REAL DAMIC CCD IMAGE (ON SURFACE)

Dark matter search in CCDs with DAMIC

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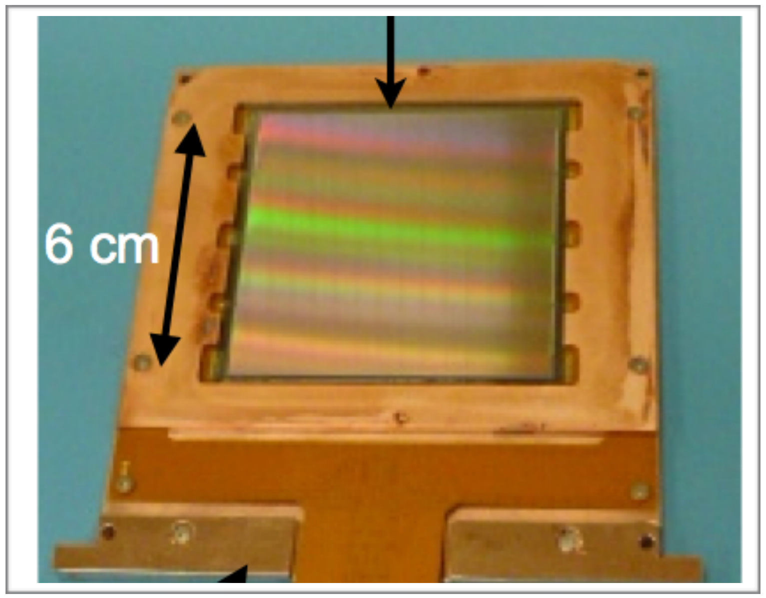
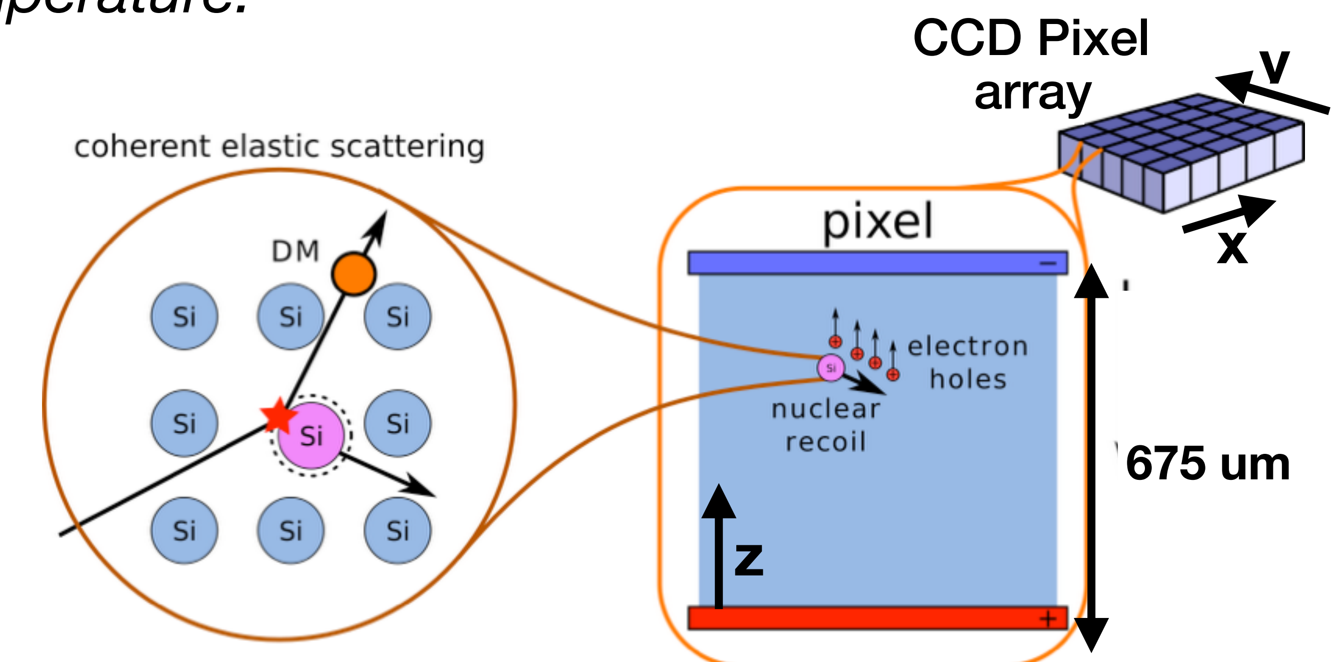
Charge Coupled Devices (CCD) for dark matter

Detection of energy deposits from nuclear and electron recoils induced by DM in the Silicon bulk of CCDs, operating at low temperature.

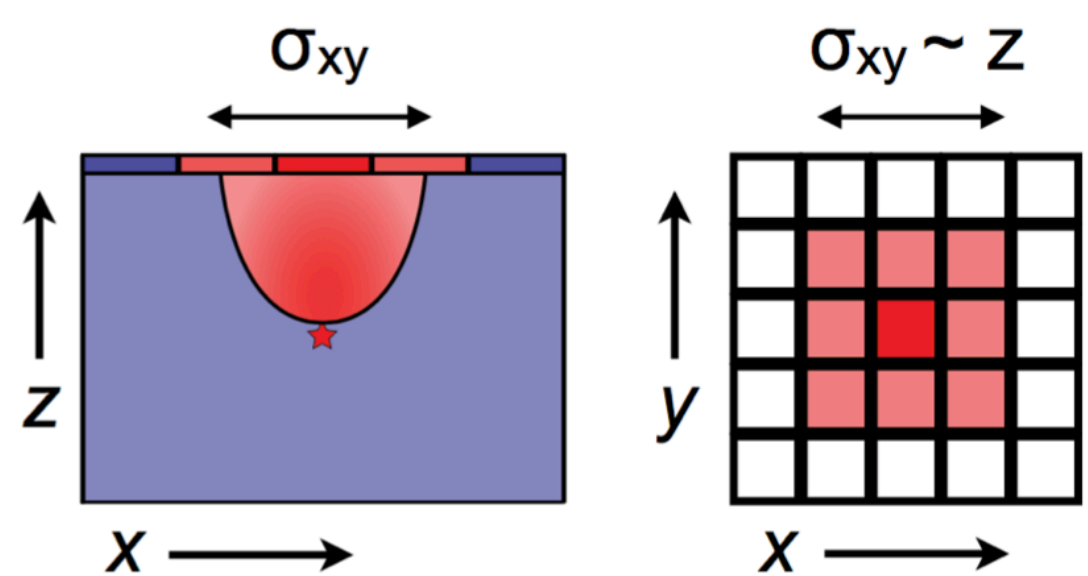


Unconventional use of CCDs :
Fully depleted, high-resistivity
16Mpix, 15 μm x15 μm,
650 μm thick, 5.9 g mass



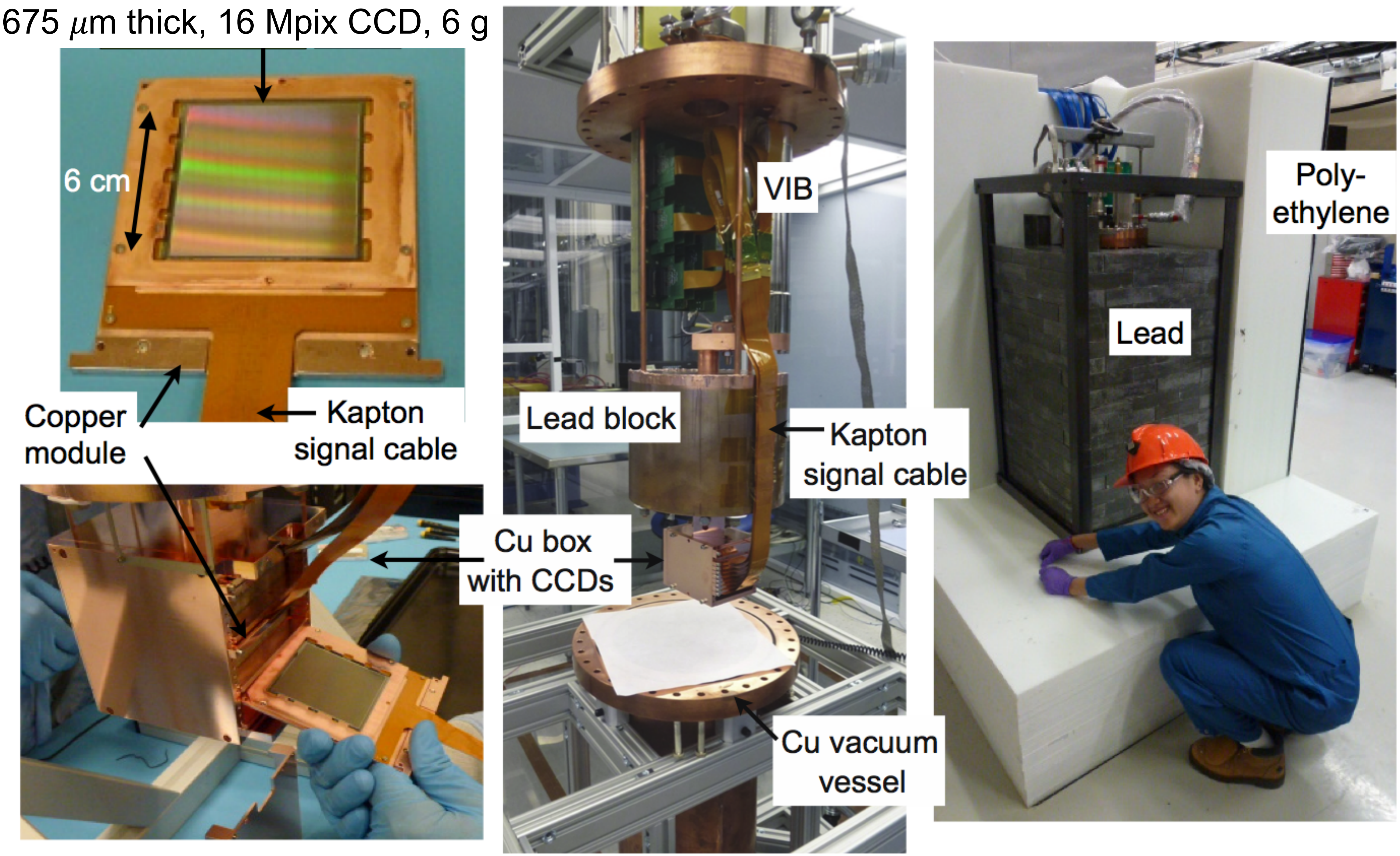
Silicon band-gap: 1.2 eV
Mean energy/e^-: 3.8 eV

Sensitivity to < 10 GeV WIMP masses (recoils ~ keV), eV hidden photons and DM electron-scattering



3D reconstruction (x, y, z)

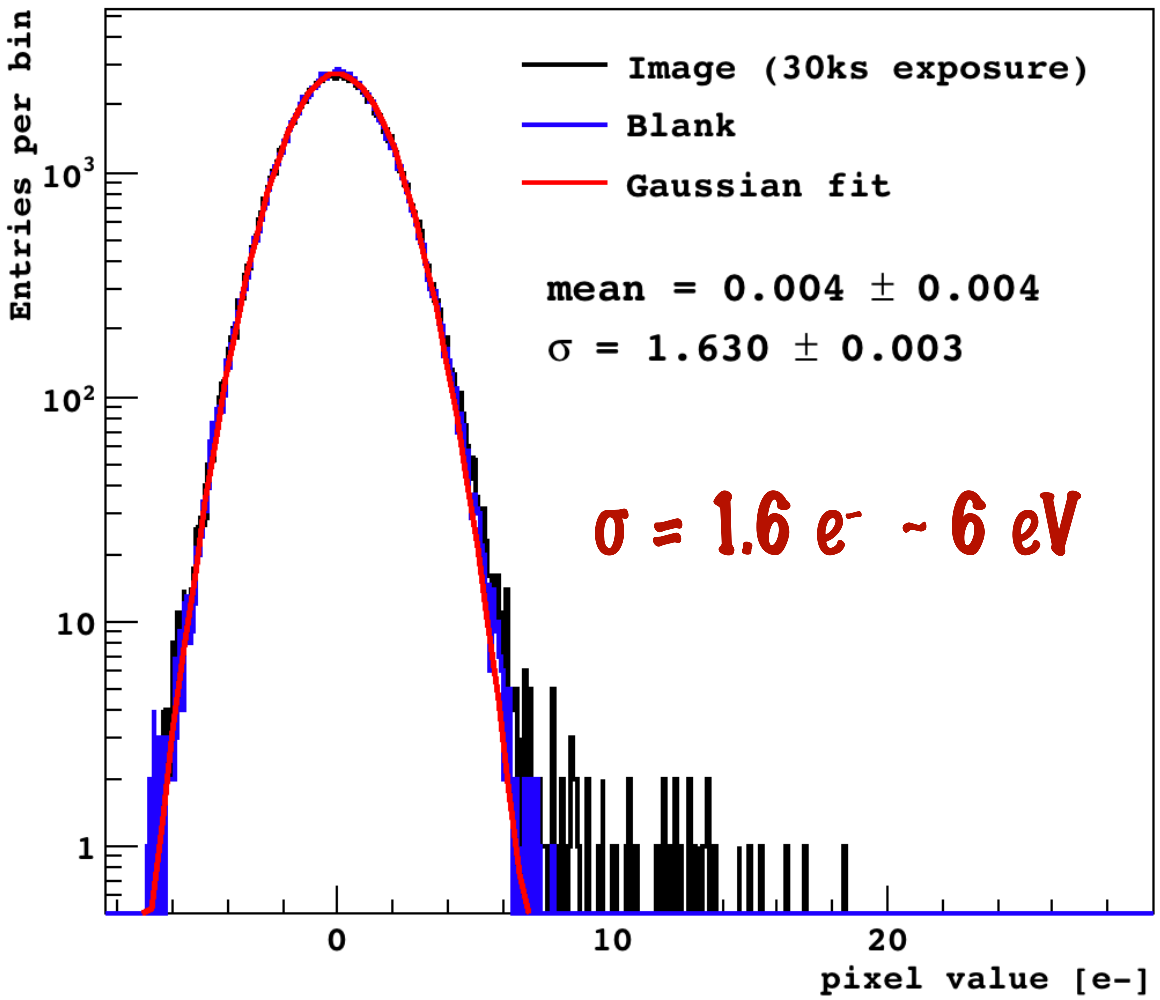
DAMIC @ SNOLAB (2000 m underground lab)



R&D program since 2011,

40g demonstrator operating at SNOLAB since 2017

Low noise and low dark current



lowest dark current ever measured in a Si detector :

