DMICA: exploring Dark Matter in natural muscovite MICA

KASHIWA DARK MATTER SYMPOSIUM 2023

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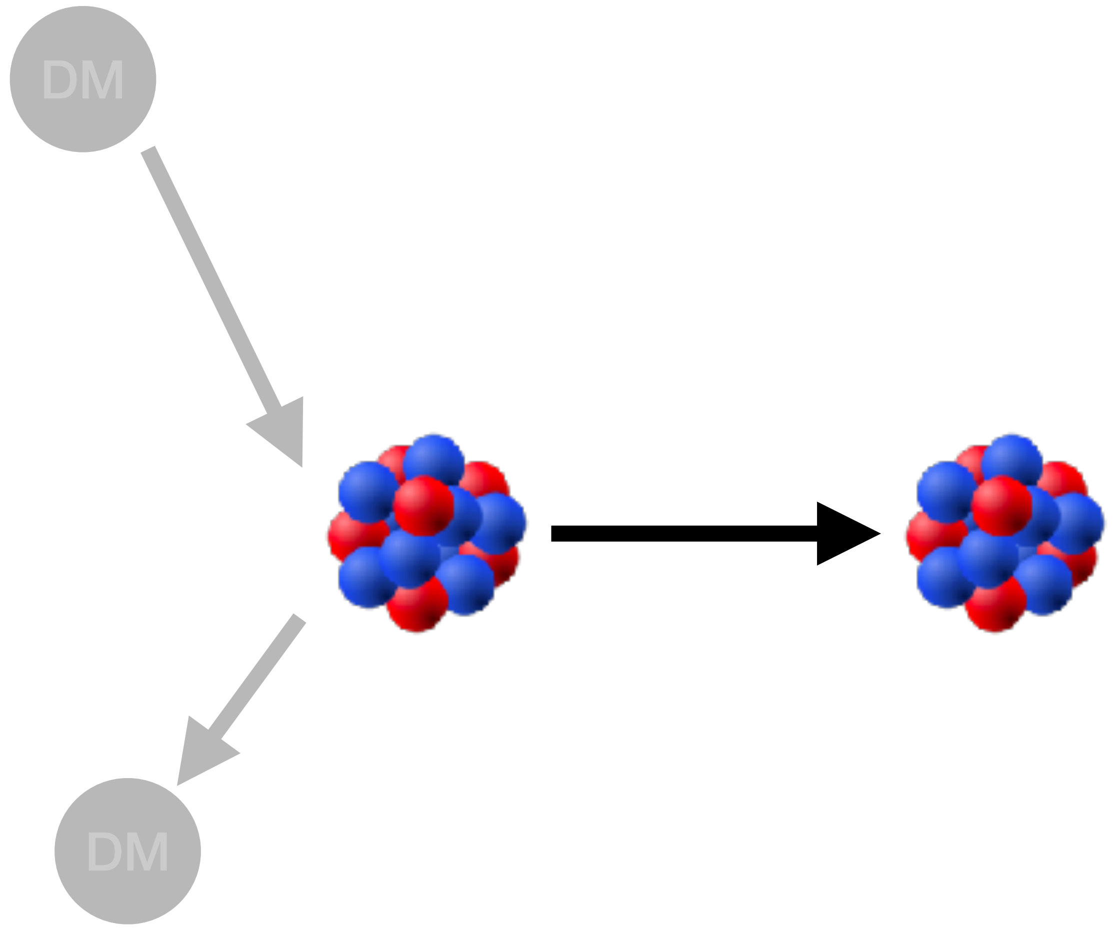
Abstracts

Searching for dark matter typically requires a large amount of material to capture extremely rare interactions. However, natural mineral crystals like mica have been around for geological time scales, offering plenty of exposure even in small samples. These crystals can hold onto nuclear recoil tracks—evidence of dark matter interactions—for periods longer than the Earth's age. When etched, these tracks appear as observable pits. Building on this, Snowden-Ifft and colleagues in 1995 studied natural muscovite mica that was 500 million years old, covering an area of just 0.08 square millimeters. We're now planning the DMICA experiment to significantly expand upon this initial research, covering much larger areas. In this presentation, we'll discuss our preliminary experiments aimed at replicating Snowden-Ifft's work as a stepping stone for DMICA. We'll also cover how sensitive the DMICA experiment could be in detecting dark matter, emphasizing that mica's large surface area to volume ratio is particularly useful for detecting very heavy dark matter particles.

Overview of DM Search with Mineral Crystals

Exposure of minerals could potentially rival Xenon experiments

https://www.danspapers.com/2022/05/olivine-beach-replenishment-questions/



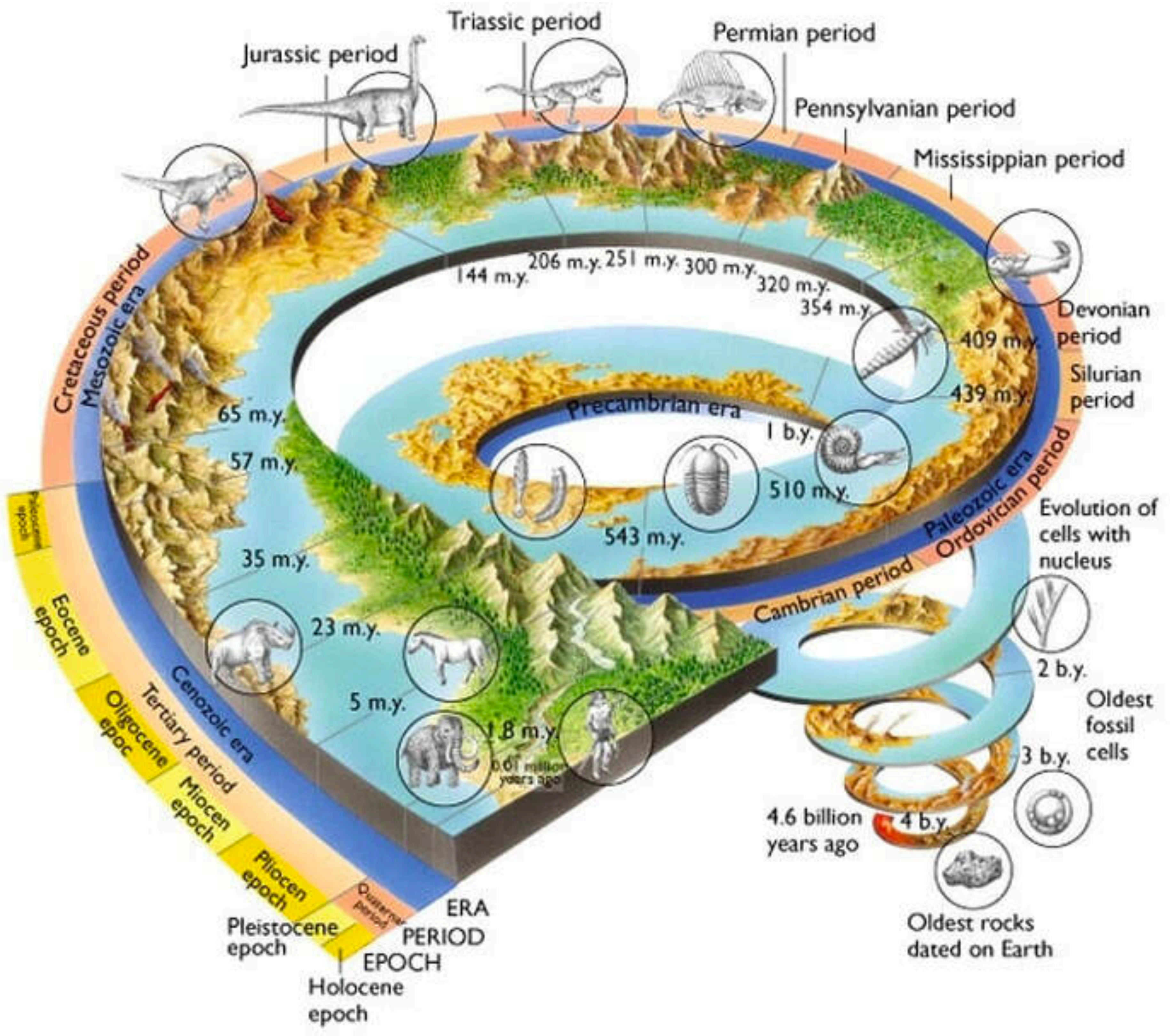
https://xenonexperiment.org/photos/

2mg × 500 Myr = 1 ton yr

1.3 ton × 278 day = 1 ton yr
Aprile et al. XENON Collaboration
Phys. Rev. Lett. 121, 111302, 2018

