DMICA: exploring Dark Matter in natural muscovite MICA

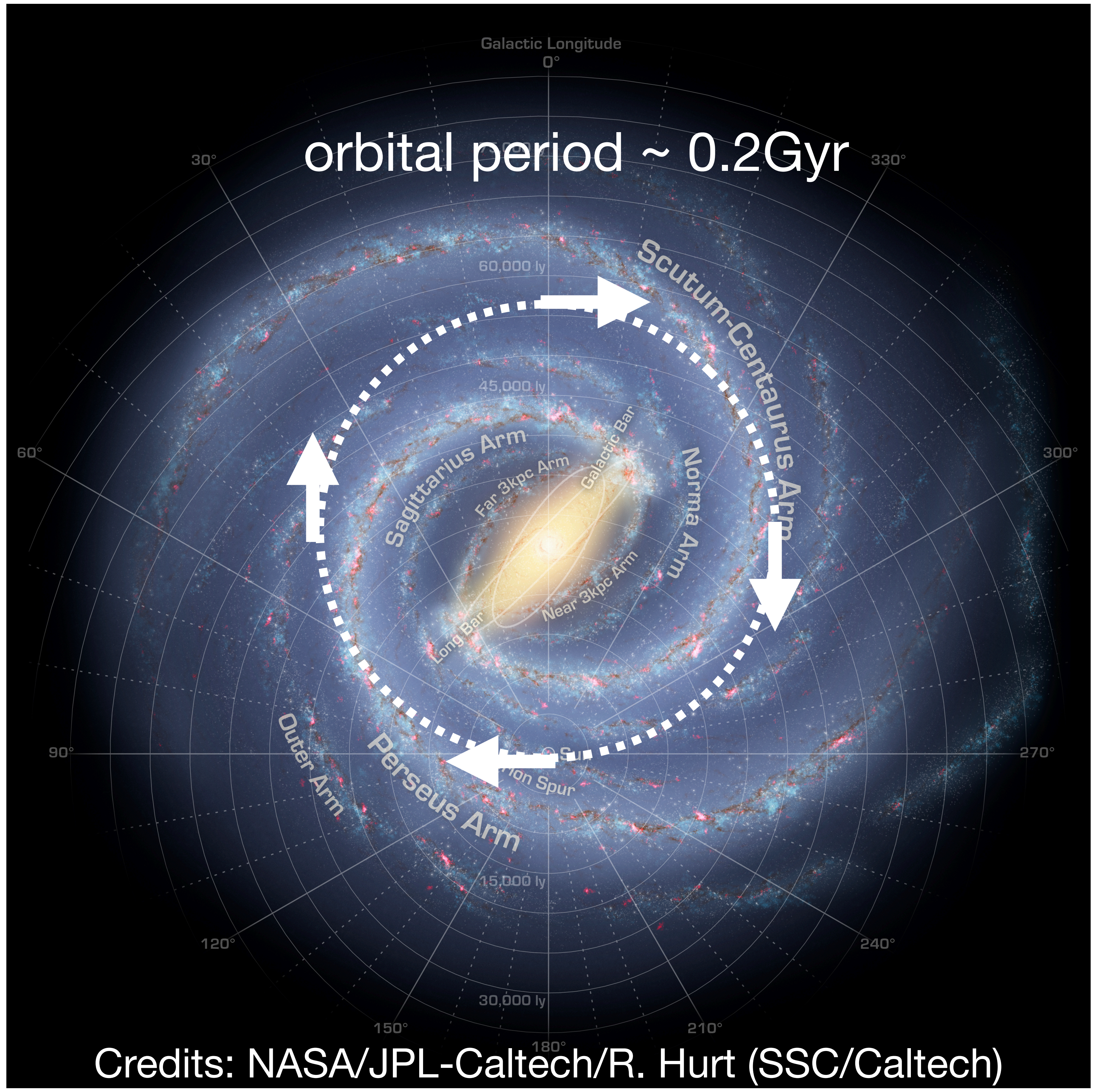
Shigenobu Hirose

Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

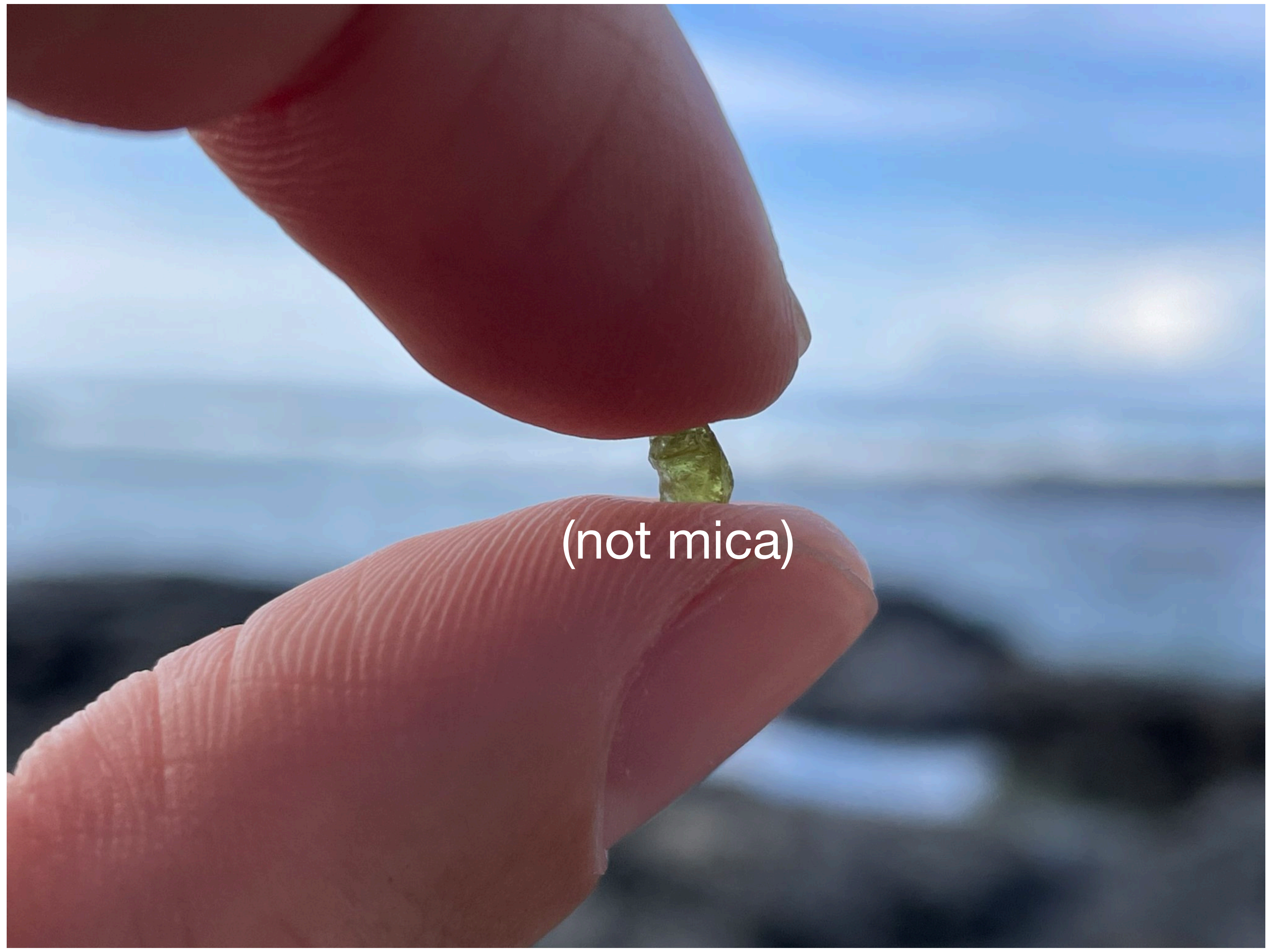
Collaboration with:
Natsue Abe[1] Qing Chang[1], Takeshi Hanyu[1], Noriko Hasebe[2], Yasushi Hoshino[3], Takashi Kamiyama[4], Yoji Kawamura[1], Kohta Murase[5], Tatsuhiro Naka[6], Kenji Oguni[1], Katsuhiko Suzuki[1], Seiko Yamasaki[7]
(JAMSTEC[1], Kanazawa U[2], Kanagawa U[3], Hokkaido U[4], Penn State[5], Toho U[6], AIST[7])

Scientific focus: exploring “past-Gyr” DM events

- Conducting a galactic-wide DM survey



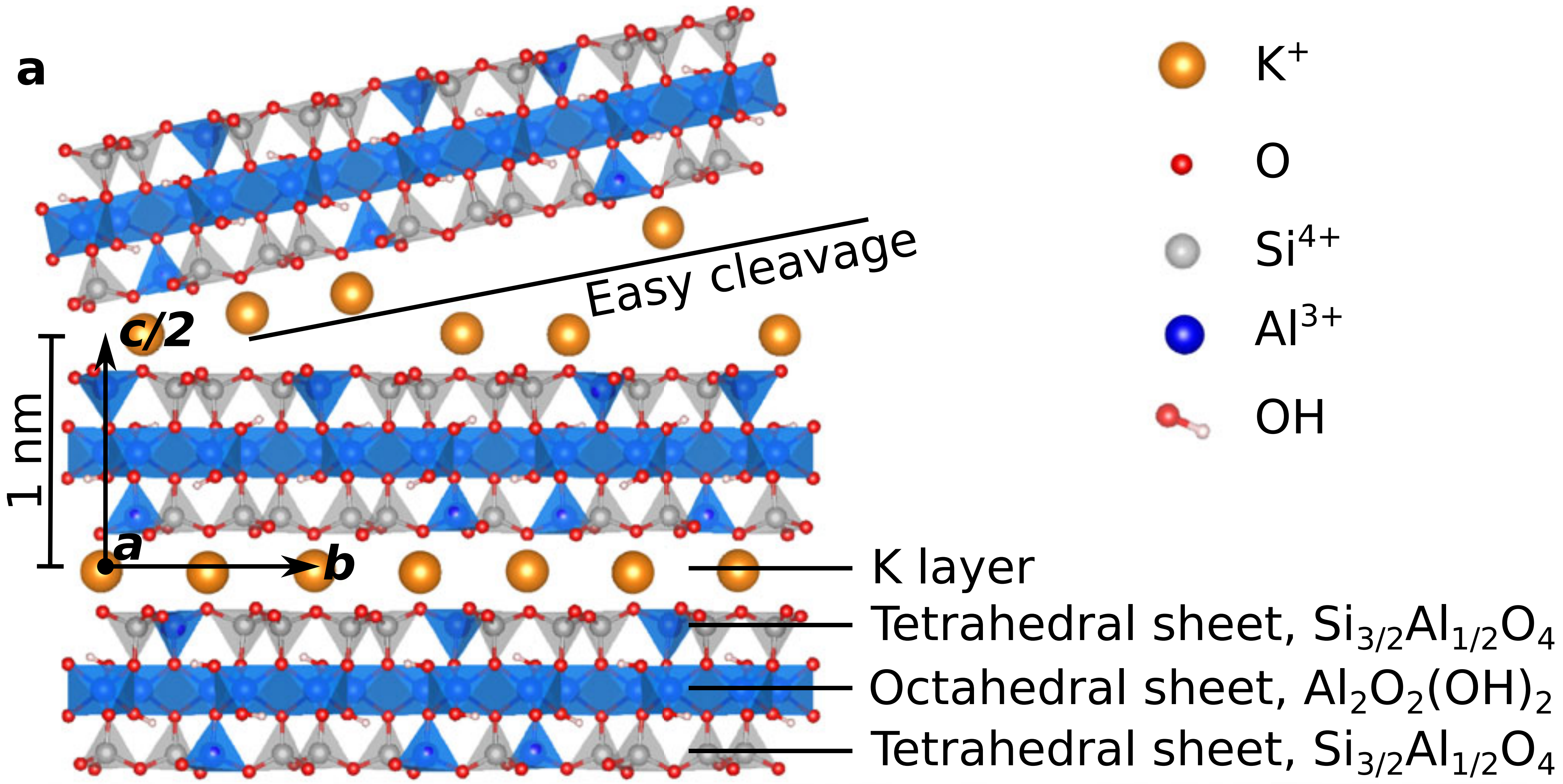
- Small target mass can achieve large exposure due to long age (e.g., 1 mg x 1 Gyr = 1 ton-year)



