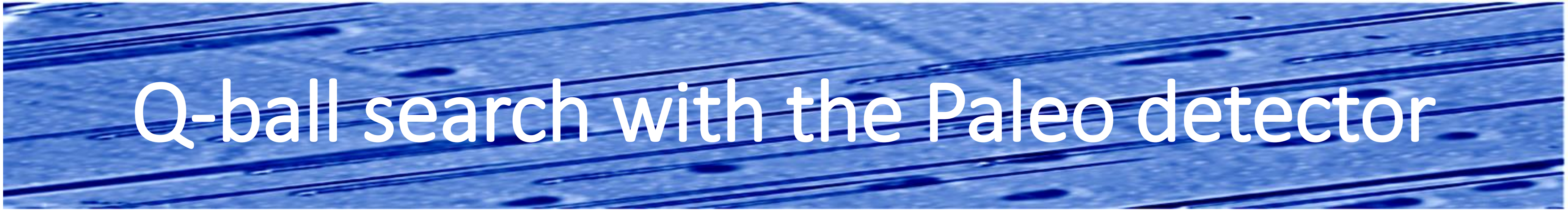
Toho University

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

Q-ball search with the Paleo detector



Tatsuhiro NAKA

Toho University /KMI, Nagoya Univ.

MDvDM'24 meeting, Jan 8-11, Washington DC (+ zoom)

Collaboration and Support

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National Institute of Technology Suzuka College
Kaito TAKAMATU
Tohma ORI

The Pennsylvania State University
Kohta MURASE

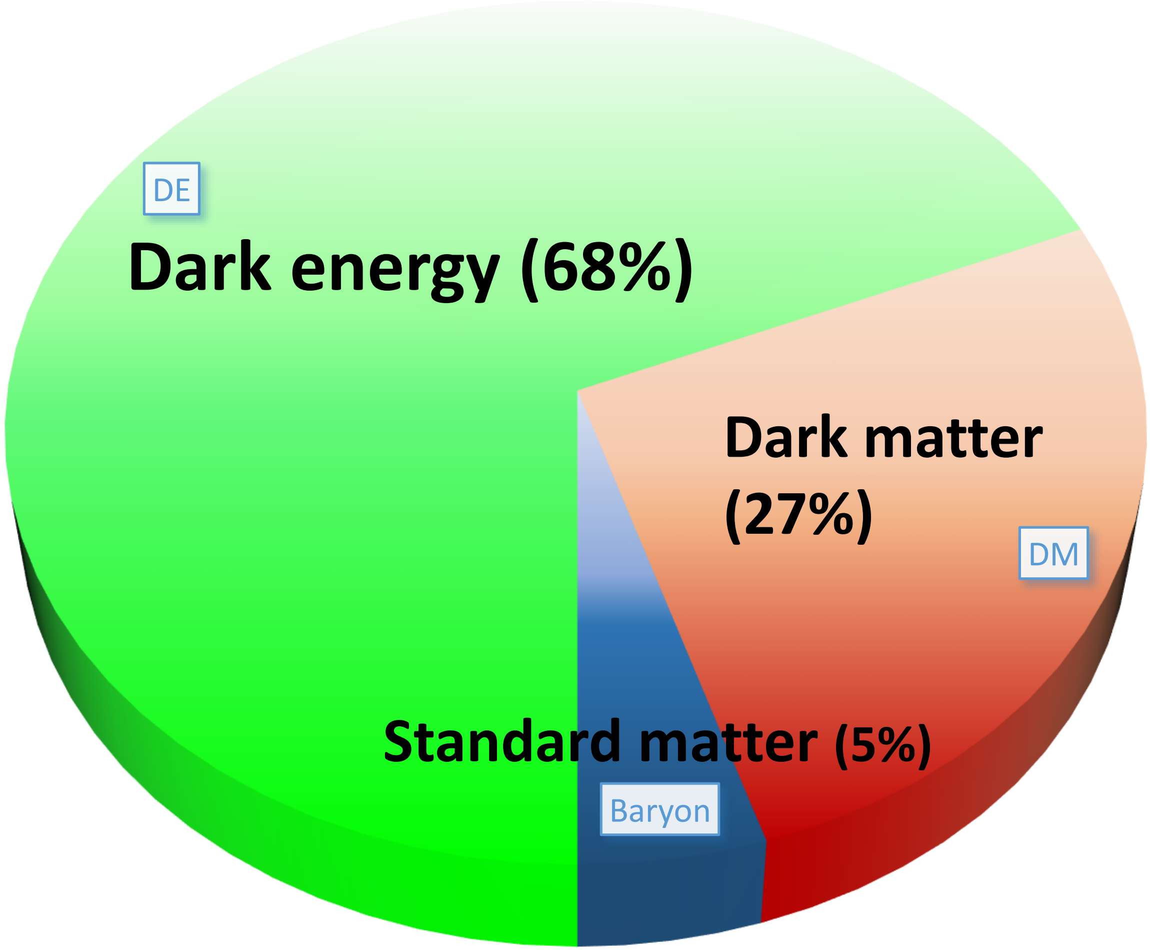
Particle Physics
×
Astrophysics
×
Geoscience
×
Material Science

Theoretical support for the Q-ball
Prof. M. Kawasaki (U. Tokyo) and Prof. K. Hamaguchi (U. Tokyo)

Dark Matter

- 95 % of the universe is consist of unknown energy and matter.

- There are various evidence of existence of dark matter, e.g., motion of galaxy, gravitation lens, cosmic microwave background and so on.



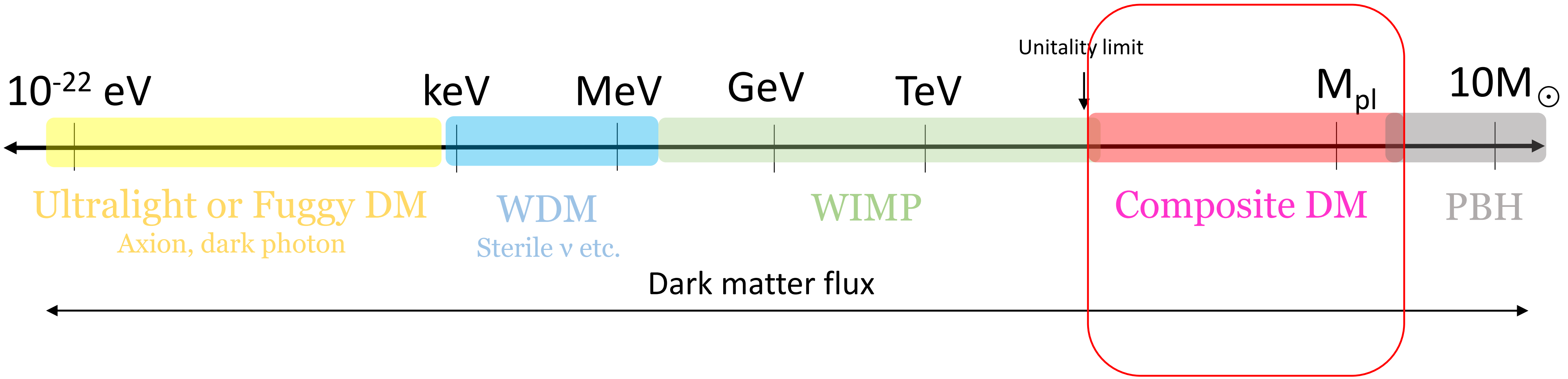
Planck 2013 results

Important problem for particle physics

- Hierarchy Problem
- GUT
- Generation of baryon and lepton number
- Asymmetry of matter-antimatter (CP violation)

Dark matter and new physics are need to understand this universe.

Dark Matter mass scale



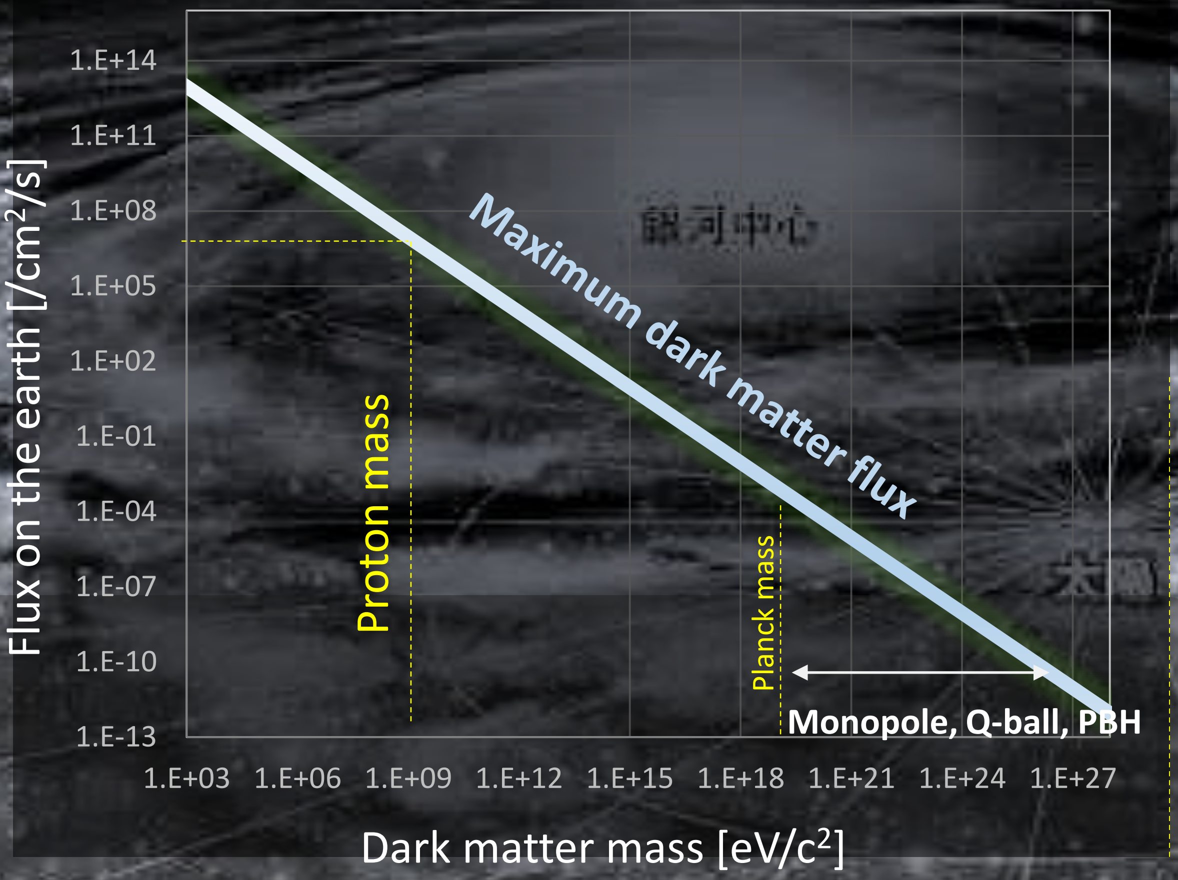
Candidate : Q-ball, quark nugget、Nuclearite, etc.
Mass scale : > 10^{20} GeV

$$DM\ flux\ on\ the\ earth = 1.2\ \times 10^{7}/\ cm^{2}/sec\left(\frac{v}{300\ km/sec}\right)\left(\frac{1\ GeV/c}{M_{DM}}\right)$$

➡ **Heavy DM expect to be very low flux**

Dark Matter in the milky way galaxy

Dark matter flux on the earth



Flux of 10^{20} GeV/c^2 : < 10^{-13} /cm^2/sec

For typical detector scale, O(1)/year or less

⬇

Paleo detector with geoscience scale is powerful methodology!

Q-ball

- Baryon or/and Lepton number generation
- Beyond Standard Model（e.g., SUSY）⇒ Grand Unified Theory
- Dark Matter Candidate

Q-ball solution

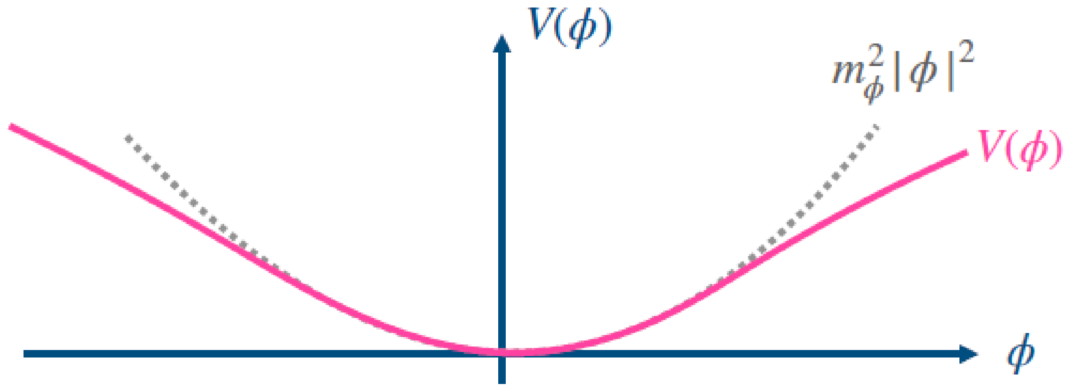
Q-ball solution (Coleman, 1985)

Complex Scalar field ϕ with global U(1) symmetry

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)^*(\partial_\mu\phi) - \mathrm{V}(\phi)$$

