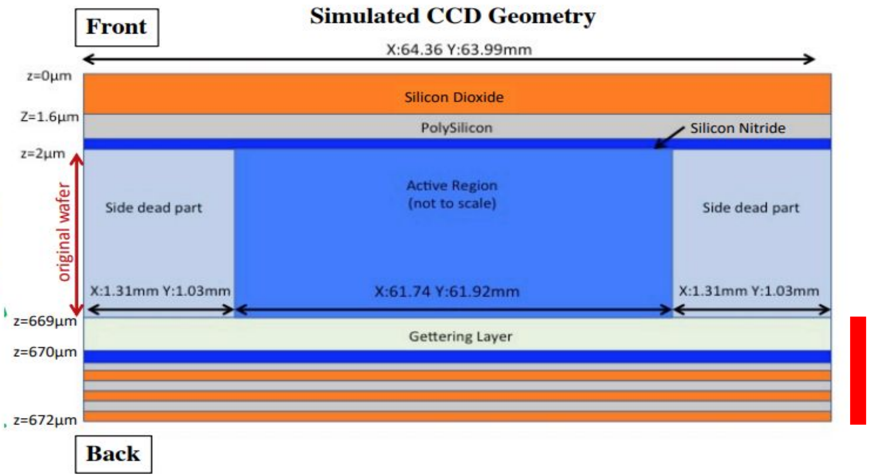
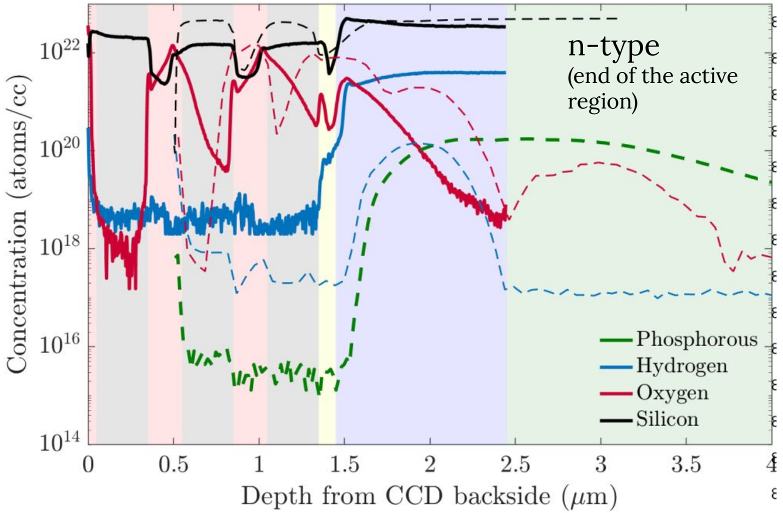
DAMIC. Partial Charge collection (PCC)



- CCD has a backside contact (gettering layer or ISDP), that contains Phosphorus (P) which diffuses a microns into the CCD bulk (green,dashed line)
  - Ionization charge will recombines with P → not all created charges will be recollected → Partial Charge collection





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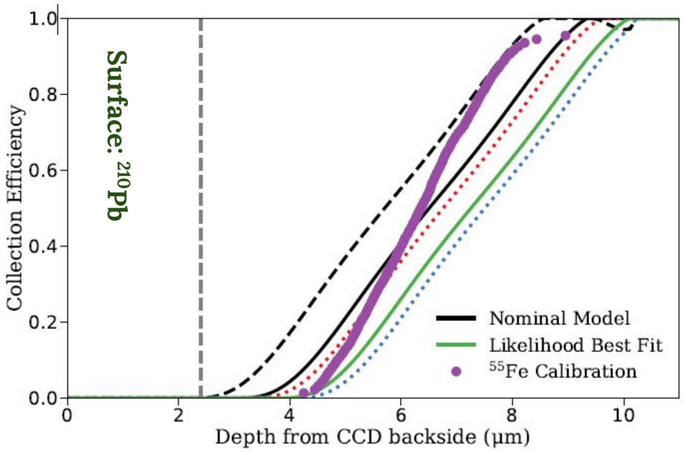
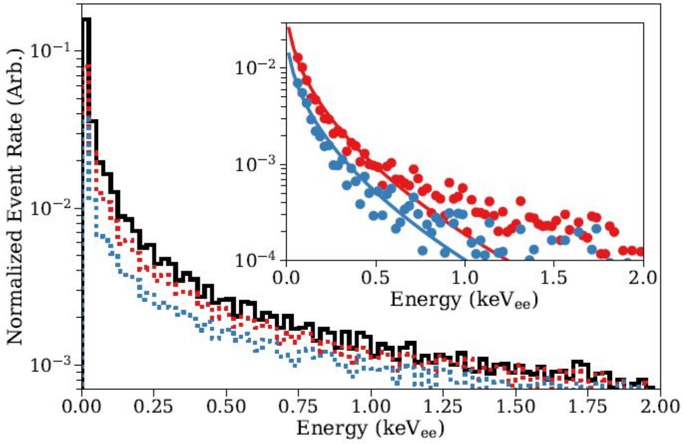
polysilicon
SiO_2
Si_3N_4
ISDP layer

DAMIC. Partial Charge collection (PCC)