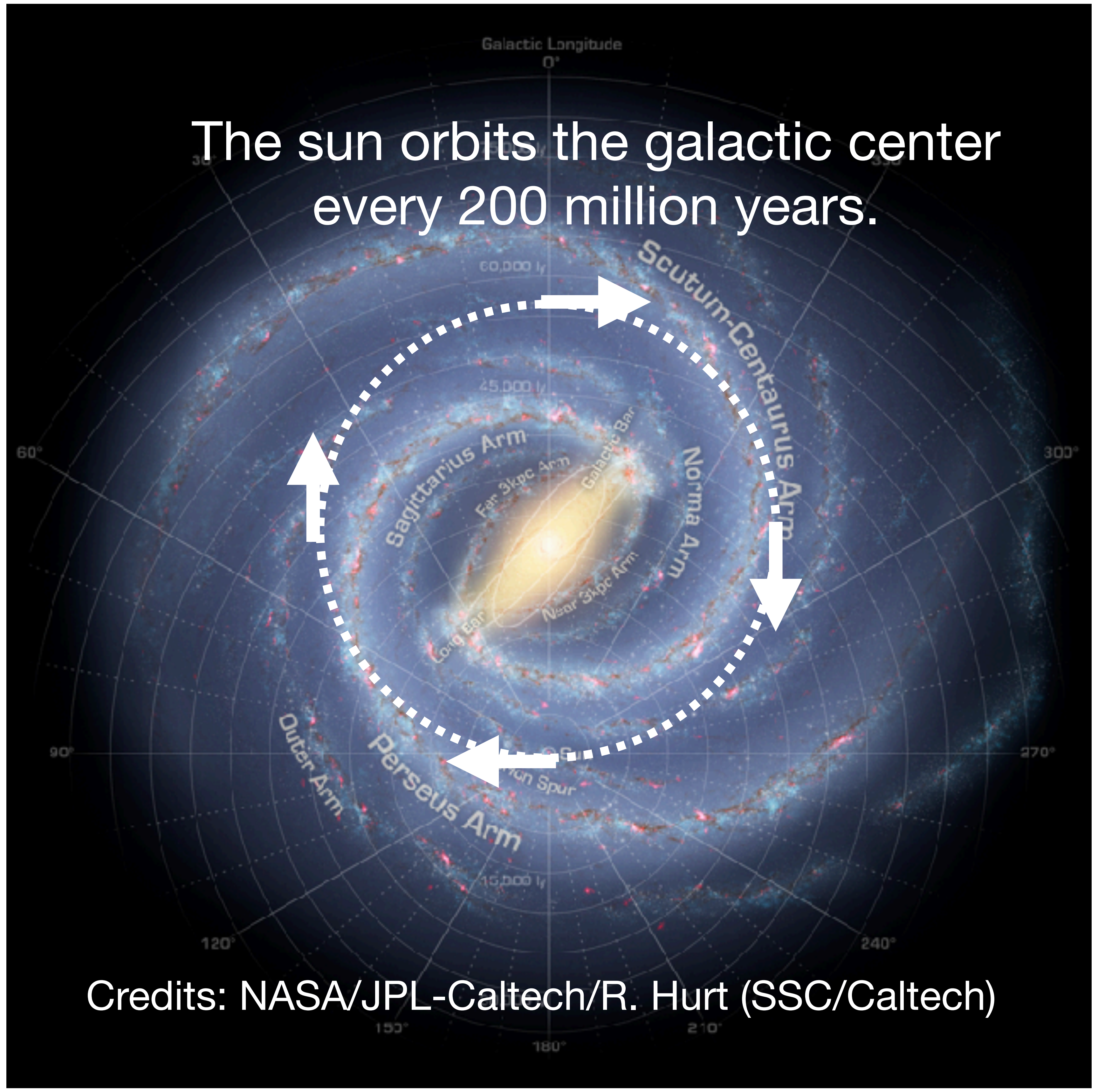
Explore past events in mineral crystals

Recording past events over geological time



https://www.matthewjkelleyauthor.com/time

Exploring dark matter on a galactic scale



Pioneering work using Muscovite mica: Snowden-Ifft et al. 1995

VOLUME 74, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1995

Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*
Physics Department, University of California at Berkeley, Berkeley, California 94720
(Received 20 September 1994)

The combination of the track etching method and atomic force microscopy allows us to search for weakly interacting massive particles (WIMPs) in our Galaxy. A survey of 80 720 μm^2 of 0.5 Gyr old muscovite mica found no evidence of WIMP-recoil tracks. This enables us to set limits on WIMPs which are about an order of magnitude weaker than the best spin-dependent WIMP limits. Unlike other detectors, however, the mica method is, at present, not background limited. We argue that a background may not appear until we have pushed our current limits down by several orders of magnitude.