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

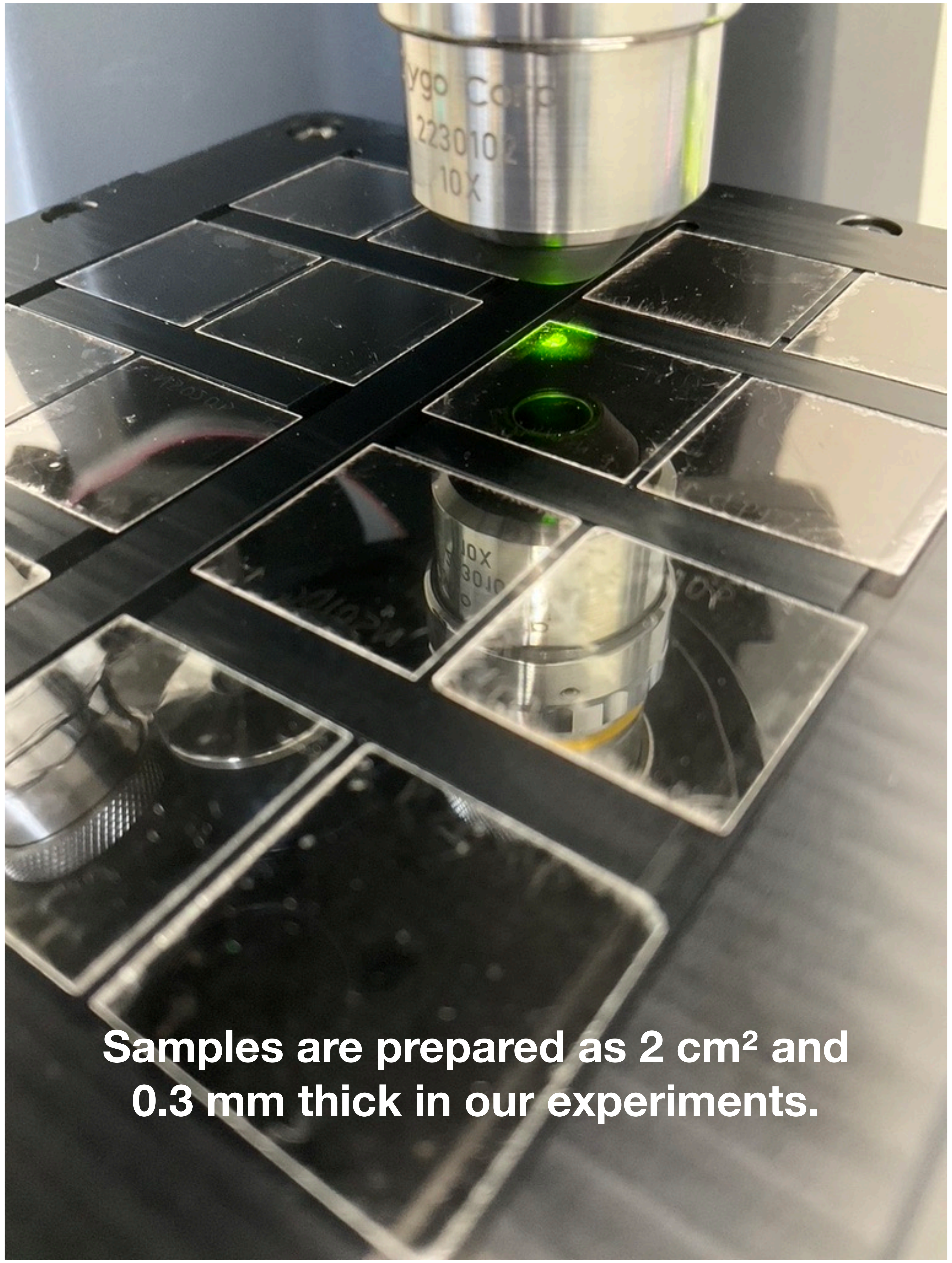
Muscovite mica is well-established as a solid state track detector in geology

Muscovite mica $KAl_3Si_3O_{10}(OH)_2$

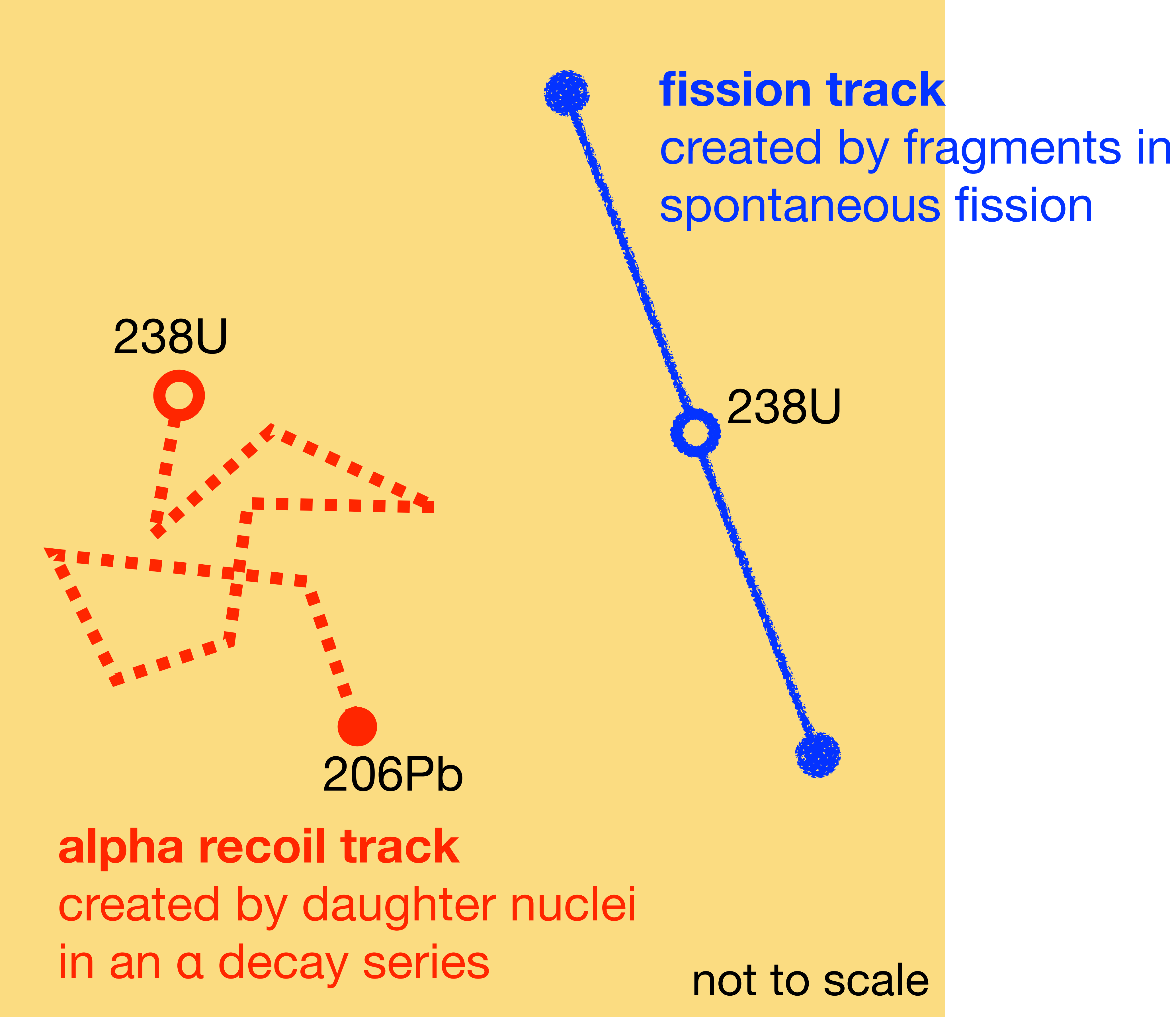


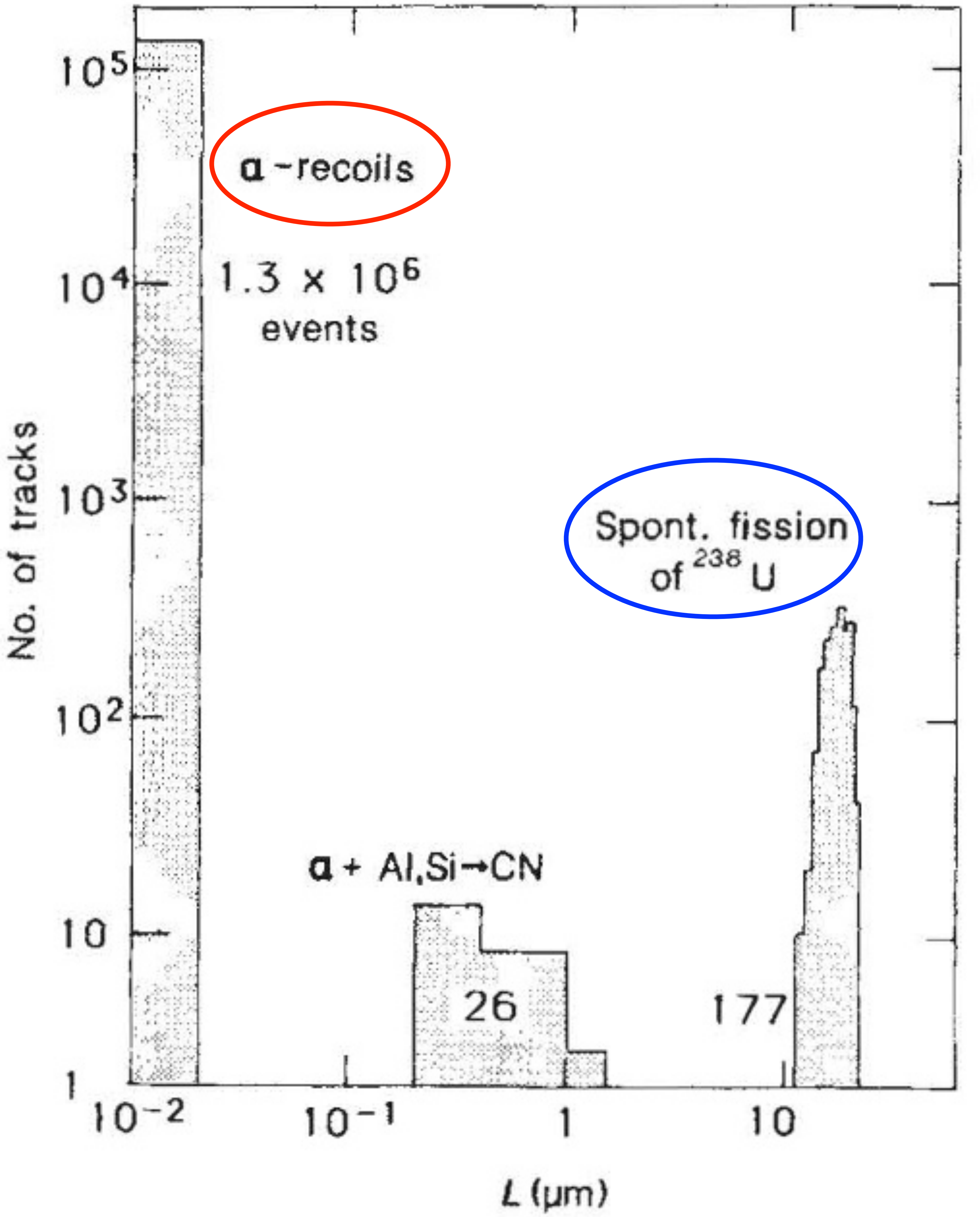
Franceschi+ 2023

- Cleavage at a potassium layer allows easy access to the crystal's interior.



