# Discussion

## What Are Tracks?

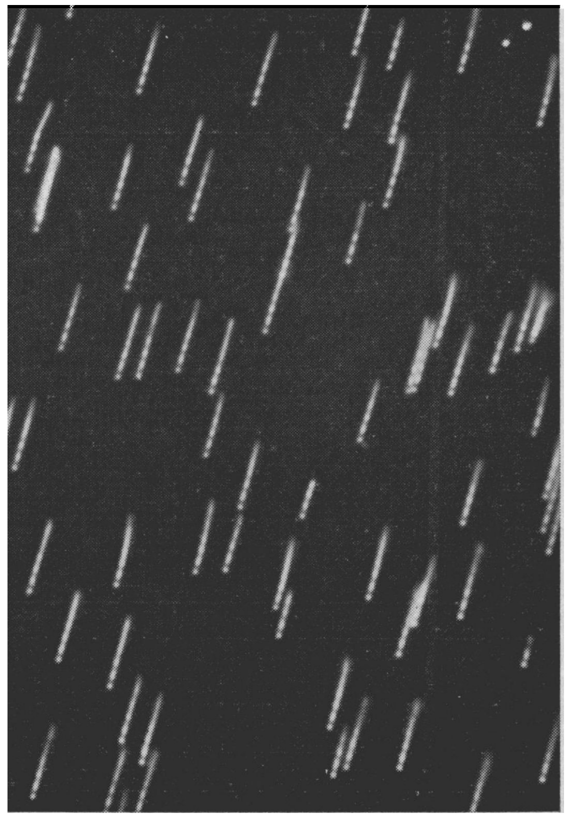
MDvDM'24

# Fission Tracks

(Induced) Fission Tracks in Mica, TEM

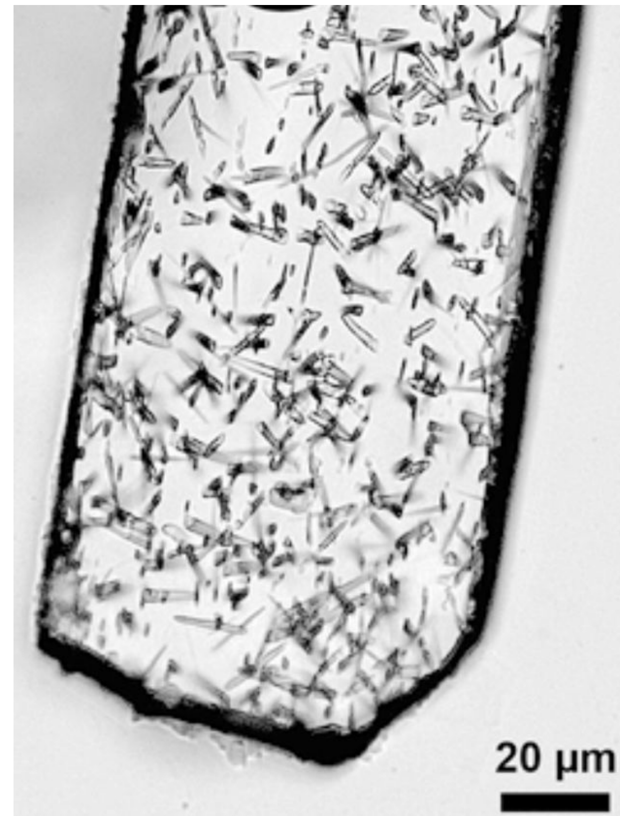

[Fleischer, Price & Walker '75]

40 MeV argon ions in Mica, chemical etch + optical microscopy



[Fleischer, Price & Walker '65]

Spontaneous fission tracks in apatite, chemical etch + optical microscopy




[Thomson '16]

# Track Formation Models

[Fleischer, Price & Walker '75]

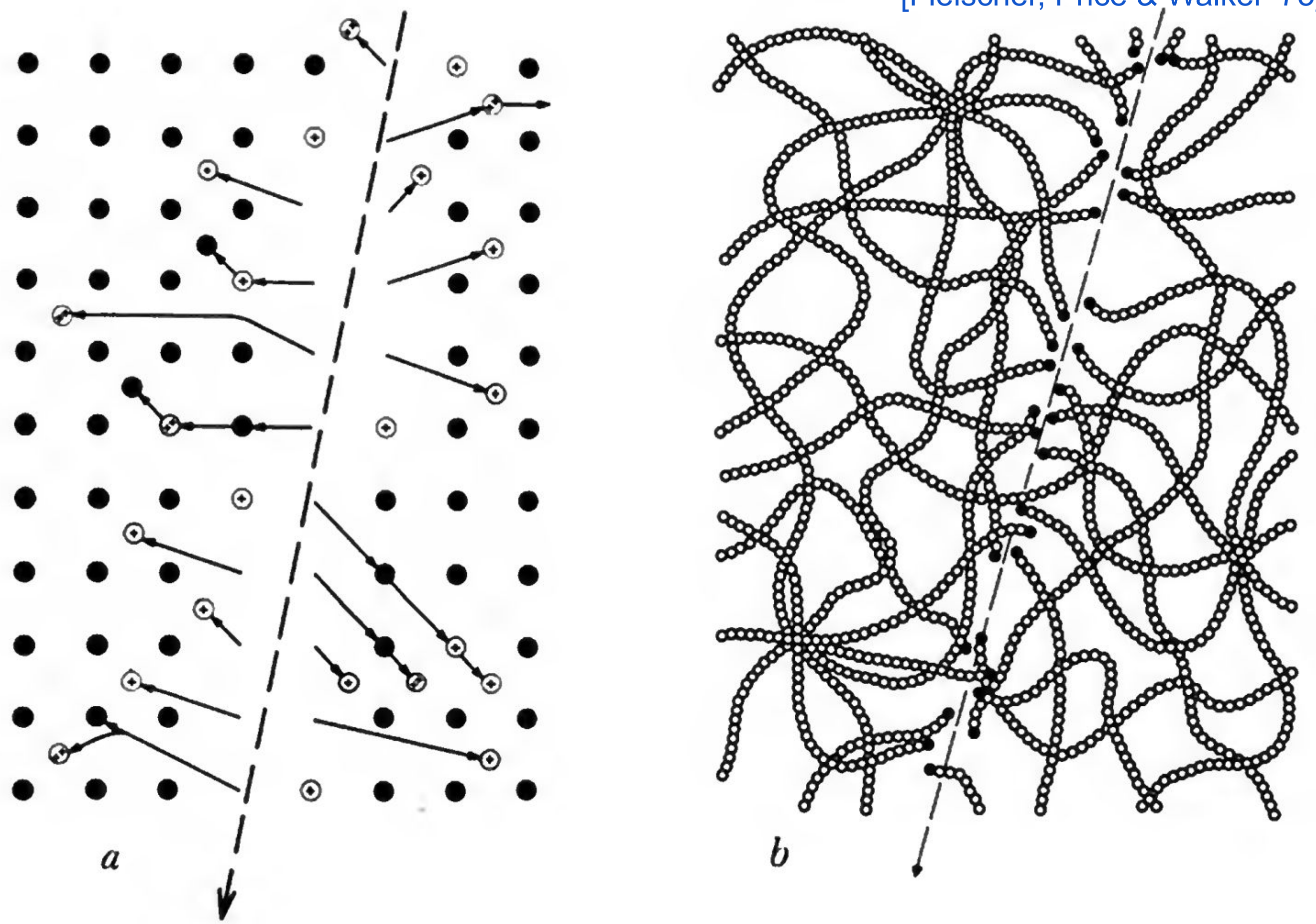
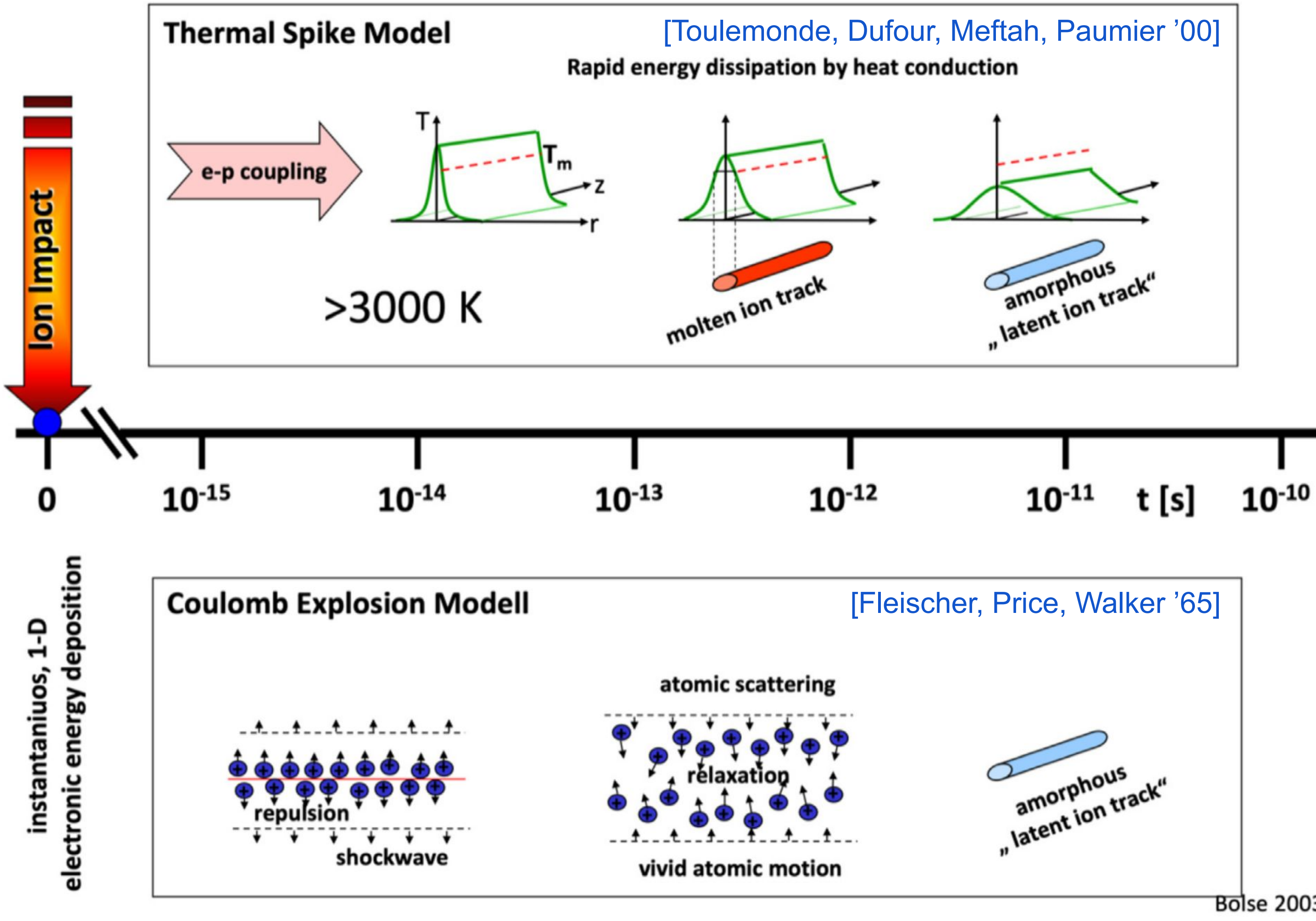



