Dark matter search results from DAMIC-M

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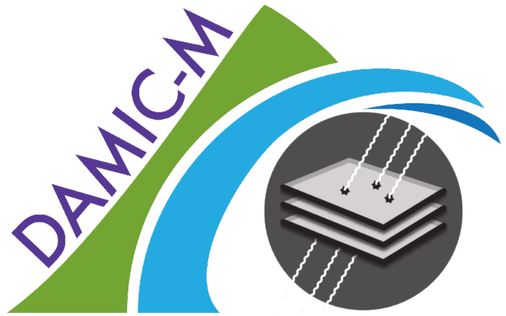
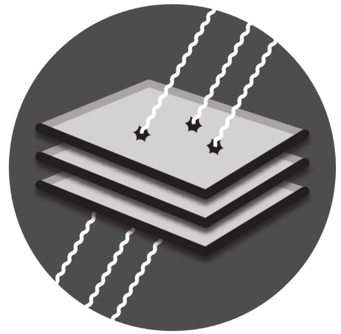


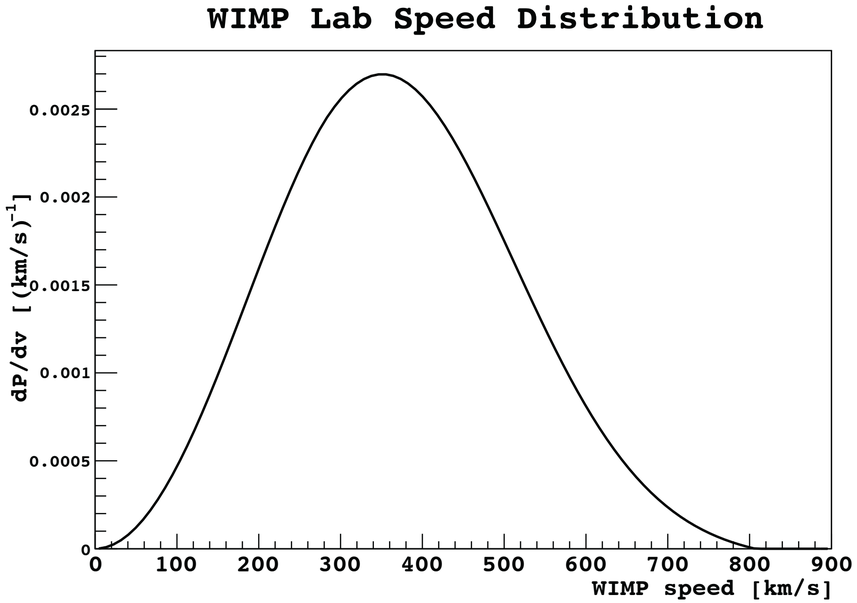


Outline

- Dark matter (DM) direct-detection signal.
- Electronic recoils to search for sub-GeV DM.
- Charge-coupled devices (CCDs) fundamentals and performance.
- DAMIC at SNOLAB and previous results.
- DAMIC-M and its Low Background Chamber.
- World-leading results in the search for sub-GeV DM!
- Conclusions and outlook.

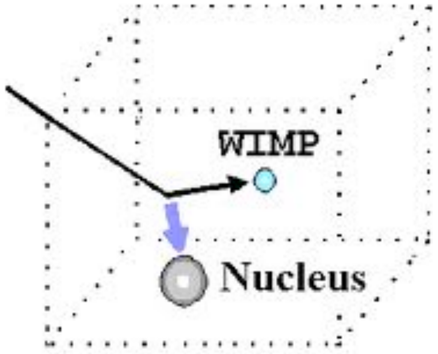
Dark matter signal

- Local density in ~0.3 GeV c^{-2} cm^{-3}.
- Interaction cross-section is small.
- Dark matter is cold, kinetic energy is ~10^{-6} Mc^2.
- Need detector with low energy threshold, largest possible exposure and correspondingly low backgrounds.



Traditional mechanism for WIMP searches:

Coherent enhancement: $\sigma_N \propto A^2$

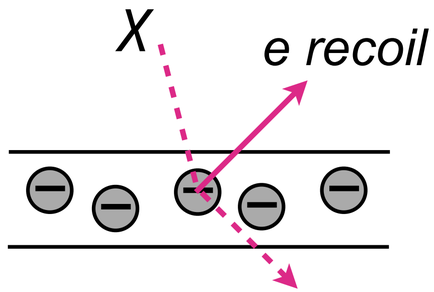


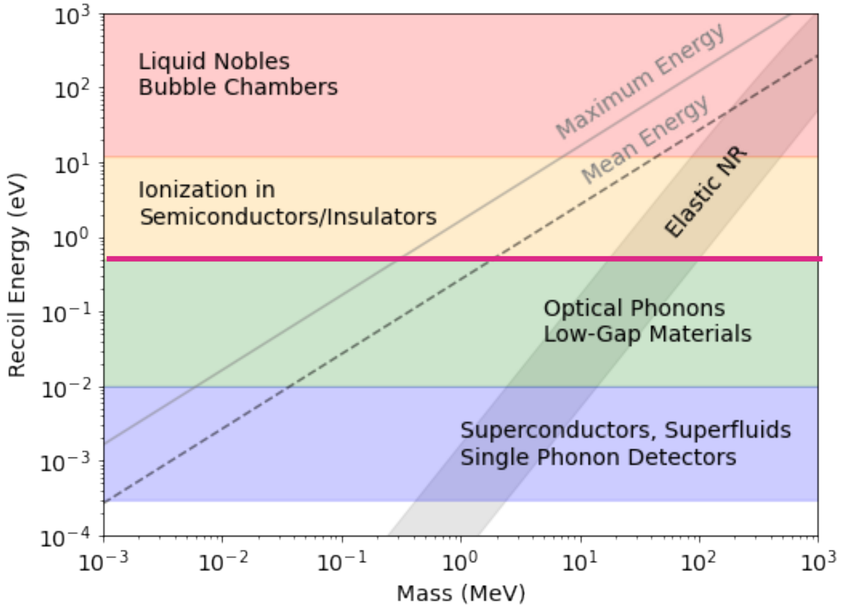
For low-mass WIMP: $M_T \gg M_\chi$

$$E_T < 4\frac{M_\chi}{M_T}E_\chi$$

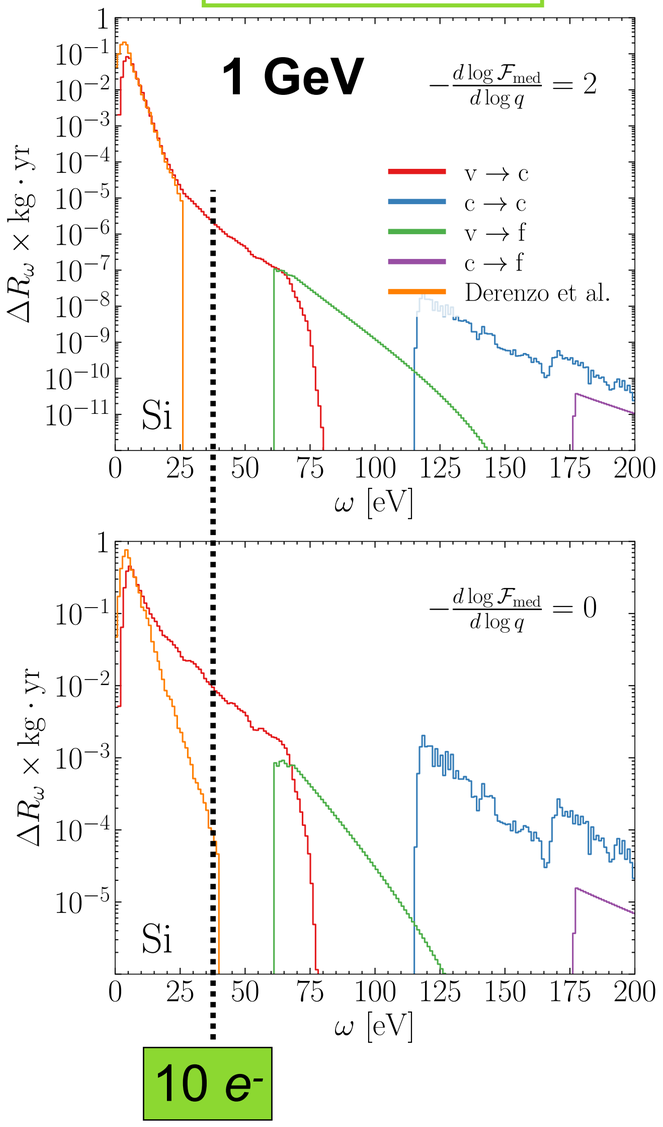
DM-e scattering

- Electrons are a lighter target and *ER visible as ionization*.
- Electrons bound with some momentum; there is a region of phase-space where the electron carries most of the WIMP kinetic energy.





