Ultraheavy Dark Matter Search with Geological Quartz

Erwin Tanin

Johns Hopkins University

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Theorists: R. Ebadi, A. Mathur, S. Rajendran

Experimentalists: R. Ebadi, M. C. Marshall, A. Ravi, R. Trubko, D. F. Phillips, R. L. Walsworth

Geologists: N. D. Tailby, R. R. Fu

October 6, 2022

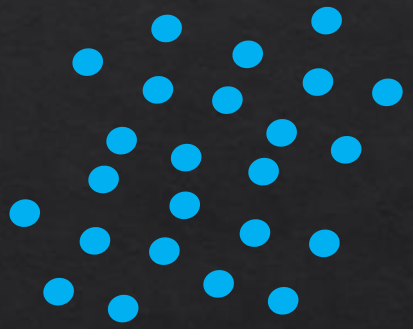
Outline

- Detecting ultraheavy dark matter
- Experimental Proposal
- Experimental Reach
- Example dark matter blob model
- Future work and summary

Detecting Ultraheavy Dark Matter

Ultraheavy Composite Dark Matter

Weak self-interactions



Light elementary particles

Strong self-interactions

nuggets, clumps, ultraheavy dark matter,…

Composite blobs

This talk: $m_{\mathrm{DM}} \sim 0.1 - 100$ **kg**

How to directly detect heavy dark blobs?

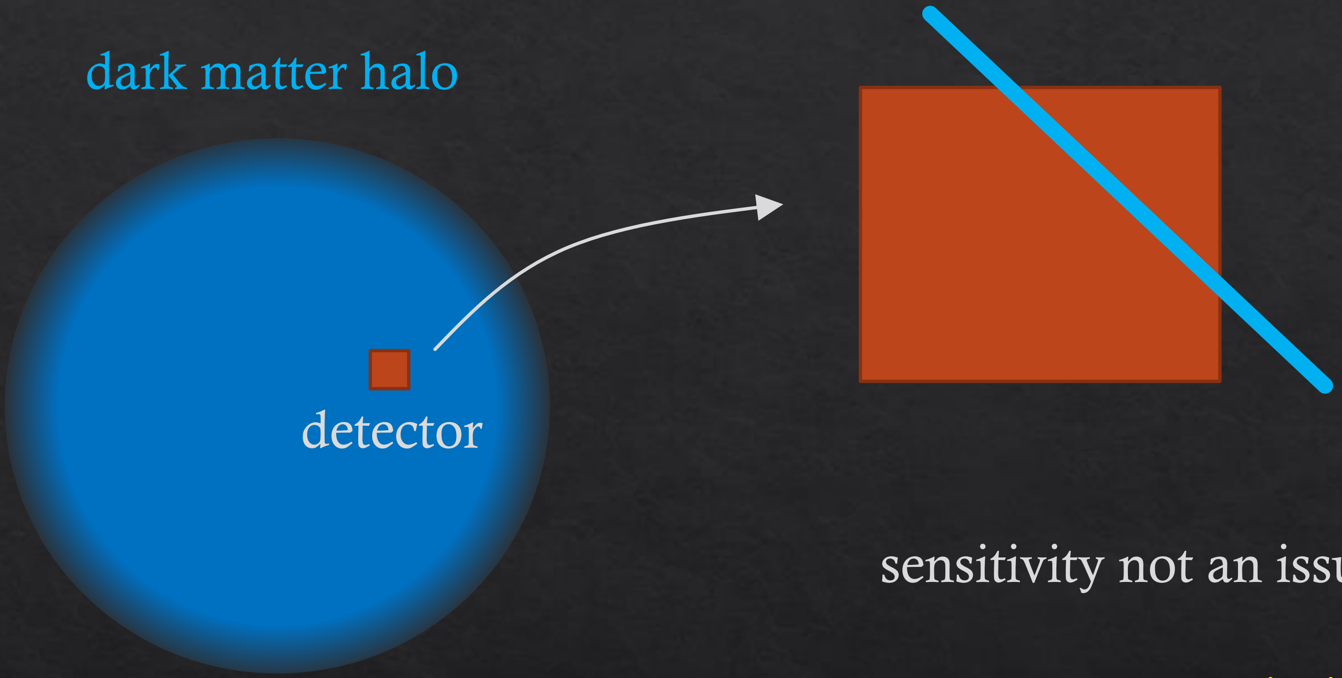
dark matter halo

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

$m_{\mathrm{DM}} \uparrow, \quad n_{\mathrm{DM}} \downarrow$

How to directly detect heavy dark blobs?

dark matter halo



heavy blobs transit rarely,

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

so each transit can be very powerful

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

$m_{DM} \uparrow$, $n_{DM} \downarrow$

sensitivity not an issue, one transit is enough

strategy: maximize exposure $T_{exp} A_{exp}$

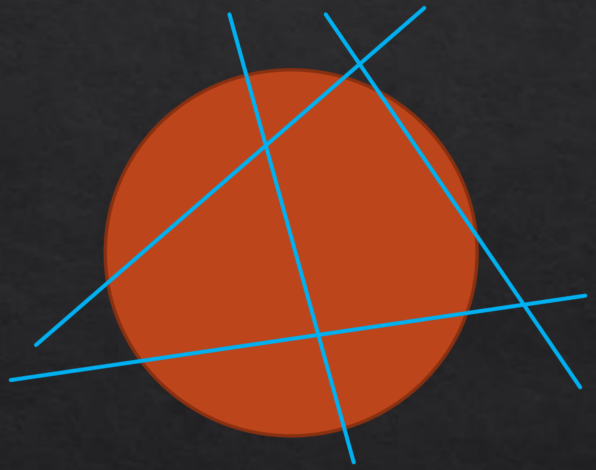
$$\#\text{ of events} \sim \left(\frac{\rho_{DM}}{m_{DM}} v_{DM}\right)\left(T_{exp} A_{exp}\right) > O(1)$$

This sets max m_{DM}

The Idea

Real-time: $10\ \text{yr} \times (100\ \text{m})^2$ ⟶ $m_{\text{DM}} < 0.1\ \text{g}$