Fig. 1-1. *The atomic character of a particle track in* (*a*) *a crystal and* (*b*) *a polymer. In the crystal the damage consists of continuous disorder composed of vacant lattice sites and of interstitial ions or atoms. In the polymer new chain ends and other chemically reactive sites are formed.* (*After Fleischer et al., 1969.*)

# Track Formation Models



# Track Formation Criteria

[Fleischer, Price & Walker '65]

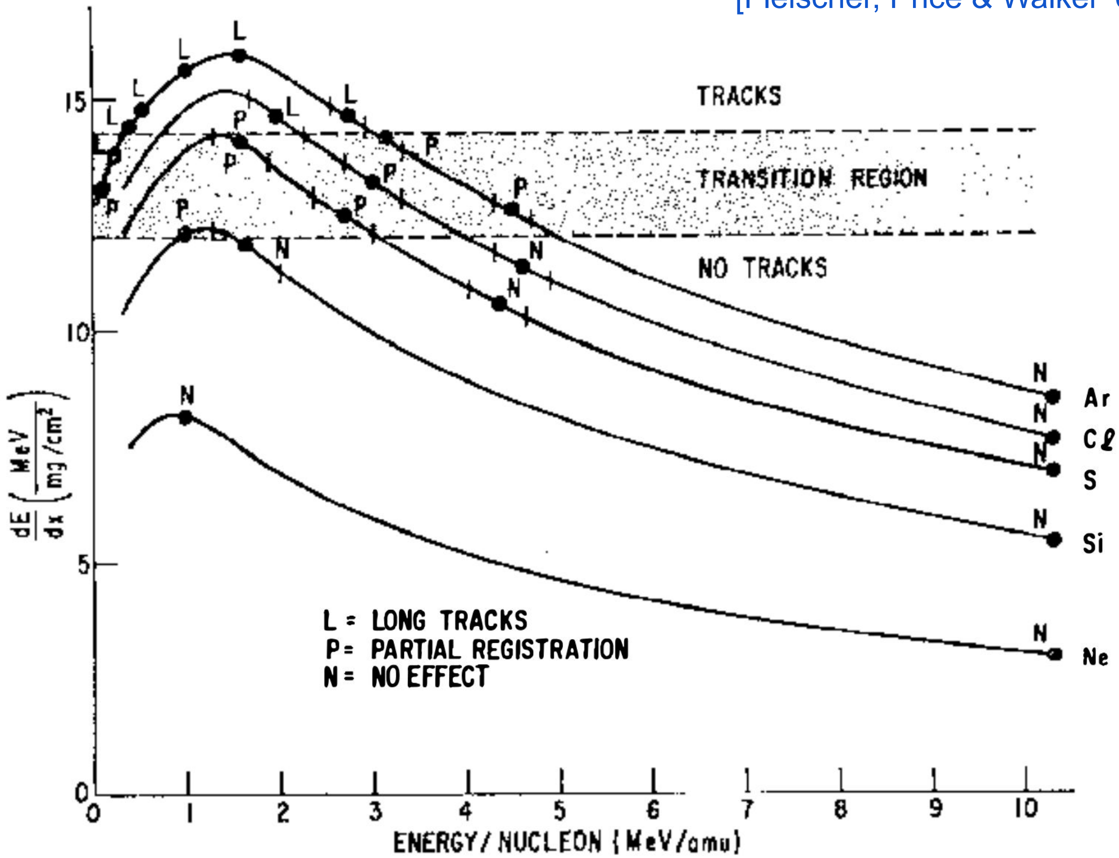



FIG. 3. Track registration in muscovite mica. The curves give the calculated rates of energy loss of various heavy ions in mica as a function of the energy per nucleon. The experimental points indicate the registration behavior in experiments such as that shown in Fig. 2a (10).