Global charge : $Q = \frac{1}{2i}\int d^3x(\phi^*\dot{\phi} - \dot{\phi}^*\phi)$

Energy : $E = \int d^3x(|\dot{\phi}|^2 + \frac{1}{2}|\nabla\phi|^2 + V(\phi))$



Q-ball = field configuration minimizing E with Q constant

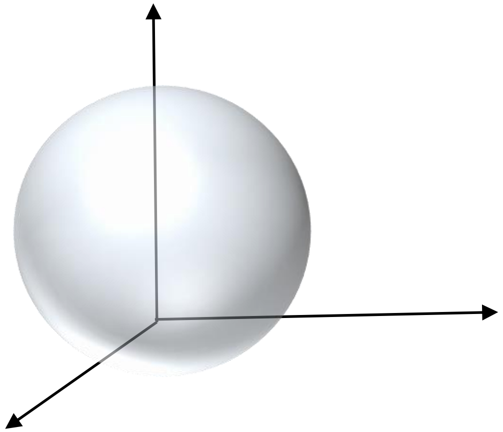
minimizing

$$E_\omega = E + \omega\left[Q - \frac{1}{2i}\int d^3x(\phi^*\dot{\phi} - \dot{\phi}^*\phi)\right]$$

$$\omega_m = Min\left[\frac{2V(\phi)}{\phi^2}\right] < m^2{}_\phi$$

Stable Q-ball exist if such potential

$\phi(x,t) = e^{i\omega t}\phi(x) = e^{i\omega t}\phi(r)$ Spherical symmetry



Charge : Q

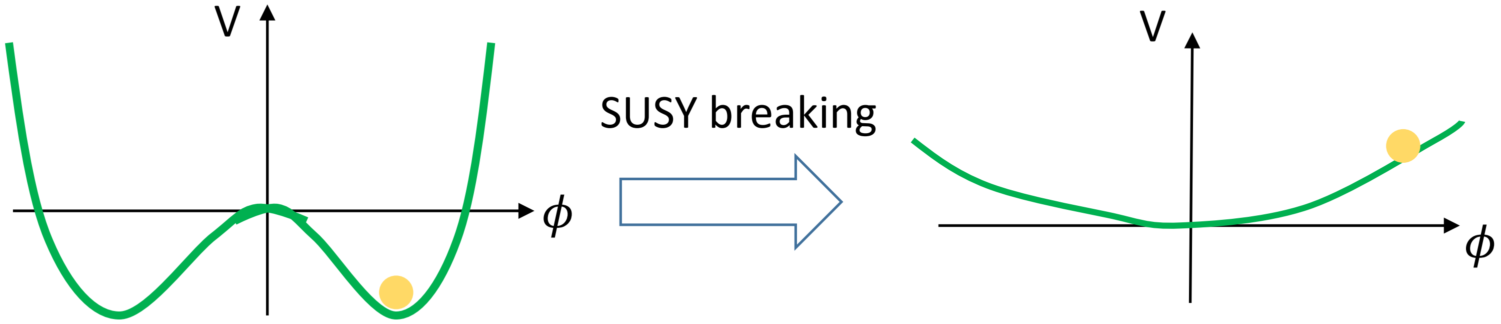
Mass : $M_Q = m_\phi Q$

Affleck Dine mechanism in early universe

Flat field direction in the minimum supersymmetry standard model (MSSM) [squark, slepton, Higgs]

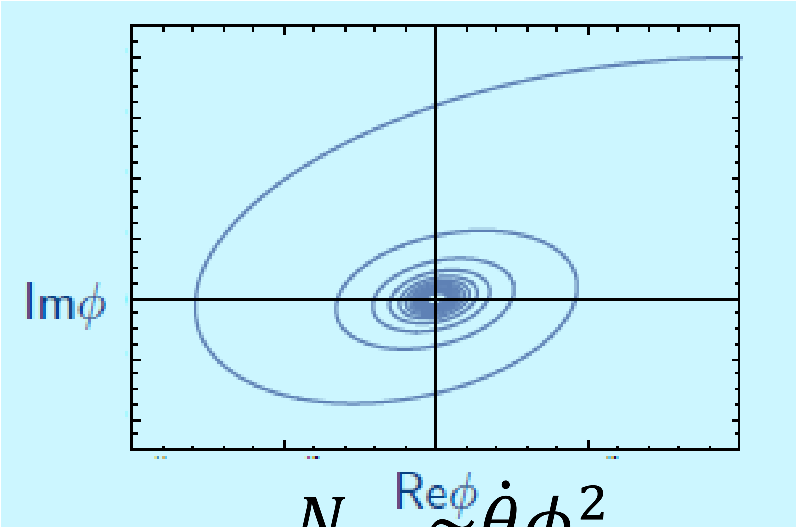
⇒ AD field as one of flat direction field ϕ has baryon or/and lepton number

Early Universe



During inflation **After inflation**

Motion in phase direction due to θ-dependence



$$N_{B,L} \sim \dot{\theta}\phi^2$$

Generation of B and L number

Q-ball dark matter

Gage mediated SUSY breaking model

$$V(\Phi) = M_F^4[\log(1+\frac{|\Phi|^2}{M_{mess}^2}]^2 + m_{3/2}^2|\Phi|^2[1+K\log\left(\frac{|\Phi|^2}{M_{mess}^2}\right)]$$

AD field oscillation has instability if V(ϕ) < ϕ^2

Gage-mediation type

Q-ball is always formed

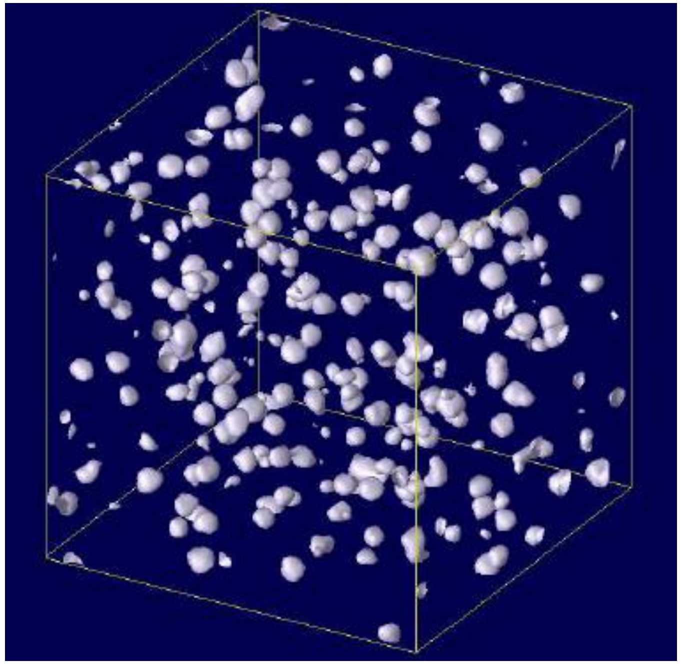
$$\frac{dM_Q}{dQ} = \sqrt{2}\pi\zeta M_F Q^{-1/4} \quad < m_p$$

new type

Q-ball is formed for K< 0

$$\frac{dM_Q}{dQ} = m_{3/2} < m_p \qquad M_Q = m_{3/2}Q$$

$* \, m_{3/2}$: gravitino masss



Hiramatsu, Kawasaki, Takahashi (2010)

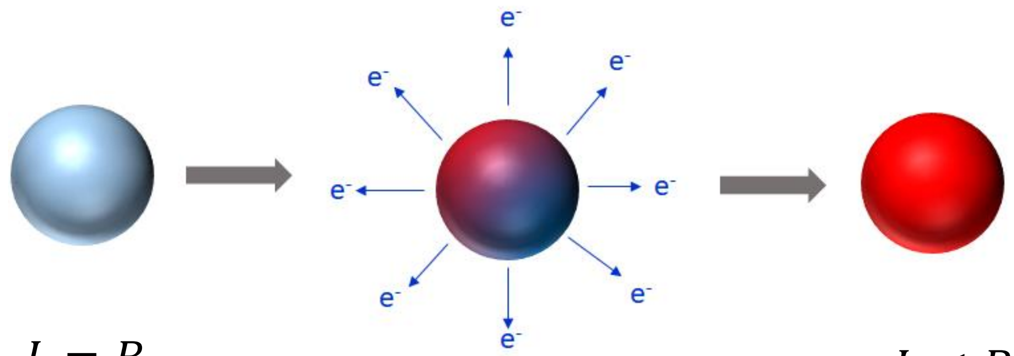
Q-ball can be the Dark Matter because there is no lighter particle with baryon number than proton.

Stable "charged" Q-ball

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

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

- 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 leptons

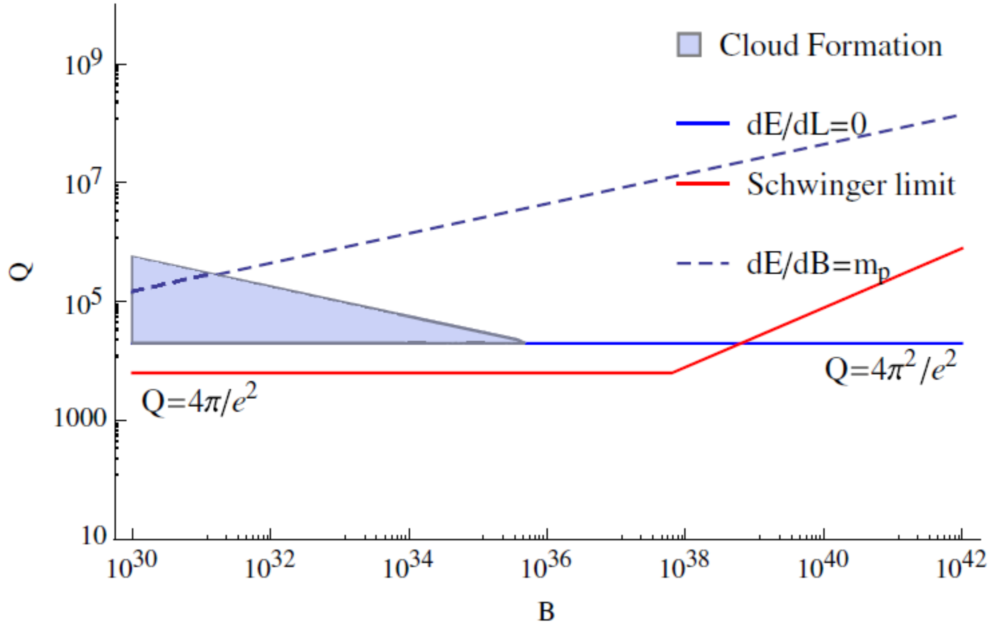


$L = B$

$Q_e = B - L = 0$

$L < B$

$Q_e = B - L > 0$

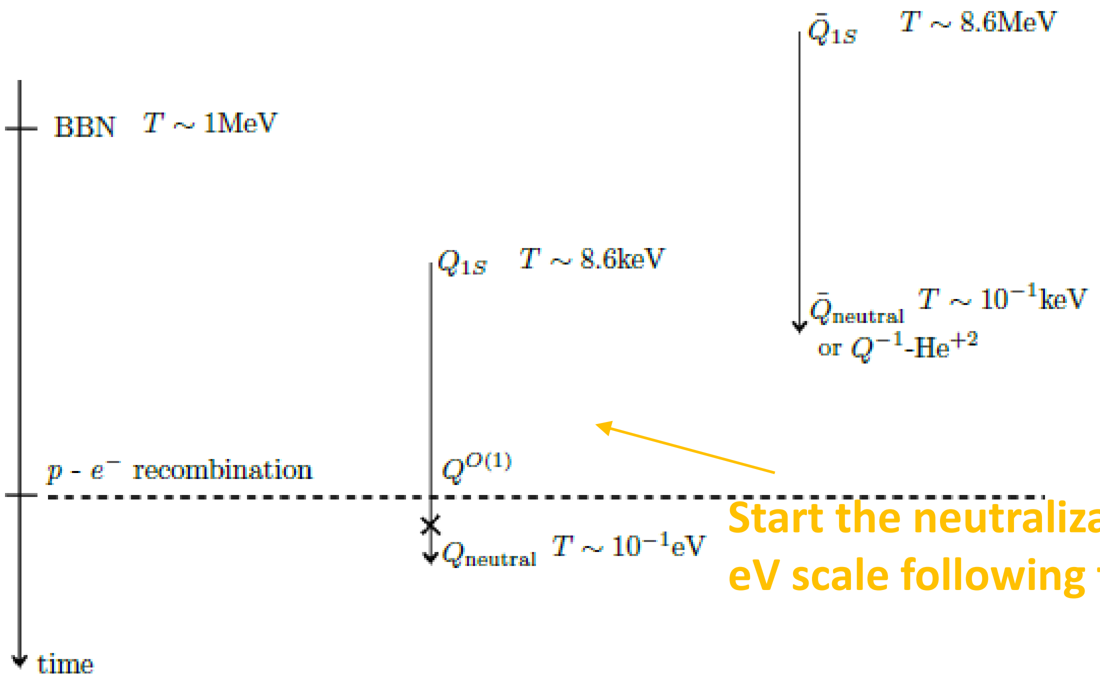


Stable charged Q-ball condition

- **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**

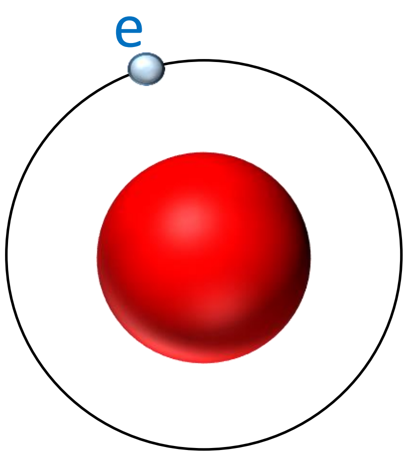
Condition of “charged” Q-ball dark matter

Evolution of charged Q-ball



Start the neutralization from keV to eV scale following the Saha fomula

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



Q-ball atom

Much heavy mass : ~ 10^{20} GeV

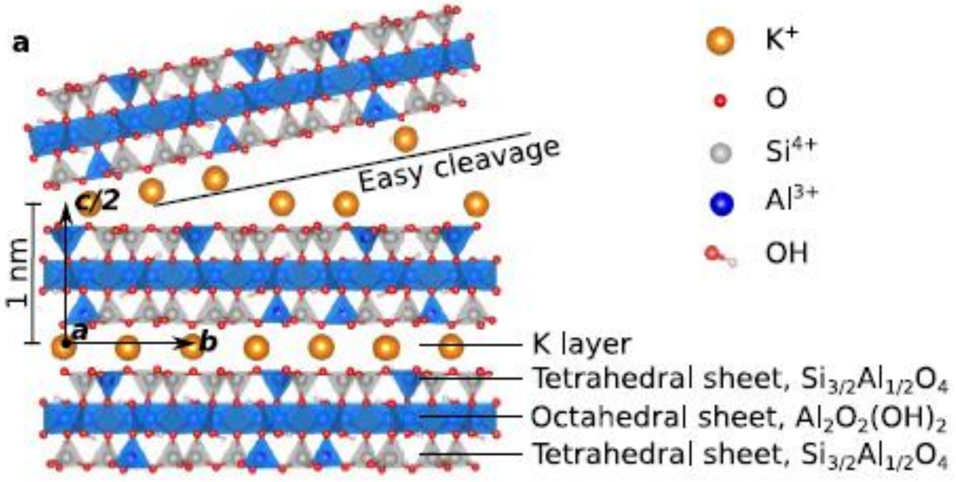
$Q_e = \alpha^{-1} \sim 137$

+O(1) ionlike

β : 10^{-3}

As quite heavy atom-like particle, it should not be stopped in the material.