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



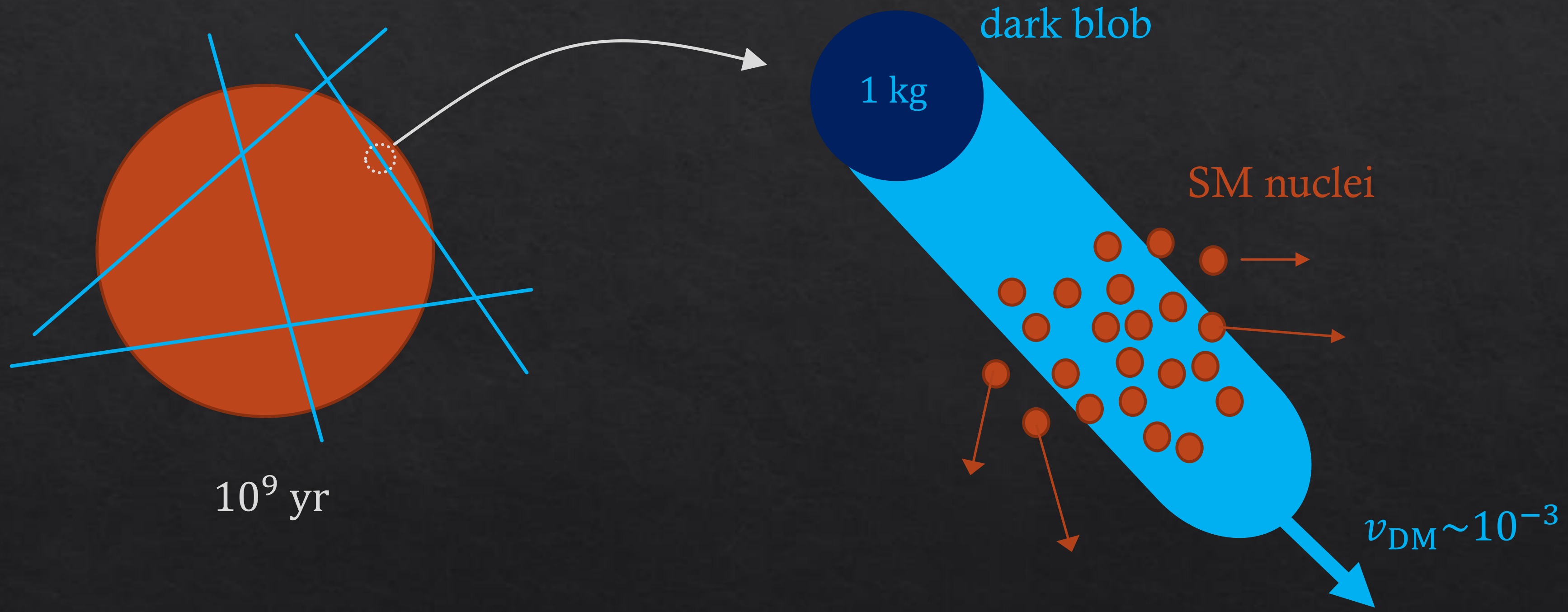
10^9 yr

Some tracks preserved

The Idea

Real-time: 10 yr × $(100\ \text{m})^2$ ⟶ $m_{\text{DM}} < 0.1$ g

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

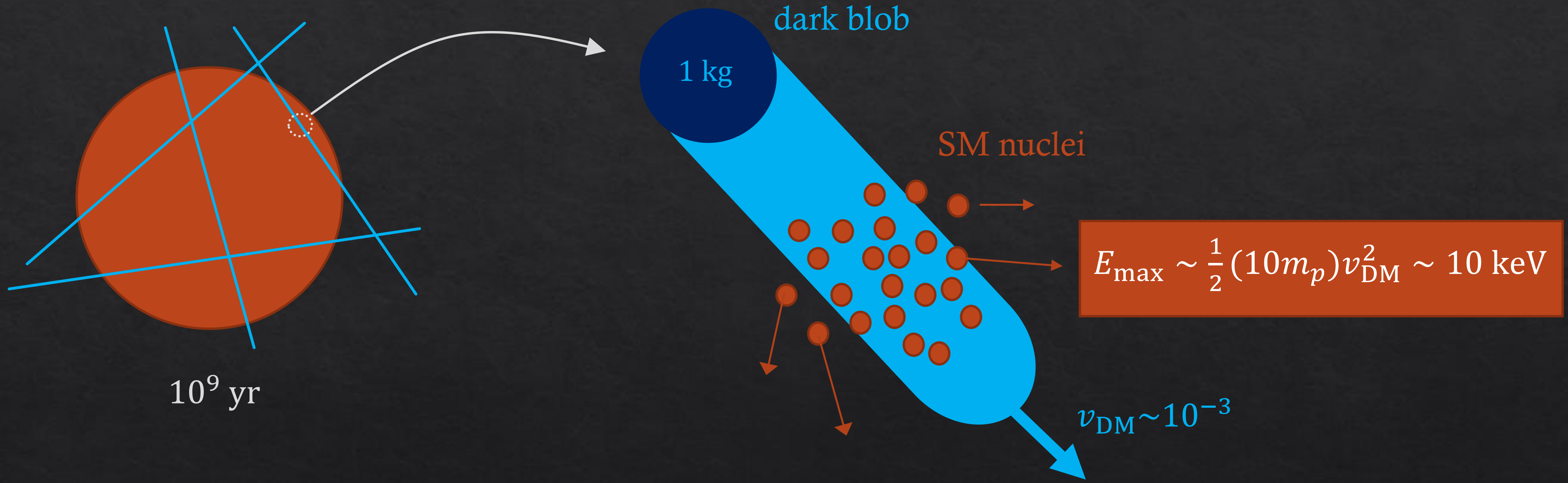


Some tracks preserved

The Idea

Real-time: $10\ \mathrm{yr} \times (100\ \mathrm{m})^2$ → $m_{\mathrm{DM}} < 0.1\ \mathrm{g}$

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



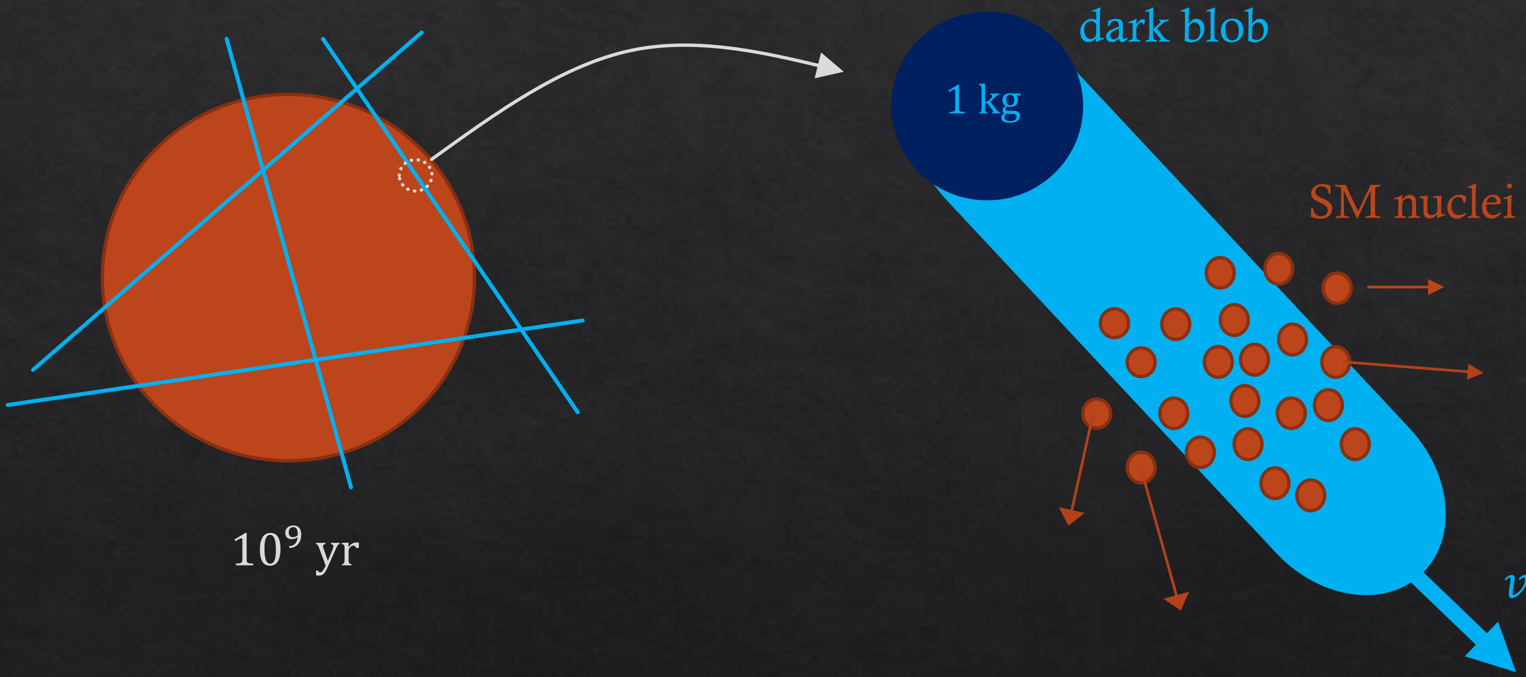
Some tracks preserved

Long, very straight, microscopic diameter tracks

The Idea

Real-time: $10\ \text{yr} \times (100\ \text{m})^2$ $\longrightarrow$ $m_{\text{DM}} < 0.1\ \text{g}$

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



10^9 yr

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

Some tracks preserved

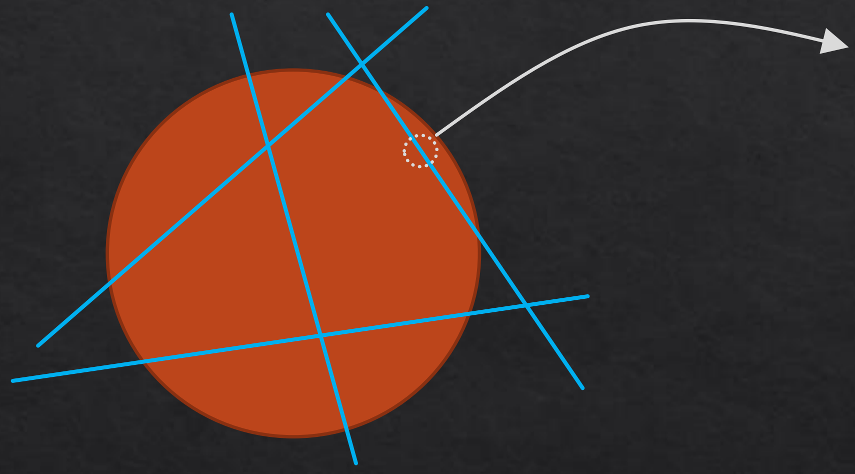
Long, very straight, microscopic diameter tracks

massive, hard to stop

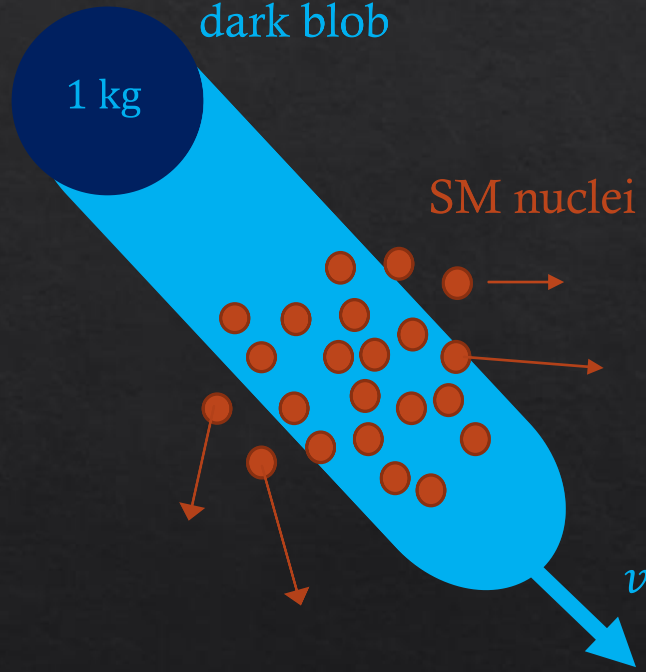
The Idea

Real-time: $10\ \text{yr} \times (100\ \text{m})^2$ ⟶ $m_{\text{DM}} < 0.1\ \text{g}$

