Toho University

# Ultra-heavy Exotic Particle Search with the Olivine in Meteorites


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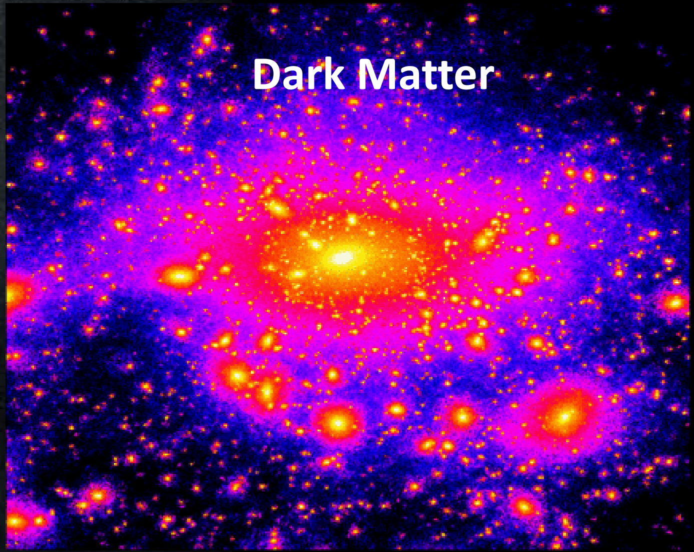
2026.4.14-17 (talk on 16th) MDvDM’26 KIT, Karlsruhe, Germany

# Paleo Detector Concept



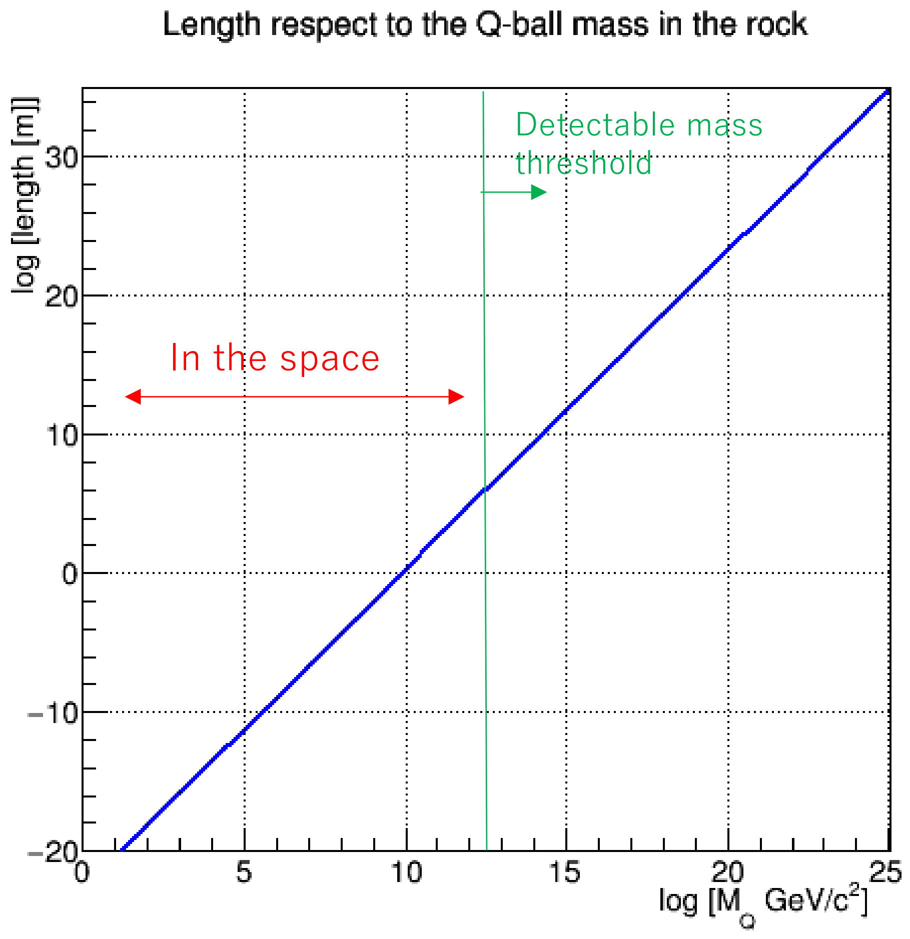

~ 1 events per 0.1 Myear




1 cycle ~ 250 Myear

# Category of exotic (charged) particle search

| Extraterrestrial | Site | Terrestrial |
|---|---|---|
| $< 10^{13}$ GeV/c$^2$ | Mass scale | $> 10^{13}$ GeV/c$^2$ |
| < 1000 m | Length in material | > 1000 m |
| $> 10^{-3}$ | Velocity (v/c) | $\sim 10^{-3}$ |
| **Olivine**<br>Pigeonite<br>Plagioclase | Minerals | Muscovite mica<br>Halite<br>Zircon |
| **GCR**<br>**SQM**<br>**(Q-ball)** | Physics Targets | Q-ball<br>SQM<br>WIMP |



# Candidate of extraterrestrial minerals

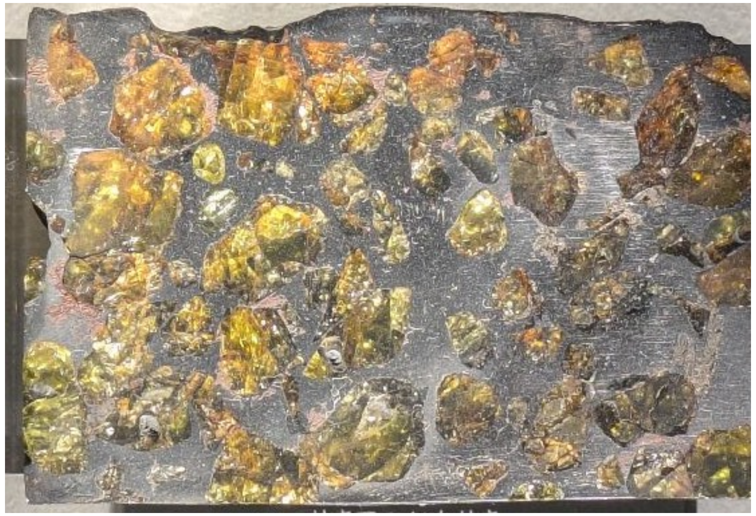
**Olivine**
**[$(Mg,Fe)SiO_4$]**

Pigeonite
[$(Mg,Fe,Ca)_2Si_2O_6$]

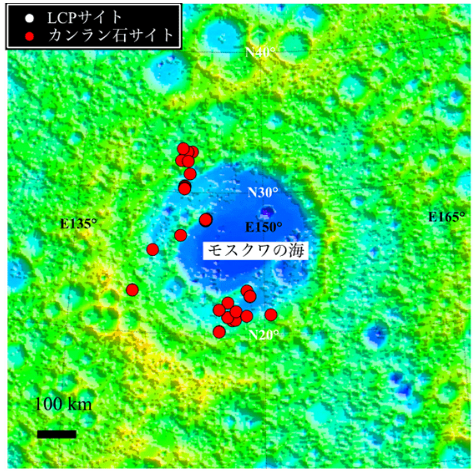
Plagioclase
[$NaAlSi_3O_8$]

- **the meteorite and the lunar surface is abundant above minerals.**
- **Low-U, Th contamination**

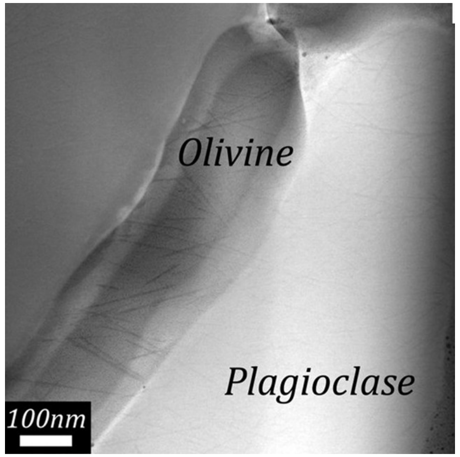
## Meteorite



## Lunar lock




「かぐや」スペクトルデータより
https://www.isas.jaxa.jp/home/research-portal/gateway/2023/0608/




Meteoritics & Planetary Science 56, Nr 9, 1685–1707 (2021)

# Long and High-Z track candidate  in the mineral on the moon

**Apolo 12 sample**
**Long track observation more than 1 mm in the pegionite [$(Mg,Fe,Ca)_2Si_2O_6$]**

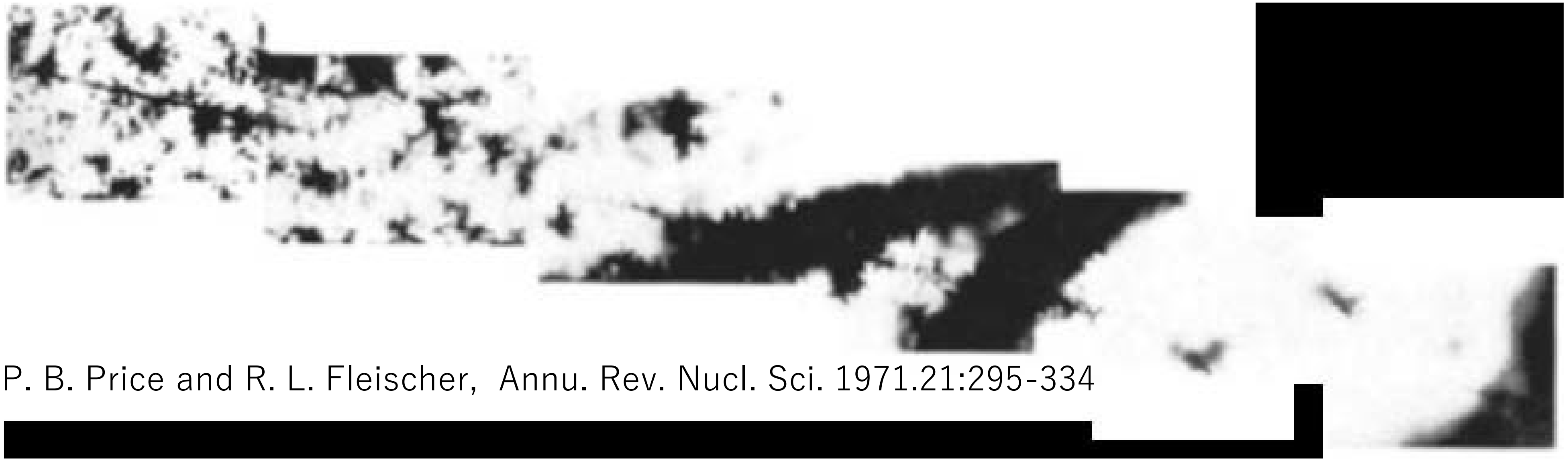
Ultra heavy element or exotic particle candidate

