Ultra-Heavy Dark Matter Search with Electron Microscopy of Geological Quartz

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2105.03998

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November 4, 2021

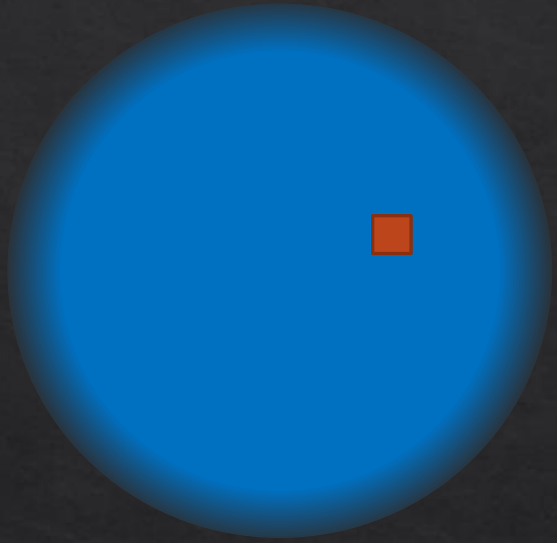
Dark Matter

$\rho_{\mathrm{DM}} \sim 0.2\ \mathrm{GeV/cm^3}$ $\quad v_{\mathrm{DM}} \sim 10^{-3}$

weak self-interactions
→ light elementary particles, e.g. WIMPs

strong self-interactions
→ ultraheavy composite blobs
($m_{\mathrm{DM}} \sim \mathrm{kg} \sim 10^{27}\,\mathrm{GeV}$)

Dark Matter



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($m_{\rm DM} \sim$ kg$\sim 10^{27}$GeV)

How to directly detect?

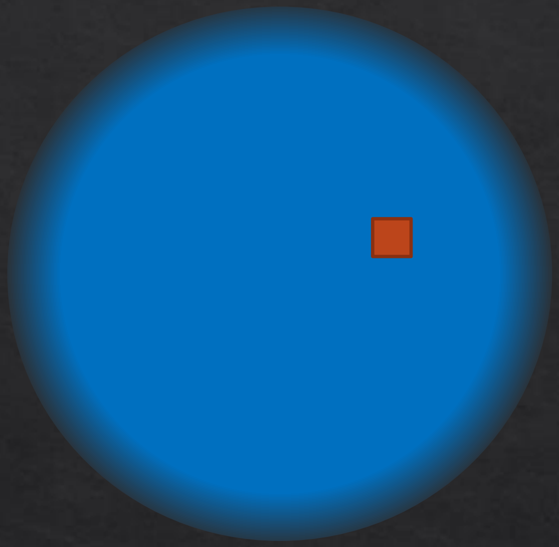
rare transit

$$\#\ \text{of events} \sim \frac{\rho_{\rm DM}}{m_{\rm DM}} v_{\rm DM} T_{\rm exp} A_{\rm exp}$$

but each very powerful

$$m_{\rm DM} v_{\rm DM}^2 \uparrow,\ \ \sigma_{\rm DM} \uparrow$$

Dark Matter



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but each very powerful

$$m_{\mathrm{DM}} v_{\mathrm{DM}}^2 \uparrow, \ \ \sigma_{\mathrm{DM}} \uparrow$$

sensitivity not an issue, one transit is enough

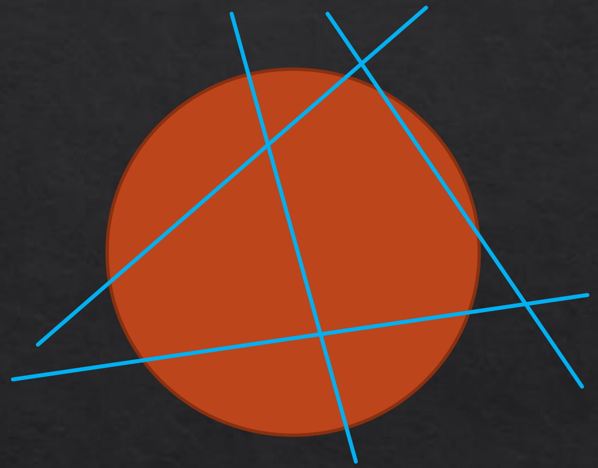
$\#$ of events $> O(1)$ $\quad$ sets max m_{DM}

strategy: maximize $T_{\mathrm{exp}} A_{\mathrm{exp}}$

The Idea

Real-time: $10\ \mathrm{yr} \times (100\ \mathrm{m})^2$

Ancient: $10^9 \mathrm{yr} \times (10\ \mathrm{m})^2 = 10\ \mathrm{yr} \times (100\ \mathrm{km})^2 \longrightarrow m_{\mathrm{DM}} < 100\ \mathrm{kg}$