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



10^9 yr



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

$v_{\text{DM}} \sim 10^{-3}$

Some tracks preserved

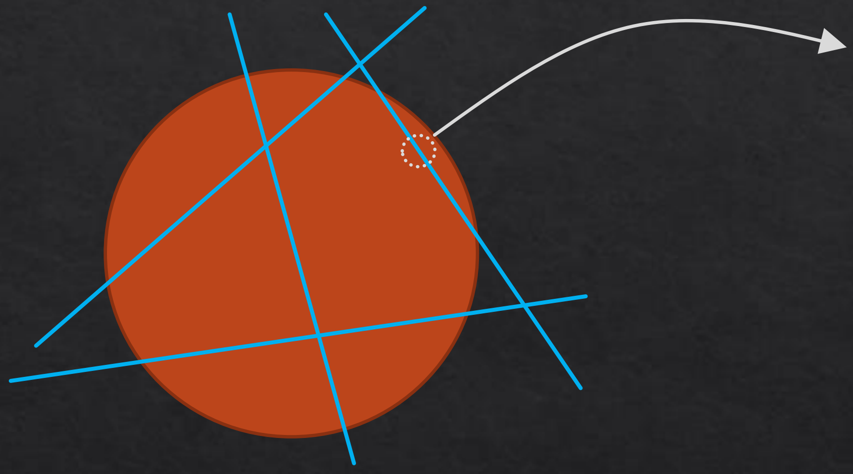
Long, very straight, microscopic diameter tracks

probe more parameter space

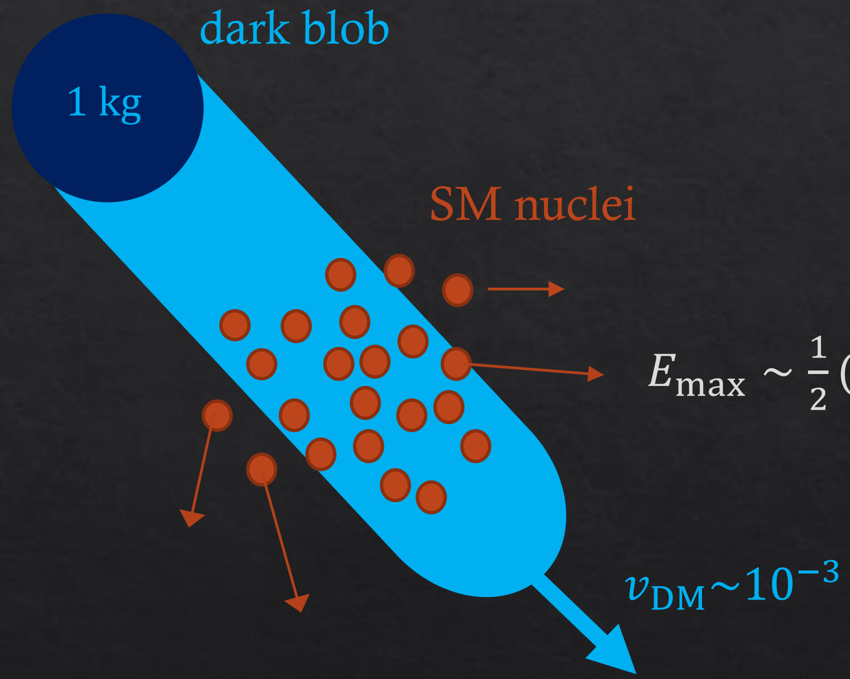
The Idea

Real-time: $10\ \text{yr} \times (100\ \text{m})^2 \longrightarrow m_{\text{DM}} < 0.1\ \text{g}$

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



10^9 yr



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

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

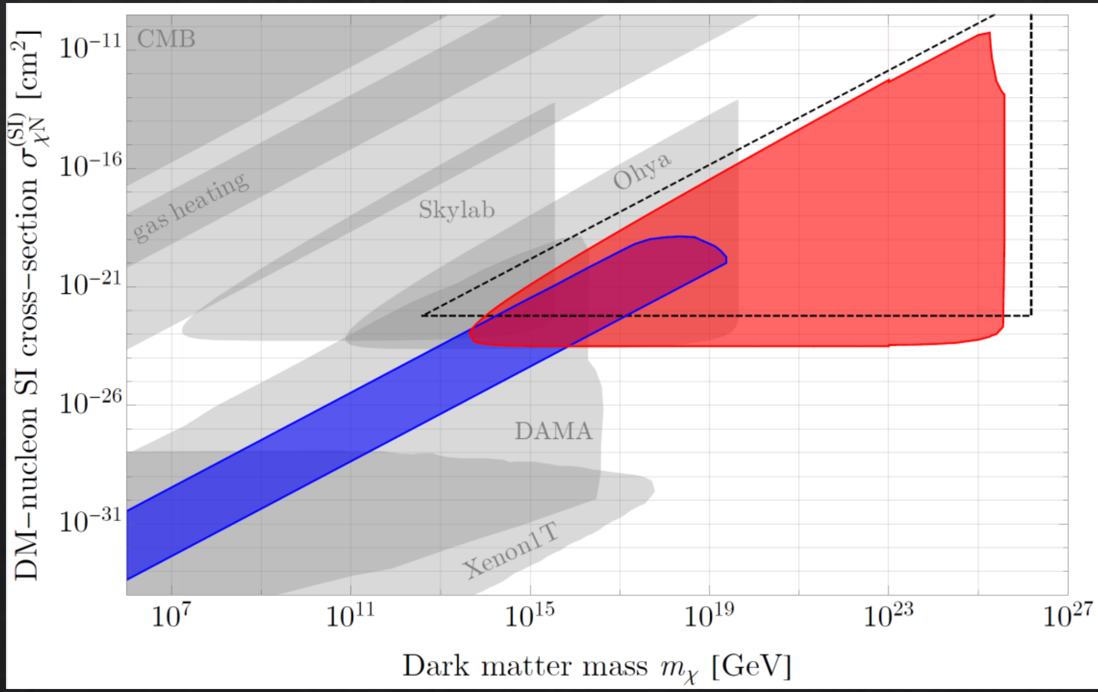
P. B. Price and M. H. Salamon

Department of Physics, University of California, Berkeley, California 94720

(Received 18 November 1985)

- Search for long tracks in mica left by monopoles
- Acid etching + optical microscopy
- Limited by the availability of clean mica samples
- $T_{\mathrm{exp}} A_{\mathrm{exp}} = \mathrm{Gyr} \times 0.1\ \mathrm{m}^2$ ($m_{\mathrm{DM}} < 0.1$ kg)
- This was ~four decades ago

Translated to limits on dark blobs



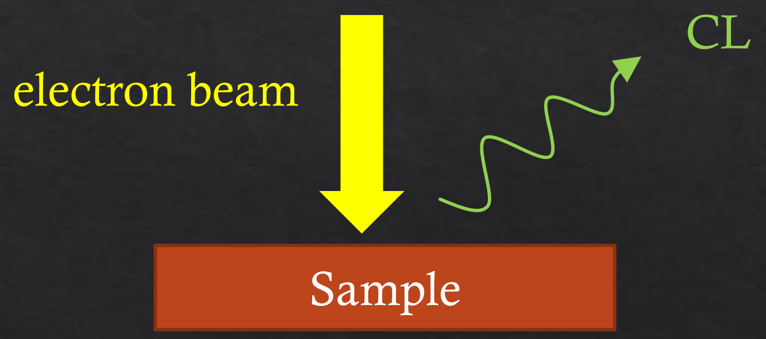
Acevedo, Bramante, Goodman 2021 [2105.06473]

Experimental Proposal

Scan Quartz with SEM-CL

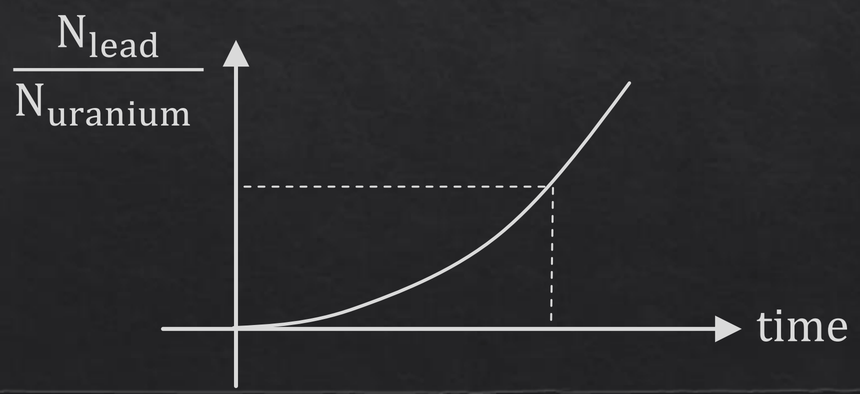
SEM-CL

- Scanning Electron Microscopy (SEM)
- Cathodoluminescence (CL)
- μm resolution, fast scanning

