Paleo Detector

technological development and future prospects

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Toho University/KMI, Nagoya

Workshop, Cutting Edge Technology for Understanding the Earth, 2022.1.12 @Tohoku Uniersity, Sendai

Collaboration

Particle Physics
×
Astrophysics
×
Geoscience
×
Material Science

■ JAMSTEC
HIROSE Shigenobu
ABE Natsue
KAWAMURA Yoji

■ ISEE, Nagoya U.
KATO Takenori
KAZAMA Shingo
ITO Yoshitaka
KOUKETSU Yui
MICHIBAYASHI Katsuyoshi

■ Pennsylvania State U.
MURASE Kota

■ Toho U.
NAKA Tatsuhiro
IDO Yuki
SHIRAISHI Takuya

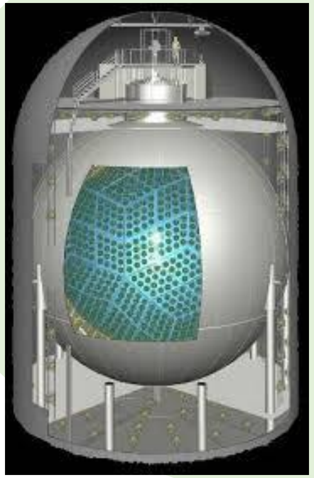
■ Kanagawa U.
HOSHINO Yasushi

■ Kochi U.
KOZAKA Yukiko

■ Kyoto U.
IGAMI Yohei

Detectors for the particle physics

Scintillator



- high energy physics
- neutrino physics
- dark matter search

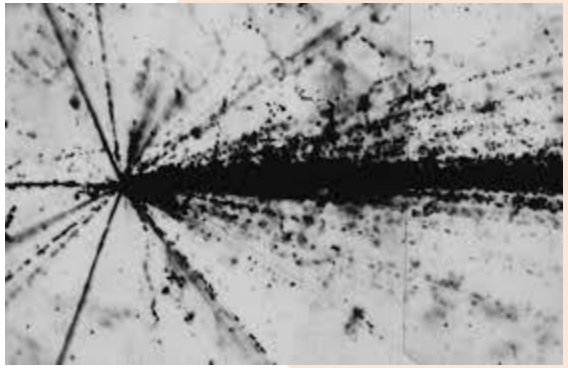
etc

Cherenkov detector

- high energy physics
- neutrino physics
- proton decay search

etc.

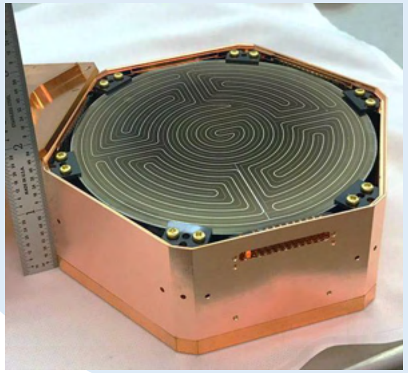
Tracking detector



- High energy physics
- Neutrino physics
- Nuclear physics
- Dark matter search

etc

Semiconductor



- High energy physics
- Neutrino physics
- Dark matter search

etc

Paleo detector → **Damage track detection in mineral**

https://en.wikipedia.org/wiki/Celestine_%28mineral

Track formation

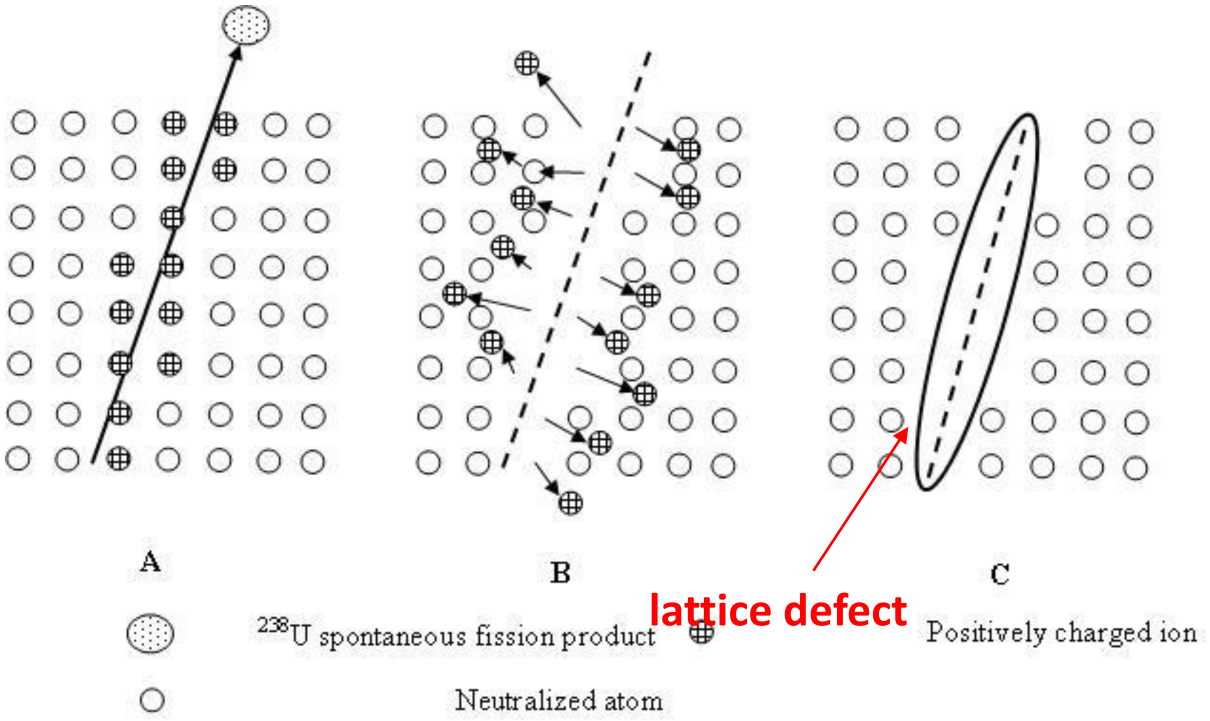


Figure 1. Track formation in a simple crystalline solid: **A** the atoms have been ionize by the massive charged particle which has just passed; **B** the mutual repulsion of the ion has separated them and forced them into the lattice; C observable track after etching (Modified after Fleischer et al., 1965a)

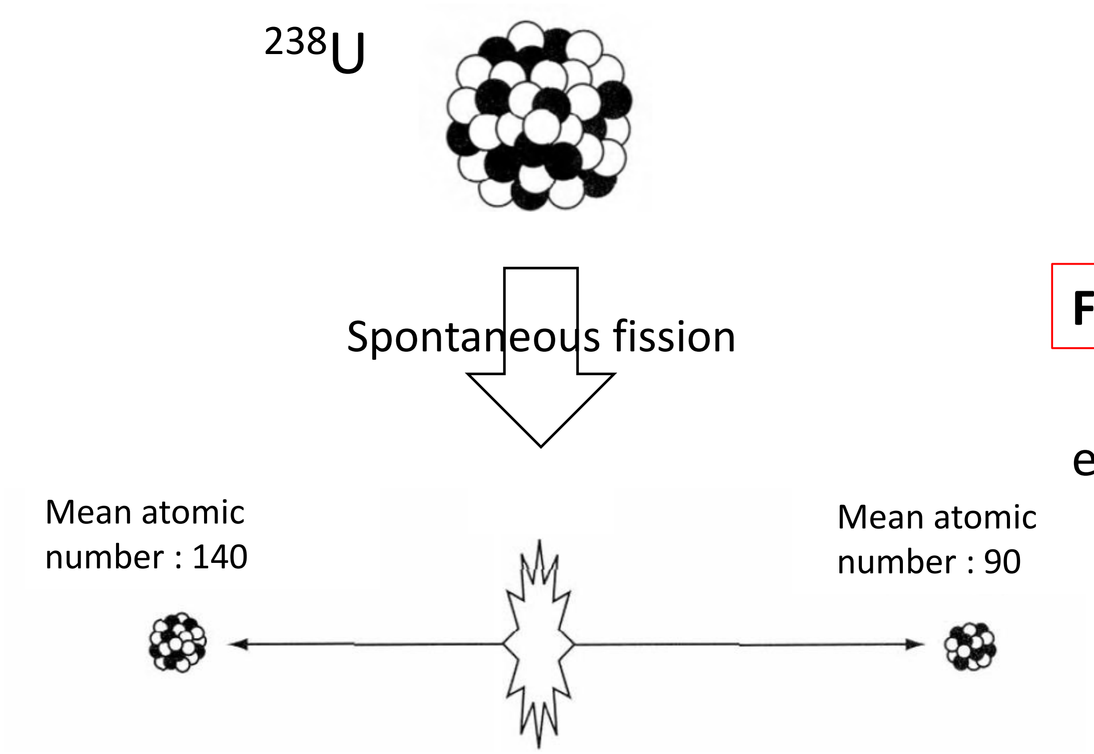
Chemical etching

Example of fission tracks by the Zircon

High energy deposition is needed to enough create the lattice defect.

Mineral as particle detector

Fission track dating



^{238}U : abundance of 99.3 % in isotope of U

Life time of S.F. : 8.2 x 10^{15} y
Decay constant λ : 8.4 x 10^{-17} y^{-1}

Fission track density = $\lambda \times$ n (density of U) $\times$ T (date)

e.g., In case of 1 ppm U contamination and 1 G year

Fission track density ~ 10^8 S.F. /g

<u>Fission tack dating by observation of the tracks</u>

Particle Physics

×

Geological science

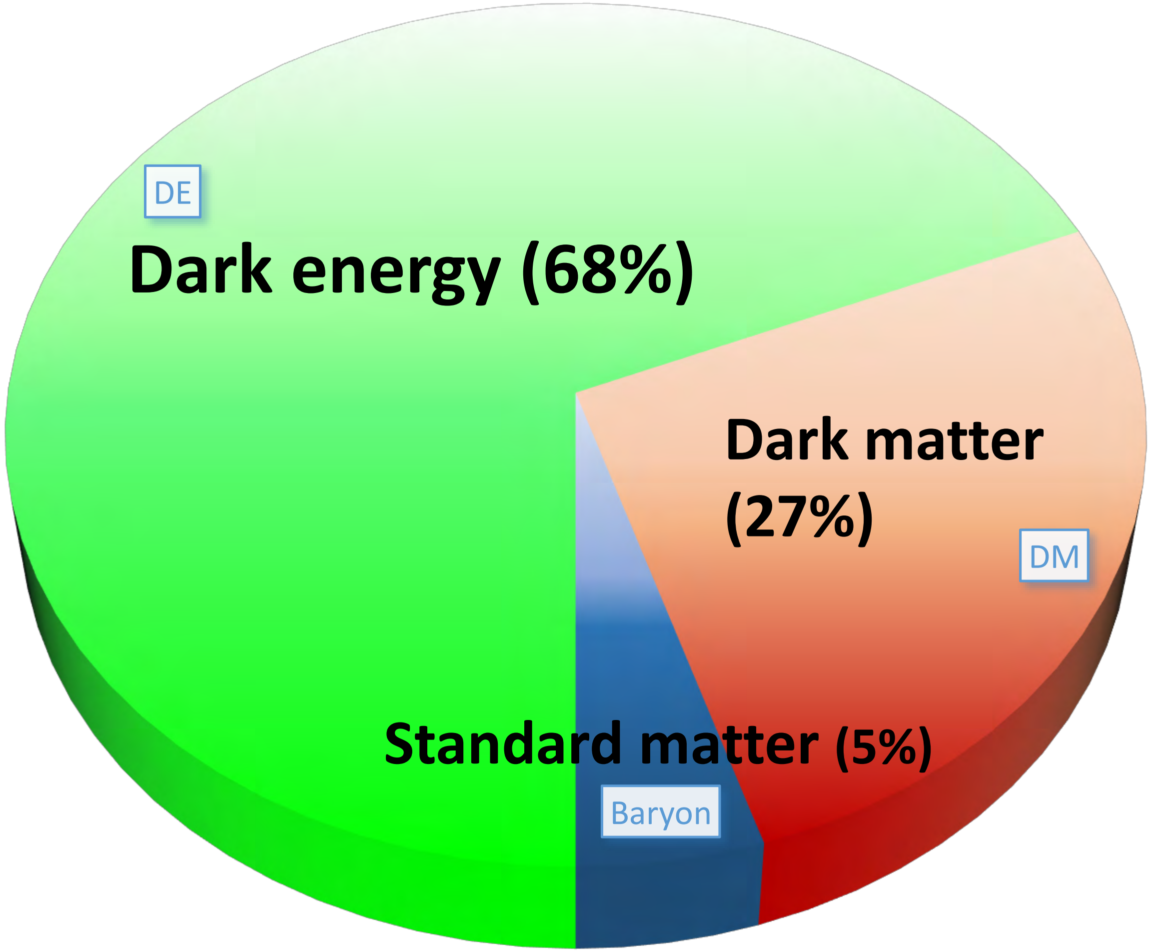
Serious problem for the particle physics

- **Symmetry breaking → asymmetry of particle and anti-particle**
- **Hierarchy Problem**
- **Neutrino mass**
- **Strong CP problem**
- **Baryogenesis (mechanism of generation of baryon in the early universe)**
- **Dark matter**
- **Dark energy**

