

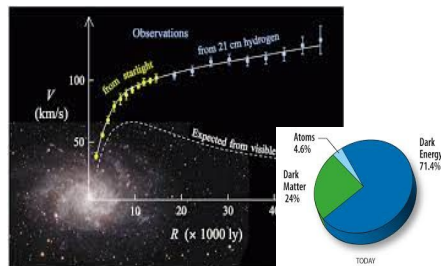
Status of the DAMIC-M dark matter experiment

DAMIC-M for DArk Matter in CCDs at Modane

Núria Castelló-Mor, on behalf of the DAMIC-M colloration
(IFCA, Santander (Spain))



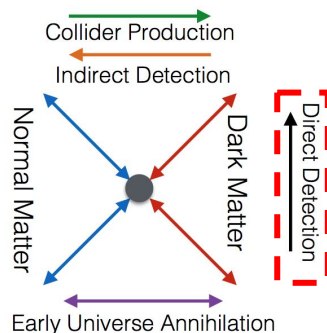
DAMIC-M in the Dark Matter (DM) context



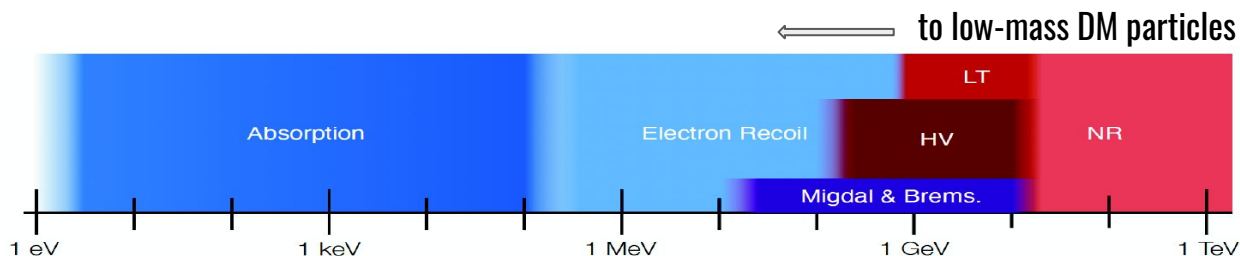
$\rho_D \sim 0.3 \text{ GeV/cm}^2$
(galaxy rotation curve, lensing, CMB, ...)

DM is known to interact

- gravity
- electromagnetic
- others? maybe, but must be really really small



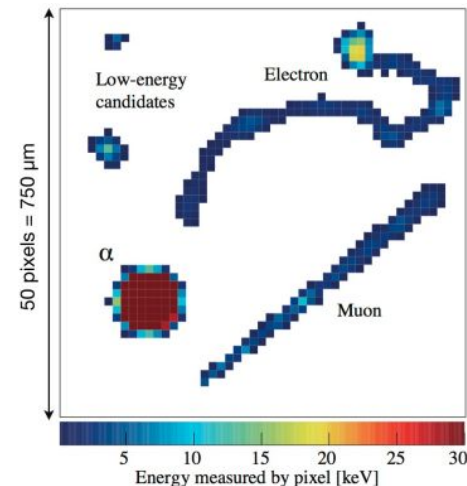
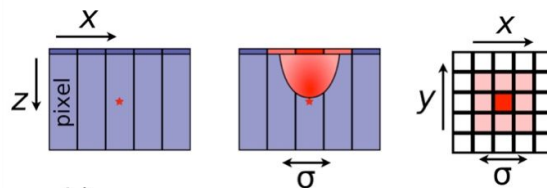
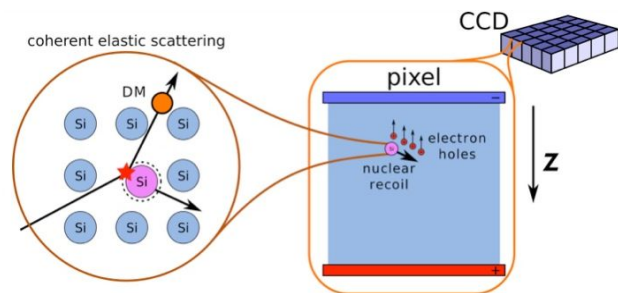
type	examples	mass threshold	ΔE	experiments
nobel liquid	Xenon Argon Helium	$\sim 5 \text{ MeV}$	$\sim 10 \text{ eV}$ (atom)	Xenon 10/100 DarkSide50
semiconductor	silicon	$\sim 200\text{-}500 \text{ keV}$	$\sim 1 \text{ eV}$ (bandgap)	SuperCMSDS SENSEI DAMIC@SNOLAB DAMIC-M (10kg) OSCURA (1kg)
scintillator	Gallium Arsenai NaI	$\sim 500 \text{ keV}$	$\sim 1 \text{ eV}$ (bandgap)	R&D ongoing GaAs photodetectors
others	Graphene, superconductors, dirac materials, ...	$> \text{keV}$	$> \text{meV}$	R&D ongoing



Technology: Charge Coupled Devices (CCDs)

CCD are n-type silicon detectors

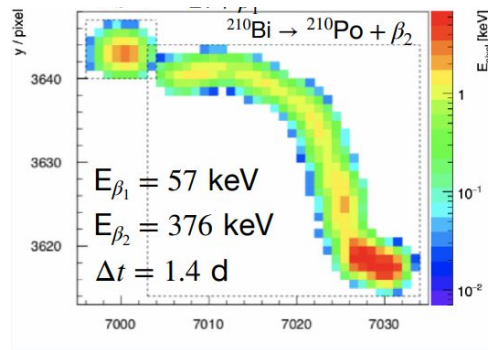
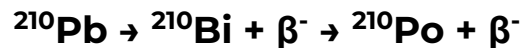
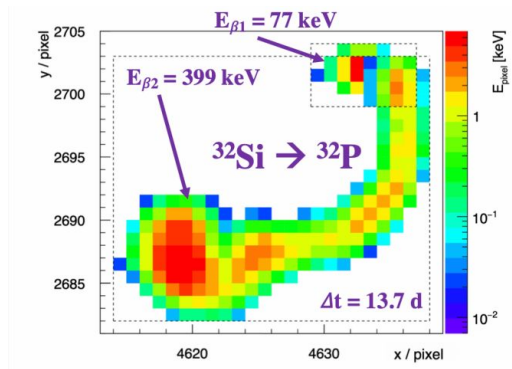
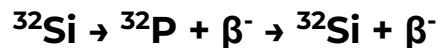
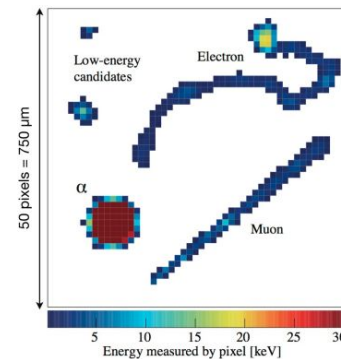
- Ionization signals due to interactions of DM or standard model particles with the Si electron or nucleus in the Si bulk of the CCD
 - e-h pair creation with only an average energy of 3.7 eV
 - holes are readout after some exposure time
- 3D reconstruction: rejection of radioactive chains through spatial coincidence
 - precise spatial resolution, pixels of $15 \times 15 \mu\text{m}^2$
 - depth-position due to charge diffusion during drifts along z