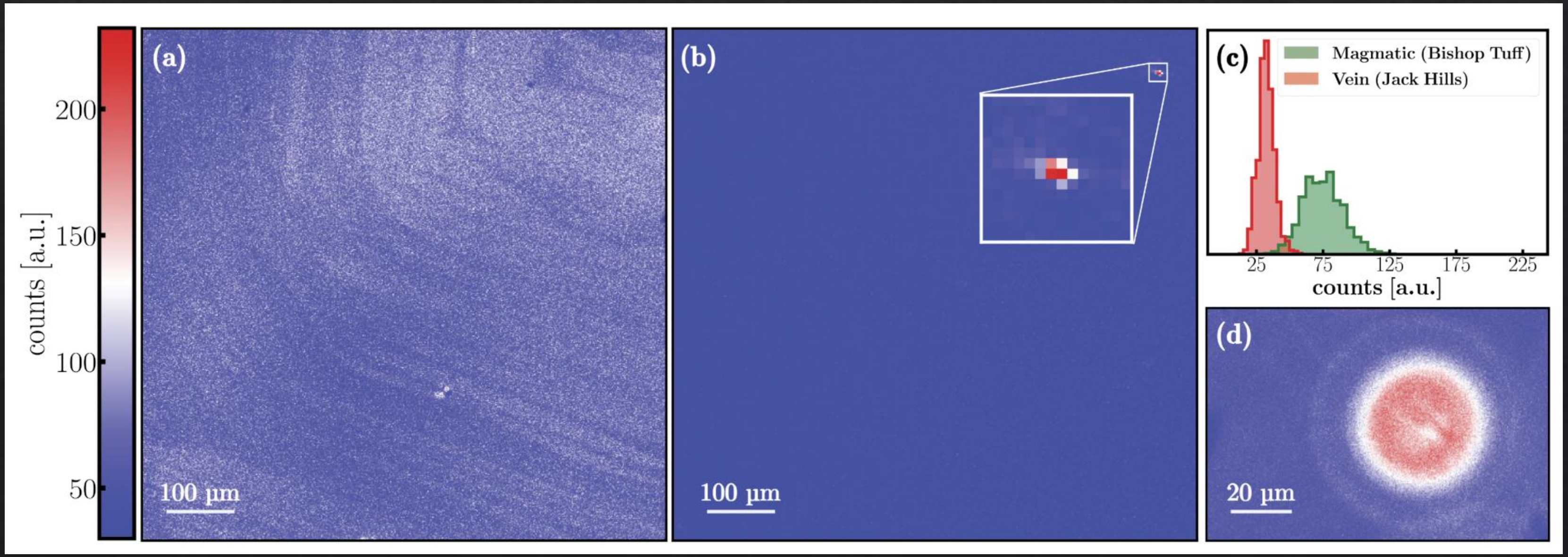


Quartz

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



Jack Hills, Australia



This took 5 $\mathrm{s/mm^2}$

(the bottleneck)