PACS numbers: 95.35.+d, 14.80.Ly, 29.40.Ym, 61.72.Ff

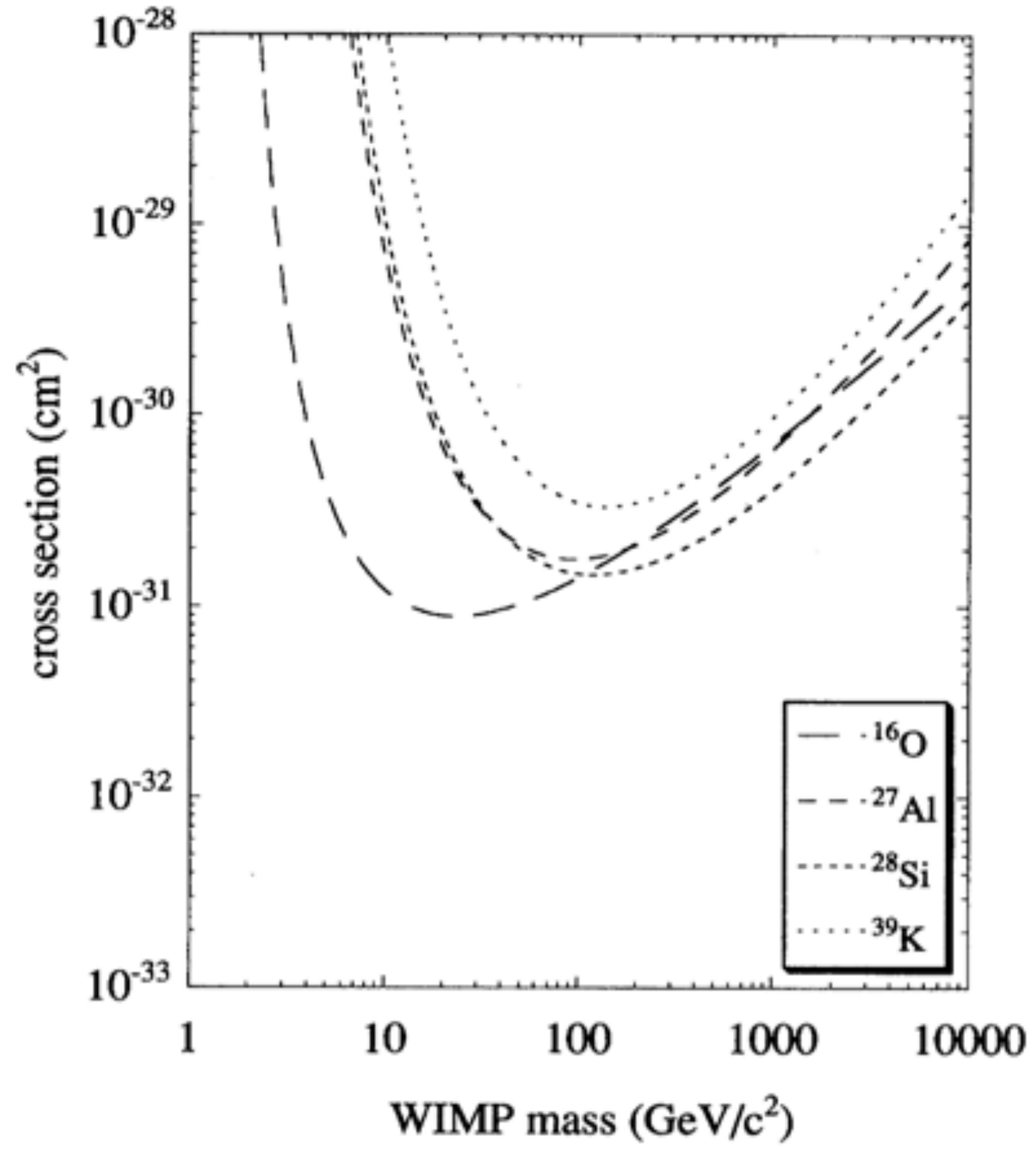


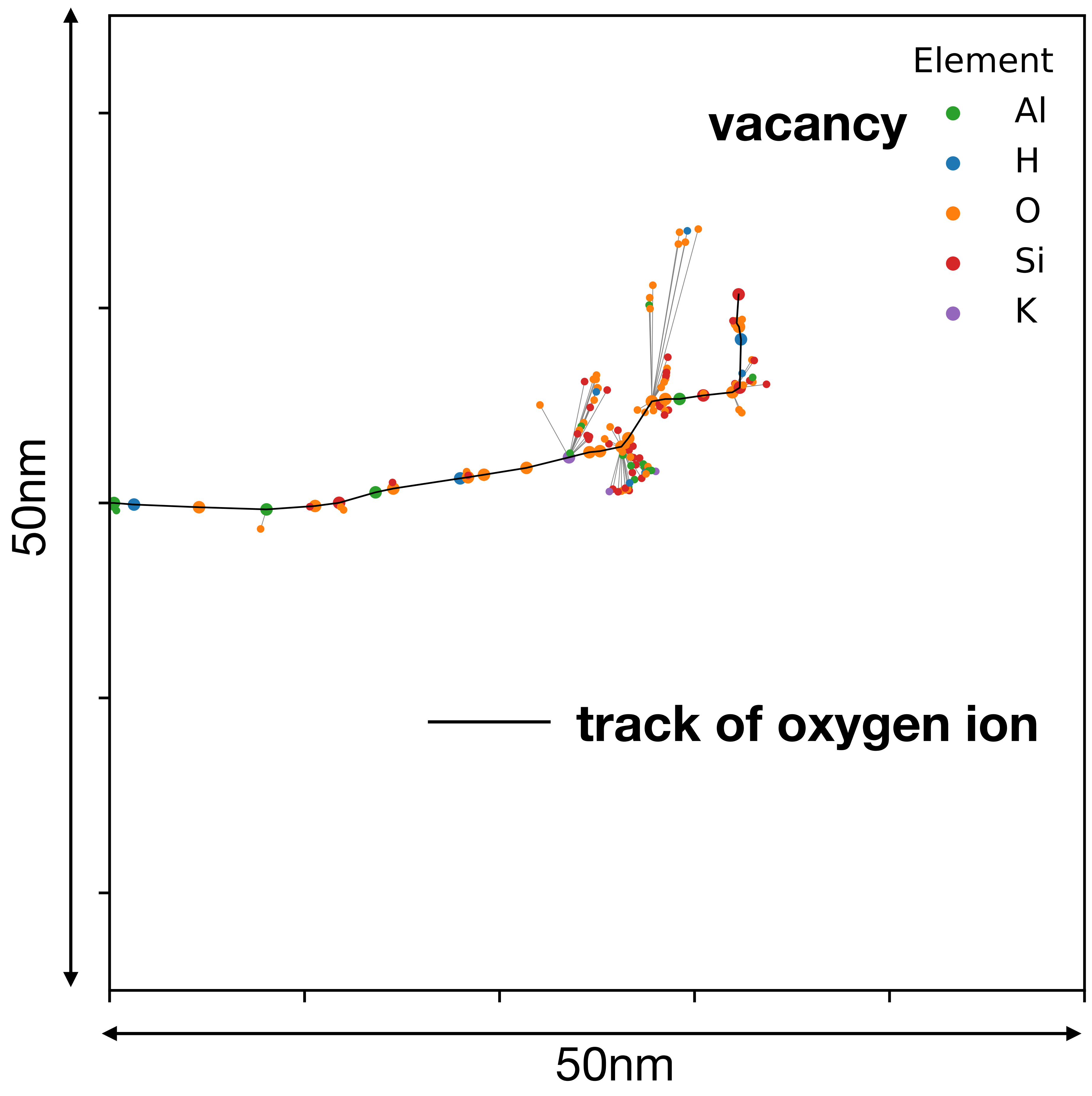
FIG. 4. Exclusion curves for each of the main constituent nuclei of mica. For a given mass, WIMPs with cross sections above these curves are ruled out at the 90% confidence level.

Following the methodology in Snowden-Ifft et al, DMICA plans to significantly extends the exploration volume beyond theirs, aiming for 1 ton yr

Mechanism of Mica Detector

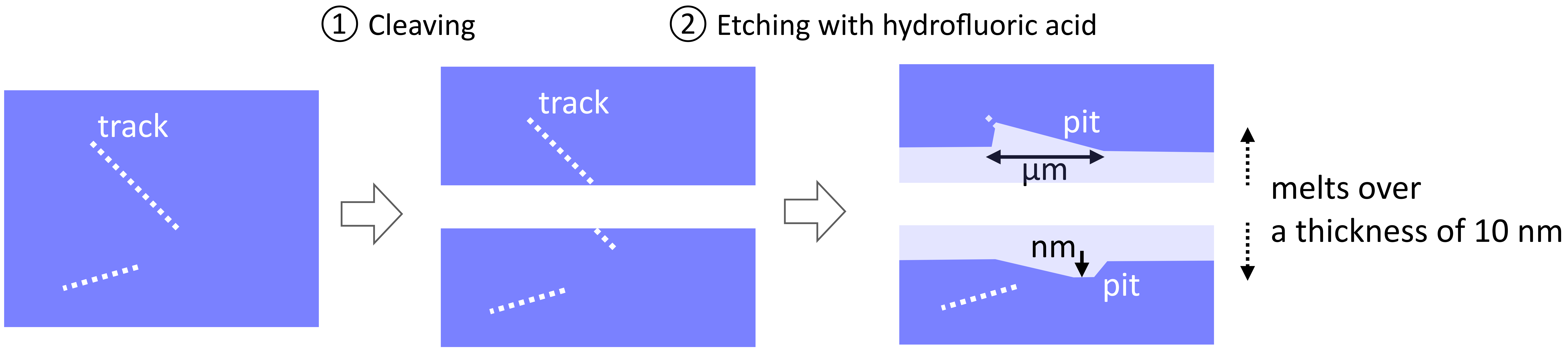
Recording: recoil nuclei create latent tracks (lattice defects)

