

# Seeing Beyond the Limits of Dark Matter Searches: Mineral Detection of Heavy Dark Matter

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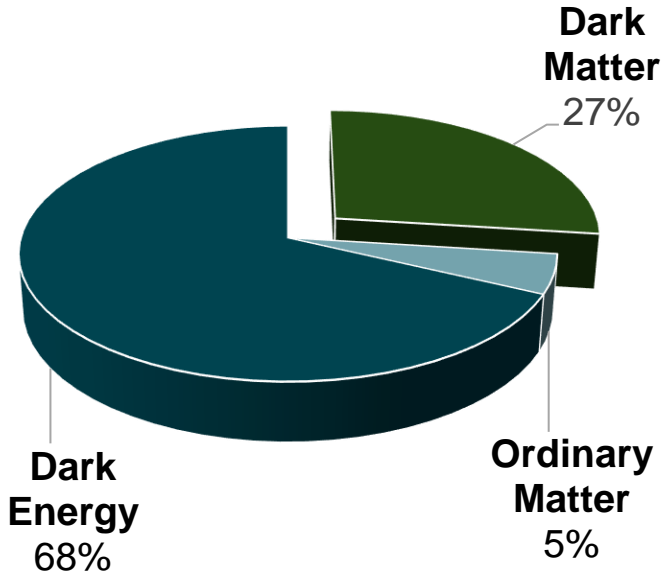


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Canadian Astroparticle Physics Research Institute



**Queen's**  
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# Why Are We Poking Around in The Dark?



Visible matter alone cannot account for the gravitational pull needed to explain the universe's large-scale structure. The missing mass is **Dark matter (DM)**.

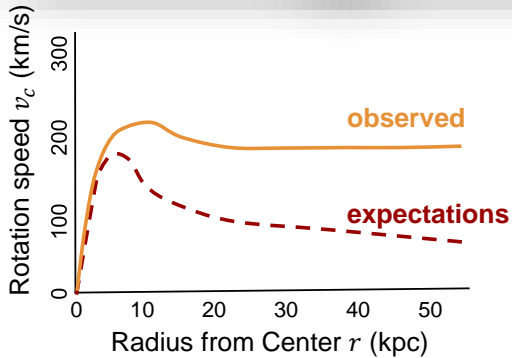
- 1 Galactic rotation curves
- 2 Gravitational lensing
- 3 Cosmic Microwave Background

# Why Are We Poking Around in The Dark?

**1** Galactic rotation curves

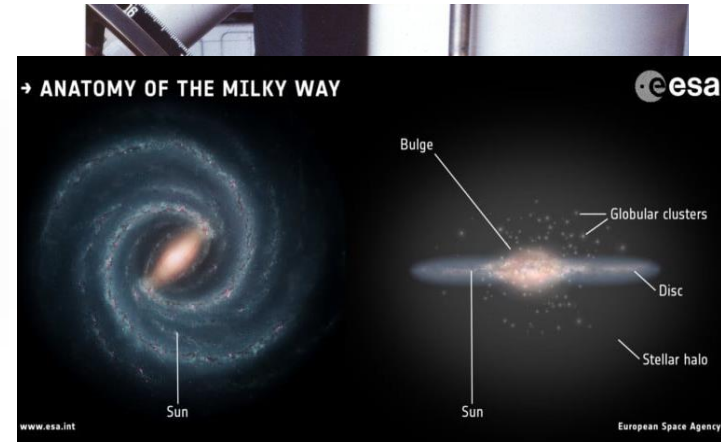
**2** Gravitational lensing

**3** Cosmic Microwave Background



Orbital velocity

$$v_c = \sqrt{\frac{M(r)}{r}}$$



Credit: Carnegie Institution, Vera Rubin, 1965  
rendering from the European Space Agency  
[https://www.esa.int/ESA\\_Multimedia/Images/2016/09/Anatomy\\_of\\_the\\_Milky\\_Way](https://www.esa.int/ESA_Multimedia/Images/2016/09/Anatomy_of_the_Milky_Way)

