TAICO project

Search for Ultra-Heavy Exotic Particles via Fossil Damage Tracks in Ancient Minerals

“Paleo Detector”

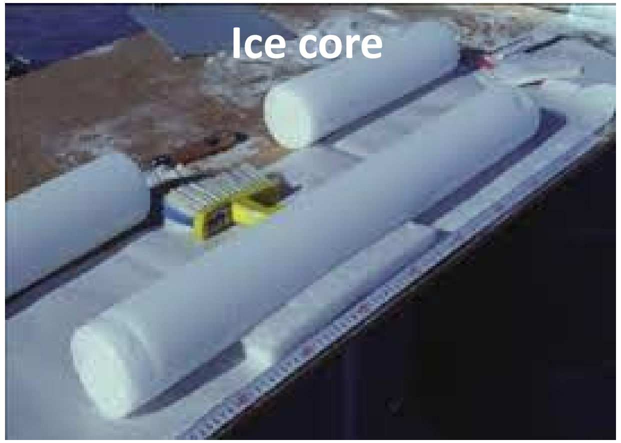
Tatsuhiro NAKA

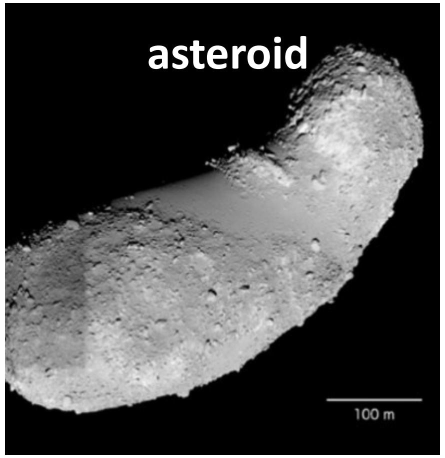
Toho University, Japan

2026.8.8-13 (talk on 12th) Summer Institute 2026@Fujiyoshida, Japan

“What is Paleo Detector ?”

- **Studying traces of cosmic rays preserved in natural samples over geological timescales.**
- **Geological materials intrinsically record phenomena induced by rare astrophysical events.**
- **By studying these records, we can obtain unique information that cannot be accessed through artificial experiments.**





✓ **Current approach dedicate to the radiochemical and component analysis**

This work

A search for rare events over geological timescales with ancient minerals

Tracking Detector as the Paleo Detector

Halite
[NaCl]

Olivine
[(Mg,Fe)SiO_4]

Muscovite mica
[$KAl_2AlSi_3O_{10}(OH)_2$]

Episomite
[$Mg(SO_4) \cdot 7(H_2O)$]

Zirconium
[$ZrSiO_4$]

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

e.g., utilizing in the fission track dating in geological science

Recording the information as fossil damage track for **0.1 – 1 Gyear age**

Artificial detector

Paleo Detector

$$\boldsymbol{Number\ of\ \ signal\ \ N = R\,[/\,kg\ or\ m^2/y]\ \times M\left[kg\ or\ m^2\right] \times T[year]}$$

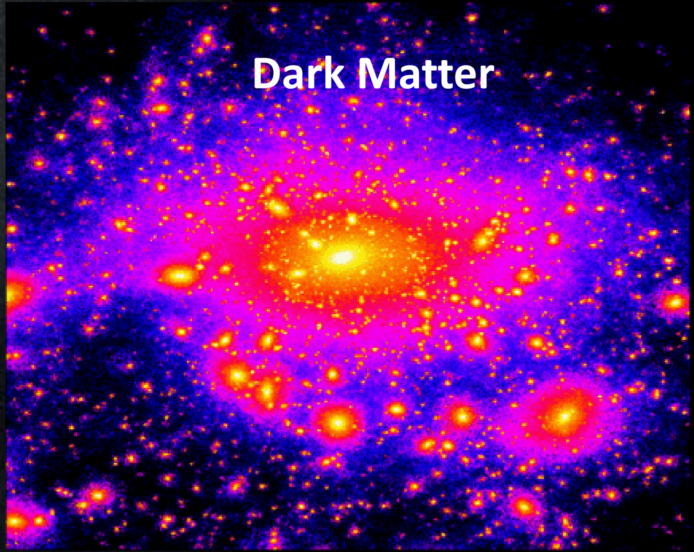
VS

Mass or area	> 1 g	10^7 g (10 t)
Time scale	10^9 years	O(1) years
Exposure (**Mass (or Area)** × **Time)**	**> 1000 t ・ year**	**10 t ・ year**

>

Paleo Detector Concept

~ 1 events per 0.1 Myear



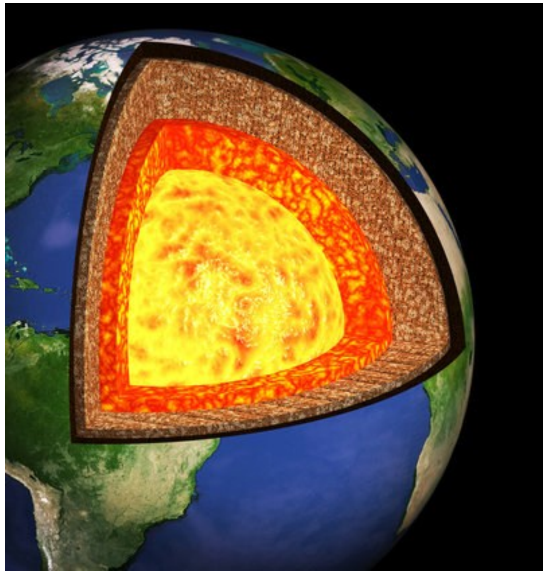
1 cycle ~ 250 Myear

NSM rate in the Milky Way galaxy

Assuming the galaxy is a disk (diameter 30 kpc,thickness 0.5 kpc), let us assume that NSM occurs once every 0.1 Myear.

Nearby region	Event rate [/year]	
< 100 pc	0.3×10^{-10}	1 events per 30 Gyear
< 0.5 kpc	3.8×10^{-9}	4 events per Gyear
< 1 kpc	0.3×10^{-7}	30 evens per Gyear

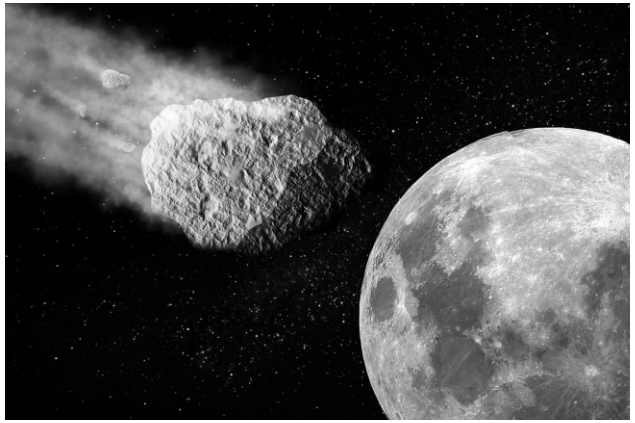
[Terrestrial sample]



Muscovite mica
[$KAl_2AlSi_3O_{10}(OH)_2$]

Olivine
[$(Mg,Fe)SiO_4$]

[Extraterrestrial sample]



Olivine
[$(Mg,Fe)SiO_4$]

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

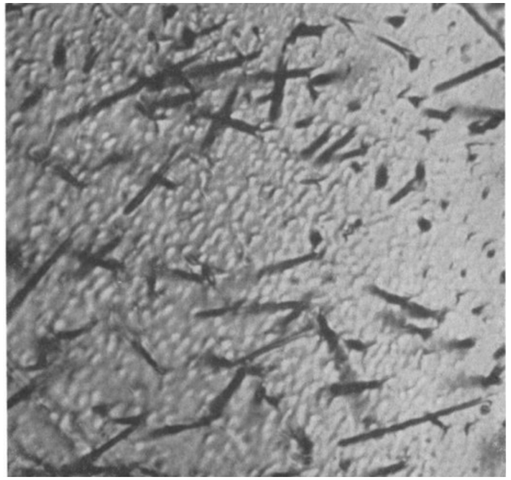
Plagioclase
[$NaAlSi_3O_8$]

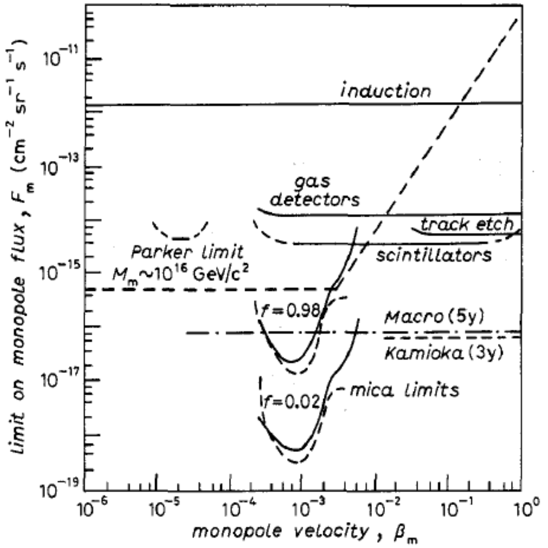
History of research with the Paleo Detector

■ Galactic cosmic-ray element

- ➢ **Analyze the tracks due to heavy-element cosmic-ray**
- ➢ **Analyze the Extraterrestrial sample (e.g., lunar rock, meteorite)**

R.L. Fleischer, P.B. Price, R.M. Walker, J. Geophys. Res. 72, 355 (1967)





Flux upper limit for monopole search with muscovite mica assumed M-Al bound condition

■ Magnetic Monopole

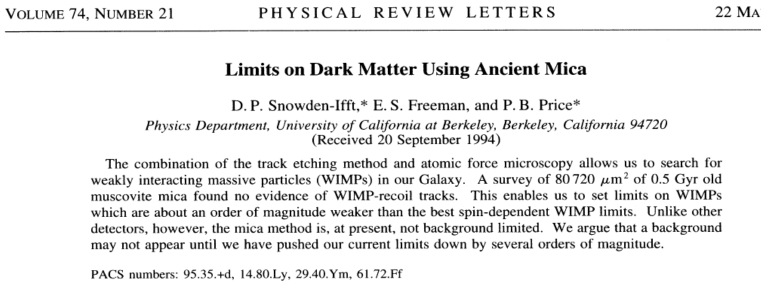
- ➢ **Heavy monopole search with the muscovite mica**
- ➢ **Assuming MM-Al bound condition to require over track formation threshold**

P.B. Price and M.H. Salmon, Phys. Rev. Lett. 56, 12(1986)

■ WIMP dark matter

- ➢ **Small etch-pit depth analysis with the muscovite mica**

D.P. Snowden-Ifft, E.S. Freeman and P.B. Price, Phys. Rev. Lett. Vol.74, 21(1995)



VOLUME 74, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MA

Limits on Dark Matter Using Ancient Mica

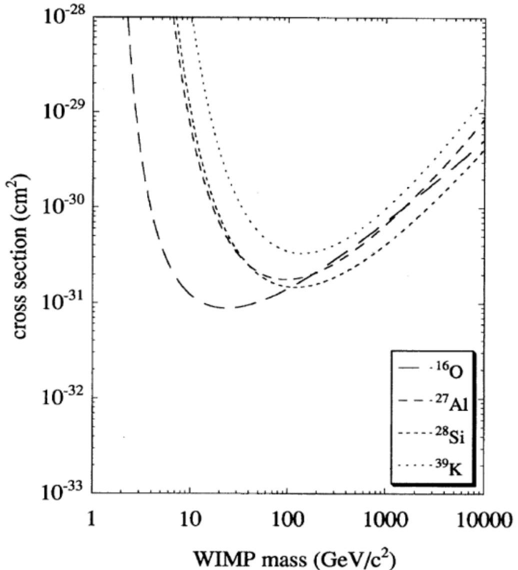
D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*

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



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

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

Ultra heavy element or exotic particle candidate

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

Exotic particle such as monopole(?)
⇒seems small energy change from uniform track structure.

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

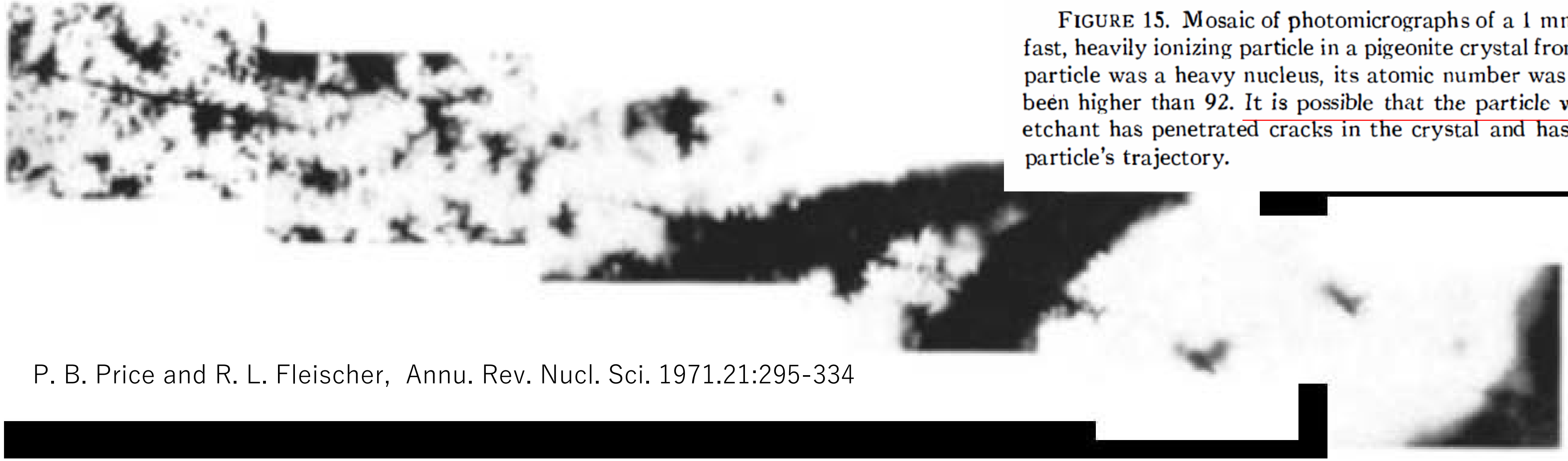


FIGURE 15. Mosaic of photomicrographs of a 1 mm portion of the trajectory of a fast, heavily ionizing particle in a pigeonite crystal from the Apollo 12 site (60). If the particle was a heavy nucleus, its atomic number was higher than 82 and may have been higher than 92. It is possible that the particle was a magnetic monopole. The etchant has penetrated cracks in the crystal and has revealed only portions of the particle's trajectory.