- PCC causes spectral distortion for decays on CCD backside
  - Due to long exposure time on surface, DAMIC CCDs has a substantial amount of ^{210}Pb on the back side, being the PCC very important in our analysis
  - This distortion has been **parametrize from simulation** and included it as FREE component in our fit to DM search region

$$f(E) = Nexp(-\sqrt{E}/\alpha)$$





DAMIC. WIMP Likelihood Search @ Low Energy

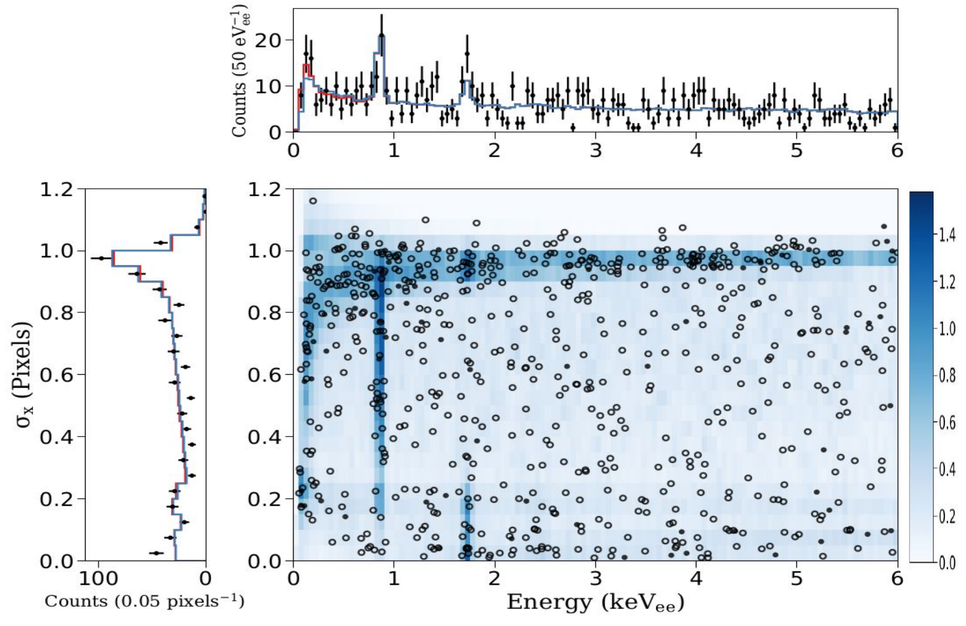
Final Fit:

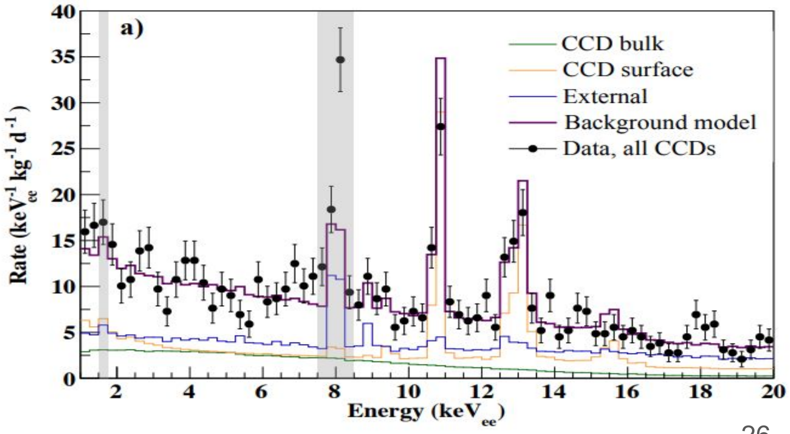
- Best background model
- Backside PCC spectral correction
- Exponential bulk signal

Main Result:

- Below 200eV$_{ee}$, there is **an excess of ~17 events**: *well described by a spatial bulk component with an* ***exponential energy profile*** (this form is the first order approximation for the most general DM models)

$$f_s(E|\epsilon) = \frac{1}{\epsilon} exp(-E/\epsilon)$$





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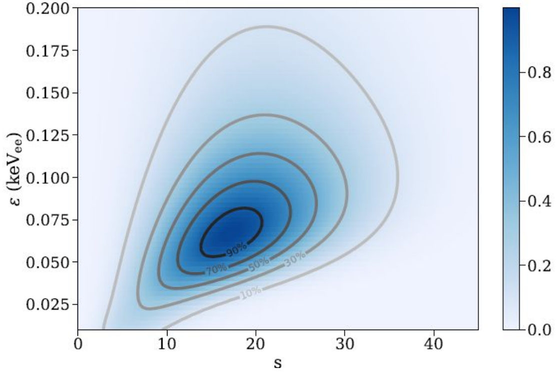
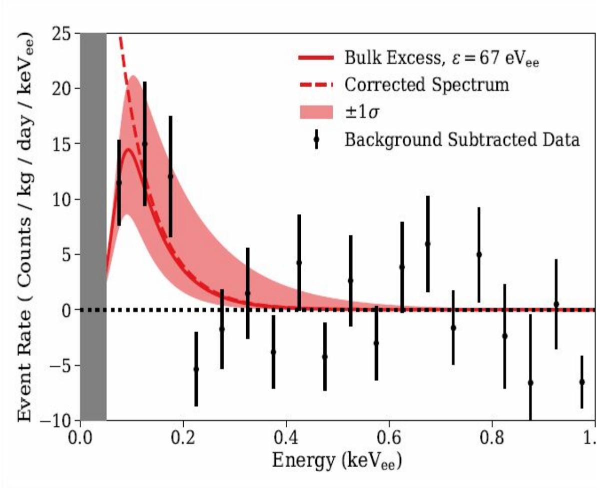
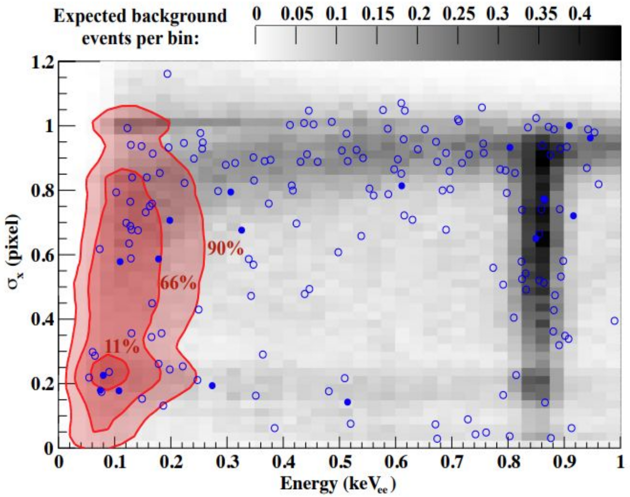
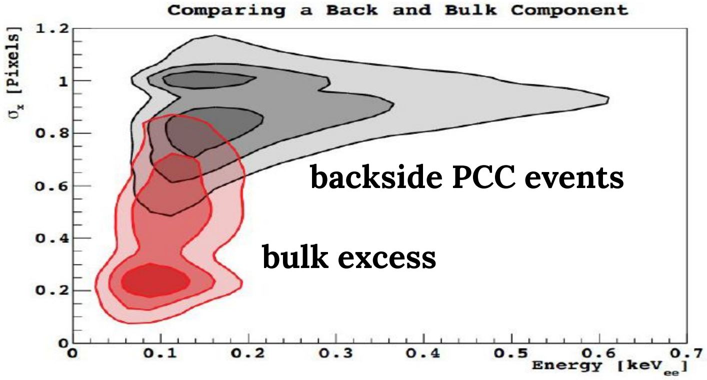
DAMIC. The Excess

