DAMIC@SNOLAB

DAMIC-M

DAMIC
(Dark Matter in CCDs)

Probing 10 orders of magnitude of dark matter mass using CCDs

Warwick EPP seminar, Feb. 11 2021

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Most of this :

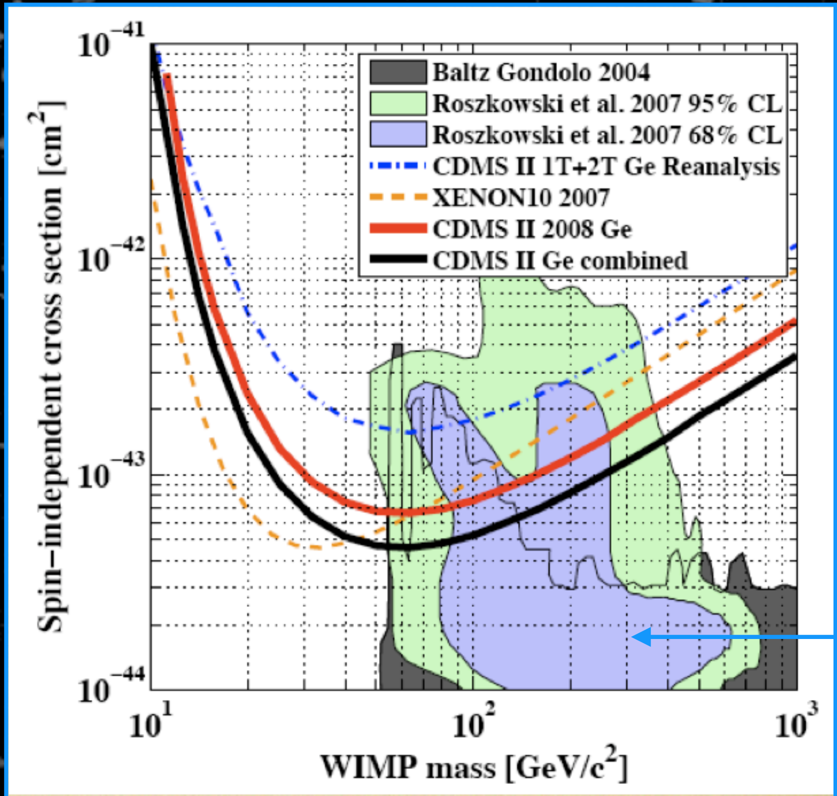
is dark matter

Where is it ?

Conventional wisdom :

Dark matter is a (yet undetected) weakly interacting particle (WIMP) motivated by supersymmetry (SUSY)

2007 : Prospects for SUSY dark matter



Cross-section

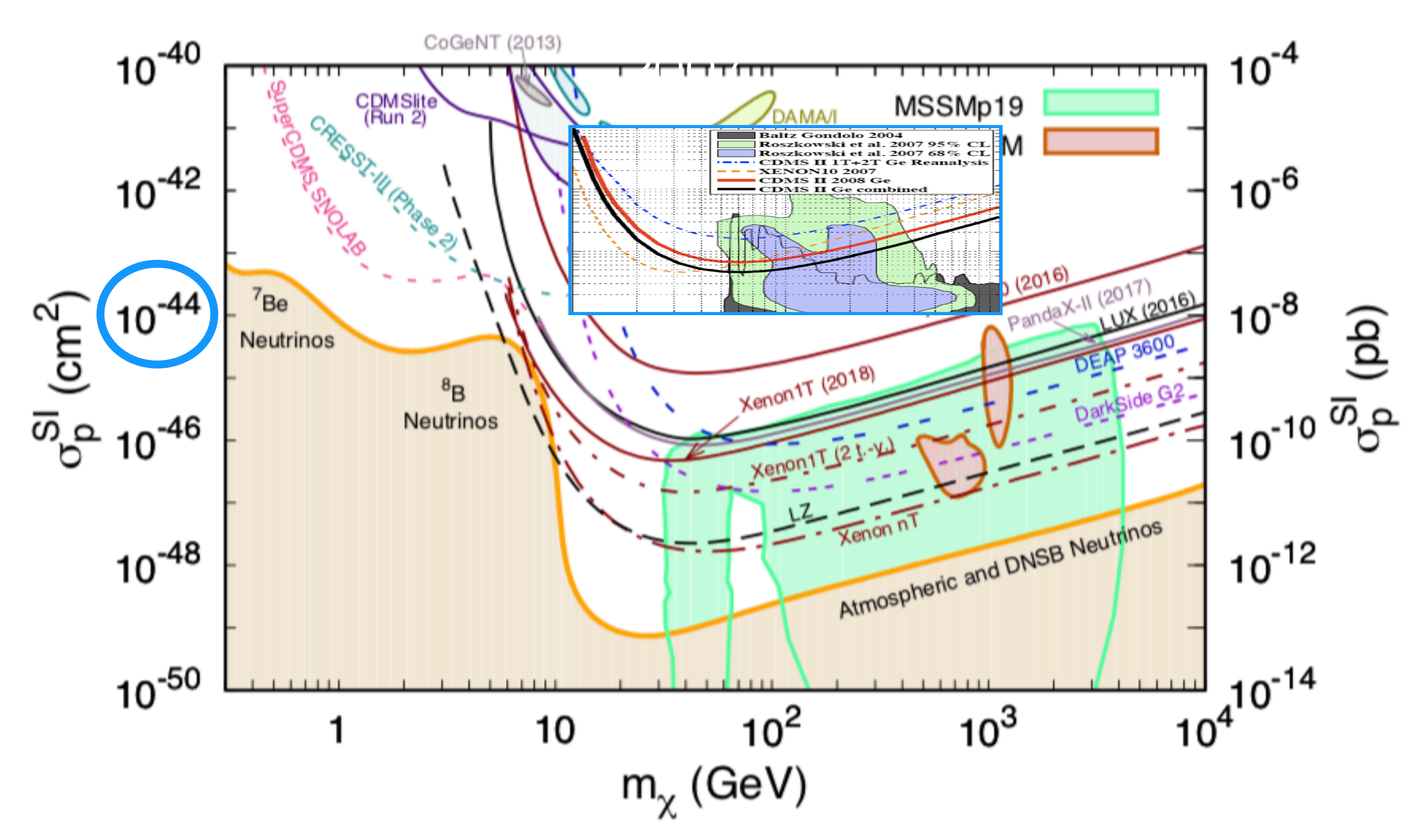
10^{-44} cm²

Mass of WIMP dark matter

Experimental searches

SUSY favored region

~Today



SUSY is a moving target

Naturalness of Dark Matter Mass scale

Standard WIMP :

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

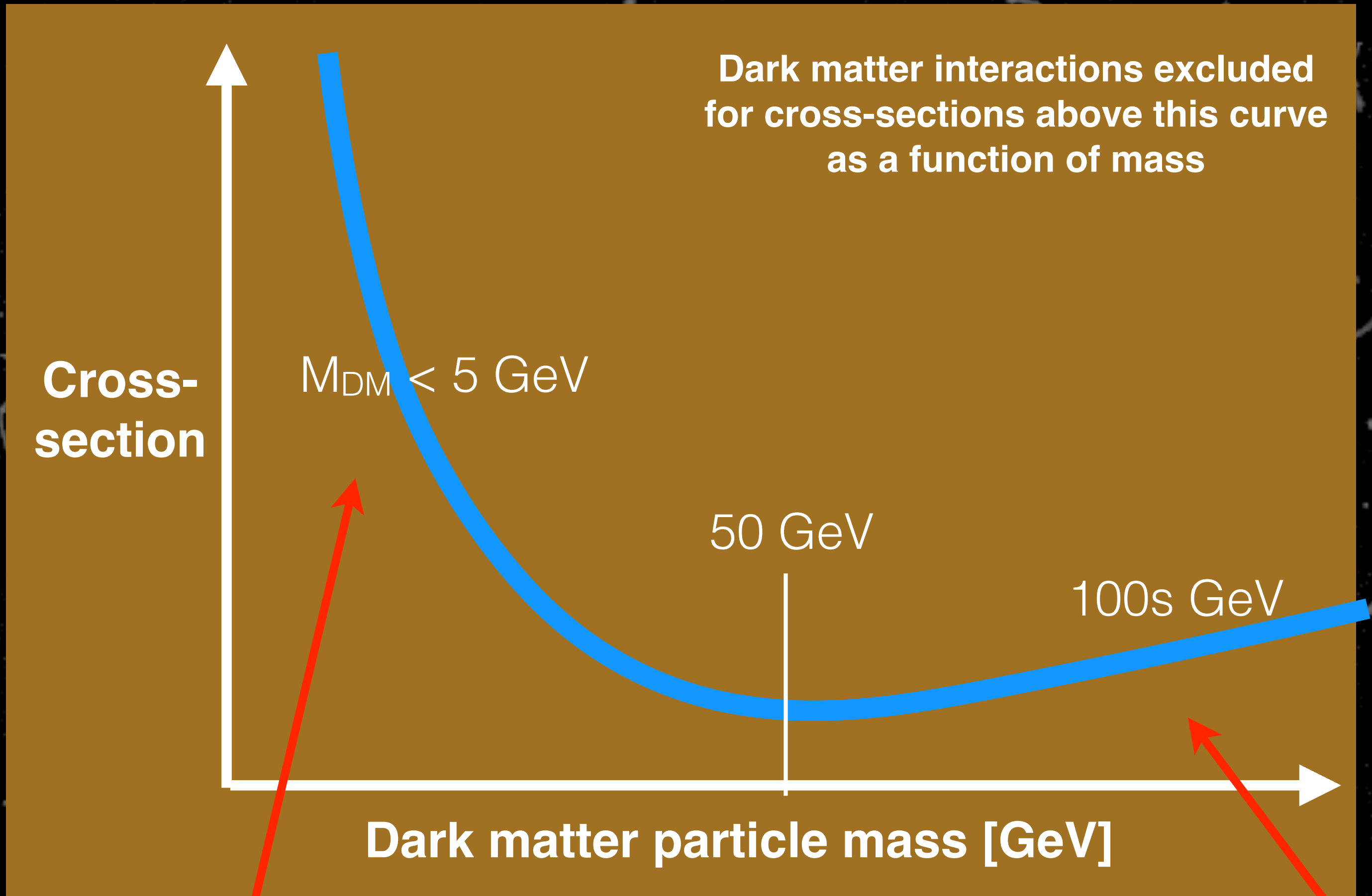
- Coincidence that SUSY weak cross-sections provide DM density relic Ω_{DM}

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 :
     → $M_{DM} = 5 * M_{proton}$

Asymmetric DM
hep-ph/1111.0293

Typical limit plot of DM search

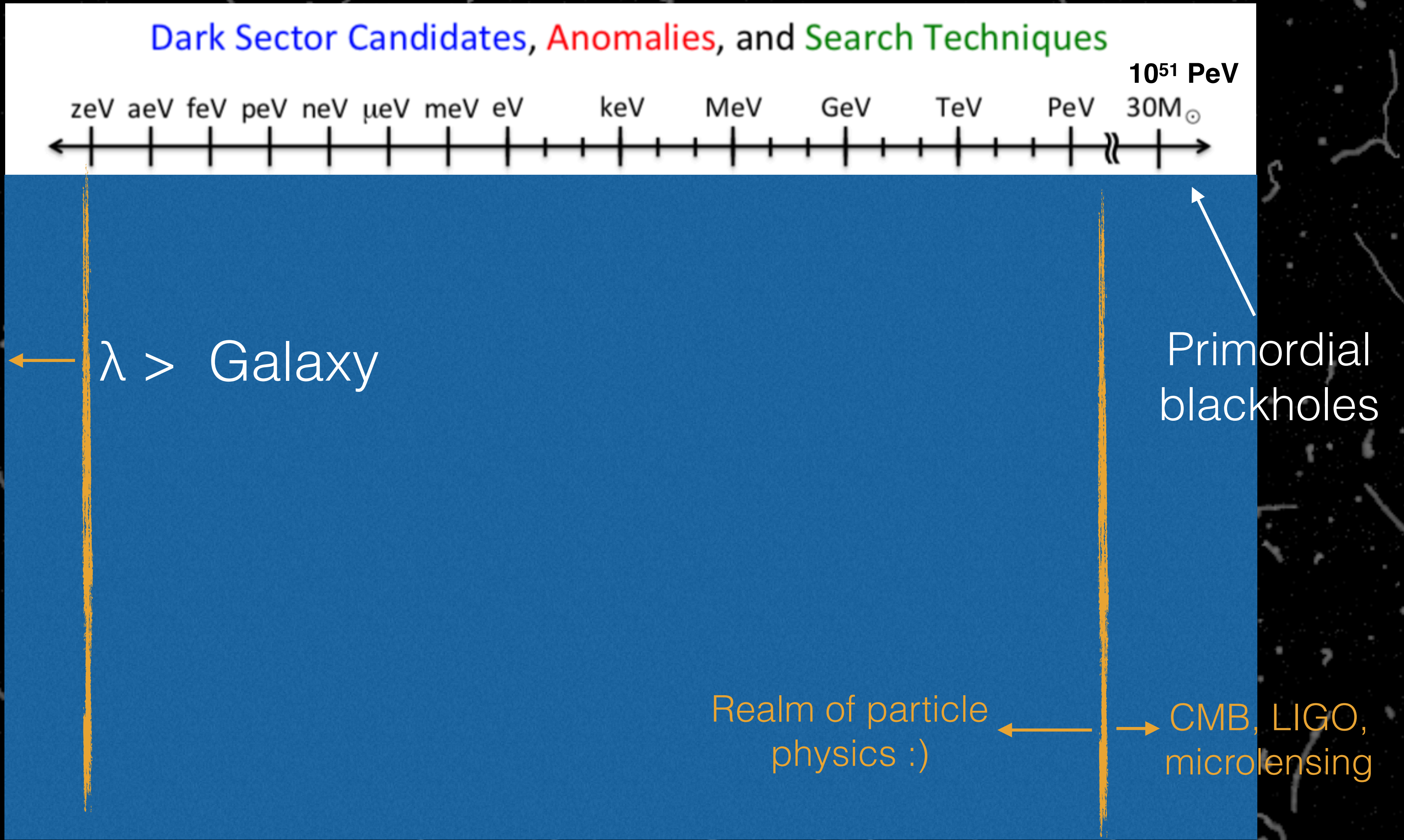


Baryon-DM coincidence:
Limited by energy threshold
(need to detect lower energies)

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

Revisiting dark matter

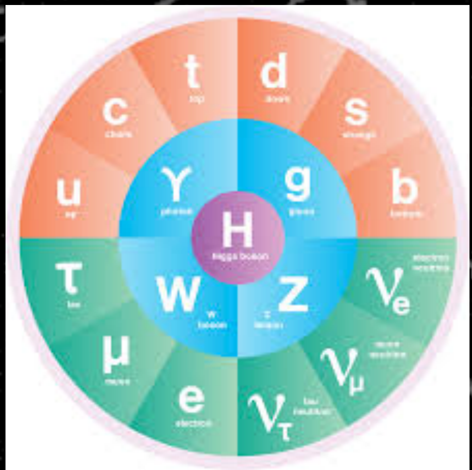
Dark matter candidates



U.S. cosmic visions report 1707.04591

Reexamine simple assumptions

- Matter 15% of universe mass



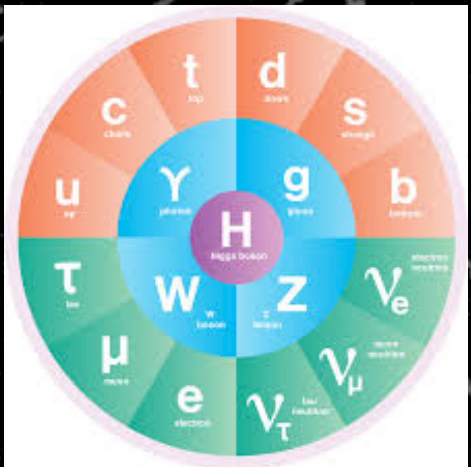
Rich substructure of forces and particles

- Dark matter 85% of universe mass

1 particle ???

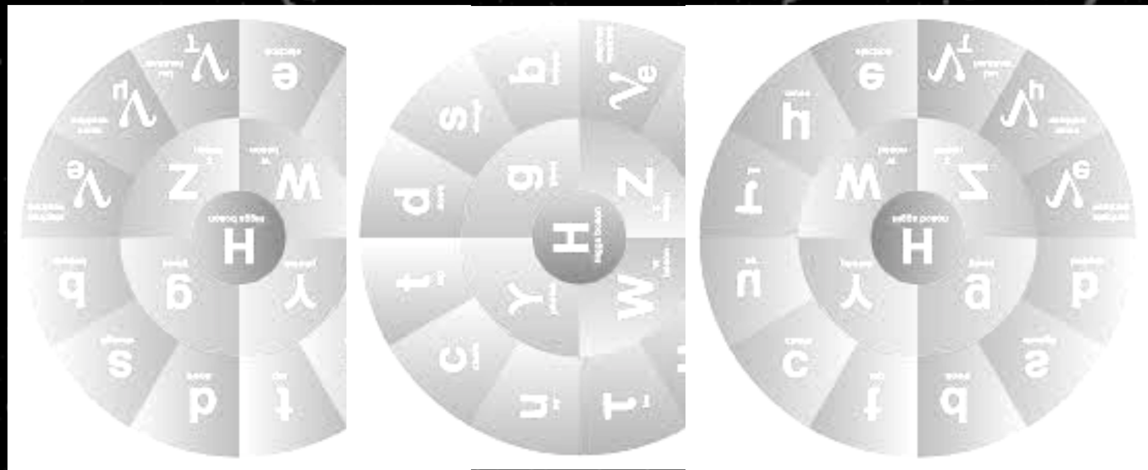
More likely

- Matter 15% of universe mass



Rich substructure of forces and particles

- Dark matter 85% of universe mass



Perhaps even more rich set of hidden forces and particles

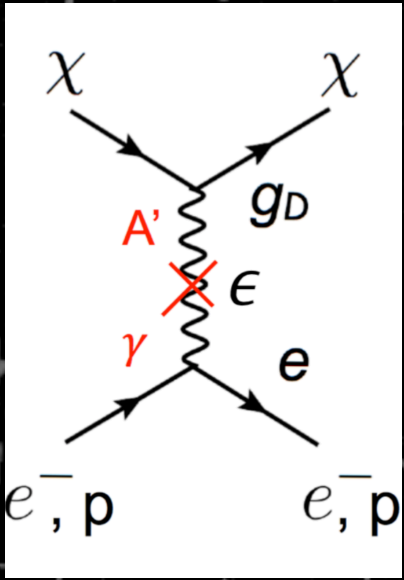
Yet $\rho_{DM} \sim \rho_{B}$ implies some connection between them

A strong possibility

- Hidden photon, A'
  - Hidden sector connected to thermal history of universe
    → its interactions set the relic DM abundance
  - Perhaps the only hidden particle that communicates with SM particles besides through gravitation
  - Interaction is many orders of magnitude below the weak interaction
  - A' interacts with SM by kinetic mixing with the SM photon

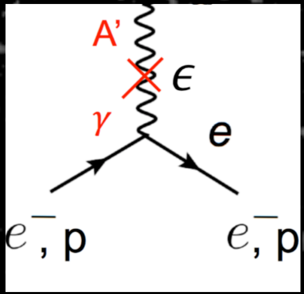
A' couples to SM particles with electric charge

Case 1:



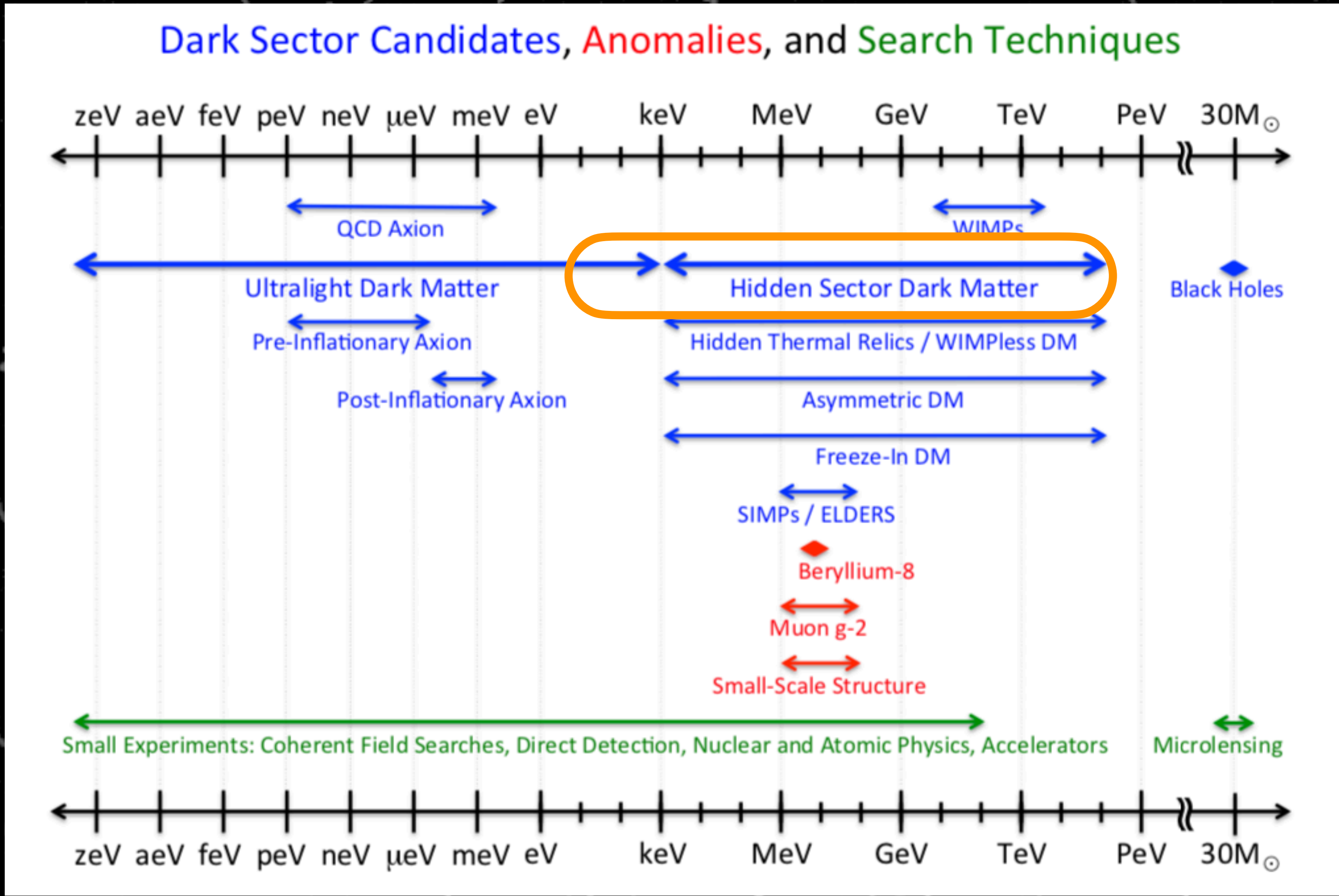
A' mediates DM-M interaction

Case 2:



A' is DM

Dark matter candidates



U.S. cosmic visions report 1707.04591

Low-mass direct dark matter searches

TeV → GeV → MeV → keV → eV→ meV

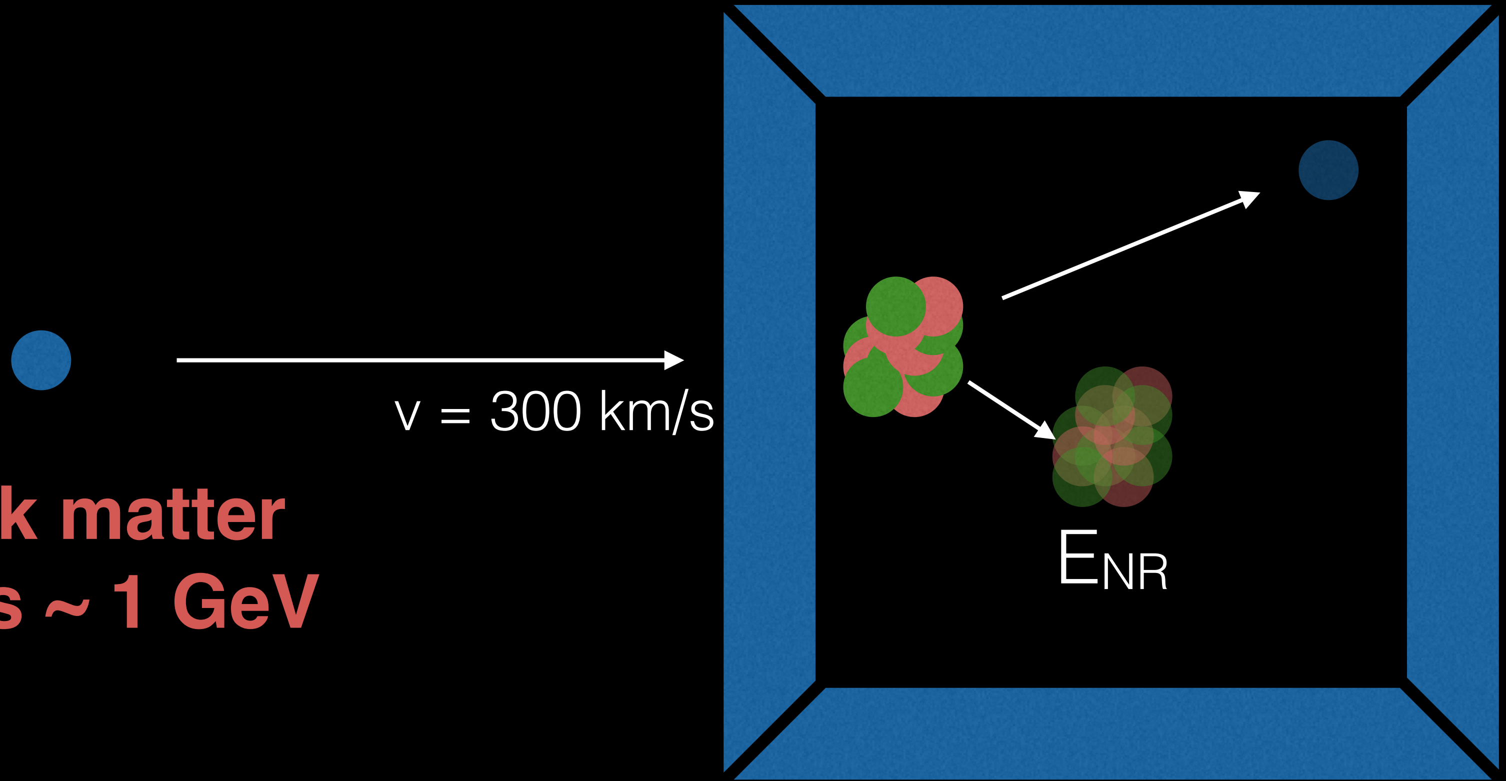
How far can we go ?

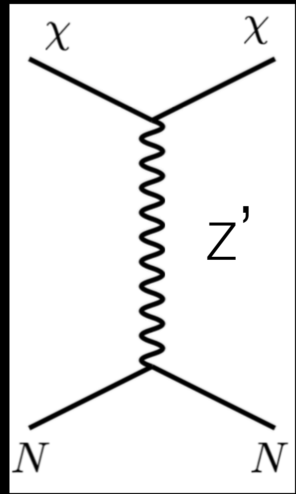
Depends on the detector

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

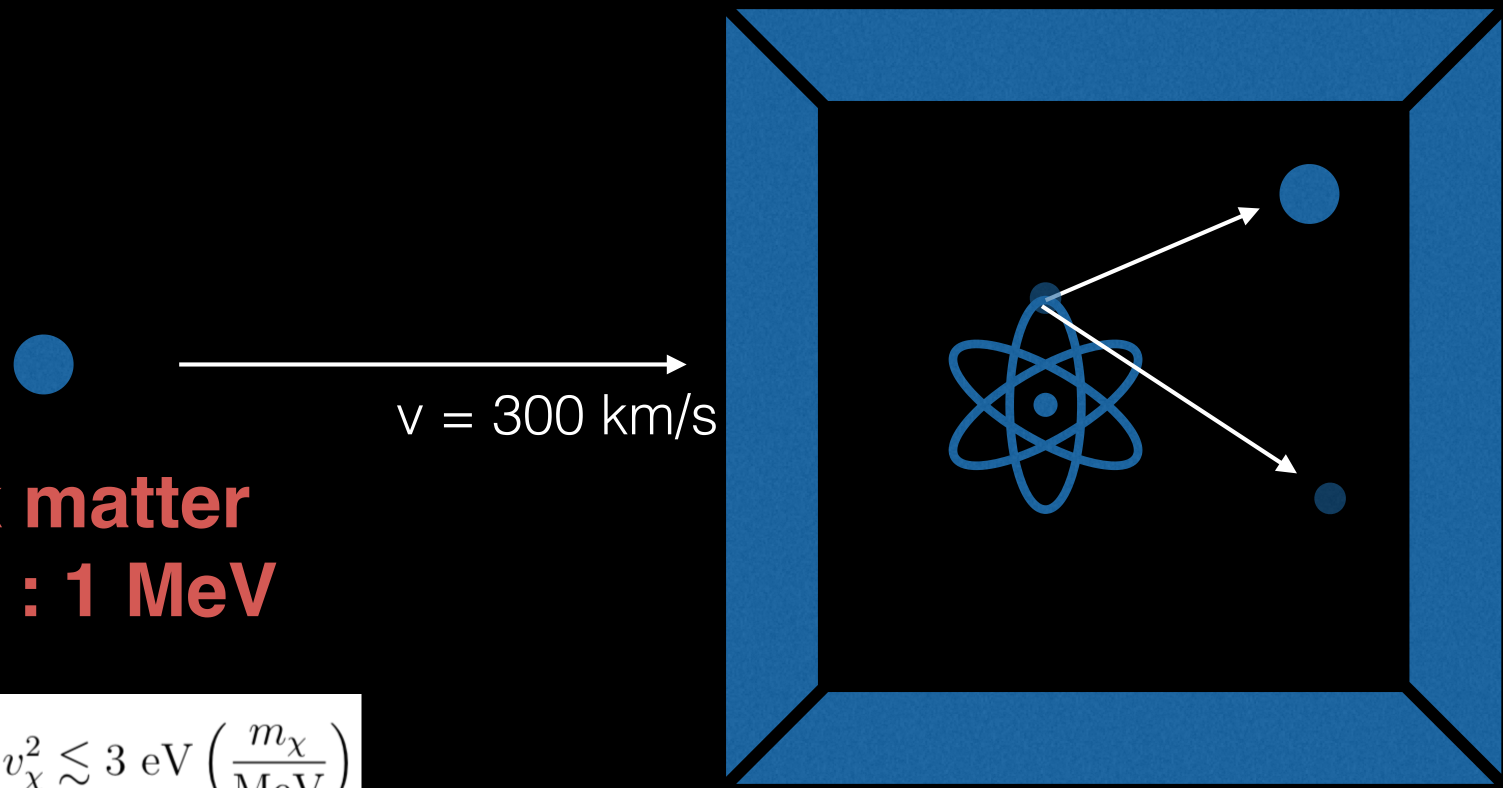
E_{NR} ~ 500 eV

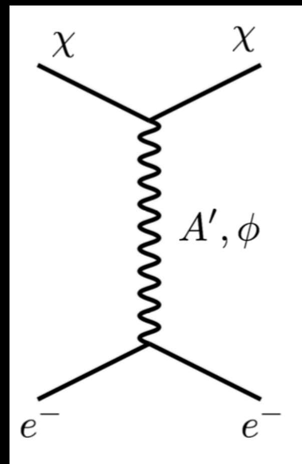
E_{ioniz} ~ 50 eV

Hidden photon mediating DM (m_{DM} ~ MeV)

DM-electron elastic scattering

- Kinetic energy of DM becomes the ionization energy measured





Dark matter
Mass : 1 MeV

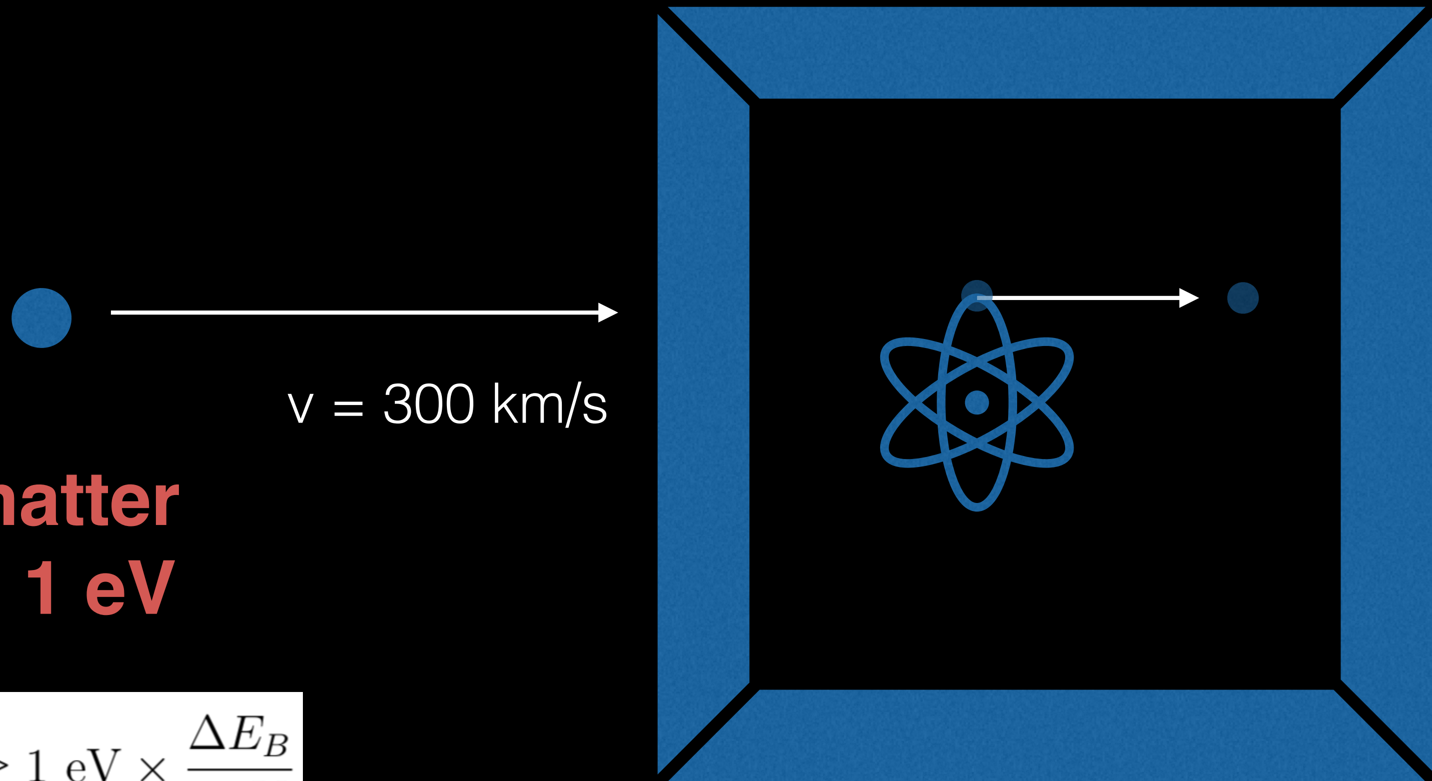
$$E_e \leq \frac{1}{2} m_\chi v_\chi^2 \lesssim 3 \text{ eV} \left(\frac{m_\chi}{\text{MeV}}\right)$$