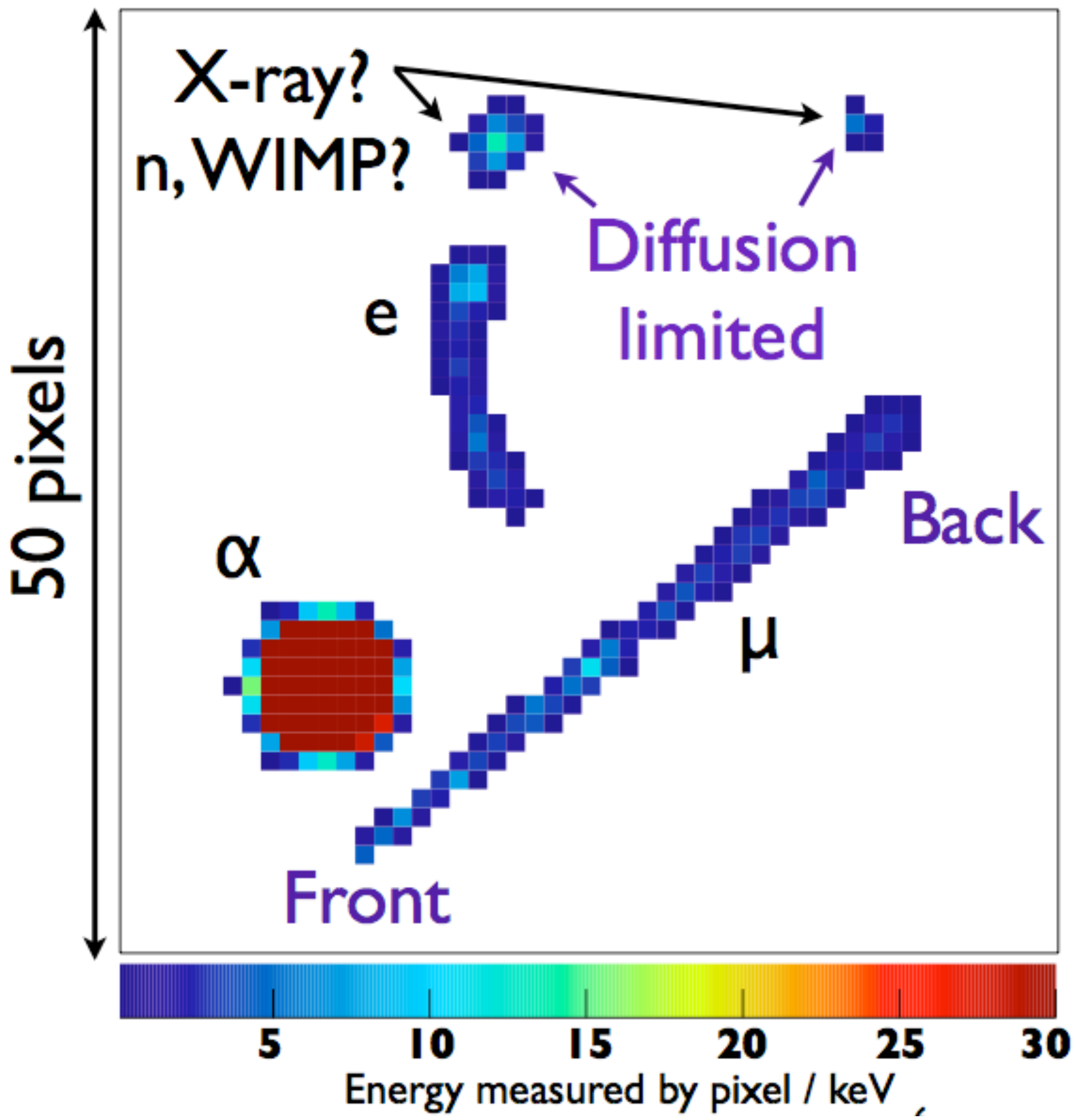
DC < 0.001 e/pix/day @ 140K

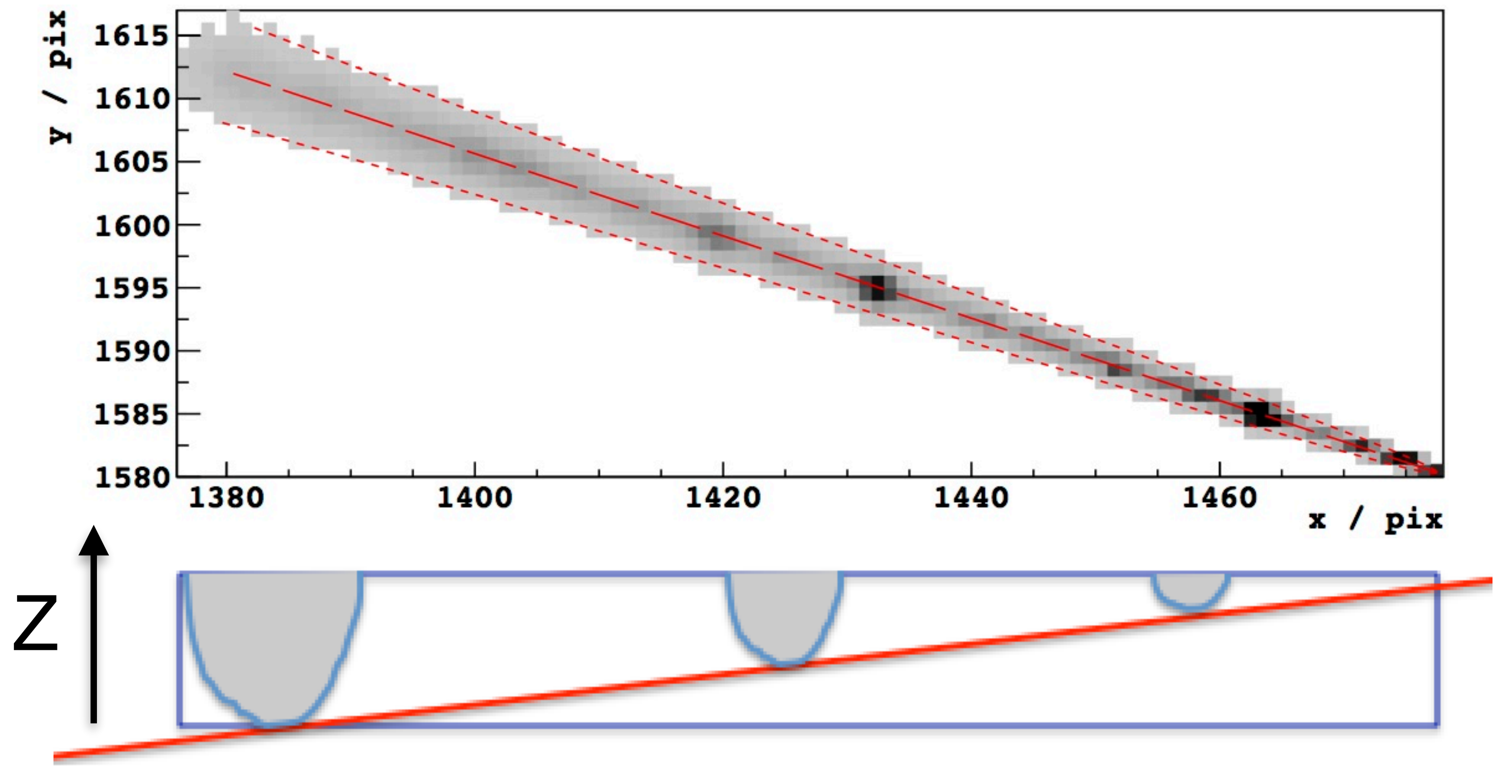
Dominant noise from Readout ~ 1.6 e^- (~ 6 eV)

Energy threshold ~ 40 eVee

Long exposures (30 ks and 100ks) to optimise signal/noise

Spatial resolution and particle identification





Diffusion parameters using events at the back of the CCD and muons passing through.

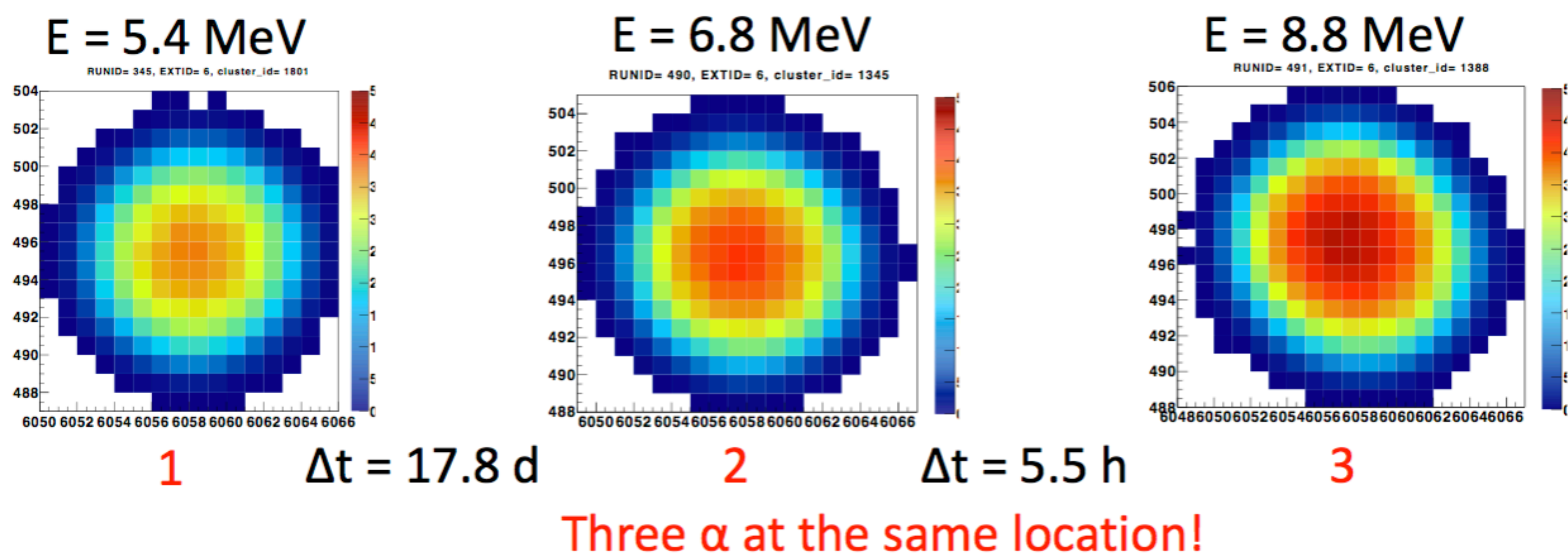
(x,y) : crucial for particle and radioactive chains identification

σ ≈ z : provides information on the depth of the energy deposit
—> **reject surface background events**

Background characterization

Spatial coincidence of betas and/or alpha decays powerful tool to identify and reject surface and bulk background from radioactive decay.

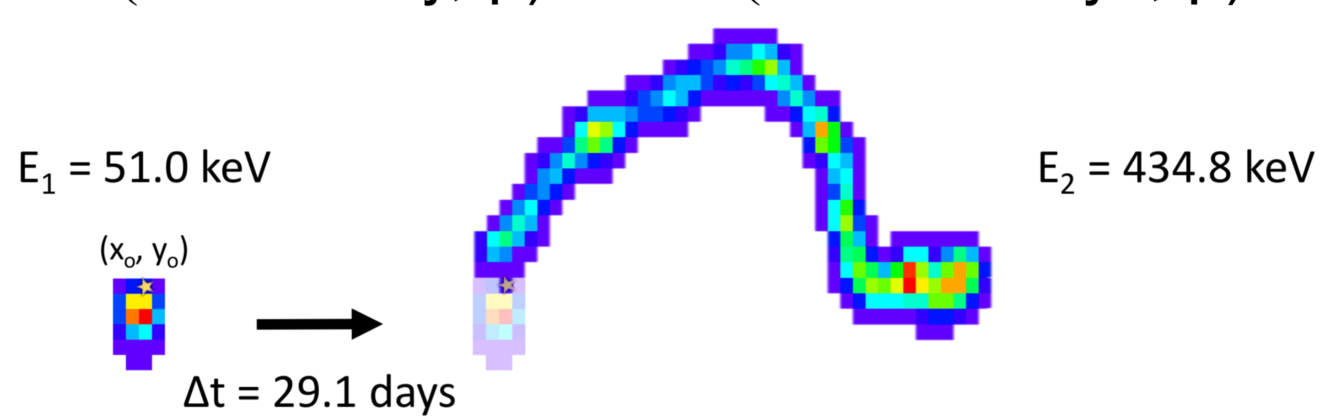
- **Surface background :** **^{210}Pb, U/Th chain**



- **Bulk background : Cosmogenic ^{32}Si** rate measured in R&D < 80/kg/day

UNAVOIDABLE BACKGROUND: essential measurement for next generation Si-detectors

^{32}Si ($T_{1/2}$= 150 y, β) ➔ ^{32}P ($T_{1/2}$= 14 days, β)



2015 JINST 10 P08014, PRD 994, 0820006 (2016)

Surface and background contamination

Measured contamination of ^{210}Pb and ^{32}Si
limits are placed on ^{238}U and ^{232}Th

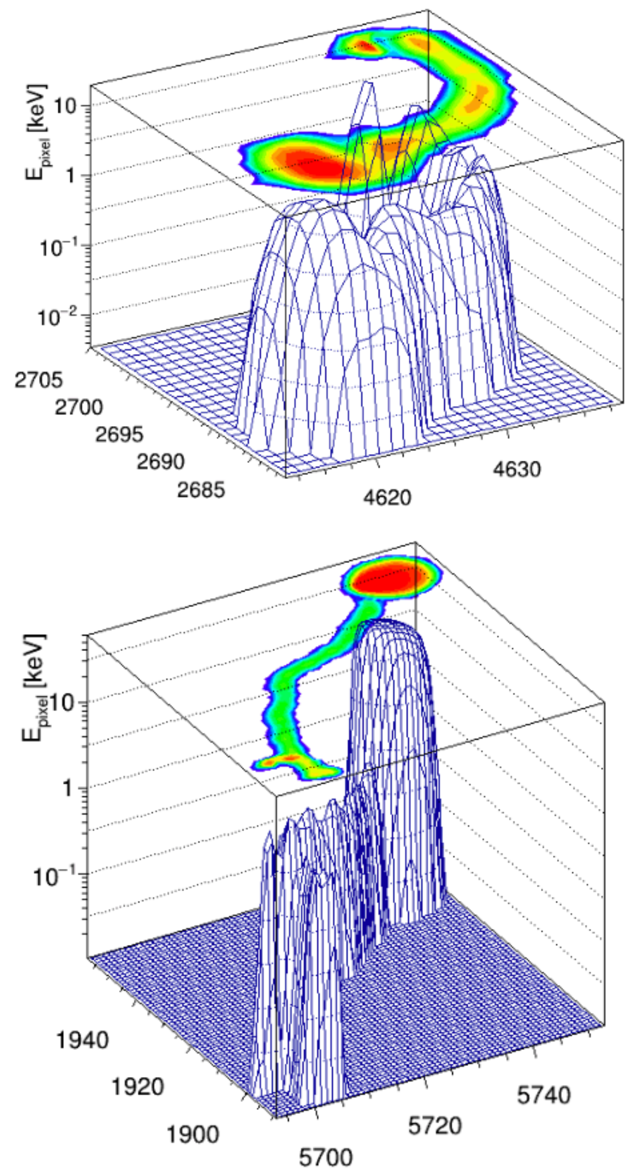
DAMIC 2019 analysis

^{32}Si
- 133.3 ± 27.8 μBq/kg

^{210}Pb
- 83.1 ± 11.8 nBq/cm²

^{238}U
- No α-β sequences
- Upper limit:
0.53/kg/day or 1.5 ppt [95%]

^{232}Th
- No α's with E = 18.7 MeV
- Upper limit:
0.35/kg/day or 1 ppt [95%]



DAMIC 2015 R&D result

^{32}Si
- 925.9 ± 1273 / 752 μBq/kg

^{210}Pb
- 902.8 ± 115.8 nBq/cm²

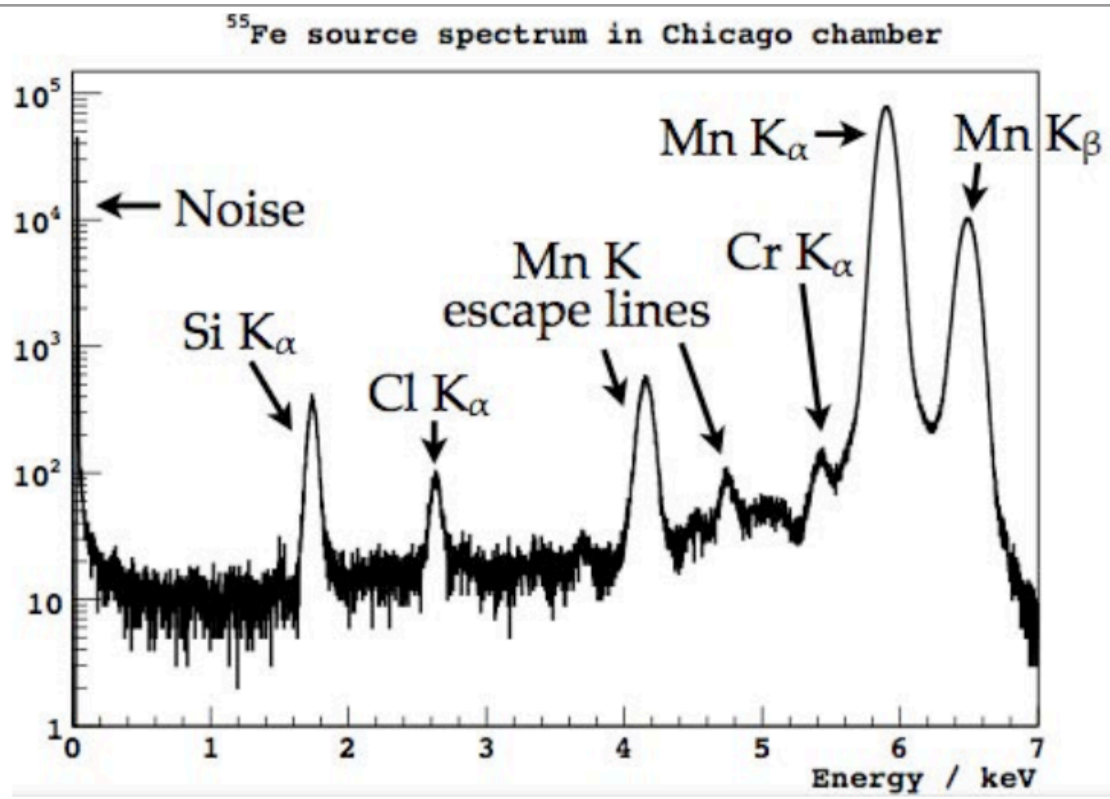
^{238}U
- Upper limit: 5/kg/day [95%]

^{232}Th
- Upper limit: 15/kg/day [95%]