*** All is the Nobel Prize-worthy theme**

Dark Matter

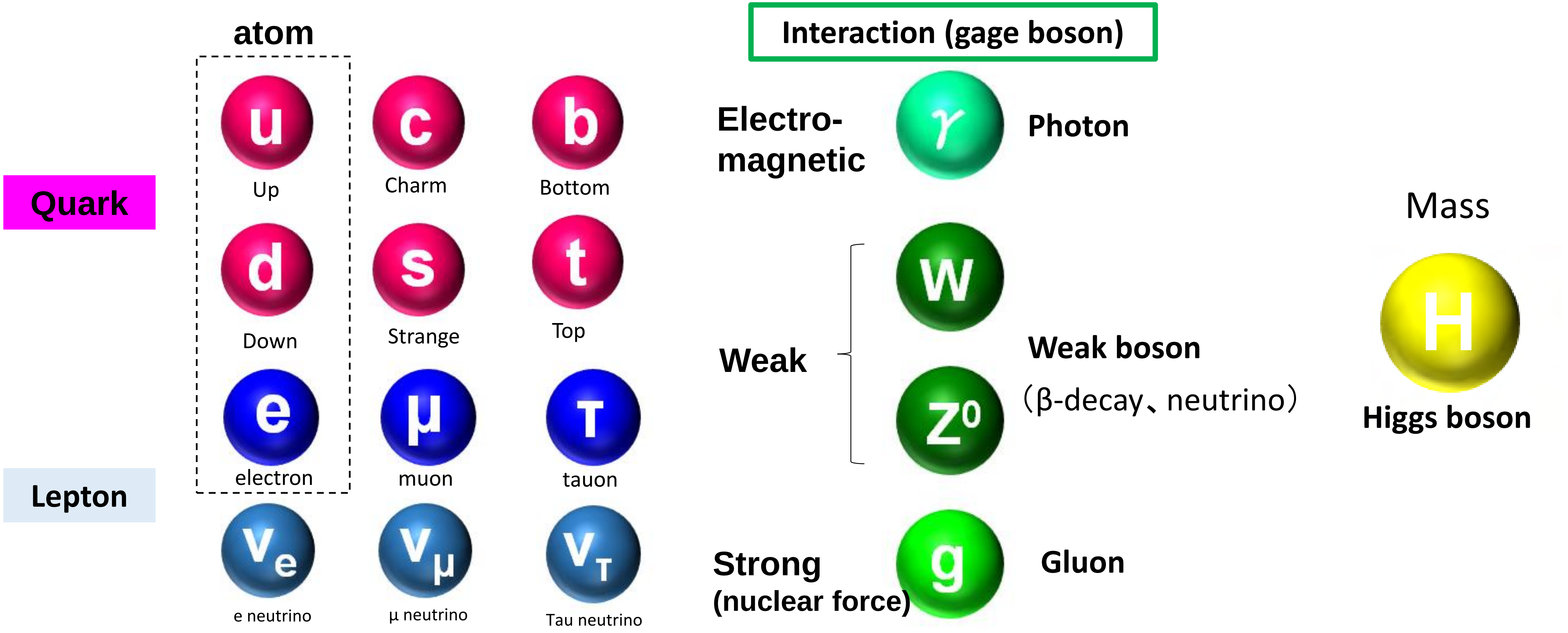
- Standard matter consist of only 5 % in the universe, and 95 % is unknown yet.
- There are various evidence of existence of dark matter from motion of galaxy, gravitation lens, cosmic microwave background and so on.



Planck 2013 results

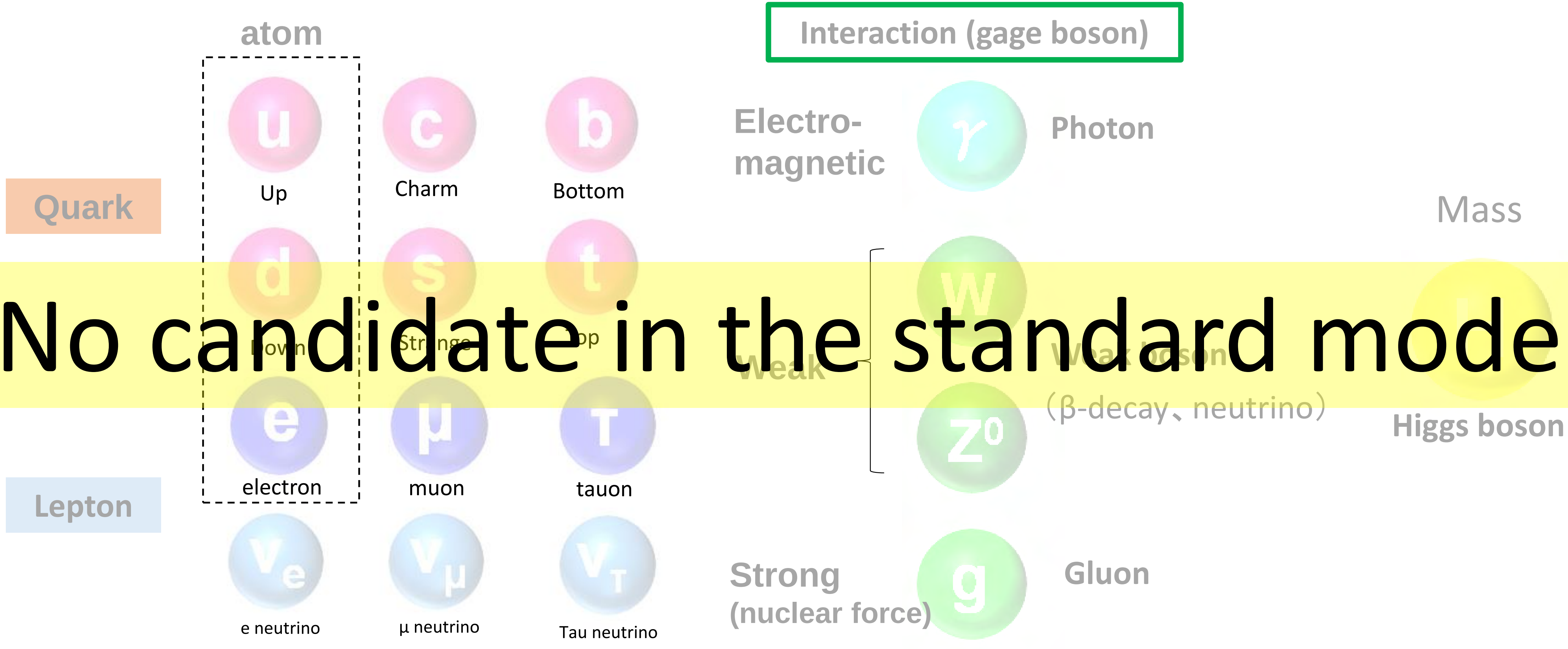
However, we don’t know the identity and properties of dark matter.

Standard model for the particle physics



＋ anti-particles

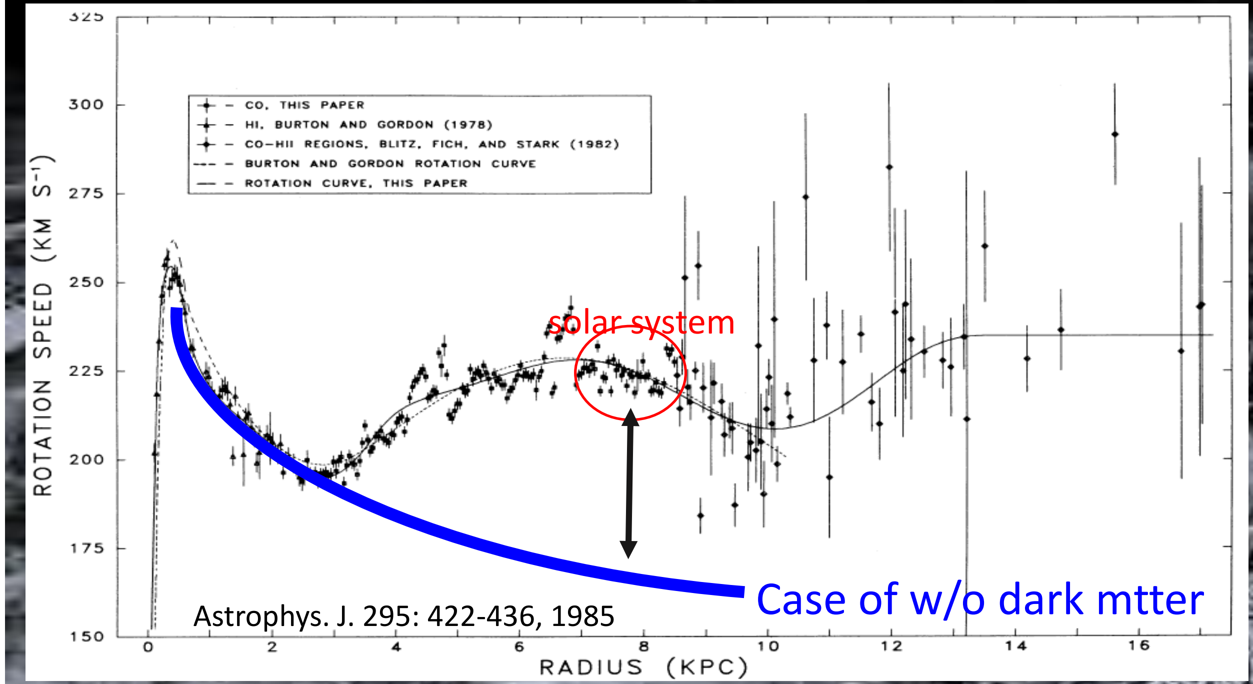
Standard model for the particle physics

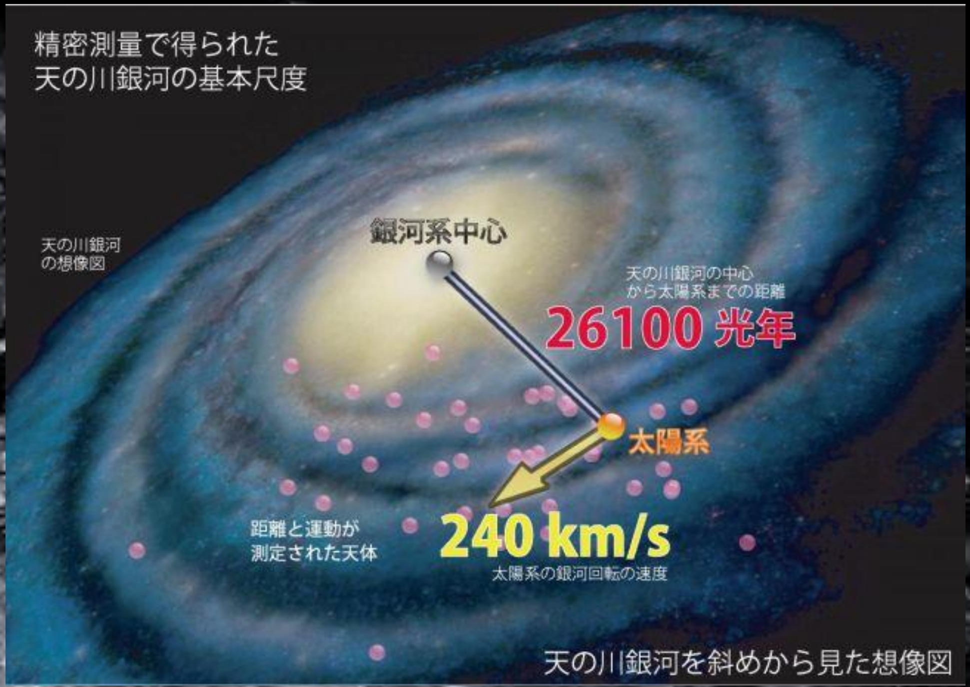


＋ anti-particles

No candidate in the standard model

Dark Matter in the milky way galaxy





$$v = \sqrt{G\frac{M(r)}{r}}$$

With out dark matter : $v \propto \frac{const.}{\sqrt{r}}$

Actual data : $v \propto const.$

$i.e., M(r) \propto r$ almost visible matter is condensed around galactic center

Local dark matter density : 0.4 GeV/cm^3

~ 1000000/cm^2/s on the earth in case of DM mass of 10 GeV/c^2

Dark matter candidate for particle physics

- Weakly Interacting Massive Particle (WIMP)
- Q-ball
- Monopole
- Axion

Paleo detector targets

⋮

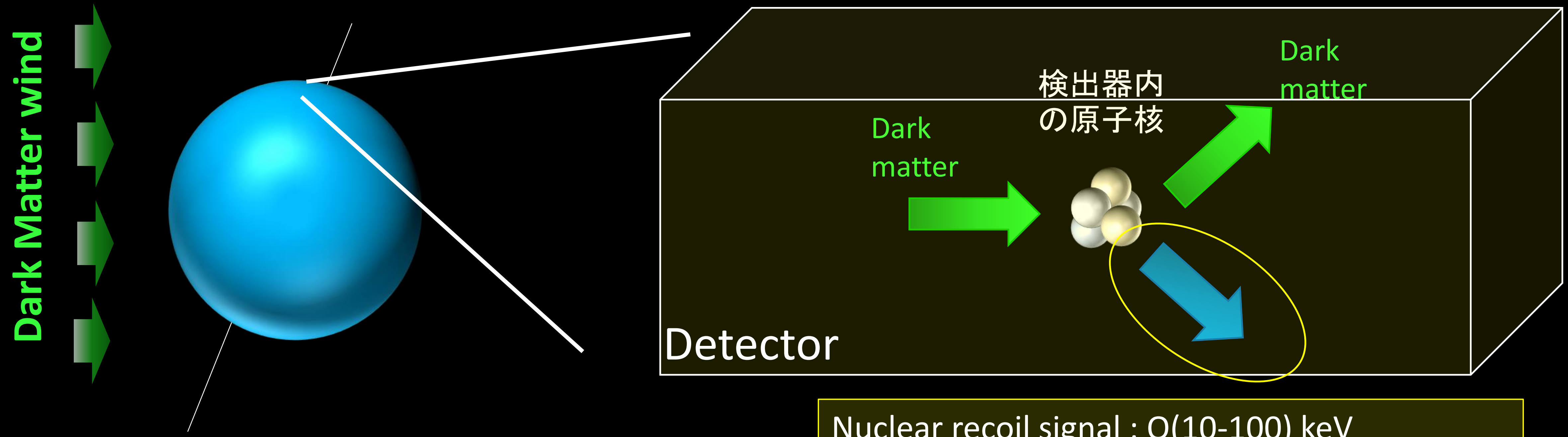
There are previous study by the mica in 1980-90.

