DMICA: exploring Dark Matter in natural muscovite MICA

MDvDM 2024

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

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Limits on Dark Matter Using Ancient Mica

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(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

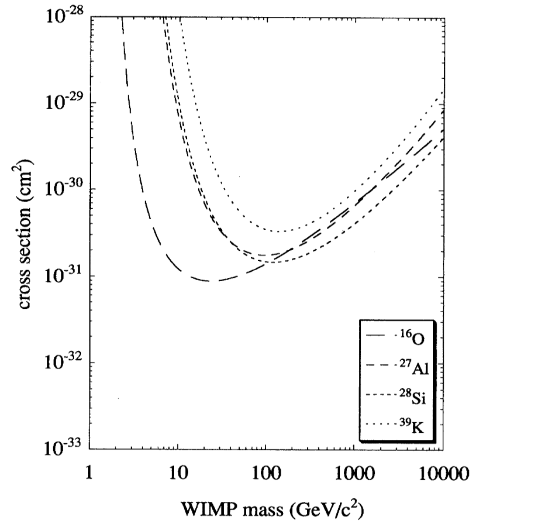


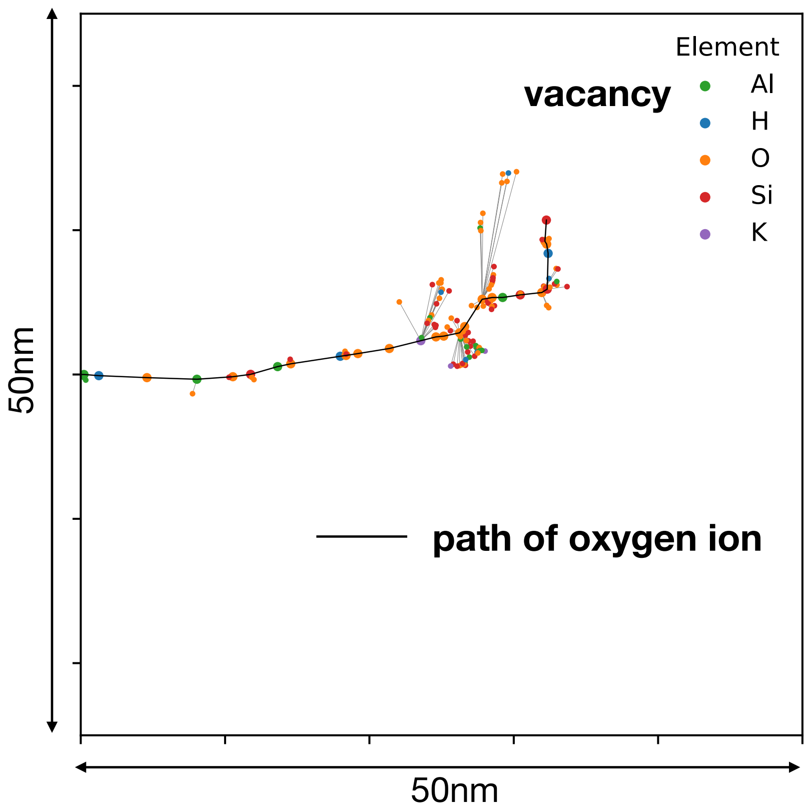
FIG. 4. Exclusion curves for each of the main constituent nuclei of mica. For a given mass, WIMPs with cross sections above these curves are ruled out at the 90% confidence level.

- Snowden-Ifft et al. set one of the strictest limits on WIMPs cross section at that time, with an exposure of just 1e-6 tonne year.
- Following the methodology established by Snowden-Ifft et al., DMICA targets an exposure of 1 tonne year, equivalent to a scanning area of 800cm^2.

How mica works as detectors in the search for DM

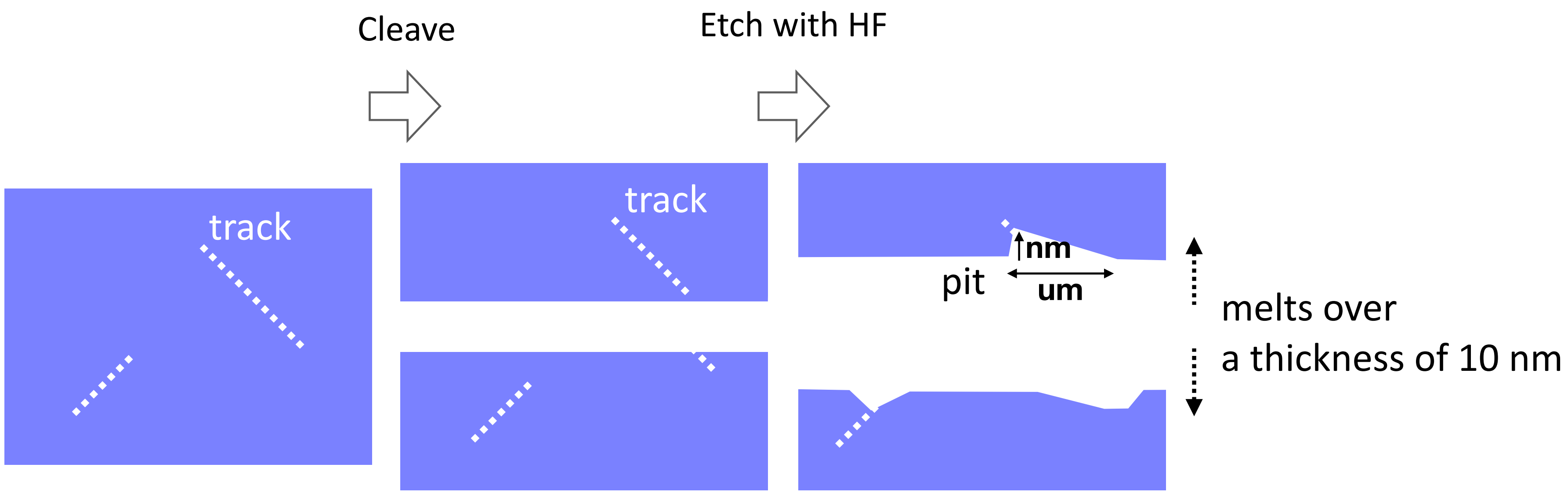
Nuclear recoil events are recorded as “latent” tracks in mica

TRIM simulation of an oxygen ion (10 keV) traveling through mica



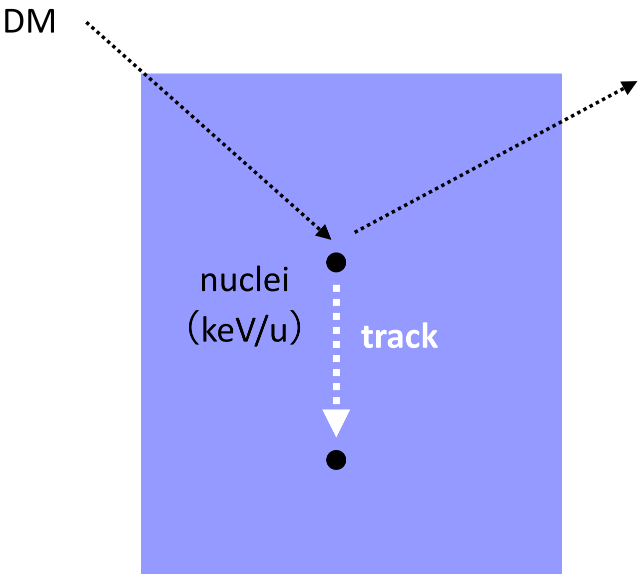
“Latent” tracks are series of atomic vacancies and invisible to microscopes.

Etching reveals latent tracks near cleavage in mica as pits

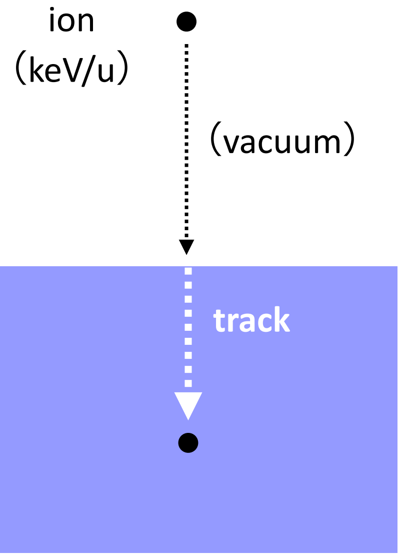


- Pits of several microns in size and nanometers in depth form at track sites.
- To effectively use mica as DM detector, the relationship between pit formation and recoil energy must be established.