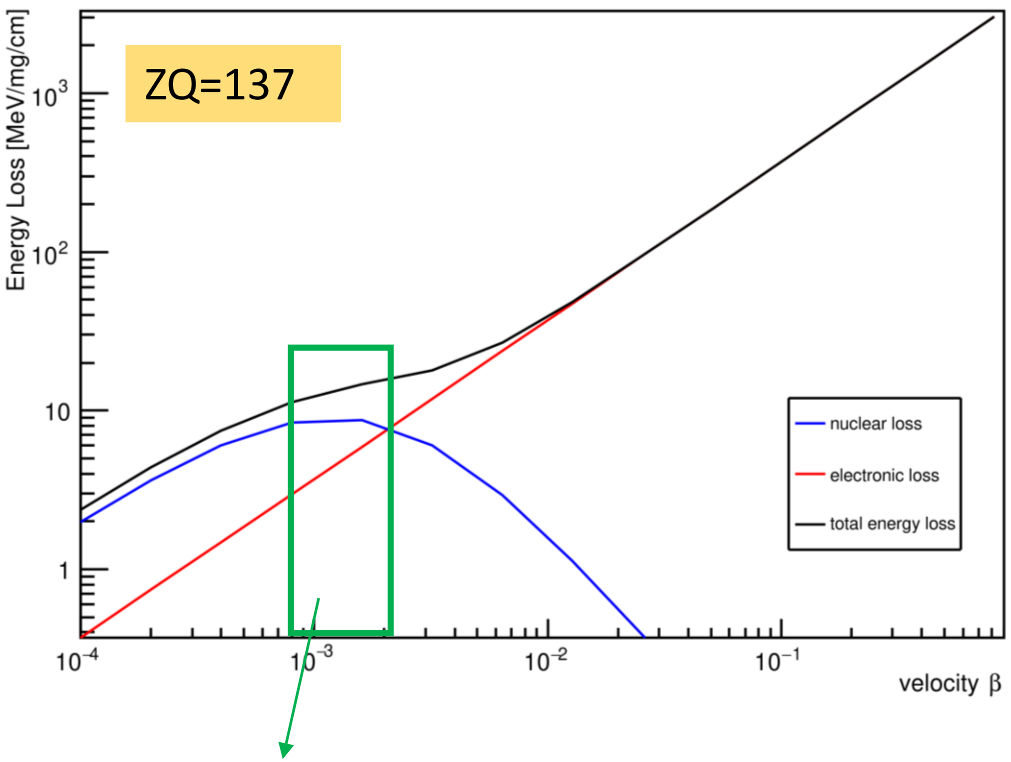
Q-ball search with the muscovite mica

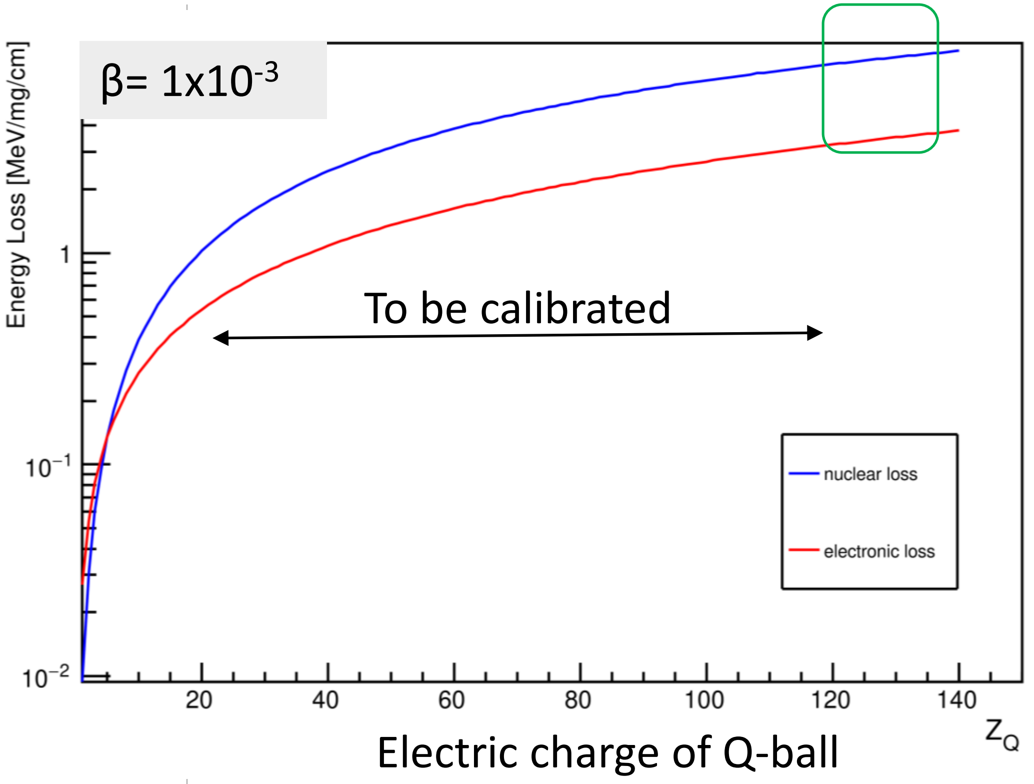


Franceschi+ 2023

Energy loss of charged Q-ball in muscovite mica

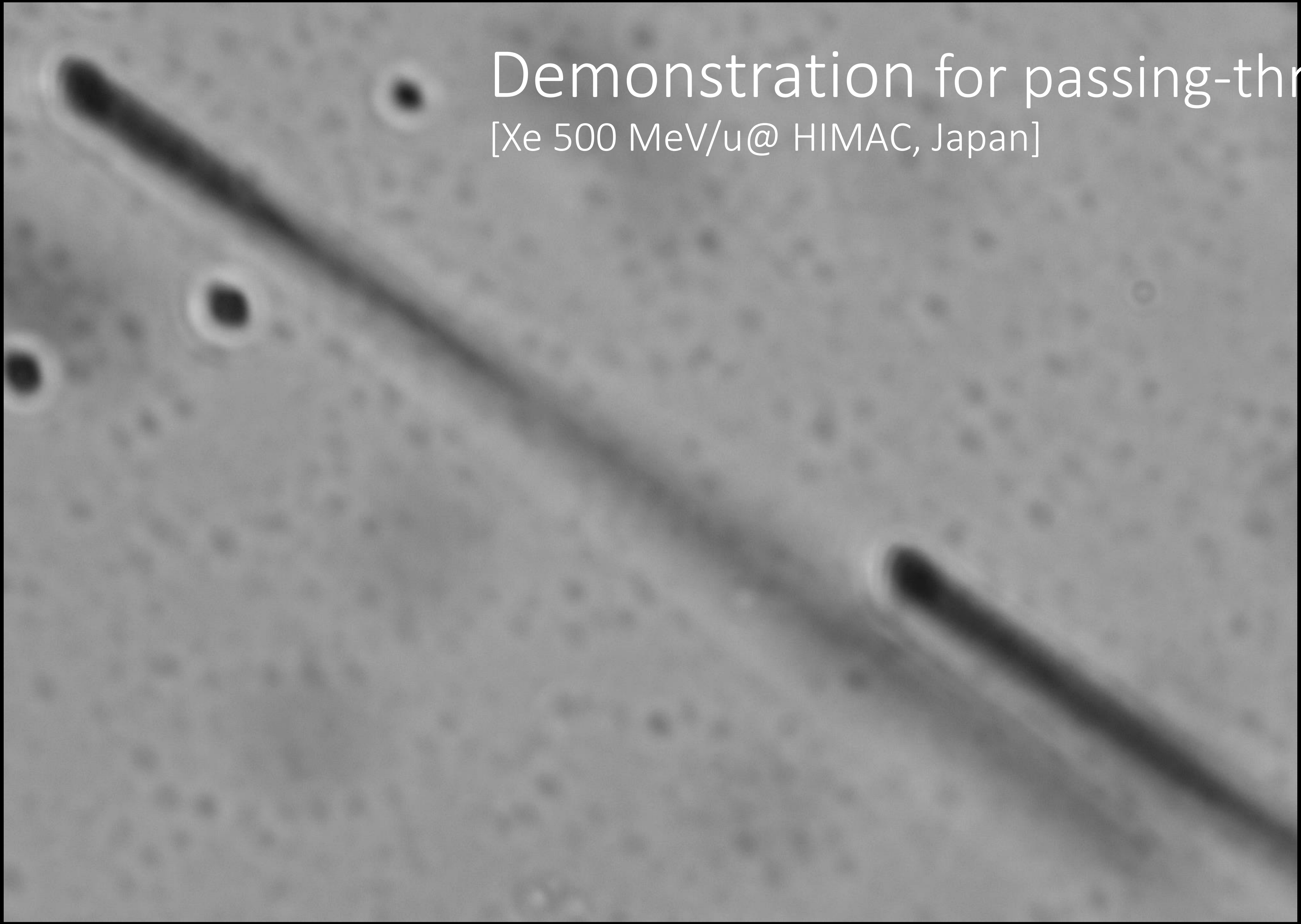
Mostly same energy loss mechanism for α-recoil

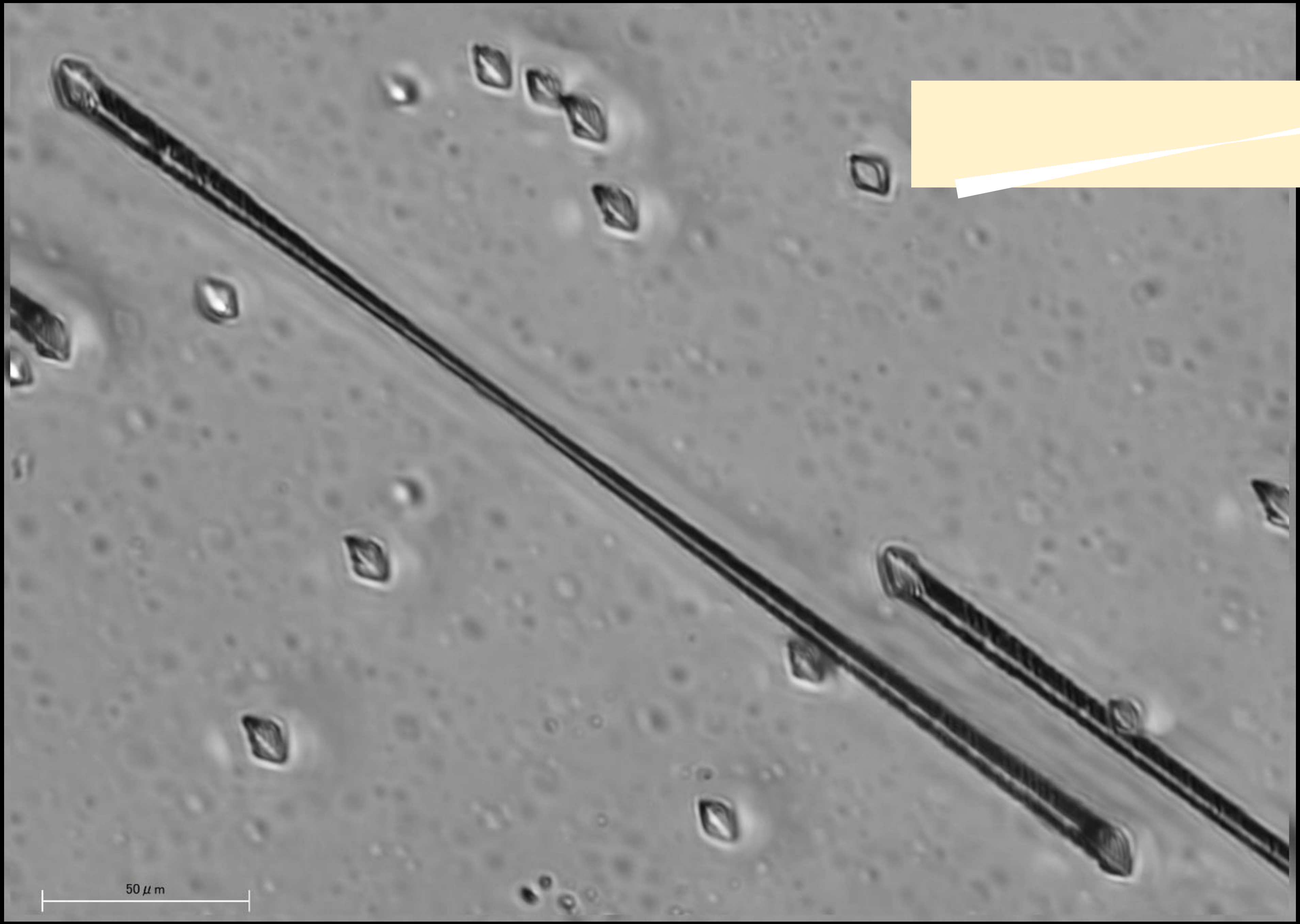




Dark matter expected
(but higher velocity component may exist
if it's not main DM component)

Demonstration for passing-through tracks
[Xe 500 MeV/u@ HIMAC, Japan]




50 μm

Long high-ionization track candidate in the mineral on the moon

The pigeonite crystals from lunar rock

* Apolo 12 sample

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

Candidate

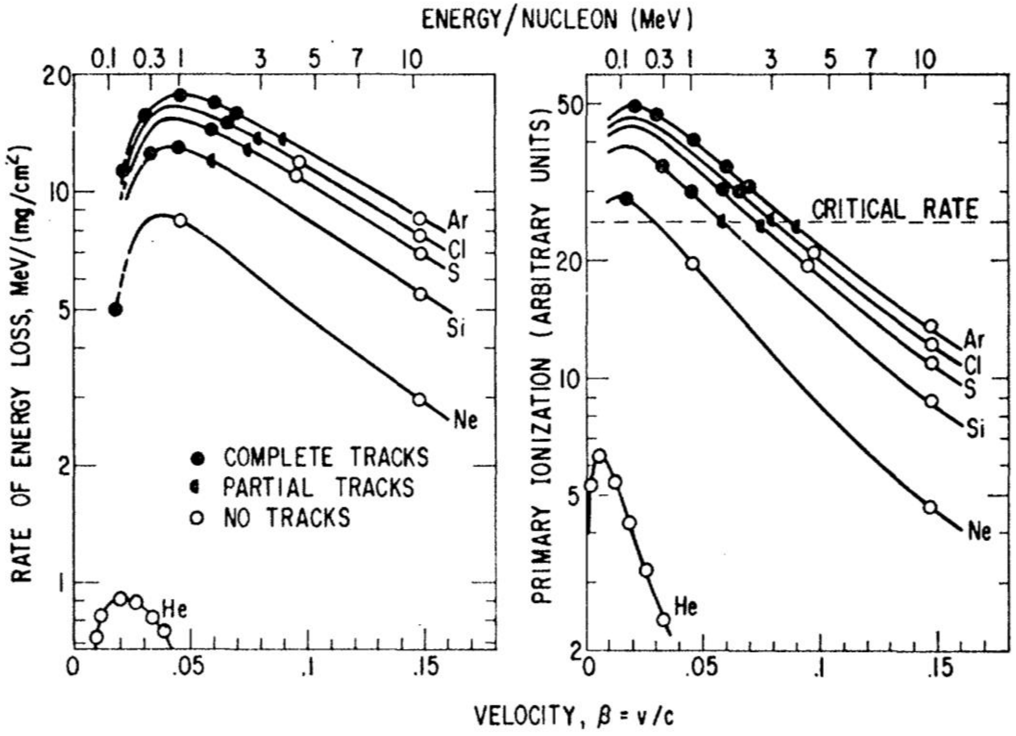
- If the heavy nuclei, it should have Z > 80
- Monopole or something ? (e.g., Q-ball)

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

Calibration of the mica

Previous research

Track formation ability for the muscovite mica



Phys. Rev. 156, 2 (1967)

- Various studies by R.L. Fleischer, P.B. Price, R.M. Walker and so on have already been done.
- However, those studies was around 1960-1970, and we should do cross-check and updated again with current cutting-edge technologies.

