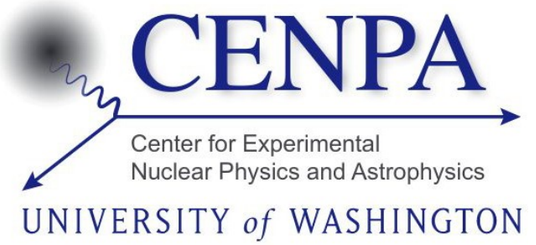
Status of the DAMIC-M dark matter experiment

Kellie J. McGuire
for the DAMIC-M collaboration
University of Washington
14 April 2023



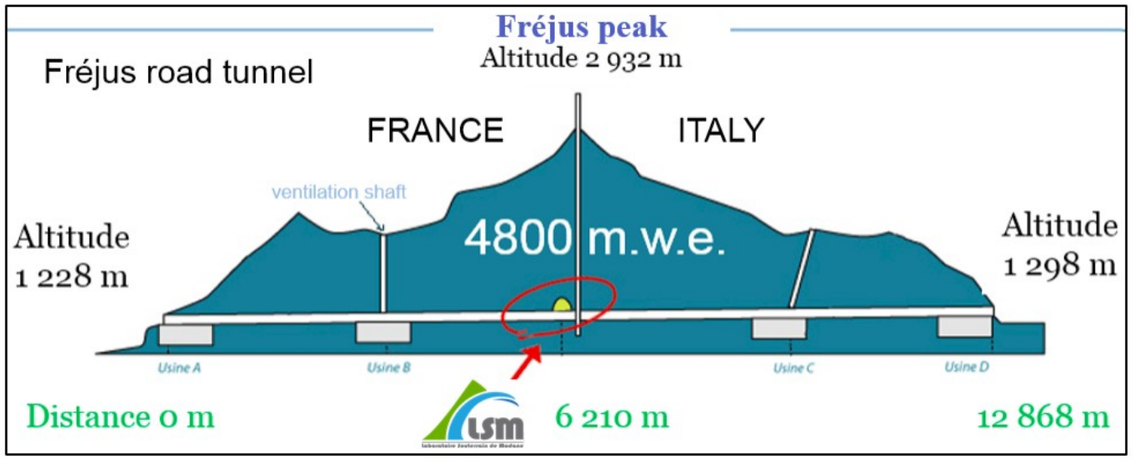
DArk Matter In CCDs at Modane

DAMIC-M: A kg-scale detector using silicon charge-coupled devices (CCDs) to search for light (sub-GeV) dark matter:

- sub-electron resolution
- 2-3 e^- energy threshold
- dark current ~10^{-4} e^-/pixel/day
- background rate < 1 dru

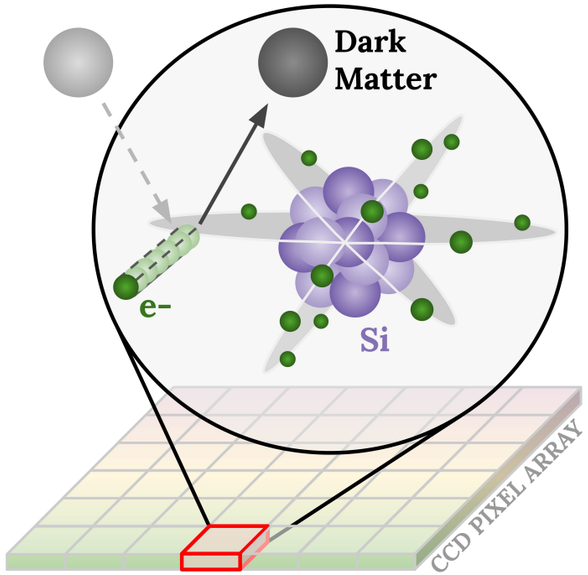
  (1 differential rate unit = 1 event/kg/keV/day)

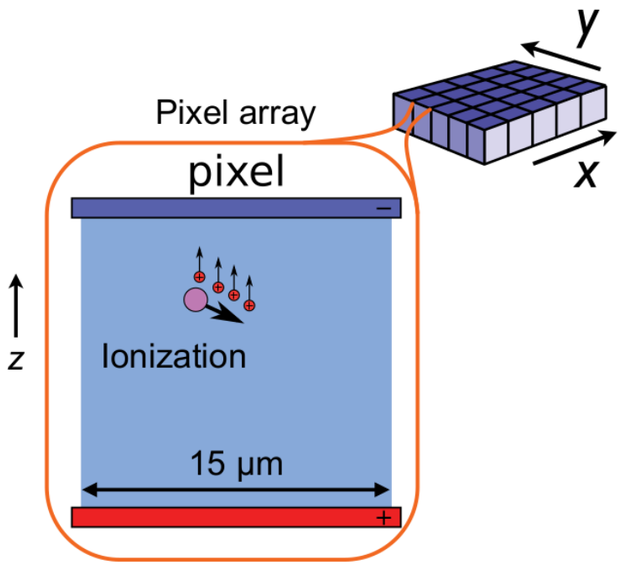
Located at the Laboratoire Souterrain de Modane (LSM) 1,700 meters below the Fréjus peak in Modane, France.



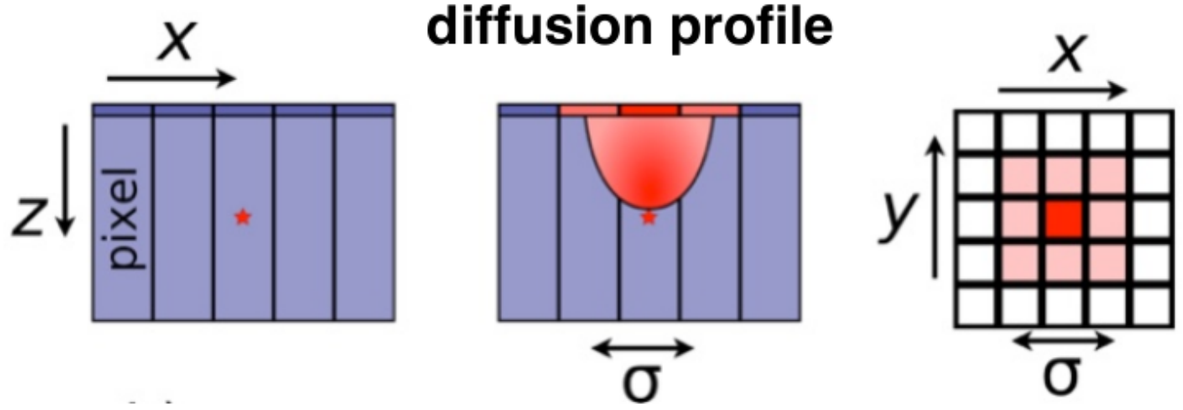
<u>Commissioning and data acquisition to begin in 2024.</u>