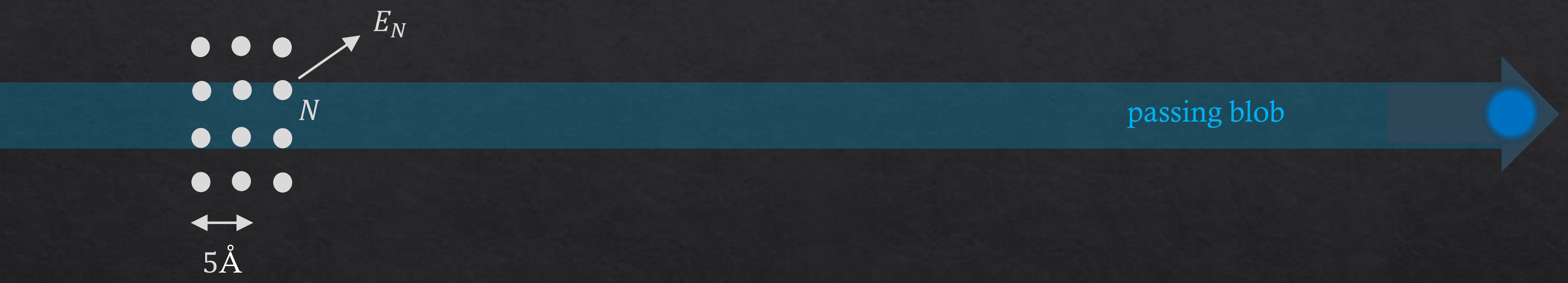
reach: $m_{\mathrm{DM}} < 100$ kg

with 100 SEM machines

running for 8 years

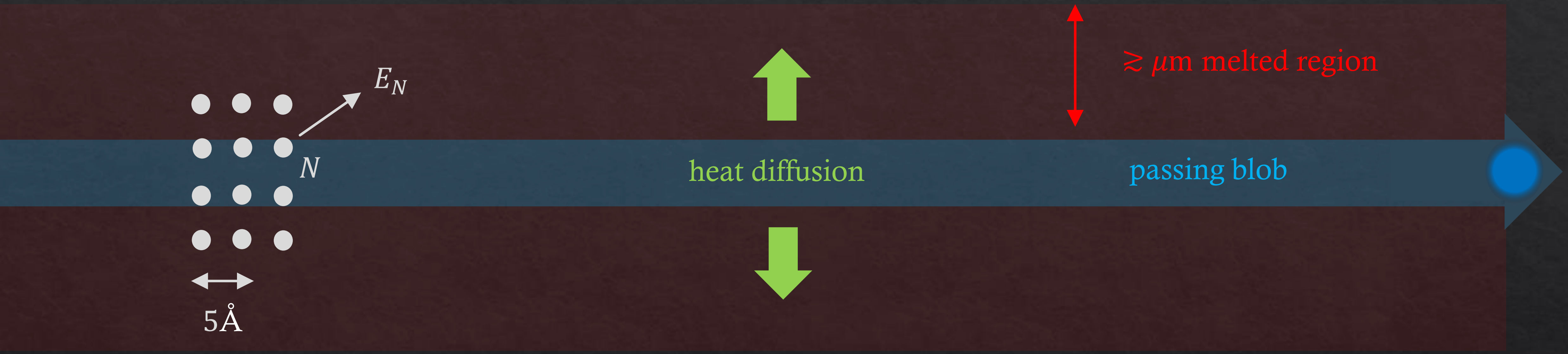
Experimental Reach

Requirements for Melting



$E_N \gtrsim \text{eV}$ ensures *some region* melts

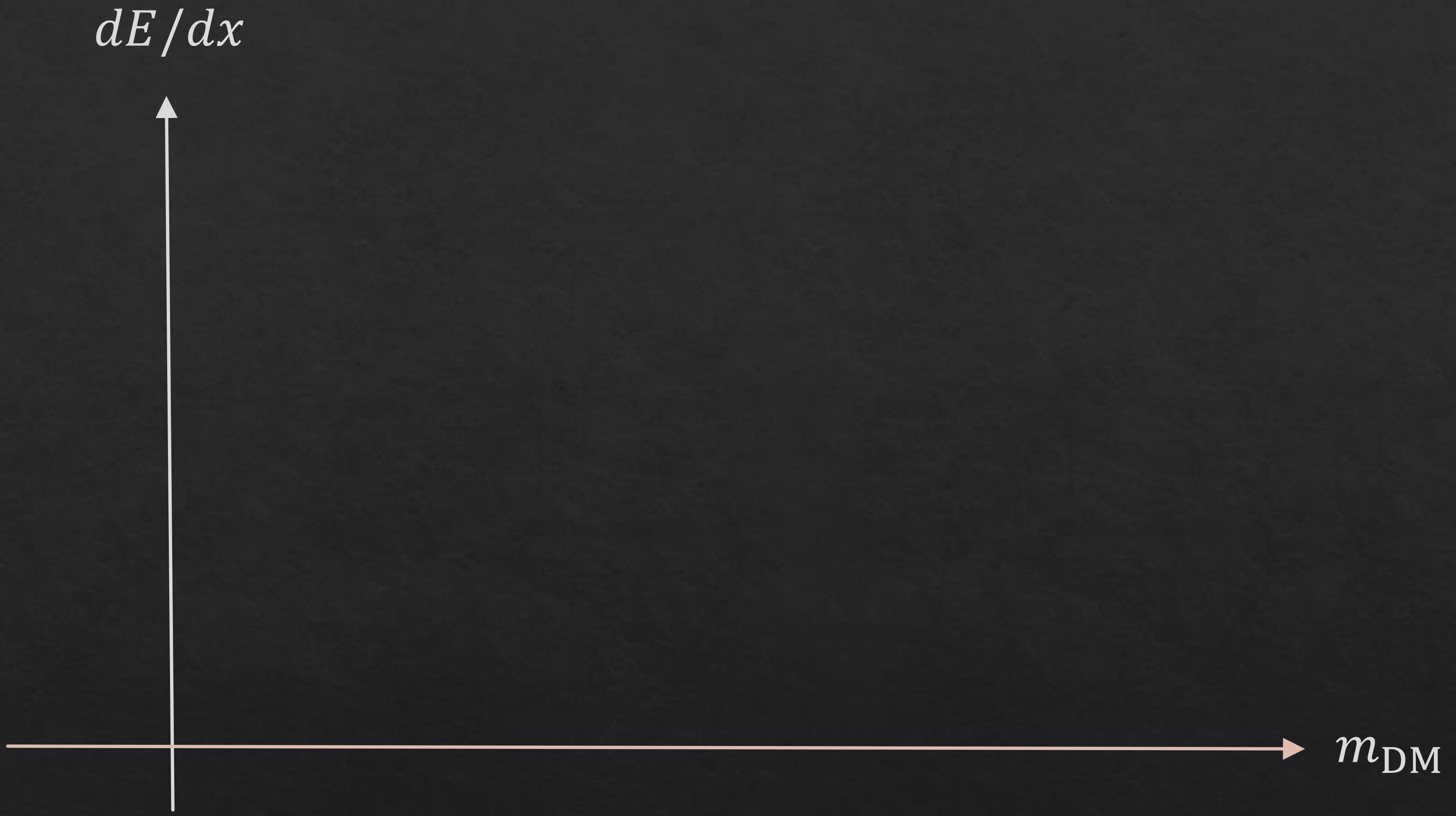
Requirements for Melting



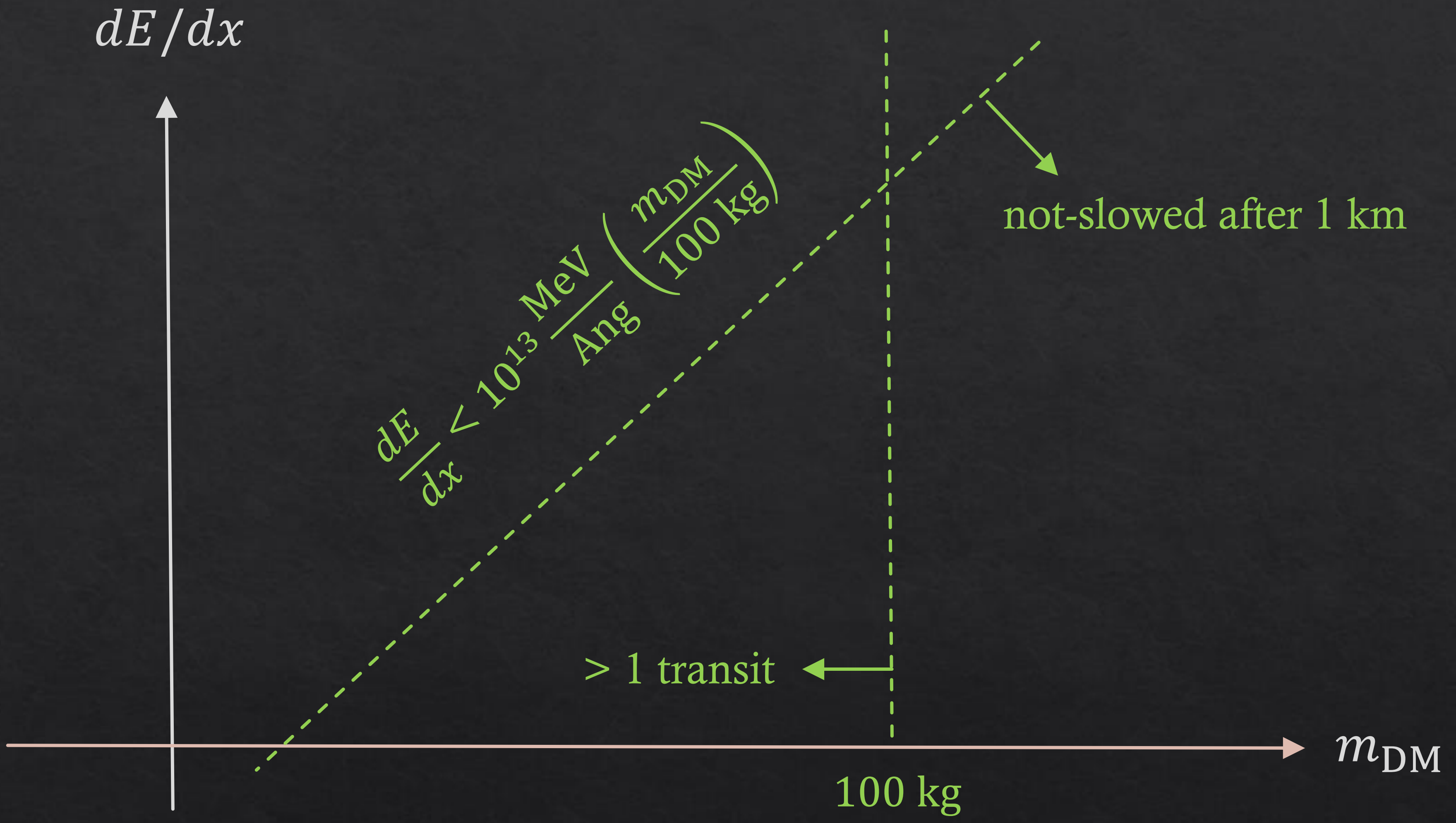
$E_N \gtrsim \text{eV}$ ensures *some region* melts

$\frac{dE}{dx} \gtrsim \text{eV}\left(\frac{\mu\text{m}}{5\text{Å}}\right)^2 \frac{1}{5\text{Å}} = \frac{\text{MeV}}{\text{Å}}$ latent heat to melt μm cylinder

Model-Independent Sensitivity

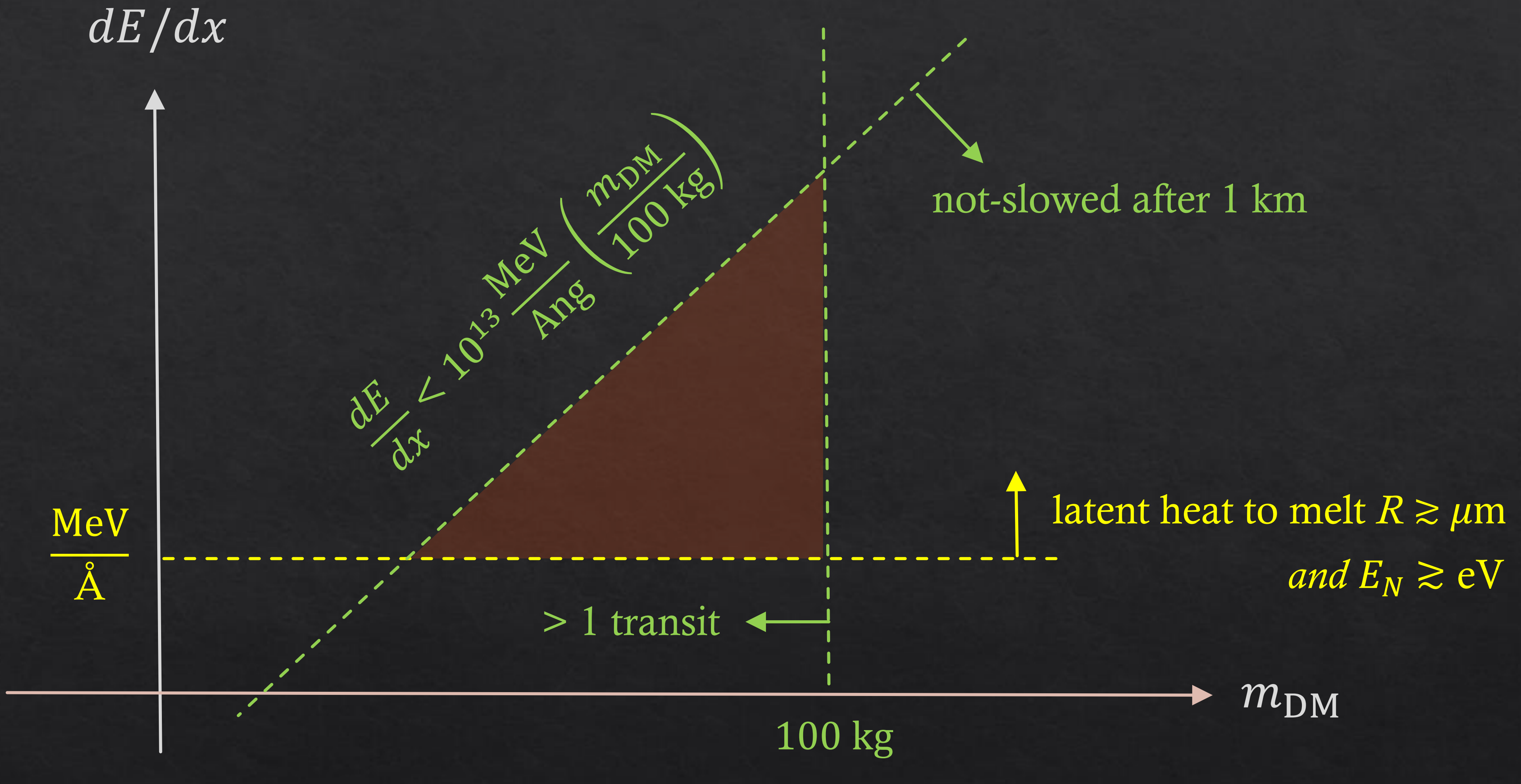


Model-Independent Sensitivity



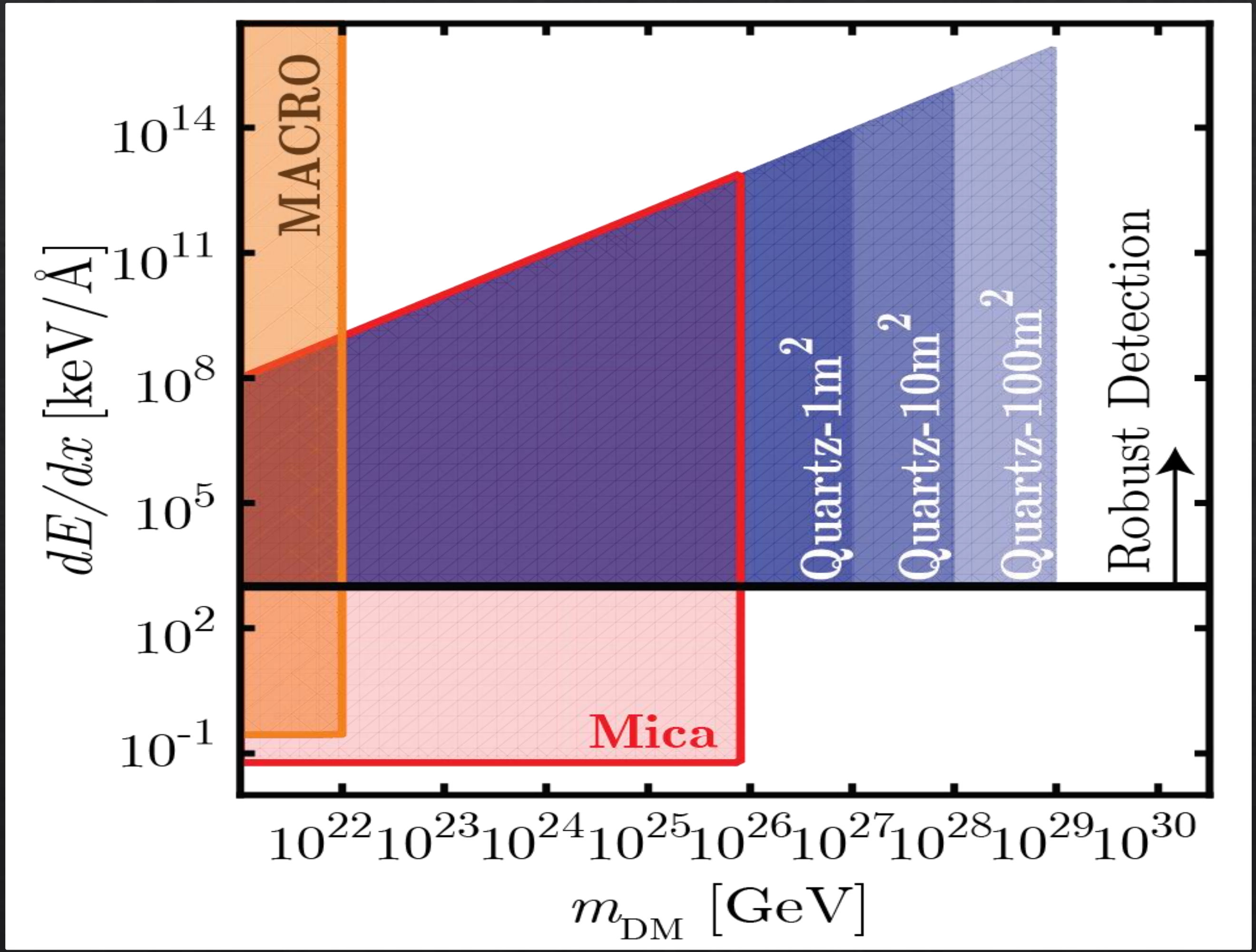
blob passing with $v_{\text{DM}} \sim 10^{-3}$