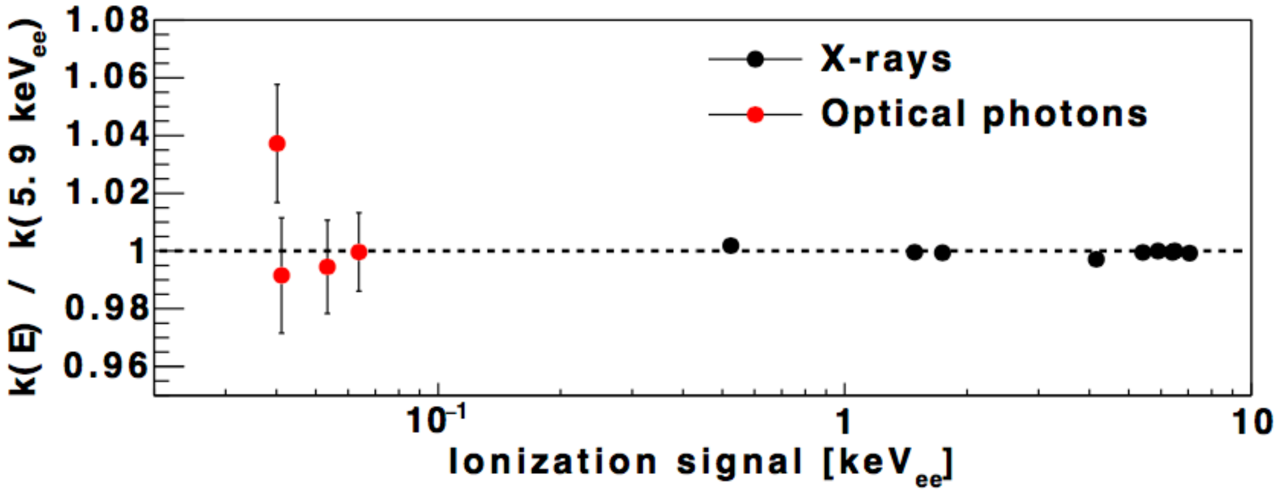
arXiv:1506.02562

Difference (factor x7) in ^{32}Si

CCD response : Energy linearity and neutron recoil



Linearity demonstrated for signals <10 e$^-$



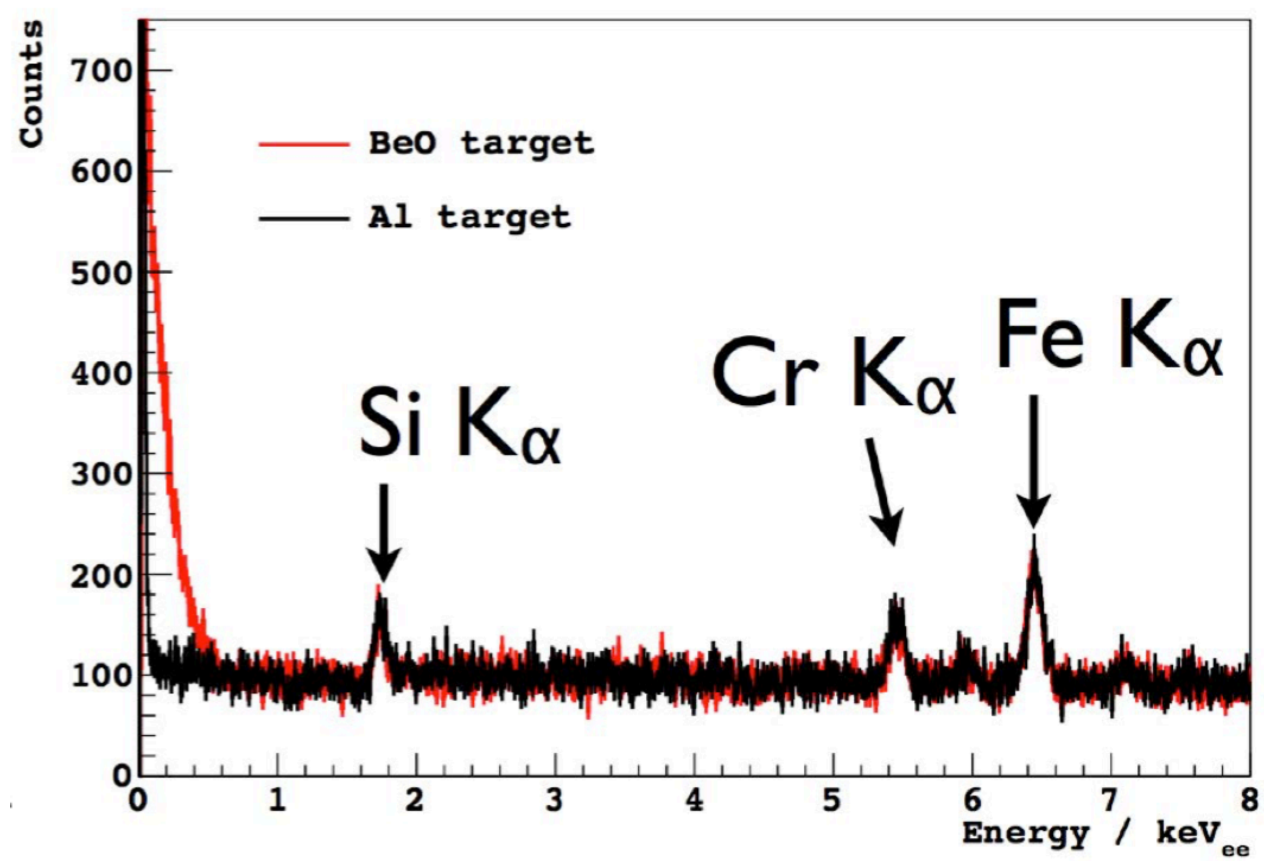
Antimony source with Be / Al cap

"Neutron-on" with BeO (n+γ)

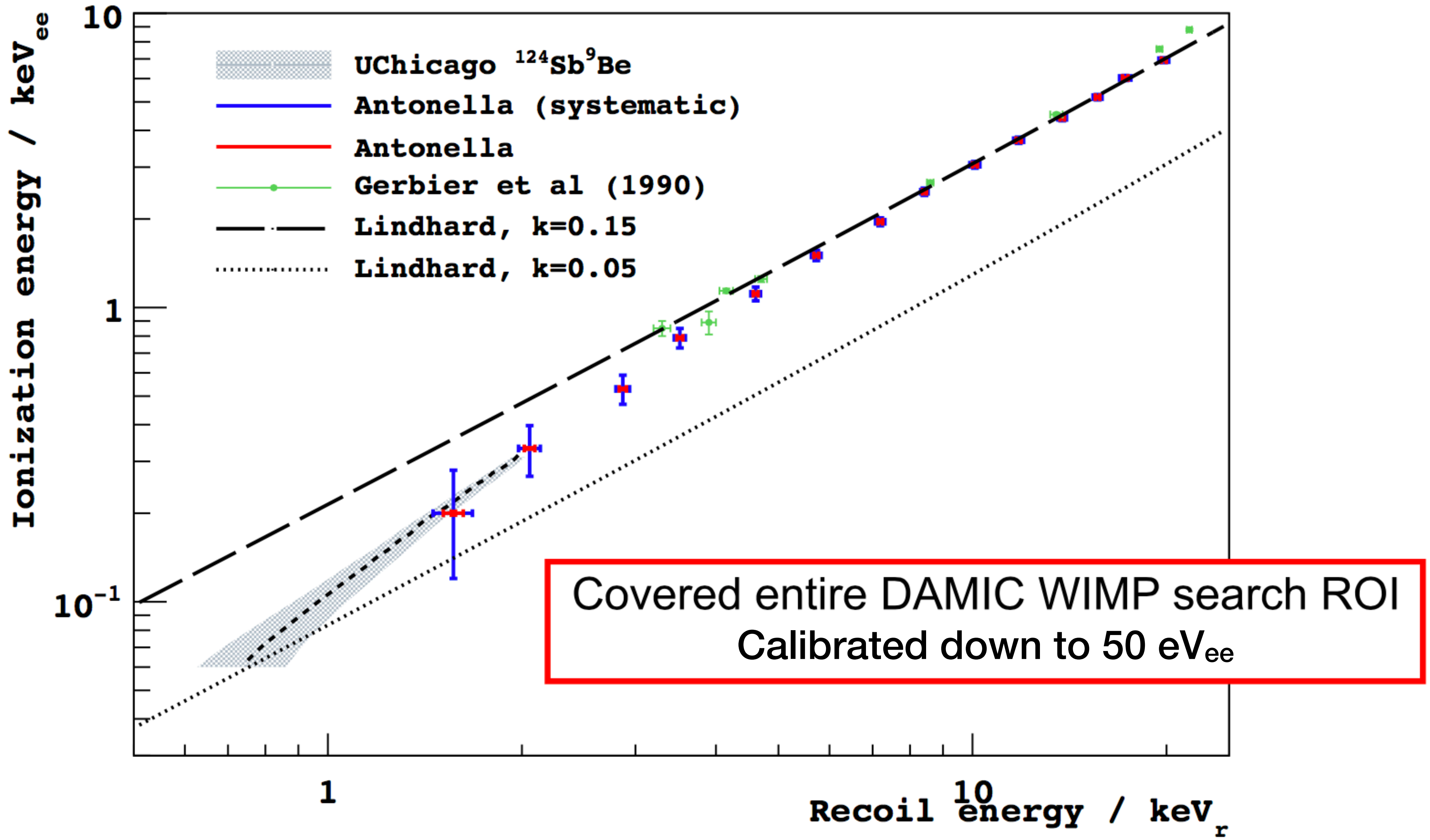
"neutron-off" with Al (only γ)

Clear signal from neutron-induced nuclear recoils

Nuclear recoil ionization efficiency from adjusting MC E_r to E_e spectrum



Nuclear-recoil Ionisation efficiency

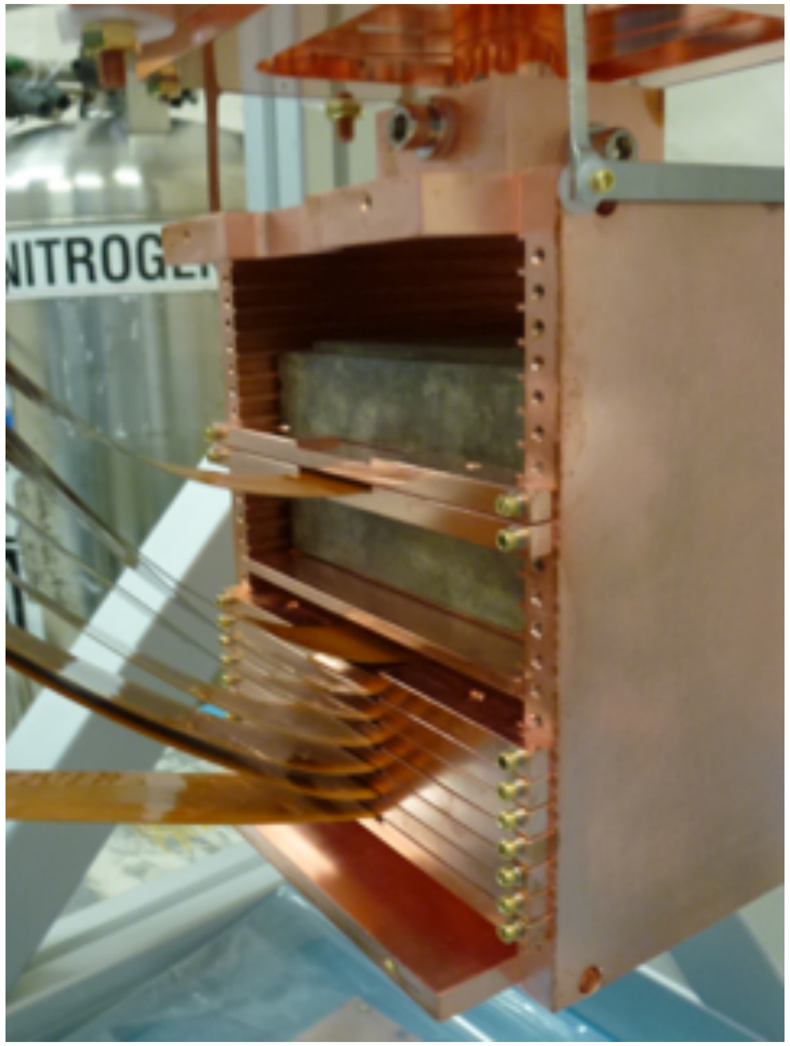


Deviation from Lindhard theory below 5.5 keV, crucial for low-mass WIMPs search in Si

PRD 94, 082007 (2016)

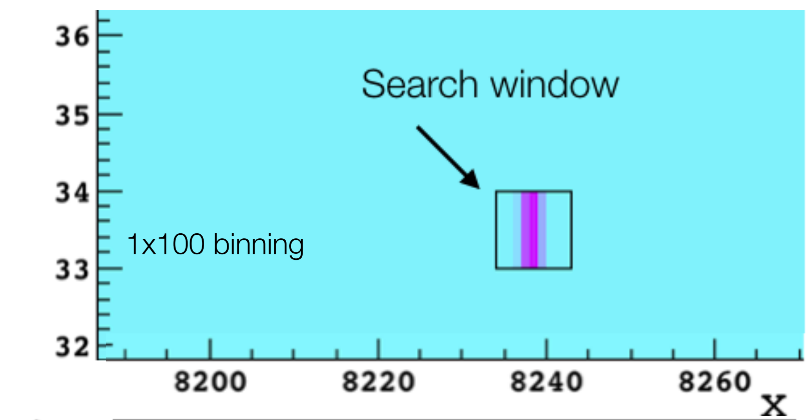
Current detector configuration

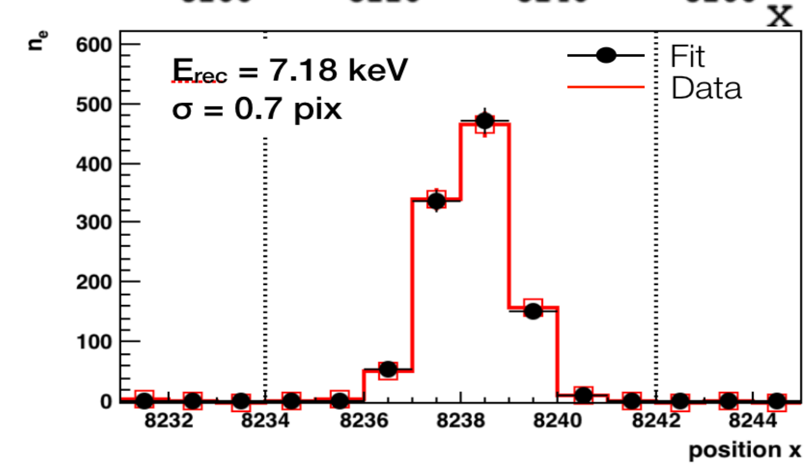
- **Seven 16 Mpix CCDs** in stable data taking since 2017 (1 CCD sandwiched in ancient lead)
- **40 g detector mass**
- Operating temperature down to **140K**
- **Exposure time for image : 8h and 24h** (each image acquisition is followed by a ‘’blank” with zero exposure)
- **7.6 kg day of data acquired for background characterisation** and 32Si, 210Pb measurements
- **13 kg day of data collected for DM search** (with 1x100 hardware binning to enhance the signal/readout noise and lower the energy threshold)
- **Since 2019**, **resumed background runs** and **detector studies** for future DAMIC upgrade



WIMPs search strategy

- **Pedestal and correlated noise subtraction** (hot pixels among several images masked)
- **LL fit in a moving window** across the image

