鉱物試料に形成された粒子飛跡と地球年代スケールでの宇宙線研究

Study for Cosmic-ray with Geological Time scale by the Ancient Mineral as the Paleo Detector

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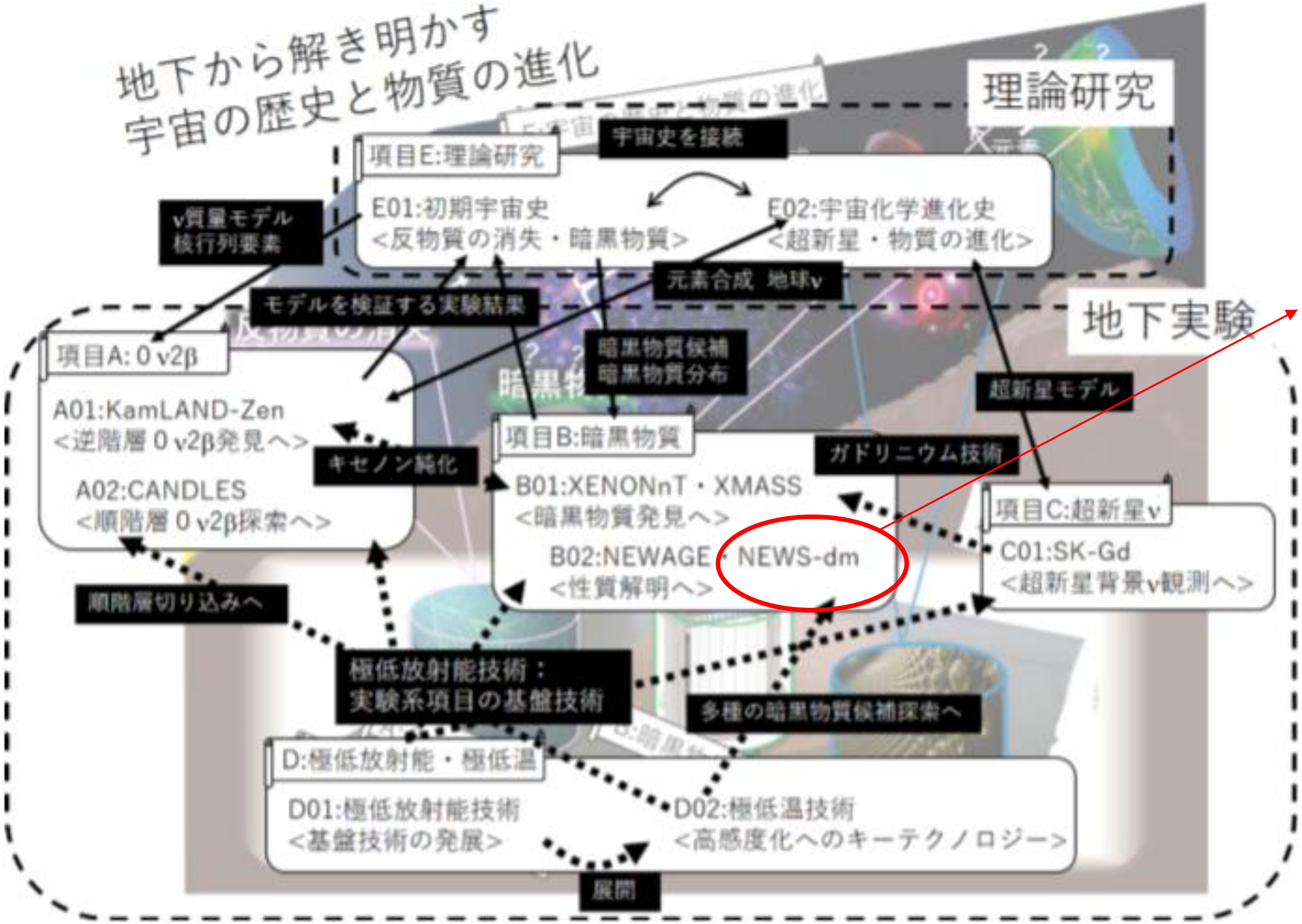
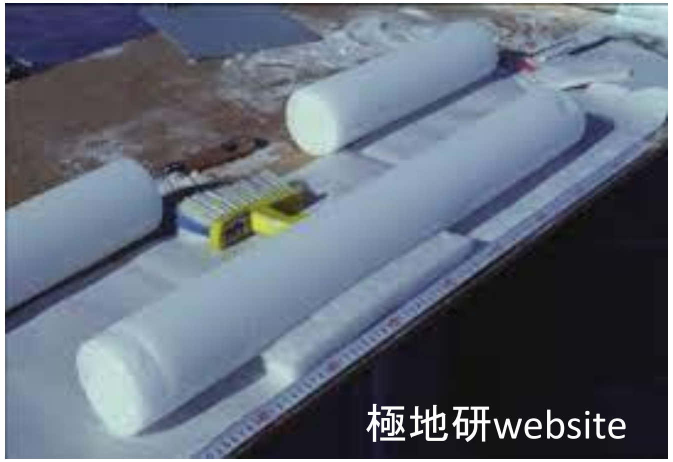
2024.2.29-3.1 超新星ニュートリノ研究会@岡山大学