CCDs as dark matter detectors

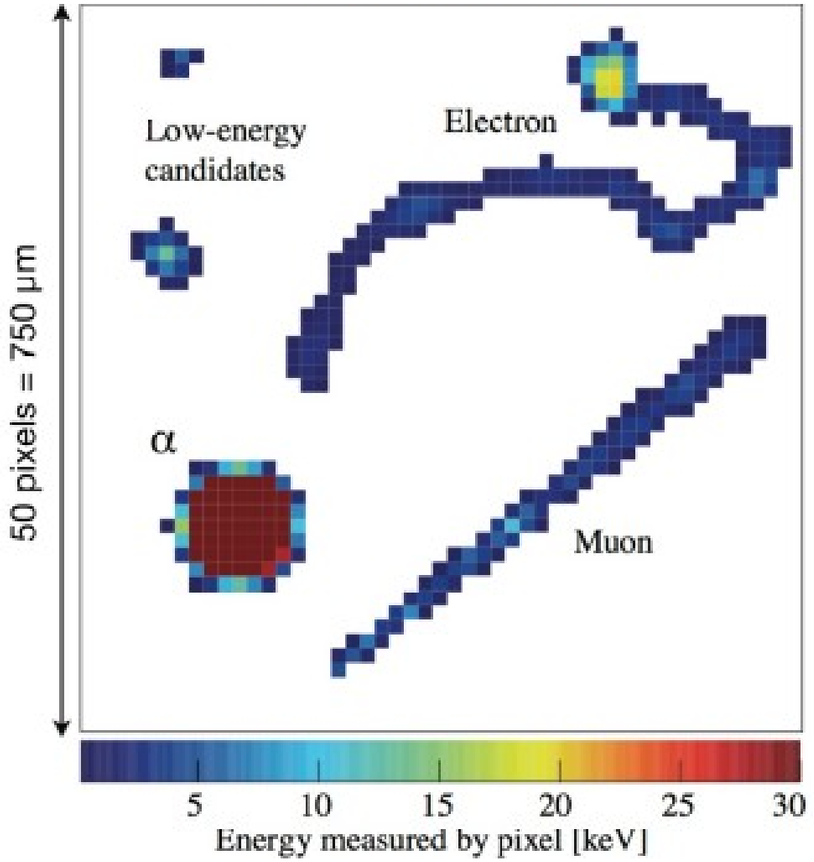




- DM particle scatters off Si nucleus or valence electron, creating ionization
- one e-h pair produced per 3.77eV (avg) deposited
- bias voltage drifts charge to readout plane
- lateral diffusion of charge proportional to drift time (3D spatial resolution)
- pixelation allows for particle identification via cluster shape
- backgrounds rejection via spatially and temporally correlated decay products



CCDs as dark matter detectors



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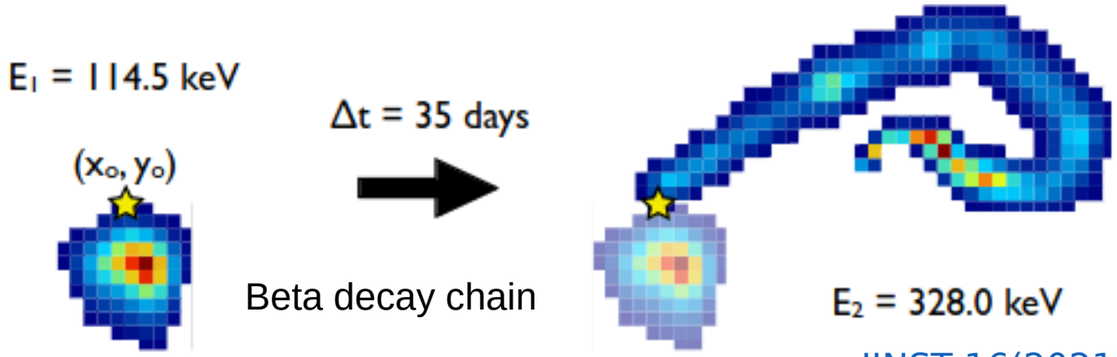
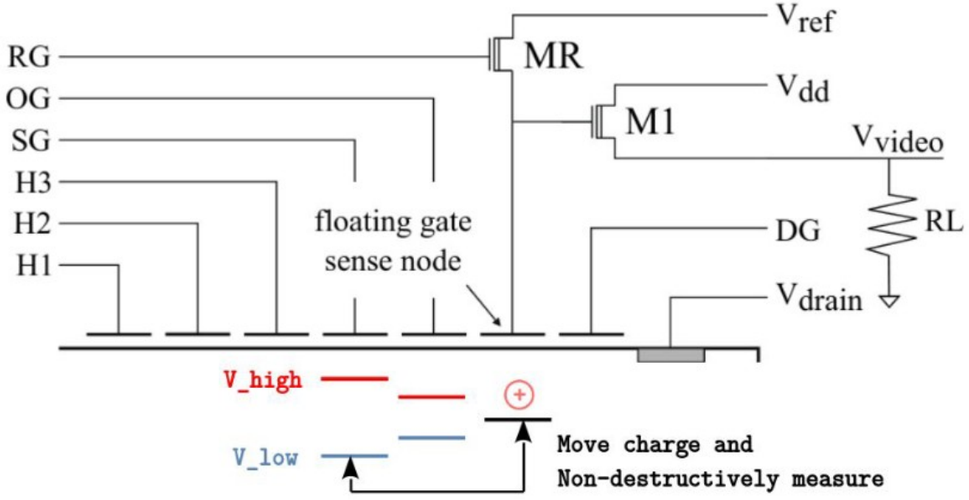


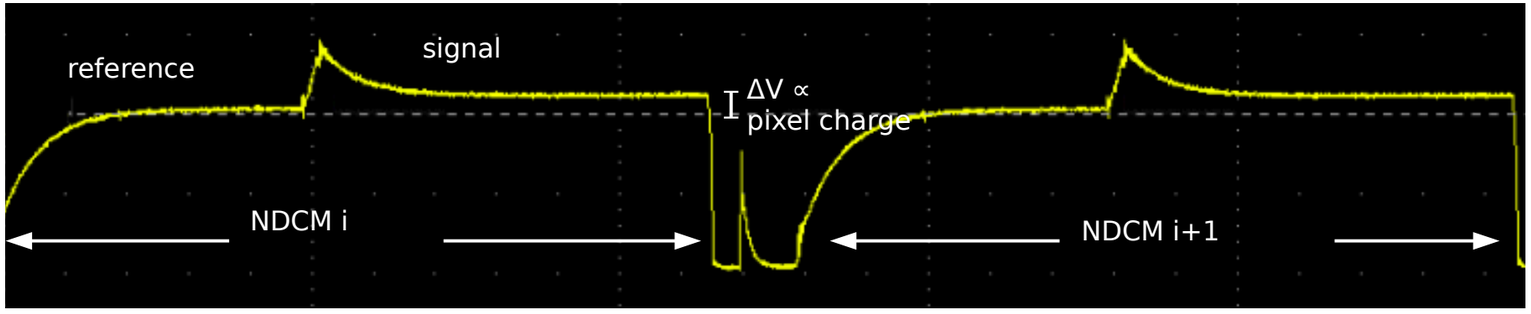
JINST 16(2021)P06019

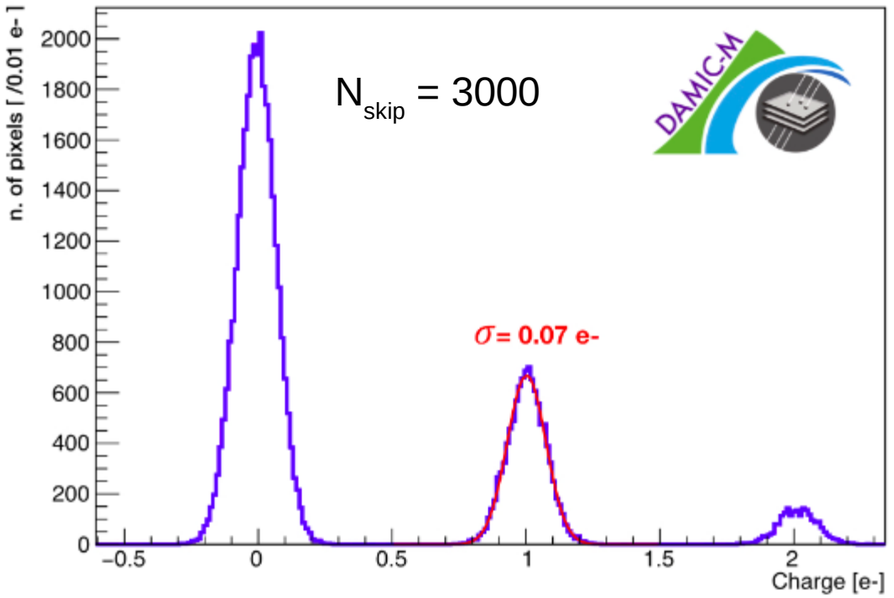
Skipper CCDs for sub-electron noise

- DAMIC-M CCDs equipped with floating gate “skipper” readout stage
- Floating gate allows for repeat non-destructive pixel charge measurements (NDCMs)
- Measure each pixel N_{skip} times for 1/sqrt(N_{skip}) noise suppression
- Achieve sub-electron resolution after a few hundred N_{skip}