10^9 yr

Some tracks preserved

The Idea

Real-time: $10\ \mathrm{yr} \times (100\ \mathrm{m})^2$

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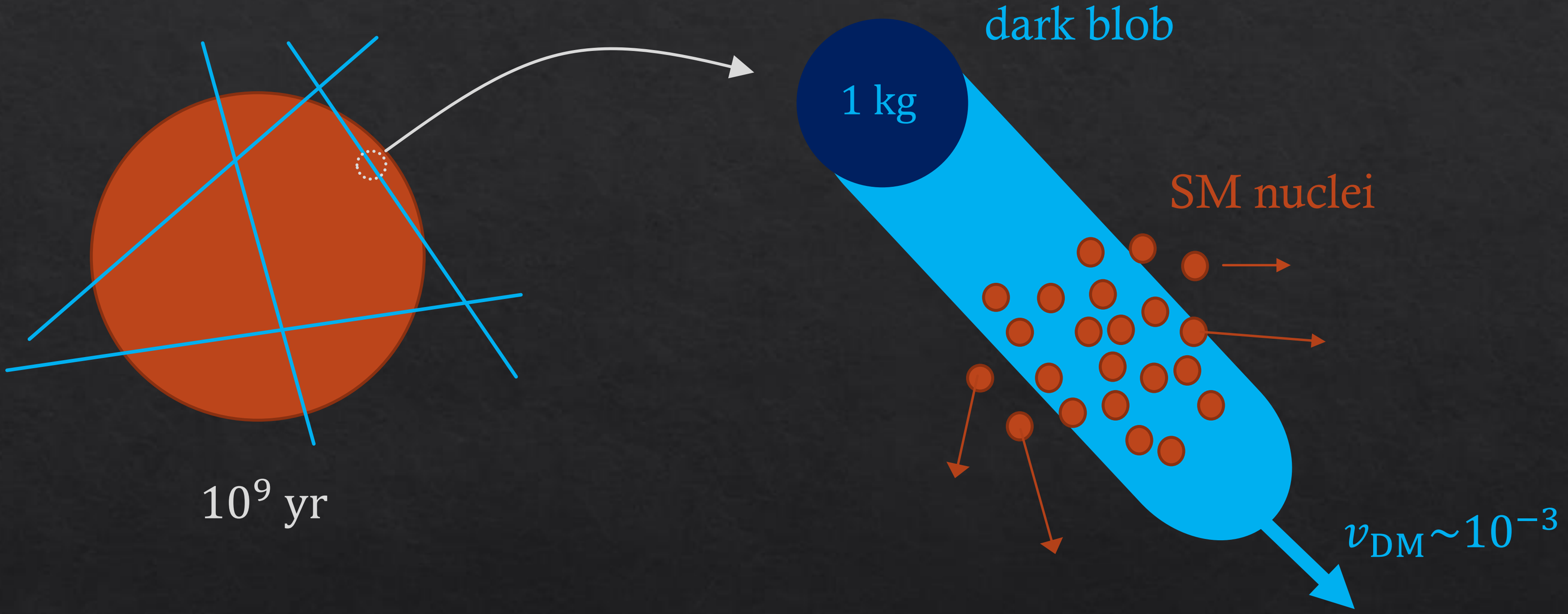
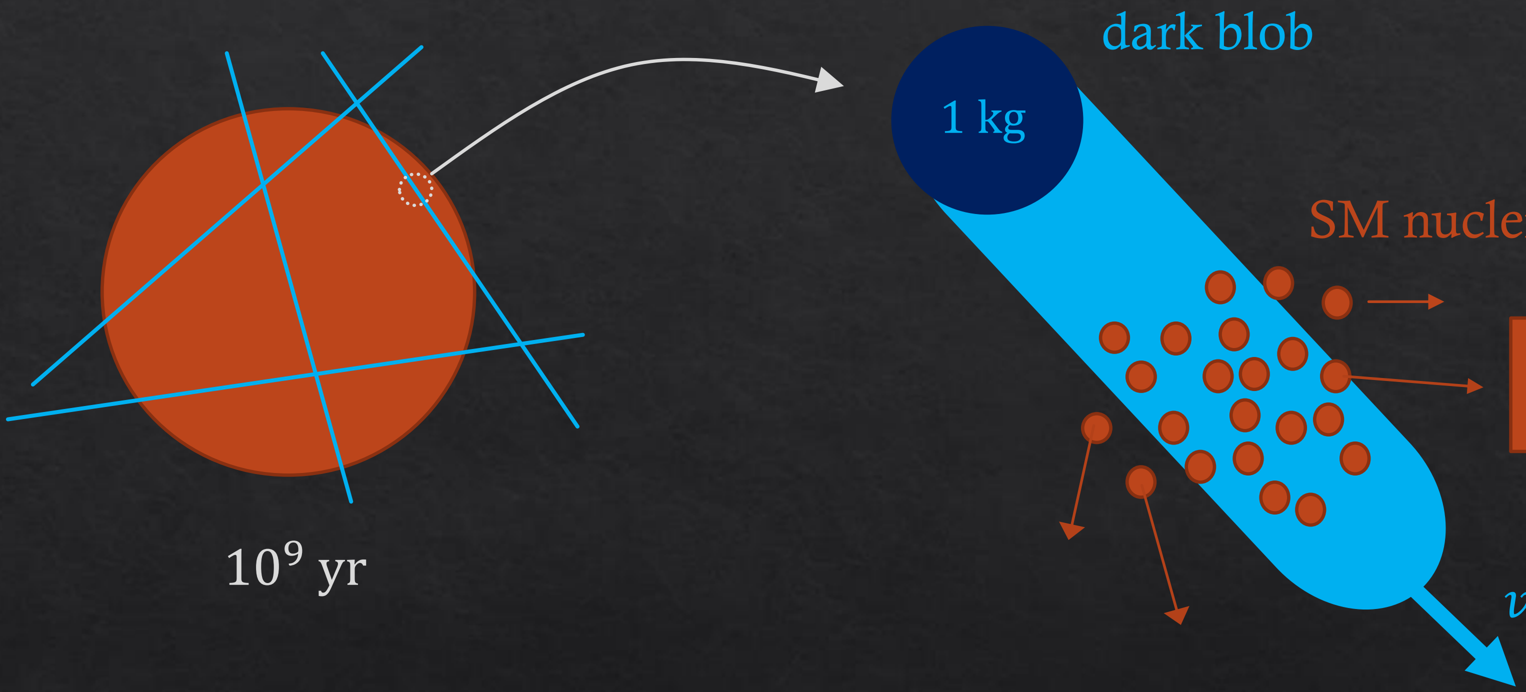


Some tracks preserved

The Idea

Real-time: 10 yr × $(100\ \mathrm{m})^2$

Ancient: 10^9yr × $(10\ \mathrm{m})^2$ = 10 yr × $(100\ \mathrm{km})^2$ ⟶ $m_{\mathrm{DM}} < 100\ \mathrm{kg}$