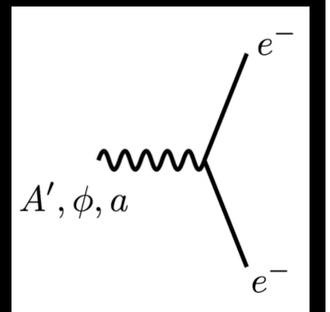
E_{ioniz} ~ 3 eV

Hidden photon as DM (m_{DM} ~ eV)

Electron absorbs bosonic DM, and recoils

- Mass of DM becomes the ionization energy measured





Dark matter
Mass : 1 eV

$$m_\chi \geq 1 \text{ eV} \times \frac{\Delta E_B}{1 \text{ eV}}$$

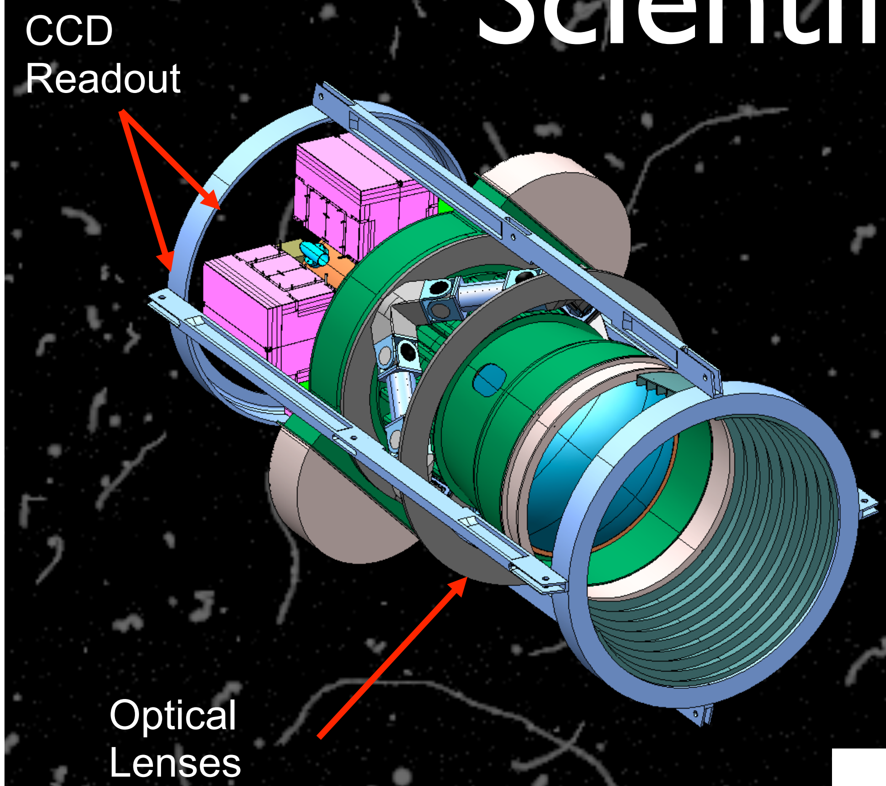
E_{ioniz} ~ 1 eV

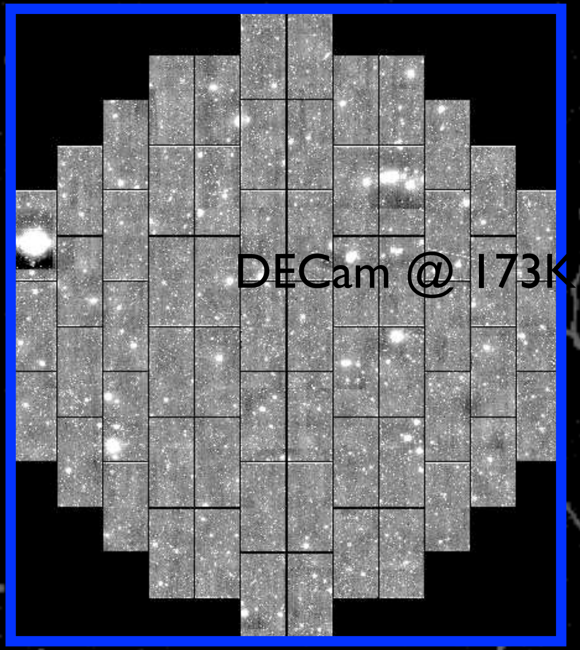
We want to detect ionization energies down to ~ 1eV

We need a low-energy threshold Detector

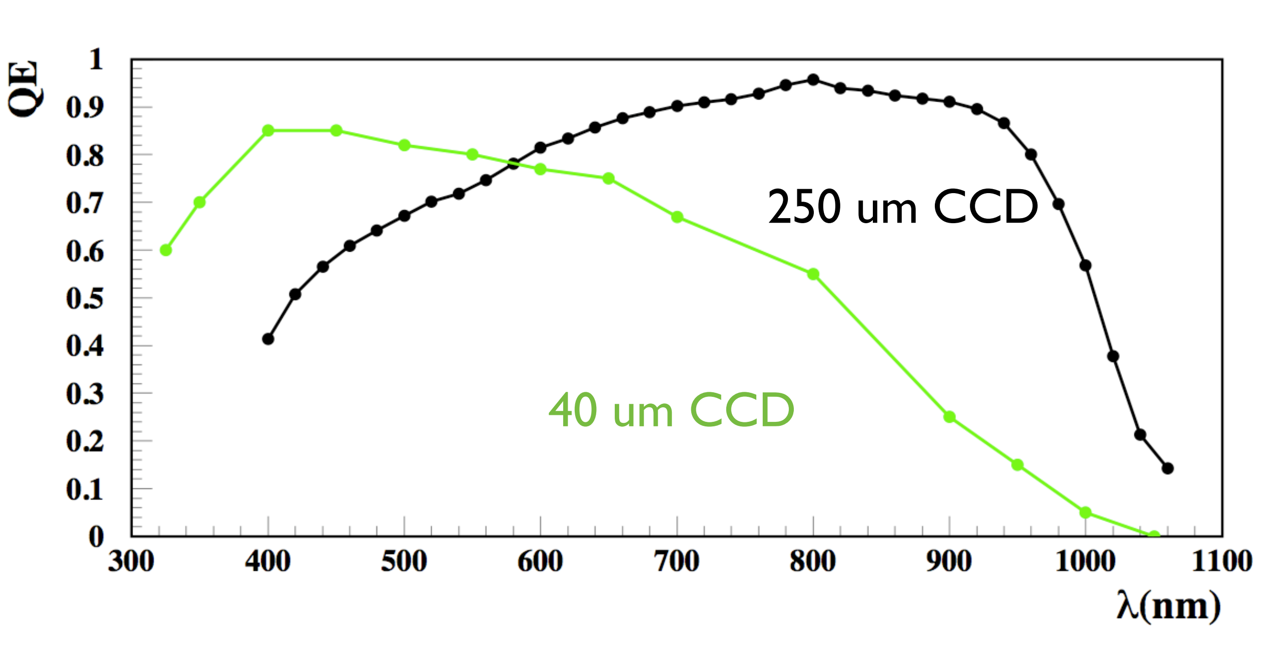
(the start of my talk)

Scientific CCDs





Images collected on ~60 CCDs ~600 Mpix

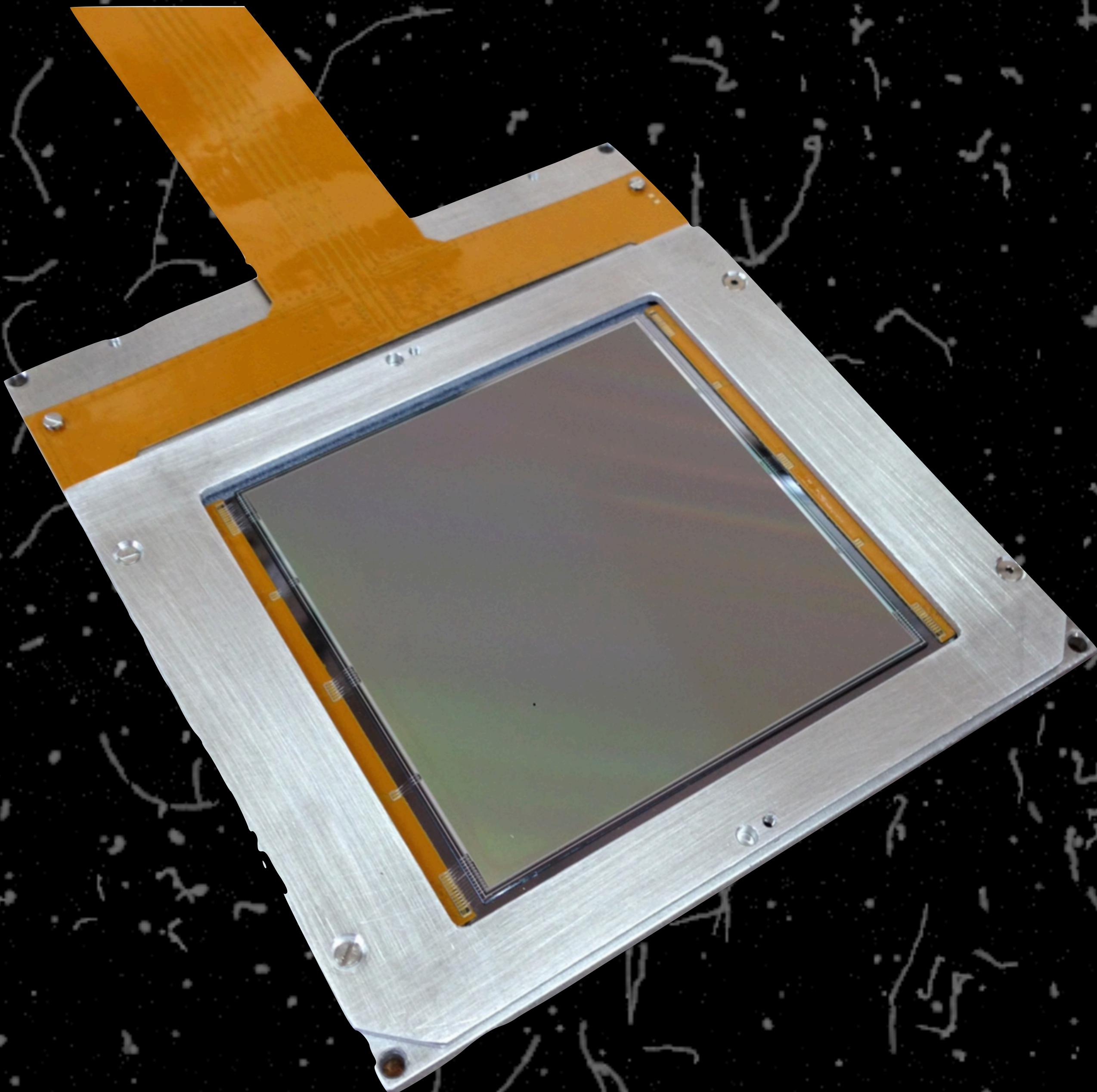


CCDs originally created for DES (DECam) by LBNL

Thick to be sensitive to infrared

= massive !

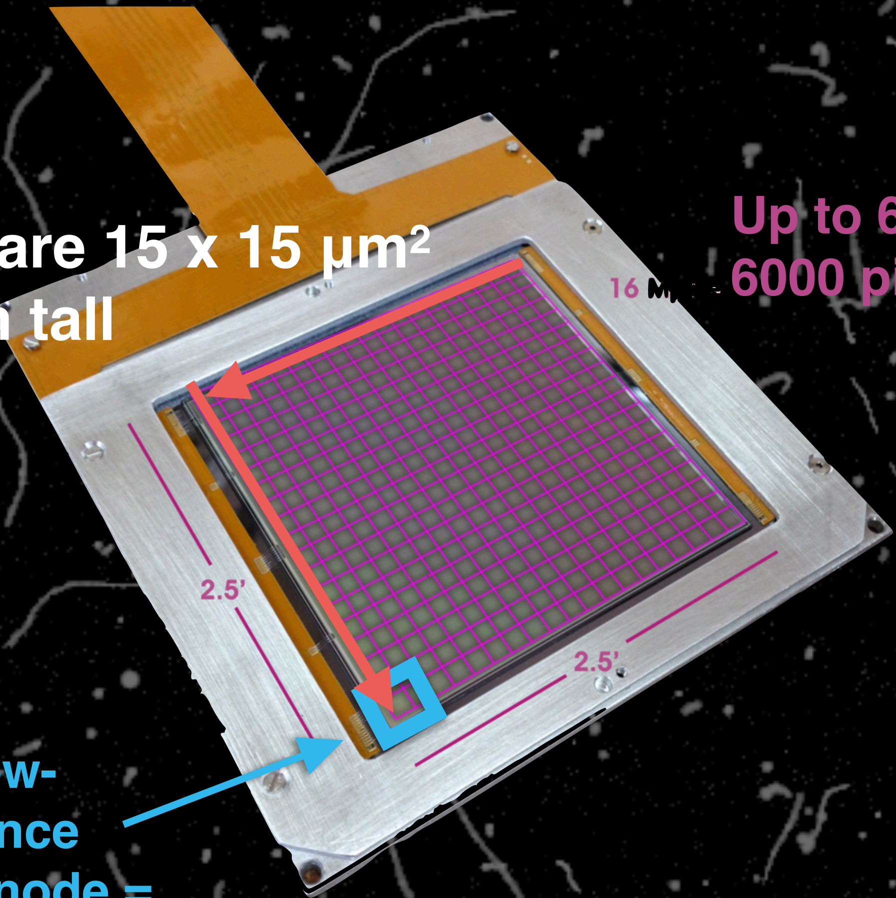
Scientific CCDs



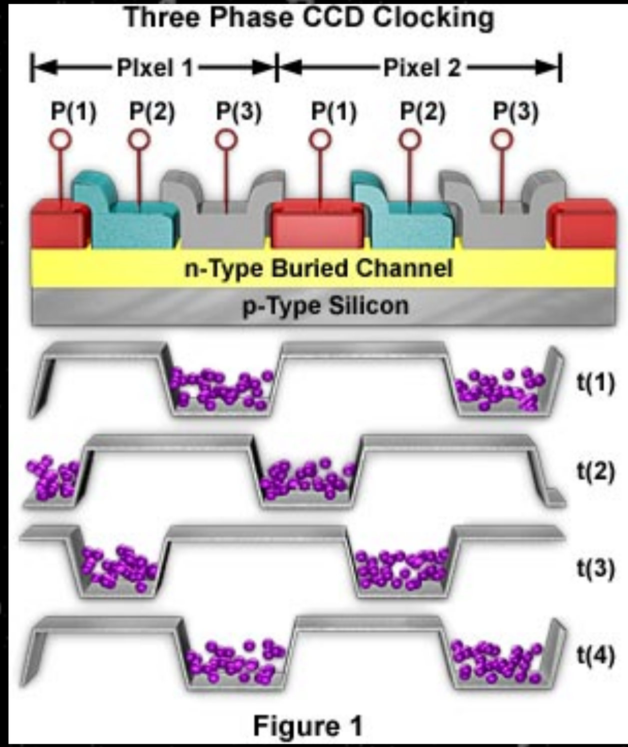
DAMIC (Dark matter in CCDs)

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



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

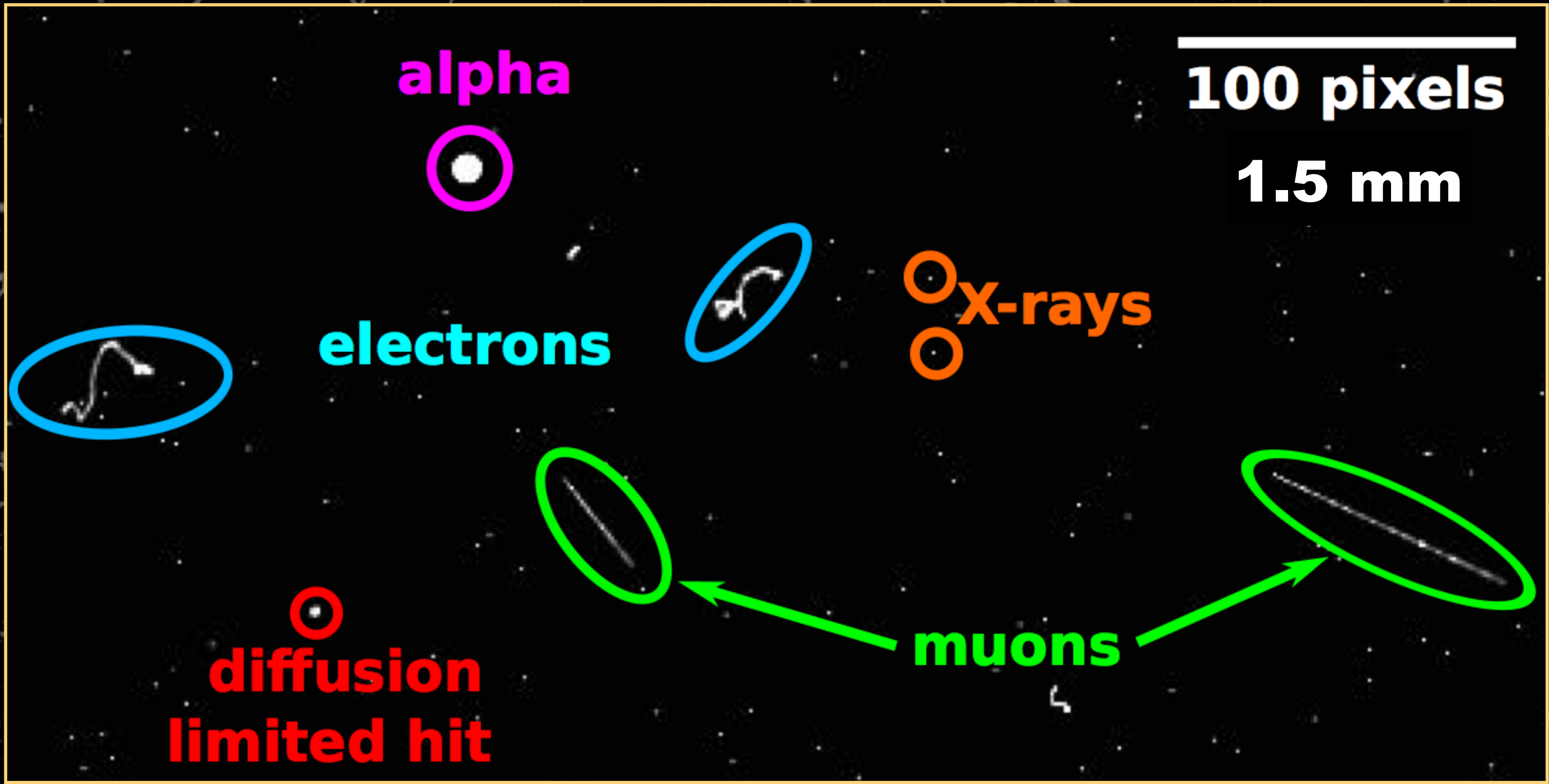
DAMIC-M will use the thickest and biggest CCDs ever made :

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

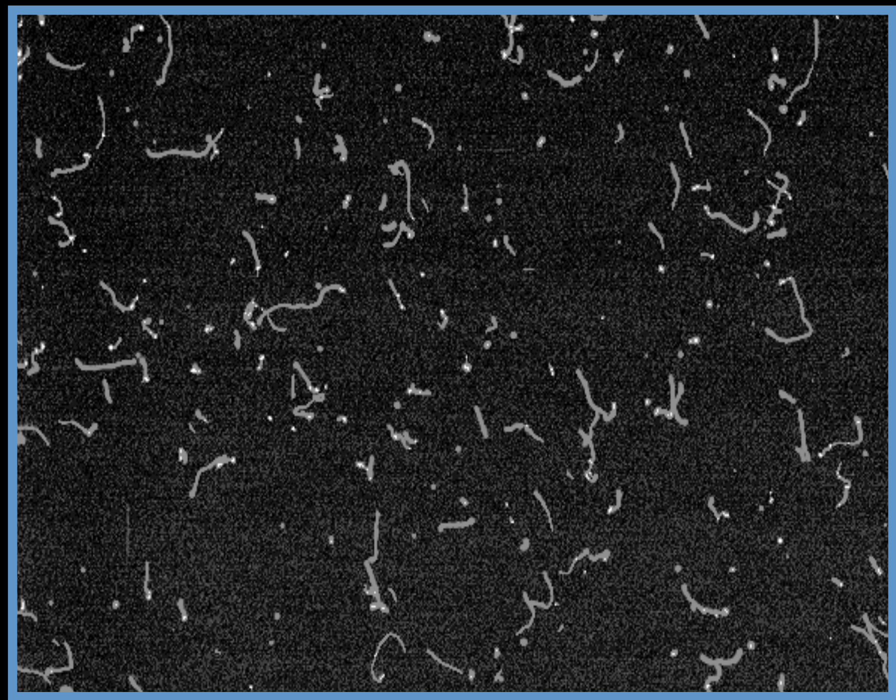
pixel size : 15 x 15 um²

We can calibrate with various sources

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

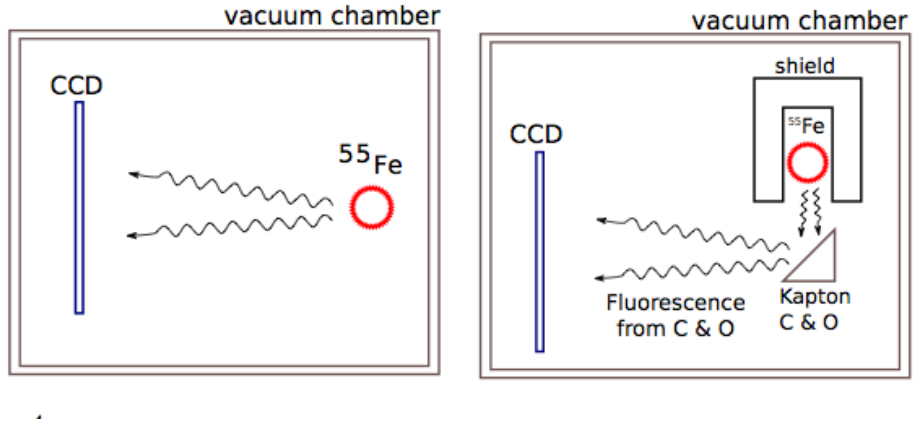
Point like hits
(diffusion limited)

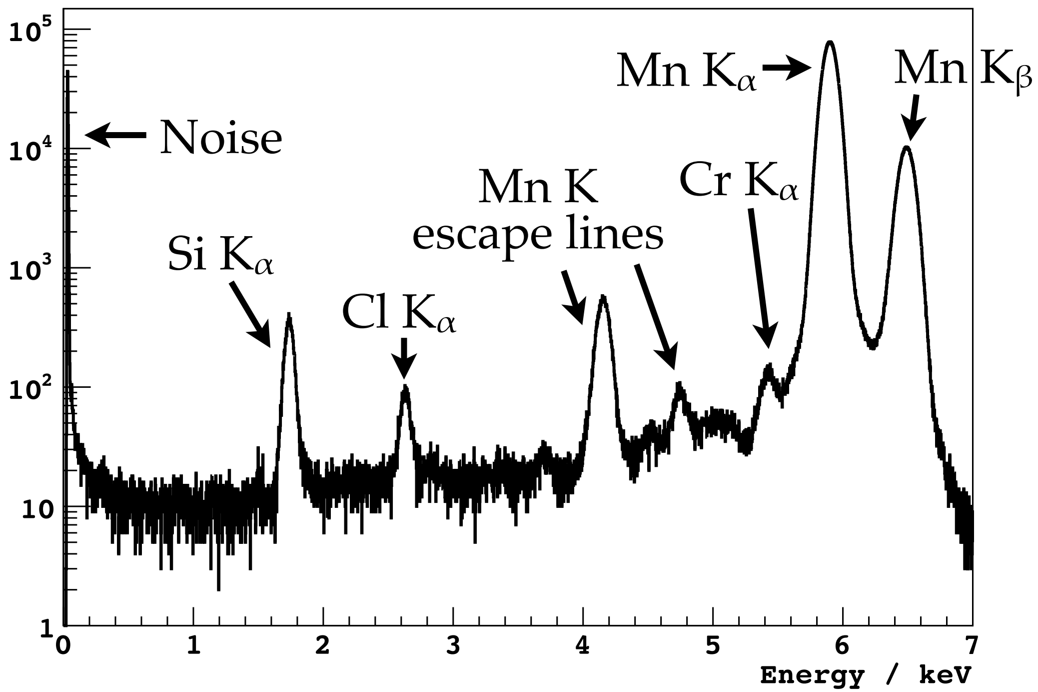
Gammas ^{60}Co (1.33 & 1.77 MeV)

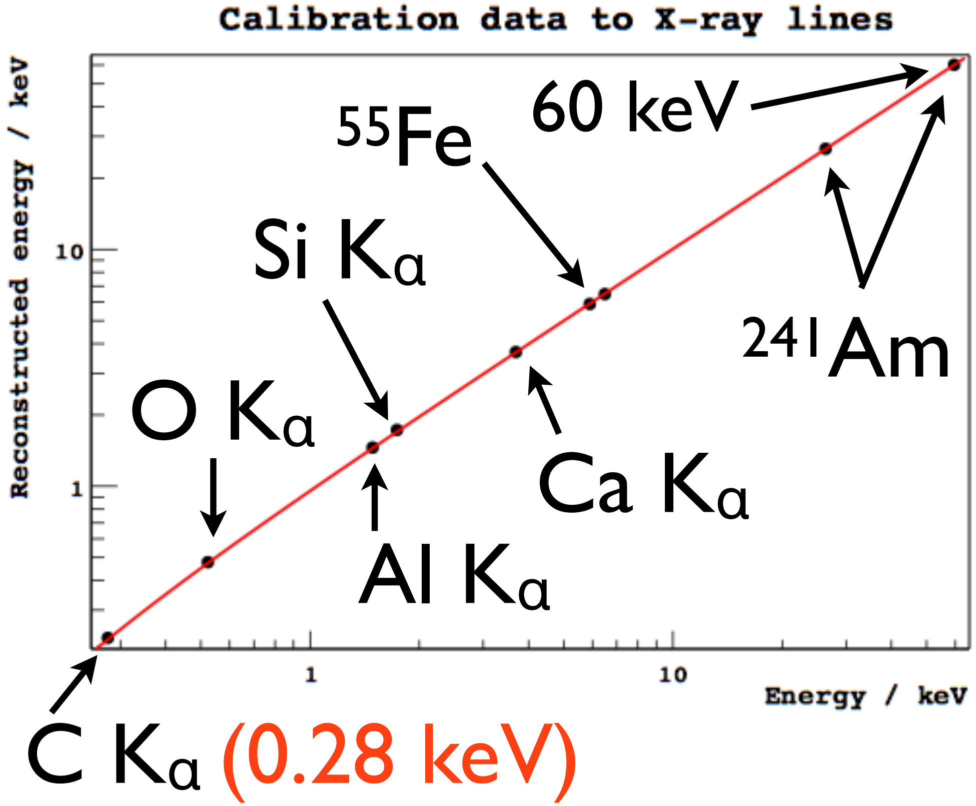


Compton
electrons
(worms) and
point-like hits.