$$f_s(E|\epsilon) = \frac{1}{\epsilon} exp(-E/\epsilon)$$





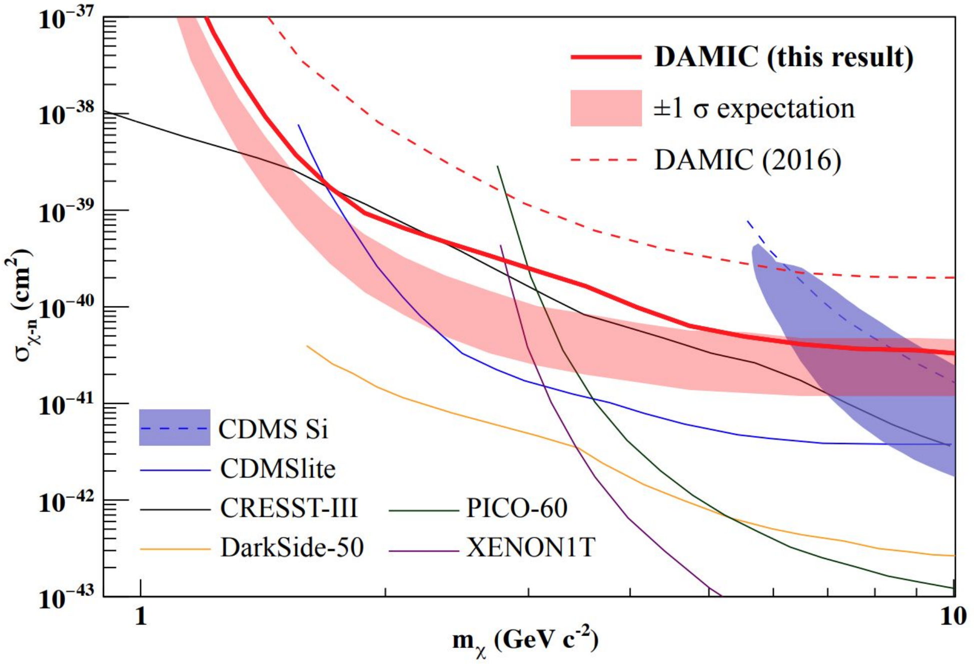




Potential source of excess

- Missing component in the background model
- Detector effect on the front side of the CCD
- Silicon new physics
- ...

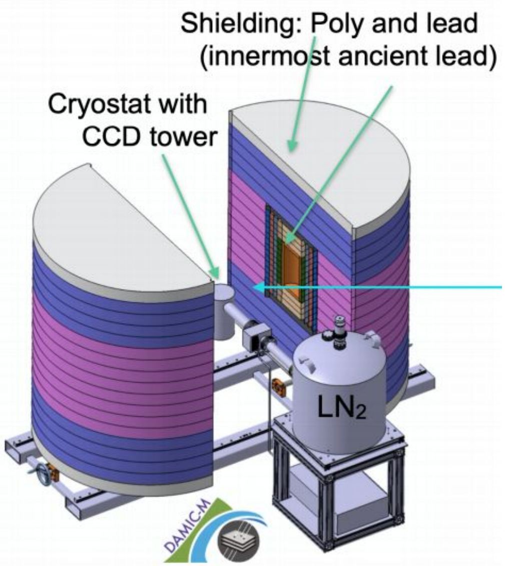
DAMIC. Background Model - WIMP Limits



- We report a limit on WIMP - nucleon Si interaction
- Significant fraction of the CDMS Si excluded

DAMIC-M
DArk **M**atter **I**n **C**CDs at **M**odane

Future: the next generation DAMIC-M



From DAMIC we know that

- CCDs are an innovative DM detector
- They have a very competitive low leakage current

But we can improve but just using Skipper CCDs

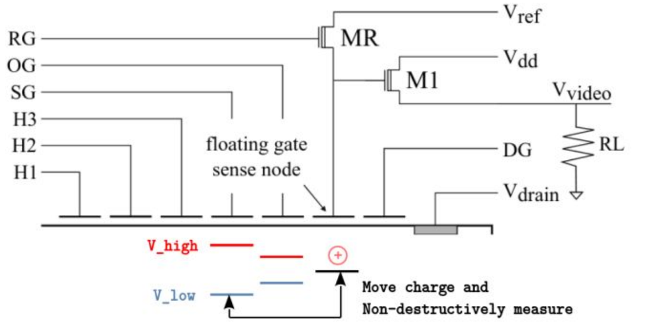
DAMIC-M

- 500 grams (10 times bigger)
- Redesigned to achieve 50 times reduction in background 5dru → 0.1 dru
- Using skipper CCD technology demonstrated in SENSEI
- Moving from SNOLAB to Modane (LSM) in France
- Approved, funded, prototype undergoing