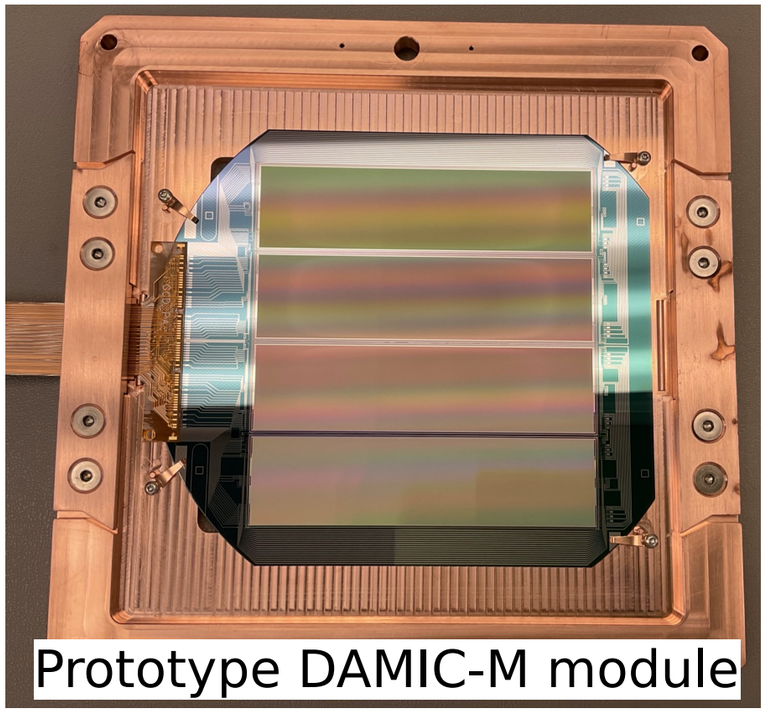
Correlated double sampling (CDS)



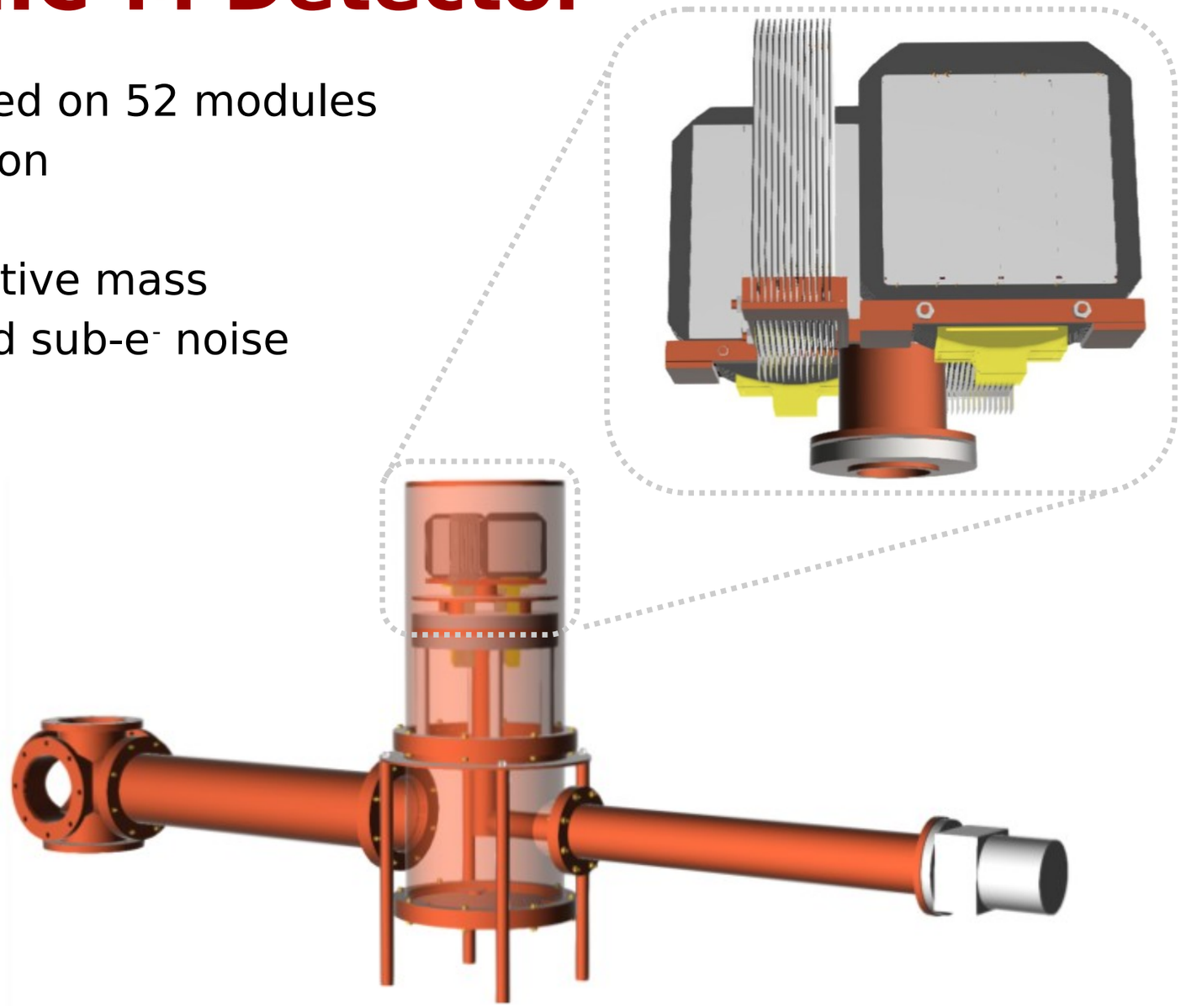


The DAMIC-M Detector

- 208 9-Mpixel (6k x 1.5k) CCDs packaged on 52 modules
- high-resistivity (>10kΩcm) n-type silicon
- pixel size: 15 x 15 x 675 um^3
- each CCD 3.5 grams --> 700 grams active mass
- custom electronics for fast readout and sub-e^- noise



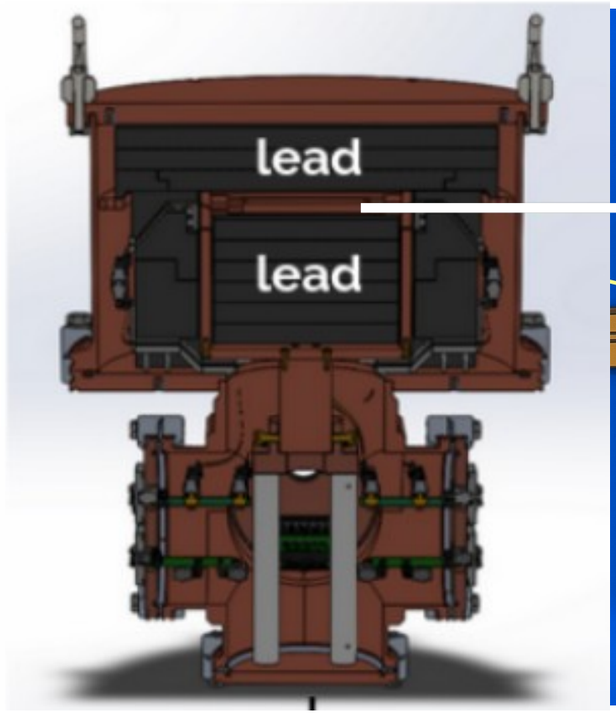
Prototype DAMIC-M module

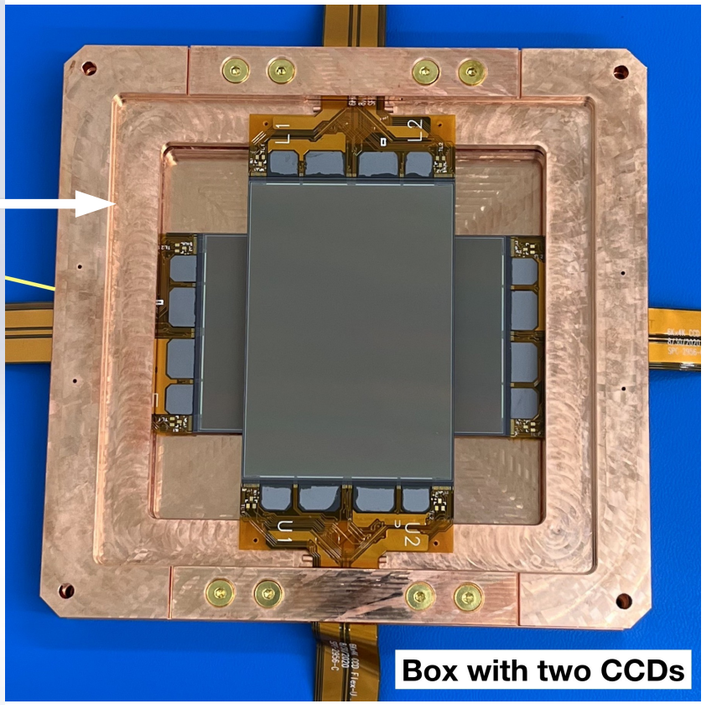


Low-Background Chamber

LBC objectives

- Demonstrate skipper CCD performance
- Characterize backgrounds and inform mitigation strategies
- Provide test bench for dark current studies and reduction stategies
- Determine sensitivity to light dark matter