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

TAICO collaboration

Toho University

Nagoya University

Penn. State Univ.

Kyoto University

JAMSTEC

Tohoku Univesity

＋ many technical and theoretical contributors

Current Physics Targets

TAICO
TRACKING ANCIENT IMPRINTS OF COSMIC ORIGINS

Ultra-heavy Exotic Particle

Magnetic Monopole

Q-ball

Strange Quark matter

Galactic Cosmic-ray element

Trans Uranium cosmic-ray element

Obtaining the information related to r-process in neutron star merger

WIMP and Heavy dark matter

To be update to previous research by cutting-edge microscope technologies

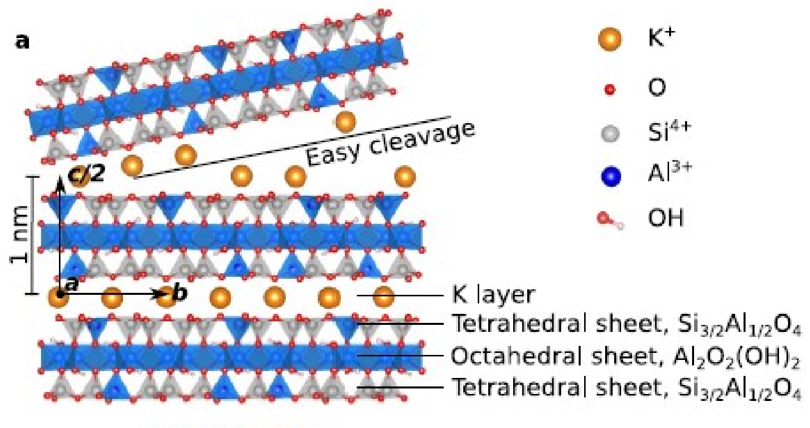
Ultra heavy WIMP-like dark matter search

Under discussing target

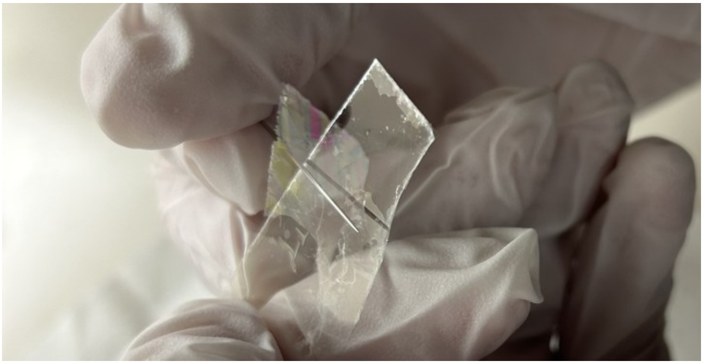
- Cosmic-wall (arXiv:2505.15764)
- Black hole with electromagnetic charge etc. (e.g., JHEP04(2021)079)

Current focusing minerals for our research

Muscovite Mica (白雲母)

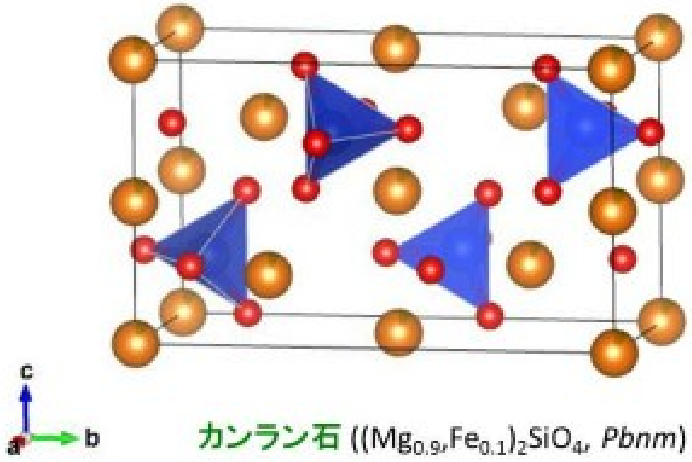


Franceschi+ 2023



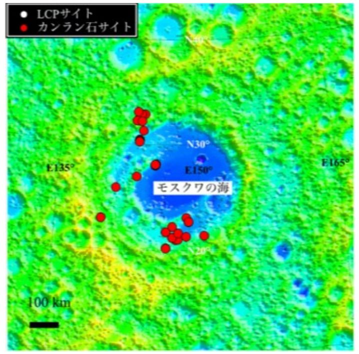
- Like film with large area and good transparency
- Good track formation ability and etching response

Olivine(カンラン石)



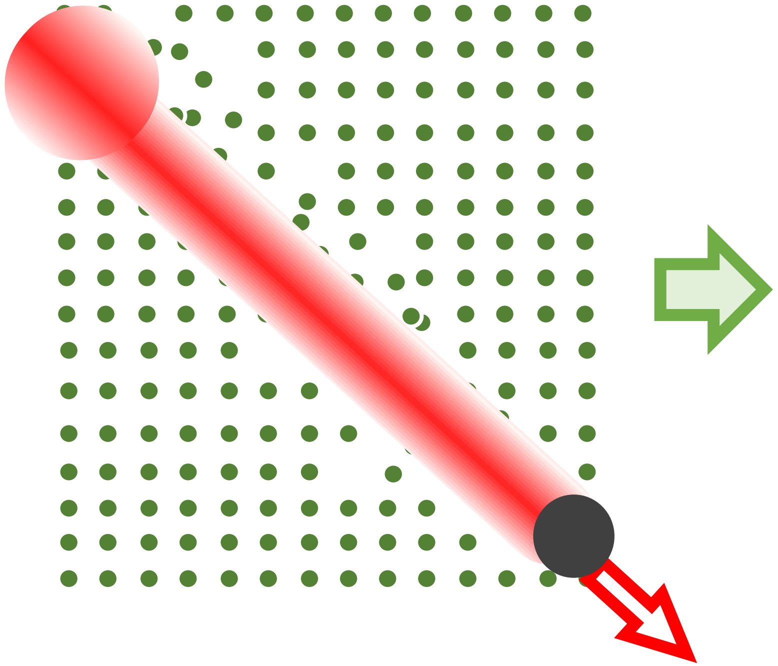
カンラン石 ($(Mg_{0.9},Fe_{0.1})_2SiO_4$, *Pbnm*)

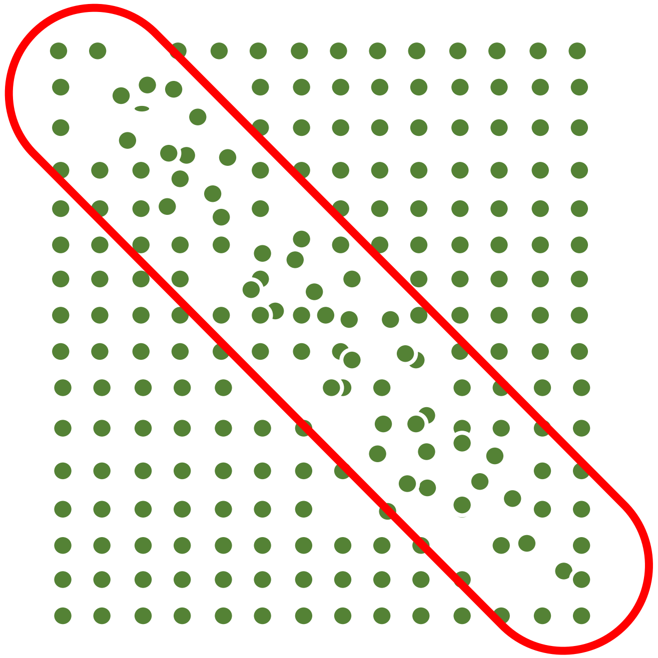
- Abundant in the meteorite and the lunar surface
- Low-U, Th contamination

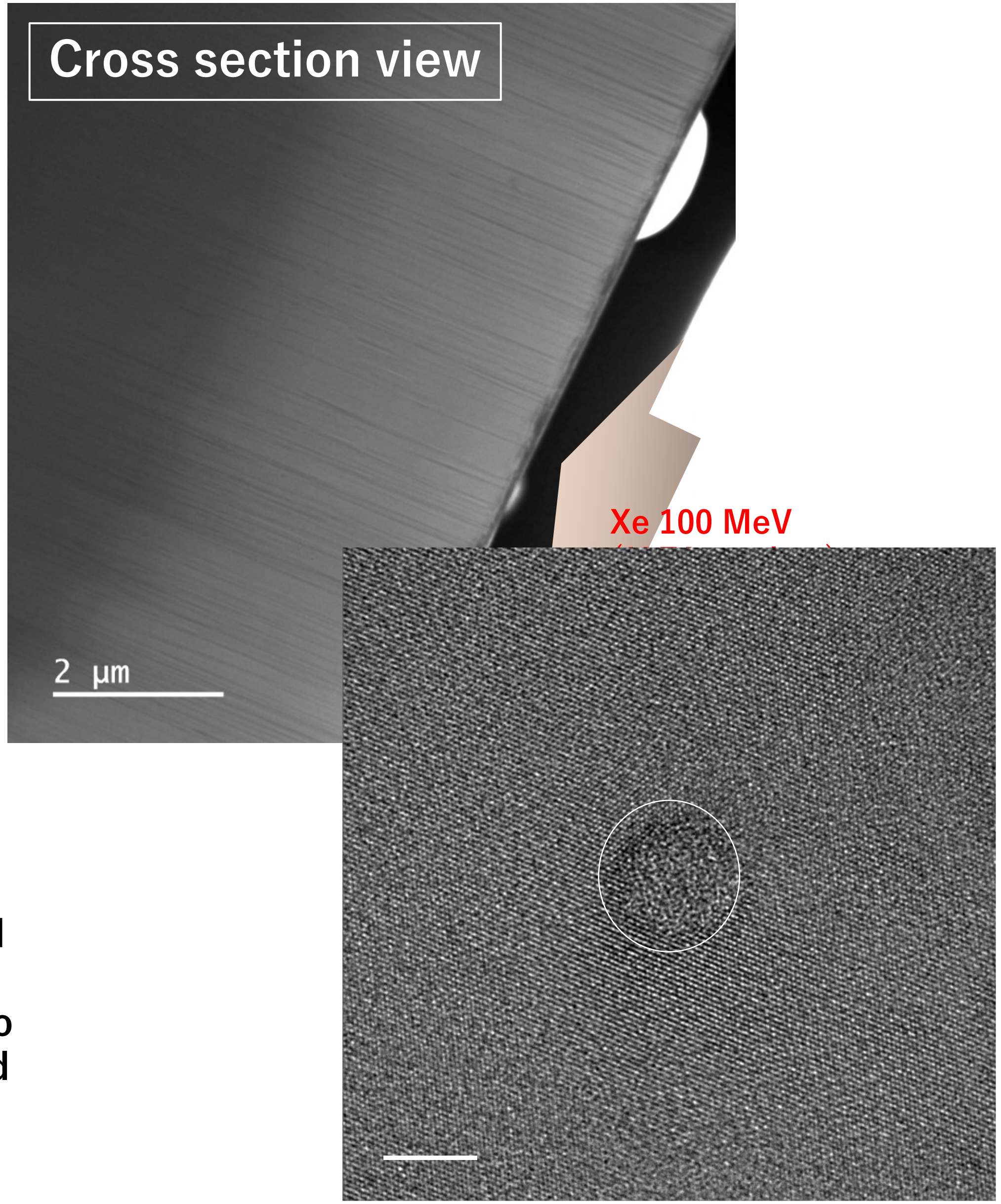


Track formation mechanism in the mineral for swift high-ionization particles (Thermal Spike model)