Direct dark matter search in the earth

Particle model: Weakly Interacting Massive Particle (WIMP)

Elastic scattering : DM + N → DM + N

DM velocity : O(100) km/s
DM mass : > O(10) GeV/c^2



Nuclear recoil signal : O(10-100) keV
Recoil range : O(10-100) nm

* Neutrino is also same signal

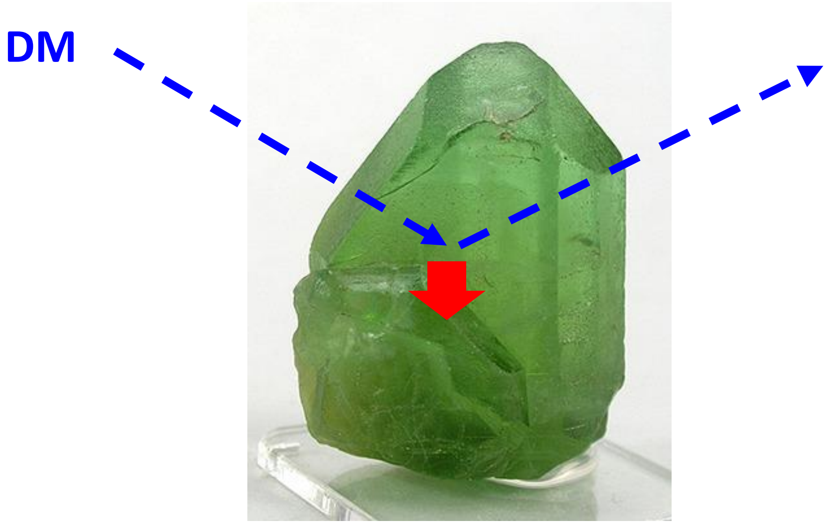
$Number\ of\ \ signal\ \ N = R\,[/\,kg/year] \times M\,[kg] \times T\,[year]$

$Event\ rate\ :\ R\,[/\,kg/year] = \rho\,[target\ nuclei/kg] \times flux\,[/\,cm^2/sec] \times \sigma\,[cm^2] \times (3.2 \times 10^7 sec/year)$

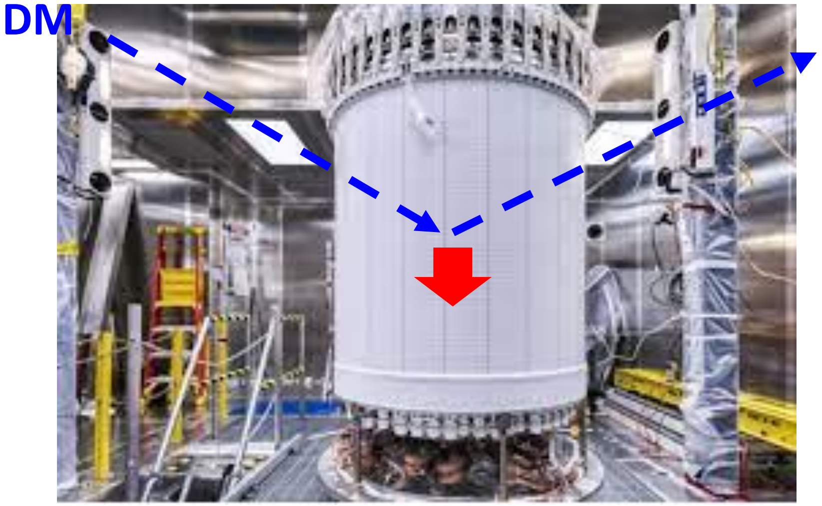
DM-nuclei cross section
(unknown parameter)

$flux = \dfrac{\rho\,[GeV/cm^3]}{M_{DM}\,[GeV/c^2]} \times v\,[cm/sec]$

ρ: local dark matter density 0.4 GeV/cm^3 $from\ rotation\ cureve\ of\ galaxy$
v: dark matter velocity (typically 300 km/sec)

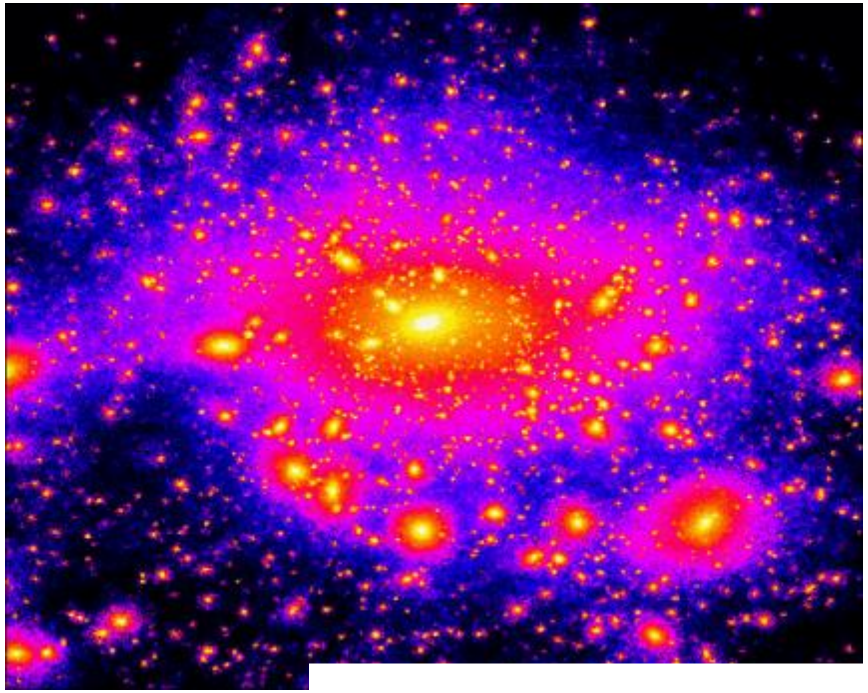


VS



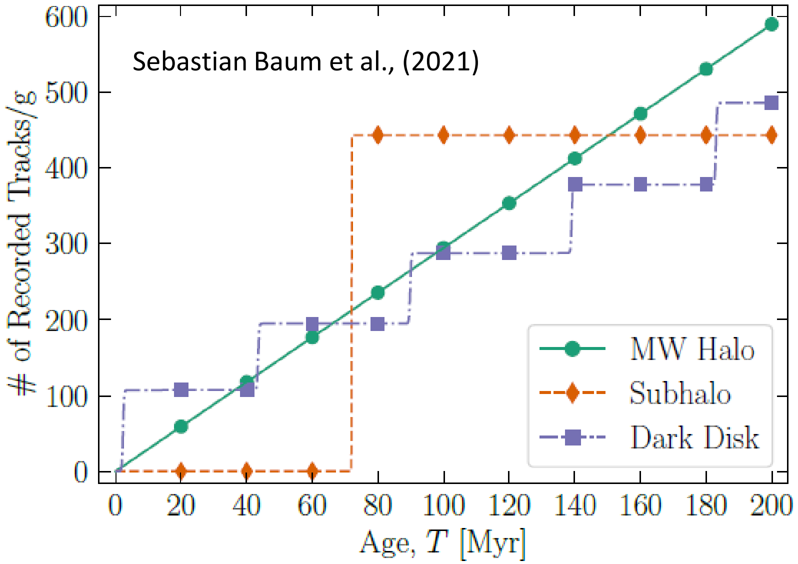
Mass scale	> 0.001 kg (1g)		~ 10^4 kg
Time scale	10^9 years		O(1) years
Exposure (Mass × Time)	**> 10^6 kg・year**	**>**	**~10^4 kg・year**

- Final sensitivity depends on the detection performance such as energy threshold, readout efficiency, background etc..



- Dark matter density is expected to be not uniform as sub-halo from the simulation.
- Solar-system is running in the dark matter halo with such density fluctuation.

Mineral may record such information during 1 Gyear because the revolution period has 0.2 Gyear.



Galactic archaeology !!

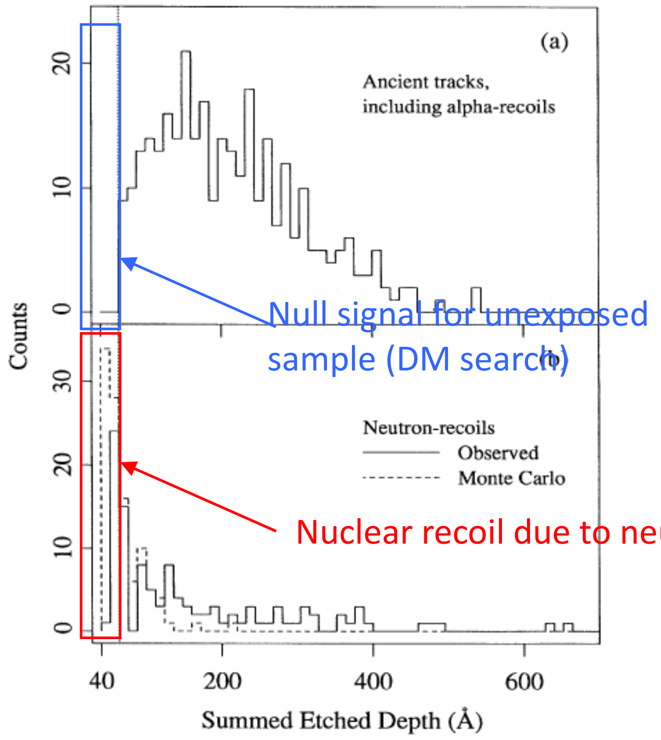
Previous research for WIMP search

VOLUME 74, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1995

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.



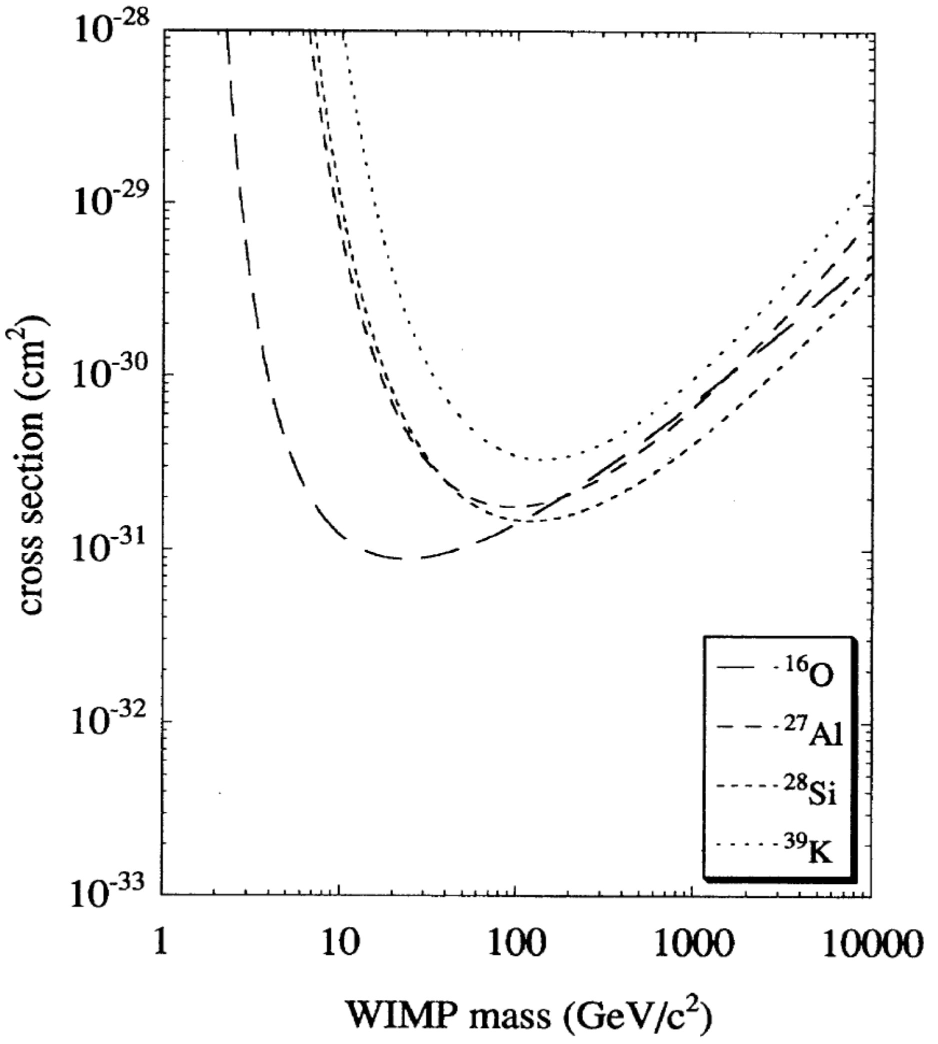
Scanning area : 80720 μm^2
$= 8 \times 10^{-4}$ cm^2
(Probably ~ 10^{-9} g)

