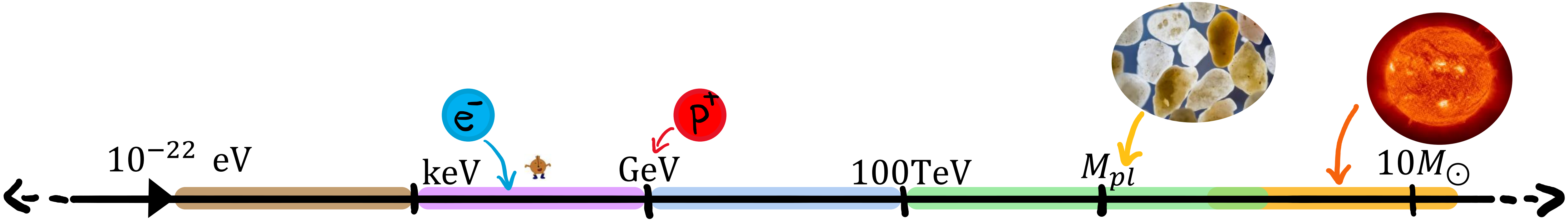
Pushing into the Ultra-Heavy Mass Frontier

ANDREW BUCHANAN

What is (Ultra)-Heavy Dark Matter?



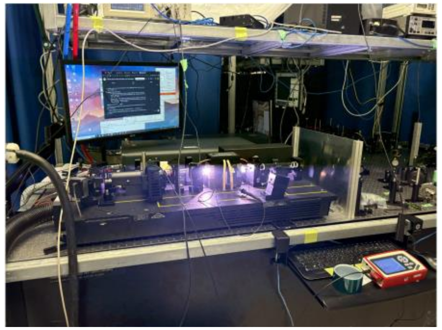
"**ultralight**" dark matter

"**light**" dark matter

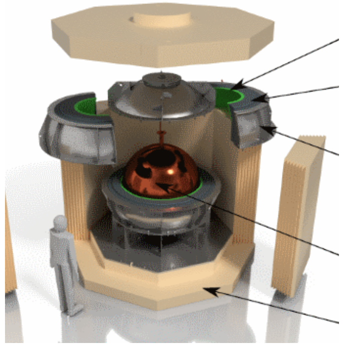
"**heavy**" dark matter

"**ultraheavy**" dark matter

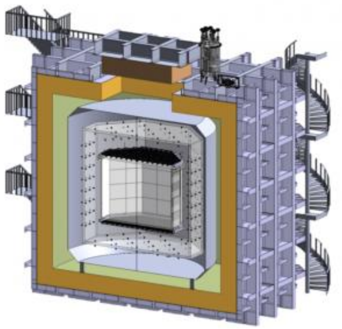
compact objects



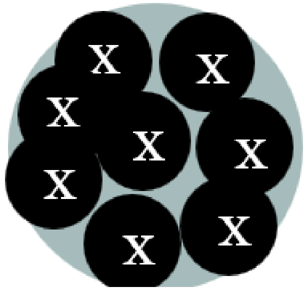
CATCHY

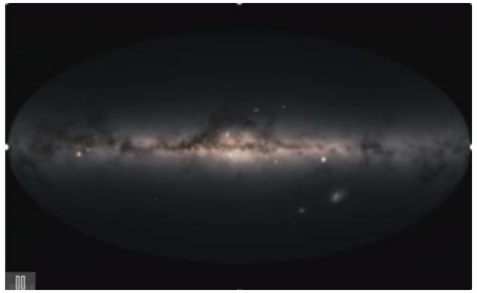


NEWS-G



DarkSide-40k





Models of Composite Dark Matter

FERMION NUGGETS

- Dirac fermion held together with a light scalar
- Easy to analyze
- Dirac fermions -> 'Asymmetric Composite Dark Matter'

$$\mathcal{L} \supset \bar{X}\left[i\partial\!\!\!/ - (m_X - g_\phi \phi)\right] X$$

Models of Composite Dark Matter

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DARK QCD

- Dark analogue of QCD
- Quarks combine to make nucleons
- Nucleons combine to make nuclei
- No EM force to cause fission

$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Heavy DM Interactions with Nuclei

PER-NUCLEON (FLUFFY CLOUD)

- Realistic for large loosely-bound composite DM
- Each DM constituent interacts coherently with whole nucleus

$$\sigma_{\chi A} = A^4 \sigma_{\chi n}$$

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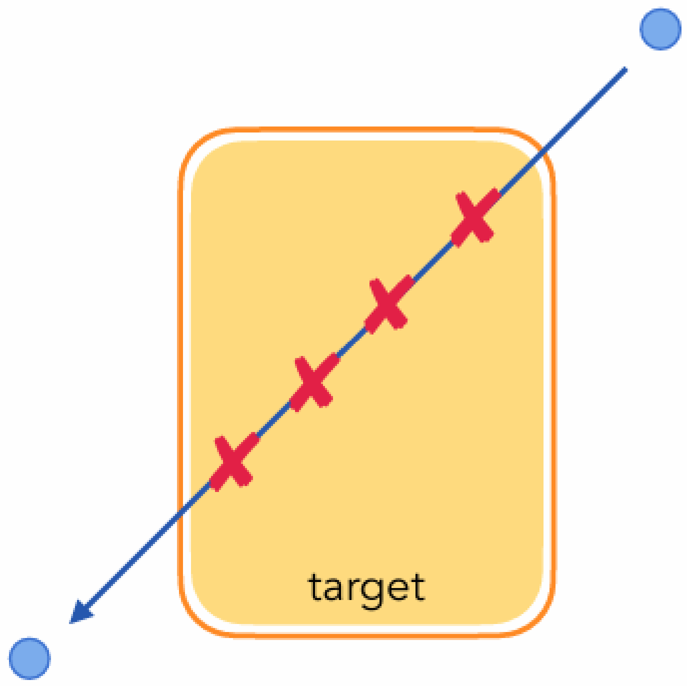
CONTACT (BOWLING BALL)

- Realistic for tightly-bound composite DM
- DM interacts with each nuclei with the same strength

$$\sigma_{\chi A} = \sigma_C$$

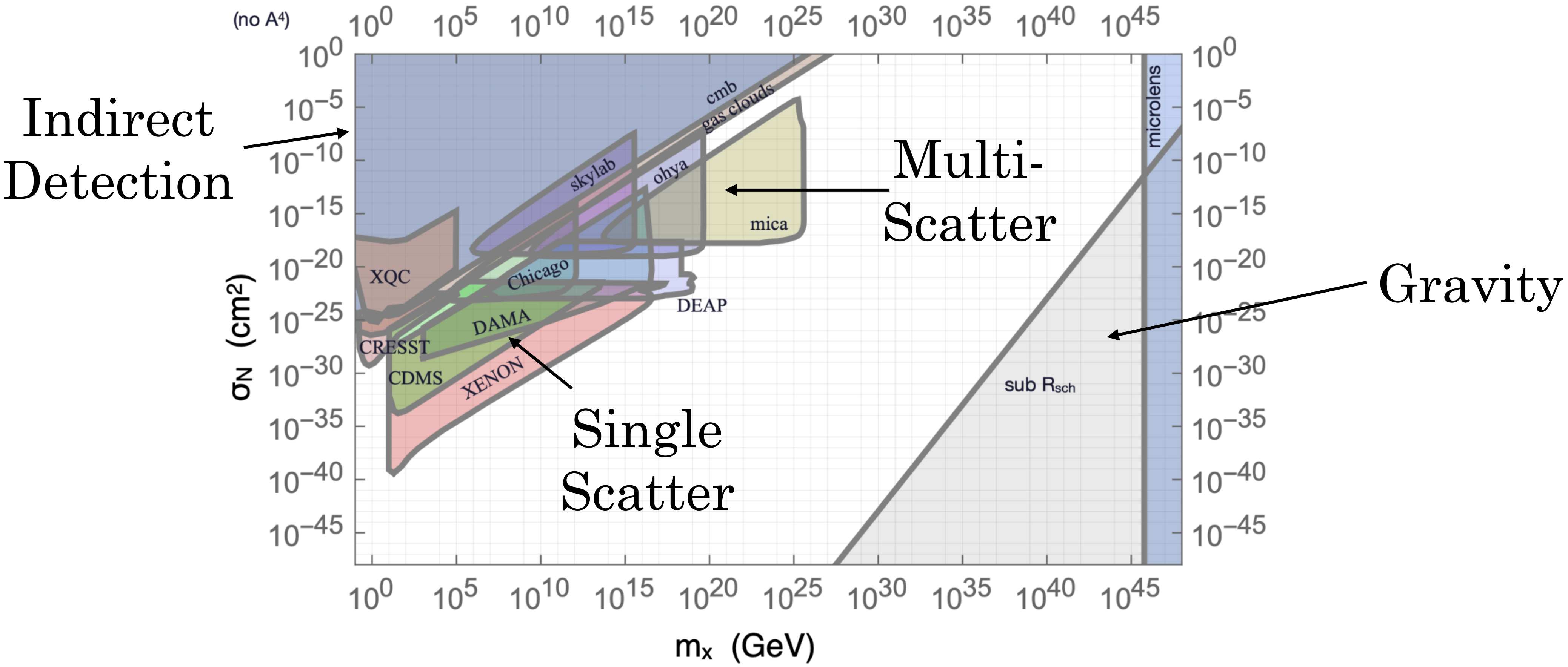
Aspects of Heavy Dark Matter Searches

- Low number density
- Unconstrained even at high cross sections ($\lesssim 10^{-8}$ cm^2)
- Much heavier than backgrounds
- Multiple nuclear scatters in a VERY straight line ($\Delta\theta < 10^{-5}$ through 20 km)
- Presents a unique frontier for direct dark matter searches



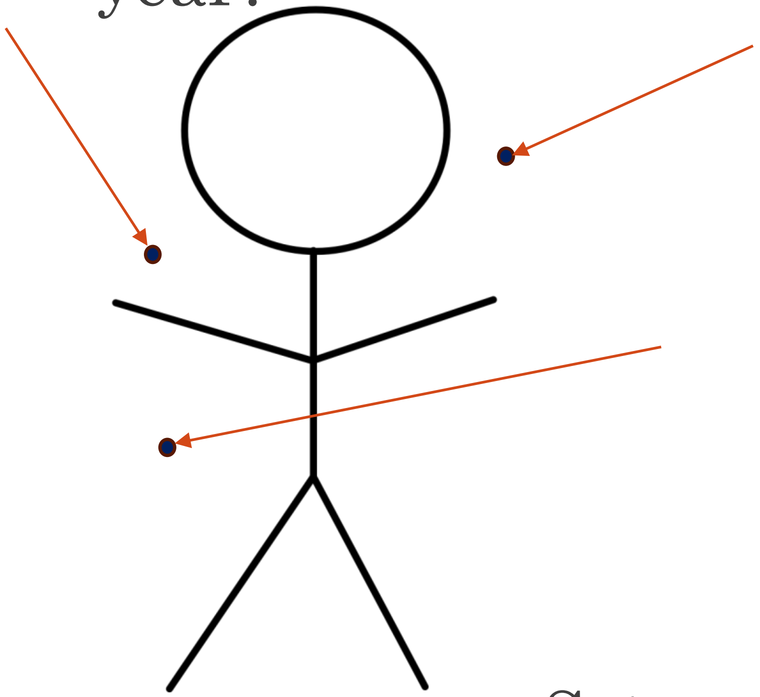
Each scatter deposits energy $m_{nuc} v_\chi^2$

The High Mass Frontier



DM Mass Flux on Human Scales

How much dark matter passes through your body each year?