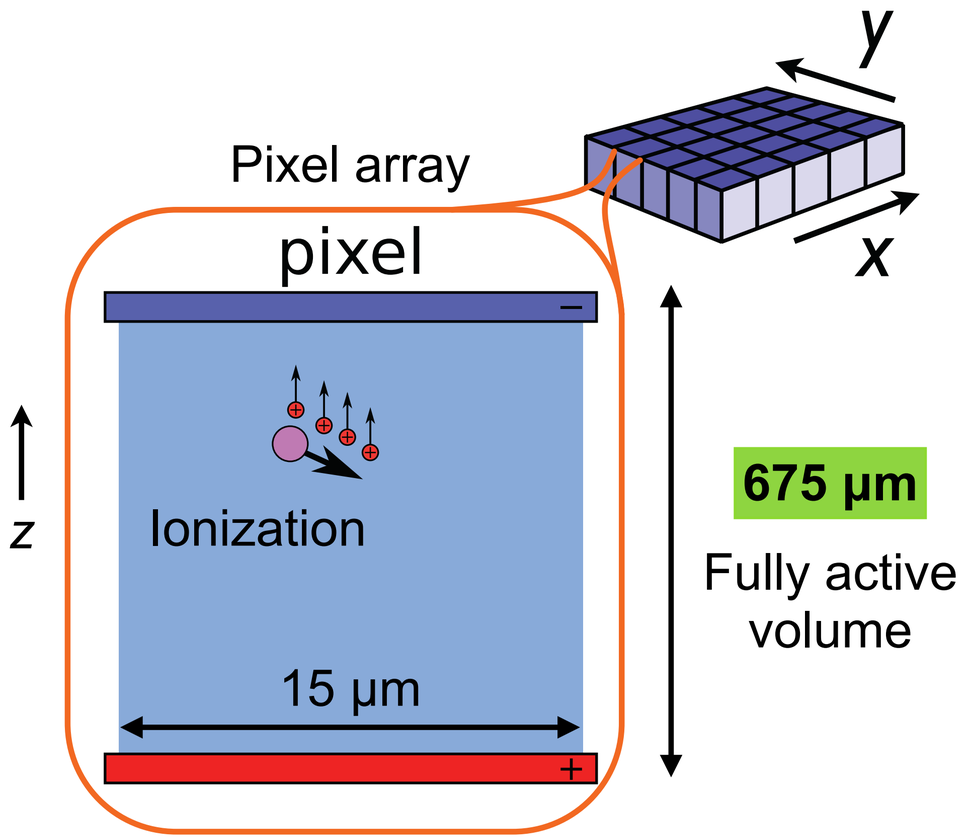
PRD104(2021)095015



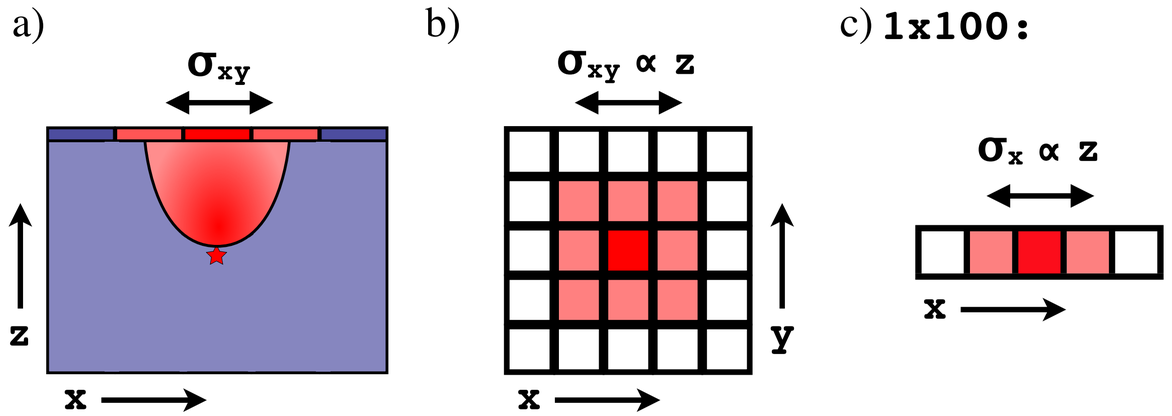
10 e^-

- Momentum distributions in some targets better “kinematically matched” to the DM than others.
- Phase-space ‘penalty,’ no coherent enhancement and probing DM-e interaction cross-section.

Charge-coupled devices



Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.



- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is “exposed,” collecting charge until user commands readout.
- Readout can be slow: **very low noise.**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).

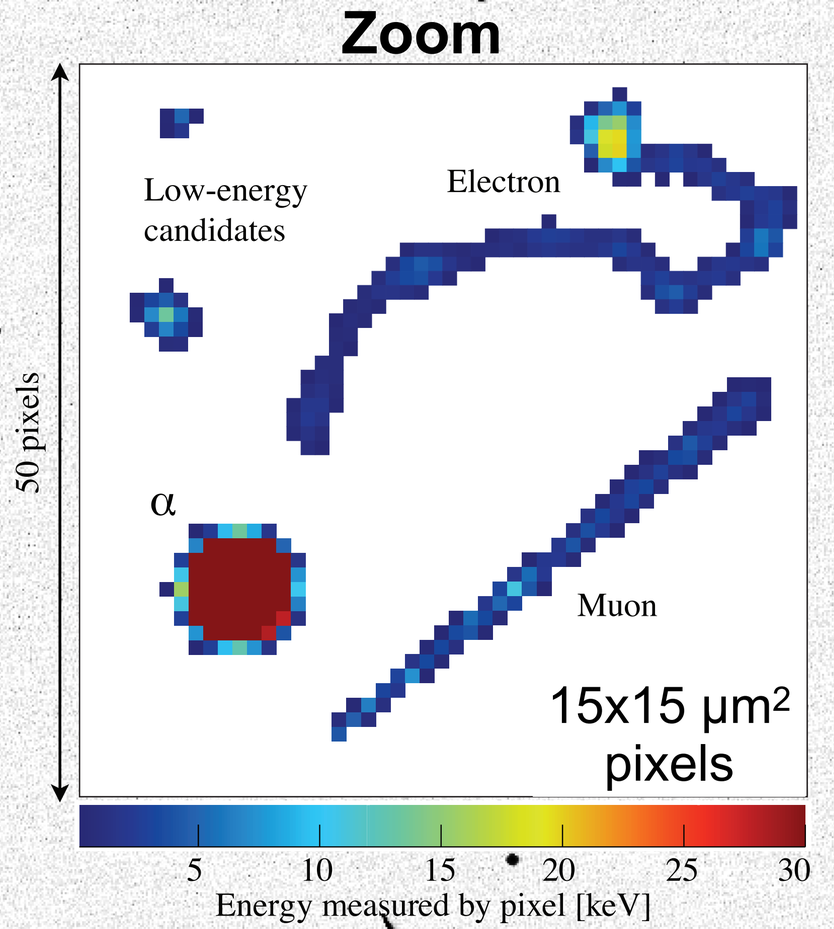
Sample CCD image (~15 min exposure) segment in the surface lab.