Natural radiation tracks (crystal defects) in mica

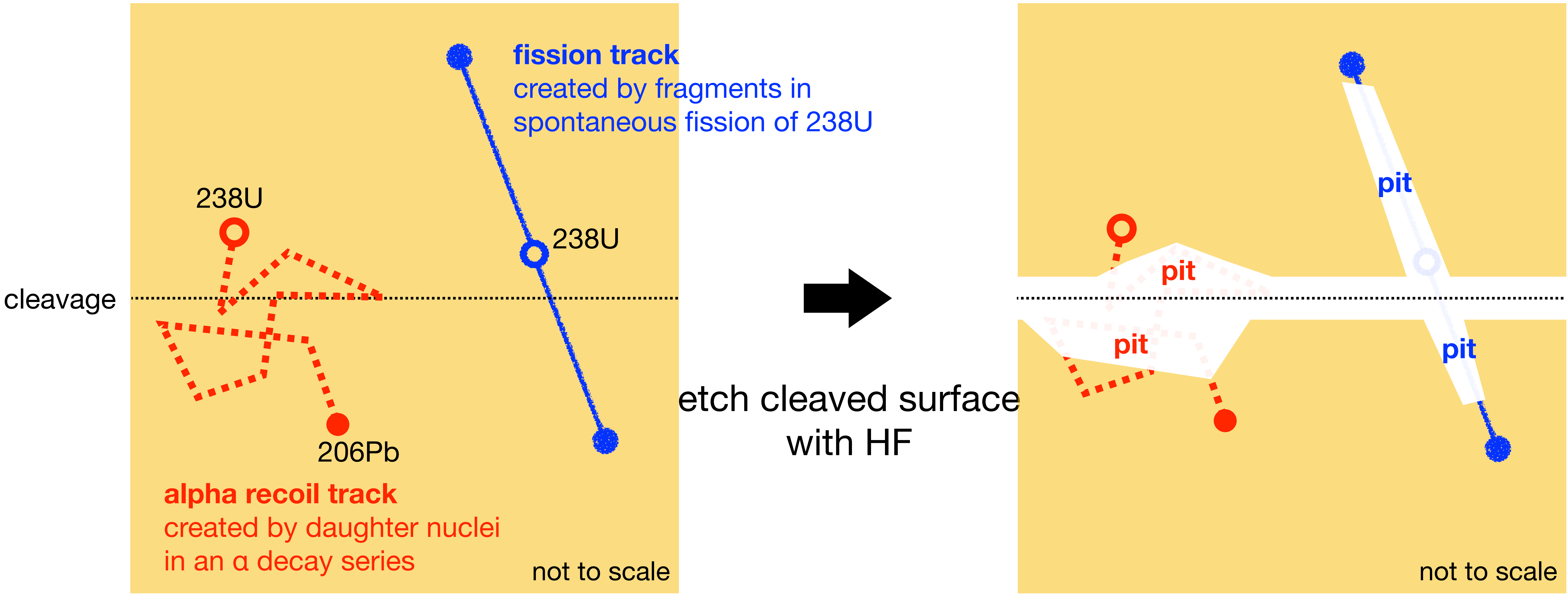




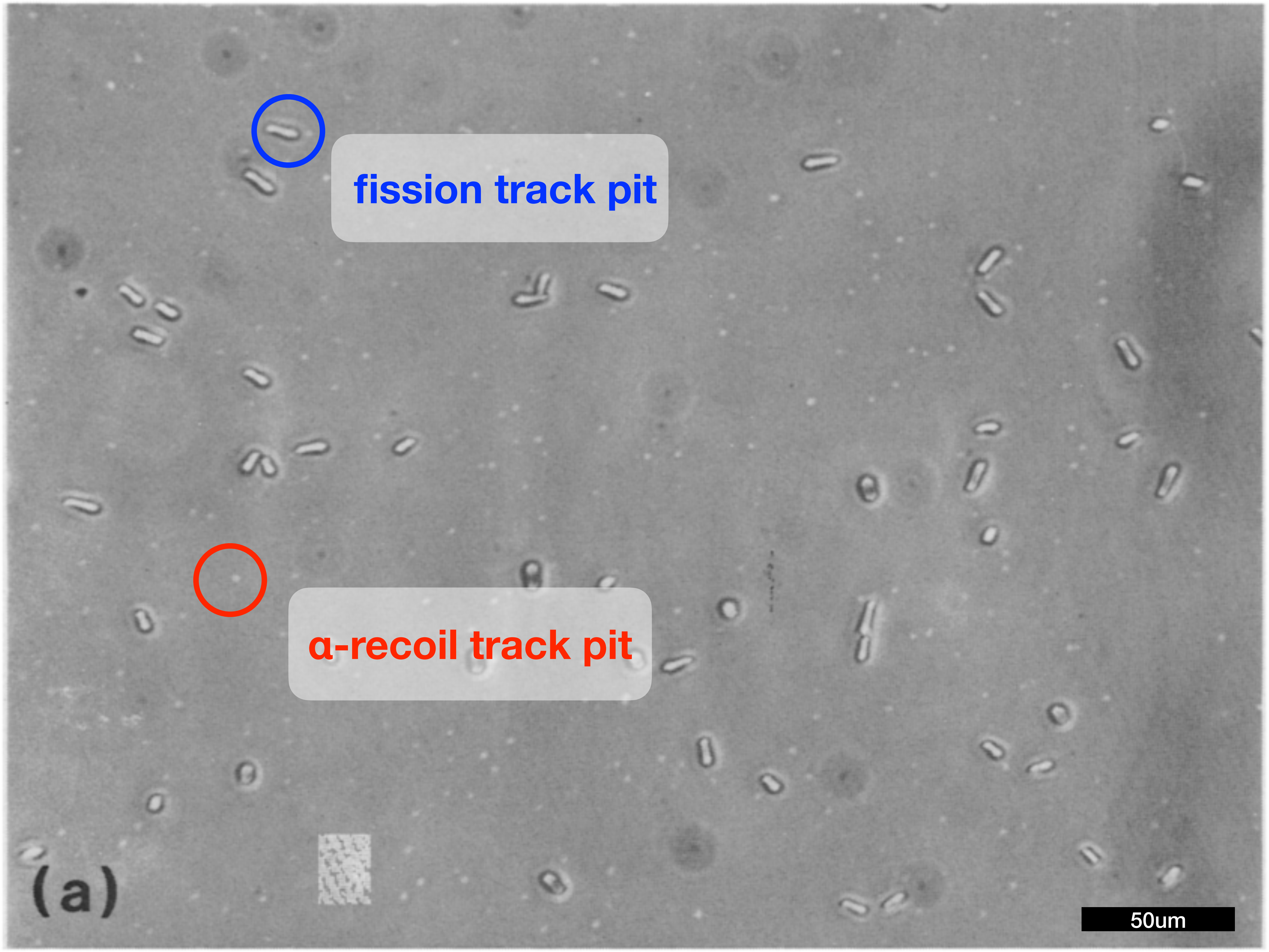
Frequency of naturally occurring tracks in muscovite mica (Price & Salamon 1986)

- Typical concentration of ^{238}U ~ O(0.1) ppb.
- α recoil tracks are most common.

“Latent” tracks intersecting a cleavage plane are revealed as pits through chemical etching



Pits of radiation tracks appearing on the etched mica surface



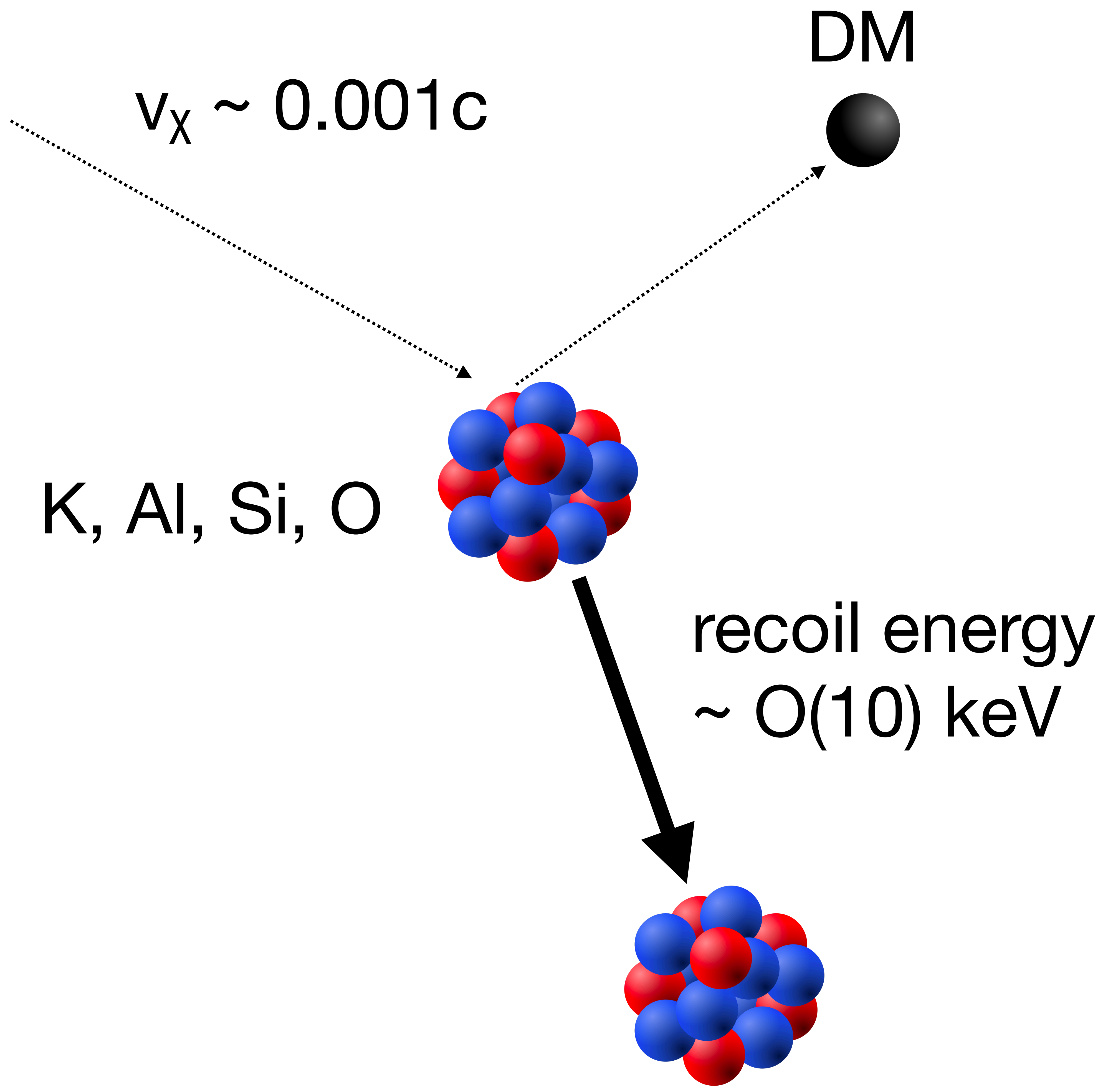
Phase contrast microscopic photograph of *induced* alpha-recoil and fission tracks on the etched surface of mica (Hashimoto et al. 1980)

	Z_{recoil}	v_{recoil} / c	dE/dx GeVcm^{2}g^{-1}	pit depth um
fission track	~38 and ~52	0.031~ 0.046	~25 electronic stopping	~20
α-recoil track	82 ~ 90	0.0013	~15 nuclear stopping	0.01~ 0.03

Comparison of natural radiation tracks
(from Price & Salamon 1986 with modifications)

Using the “cleave-and-etch method”, can we readout DM nuclear recoil tracks as well if they exist in mica?