CCDs background rejection from DAMIC @ SNOLAB

Advantage of CCD for background rejection

- 3D reconstruction \Rightarrow unique ability to reject backgrounds with spatially-correlated decay products over time (probed by DAMIC at SNOLAB)



arXiv:1506.02562

arXiv:2011.12922

*for the bulk contamination

- ^{210}Pb : $< 160 \mu\text{Bq/kg}$
- ^{32}Si : $140 \pm 30 \mu\text{Bq/kg}$
- ^{238}U : $< 11 \mu\text{Bq/kg}$
- ^{232}Th : $< 7.3 \mu\text{Bq/kg}$

DAMIC-M: sub-e⁻ resolution DM detector

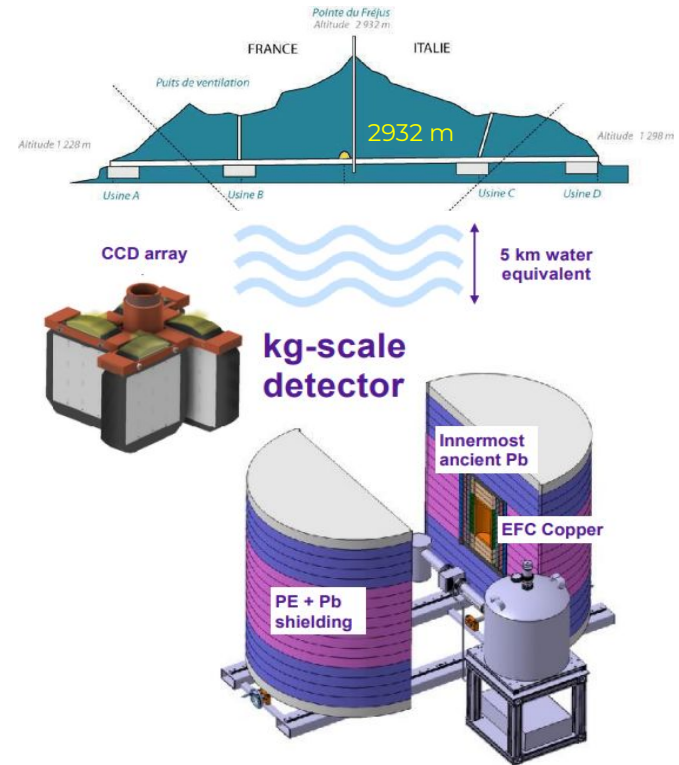
Dark Matter In CCDs at Modane

Physics goals:

- detect **nuclear and electron recoils** to search for **light dark matter** candidates (eV to GeV)
- Sub-electron resolution: operate ionization detector with **2-3 electron threshold** (~eV)
- **background rate of 0.1 dru** (1 event/kg/day/keV)

CCD objectives:

- **Build CCD array with kg-scale silicon target mass**, with thick (675μm), massive (~3.5g) and 9Mpix CCDs
- Operate with 'skipper' amplifier readout to provide **single electron energy resolution (sub-eV)** and **self-calibration**
- Use pixelization for background rejection



@ Laboratoire Souterrain de Modane (LSM) in France

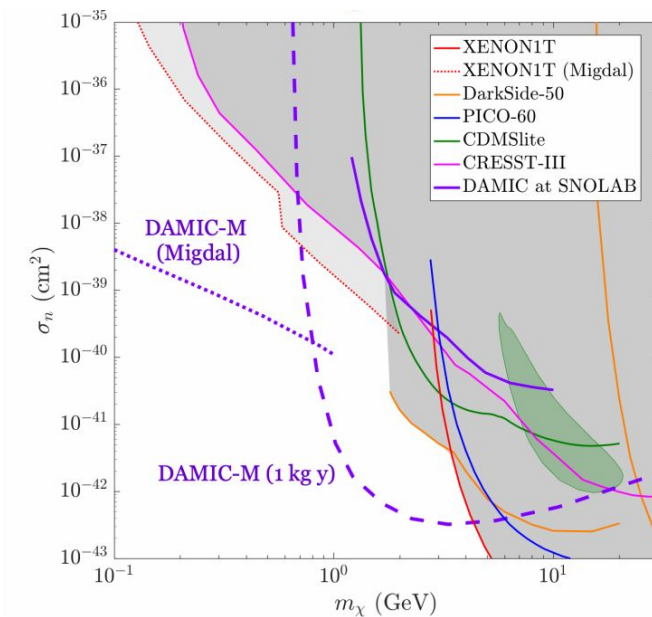
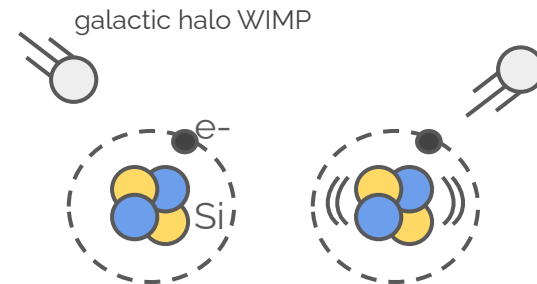
DAMIC-M Physical Goals

what we can do

explore light WIMPs via nuclear recoils (elastic scattering)