X-ray calibration of CCDs





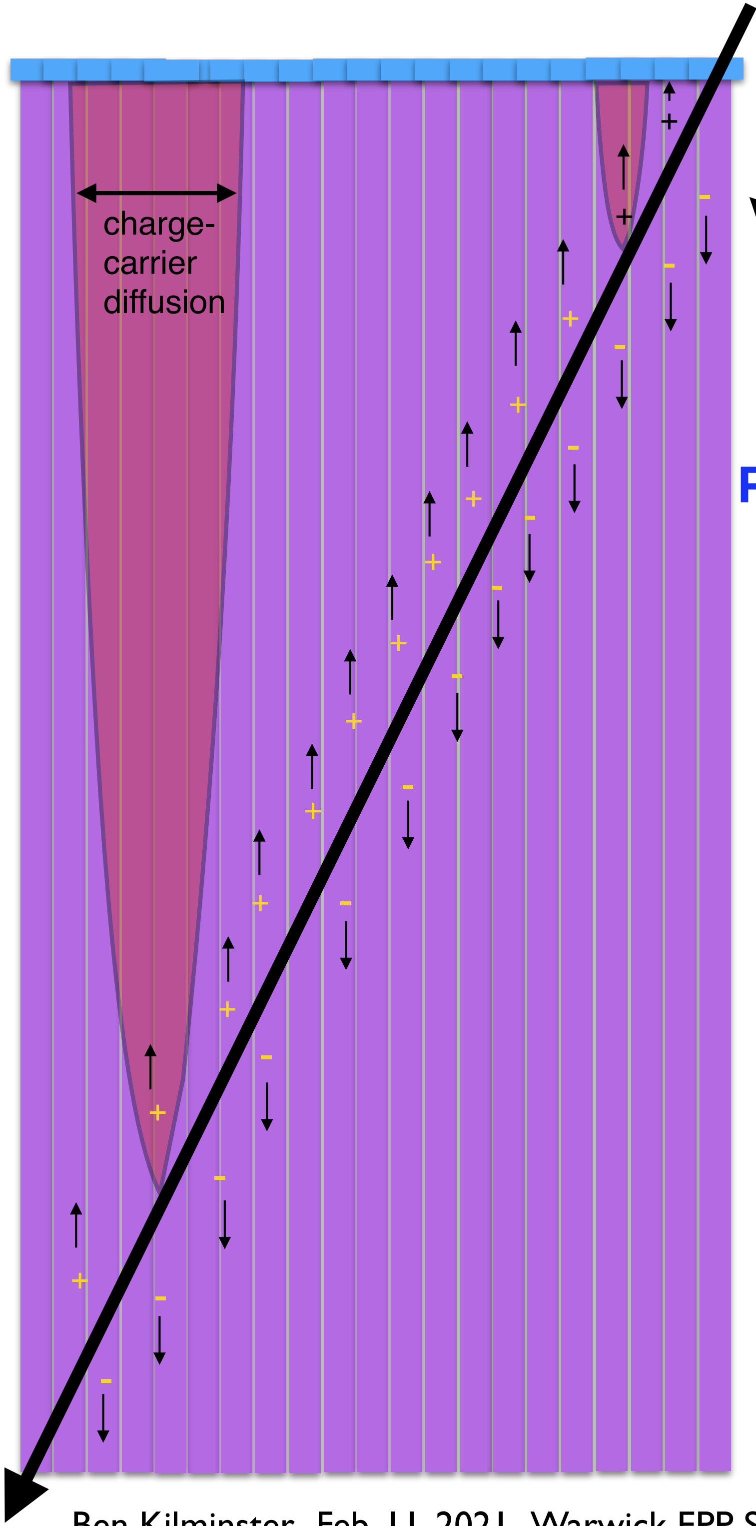


E resolution 53 eV at 5.9 keV

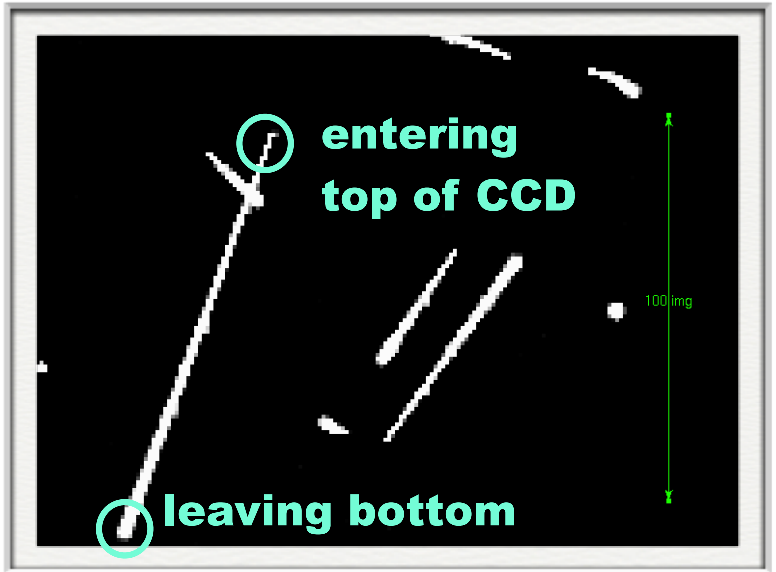
Linear response, good resolution

Cluster size vs. depth

$\overline{E}$ ⬆

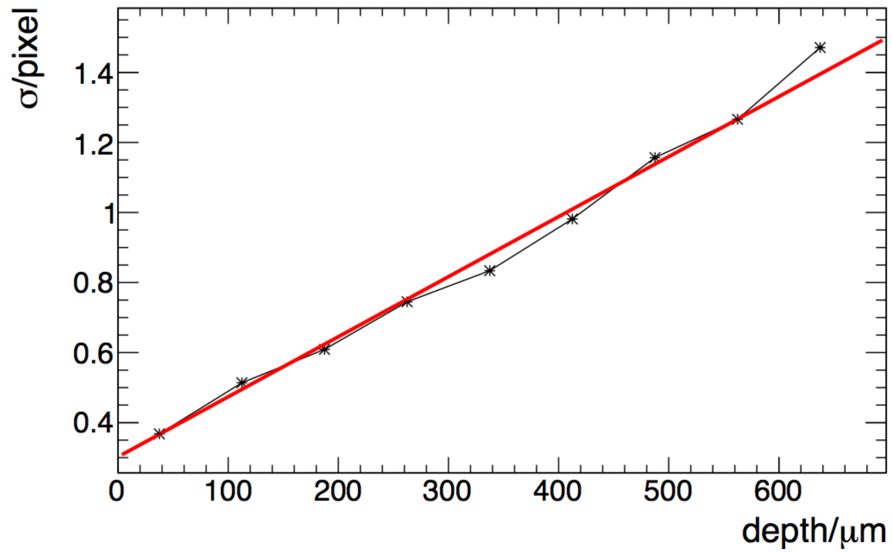


Muon



Pixels to scale
15 x 675 um

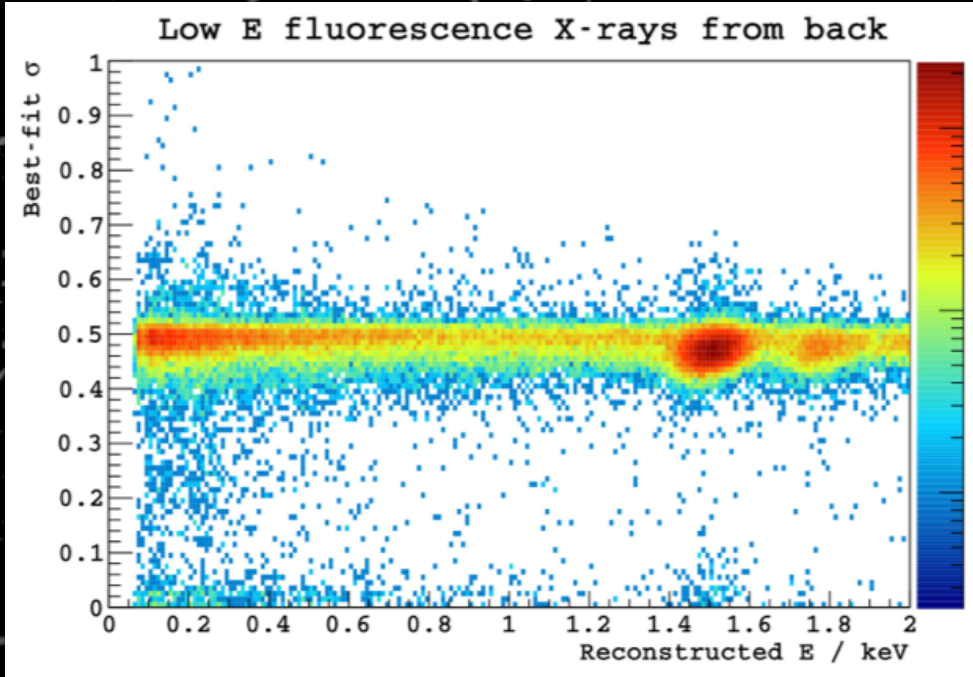
Calibration of cluster size σ vs. interaction depth

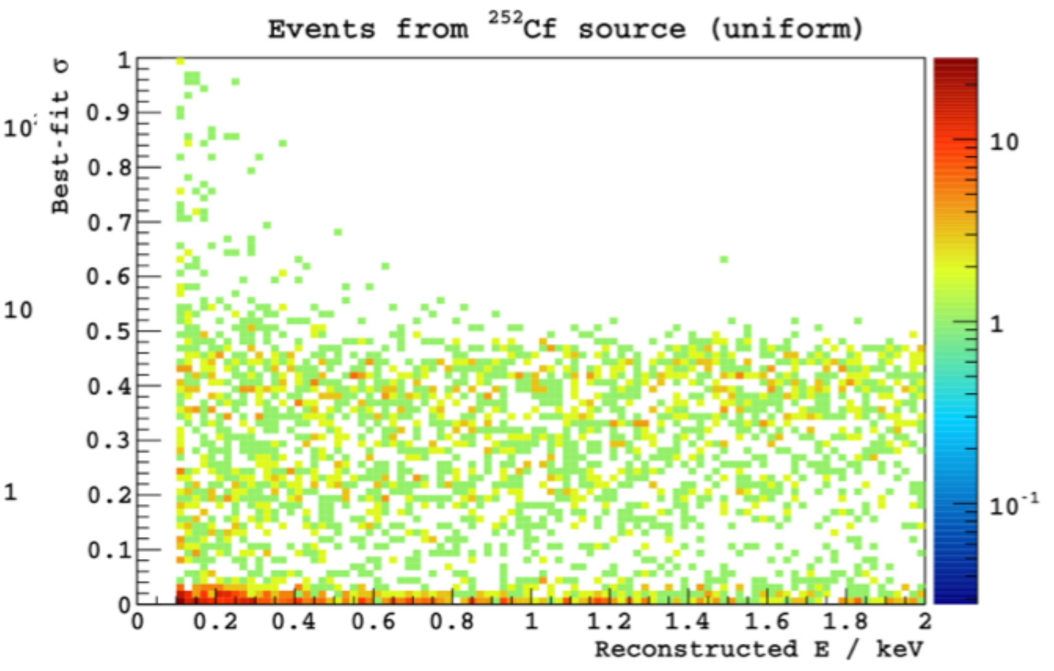


Useful for removing surface events

X-rays vs neutrons

Size of pixel clusters vs. Energy



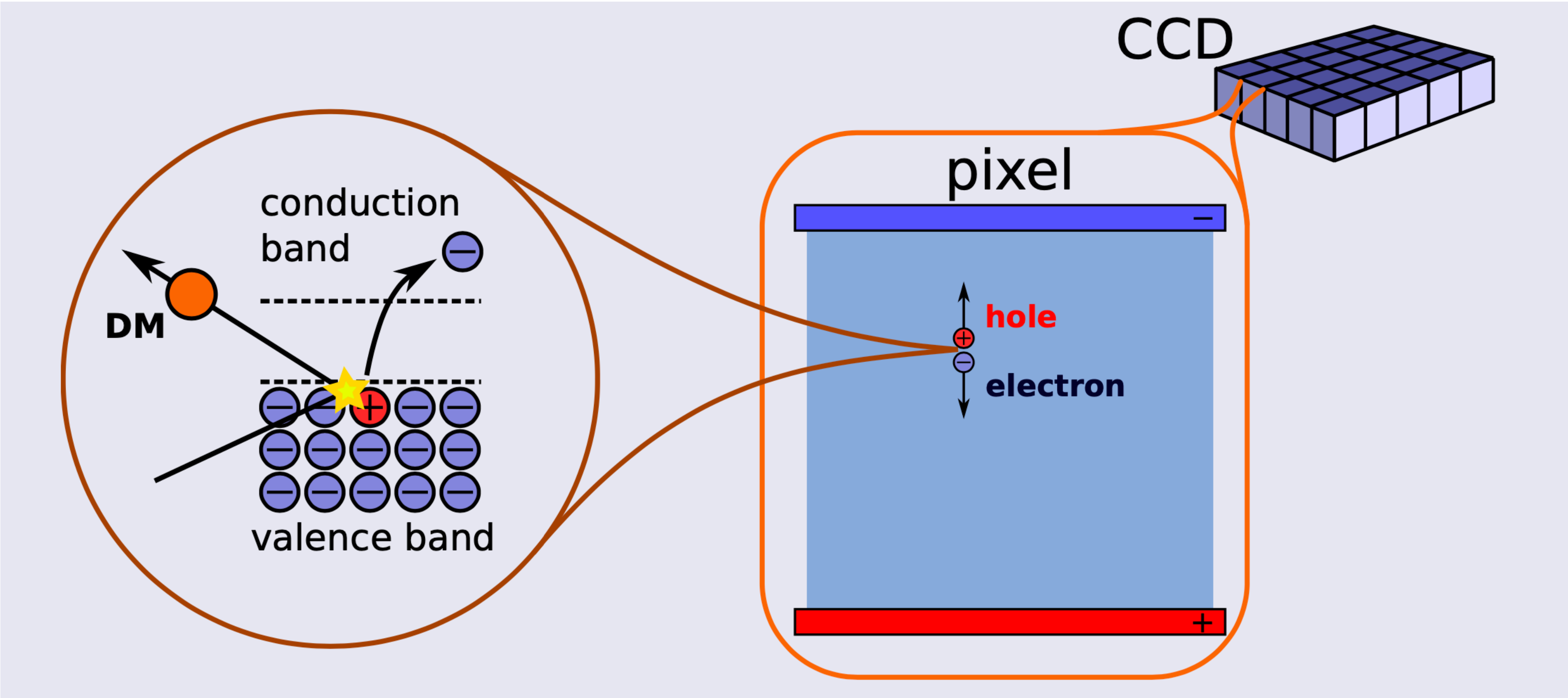


X-rays
bkg-like

Neutrons
“DM-like”
(No dependence on depth)

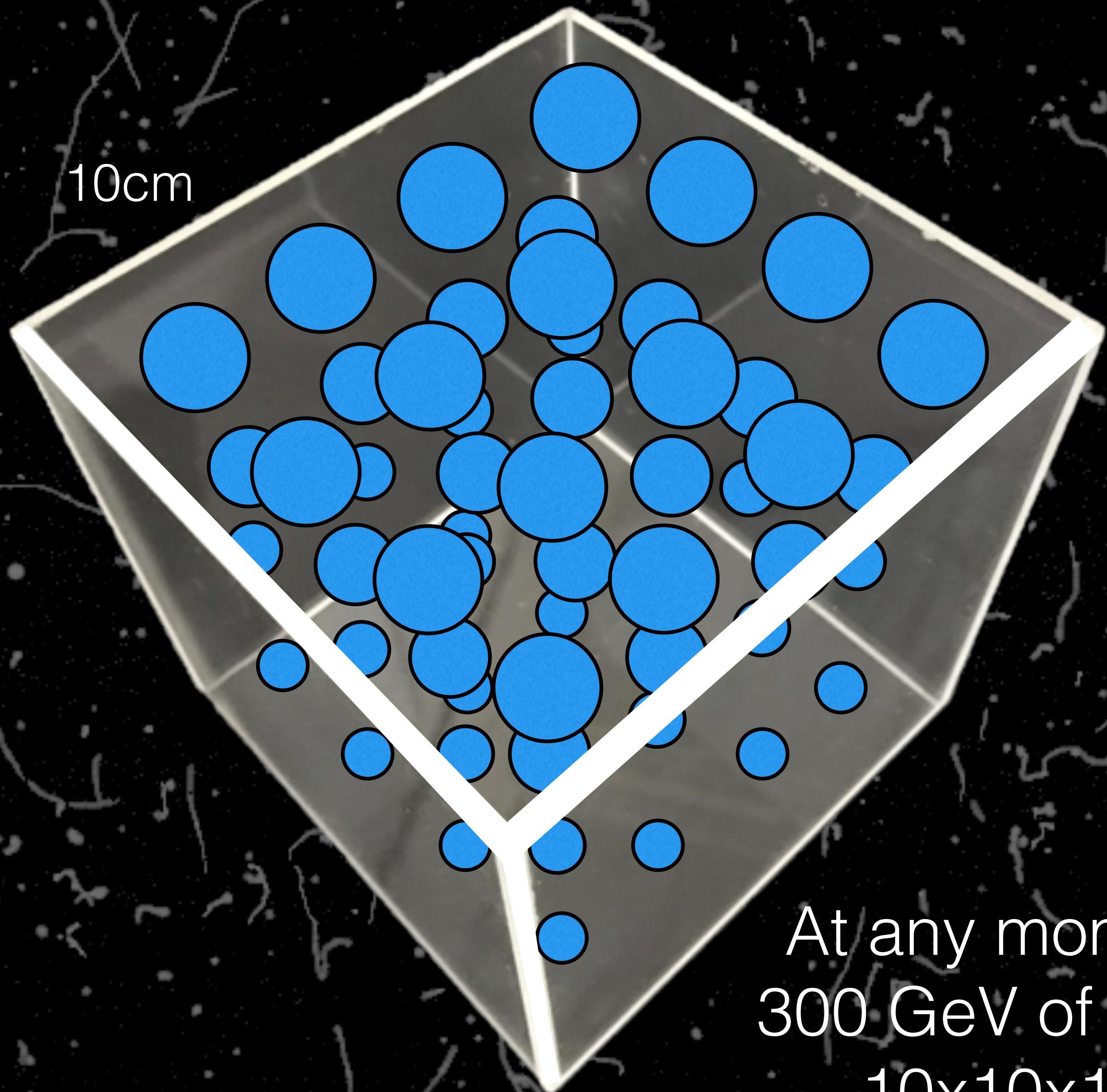
Cluster size → Determines depth used to reject backgrounds

Detecting DM in a CCD



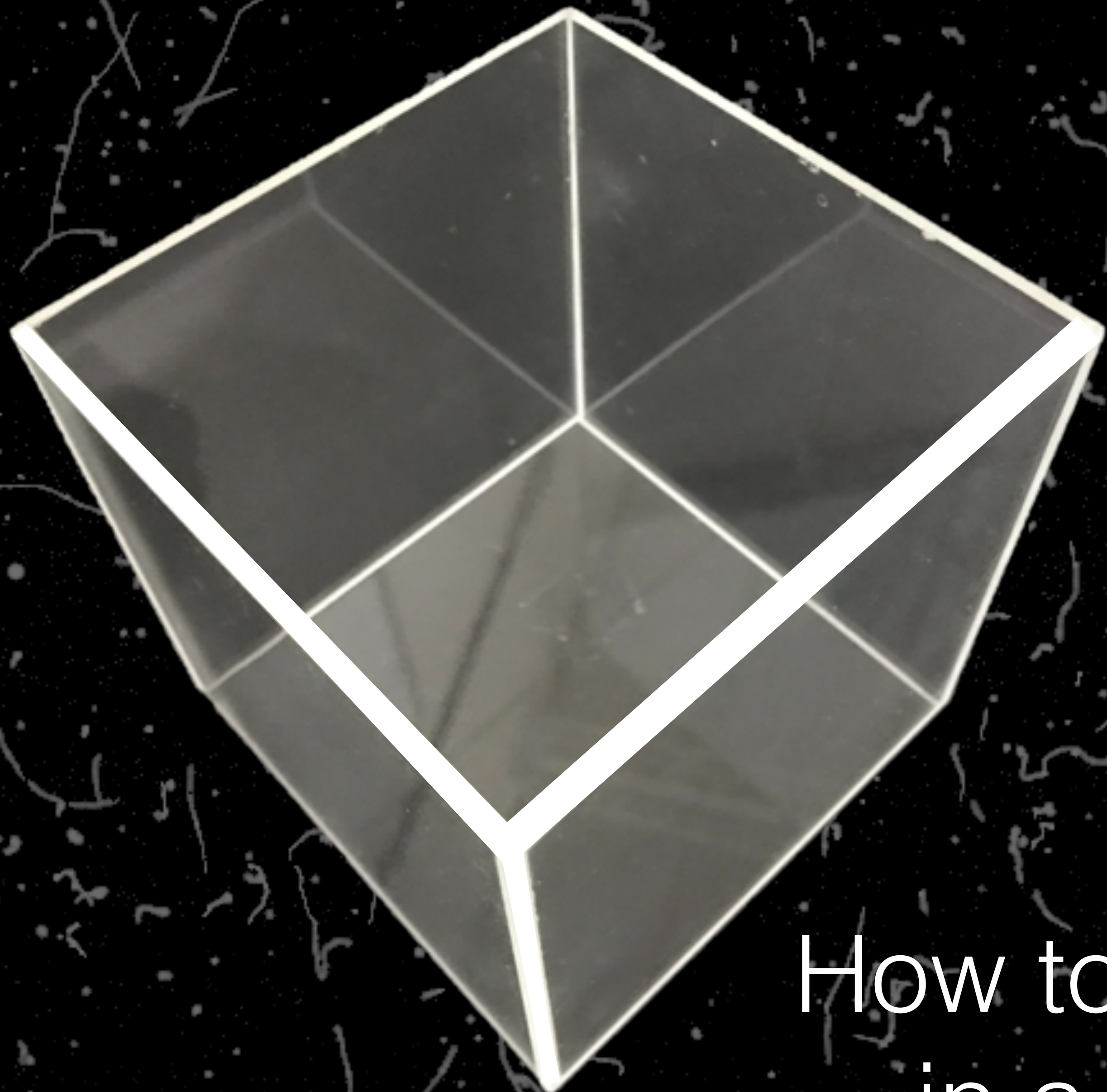
Minimum energy ~ 1 eV to move charge from valence to conduction band

Finding DM



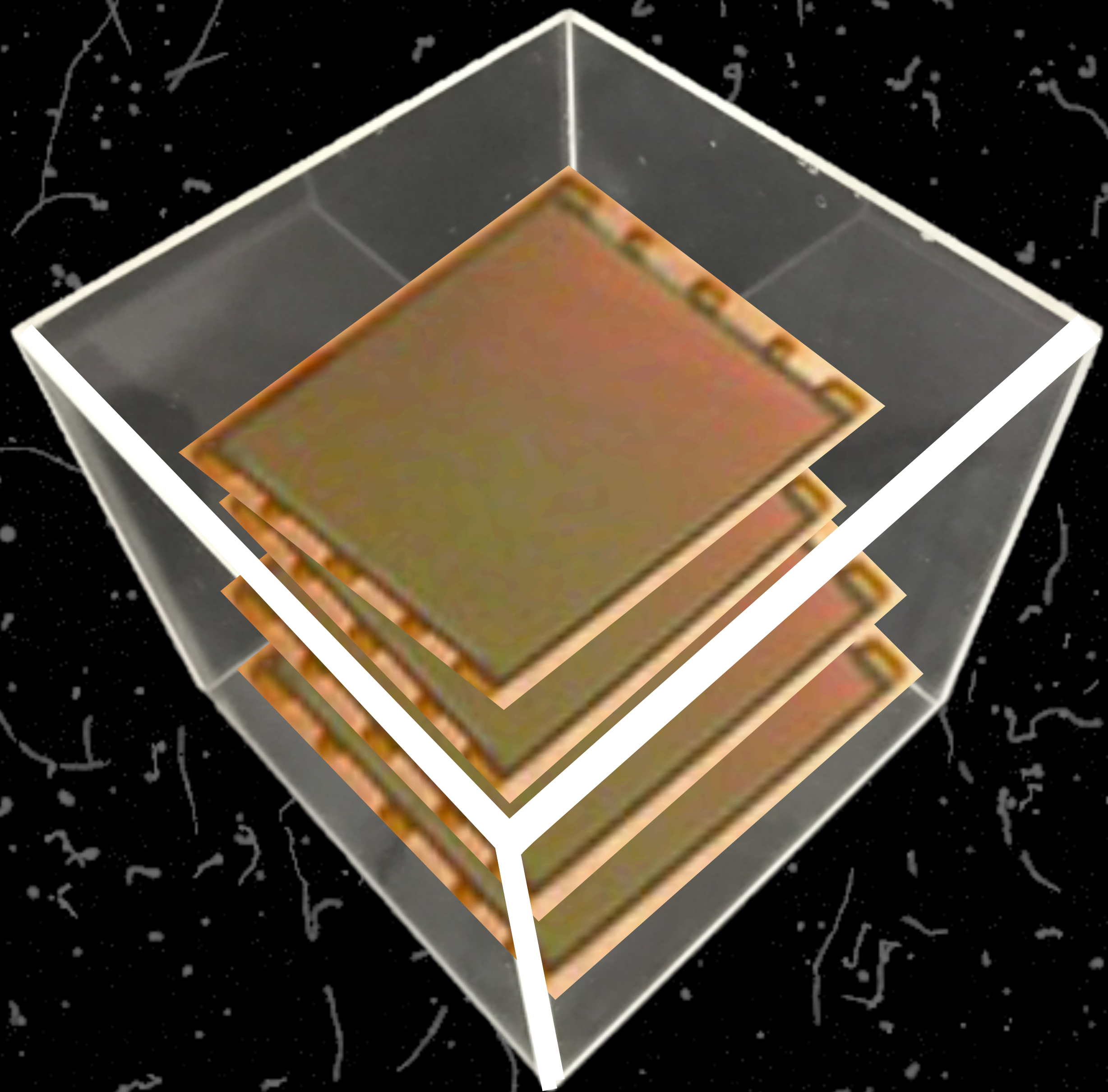
At any moment, there is 300 GeV of DM mass in a $10x10x10\ cm^3$ box

Per second, Σ(DM mass) through box = 10 000 000 TeV



How to find DM in a box ?

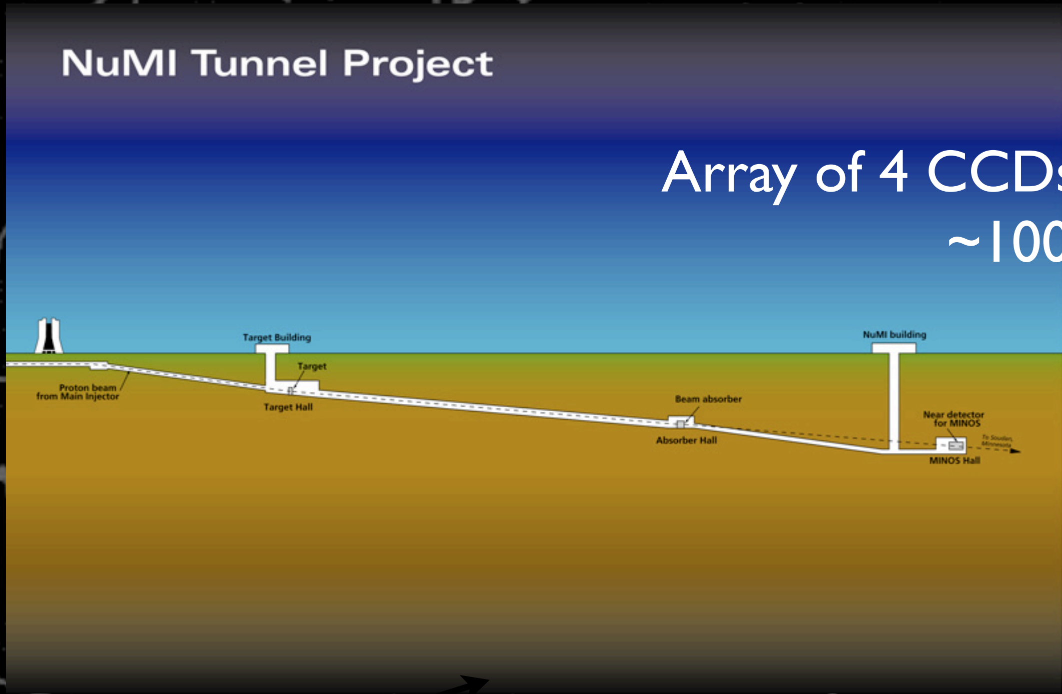
Put CCDs in a box



DAMIC experiment generations

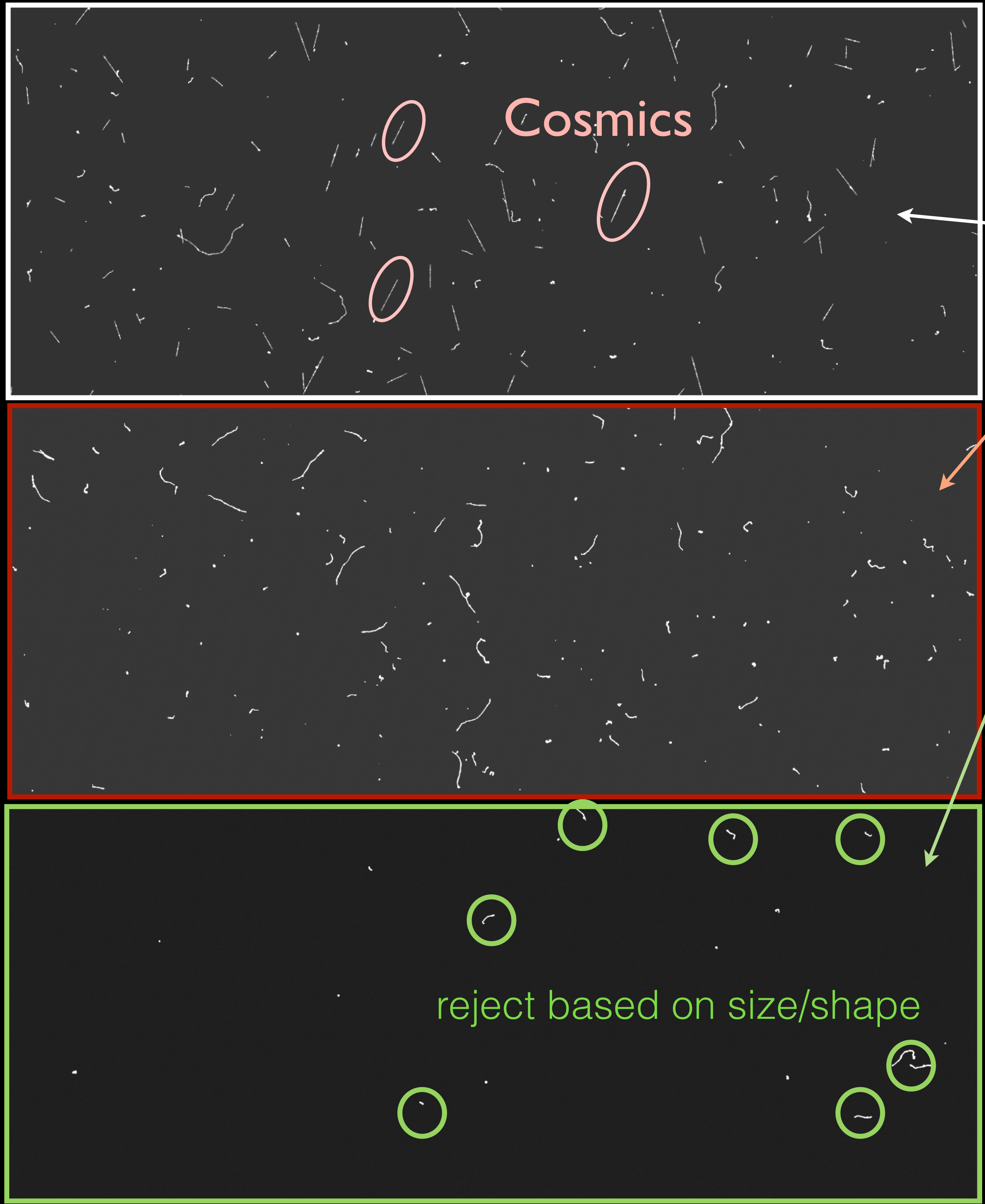
- 2010-2011 : DAMIC first run at Fermilab
  - Best DM limits for WIMPs below 4 GeV
- 2015- now : DAMIC @ SNOLAB
  - Hidden photon DM search
    - 2017 : First eV-scale results
    - 2019 : Result reported today
  - WIMP search
    - 2016 : First result
    - 2020 : New result today
- 2023 : DAMIC-M @Modane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