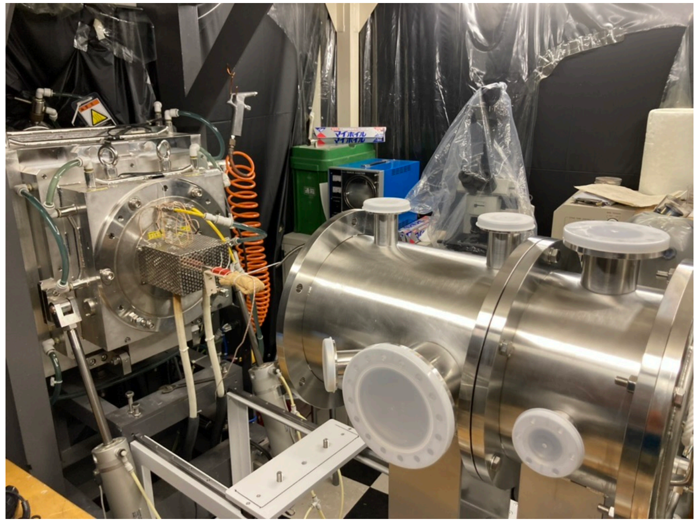
Pit formation-recoil energy relation is examined through ion irradiation experiments varying ion species/energies



Natural muscovite



Natural muscovite,
with natural tracks
removed by annealing



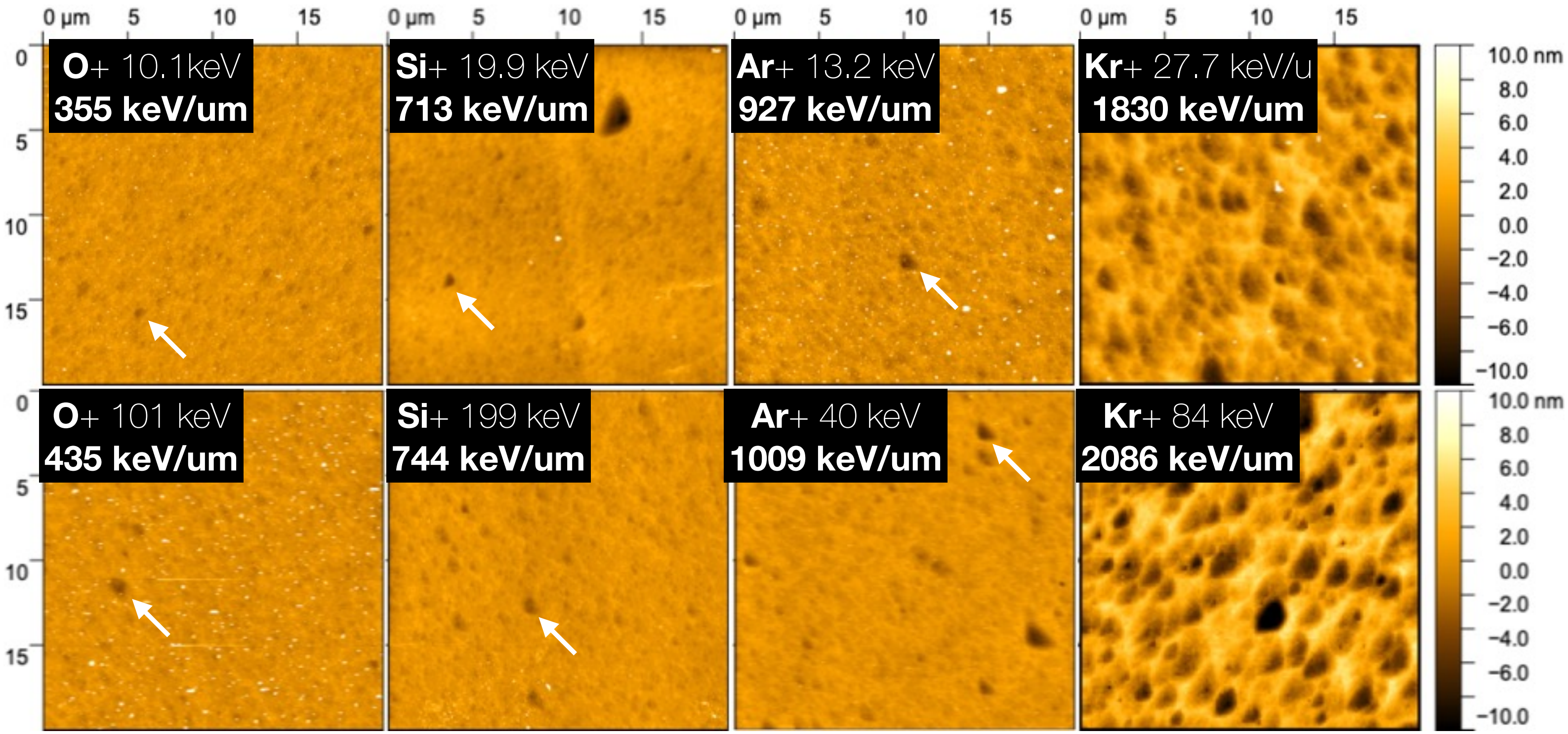
Experiments at Kanagawa U

- Irradiating keV/u energy ions to simulate nuclear recoil in dark matter scattering

Larger stopping power results in higher pit formation efficiency

arXiv:2301.07118

Irradiation dose is 80 ions per field of view (20umx20um).



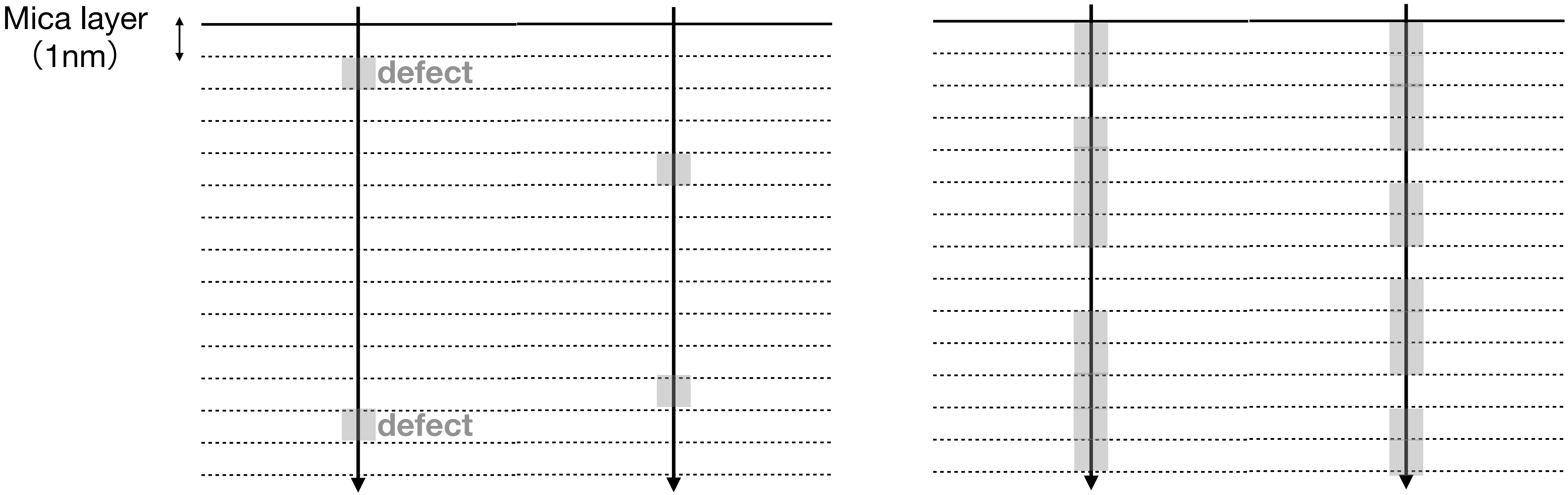
proxy	DM scattering	alpha recoils
pit formation efficiency	several to 10 %	~ 100%

Track etch model explaining pit formation efficiency

(Snowden-Ifft and Chan 1995)