Model-Independent Sensitivity



blob passing with $v_{\text{DM}} \sim 10^{-3}$ + melting quartz in its path

Model-Independent Sensitivity

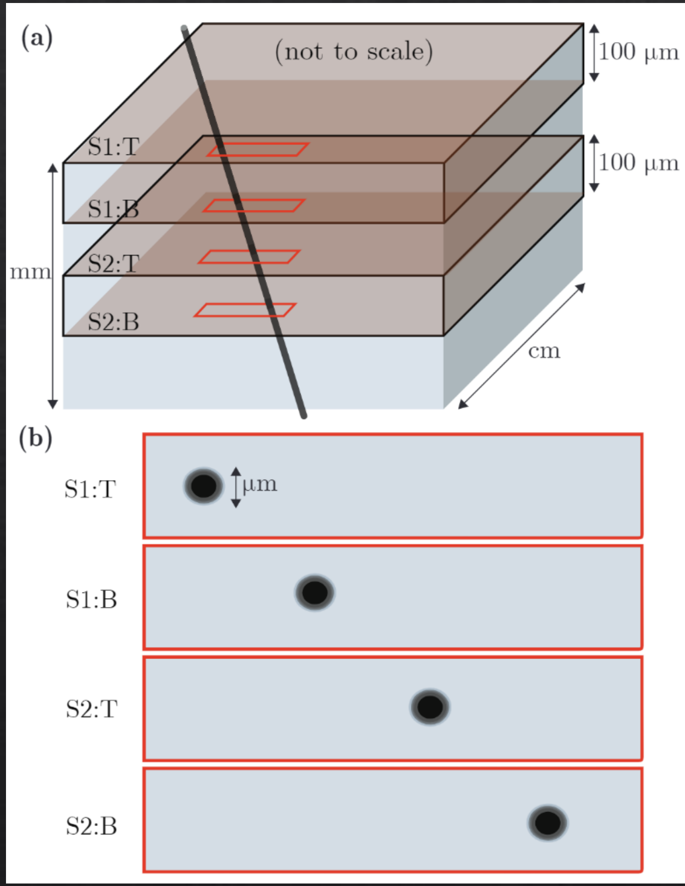


and sufficiently strong
Individual nuclear recoil
$E_N \gtrsim \mathrm{eV}$

Our signal is difficult to fake

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

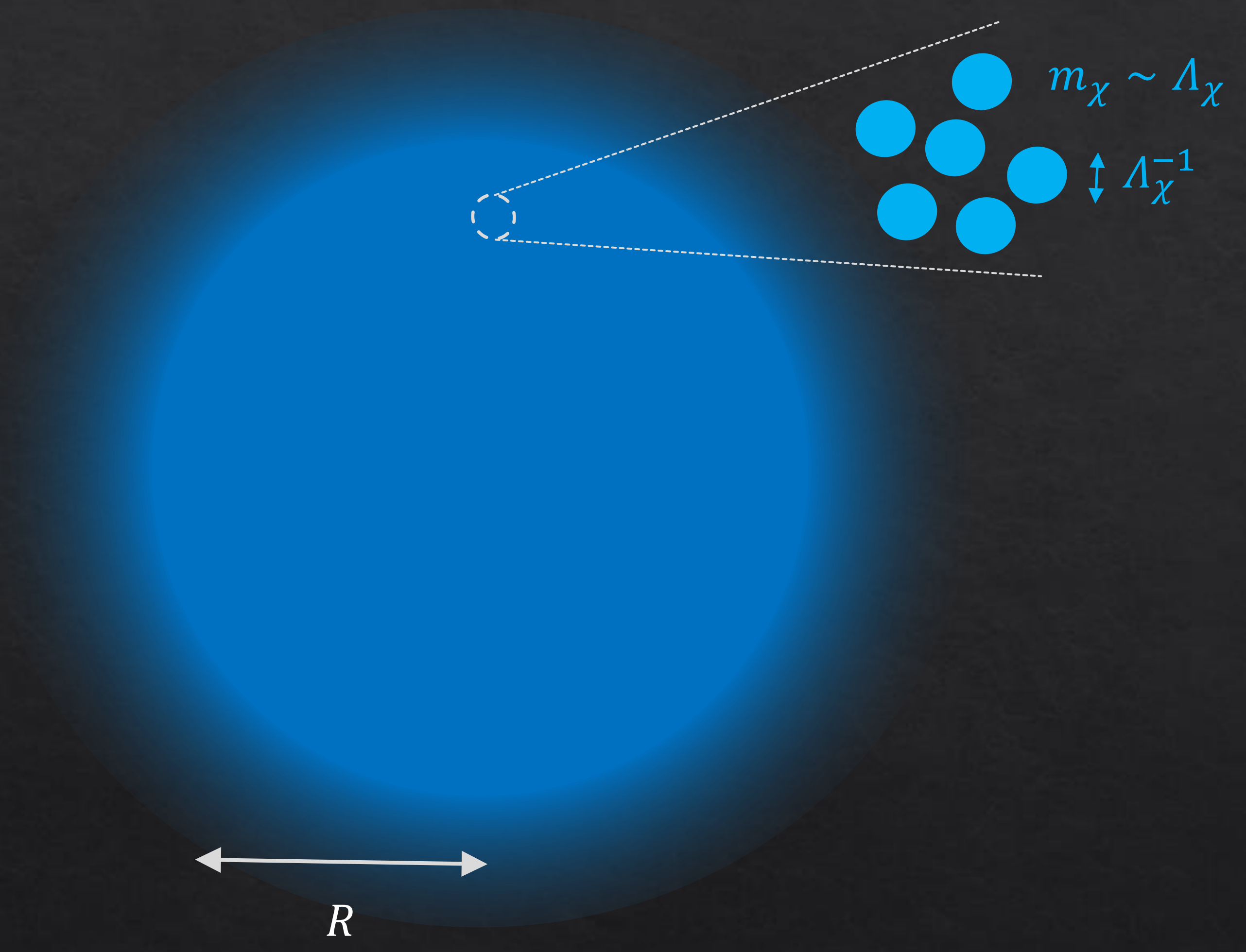
Geometric rejection



Example Dark Blob Model

Example Model

Fermionic blobs with dark QCD "glue"