Unseen mass must be distributed such that  $M(r)$  grows  $\propto r$

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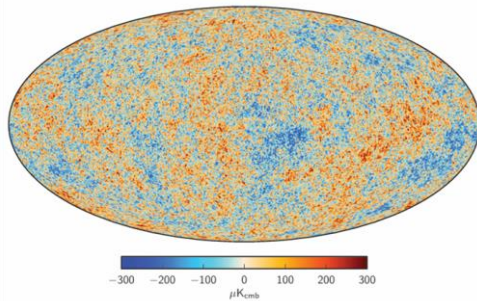
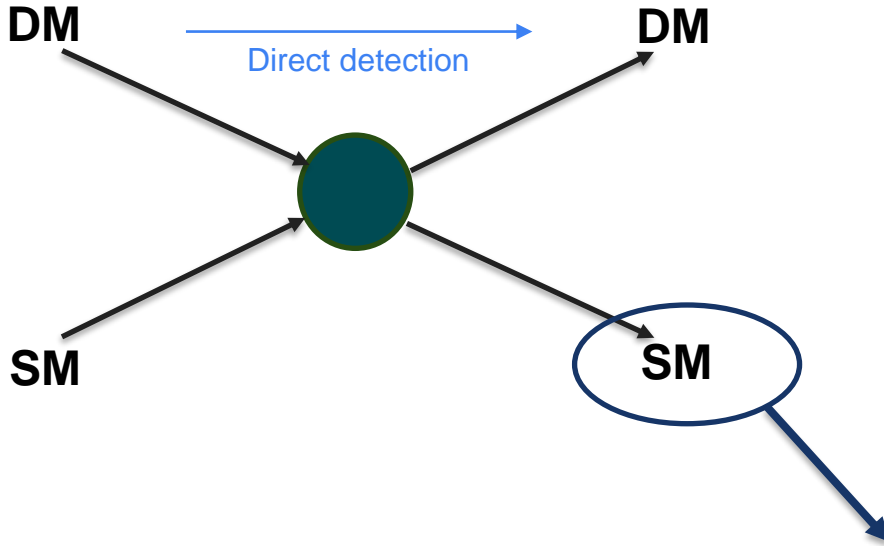


Image Credit: ESA/Hubble & NASA

# What sets the DM signal?



## Standard Halo Model (SHM)

Local DM density  $\rho_0 \approx 0.3 \frac{\text{GeV}}{\text{cm}^3}$

Dark matter speed  $v_x \sim 10^{-3} c$

We search for composite DM of heavy enough mass to produce a measurable nuclear recoil that would melt the mineral

# The exposure problem

$$\text{Signal} = \text{Area} \times n_x^* v_x t$$

$$n_{DM} = \frac{\rho_0}{m_{DM}}$$

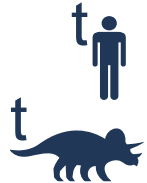
$n_x^*$  = number density above threshold  
 $t$  = exposure time  
 $m_{DM}$  = DM particle mass