Prototype performance

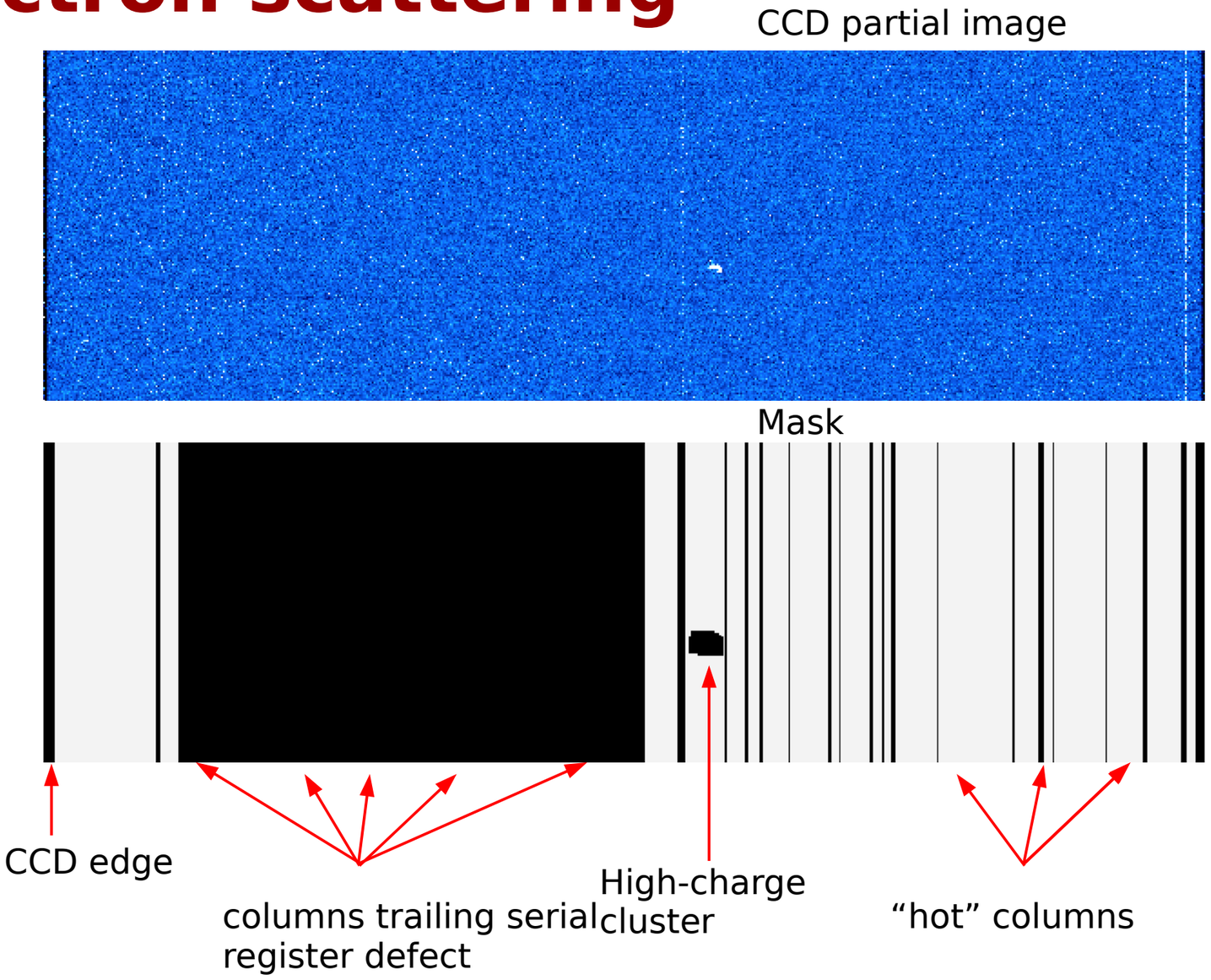
- ~10 dru background rate
- Dark current ~4.5 x 10^{-3} e^-/pixel/day (~20e^-/mm^2/day)
- 0.2 e^- noise at N_{skip} = 650
  (using commercial readout electronics)

Sensitive to unexplored DM-e^- scattering parameter space...

LBC DM-electron scattering

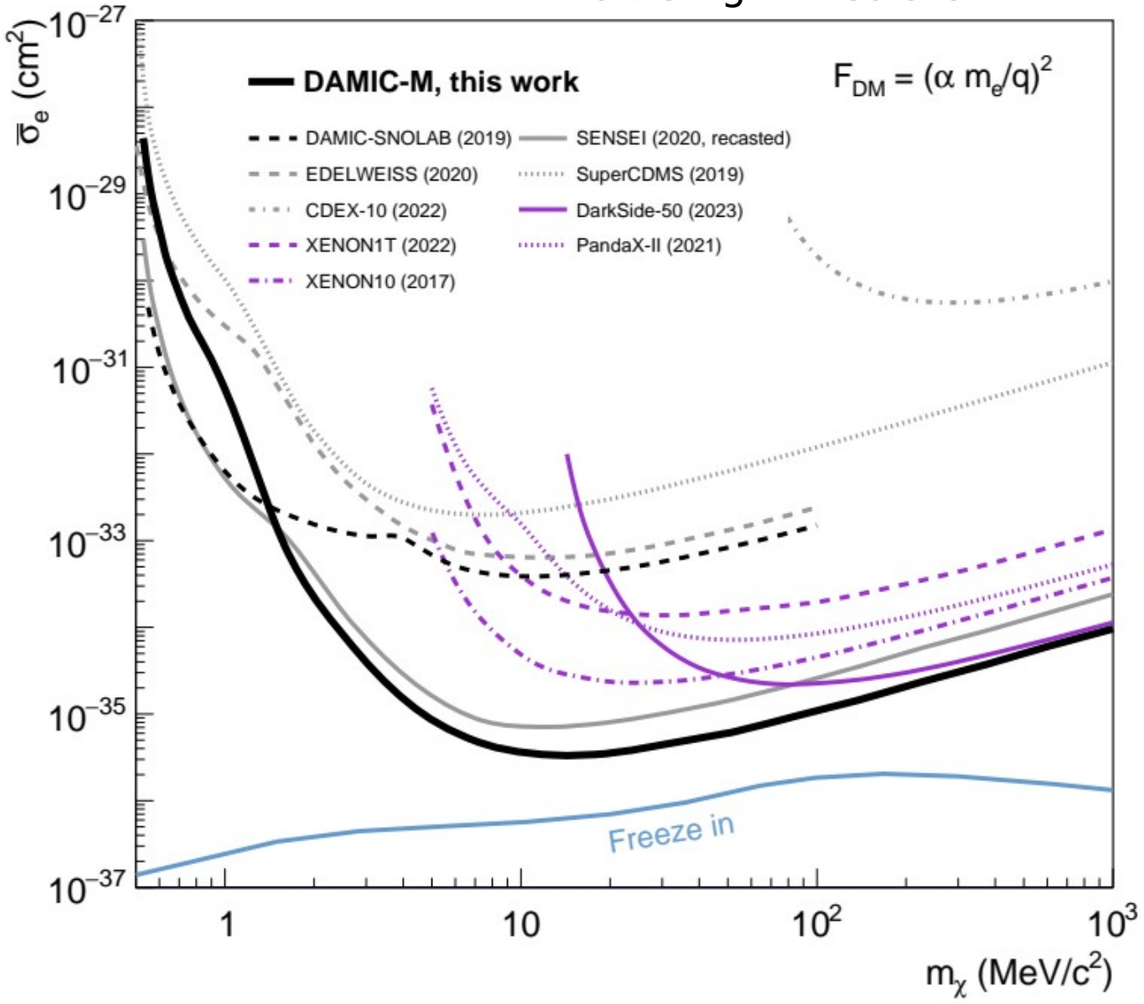
Mask

- All pixel clusters ≥ 7 e^-, plus 10 trailing horizontal and vertical pixels (charge-transfer inefficiencies)
- Columns containing defects, indentified by:
  - Excess of 1e^- pixels (1e^- rate a function of column number)
  - High-charge pixels appearing in multiple 3-hour exposures
  - Deficit of 1e^- pixels (indication of serial register defect); mask all trailing columns
- Five-pixel window surrounding image