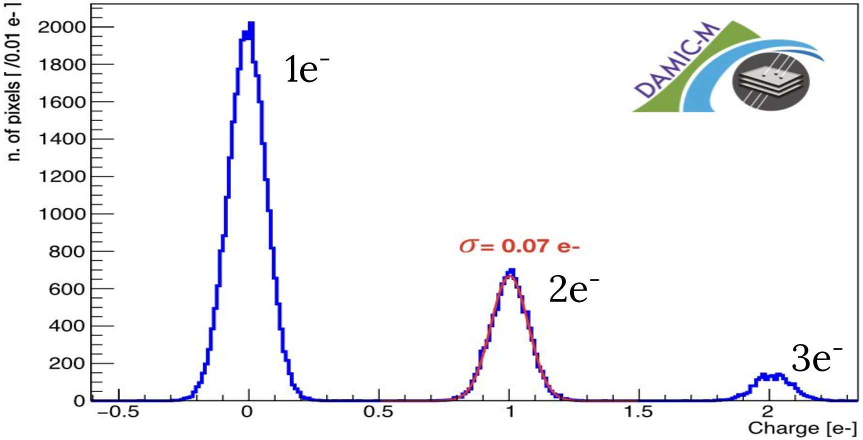
SENSITIVE to nuclear recoils, electron recoils, photon absorption from hidden photon

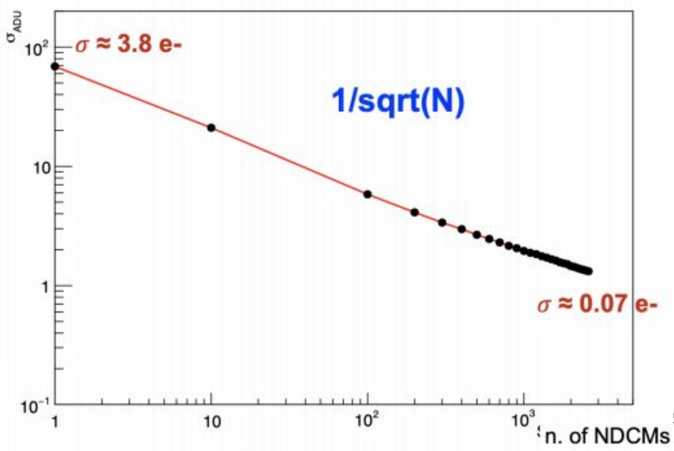
DAMIC-M: skipper CCDs → single electron resolution

standard amplifier → skipper amplifier



Tiffenberg, Javier, et al. PRL 119(13): 131802





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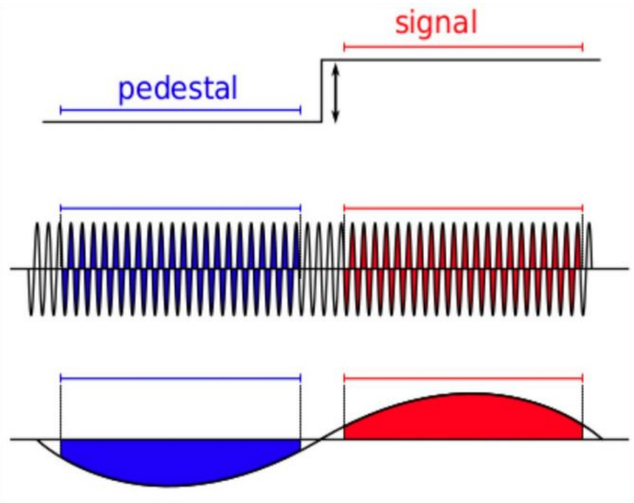
Lowering the noise: skipper CCDs

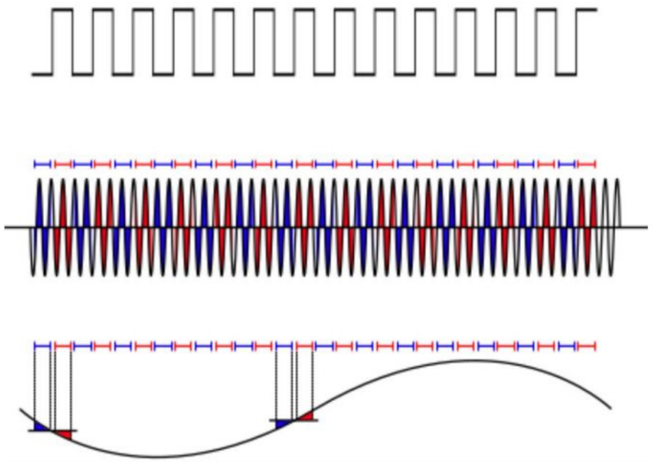
Conventional CCDs | **skipper CCDs**



pixel charge measurement

high frequency noise

low frequency noise

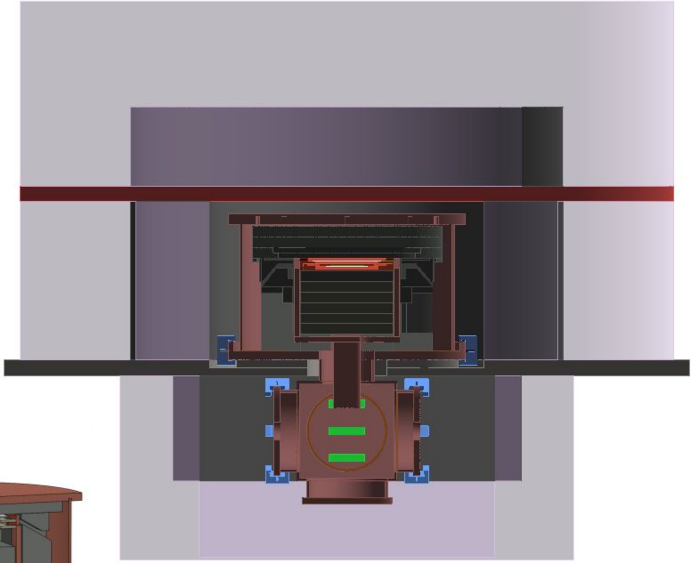


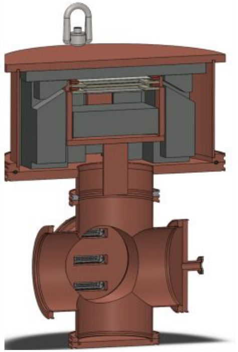
$$\text{pixel value} = \frac{1}{N}\sum_i^N (\text{pixel sample})_i$$