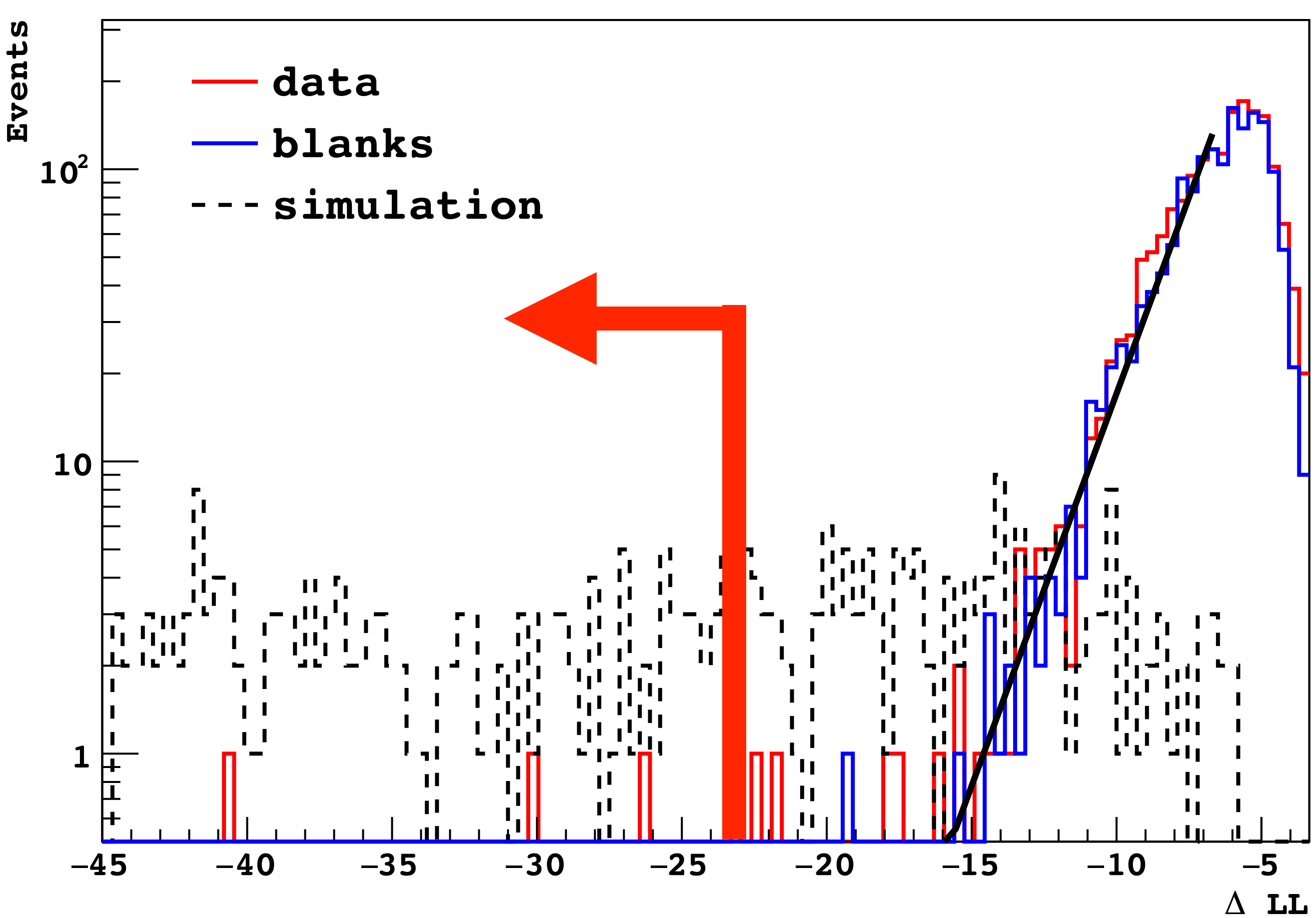




$$\Delta LL = \mathscr{L}_n - \mathscr{L}_s$$

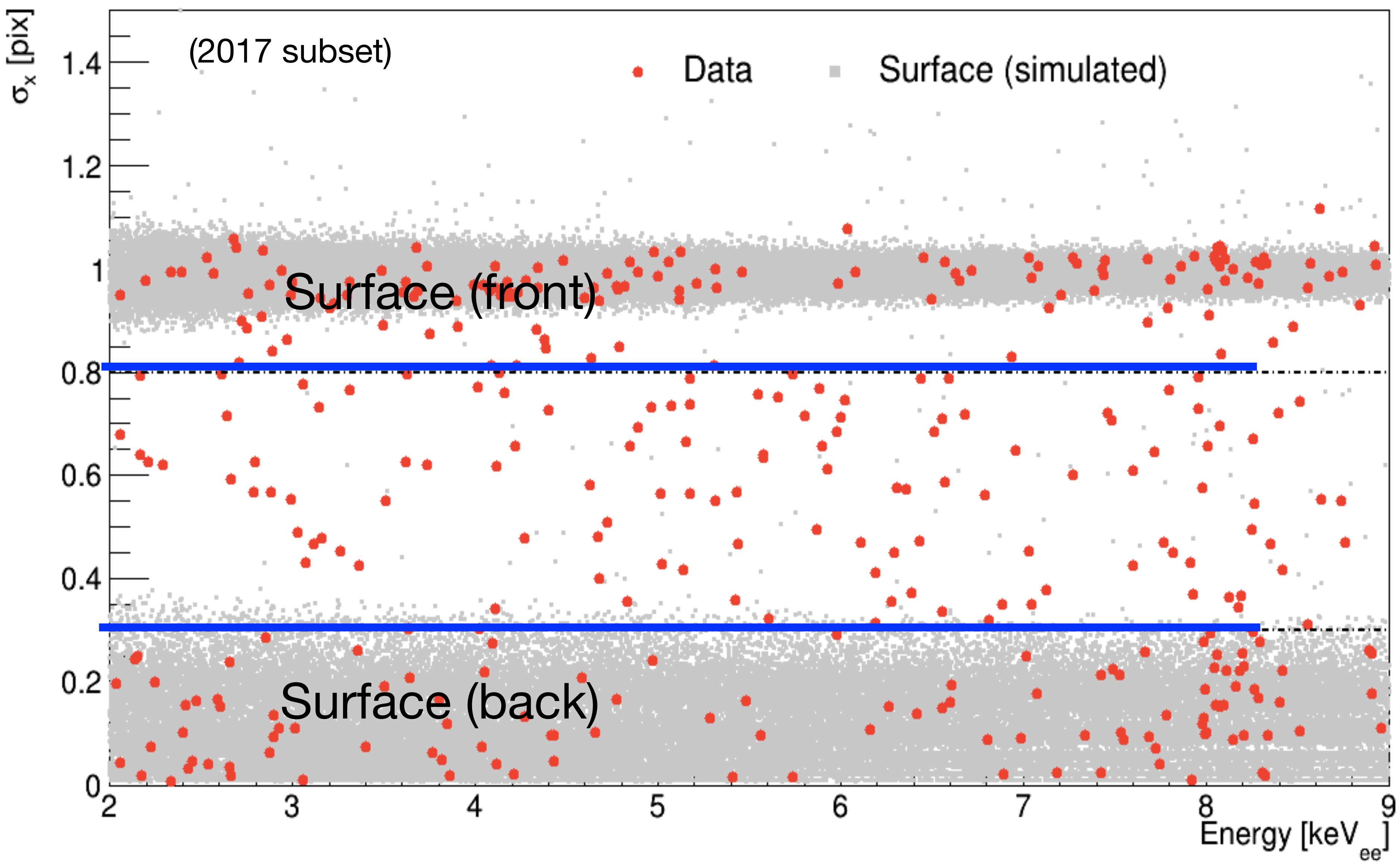
flat noise **Gaus signal + flat noise**

- **ΔLL profile for noise clusters (in blanks)**



- Define **ΔLL cut** at < 0.001 noise events;
- **Selection efficiency** ~10% at 50 eV_{ee} and > 80% at 100 eV_{ee}

Background handling



Fiducial volume

0.3 < σ < 0.8

Background handling approaches

(a) Surface bkg rejection (2016) : fiducial cut in depth to remove surface events (2016 results)

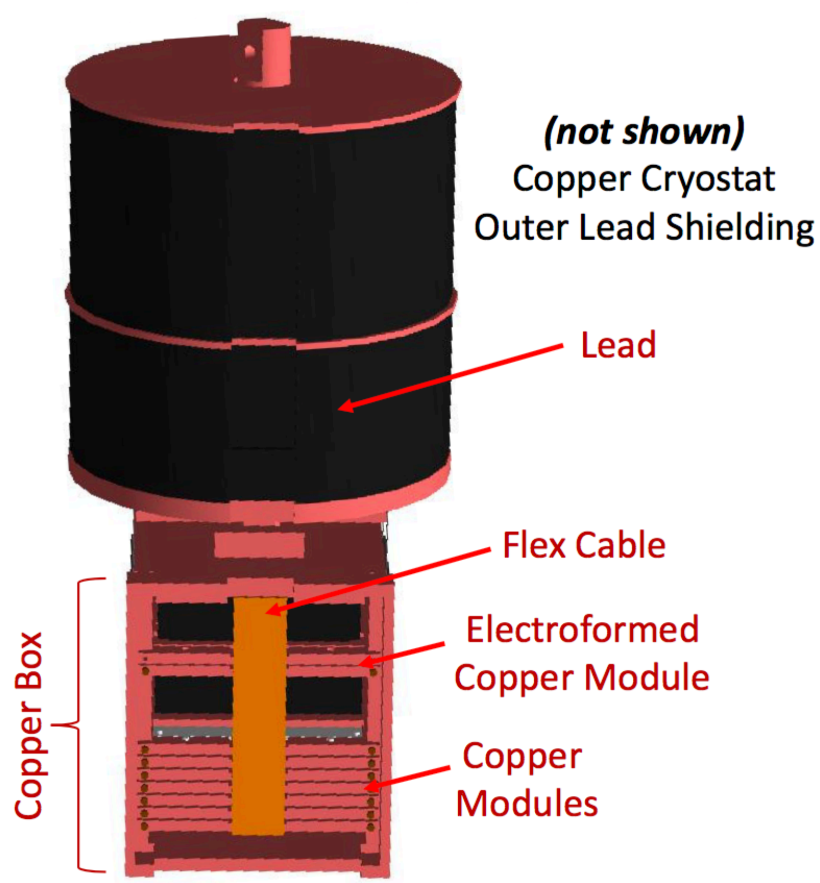
(b) *New 2019* Bkg model : based on Geant4 simulations of isotopes in the CCD bulk and surrounding materials and 2D binned LL fit to data

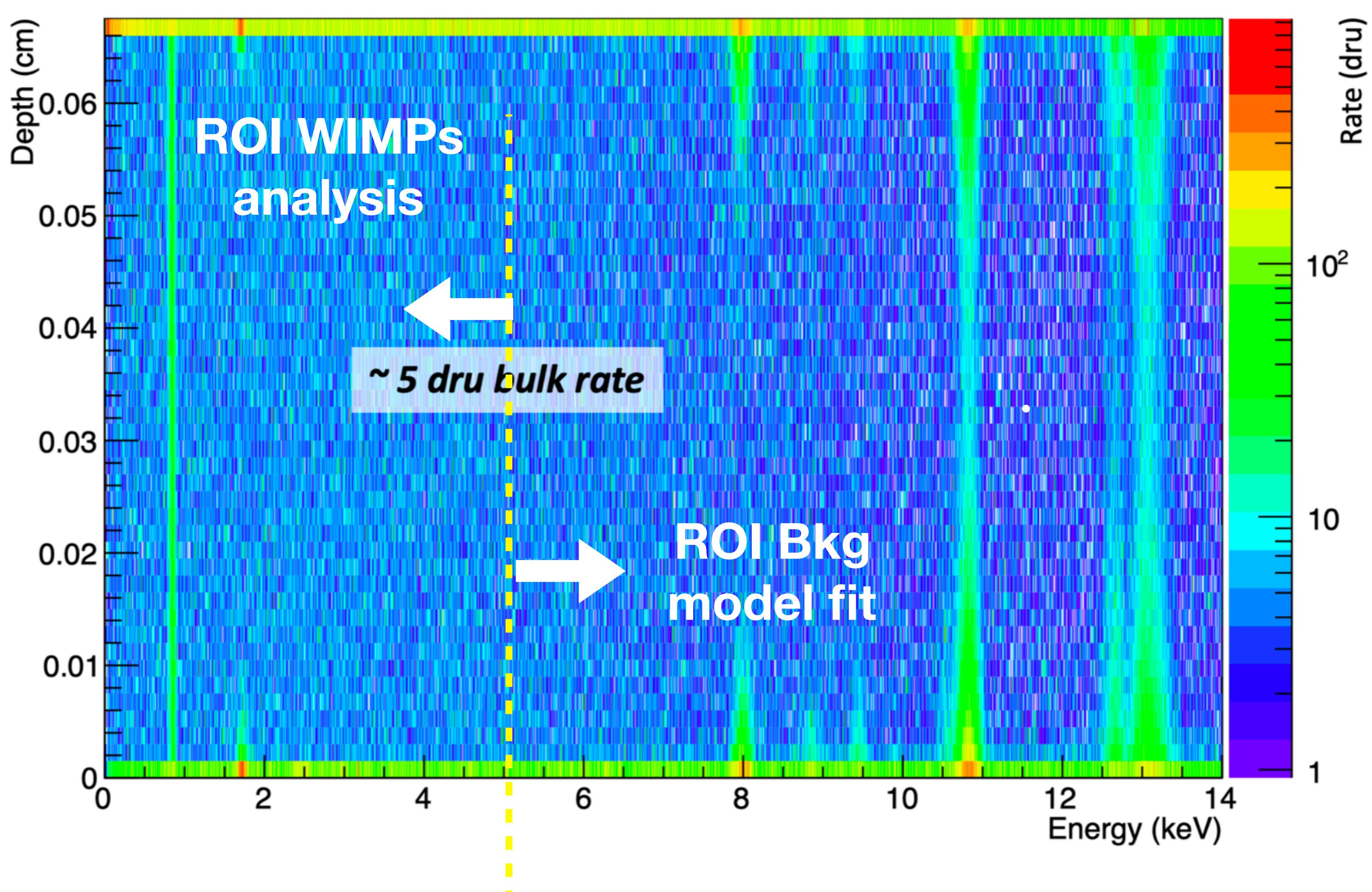
Background model

- **Geant4 simulation + detector readout** of isotopes in detector material (assays to measure the activity of each component)

- Cluster reconstruction (energy, position and depth parameter σ) as in data.

- **2D binned likelihood fit of (E,σ)** to data in the range 6-20 keV_{ee} and we use it to construct the model at low energies



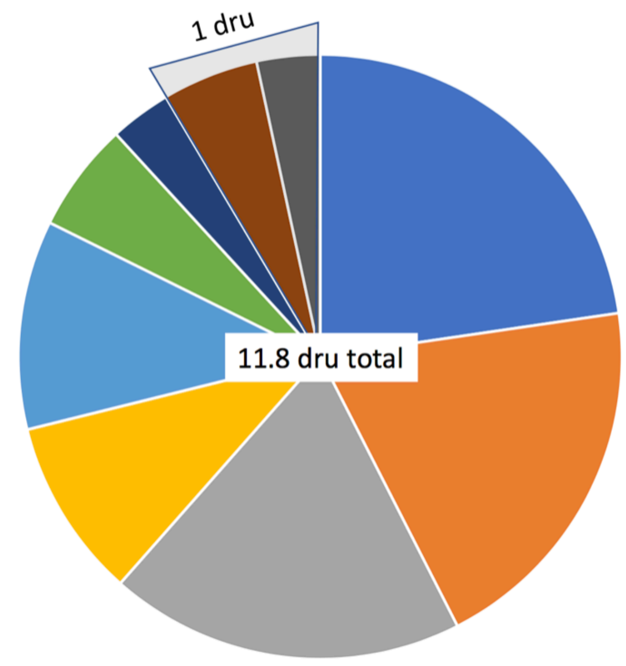


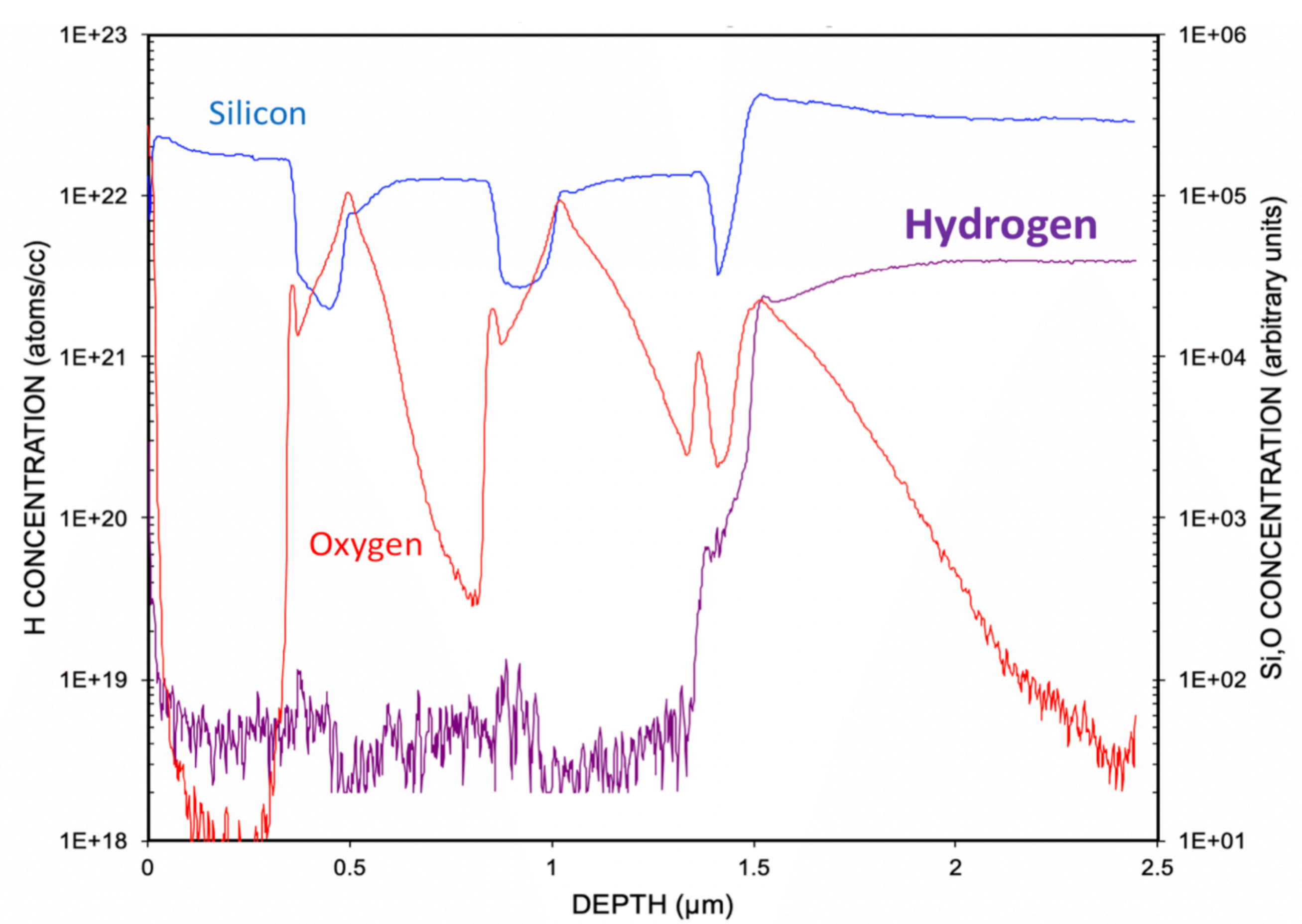
Main background contributions

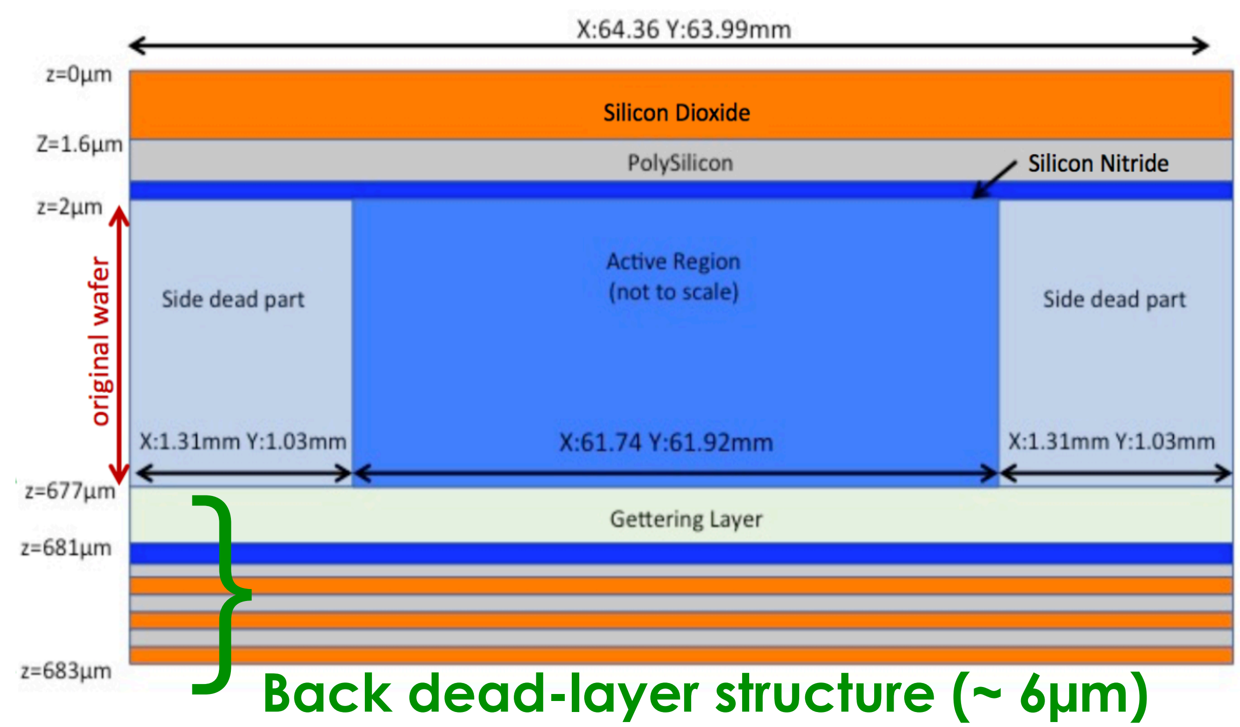
Main contributions in (6 - 7.5keV):