The https://www.mindat.org/min-3210.html crystals from lunar rock

**Atomic number : Z ＞ 80～90**
**→ energy ＞ 100 MeV/u**

⇔

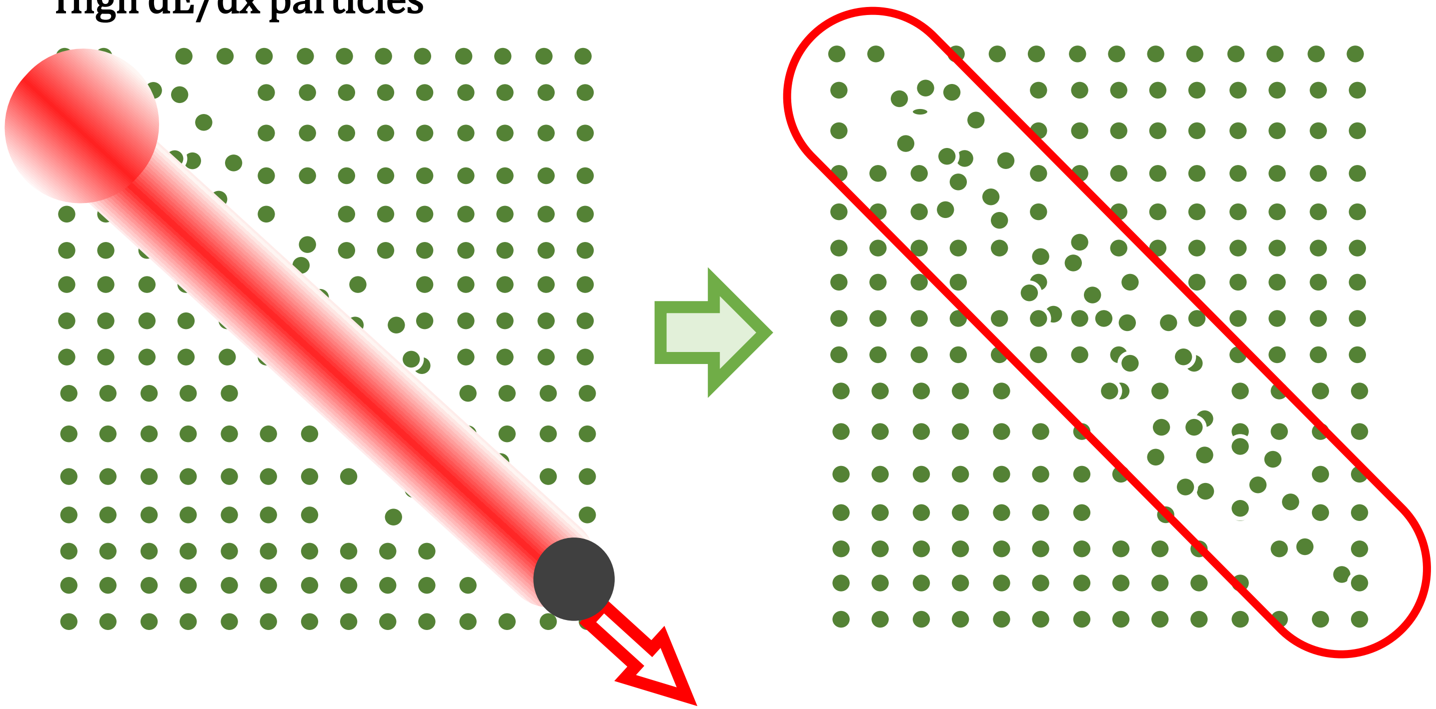
**Exotic particle (?)**
**⇒seems small energy change from uniform track structure.**



P. B. Price and R. L. Fleischer,  Annu. Rev. Nucl. Sci. 1971.21:295-334

# Track formation mechanism in the mineral for swift high-ionization particles (Thermal Spike model)

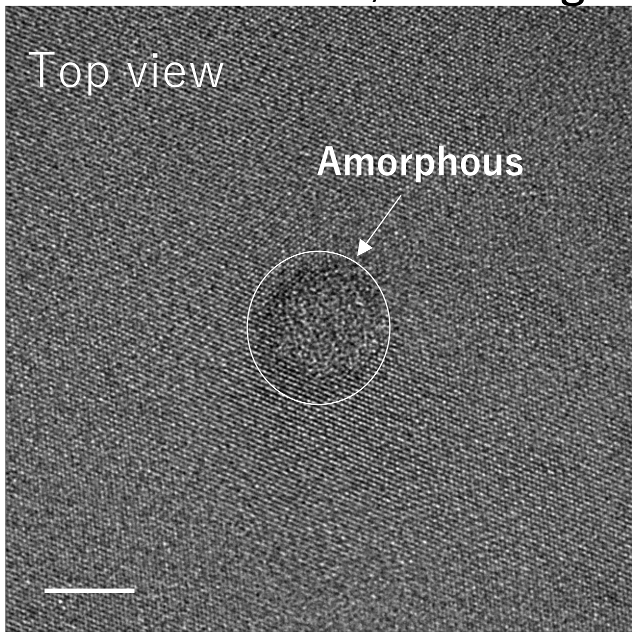
**High dE/dx particles**



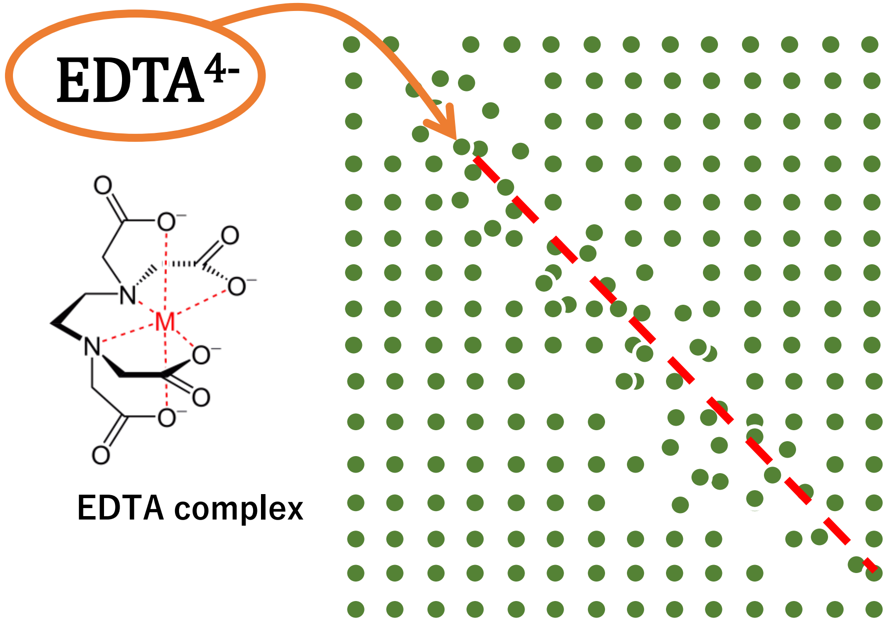
**The region along the trajectory of a charged particle is locally heated to a high temperature, leading to melting of the crystal.**

**The molten region is rapidly cooled by the temperature difference with the surrounding medium, leading to the formation of lattice defects and damage tracks..**

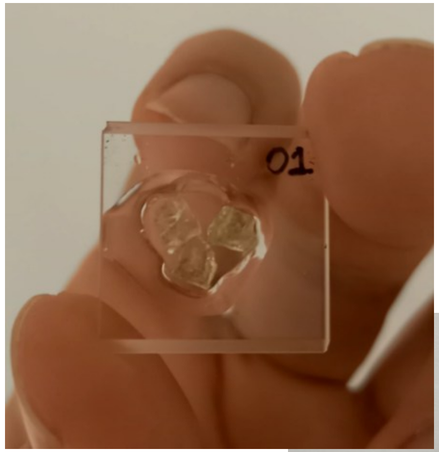
**Xe 100 MeV w/o etching**



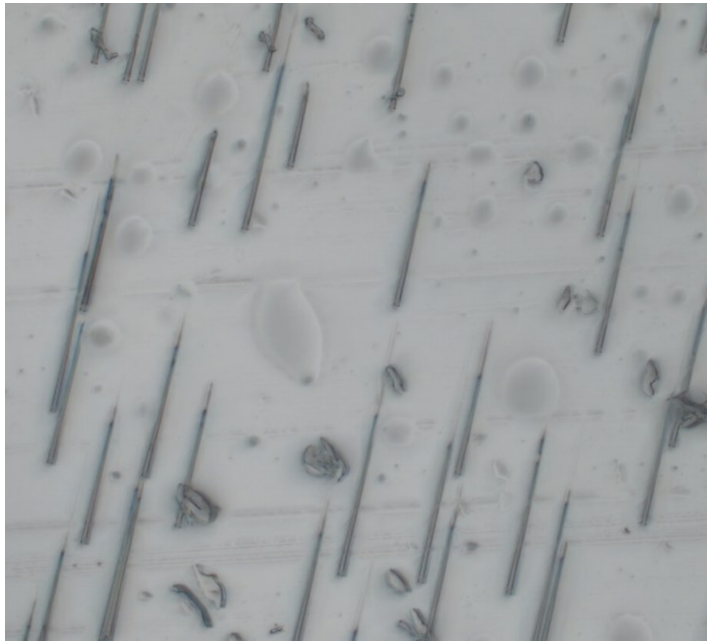
# Etching process for the olivine




$$M^{2+} + EDTA^{4-} \rightleftarrows [M - EDTA]^{2-}$$



Optical microscope

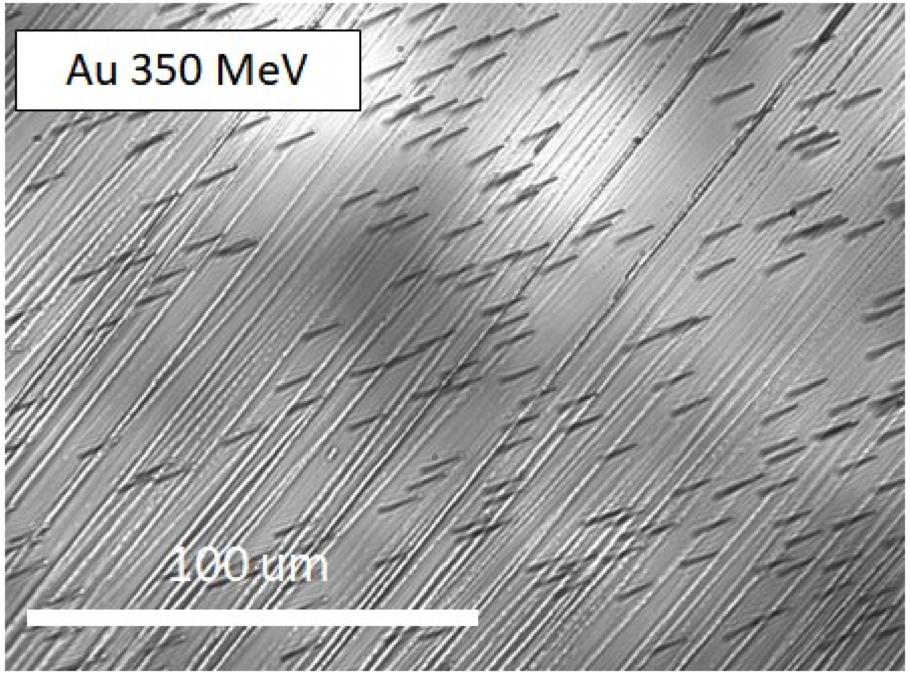


Xe 0.5~2 GeV 30d 14h etching

**Etching selectively dissolves defect regions, where metal ions form complexes with EDTA, causing the crystal to break down.**

# Tracks by chemical etching treatment for the Olivine

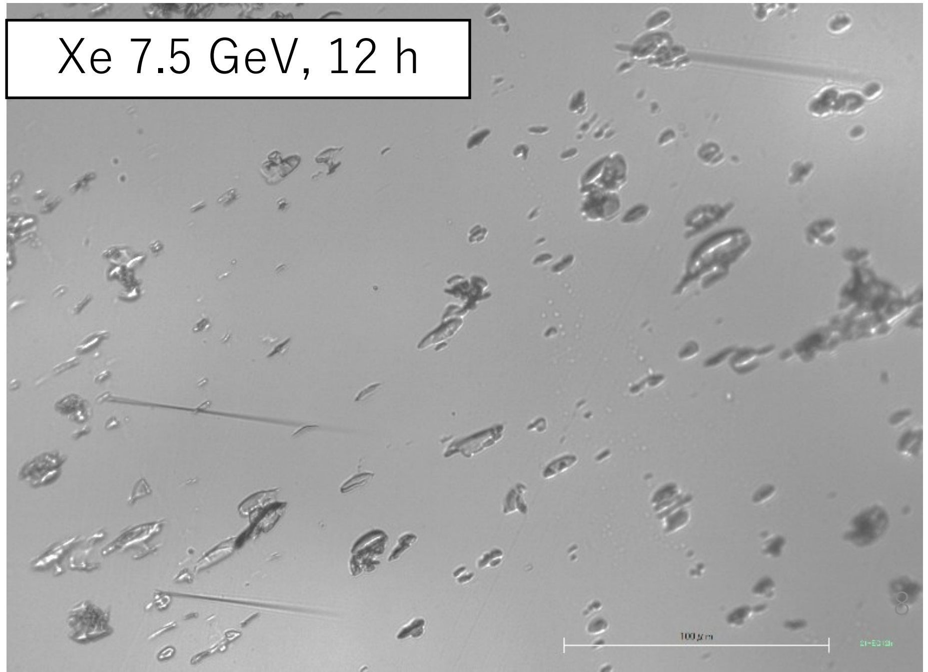
- EDTA based solution
- Treatment temperature : ~100 °C
- Etching time : > 1 hours