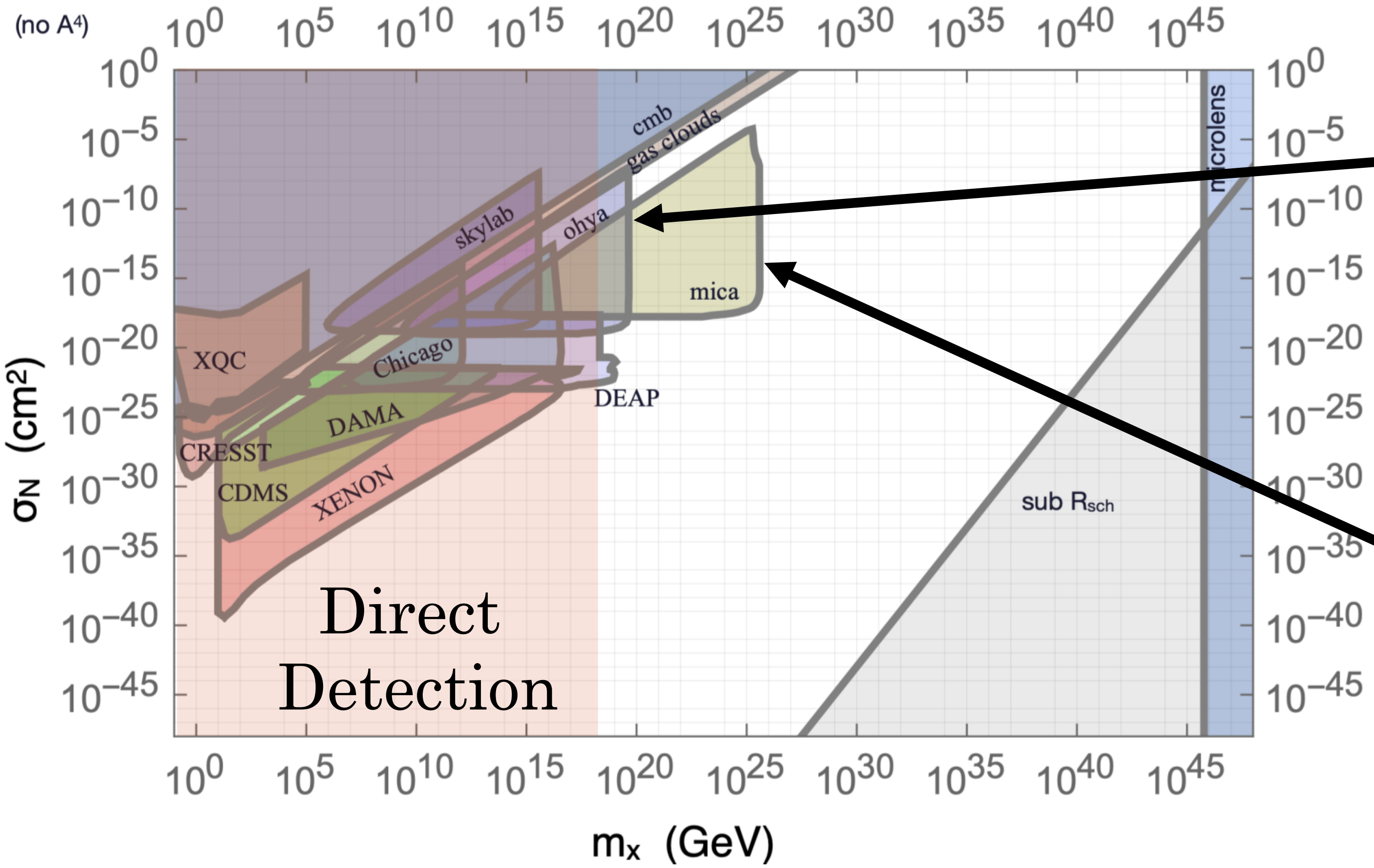
$$\text{Mass Flux} = A_{\text{human}}\,\rho_{\text{DM}}\langle v_{\text{DM}}\rangle$$

$$= 5.3 \times 10^{18}\,\text{GeV yr}^{-1}$$

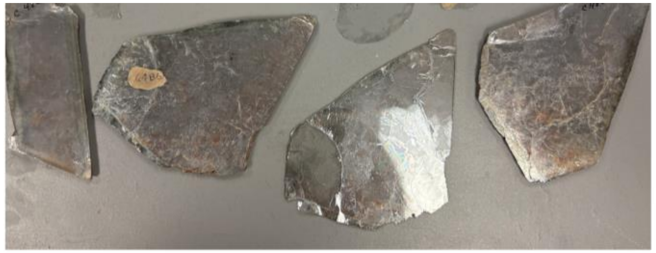
$$= 9.4\,\mu\text{g yr}^{-1}$$

Sets a soft limit on human scale experiments

Getting To The High Mass Gap



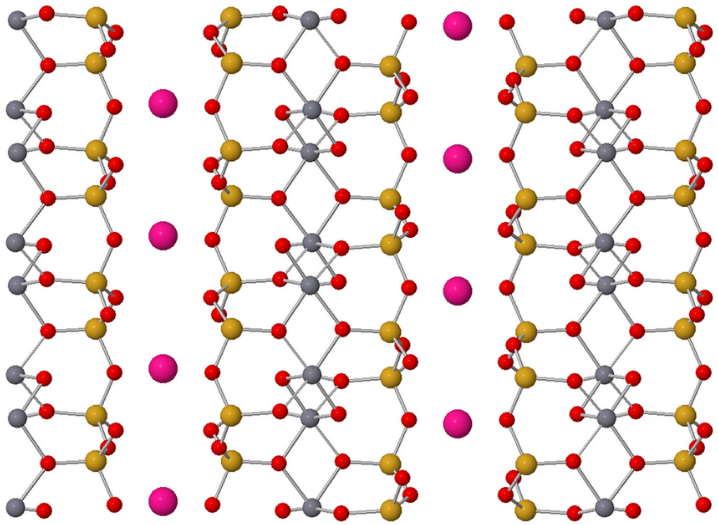
Need a large area (e.g. Ohya 1000 m^2)



Or a longer active time (e.g. muscovite mica 1 billion years)

Why Muscovite Mica?

- Mineral with layered molecular structure
- Weak bonds between layers
- Can be easily cleaved into large ($10^2 - 10^3$ cm^2) flat sheets
- Is plentiful in geologically stable sections of crust (“cratons”)
- DM damage will not anneal or melt away over one billion years
- Geological stability verifiable with observable fission tracks

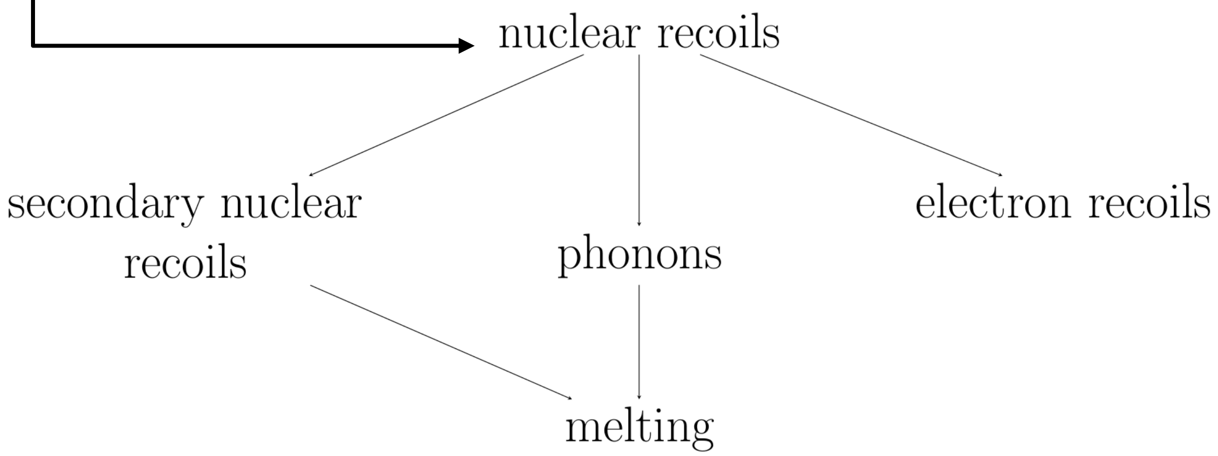


Canadian Shield Craton

New Bounds: Searching for Melt Tracks

- Large enough DM can make ‘melt tracks’
- Energy from nuclear recoils melts surrounding mica
- Produces a straight track of vitrified mica
- Ongoing experimental program at Queen’s University to search for melt tracks from DM

$$\eta_{\text{eff}}\, \underbrace{\rho_{\text{mica}} v_\chi^2 (\pi R_D^2)}_{\text{energy deposited to nuclear recoils}} = \underbrace{\rho_{\text{mica}} (C_p \Delta T_{\text{melt}} + H_f) \pi R_{\text{melt}}^2}_{\text{energy to melt}}$$

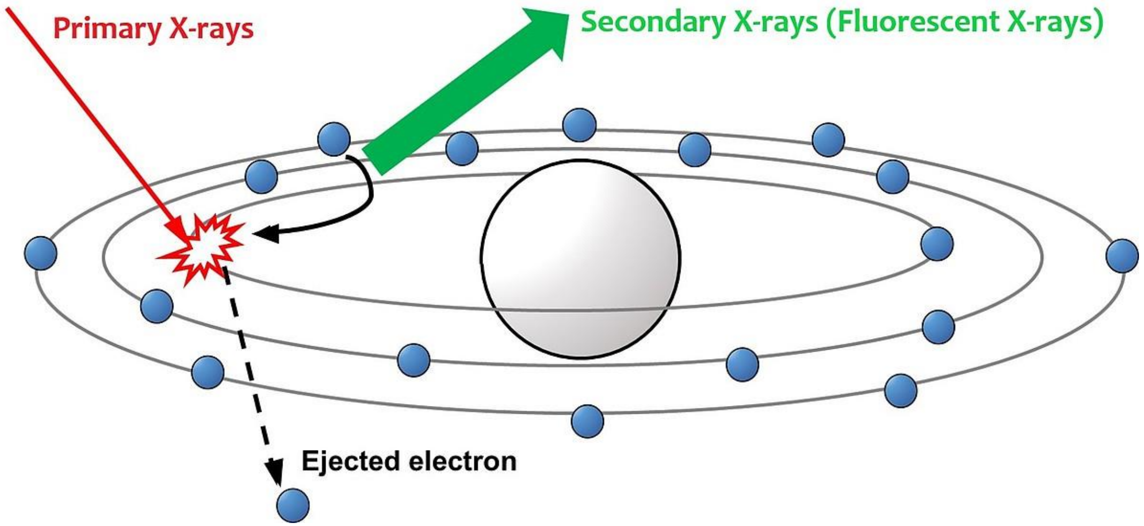


With $\eta_{\text{eff}} \approx 0.7$:

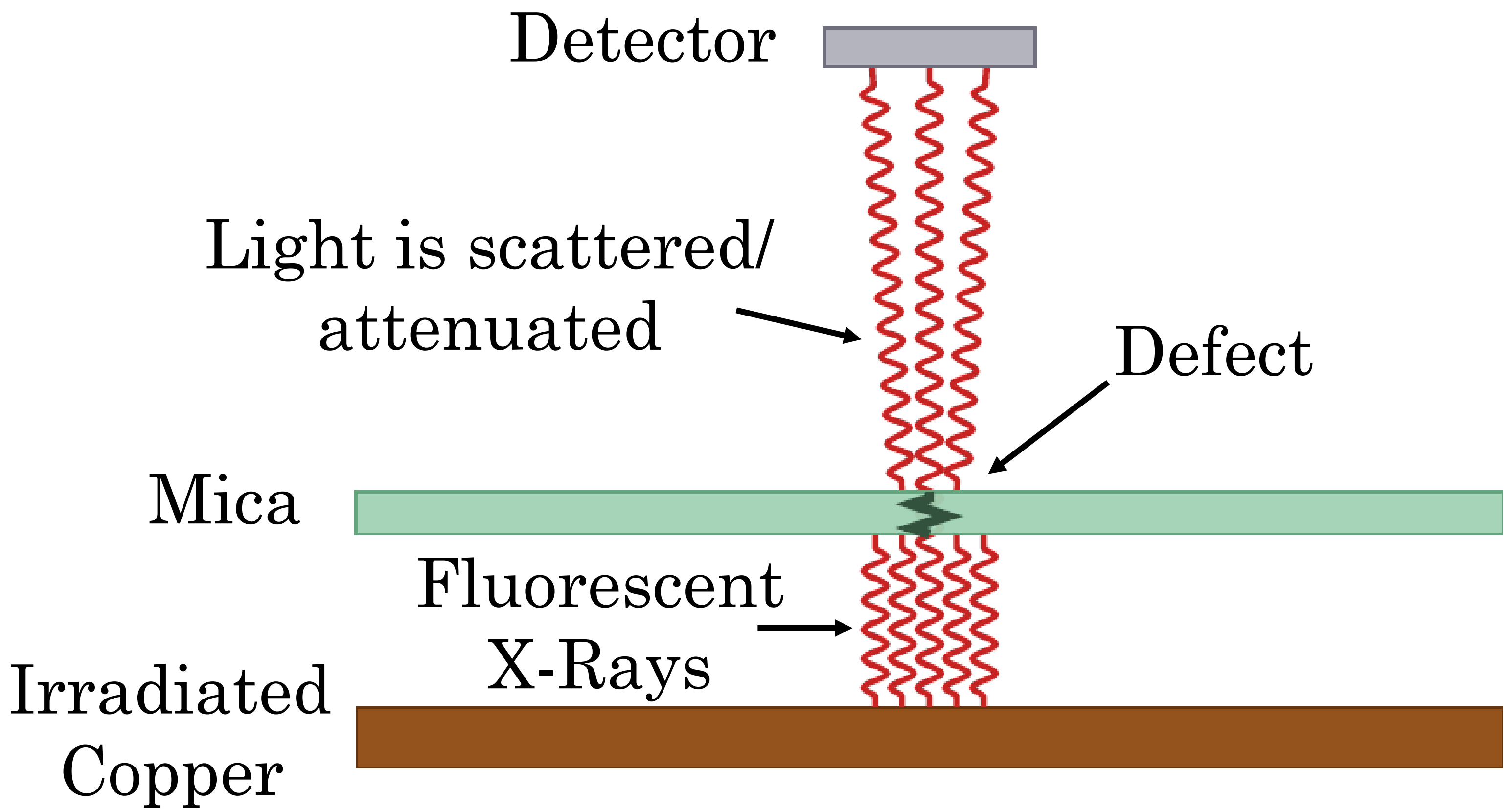
$$R_{\text{melt}} \approx 220 R_D$$

X-Ray Fluorescence

- Non-destructive imaging technique
- Irradiate a sample with X-rays
- Spectrum of subsequent deexcitations are unique to each element
- Provides a spatial map of elemental abundance



Schematic of Imaging Technique



- Why copper?
- Not present in mica; no background Cu

$$KAl_2(AlSi_3)O_{10}(OH)_2$$

- Strong characteristic emissions:
  2p → 1s (8.0 keV)
  3p → 1s (8.9 keV)

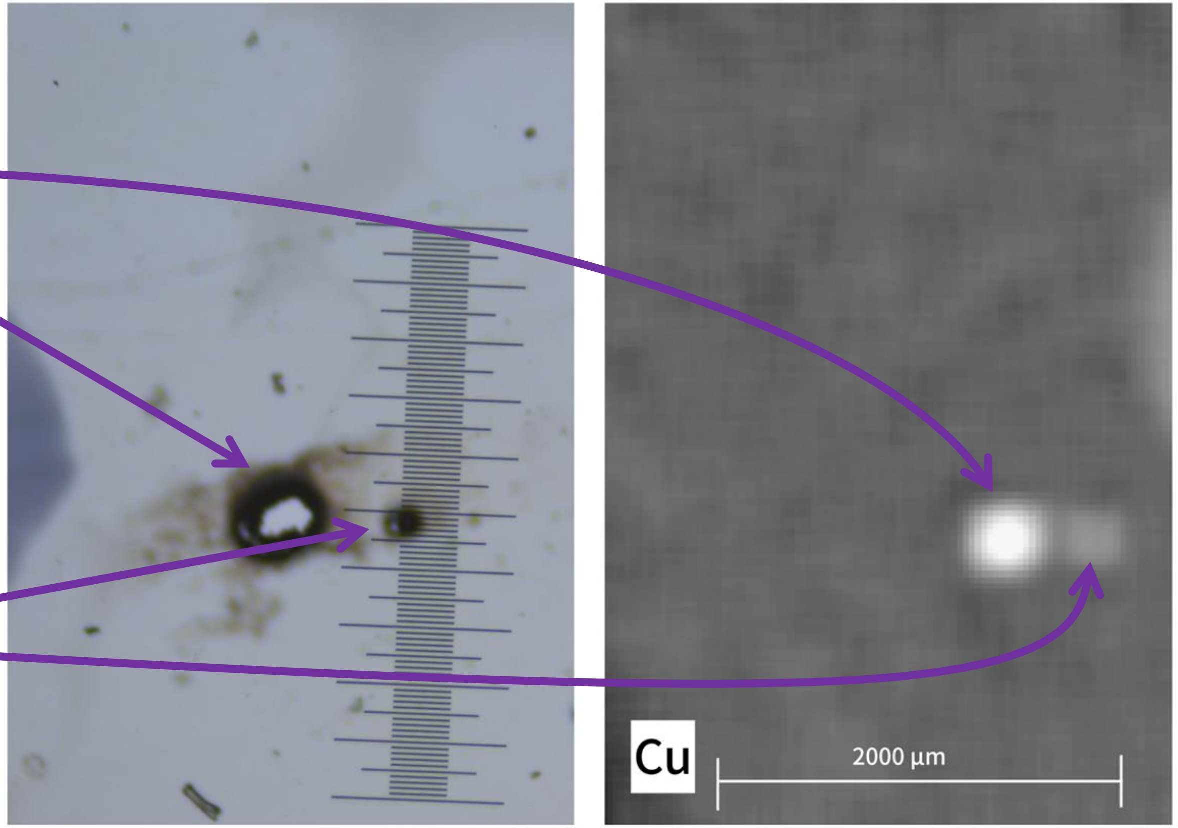
Preliminary Size Calibration with Laser-Damaged Mica

$R_{\text{melt}} = 75\ \mu\text{m}$

$R_{\text{melt}} = 25\ \mu\text{m}$

Optical

XRF



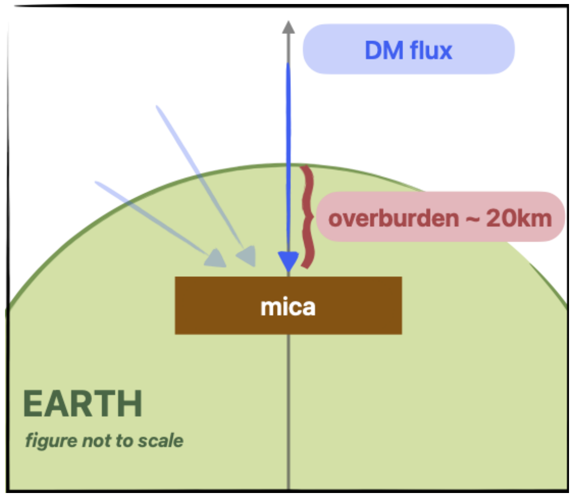
Smallest observable R_{melt} is 25 microns