strong damage

$$E_{\max} \sim \frac{1}{2}(Am_p)v_{\mathrm{DM}}^2 \sim 10\ \mathrm{keV}$$

Some tracks preserved

Long, very straight, microscopic diameter tracks

The Idea

Real-time: $10\ \text{yr} \times (100\ \text{m})^2$

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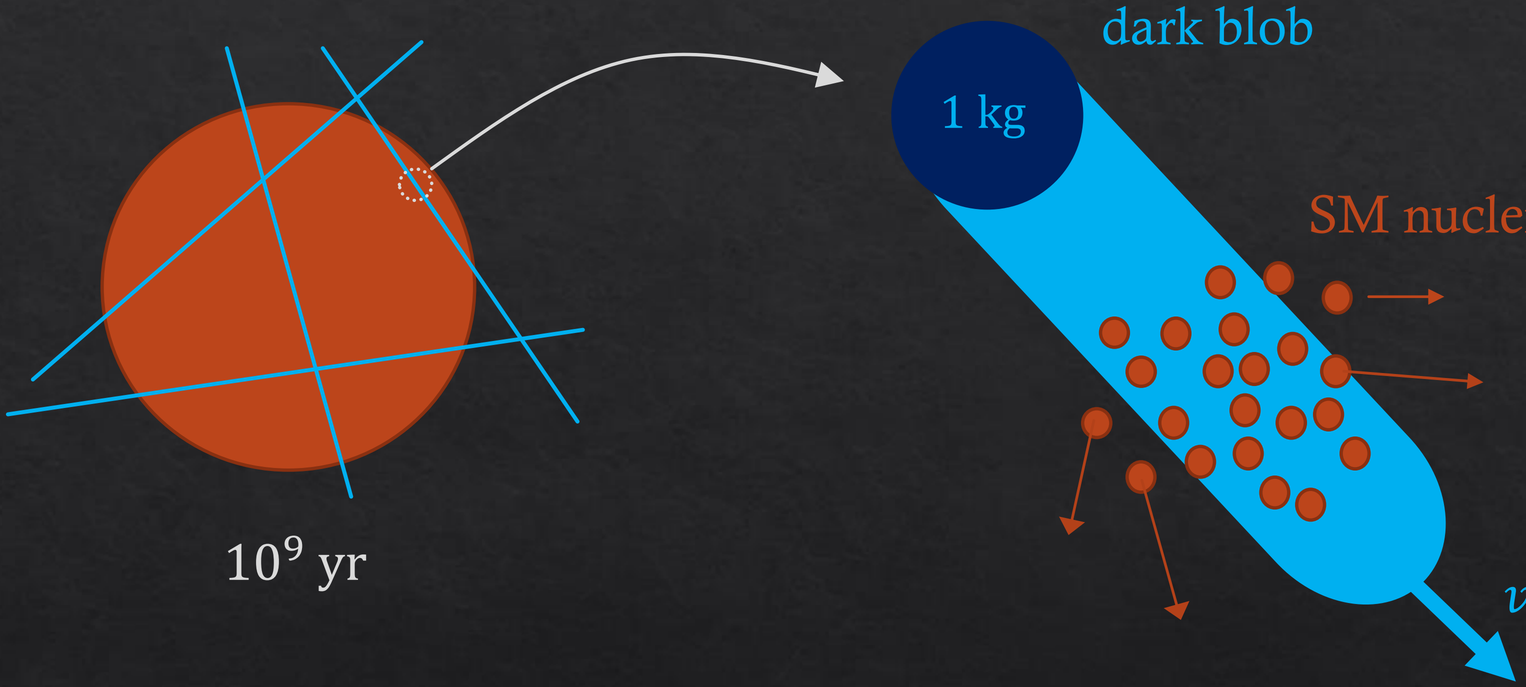

$$E_{\max} \sim \frac{1}{2}(Am_p)v_{\text{DM}}^2 \sim 10\ \text{keV}$$

Some tracks preserved

Long, very straight, microscopic diameter tracks

massive, hard to stop

The Idea

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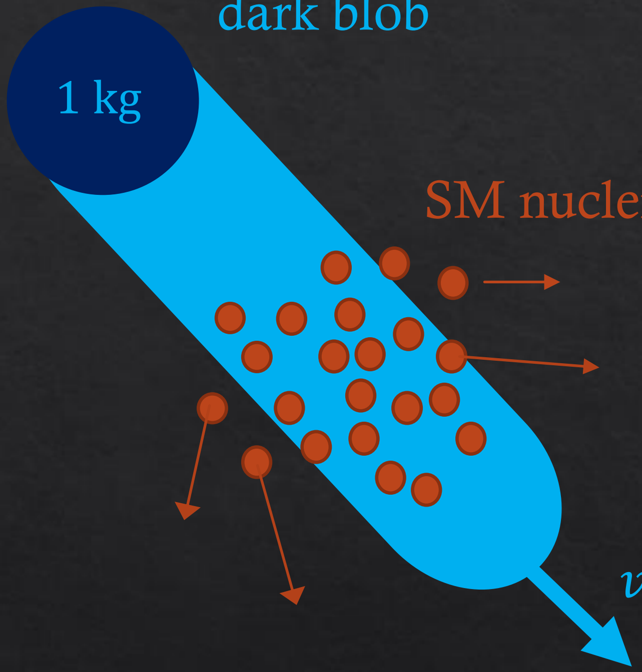
10^9 yr

Some tracks preserved



$$E_{\text{max}} \sim \frac{1}{2}(Am_p)v_{\text{DM}}^2 \sim 10\ \text{keV}$$

Long, very straight, microscopic diameter tracks

probe more parameter space

The Idea

Real-time: $10 \text{ yr} \times (100 \text{ m})^2$

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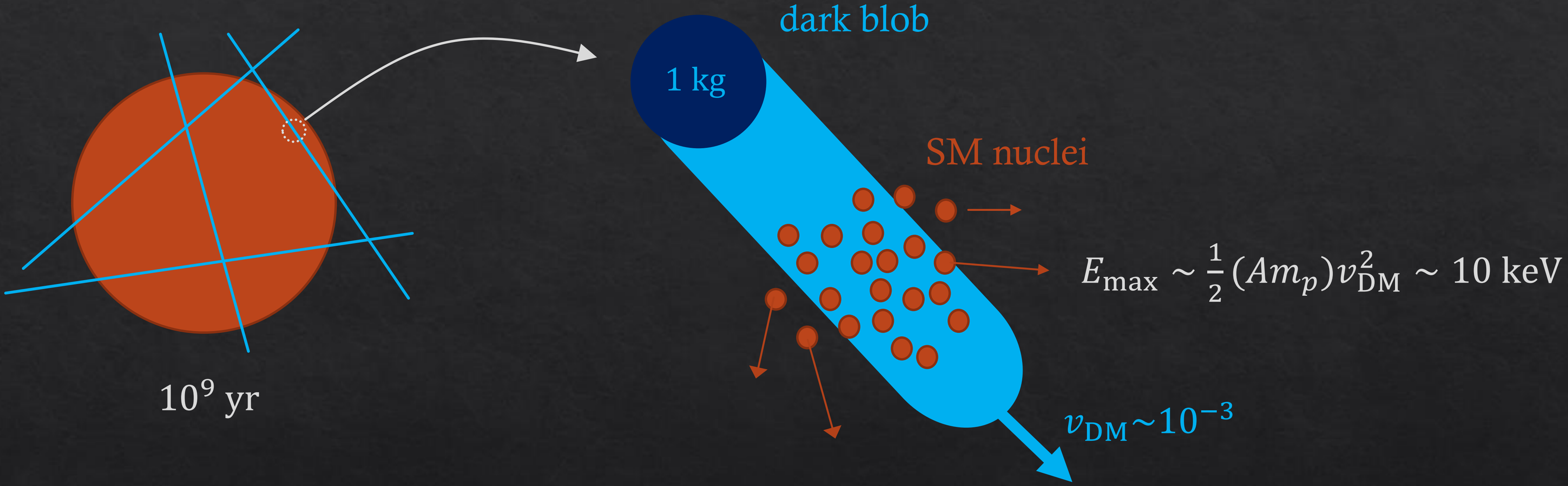


Some tracks preserved

Long, very straight, microscopic diameter tracks

Which rock?