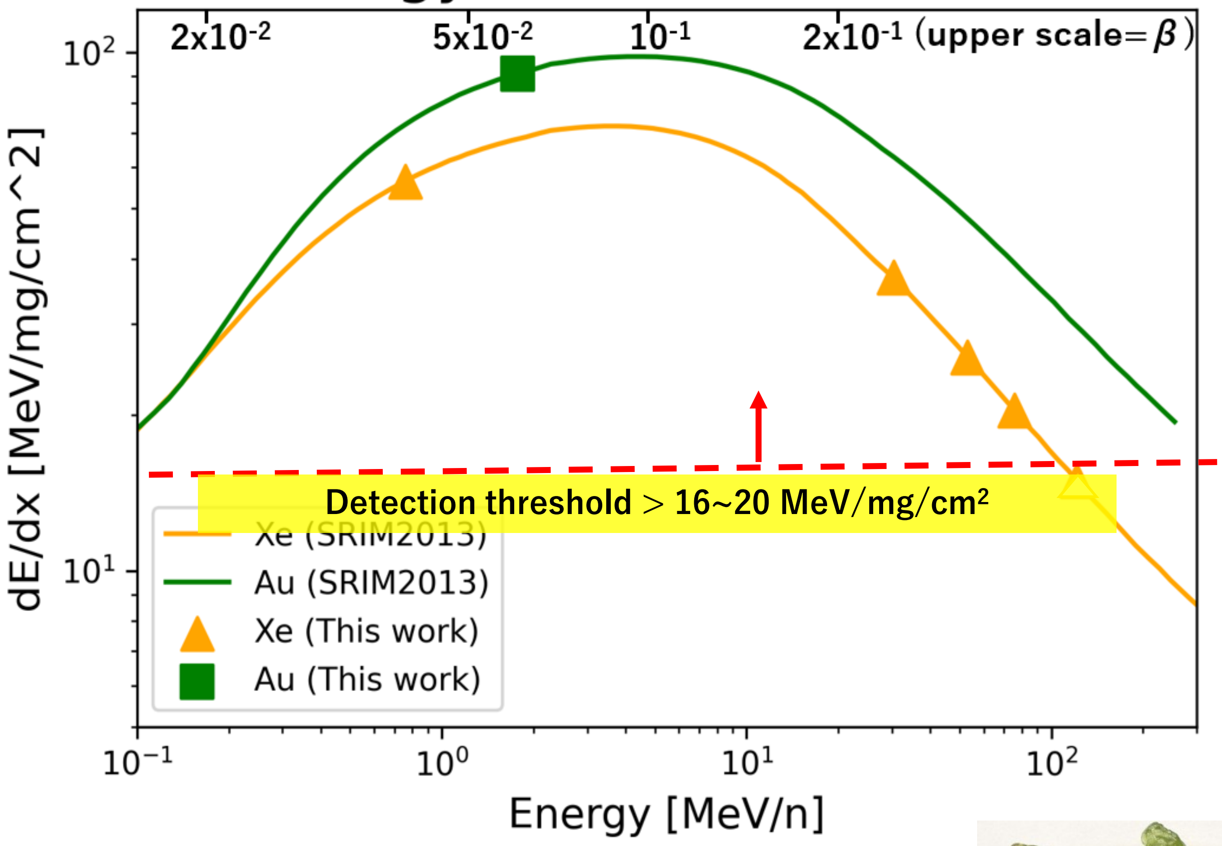

| Irradiated Nuclide | Effective Irradiation Energy | $S_e, S_n$ [MeV/mg/cm$^2$] | Details (Irradiation Energy, Moderator, Thickness) | Facility |
|---|---|---|---|---|
| Xe | 16 GeV | 14.91 0.004870 | 290 MeV/n, BF, 6.40 mm | 1 |
| Xe | 10 GeV | 20.39 0.007439 | 290 MeV/n, BF, 8.68 mm | 1 |
| Xe | 7.5 GeV | 25.85 0.01024 | 290 MeV/n, BF, 9.83 mm | 1 |
| Xe | 4 GeV | 36.78 0.01687 | 290 MeV/n, BF, 10.96 mm | 1 |
| Xe | 100 MeV | 56.08 0.3955 | | 2 |
| Au | 350 MeV | 3.805 1.436 | | 2 |

**QST, HIMAC** (Xe 16 GeV, 10 GeV, 7.5 GeV, 4 GeV)

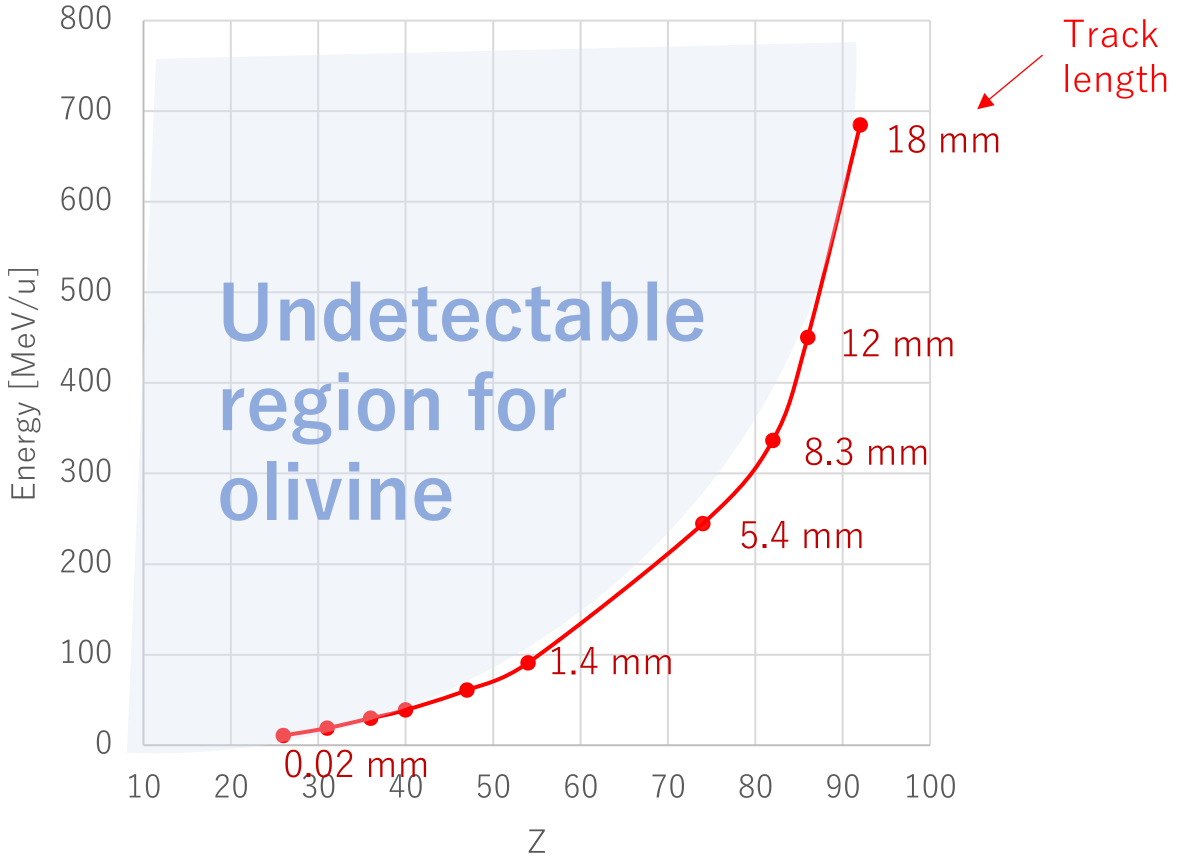
**JAEA, Tandem** (Xe 100 MeV, Au 350 MeV)



# Energy loss rate in Olivine




Upper limit of detectable energy for each Z (atomic number)



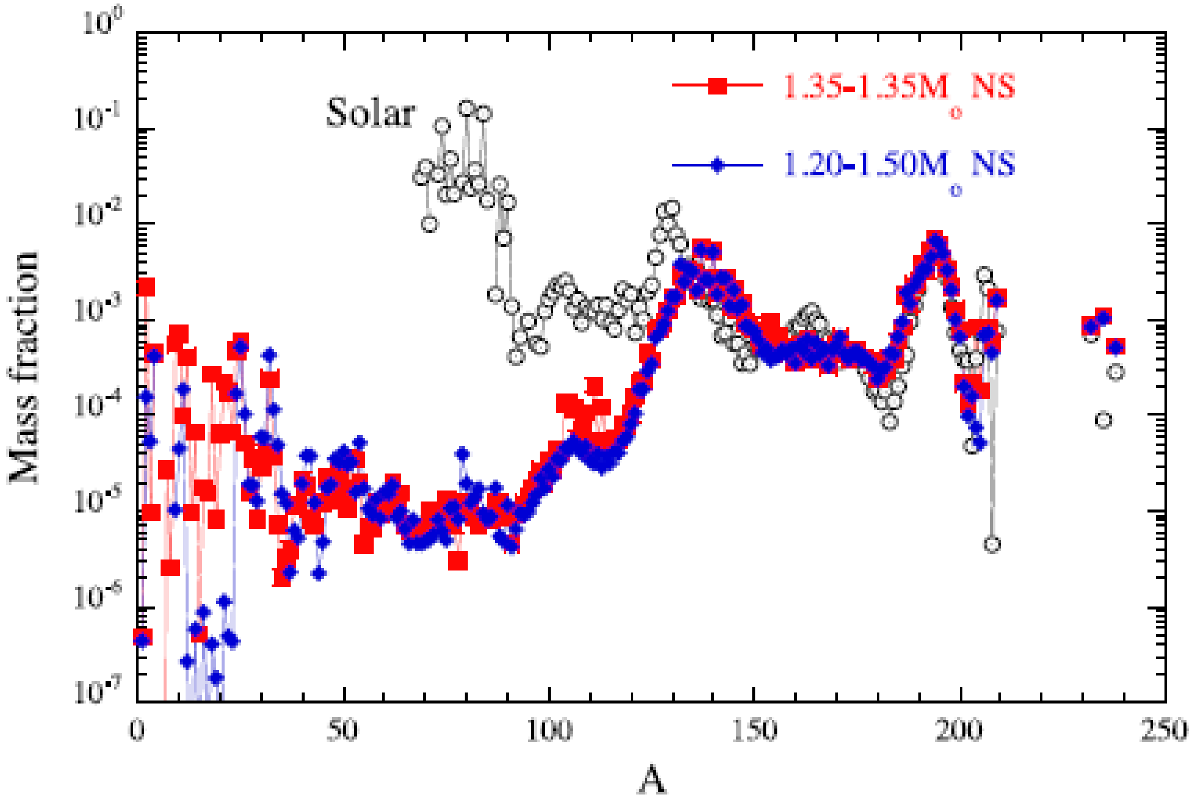

calculated by SRIM

# Nucleosynthesis in the Neutron Star Merger (NSM)


Credit: Tohoku University

**r-process nucleosynthesis calculation in NSM using relativistic hydrodynamic simulations**

Nucleosynthesis is calculated based on the neutron richness, entropy, initial density evolution, expansion timescale, and ejecta mass.