Exposure : 0.5 Gyear

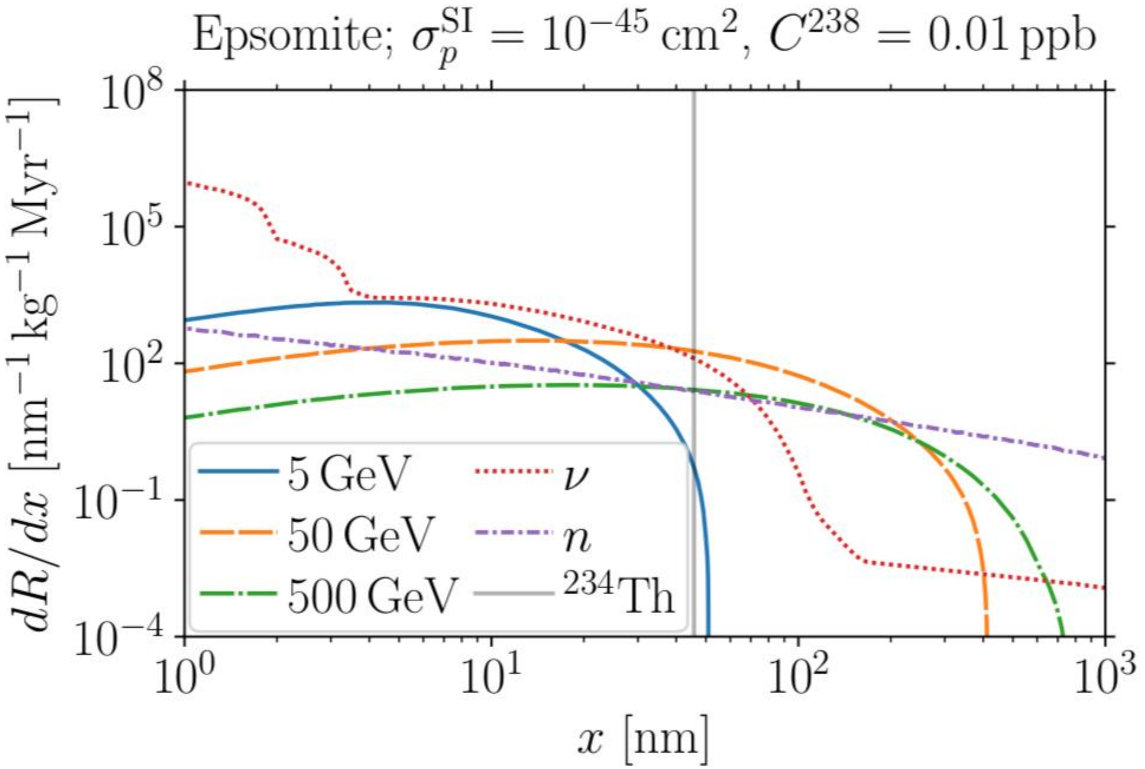
~ 0.5 g・year exposure

Readout technique : AFM

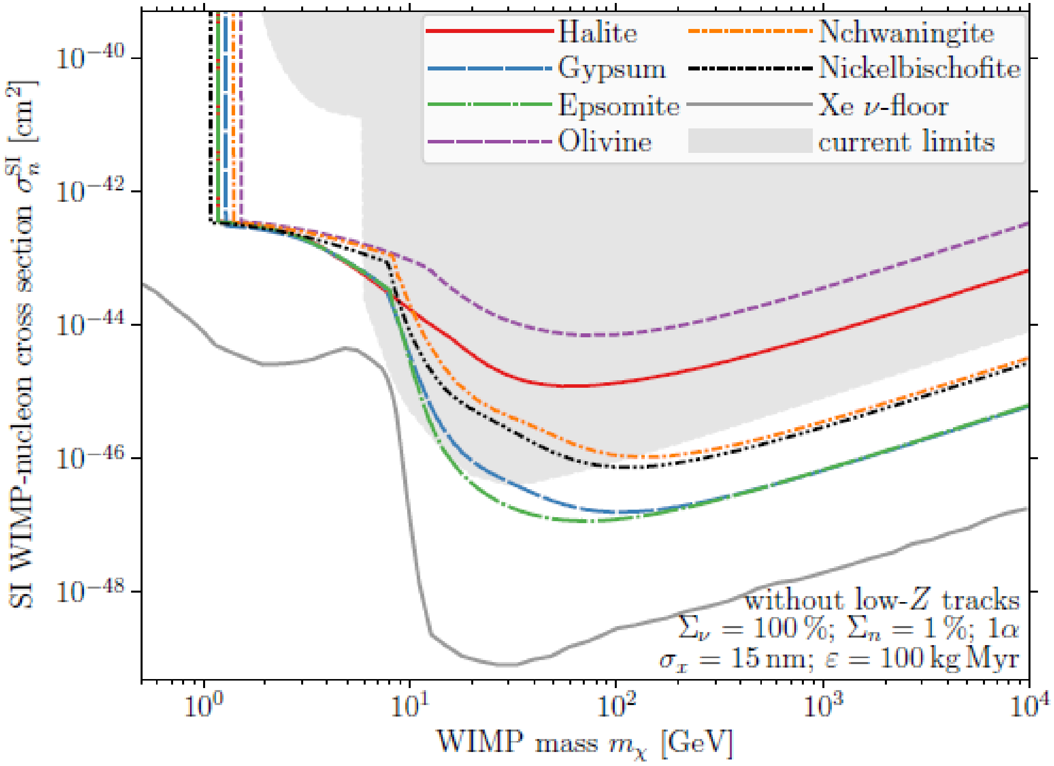
First upper limit of WIMP dark matter using the mineral



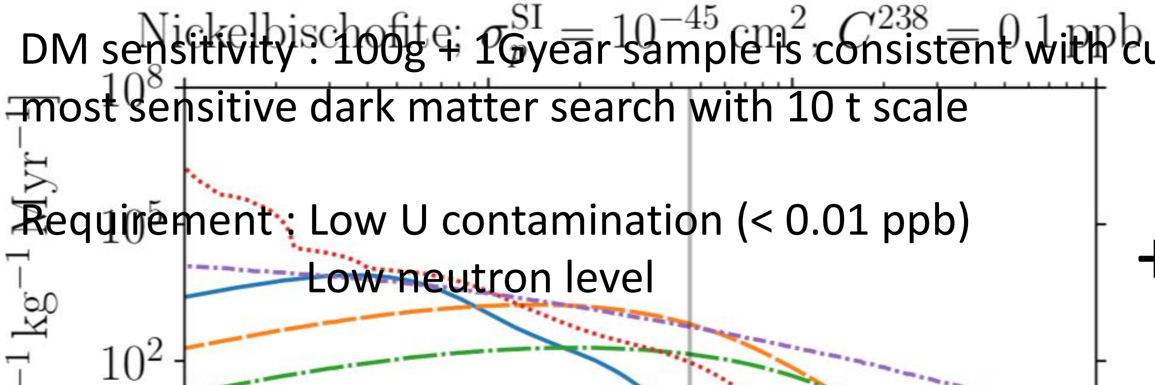
Prospect of WIMP search for each mineral



Sensitivity limit of WIMP DM



Sebastian Baum *et al*., Phys. Lett. B 803 (2020) 135325



DM sensitivity : 100g + 1Gyear sample is consistent with current most sensitive dark matter search with 10 t scale

Requirement : Low U contamination (< 0.01 ppb)
Low neutron level

\+

How much the track formation efficiency ?
Efficient readout system

Q-ball dark matter

Non-topological soliton by scalar field theory with global U(1) symmetry

➡ Bound quantum condition with squark, slepton in the SUSY

Afleck-Dyne mechanism *(Nucl. Phys. B.* **B249** (1985) **)**

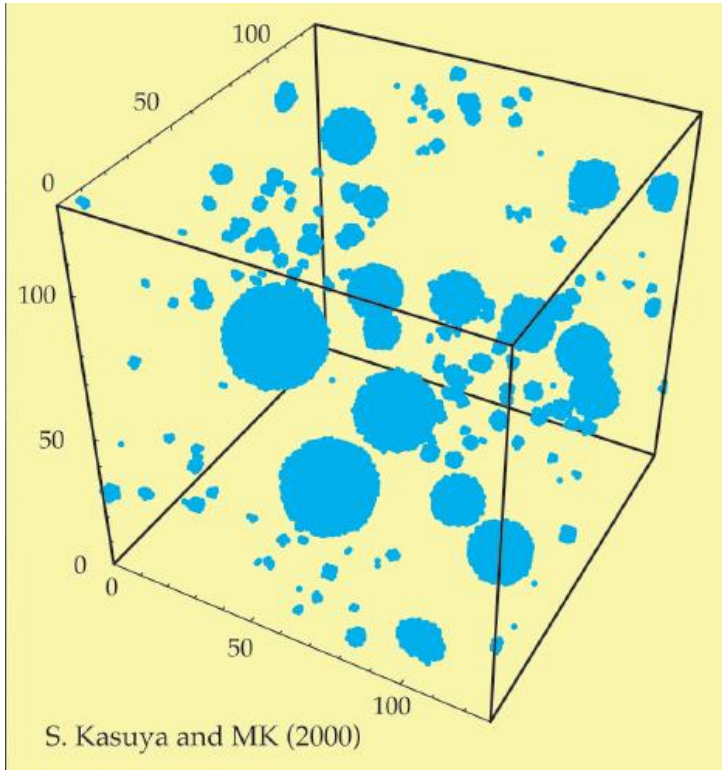
Baryogensis by inflation and SUSY
→ coherent oscillation and large fluctuation for the A-D field ： Q-ball

Supersymmetric Electrically Charged Soliton *JCAP 1608, 053 (2016)*

- positive charge by gage mediated lepton decay
- EM interaction

Charged Q-ball (Z_Q<137) exist and candidate dark matter as the state of Q-ball atom or ions in the universe

Very heavy charged dark matter (M_Q > 10^{10} GeV/c^2)



From Prof. M. Kawasaki's slide

Serious problem for the particle physics

- **Symmetry breaking → asymmetry of particle and anti-particle**
- **Hierarchy Problem**
- **Neutrino mass**
- **Strong CP problem**
- **Baryogenesis (mechanism of generation of baryon in the early universe)**
- **Dark matter**
- **Dark energy**

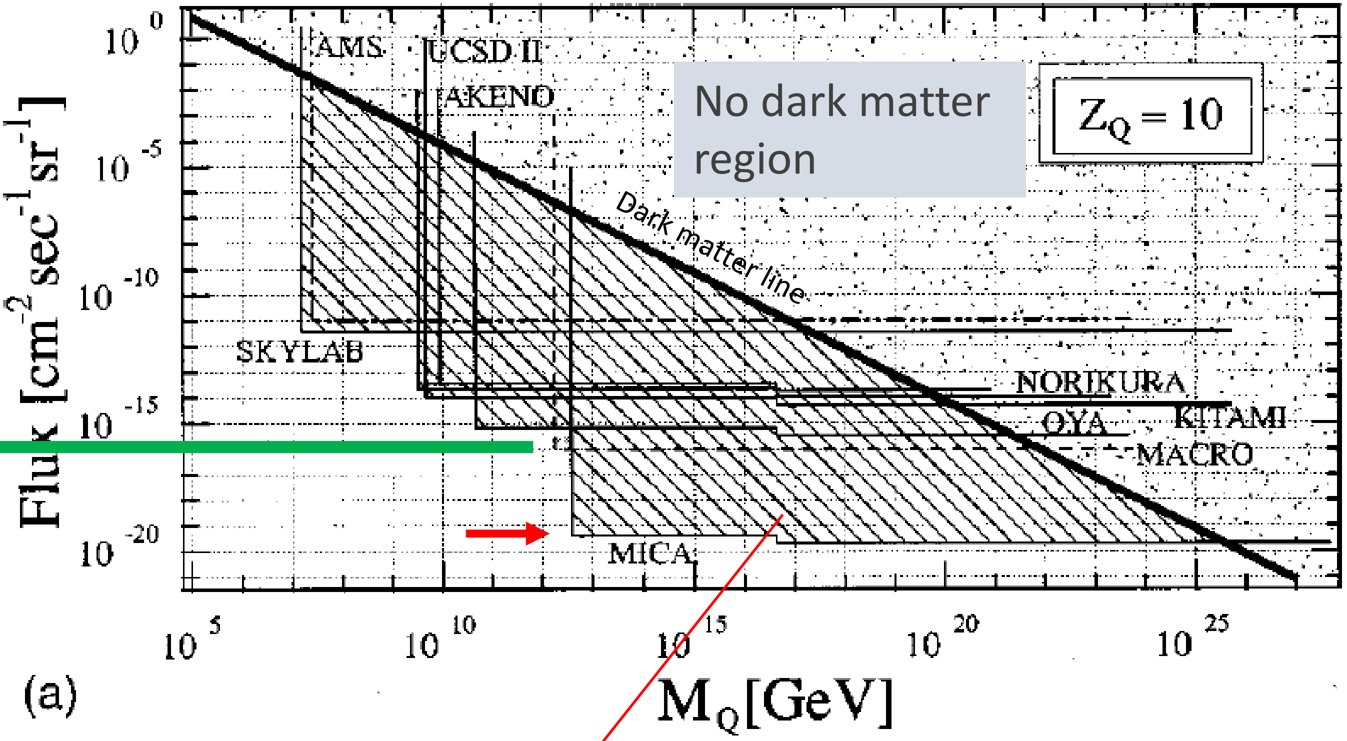
Q-ball related

*** All is the Nobel Prize-worthy theme**

Current charged Q-ball search limit

MACRO experiment [1989-2000]

PRD,62 (2000) 105013



CR-39 (plastic damage detectors)

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

Exposure time : O(1) year

The Mica limit is converted from the monopole search by P. B. Price and M. H. Salamon, Phys. Rev. Lett. 56, 1226 (1986).

Past highest sensitive Q-ball search

MACRO experiment [1989-2000]

CR-39 (plastic damage detectors)

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

Exposure time : O(1) year

$<$

MICA [1986]

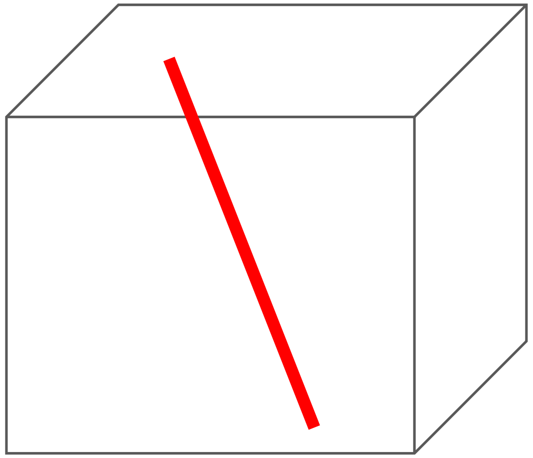
Mica (mineral detector)