TRIM simulation of an oxygen ion (10 keV) traversing through muscovite



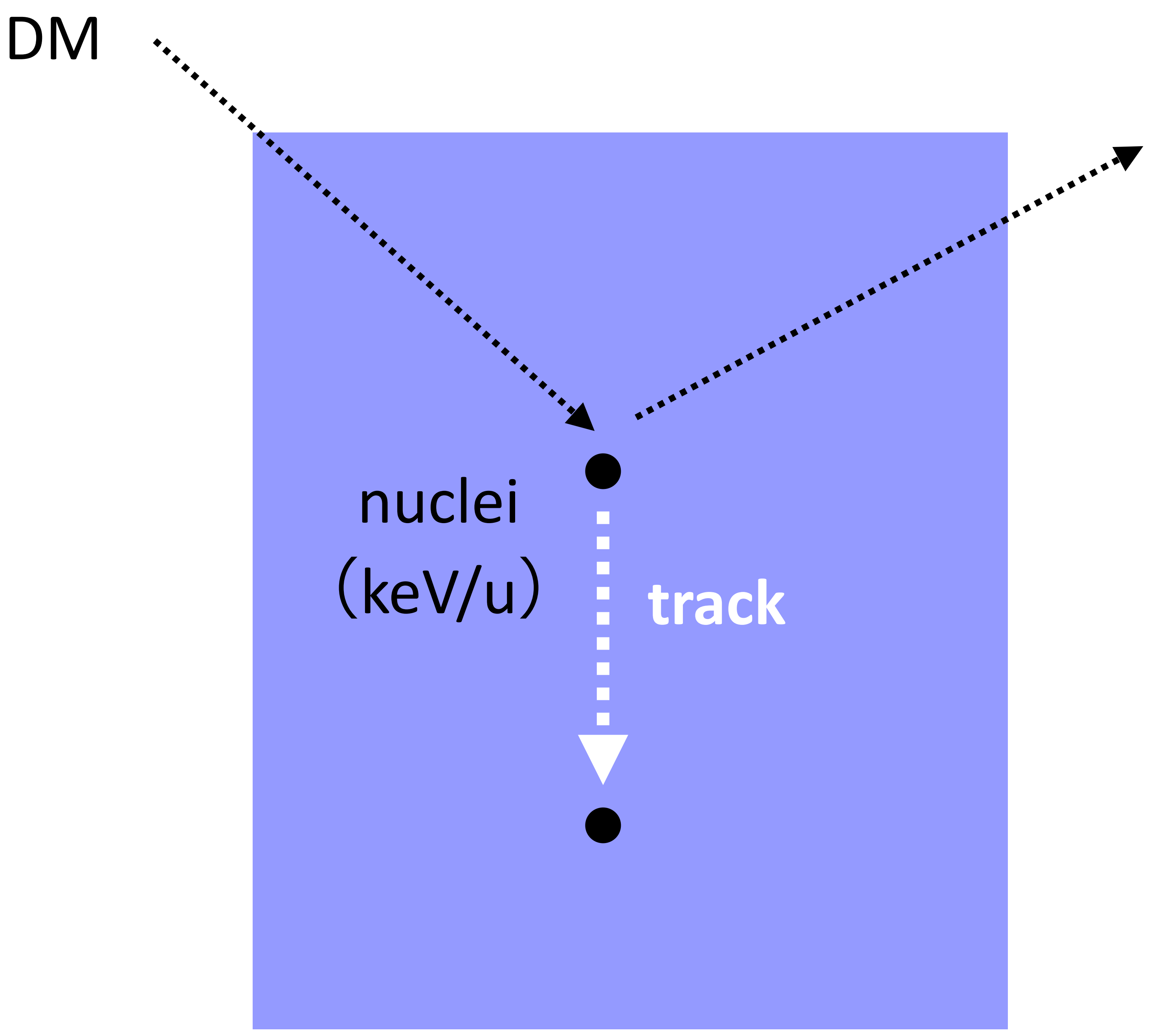
- Nuclear recoil is recorded as lattice defects, or "latent tracks" (invisible to microscopes)
- Latent tracks can be preserved longer than the age of the Earth

Reading out: “developing” tracks by etching with HF

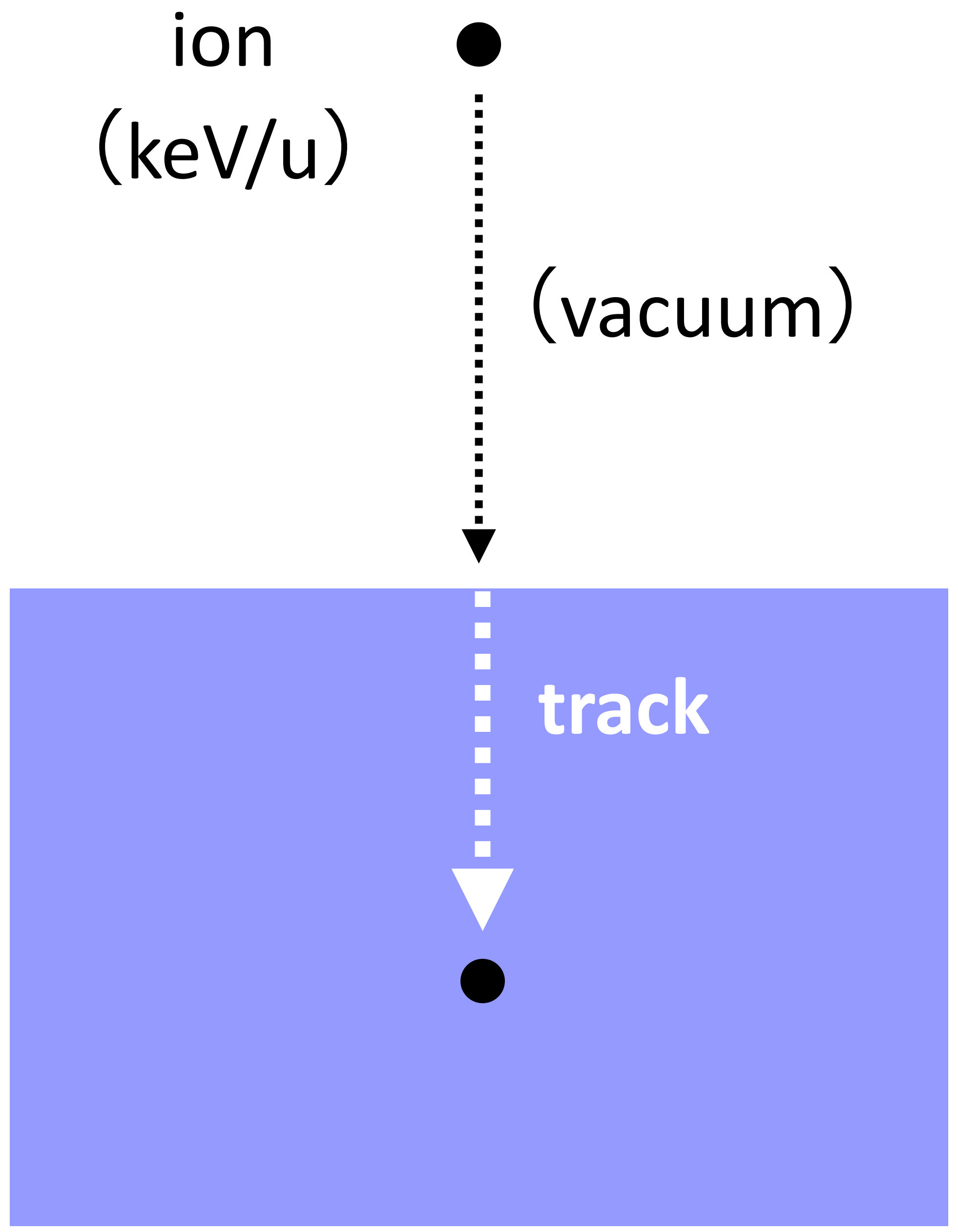


- Pits of several microns in size and nanometers in depth form at track sites
- Relationship between pit formation and recoil energy is relevant for mica to function as a DM detector