- WIMP hits target Si nucleus
- nucleus absorbs some energy and recoils
- creates electron-hole pairs
- CCD drifts charges and read out

[secondary electrons (Migdal) can also be detected]

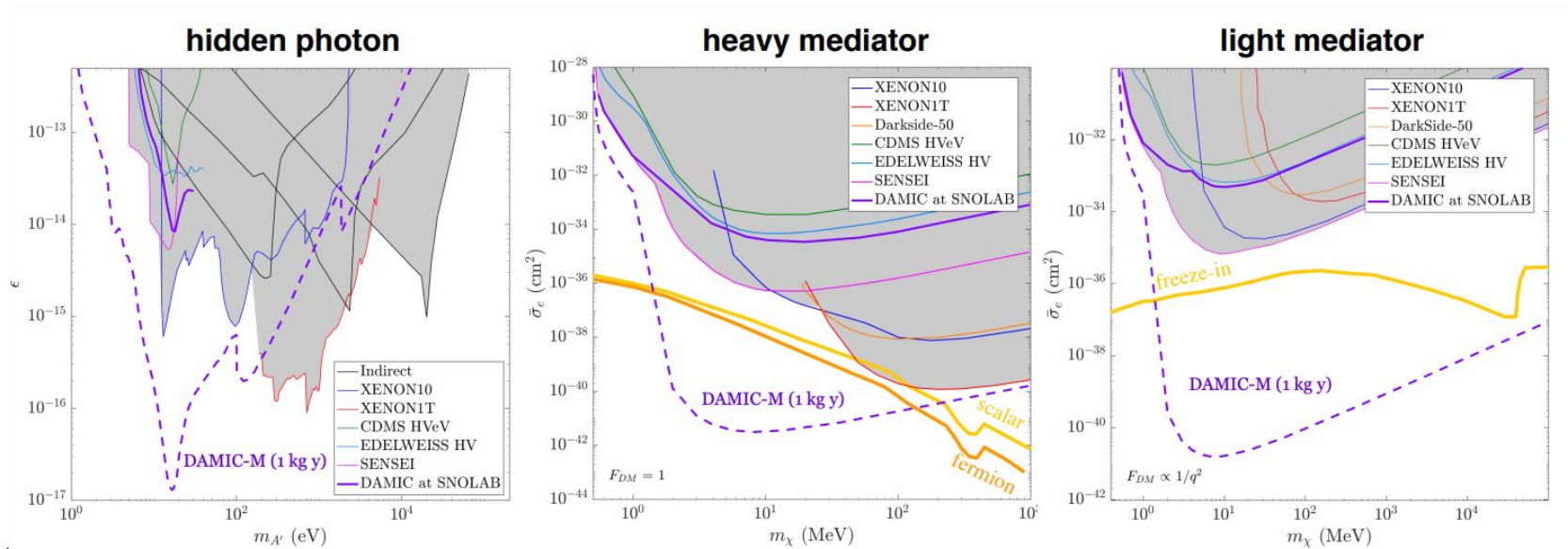
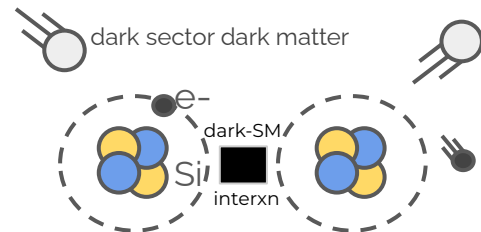


DAMIC-M Physical Goals

what we can do

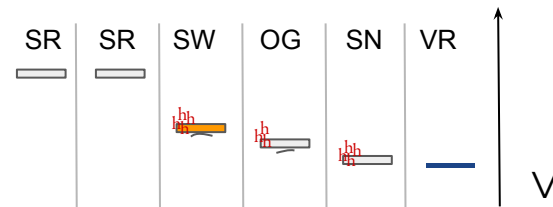
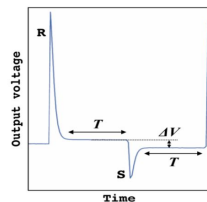
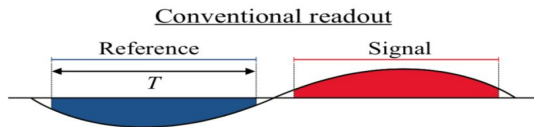
explore sub-GeV DM via electron recoils and absorption

- dark sector DM hits target Si valence electron
- Electron absorbs some energy and recoils
- creates electron-hole pairs
- CCD drifts charges and read out

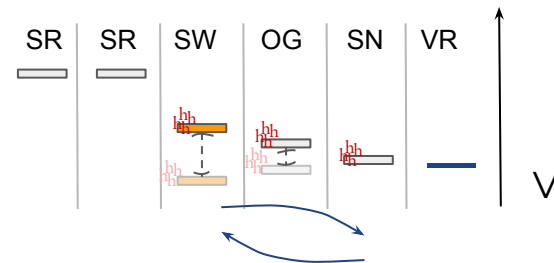
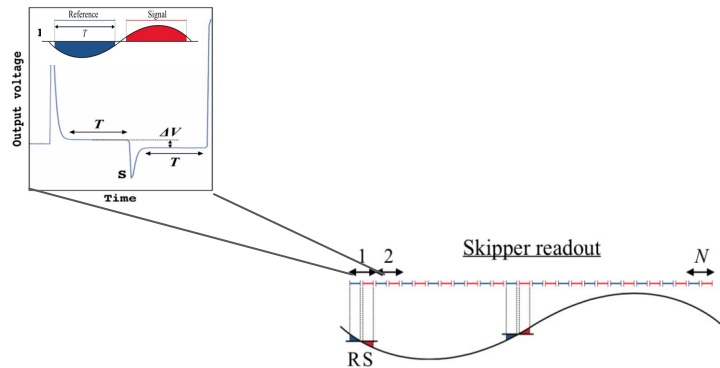


What is new? SINGLE e^- with SKIPPER CCDs

In conventional CCDs, $1/f$ low frequency noise of amplifier dominates readout noise level