What pit can we expect for DM nuclear recoil tracks?

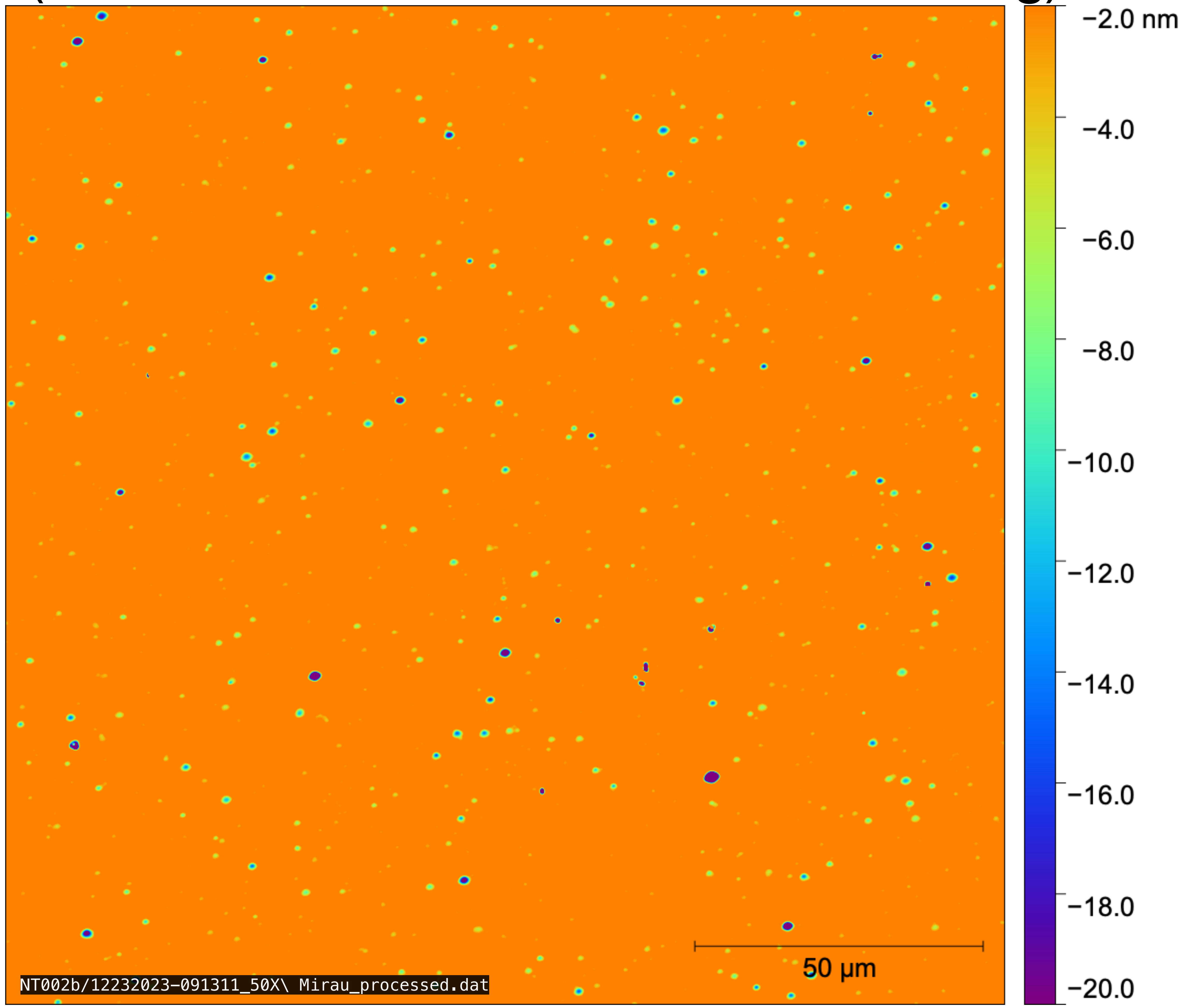


	Z_{recoil}	v_{recoil} / c	dE/dx GeVcm^{2}g^{-1}	pit depth um
fission track	~38 and ~52	0.031~ 0.046	~25 electronic stopping	~20
alpha recoil track	82 ~ 90	0.0013	~15 nuclear stopping	0.01~ 0.03
DM recoil track	8 ~ 19 (K, Al, Si, O)	~ 0.001	~O(1) nuclear stopping	**?**

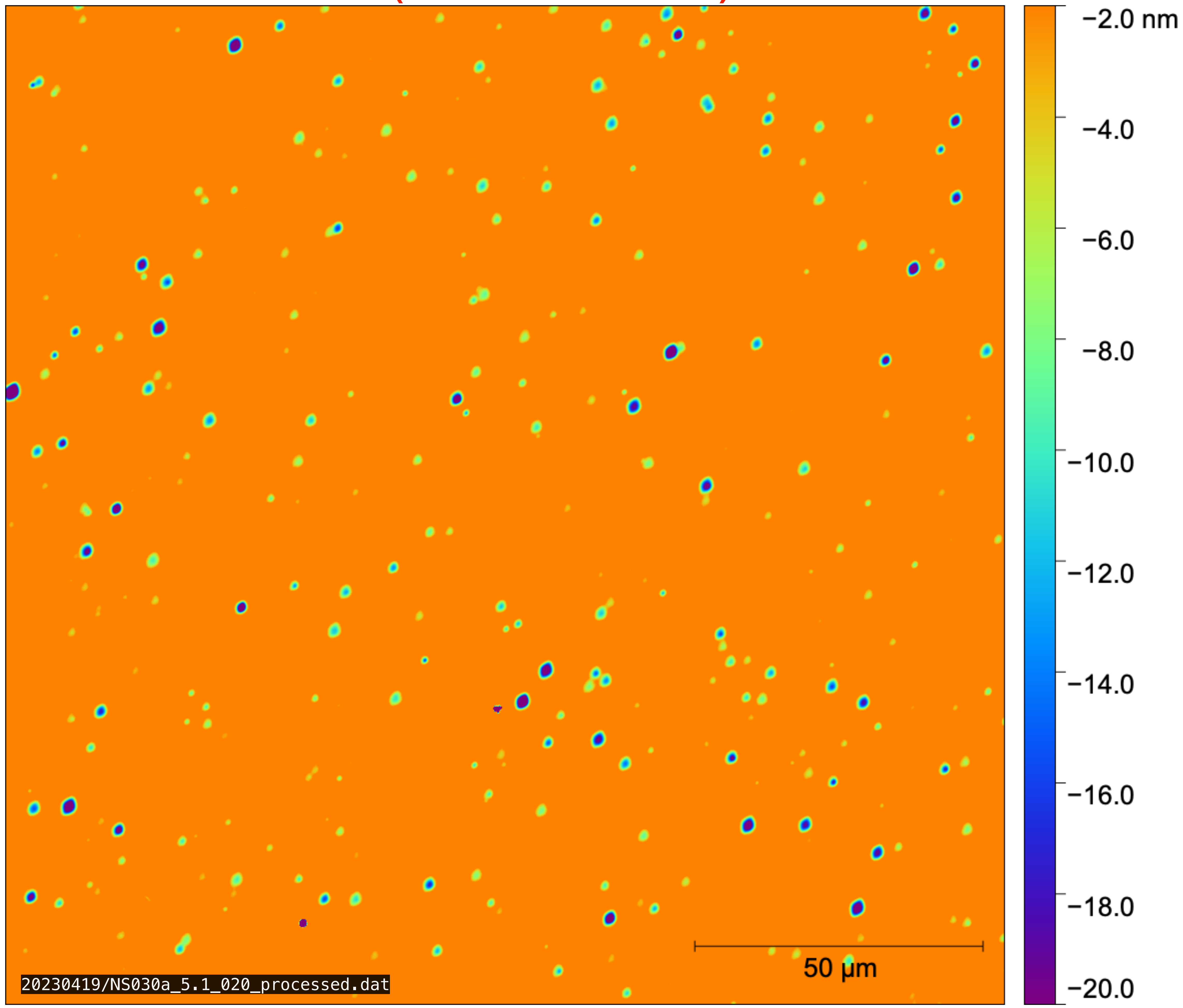
- Fast neutrons (~ MeV) mimic DM nuclear recoil (, which means they are genuine backgrounds).

Neutron (pseudo DM) recoil pits are shallower but observable

neutron-recoil track pits
(neutron-irradiated mica after annealing)

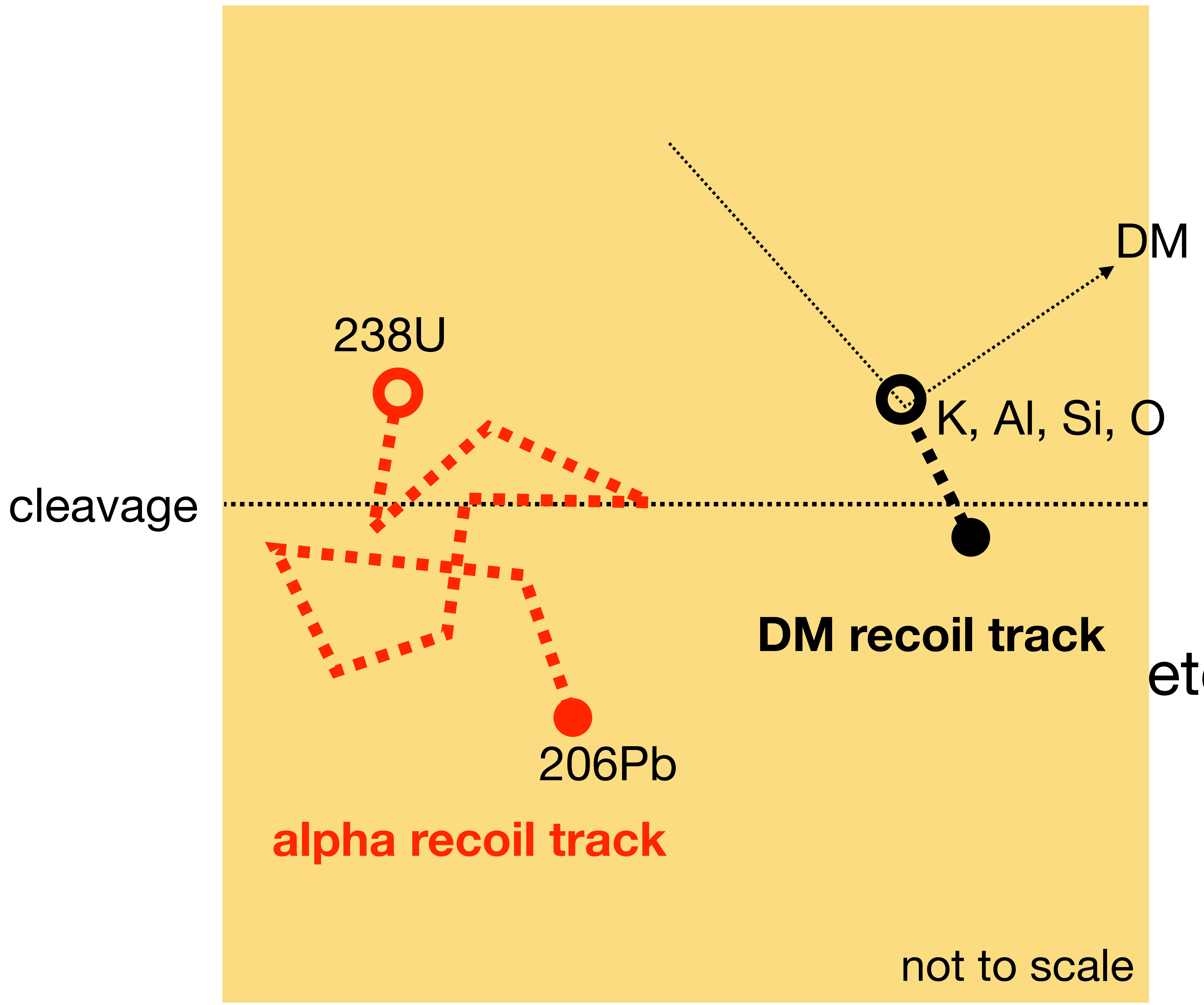


alpha-recoil track pits
(natural mica)