Low stopping power
low probability of defect formation

High stopping power
high probability of defect formation



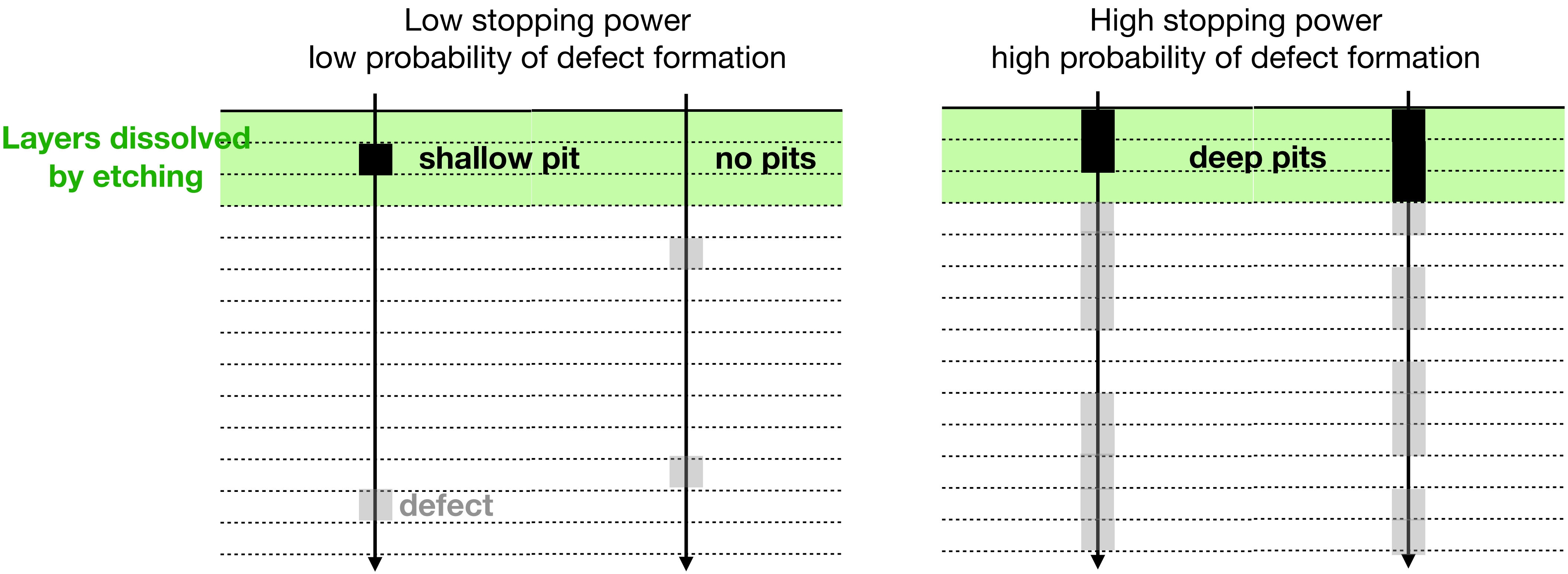
parameter↓ ↓energy

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

↑stopping power

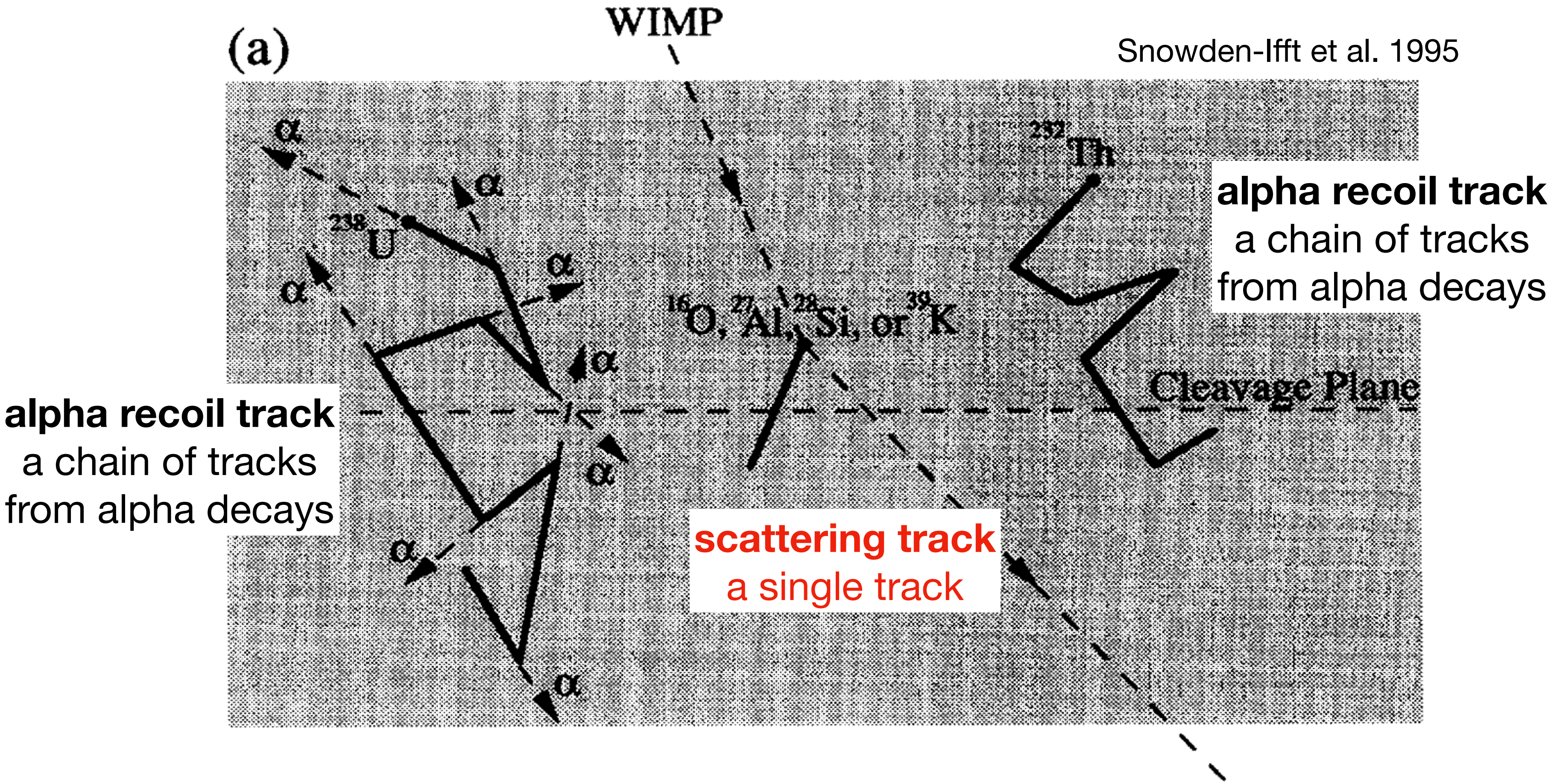
Track etch model explaining pit formation efficiency

(Snowden-Ifft and Chan 1995)

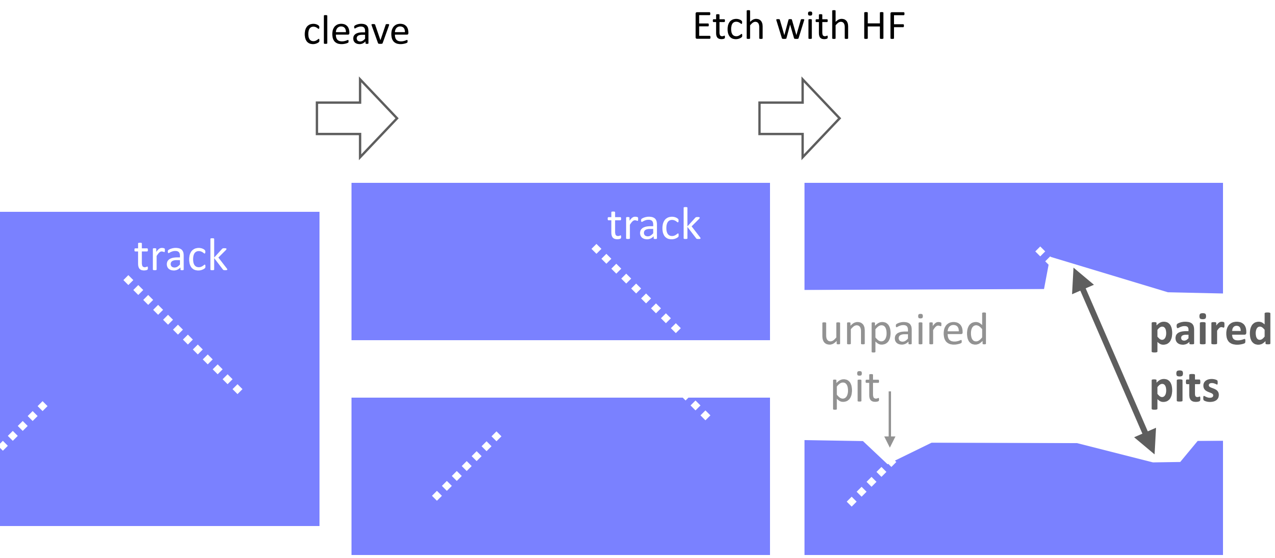


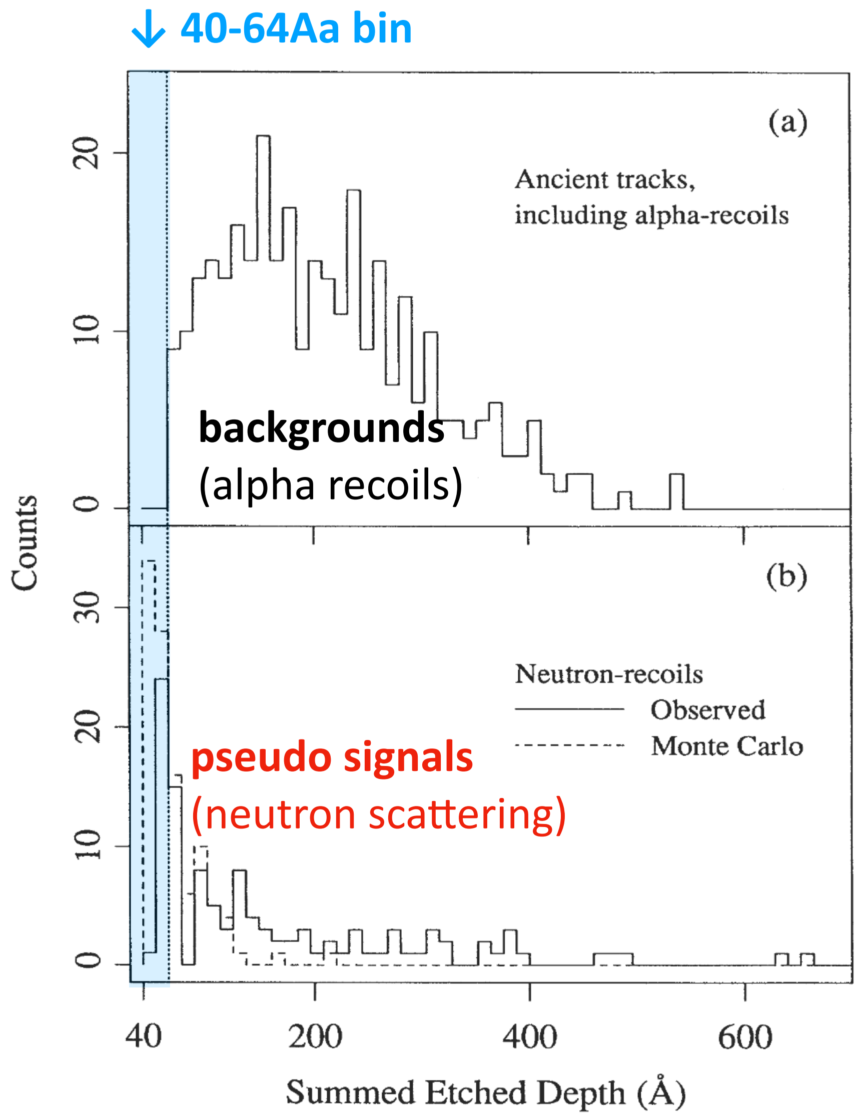
- Pit depth is the number of defects attacked by the etchant.
- The model predicts the observed pit depth histogram from the recoil energy spectrum.

alpha recoil tracks (ARTs), the most prevalent background



How to differentiate alpha recoil tracks





- Snowden-Ifft et al. (1995) found that paired-pits histogram shows zero for ARTs but a peak for neutron scattering tracks in the 40-64Aa bin.