DAMIC @ Fermilab : First underground run



Array of 4 CCDs in underground cavern
~100 meter depth

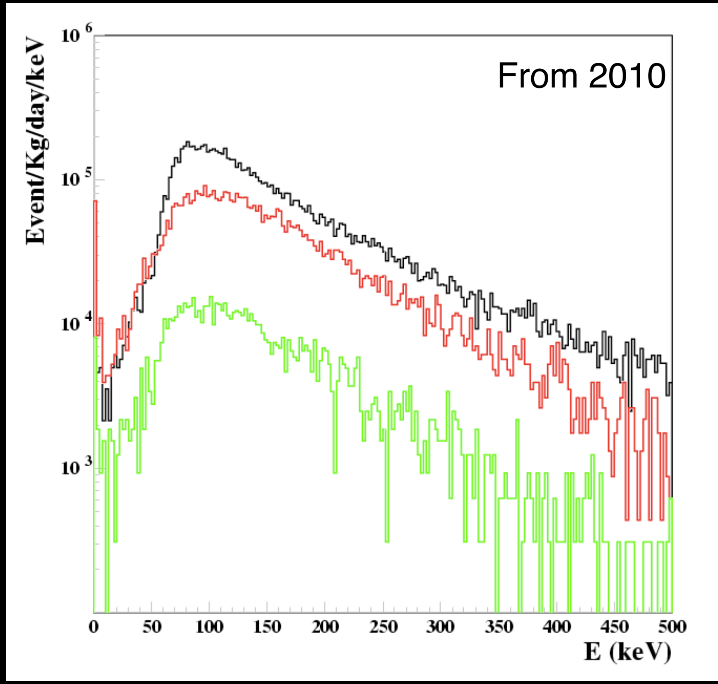
Background reduction



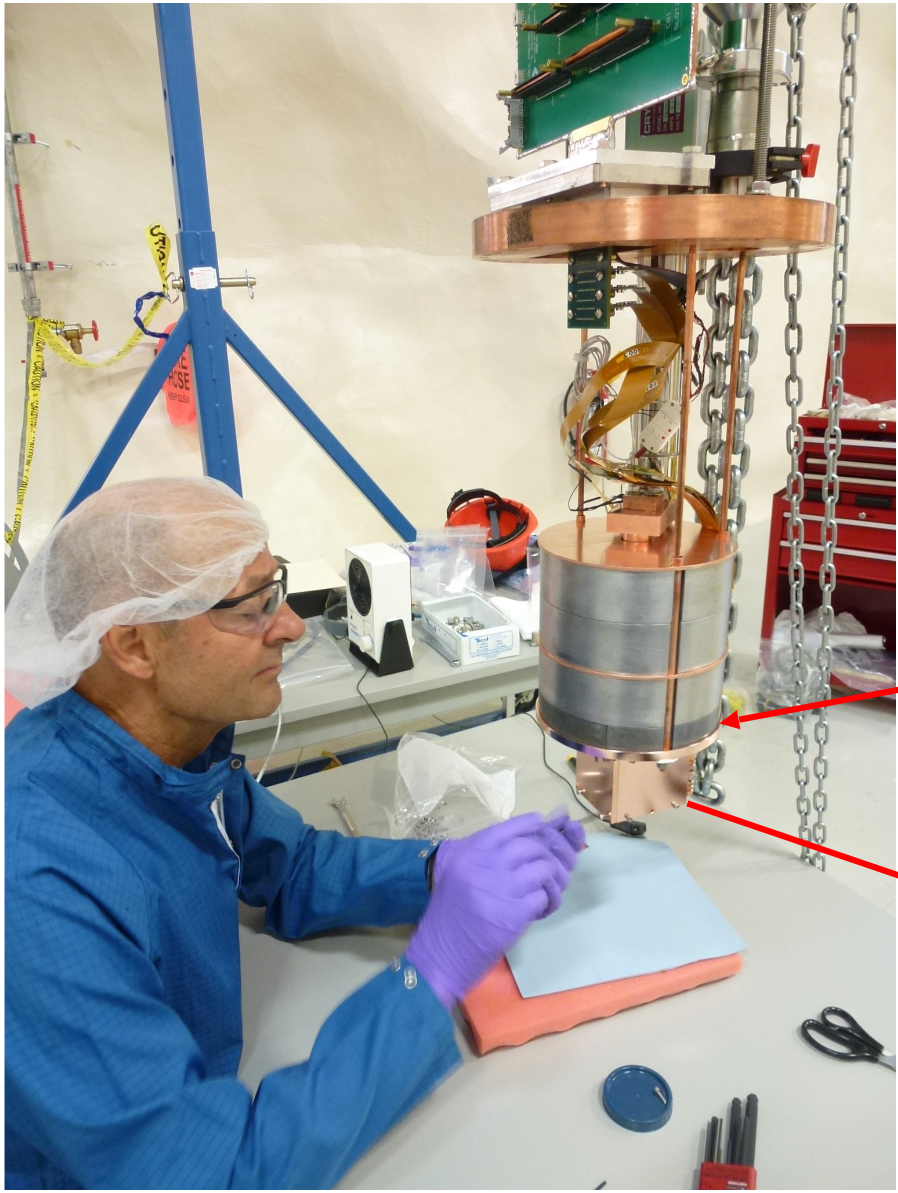
Above ground

350 ft underground

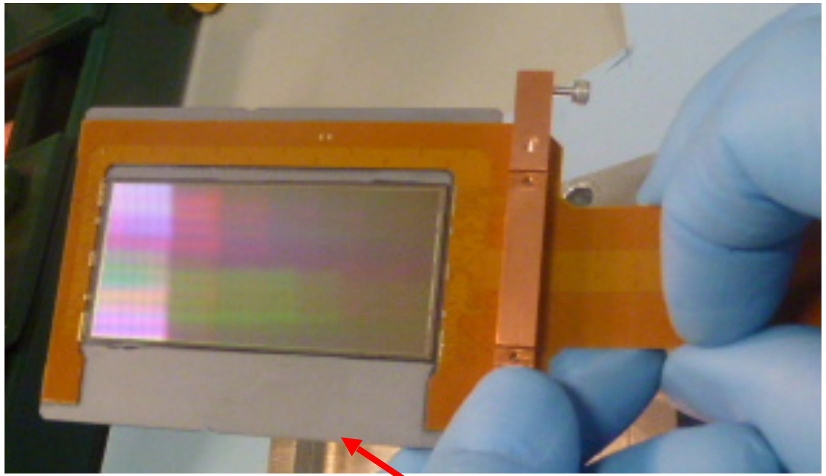
With lead brick shielding



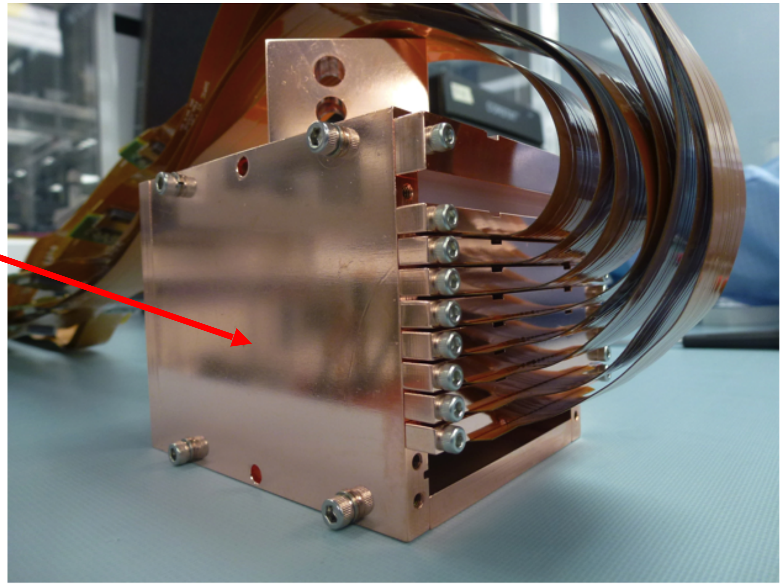
DAMIC @ SNOLAB



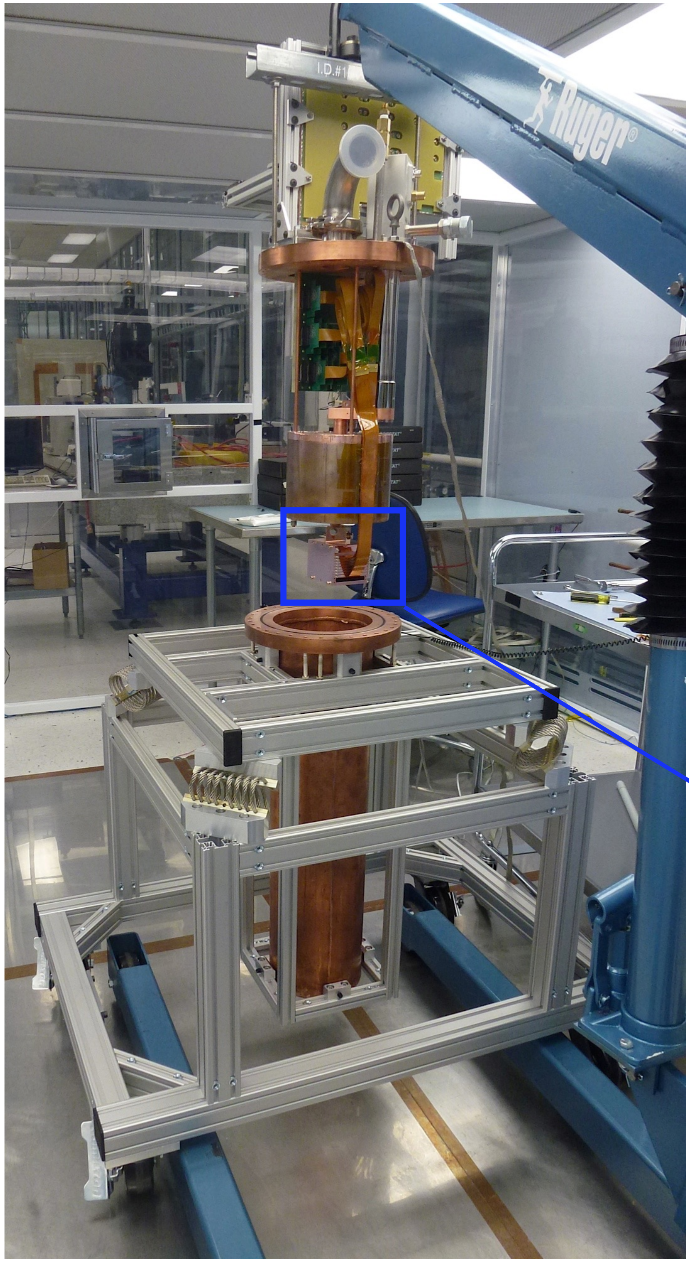
1” Spanish galleon lead

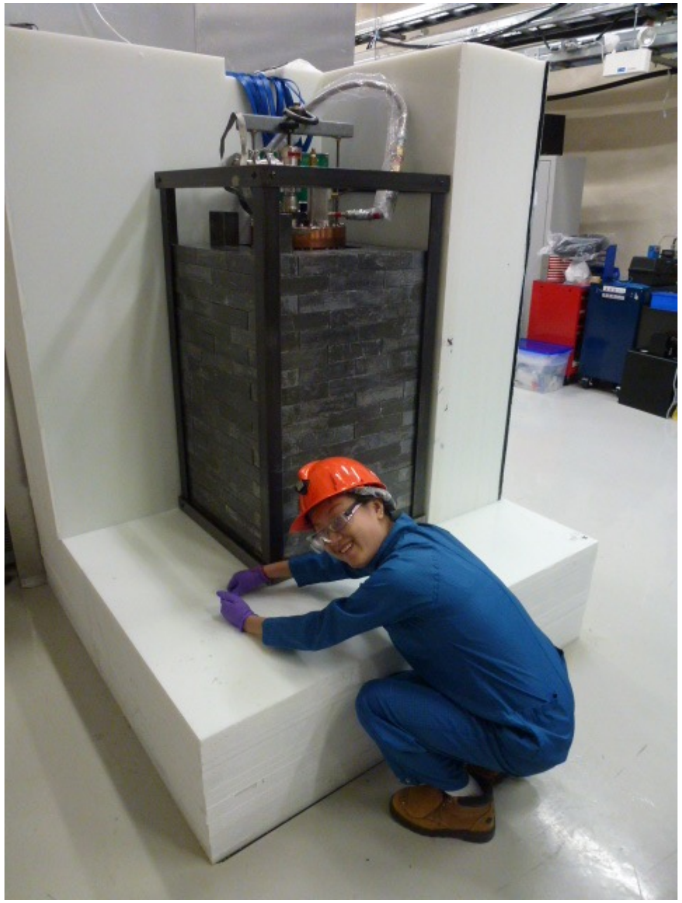


Si support

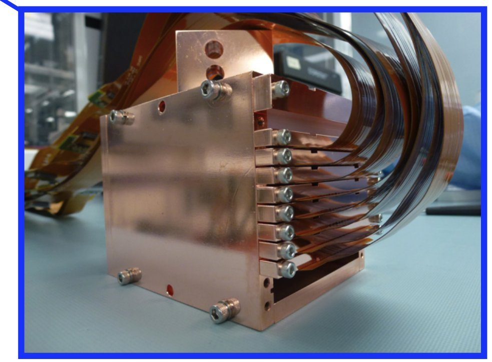


DAMIC @ SNOLAB



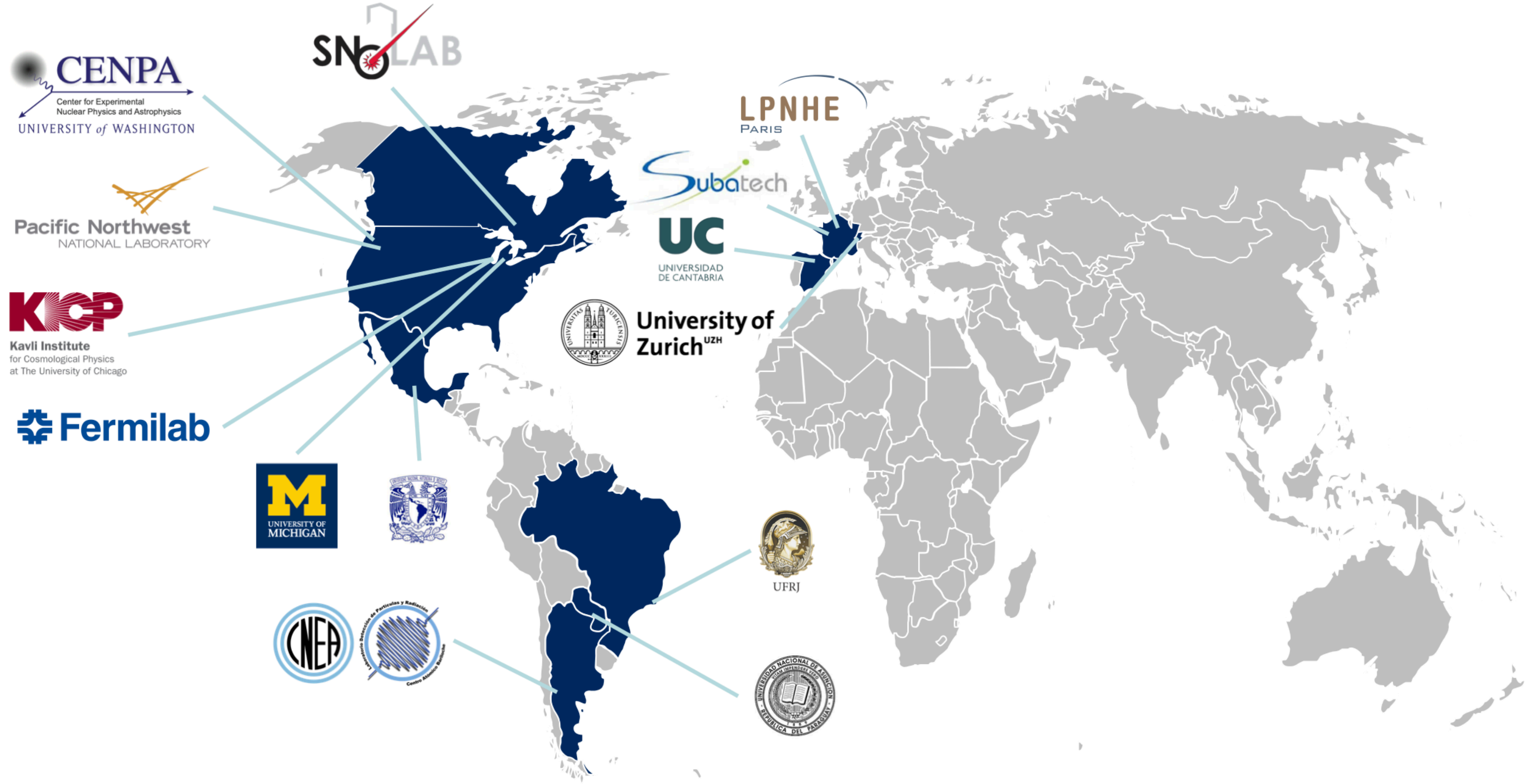


In SNOLAB 6010m water equivalent depth : suppresses cosmics



Operated 7 CCDs = 40 g

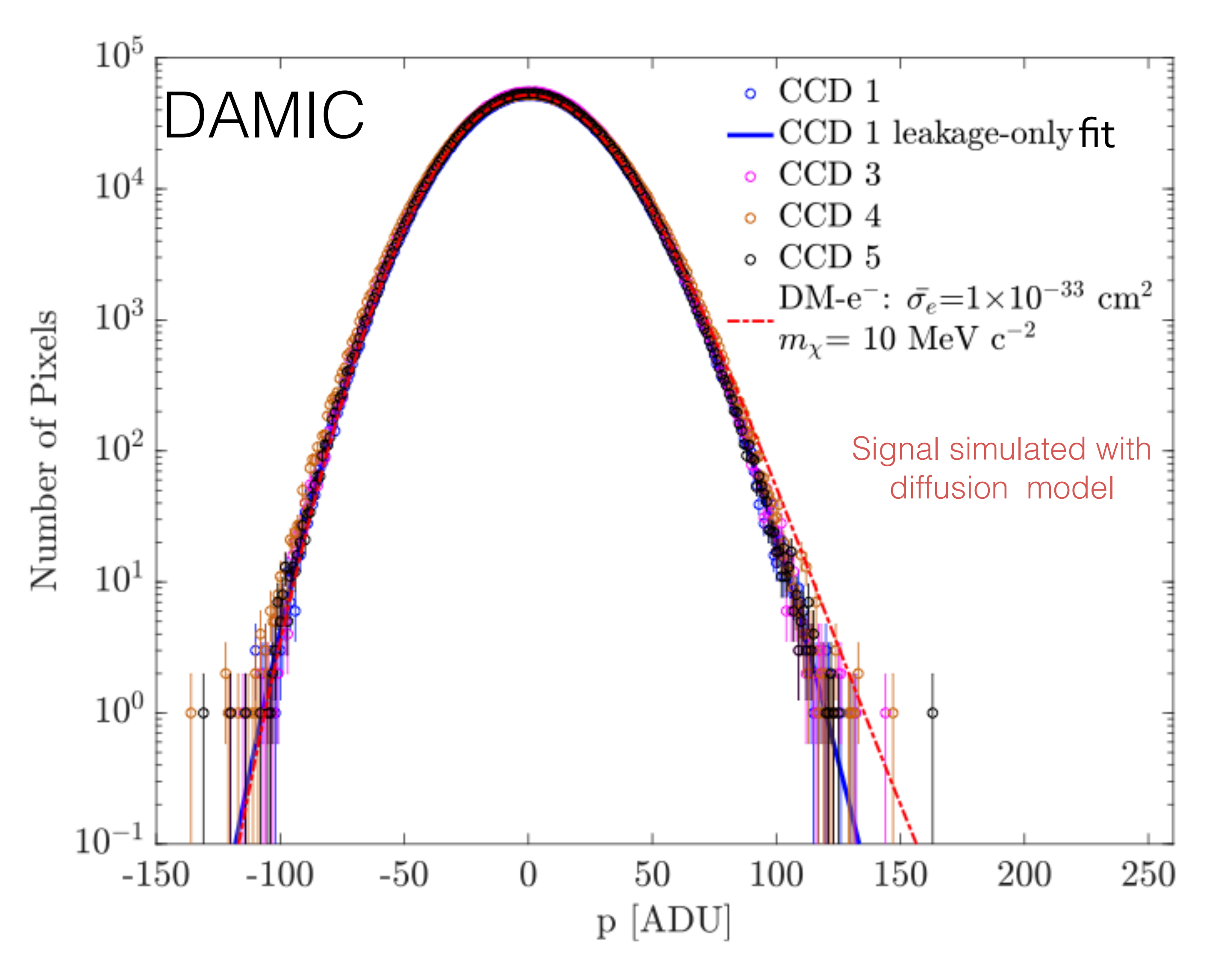
DAMIC@SNOLAB Collaboration



Hidden DM results

Recoils and absorption of DM on electrons

- Background is electronics readout noise + leakage current



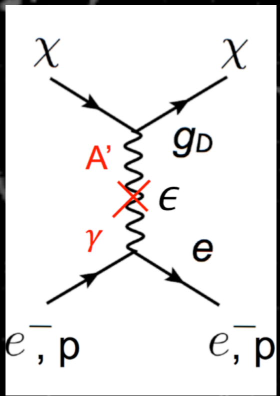
Charge resolution
σ ~ 2e-

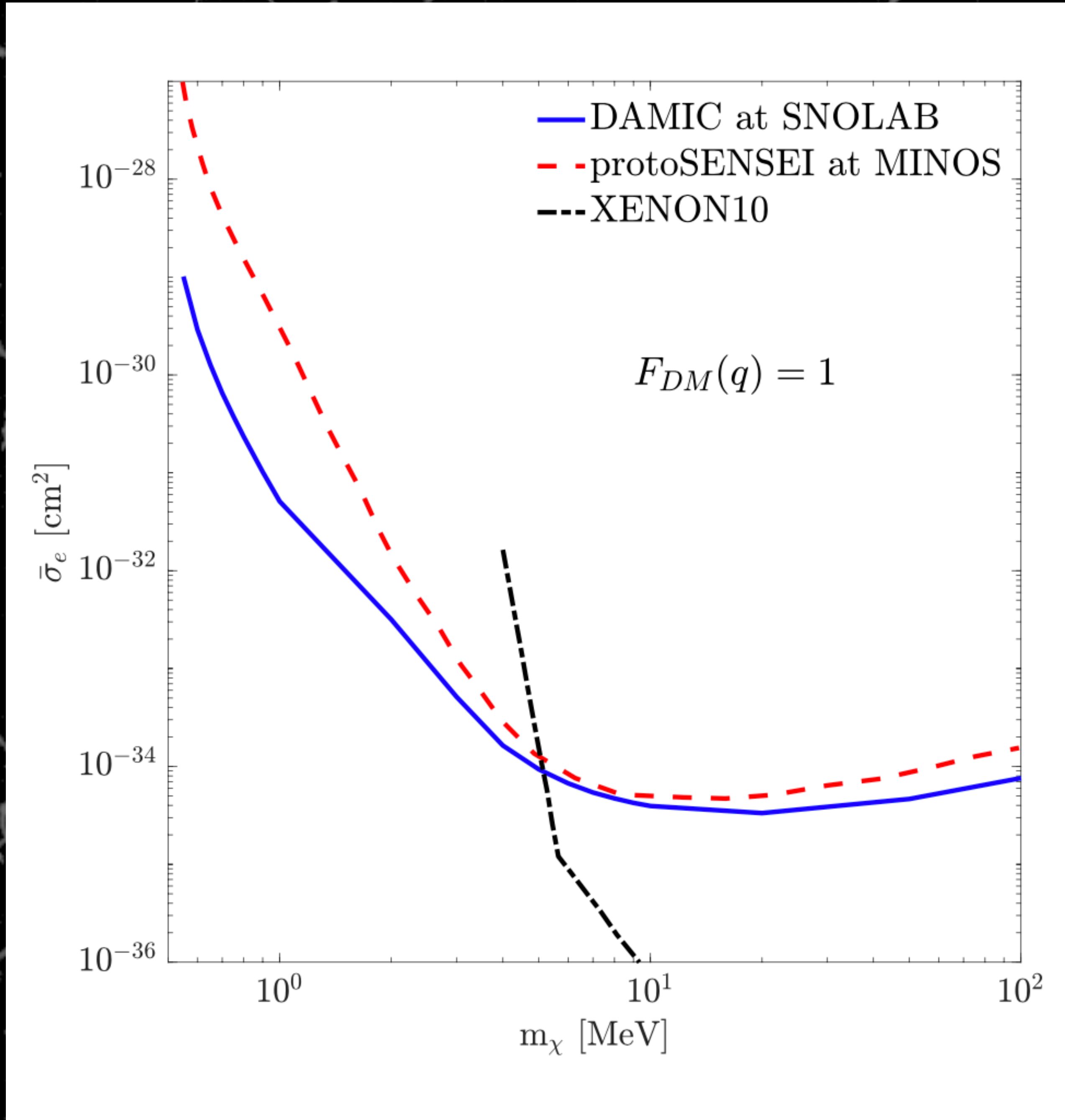
Leakage current :
1E-3 e-/pixel/day
(4 e- /mm²/day)
(8.2 E –22 A / cm²)

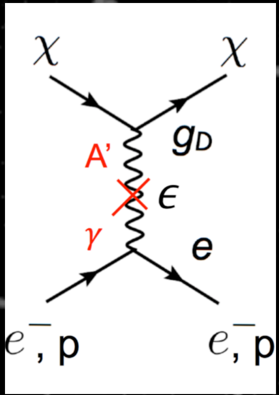
1907.12628
Phys. Rev. Lett. 123, 181802 (2019)

Results MeV-scale DM

MeV-scale DM recoils off electrons

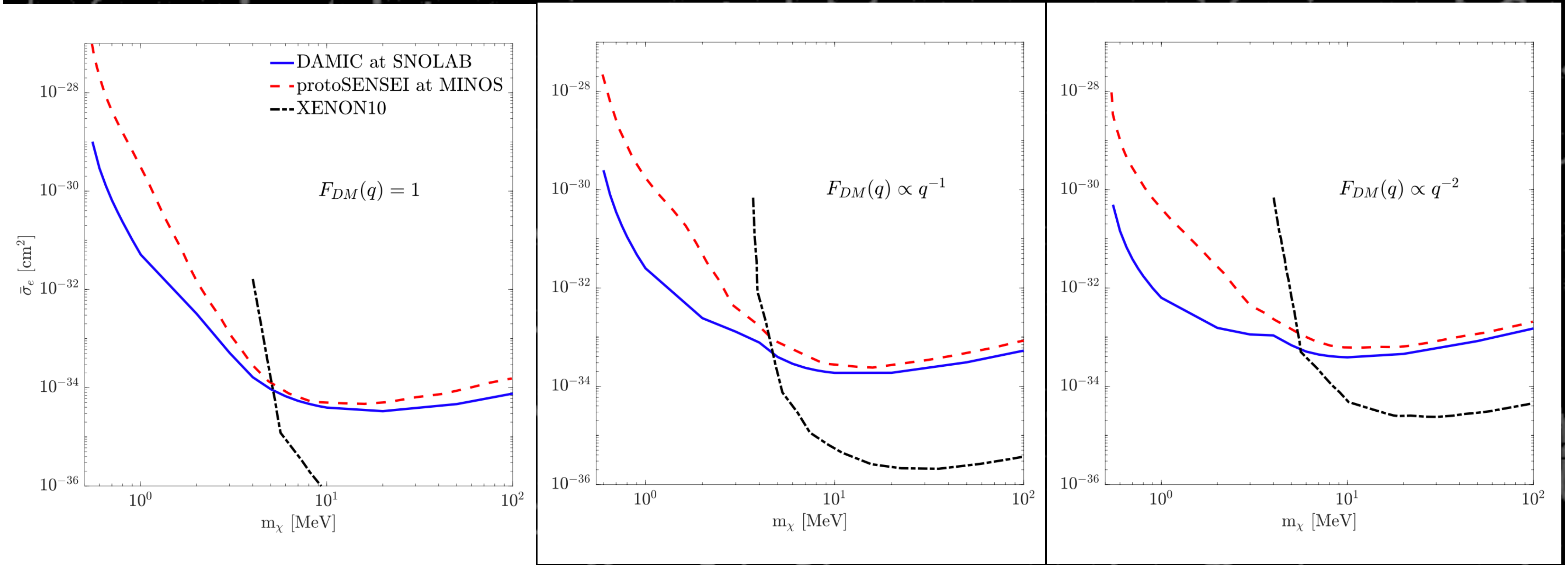






Results MeV-scale DM

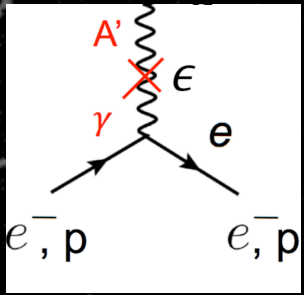
- MeV-scale DM recoils off electrons



Results vary on dependence of q of the dark matter interaction form factor

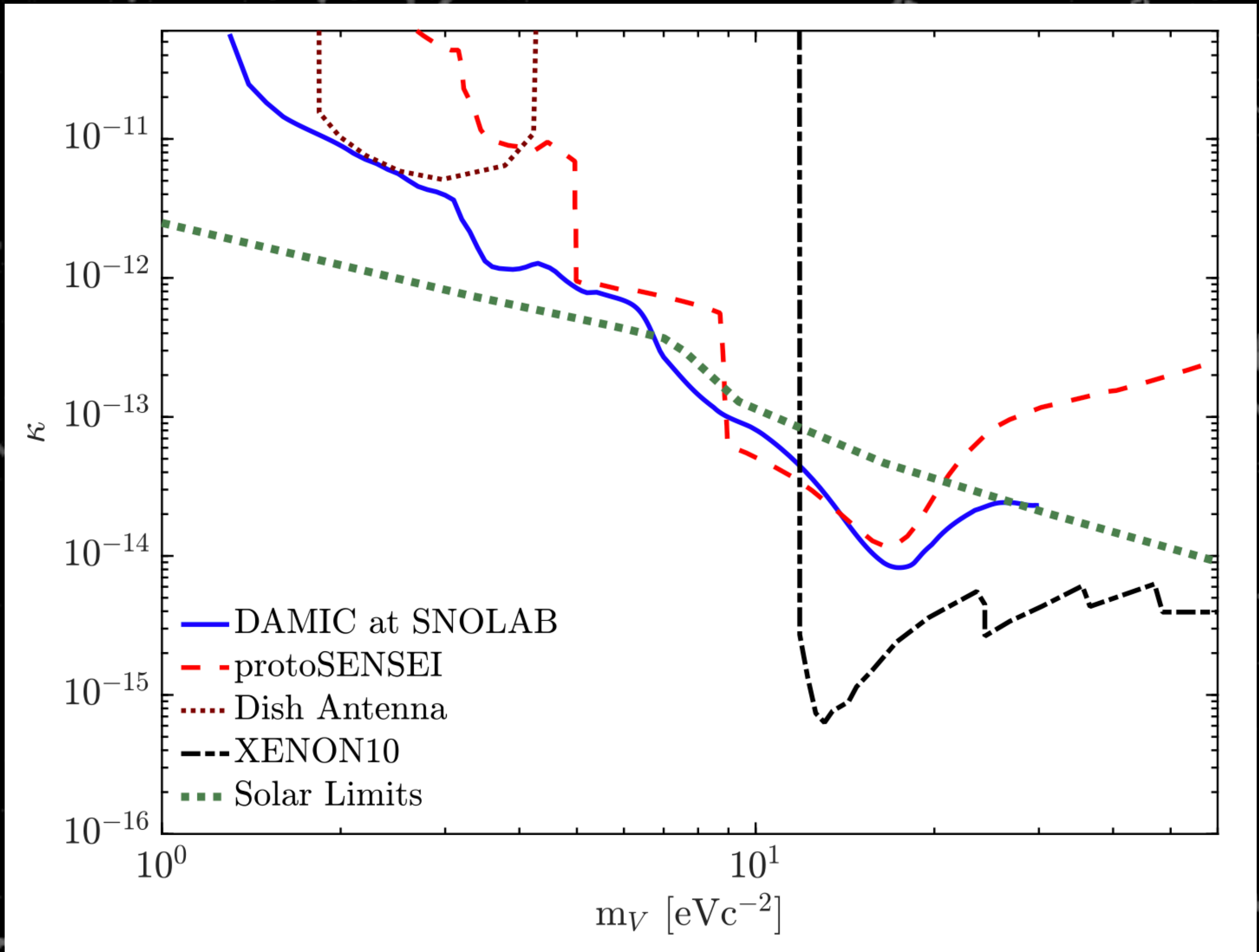
$$\frac{dR}{dE_e} \propto \bar{\sigma_e} \int \frac{dq}{q^2} \, \eta(m_\chi, q, E_e) |F_{DM}(q)|^2 |f_c(q, E_e)|^2$$

Results eV-scale DM



- Electrons absorb the eV-scale DM and are excited to conduction band

Y-axis is kinetic mixing parameter between γ and A'



WIMP results

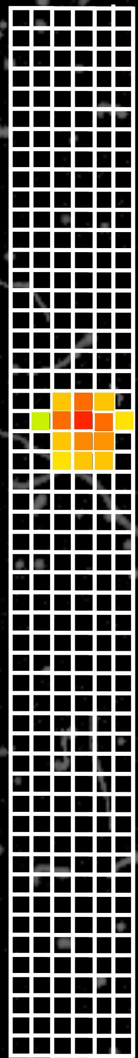
(Pretty) New !

Pixel readout

σ_{noise} ~ 1.6 e- per readout

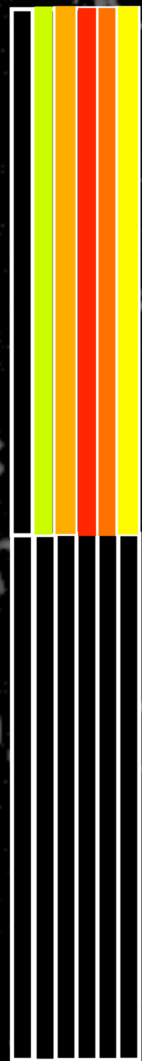
WIMP signal

Energy cluster



15 x 15 µm^2

100 pixels grouped before readout



15 x 1500 µm^2

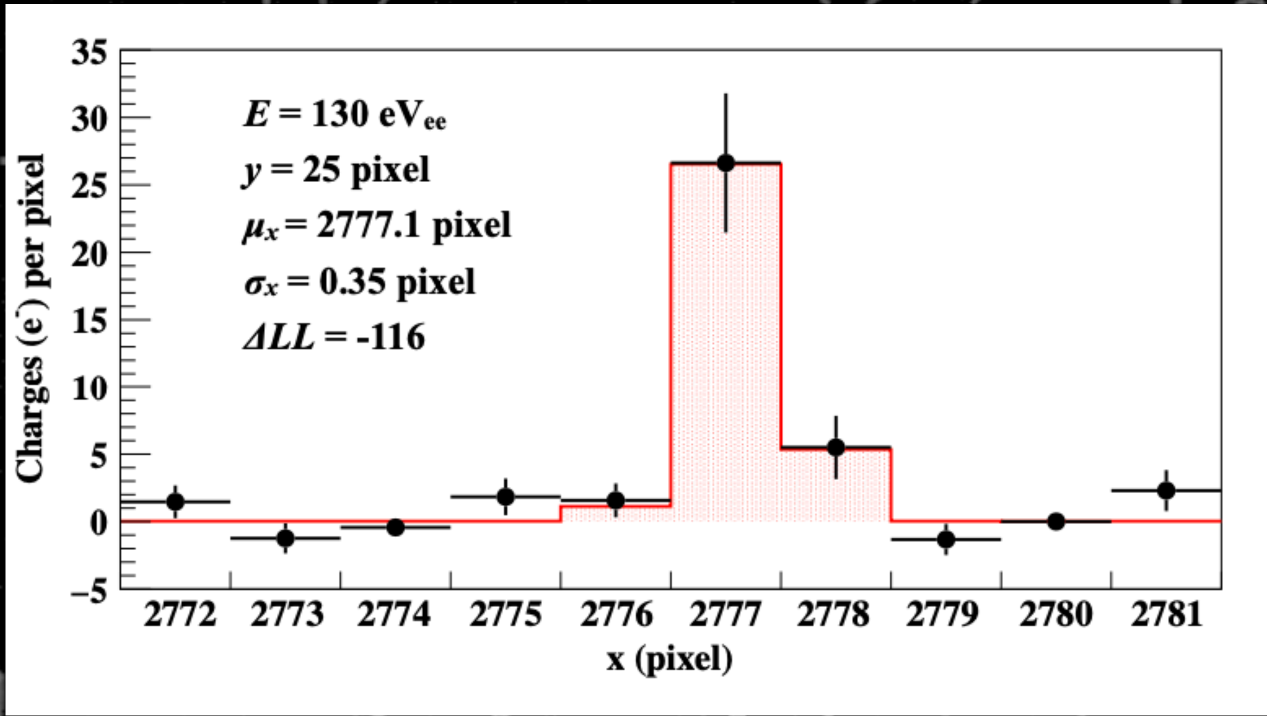
Tradeoff:

- Improved signal/noise
- Poor y-position resolution

Cluster finding

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

Example of cluster

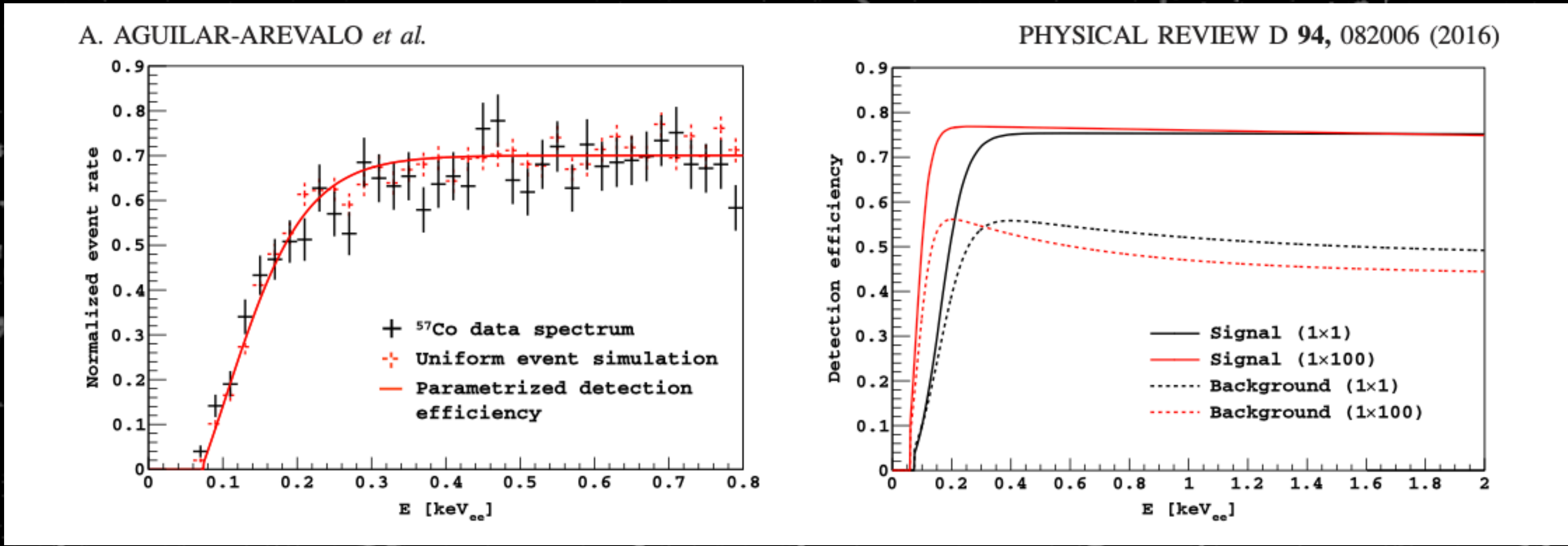


Size of cluster σ_x → Determines depth of interaction, z

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

A, b : from cosmic ray tracks

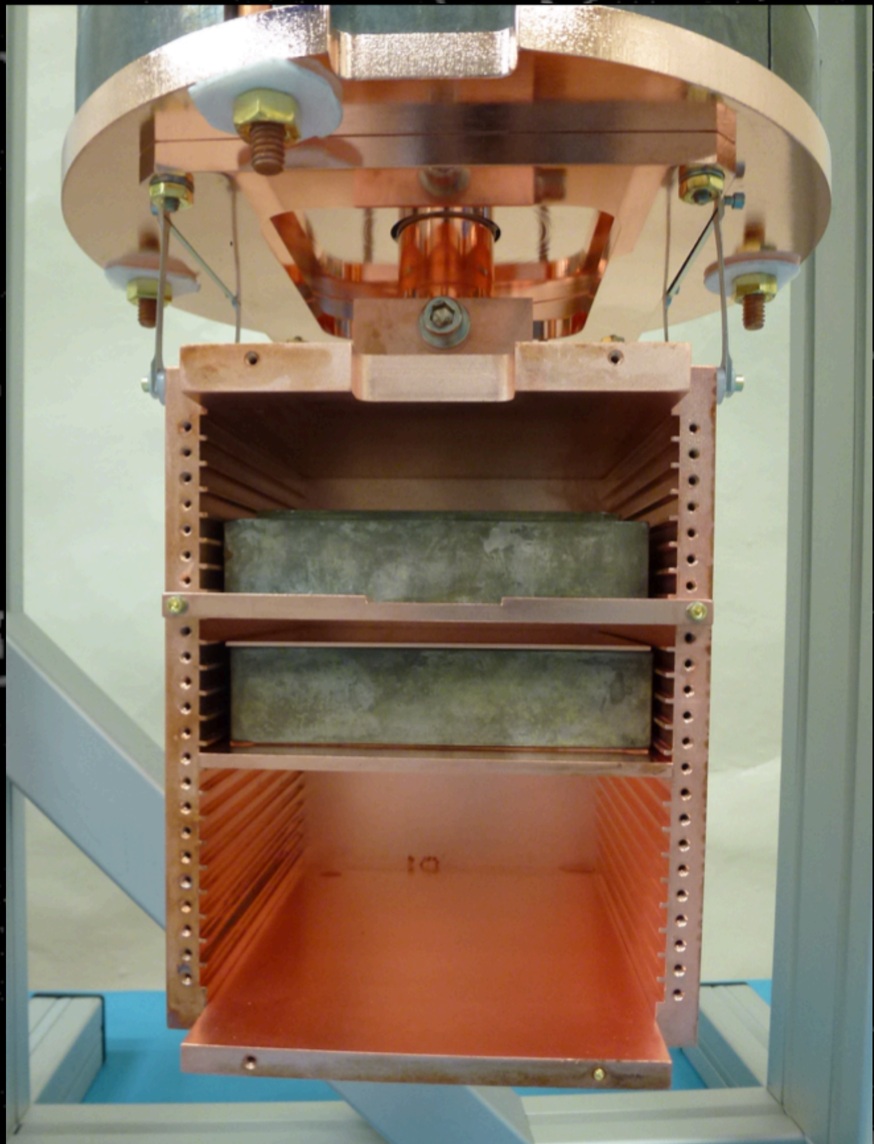
Efficiency

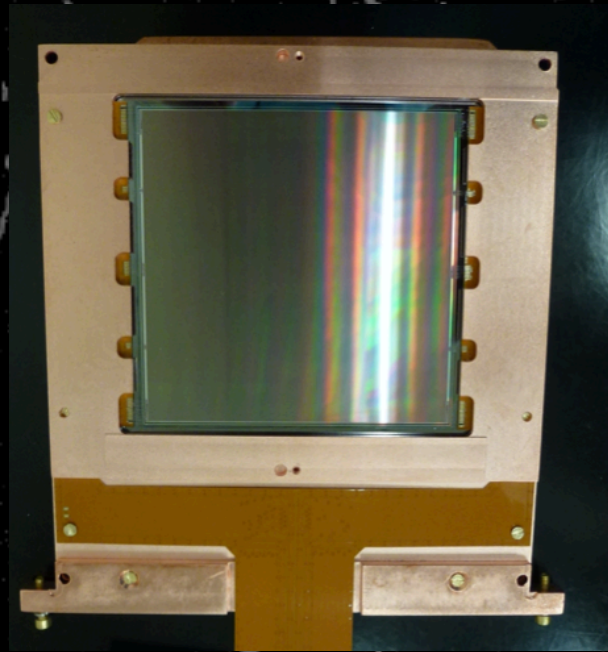


- Efficiency model validated with data
- Reading out 100 pixels improves detection efficiency (by reducing noise)

arXiv:1607.07410

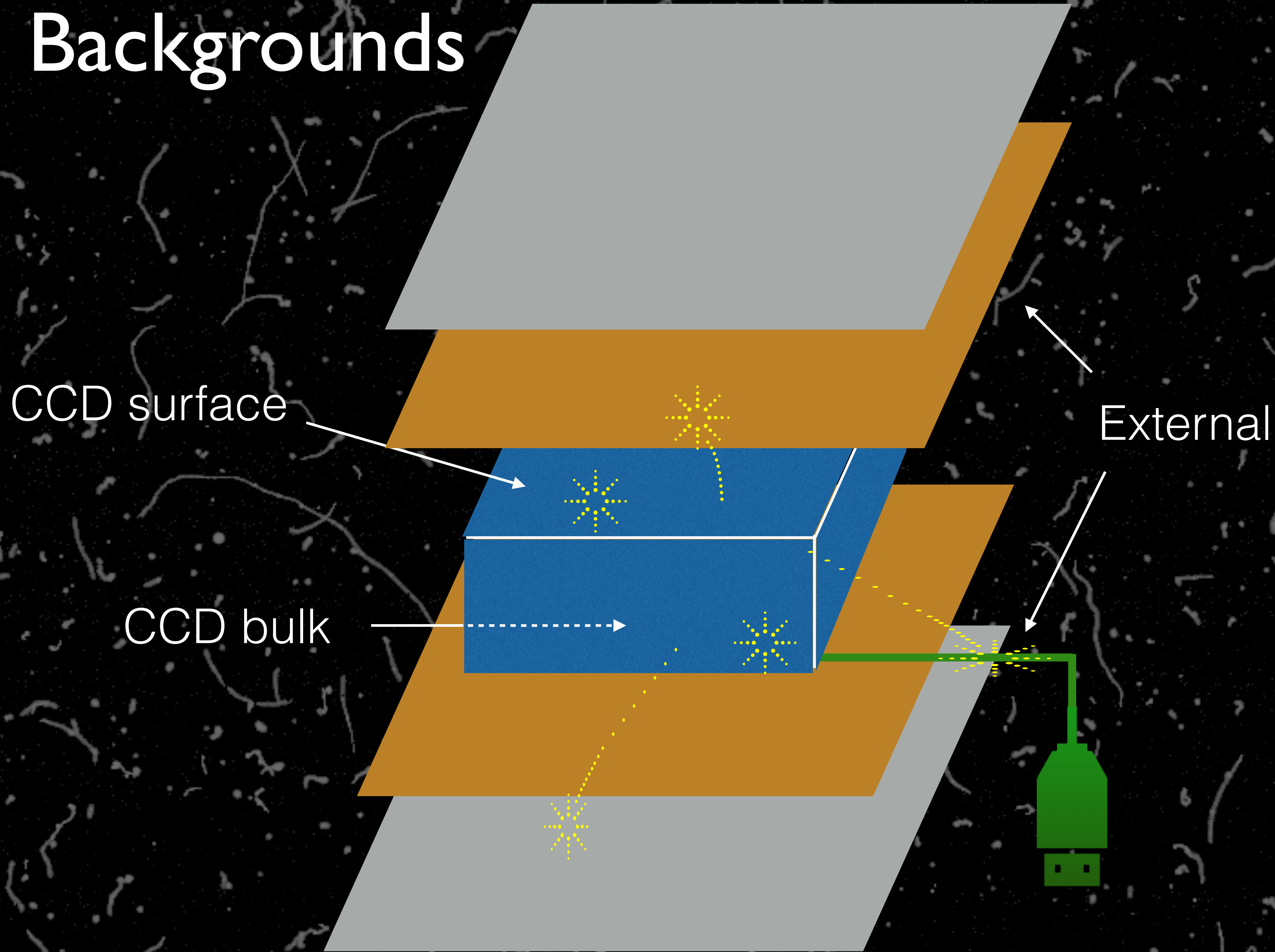
Backgrounds





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

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**

All can be reduced !

Reducing backgrounds for DAMIC-M

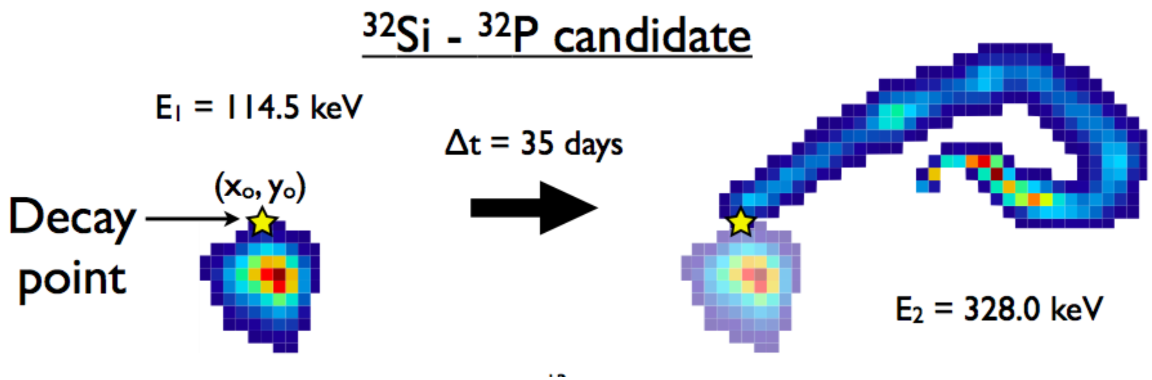
Dominant Backgrounds	**How to reduce**
^{60}Co, ^{210}Pb ^{238}U, ^{232}Th	Electro-forming copper underground
^{210}Pb	Cleaner CCD processing/ fabrication
^{3}H & ^{22}Na	Shielding silicon Underground storage & processing
^{32}Si & ^{32}P	**Silicon vertex tagging***

* Not what you expect !

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)



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

2015 *JINST* **10** P08014   1506.02562

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

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

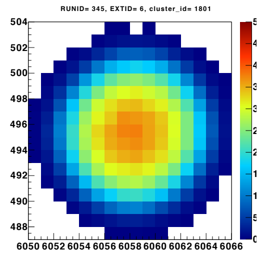
CCDs have unique spatial resolution

Three α at the same pixel location!

Corresponds to decay chain of Thorium

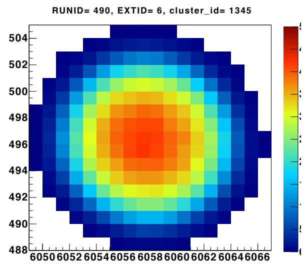
E = 5.4 MeV

1



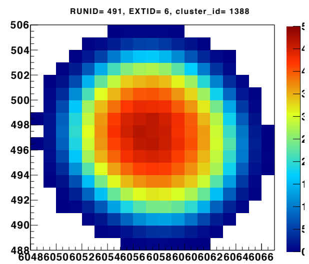
E = 6.8 MeV

2



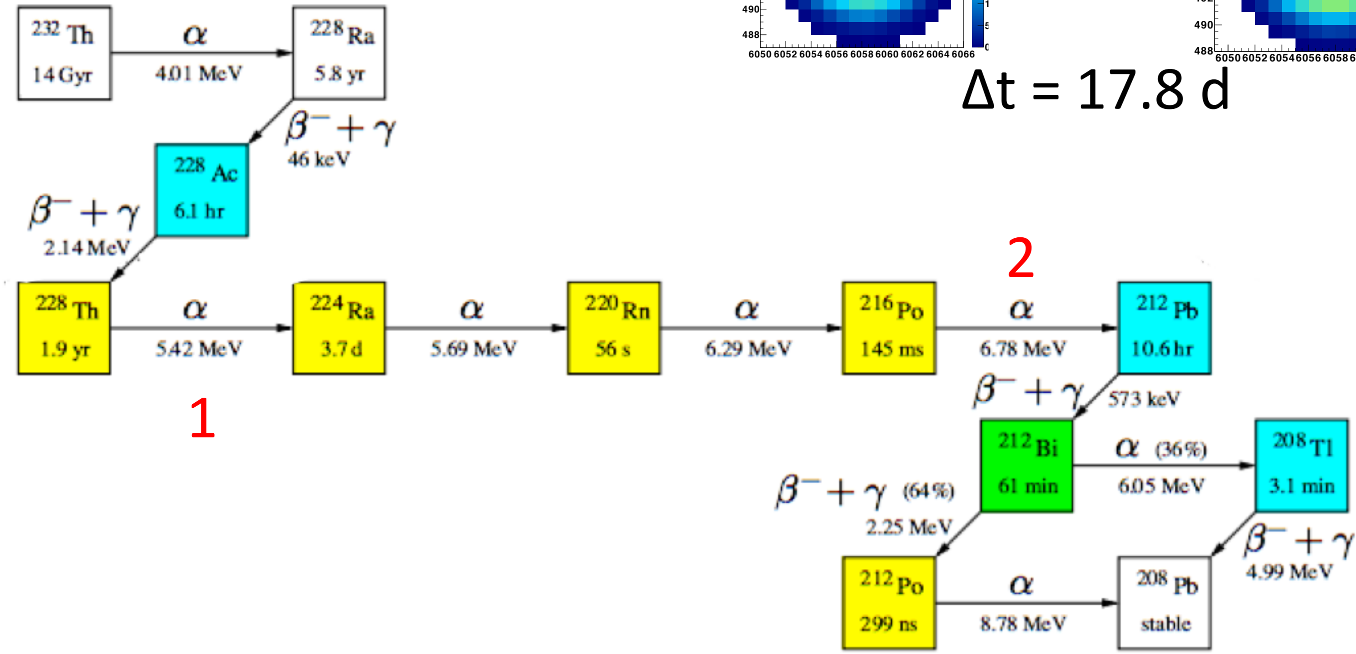
E = 8.8 MeV

3



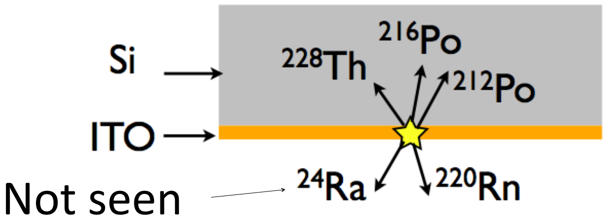
Δt = 17.8 d

Δt = 5.5 h



arXiv:1506.02562

2015 *JINST* **10** P08014

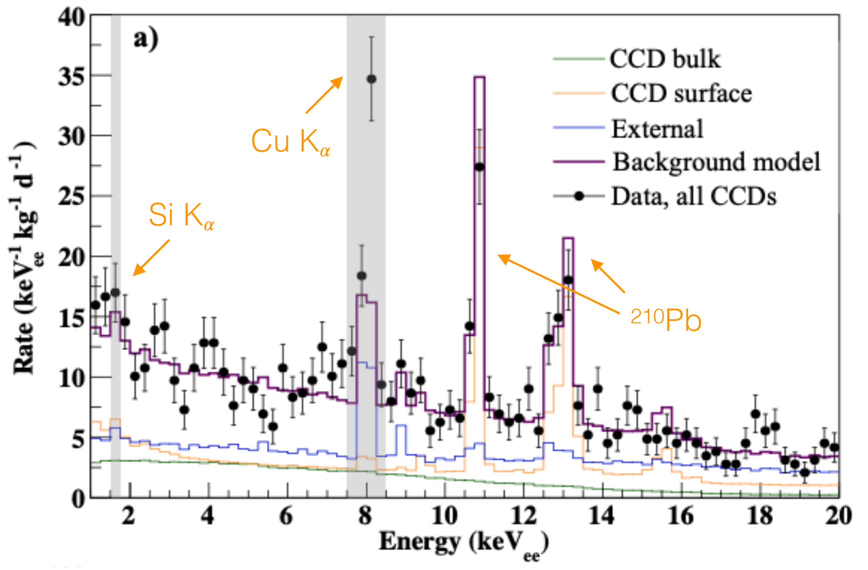


We set in situ limits on contamination:
^{238}U < 5 kg^{-1} d^{-1} = 4 ppt
^{232}Th < 15 kg^{-1} d^{-1} = 43 ppt

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 :

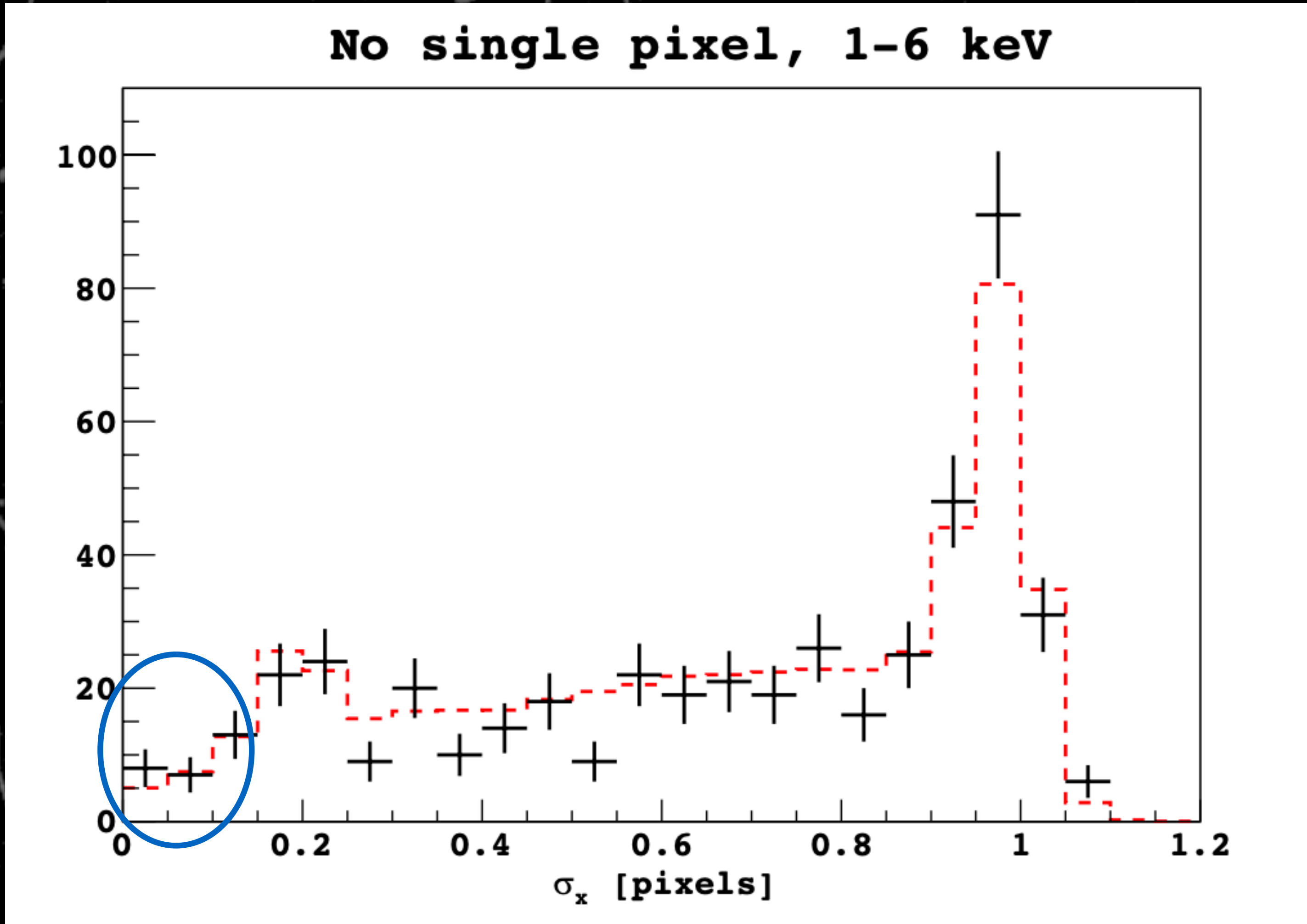
- GEANT simulation compared to data
- 2D model : energy vs. cluster size