原子核乾板を用いた暗黒物質の
方向感度探索実験

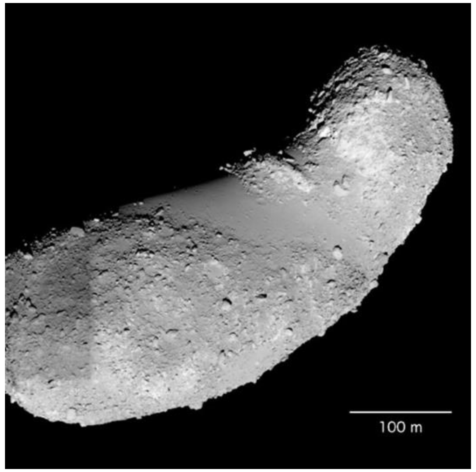
地質学試料に残った宇宙線の痕跡

アイスコア



樹木

小惑星・月面サンプル



成分分析・放射化学分析

＋

放射線計測による分析 (エネルギー）

Paleo Detector

鉱物 (Ancient Minerals）

Geologic time scale
> O(100) M year

この中に宇宙線の情報が記録されているのであれば、数億年スケールの観測を行った検出器となる

Contents

■Galactic CC SN neutrino

■Dark Matter

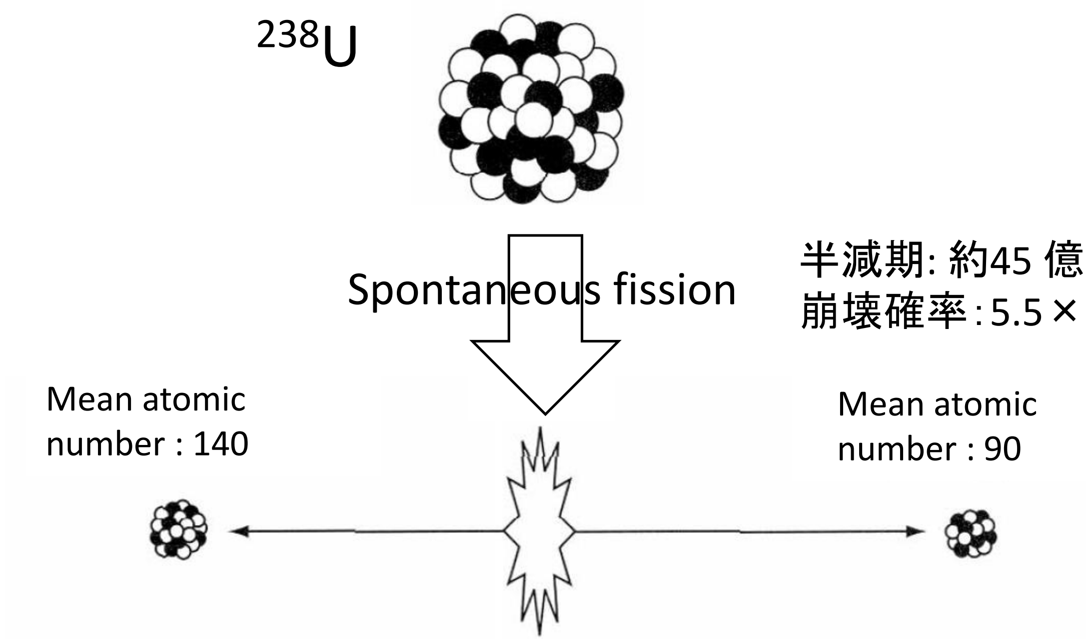
- WIMP
- composite DM (Ultra-heavy DM)