Primary specific ionization rate

$$J = \frac{dI}{dt} = \left(\frac{\alpha Z_1^2}{I_0 \beta^2}\right)\left[ln\left\{\frac{2m_e c^2 \beta^2}{(1-\beta^2)I_0}\right\} - \beta^2 + 3.04\right]$$

➡ **Detection ability has good correlation with primary ionization.**

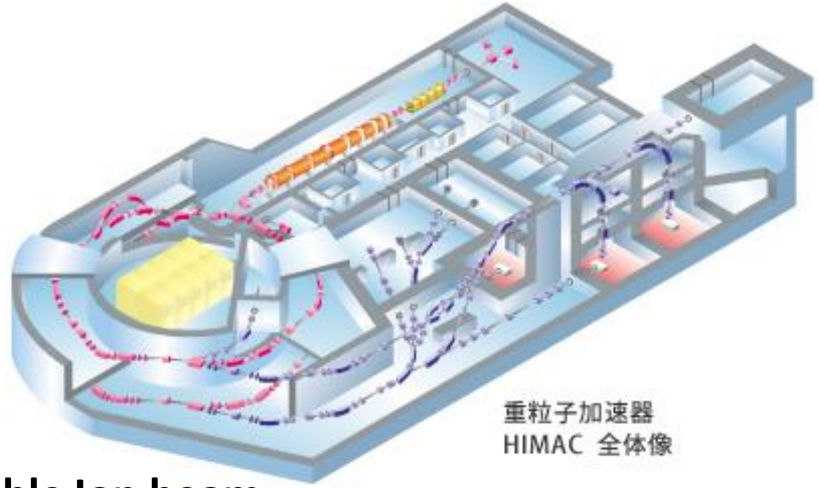
High energy ion beam

HIMAC @ QST

National Institute for Quantum Science and Technology, Japan

https://www.qst.go.jp/site/qst-english/

[Accelerator for heavy ion therapy]

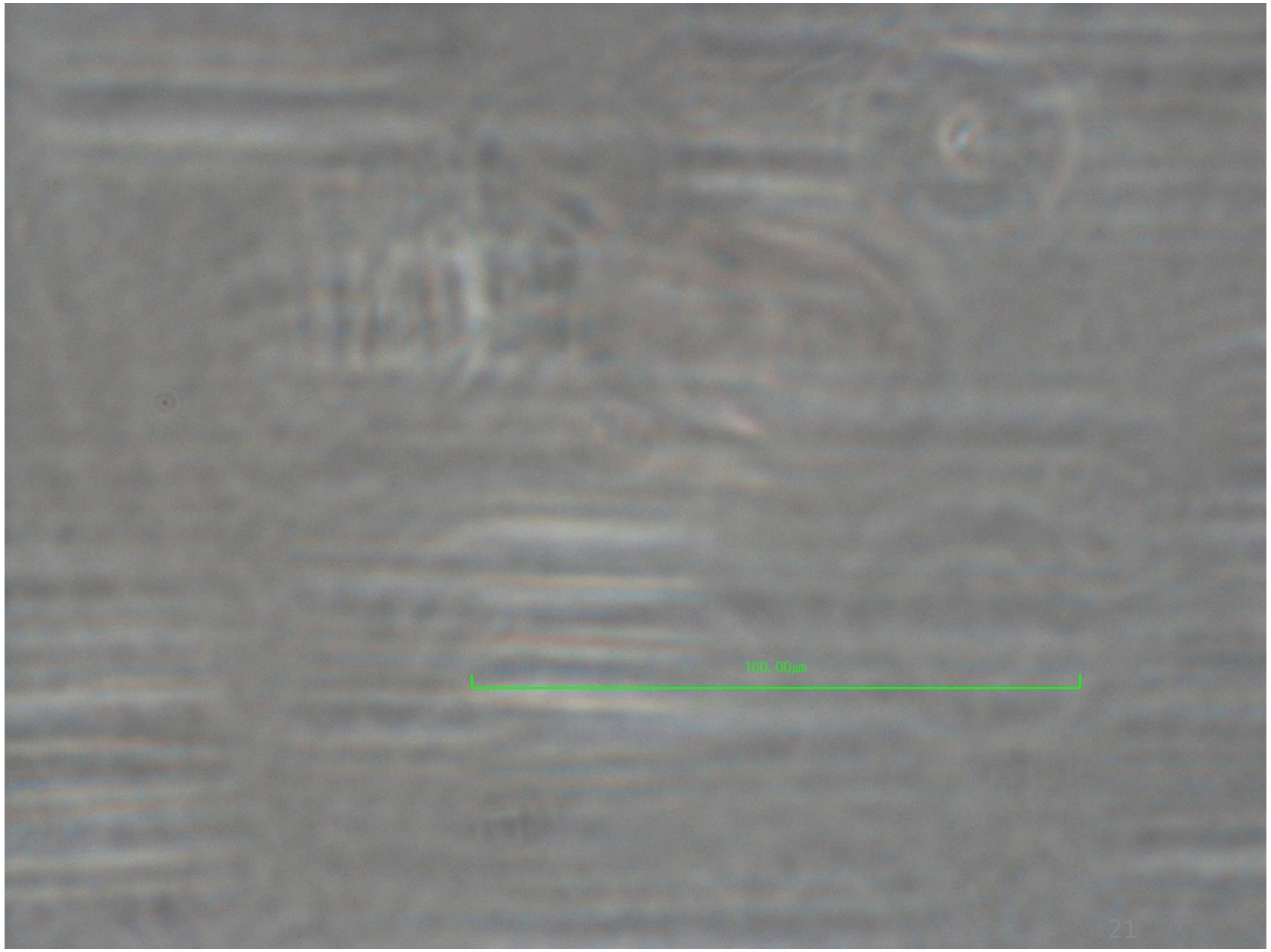


<u>Available Ion beam</u>

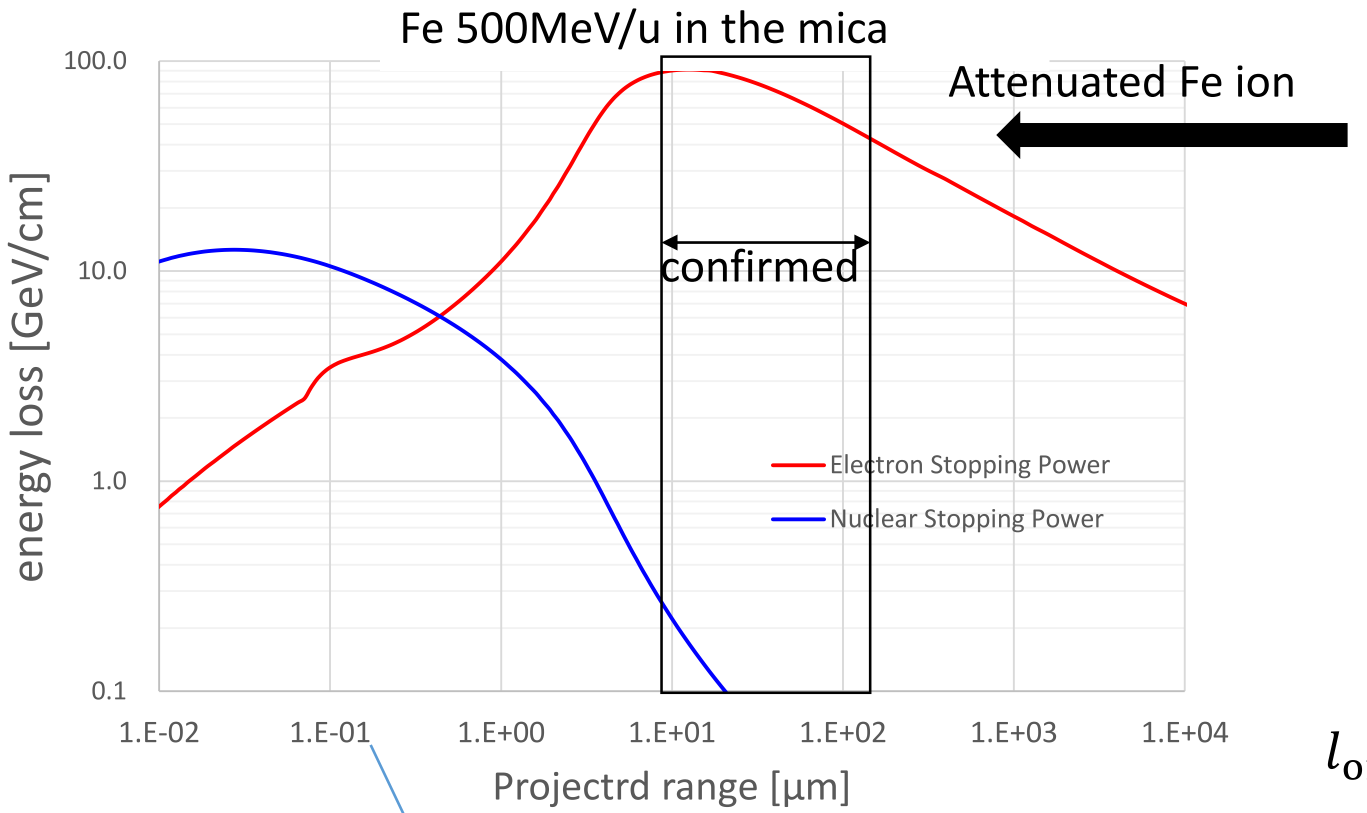
Ion	Energy [MeV/u]
He	150
C	135,290,350,400
Ne	230,400
Si	490
Ar	500
Fe	500
Xe	290

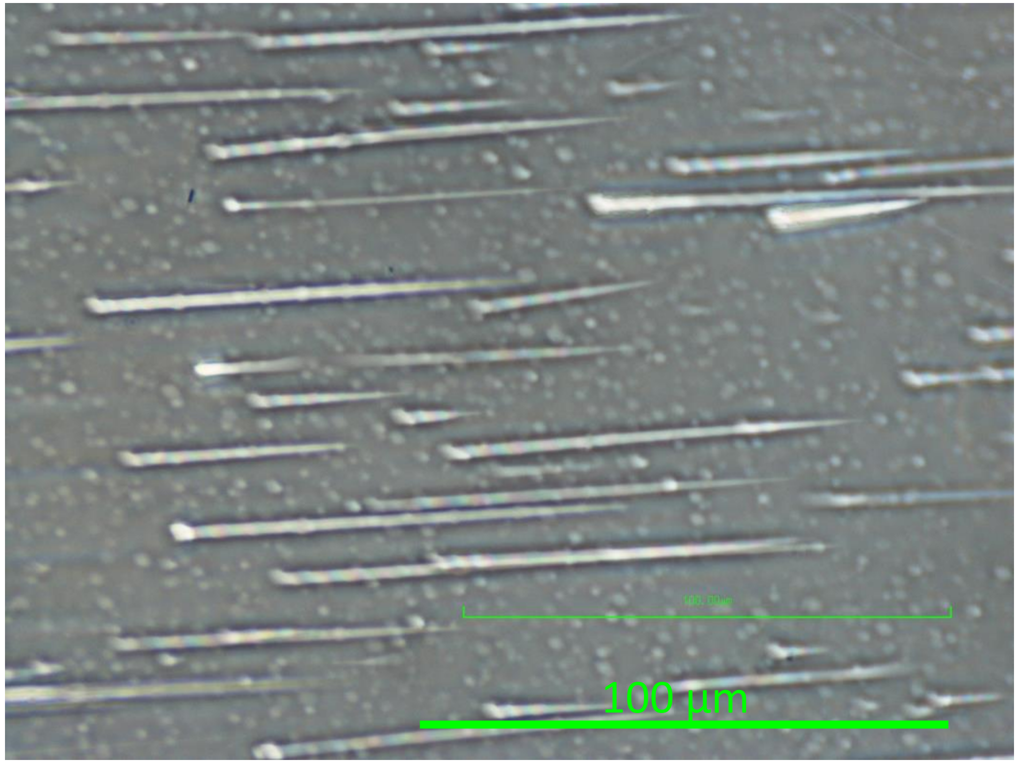
Candidate for the Paleo detector calibration

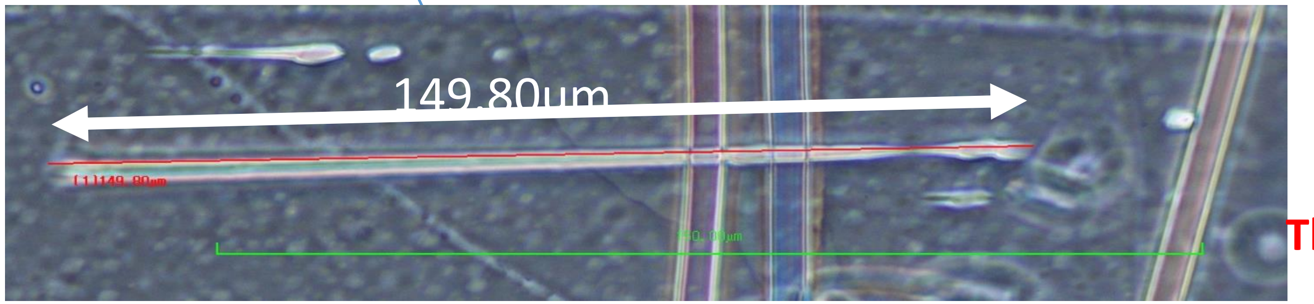
Phase contrast optical microscope image of Fe ion beam (500 MeV/u) [chemical etching with HF 46 % 25℃, 80 min]