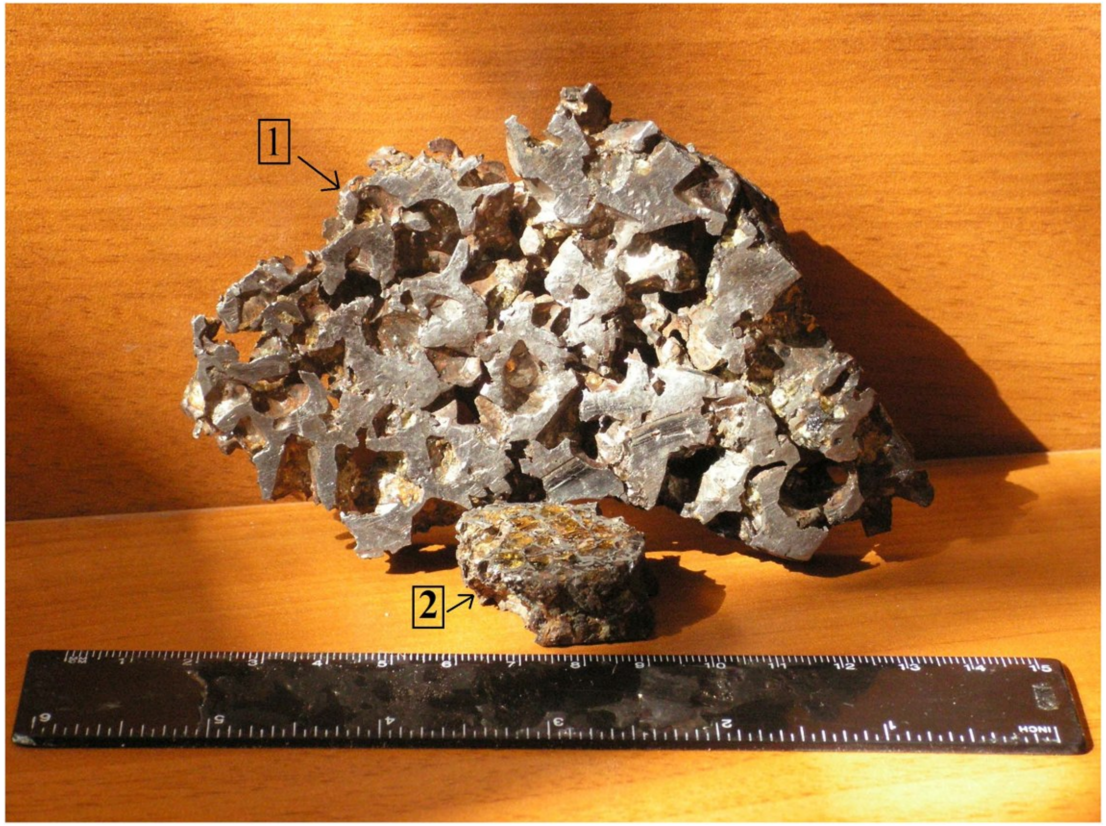

Stephane Goriely et al., The Astrophys. J. Lett., 738:L32 (6pp), 2011

An NSM rate of ~1 per 0.1 Myr can account for the solar-system abundances for A> 140, implying an ejecta mass of $10^{-3}$ – $10^{-2}$ M☉ per event.

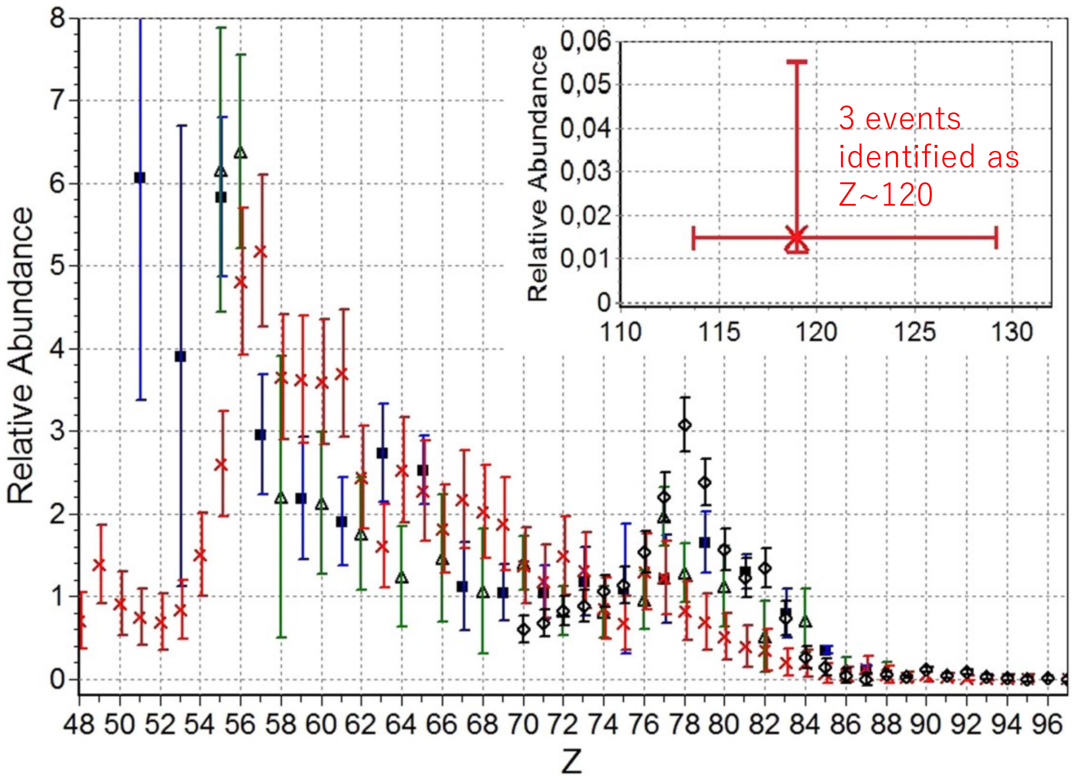
# OLIMPIYA experiment @Russia

Victor Alexeev*et al*, ApJ, 829:120 (2016)