**Assume**

$$m_{DM} = 10^{22} \text{ GeV}$$

1.5 x 1.5 m<sup>2</sup> detector

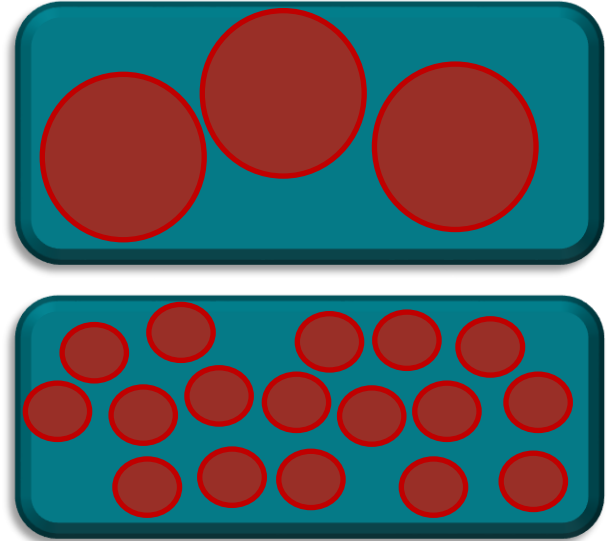
**The # of detection**



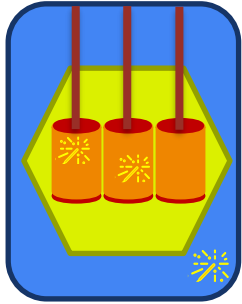
5 events in 10 000 years

500 000 events in exposure time

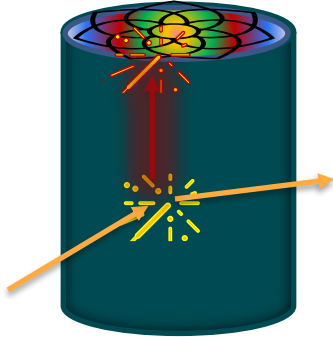
Mass  $n_{DM}$

A diagram illustrating the relationship between mass and number density. It shows two rectangular boxes. The top box contains three large red circles, representing a high mass but low number density. The bottom box contains many small red circles, representing a low mass but high number density. An upward-pointing arrow is labeled 'Mass' and a downward-pointing arrow is labeled ' $n_{DM}$ '.

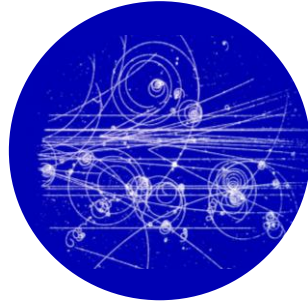
# Current direct detection experiments



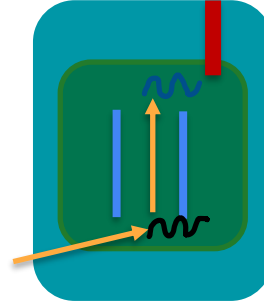
Scintillation in NaI(Tl) crystal



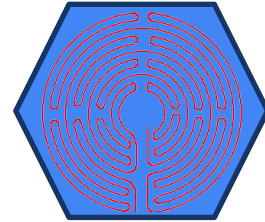
Scintillation in noble gases (Xenon, Argon)