Limits on dark matter from 80,720um^2 mica scan based on the null result in the smallest bins

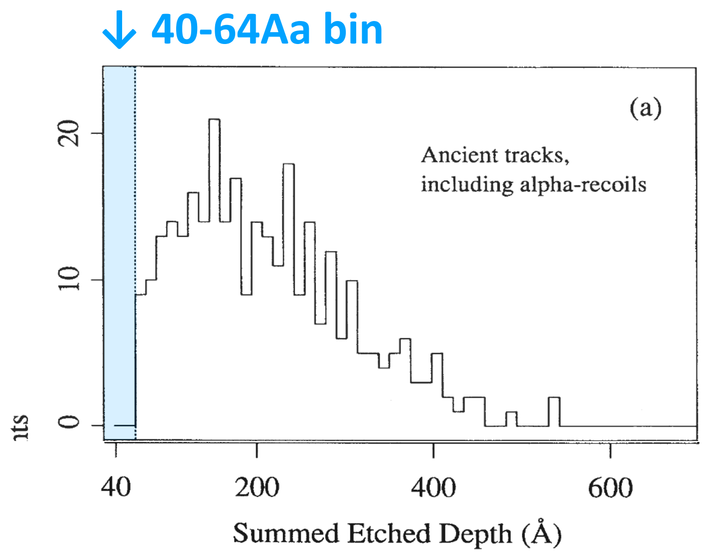


FIG. 3. (a) The summed etched depths of tracks recorded in a 80 720 μm^2 scan of 0.5 Gyr old muscovite mica. No events appear between our cutoff of 40 and 64 Å (shown with a dashed vertical line). (b) The solid line shows the summed depths of etched neutron-recoil tracks. The dashed line shows the results of a MC program of these data. In both the real and MC data a large fraction of the events appear in the 40–64 Å gap.

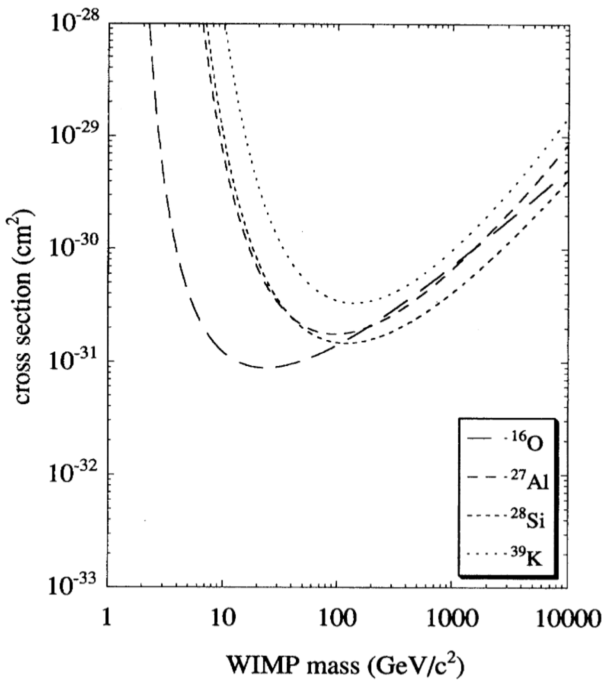


FIG. 4. Exclusion curves for each of the main constituent nuclei of mica. For a given mass, WIMPs with cross sections above these curves are ruled out at the 90% confidence level.

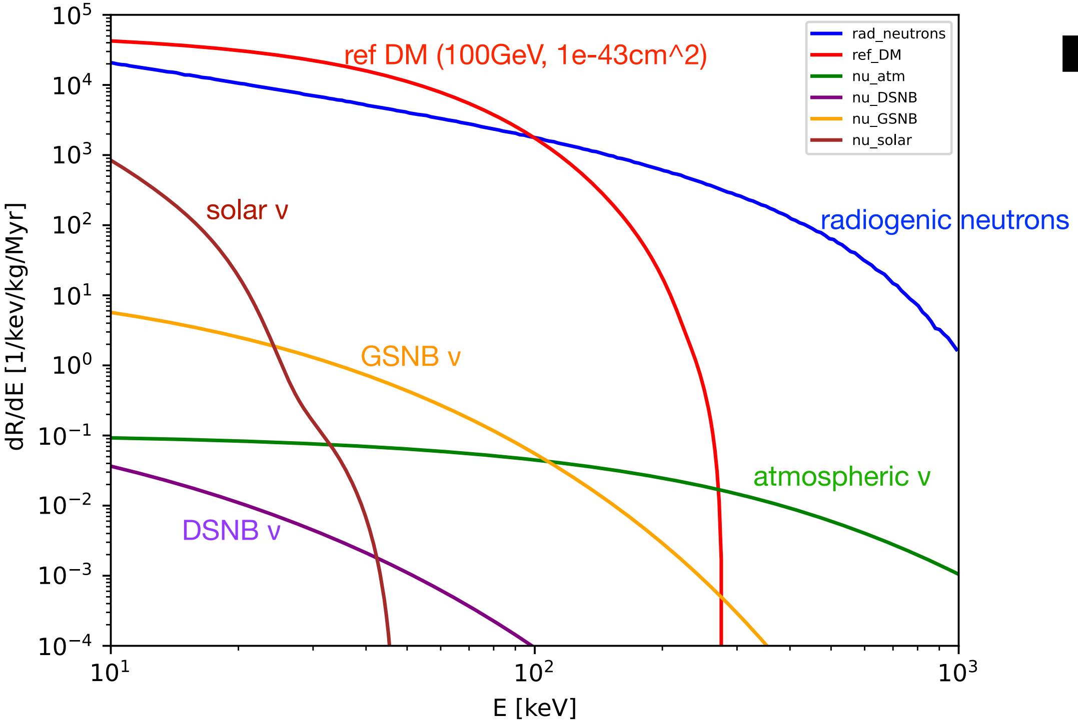
Snowden-Ifft et al. 1995

Sensitivity projection for DMICA using paleoSpec/paleoSens

Pit depth histogram predicted using paleoSpec

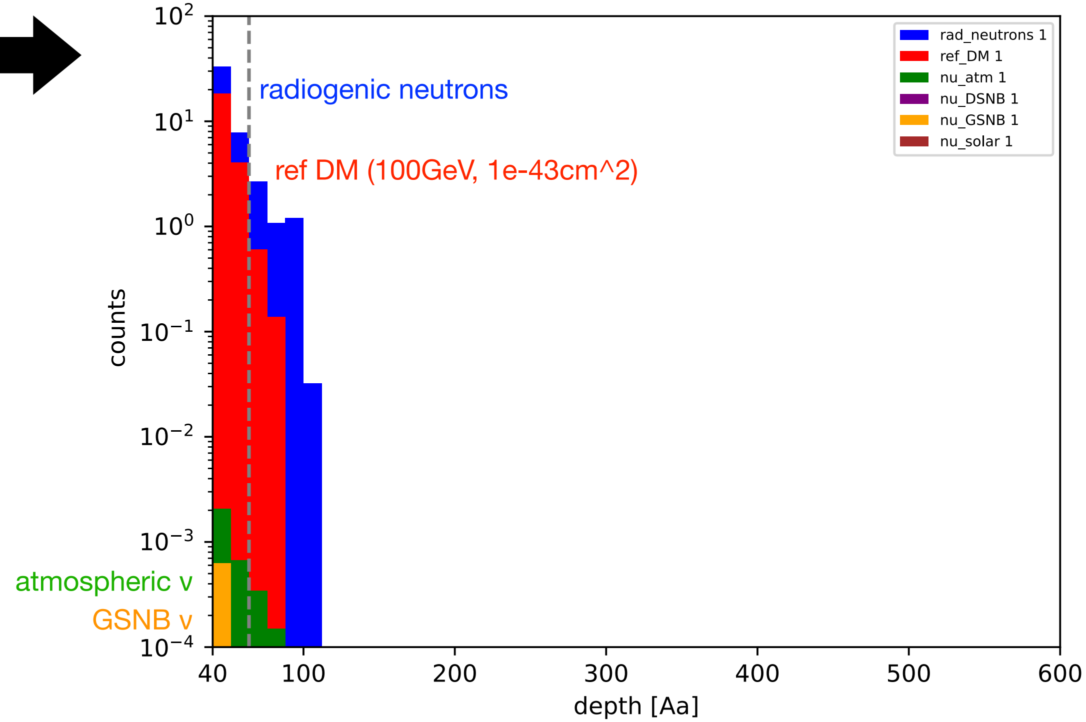
- Muscovite mica
  - age: 500 Myr
  - Uranium concentration: 0.1ppb
  - exposure: 1 ton yr