- **^{210}Pb on CCD and OFC Copper** surfaces
- **Tritium** on **bulk** (cosmogenic activation) and trapped in **back** dead-layers during CCD manufacturing

SIMS measurements on the back of CCD confirmed the presence of 10^{21} H atoms/cm^3 consistent with ^{3}H decay (assuming ^{3}H/H fraction of 10^{-18} as in water)





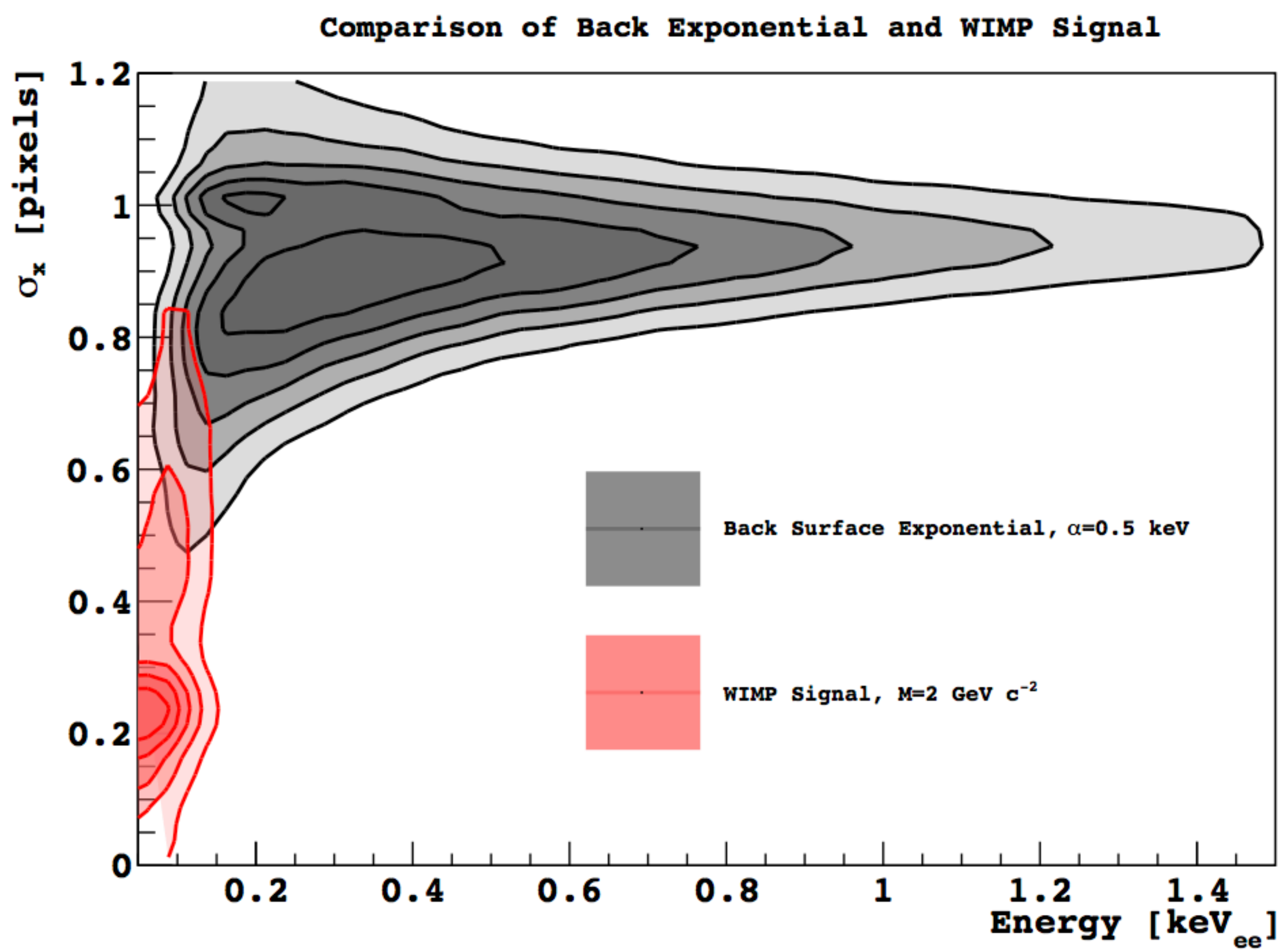


New R&D programs using SNOLAB setup to improve bkg in CCD production

Systematic uncertainties

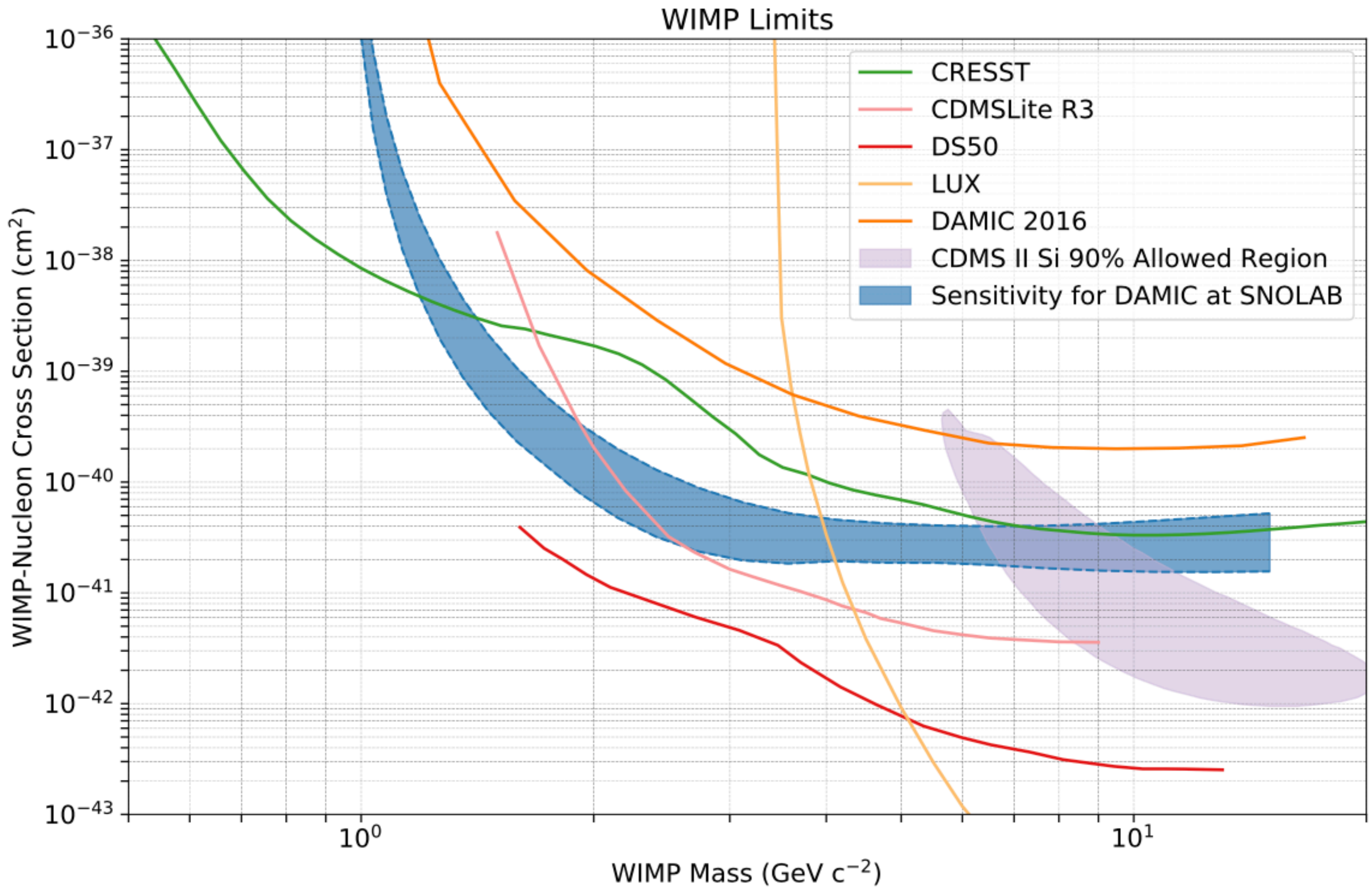
- Dominant systematic uncertainty are radioactive contaminants on the back surface (^{210}Pb, ^{3}H) from production and handling of CCDs

- The fit prefers ^{210}Pb on the back of the active region
- By manually removing some of the ^{210}Pb templates and repeating the fit, we are able to **quantify the systematic uncertainty** in the background model due to the location of 210Pb.
- Resulting difference is a **back-side exponential component non-degenerate with an a low WIMPs signal**



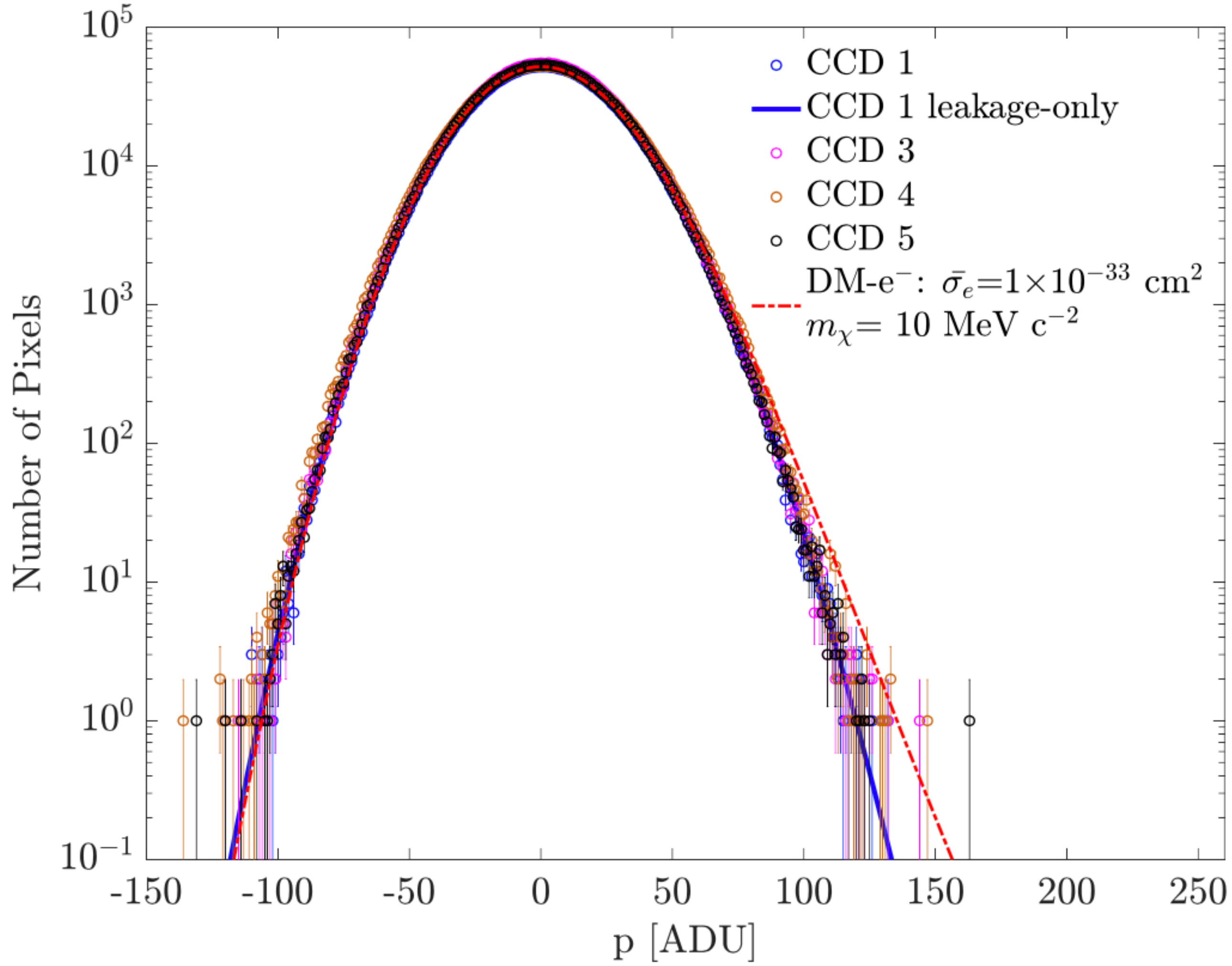
Expected sensitivity

Sensitivity with 2017-2018 data.



Exploring for the 1st time the CDMS signal with the silicon target and a much lower energy threshold (0.6 keV_{nr} ~ 0.05 keV_{ee})

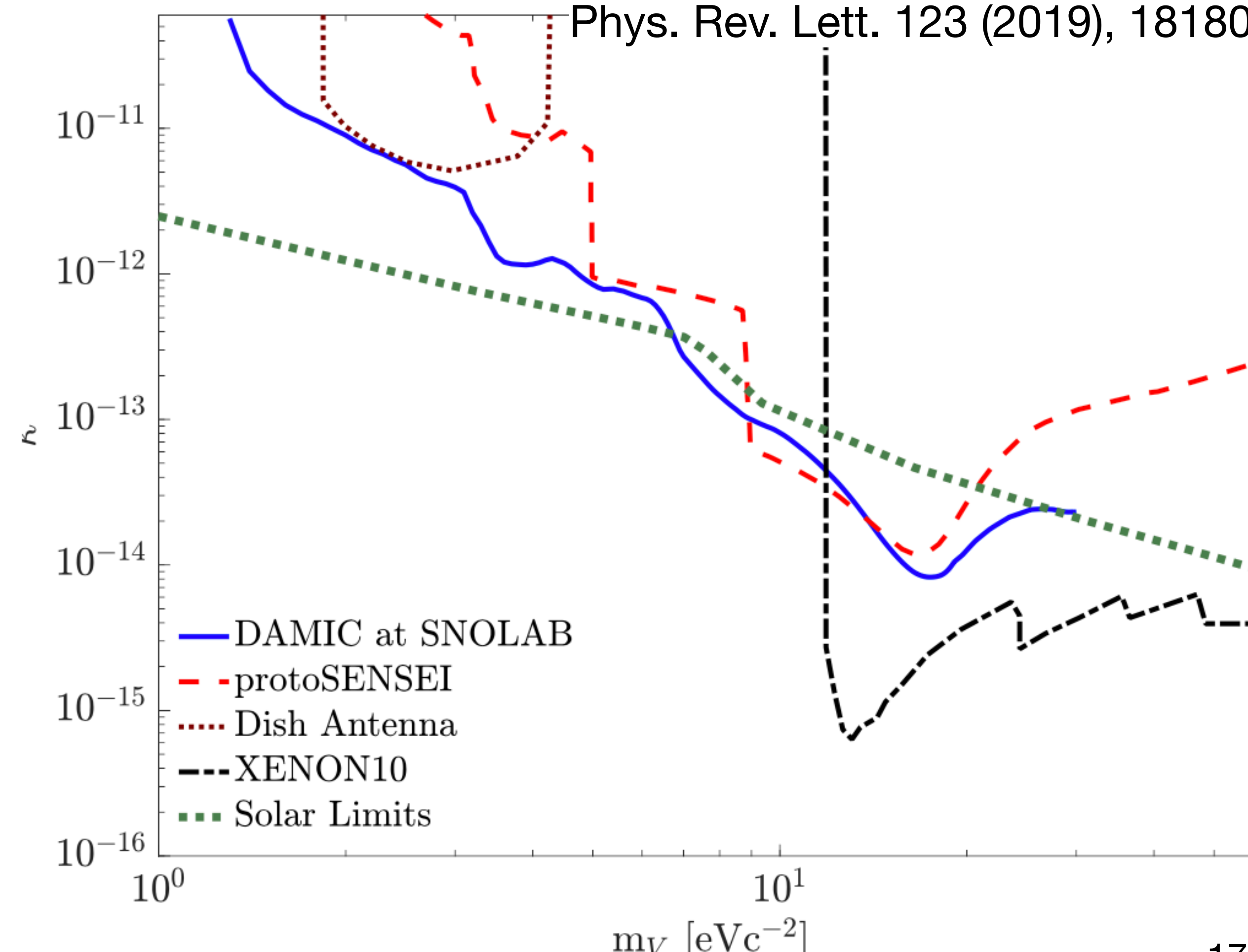
Hidden photon search



LL fit to compare charge distribution to **leakage only model** and to **noise + signal** (hidden photon absorption / DM e-scattering signal)

Best limit for masses 1-10 eV/c^2

- Evaluate the charge distribution of pixels with < 10 e$^-$ for contributions beyond the leakage current
- Select images with similar dark current. Data set: **200 g d exposure** in 100ks images