**pallasite meteorite**

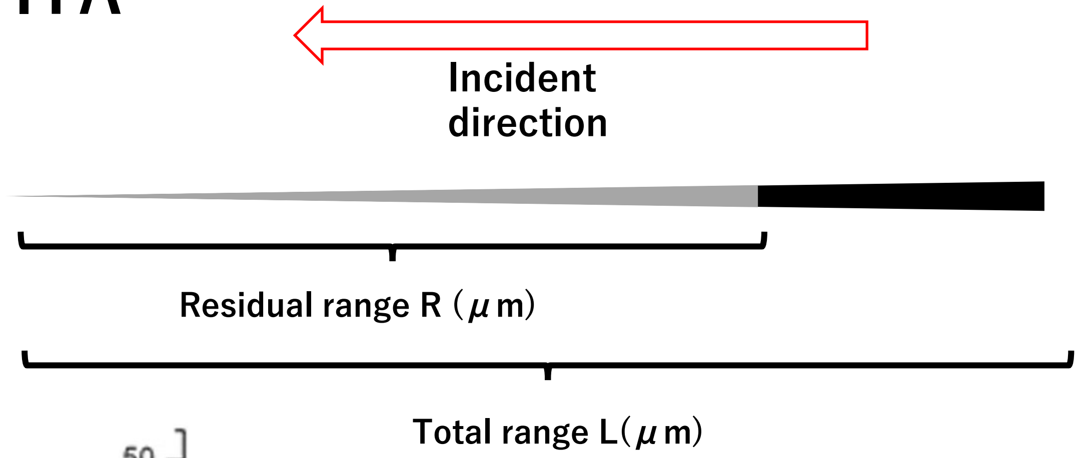



Olivine track analysis for heavy element with charge identification

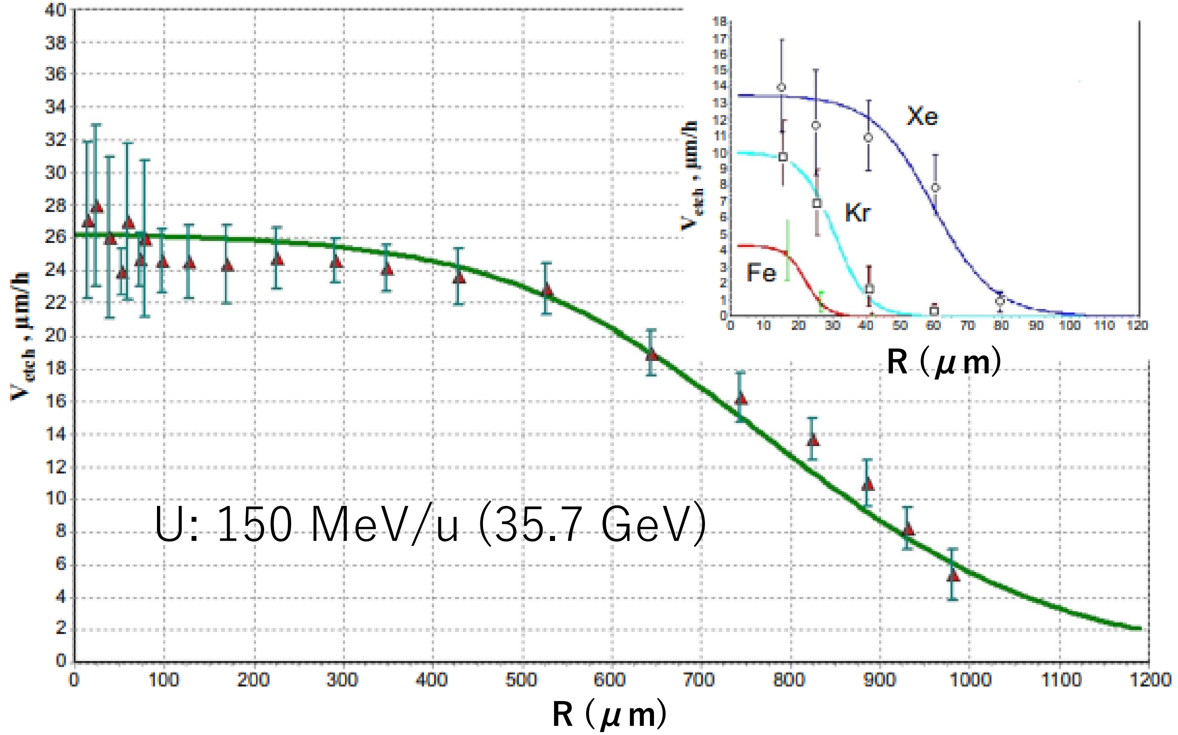


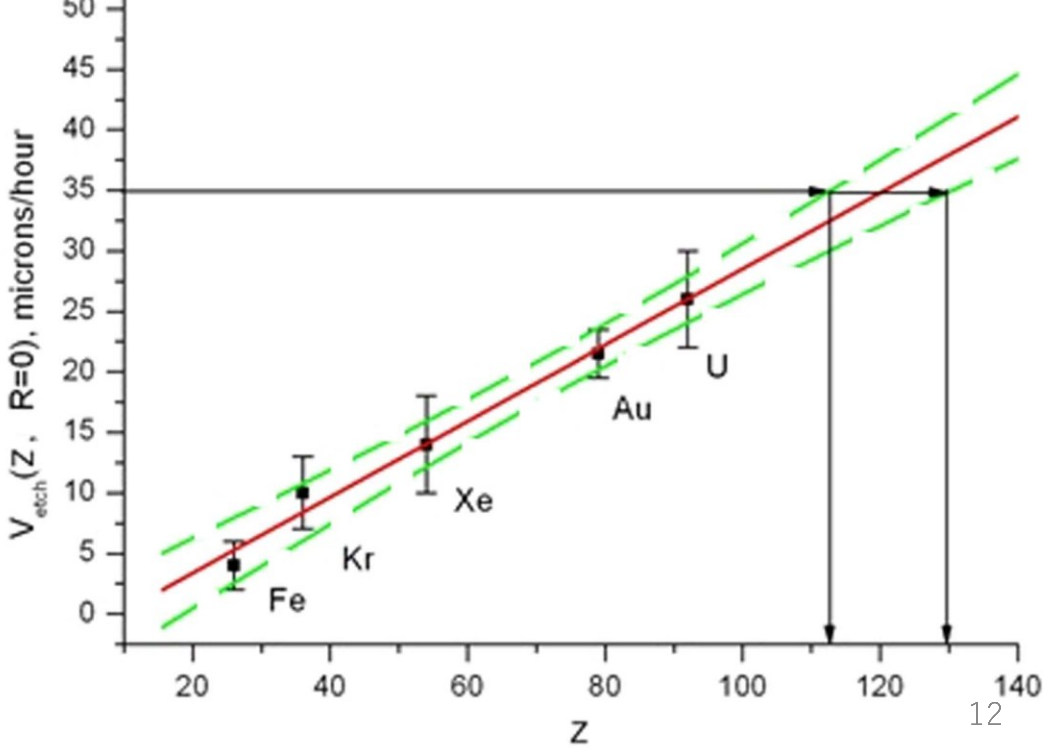

× : OLINPIYA
△ : ARIEL-6 (Fowler *et al.*, 1987)
■ : HEAO-3 (Binns *et al.*, 1989)
◇ : UHCRE (Donnelly *et al.*, 2012)

# Charge identification method for OLIMPIYA




## Ion beam calibration by OLIMPIYA project




**Citation** Victor Alexeev *et al* 2016 *ApJ* **829** 120
**DOI** 10.3847/0004-637X/829/2/120

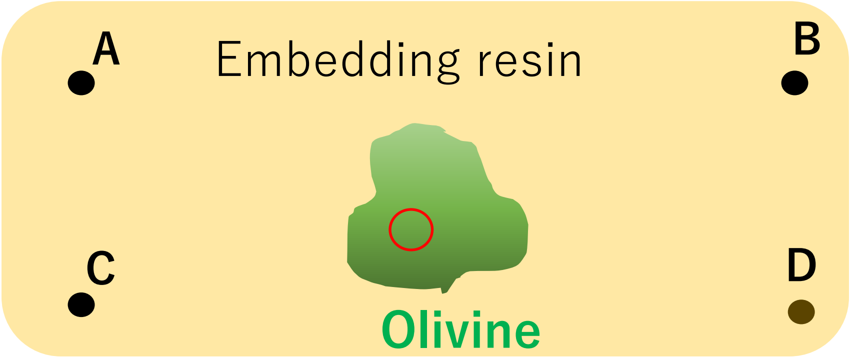
$$V_{\text{etch}}(Z, L) = \frac{A(Z) \cdot (1 + E(Z) \cdot L^2)}{1 + B(Z) \cdot \exp\left[\frac{L - C(Z)}{D(Z)}\right]}.$$

# Etching velocity measurement

- Define the coordinate by fiducial marking

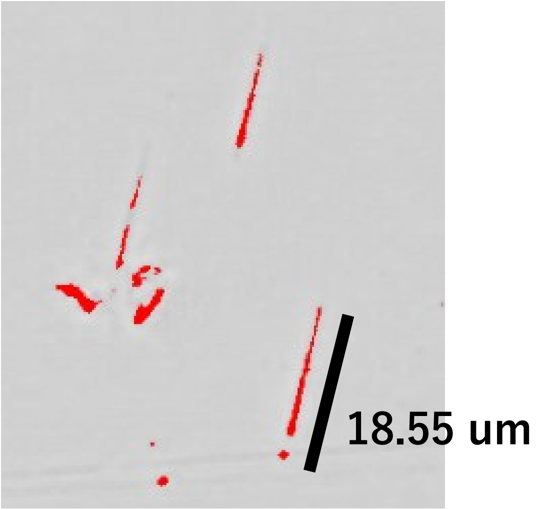
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} T_x \\ T_y \end{pmatrix}$$

Matching accuracy of few μm

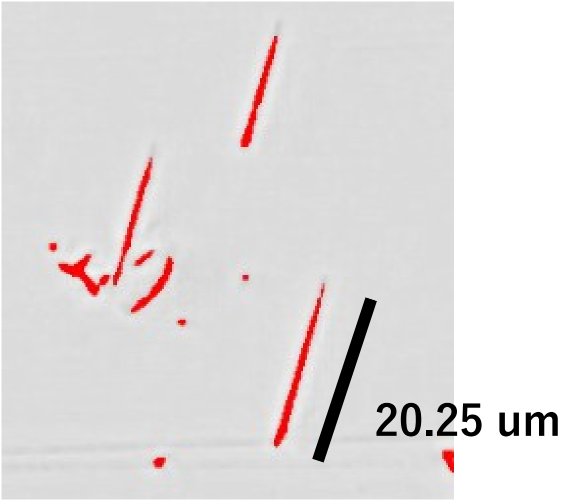



- Event by event analysis with optical microscope
- Evaluation of etching velocity from elongate rate of each tracks