High dE/dx particles



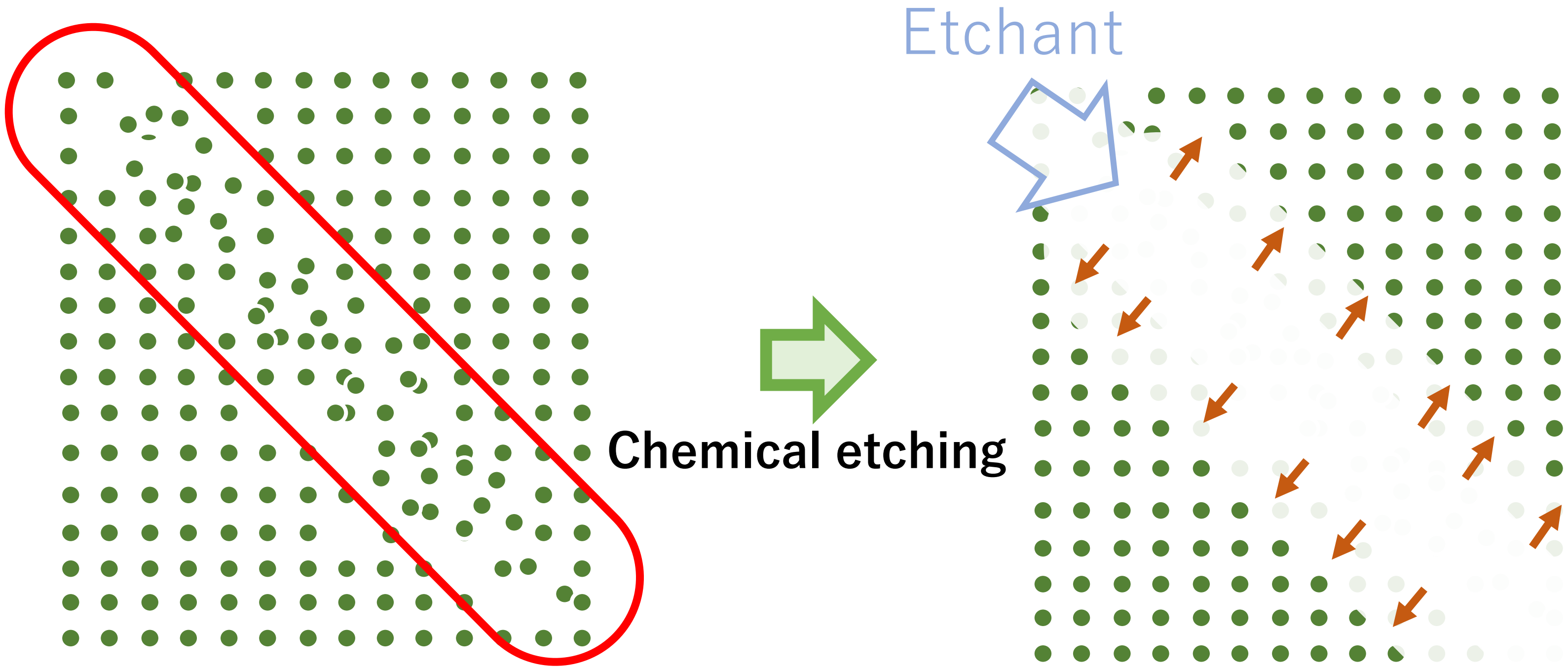


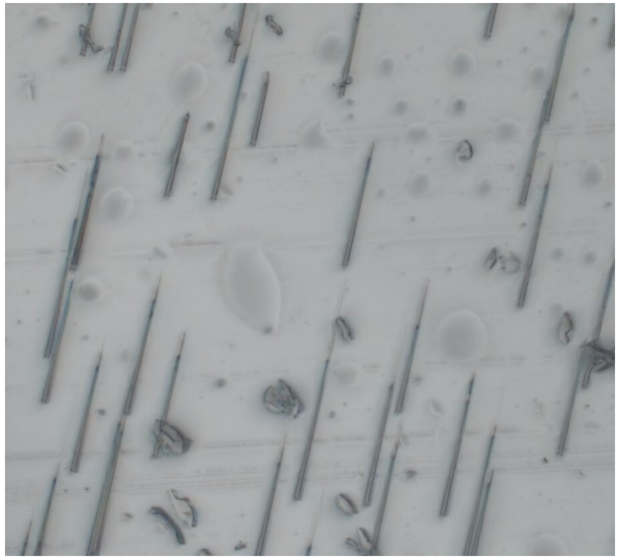


The region along the trajectory of a charged particle is locally heated to a high temperature, leading to melting of the crystal.

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

Etching process to observe the optical microscope



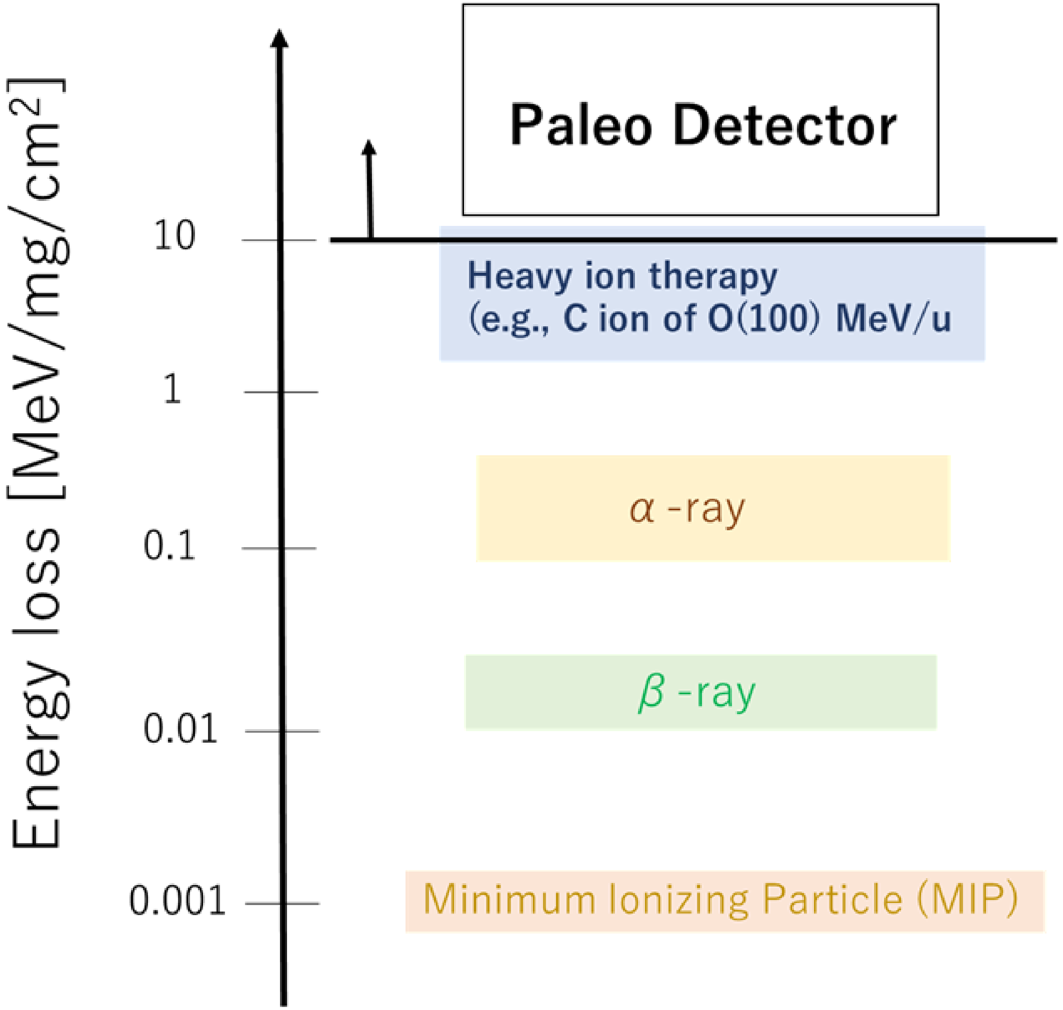


Xe 0.5~2 GeV 30d 14h etching

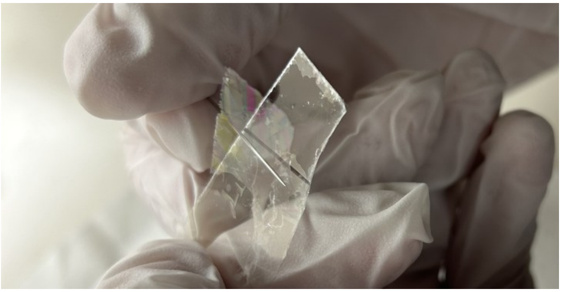
Etching condition and type of etchant depend on each mineral.

(e.g., HF for the mica, EDTA for the olivine)

[Case of Velocity β >~10^{-2}]

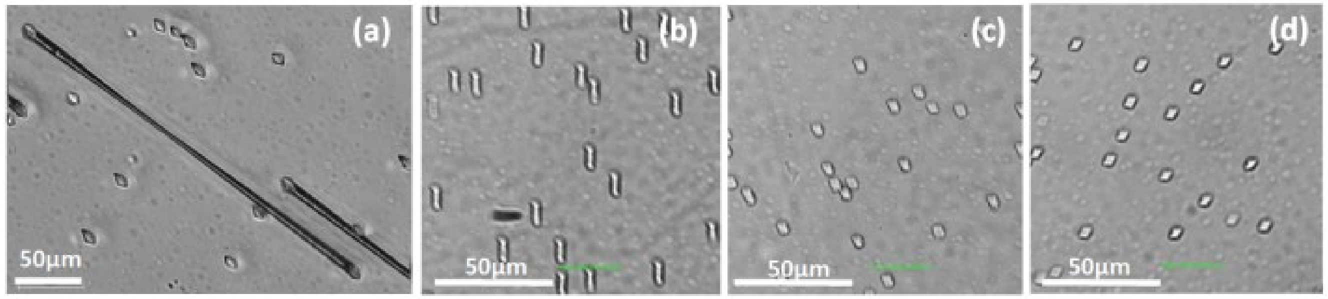


Ion beam calibration



[Muscovite mica]

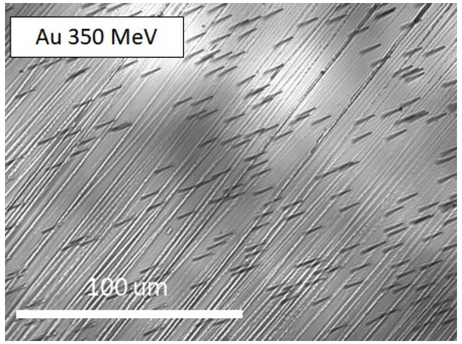
Track formation > ~ 10 MeV/mg/cm^2

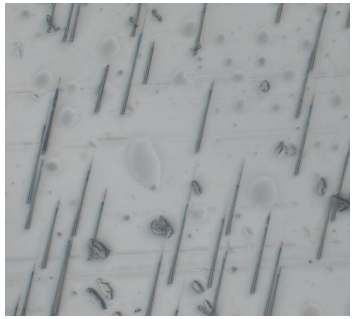


※HF (47 %, 25°C) etching

[Olivine]

Track formation > ~ 18 MeV/mg/cm^2





※EDTA (103 °C) etching

Monopole

Very thanks to Prof. Takeshi Kobayashi @ SISSA for discussion and calculation for monopole acceleration

■ Dirac monopole

Theoretical origin of monopole

$$eg = \frac{n\hbar c}{2} \qquad Dirac\ charge:\ g_D = \left(\frac{137}{2}\right)e$$

→ Magnetic charge is compatible with quantum mechanics

■ t'Hoot - Polyakov monopole

Early Universe → GUT symmetry breaking → Kibble mechanism → Monopole production → Cosmological relics

Spontaneous symmetry breaking $e.g., SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

Magnetic monopole as topological soliton

Monopole mass $M_M \sim \frac{4\pi v}{g}$ $\quad v$: $symmetry\ bracking\ scale$

Accelerated monopole in the universe

Monopole can be accelerated by the magnetic field

$$m(\gamma - 1) \propto gB\lambda \qquad \lambda: coherent\ length$$

- Galactic magnetic field : $\boldsymbol{B_G} \sim 10^{-6}$ G

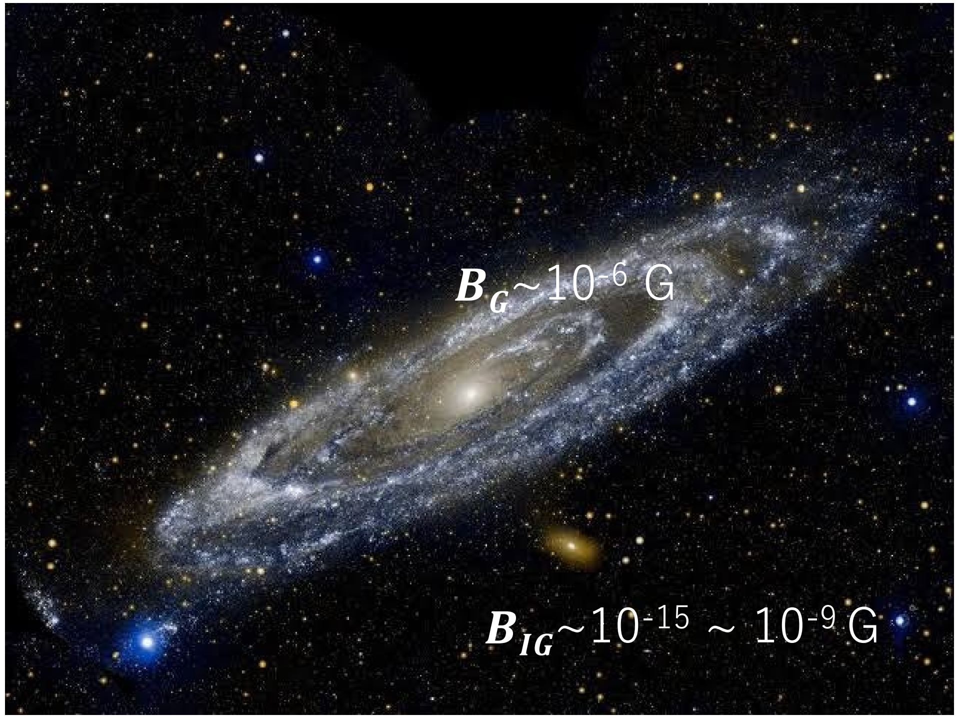
Parker Bound

Upper bound on the monopole flux from the survival of the Galactic magnetic field.
⇒ ~10^{-16} /cm²/s/sr