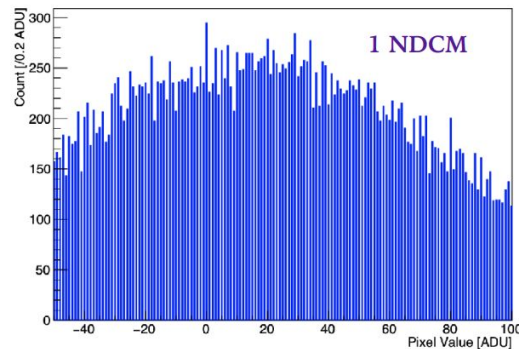
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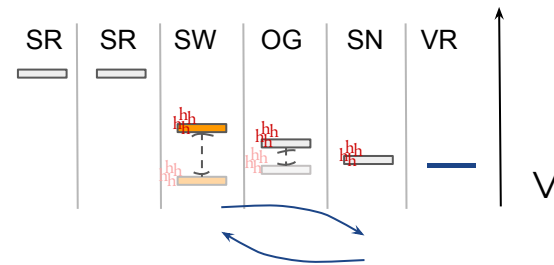
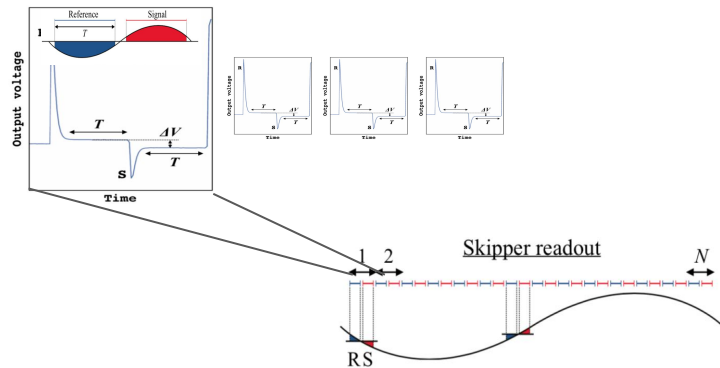
Skipper amplifiers:

- skipper amplifier (floating gate) allows **charge to move back-and-forth** across measurement node **before destruction**
- **measure** charge **fast kills $1/f$**
- measure each pixel N times \Rightarrow readout noise follows $\sim 1/\sqrt{N}$
- can see single electron ionization signals!

skipper readout + low leakage current push energy threshold to eV-scale



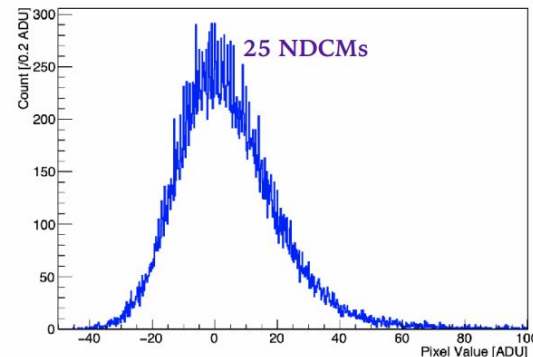
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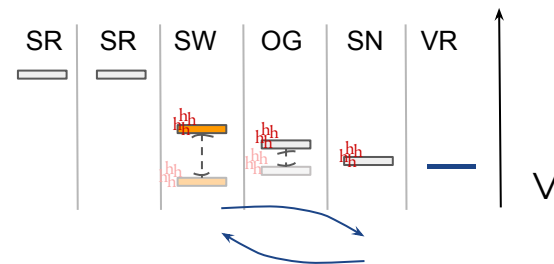
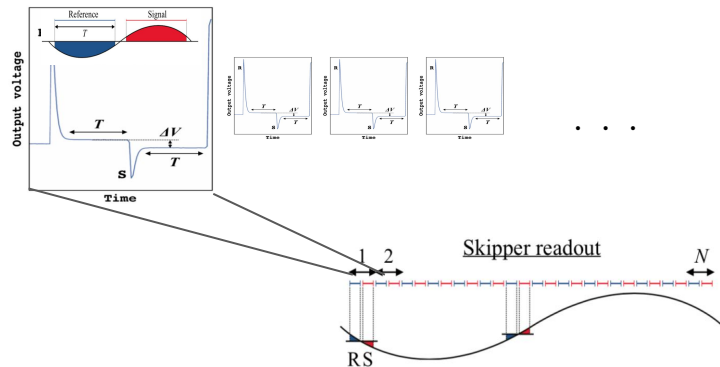
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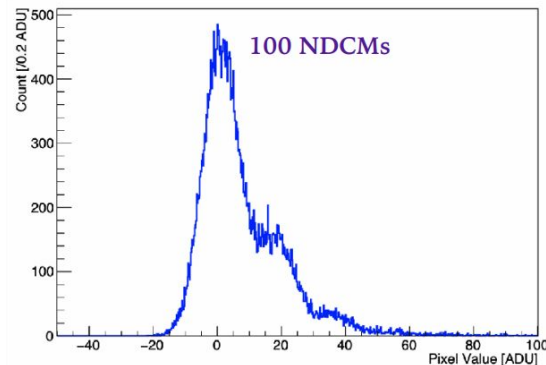
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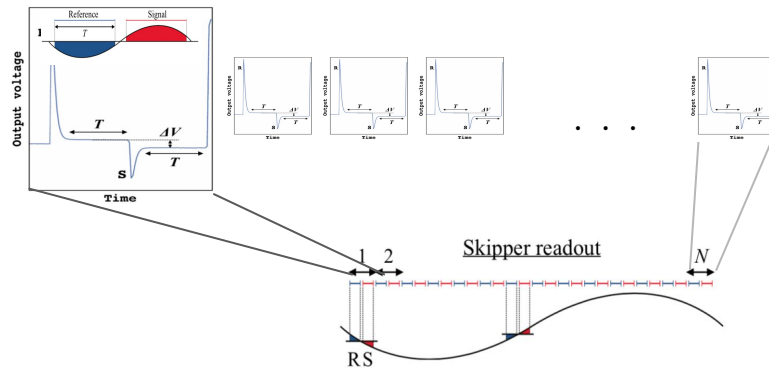
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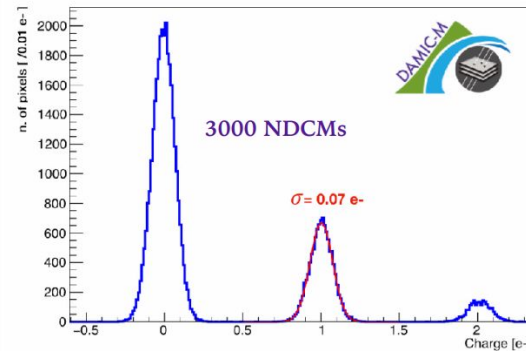
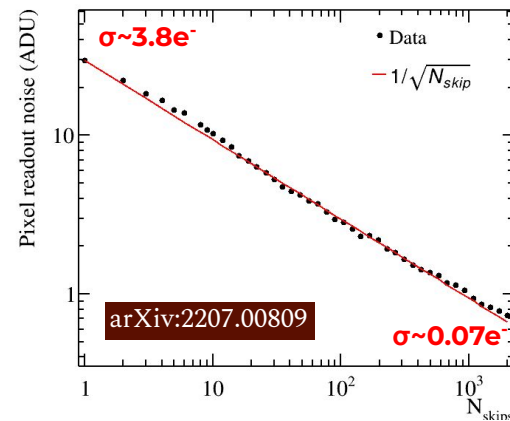