Fe ion calibration at the HIMAC







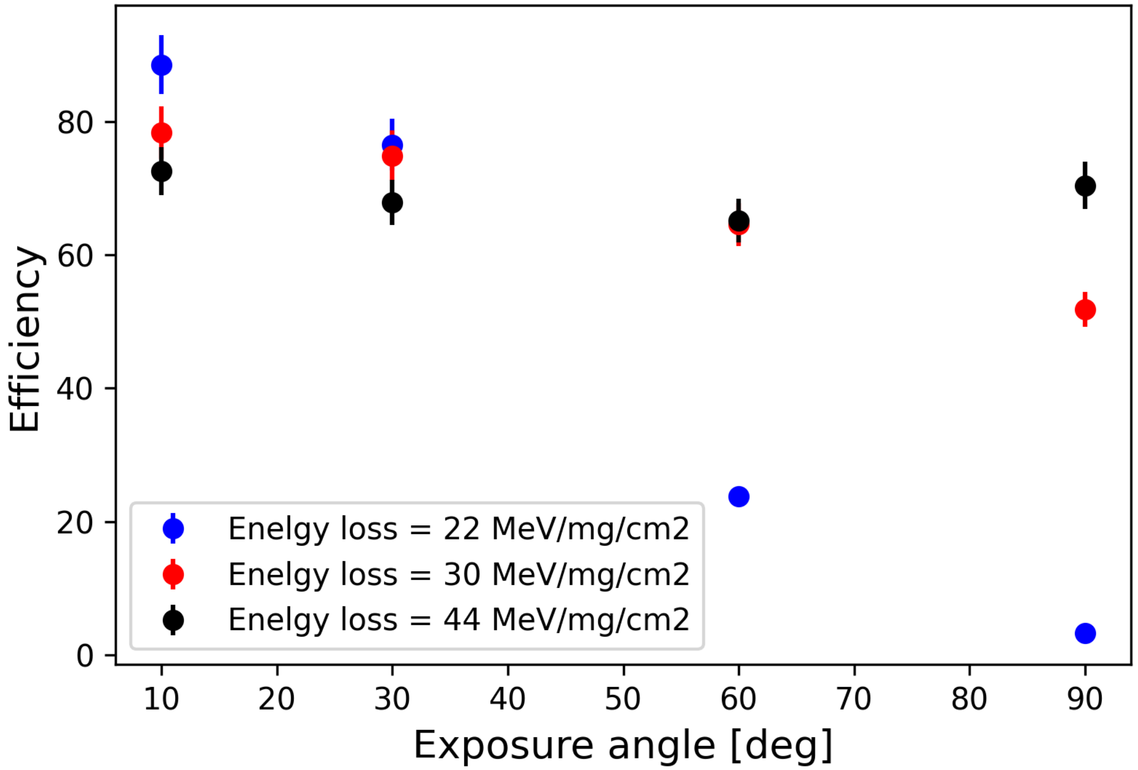
$$l_{\text{origin}} = l_{\text{Experimental value}} - 2v_{EC}t_{EC}$$
$$= 147.05\ [\text{um}]$$

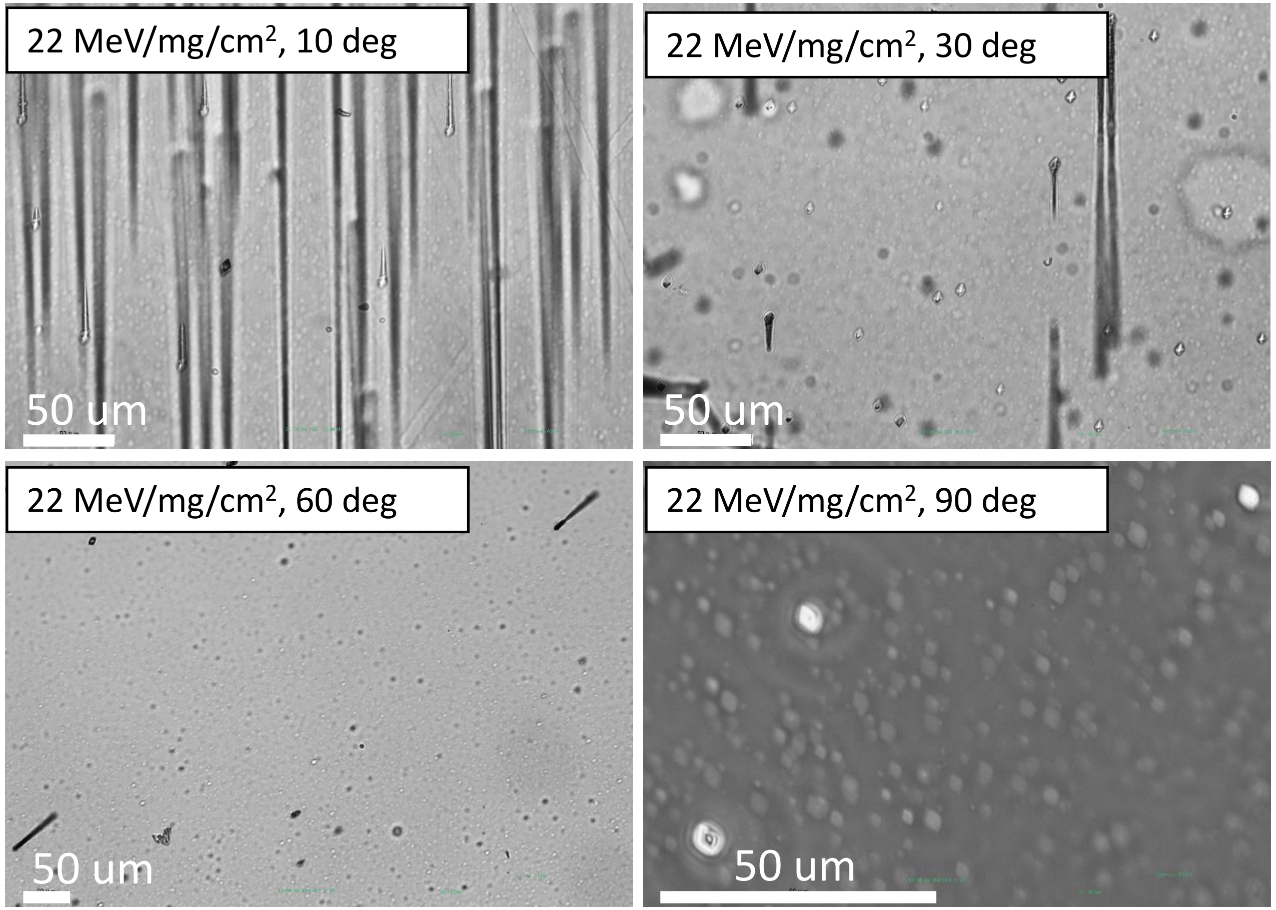
l_{origin} : original length v_{EC} : etching velocity (~ 0.03μm/min) t_{EC} : etching time (80 mi

$l_{\text{Experimental value}}$: experimental track **length** by microscope

Threshold in high-speed area→ 14.26 ~ 14.43 MeV/mg/cm²

Angular dependence in track formation efficiency and optical track image with Xe ion beam at HIMAC





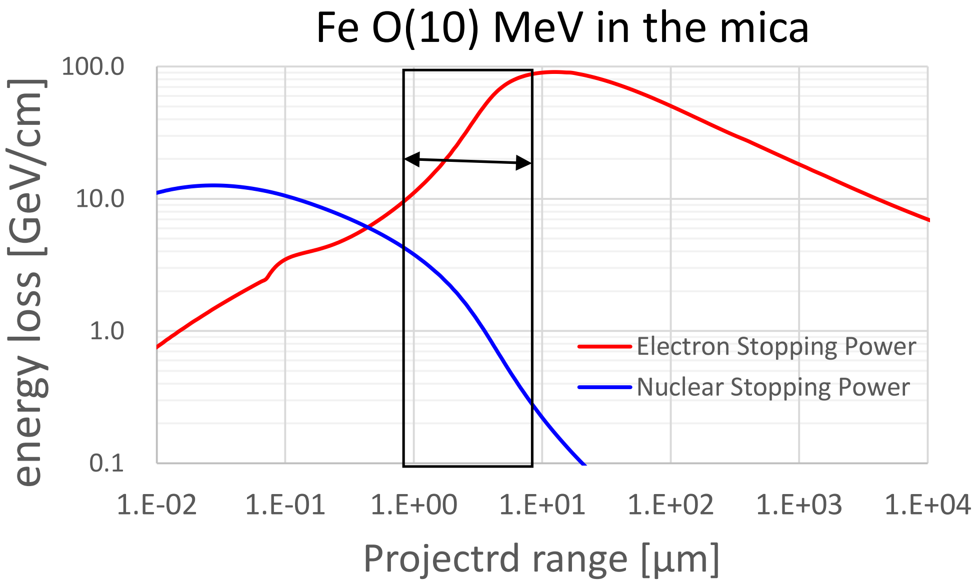
- Potential track volume related to etching might be related?
- Not much change in angle because the potential tracks are already developed where the stopping power is large?