# Track Formation Criteria

[Fleischer, Price & Walker '65]

TABLE II. Sequence of sensitivities of various materials.

| Material | Critical rate of energy loss |
|---|---|
| Olivine<br>Hypersthene | ~20 MeV/mg/cm² |
| Zircon<br>Laboradorite | |
| $P_2O_5$-glass<br>Soda lime glass<br>Tektite glass<br>Orthoclase<br>Quartz | ~15 MeV/mg/cm² |
| Mica (18) | ~13 MeV/mg/cm² |
| Polyester resin (Mylar)<br>Bisphenol-A polycarbonate resin (18) (Lexan) | ~4 MeV/mg/cm² |
| Hydroquinone-bisphenol-A<br>Isophthalic terephthalate (HBpaIT) | |
| Cellulose acetate butyrate<br>Cellulose nitrate (18) | ~2 MeV/mg/cm² |

[Fleischer, Price & Walker '75]

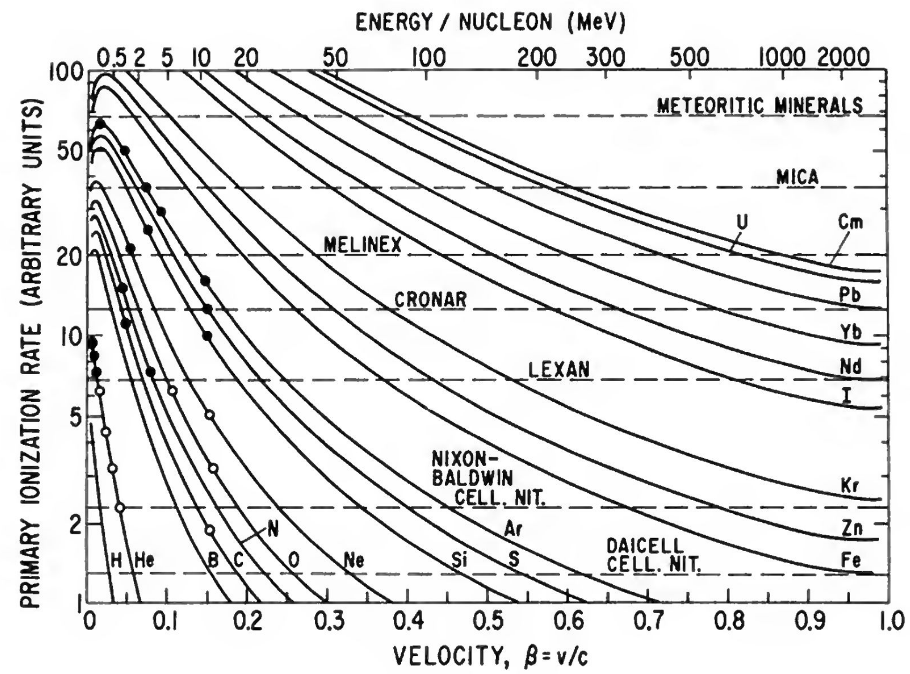



Fig. 1-8. *Damage vs. velocity for different charged particles. Each detector has a level below which no tracks are etched and one above which all particles create tracks. The experimental points for accelerator ions in Lexan polycarbonate are given as open circles for zero registration and as filled circles for 100% registration. Thresholds for other detectors are also indicated.*

# Any hope for keV recoils?

[Fleischer, Price & Walker '65]

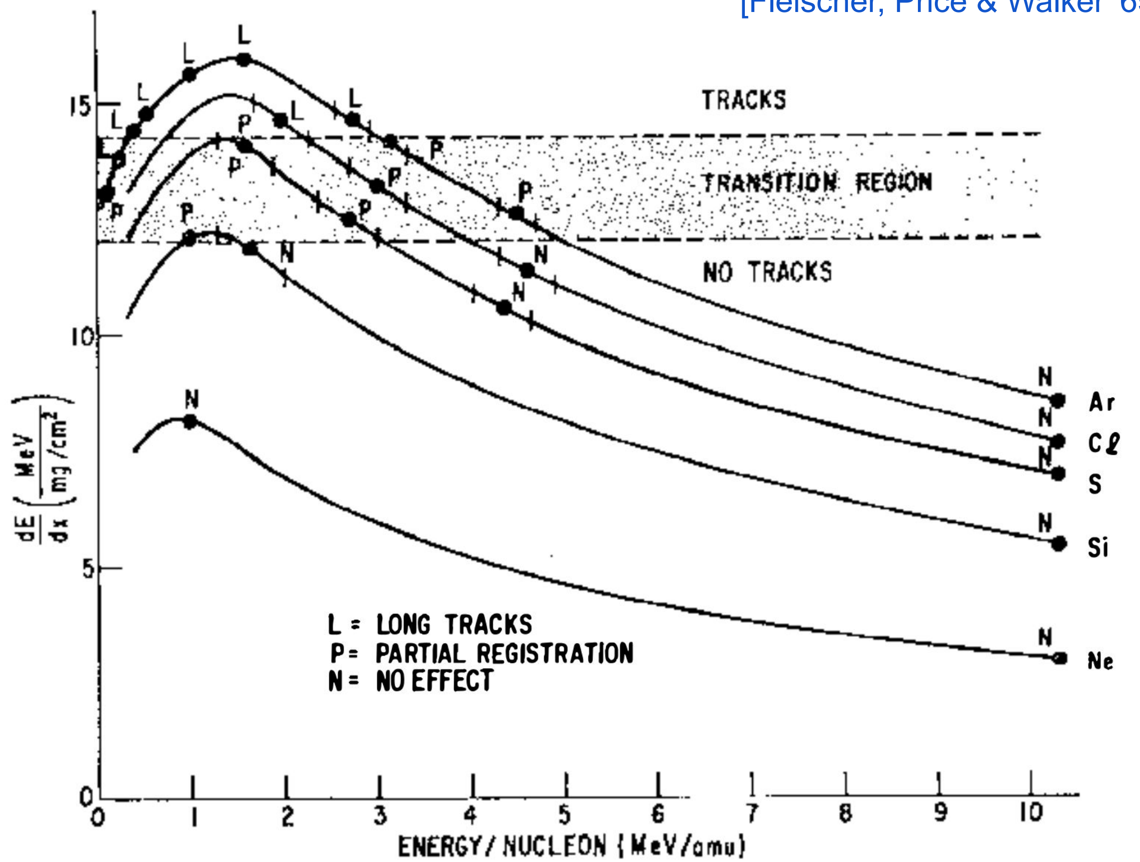



FIG. 3. Track registration in muscovite mica. The curves give the calculated rates of energy loss of various heavy ions in mica as a function of the energy per nucleon. The experimental points indicate the registration behavior in experiments such as that shown in Fig. 2a (10).

# Alpha Recoil Tracks

## A Monte-Carlo calculation of the size distribution of latent alpha-recoil tracks

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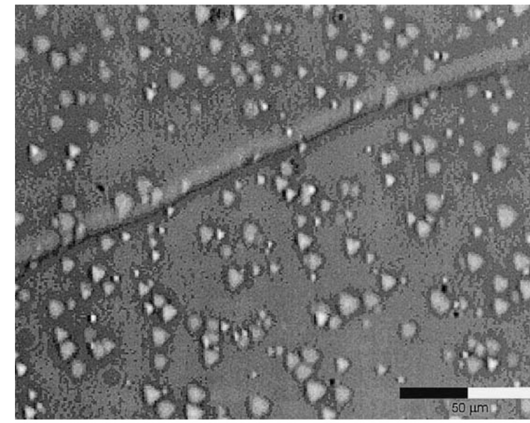
**Abstract**

This paper proposes a Monte-Carlo method for calculating the time-dependent size distribution of alpha-recoil tracks in minerals. The results show that, in the case of recoil tracks in phlogopite, produced by the uranium-series isotopes in the time interval between 0 and 1 Ma, the size distribution comprises two distinct track-populations. The first has a mean size of ~30 nm and standard deviation of ~5 nm and consists of tracks that are the result of a single alpha decay. The second has a broad range of sizes with a mean of ~125 nm and standard deviation ~50 nm and consists of tracks that, for the most part, result from complete decay of $^{238}U$ and $^{234}U$ to stable $^{206}Pb$. The first population saturates at around ~1 Ma, whereas the second shows approximately linear growth. On the basis of the present results, it becomes possible to calculate both the number of recoil tracks intersecting a unit surface of natural minerals and the interconnectedness of recoil damage as a function of time, which has direct implications for alpha-recoil track dating of mica and for the prediction of the long-term behaviour of mineral host phases for the disposal of high-level nuclear waste. 




g. 1. Triangular recoil tracks in a cleaved internal surface of ılogopite mica, etched for 6 min in 40% HF, at 25°C.