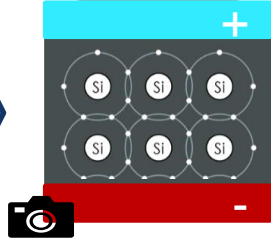
Nucleation in bubble chamber



Axion to photon conversion

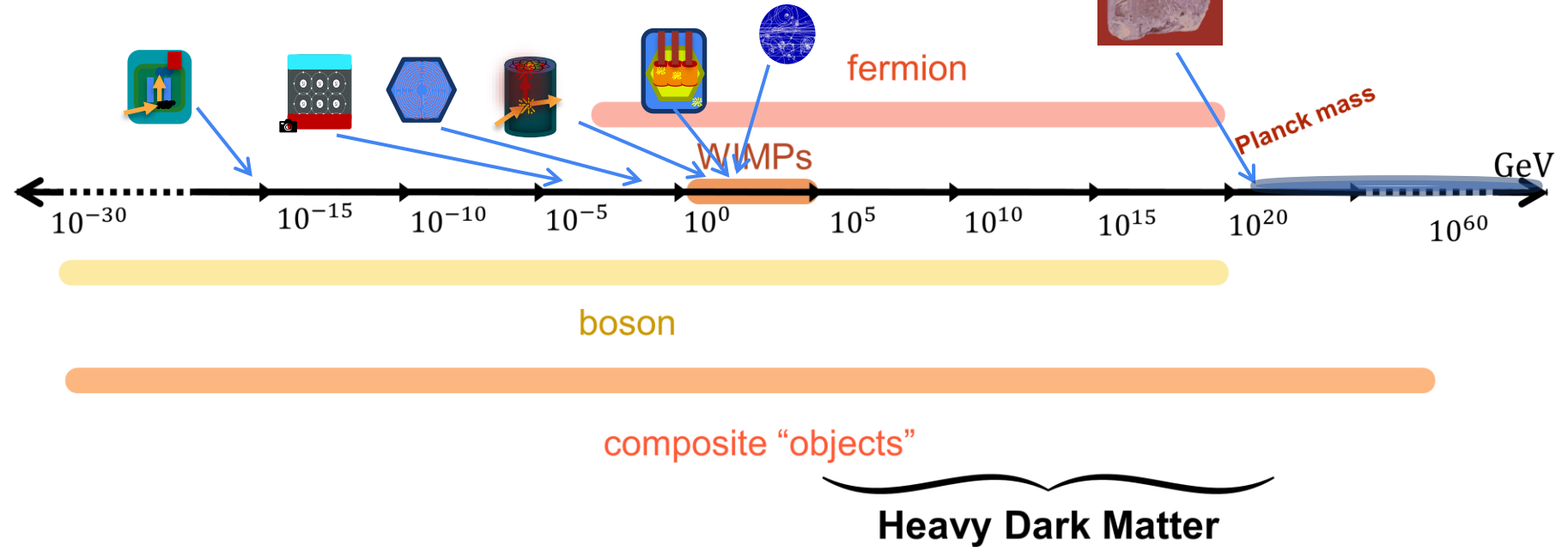


Nuclear and electronic recoils in semiconductor crystals

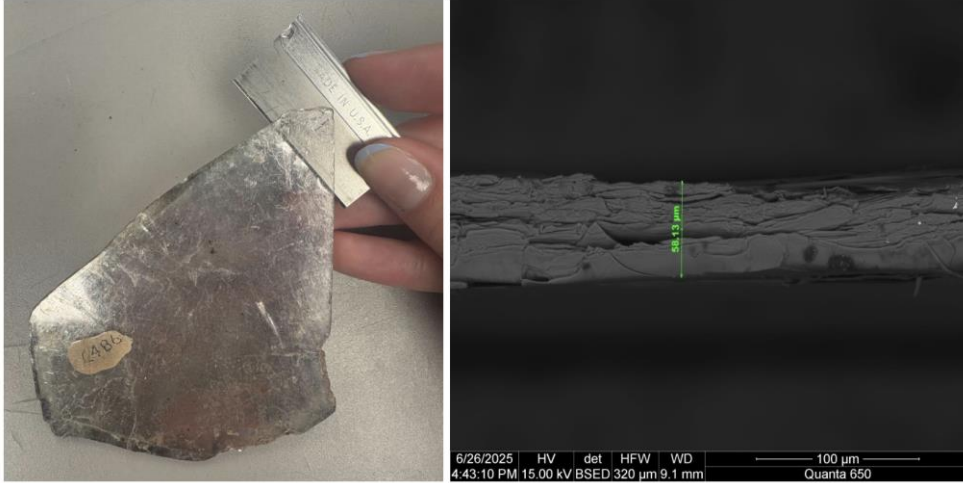


# Current direct detection experiments

- They all face backgrounds.
- Cost ineffective to scale



# Mineral Detector: Muscovite Mica



Alex Queen's University

Muscovite Mica:  
 $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$

- Flat surface → {001} basal cleavage
- Pegmatite-hosted, Canadian Shield, 1.0–2.6 Gyr old, validated by dual dating (Rb/Sr +  $^{238}\text{U}$  fission tracks)
- Below closure temp  $T_c \approx 325^\circ\text{C}$  ( $\approx 600\text{ K}$ )
- Over Gyr timescales, velocities still average out to the Standard Halo Model

# DM creates a melt signature in Mica

$R_D$  → transverse scale of  $E_{dep}$

Lattice displacement  $E$  (~10-30 eV)  
Enthalpy  $H_f$  of melt (~0.1 eV per atom)