  Cluster size constrains depth

A priori uses fast clustering algorithm - not perfect

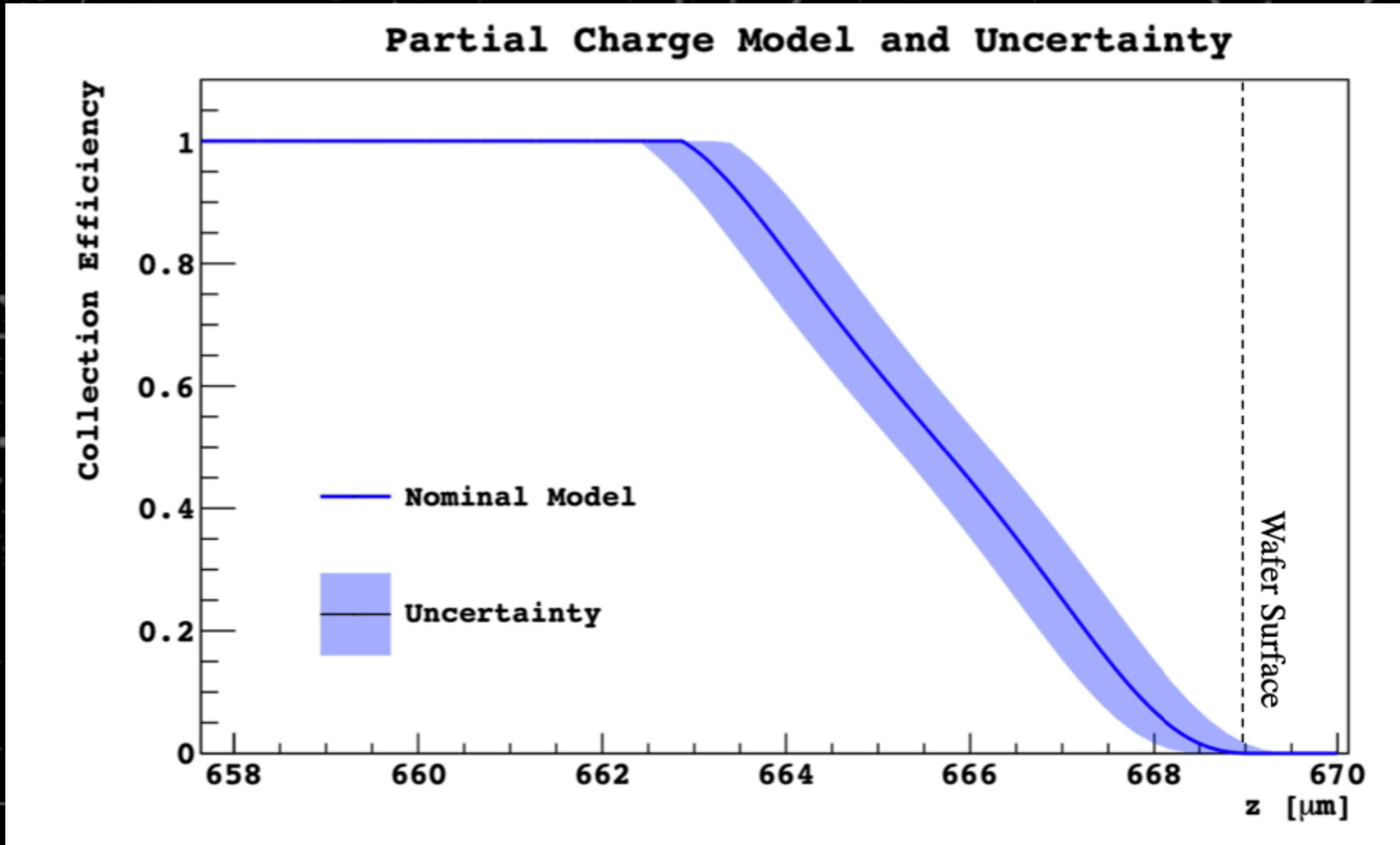
Using log-likelihood clustering

Clustering used in analysis

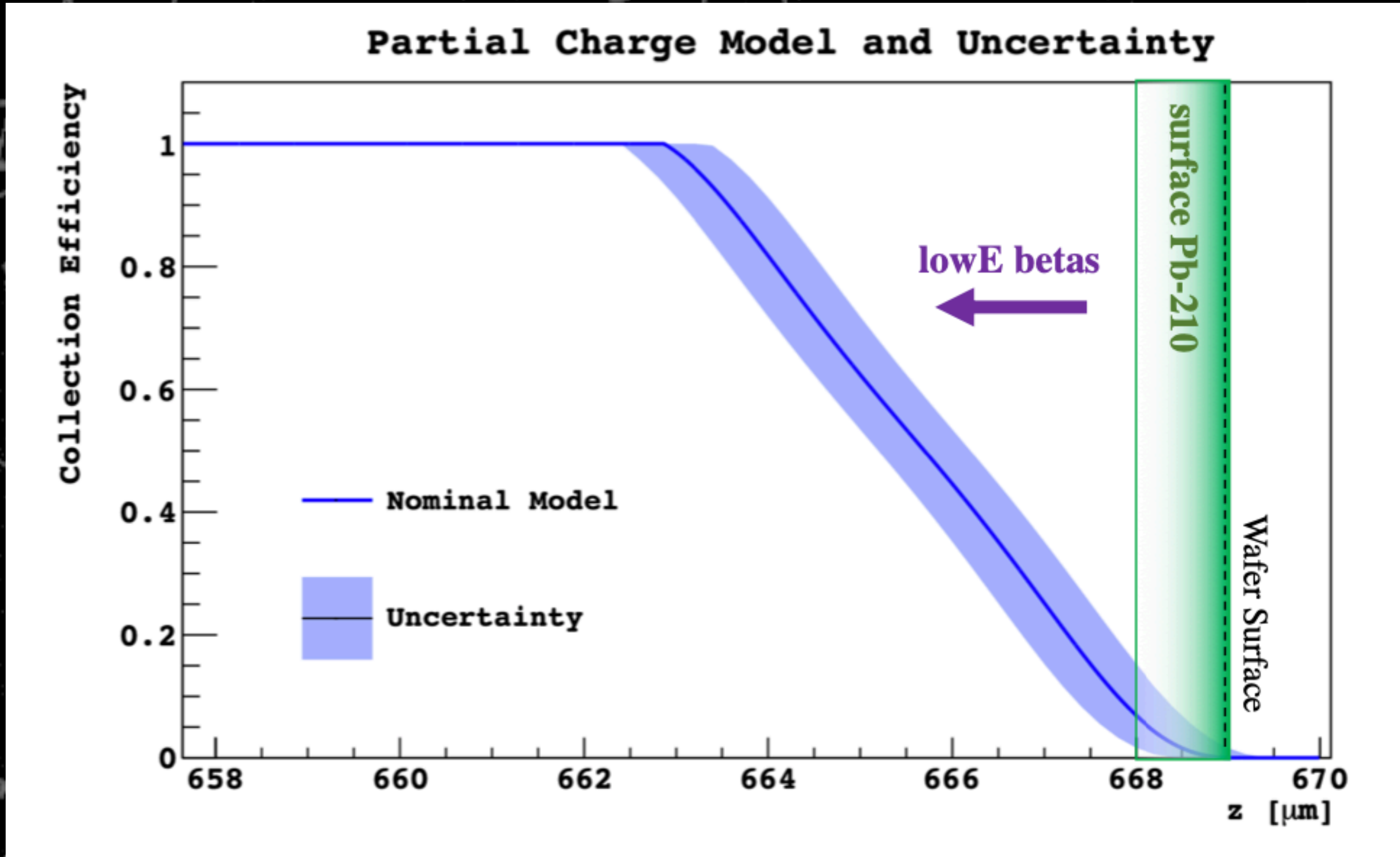


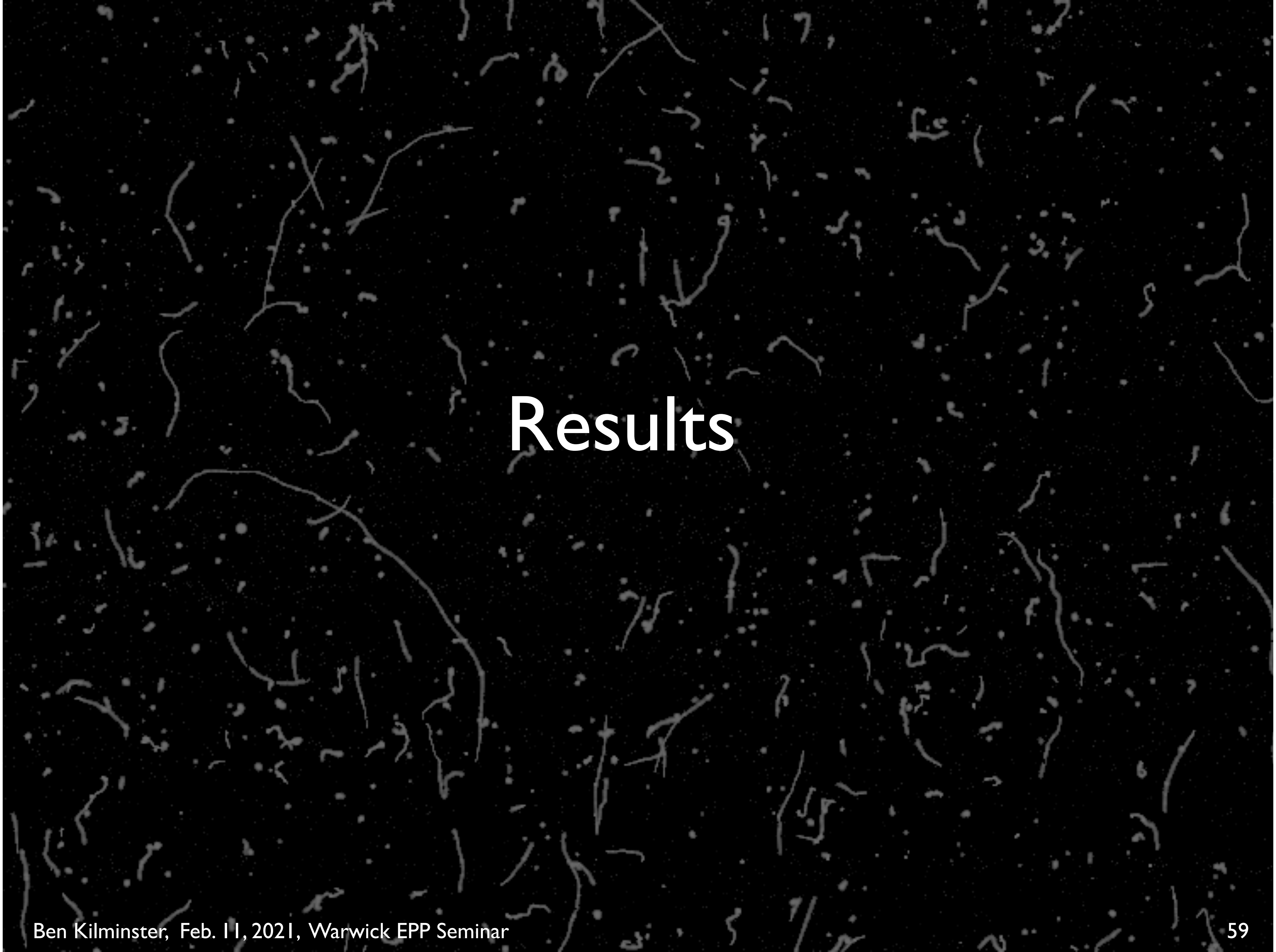
Good agreement at low σ_x

Systematic uncertainty : Partial charge collection region



Partial charge collection region



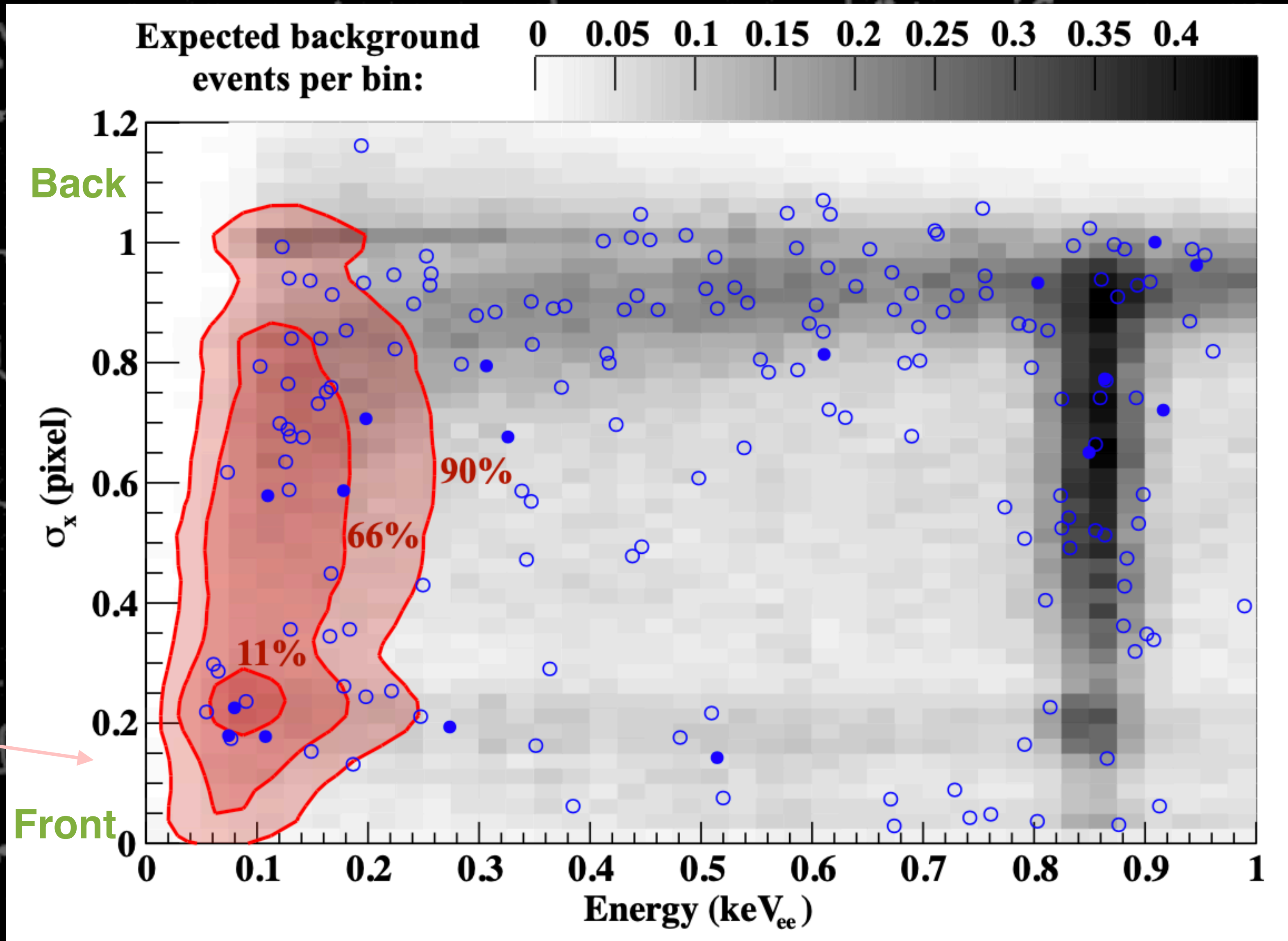


Results

Results of background + signal fit

Fit of cluster size vs. energy

3.4 σ excess

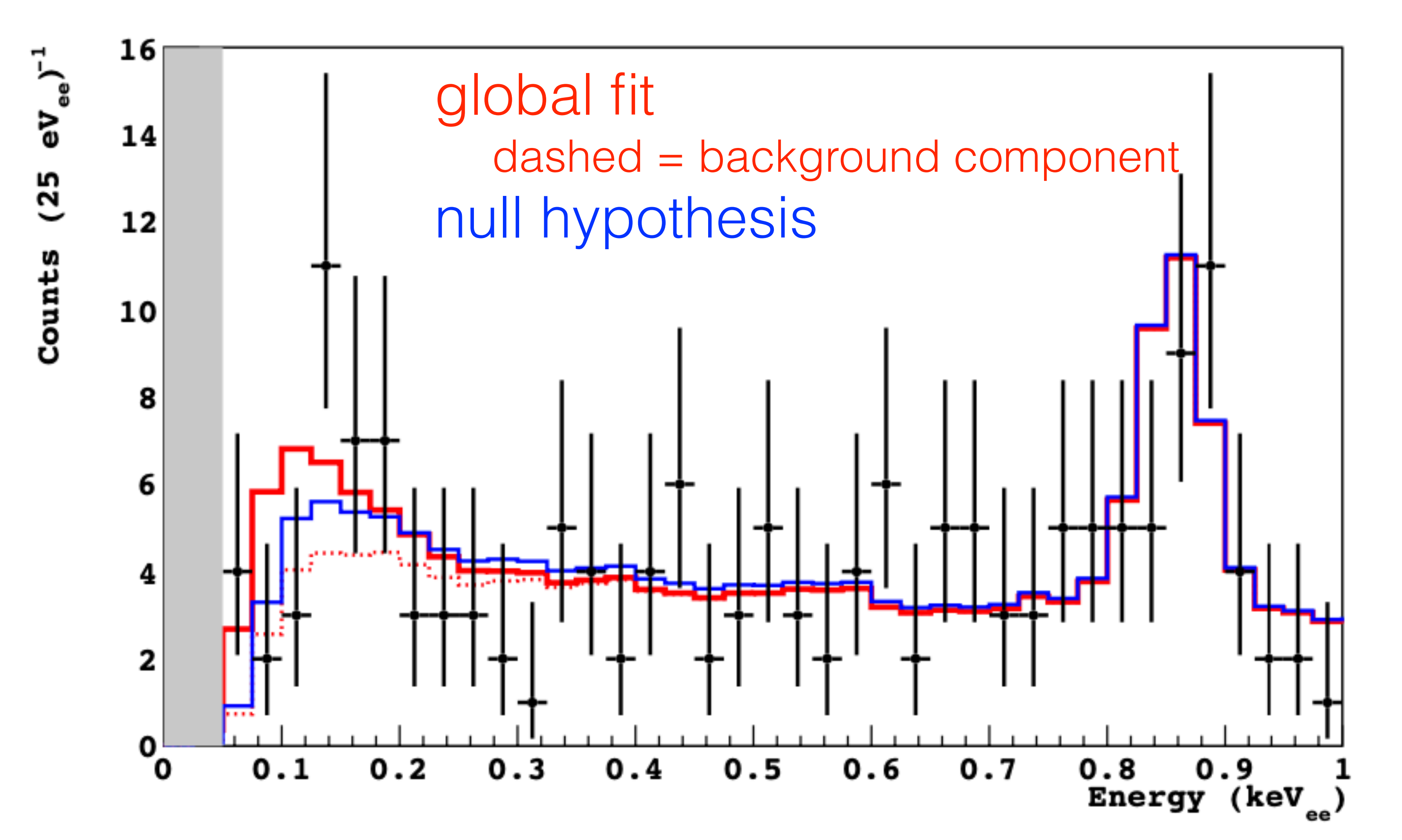


Possible explanations of excess

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

Energy projection

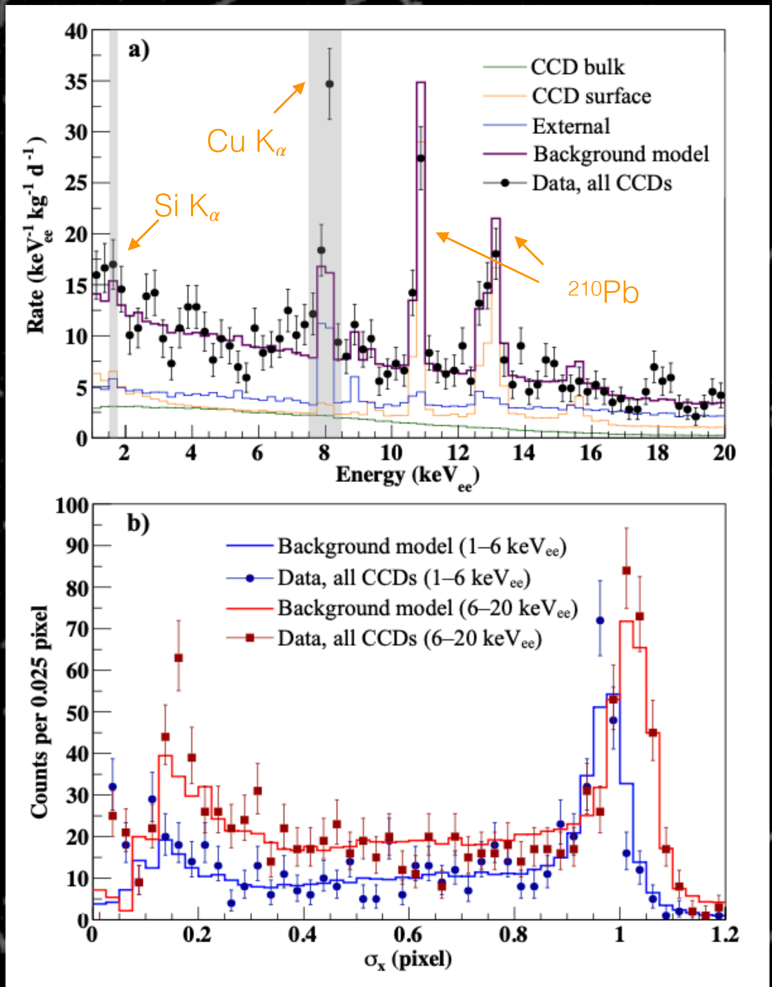
summed over all σ_X

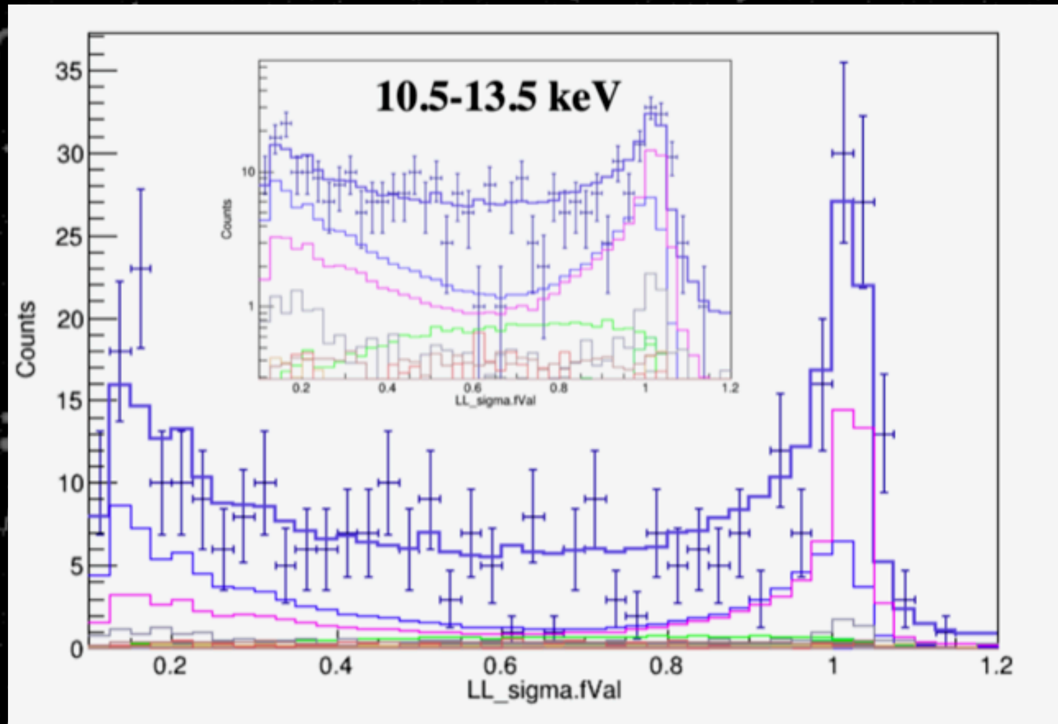


Does not appear to be energy-threshold effect

Surface background modeling ?

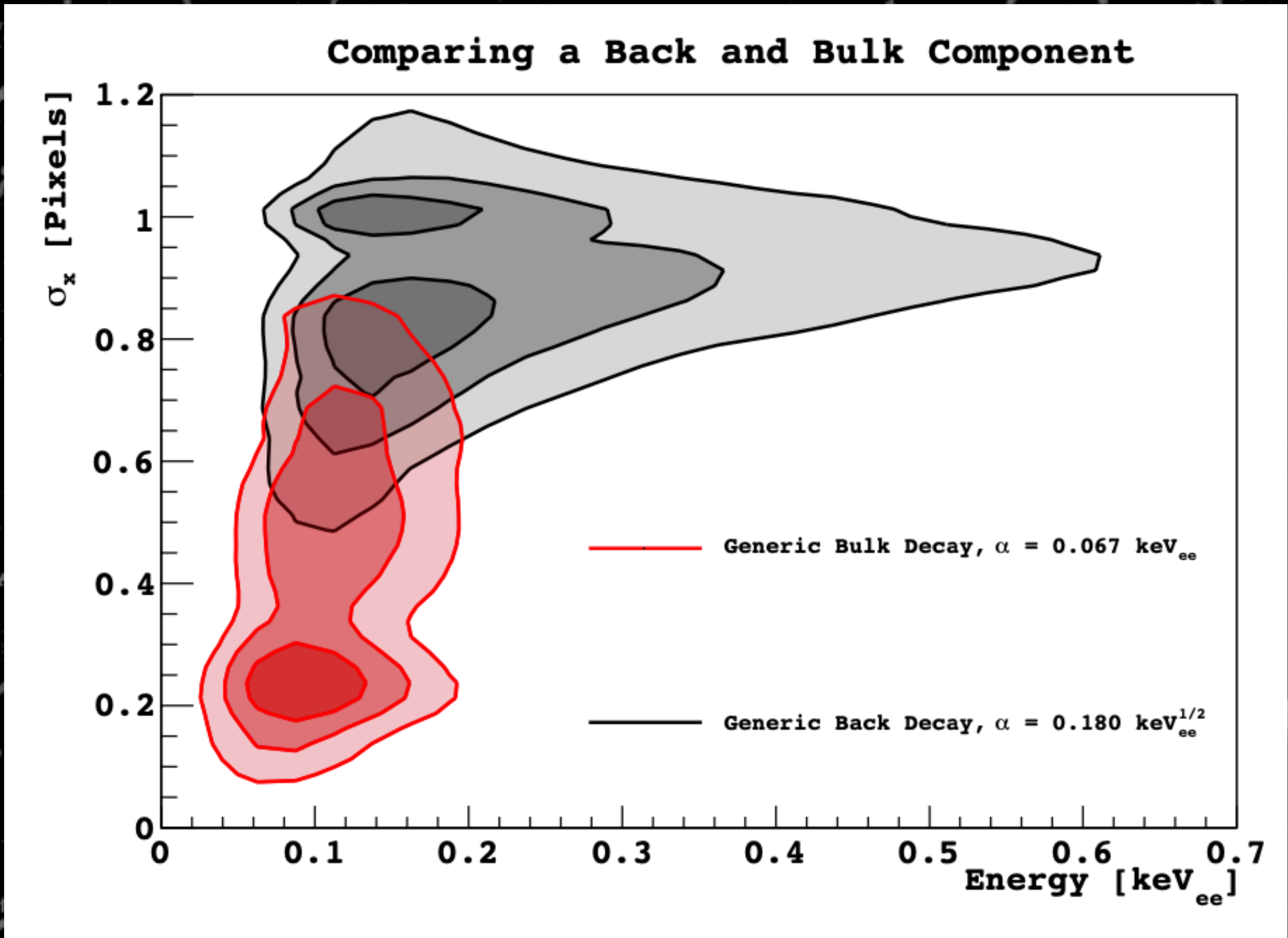
- ^{210}Pb peak can be studied





Appears well modeled

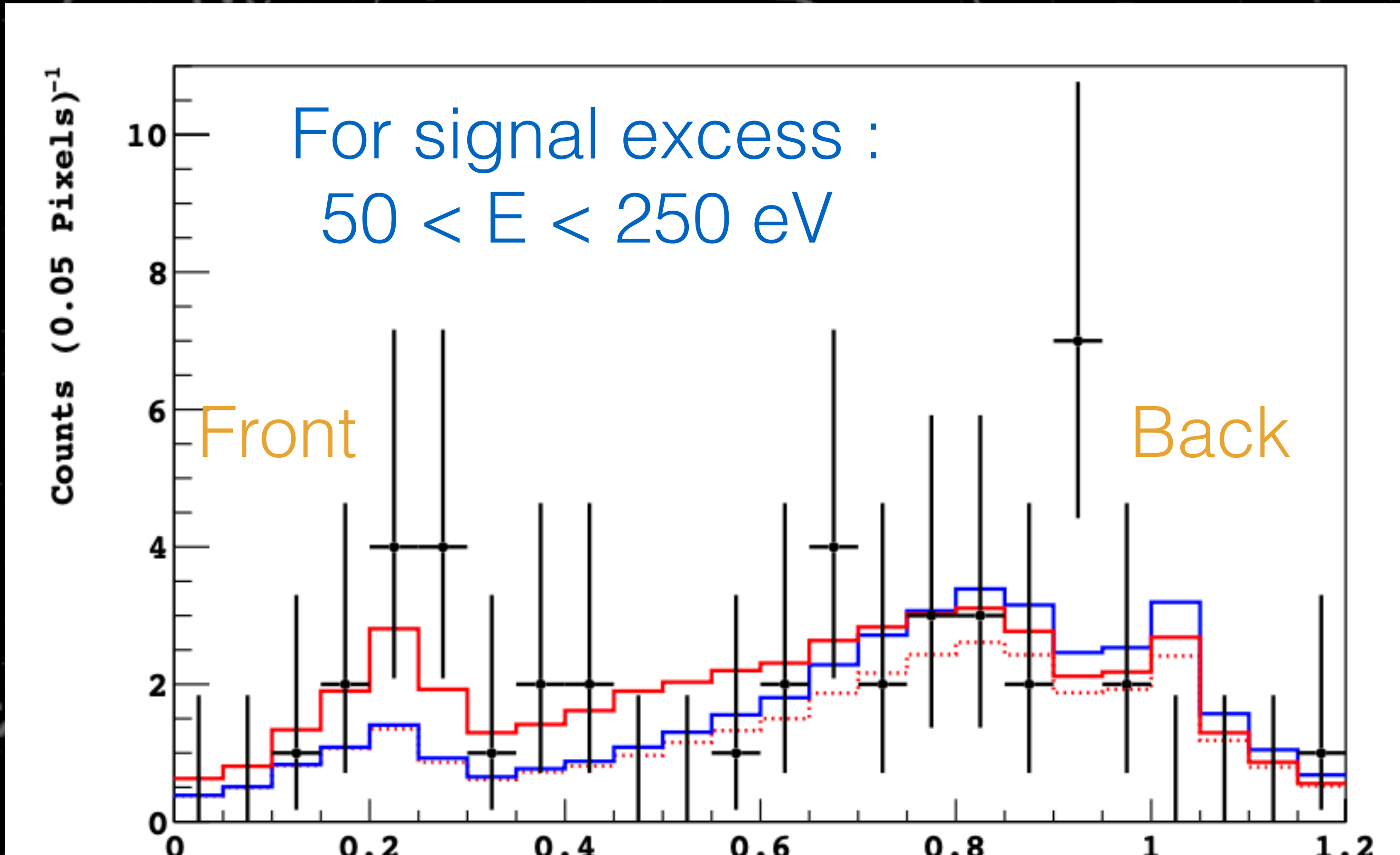
Problem with Partial Charge Collection (PCC) model?



Model of PCC on backside with systematic uncertainties

Cannot explain excess

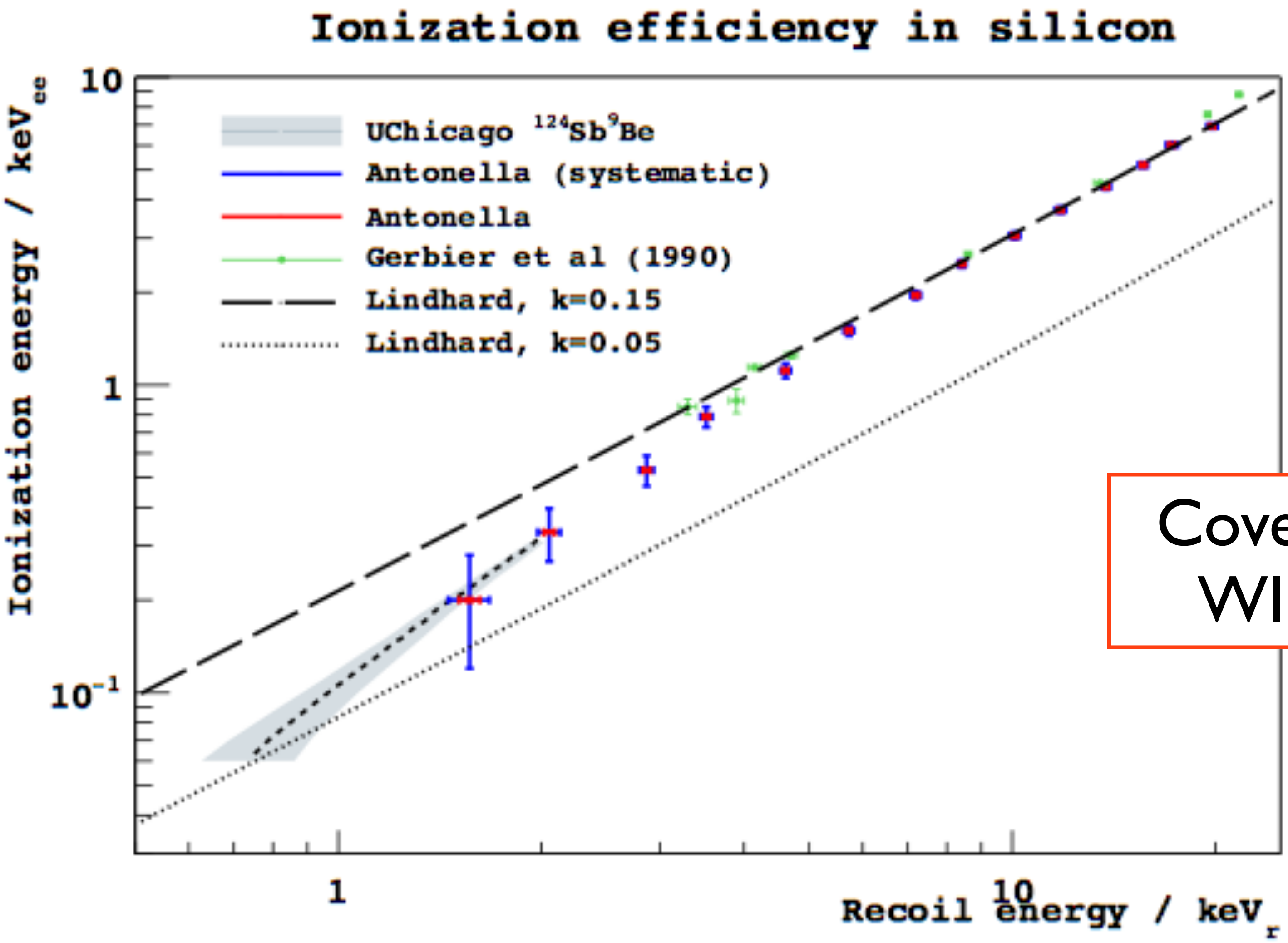
Is signal localized in one part of CCD ?



Cluster size projection

Excess is spread out - not just one part of CCD

Nuclear recoil calibrations



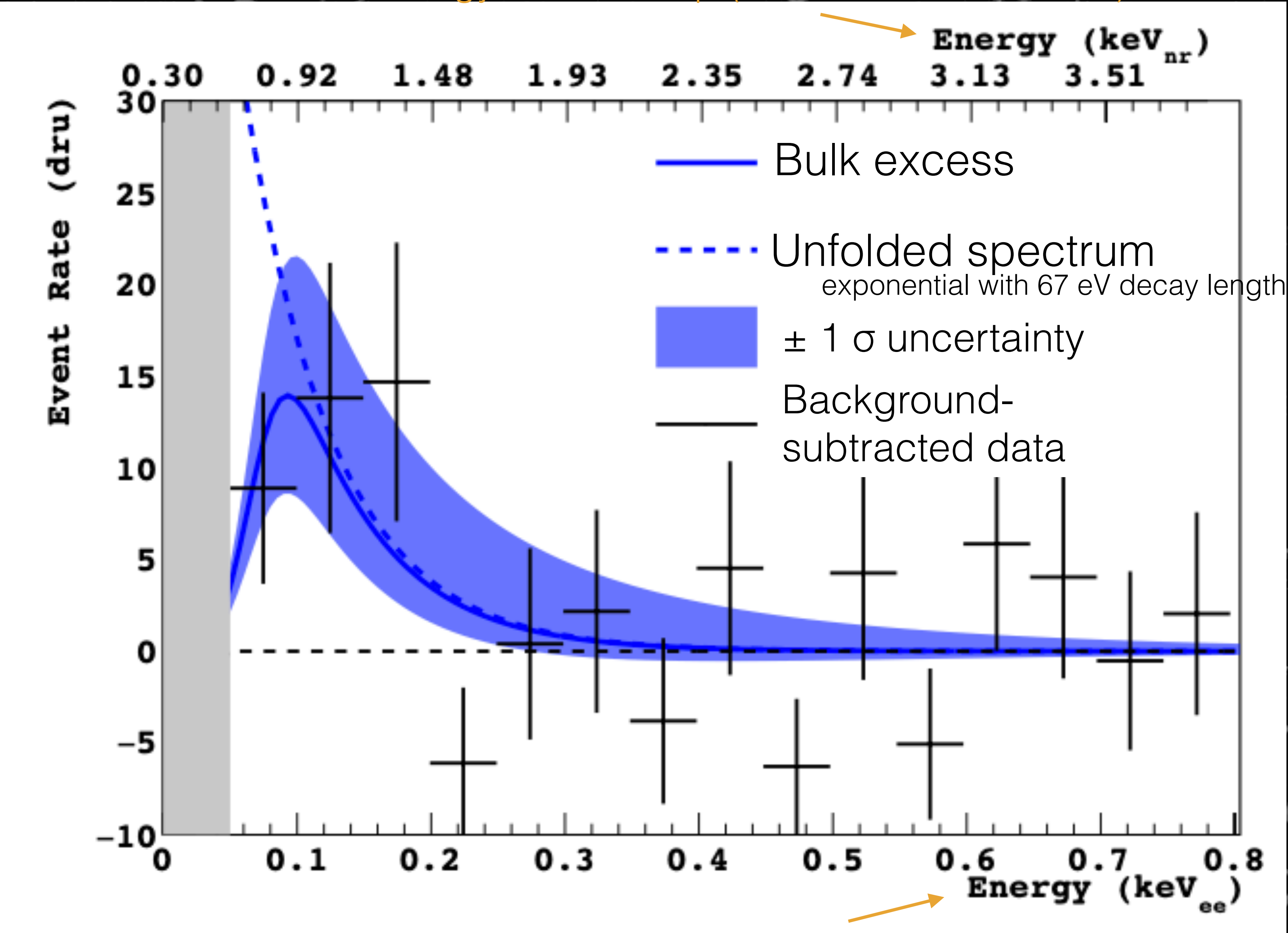
Antonella : 1702.00873
U.Chicago : 1608.00957

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**

Signal excess energy distribution

Nuclear recoil energy scale on top (calibrated to neutrons)

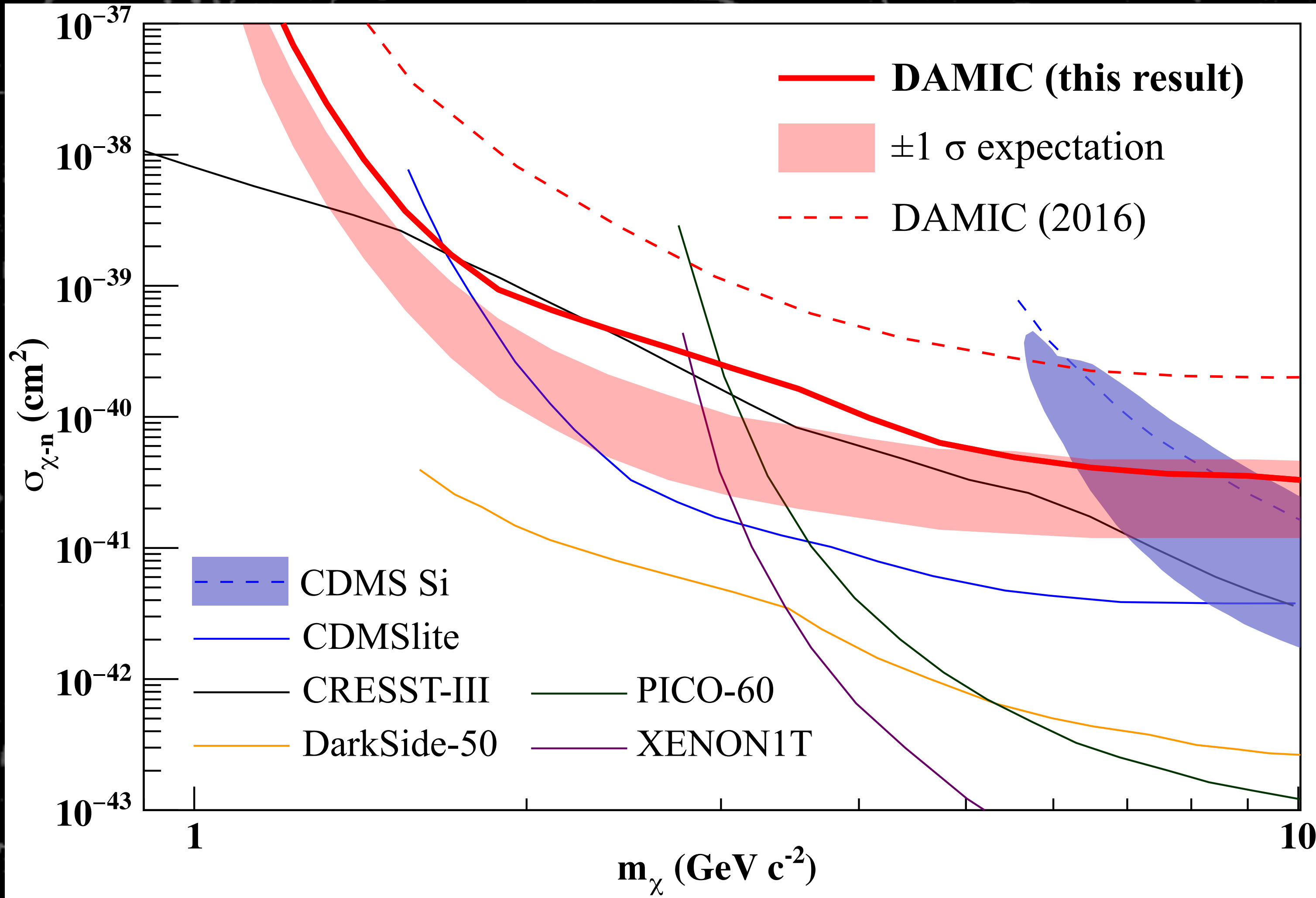


Ionization energy scale (calibrated to X-rays)

Possible explanations of excess

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

DAMIC 2020 limits



Observed limit is, of course, worse than expected

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

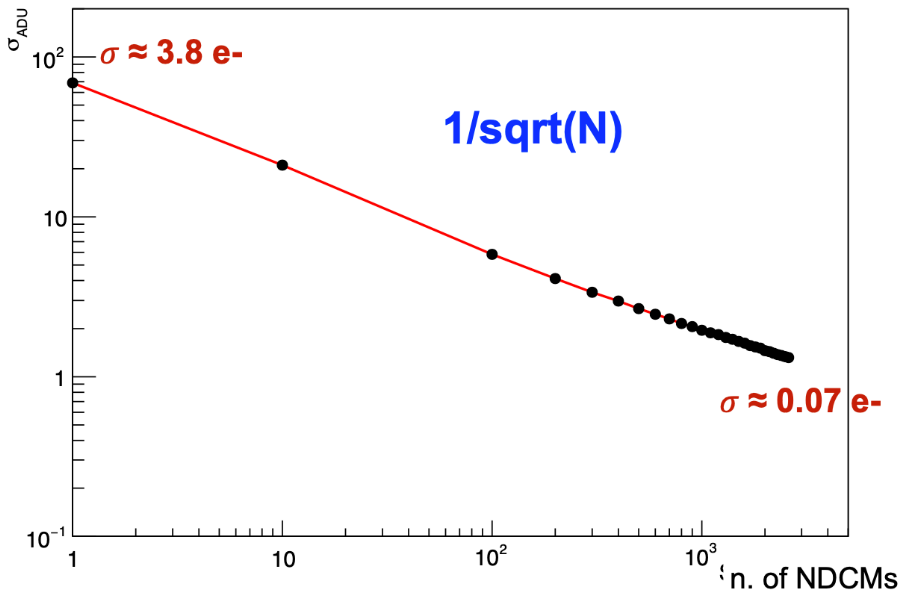
- Sensitive to nuclear recoils, electron recoils, γ absorption from A'

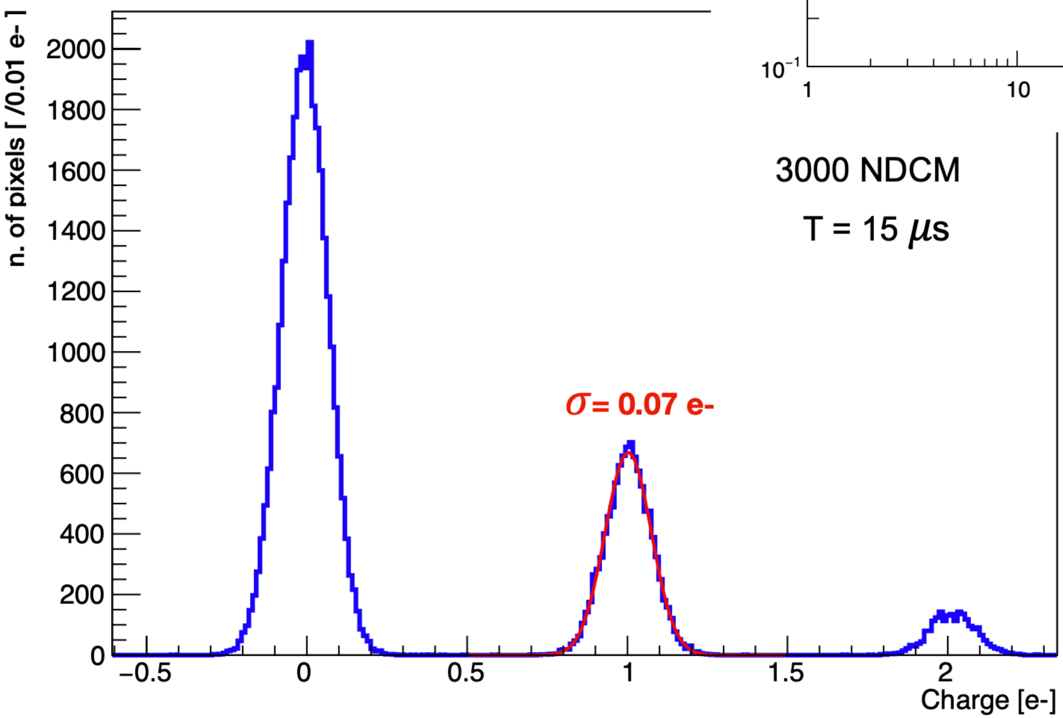
Achieving a factor of 10 reduction in noise threshold

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

Achieved energy resolution : 0.07 e- !