# Any hope for keV recoils?

Mica irradiated with ~keV/amu ions,
Chemical etch + AFM microscopy

[Snowden-Ifft & Chan '95]

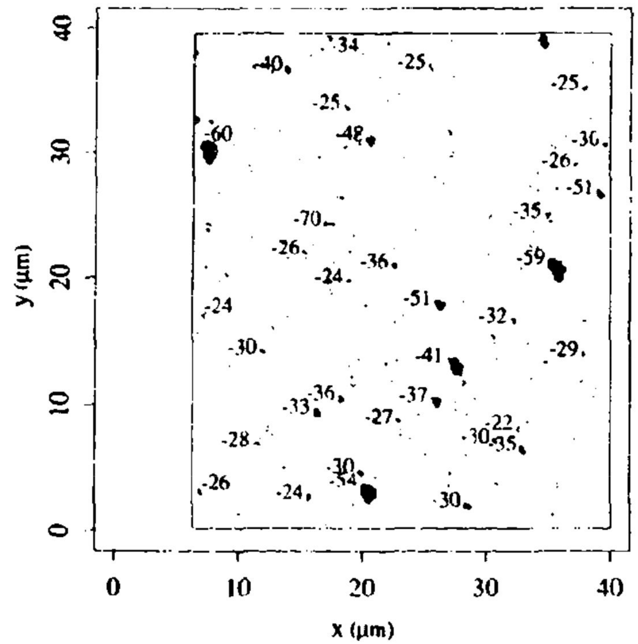



Fig. 2. A processed AFM image. The numbers are the heights in Å of the deepest pixels in clusters passing a 20 Å/4 pix cut.

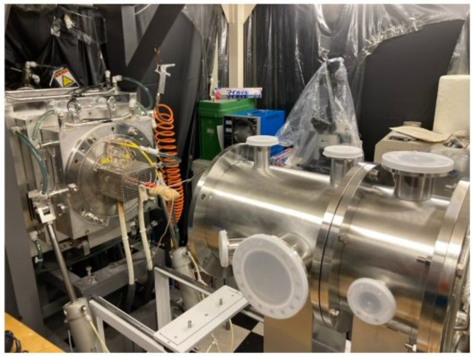
**Table 1**
Summary of data and calculations for the various ions used in this experiment

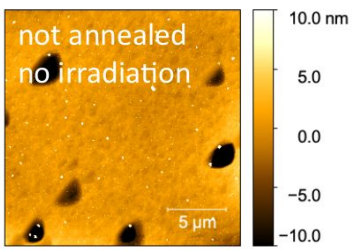
| Ion | Energy [keV] | Calculated range [Å] | Observed density in mica [$10^6 cm^{-2}$] | Incident density in CR-39 [$10^6 cm^{-2}$] | $S_e$ [$MeV g^{-1} cm^{-2}$] | $S_n$ [$MeV g^{-1} cm^{-2}$] | Ratio (data) | Ratio (MC) |
|---|---|---|---|---|---|---|---|---|
| $^{16}O$ | 30 | 551 | 1.09 ± 0.08 | 14 ± 2 | 826 | 715 | 0.08 ± 0.01 | 0.079 ± 0.003 |
| $^{16}O$ | 400 | 5716 | 1.7 ± 0.1 | 14 ± 2 | 3086 | 168 | 0.13 ± 0.02 | 0.111 ± 0.004 |
| $^{29}Si$ | 45 | 511 | 1.6 + 0.1 | 8 ± 1 | 734 | 1791 | 0.22 ± 0.03 | 0.238 ± 0.006 |
| $^{29}Si$ | 400 | 4890 | 1.0 ± 0.1 | 8 ± 1 | 2069 | 661 | 0.14 ± 0.03 | 0.129 ± 0.005 |
| $^{39}K$ | 65 | 509 | 2.2 ± 0.2 | 4.5 ± 0.9 | 1281 | 2763 | 0.5 ± 0.1 | 0.43 ± 0.02 |
| $^{39}K$ | 200 | 1543 | 1.8 ± 0.2 | 4.5 ± 0.9 | 2167 | 1900 | 0.4 ± 0.1 | 0.35 ± 0.01 |

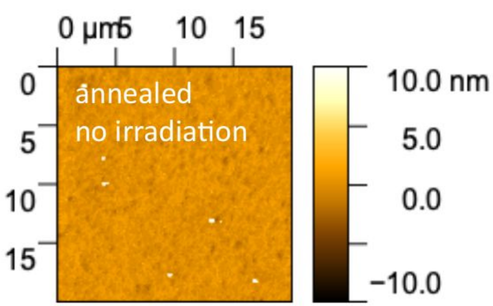
# Any hope for keV recoils?

Mica irradiated with ~keV/amu ions,
Chemical etch + AFM microscopy

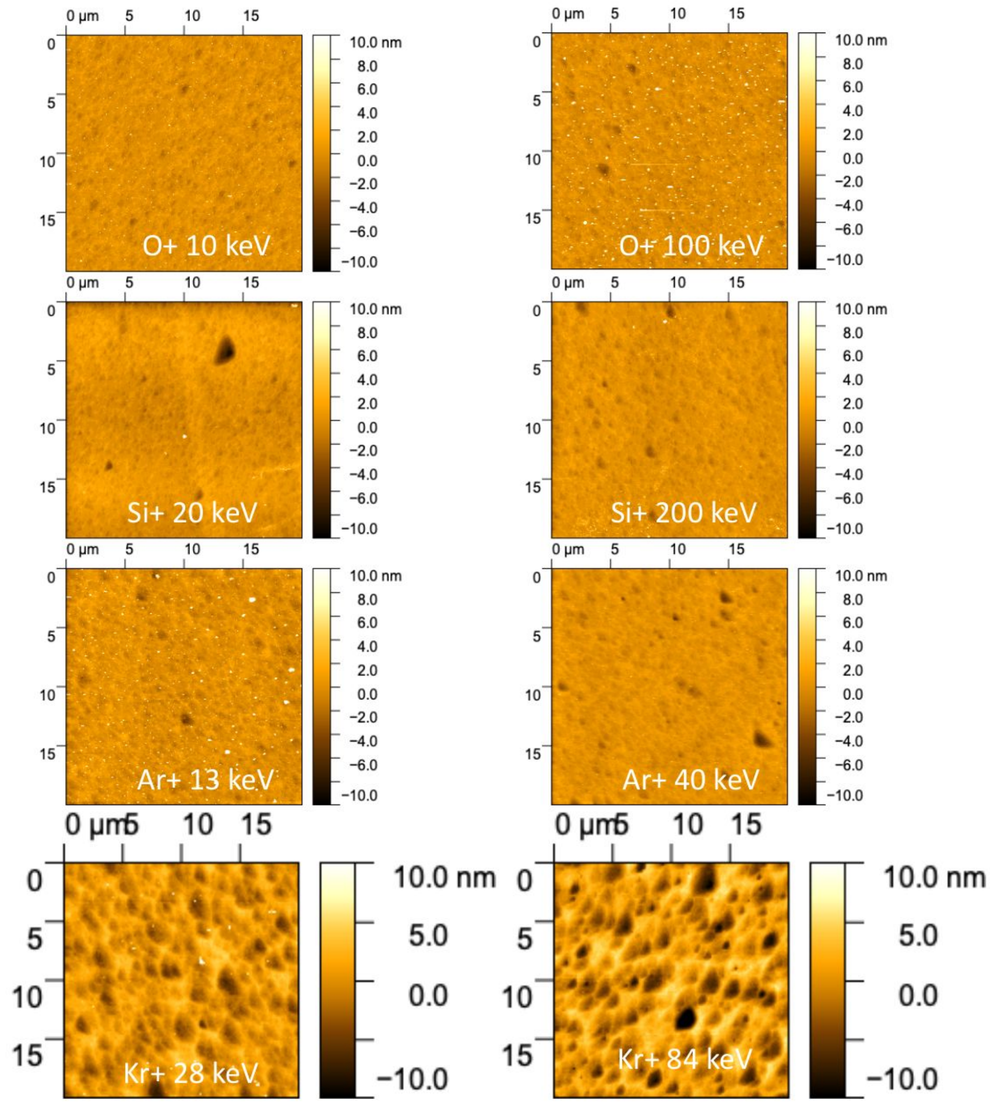
Ion beam experiments at Kanagawa U.