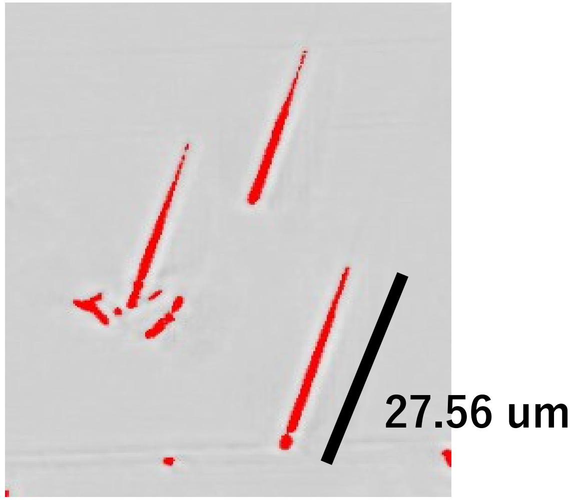
**4h etching**



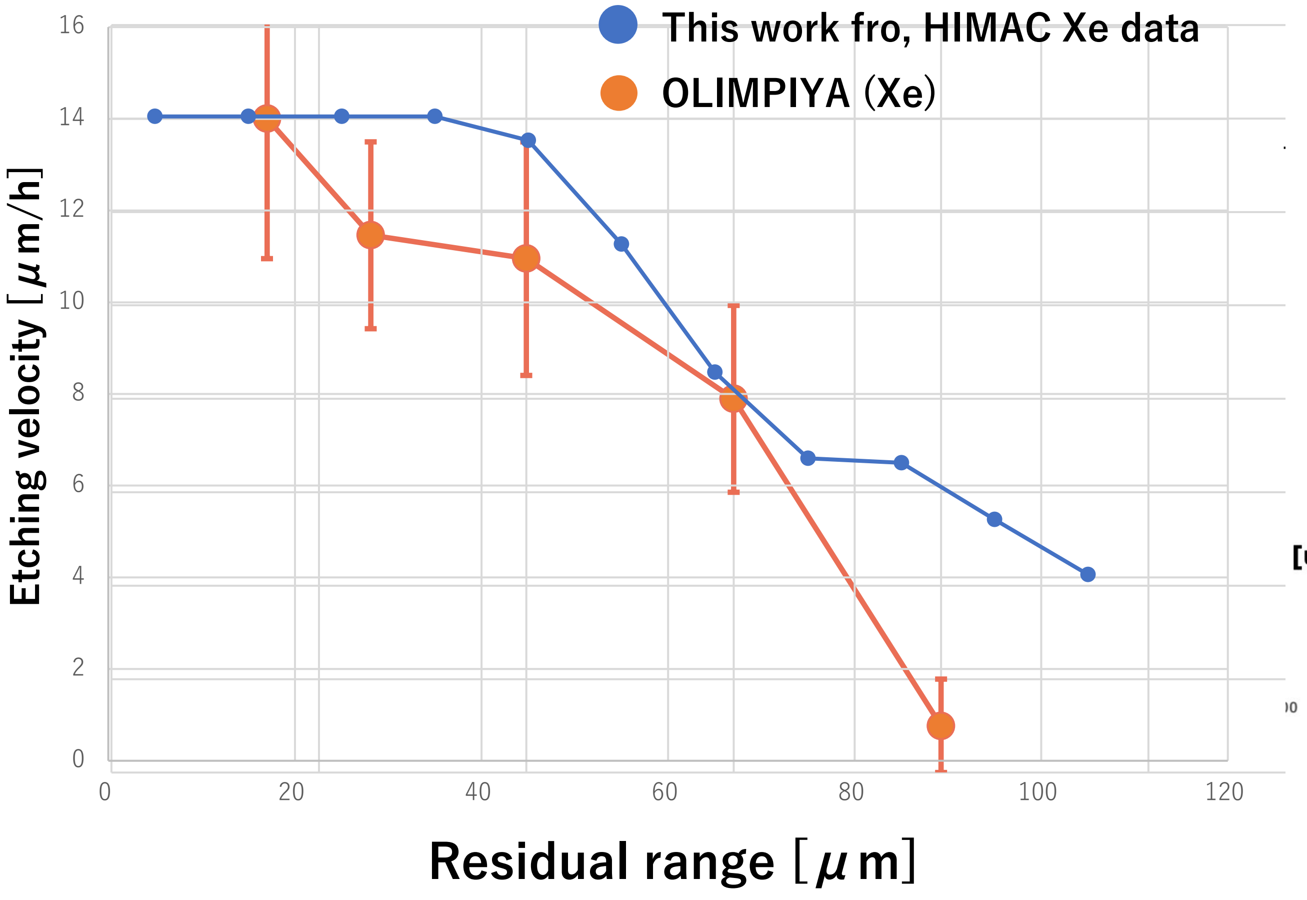

**5h etching**

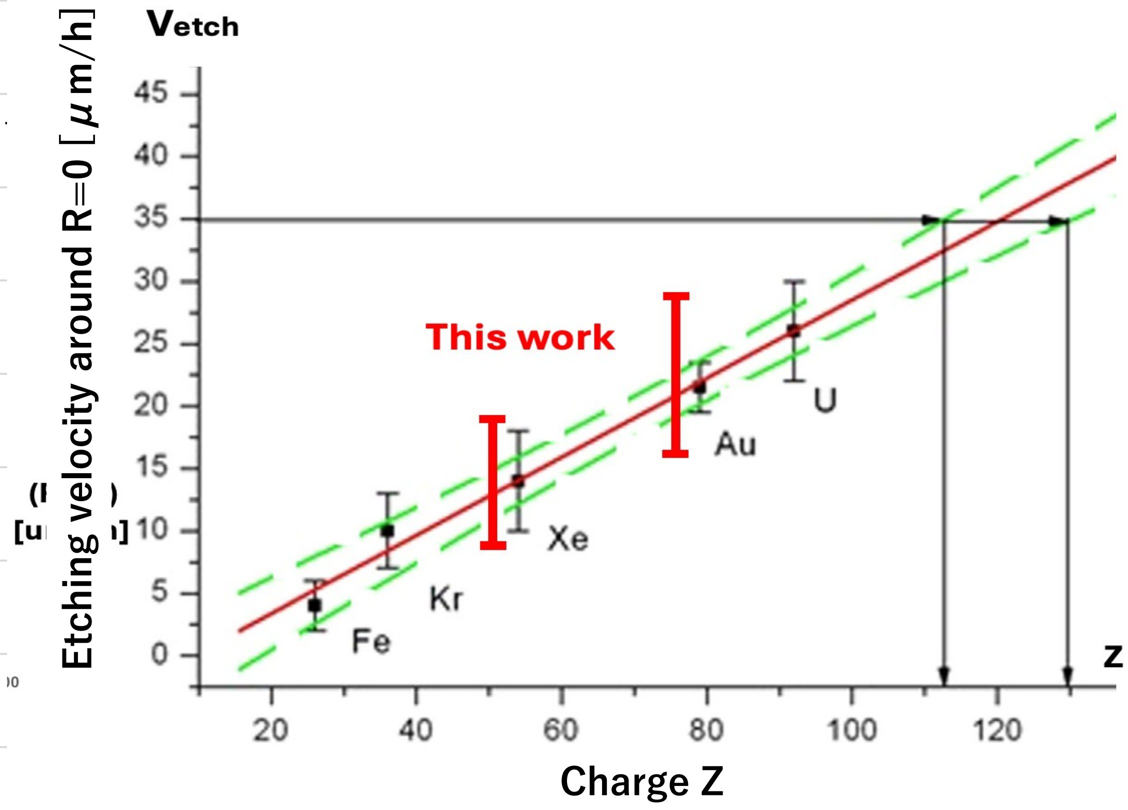



**6h etching**



# Cross check of OLYMPIYA in our group (preliminary)




JAEA Tandem : Au 350 MeV

QST HIMAC : Xe ≒4 GeV

# Exotic charged particle search

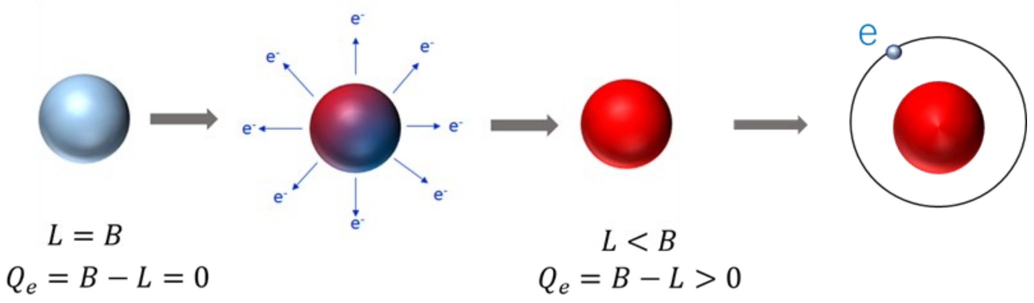
## Charged Q-ball

- non-toplogical soliton on the scalar field, and it has the quantum number (e.g., Baryon number, Lepton number) due to U(1) symmetry and Affleck-Dyne mechanism.

- May have electric charge up to 137

**J.P. Hong, M. Kawasaki, M. Yamada, PRD, 92, 063521 (2015)**

**J.P. Hong, M. Kawasaki , PRD, 95, 123532 (2017)**




Electric charge Z< 137

Velocity (v/c)~ $10^{-3}$

**Stable charged Q-ball condition**

- **Size of the electron cloud becomes smaller than the Q-ball radius**
- **Bohr radius is smaller than the Q-ball radius when the cloud starts to from**
- **Schwinger effect become effective**

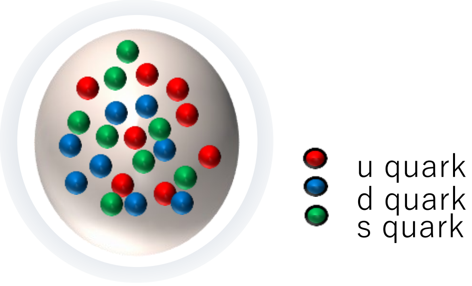
## Strange Quark Matter

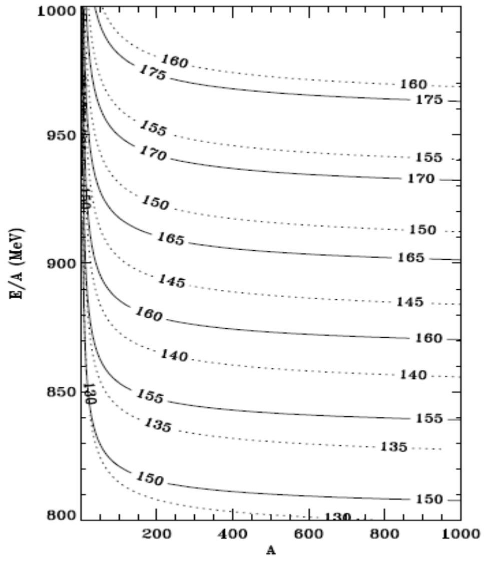
- A hypothetical state of matter composed of **up (u), down (d), and strange (s) quarks**

- Proposed as a more stable form of matter than ordinary nuclei under certain conditions (based on the MIT bag + Color-flavor lock model)

E. Witten, Phys. Rev. D30 (1984) 272.)

A. De Rujula and S. L. Glashow, Nature 312 (1984) 734




— : MIT bag

--- : Color-Flavor lock

Absolutely stable condition : $\frac{E}{A}$ <930 MeV (Fe nuclei)

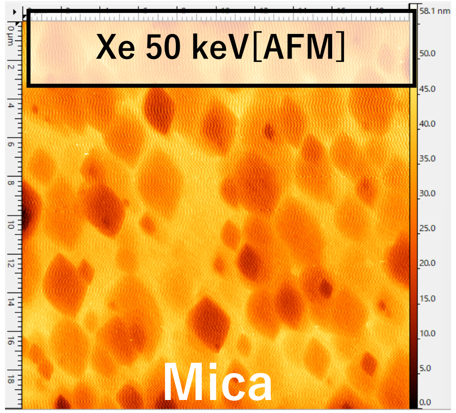
Baryon number A > $10^4$ as stability condition

Electric charge Z : $0.37A^{2/3}$ for CFL phase

Velocity (v/c) > $10^{-3}$

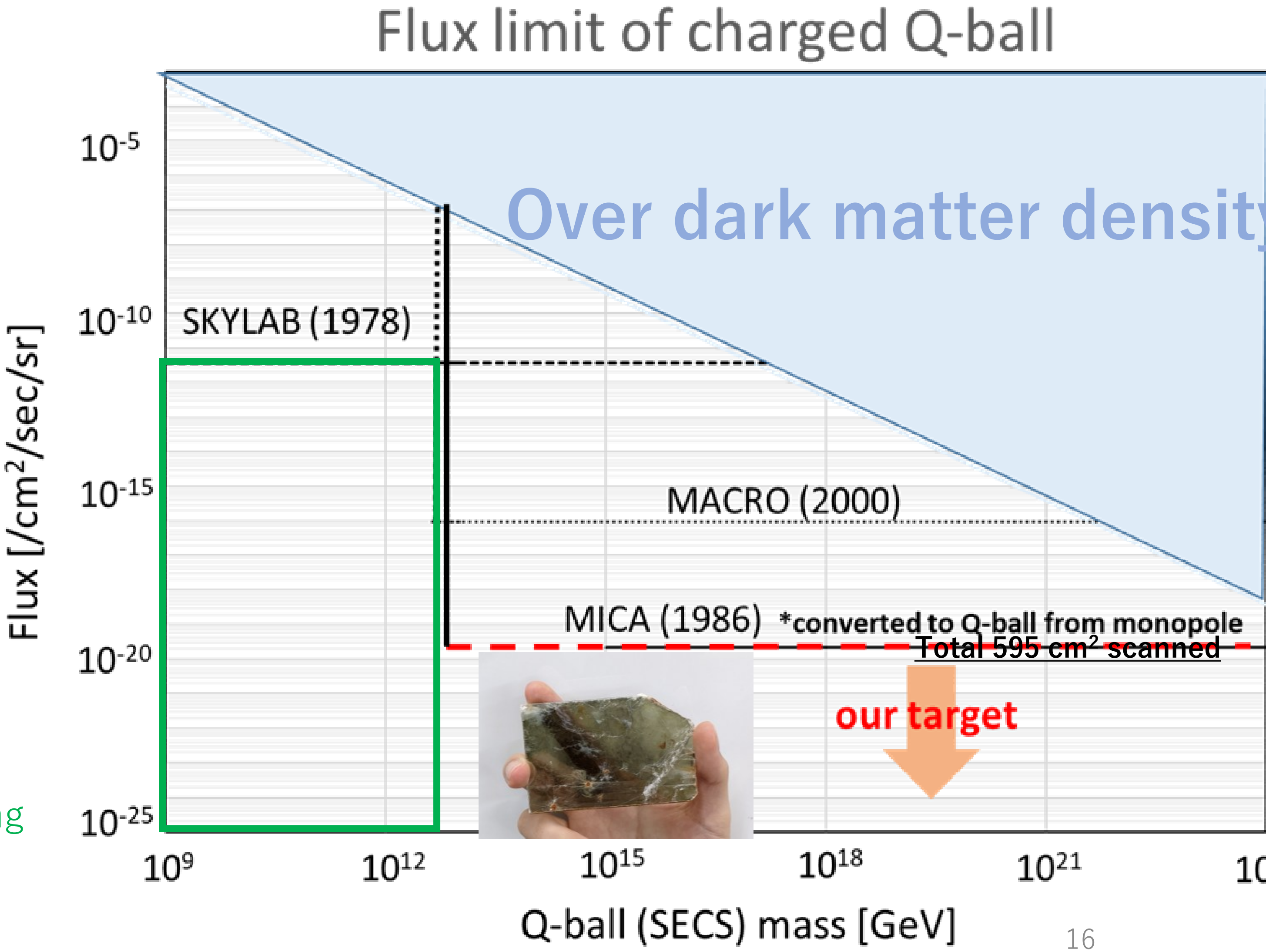
# Expected sensitivity for Q-ball and SQM with $\beta \sim 10^{-3}$

- Mica has capability of forming the track by low-velocity heavy particles, but it's not clear for major mineral in the space (e.g., olivine, pegeonite ・・)




- The parameter region of mass < $10^{13}$ GeV/$c^2$ should be searched by the mineral in the space (e.g., meteorite, lunar rock)

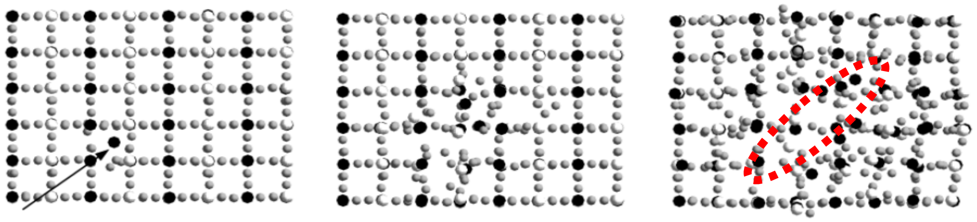
⇨ Currently, no evidence of capability of detecting low velocity heavy ion with the mineral in the space (e.g., olivine, pegeonite etc. )



# Track formation for the low velocity particles ?

- Energy Loss mechanism is difference from swift heavy ion.