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- can see **single electron ionization signals!**

skipper readout + low leakage current push energy threshold to eV-scale

DAMIC-M: Compton Setup



CCD challenges: radiogenic and cosmogenic backgrounds

Lessons from DAMIC @ SNOLAB

55% in-CCD contaminants

- ^3H from CCD activation + Surface ^{210}Pb from Rn deposition \Rightarrow **Improved fabrication/storage/transportation protocols**
- intrinsic ^{32}Si traces \Rightarrow rejection of radioactive chains through spatial coincidence

30% OFHC Copper

- Cu activation and bulk ^{210}Pb contamination \Rightarrow **use electroformed Cu** (EFCu) with minimized activation time

15% mixed material contribution (lead shielding, flex cables, etc.)

- about 2 dru \Rightarrow optimizing detector design, material selection and handling, analysis
- with the prototype low background chamber (LBC) paves the way to achieve DAMIC-M desired low backgrounds

Status of DAMIC-M



- Final **detector design** is still under development

electronics:

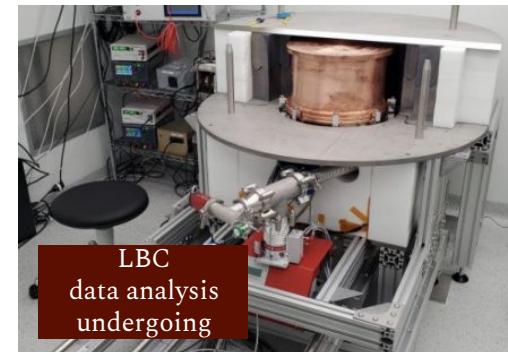
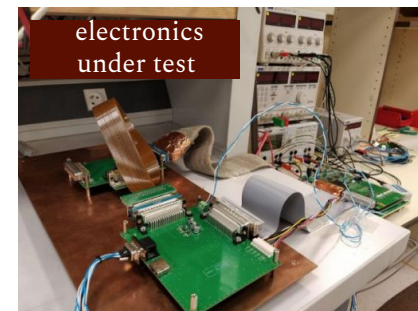
- electronics designed**, under test

core-detector:

- CCD pre-production is ongoing
- CCDs ready to package and test science-grade CCDs
- cold probing, packaging and testing in 2023
- EFCu the inner detector parts to be grown in 2023

prototypes already taken data:

- Calibration** with radioactive sources ongoing (**Compton** done and **photo-neutron** ongoing)
- LBC prototype** takes science data since Feb 2022 (results soon)

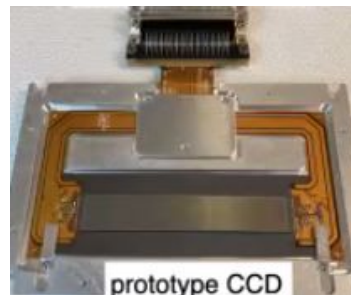


DAMIC-M 1kg detector with sub-e performance

where we are

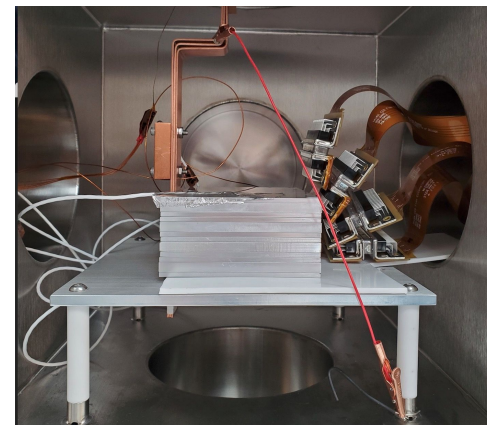
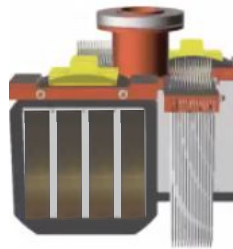
CCDs

- high resistivity, n-type, high purity silicon
- 6k x 1k pixels ($15 \times 15 \times 675 \text{ um}^2$)
- fully depleted (no charge loss when drifting)
- $47/6 \text{ um}^2$ skipper amplifiers
- Low background cable



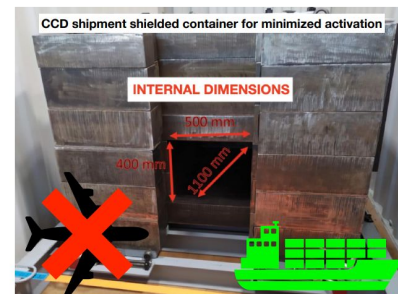
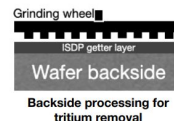
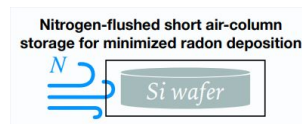
Detector

- kg-scale, 4 CCDs per wafer in array
- electro-formed copper cryostat, IR shield
- operate at 130K and $1\text{e-}7$ mbar
- Layer poly+lead shielding, innermost layer of ancient lead,
- Custom electronics for fast readout and low noise