[Hirose+ @JAMSTEC] (see Tue talk)



# Any hope for keV recoils?

[Snowden-Ifft & Chan '95]

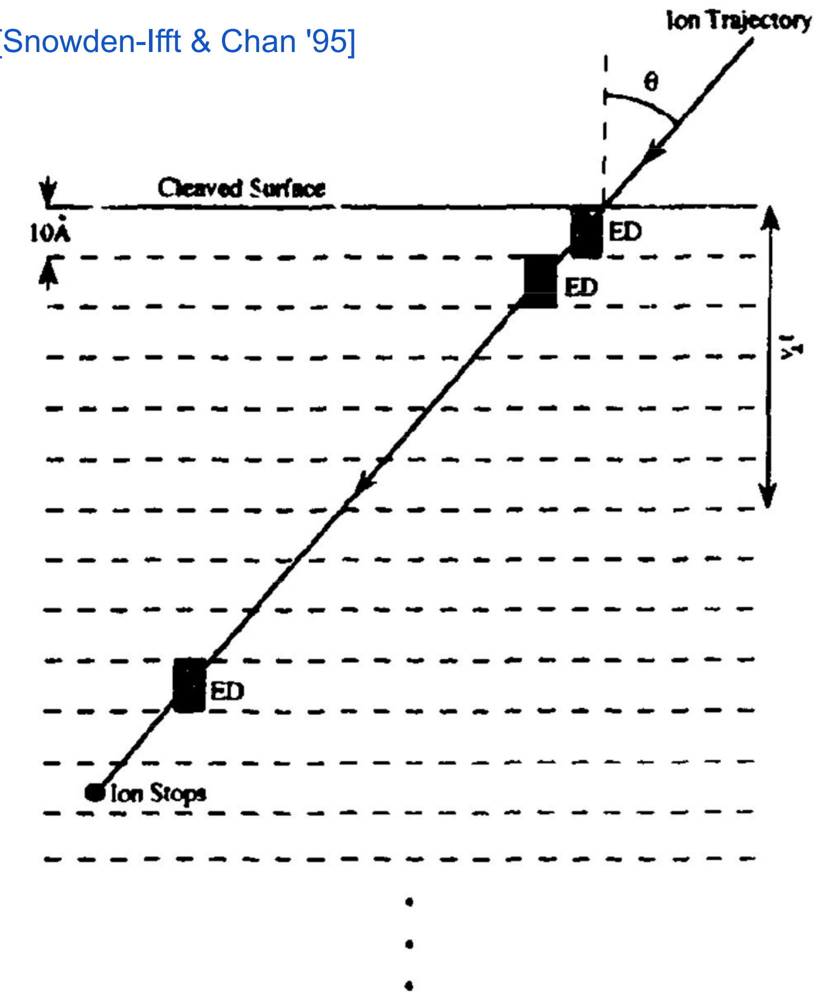



Fig. 1. A schematic showing an ion penetrating mica with incident angle *θ*. The ion creates Etching Defects (EDs) randomly in mica's 10 Å layers. If 60 Å is removed from the surface, as shown, the etched depth would be 20 Å. The last ED is not revealed until more material is removed from the surface.

# Fluorescent Nuclear Track Detectors: $Al_2O_3$:C,Mg

[Akselrod, Akselrod, Benton & Yasuda '06]

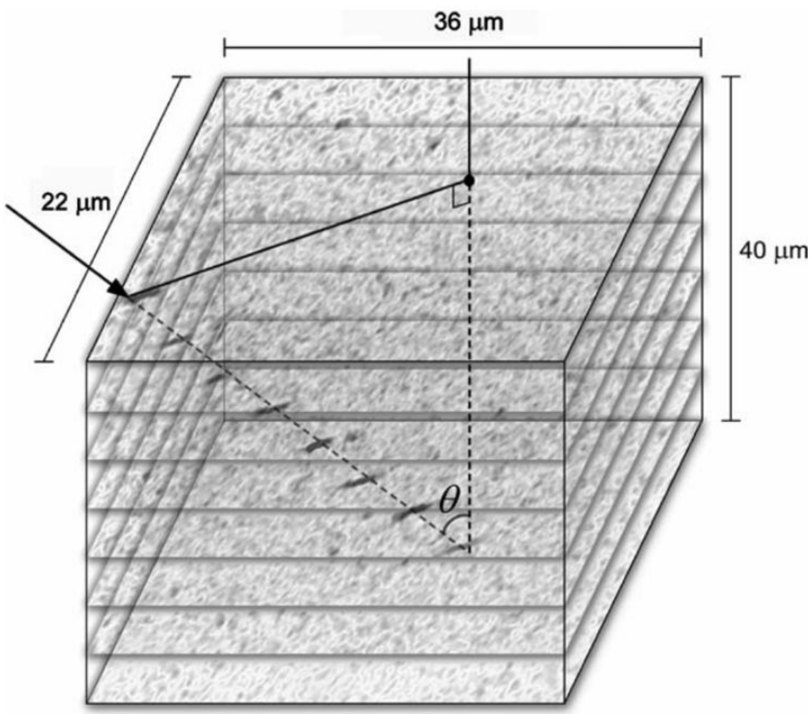



Fig. 5. 3-D reconstruction of a single track from a recoil proton entering the crystal at an angle $\theta$ to the normal. The image is composed of eight images obtained by laser scanning at 5 μm increment depths. The fluorescence images are shown in negative contrast and are semitransparent for better presentation.