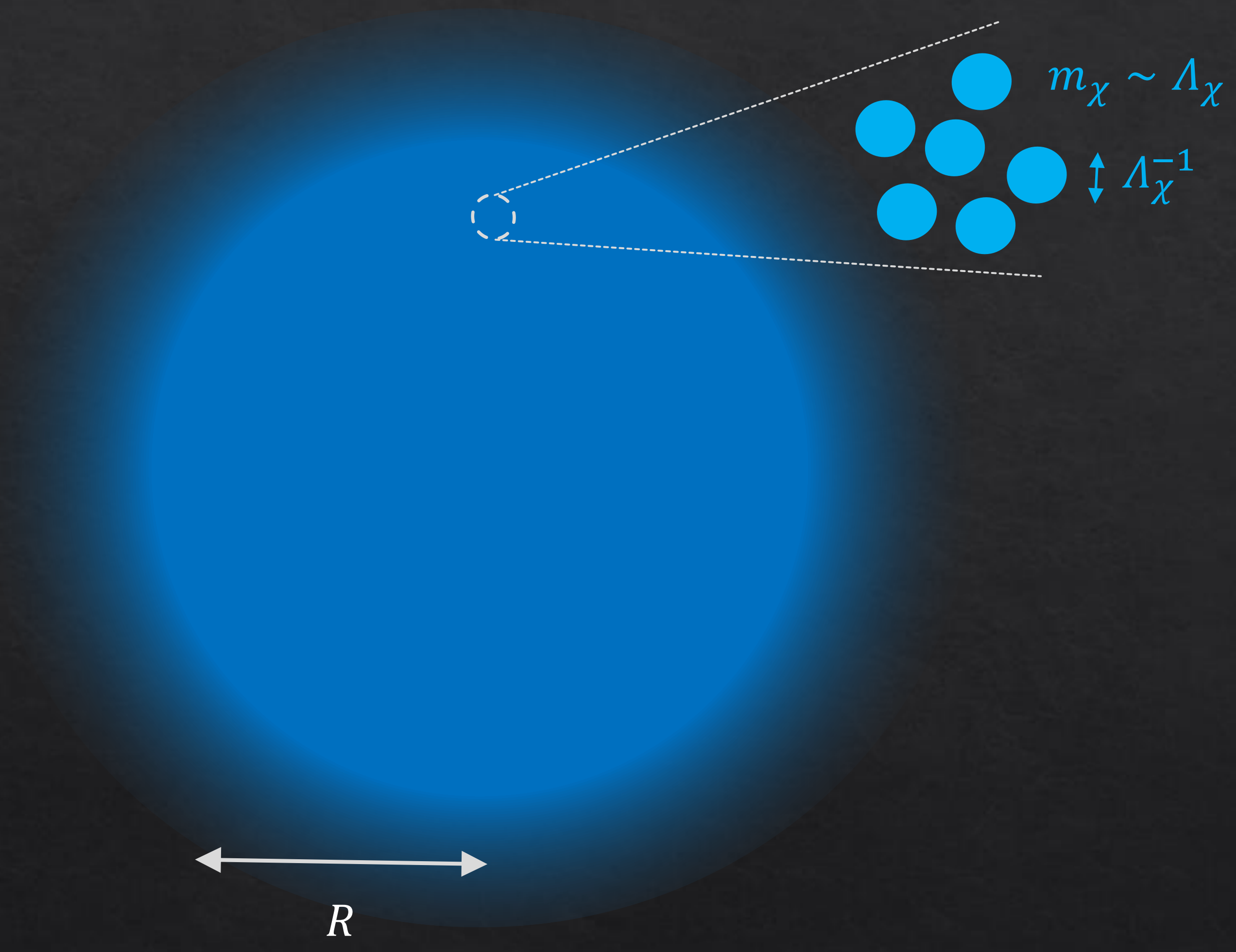


Repulsive Yukawa coupling with SM nuclei

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

Example Model

Fermionic blobs with dark QCD "glue"



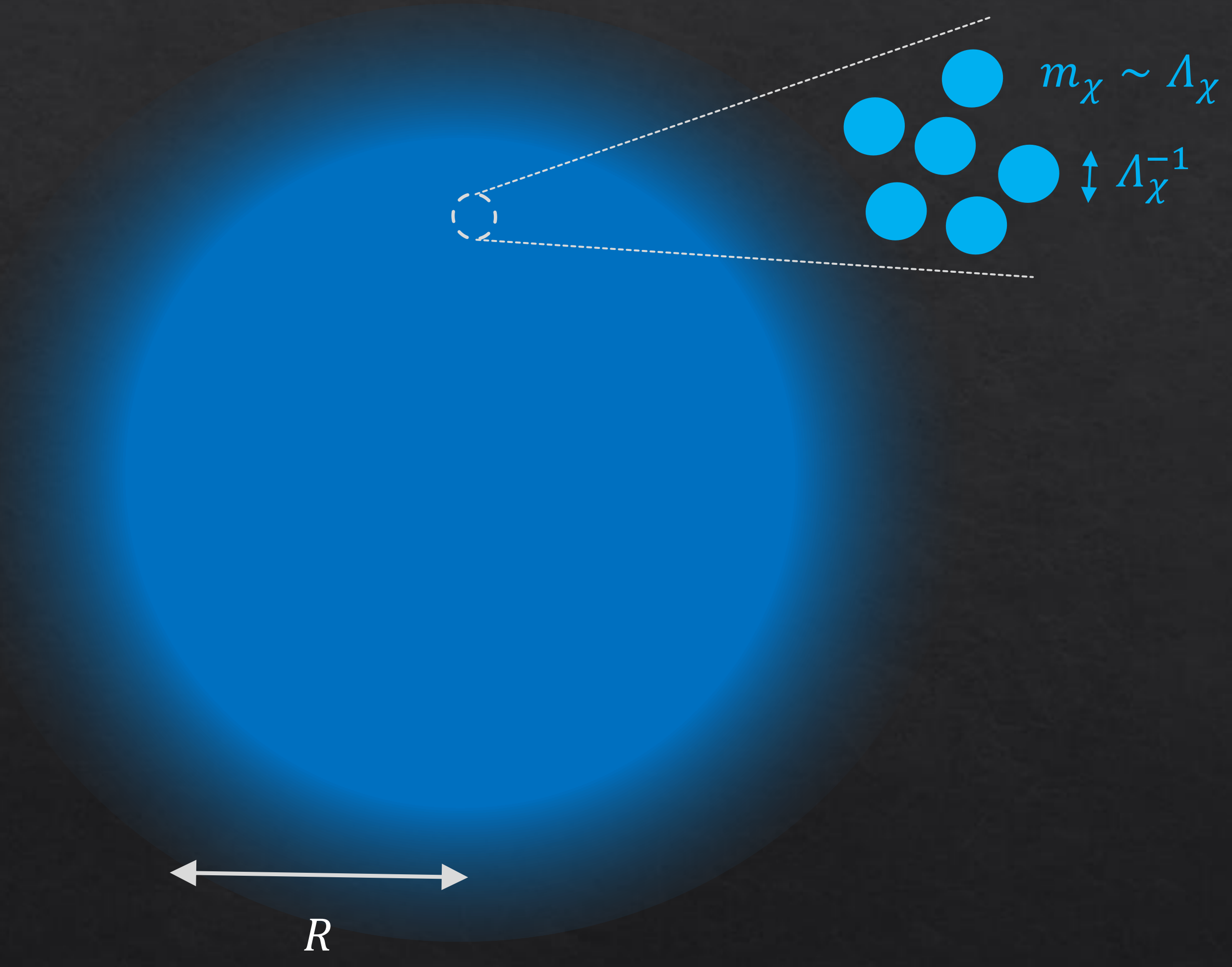
Repulsive Yukawa coupling with SM nuclei

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

can be made as large as possible,
blob stable as long as $g_\chi \ll \frac{m_\phi}{\Lambda_\chi}$

Example Model

Fermionic blobs with dark QCD "glue"



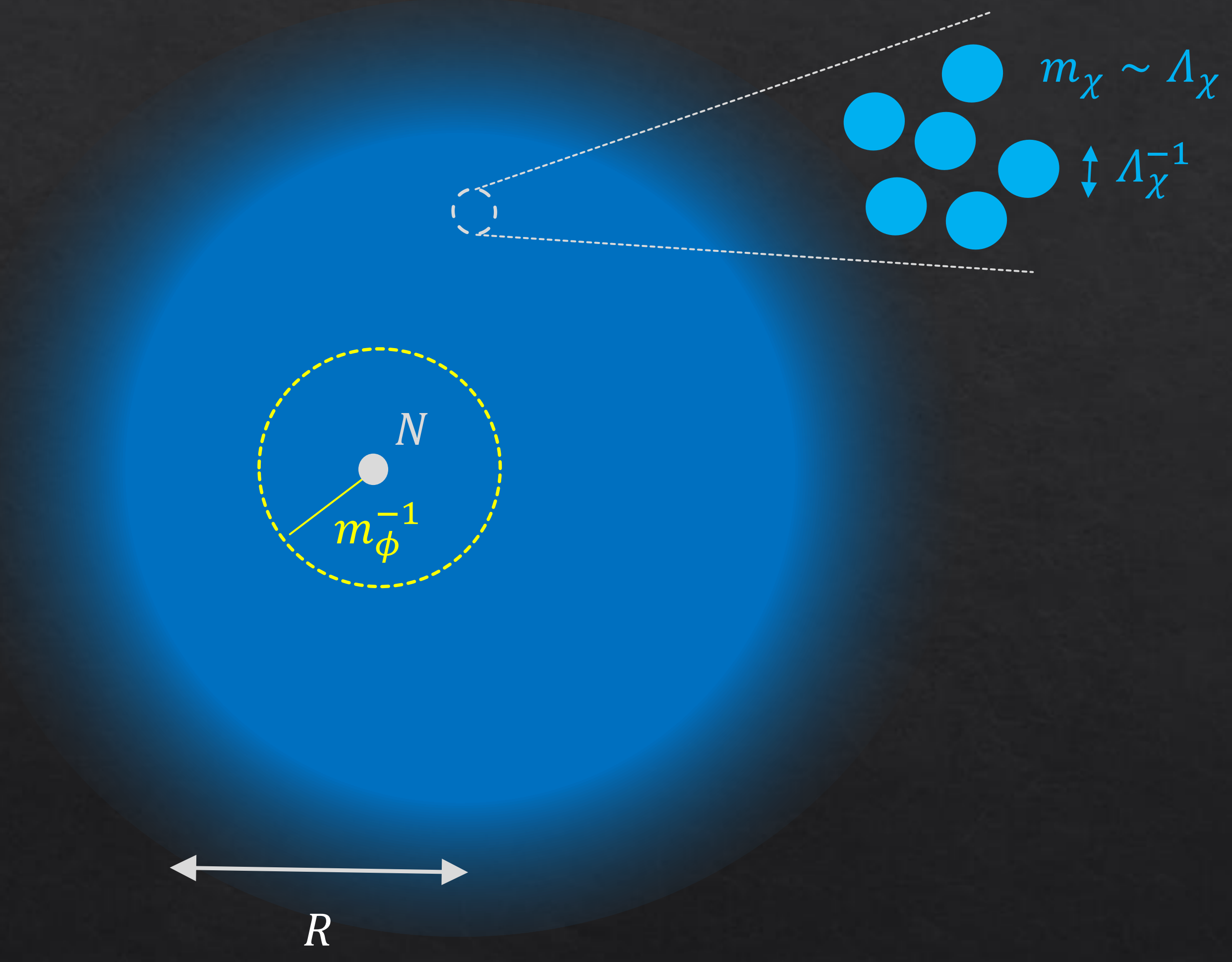
Repulsive Yukawa coupling with SM nuclei