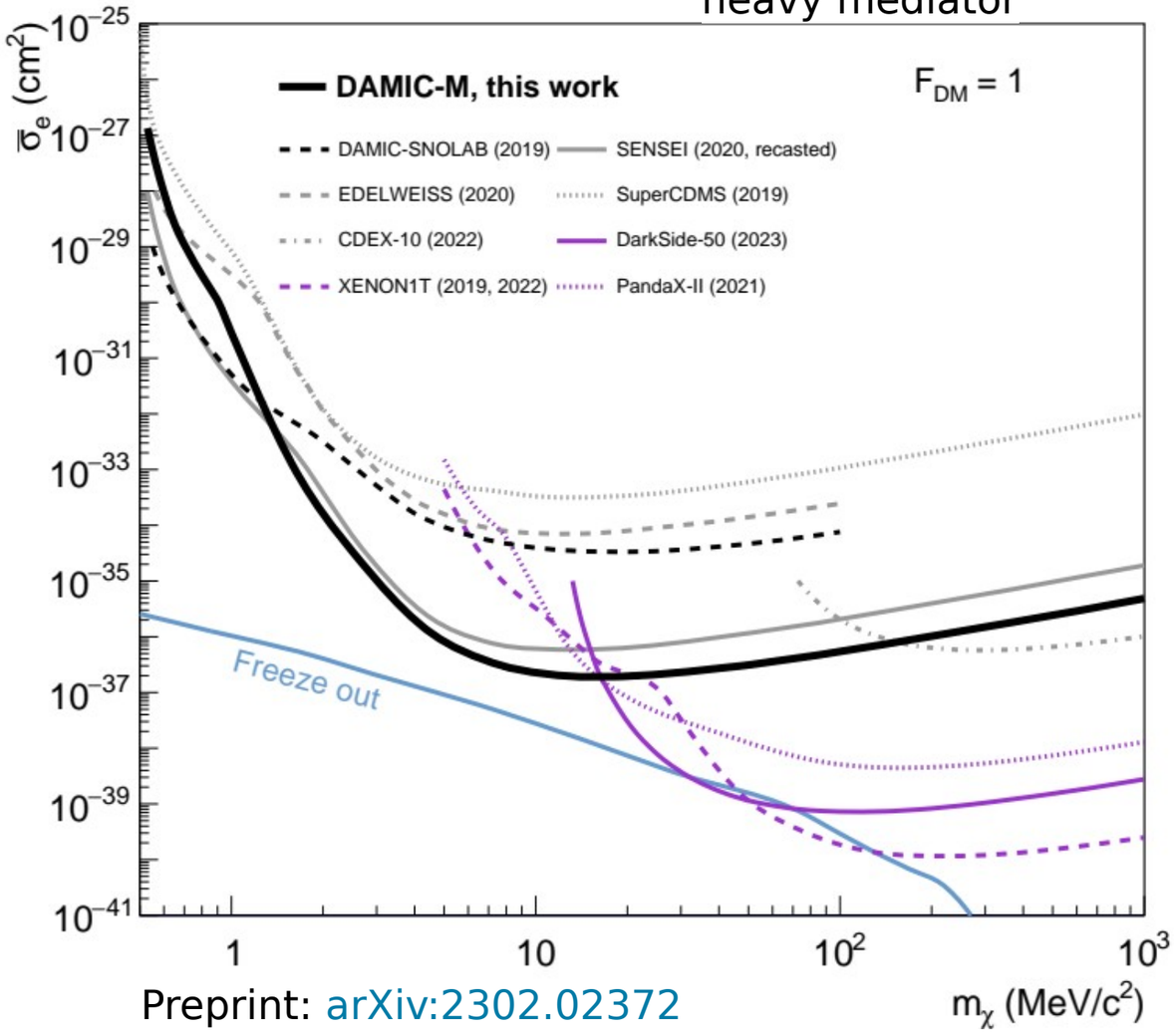


LBC 90% CL upper limits

ultra-light mediator



heavy mediator



Preprint: arXiv:2302.02372
accepted for publication in PRL

Toward DAMIC-M's sensitivity goals...

Improve sub-electron resolution

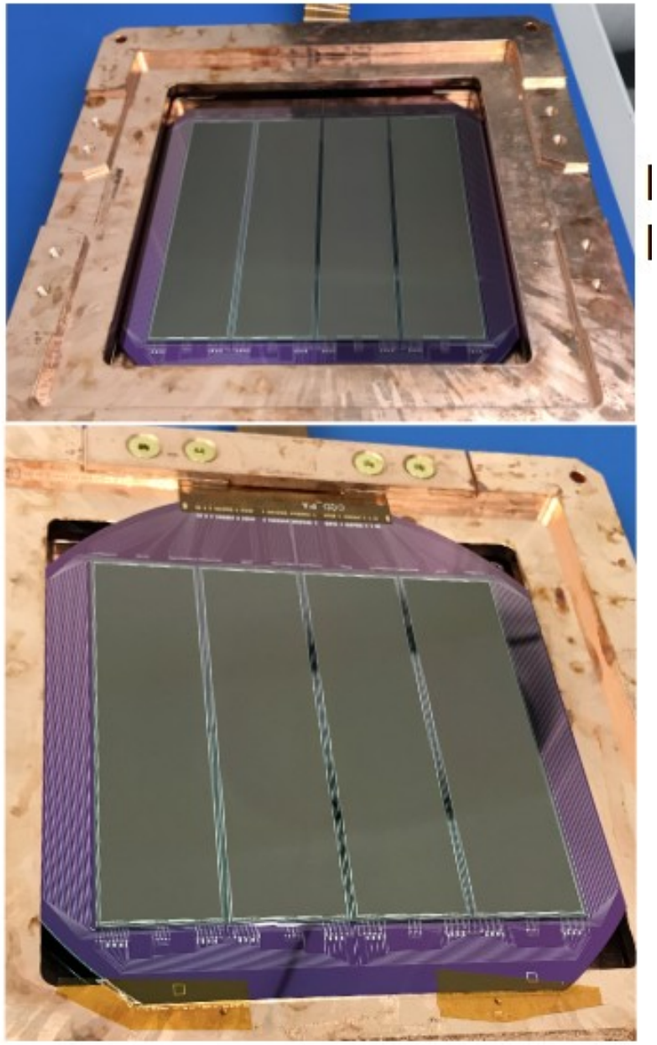
- Custom readout electronics for lower noise with fewer N_{skips}

Lower dark current levels

- Smaller-format CCDs (two DAMIC-M CCD modules with 8 6k x 1.5k CCDs are installed and operating at LSM; immediate 3x improvement in DC)
- Improved cooling
- Studies into sources of few-electron events (e.g., charge traps, transition radiation, radiative recombination, persistent images)
- Optimization of operating parameters