Stopping Power $S_{total} = S_n + S_e \quad (S_n > S_e)$



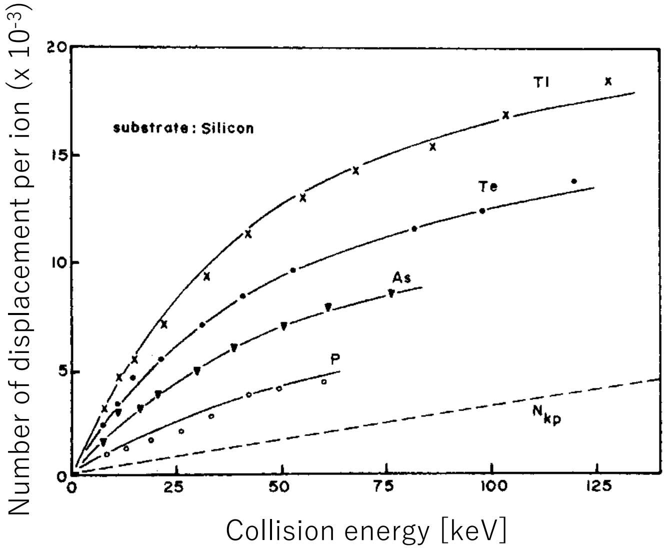
**Low velocity UHP**

Liner cascade model

+

**Displace spike effect**

J.A. Brinkman, J. Appl. Phys. 25 (1954) 961




*D.A. Thompson, Rudiutioii Effects,* 1981, Vol. 56. **pp.** 105-150

- **Directly observation is important using ion beam**
- **Various measurement with cutting-edge technologies (e.g., TEM, Laman, X-ray. EPMA ・・)**

- How about the track formation for the macroscopic object ?

  - Strange Quark Matter : $R = (\frac{3M_{SQM}}{4\pi\rho_N})^{1/3} \quad M_{SQM} > \sim 10^{14}\ GeV/c^2 \quad (R > \sim 1\ \text{Å})$

  - Any other composite DM model

# SQM from astrophysical events (e.g., NSM)

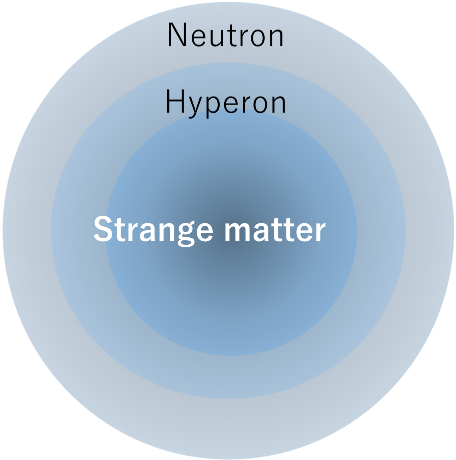
- The core of a neutron star may be composed of strange matter.
- SQM might be emitted from NSM
- On the long timescales accessible to paleo-detectors, there is a possibility that a neutron star merger (NSM) occurs in the vicinity of the solar system.

**e.g., 30 times in 1 Gyear for < 1kpc**

$$pc \sim eBR\left(\frac{v}{c}\right) < 10^{10}\ \text{GeV}$$

Kinematically, SQM of A< $10^{11}$ can be accelerated to $\beta \sim 0.1 - 1$

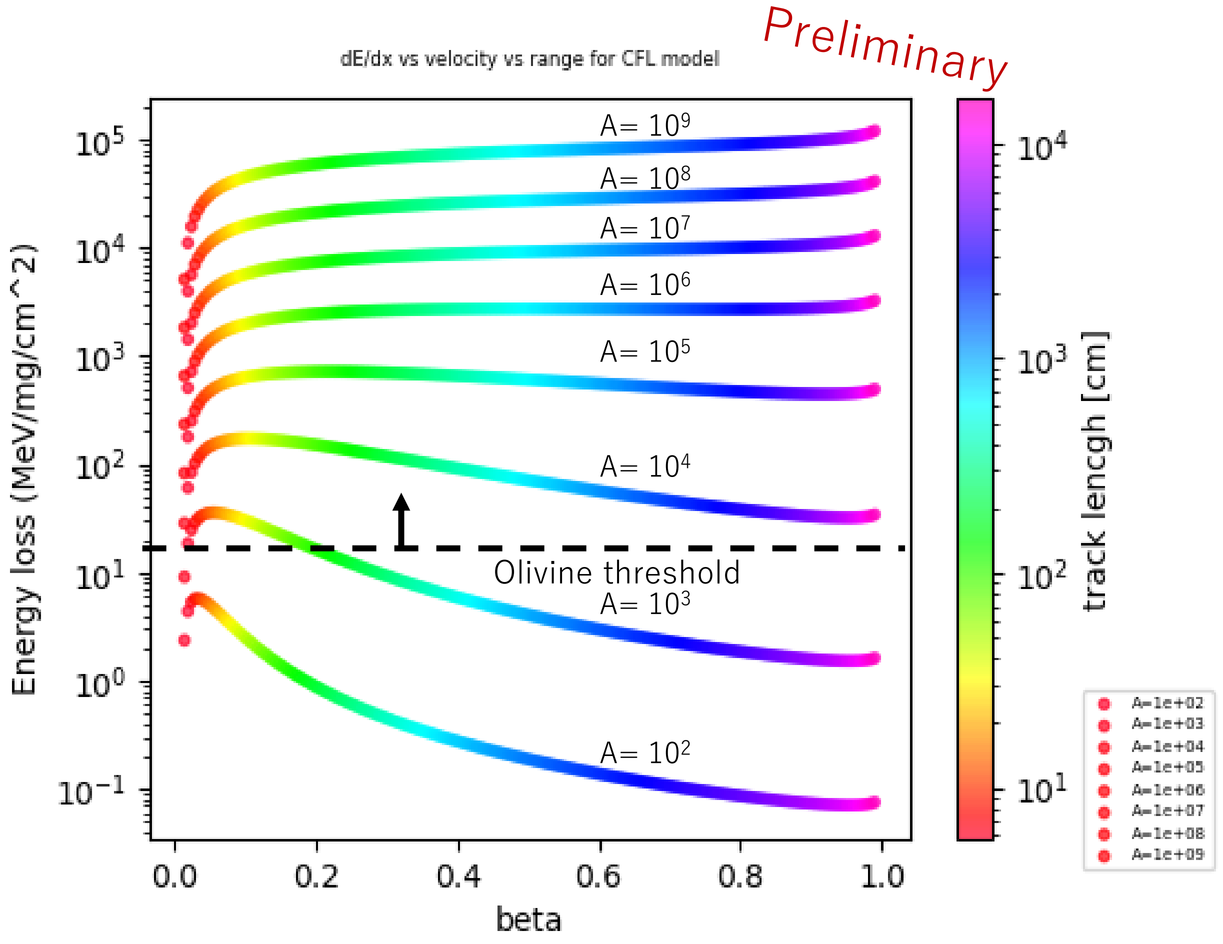
**<u>Emitted as swift (ultra)-heavy ions</u>**

# Discussion of accelerated SQM search

$$pc \sim eBR\left(\frac{v}{c}\right) < 10^{10}\ \text{GeV}$$

- Kinematically, SQM of baryon number A$< 10^{11}$ (mass $\sim 10^{11}$ GeV/$c^2$) can be accelerated to $\beta \sim 0.1 - 1$
- Stable SQM (i.e., A $> 10^4$ ) is possible to detector with long track in the paleo detector.
- Long tracks passing through the meteorite is expected.
  ⇒ It's possible to distinguish that from typical galactic cosmic-rays.



# On-going study using meteorite

■ Meteorite analysis

- For the olivine in the meteorite, different component, inclusion, any other alteration might be included.

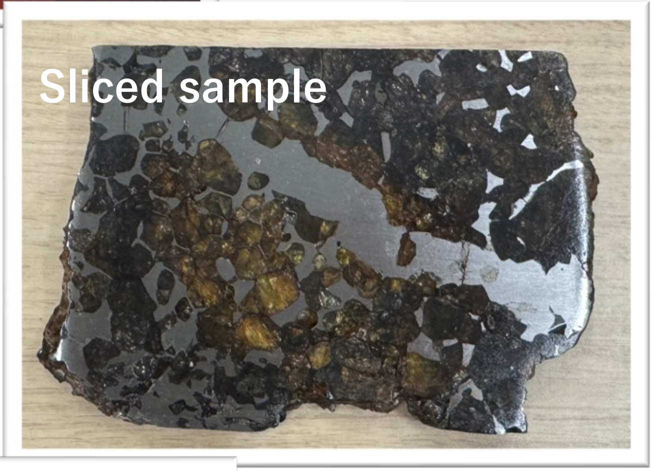
- Obtain the information from various analysis method (TEM, Raman, EPMA, X-ray・・)
  ⇒ Now on discussion with collaborators

- Expose the heavy ion beam to the olivine picked out from meteorite. (HIMAC of QST, Tandem of JAEA, JAPAN)

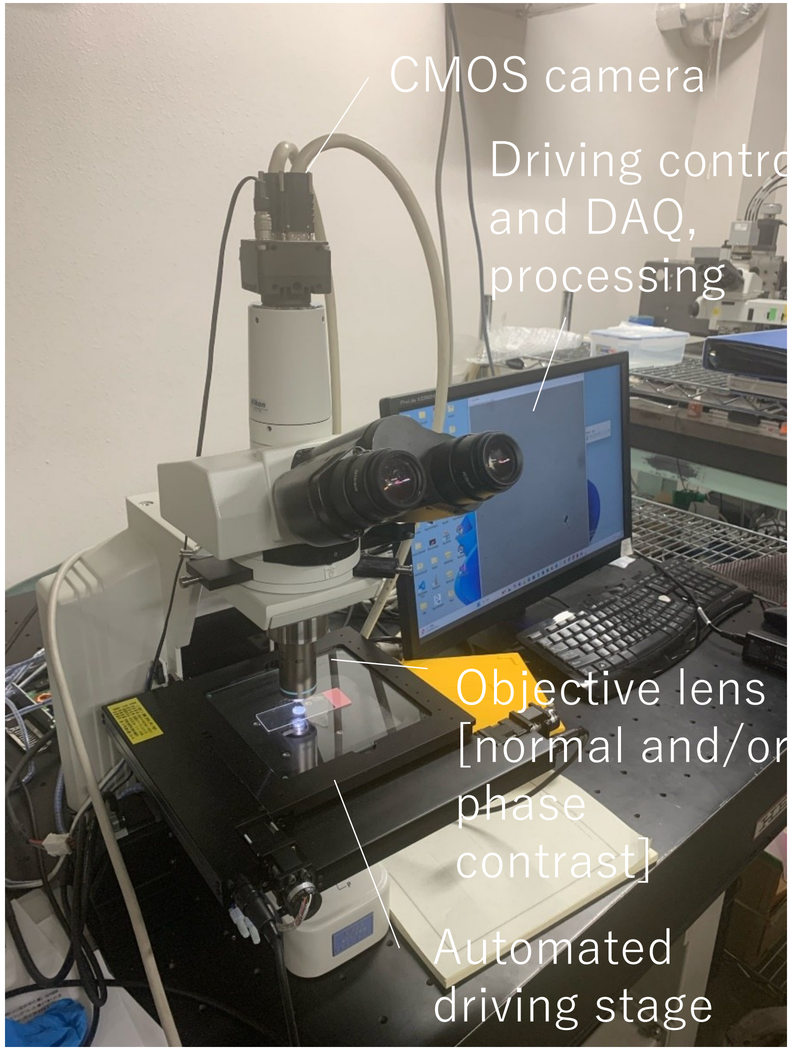
- Try to get the additional meteorite

■ Direct irradiation of low-velocity ion dependence on dE/dx is on going .