Observed area : > O(0.1 x 0.1) m^2

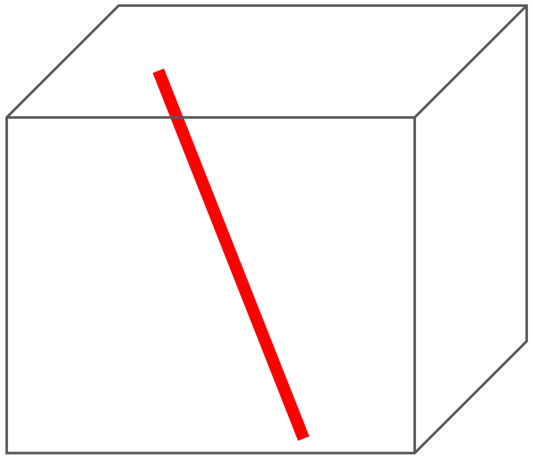
Exposure time : O(10^9) year

Expected signature

Q-ball

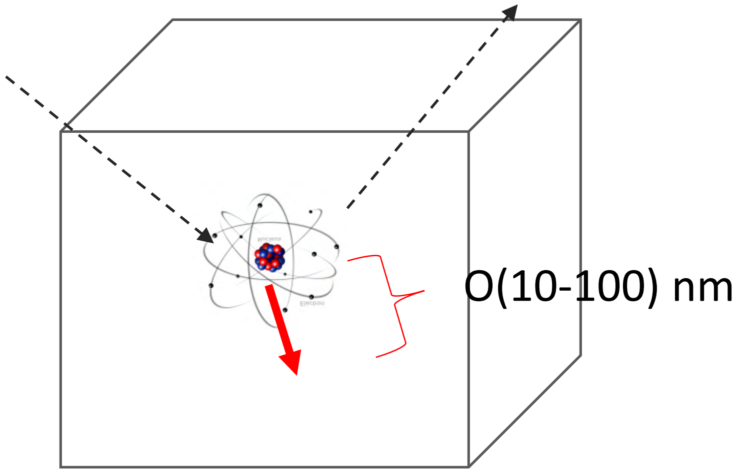


Monopole



* Required specific model to form the track in mineral

WIMPs, neutrino



Easier ⟷ **Challenging**

Subjects from experiment side

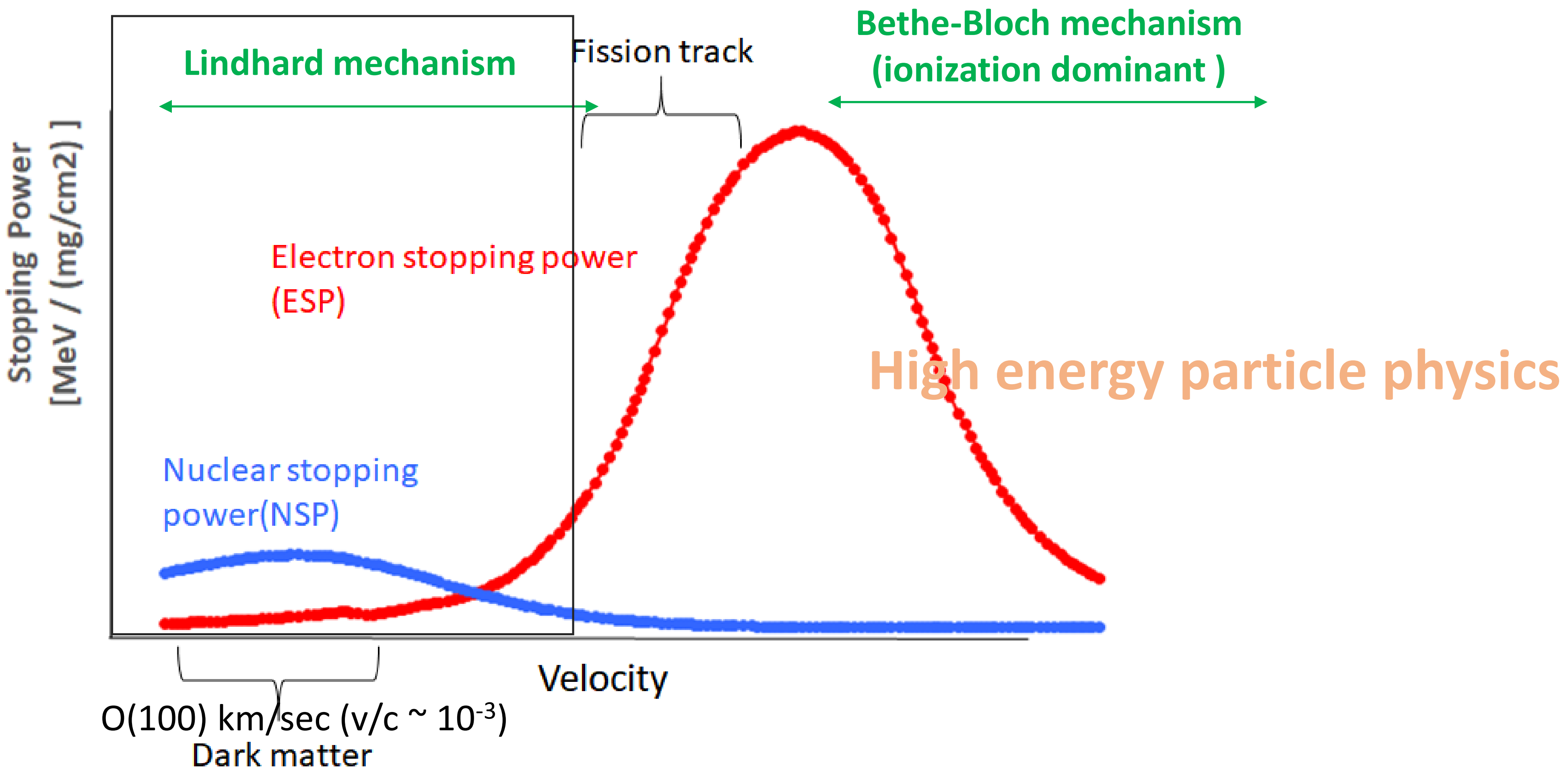
- Track formation efficiency
- Handling optimization such as chemical etching
- Readout technology

Our side

- Older sample
- Low-background sample

Geoscience side

Energy loss mechanism



Our target

Low-velocity region ($\beta < 10^{-3}$) : NSP + ESP (NSP>ESP) ➡	**Nuclear collision + excitation, ionization**

High-velocity region ($\beta < 10^{-3}$) : ESP (ESP >> NSP) ➡ **High density electron excitation**

Required energy loss for track formation in the mineral

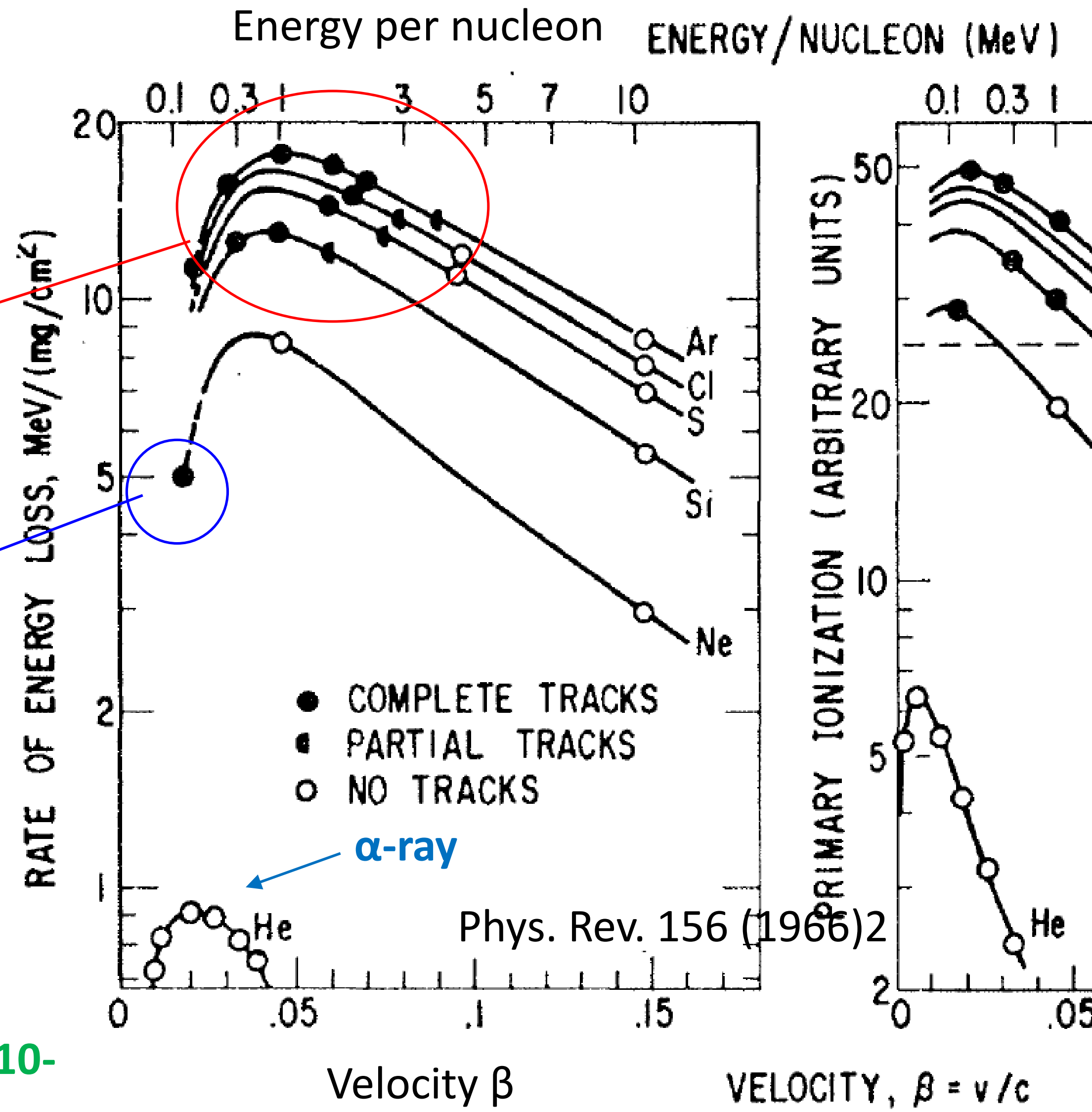
Case of “muscovite mica”

Required energy deposition due to ionization

$$\frac{dE}{dx} > \sim 10 \ MeV/mg/cm^2$$

(~ 30 GeV/cm in the mica)

However, it’s possible to form the track in low-velocity region

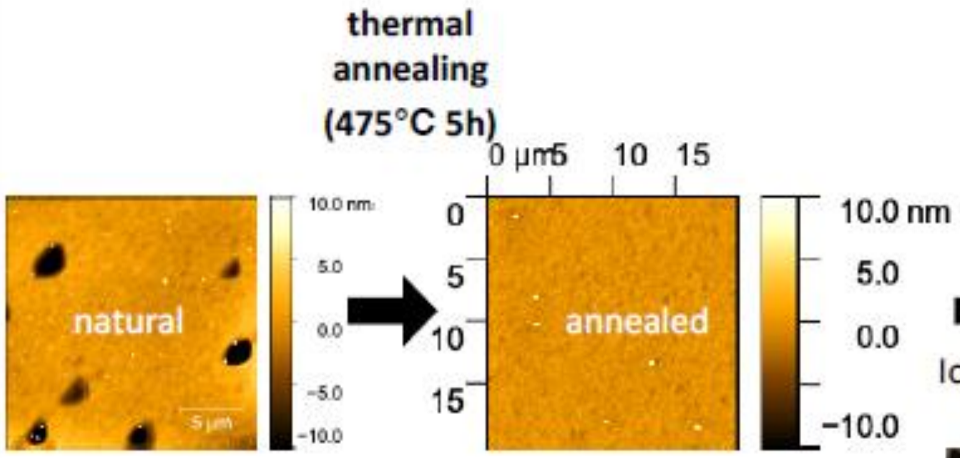


Phys. Rev. 156 (1966)2

Low-velocity region of around 10-3 is easier to form the tracks ?