~1 cm

Cosmic muon

Point-like

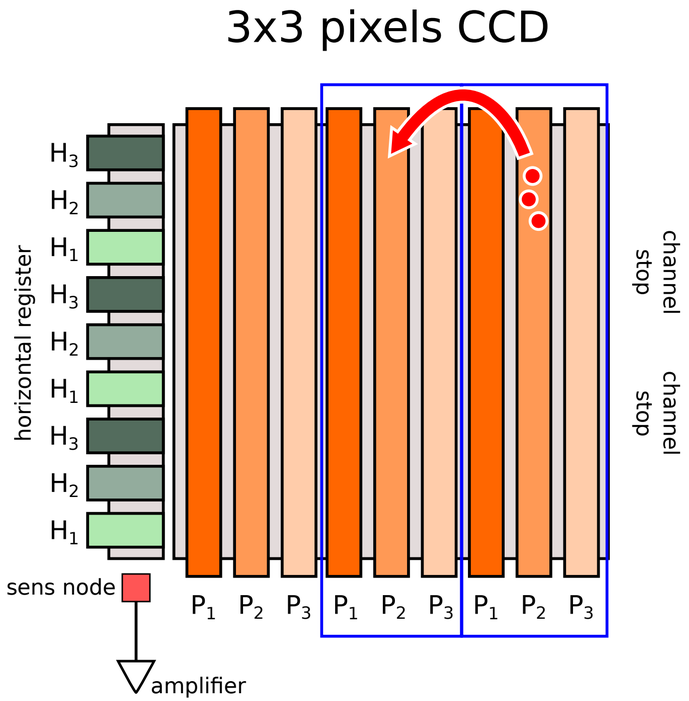
β particle

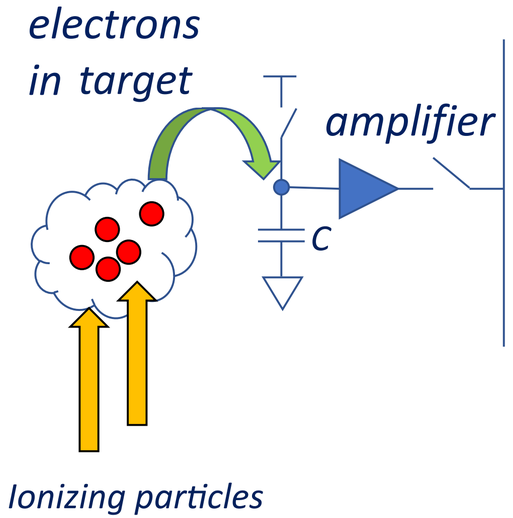


Spatial resolution for decay identification and mitigation of radioactive backgrounds

arXiv:2212.05012	JINST16(2021)P06019	JINST16(2021)P06019

Readout





$$\Delta V = \Delta Q / C$$

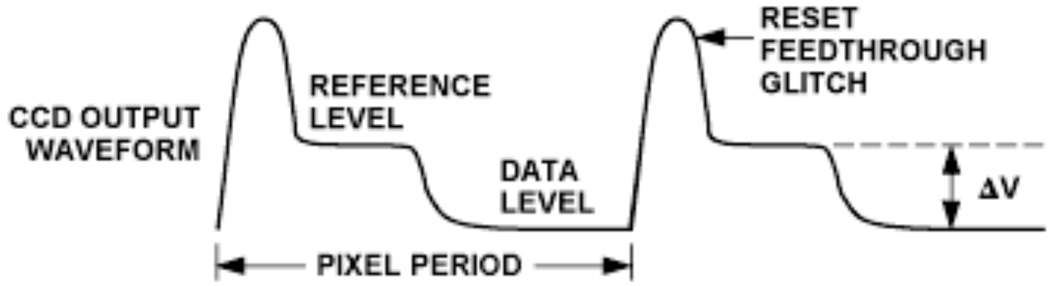
For ***C*** **~ 10 fF**: **ΔV/ΔQ ~ 16 μV/e⁻**

Signal that you can measure

Small capacitance with ***physically*** **small** components, e.g., $C \propto A/d$ ~ *linear scaling* for a parallel plate capacitor.

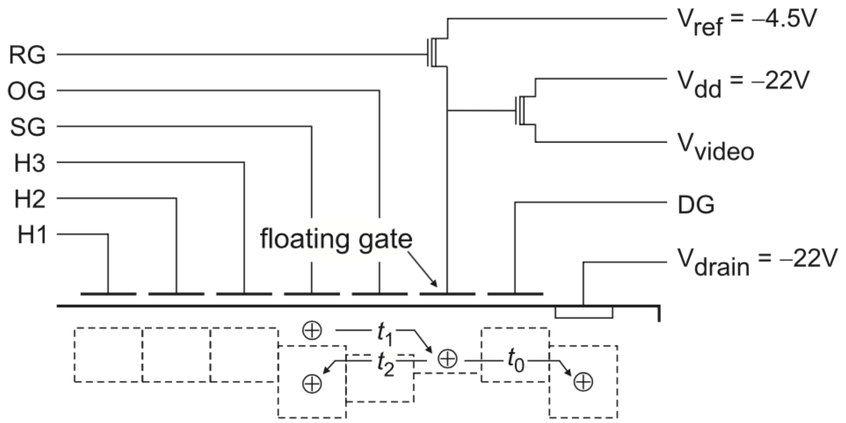
Correlated double sampling (CDS):

Readout strategy to efficiently filter "reset" and high frequency noise



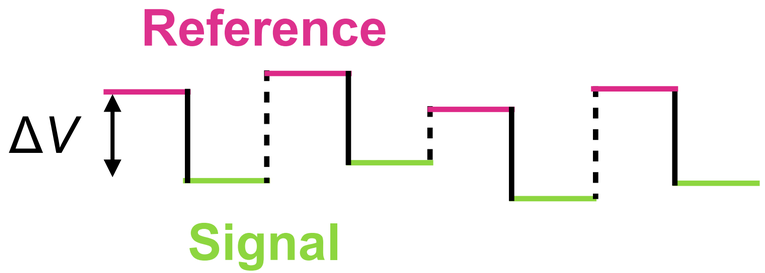
Skipper CCD

“Skipper” readout: Perform *N* uncorrelated measurements of the same pixel.

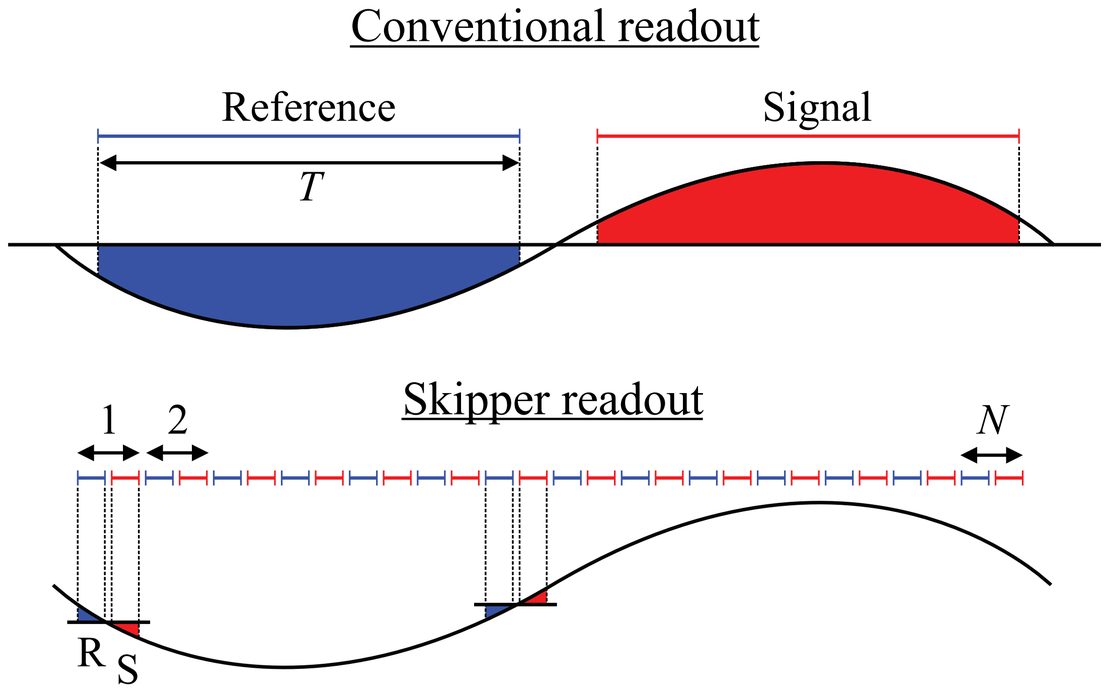


move charge back and forth

Measure Δ*V* *N* times:



Effect on low frequency noise:



Design by S. Holland at Berkeley Lab

Skipper CCD

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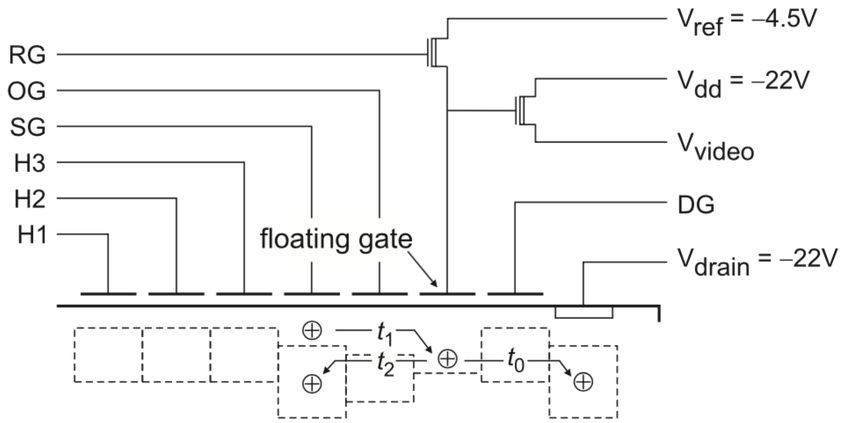