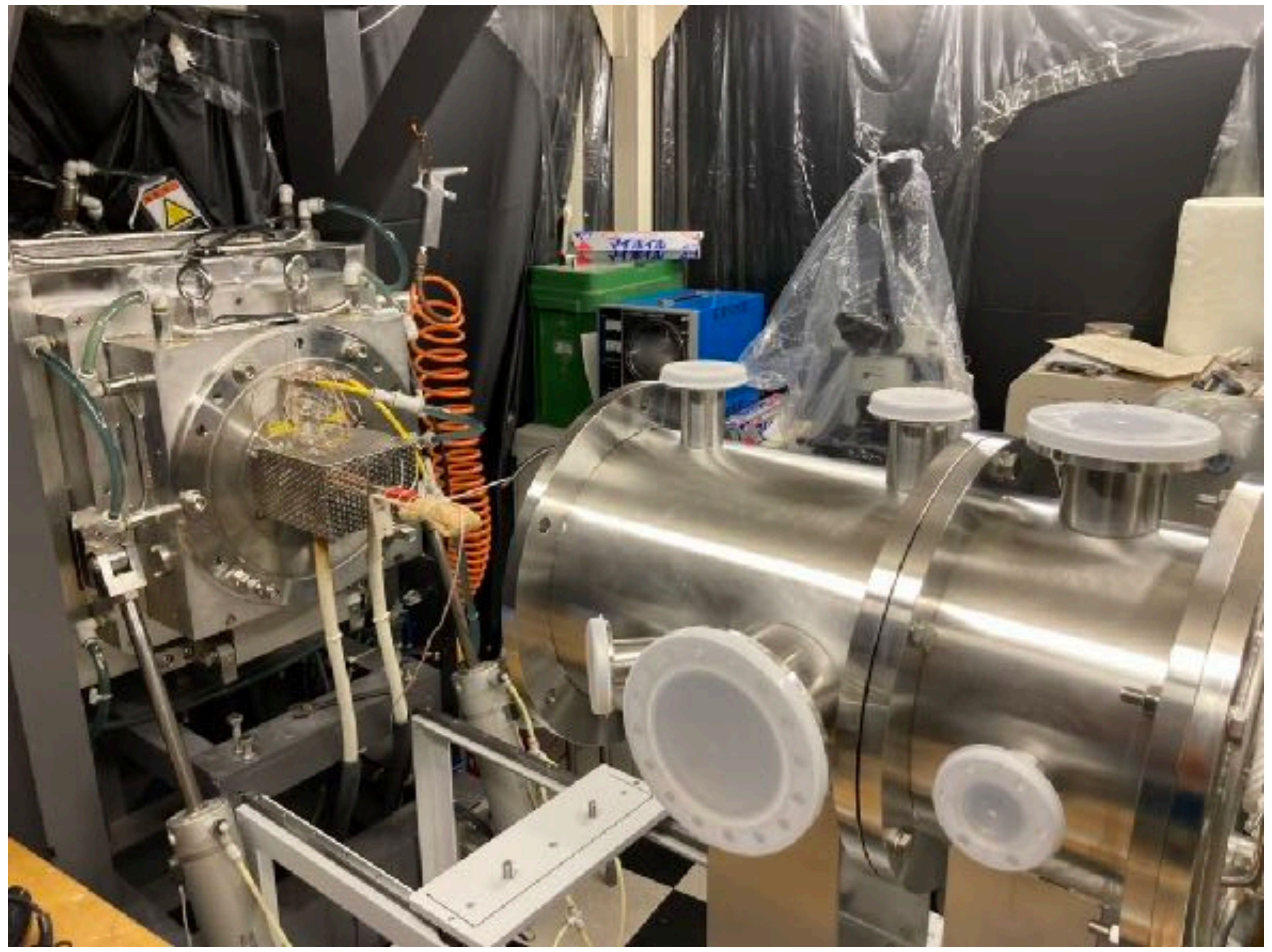
Investigate the relationship between recoil energy and pit formation by ion irradiation of samples



Natural muscovite



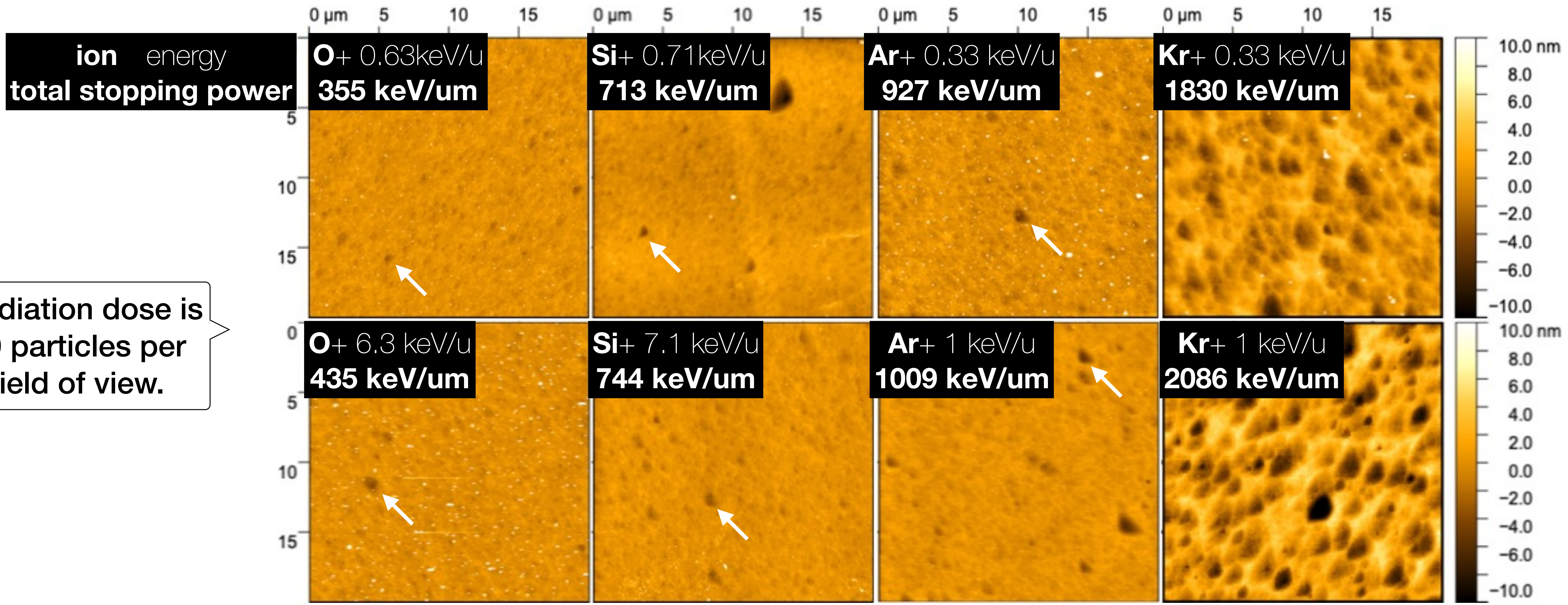
Natural muscovite,
with natural tracks
removed by annealing