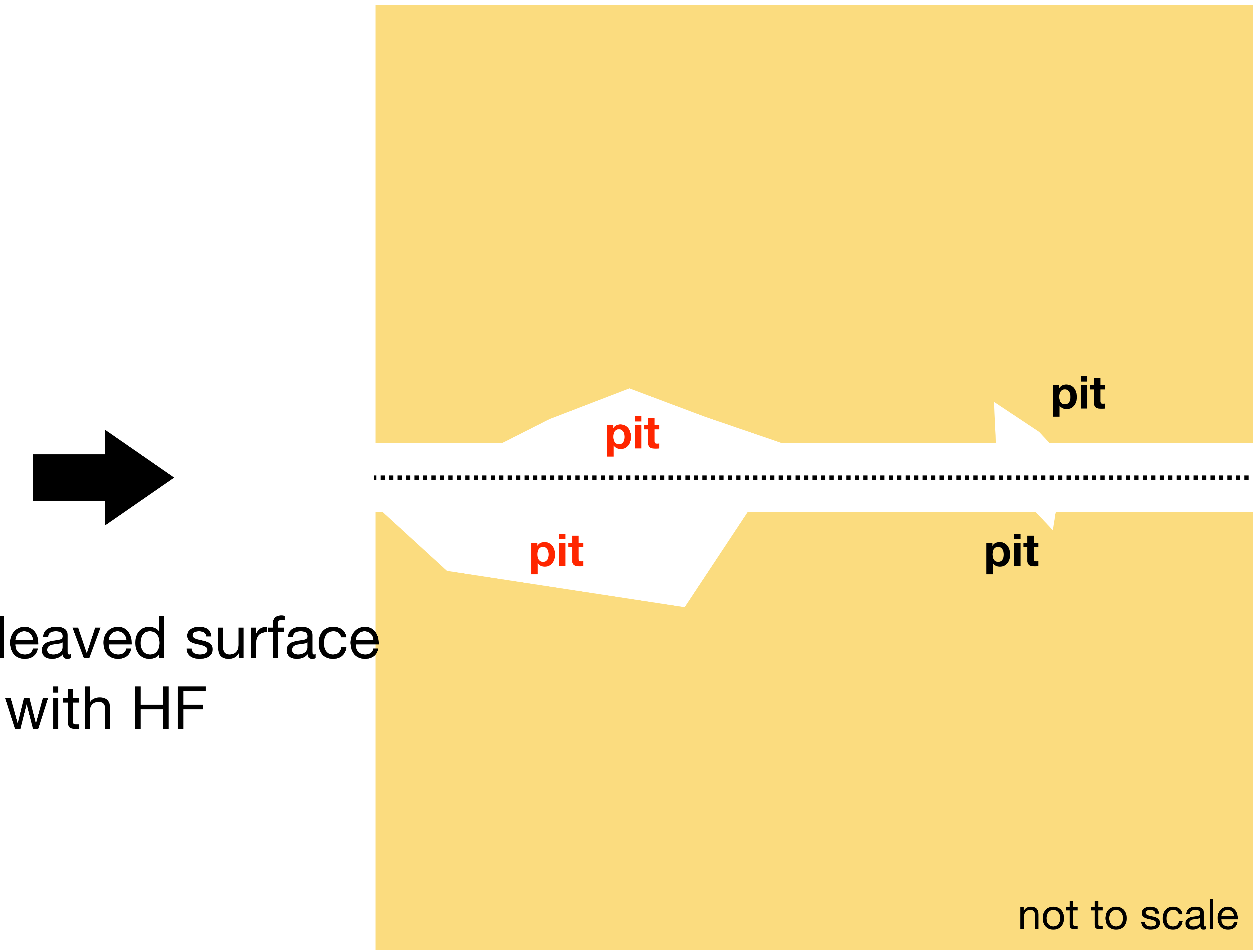


Surface topography optained by optical profiler (preliminary results)

Cleave-and-etch method reveals tracks crossing cleavage plane



etch cleaved surface
with HF



- Target volume: V ~ S * L/2 (L: track length = O(10)nm, S: surface area)
- To increase the target volume, more surface area needs to be scanned.

Pioneering DM search using muscovite mica by Snowden-Ifft et al. 1995

Pioneering DM search using muscovite mica by Snowden-Ifft et al. 1995 (SI95)

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

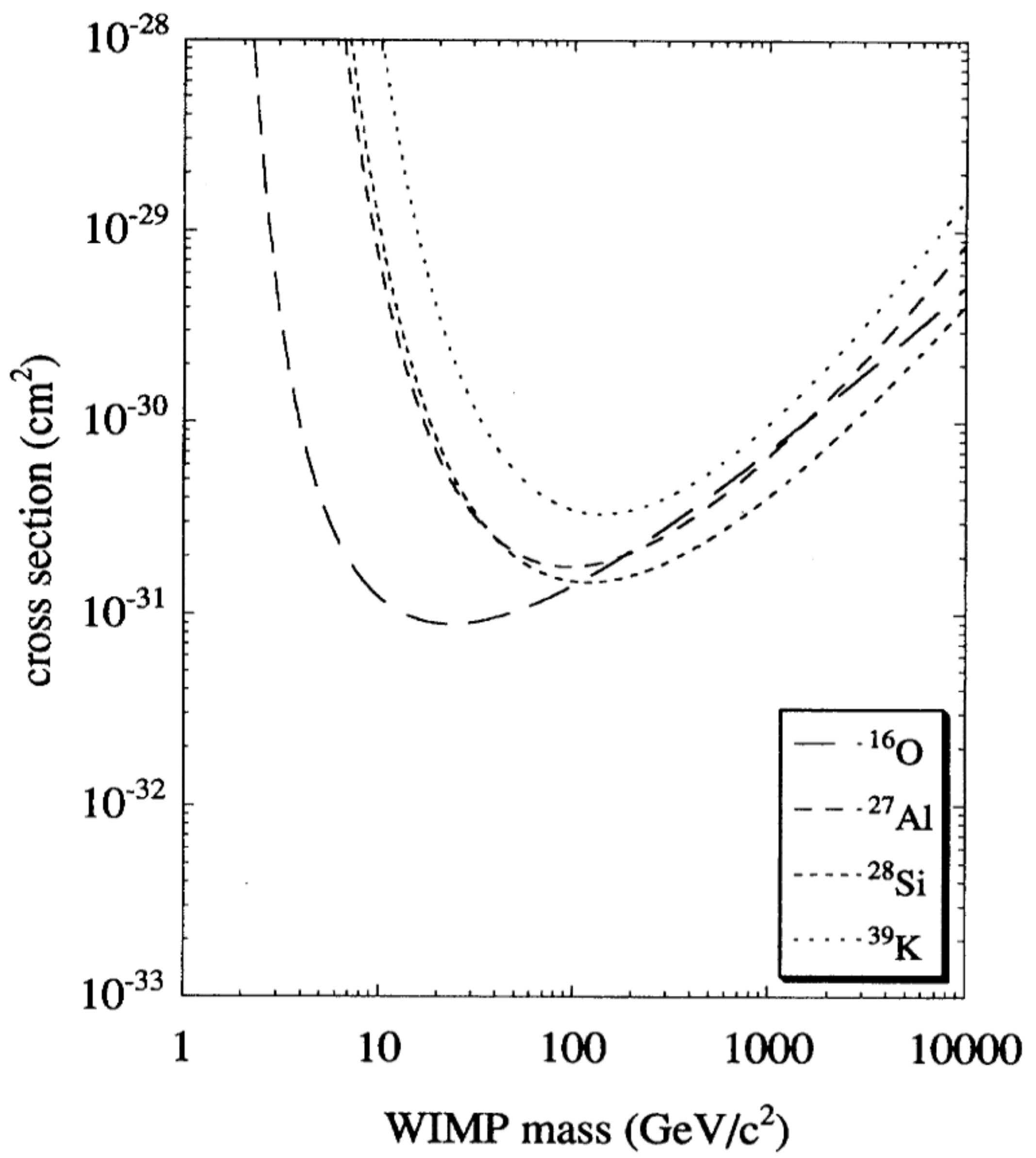
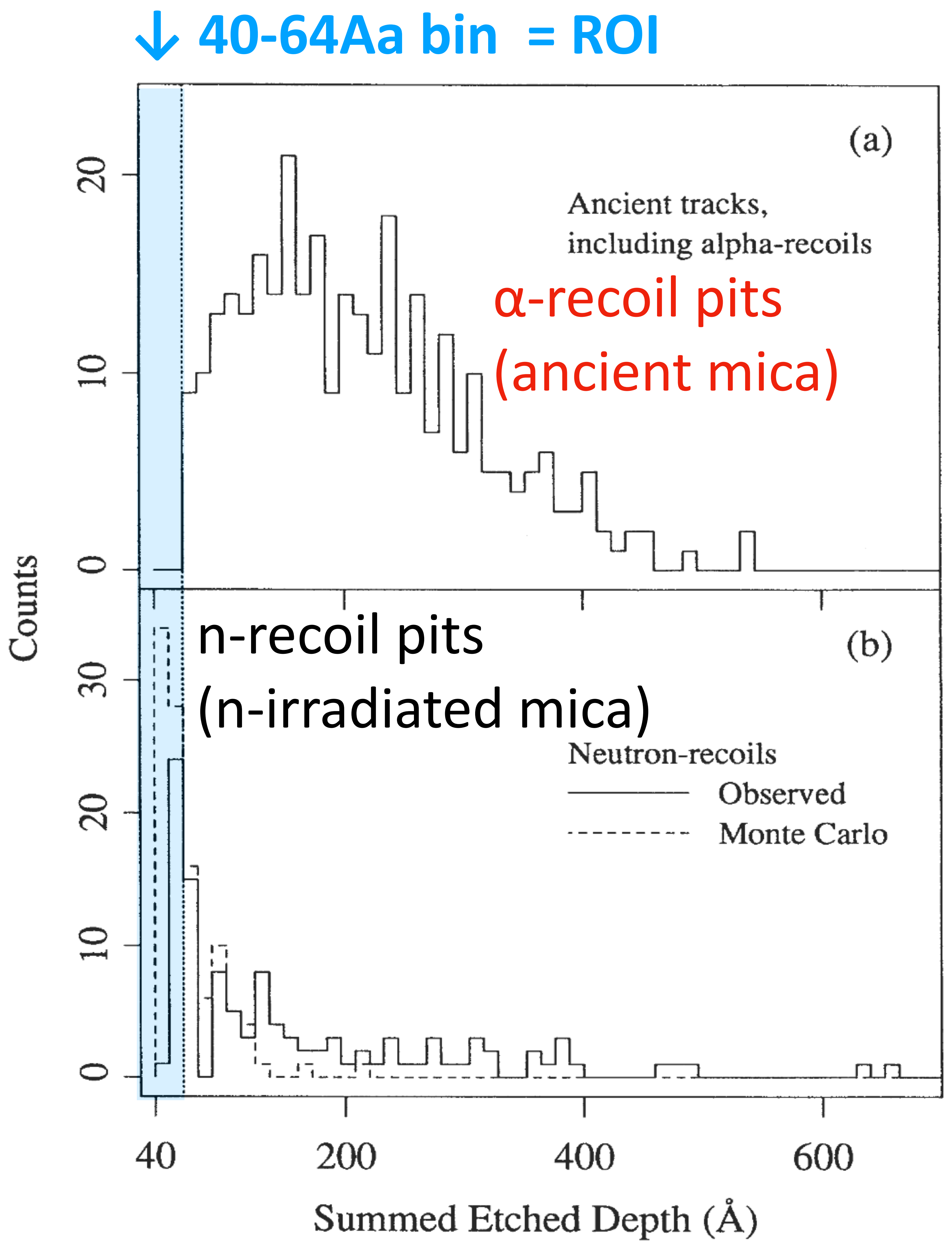