+

Intergalactic magnetic field : ~10^{-15} G < $\boldsymbol{B_{IG}}$ < ~10^{-9} G

R. Durrer and Andrill Neronov, The Astron. and Astrophys. Rev. 21:62, 2013



⇨ **New Parker bound taken into account IGMF is discussed.**

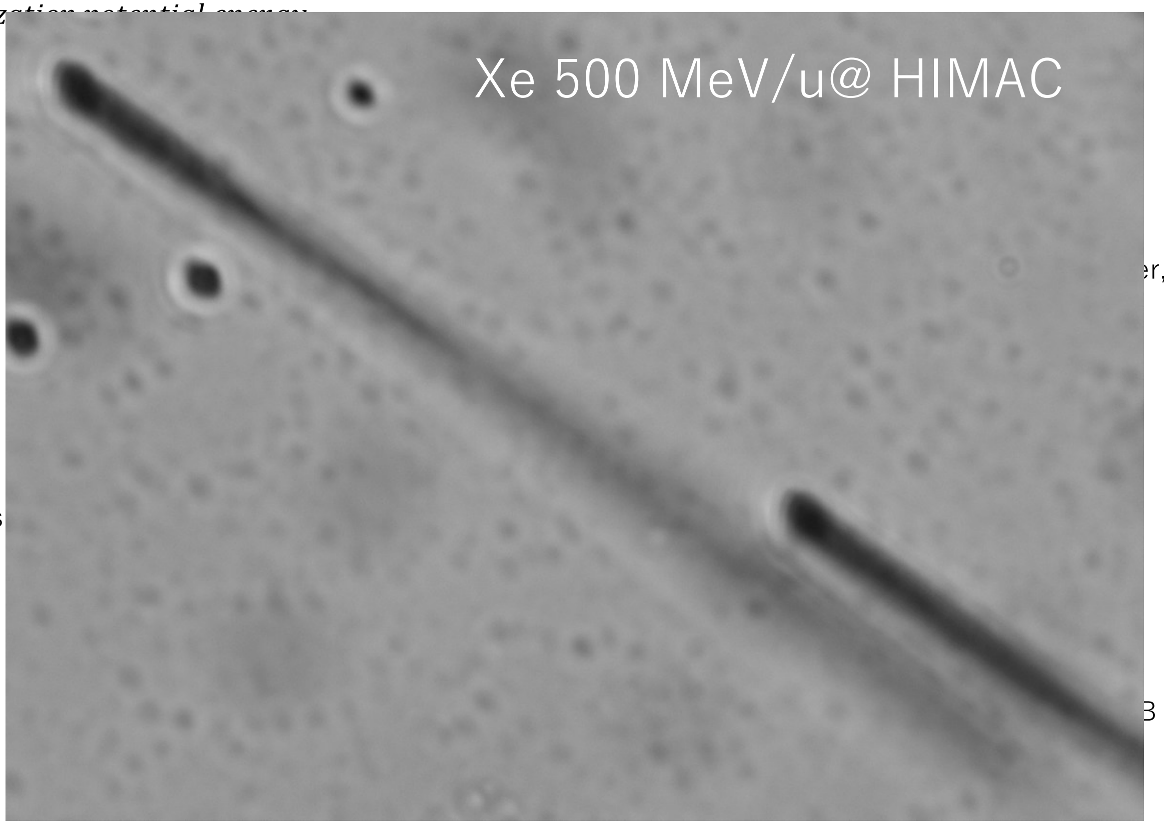
Daniele Perri *et al.*, Phys. Dark Univ., 2024, 101704 (arXiv:2401.00560)
Daniele Perri *et al.*, Phys. Dark Univ., 2025, 50, 102134 (arXiv:2507.05136v2)

dE/dx of monopole in the mineral

$$\frac{dE}{dx} = \frac{4\pi N g^2 e^2}{mc^2}\left[ln \frac{2mc^2\beta^2\gamma^2}{I} + \frac{K(|g|)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(|g|) \right]$$

S.P. Ahlen Phys. Rev. D, 17, 1 (1978)

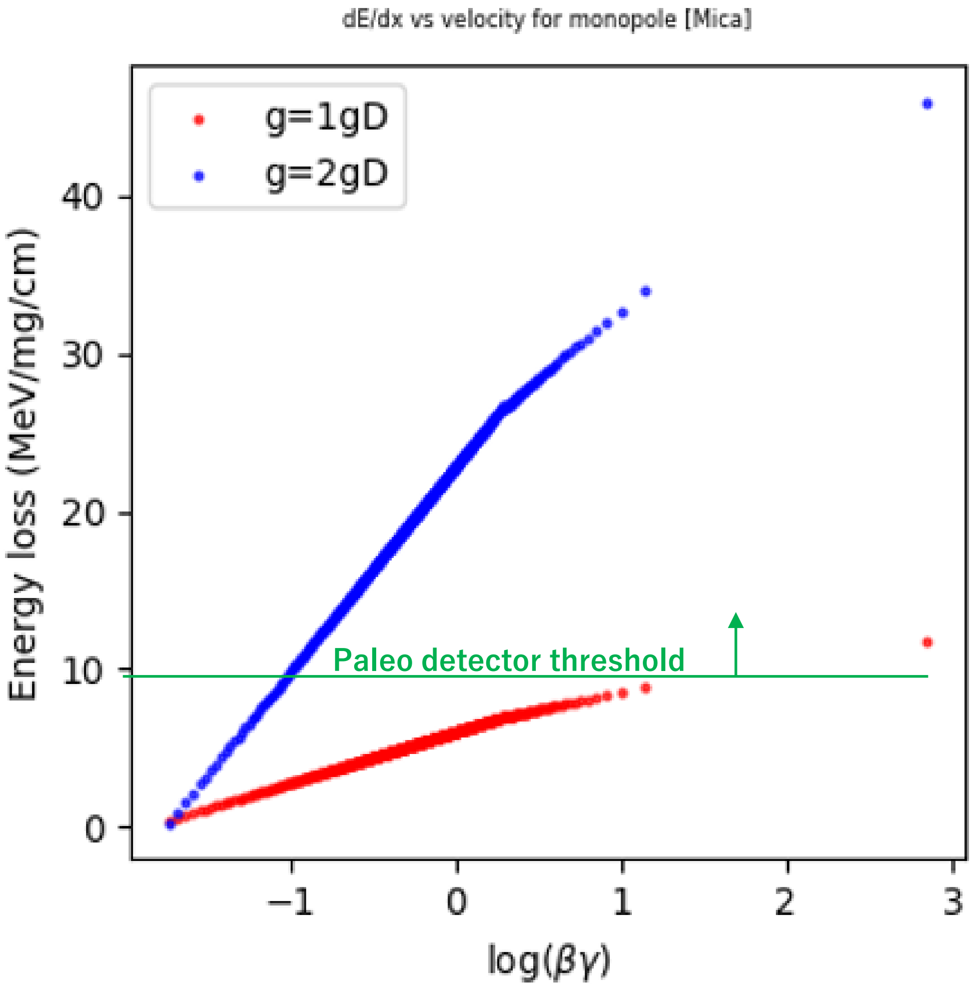
N: *electron density,*
mc^2: *electron rest energy,*
g: *charge of monopole,*
I: *ioniz*



er, Phys.

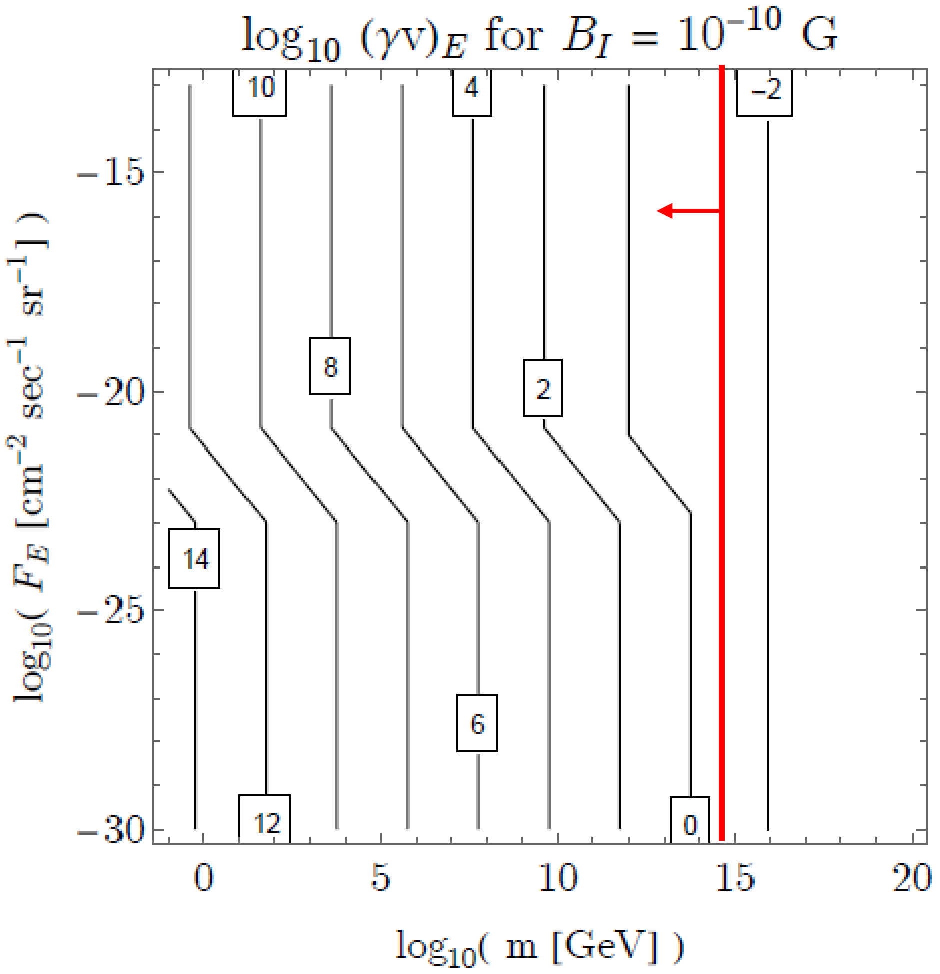
Dens

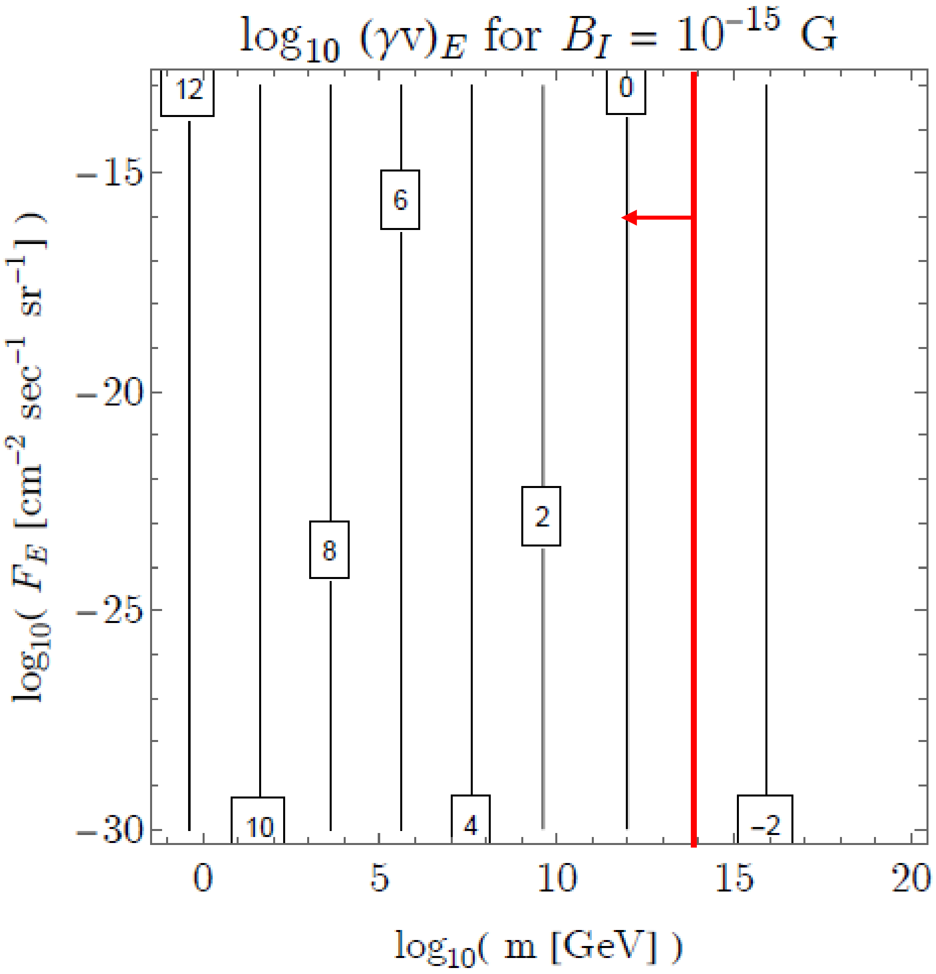
B 3, 3681 (1971)