**Opaque limit**  $R_D = dm$  radius

Everything in its cross-section  $\sigma_{geo} = \pi R_D^2$  scatters.



$$\left. \frac{dE_{dep}}{dx} \right|_{geo} \approx n_{mica} \cdot \pi R_D^2 \cdot \langle E_R \rangle = 3 \times 10^8 \frac{GeV}{cm}$$

**Diffuse limit:** composite is loosely bound; constituents interact via per-nucleon cross-section. Mean scatters is:

$$\tau_A = \frac{4}{3} \sigma_{xA} n_x R_D$$

Both regimes deposit energy on the transit timescale  $t_{dep} \sim RD/vx$

# What does the melt trail look like?

$t_{dep} \ll t_{diff}$  by ( $\sim 8$  orders of magnitude)

Energy deposits before heat can spread, driving hypersonic cylindrical shock. **Effectively instantaneous!**

diffusion time scale radially outward in plane over L:  $t_{diff} = L^2 \rho C_p / K_d$  (Heat capacity  $C_p$ , Conductivity  $K_d$ )

Energy required to melt Mica

T increase to melt point

$$\frac{dE_{req}}{dx} = \rho(C_p \Delta T_{melt} + H_f) \pi R_{melt}^2$$

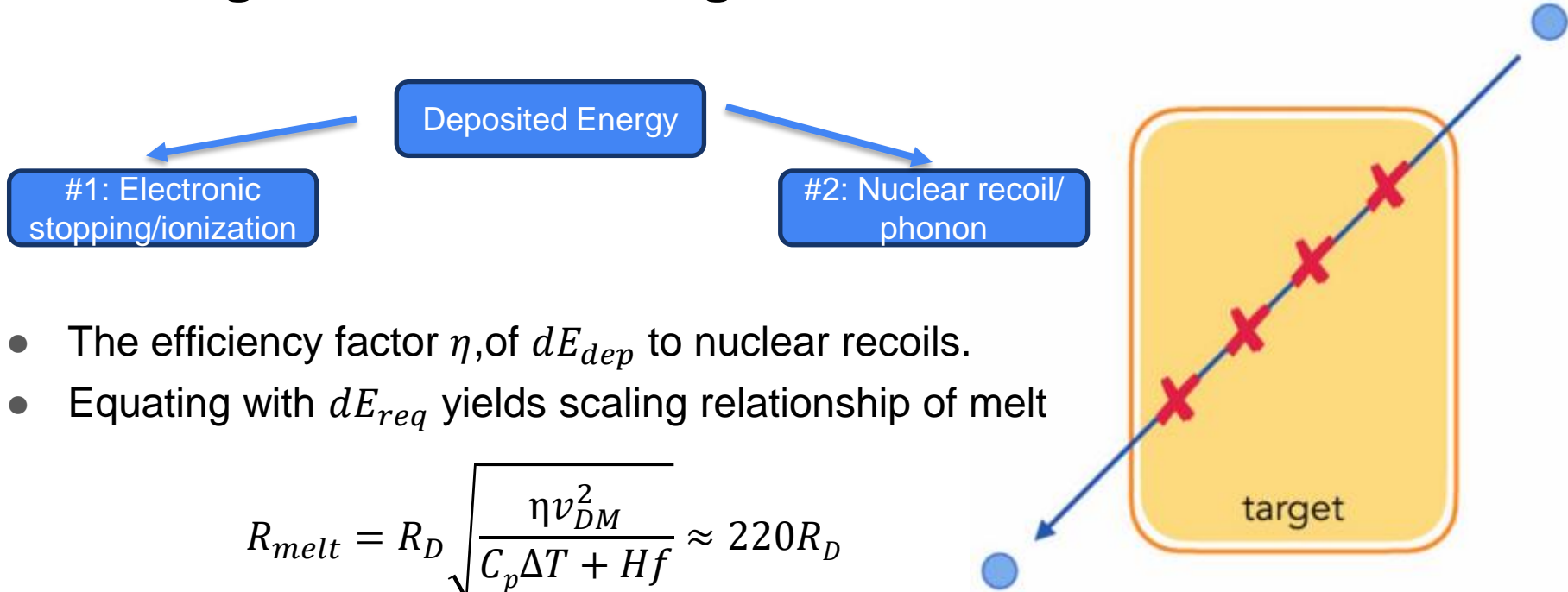
specific latent heat, goes into displacing nuclei