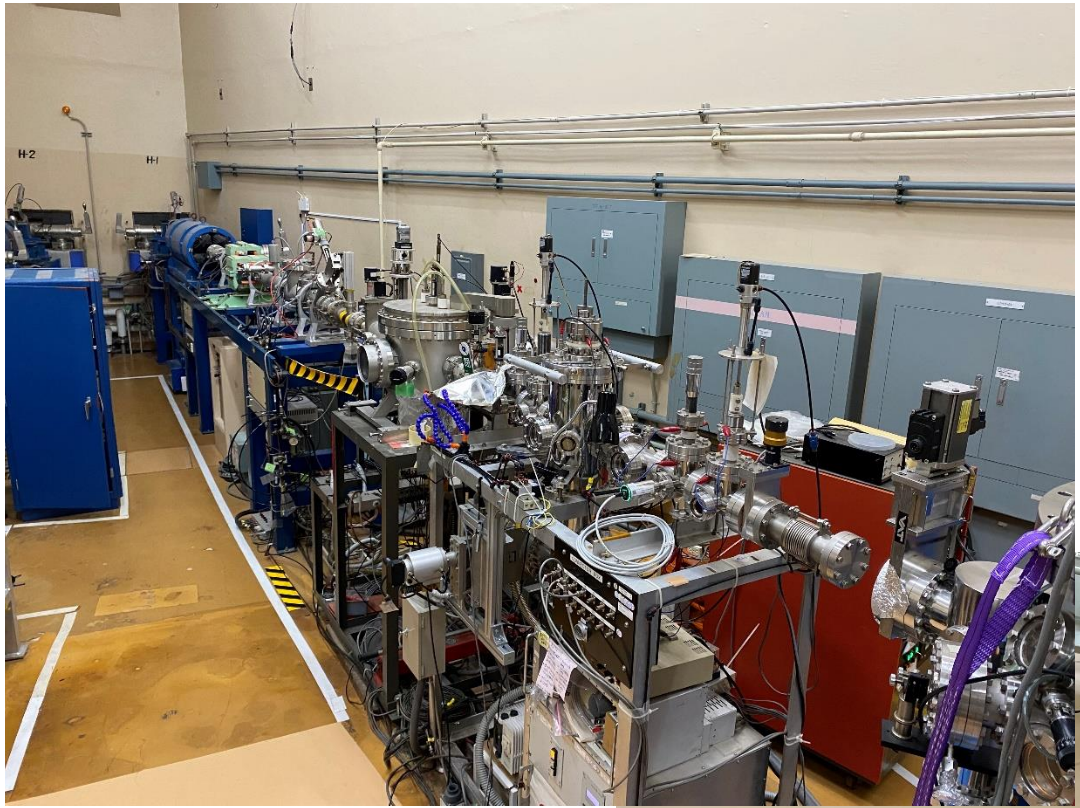
Tandem ion beam @JAEA, Japan

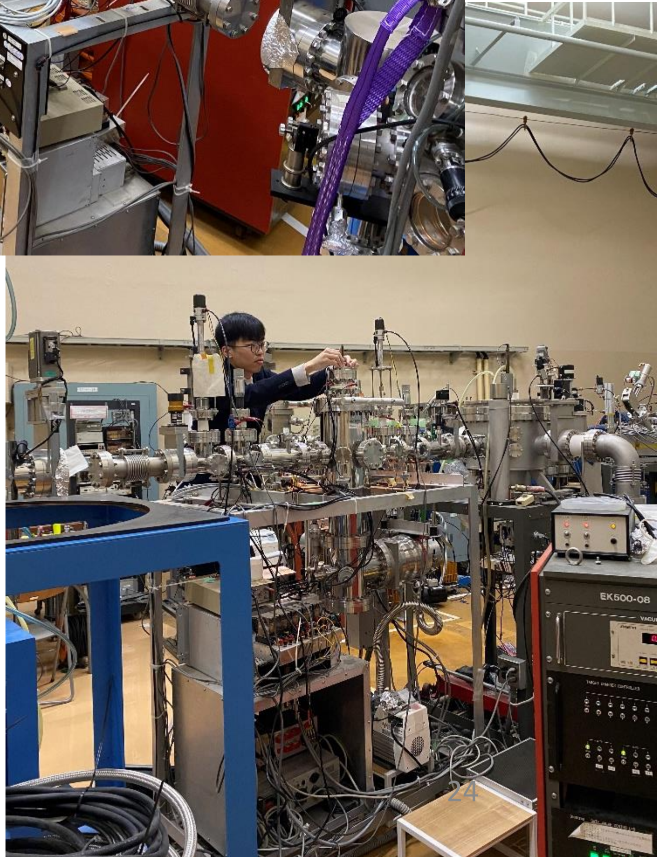
Ion : Fe

Energy : 50 ~ 70 MeV

Target : **muscovite mica**, artificial glass





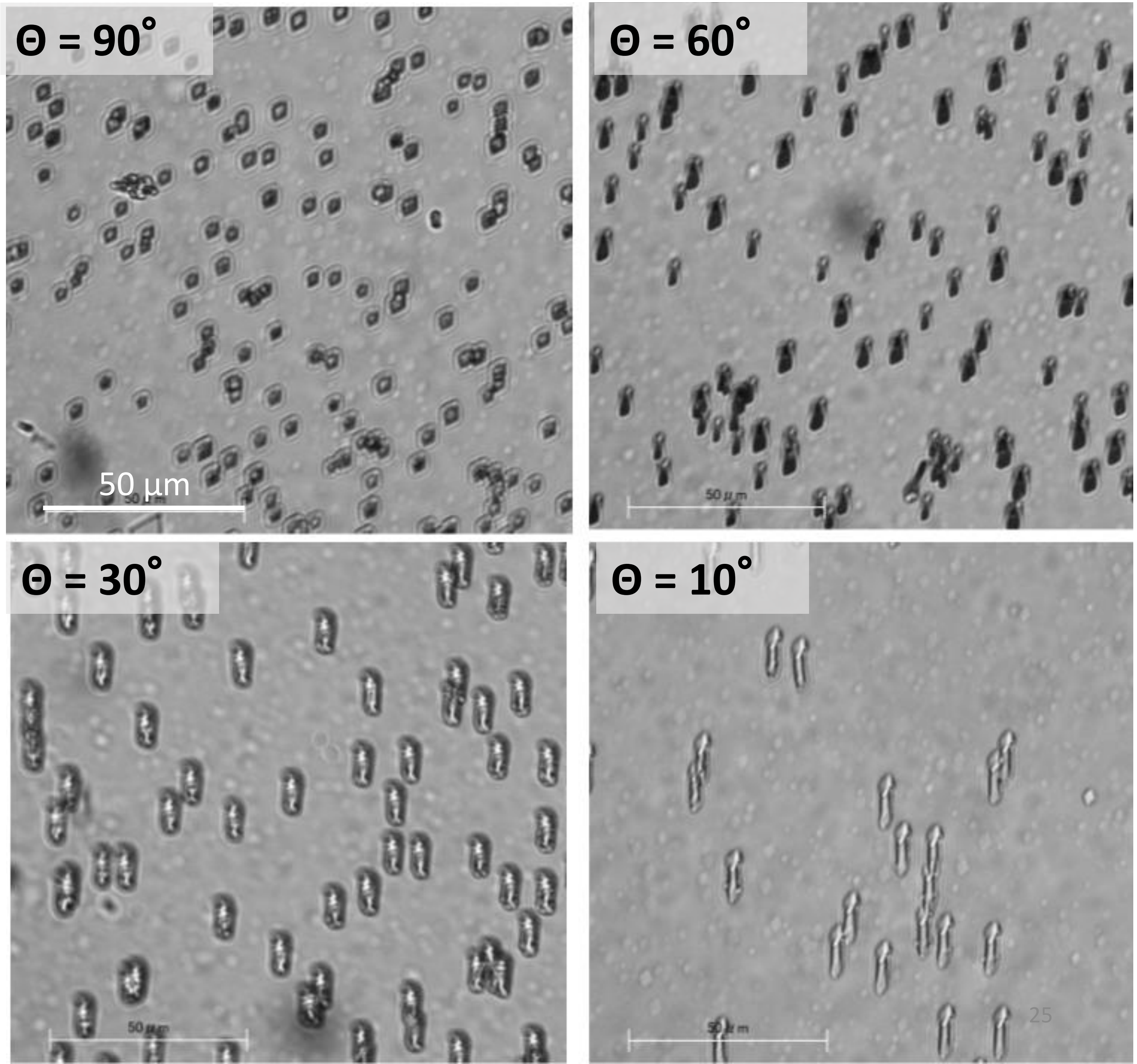


Fe ion beam

Kinetic energy : 70 MeV

* Direct expose with monochromatic energy

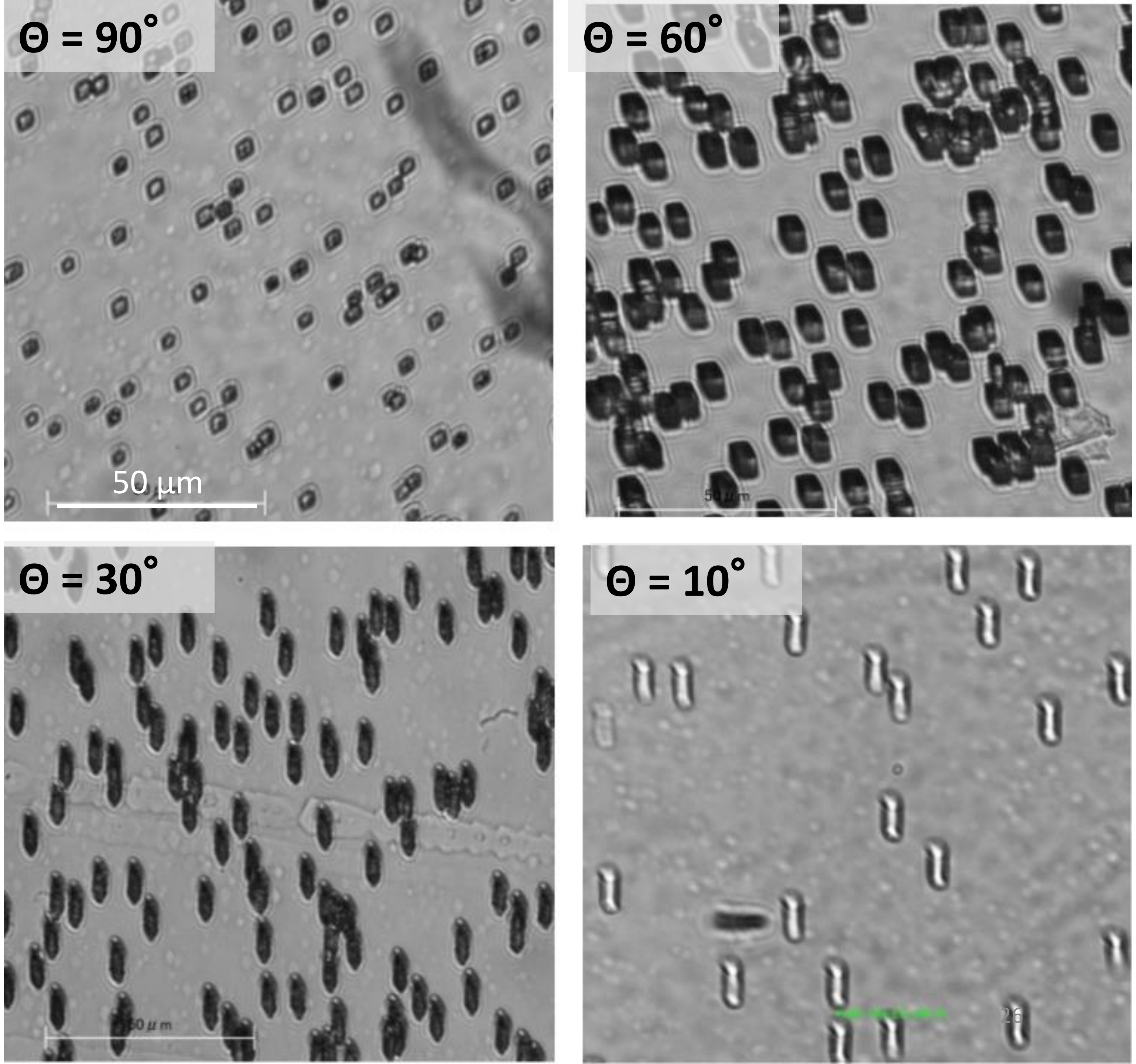
Chemical etching condition
- HF (45 %)
- 20℃, 80 min



Fe ion beam

Kinetic energy : 60 MeV

* Direct expose with monochromatic energy

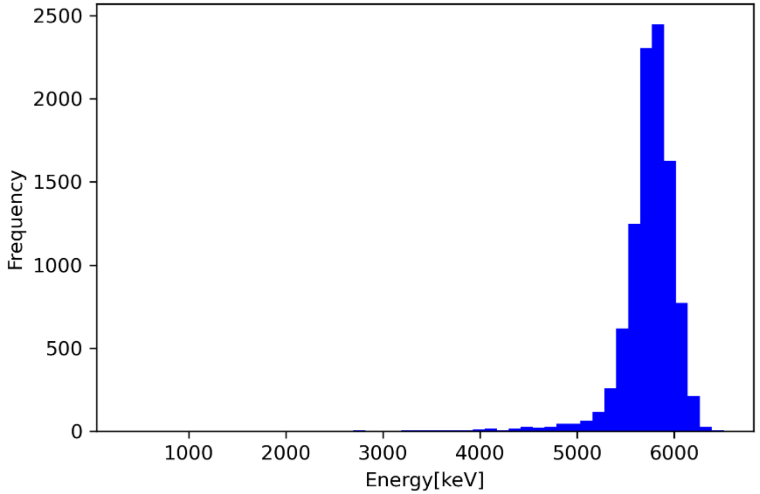


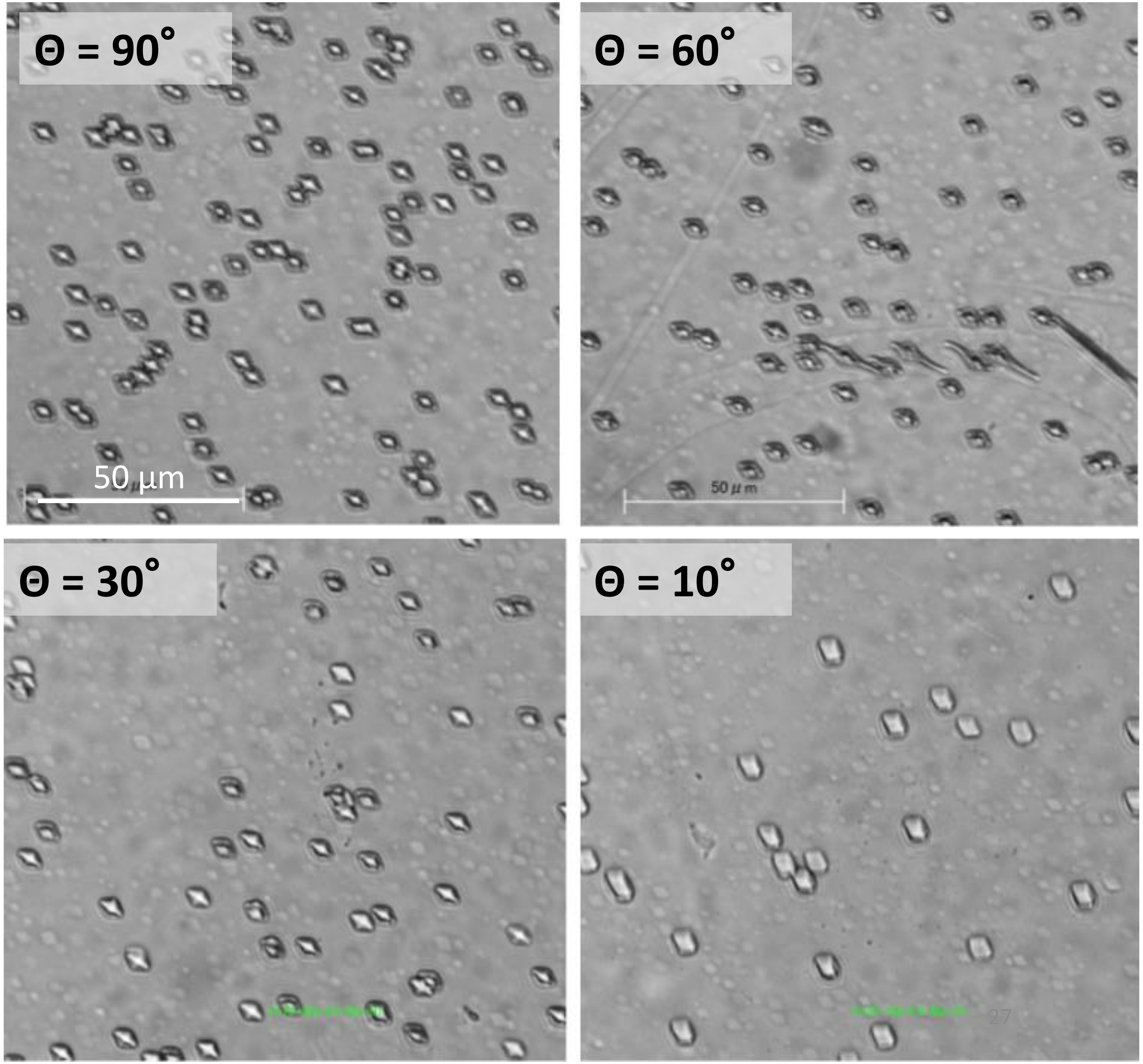
Chemical etching condition
- HF (45 %)
- 20℃, 80 min