Paleo detector has capability of tracking for $2g_D$ and $\gamma\beta > 0.1$
$(1g_D$ *may be able to exceed threhosld in high velocity region*$)$

$g = 2g_D$ case





calculated by T. Kobayashi @ SISSA

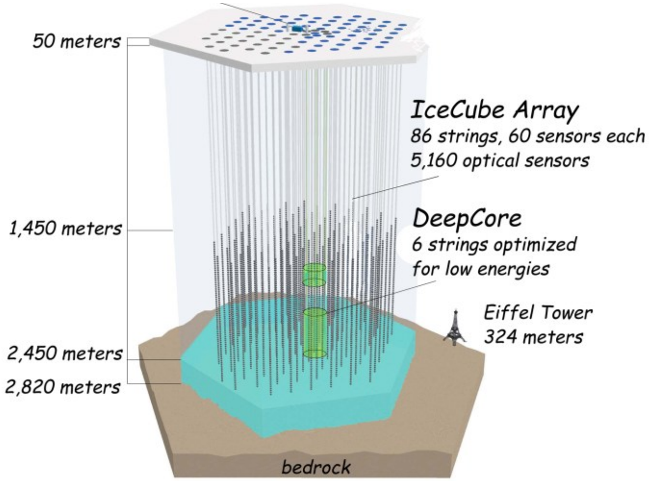
Paleo detector potential

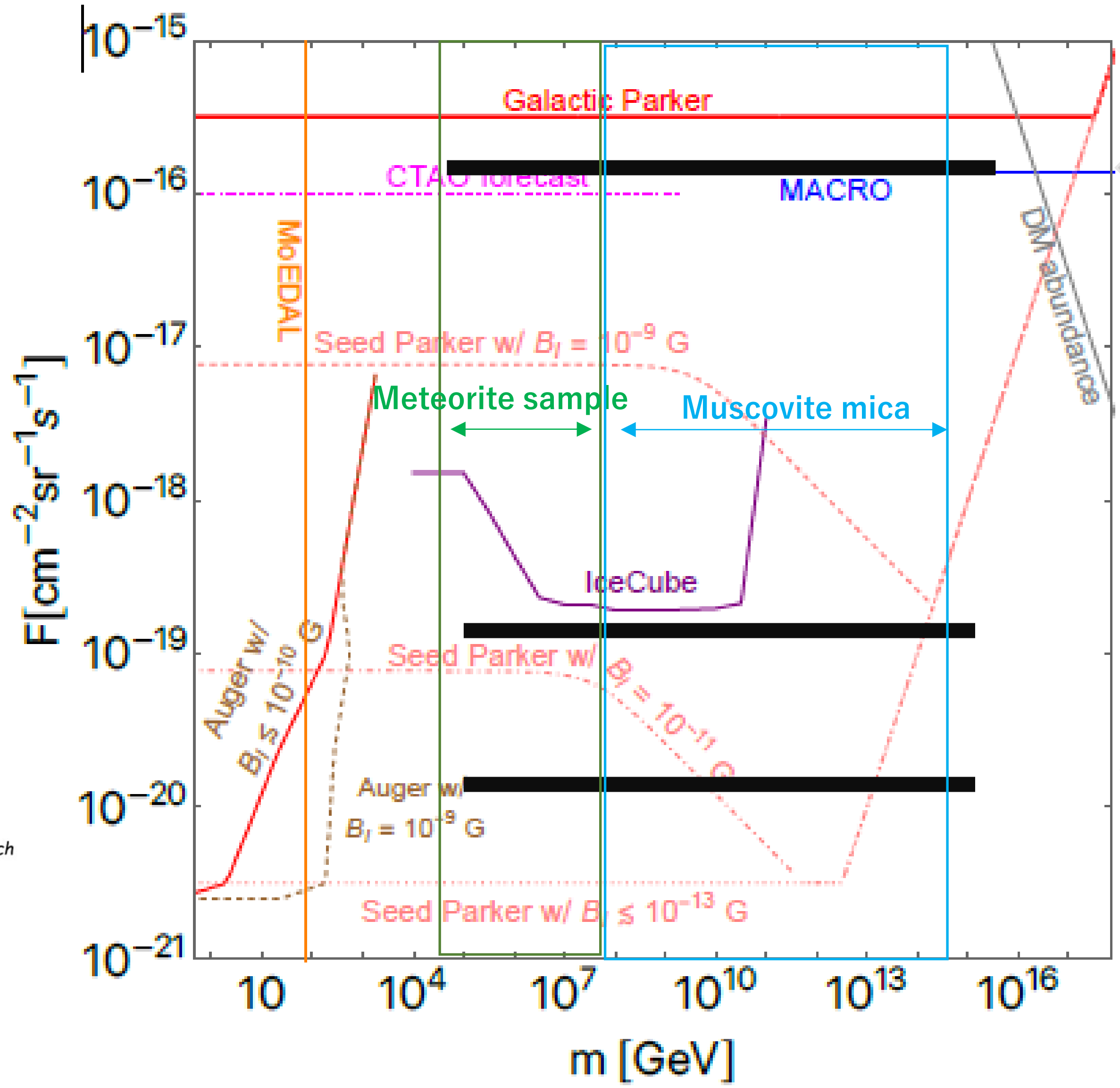
CR-39 (plastic damage detectors)

Observed area : O(10 x 10) m^2

Exposure time : O(1) year

IceCube detector





1~3 cm^2, 0.1 Gyear

O(1000) cm^2, 0.1 Gyear

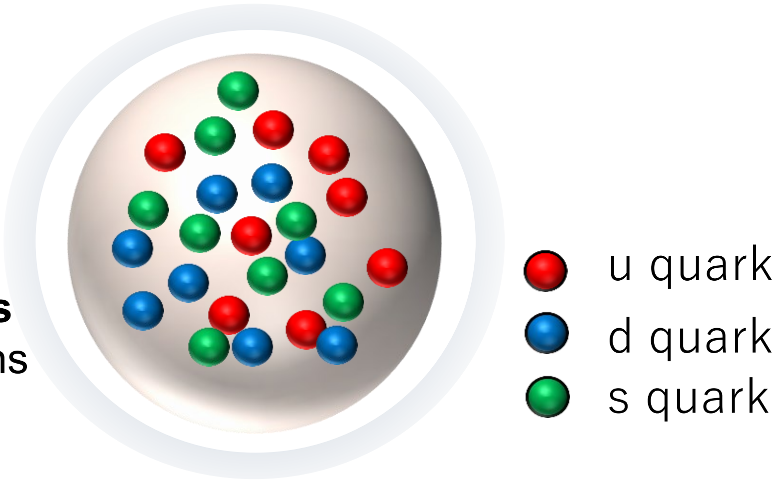
O(1) m^2, 0.1 Gyear

Daniele Perri *et al.*, Phys. Dark Univ., 2025, 50, 102134 (arXiv:2507.05136v2)

Strange Quark Matter

(Nuclearite, Strangelet)

■Strange Quark Matter（SQM)



Strange Quark Matter (SQM)

- ✓ 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 model + color-flavor rock (CFL) phase)

Basic Properties

- ✓ Nearly equal numbers of **u, d, s quarks** (flavor symmetry)
- ✓ Extremely **high density** (~ nuclear density or higher)
- ✓ Can be **slightly positively charged** ($Z = 0.3A^{2/3}$ for CFL model)
- ✓ Stabilized by the presence of **strange quarks** (reduces Fermi energy)

Stability

- May be the **true ground state of hadronic matter**

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

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

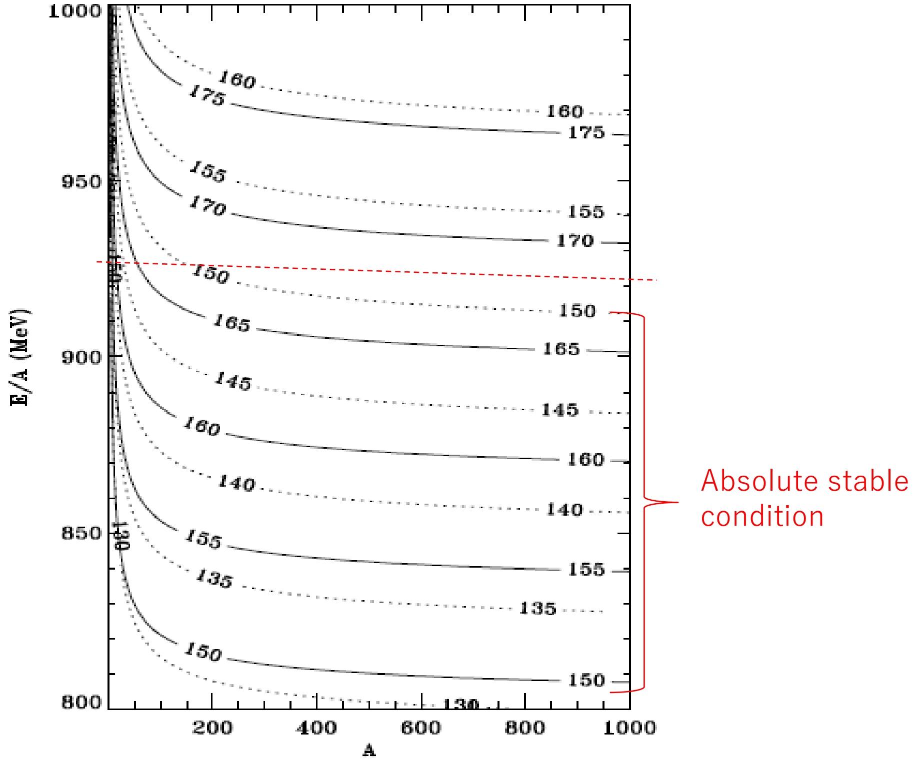
$$E = E_{quark} + BV$$

B: *bag constant* (energy density difference of QCD vacuum between outside and inside of SQM)

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

➡ **SQM becomes more stable at larger baryon numbers.**

※If stable → ordinary nuclei are **metastable**



Jes Madsen, Phys.Rev.Lett. 87 (2001) 172003

— : MIT bag

--- : Color-Flavor lock

Electric charge of CFL SQM

In the CFL phase, the bulk is electrically neutral, with equal numbers of u, d, and s quarks.

→ Near the surface, the finite mass of the s quark suppresses its abundance relative to the u and d quarks, resulting in a positively charged surface.

$\boxed{\textbf{Surface electric charge } Z=0.3A^{2/3}}$

Jas Madsen, Phys.Rev.Lett. 87 (2001) 172003

Energy loss (Bethe-Bloch formula)

$$-\frac{1}{\rho}\frac{dE}{dx} = 0.15\frac{Z^2}{\beta^2}\left[ln\frac{\beta m_e c^2\beta^2\gamma^2}{I} - \beta^2\right] > \text{paleo detector threshold (e.g., Olivine)}$$

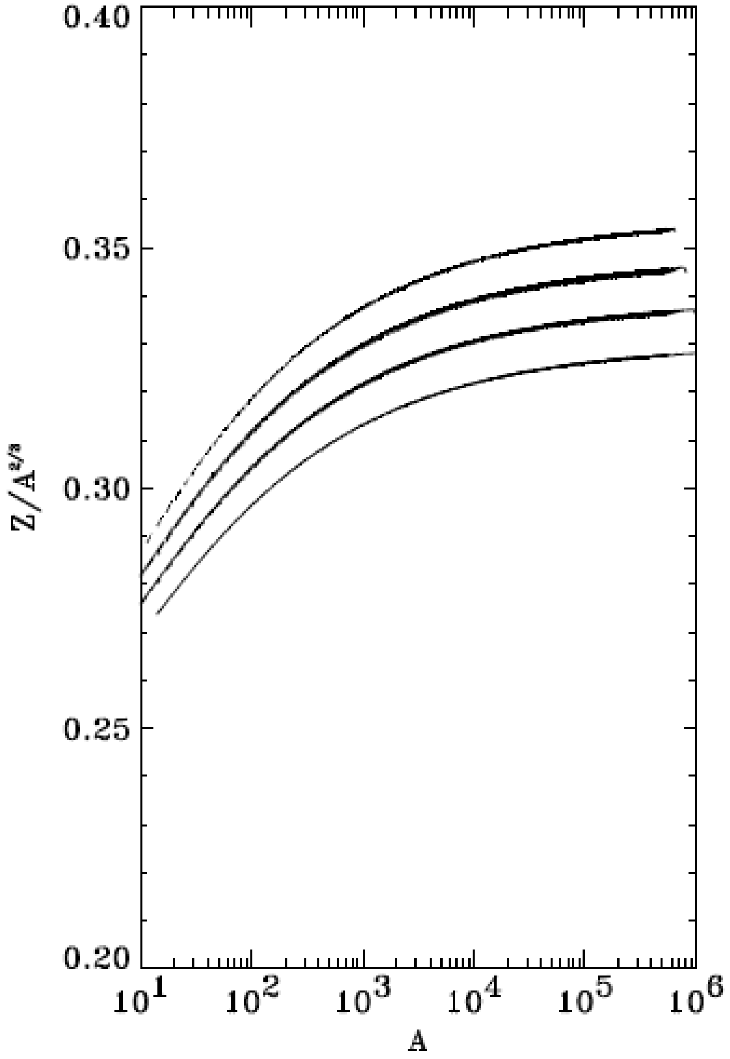


FIG. 3. Charge divided by $A^{2/3}$ as a function of A for CFL-strangelets with $B^{1/4}$ = 150, 160, 170, and 180 MeV (top to bottom), Δ = 100MeV and m_s = 150MeV.