Recoil Energy Spectrum using paleoSpec



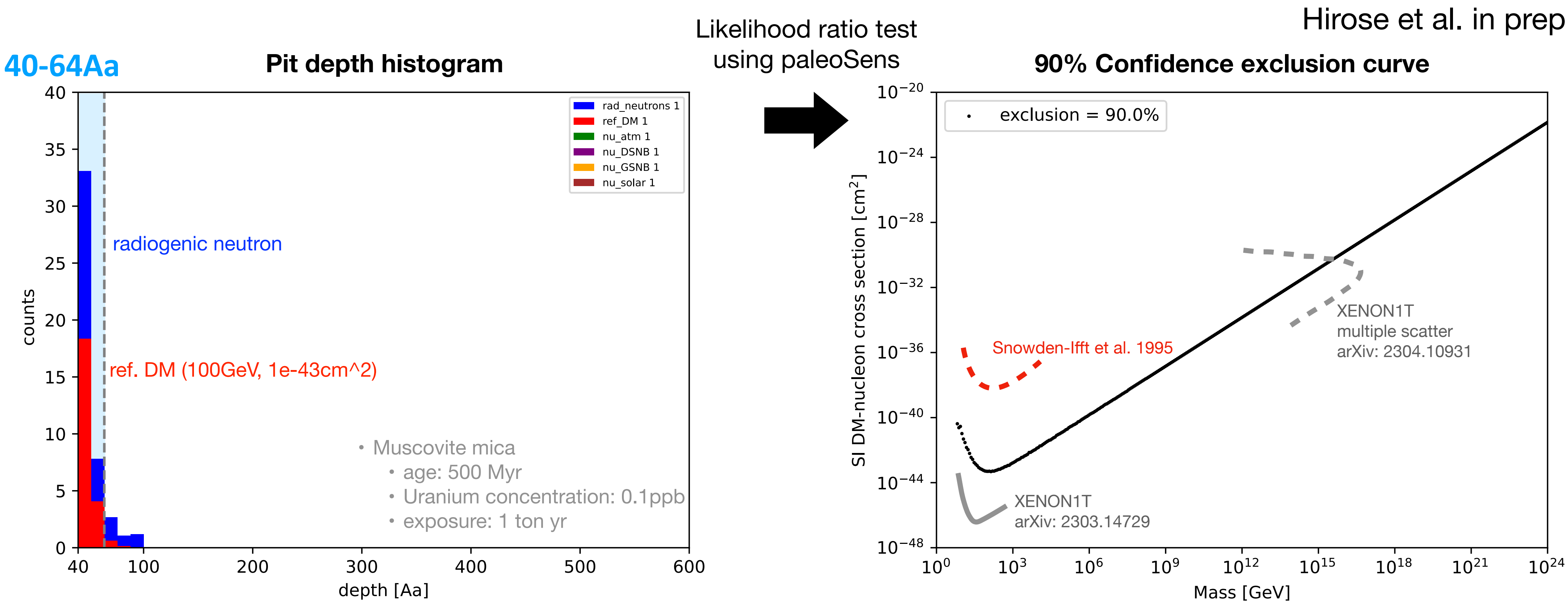
Monte Carlo simulations basend on the track etch model

Pit depth histogram



- 234Th recoiling tracks are not considered due to undetermined parameters in the etch model.

Exclusion curve derived for DMICA's target exposure of 1 ton yr



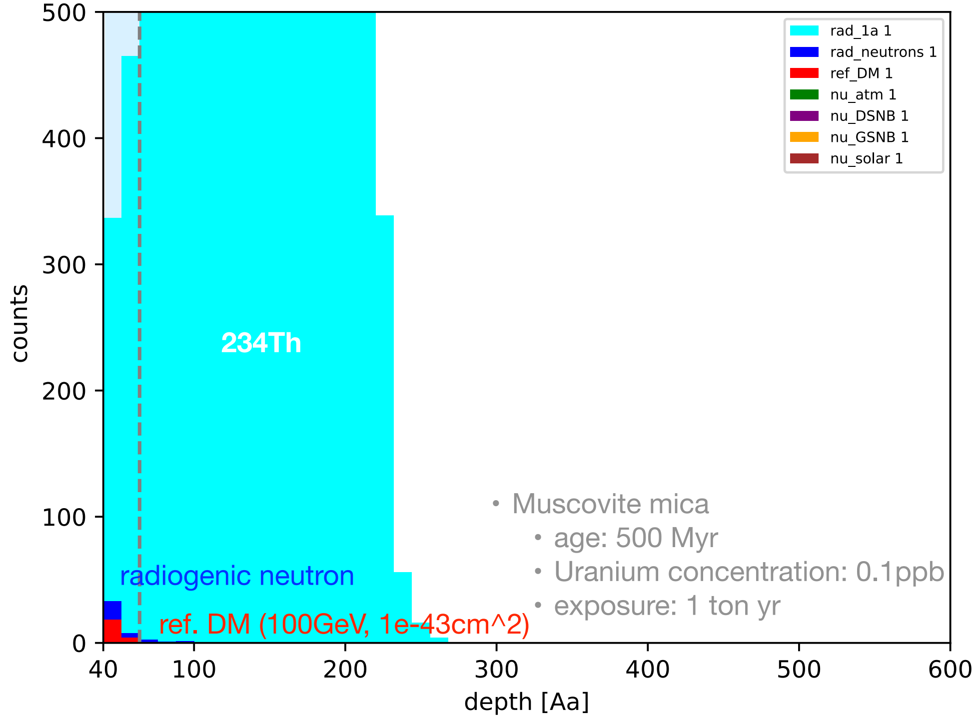
- High-mass end of the curve of DMICA could be significantly larger than that of the XENON1T experiment.

Impact of 234Th recoil on sensitivity projection

Hirose et al. in prep

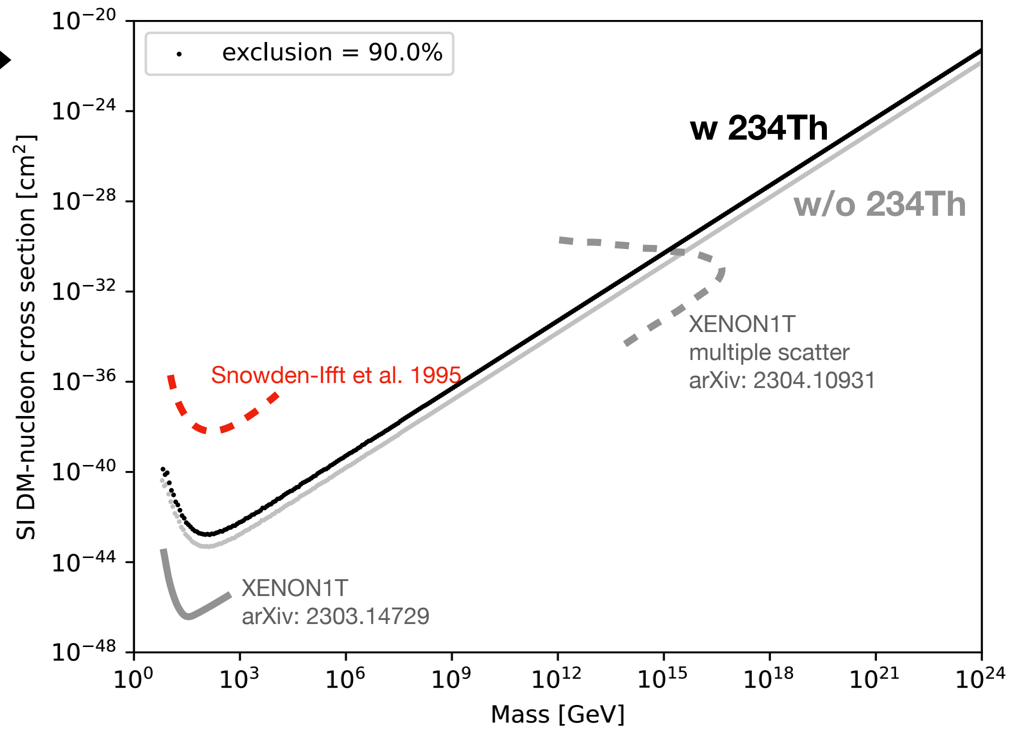
40-64Aa

Pit depth histogram



Likelihood ratio test
using paleoSens

90% Confidence exclusion curve



- For 234Th recoil, pit formation efficiency is assumed to be 100%.