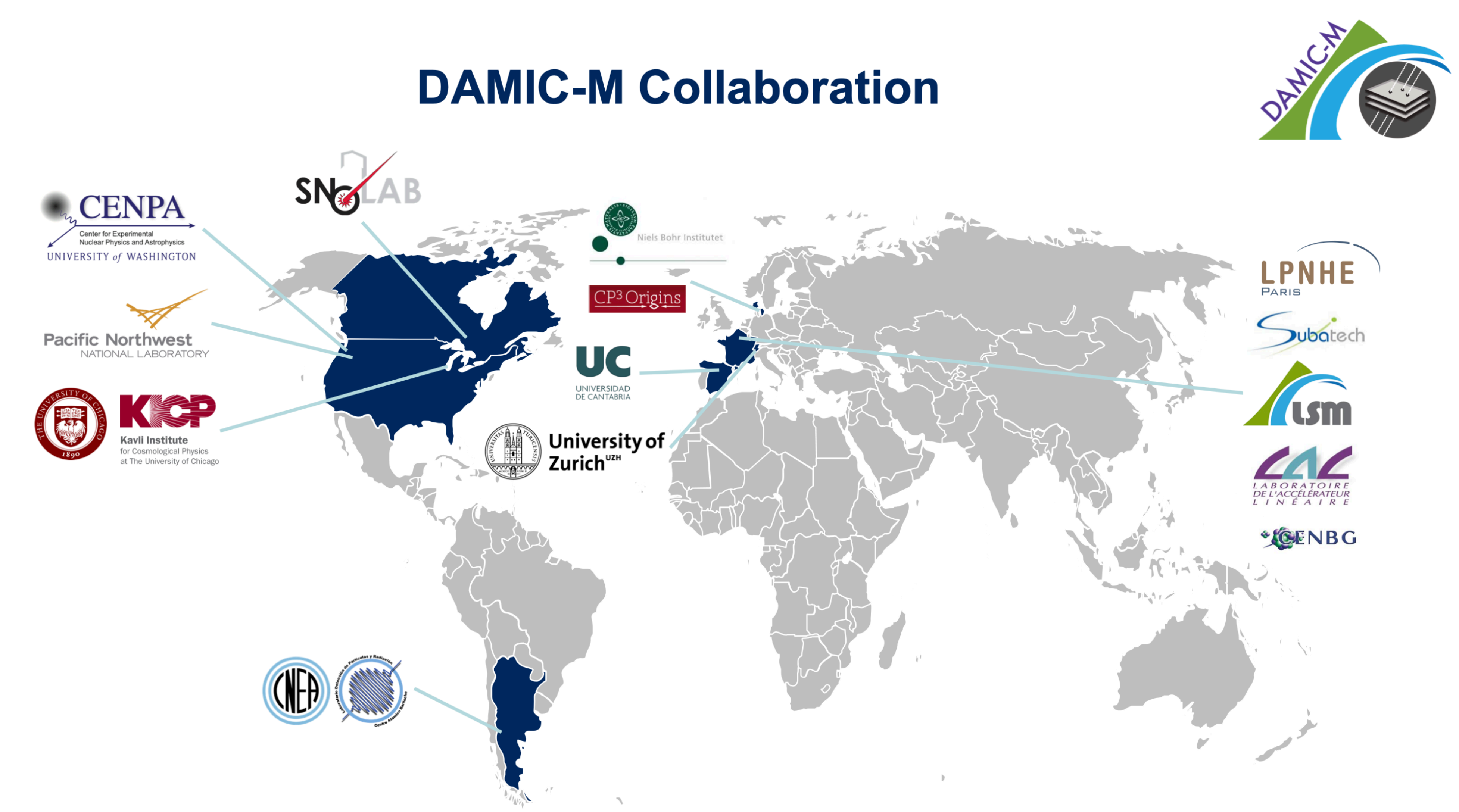
- Reduce noise by √N by repeatedly reading out pixels (skipper CCD)





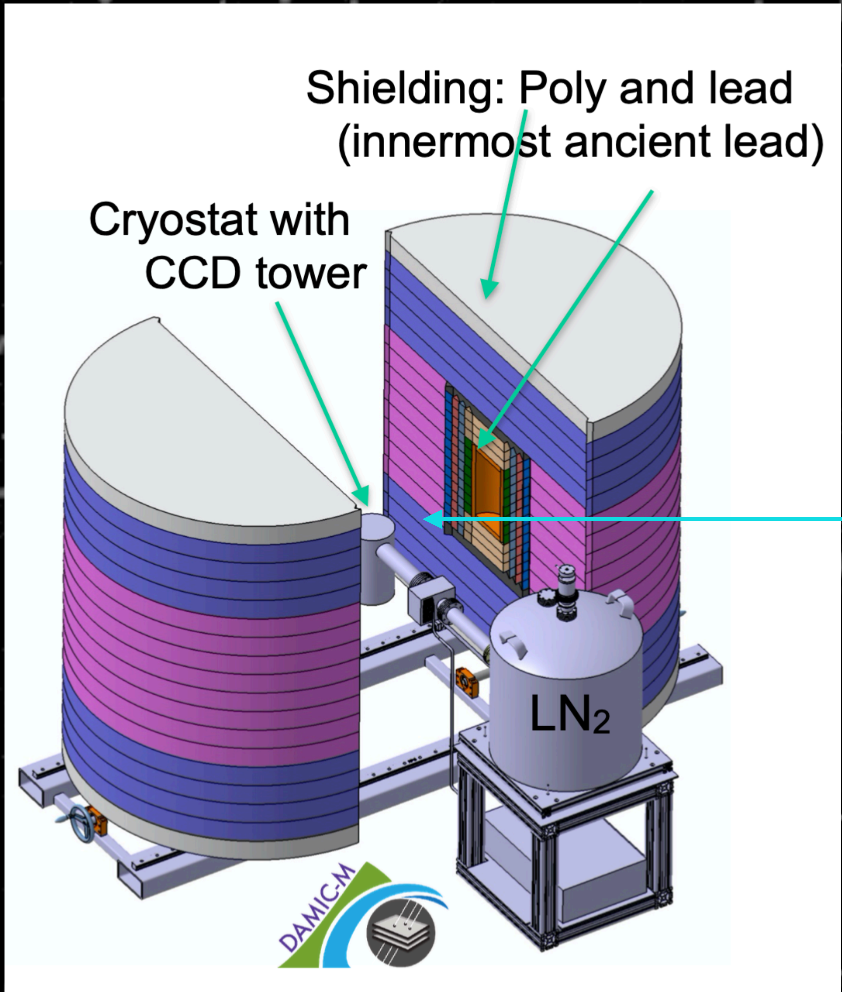
Skipper CCD allows identification of single electrons of produced ionization!

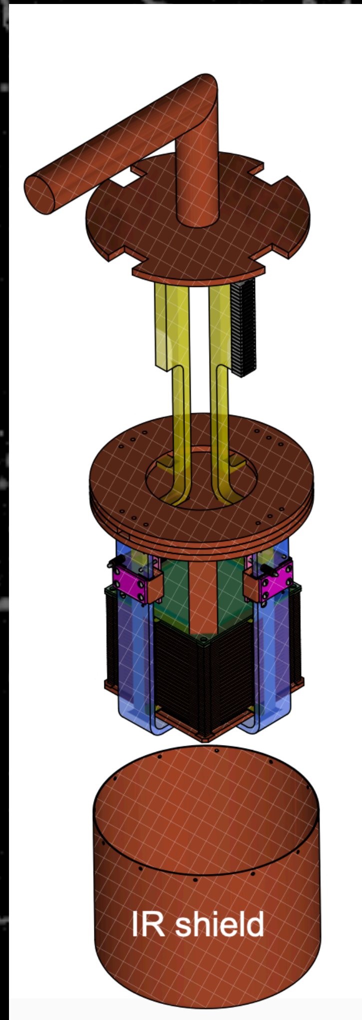
DAMIC-M Collaboration



DAMIC-M

- R&D and prototyping ongoing

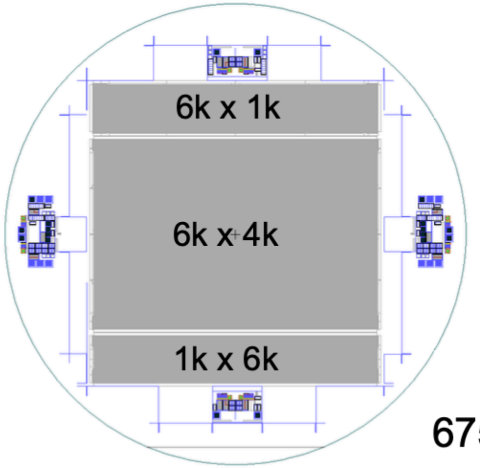




Electro-formed copper at PNNL

DAMIC-M CCDs

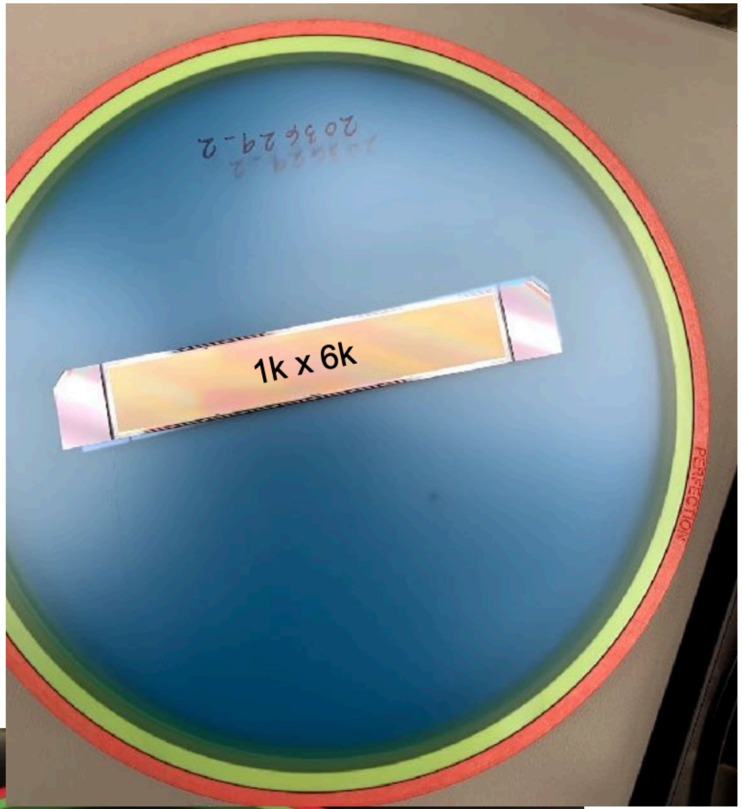
design by S. Holland (LBNL), fabricated by Teledyne/DALSA

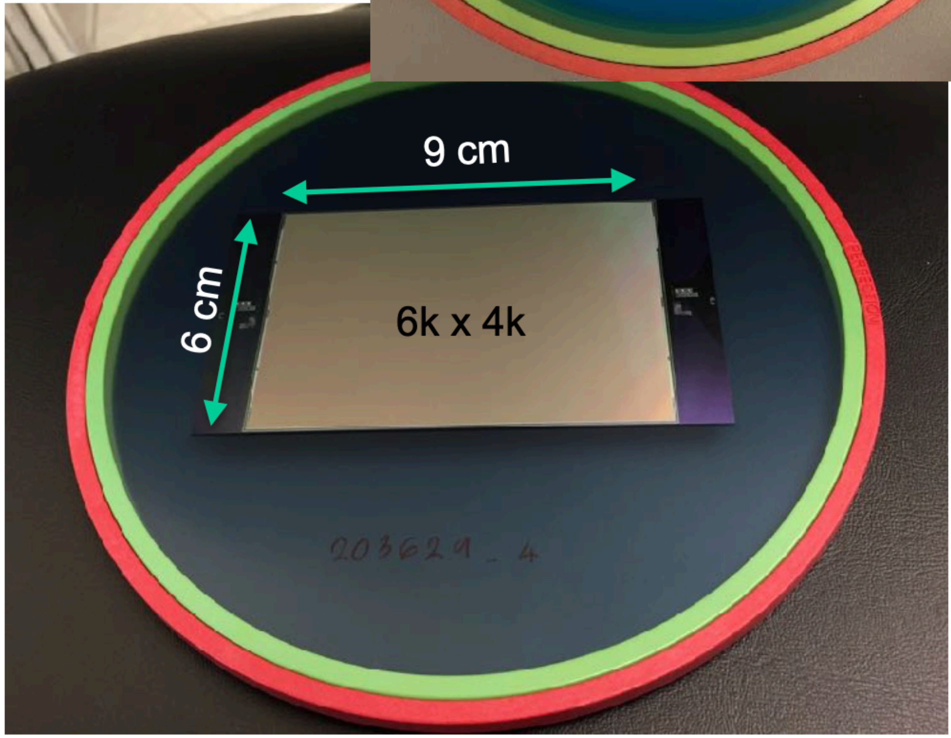


DAMIC-M prototype skipper CCDs

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

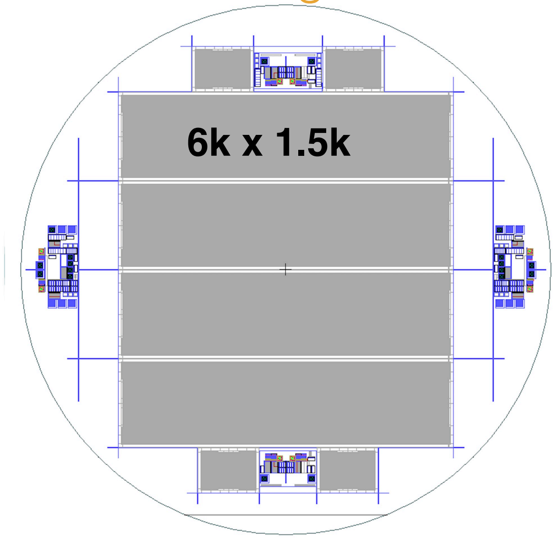
675 μm thick





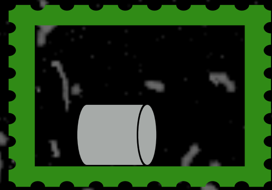
DAMIC-M production skipper CCD design

Yield better dividing CCD in 4



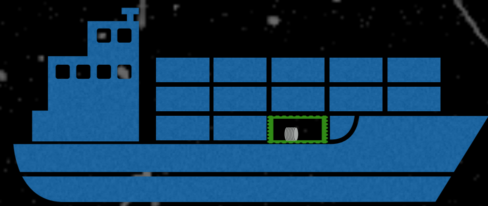
Recent progress with DAMIC-M CCDs

1) Silicon crystal produced (Denmark)

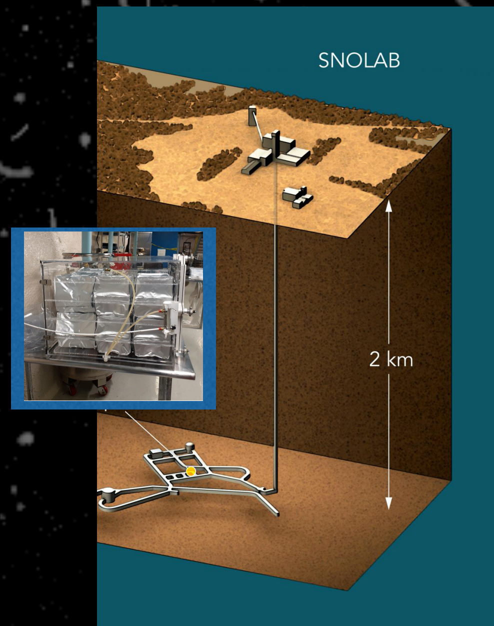


2) Wafers cut (U.K.)

3) Wafers shipped across ocean



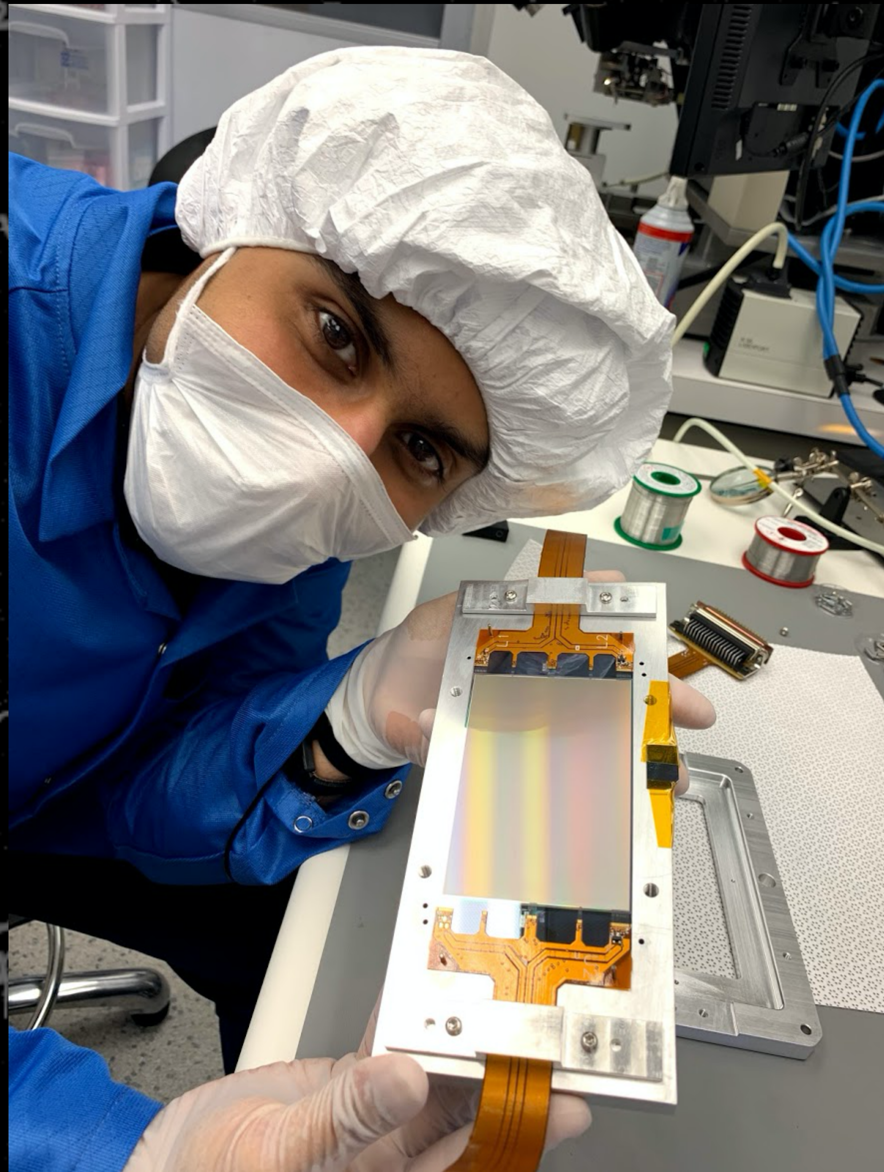
4) Wafers stored (Canada)



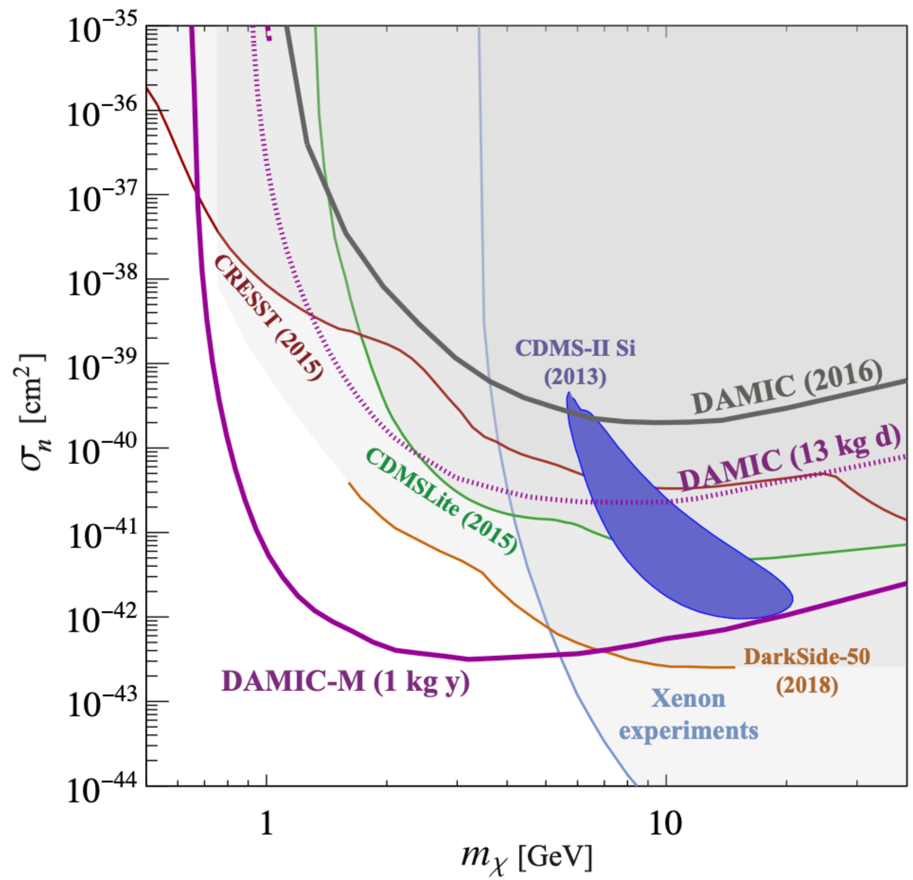
Total equivalent surface exposure
14.3 days !
Cosmogenic activation minimized !

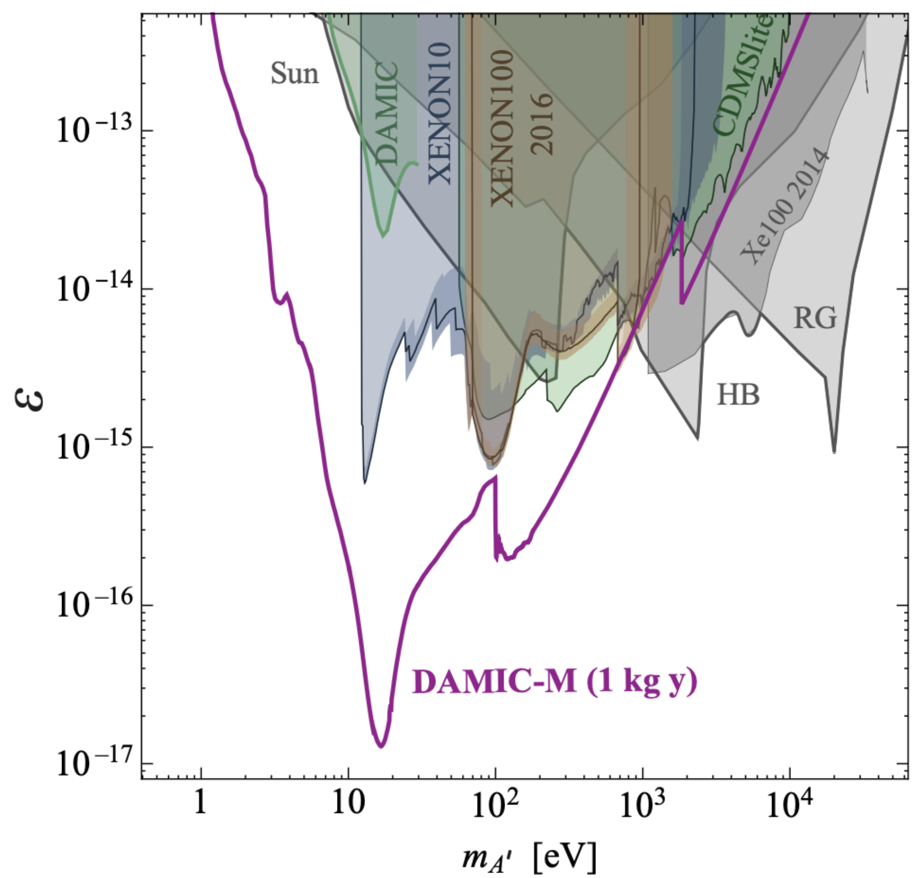
CCD packaging

Progress packaging different size CCDs



DAMIC-M reach





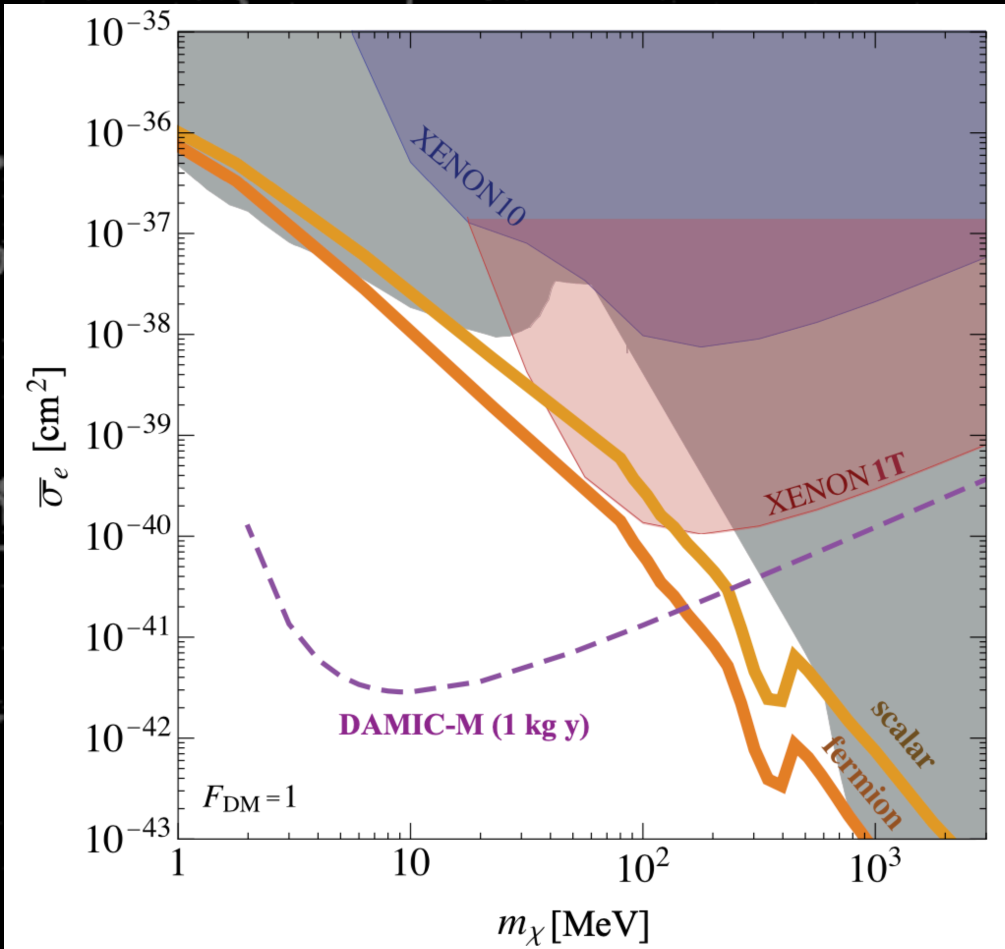
DAMIC-M reach for nuclear recoils of WIMP

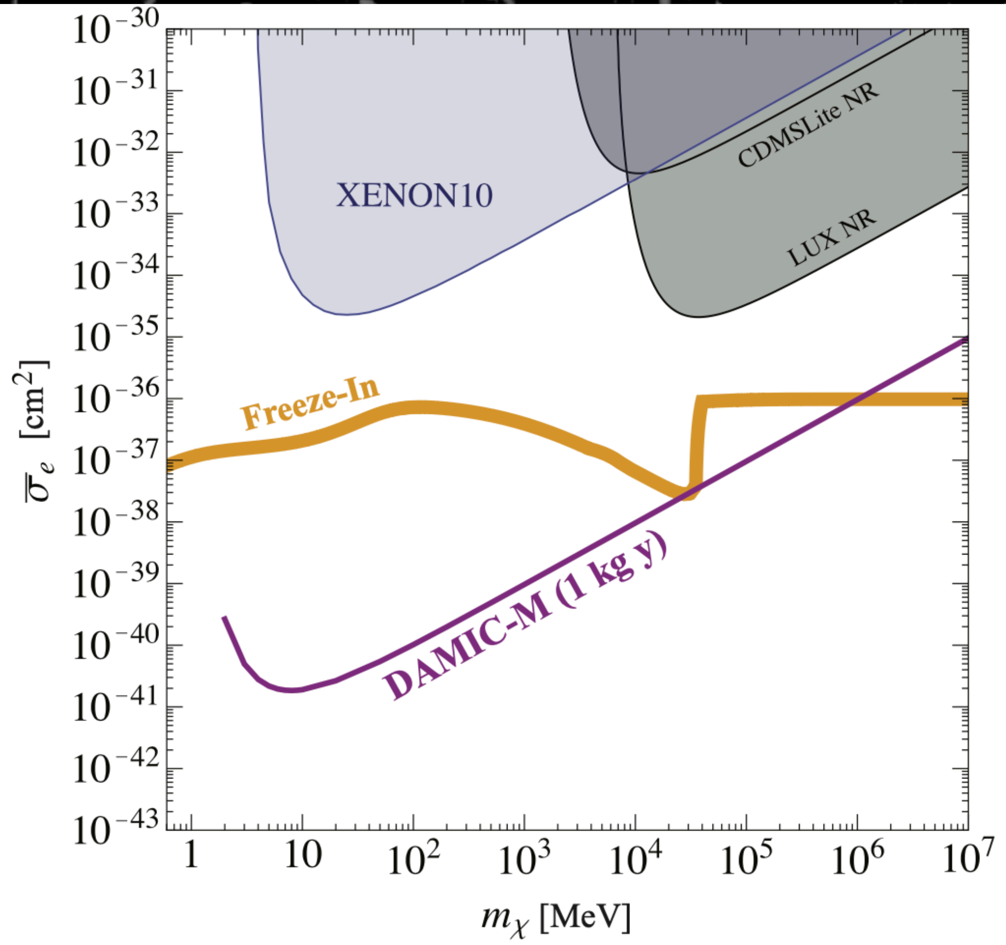
As a function of kinetic mixing parameter (A' with γ) assuming A' constitutes all dark matter

DAMIC-M reach

DM-electron cross-sections

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



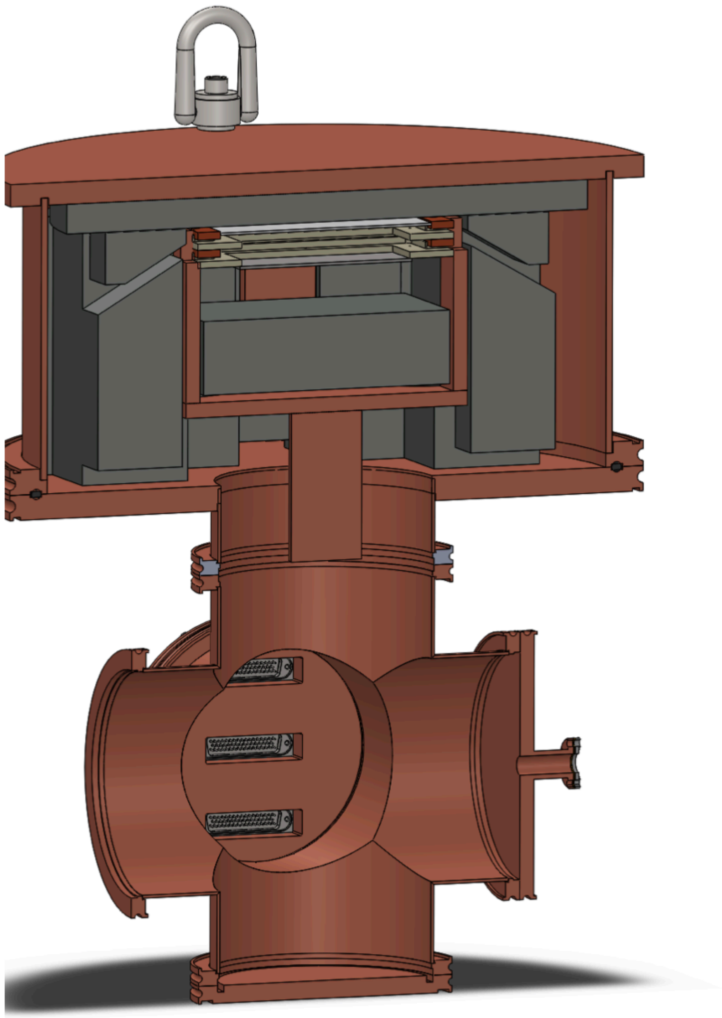


Weakly-coupled χ does not reach thermal equilibrium, and "freezes in"

Orange are theoretical predictions

Now: First phase of DAMIC-M

Low Background Chamber

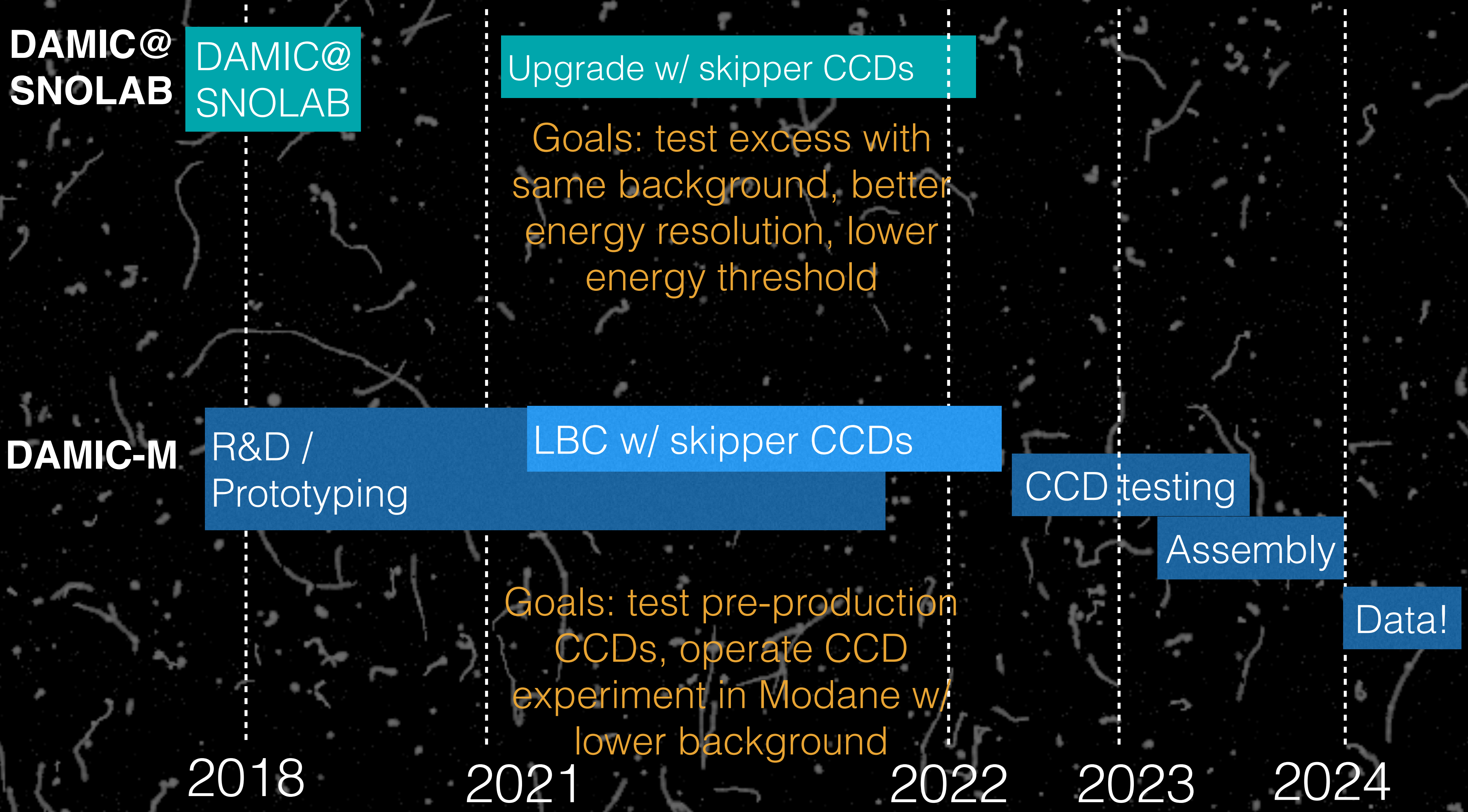


- A low-background chamber (background level ≈ dru) is in preparation
- Main objectives:
  - characterization of DAMIC-M CCDs in low-bkg environment: dark current; ^{32}Si rate; ^{210}Pb surface bkg; CCD packaging
  - first science results with a few CCDs
- **Installation in 2021**

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

Timeline


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
2018
2021
2022
2023
2024

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)

Summary

- DAMIC@SNOLAB results
  - Pioneered direct-detection searches of hidden photon DM
  - New WIMP search has 3.4σ excess, still sets strong limits

- DAMIC-M is a new experiment at Modane (LSM)
  - 2 hours from CERN !
  - Will be sensitive to low-mass WIMPs (~1 GeV)
  - Sensitive to predicted cross-sections for several hidden photon DM candidates over 10 orders of magnitude in mass
  - Status
    - 2019-2021 : R&D & prototyping
    - 2021 : Low-background chamber (LBC)
    - 2022 : construction
    - end 2023 : Ready for data taking

- Future looks bright - or perhaps if we're lucky - dark !