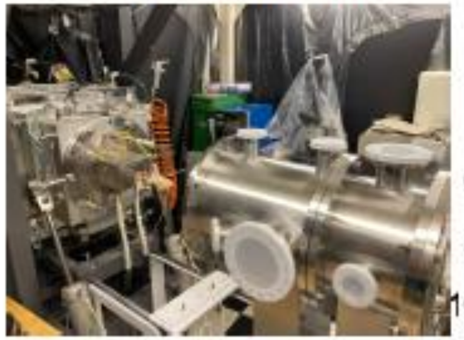
keV/u ion implantation experiments

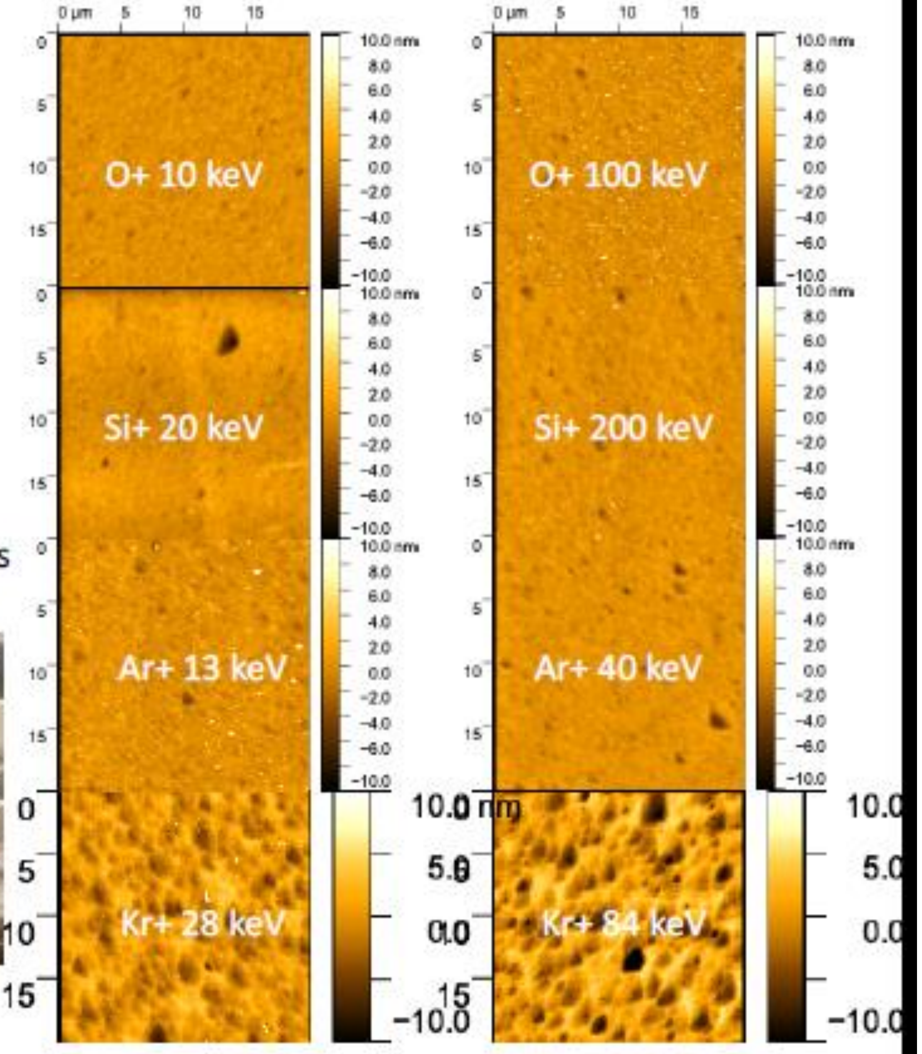
Etching + AFM observations



80 ions in FOV

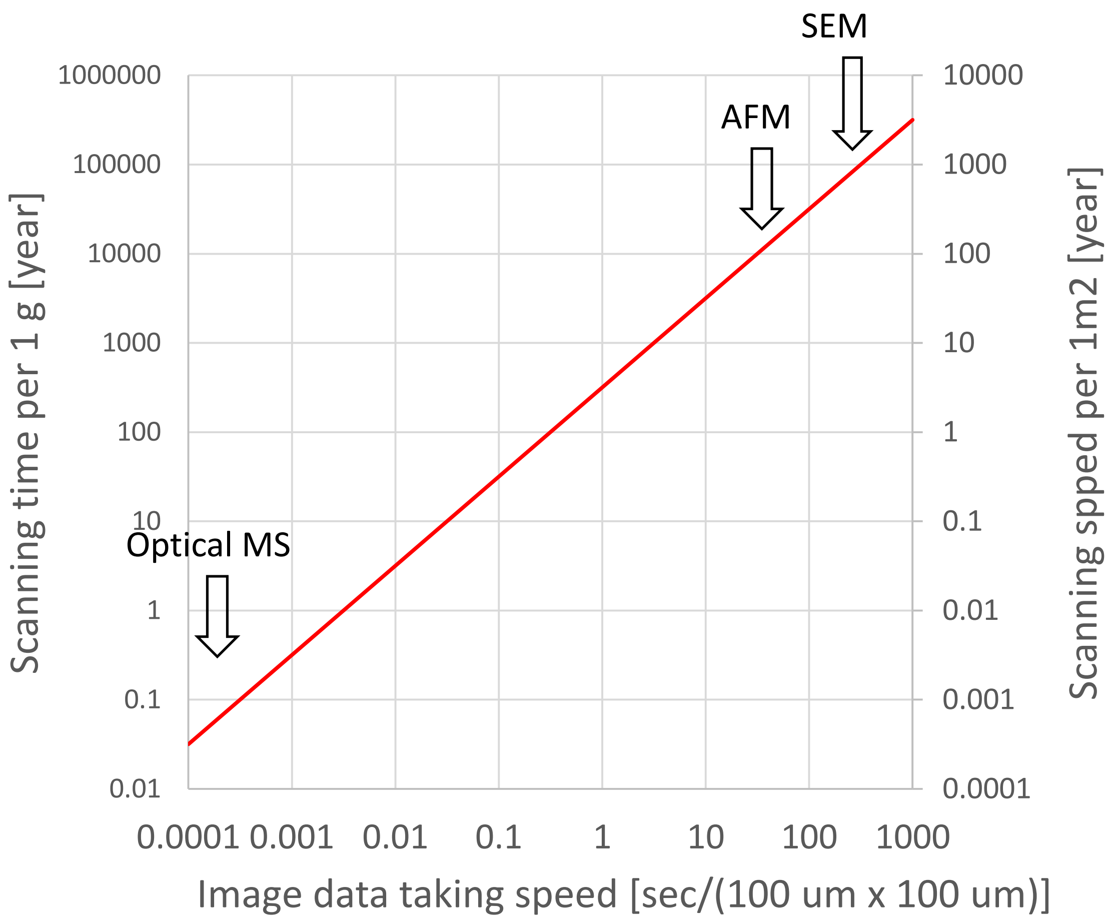
Ion implantation experiments at Kanagawa U.





Study by Dr. Hirose et al., at JAMSTEC

Readout scale for each microscope techniques

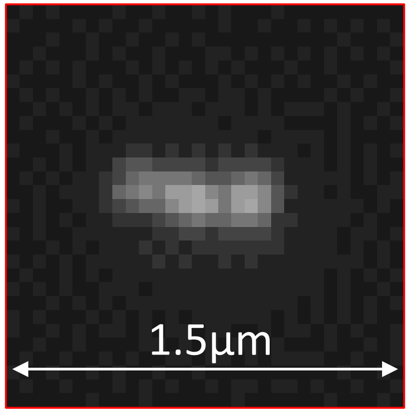


- Higher speed readout will be required
- Optical microscope is promising for first candidate trigger.
- Finally, combined analysis between optical microscope and higher resolution microscope should be important

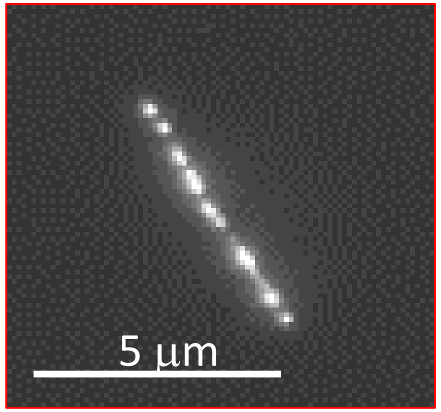
Optical readout technology for the nuclear emulsion

PTS system for nuclear emulsion scanning

Tracks in the nuclear emulsion



Nuclear recoil
(DM candidate)



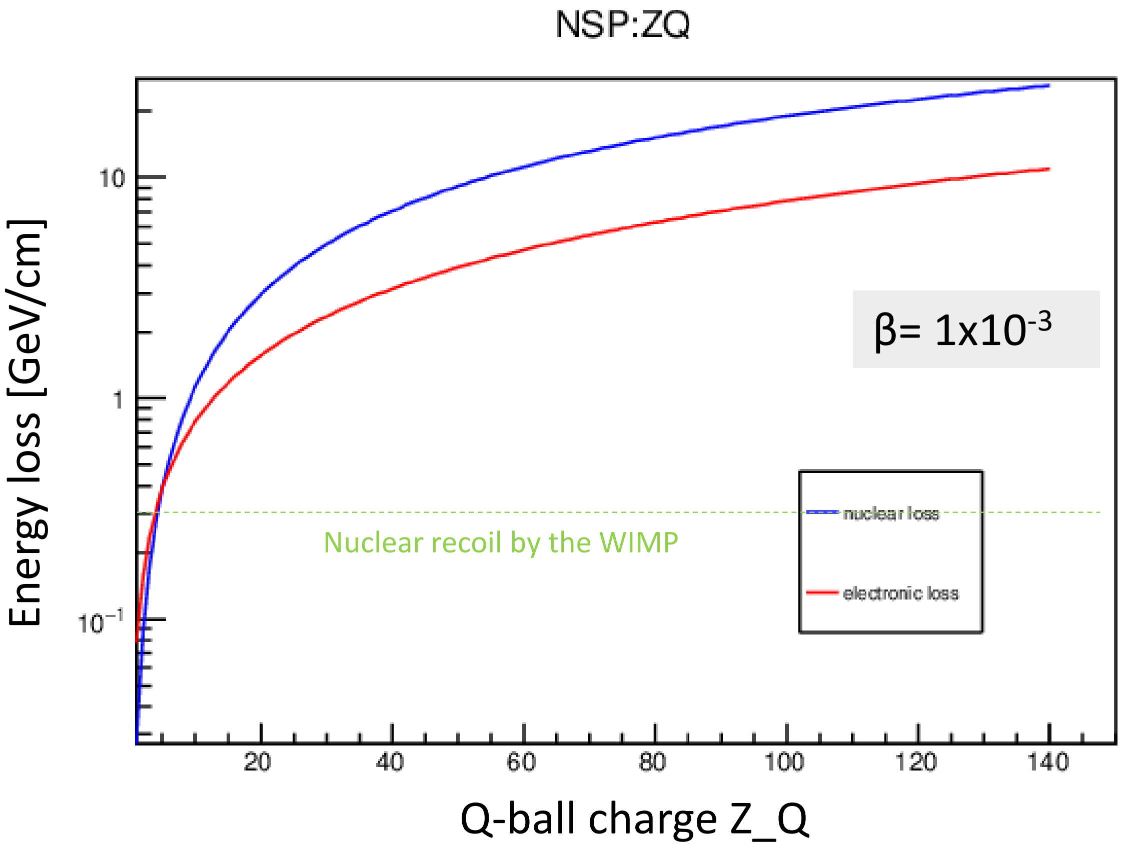
proton recoil
(neutron)

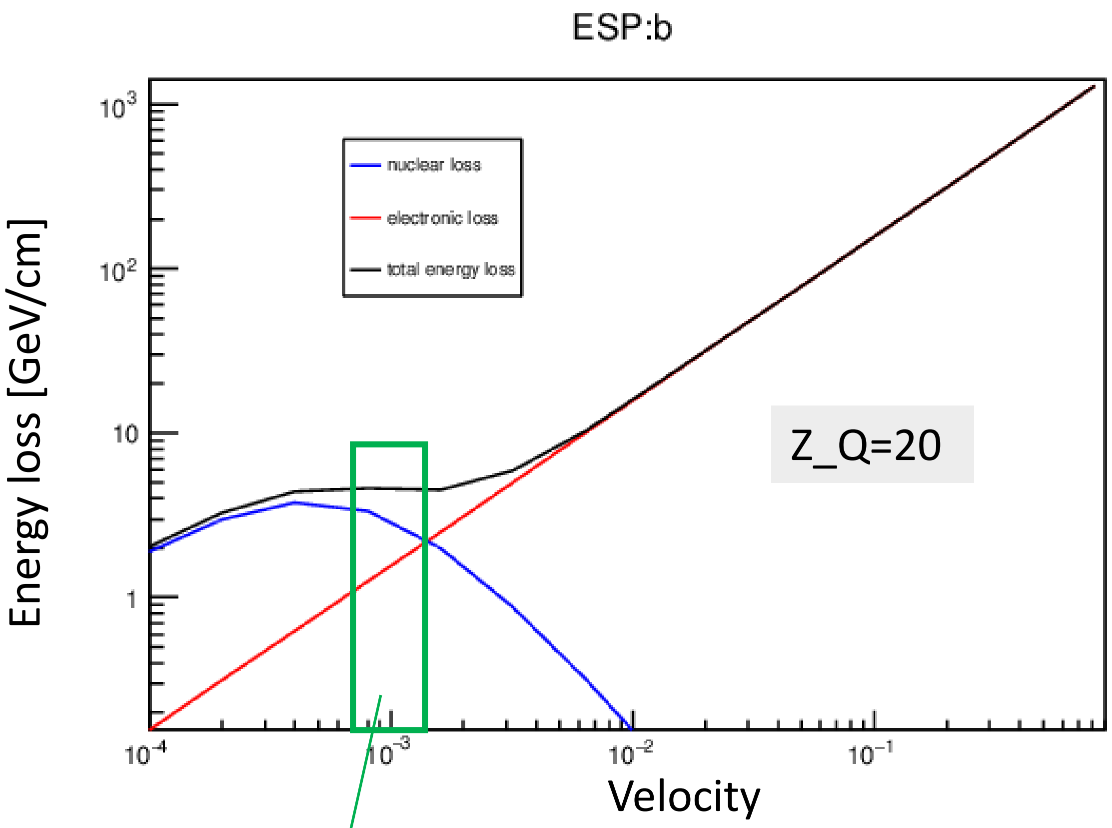
High energy interaction

Automatic readout of charged particle in the nuclear emulsion

This system will be applicable to the Paleo detector

Energy loss of charged Q-ball (Preliminary)





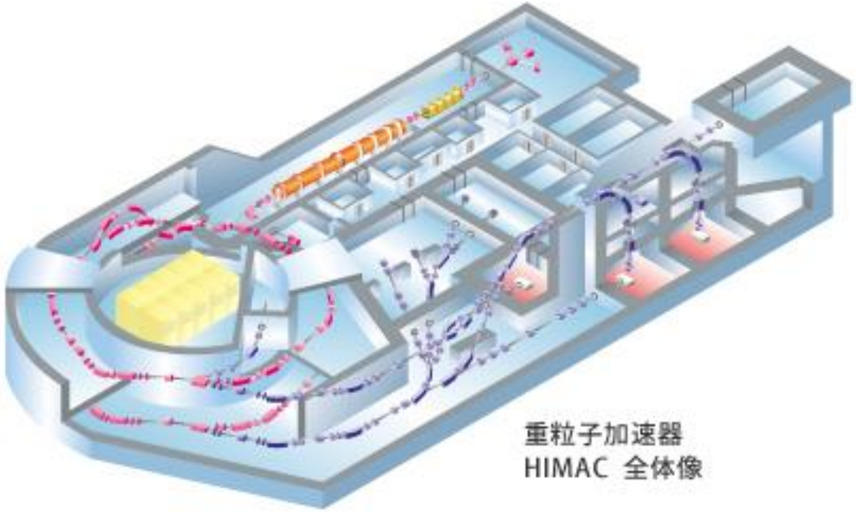
Dark matter expected

HIMAC @ QST

National Institute for Quantum Science and Technology

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

[Accelerator for heavy ion therapy]