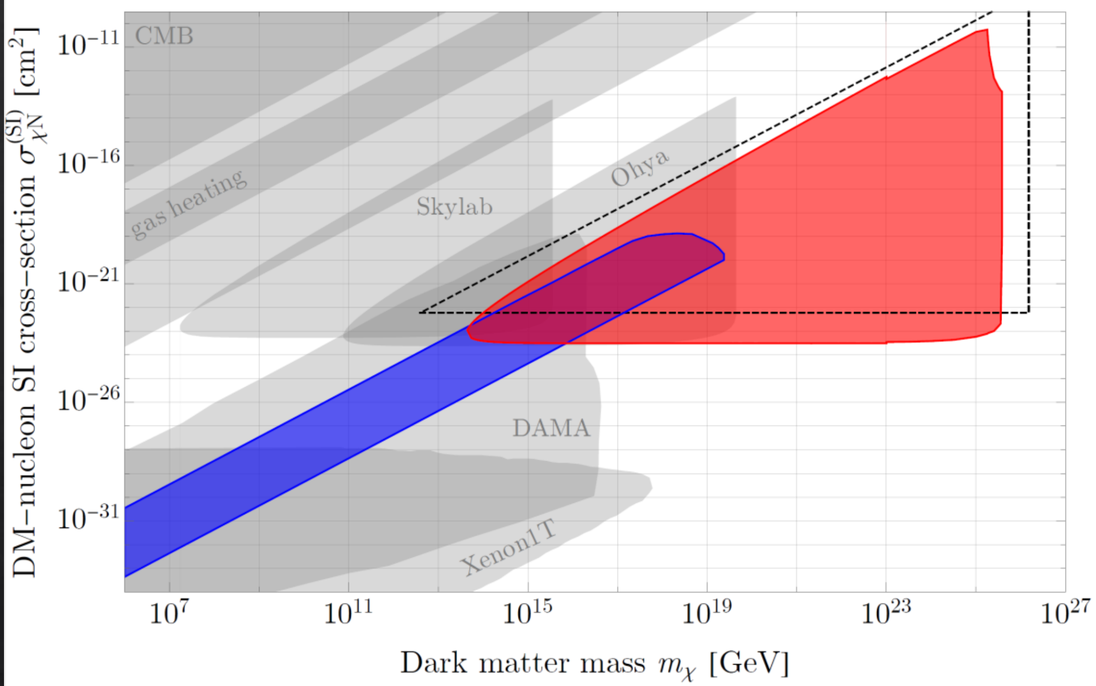
How to scan?

VOLUME 56, NUMBER 12 PHYSICAL REVIEW LETTERS 24 MARCH 1986

Search for Supermassive Magnetic Monopoles Using Mica Crystals

P. B. Price and M. H. Salamon
Department of Physics, University of California, Berkeley, California 94720
(Received 18 November 1985)

- Long tracks in mica
- Acid etching + optical microscopy
- $T_{\mathrm{exp}} A_{\mathrm{exp}} = \mathrm{Gyr} \times 0.1\ \mathrm{m}^2$
- $m_{\mathrm{DM}} < 10^{26}\mathrm{GeV}$

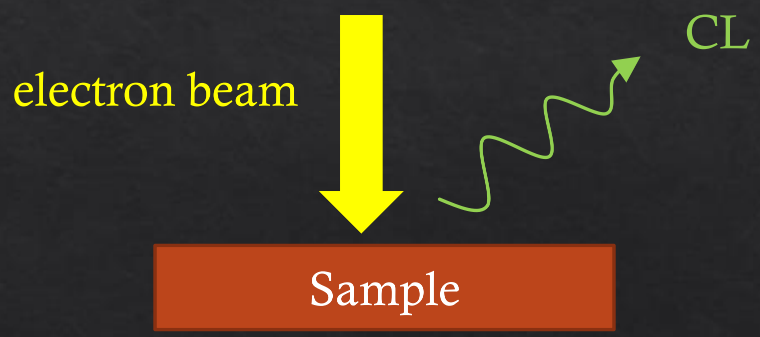


Acevedo, Bramante, Goodman 2021 [2105.06473]