Background controls

- Cosmic activation and radon limited by time above ground/in air (fabrication, transportation, etc)



DAMIC-M Experiment

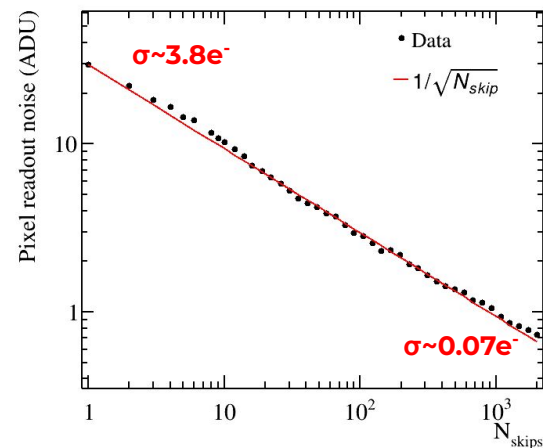
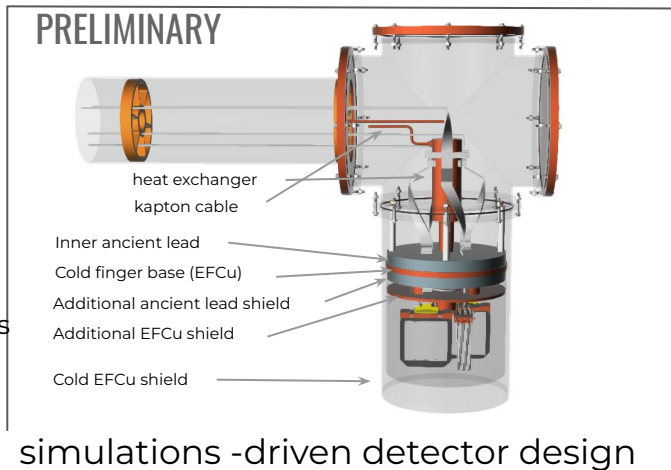
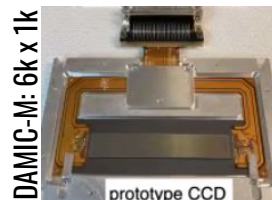
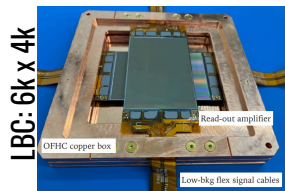
where we are

Accomplishments

- preliminar detector design
- silicon ingot production with low cosmogenic exposure
- demonstrated single electron resolution with large format, thick skipper CCDs
- tested multiple CCDs format to understand performance
- developed low background CCD packaging procedures
- analysis /simulations frameworks ready and used in recent analysis
- installed the low background chamber prototype (LBC)
- measured Compton scattering in silicon to 23eV

In progress

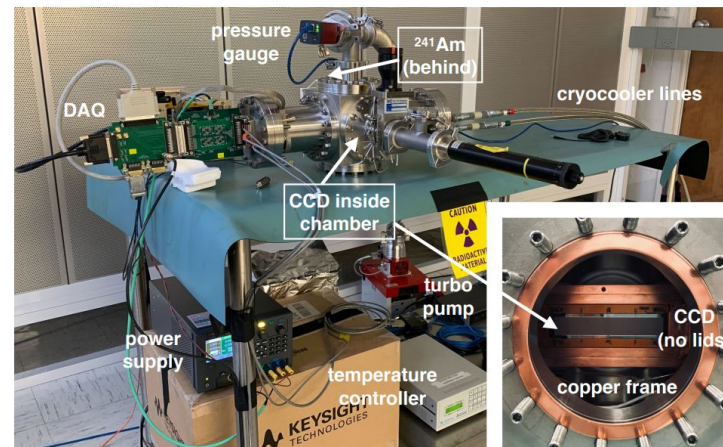
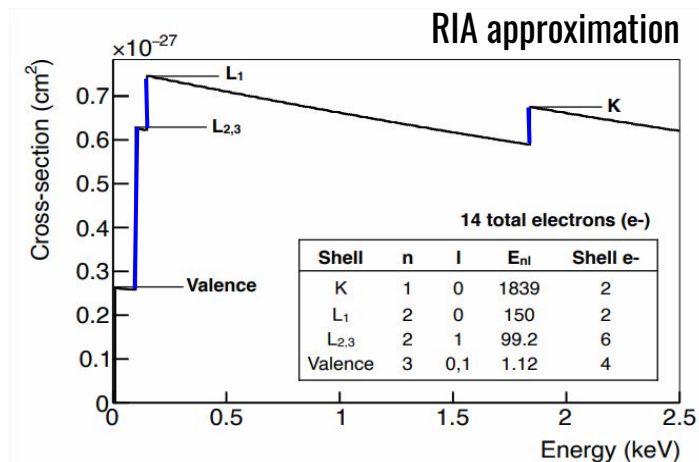
- development of low-background infrastructure (+models)
- testing new CCD controller electronics
- packaging newly produced DAMIC-M CCDs
- evaluating performance of new DAMIC-M CCDs
- performing nuclear ionization efficiency measurements



DAMIC-M: calibrations ongoing @ Chicago

arXiv:2207.00809
submitted to PRD

Parametrized Compton spectrum at low energy (main source of background for DM search)



Compton scattering is conventionally approached using the Klein-Nishina formula from free electron approximation but with a constrained momentum distribution:

$E_{\text{dep}} > E_{\text{nl}}$ freed electron energies do impulse approximate, E_{dep} fall