⟷ move charge back and forth

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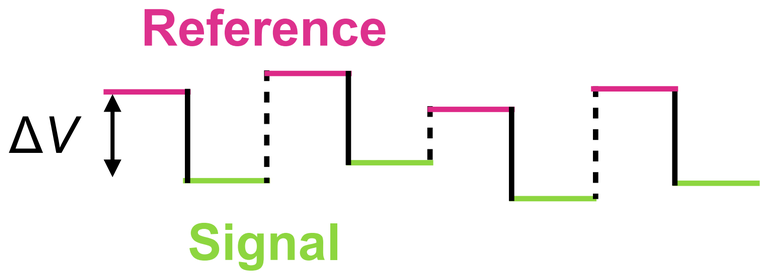
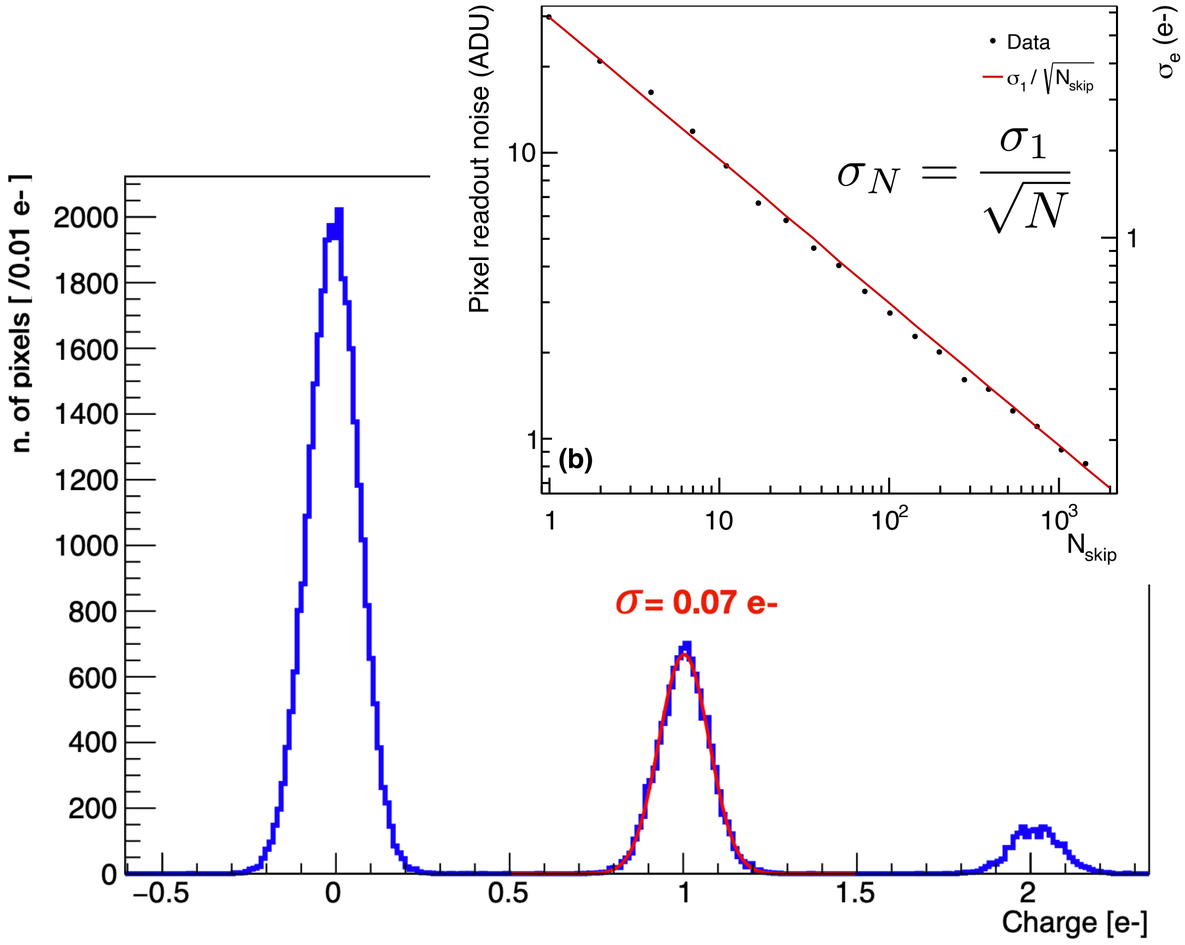
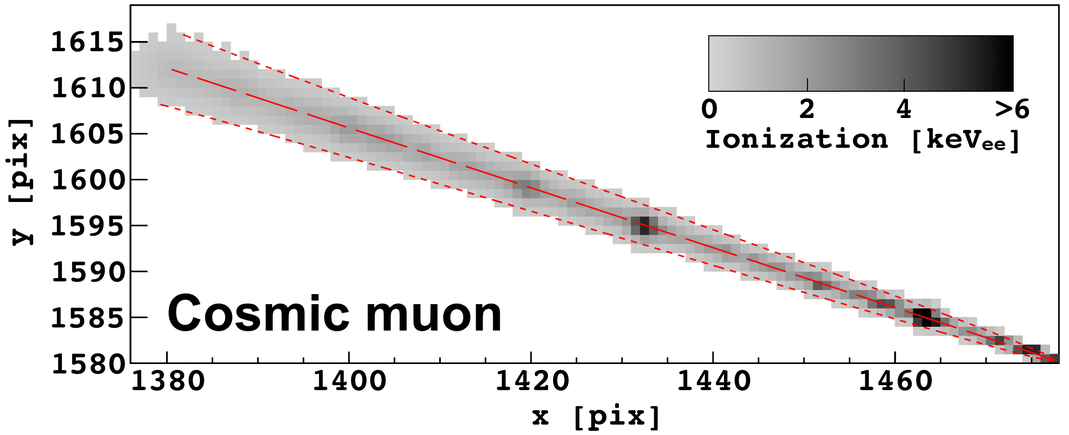
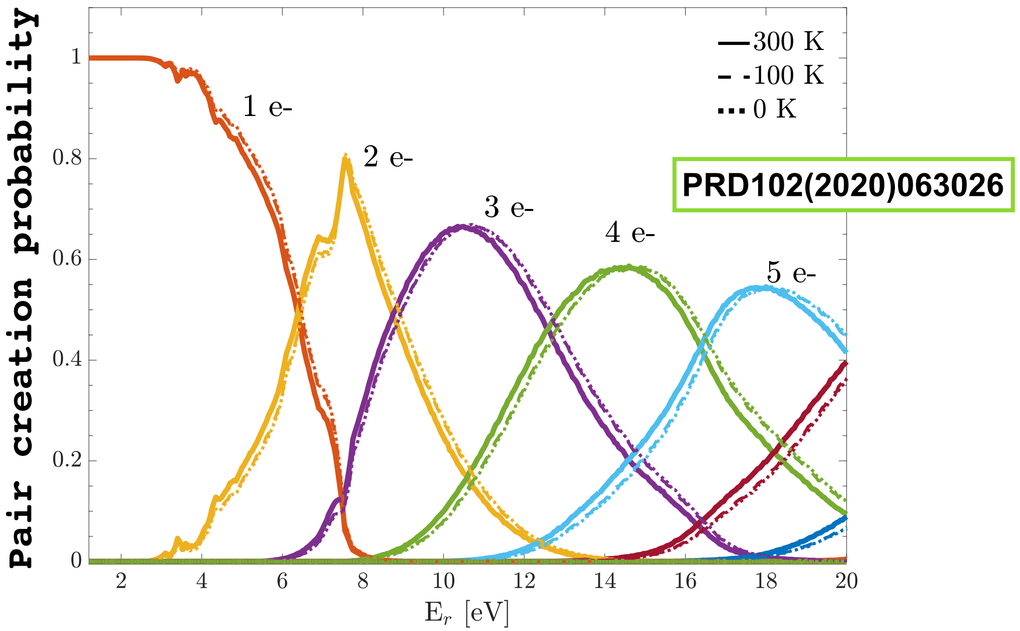