Energy loss- track length – β for CFL SQM

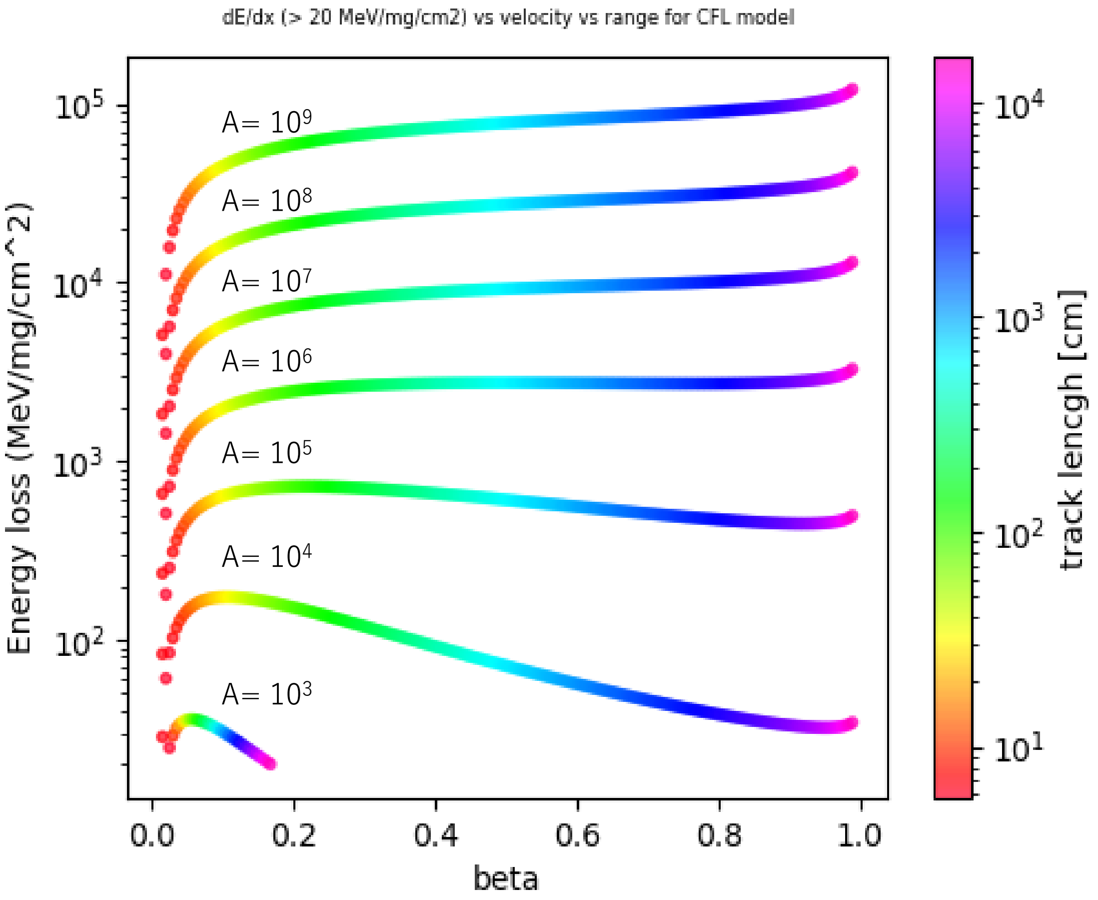
Case of acceleration in the Neutron Star Merger

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

accelerated in the condition of $M \leq 10^{11}\ GeV/c^2$

Track length : 0.1 ~10 m

Minerals in the meteorite (e.g., olivine) are target as the paleo detector



Geometrical effect for heavier SQM

Size scale : $R = \left(\frac{3M_{SQM}}{4\pi\rho_N}\right)^{1/3}$

$$\begin{cases} M_{SQM} > \sim 10^{15}\ GeV/c^2 & (R > \sim 1\ \text{Å}) \\ (\rho_N = 3.6\times10^{14}\ g/cm^2) & \\ M_{SQM} < \sim 10^{14}\ GeV/c^2 & (R < \sim 1\ \text{Å}) \end{cases}$$

➡ Gradually approaching macroscopic objects

$$\frac{dE}{dx} = -\sigma\rho v^2 = -\pi R_{SQM}^2\rho v^2$$

$$L[m] = 1.8\times10^4 \left(\frac{3.0\ g/cm^2}{\rho}\right)\left(\frac{M_{SQM}}{10^{14} GeV/c^2}\right)^{1/3}$$

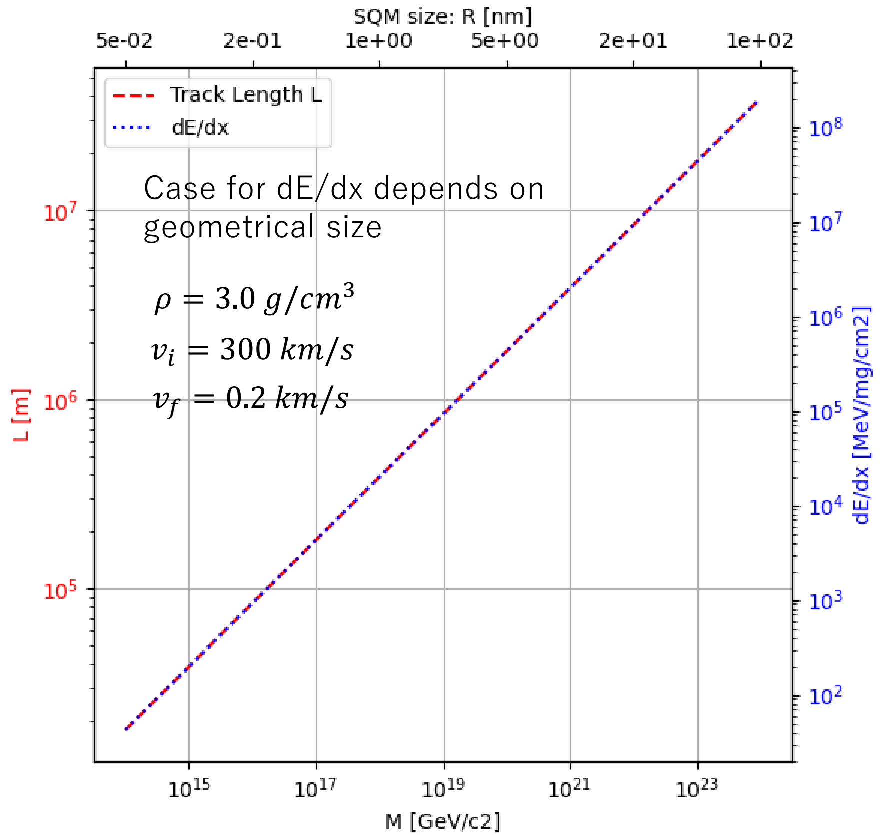
Heavy SQM case ($M_{SQM} > \sim 10^{14}\ GeV/c^2$)

- Cross section should be defined geometrical size.

Velocity β : 10^{-3}
Passing through the rock on the earth

- Mica is the best device to detect that

- Mostly ballistic damage is expected.

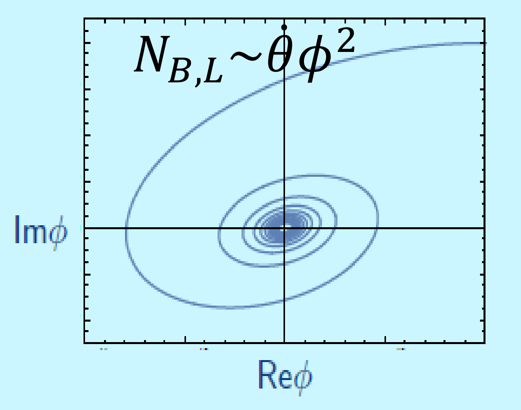


Q-ball

- Non-topological soliton on the scalar field, and it has the quantum number (e.g., Baryon number, Lepton number) due to U(1) symmetry.

➡ **Obtain the solution of the matter-dominated universe**

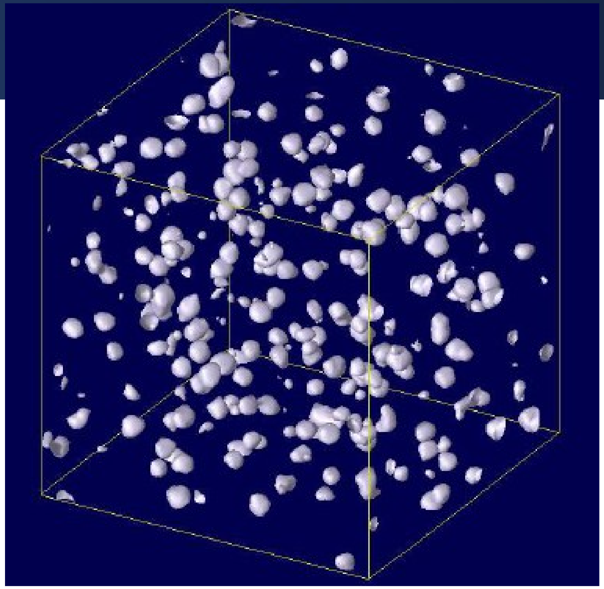
- Affleck-Dyne mechanism during inflation and Motion in phase direction due to θ -dependence



➡ **Baryon- and Lepton number generation**

- Very stable quantum field for $\frac{M_Q}{Q} < m_p$

➡ **Candidate of dark matter or part of dark matter**



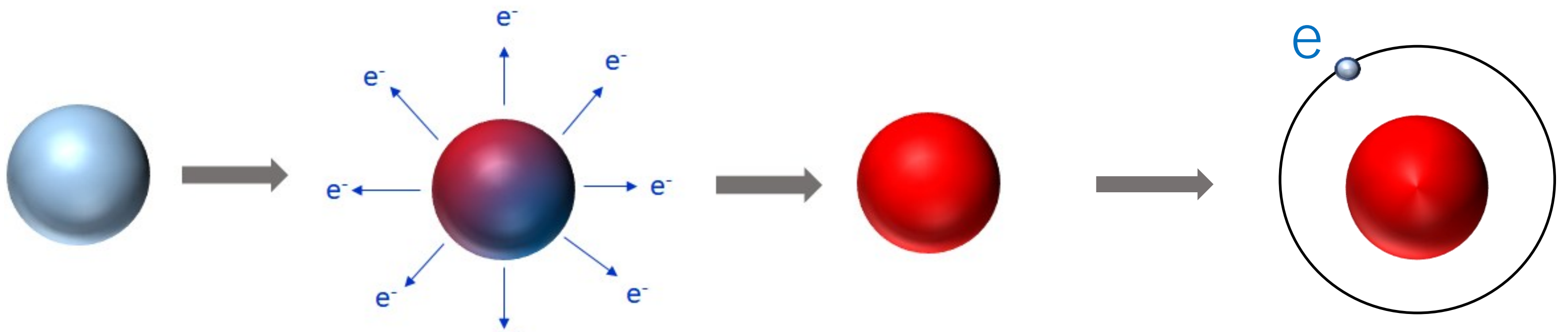
Hiramatsu, Kawasaki, Takahashi (2010)

Benchmark model

Stable “charged” Q-ball

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

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



$L = B$

$Q_e = B - L = 0$

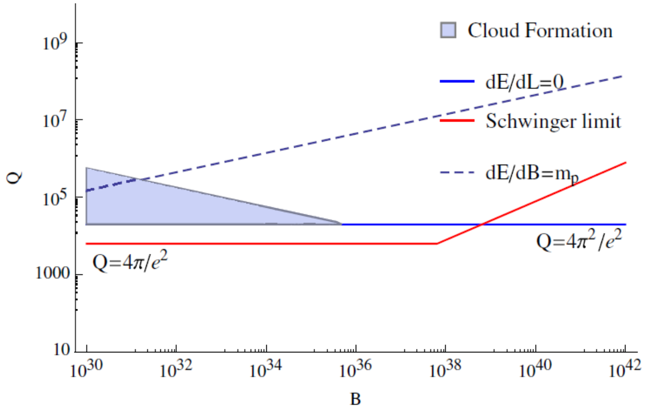
$L < B$

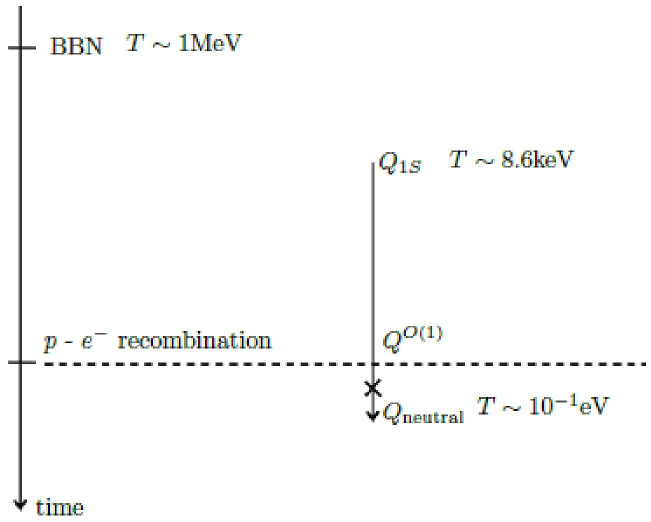
$Q_e = B - L > 0$

Much heavy mass : ~ 10^{20} GeV
$Q_e = \alpha^{-1} \sim 137$
+O(1) ionlike
β : 10^{-3}