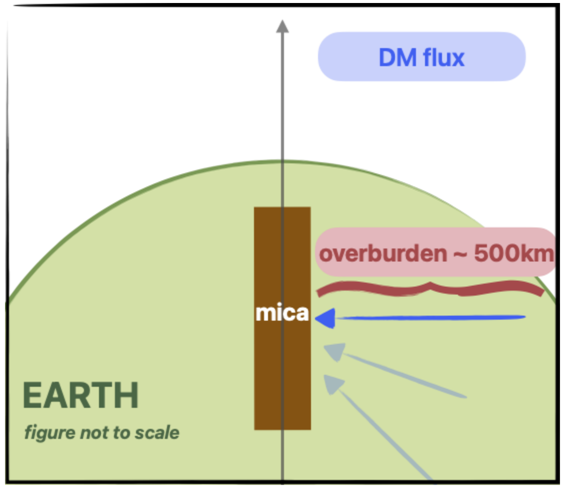
Sets sensitivity threshold

Projected Sensitivity

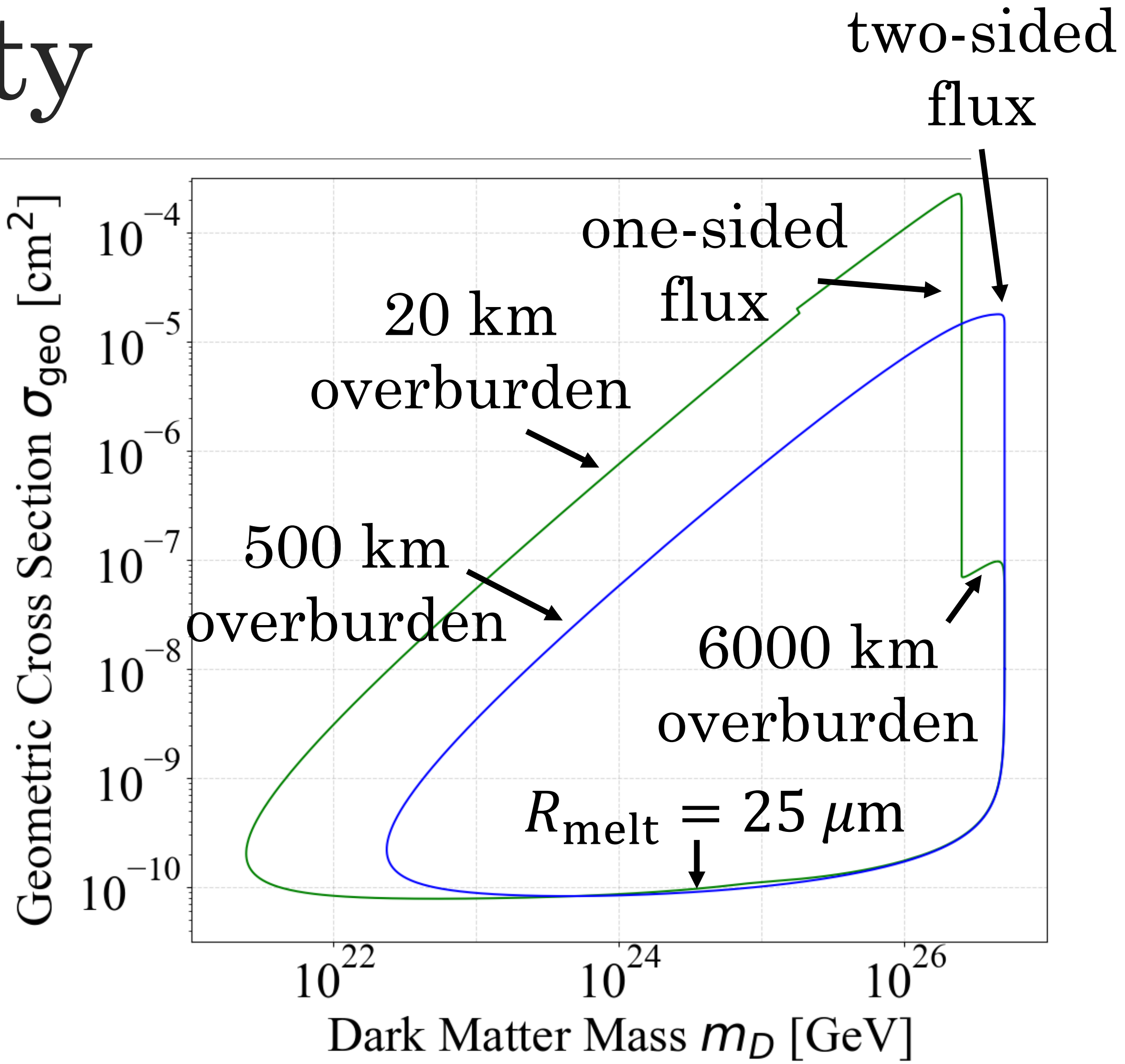
Mica is parallel to Earth surface

Mica is perpendicular to Earth surface



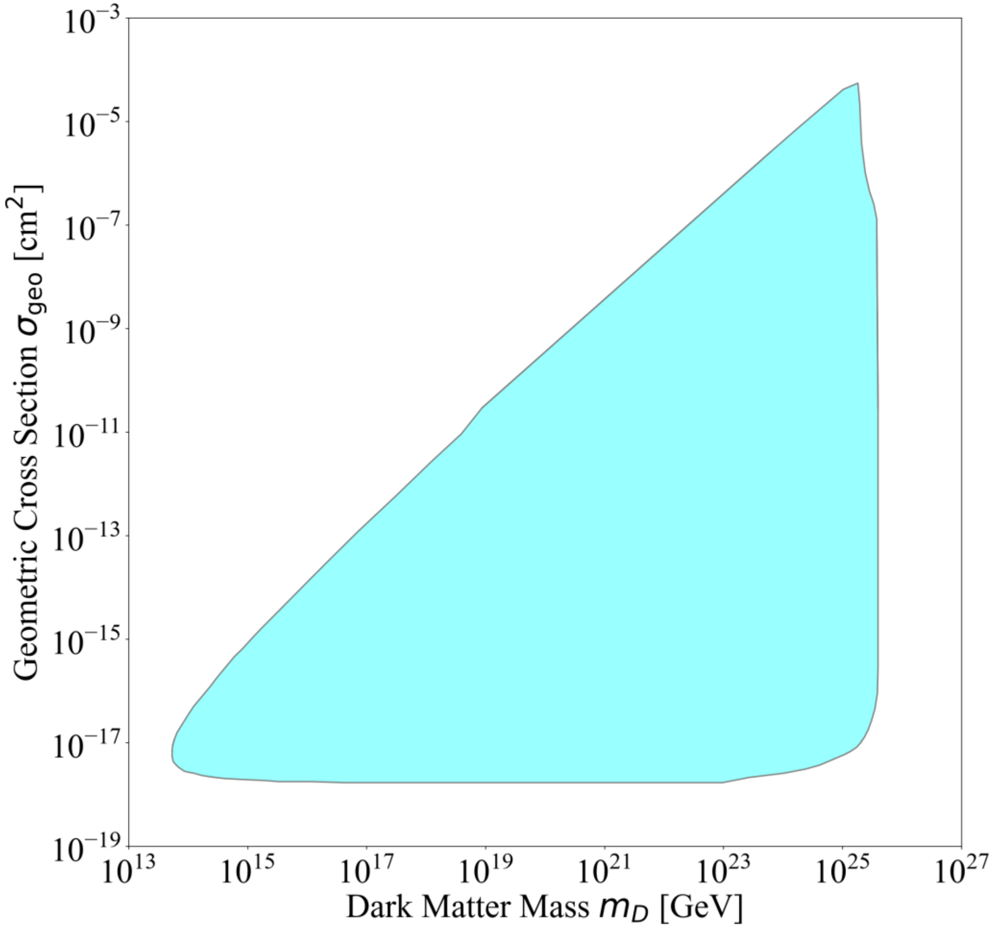


$$A_{\text{mica}} = 1\ \text{m}^2$$
$$T_{\text{mica}} = 1\ \text{Gyr}$$



Refinements to Previous Bounds

- Recast bounds from magnetic monopole search in mica (Price and Solomon 1986)
- Finds tracks with acid etching, like Skylab and Ohya
- Less parameter space is excluded than initially thought



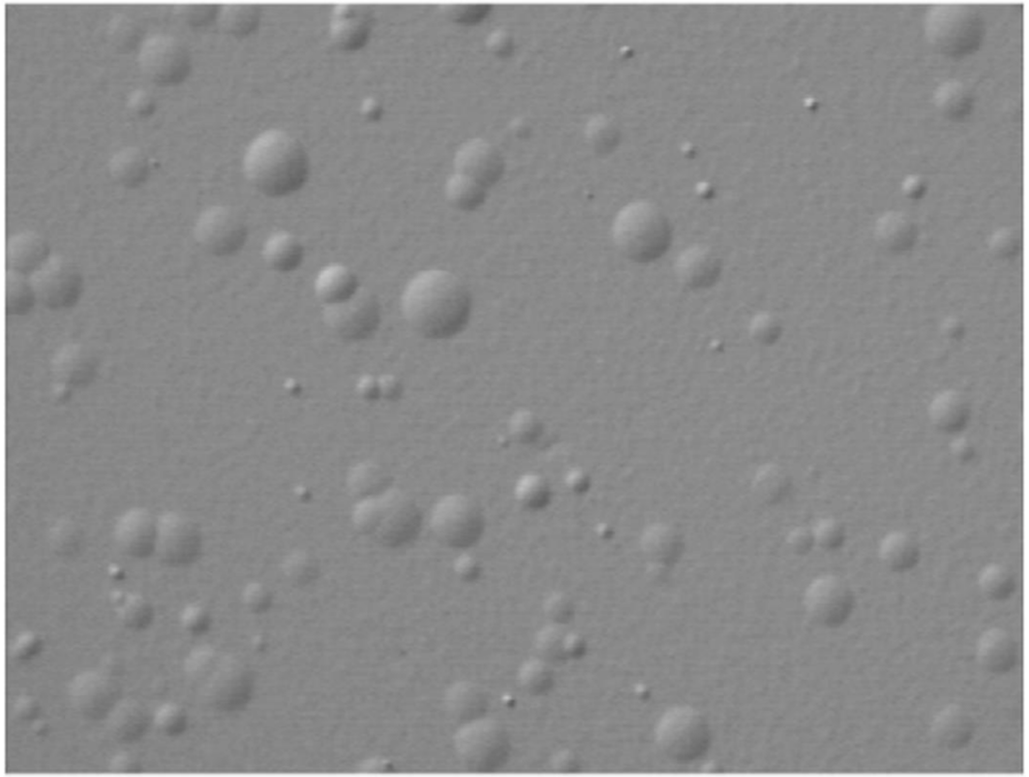
Refinements: Annealing

- Monopole search and DM recast used etching threshold based on alpha bombardment

$$\left(\frac{dE}{dx}\right)_{\text{thresh}} = 6.8\,\text{GeV}/\text{cm}$$

- Studies suggest damage from alphas anneal over million-year timescales (Yuan et al 2009)
- Likely small DM tracks would also anneal