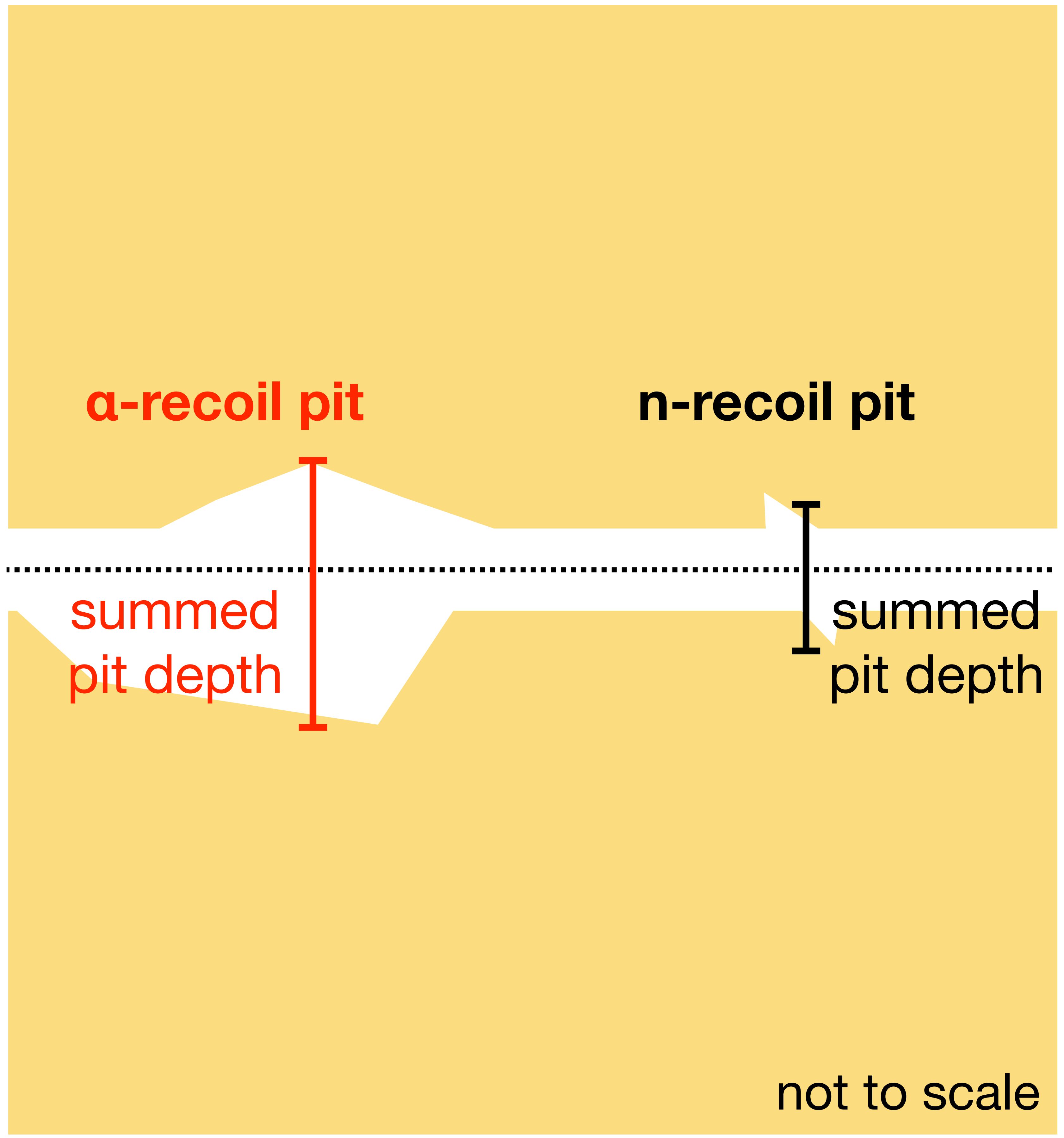
FIG. 4. Exclusion curves for each of the main constituent nuclei of mica. For a given mass, WIMPs with cross sections above these curves are ruled out at the 90% confidence level.

- They set one of the strictest limits on WIMPs cross section at that time, with an exposure of just 1e-6 ton-year,

Identified in the pit-depth histogram ROI free from α-recoil pits

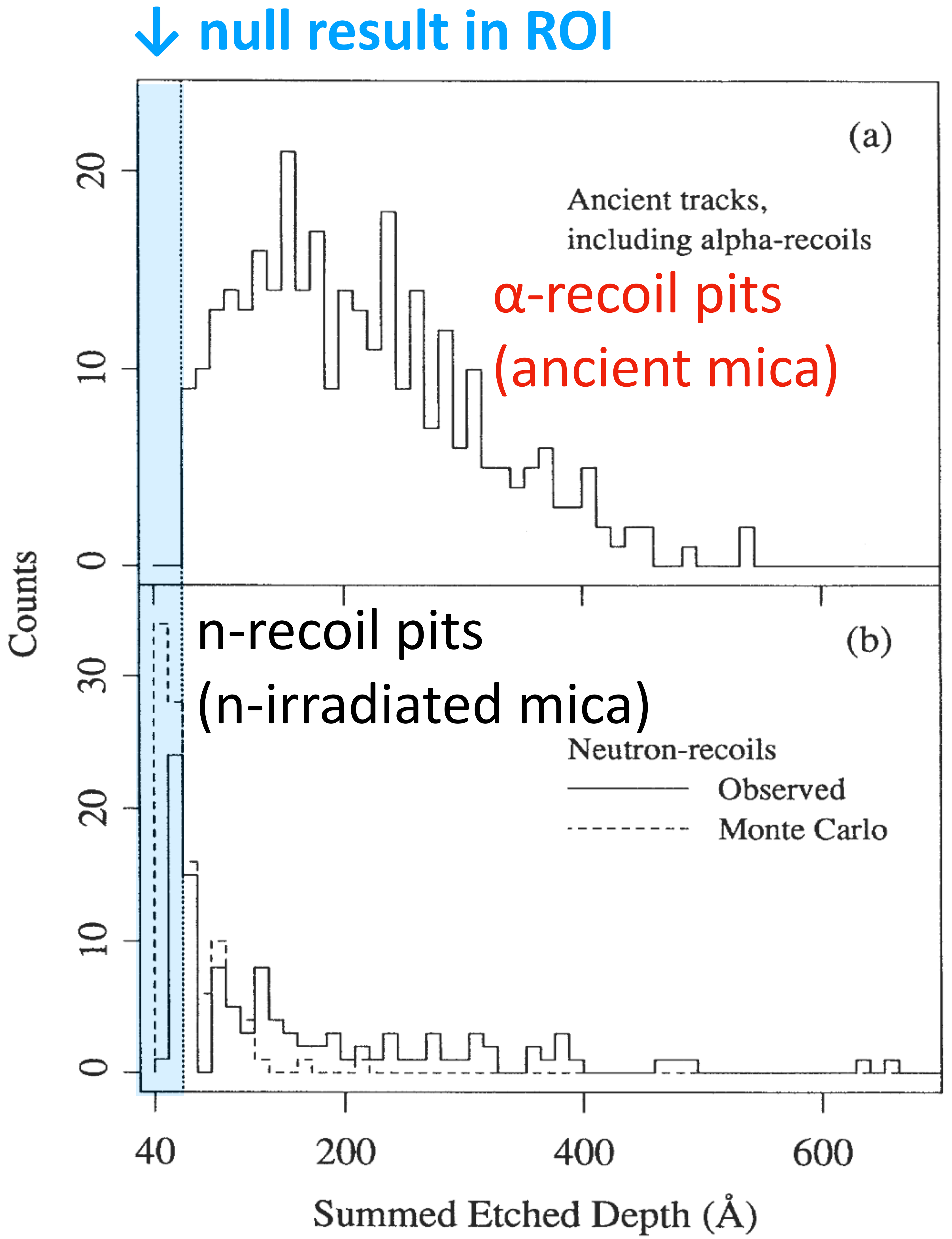


Snowden-Ifft et al. 1995



- SI95 found that the summed pit depth histogram showed null for α-recoil pits but a peak for n-recoil pits in the smallest (40-64Aa) bins.

Limits on dark matter from 80,720um² mica surface scan by atomic force microscopy (AFM)