High surface area-to-volume ratio in DMICA enables search for extremely heavy dark matter

- 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)

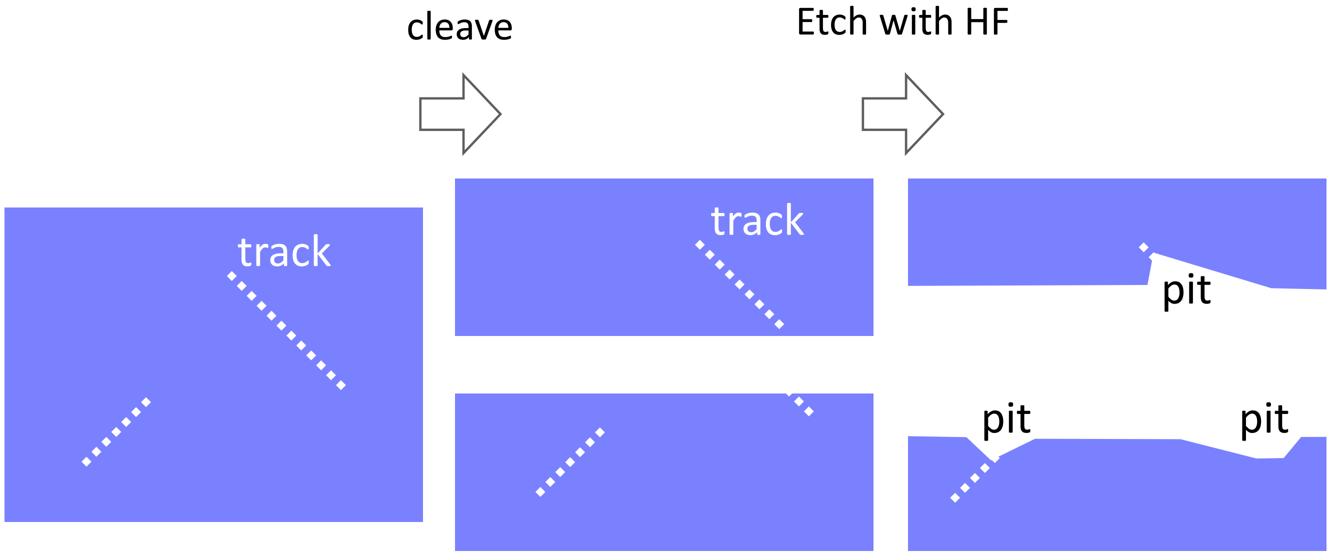
XENON1T: $$\left(\frac{m_\chi}{\mathrm{GeV}} \right) < 10^{18} \left(\frac{Mt}{1\mathrm{ton}\cdot\mathrm{yr}} \right) \left(\frac{A/V}{(1\mathrm{m})^{-1}} \right)$$

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

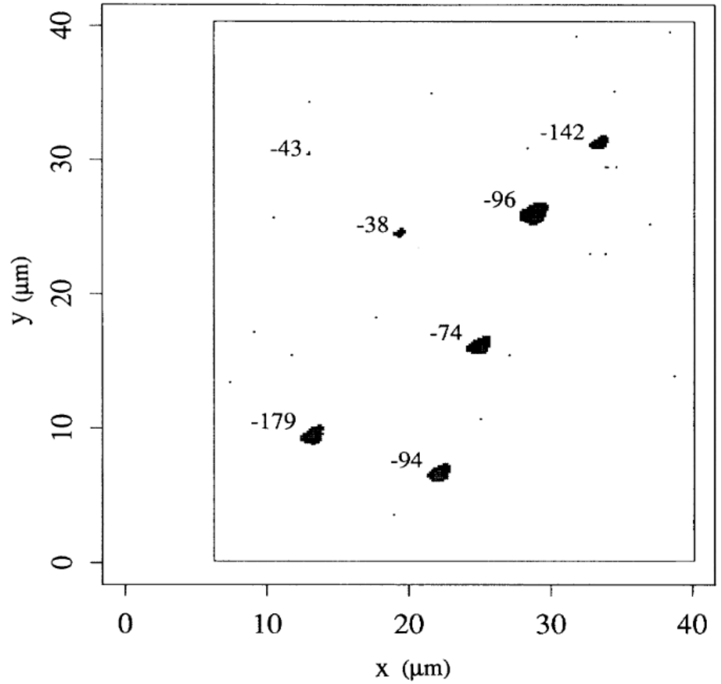
(not to scale)

How can we achieve the target exposure of 1 ton year?

Using AFM for mica scan restricts DM search throughput

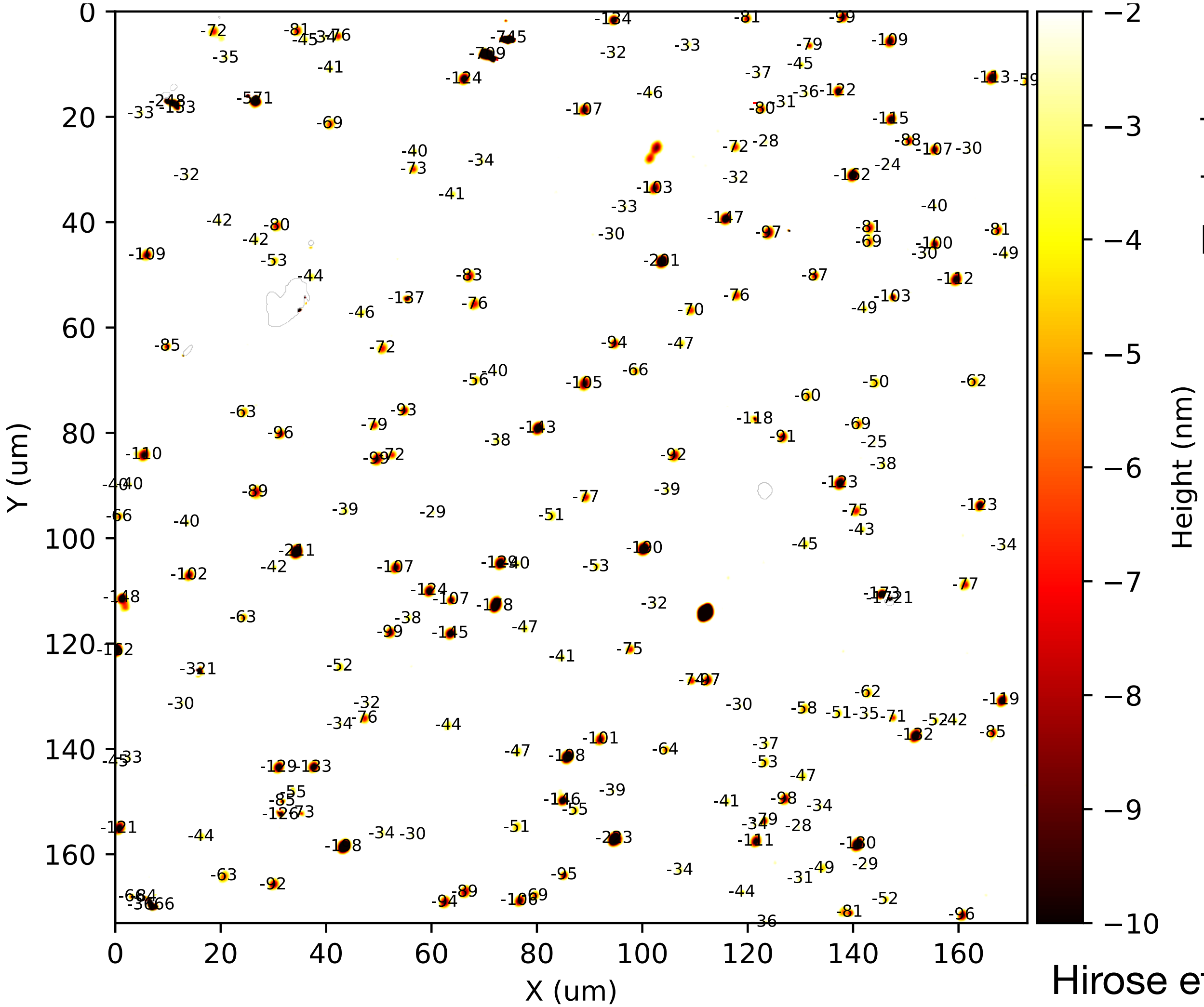


Scanning with AFM



- Generally, AFM involves a compromise between accuracy and scanning speed.
- Using optical profiler, through its non-contact measurement, significantly enhances mica scan throughput.

Pit measurement using an optical profiler



Hirose et al. in prep

173umx173um with 1000x1000 px

The numbers are the heights in Å of the deepest pixels in clusters passing a 20 Å, 16 pixels

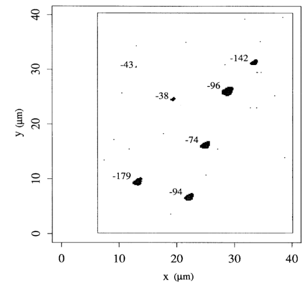
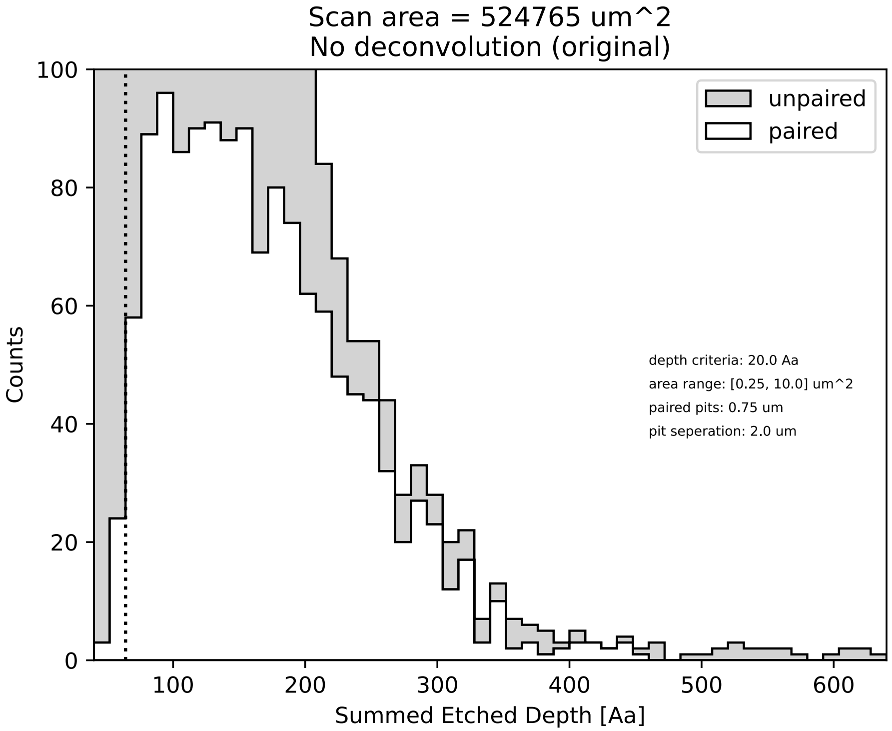


FIG. 2. A processed AFM image. The numbers are the heights in Å of the deepest pixels in clusters passing a 20 Å, 3 pixel cut.