Main difference: the skipper CCD allows multiple sampling of the sample pixel without corrupting the charge packet.
The final pixel value is the average of the samples:
Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)

LBC (Low Background Chamber) the first phase of DAMIC-M

Geant4 Geometry

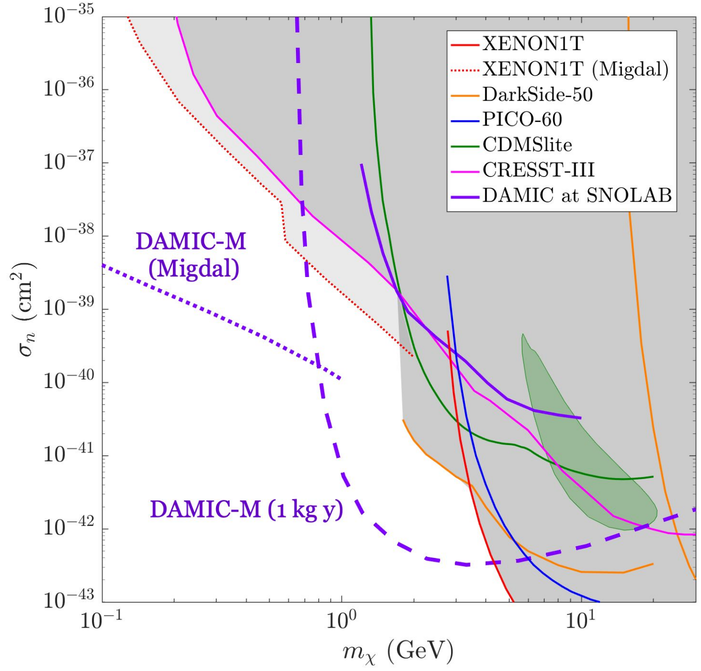




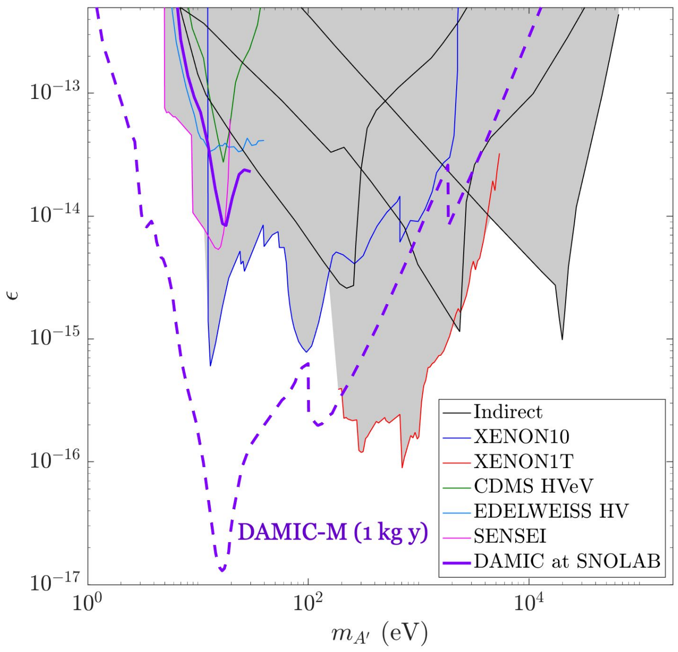
- A low-background chamber (bkg level a few dru) is in preparation
- Main objectives
  - Characterization of DAMIC-M CCDs in low-bkg environment: **dark current, 32Si rate, ^{210}Pb surface background, CCD packaging**
  - First science results with a few CCDs
- Almost ready to send all components to Modane
- **Starting to take data … end of this year!**