- Q-ball with both B and L charge (e.g., $u^c u^c d^c e^c$)
- Stable against decay into protons
- Lepton component can decay into lepton

Stable charged Q-ball condition



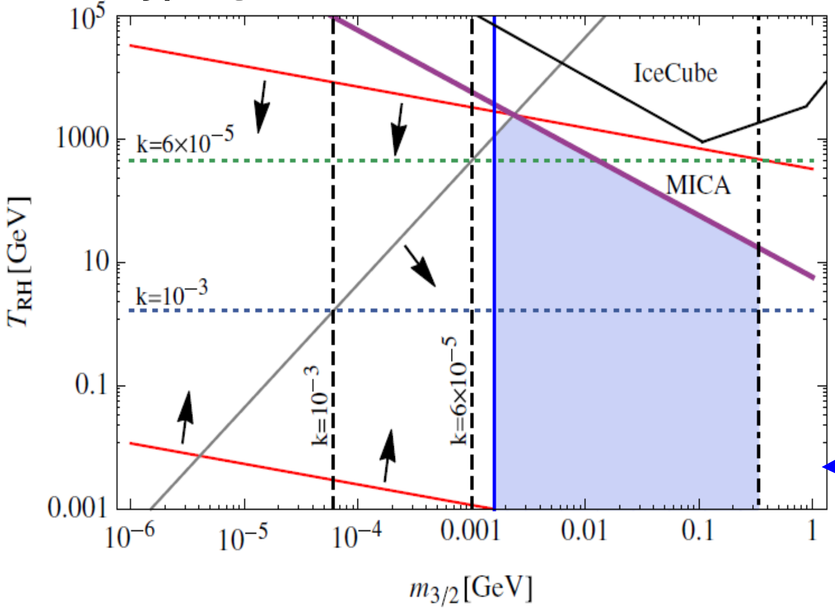


Jeong-Pyong Hong *et al* JCAP08(2016)053

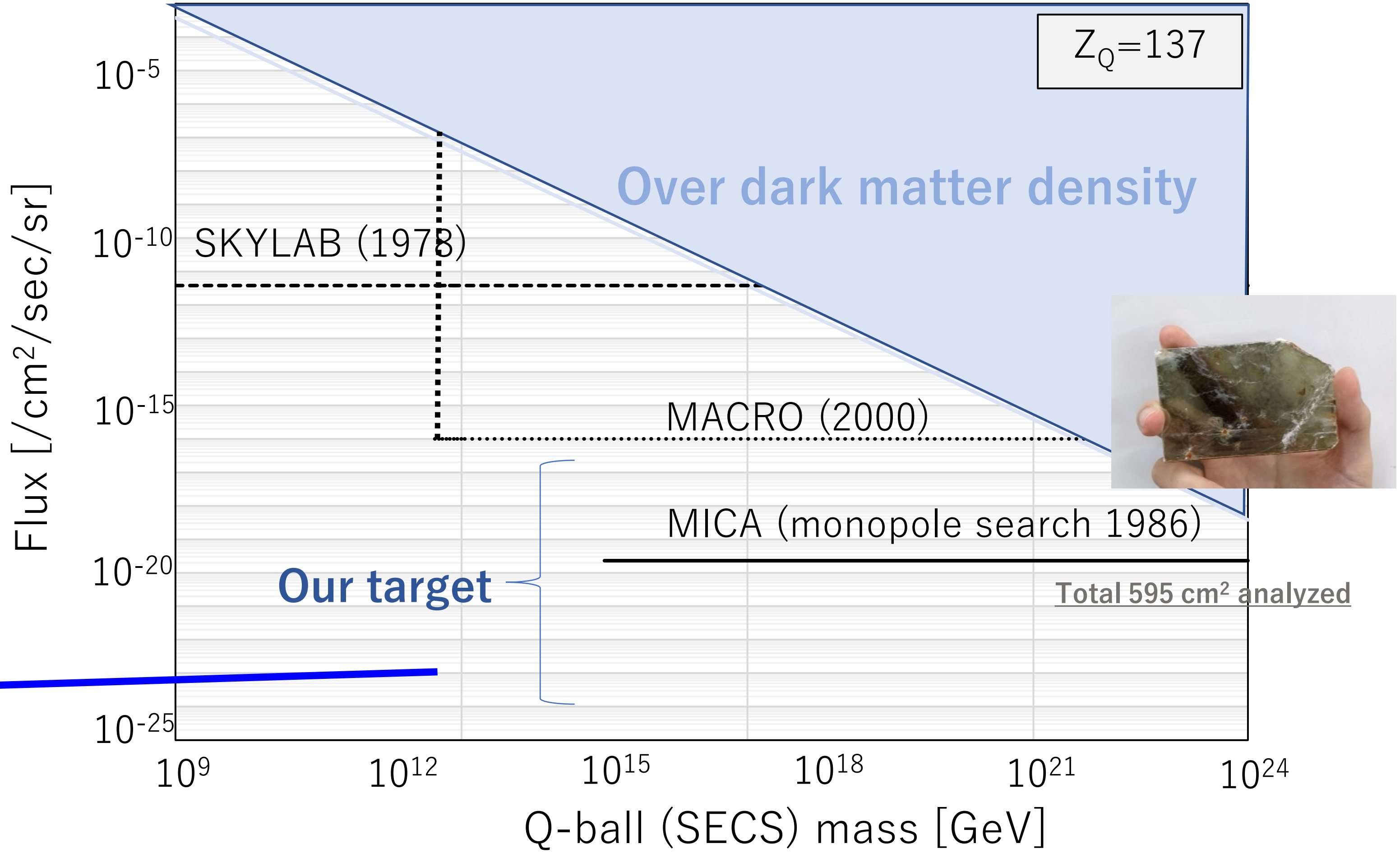
- **Size of the electron cloud becomes smaller than the Q-ball radius**
- **Bohr radius is smaller than the Q-ball radius when the cloud starts to from**
- **Schwinger effect become effective**

Expected sensitivity for Q-ball search with the paleo detector

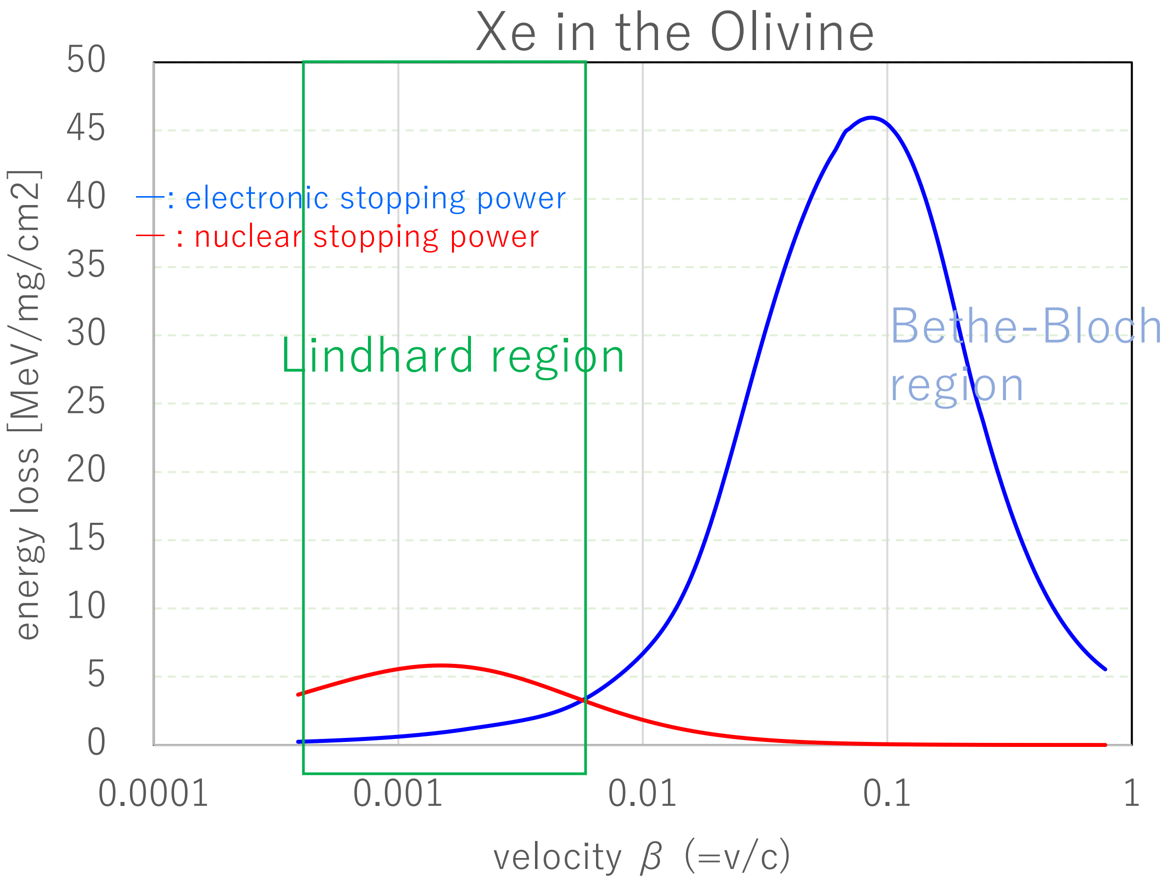
New type Q-ball



J.P. Hong and M. KawasakiPhysRevD.95, 123532(2017)



Stopping Power for $\beta \sim 10^{-3}$



Stopping Power of particle in medium

$$S = S_n + S_e$$

Nuclear stopping power (S_n)

electronic stopping power (S_e)

Bethe-Bloch region (β >O(0.01))

$S_e \gg S_n$ Ionization dominated

Lindhard-Scharff region (β <0.01)

$S_n \geq S_e$ Large effect with cascade atomic collision in the medium

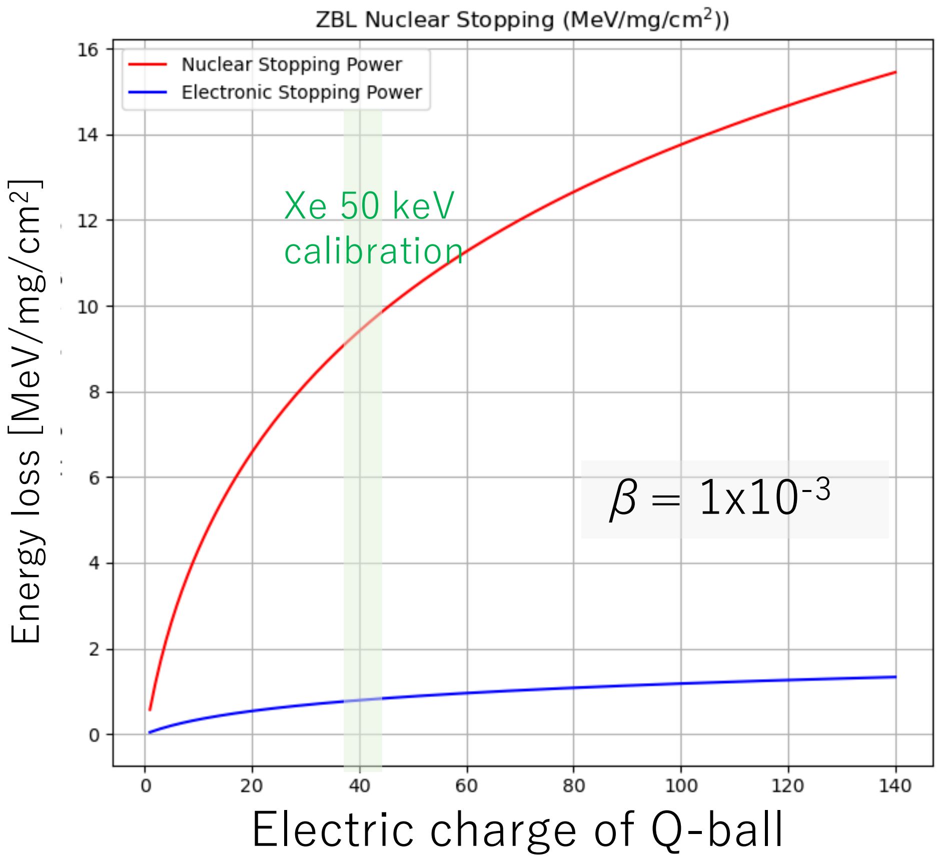
S_e : J. Lindhard, M. Scharff theory[1]

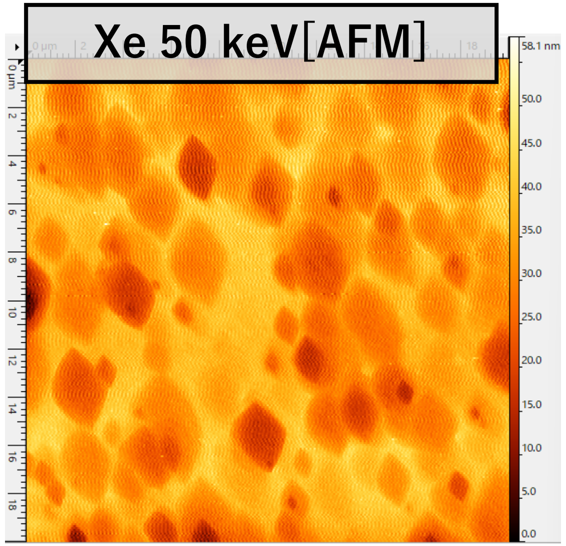
S_n : J. F. Ziegler, J. P. Biersack theory[2]

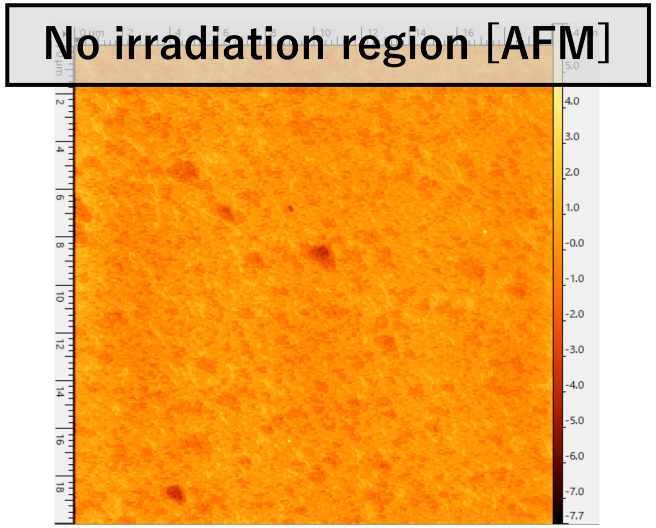
[1]J. Lindhard and M. Scharff, Phys. Rev. **124**, 128(1961).
[2]Biersack, J. P. and Ziegler, J. F. Springer Berlin Heidelberg 122 (1982).