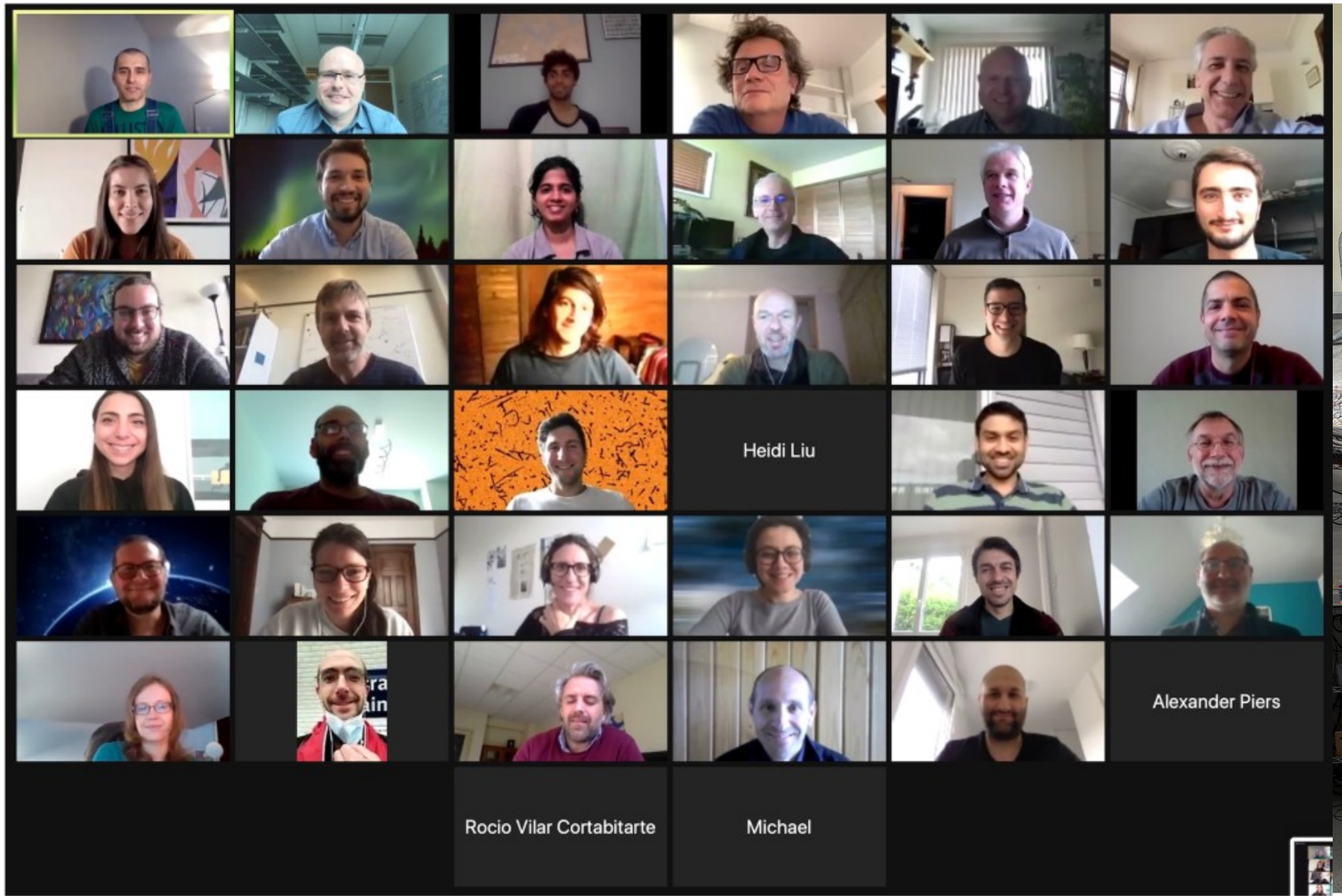
Lower backgrounds

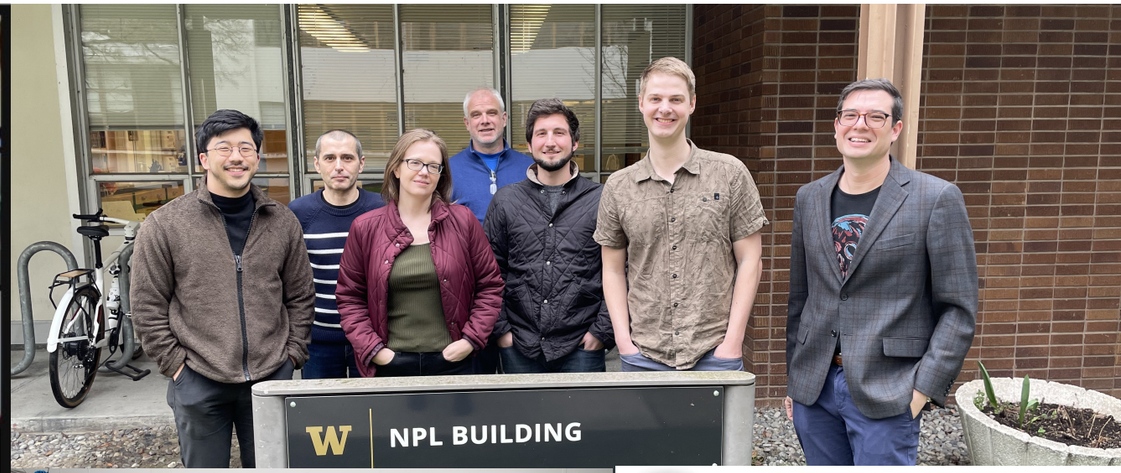
- Cleaner CCDs (shorter surface exposure)
- More electroformed copper parts
- Low-activity cables



DAMIC-M modules installed at LSM

Thank you!





CENPA
Center for Experimental
Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

The DAMIC-M Collaboration

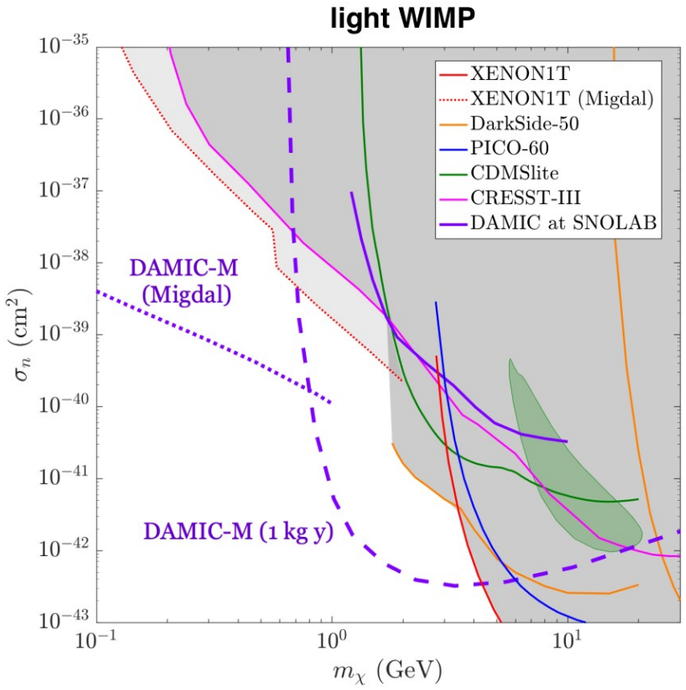
Additional slides...