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

$g_N \lesssim 10^{-12}$ by stellar cooling,
and fifth force exp. for $m_\phi^{-1} \gtrsim \mu\text{m}$

Example Model

Fermionic blobs with dark QCD "glue"



Repulsive Yukawa coupling with SM nuclei

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

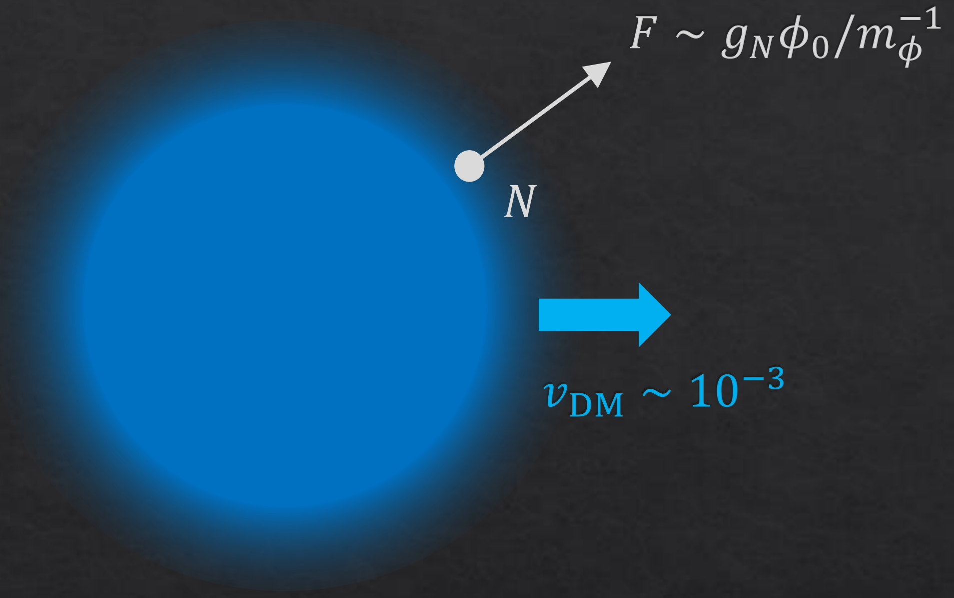
Interesting regime:

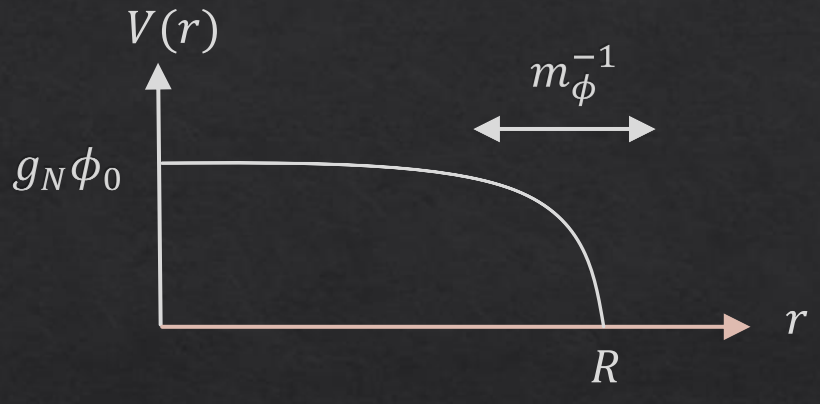
$$\Lambda_\chi^{-1} \ll m_\phi^{-1} \ll R$$

Nuclei receive an effective mass inside the blob

$$g_N \phi_0 \sim \frac{g_\chi g_N}{m_\phi^{-1}} \left(\frac{m_\phi^{-1}}{\Lambda_\chi^{-1}} \right)^3 = \text{constant}$$

Moving Potential Hill



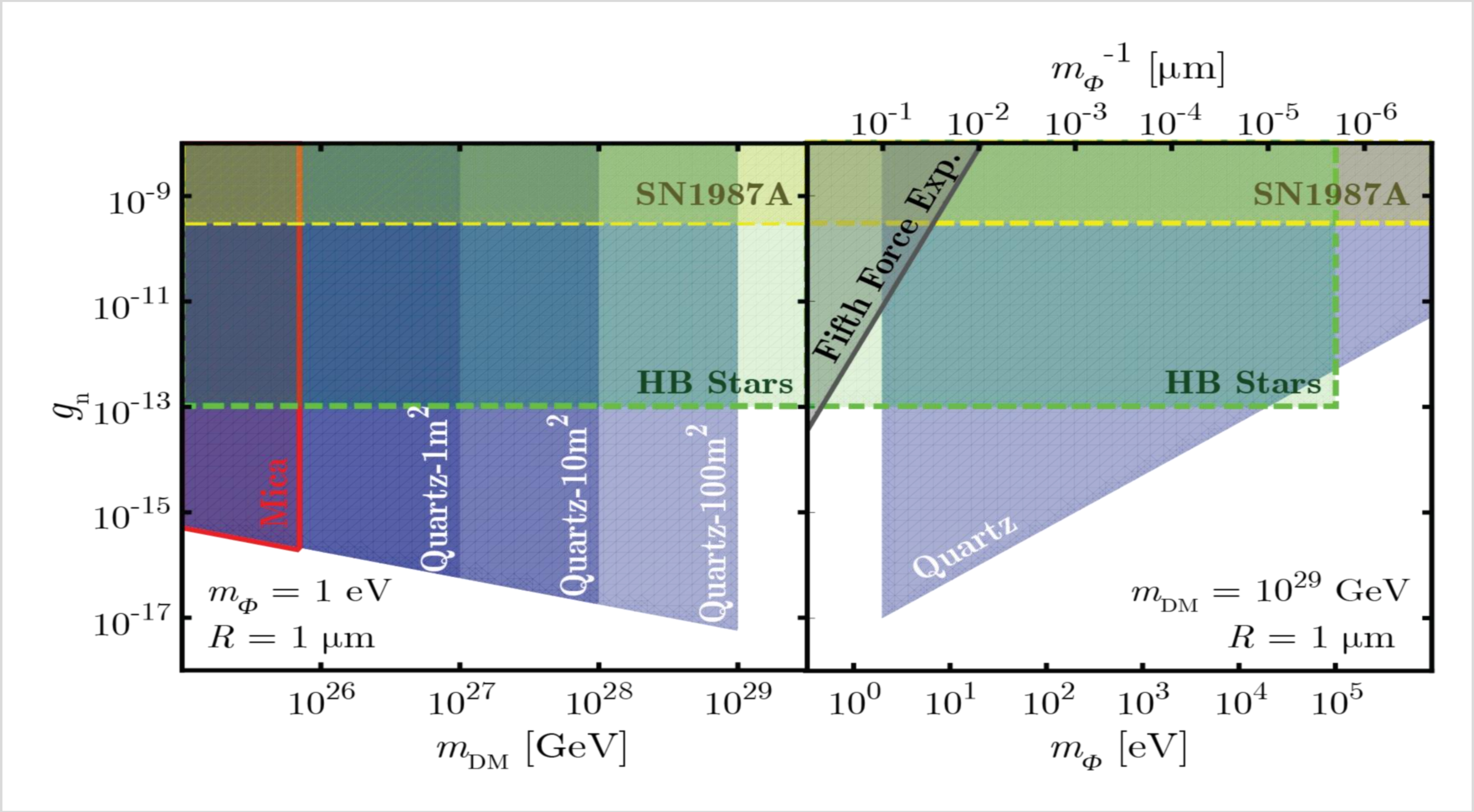


$$p_{\rm N} \sim \max\left[F\frac{m_\phi^{-1}}{v_{DM}}, m_N v_{\rm DM}\right]$$

$$\frac{dE}{dx} \sim E_{\rm N}\left(\frac{R}{5\text{Å}}\right)^2 \frac{1}{5\text{Å}} \gtrsim \frac{\rm MeV}{\text{Å}}$$

$$E_{\rm N} \sim \frac{p_{\rm N}^2}{2m_N} \sim 10\ {\rm keV}\ \min\left[1, \left(\frac{g_N\phi_0}{10\ keV}\right)^2\right] \gtrsim {\rm eV}$$

Example Model Sensitivity



Future

- Signal calibration
  - Create damage tracks artificially (with high-pulsed laser), put under SEM-CL
  - Lattice defects below the melting threshold, can probe DM microphysics
- Noise calibration
  - Check the CL level of natural and synthetic samples with different levels of CL activators
- Other class of targets
  - Dark blobs are “easy targets”
  - PeV neutrinos, …

Summary

- Ultraheavy (~kg) dark matter search needs high exposure (high $T_{\mathrm{exp}} A_{\mathrm{exp}}$)
- Idea: scan $T_{\mathrm{exp}} \sim$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, but there are likely many more
- Worth doing anyway, for geology purposes

Backup Slides

Model-Independent Reach

[ancient mica] 10^{26} GeV $\lesssim m_{\mathrm{DM}} \lesssim 10^{29}$ GeV [O(1) blob transit]

[melting threshold] eV $\lesssim E_N \lesssim 10$ keV [kinematics]

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

The Stopping and Range of Ions in Matter (SRIM)

- Inject 10 keV ion in quartz, mimicking DM-kicked nucleus
- Plot of oxygen vacancy distribution
- Track length ~ 100 Å