The track formation mechanism for β <0.01 is not trivial.

Energy loss of charged Q-ball in muscovite mica







- Tracks can be formed in expected charged Q-ball region with mostly 100 % efficiency
- Tracks due to Q-ball or ultra-heavy particles could be enough longer than ions in this test

Nuclear loss : 8.7 MeV /mg/cm^2
Electronic loss :0.7 MeV/mg/cm^2

A More detailed investigation is needed to understand the track formation mechanism.

Experimental Preparation

Optical microscope scanning system for nuclear emulsion

PTS system for nuclear emulsion scanning (NEWSdm experiment for directional DM search)

Application of optical readout system for nuclear emulsion

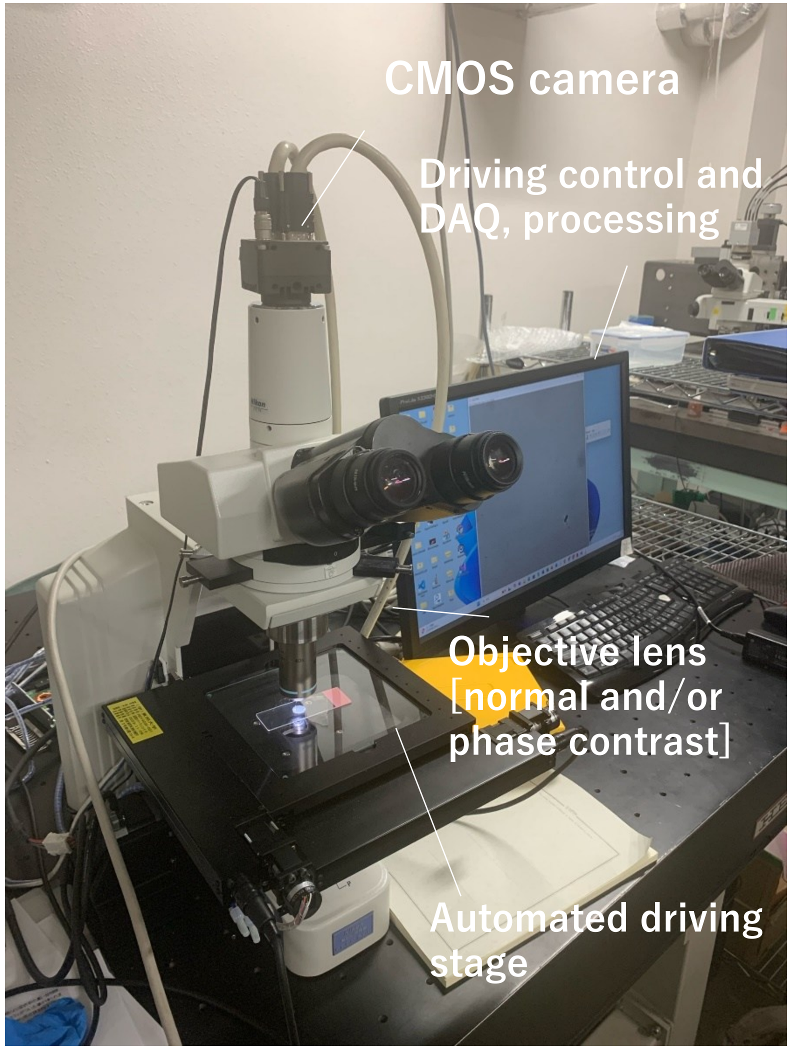
Current system : ~20h /100 cm^2
(optimized for nano-metric tracking with nuclear emulsion)

Optimization for long track : 1h /100 cm^2 (for Paleo detector)

Wide view scanning : 10 min /100 cm^2 (only surface)

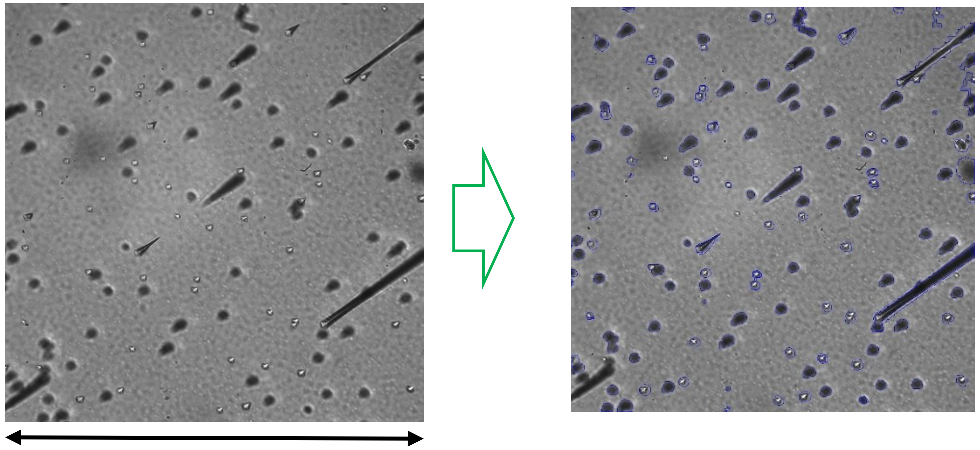
Aim to achieve high-speed data acquisition using nuclear emulsion scanning systems.

Optical Microscope Scanning System for the Paleo Detector

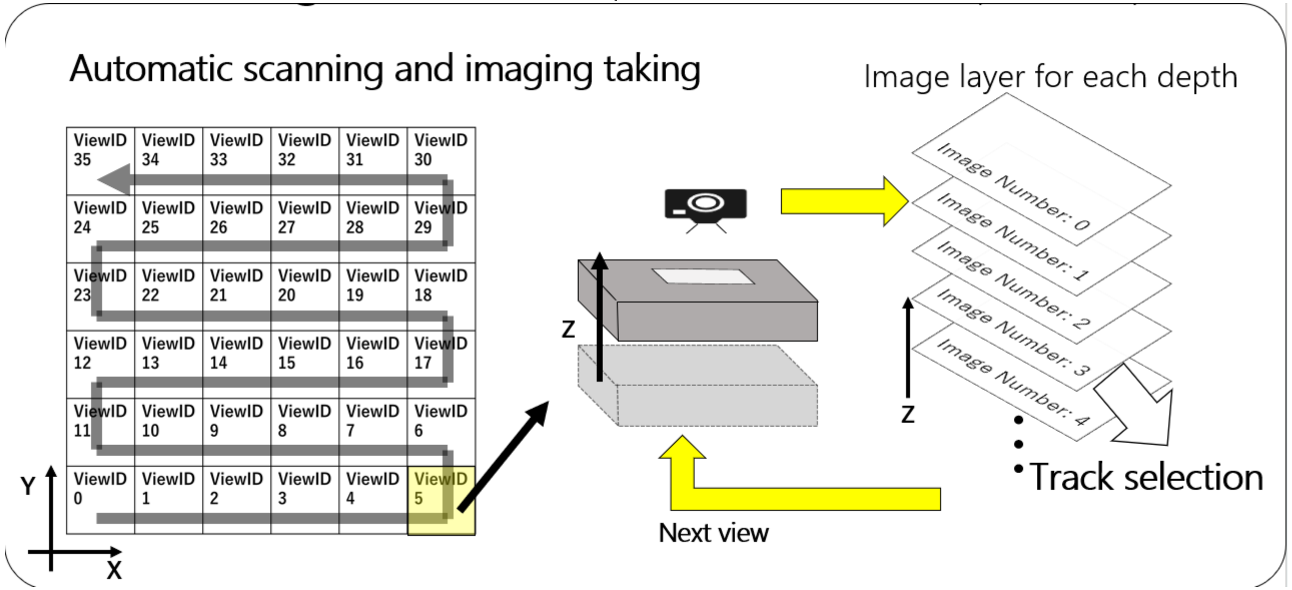


Automatic scanning and image taking

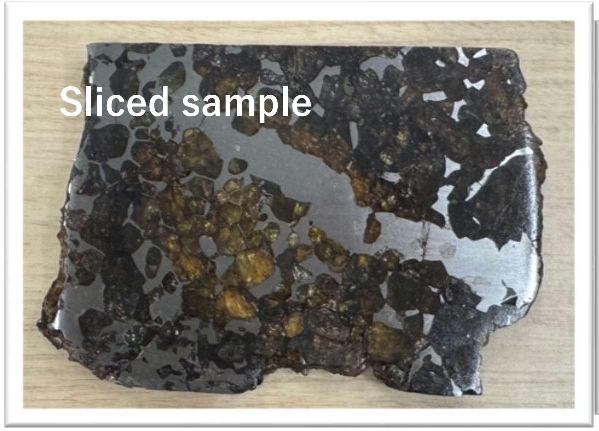
Swift ion tracking
[Xe : 69 MeV/u]

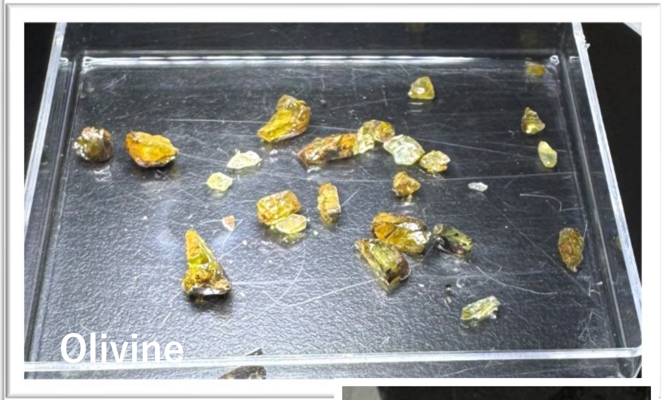


400 μm



Sample analysis and calibration





■ **<u>Obtain the meteorite sample and handling</u>**

Current test sample
Imillac (1822, Atacama)

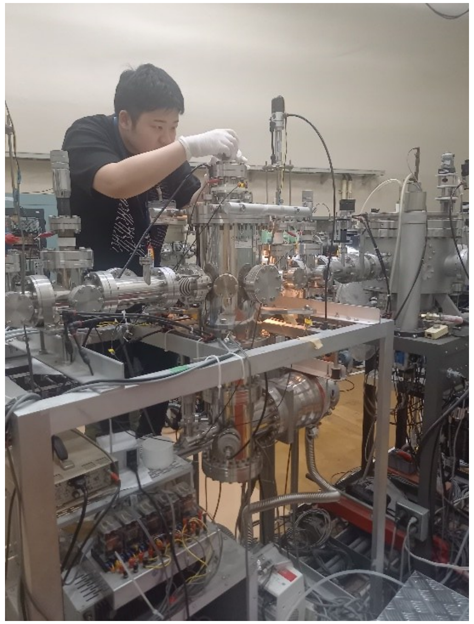
In parallel, searching for optimal meteorite with older exposure age.

■ **<u>Element analysis + dating</u>**

- EPMA analysis
- Radiochemical analysis

■ **<u>Beam calibration + optimization of etching treatment</u>**

- Heavy ion beam (e.g., JAEA, QST beam line)
- Ion-implant system for investigating of low-velocity heavy particle detection



Summary

- Paleo detectors provide a new approach to astroparticle physics using natural mineral detectors.
- Geological timescales allow minerals to record and provide unique information on the history of the Milky Way Galaxy.
- Search for dark matter and exotic particles with ultra-high mass and extremely low flux.
- Measurement of heavy galactic cosmic-ray elements, including their charge and energy.

TAICO
TRACKING ANCIENT IMPRINTS
OF COSMIC ORIGINS

Dark Matter or exotic particle

・monopole
・composite dark matter (Q-ball, SQM・・)
・WIMP
・another new physics

Ultra Heavy Element

- Galactic cosmic-ray element
- Element from solar flare
- Exotic particle from astrophysical source (e.g., NSM)

We welcome new ideas and collaborations using the Paleo Detector approach!