40umx40um with 256x256 px
Snowden-Ifft et al. 1995

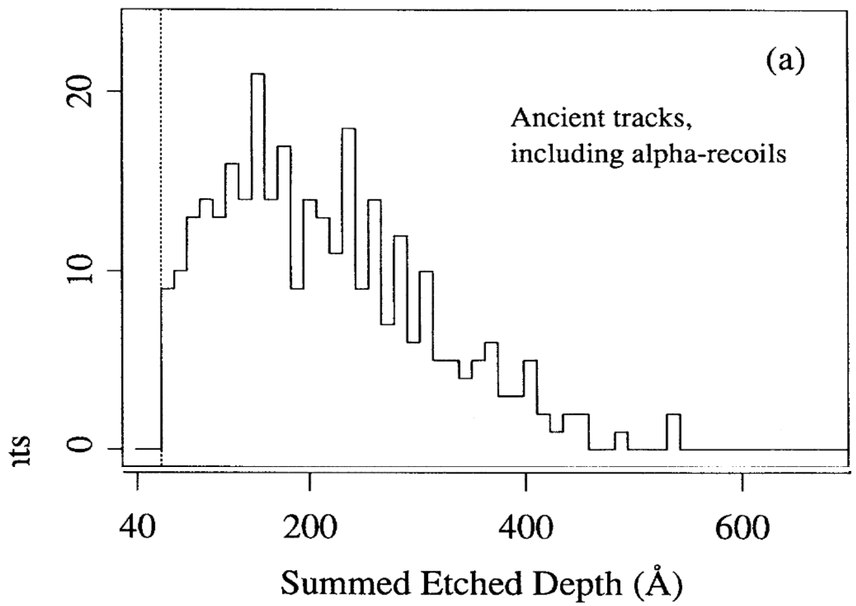
DMICA has tentatively processed mica of 524,765 um^2, 6.5x Snowden-Ifft et al.

DMICA: 524,765 um^2 scan
(1.5 min. / 6.5e-6 ton yr = 0.45 yr / 1 ton yr)



Hirose et al. in prep

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



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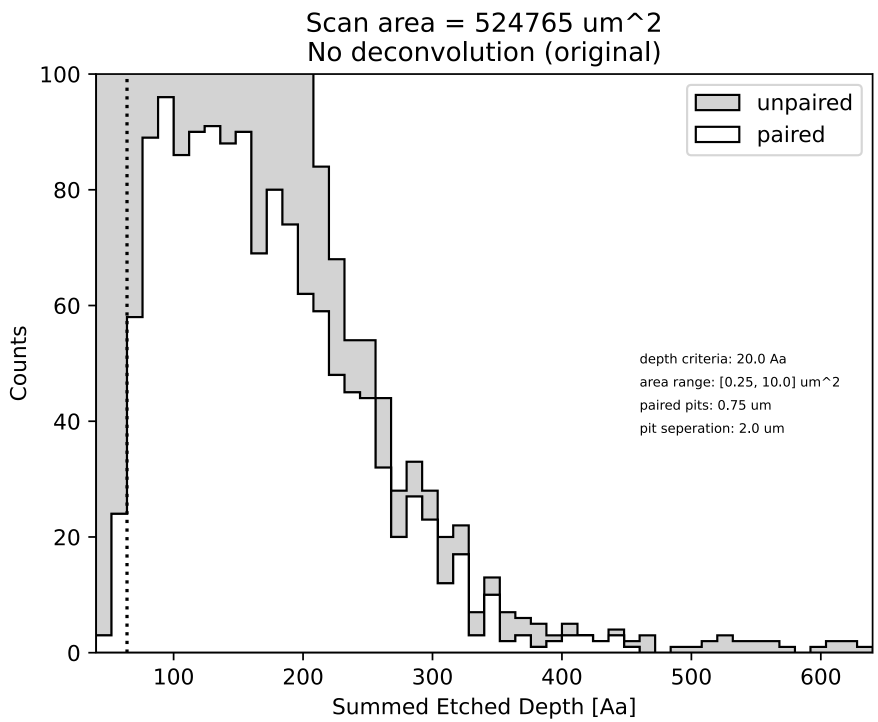
Summary

- DMICA targets a 1-ton-year exposure in DM search in mica.
  - We employ the practical methodology established by Snowden-Ifft et al. (1995), substituting AFM with optical profiler for rapid mica scanning.
  - The projected sensitivity of DMICA assessed using paleoSens/paleoSpec is about 3 orders of magnitude worse than XENON1T.
  - Given our tentative processing of mica, 6.5 times greater than that achieved by Snowden-Ifft et al. (1995), we anticipate reaching the targeted exposure within a year.

Strategy to overcome alpha recoil backgrounds

- 8-chained tracks → make the gap in the smallest bins wider by increasing etch time
- 234Th single tracks → construct an appropriate track etch model by conducting irradiation experiments of heavy and energetic ions



Snowden-Ifft, Freeman, and Price Reply: The preceding Comment [1] by Collar brings up several interesting points which need to be considered when using ancient mica to set limits on dark matter [2]. The first considers a potential background from ^{234}Th recoiling from the first decay of ^{238}U. Its range is similar to that of WIMP recoils, and a fraction $\sim T_{1/2}^{234}/T_{1/2}^{238} \approx 10^{-4.3}$ of ^{238}U decays would stop at ^{234}Th. We, however, observed no matched etched pits whose summed depth was larger than 64 Å. Furthermore, the requirement that each etch pit be at least 20 Å deep places a lower bound of 40 Å on the summed depth. Our limits resulted from no events having been observed in this gap. To estimate the background of recoiling ^{234}Th that fall in this gap one must use the correct etching model [3]. Collar uses a now discounted model. According to this new etching model [3] the observed density of etched pits in the gap resulting from these recoils is given by

$$\rho = N(\ln 2)\,(T_{1/2}^{234}/T_{1/2}^{238})\,(P/2) \times [(d/P)^2 - 4dt/P^2 + 4t^2/P^2],$$

where d is the maximum summed depth in the gap, 64 Å, P is the range of the ^{234}Th recoil, 290 Å, and t is the threshold depth for an etched pit on one surface, 20 Å. We measured the uranium density for our mica to be $N = (1.7 \times 10^{-11})\,(9 \times 10^{22}/\text{cm}^3) = 1.5 \times 10^{12}$ atoms/cm^3. Using these numbers we estimate a background from ^{234}Th at $\rho = 0.5/\text{cm}^2$. Since we have currently scanned only 8×10^{-4} cm^2, we expect to be able to improve our limits by at least a factor of 2500 before running into this background. Further improvements are possible because the spectrum of summed depths for these events differs markedly from that for WIMP recoils. As discussed in our paper, a much more serious threat comes from fast neutrons from U fission in the rock surrounding the mica. Finally, looking for tracks with etched depths greater than 500 Å, as suggested by Collar [4], is difficult because the flux distribution of WIMP's and the incoherence of the momentum transfer severely limit the number density of recoils which could produce such large etched pits.

We agree with Collar that the technique cannot be used to observe neutrinos from stellar collapse and support his suggestion that it could be used to place limits on clumps of dark matter.