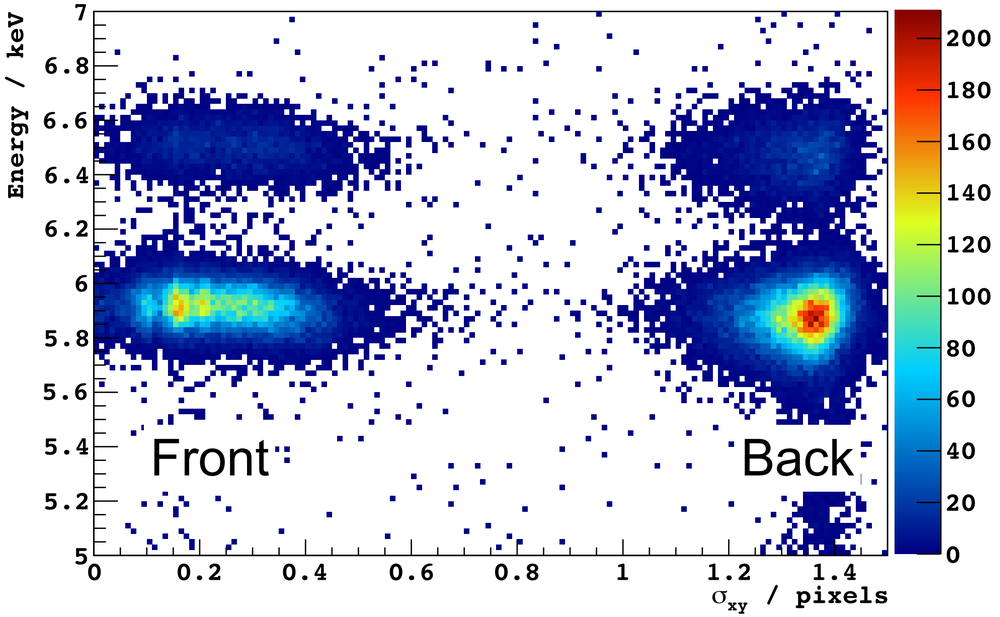
Characterization

- Extensive research program to characterize the response of CCDs: energy / *z* recon.
- Sources: optical photons, X rays, γ rays, neutron sources, etc. **PRD106(2022)092001**
- Detailed models, e.g., charge generation, diffusion and collection.





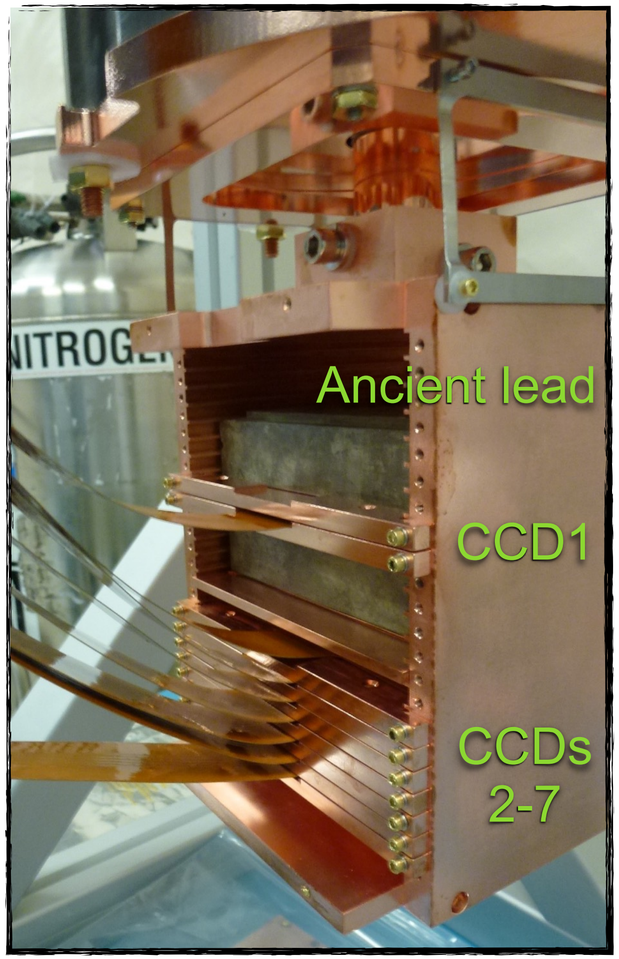
PRD102(2020)063026



DAMIC at SNOLAB

- First array of CCDs operated underground for a DM search. Several iterations from 2012 to 2019.
- 7 CCDs (6.0 g, 16 Mpix) cooled to 140 K.
- Total (bulk) background rate: ~10 (5) d.r.u.
- Low pixel noise 1.6 e^- with conventional readout.
- Extremely low leakage current: 2 x 10^{-22} A cm^{-2}.
- First DM search results from ~eV signals: PRL118(2017)141803
- DM-e^- scattering results: PRL123(2019)181802
- "WIMP search" with 11 kg-day exposure:

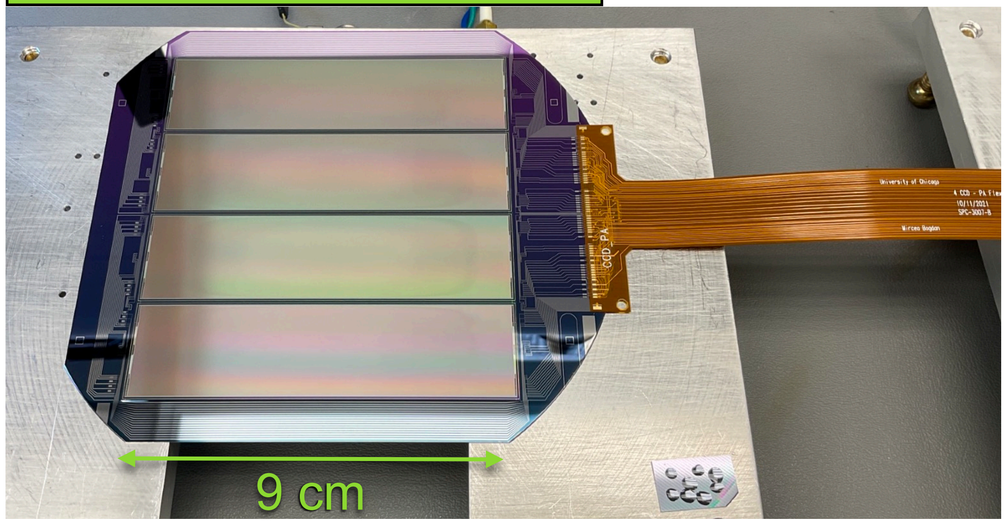
  Exclusion limit: PRL125(2020)241803 **Full details:** PRD105(2022)062003