重粒子加速器
HIMAC 全体像

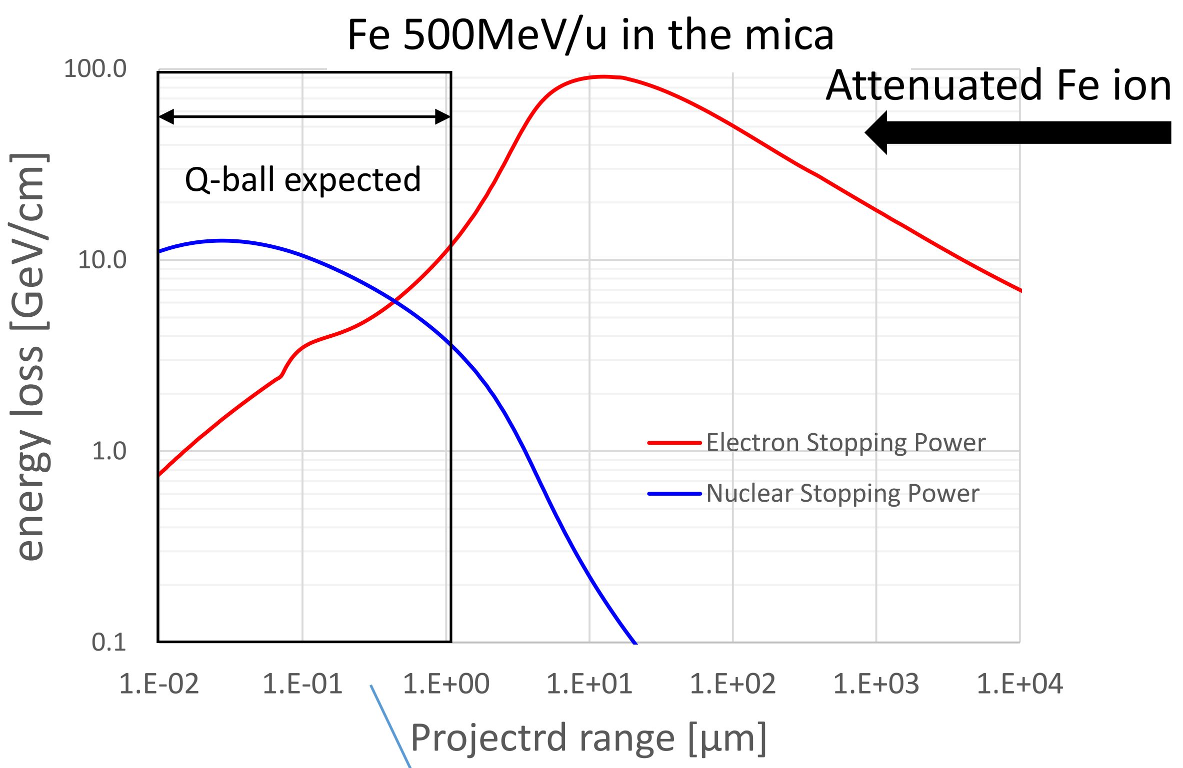
重粒子線棟

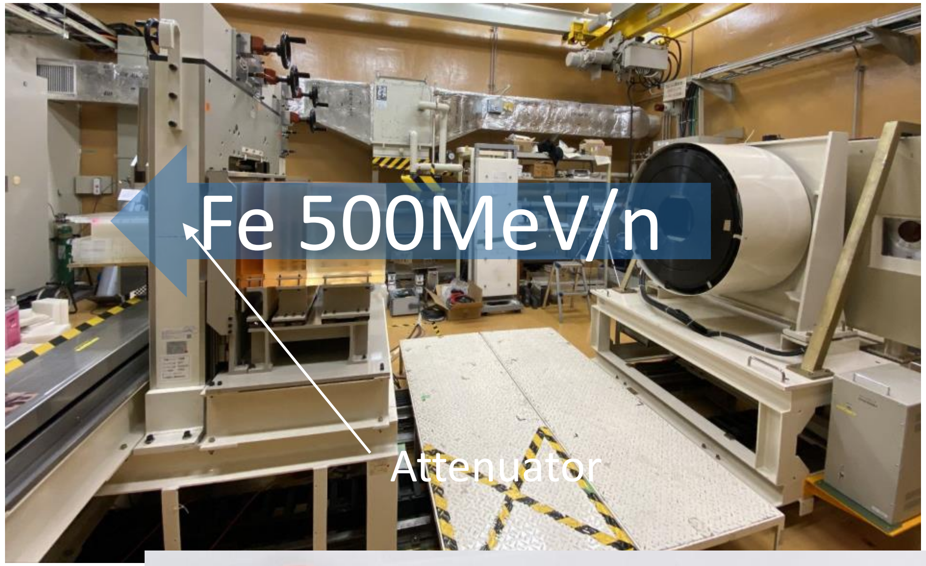
Available Ion beam

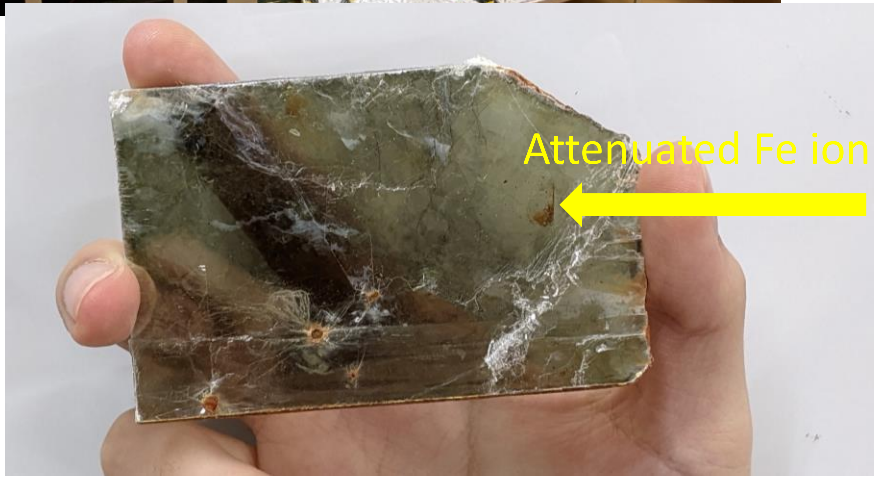
Ion	Energy [MeV/u]	Max. Intensity [/s]
He	150	1.2×10^{10}
C	135,290,350,400	2.0×10^{9}
Ne	230,400	5.5×10^{8}
Si	490	4.7×10^{8}
Ar	500	2.7×10^{8}
Fe	500	2.5×10^{8}

Candidate for Q-ball calibration

Fe ion calibration at the HIMAC



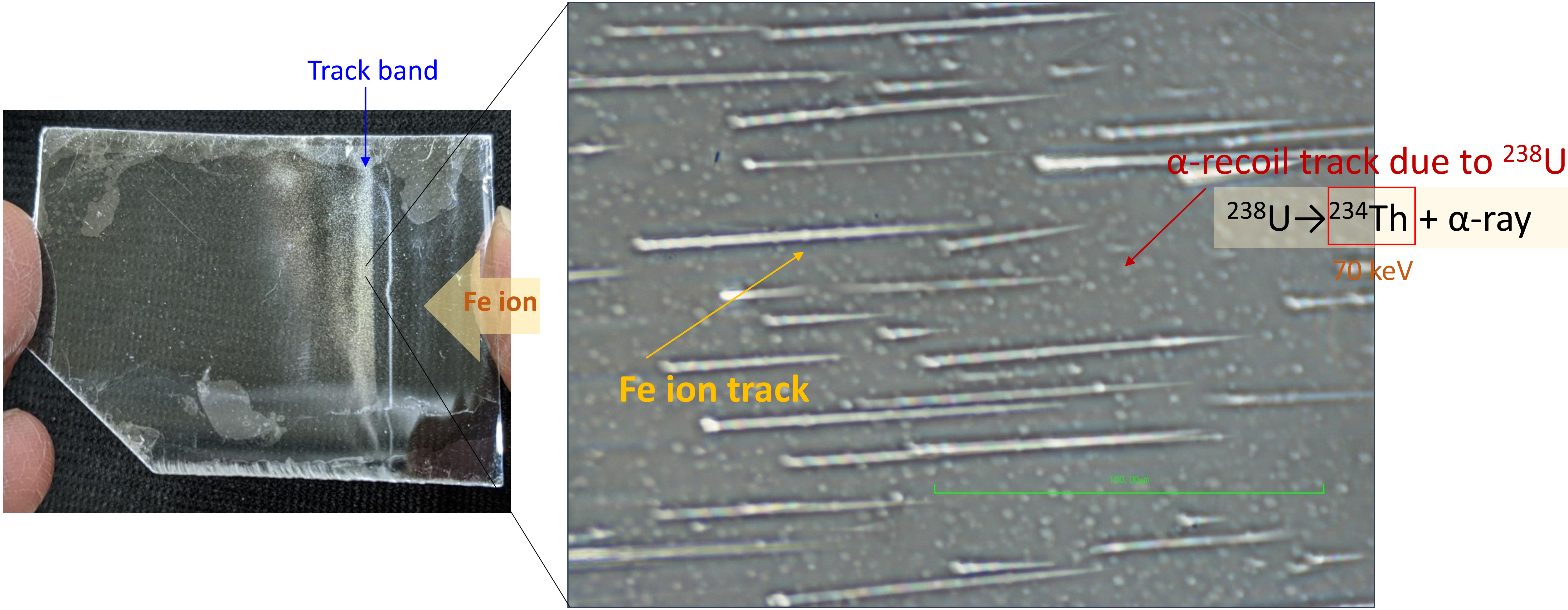


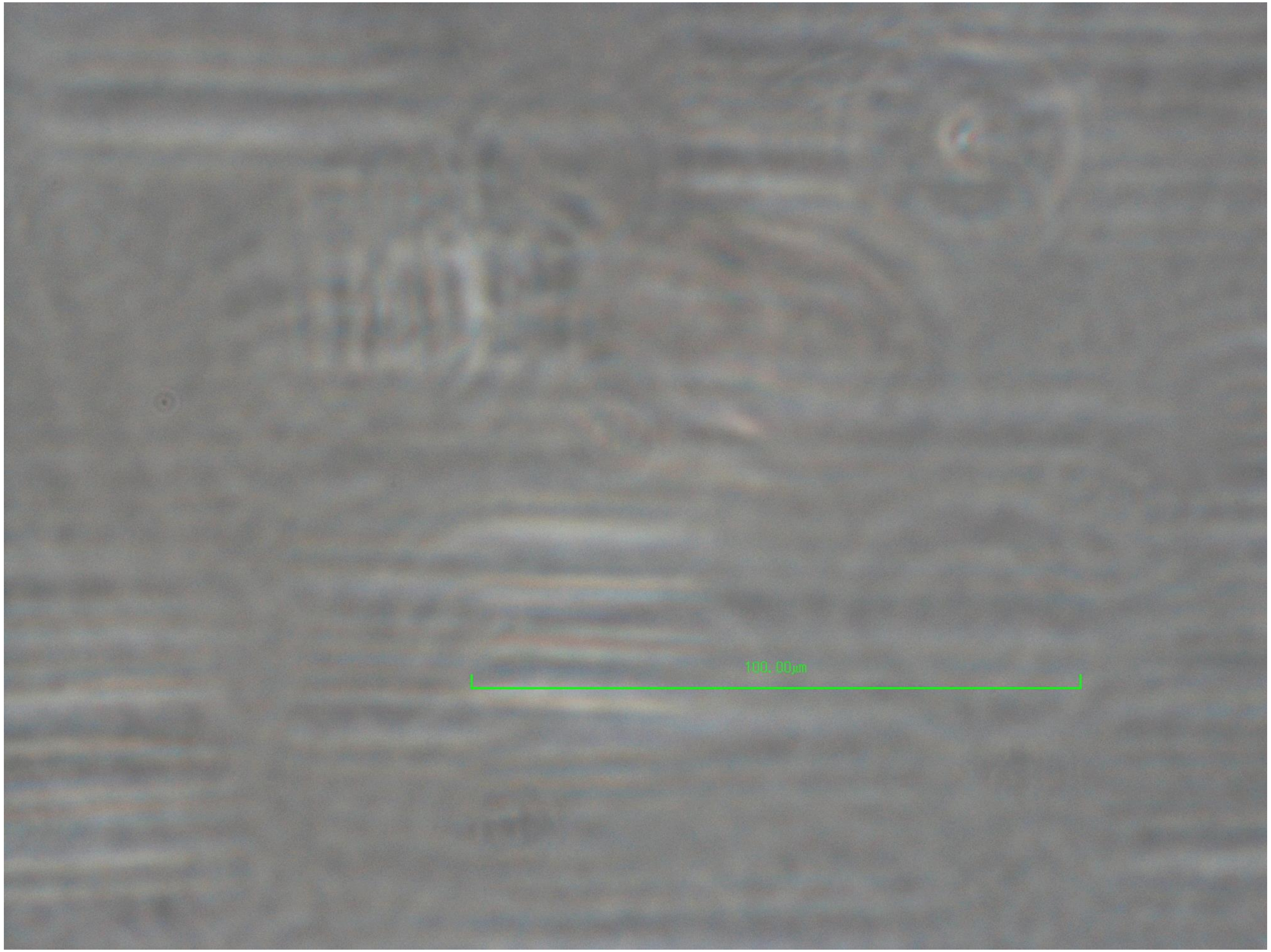


Similar energy loss process with charged Q-ball

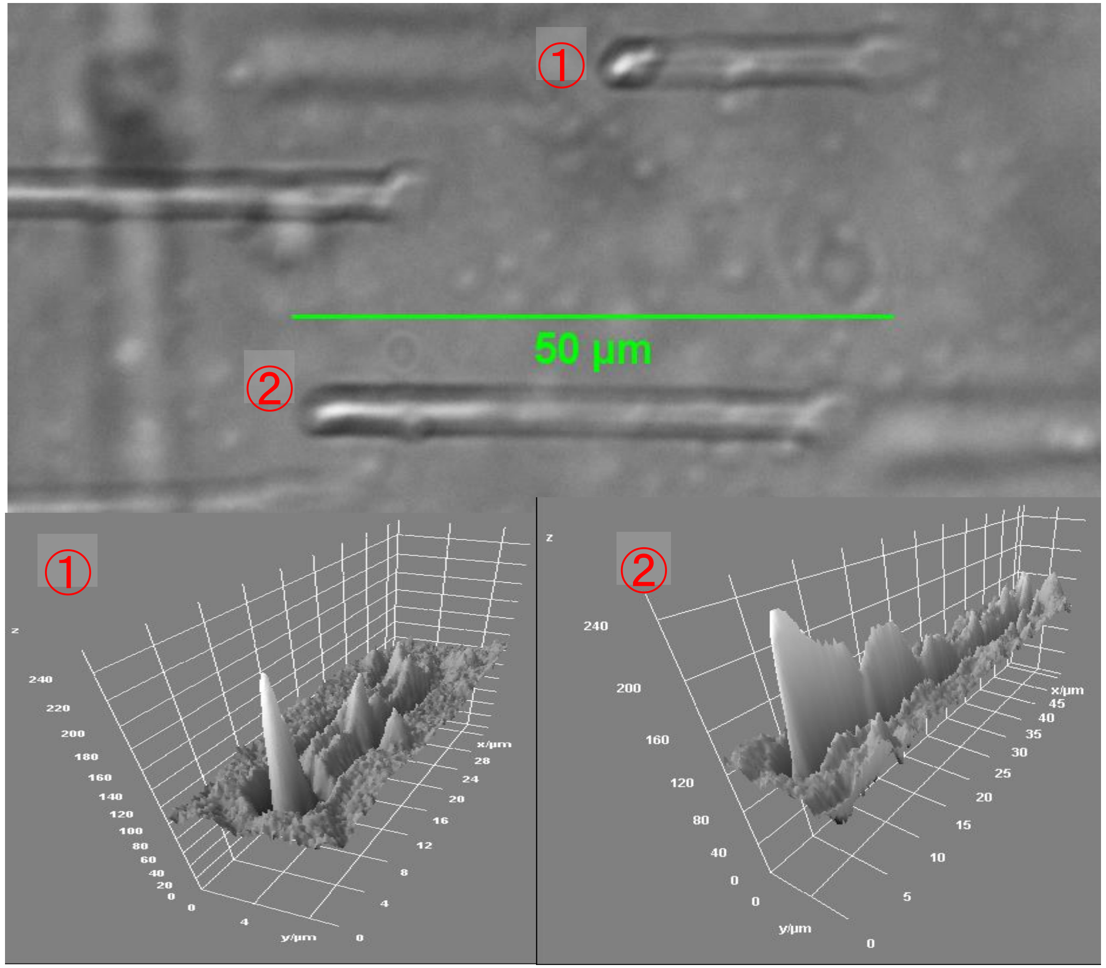
- ✓ **Optical recognition ability**
- ✓ **Tracking threshold depending on the dE/dx**
- ✓ **dE/dx dependence for above factor**