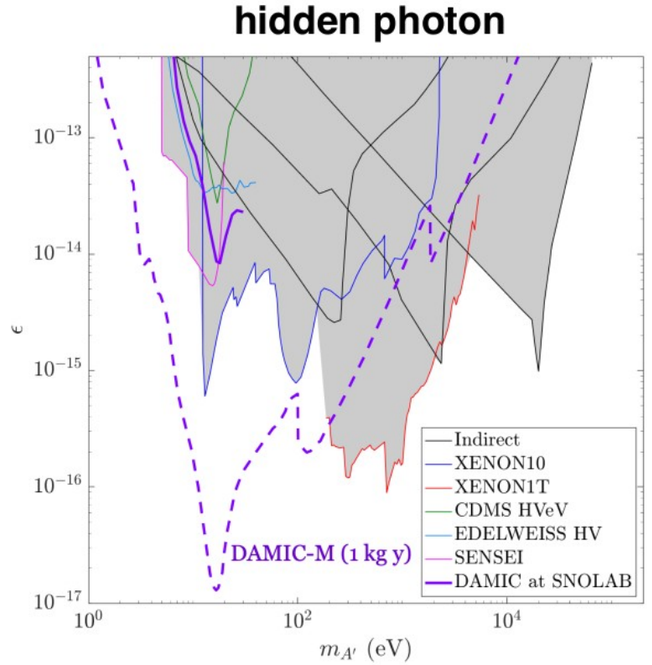
Science reach

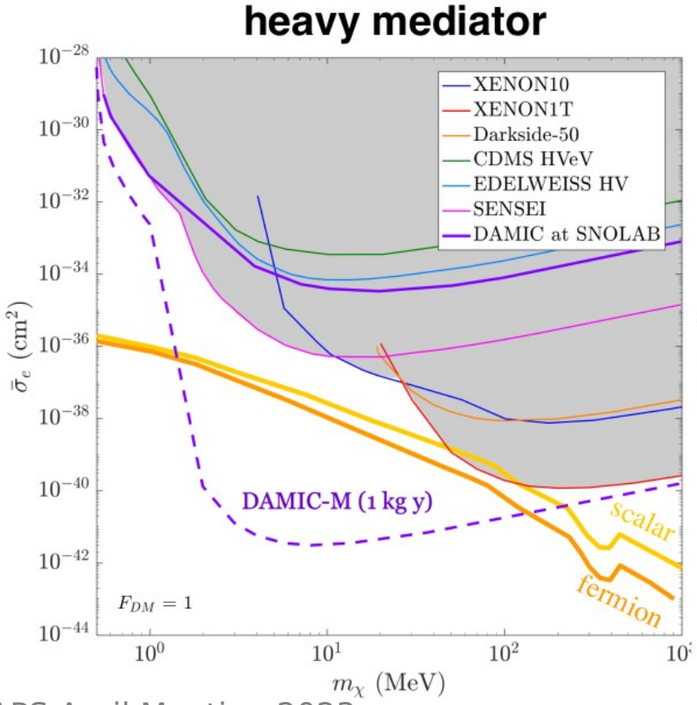
DAMIC-M will be sensitive to...

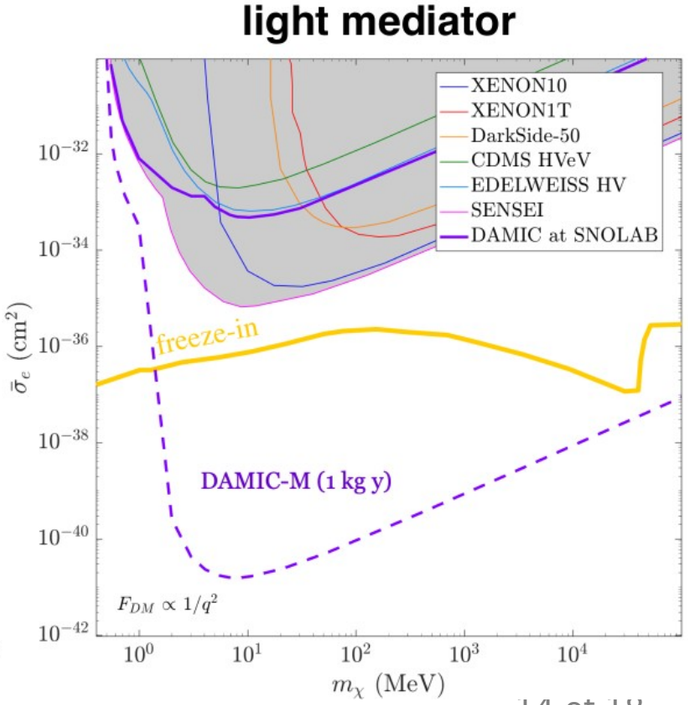
light WIMPs via DM-nucleus elastic scattering and inelastic scattering (Migdal effect)
PRL 127, 081805 (2021)

hidden-sector candidates via DM-electron scattering and DM absorption
arXiv:1707.04591v1







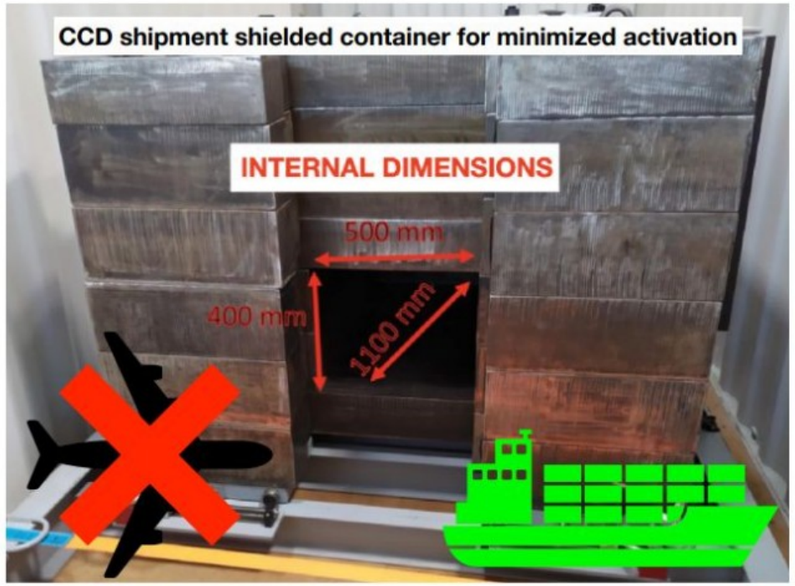


Background reduction

DAMIC-M backgrounds target < 1 dru

Mitigation

- Silicon wafers stored underground
- Minimal total surface exposure
- CCDs to be packaged and tested underground onsite
- Nitrogen storage to minimize radon deposition



Shielding

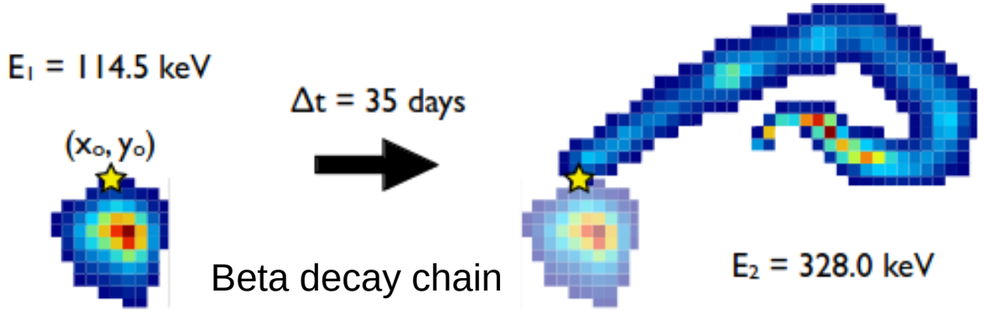
- External shield: polyethylene + low-background lead
- Internal shield: ancient lead

Materials Selection

- Electroformed copper: vacuum chamber, IR shield
- High-purity OFHC copper: parts outside IR shield
- Low-background flex cables arXiv:2303.10862

Rejection

- Topology cut: a DM interaction would be pointlike
- Identify surface events from diffusion
- Spatially correlated decay products



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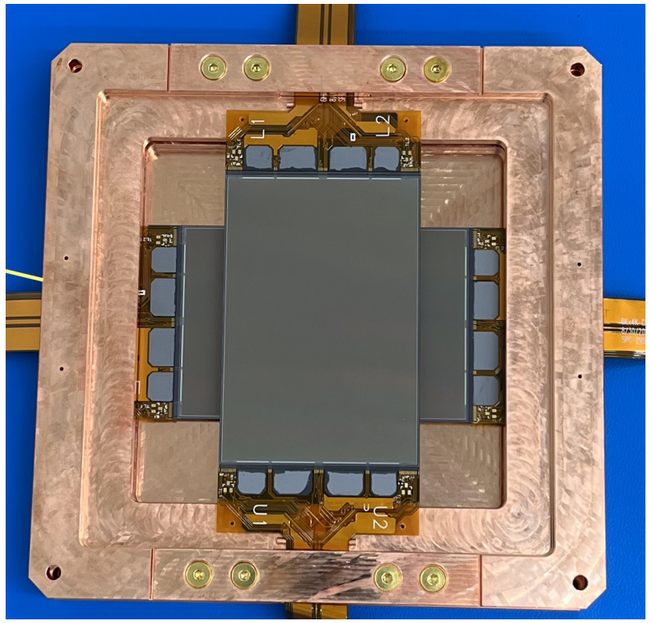
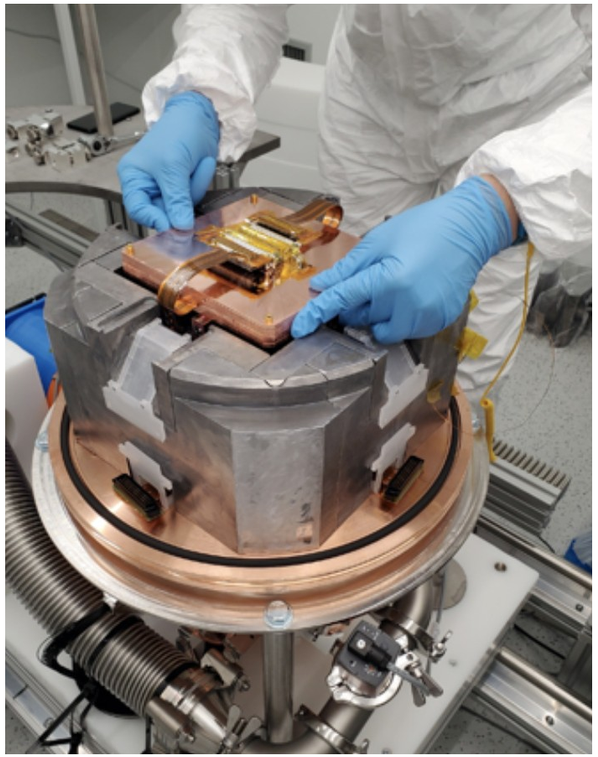
Low-Background Chamber