Experiments at Kanagawa U

AFM images of ion-irradiated sample surfaces after etching

arXiv:2301.07118

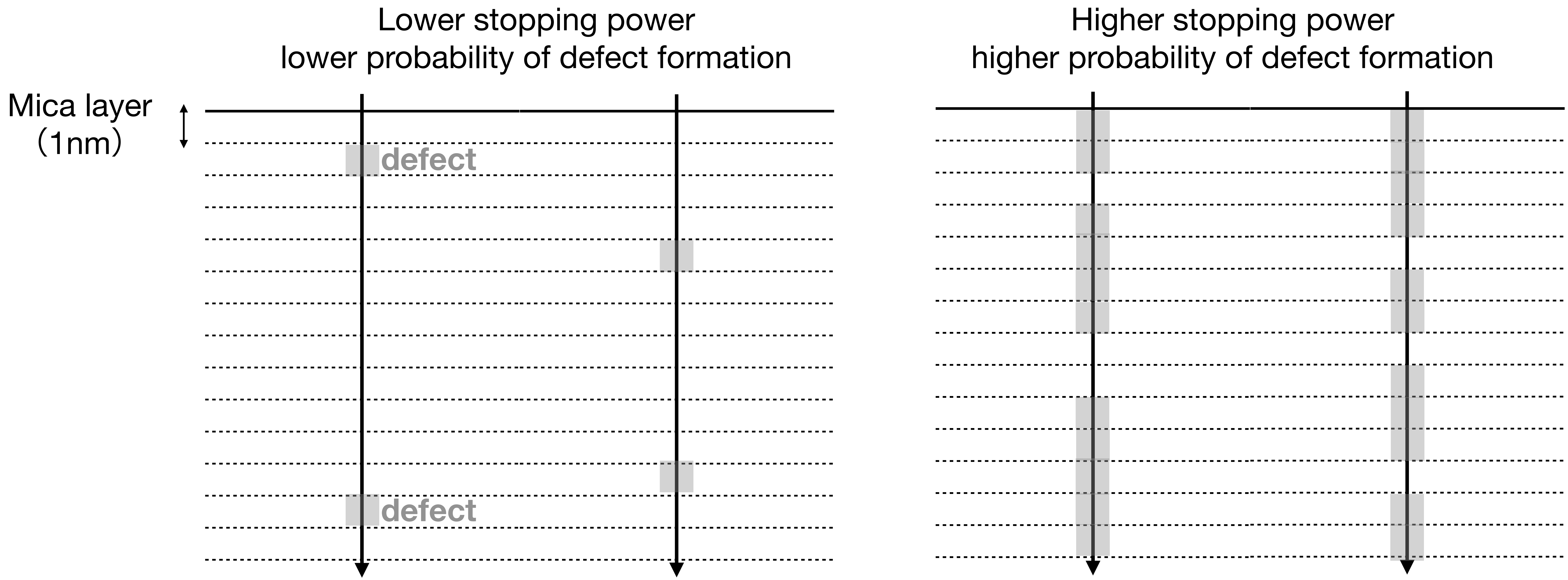


Irradiation dose is 80 particles per field of view.

- Mica detector efficiency, the probability that recoil tracks of atoms constituting muscovite (O, Al, Si, K) become pits, is about several % to 10%
- Detection efficiency tends to increase with higher stopping power

Sensitivity Evaluation of Mica Detector

Mathematical model describing the relationship between pit formation and stopping power (Snowden-Ifft and Chan 1995)

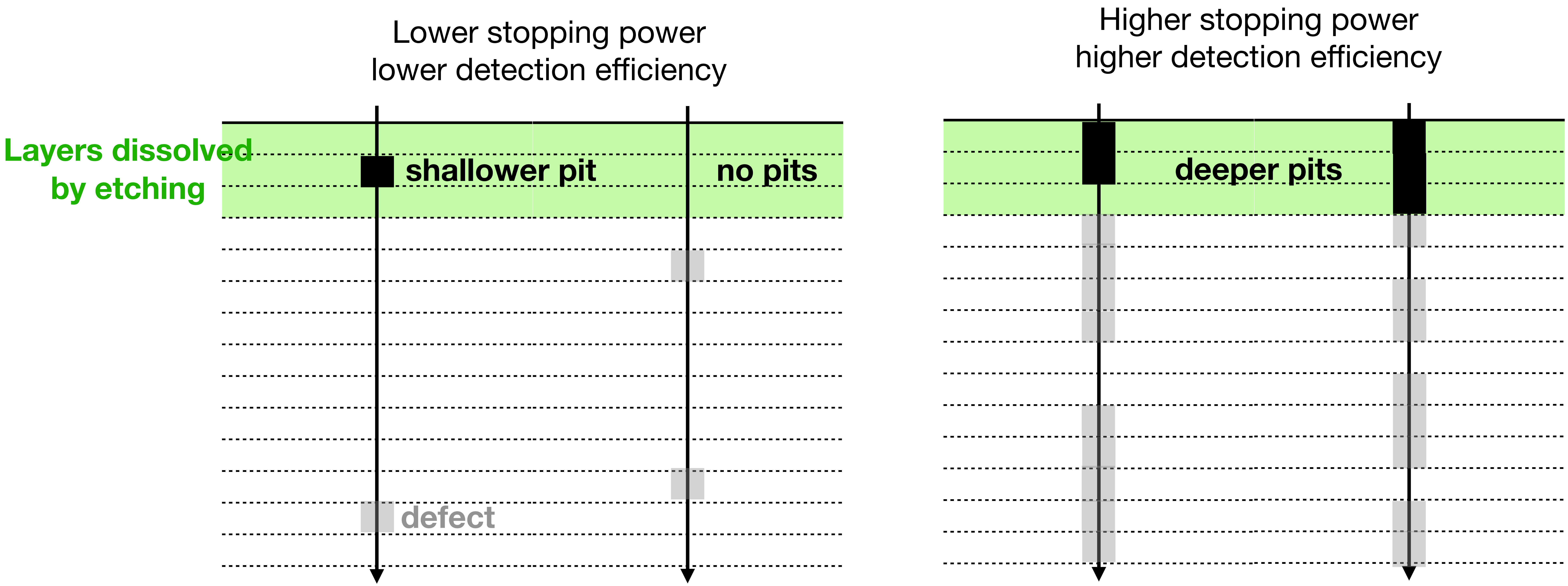


parameter↓ ↓energy

Probability of defect formation in a certain layer: $P(E;k) = 1 - \exp\left(-kS(E)\right)$