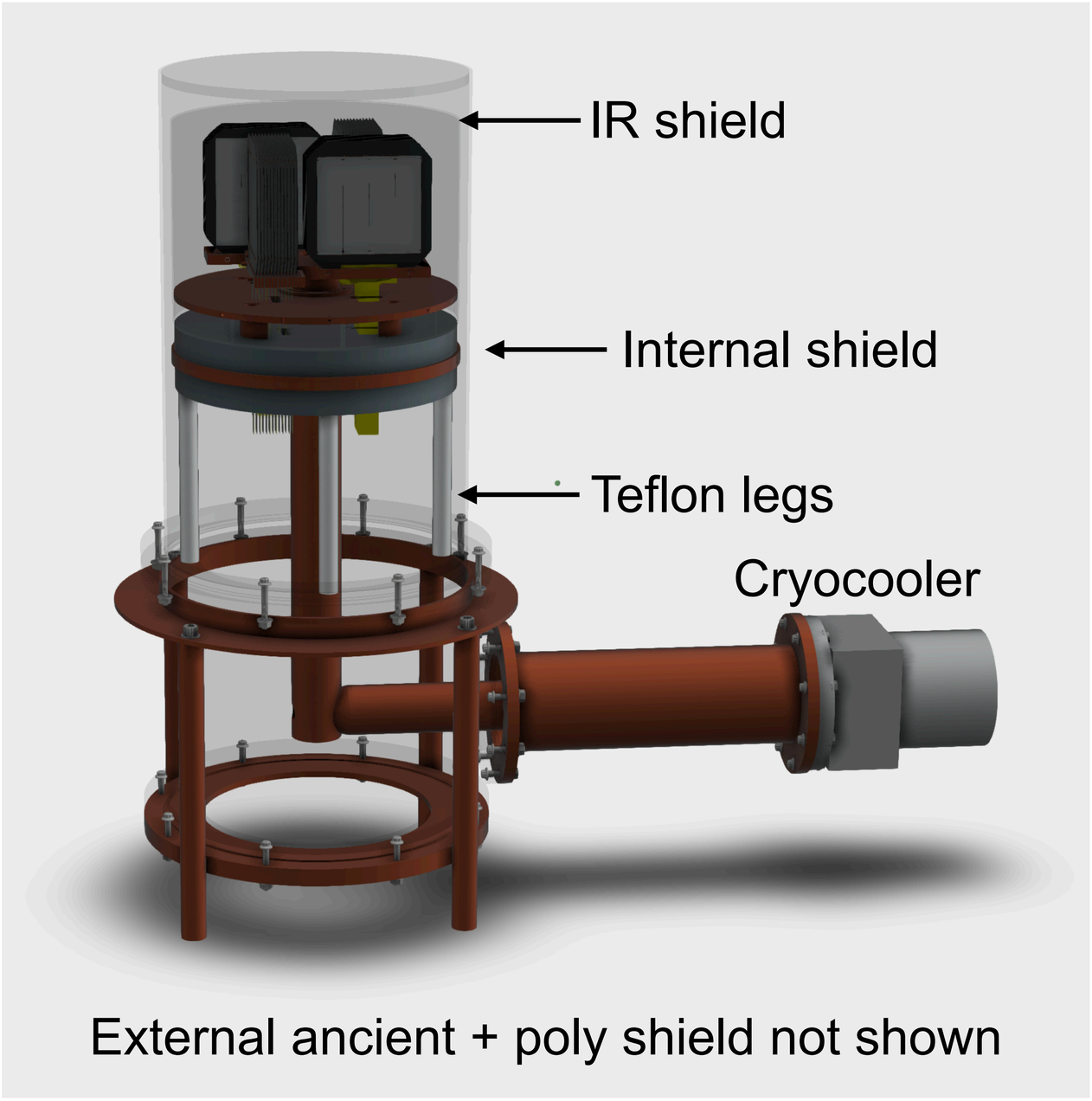


DAMIC-M

- 52 CCD modules in LSM (France) for kg-year target exposures.
- Skipper readout for 2 or 3 e- threshold.
- Background reduction to a fraction of d.r.u. (events per kg-day).
- Under construction. Commissioned by end of 2024. Science run to start in 2025!

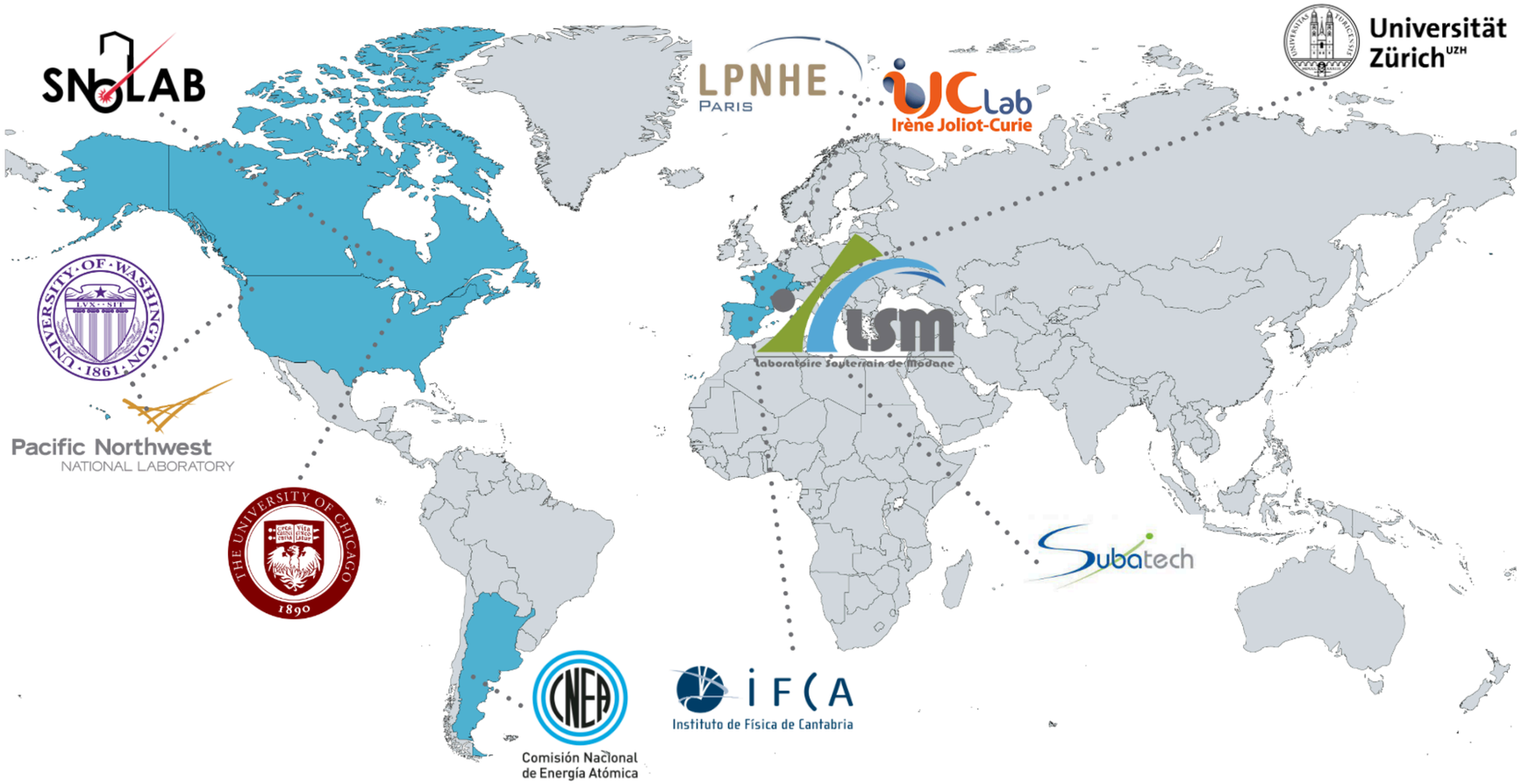
DAMIC-M module at UW:





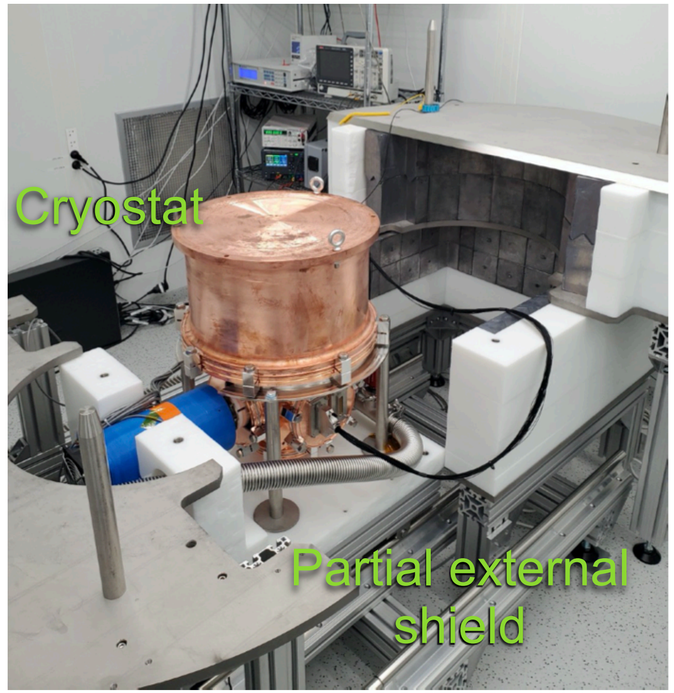
External ancient + poly shield not shown