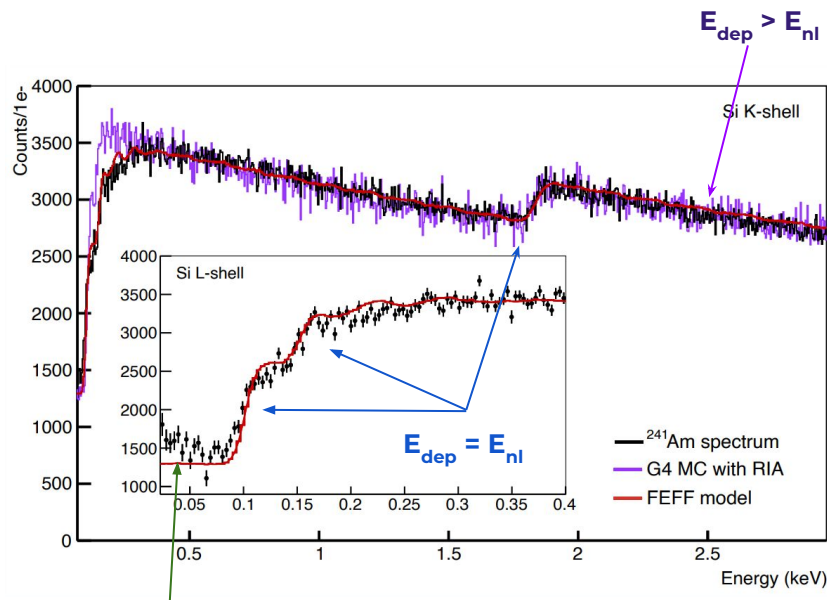
$E_{\text{dep}} = E_{\text{nl}}$ just enough to free electron, but refills vacancy and emits secondary Auger electron or fluorescence x-ray \Rightarrow deposited energy is thus a result of refilling the atomic vacancy by emission of secondary Auger/x-ray

DAMIC-M: calibrations ongoing @ Chicago

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Parametrized Compton spectrum at low energy

(main source of background for DM search)



plateau due to Compton scattering on valence e^-
(amplitude with the $\#e^-$ available in the shell, as expected)

RIA model

- ⇒ succeed in describing Compton edge,
- ⇒ succeed in describing the K-shell transition step
- ⇒ but **fails on the L-shell steps**, which is much softer than RIA predictions

at very low-E the atomic binding effects are not negligible, and the approximation of a free electron is not adequate

FEFF model: performed a full quantum mechanical treatment to sum over all transition probabilities from the initial state to all possible atomic final states in the target material

⇒ excellent agreement with data over the full energy range

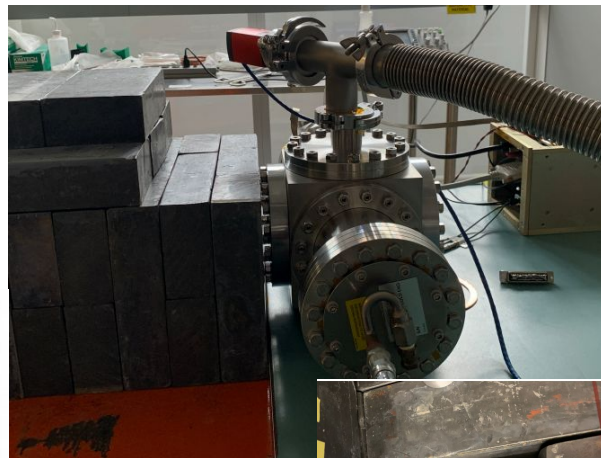
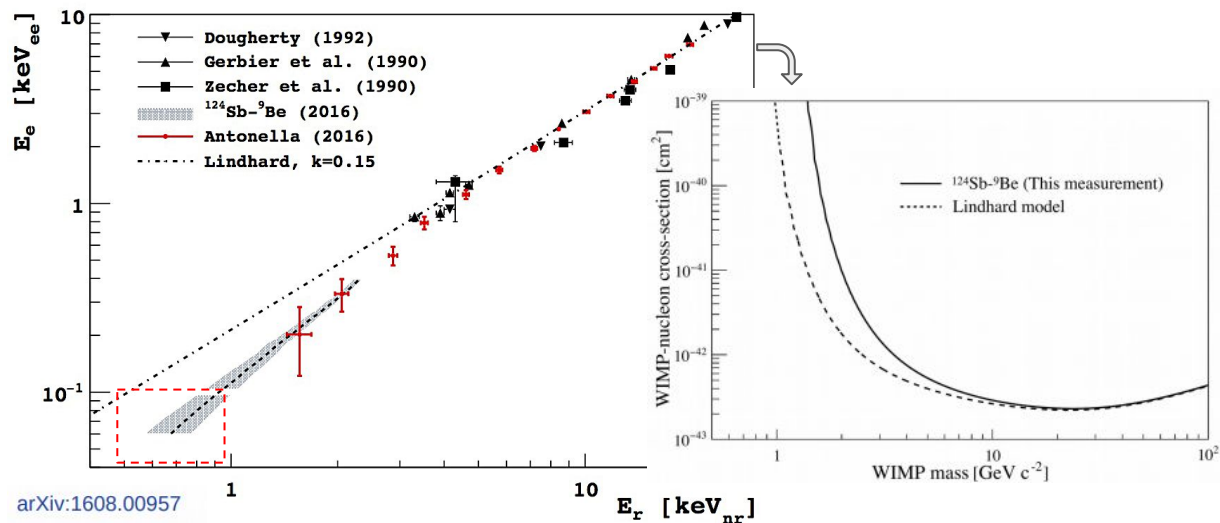
DAMIC-M: calibrations ongoing @ Chicago

extending ionization efficiency to low-E (results coming very soon)

Nuclear recoil and ionization energy conversion

for WIMPs searches

⇒ Data taken is ongoing



Low Background Chamber at LSM

Prototype detector: test bench for DAMIC-M, with competitive DM search capabilities

LBC detector

- 2 skipper CCDs (6k x 4k pixels) with sub-electron resolution
- 18 g target mass

Goals

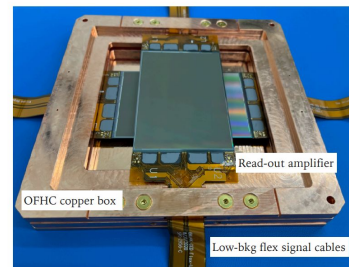
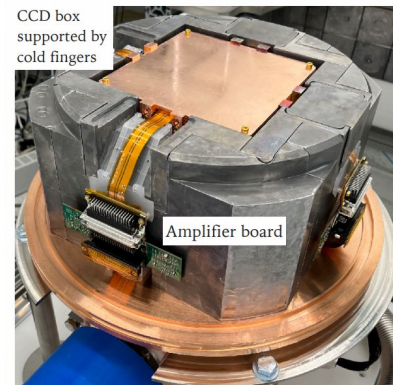
- demonstrate the ability to control backgrounds for DAMIC-M
- integration /operation of DAMIC-M electronics
- achieve intermediate background goal ~ 1 dru