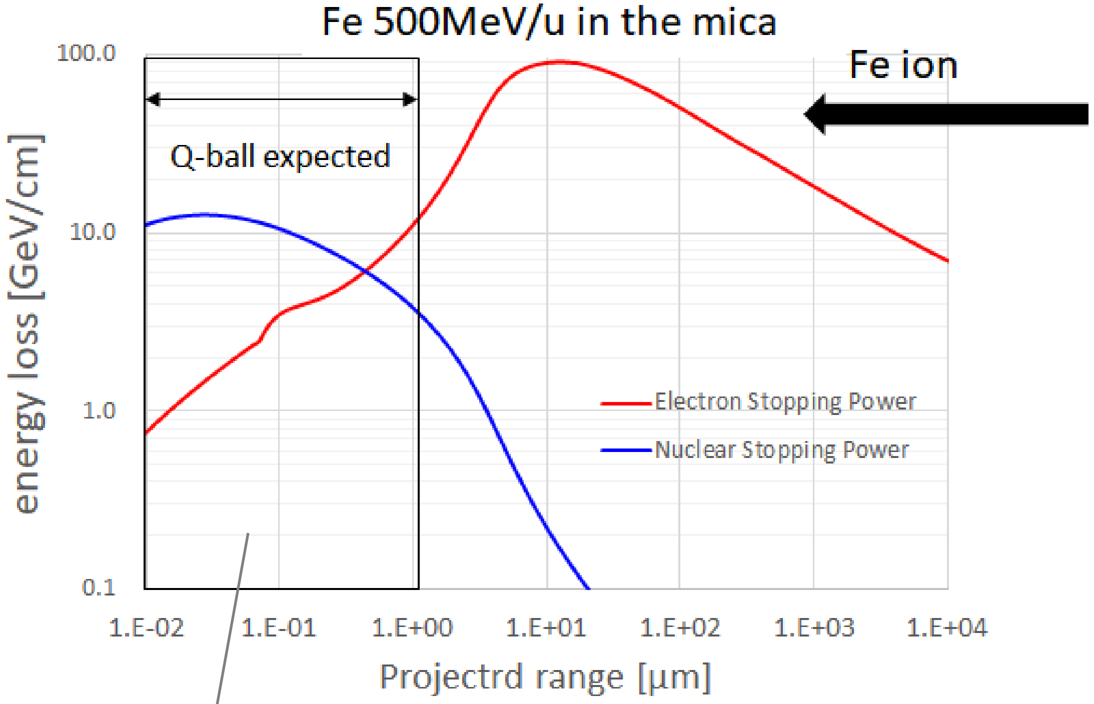
Phase contrast optical microscope image of Fe ion beam (500 MeV/u) [HF 20℃, 80 min etching]

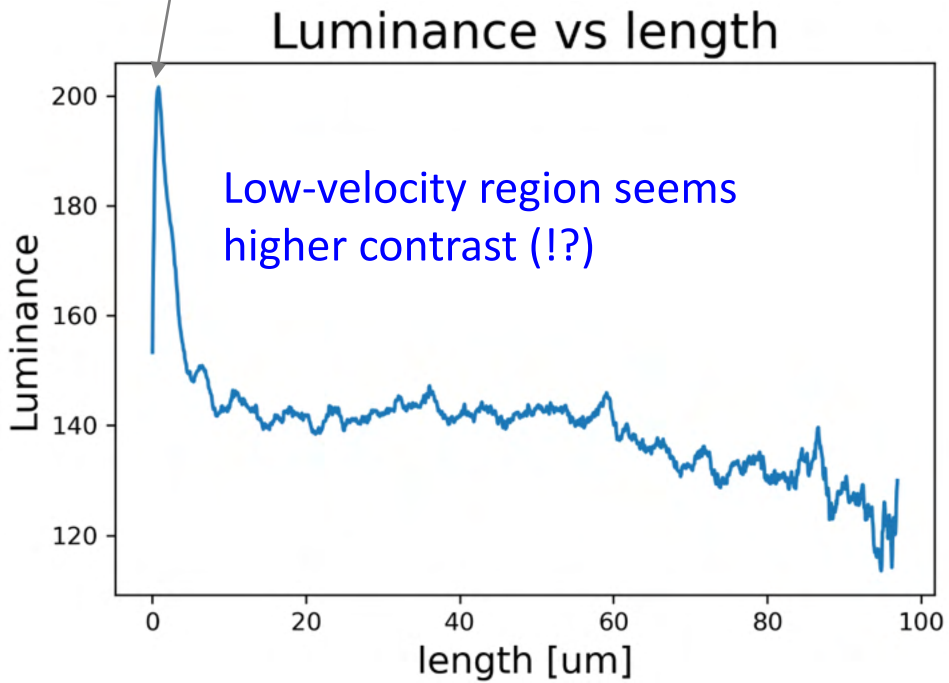



100.00μm

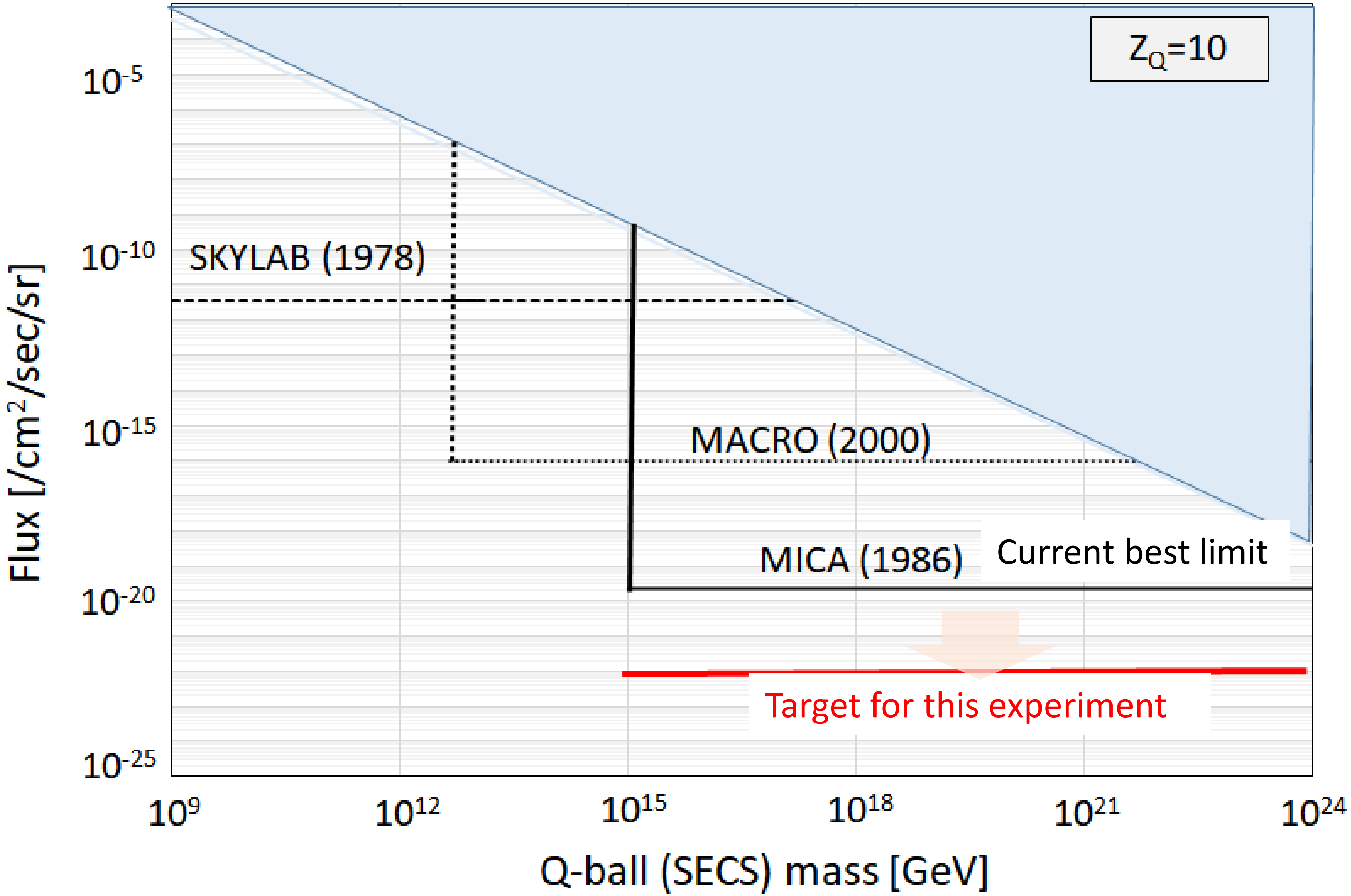
Brightness of Fe ion tracks around stopping region (on going study)







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



Conclusion

Particle physic
×
Geoscience

Paleo detector using mineral

→ Recorded signal in the galaxy during 1 Gyear scale

New value for galactic archeology!!

Detection target

- ■ WIMP dark matter
- ■ Neutrino
- ■ Q-ball as the DM
- ■ Monopole

Damage tracking in the mineral

- ➢ Readout technology
- ➢ Selection of suitable mineral
- ➢ Understanding the background and detection performance

- **Lower Uranium contamination**
- **Track formation possibility**
- **observation with chemical etching**

On going the experimental study!!

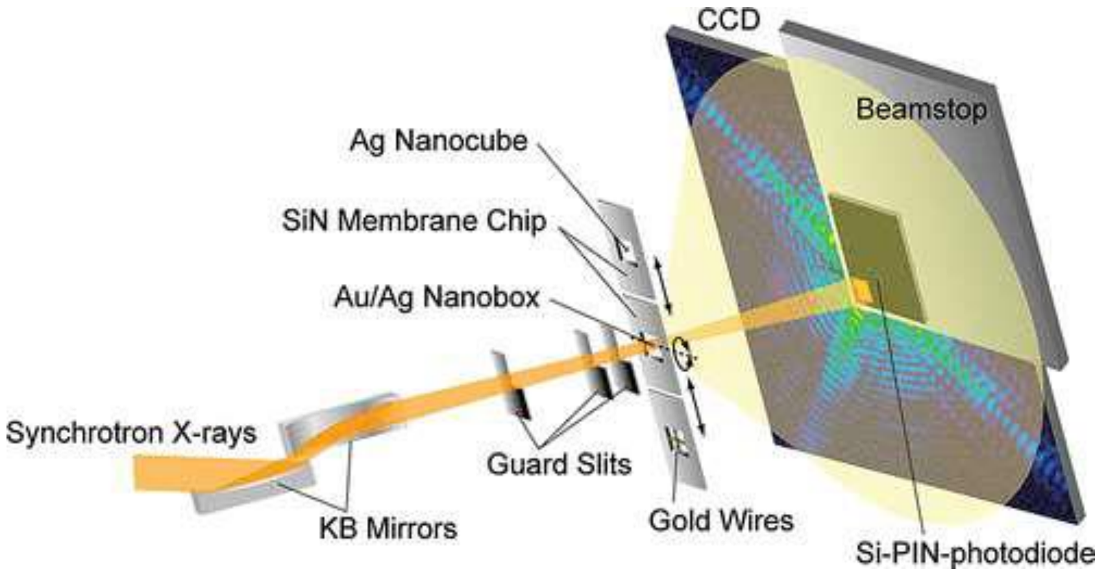
It will be able to start to search in our group soon!

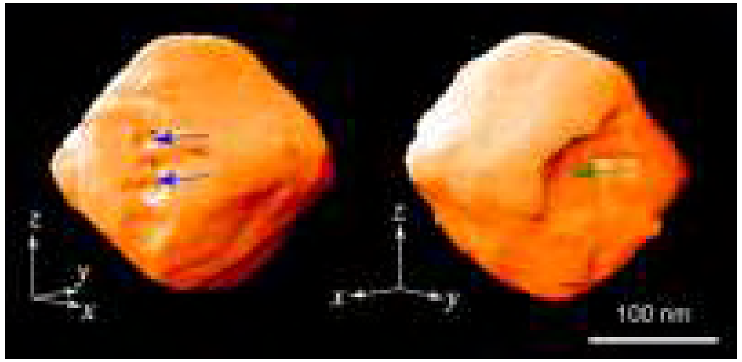
High-resolution readout

Coherent X-ray microscope imaging

- Imaging technique with reconstruction from coherent X-ray diffraction pattern
- Tomographic imaging with **<u>10 nm</u>** resolution is possible

Now, we started to discuss about application of the NanoTeras with Prof. Yoshida of SRIS (International Center for Synchrotron Radiation Innovation Smart), Tohoku University about application of the NanoTeras.





http://www.spring8.or.jp/ja/news_publications/press_release/2010/100420/

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