Scan Quartz with SEM-CL

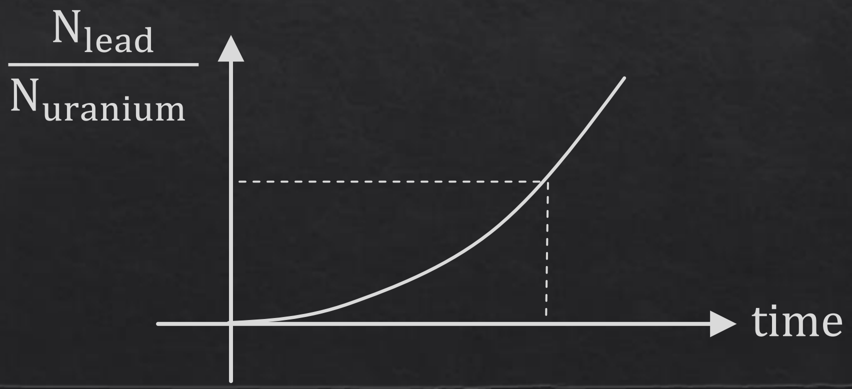
SEM-CL

- Scanning Electron Microscopy (SEM)
- Cathodoluminescence (CL)
- μm resolution



Quartz

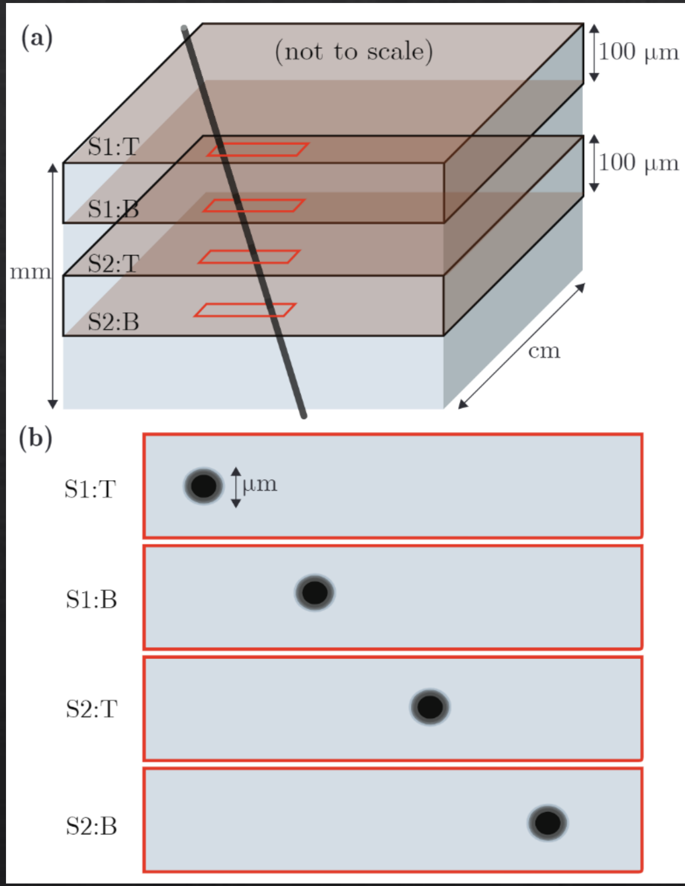
- Crystalline form of silica, melts at $T \sim$ eV
- Passing blob leaves behind amorphous silica
- Old ($T_{\mathrm{exp}} \uparrow$), abundant ($A_{\mathrm{exp}} \uparrow$)



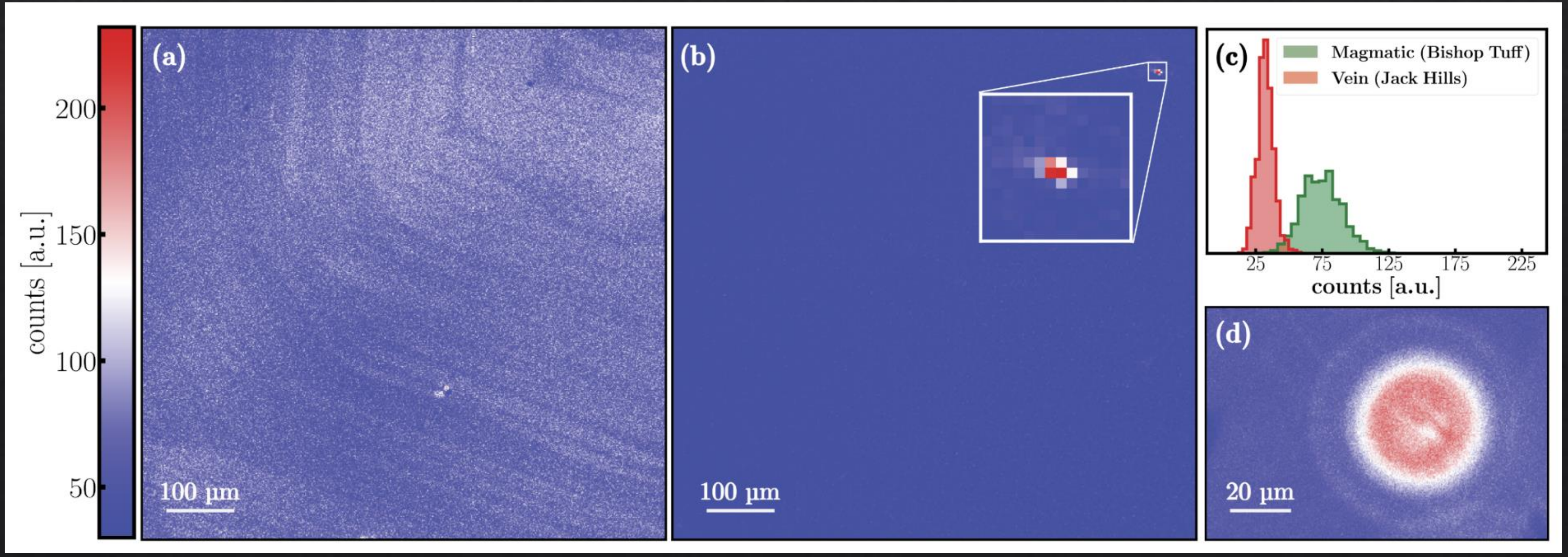
Our signal is difficult to fake

- Our signal
  - $> \mu m$ radius, straight, macroscopically long (1D)
- Geological fractures
  - macroscopic (2D or 3D)
- Cosmic rays, neutrinos
  - scattered little dots (0D)
- Uranium fission tracks
  - 10 μm balls (0D)