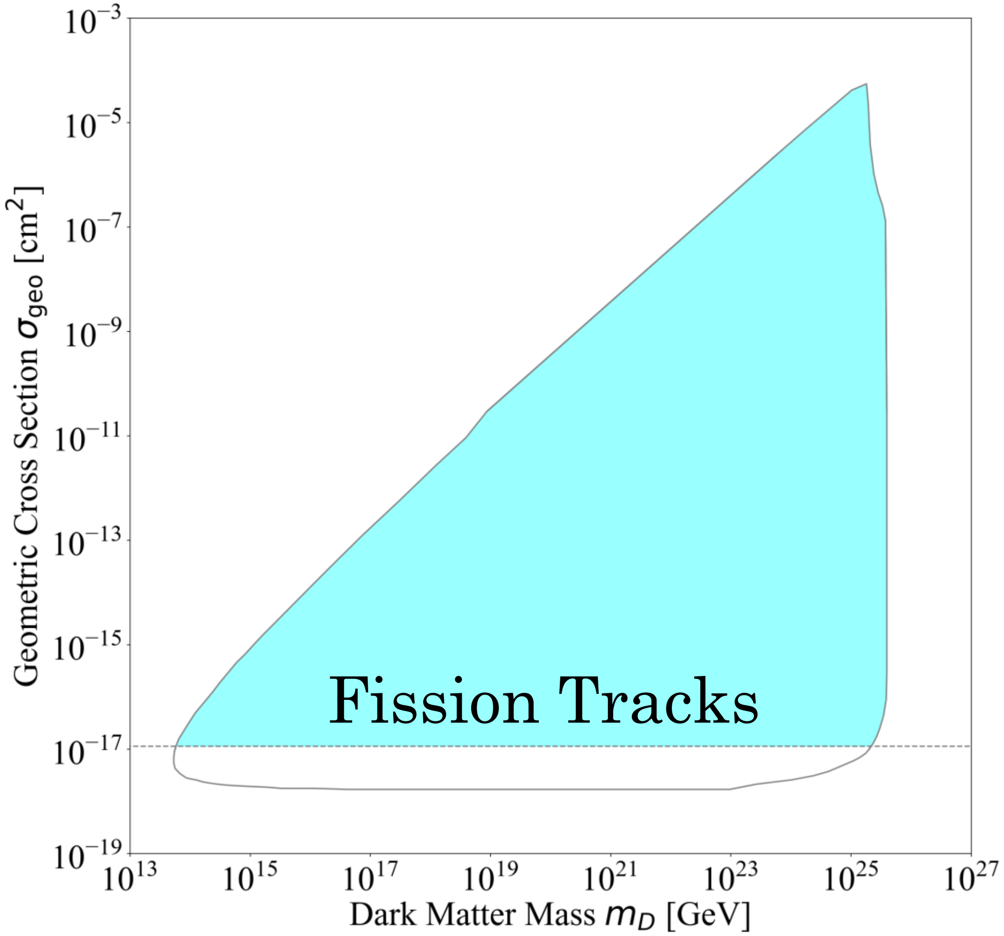
Alpha Tracks



Refinements: Fission Track Validation

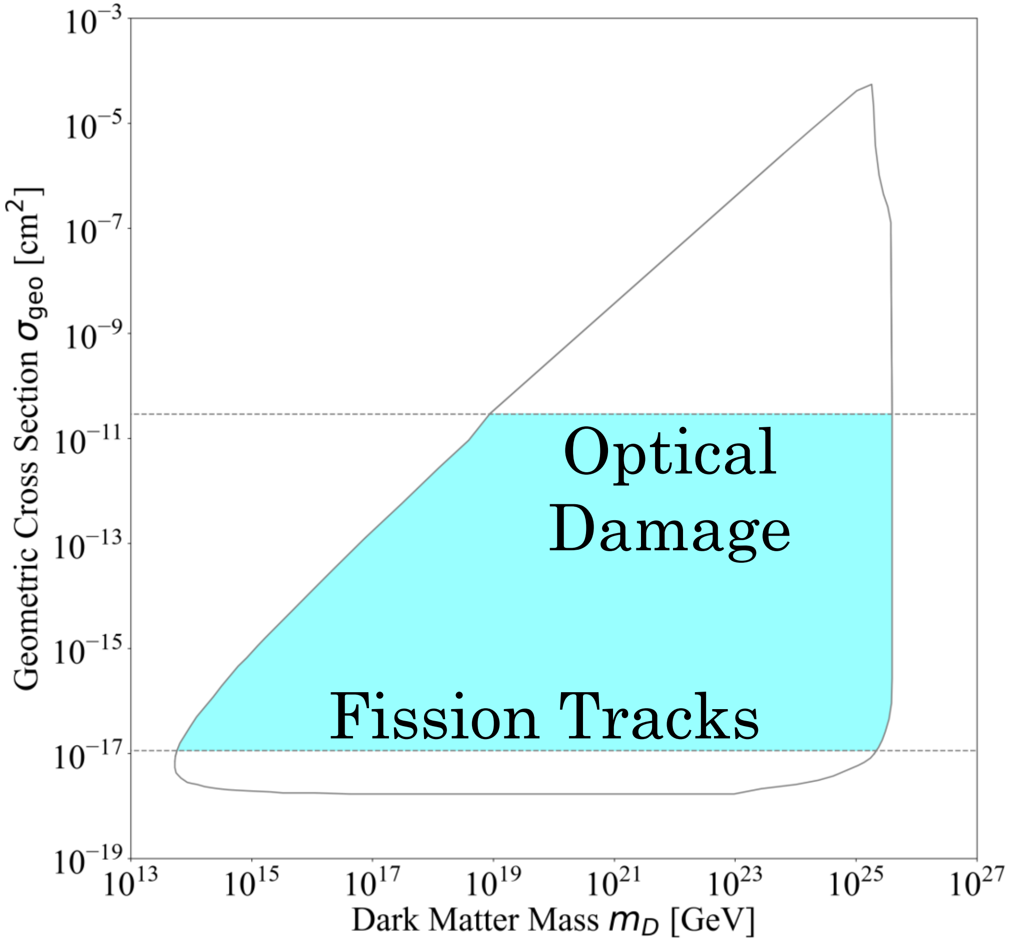
- Spontaneous fission tracks are directly observable
- Occurs over actual lifetime of rock; verifying mica was never hot enough to anneal
- Sets a new threshold for no annealing:

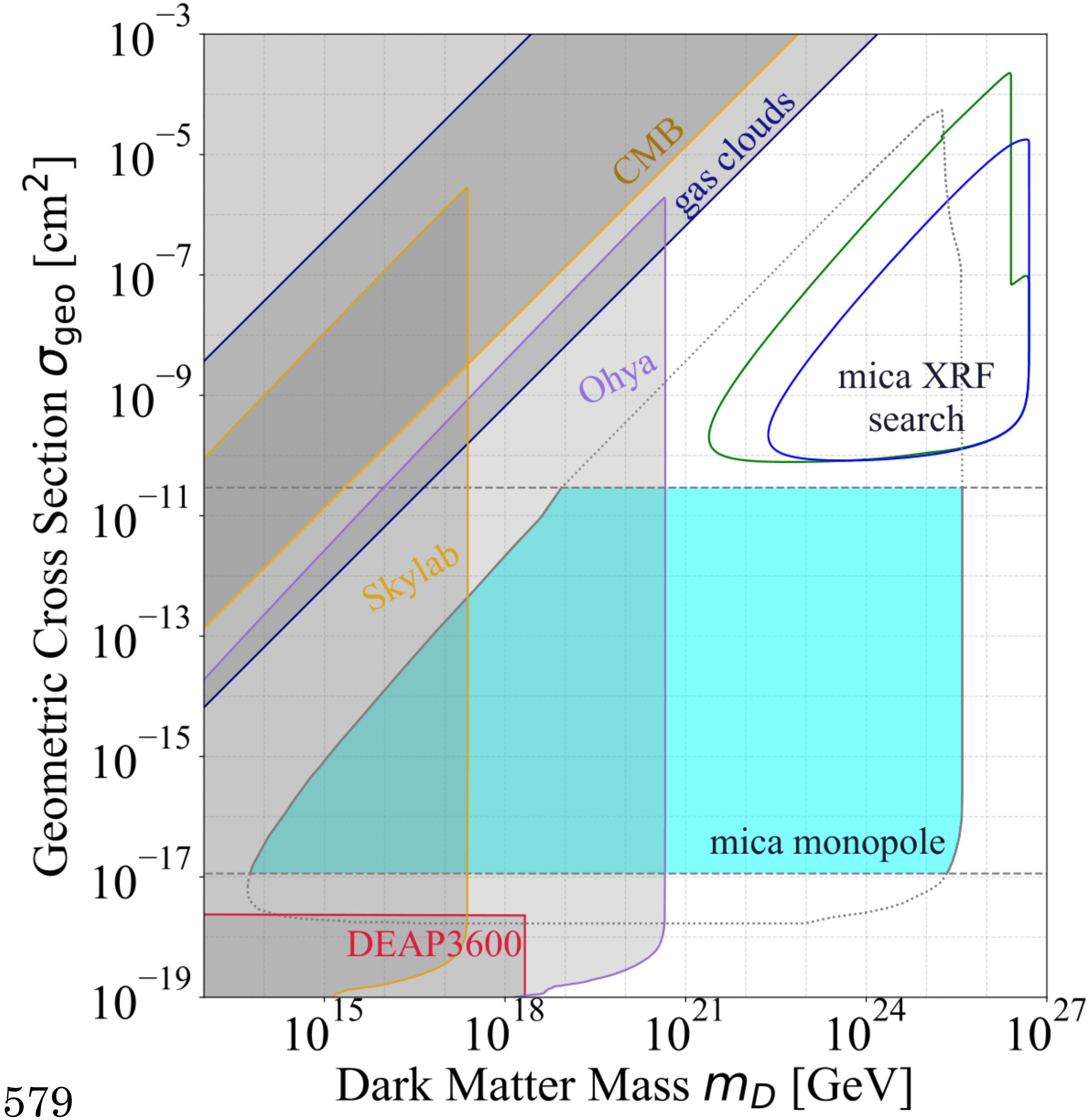
$$\left(\frac{dE}{dx}\right)_{\text{thresh}} = 43.4\,\mathrm{GeV/cm}$$



Refinements: Selection Cuts

- If DM is too big, its damage would be visible to naked eye
- DM-damaged mica could have been excluded by quality cuts in original monopole search
- Set an upper limit on excluded cross sections by imposing a max melt radius of 10 microns





2606.02579

Full Mica Sensitivities

Conclusion

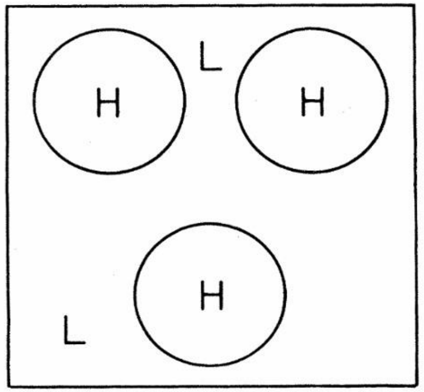
- Mineral searches can reach into parameter space with extremely large masses
- Ongoing search at Queen’s looking for melt tracks in muscovite mica
- Preliminary paper out; onto calibration, measurement and more theory work to find final bounds
- Also re-examined old bounds from monopole searches in mica; less parameter space than originally though

Thank you!