Fe ion beam

Kinetic energy : ~ 6 MeV by attenuator

simulated incident energy spectrum



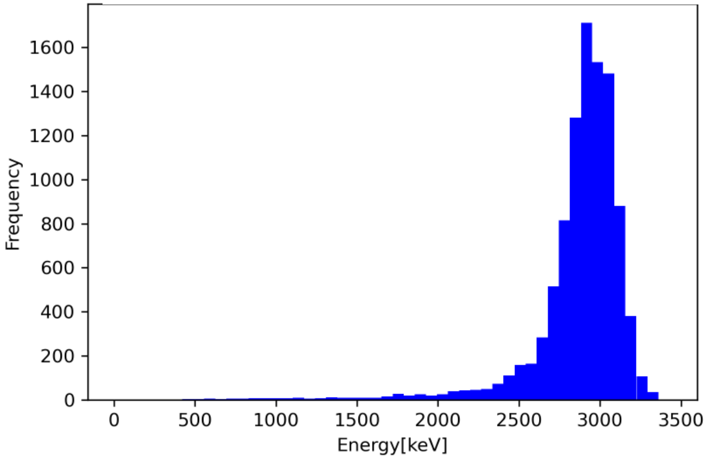


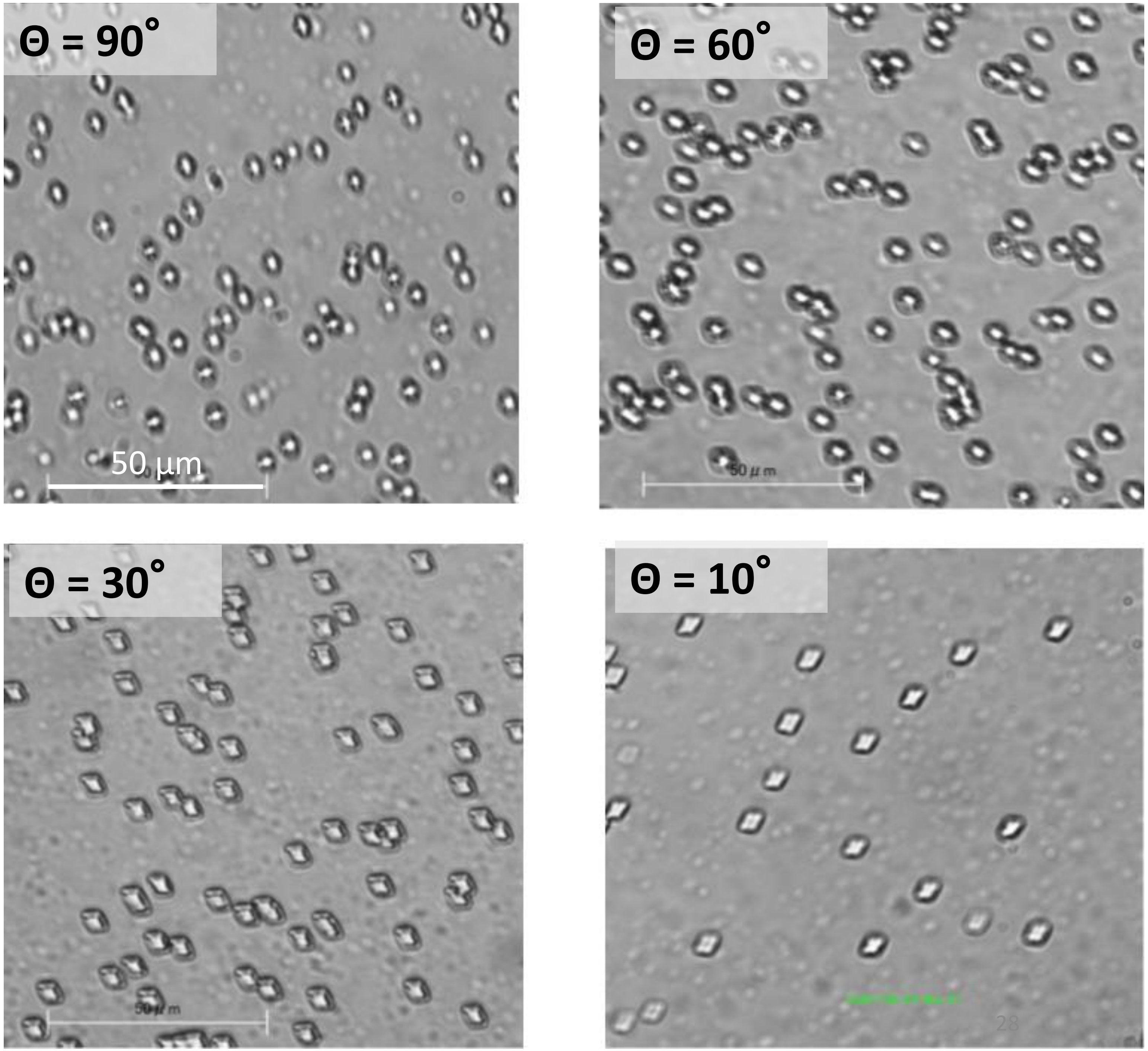
Chemical etching condition
- HF (45 %)
- 20℃, 80 min

Fe ion beam

Kinetic energy : ~ 3 MeV by attenuator

simulated incident energy spectrum





Chemical etching condition
- HF (45 %)
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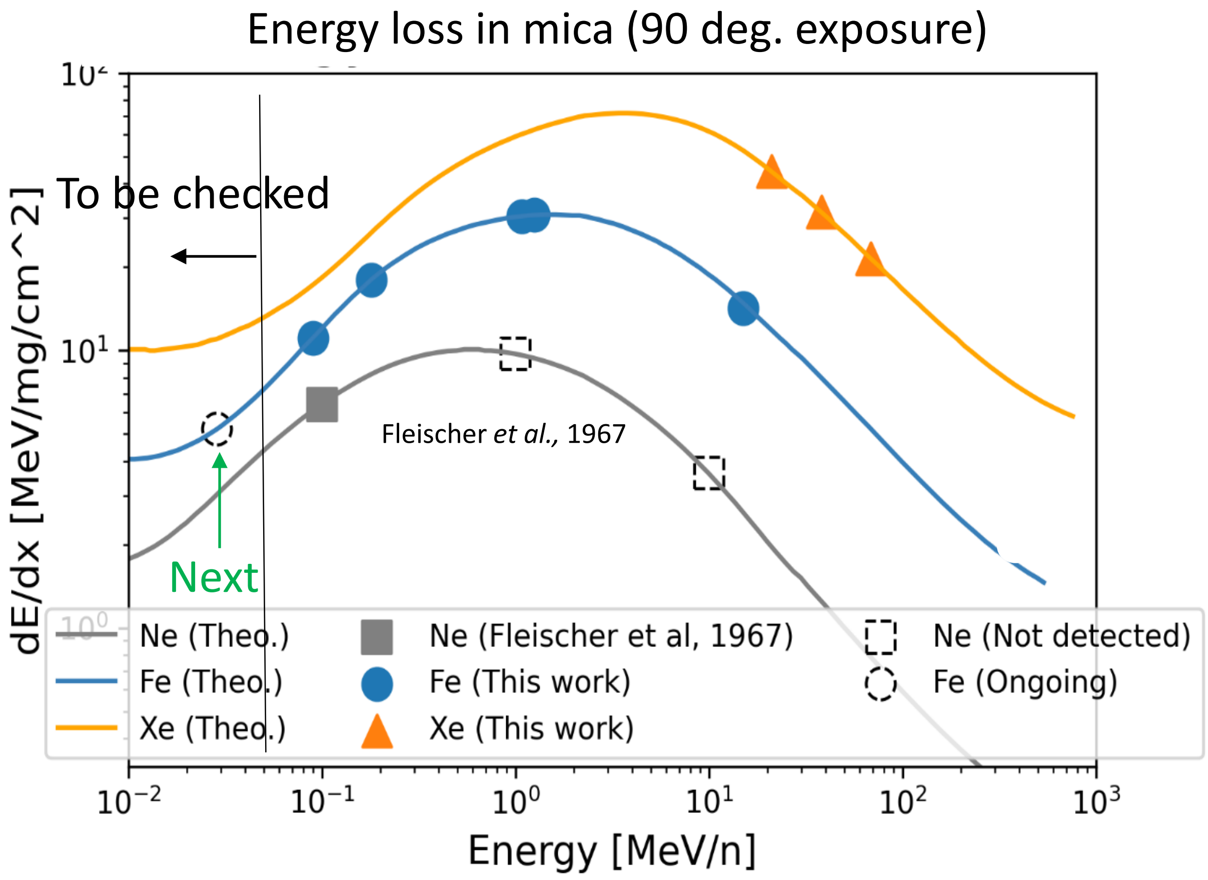
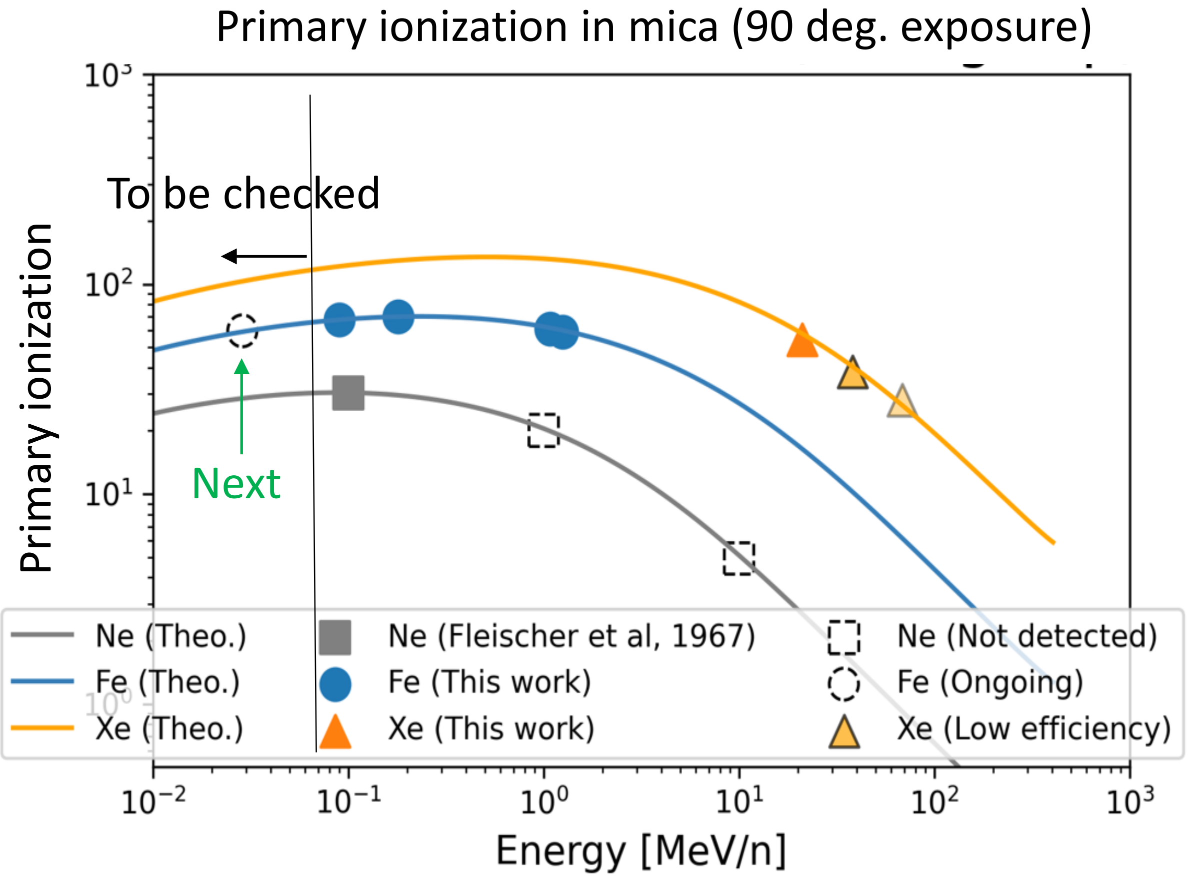




Almost consistent response was observed with previous study by Fleischer, Price et al..

Automatic readout system

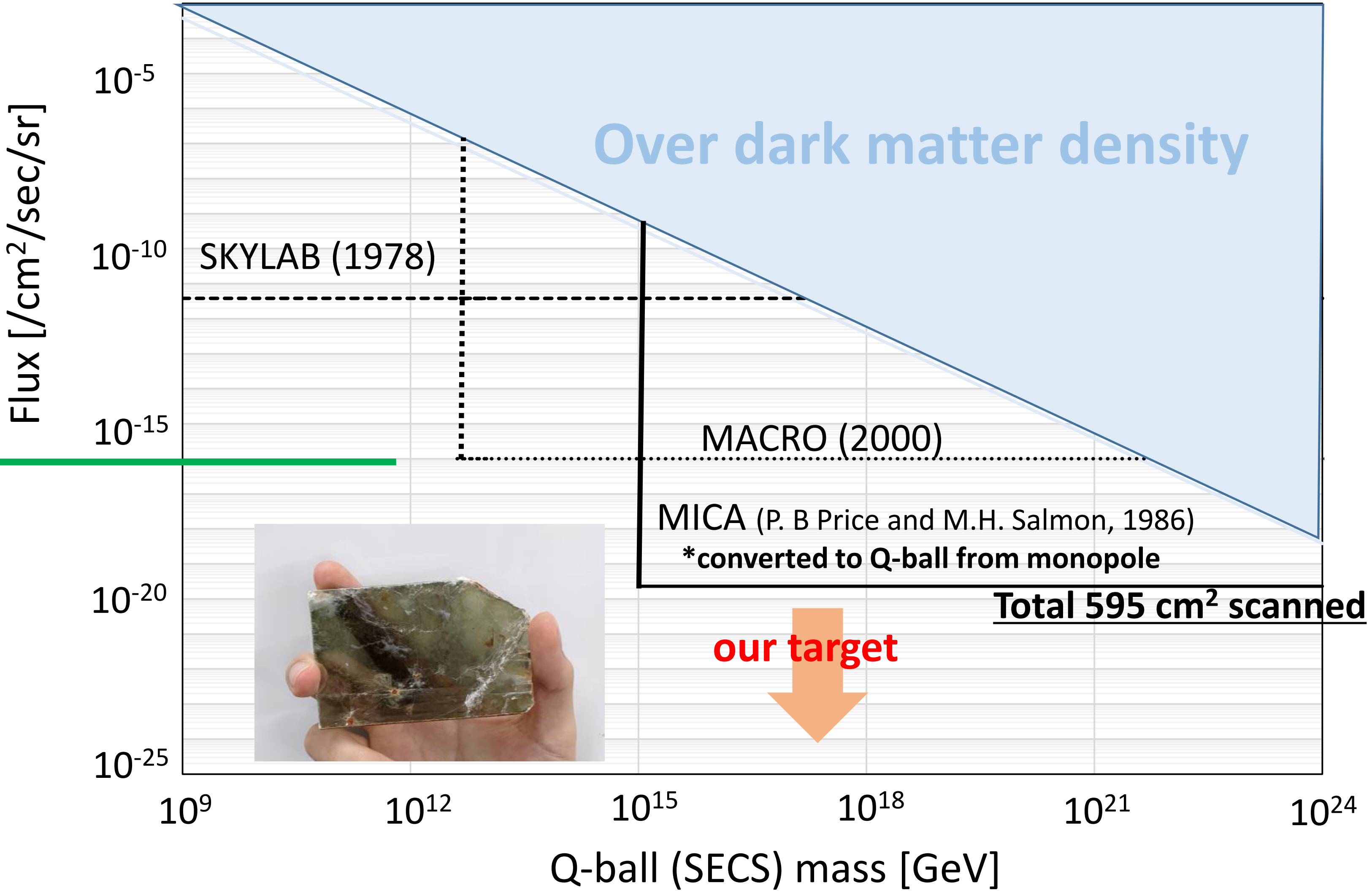
Expected achievement for Q-ball search with the mica + current cutting-edge technologies

MACRO experiment [1989-2000]

CR-39 (plastic damage detectors)