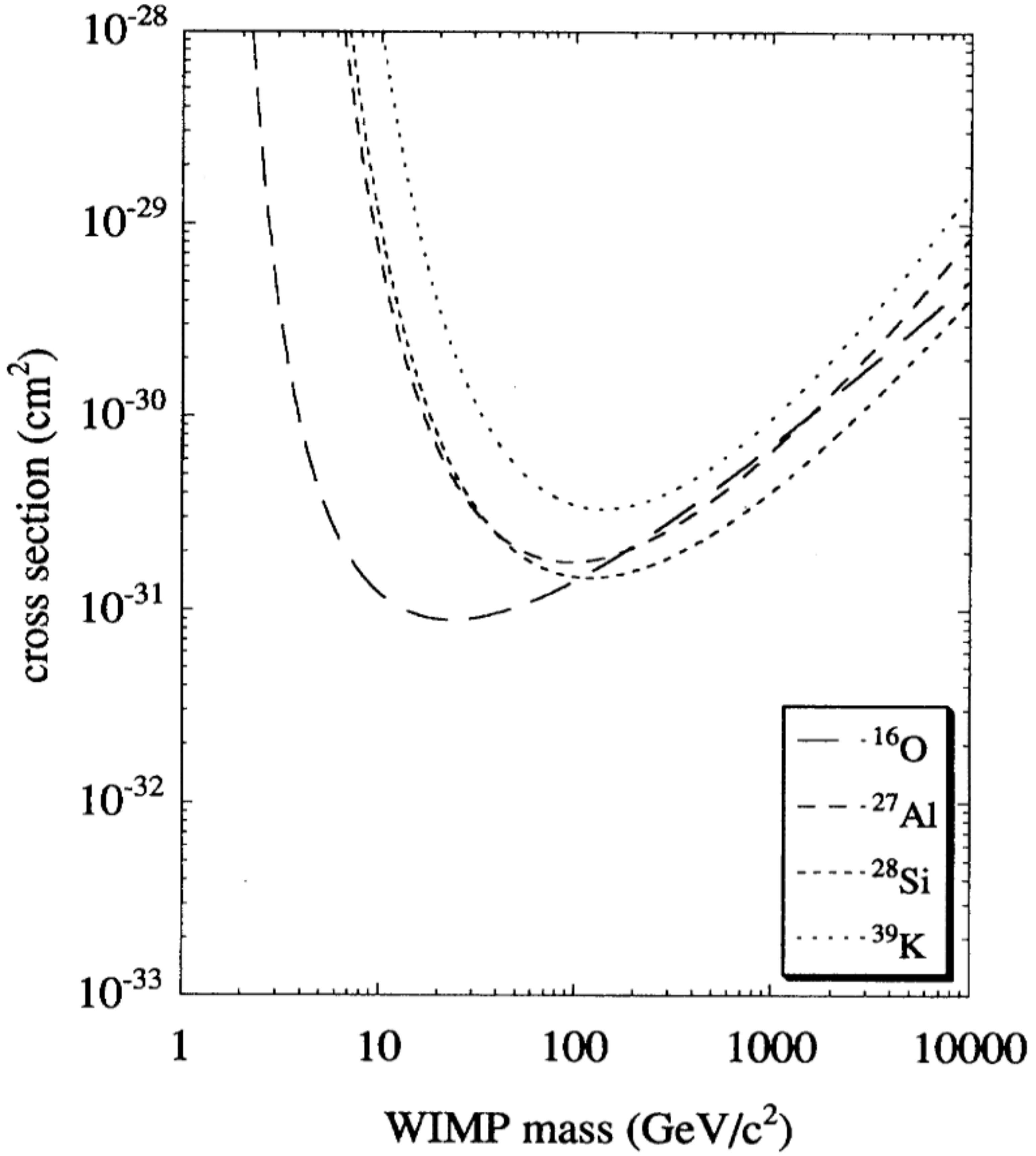
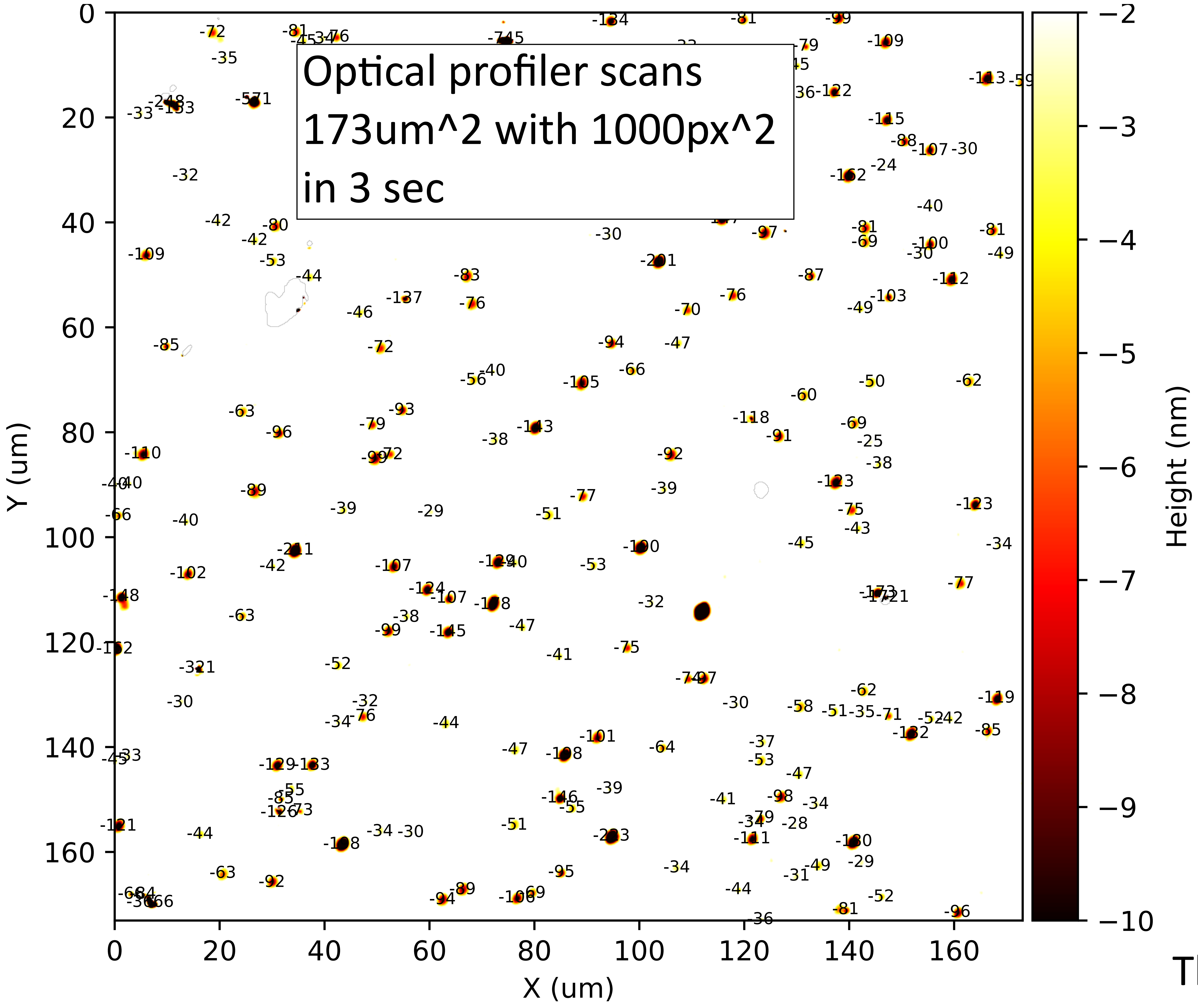


FIG. 4. Exclusion curves for each of the main constituent nuclei of mica. For a given mass, WIMPs with cross sections above these curves are ruled out at the 90% confidence level.

Snowden-Ifft et al. 1995

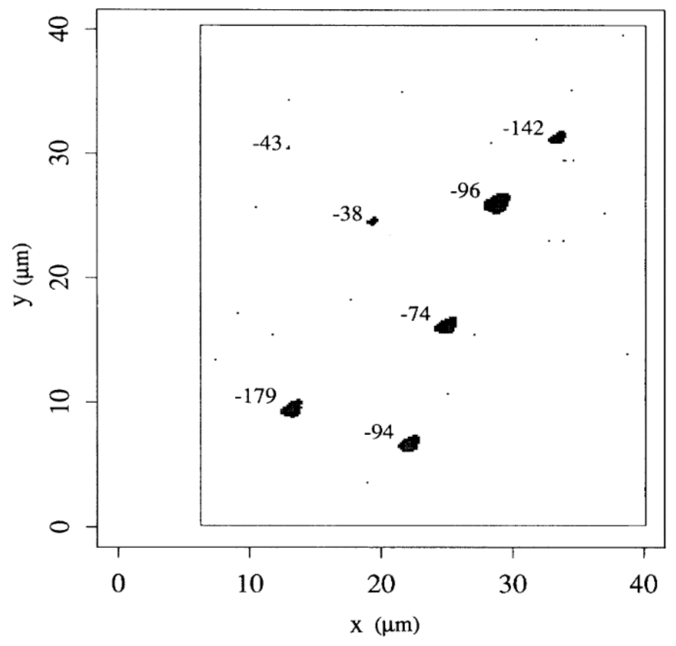
DMICA revisits Snowden-Ifft et al. 1995 with an efficient method of scanning mica, aiming at an exposure of 1 ton-year

Optical profiler scans mica much faster than AFM



Optical profiler scans
173um^2 with 1000px^2
in 3 sec

AFM scans
40um^2 with 256px^2
in several min

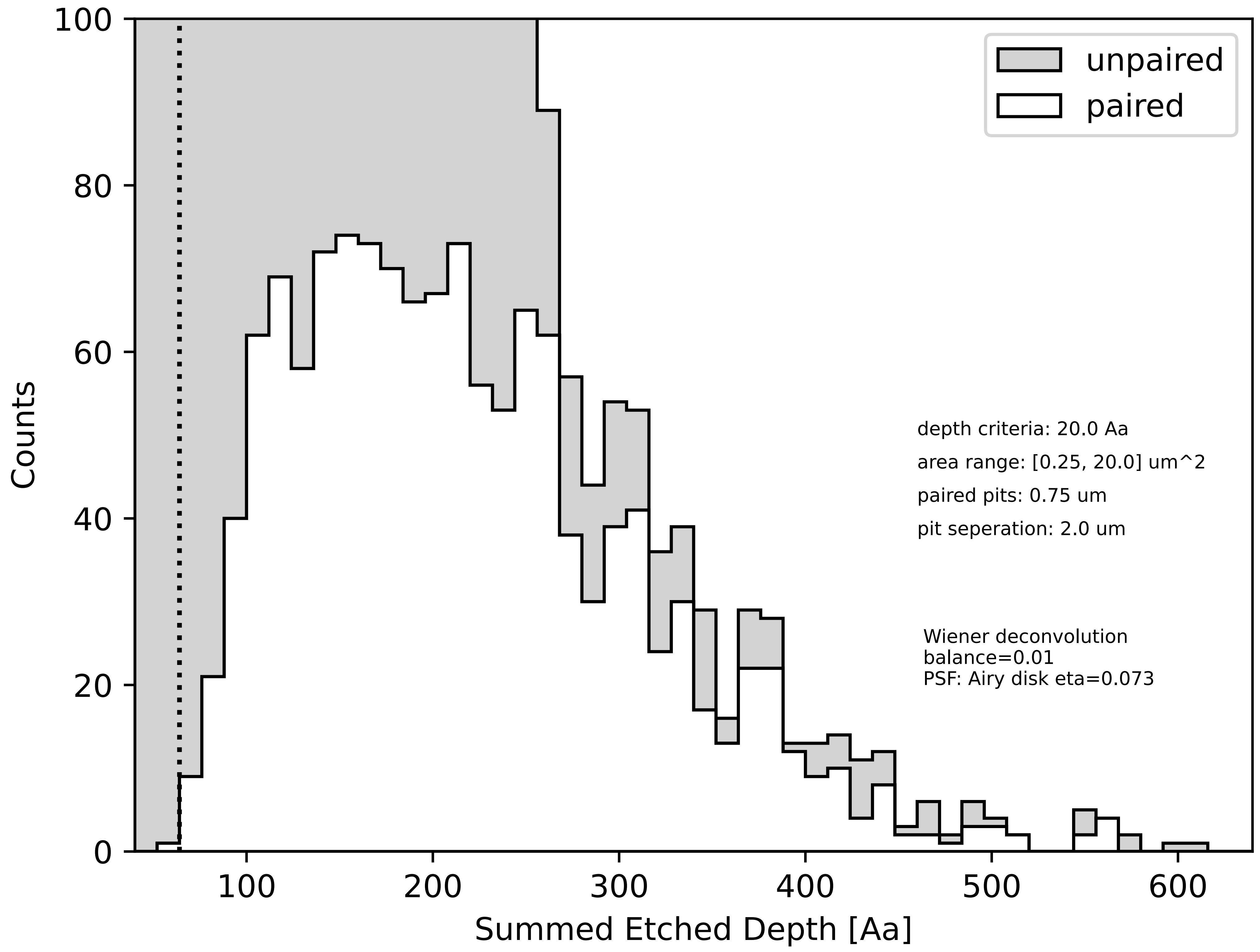


Snowden-Ifft et al. (1995)

The numbers in the figures are depths of pits in Aa.