target

$$\rho = n_{mica} \bar{m}_N$$

# What signal are we looking for?



- The efficiency factor  $\eta$ , of  $dE_{dep}$  to nuclear recoils.
- Equating with  $dE_{req}$  yields scaling relationship of melt

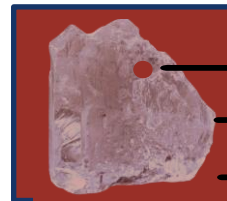
$$R_{melt} = R_D \sqrt{\frac{\eta v_{DM}^2}{C_p \Delta T + Hf}} \approx 220 R_D$$

- **Morphology very very straight**  $\rightarrow \theta_{DM} \sim m_N / m_{DM}$

# Readout mechanism: X-Ray Fluorescence Mapping Copper-backing method

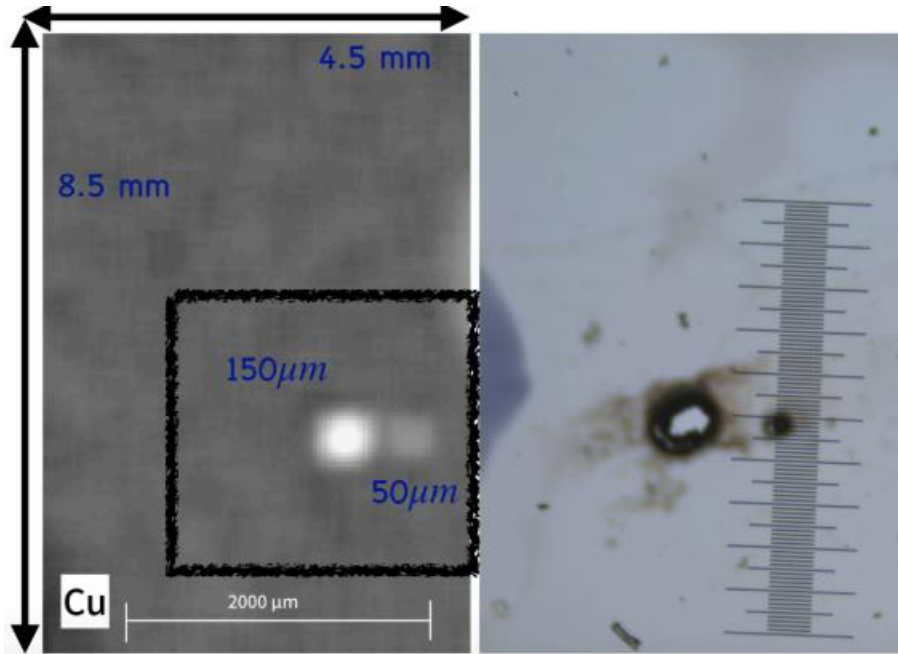


- Cleave mica along its {001} basal
- X-ray fluorescence maps elemental composition across the cleaved surface
- Localized melt features appear as distinct X-ray emission signatures



- 50 micron melt region
- Mica
- Copper substrate

# Current calibration results



Laser ablated melt regions: 150  $\mu\text{m}$  and 50  $\mu\text{m}$  diameter — proxies for DM tracks

Scan area: 8.5 x 4.5 mm<sup>2</sup>  
Spot size: 30  $\mu\text{m}$   
Step size: 36  
Dwell time: 25