D. P. Snowden-Ifft, E. S. Freeman, and P. B. Price
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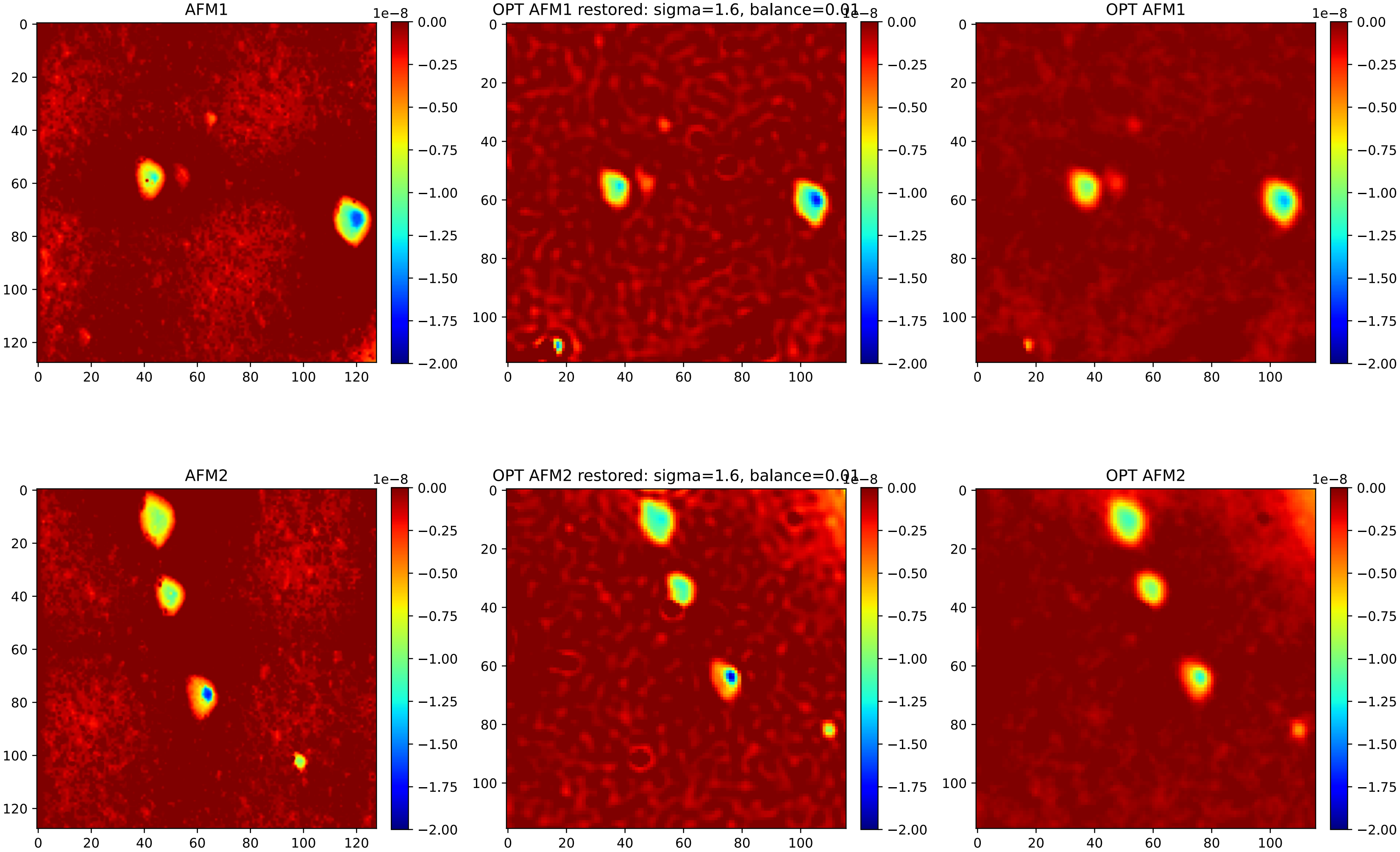
[1] J. I. Collar, preceding Comment, Phys. Rev. Lett. **76**, 331 (1996).
[2] D. P. Snowden-Ifft, E. S. Freeman, and P. B. Price, Phys. Rev. Lett. **74**, 4133 (1995).
[3] D. P. Snowden-Ifft and M. K. Y. Chan, Nucl. Instrum. Methods Phys. Res., Sect. B **101**, 247 (1995).
[4] J. I. Collar and F. T. Avignone III, Nucl. Instrum. Methods Phys. Res., Sect. B **95**, 349 (1995).

AFM

optical profiler
(restored by deconvolution)

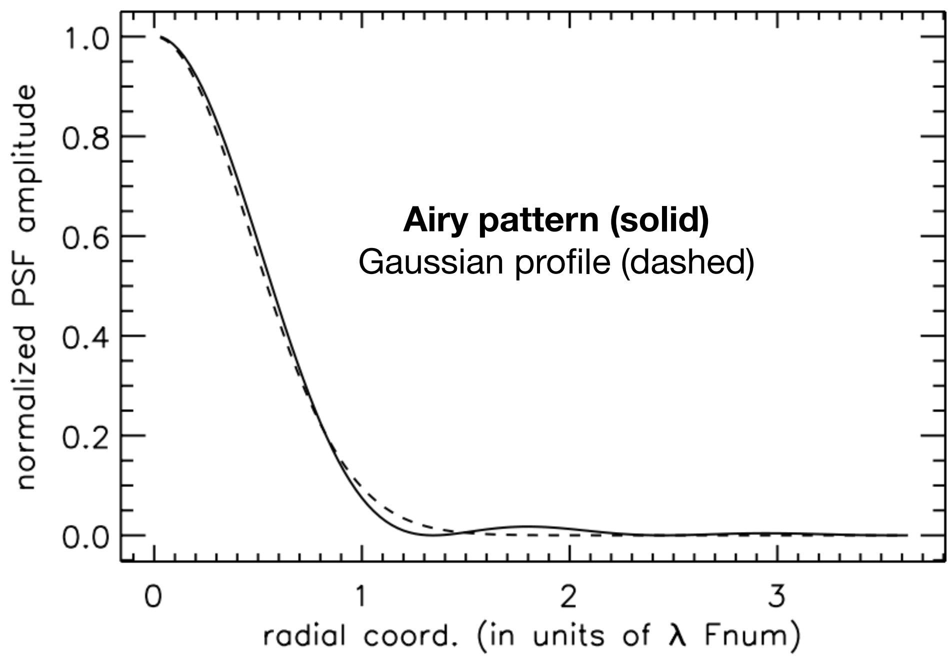
optical profiler
resolution = 0.5um



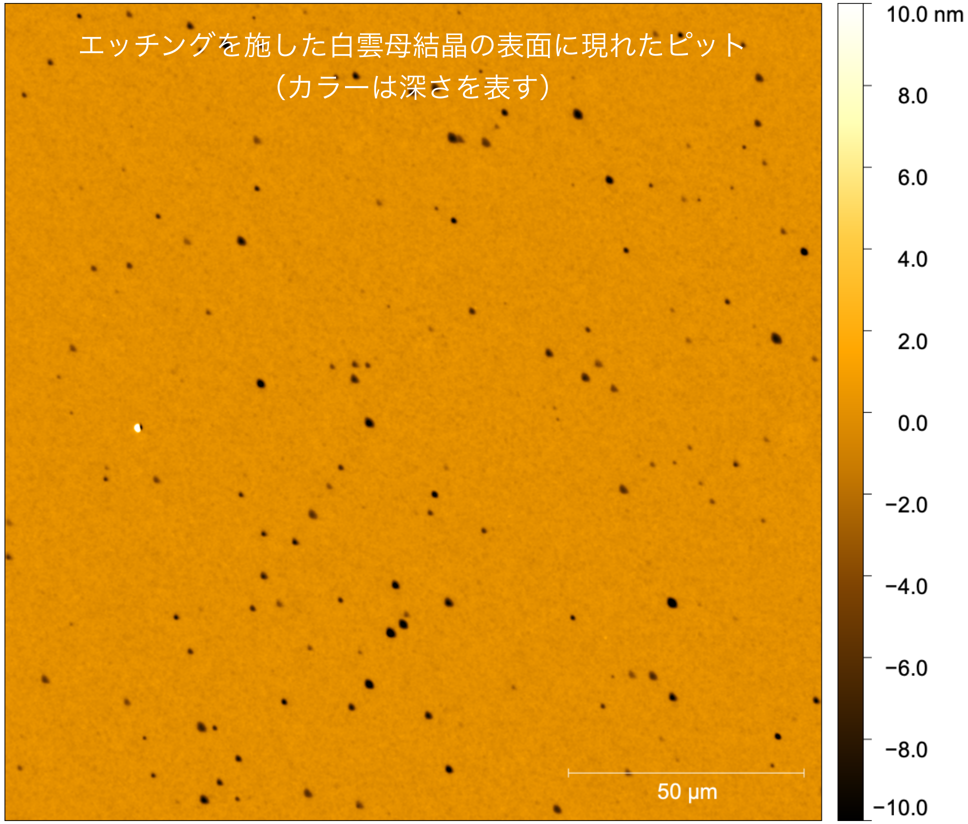
In microscopy, the PSF (Airy pattern) can be approximated with a Gaussian profile having a variance of (e.g., Zhang et al. 2007)

$$\sigma \approx 0.22 \left(\frac{\lambda}{\mathrm{NA}} \right) = 0.22 \text{ um} = 1.27 \text{ pixel},$$

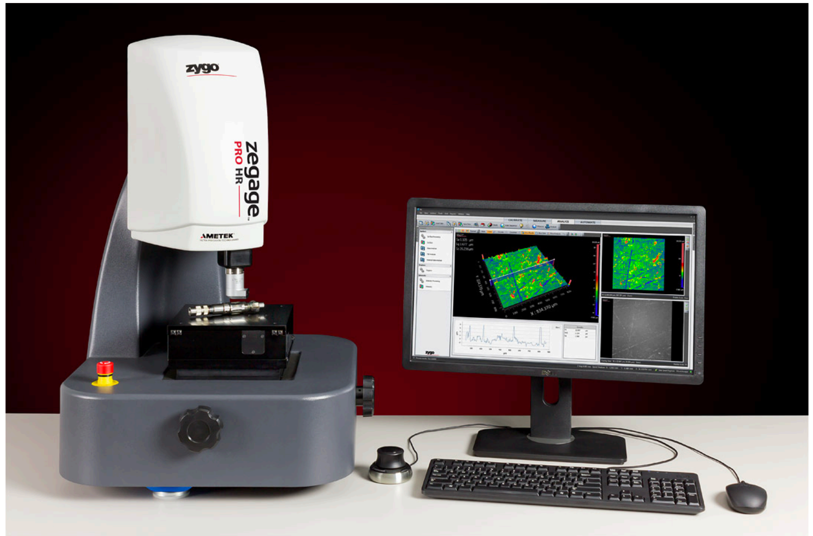
where $\mathrm{NA} = 0.55$ and $\lambda = 0.55$ um are applied.



ピットの個数・深さを読み出すために白色干渉計を用いる



劈開面から10nm程度の深さまでに存在したトラックがピットとして現れている



- **DMICAでは800cm^2の劈開面測定を目指す**
  - 1視野（3e-4cm^2）の測定に5秒かかる
  - 1試料（2cm^2）の測定が1日（9.2時間）で完了する
  - のべ400日でのべ800cm^2の測定を達成

JAMSTEC
will host the next MDvDM meeting in Yokohama, Japan

tentative schedule: May 20-23, 2025