DAMIC-M. DM searches

WIMP nuclear recoil search

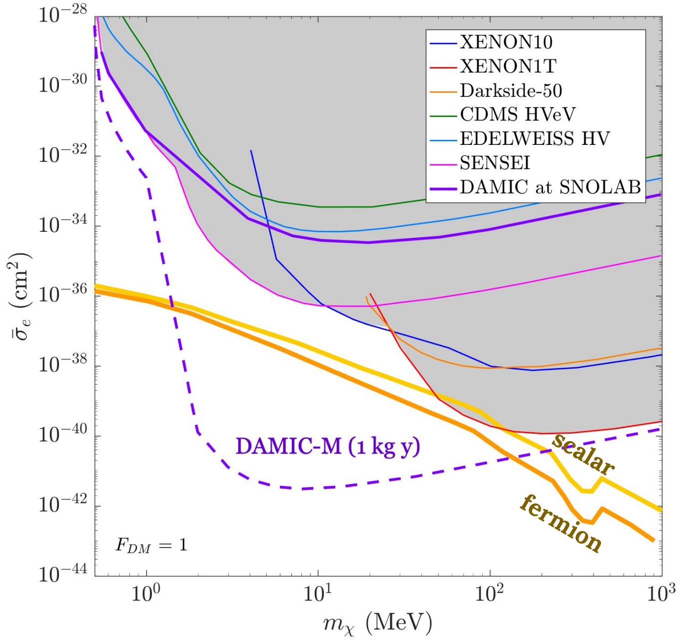


Hidden photon search

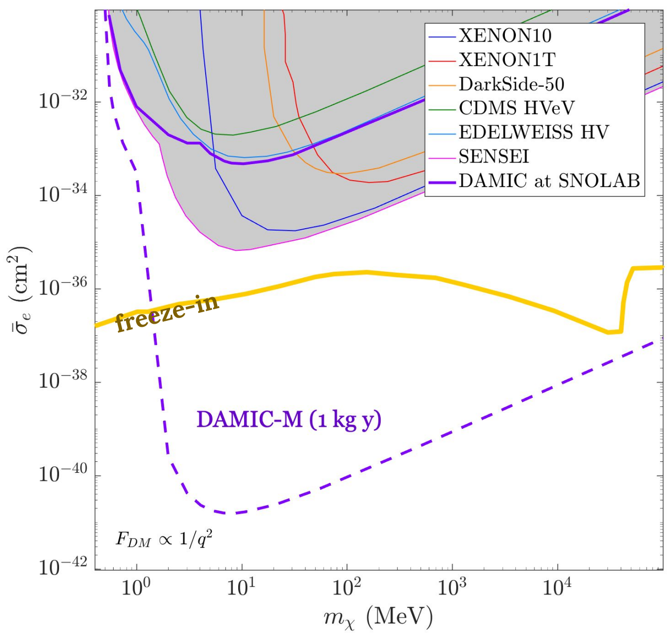


DAMIC-M. DM searches: DM-electron cross-sections

Heavy mediator >> keV



Light mediator << keV



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Summary

DAMIC-M is a new experiment at Modane (LSM)

- Sensitive to predicted cross-sections for several hidden photon DM candidates over 10 orders of magnitude in mass

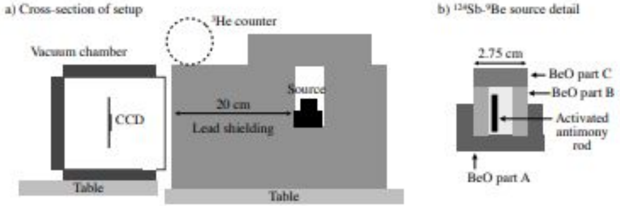
- Status
  - 2019-2021: R&D & prototype
  - 2021: Low-background chamber tests
  - 2022: Construction
  - 2023: Commissioning

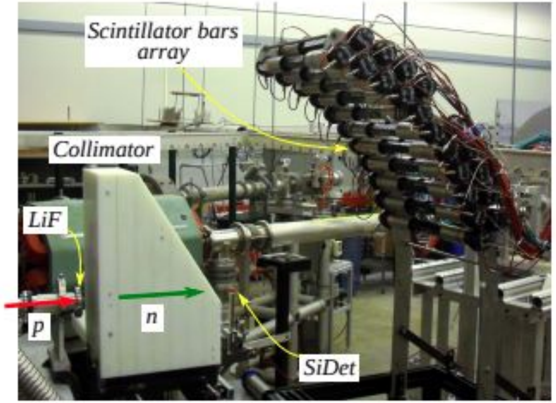
Future looks bright or perhaps if we are lucky dark!