Backup Slides

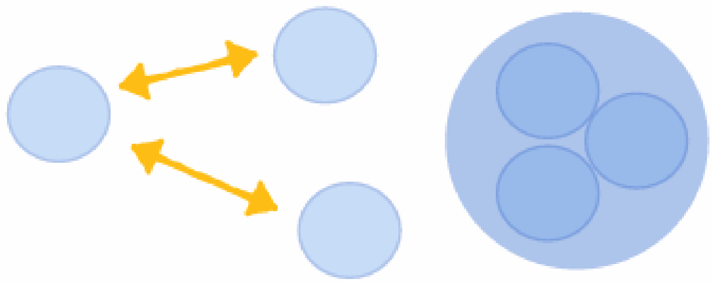
How Can Heavy Dark Matter Form?

Production from False Vacuum Bubbles



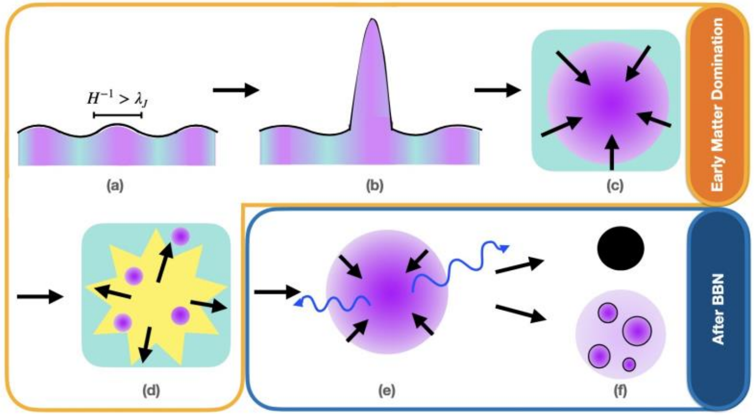
E.g. Witten PhysRevD.30.272

Dark Nucleosynthesis



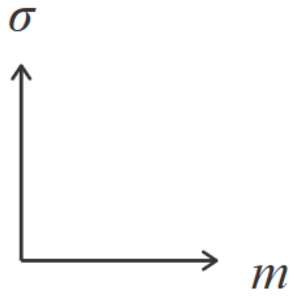
E.g. Sigurdson and Krnjaic 1406.1171

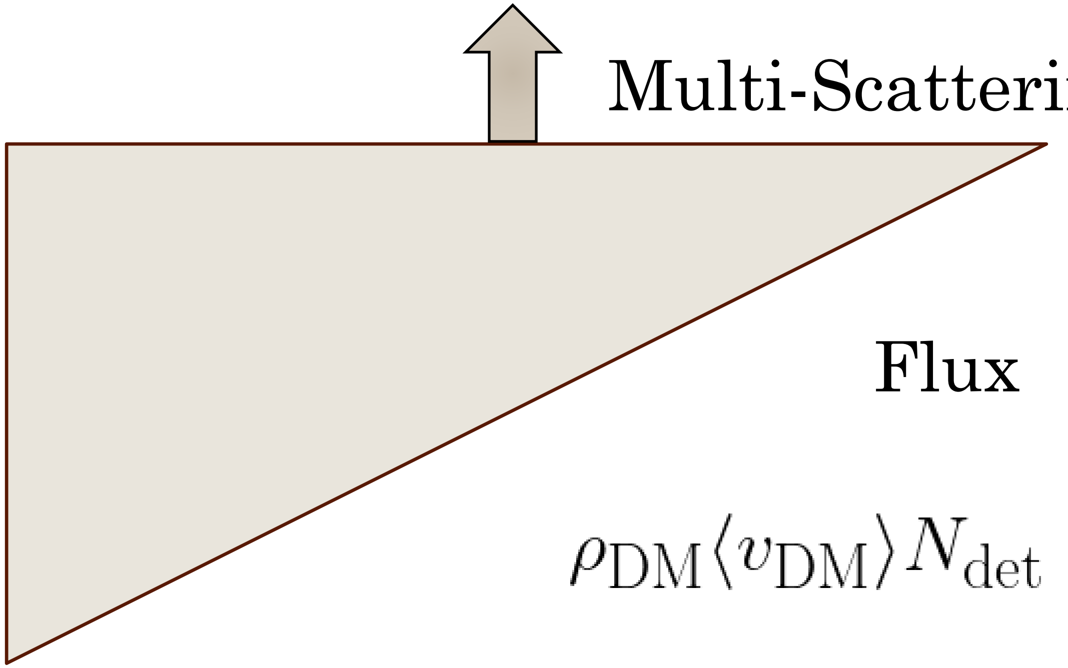
Dissipative Processes



E.g. Bramante, Cappiello, Diamond, Kim, Liu, Vincent 2405.04575

Single Scatter Bounds





Multi-Scattering Regime

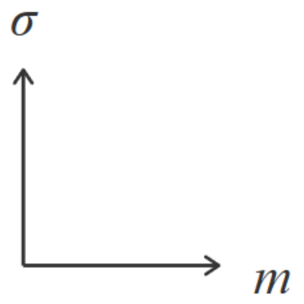
Sensitivity

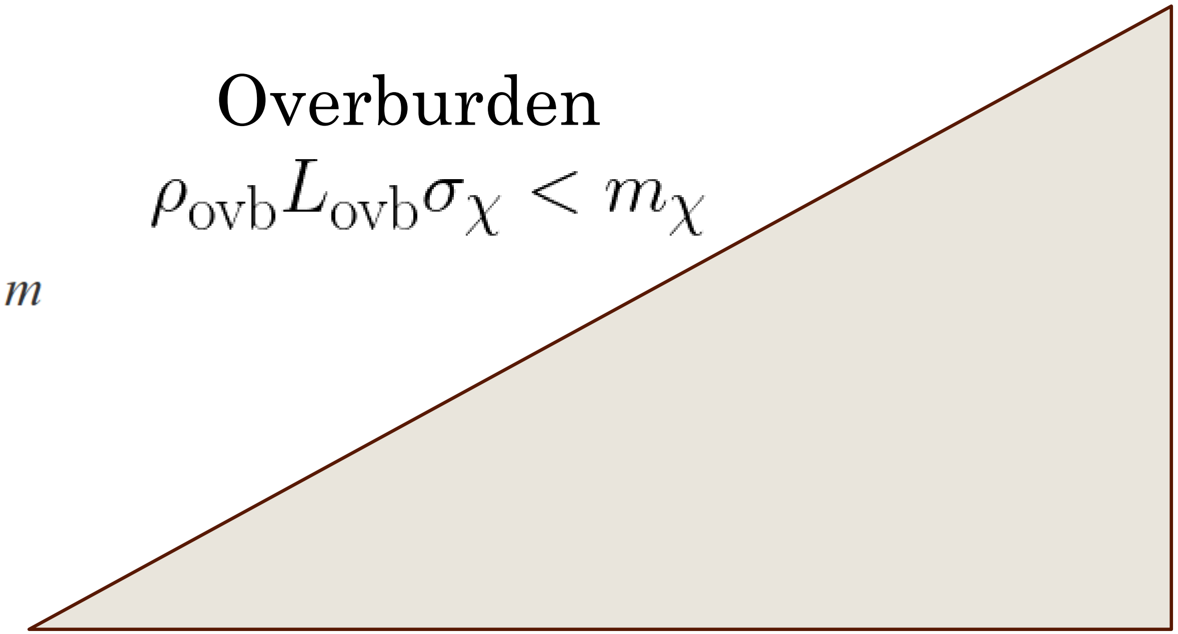
$$\mu_{\rm SM,DM} v_{\rm DM}^2 > E_{\rm thresh}$$

Flux

$$\rho_{\rm DM} \langle v_{\rm DM} \rangle N_{\rm det} \left(\frac{\sigma_{\rm DM}}{m_{\rm DM}} \right) > 1$$

Multi-Scatter Bounds





Overburden

$$\rho_{\text{ovb}} L_{\text{ovb}} \sigma_\chi < m_\chi$$

Flux

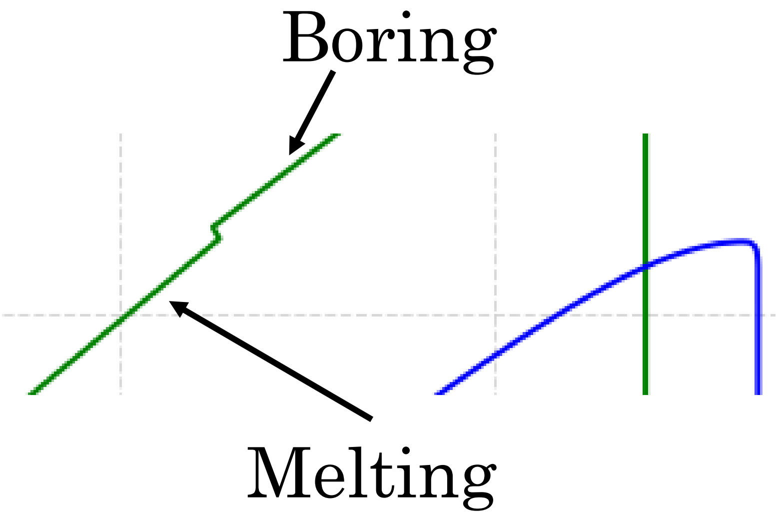
$$1 < \frac{A_{\text{det}}\, T\, \rho_{\text{DM}}\, \langle v_{\text{DM}} \rangle}{m_\chi}$$

Sensitivity $\rho_{\text{det}}\, \sigma_\chi\, v_{\text{DM,max}}^2 > \left(\frac{dE}{dx}\right)_{\text{thresh}}$

Extra Large DM: Boring Bowling Balls

- If $R_D > 25\ \mu$m in bowling ball case, not all energy is deposited inside melt radius
- DM will bore through rather than melt mica.
- Requires less energy to make a bore track.
- Melting around bore hole? Closure from pressure? Needs to be considered in proper bounds

$$\underbrace{\rho_{\text{mica}} v_\chi^2 (\pi R_D^2)}_{\text{energy deposited}} = \underbrace{\rho_{\text{mica}} (C_p \Delta T_{\text{melt}} + H_f) \pi R_D^2}_{\text{energy to push nuclei out of the lattice}}$$