↑stopping power

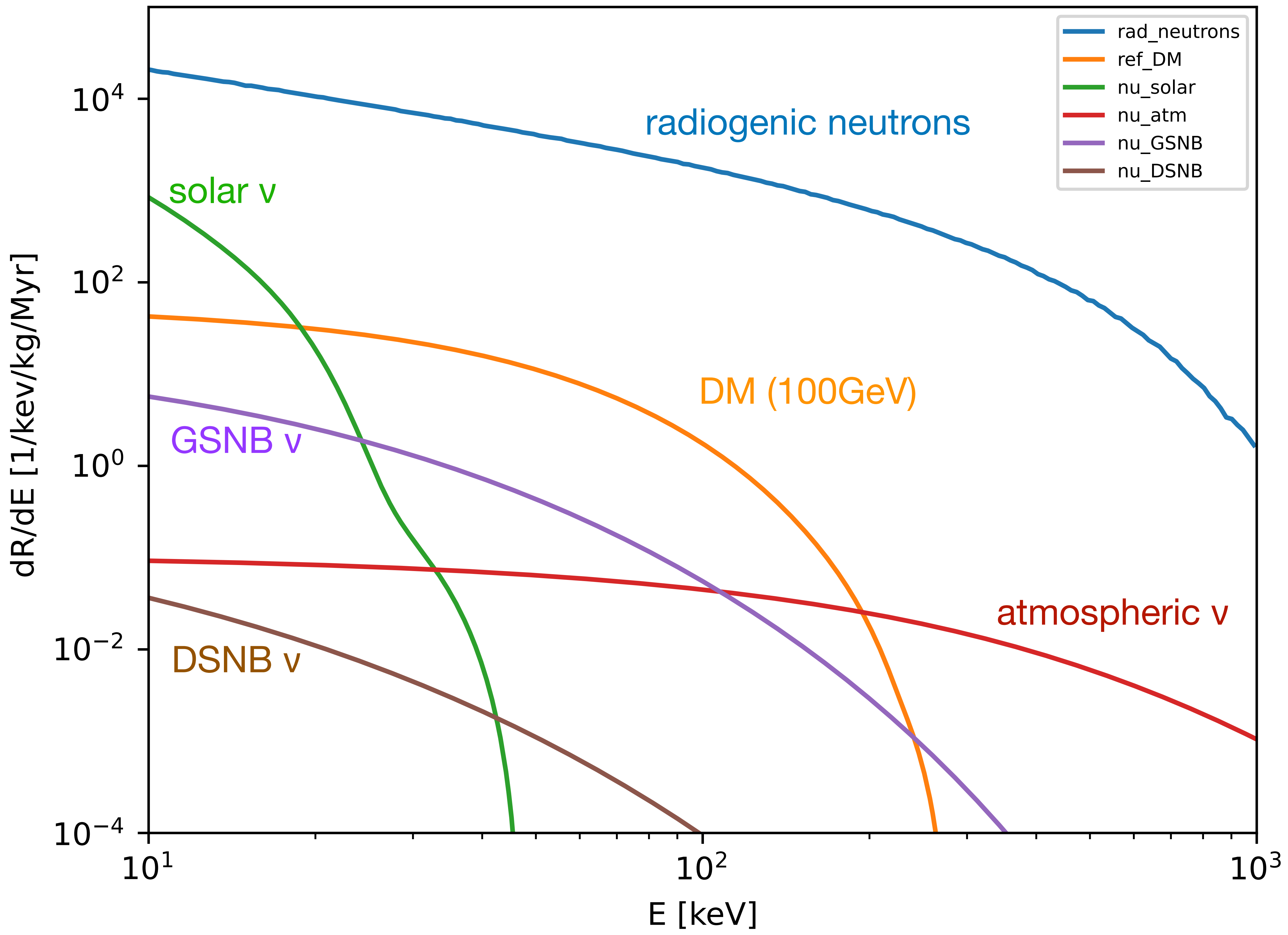
Mathematical model describing the relationship between pit formation and stopping power (Snowden-Ifft and Chan 1995)



- Etched layer defects manifest as pits, illustrating detection efficiency's stopping power reliance
- Pit depth, determined by number of defects, is calculable from recoil energy

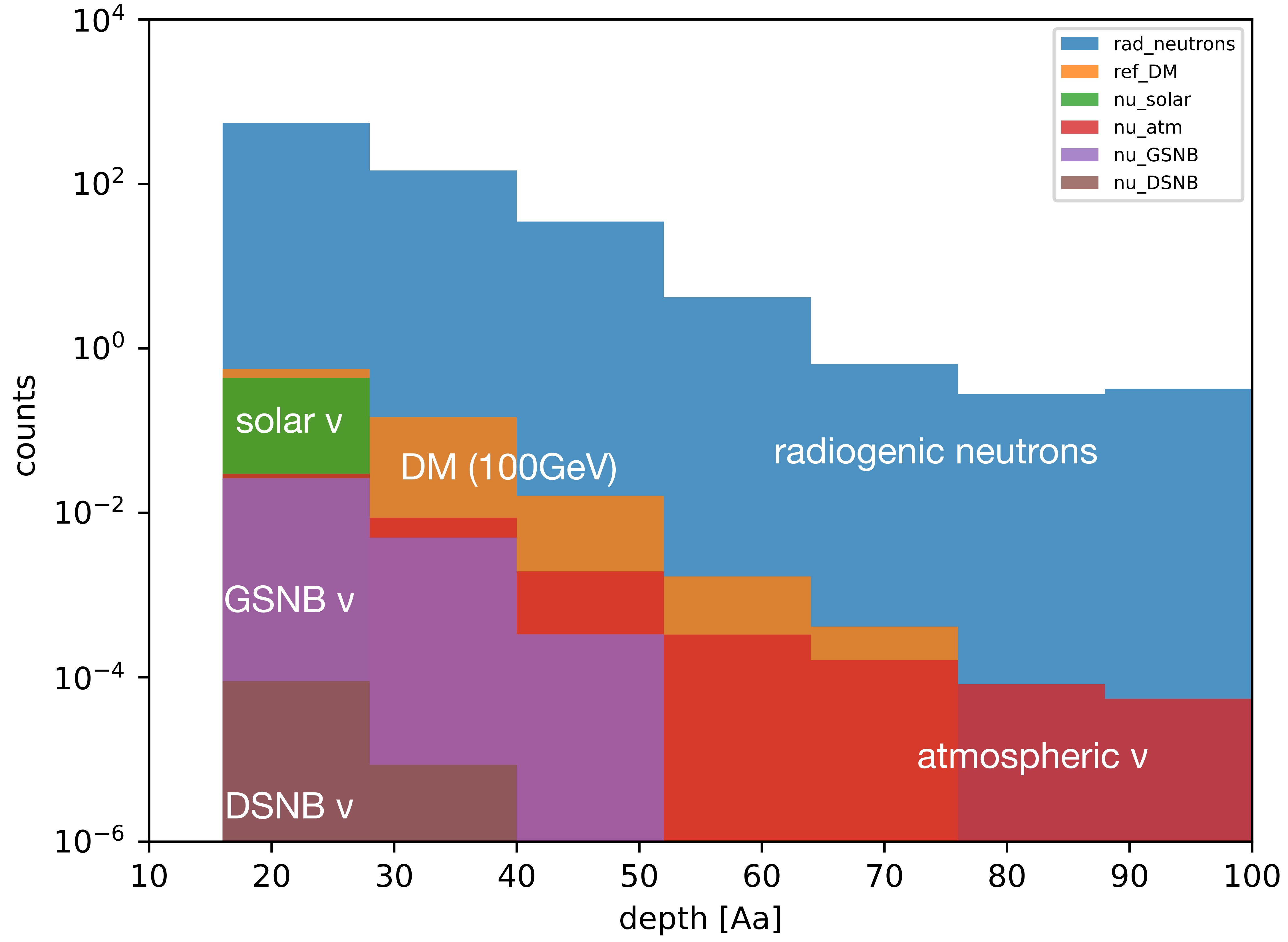
Calculate pit depth histogram from recoil energy spectrum