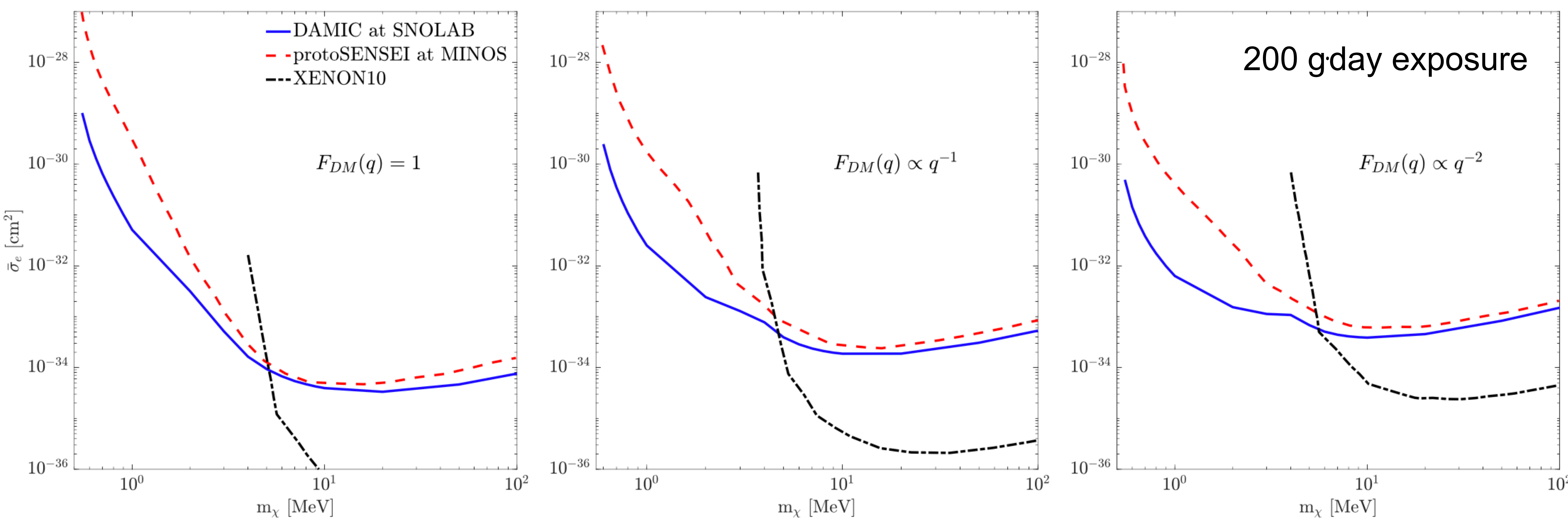


Phys. Rev. Lett. 123 (2019), 181802

DM - electron scattering

- Leakage current analysis as for hidden photon search
- Compare pixel distribution to **noise + signal from DM-e scattering**

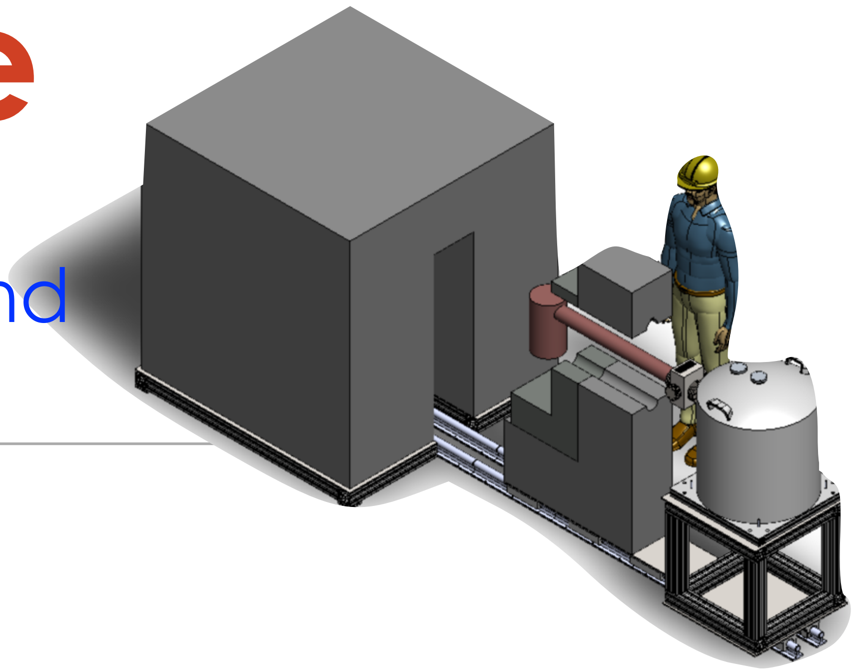
Phys. Rev. Lett. 123 (2019), 181802



Best exclusion limits for the scattering of DM particles with masses < 5 MeV/c^2

Next phase of DAMIC is started

DAMIC-M at Modane

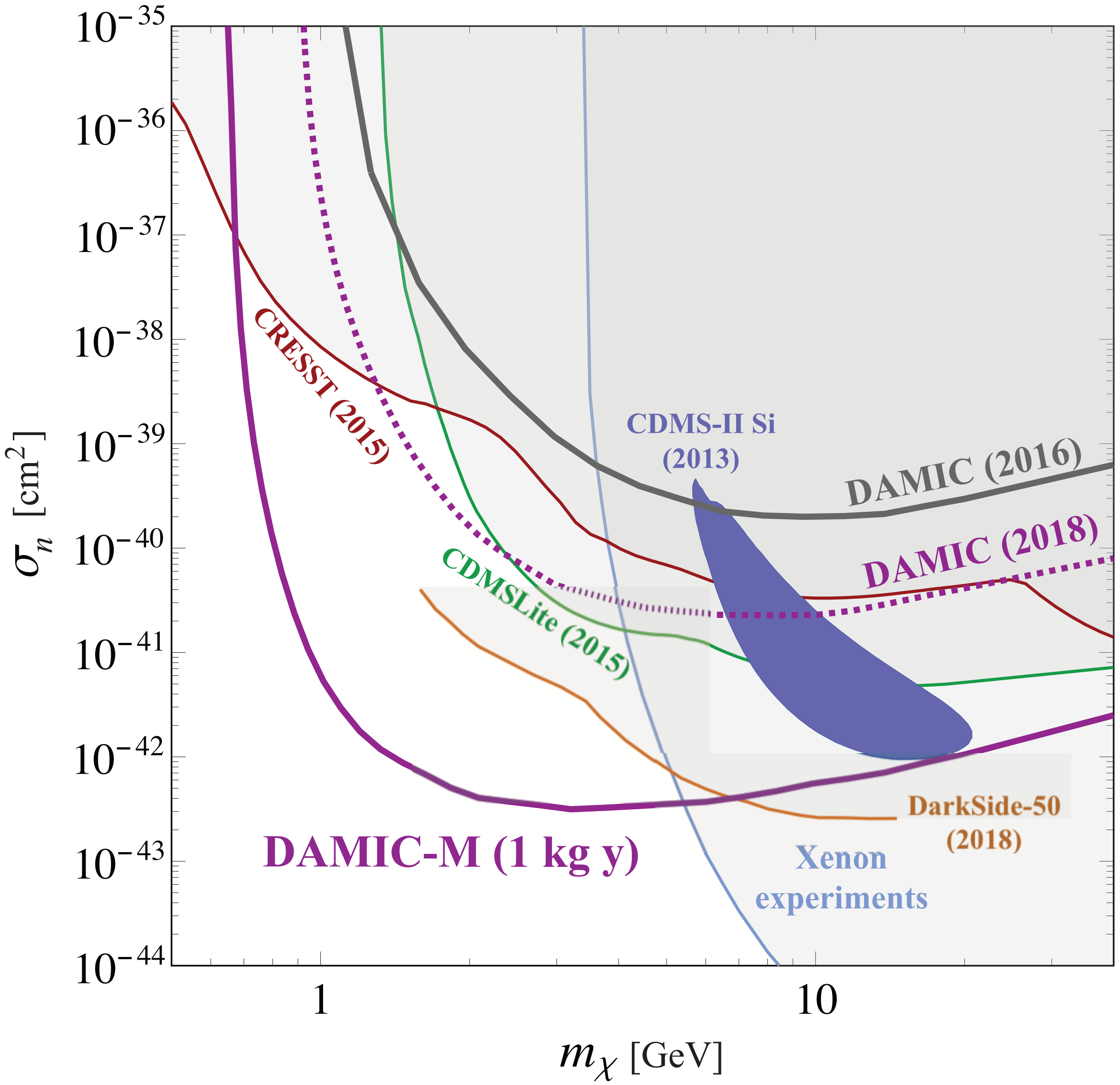


A kg-size improved detector for WIMPs and dark-sector candidates at low-masses:

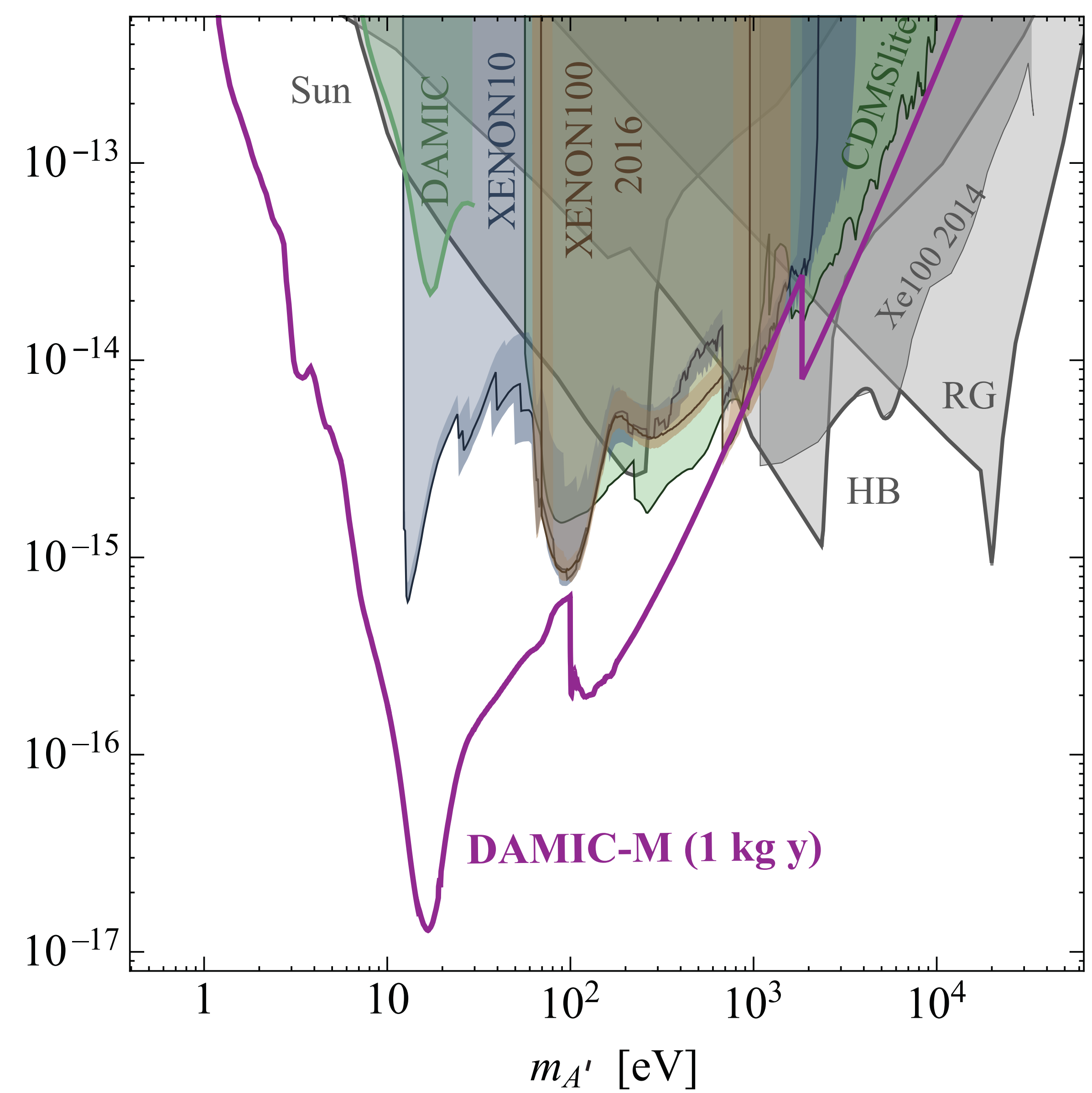
European Research Council
Established by the European Commission

Low mass WIMPS and Hidden photons

WIMP nuclear recoil search



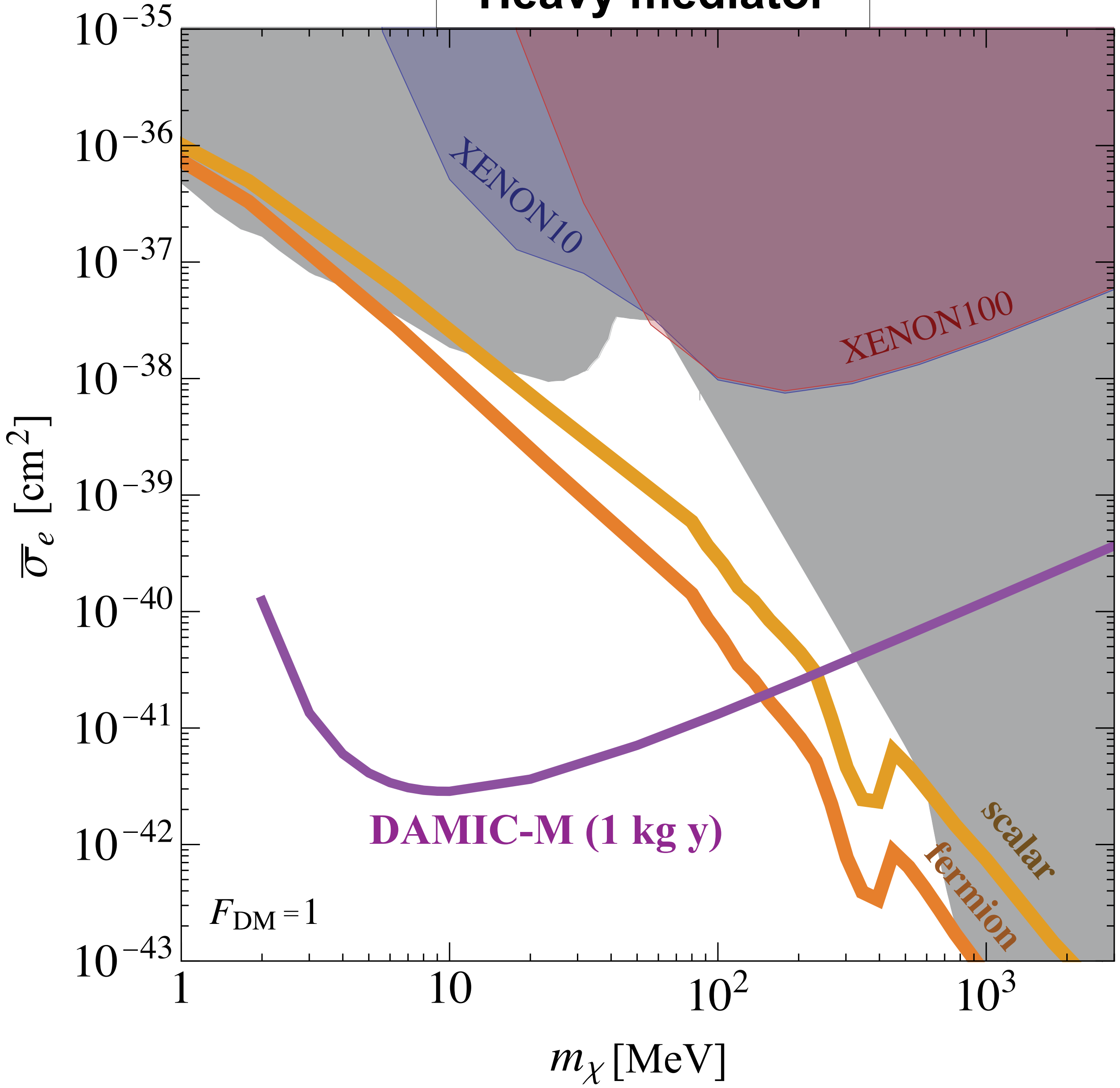
Hidden photon search



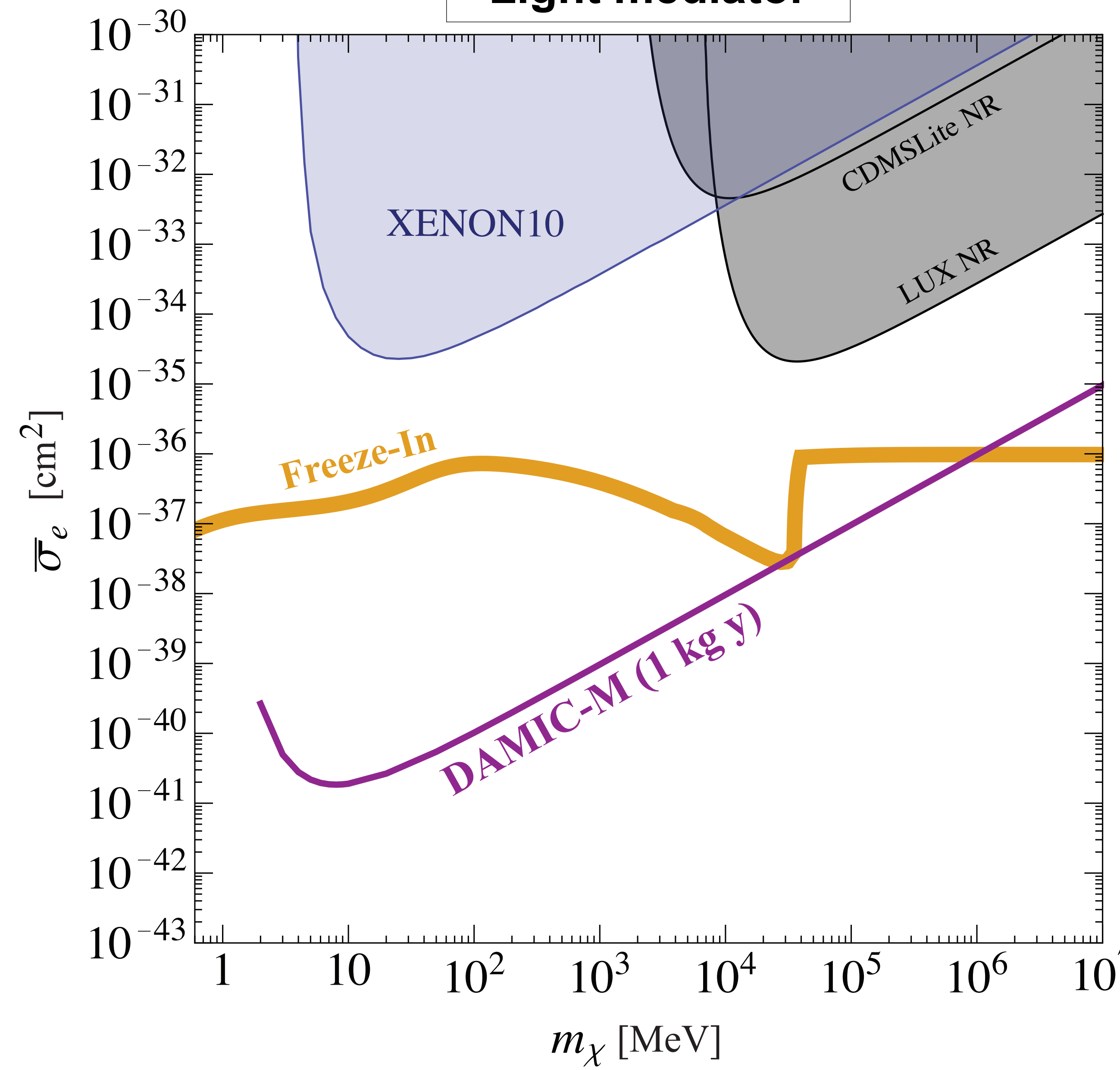
Light dark matter (hidden sector)