Doped sapphire
+ fluorescent microscopy

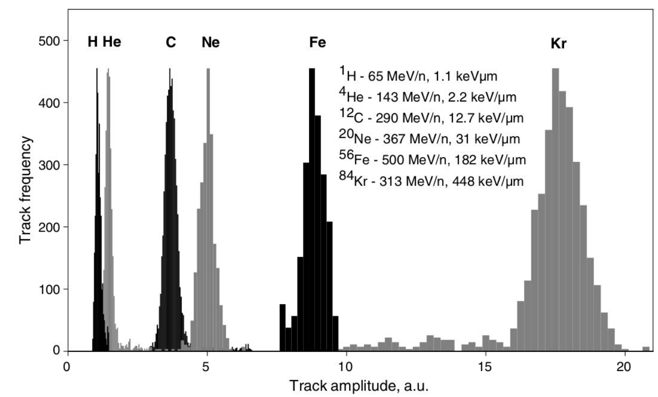



Fig. 8. Distribution of fluorescence peak amplitudes for six high energy heavy ions: 65 MeV protons (LET = 1.1 keV/μm in water), 143 MeV/n $^{4}He$ (2.2 keV/μm), 290 MeV/n $^{12}C$ (12.6 keV/μm), 367 MeV/n $^{20}Ne$ (31 keV/μm), 500 MeV/n $^{56}Fe$ (182 keV/μm) and 313 MeV/n $^{84}Kr$ (440 keV/μm).

No tracks seen for GeV protons -> estimated threshold to ~1 keV/micron

# Fluorescent Nuclear Track Detectors: $Al_2O_3$:C,Mg

Doped sapphire
+ fluorescent microscopy

[Akselrod & Kouwenberg '18]

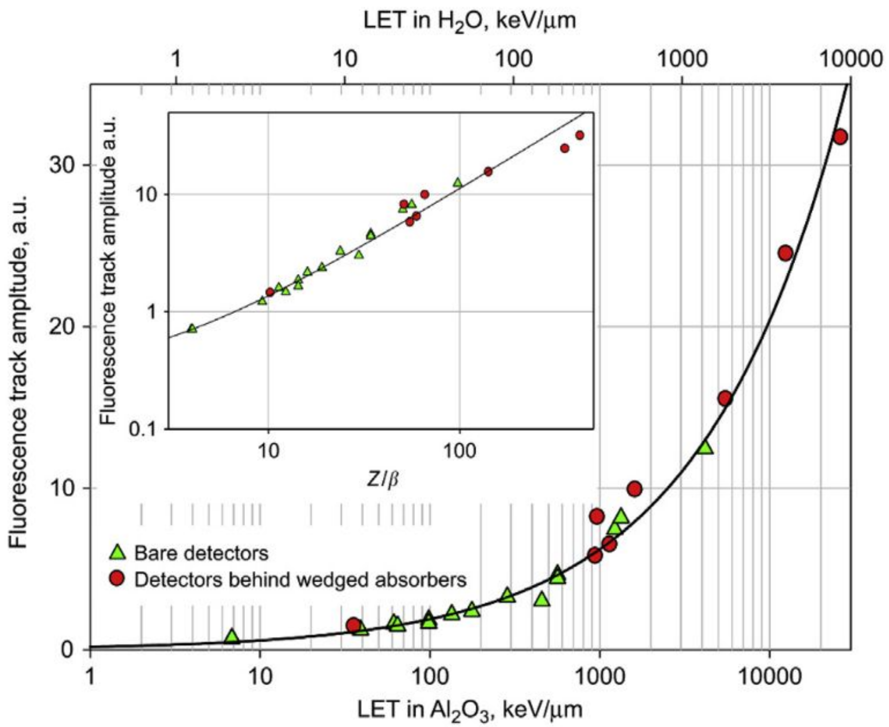



**Fig. 30.** LET in $Al_2O_3$:C, Mg versus fluorescence track amplitude. The insert shows the relation between the fluorescence track amplitude and Z/β, where Z is the effective charge of the ion and β is the relativistic ion velocity (Sykora et al., 2008a).

[Kouwenberg+ '18]

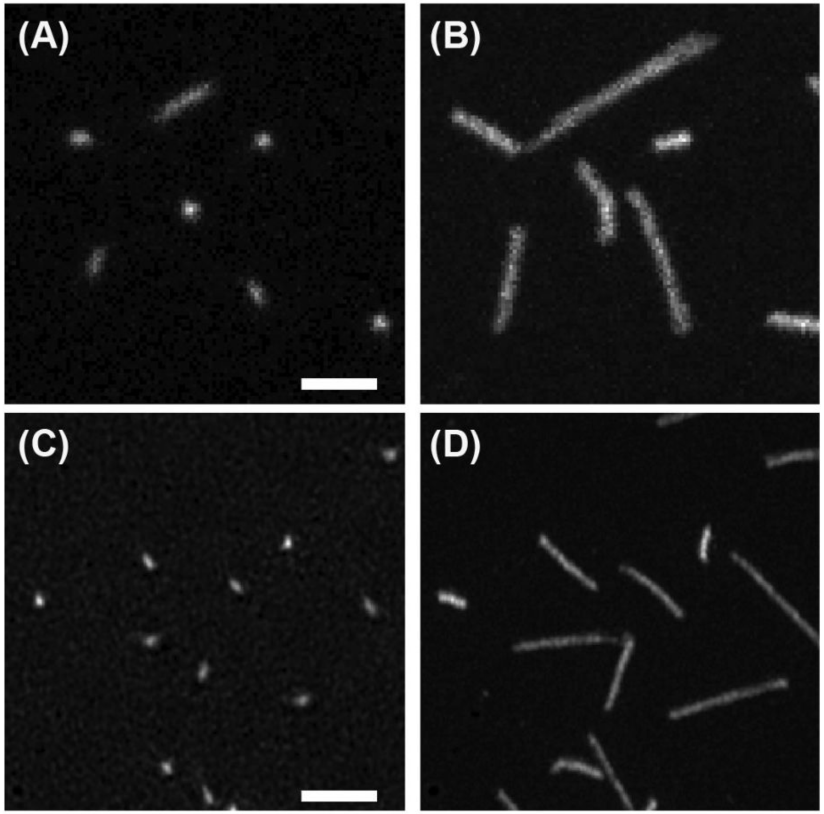



**Fig. 2.** Close-up of FNTDs irradiated with alpha radiation and imaged with CLSM (A and B) and SIM (C and D). Panels A and C show single images and panels B and D show the maximum projection of the 3D image stacks. Scale bars are 2 μm. Note that panels A and B show a different field of view than panels C and D.

# Fluorescent Nuclear Track Detectors: LiF

LiF + fluorescent microscopy

[Bilski & Marczewska ‘17]

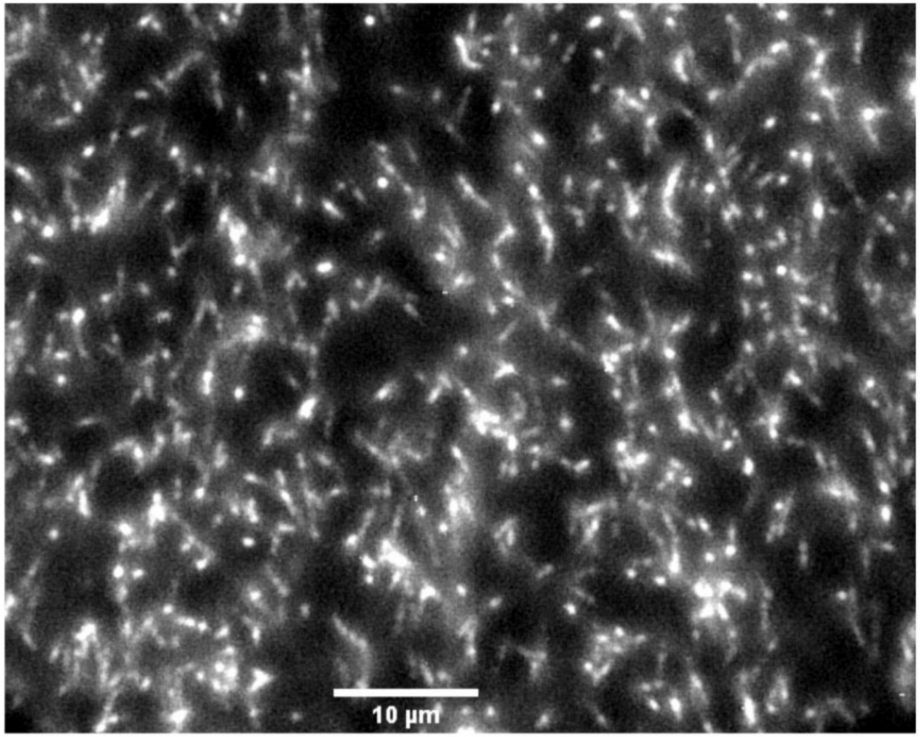



**Fig. 7.** Fluorescent image of the sample irradiated with a broad uncollimated flux of alpha particles acquired at depth of about 2 µm. Irradiation time 1 min, particle fluence $2.05 \times 10^5$ $mm^{-2}$. Acquisition time 30 s. A video showing images acquired at different focal depth is available.