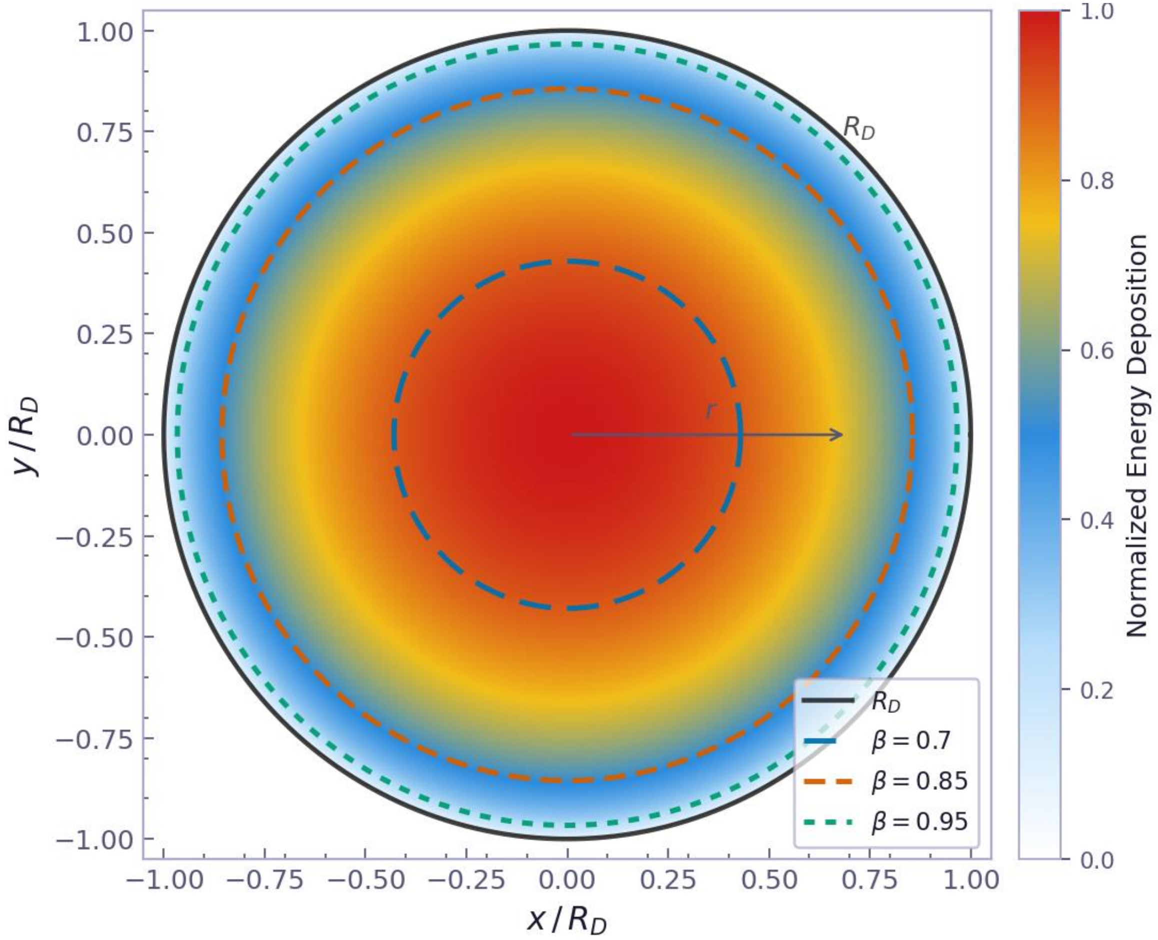


Extra Large DM: Fluffy Cloud

- In per-nucleon/fluffy cloud can melt inside an inner radius 25 μm $< R < R_d$
- Requires a choice of optical depth $\tau = \frac{\sigma_{\text{interaction}}}{\sigma_{\text{geometric}}}$
- Melt radius set by

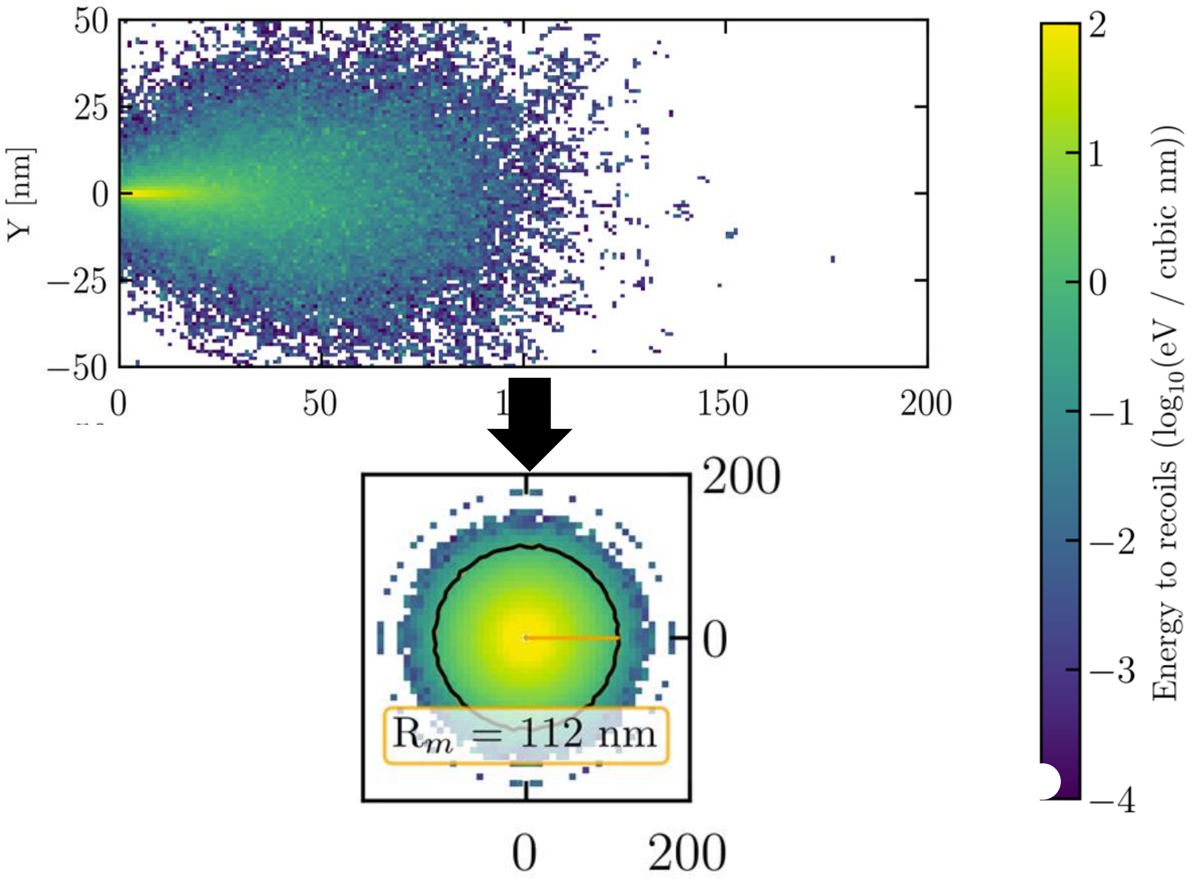
$$\beta = \frac{\pi \eta_{\text{eff}} \tau_{\text{mica}} v_D^2}{C_p \Delta T_{\text{melt}} + H_f}$$

$$\frac{2}{3} \le \beta \le 1$$



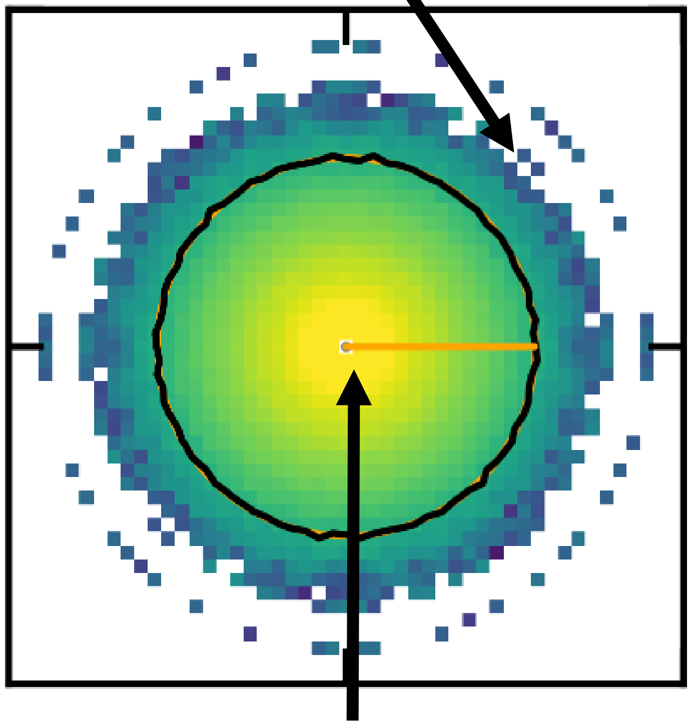
Modeling With SRIM

- SRIM (Stopping and Range of Ions in Matter) models knock-on nuclear scattering and melting
- Models the shower caused by a recoiled nuclei at $v_{\text{recoil}} = 330$ km/s
- Repeated for all nuclei in DM path