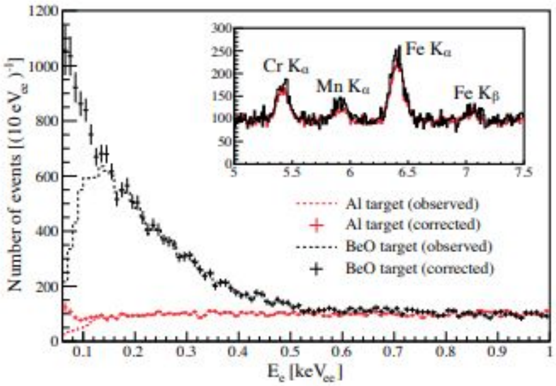
Extra slides

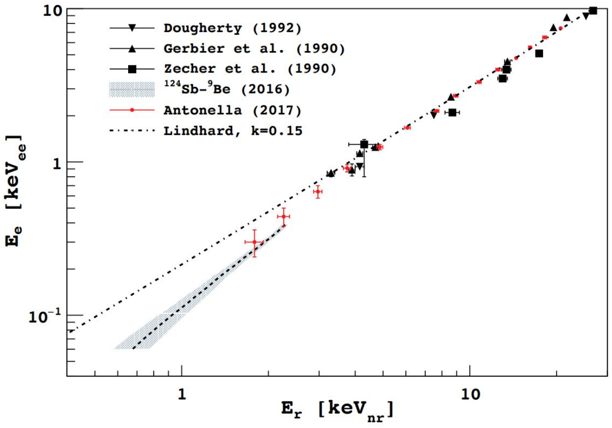
DAMIC. Nuclear Recoil Calibrations

low E neutrons







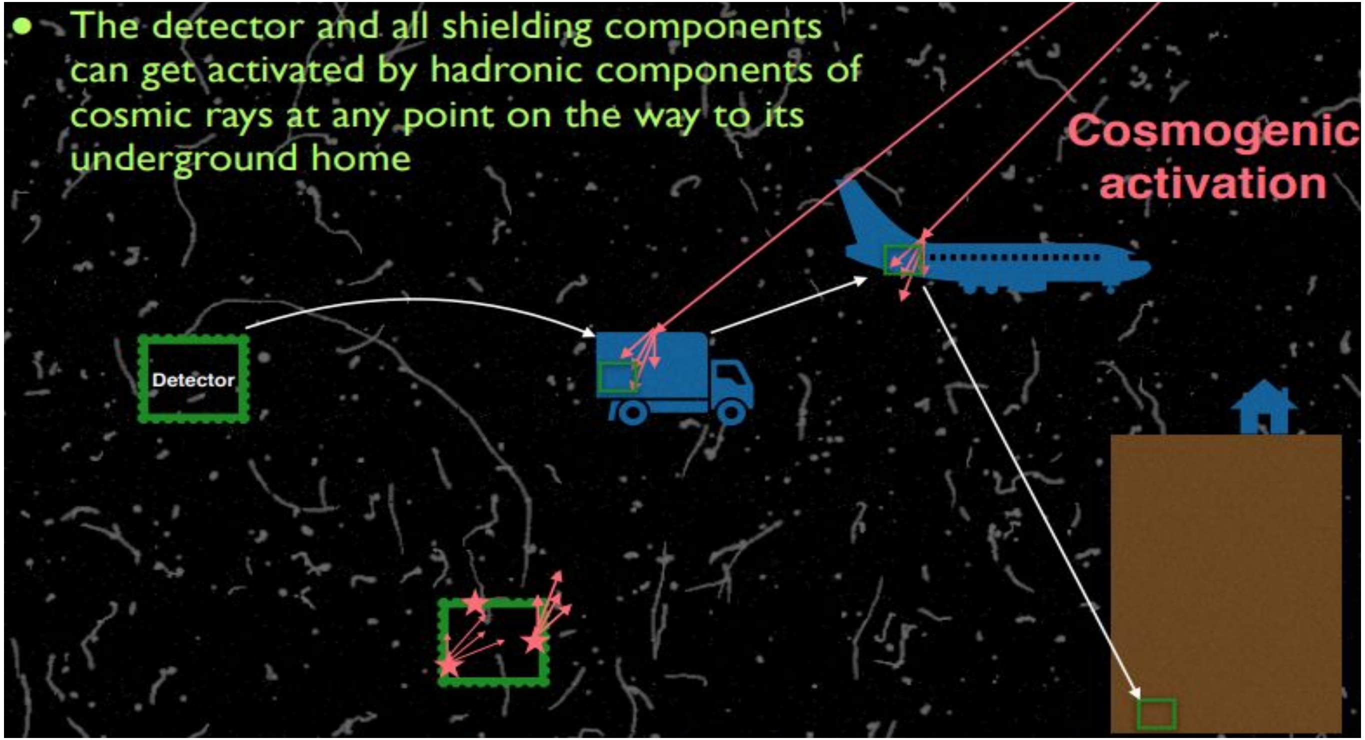


Mitigating radioimpurities in Silicon

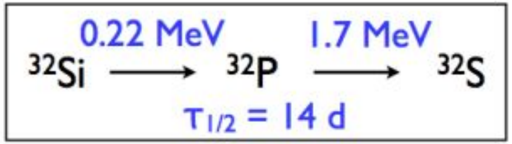
Cosmogenic activation:

- Tritium: half-life 12.5 years
- Uranium chain
- One particularly bad one is ^{32}Si
  - Half-life of 133 years
  - Silicon gathered at sea level - so affects all known silicon boules
- DAMIC has unique method for measuring impurities in silicon CCDs

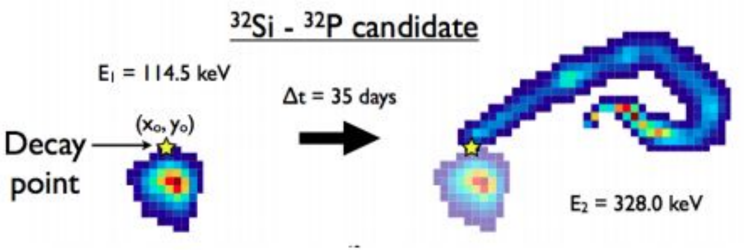
Mitigating radioimpurities in Silicon
Shipping detector components



Mitigating radioimpurities in Silicon
DAMIC measurement of cosmogenic ^{32}Si



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



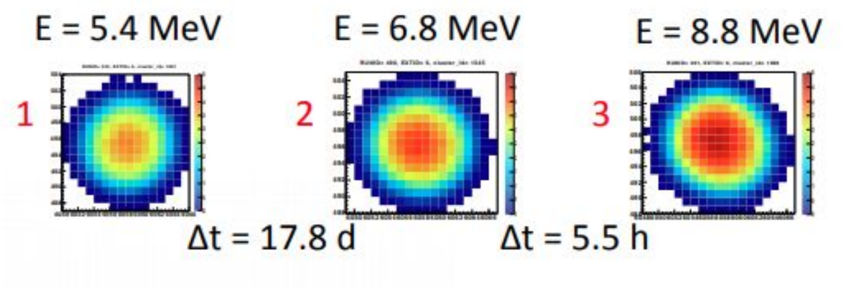
$^{32}\mathbf{Si} = 80^{+110}_{-65}\,\mathrm{kg}^{-1}\,\mathrm{d}^{-1}$ (95% CI)

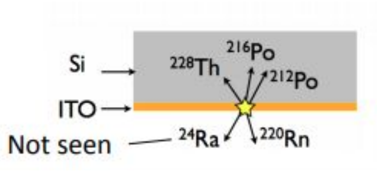
2015 *JINST* **10** P08014 1506.02562

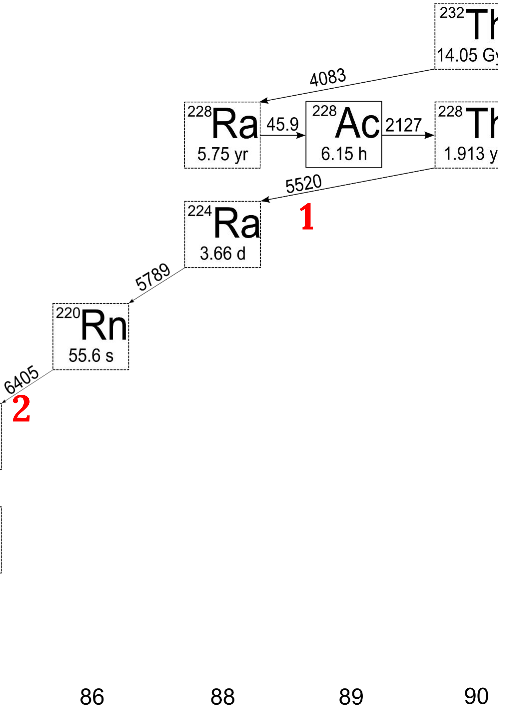
- New paper being reviewed with reduced uncertainties
- DAMIC unique spatial resolution and excellent duty cycle allows to reject this background (also other beta-beta sequences, as ^{210}Pb)

CCDs: Unique spatial resolution

Three alpha at the same pixel location!