[Bilski+ ‘19]

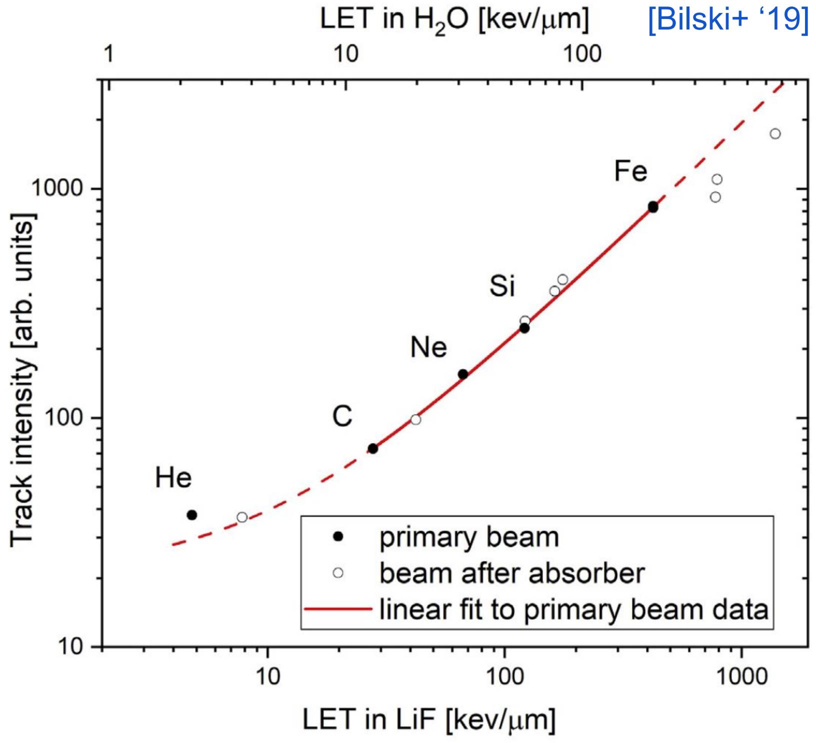



**Fig. 9.** Track intensity vs. LET in LiF. The line represents a linear fit to the primary beam data points (without He), with parameters $a = 1.92$, $b = 20.25$. Uncertainty bars not plotted for clarity.

# Fluorescent Nuclear Track Detectors

[Cogswell, Goel & Huber '21] (see Thu talks)

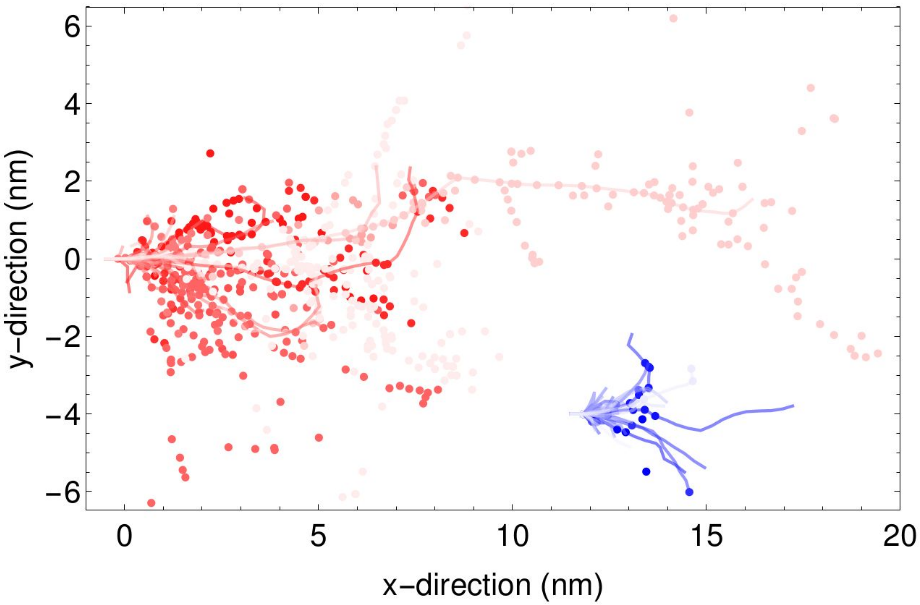



Figure 1. Shown is the overlay of 50 typical cosmic ray neutron (red) and reactor CEvNS events (blue) in NaI. Vacancies are marked by disks and tracks created by the primary recoil are marked by a line.