**Pallasite meteorite**

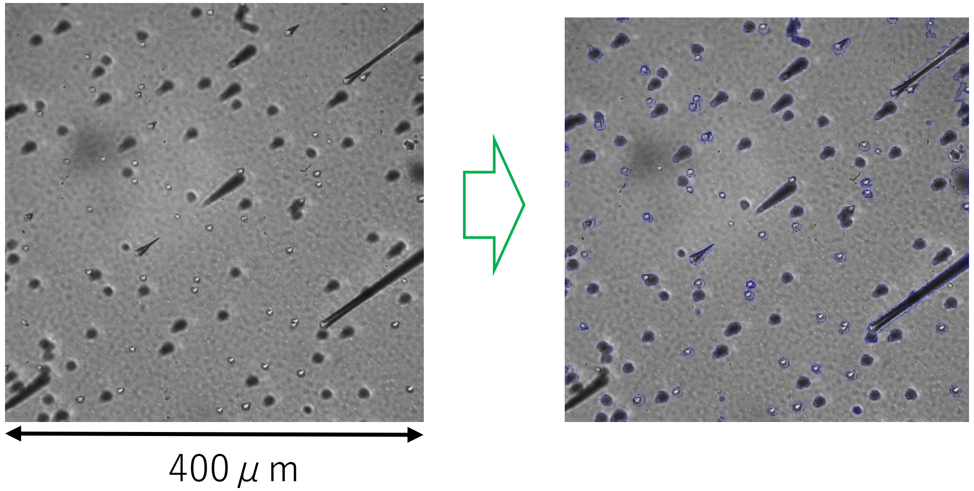




# Optical microscope system [QTS]

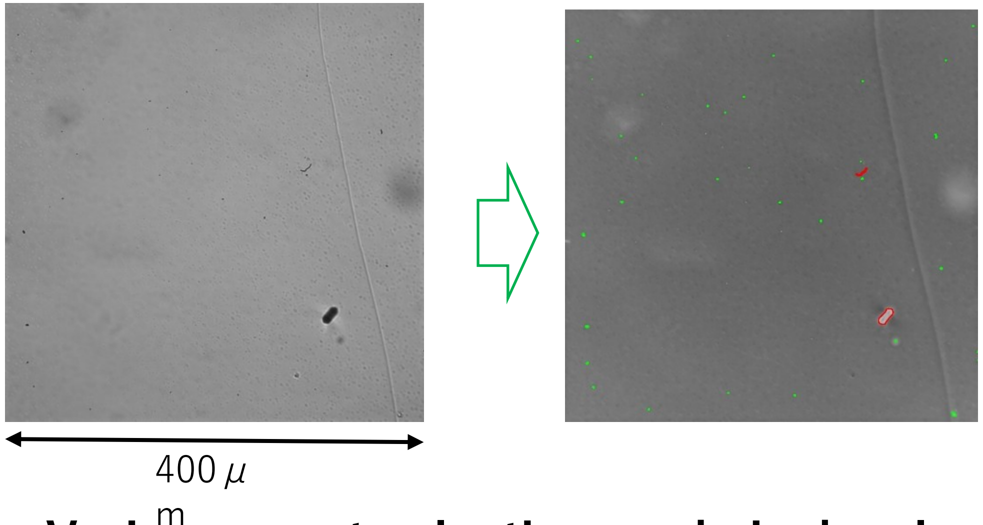



**Based on the high speed scanning system for nuclear emulsion**

Swift ion tracking
[Xe : 69 MeV/u]




ART and fission tracks



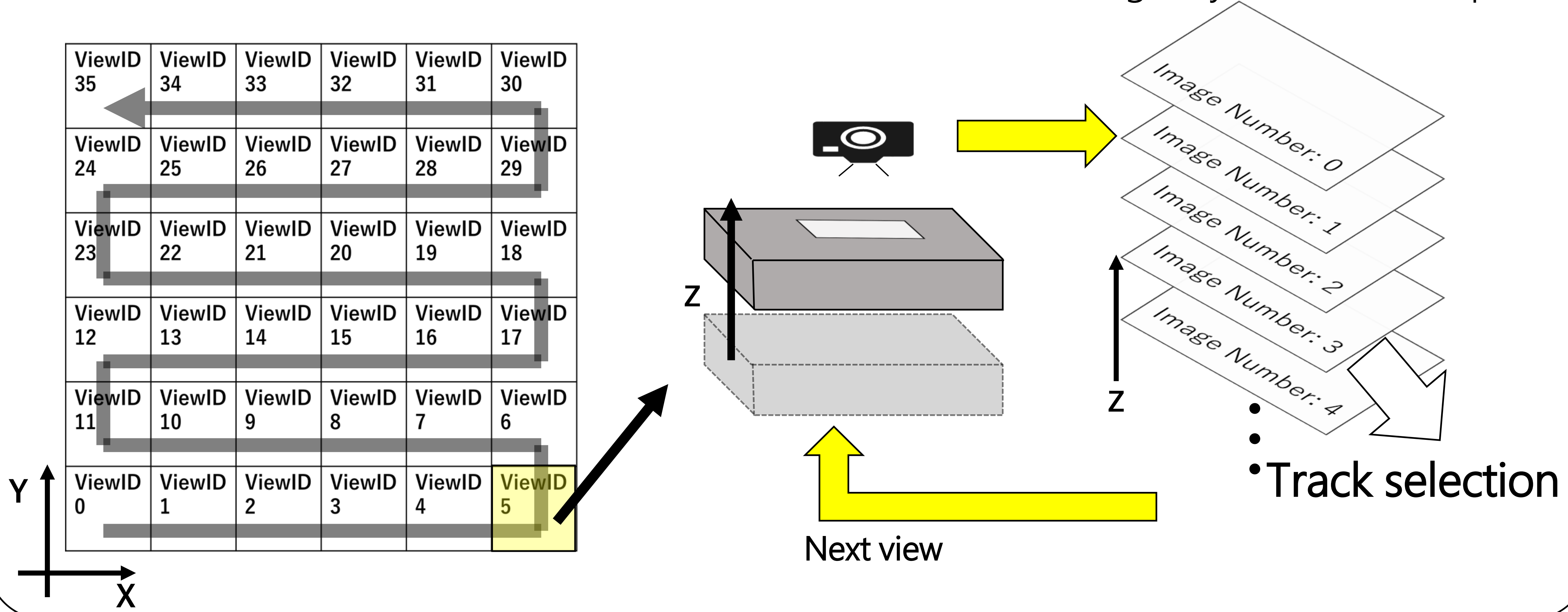

**Various event selection mode is developing now.**

# QTS scanning

Current field of view: 400µm×400µm
(2048pixel×2048pixel)

## Automatic scanning and imaging taking

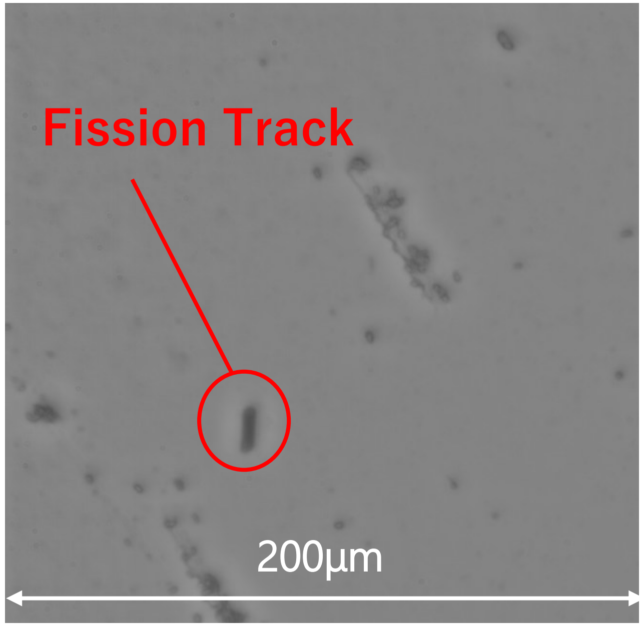
Image layer for each depth



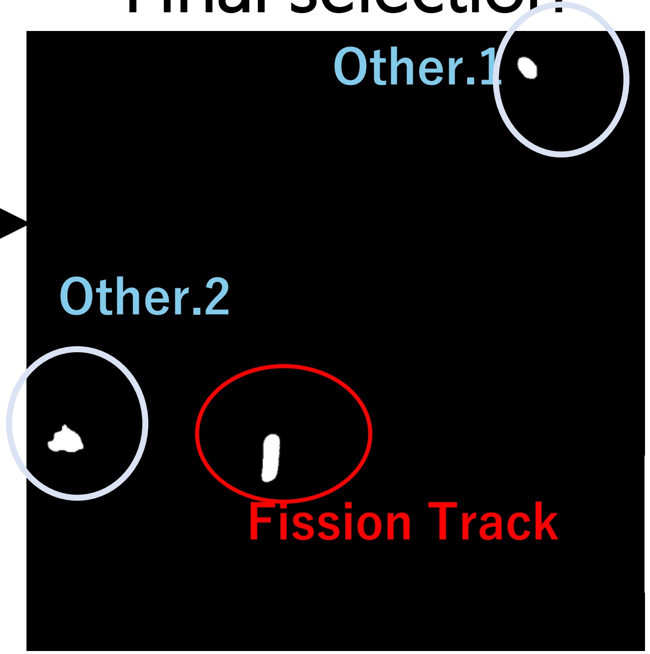
# Fission Track selection and Dating (Preliminary)

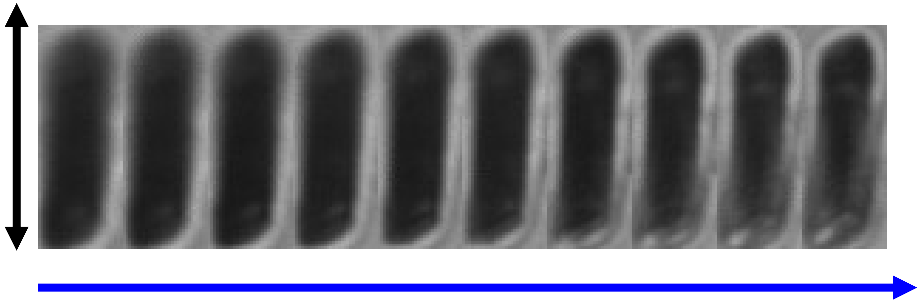
## Selection flow

Average image




Final selection




675 FT observed for 1.01 x 1.01 $cm^2$ scan

$\Rightarrow$ FT density : $(5.19 \pm 0.20) \times 10^5$個$/cm^3$

$U^{238}$ *density from ICM-MS*

$\tilde{\rho} = (4.2 \pm 0.4) \times 10^{13}$個$/cm^3$

preliminary

$$T = \frac{1}{\lambda_D}\ln\left(\frac{\lambda_D}{\lambda_F}\frac{\rho}{\tilde{\rho}}+1\right) = (1.58 \pm 0.16) \times 10^8 \text{ y}$$

$\lambda_D$ : $U^{238}$ decay constant= $1.54 \times 10^{-10}$ $yr^{-1}$

$\lambda_F$ : $U^{238}$ decay constant for spontaneous fission= $6.89 \times 10^{-17}$ $yr^{-1}$

# Summary

- We are studying searches for exotic charged particles. Candidate minerals are categorized into terrestrial and extraterrestrial samples.

  Terrestrial minerals (e.g., muscovite mica): $M>10^{13}$ GeV/ (e.g., Q-balls, SQM)

  Extraterrestrial minerals (e.g., meteorites, lunar rocks): $M<10^{12}$ GeV/$c^2$ (e.g., GCR, SQM)

- For olivine, the charge Z can be identified by measuring the etching rate. Calibration with heavy-ion beams is currently in progress.

  → Our results are consistent with previous studies (e.g., OLYMPIA project).

- SQM may be emitted from neutron star mergers and could be detected in meteorites.

- If low-velocity heavy particles are observed in extraterrestrial minerals, current sensitivity to UHEPs ($M<10^{10}$ GeV/$c^2$) could be significantly improved, even with small-area scans. However, track formation for low-velocity heavy ions has not yet been fully demonstrated.
  → Ongoing investigation

- An automatic optical microscope system (QTS) has been constructed and commissioning has begun. As a first demonstration, we performed FT selection on mica and successfully obtained date of the mica as preliminary.

- We got the first meteorite sample (Imilac, 1822) and started the analysis by picking out the olivine.

  In parallel, discussing about the additional meteorite samples.