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

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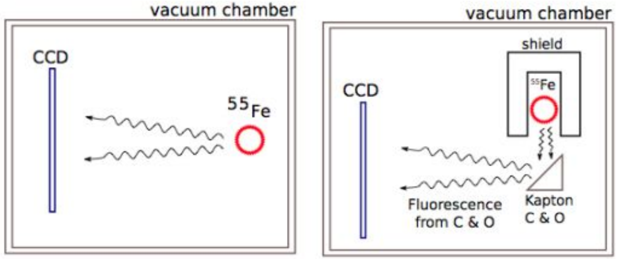
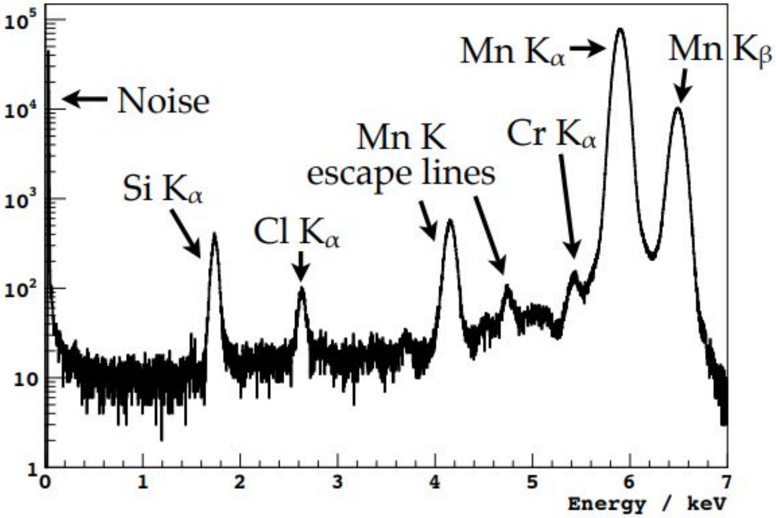
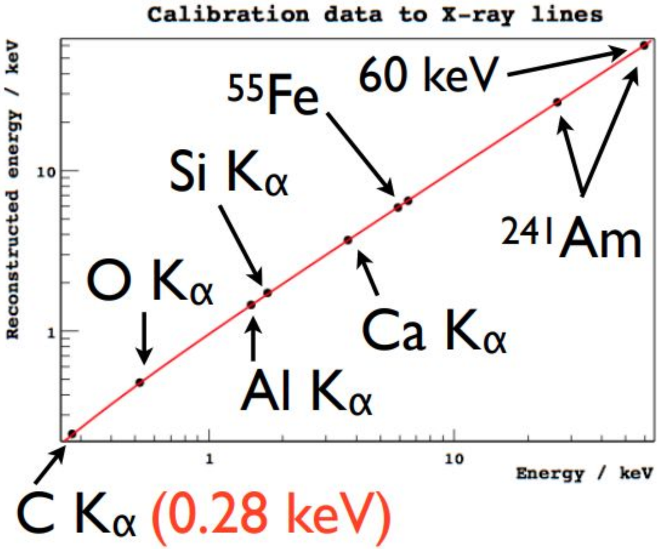
DAMIC. X-ray Calibration of CCDs



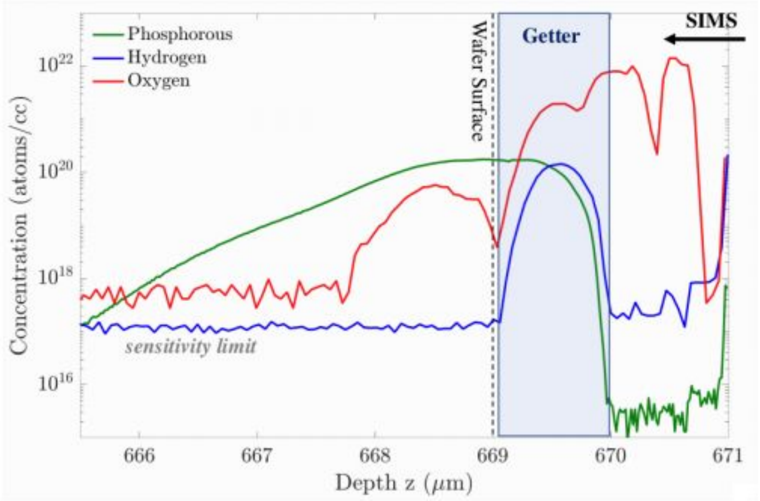
Linear response, good resolution!

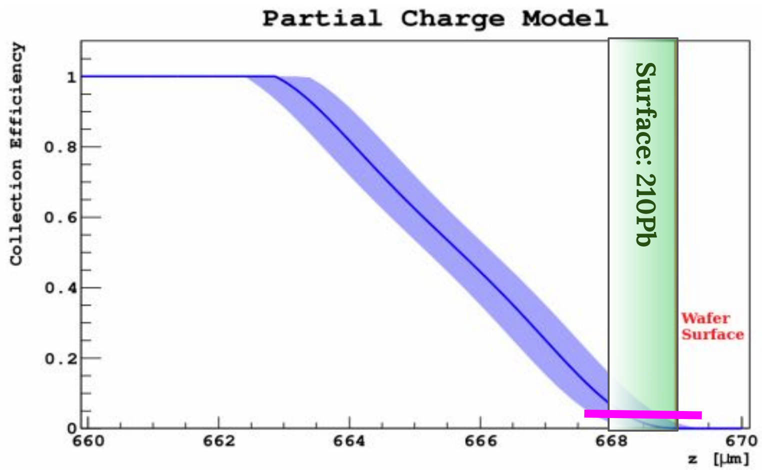




E resolution 53 eV at 5.9 keV

DAMIC. Background Model - Uncertainties





Phosphorus concentration

The full charge collection in our CCDs starts at 10 microns inside the active region → *non-negligible partial charge collection region!* (CCDs where in surface for a long period of time which lead to a substantial amount of ^{210}Pb)

PCC model: the spectrum essentially to first order only depends on where this endpoint is located. This dependency can be parametrized with an exponential

$$f(E) = Nexp(-\sqrt{E}/\alpha)$$

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