Achievements

- Installed at LSM at the end of 2021, and working non-stop since then
- 1st run collected with open shielding (bkg rate ~ 300 dru)
- 2nd run collected with close shielding and 2 CCDs (bkg rate ~ 10 dru, as in DAMIC@SNOLAB)
- 3rd run collected for science data
- 4th run ongoing with lower dark current

Next steps

- next steps: swap OFHC to EFCu to reduce background



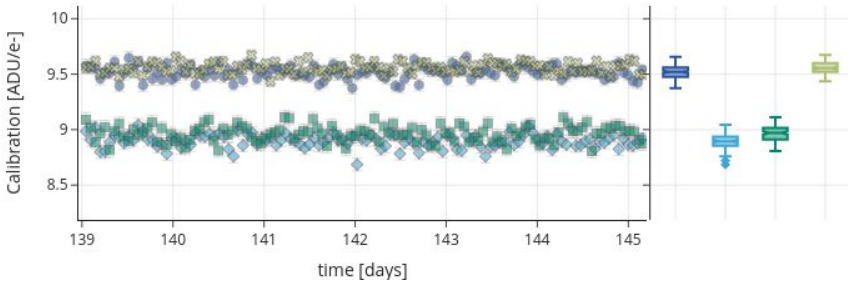
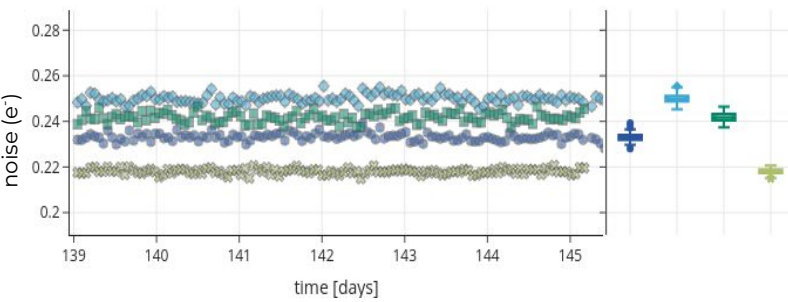
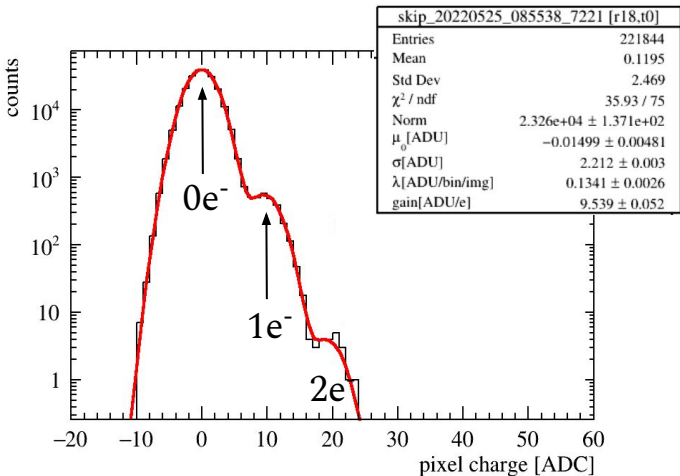
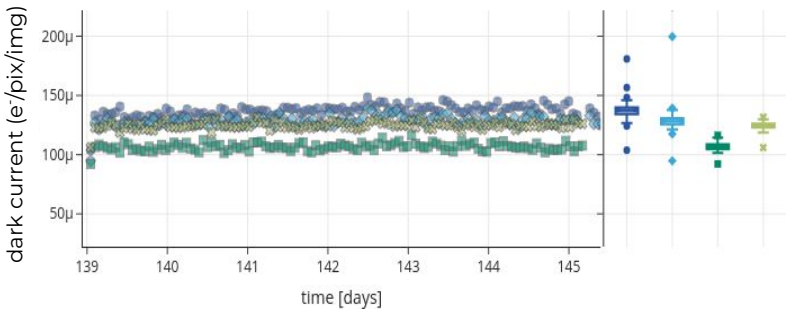
Installation of LBC at LSM



Cleaning, clean room preparation, support structure, cryostat, CCDs, external shielding, electronics, slow control, grounding, troubleshooting, ...

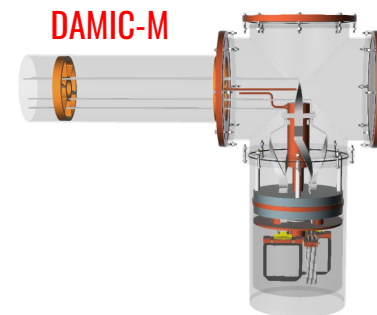
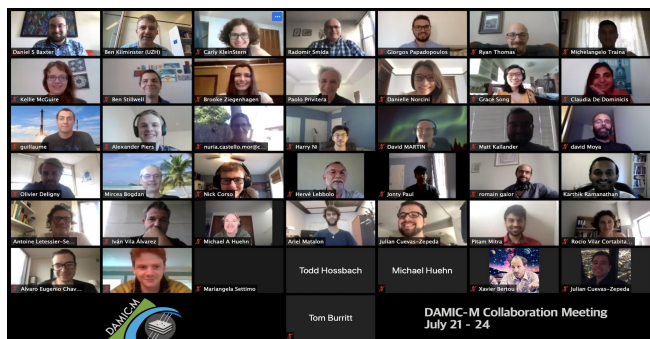
Performance of the LBC at LSM

Good stability over time



Outlook

- DAMIC-M is using novel skipper CCDs to push energy threshold limits and explore light dark matter regime
- Experiment is in the development phase towards building a kg-scale CCD array housed within an extremely low background environment at LSM
- Demonstrated the performance of skipper CCDs, measuring low-energy Compton scatters (submitted to PRD)
- Prototype detector at LSM is running and first physics results expected soon



DAMIC-M Collaboration



Thank you for your attention!