Light dark matter - electron scattering

Heavy mediator

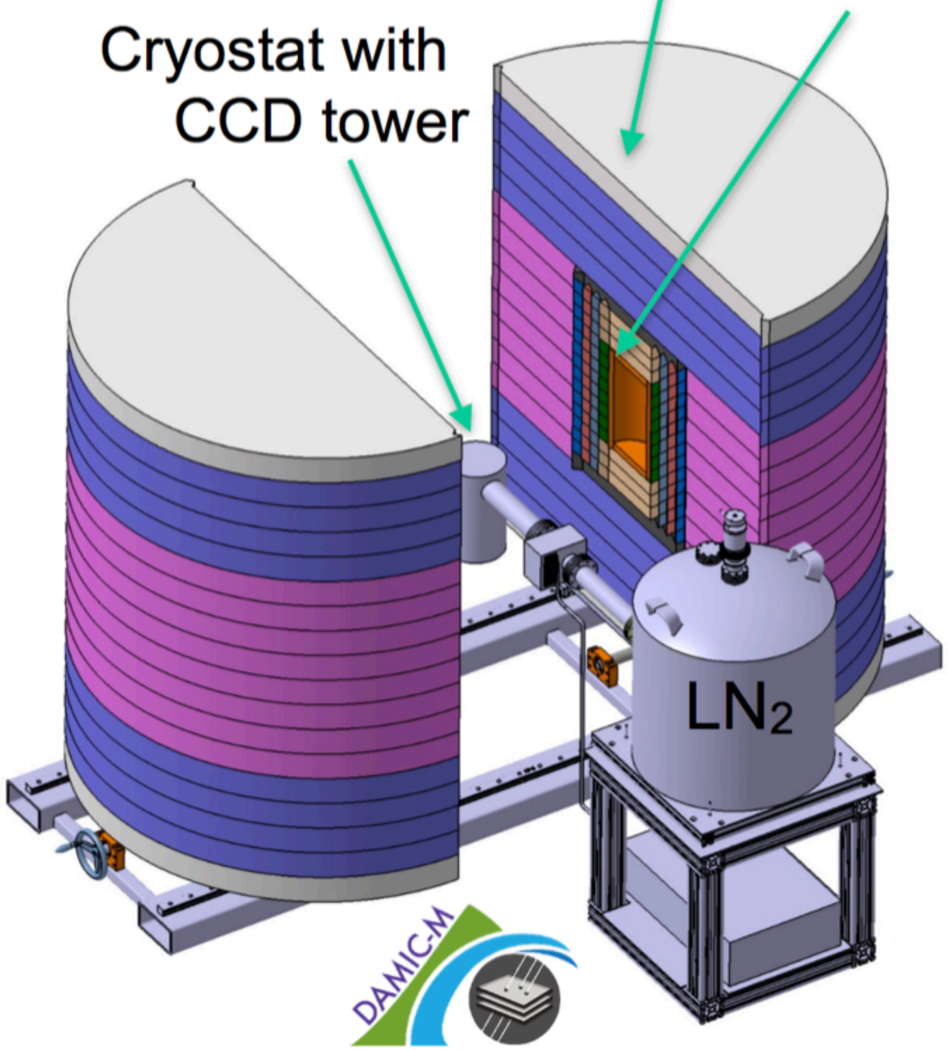


Light mediator



DAMIC-M will be sensitive to light dark matter even if these candidates constitute only a small fraction of the total DM in the universe

DAMIC at Modane: what's new

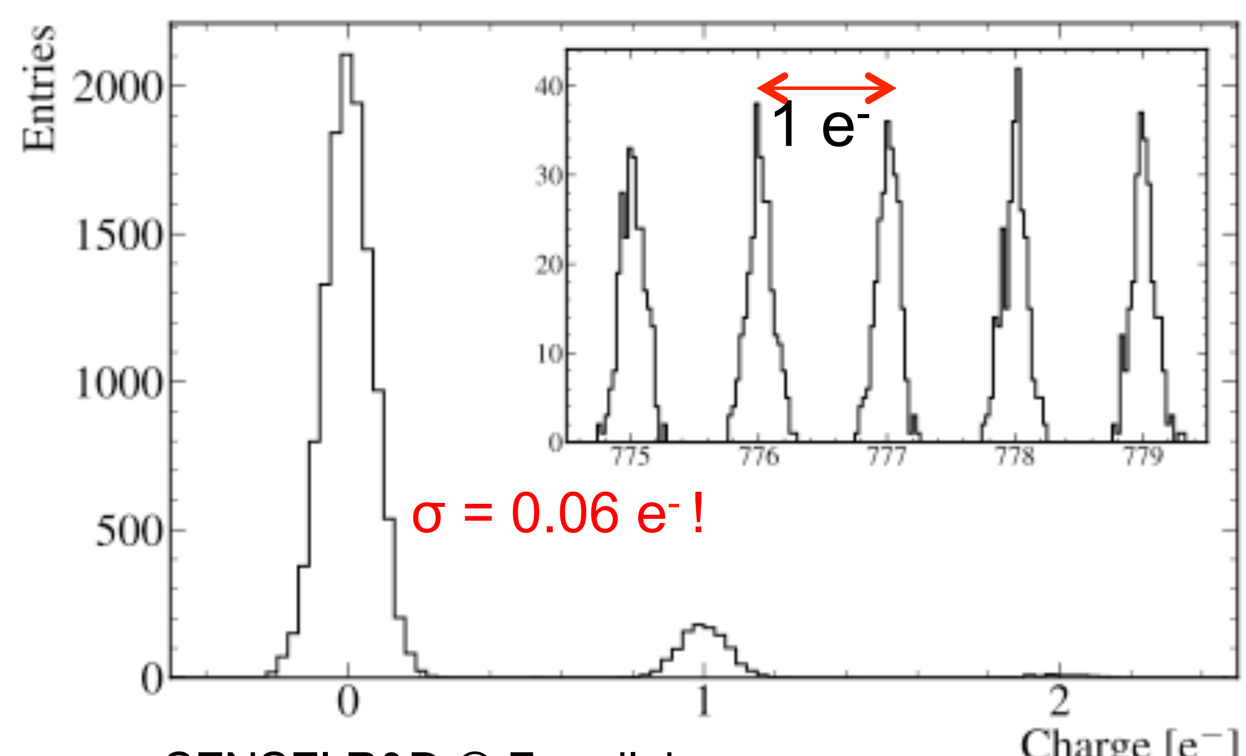


R&D and design up to 2021

Construction 2022

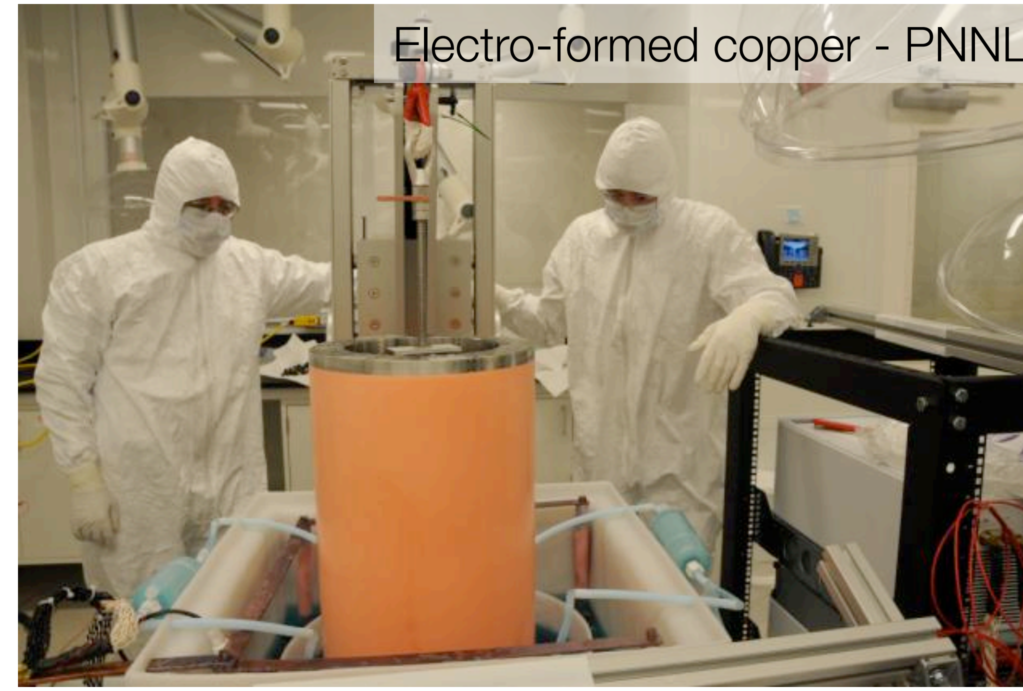
Installation in 2023

- 50 CCDs (kg-size detector)
- CCD mass > 10 g
- Skipper readout for single electron resolution (sub-eV noise) demonstrated by SENSEI project
- Bkg reduction to a fraction of dru
  (improved design, materials, procedures)



SENSEI R&D @ Fermilab

Background improvements for DAMIC-M



Background (to be reduced to fraction of DRU)

- **External background:** better material selection and handling (e.g. electroformed copper, surface contamination, Rdn)
- **Bulk background:** ^{32}Si et tritium

Produced by cosmic rays on the Ar in atmosphere, it deposits on ground with precipitations (rain, snow,…)

Tritium : expected to be the dominant background

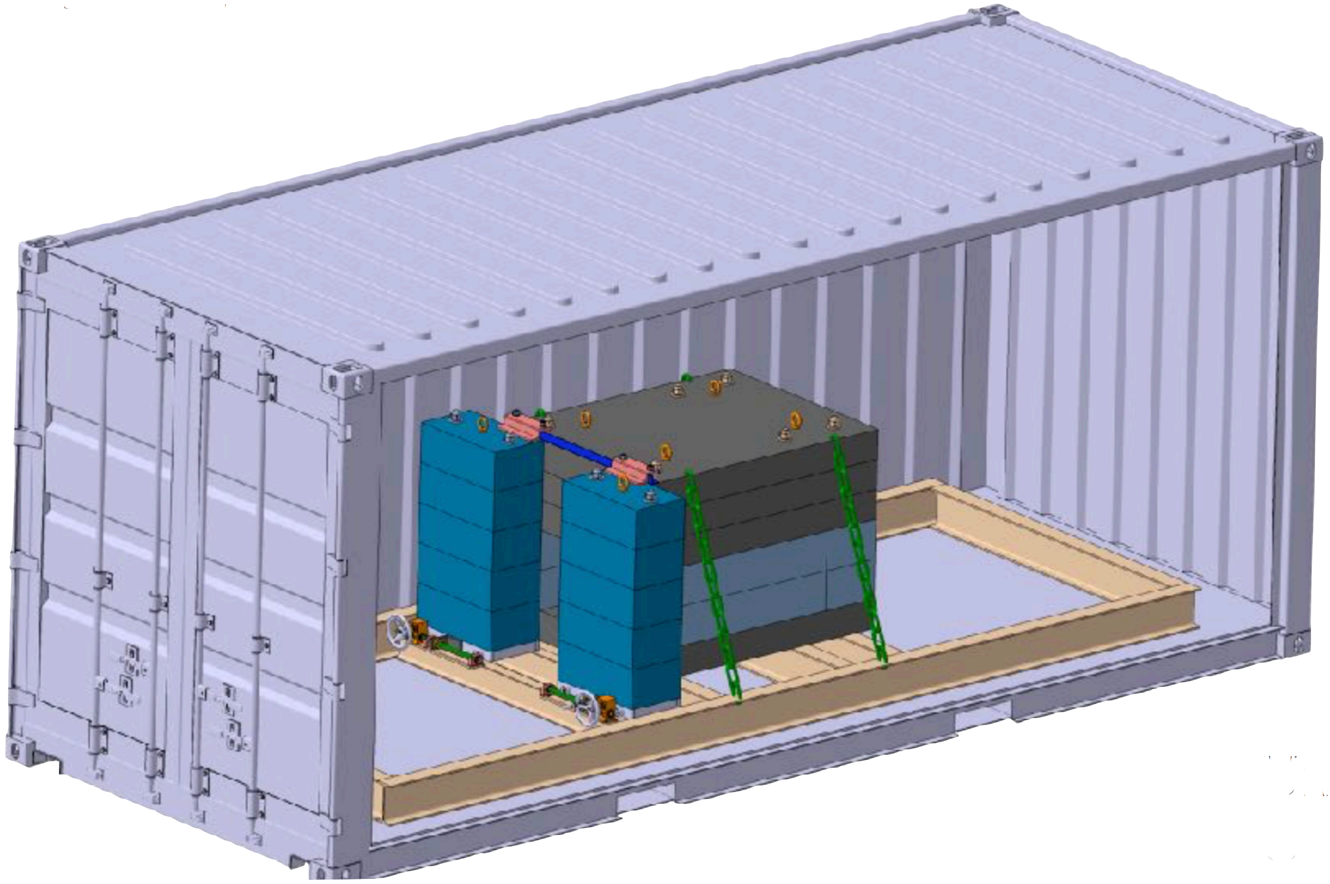
Produced by the cosmic neutrons and muon spallation in the Si bulk. production rate ~ 25 - 100/Kg/day (s.l.)