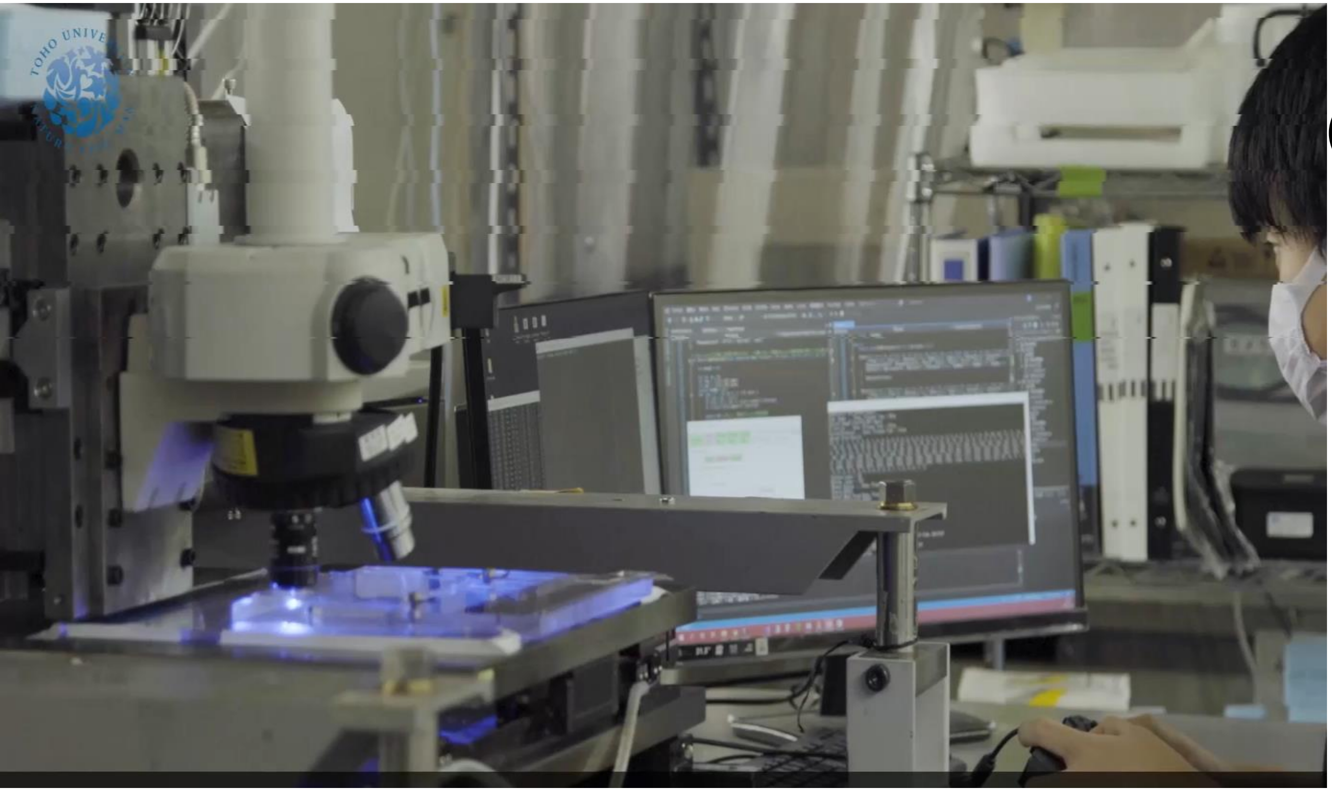
Observed area : O(10 x 10) m^2

Exposure time : O(1) year



Optical microscope scanning system

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)

⇩

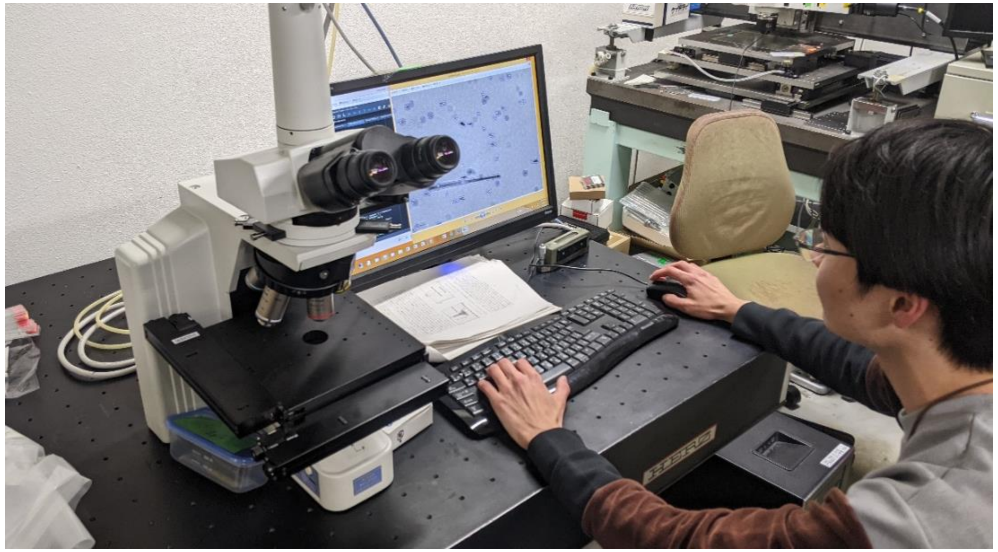
Optimization : 1h /100 cm^2 (for Paleo detector)

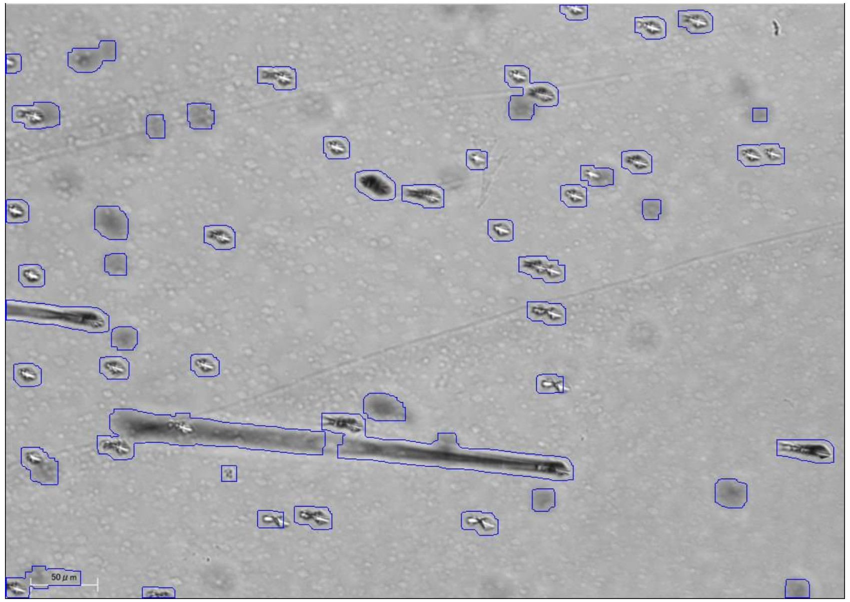
⇩

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

Now on construction !

New scanning system for the Paleo detector





Construction of automatic optical scanning system

- Driving stage installation was done
- Piezo actuator for Z driving and high speed camera will be installed soon.
- Scanning program will be diverted from nuclear emulsion scanning

Image Processing study

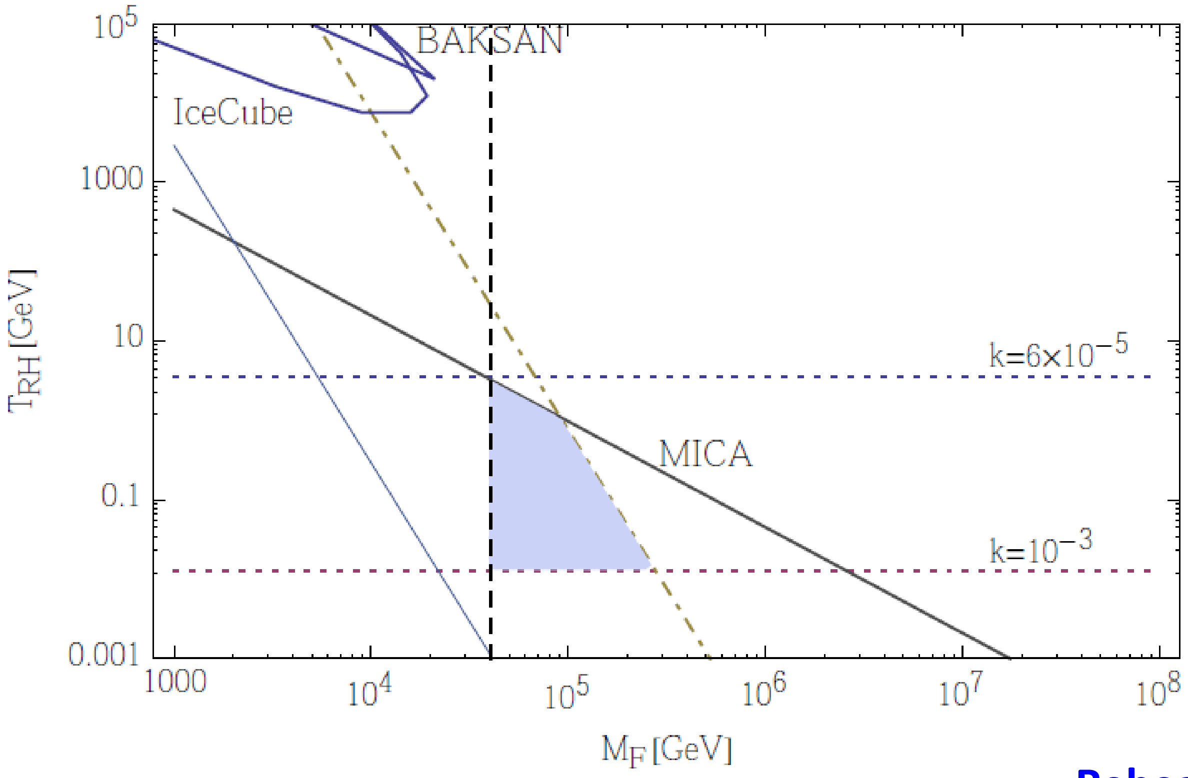
- Optimal image processing is investigating
- Deep learning will be installed for more efficient event selection

First operation and search of the Q-ball-like tracks will be started in this year.

Expectation for searching the astroparticle physics parameter space

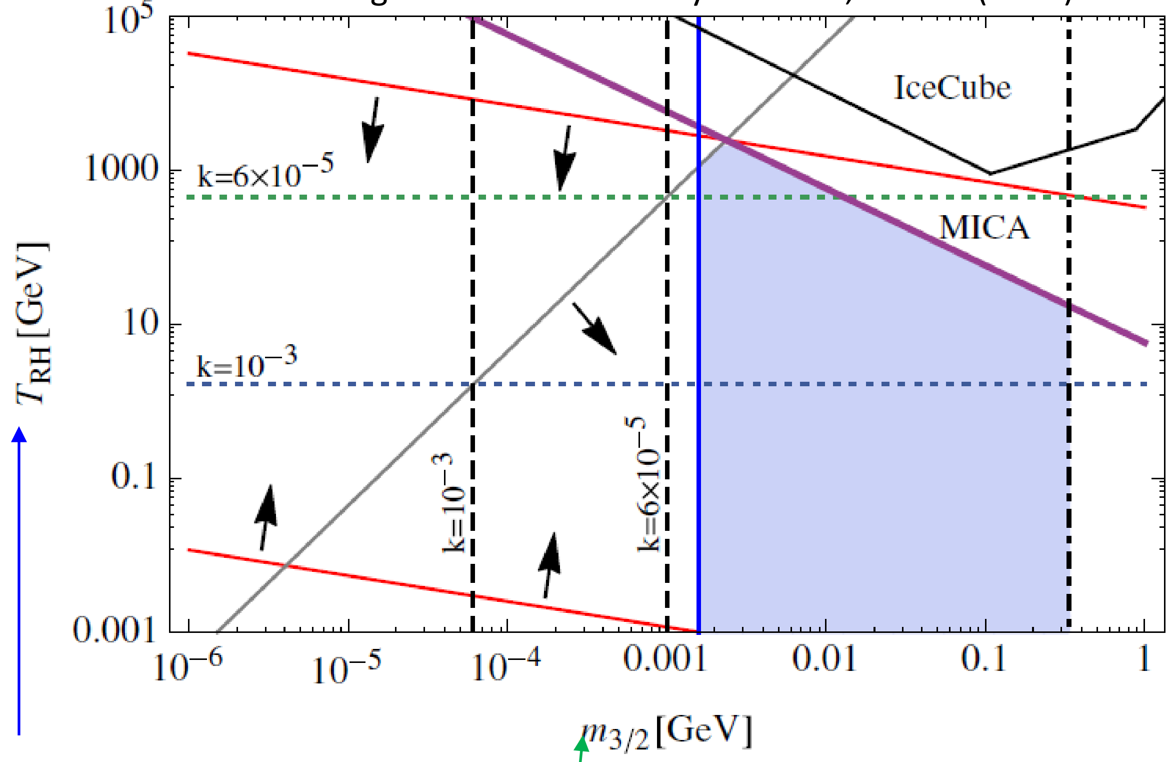
Gage mediated Q-ball

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



New type Q-ball

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



Reheating temperature

Gravitino mass

$$\frac{\rho_{DM}}{s} \sim \frac{3T_{RH}}{4}\frac{M_Q n_\phi/Q}{3H_{osc}^2 M_P^2} \sim \frac{9}{4} T_{RH} \frac{\phi_{osc}^2}{M_P^2},$$

Conclusion

- **Mineral is powerful detector for very low flux particles.**
- **Very heavy dark matter such as composite DM (e.g., Q-ball, quark nugget ・・) are important targets.**
- **"Charged" Q-ball can be stable with around Z_Q~137, and it is expected to exist as very heavy atom**
- **Such charged Q-ball can be detected by the muscovite mica, and it's capability of searching with the highest sensitivity to any other experiment.**

Any other candidates are targets such as the quark nuggets, monopole etc.

- **In this study, we conducted research to better understand detector (i.e., muscovite mica) more universally using any heavy ion accelerator.**

Task

- Detection capability for lower energy range (few MeV or less) will be researched.
- Investigation of track formation mechanism for low-velocity region which nuclear stopping power is higher than electron stopping power, also surely chemical etching effect.
- Optical microscope system for large area scanning is constructing, and start the operation in this year.