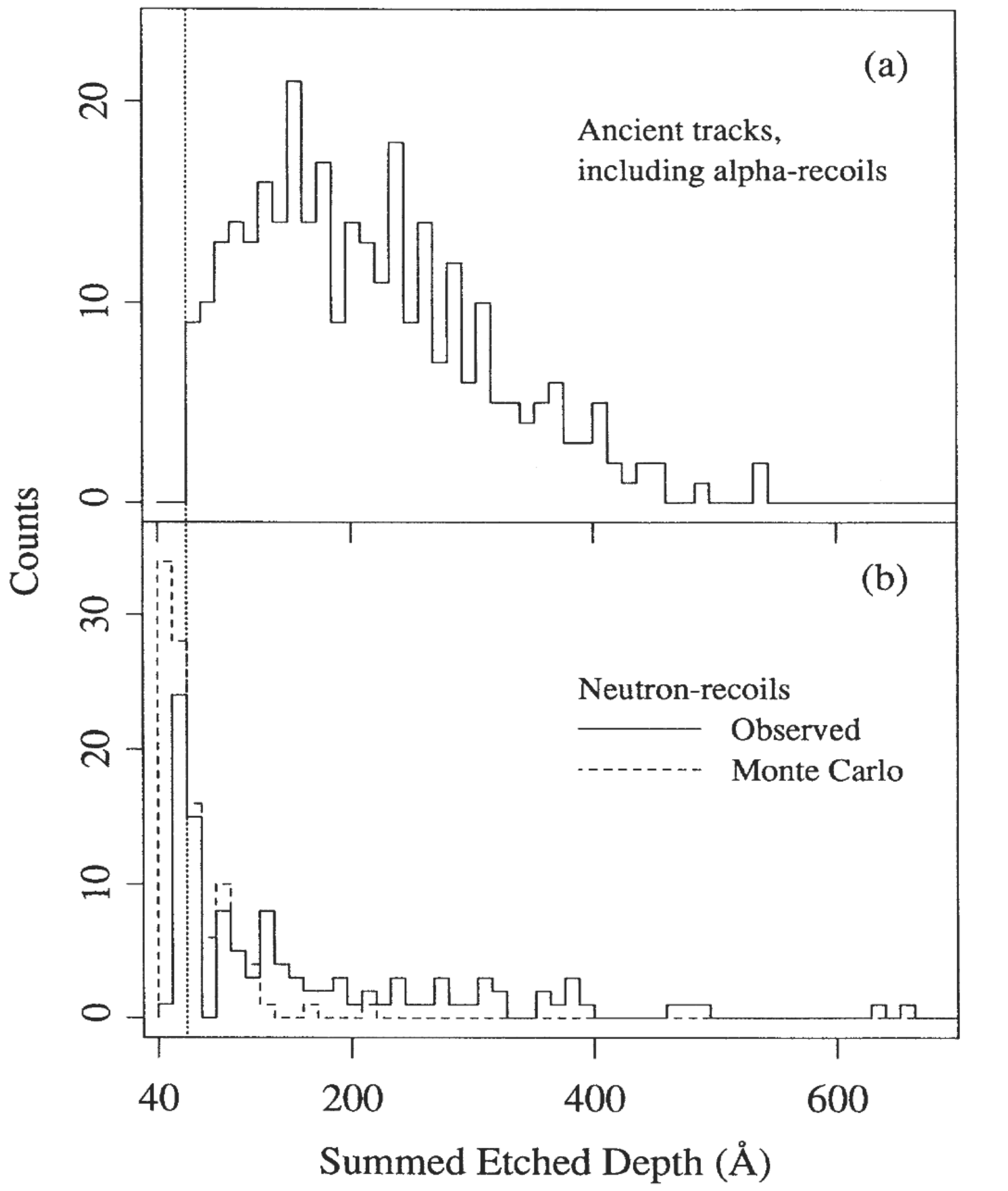
Preliminary test has processed mica surface of 524,765 um^2

DMICA: 524,765 um^2



6.5x

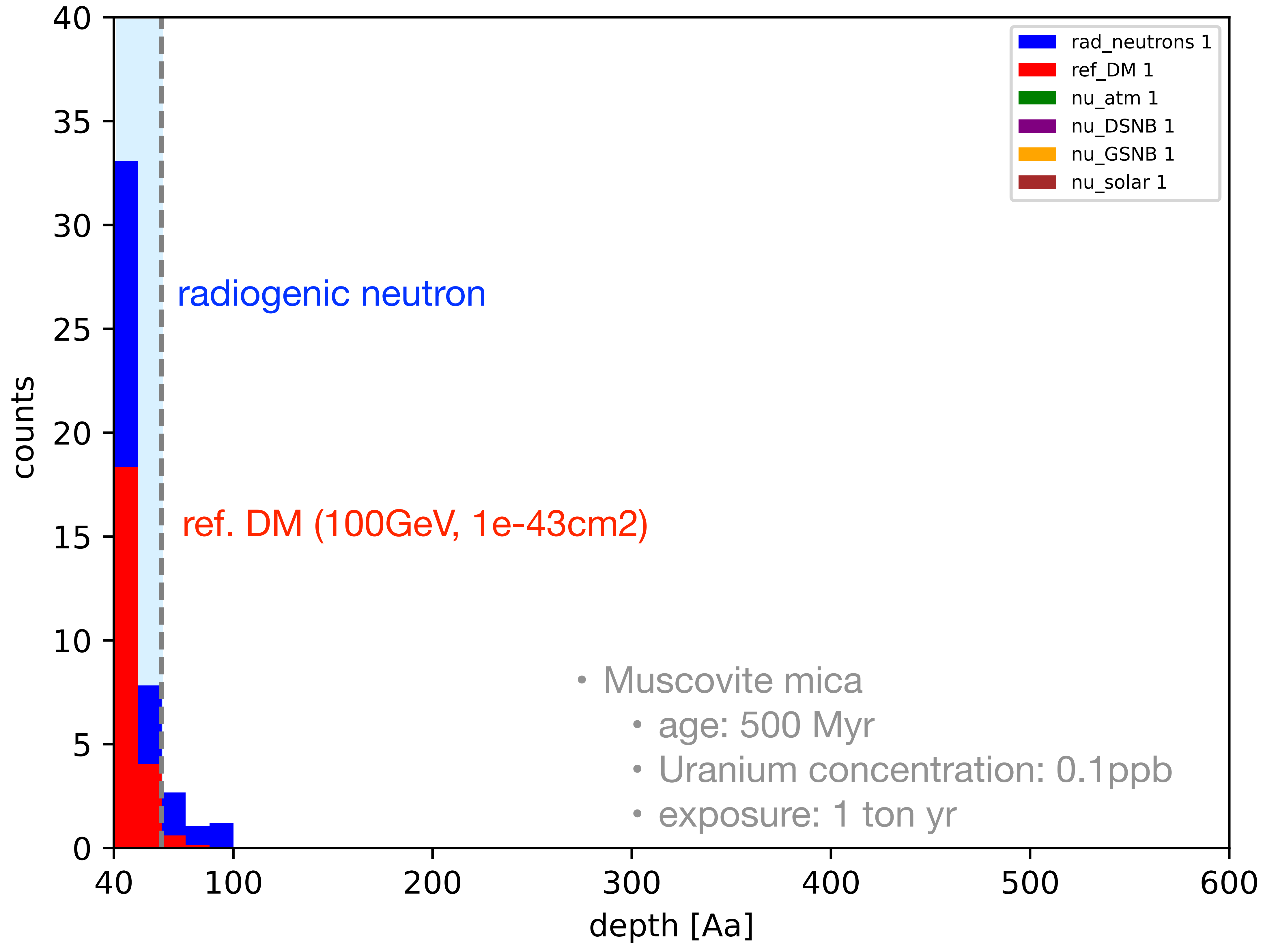
Snowden-Ifft et al. 1995: 80,720 um^2



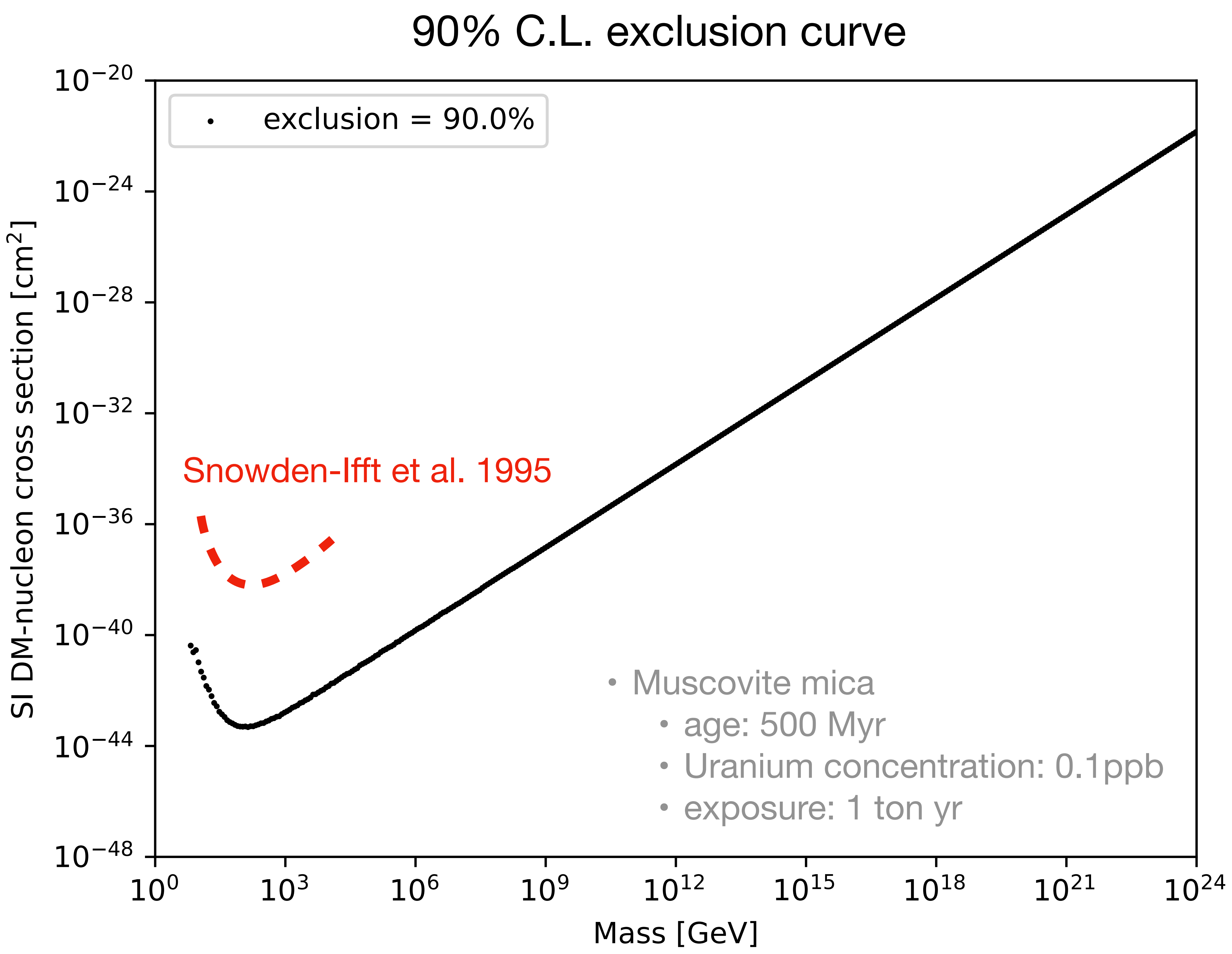
Comparison of DMICA with Snowden-Ifft et al. 1995

	Snowden-Ifft et al. 1995	**DMICA**
Exposure (Scan area)	1e-6 ton-year (80,000 um^2)	**1 ton-year** **(800 cm^2)**
Readout (Scan speed)	Atomic Force Microscopy (0.3 s/um^2)	**Optical profiler** **(0.0001 s/um^2)**
Nominal scan time	10 hours	**92 days**
Backgrounds in ROI	no background	**radiogenic fast neutrons**

Projected sensitivity for 1 ton-yr exposure with 0.5Gyr time-integration and 800cm² scan



predicted pit depth histogram
based on a pit-creation model (Snowden-Ifft and Chan 1995)



- Upper limit on detectable mass:

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

Summary

- DMICA explores DM nuclear recoil events in natural mica.
  - scientific focus: exploring “past-Gyr” DM events, or conducting a galactic-wide DM survey
  - sensitive to ultra-heavy DM due to large surface-to-volume ratio of the target
- DMICA uses an optical profiler instead of AFM for rapid scanning of mica, enabling a 1 ton-year exposure, a 6-order-of-magnitude jump from the previous study, in a practical time.
- DMICA is still in the R&D phase, but pleliminary test has demonstrated reproducing SI95 with 6.5 times larger exposure.
  - Obtaining samples with a low concentration of radiative impurities is crucial for the production phase.