—> Minimize the time CCDs are exposed to cosmic rays (stock CCD underground, shielded container for transportation,…)

Progresses on CCD production

- Silicon Ingot production by TOPSIL, Denmark

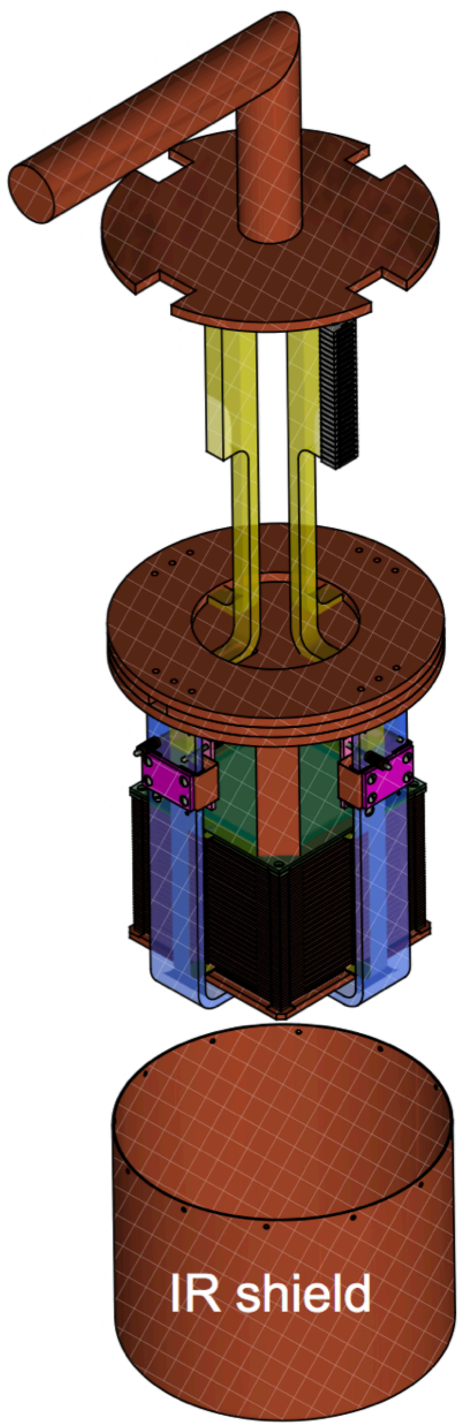
- Now at Boulby Underground Laboratory waiting for wafering by Shin-Etsu Handotai Europe (UK)



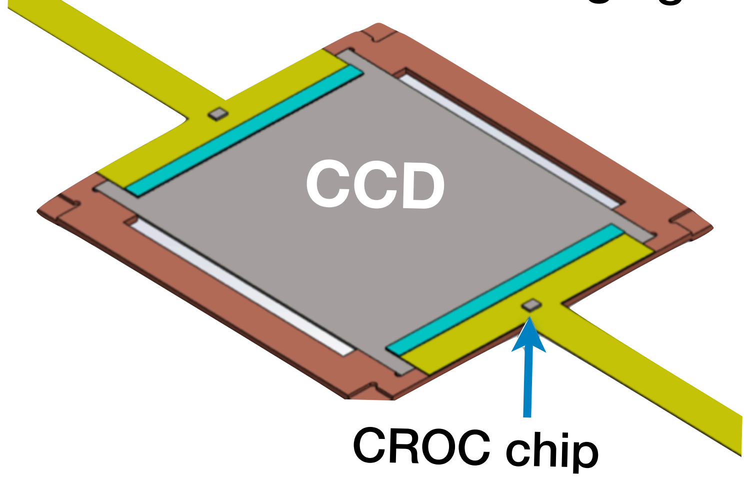
- To be shipped to DALSA (Canada) by sea: 8-15 days journey in a custom-made shielded container

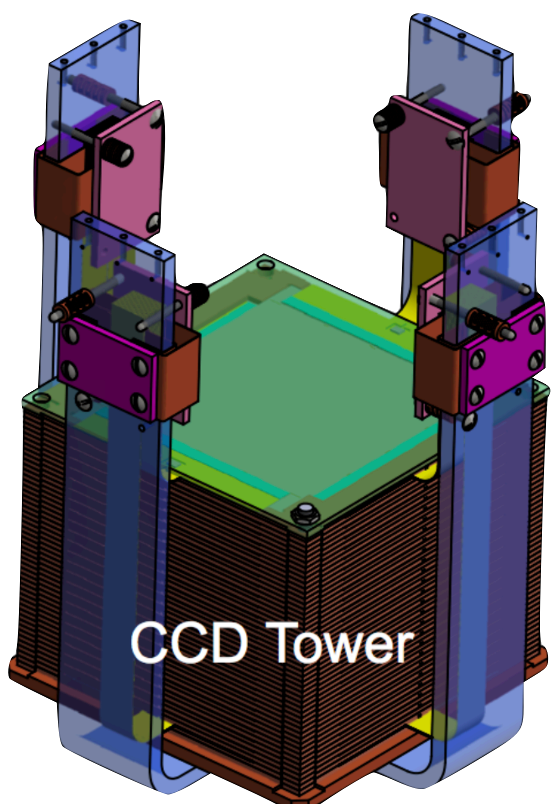
- DAMIC-M Skipper CCDs Pre-production ~spring 2020

Detector design and CCD tests



6k x 6k CCD packaging



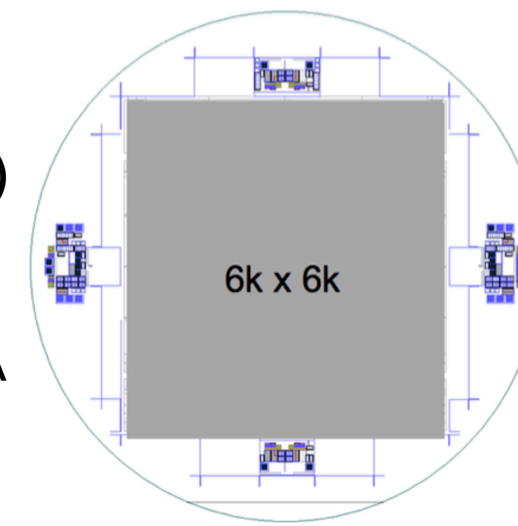


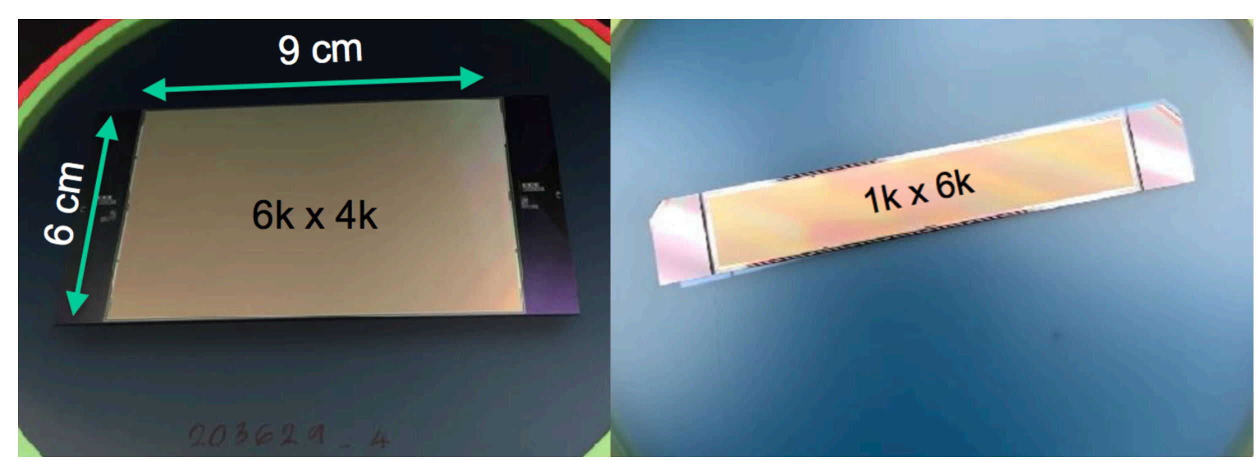
Design will be finalised by 2021

- Improvement of **packaging** procedures
- **Evaluating new low bkg flex cables vs pico-coax** (similar to Majorana's ones)
- **Three prototype skipper-CCDs** (675um thick) produced to test different readout amplifiers

DAMIC-M skipper CCDs :
6k x 6k pixels (i.e. 9cm x 9cm)

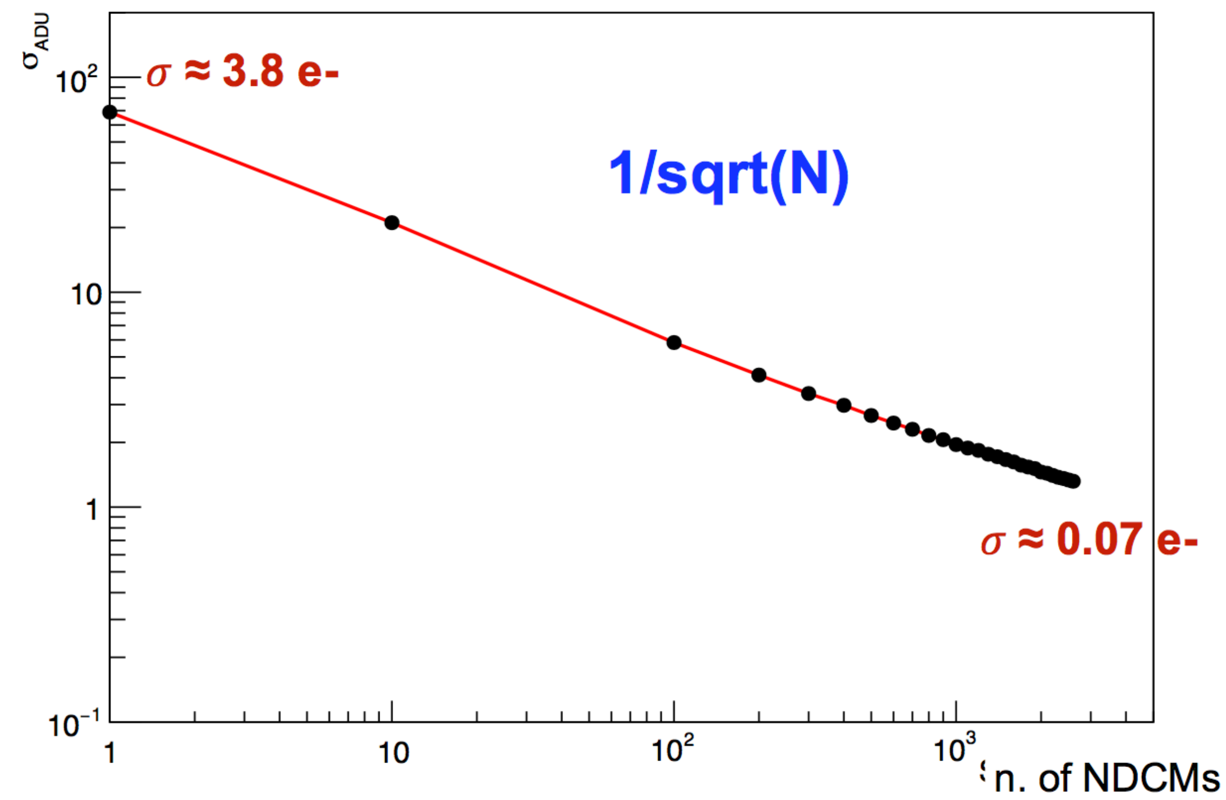
Design by S. Holland (LBNL), fabricated by Teledyne/DALSA

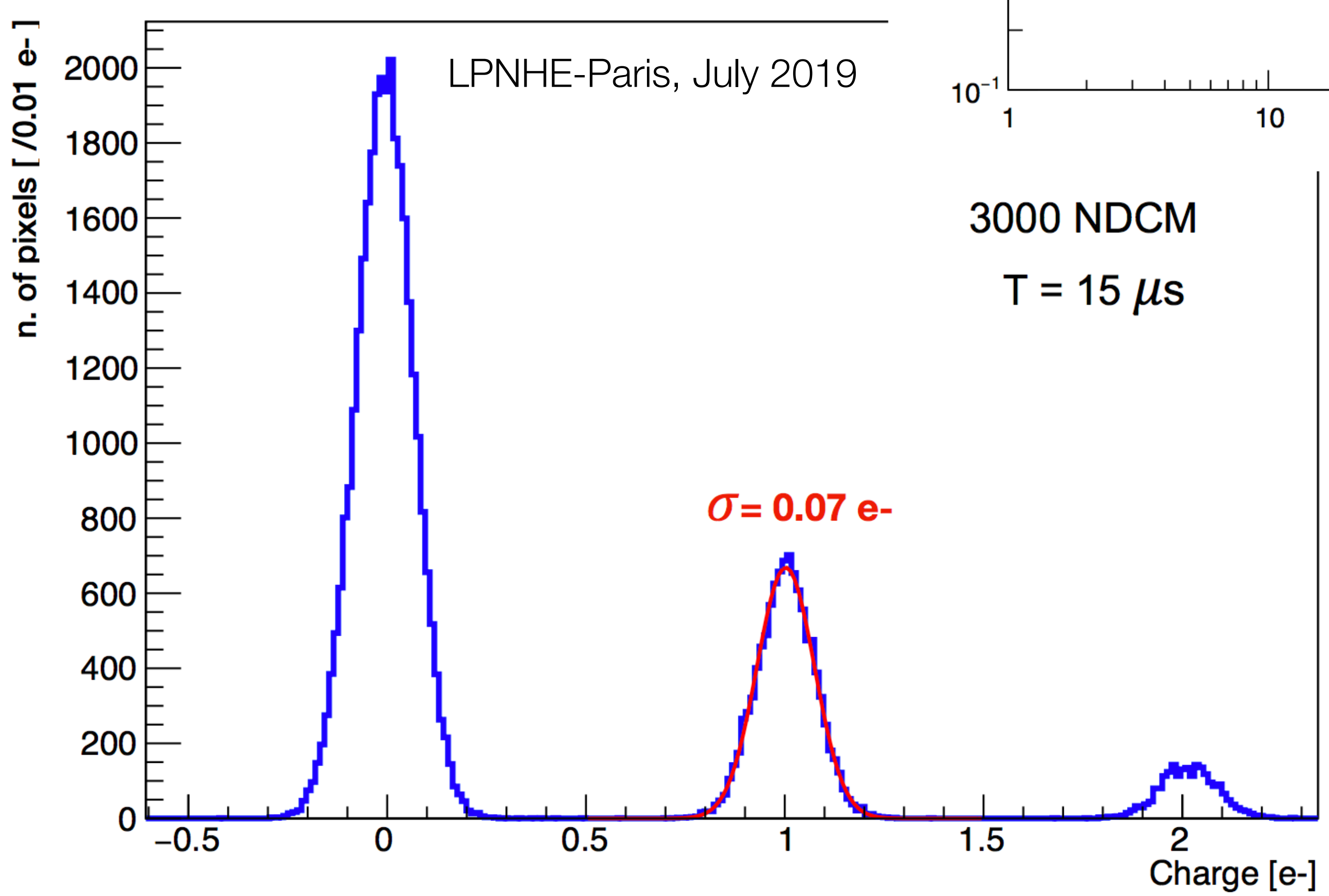




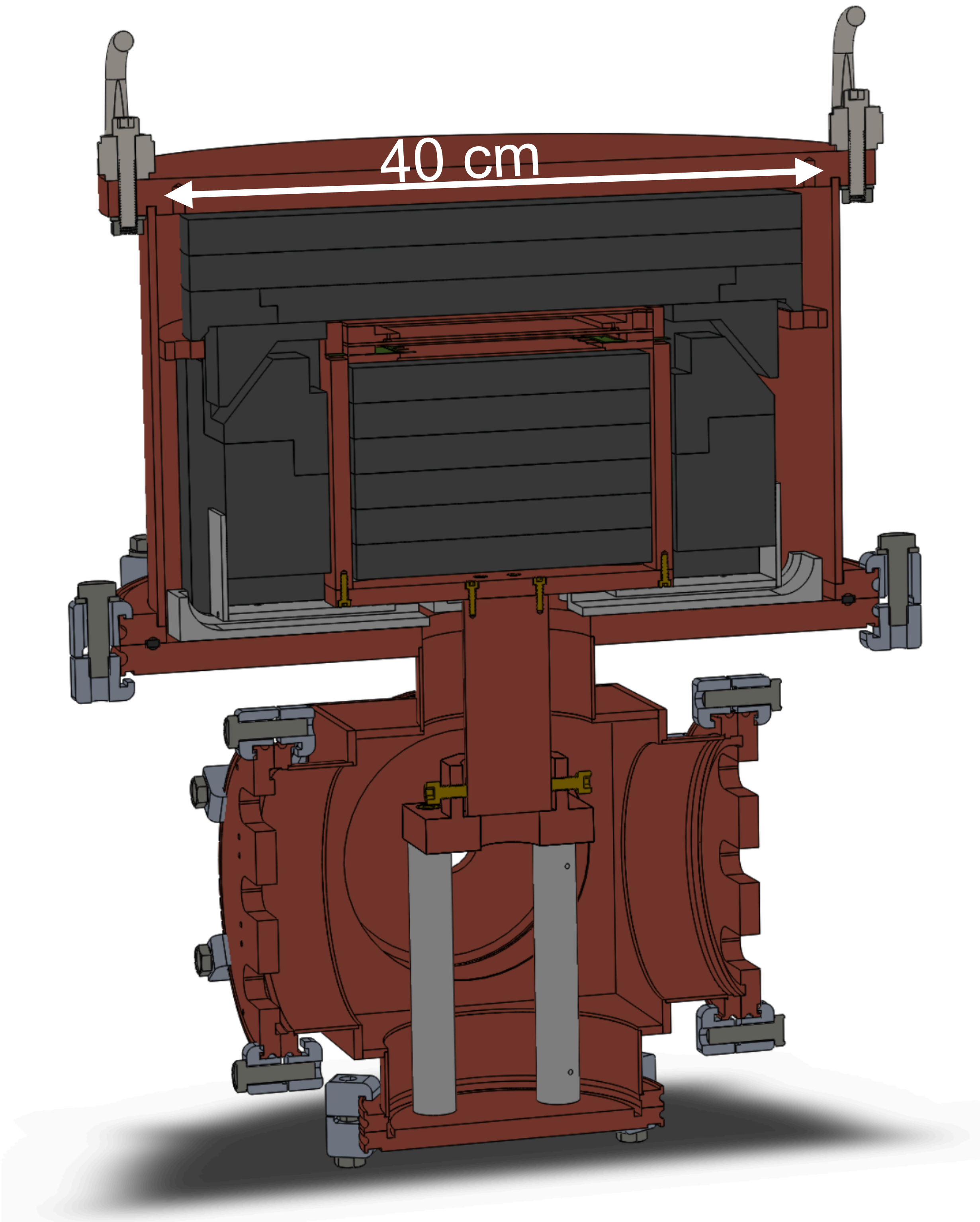
DAMIC-M skipper CCD performance

Single electron resolution obtained for a wide range of integration times (T = 4 - 20 μs) allowing optimization with respect to electronics noise





"Low Background Chamber" prototype @ LSM



- Small detector hosting a 6k x 6k skipper-CCD
- Characterisation of DAMIC-M CCDs with low background (few dru)
- Study of ^{32}Si background, ^{210}Pb surface;
- Tests of new CCD packaging
- dark current and skipper CCD tests
- Installation at LSM beginning 2020

Conclusions

- **DAMIC has proved the CCD technology as a competitive technique for the search of low-mass Dark Matter candidates :**
  - Sensitivity for **WIMPs masses below 10 GeV**
  - Constrain **Hidden photon absorption** (m < 10 eV) and **electron scattering** (< 5 MeV)

- Post-DAMIC R&D at SNOLAB: **background measurements for future Si-based experiments** and **CCD production and handling improvements** under evaluation

- **Next phase: A kg-size detector at LSM (France)**
  - **sub-electron resolution** + increased **detector mass** + **improved bkg** to reach **eV energy thresholds** and **sensitivity to MeV DM candidates in the hidden sector**
  - Detector design, material procurements and CCD tests ongoing
  - A **"low-background chamber"** at the LSM taking data this year

DAMIC Collaboration

Thank you!