Geometric rejection



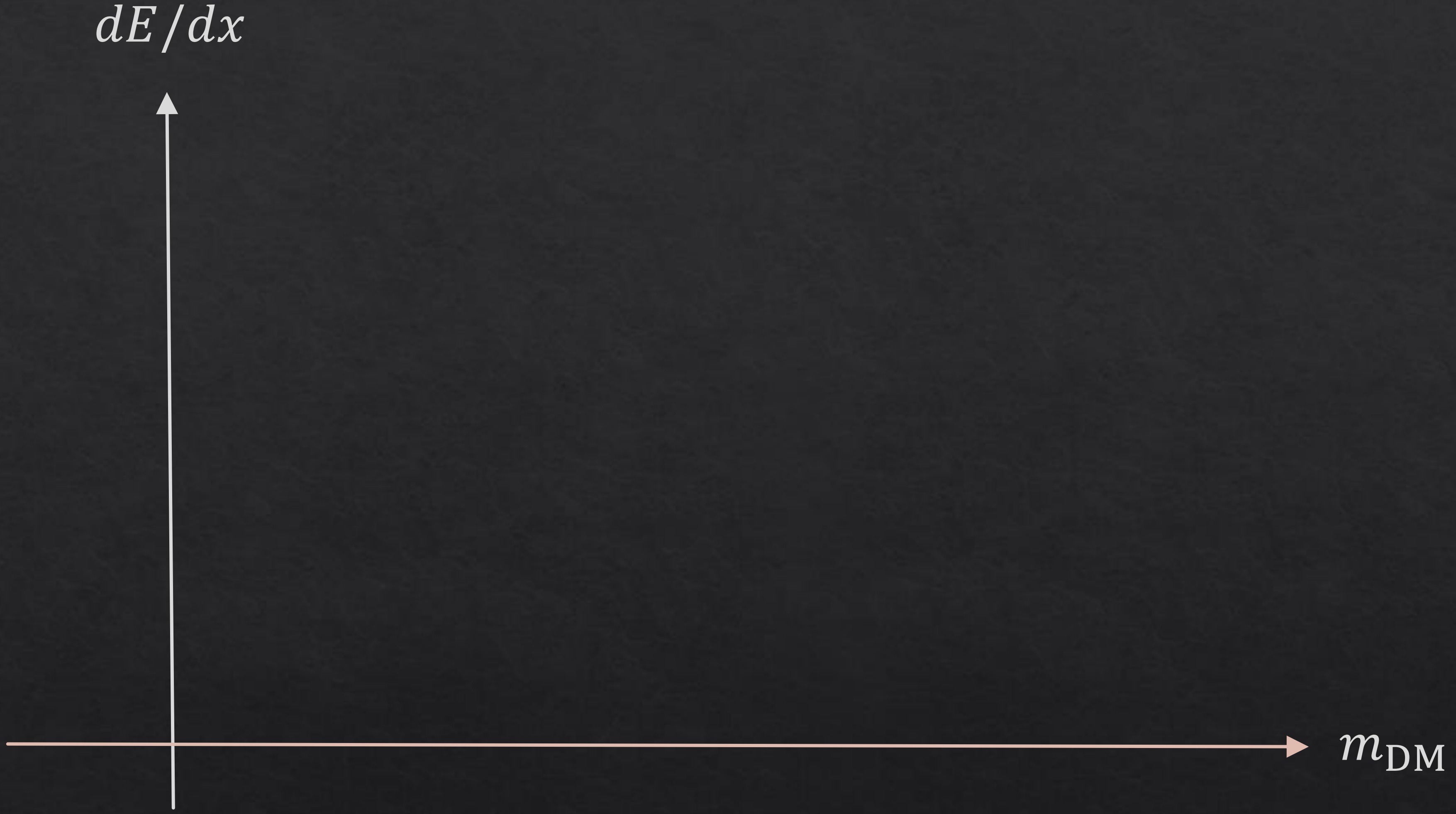
Jack Hills, Australia



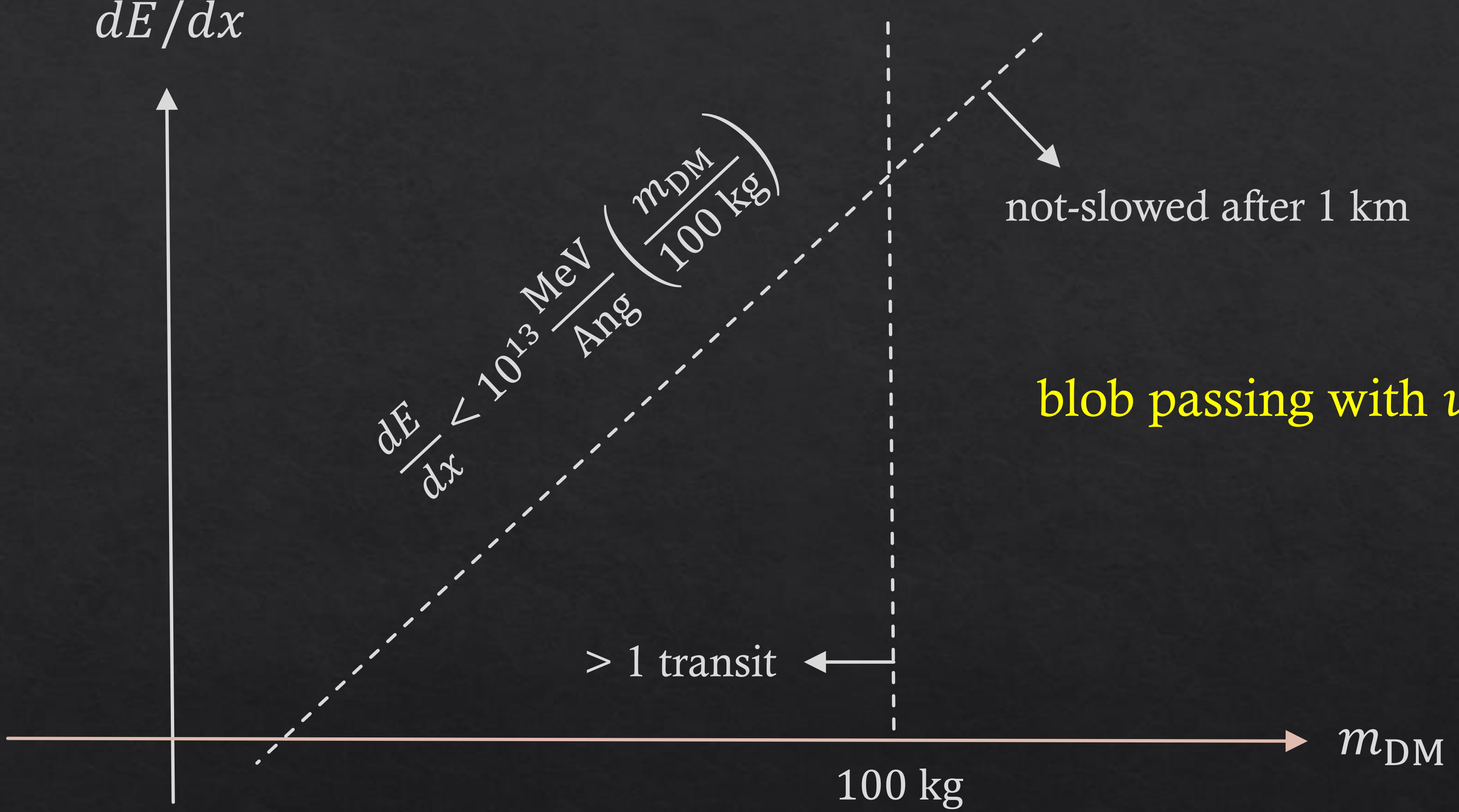
This took 5 $\mathrm{s/mm^2}$
(the bottleneck)