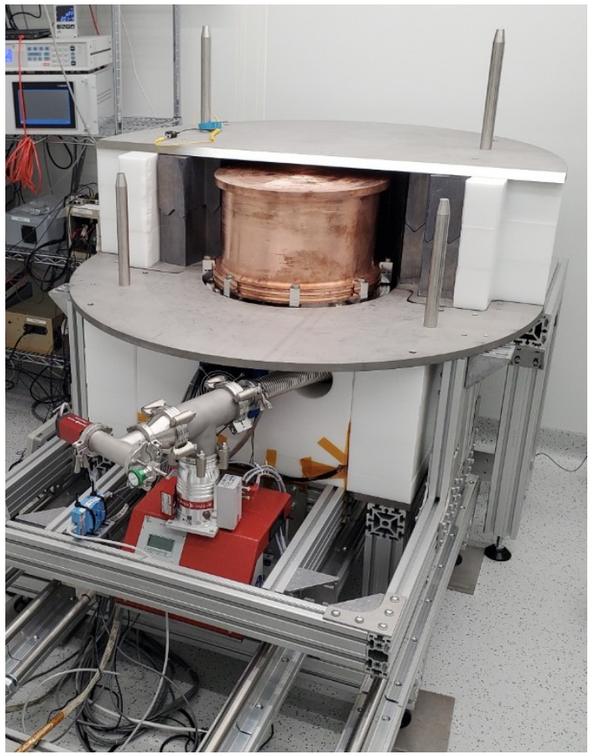
Prototype detector located underground at LSM in operation since early '22



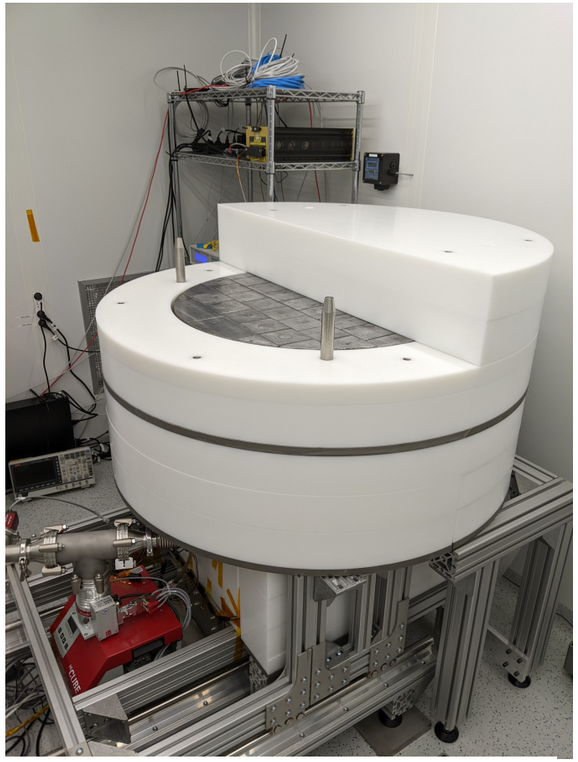
Two 6kx4k skipper CCDs (18 grams active mass) installed in high-purity, oxygen-free copper box



Copper box surrounded by 7.5+ cm low-background lead, innermost ancient



Detector enclosed in copper cryostat, external shield open

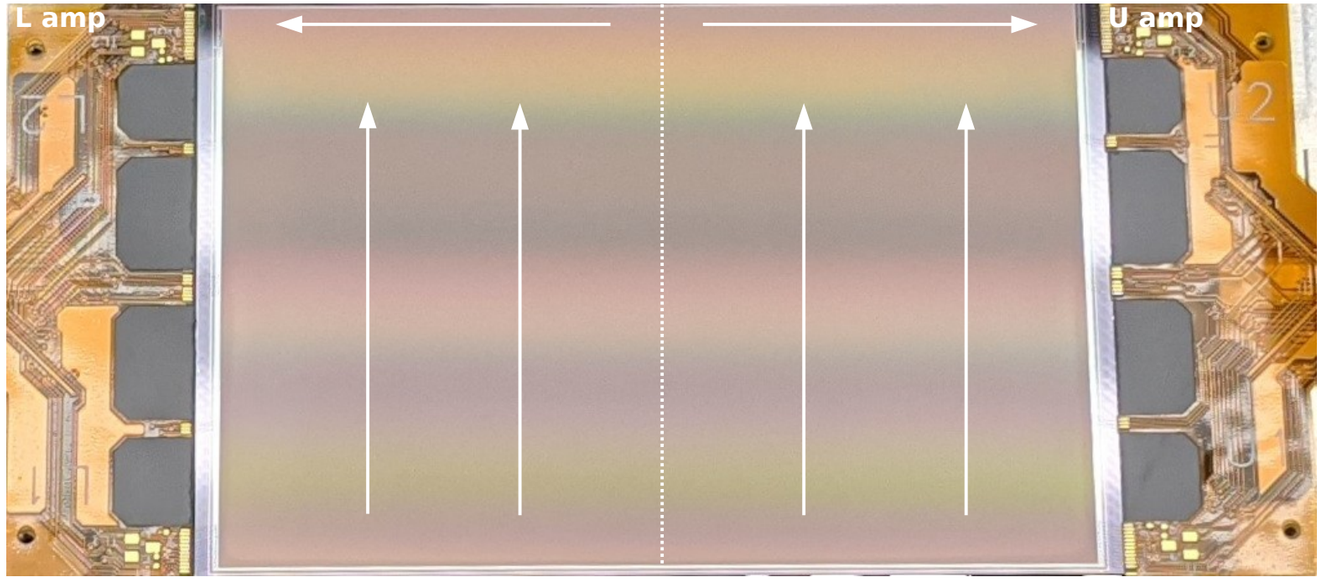


Low-background lead and polyethylene external shield in place

LBC DM-electron scattering

Operation

- Substrate voltage: 70V
- CCD temperature: 130K
- Vacuum pressure: 5 x 10^{-6} mbar
- Each CCD half read through a separate skipper amplifier



Data sets

- Two science runs, both using 10x10 hardware binning (pixels summed before readout)
- SR1: continuous readout
- SR2: read first 110 (binned) rows; CCD cleared of charge before readout
- Total SR1 + SR2 exposure: 85.23 g-days

LBC DM-electron model

Generate DM signal templates

- QEDark to get differential rate for DM-e^- interactions
- Halo parameters from Phystat-DM
- Detector response:
  - Readout noise -- different for each amplifier
  - Electron recoil ionization yield from PRD 102, 063026 (2020)
  - Diffusion model from PRD 94, 082006 (2016) using LBC parameters

Build pixel charge distribution

- DM signal component
- Poisson background (dark current estimated per pixel)
- Gaussian noise

Perform joint binned likelihood fit

- four separate pixel distributions (2 amplifiers + 2 data sets)

Fit to pixel charge distribution from one ampilifier from SR2 data set