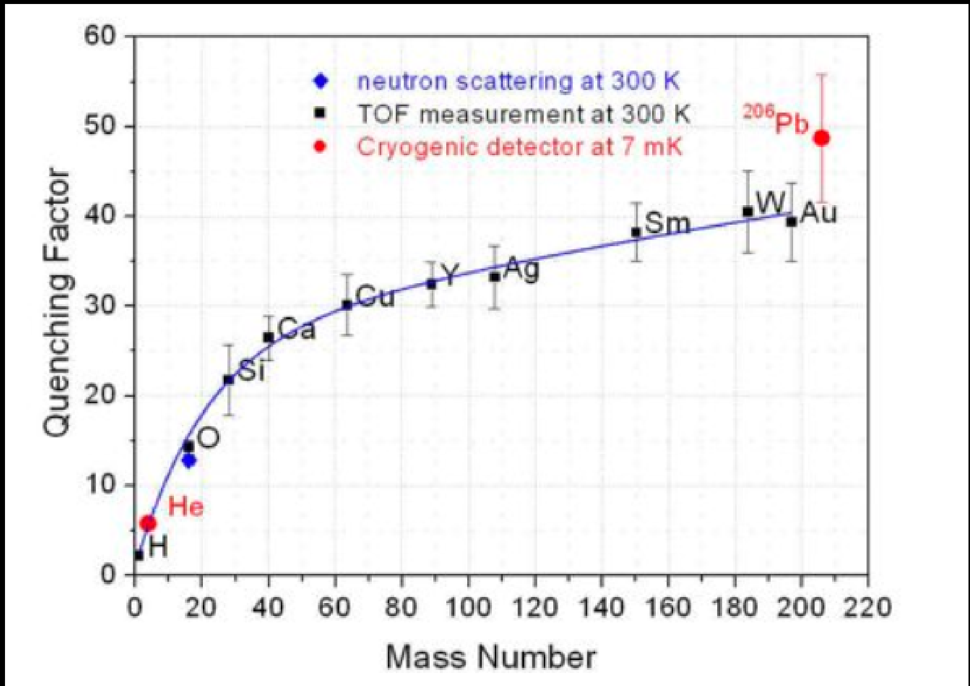
BACKUPS

Quenching factor

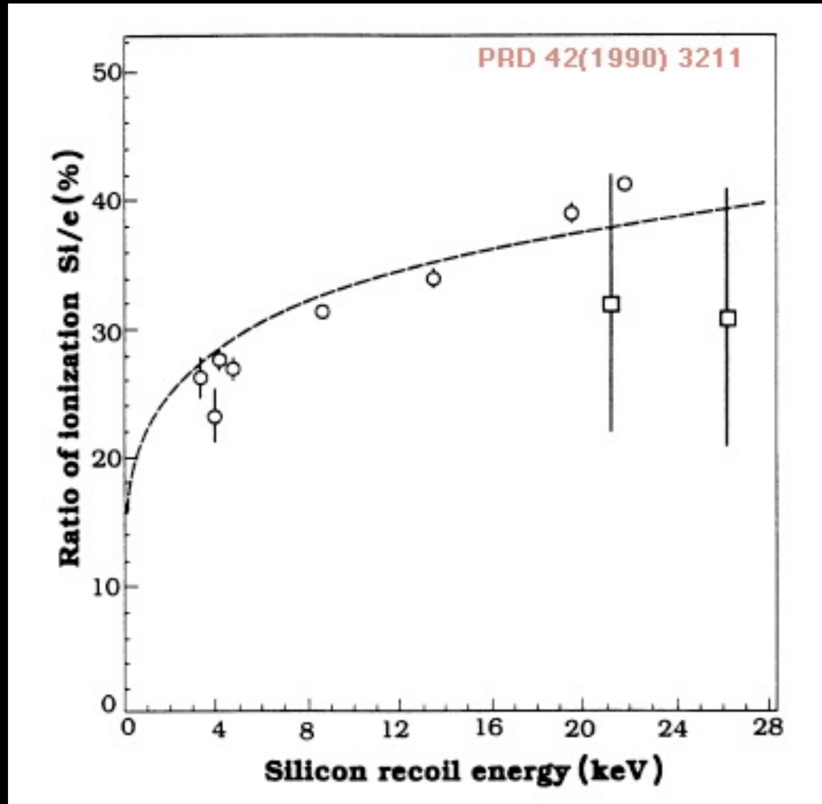
(the start of my talk)

Nuclear recoils are "quenched"

Only a fraction of recoil energy produces ionization or scintillation



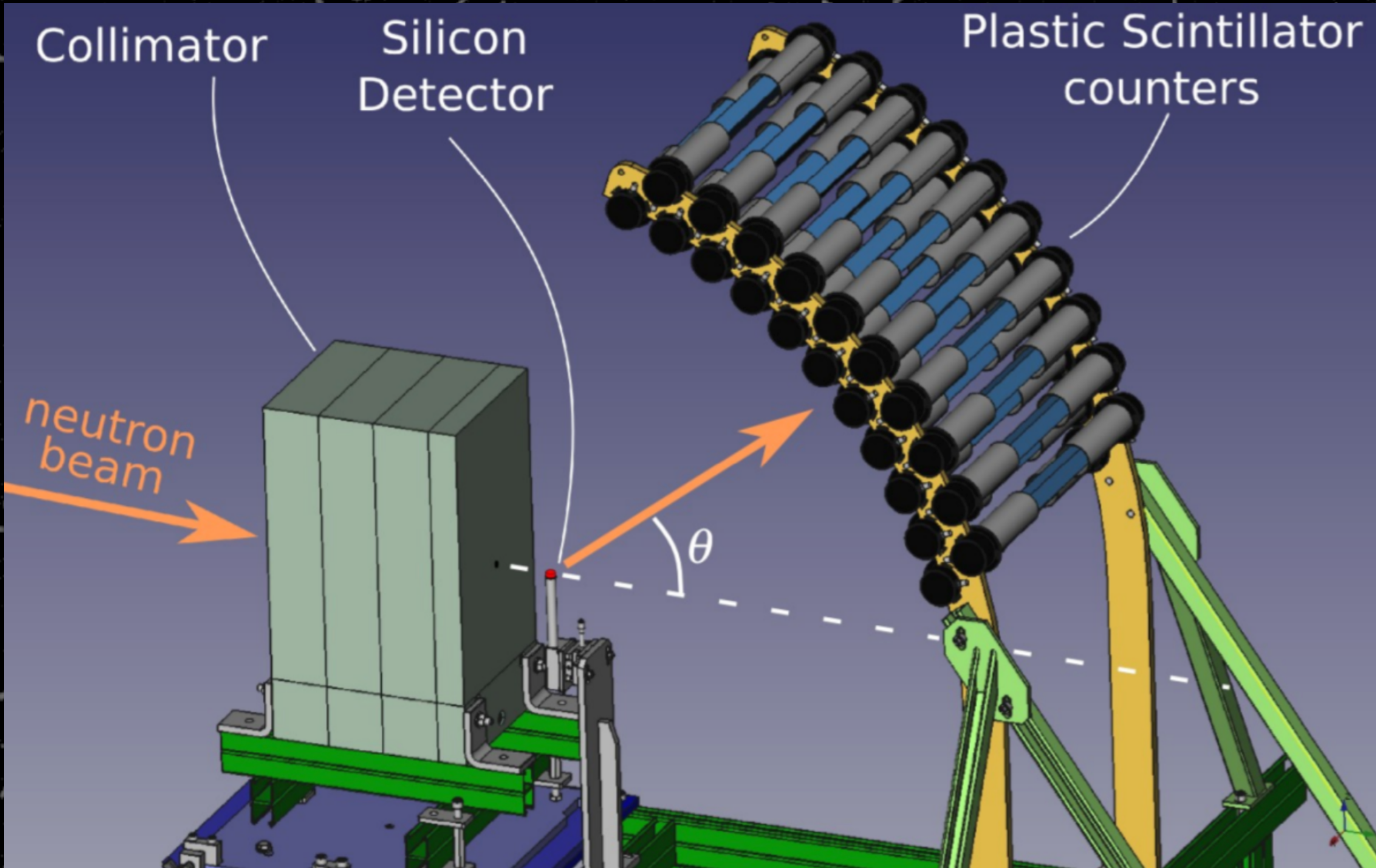
Fraction of observed energy : "Quenching factor" depends on Mass Number ...



... but also on recoil energy :

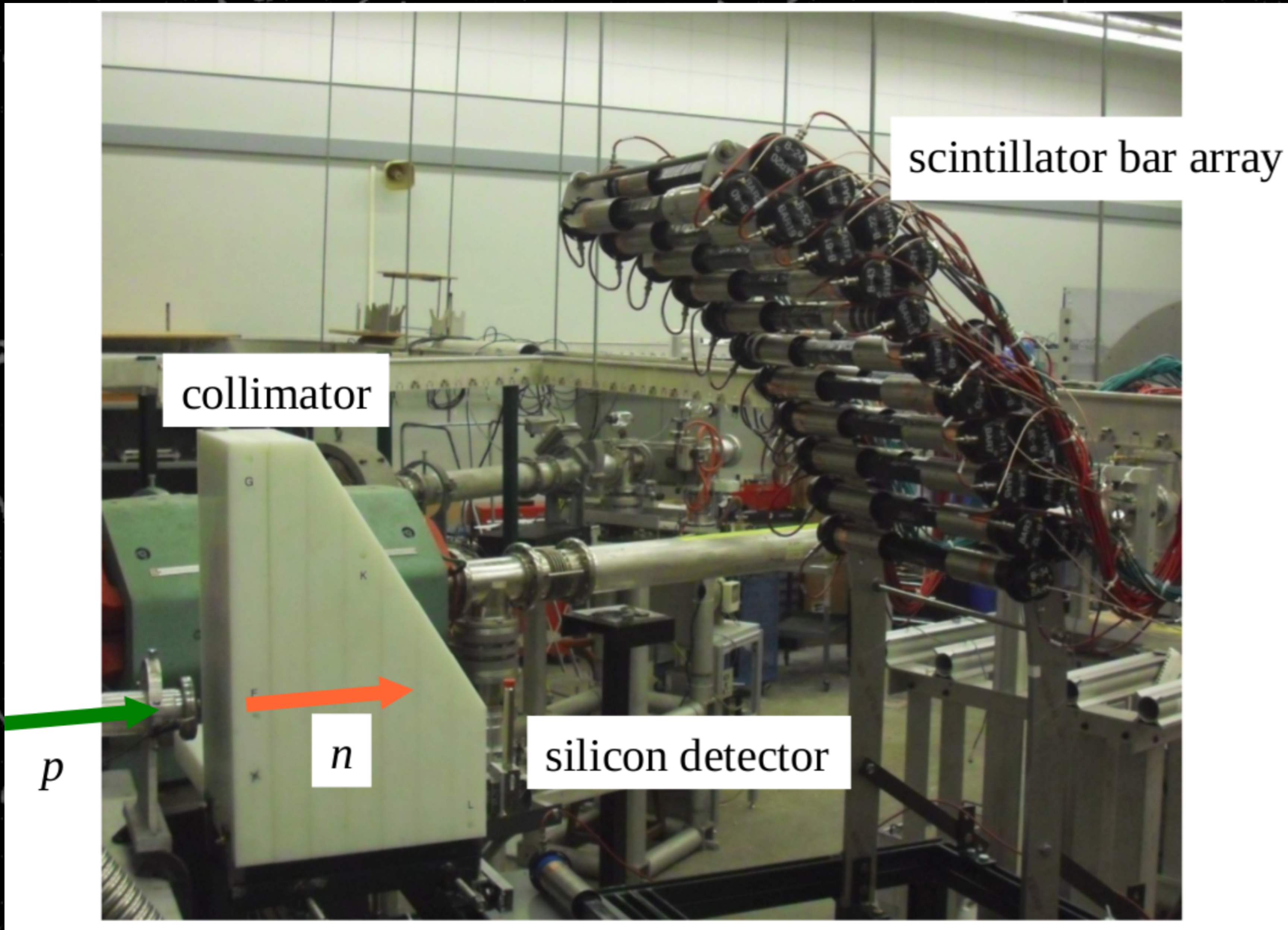
Note lack of data below 4 KeV

Typical quenching factor experiment



Uses neutrons to mimic DM

Quenching factor experiment in silicon by DAMIC



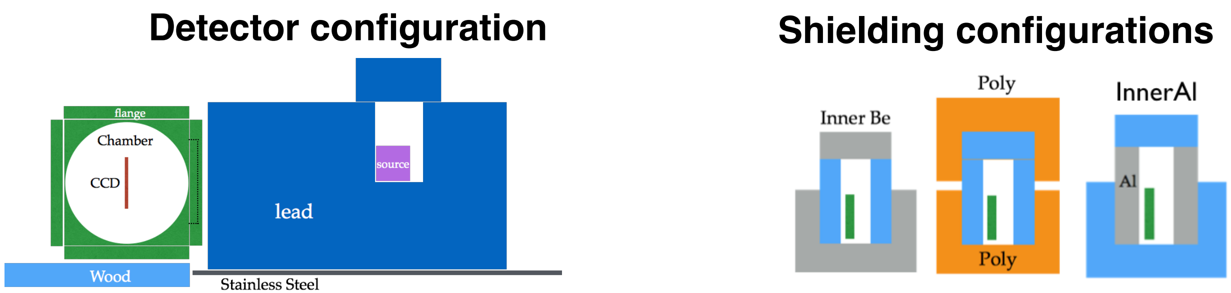
Alternate QF calibration using photoneutrons

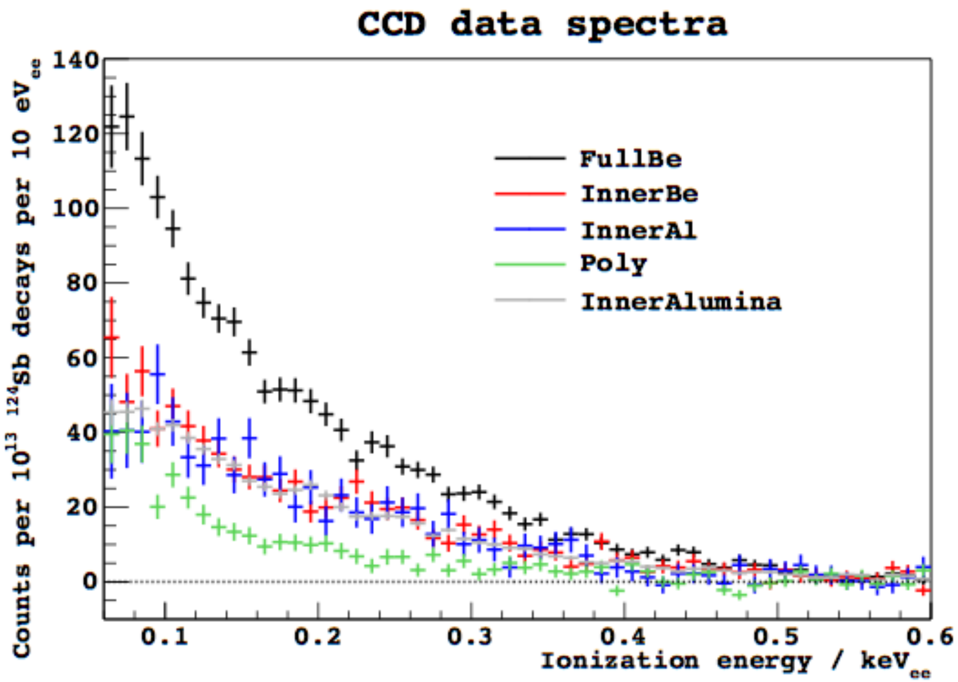
^{124}Sb source produces γs

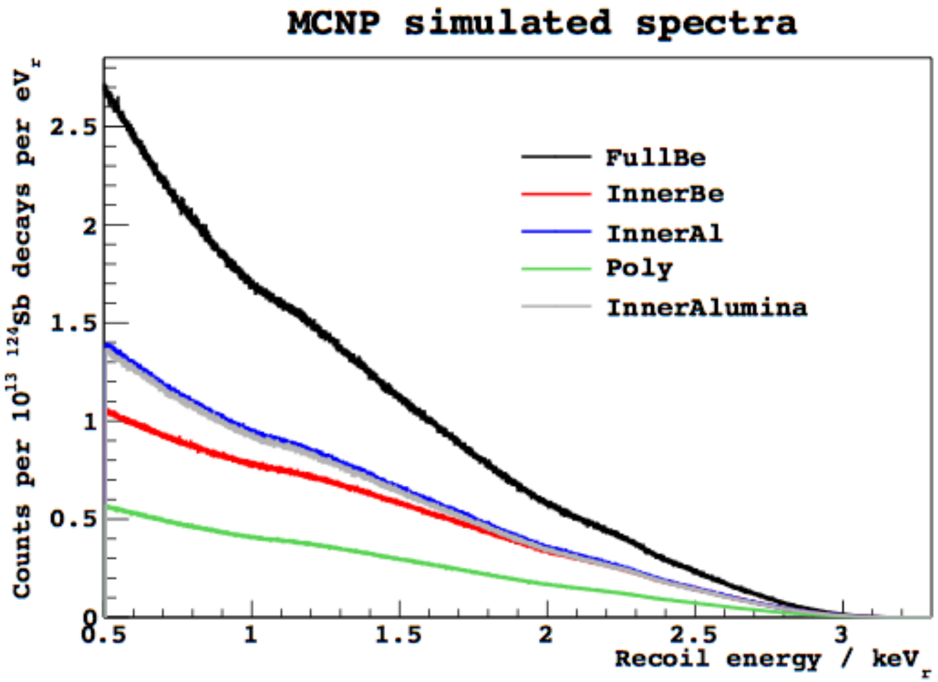
24 keV
neutrons from
^{9}Be(γ,n) reaction

Comparison of measured ionization energy and simulated recoil energy yields ionization efficiency

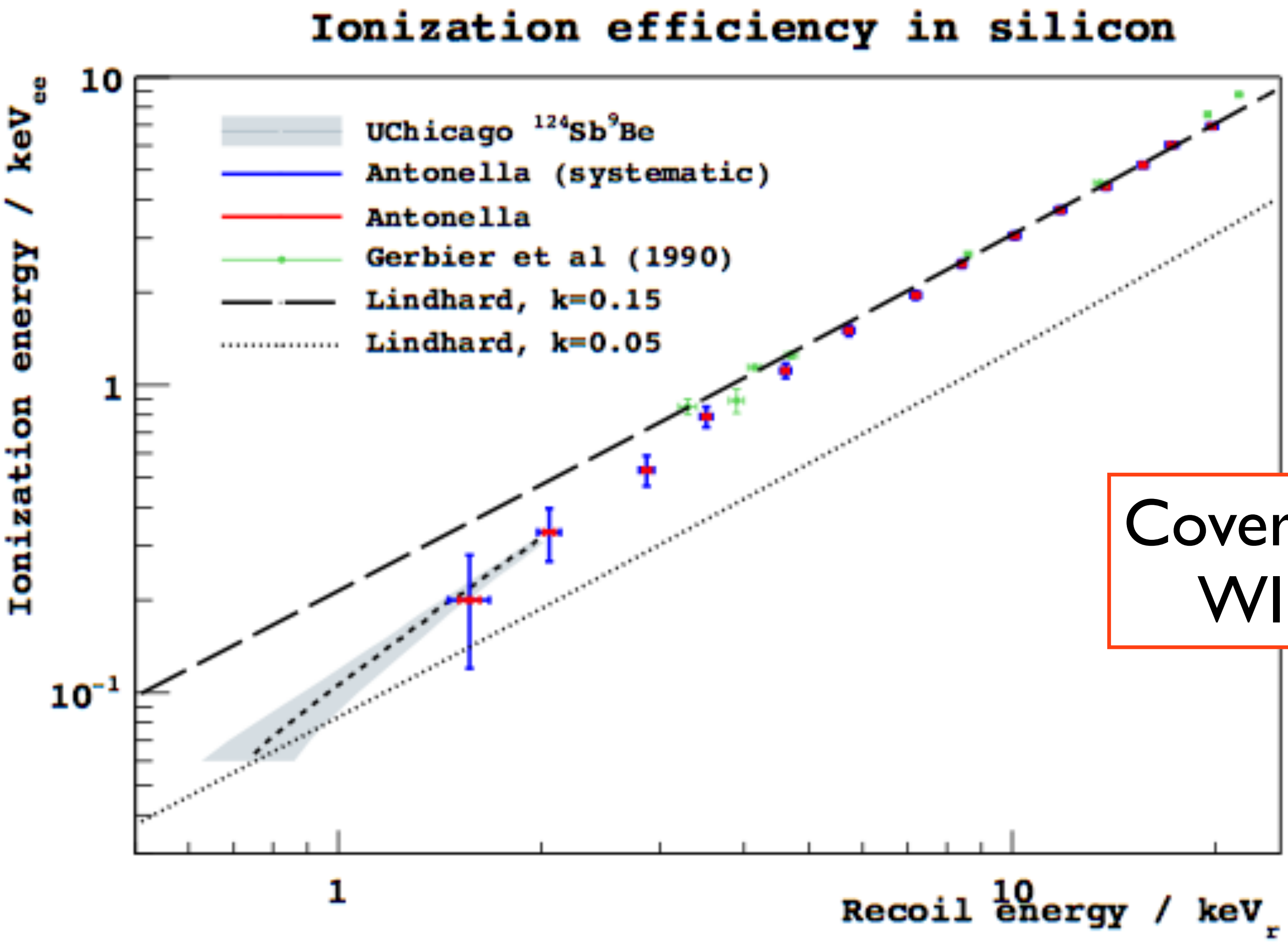
To constrain uncertainties from simulation, a number of shielding configurations were used







Two DAMIC QF calibrations

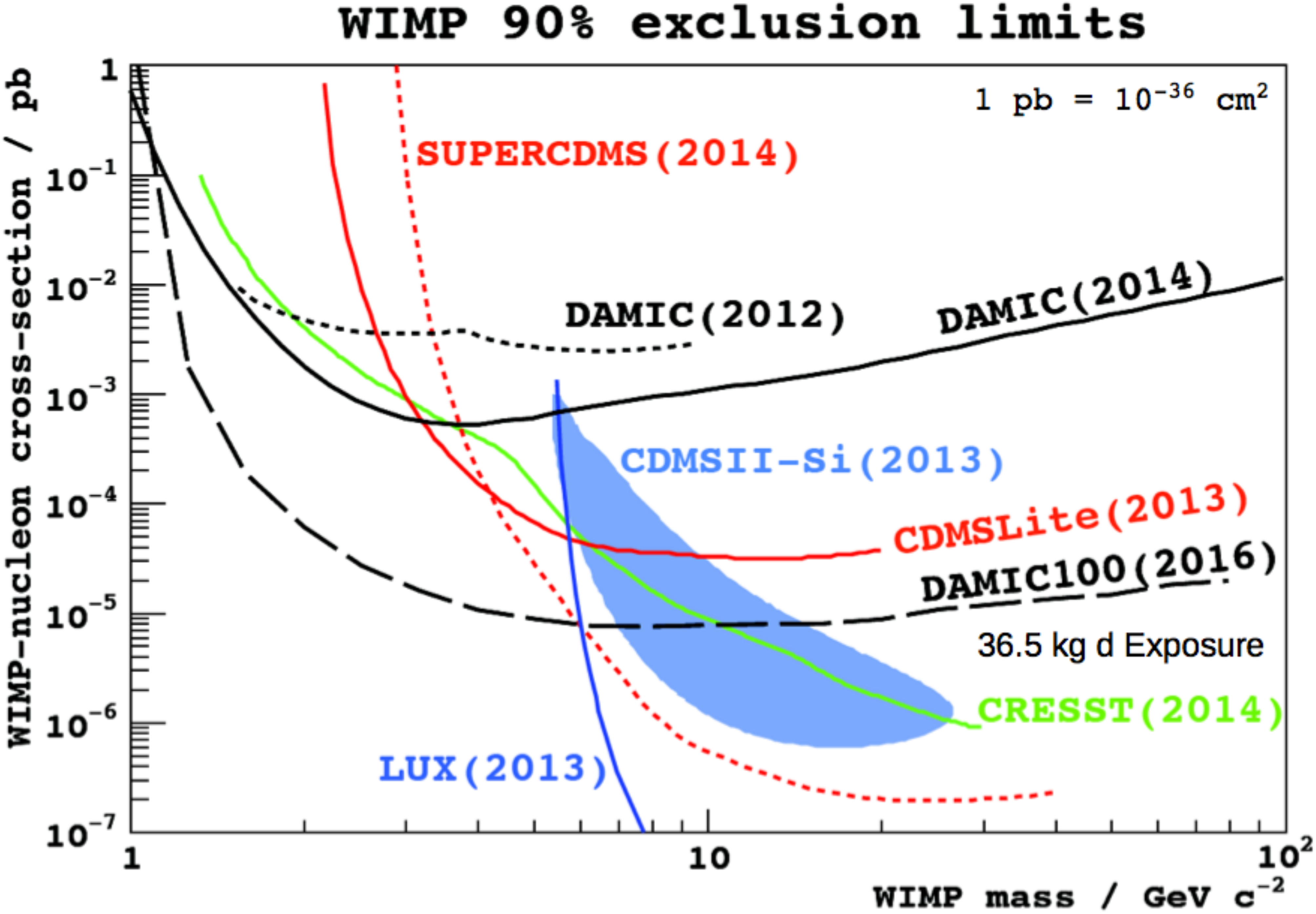


Antonella : 1702.00873
Chicago : 1608.00957

Covered entire DAMIC WIMP search ROI

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

DAMIC sensitivity



Beyond nuclear recoils

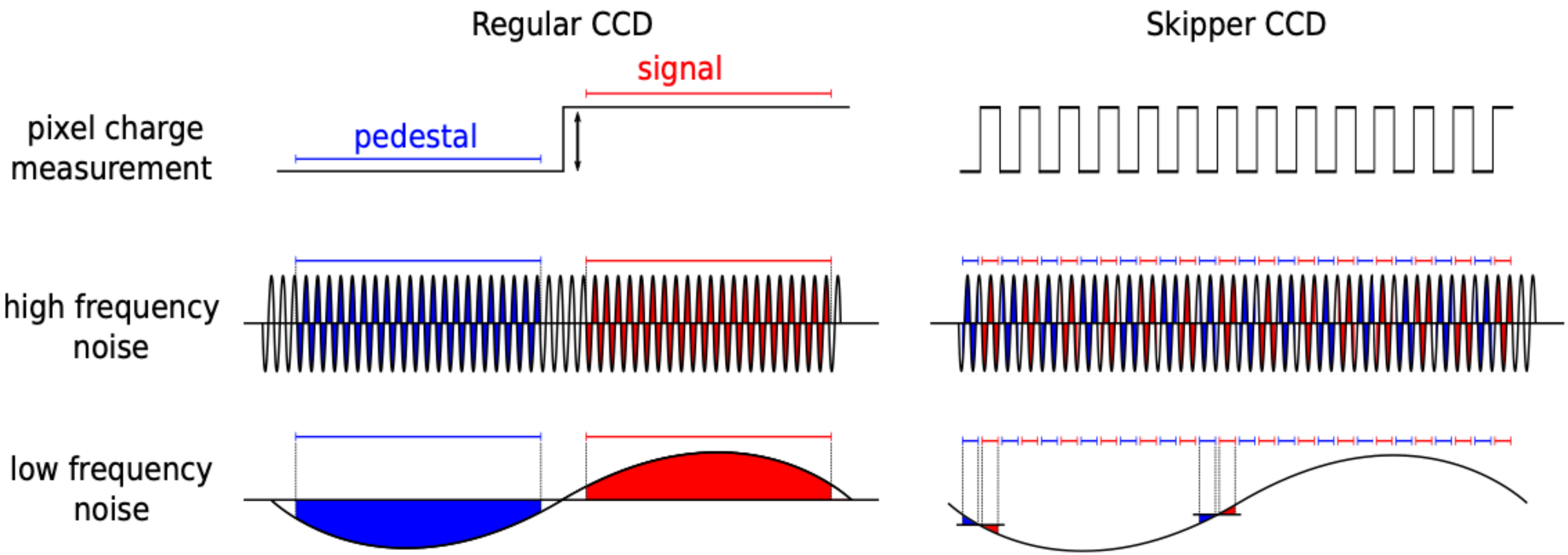
- Nuclear recoils are limited by small energy deposits
  - Nuclear recoil energy small compared to incoming DM energy
  - Quenching factors reduce signal yield for ionization and scintillation
    - Only ~10% of collision energy measured

- However, can search for :
    - Electron recoils
    - Photon absorption (hidden photon mixes with SM photon, which excites electron-hole
  - No nuclear recoil penalties

CCDs

Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)



Lowering the noise: Skipper CCD

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- The final pixel value is the average of the samples
  $$\textbf{Pixel value} = \frac{1}{N}\Sigma_i^N\,(\textbf{pixel sample})_i$$
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