reach: $m_{\mathrm{DM}} < 100$ kg

Model-Independent Sensitivity

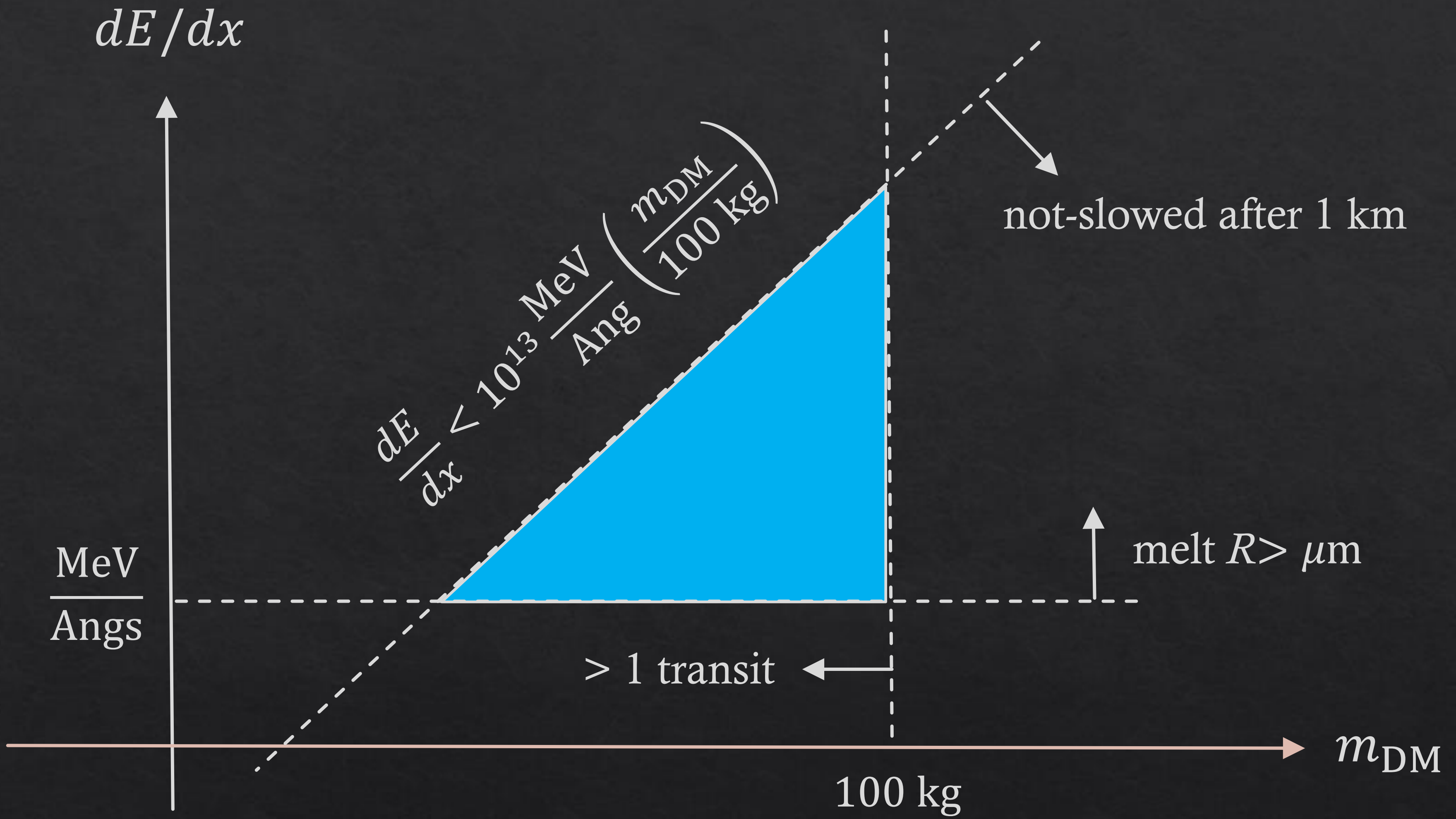


Model-Independent Sensitivity



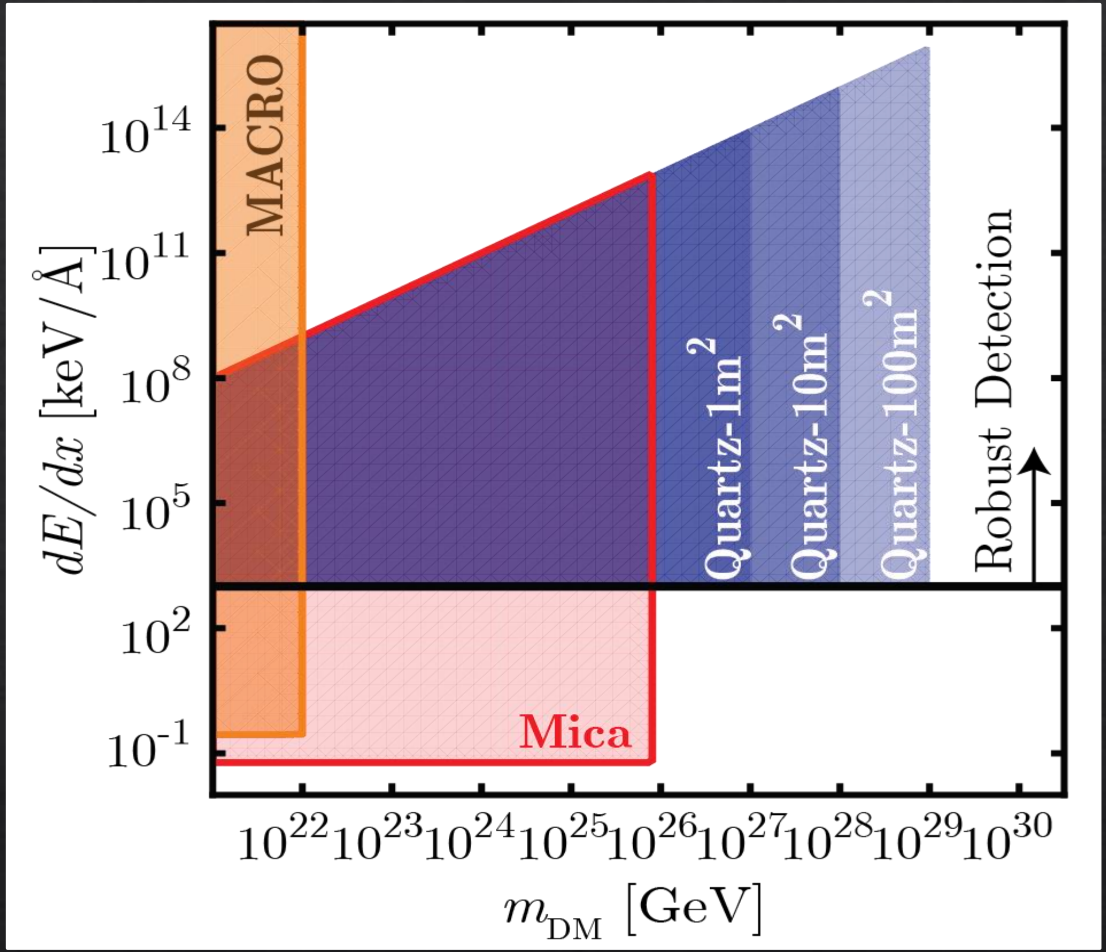
blob passing with $v_{\mathrm{DM}} \sim 10^{-3}$