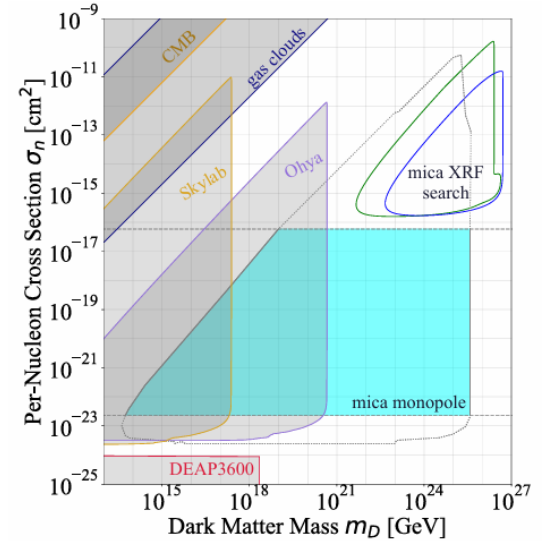
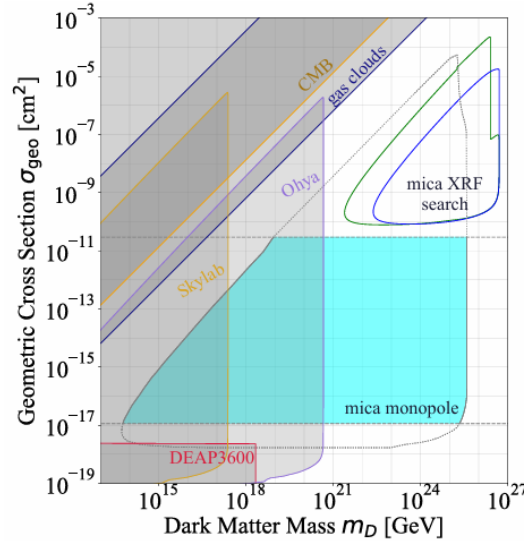
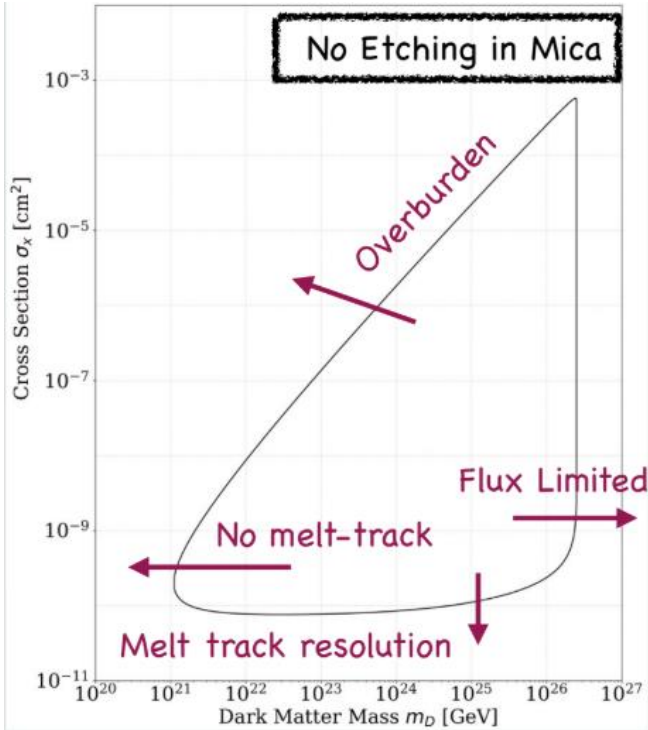
Total scan time  $\approx$  18 min

Target area 1 x 1 m<sup>2</sup>

$\approx$  300 days

# Old and New projected Sensitivities with Mica search

Boukhtouchen 26'



- Mineral detection turns geological time into detector time
- Need careful treatment of track annealing and readout sensitivity
- Future directions: scale search to 1 m<sup>2</sup>

**THANK YOU!**

**New Windows on Heavy Dark Matter: Mineral Melt Modelling and X-Ray Readout for Muscovite Mica**

**arXiv:2606.02579v**

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