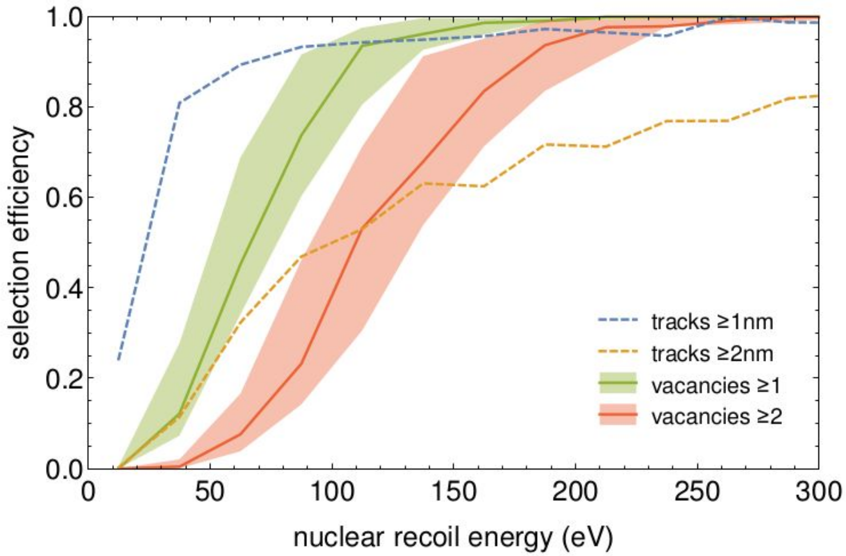


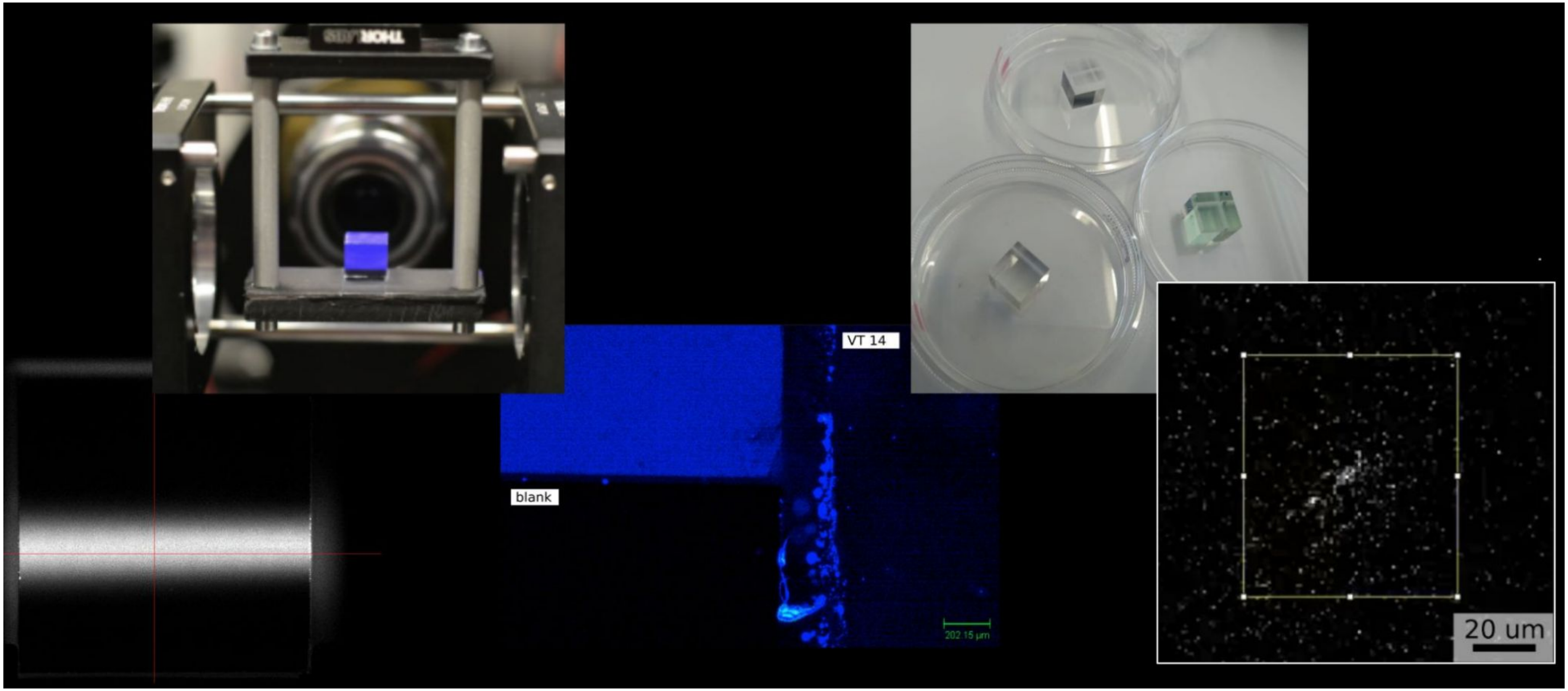

Figure 2. Shown is the nuclear recoil energy threshold in NaI for either track-based event selection (dashed lines) or vacancy-based event selection (solid lines). The bands result from a ±20% variation of the threshold damage energy.

[see also Budnik, Chesnovsky, Slone and Volansky '17]

# Fluorescent Nuclear Track Detectors: $CaF_2$

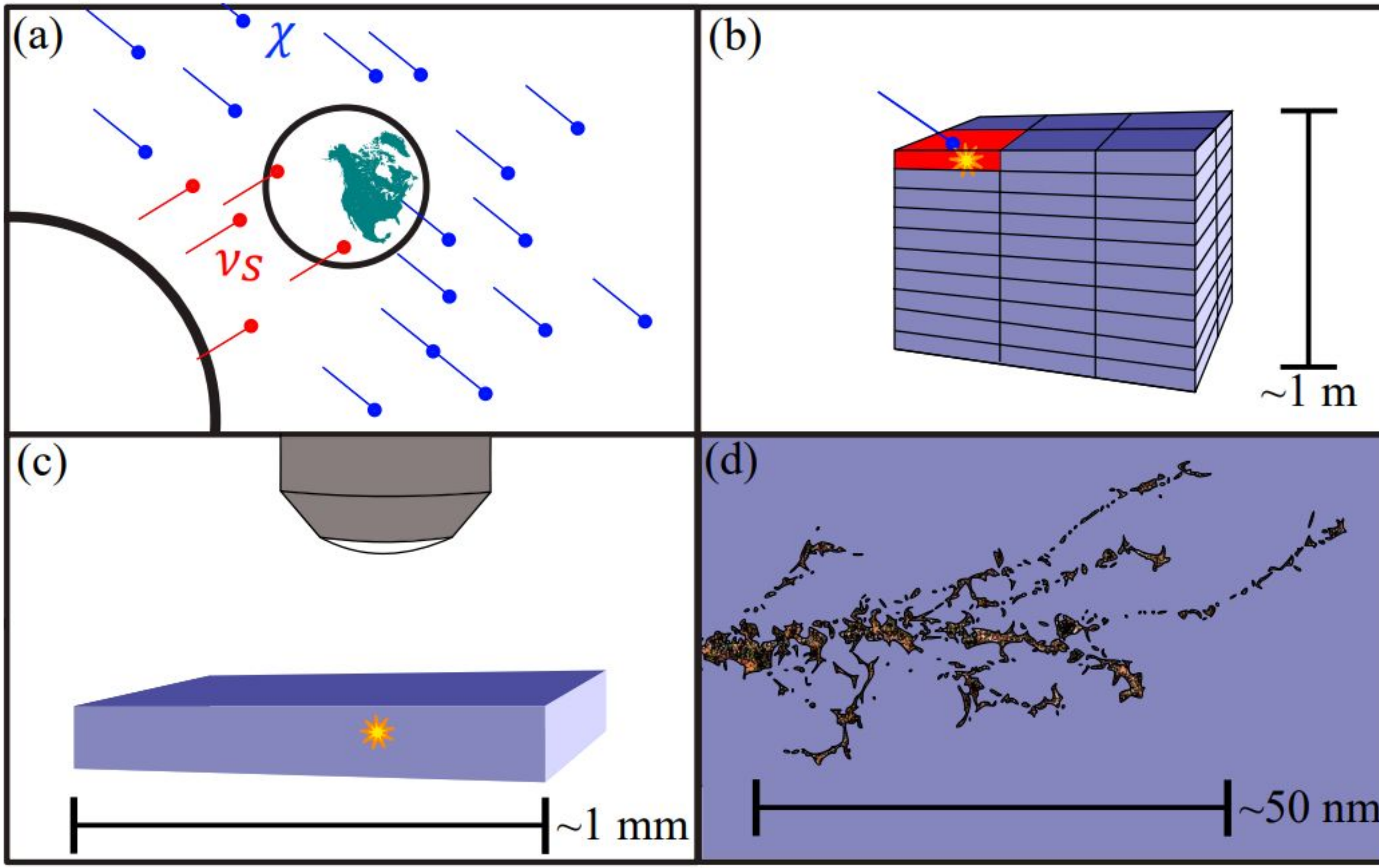
$CaF_2$ + fluorescent microscopy

[Gabriela Araujo/PALEOCEENE] (see Thu talk)



# Strain mapping via NV spectroscopy in Diamond

[Marshall+ ‘09, ‘21, ‘22 (see Daniel Ang’s Tue talk)



# New Track Formation Criteria?

- Are any track formation criteria necessarily readout and material dependent?
- What are “etching defects”?
- Is electronic stopping/linear energy transfer (LET) a good proxy?
- Is vacancy density a good proxy?

# Some other open questions

- How do we define the length of a “track”?
- What is the efficiency of “track” readout?
- What is the energy resolution?
- Can we do particle ID?

- What about “track” stability? (partial annealing, …)

- Which modeling tools are available and how to we adapt/modify them?