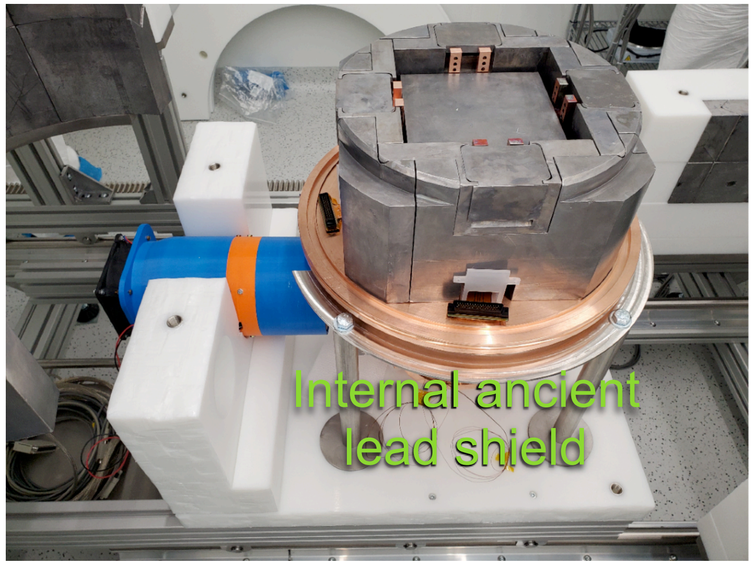
The DAMIC-M Collaboration

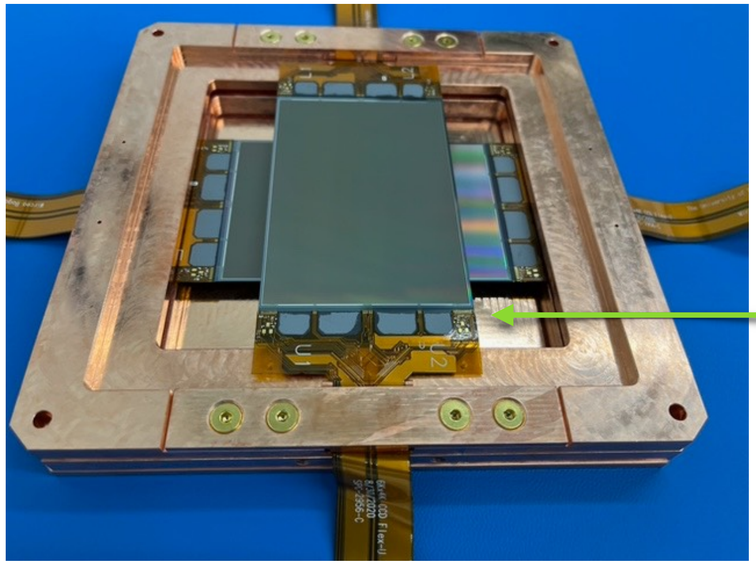


Low Background Chamber

- Low Background Chamber (LBC) test setup for DAMIC-M at LSM for performance and background studies.
- Two 24 Mpixel DAMIC-M prototype skipper CCDs.
- Single-e^- resolution, 2 x 10^{-3} e^-/pix/day, 10 d.r.u., 18 g.
- First DM-e^- exclusion limits from deep underground!



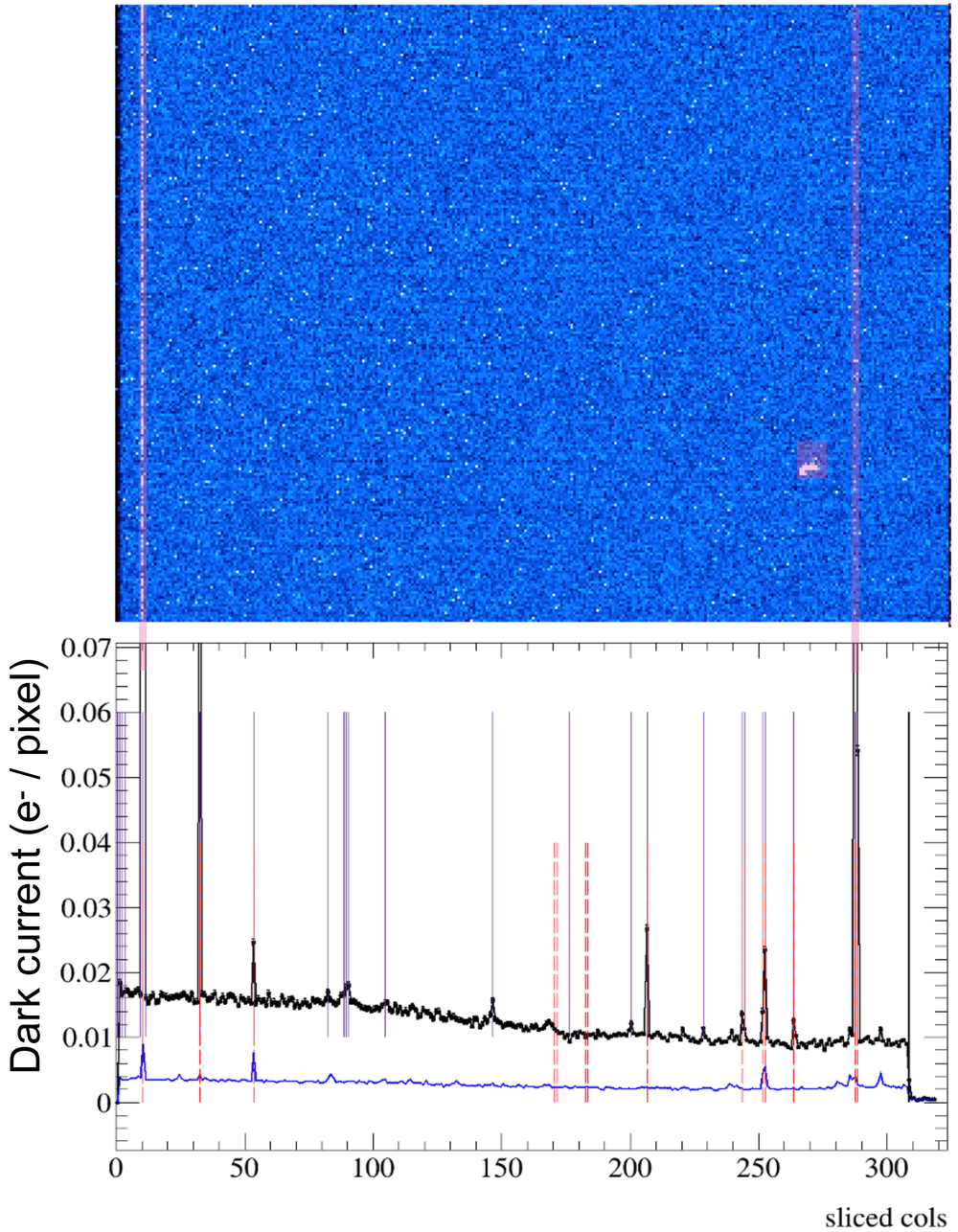




9 x 6 cm^2 CCDs packaged and tested at UW

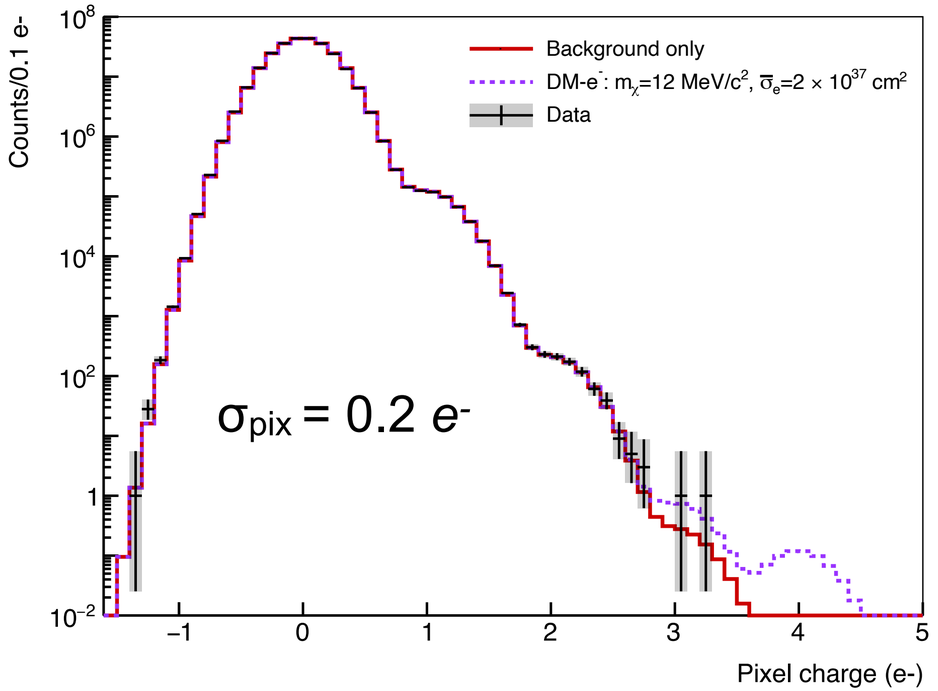
Data selection

- Acquired images with 2 amplifiers per CCD in 10x10 configuration, 650 skips.
- Science Run (SR) 1: continuous readout, same exposure per pixel
  ➡ Maximize exposure.
- SR2: read 110 rows after a “clear,” exposure that increases with row
  ➡ Smaller rate of pixels with >1 e^-.
- Mask clusters / pixels with >7 e^- and 10 trailing pixels.
- Identify and mask hot columns (defects).



Fit with DM signal

- Final selection: 85 g-day of data.
- Fit pixel distributions (1 per amplifier per SR) with background + signal model.
- Poisson background: uncorrelated single-e^- rate for each pixel.
- Signal:
  - DM deposited-energy spectrum from QEDark with PhystatDM halo parameters.
  - Ionization yield from **PRD102(2020)063026**
  - Diffusion model calibrated on surface.
- 90% C.L. upper limit from binned joint likelihood minimization.