Recoil Energy Spectrum using paleoSpec



Monte Caro simulations
basend on
the mathematical model

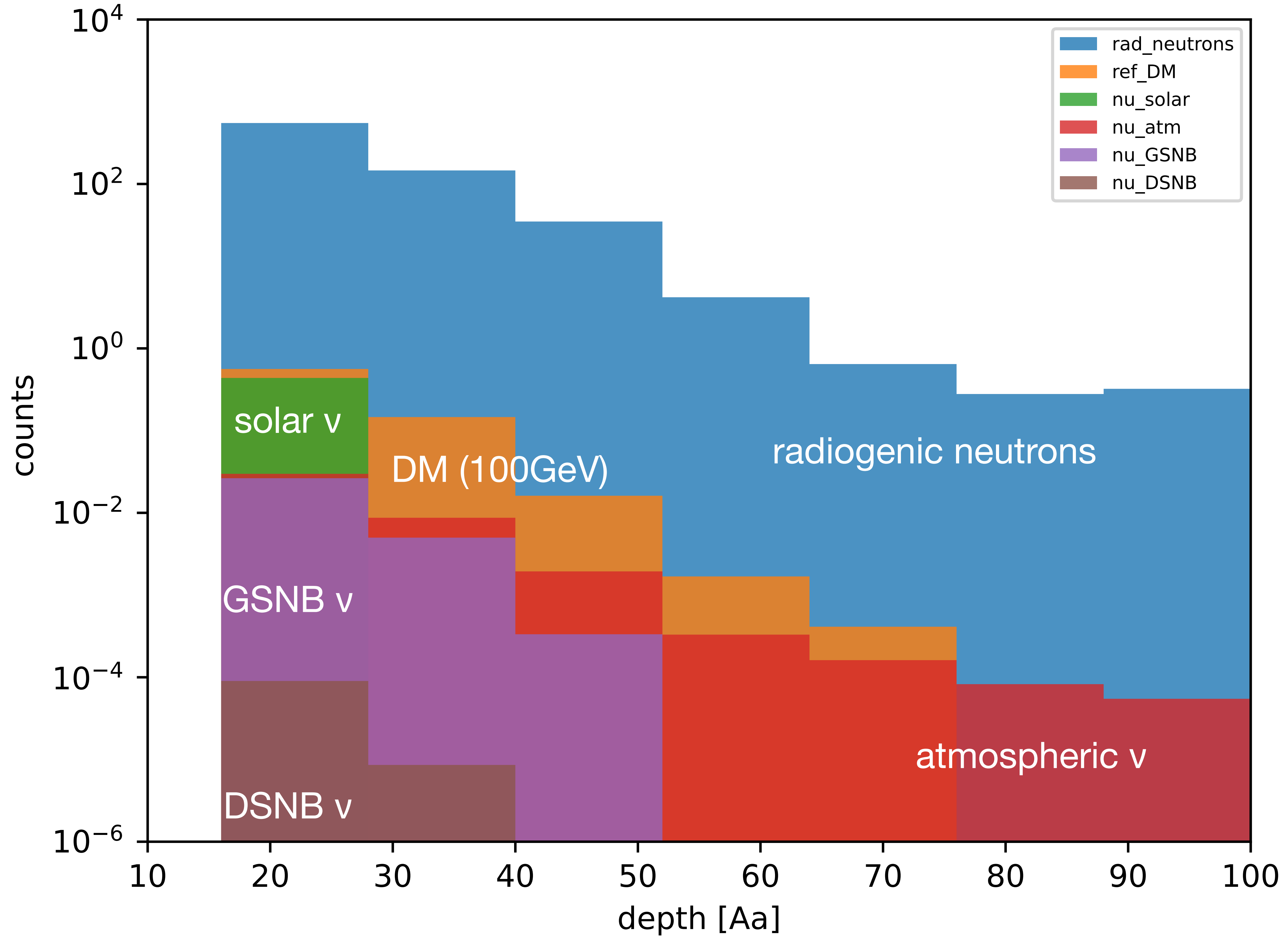
Pit depth histogram



- Muscovite mica
  - age: 500 Myr
  - Uranium concentration: 0.1ppb
  - exposure: 1 ton yr

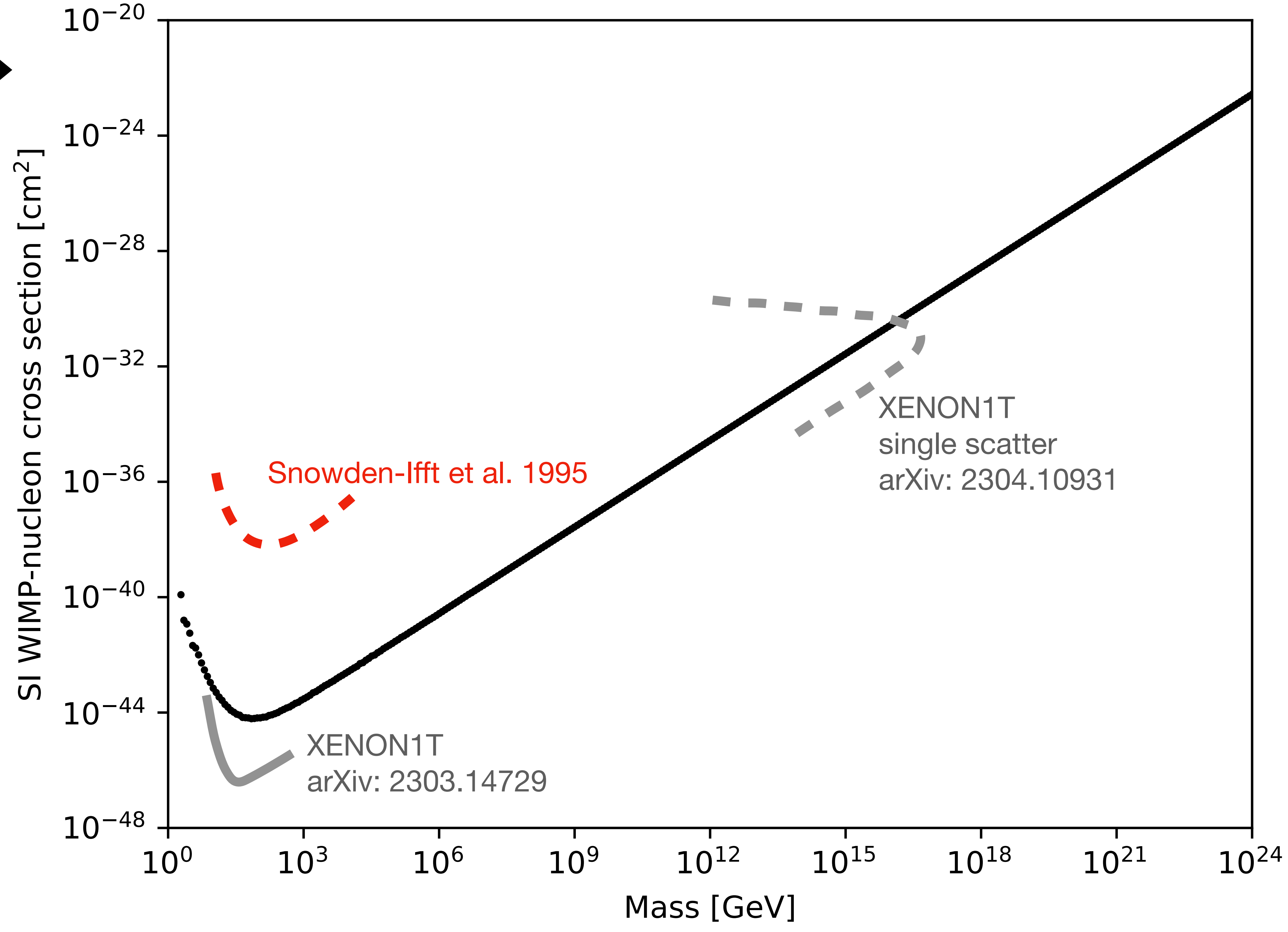
Performance Evaluation of Detector Using Pit Depth Histogram

Pit depth histogram



Likelihood ratio test using paleoSens

90% Confidence Detection Limit



- Muscovite mica
  - age: 500 Myr
  - Uranium concentration: 0.1ppb
  - exposure: 1 ton yr

Exploration possible for extremely heavy dark matter due to high surface area-to-volume ratio

- Number of DMs Passing through a Detector with Surface A during $t > 1$

$$A t v_\chi \left(\frac{\rho_\chi}{m_\chi}\right) > 1$$

- Upper Limit on Detectable DM Mass $\propto$
  Exposure (Mt) $\times$ Surface Area per Volume (A/V)

XENON1T: $$\left(\frac{m_\chi}{\text{GeV}}\right) < 10^{18} \left(\frac{Mt}{1\text{ton}\cdot\text{yr}}\right) \left(\frac{A/V}{(1\text{m})^{-1}}\right)$$

DMICA: $$\left(\frac{m_\chi}{\text{GeV}}\right) < 10^{26} \left(\frac{Mt}{1\text{ton}\cdot\text{yr}}\right) \left(\frac{A/V}{(10\text{nm})^{-1}}\right)$$

Summary

- **DMICA experiment utilizes mica as a detector for dark matter:**
  - detects nuclear recoil events with an efficiency ranging from a few to 10%
  - pit depth histogram reflects the recoil energy spectrum

- **Mica detector possesses unique characteristics:**
  - records ancient events, enabling DM exploration on a galactic scale
  - geometrically thin nature allows for investigation of extremely heavy DM