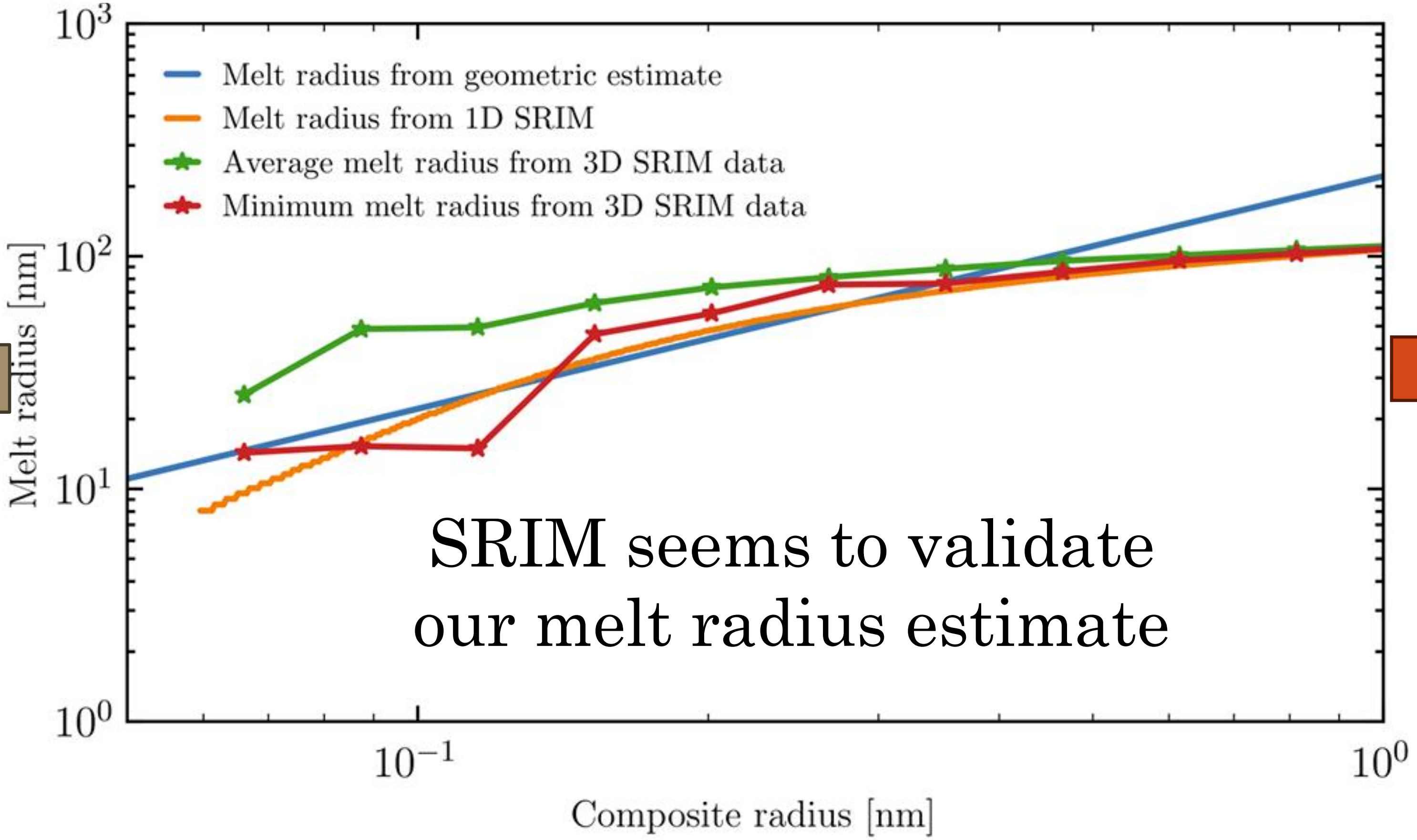
Modeling With SRIM

- SRIM does not properly treat damaged mica
- Does not model melt shockwave front properly for large R_D
- Underestimates true melt radius
- Validity of SRIM: $R_D < 1$ nm (half of border atoms are displaced)



Modeling With SRIM

Not enough recoils for continuous defect

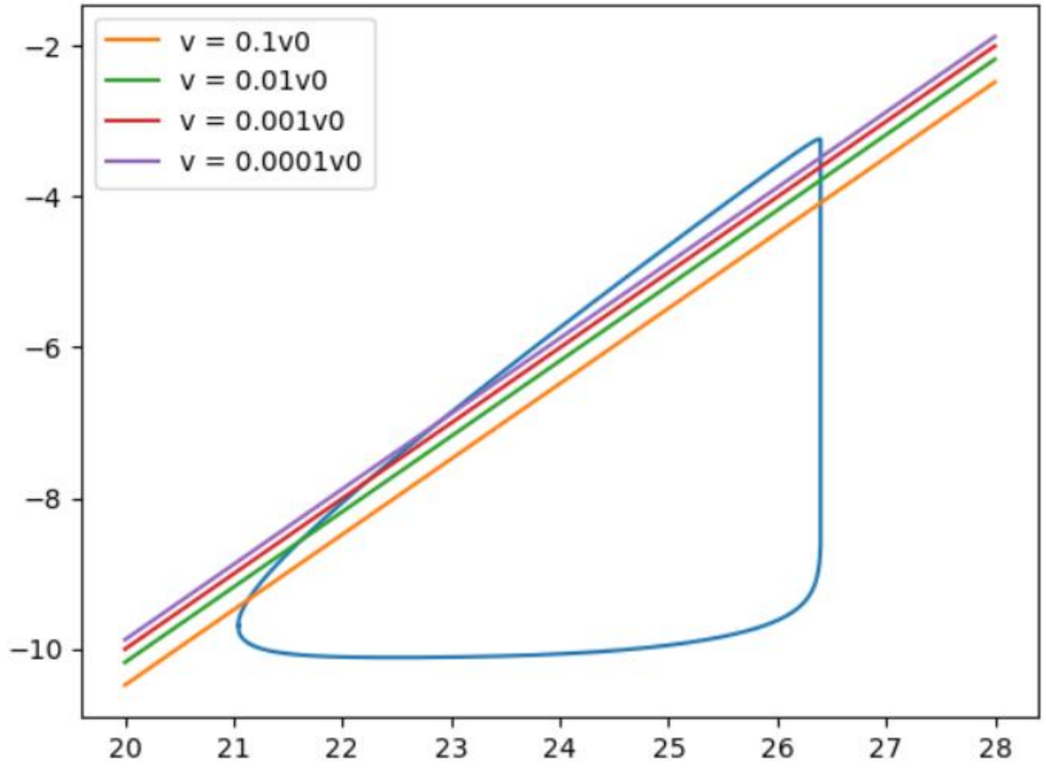


SRIM seems to validate our melt radius estimate

SRIM invalid

DM is Very Fast in Most of Parameter Space

$\log_{10}(\sigma_{\mathrm{geo}}/\ 1\ \mathrm{cm}^2)$

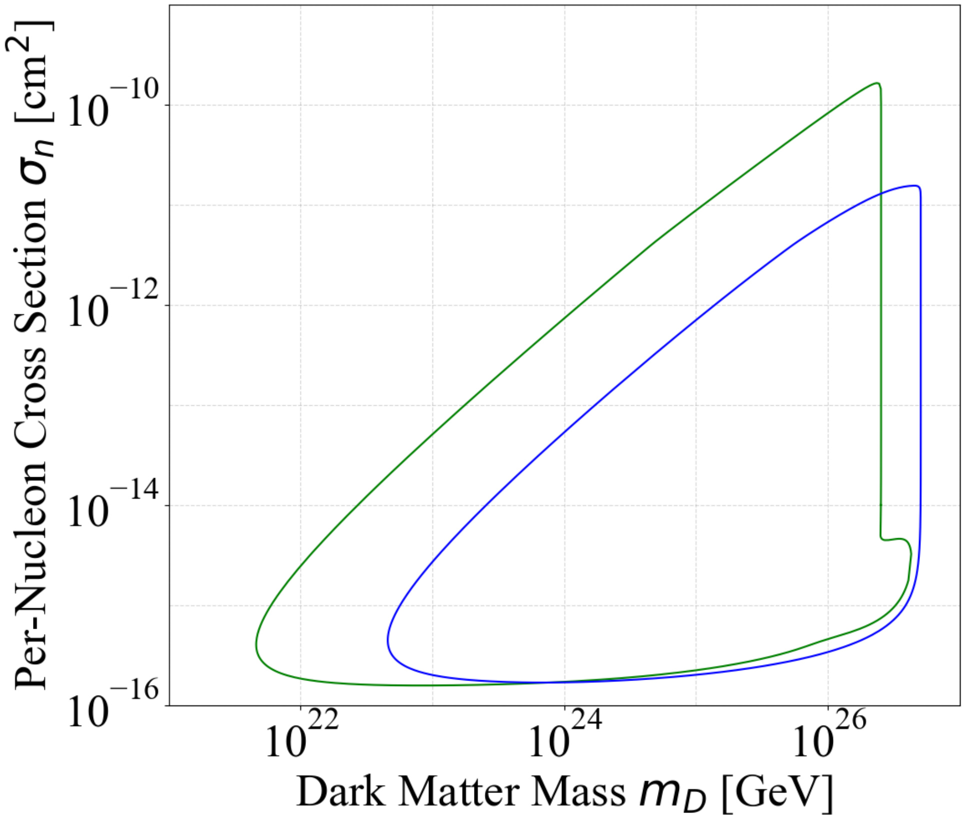


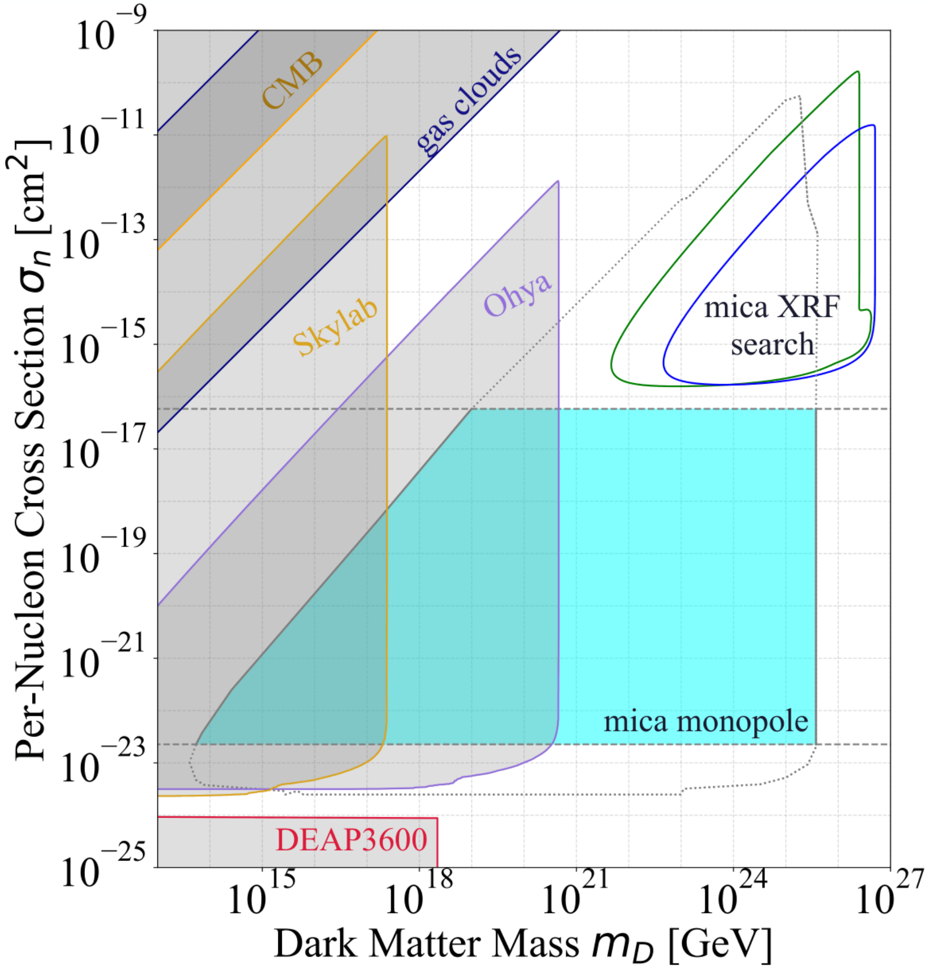
$\log_{10}(m_\chi/\ 1\ \mathrm{GeV})$

Schematic plot of fraction of DM initial speed left when DM hits mica

Assumes constant 20 km overburden

Mica Sensitivities in Per-Nucleon Case





Astrophysics is Complicated

Like Skylab/Ohya, direction of the detector matters

- Daily rotation of Earth
- Axial procession of Earth
- Oscillation of Sun through galactic plane
- Angle between sun orbit and solar system plane
- Plate tectonics changing the mica's latitude

Just average like Skylab!

Has the DM speed distribution changed over the last 1 Gyr?

- LMC + MW dynamics
- Changing solar distance from galactic centre

- Full treatment should include a simulation of velocity distribution.
- Preliminary results use unchanging modern values