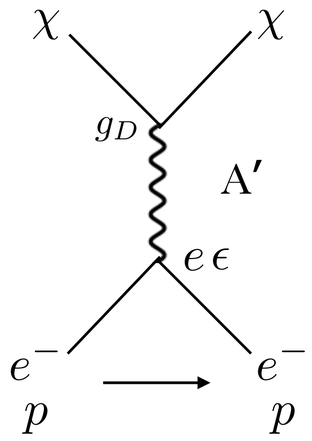


Poisson background model

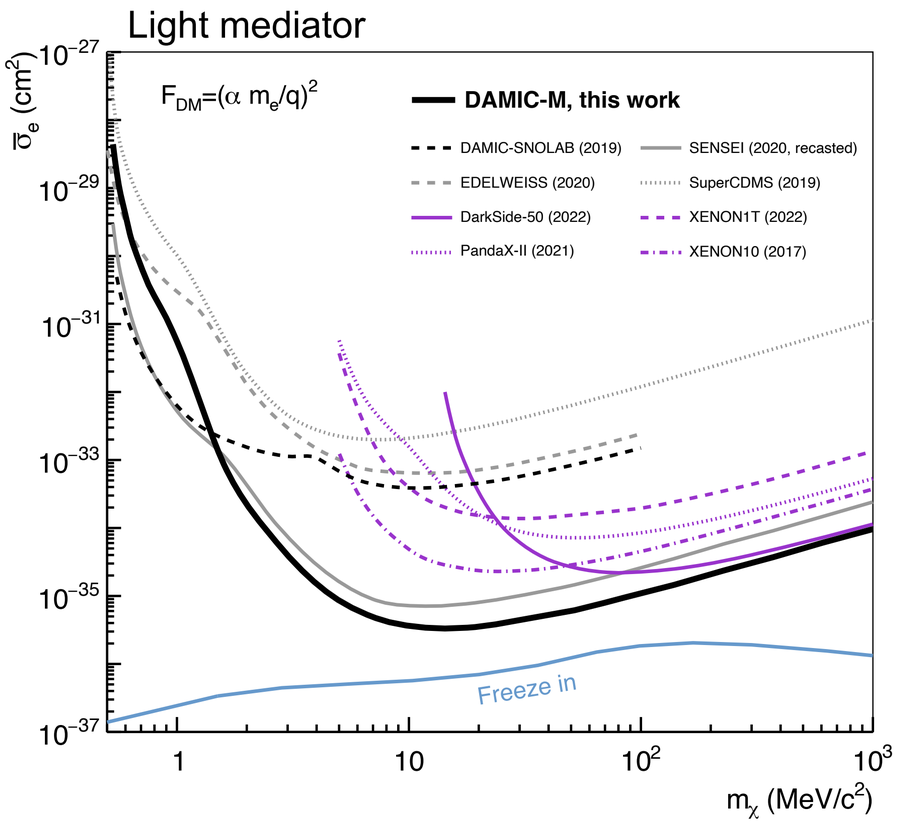
+ 90% C.L. upper limit for M_χ = 12 MeV

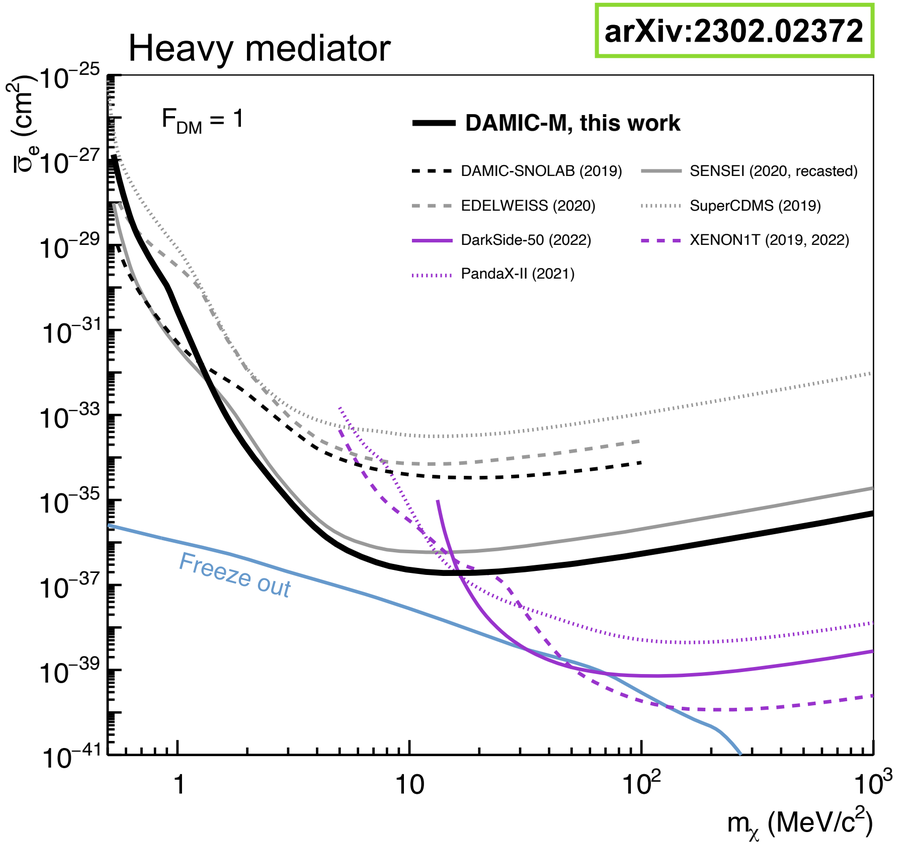
No radiogenic background
(<0.1 event expected)

DM-e exclusion limits



- ER searches allow us to probe DM masses as small as ~**MeV**!

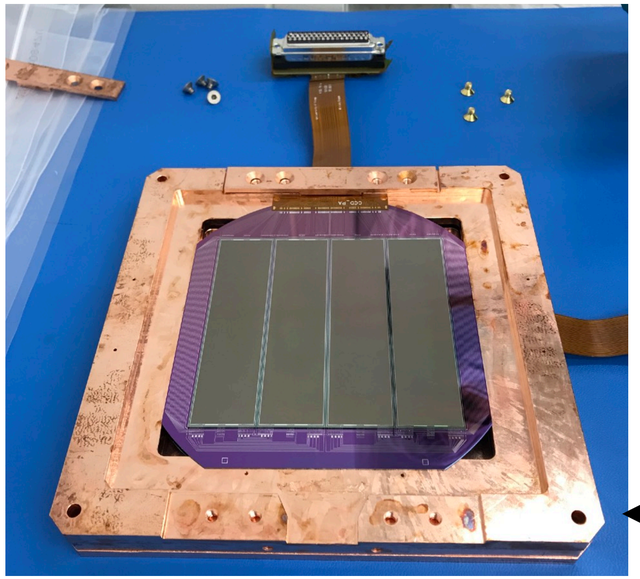




- **DAMIC-M has world-leading exclusion limits for sub-GeV hidden-sector DM!**

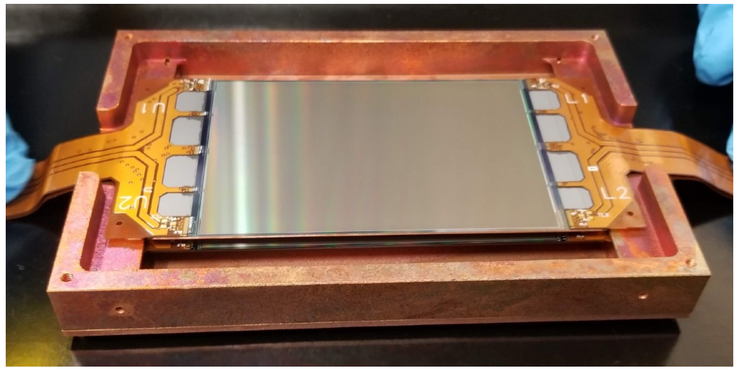
Conclusions

- Low-energy ionization signals from electronic recoils allow us to search for sub-GeV DM.
- DAMIC demonstrated CCD arrays can be operated as DM detectors deep underground.
- DAMIC-M skipper CCDs demonstrated few-electron (eV-scale) energy thresholds.
- DAMIC-M's LBC placed world-leading exclusion limits on sub-GeV DM!
- Expect more results soon from DAMIC at SNOLAB and DAMIC-M!



Two DAMIC-M prototype modules in LBC

Two 24 Mpix CCDs at SNOLAB



DAMIC-M forecast