Model-Independent Sensitivity



melting condition: $E_{\text{kick}} >$ eV

Model-Independent Sensitivity



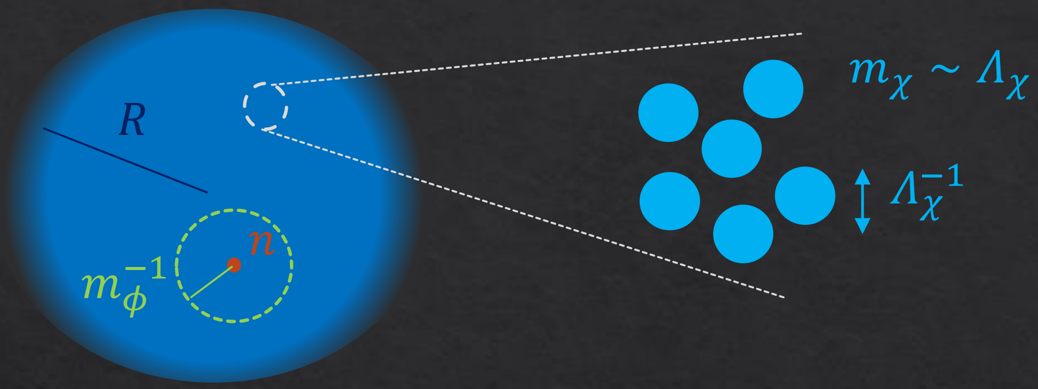
Summary

- Ultraheavy (~kg) dark matter search needs high exposure (high $T_{\text{exp}} A_{\text{exp}}$)
- Idea: scan T_{exp}~Gyr old quartz with SEM-CL
- Sensitive to any dark matter that leaves detectable long tracks in quartz
- We gave one example model that does that, and there are likely many more
- Worth doing anyway, for geology purposes

Thank You

Example Model

QCD-like theory with fermionic blobs



Repulsive Yukawa coupling with SM nucleons

$$\mathcal{L} = \cdots - \frac{1}{2} m_\phi^2 \phi^2 - g_\chi \phi \chi \bar{\chi} + g_n \phi \bar{n} n$$

Interesting regime: $\Lambda_\chi^{-1} \ll m_\phi^{-1} \ll R$

Nucleons receive an effective mass inside the blob

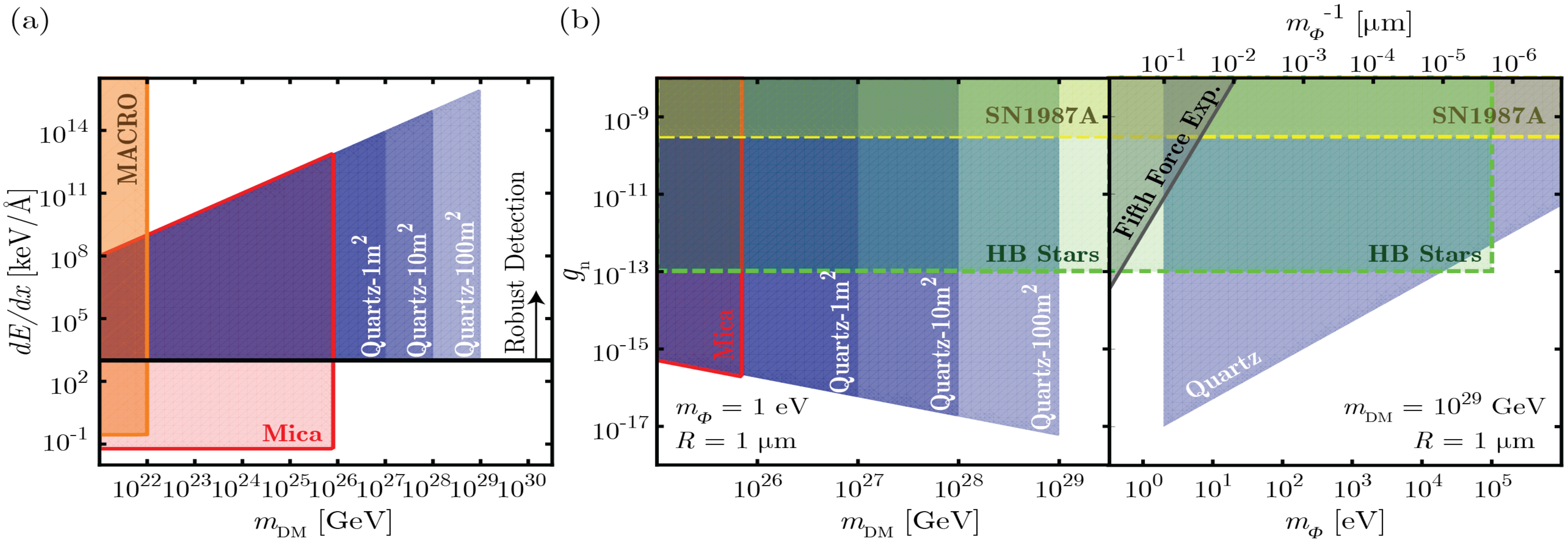
$$g_n \langle \phi \rangle \sim \frac{g_n g_\chi}{m_\phi^{-1}} \left(\frac{m_\phi^{-1}}{\Lambda_\chi^{-1}} \right)^3 = \text{constant}, \qquad r < R$$

Moving potential hill, $V_0 = g_n \langle \phi \rangle$

$$E_{\text{kick}} \sim 10 \text{ keV} \min \left[1, \left(\frac{V_0}{10 \text{ keV}} \right)^2 \right]$$

$$\frac{dE}{dx} \sim \frac{E_{\text{kick}}}{5 \text{ Ang}} \left(\frac{R}{\text{Ang}} \right)^2$$

Example Model Sensitivity



Future

- Signal calibration
  - Create damage tracks artificially (with high-pulsed laser), put under SEM-CL
- Noise calibration
  - Check the CL level of natural and synthetic samples with different levels of CL activators
- Look for long tracks of lattice defects
  - Sensitive to energy depositions below the melting threshold, can probe DM microphysics

Model-Independent Reach

[ancient mica] 10^{26} GeV < m_{DM} < 10^{29} GeV [O(1) blob transit]

[melting threshold] eV < E_{kick} < 10 keV [kinematics]

[melting μm-radius cylinder] $\frac{\mathrm{MeV}}{\mathrm{Ang}} < \frac{dE}{dx} < 10^{13}\,\frac{\mathrm{MeV}}{\mathrm{Ang}}\left(\frac{m_{\mathrm{DM}}}{100\ \mathrm{kg}}\right)$ [blob not slowing]