■Ultra-heavy cosmic-ray

My main targets

Mineral as tracking detector

Fission tracks in the Zircon



半減期: 約45 億年
崩壊確率 : 5.5×10^{-5} %

Fission track density = λ × n (density of U) × T (date)

e.g., In case of 1 ppm U contamination and 1 G year
Fission track density ~ 10^8 S.F. /g

Detection model

Ion explosion model

(R.L. Fleischer, P. B. Price, R.M.Walker *et al.*)

$$F_c = \frac{n^2 e^2}{\varepsilon a_0^4} > \sigma_{tens.} \cong \frac{E}{10}$$

↑

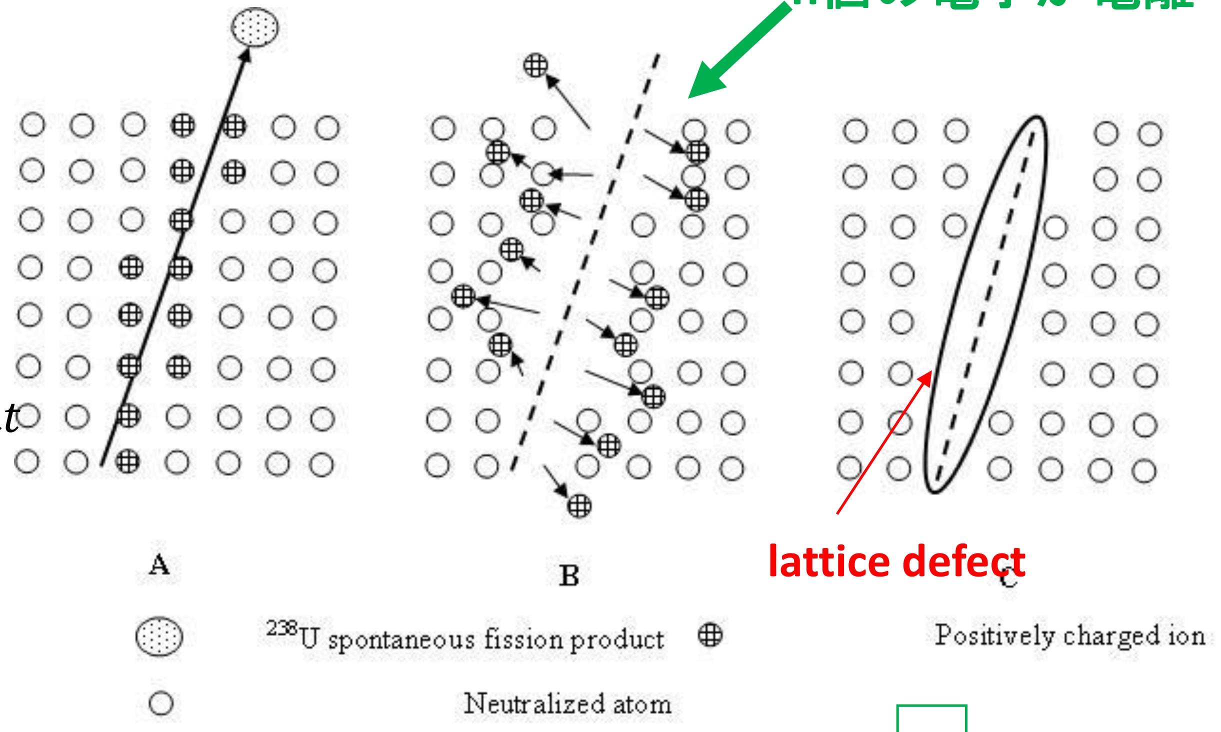
抗張力

$a_0: atomic\ distance$

$\varepsilon: dielectric\ constant$

$E: Young's\ modulus$

n個の電子が電離



$$n^2 > \frac{E\varepsilon a_0^4}{10e^2} \equiv R$$

化学エッチング処理で拡大し、顕微鏡観察

$$n = n(J)$$

電離した電子数が一次イオン化率に依存する

Primary specific ionization rate
(1次イオン化率)

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

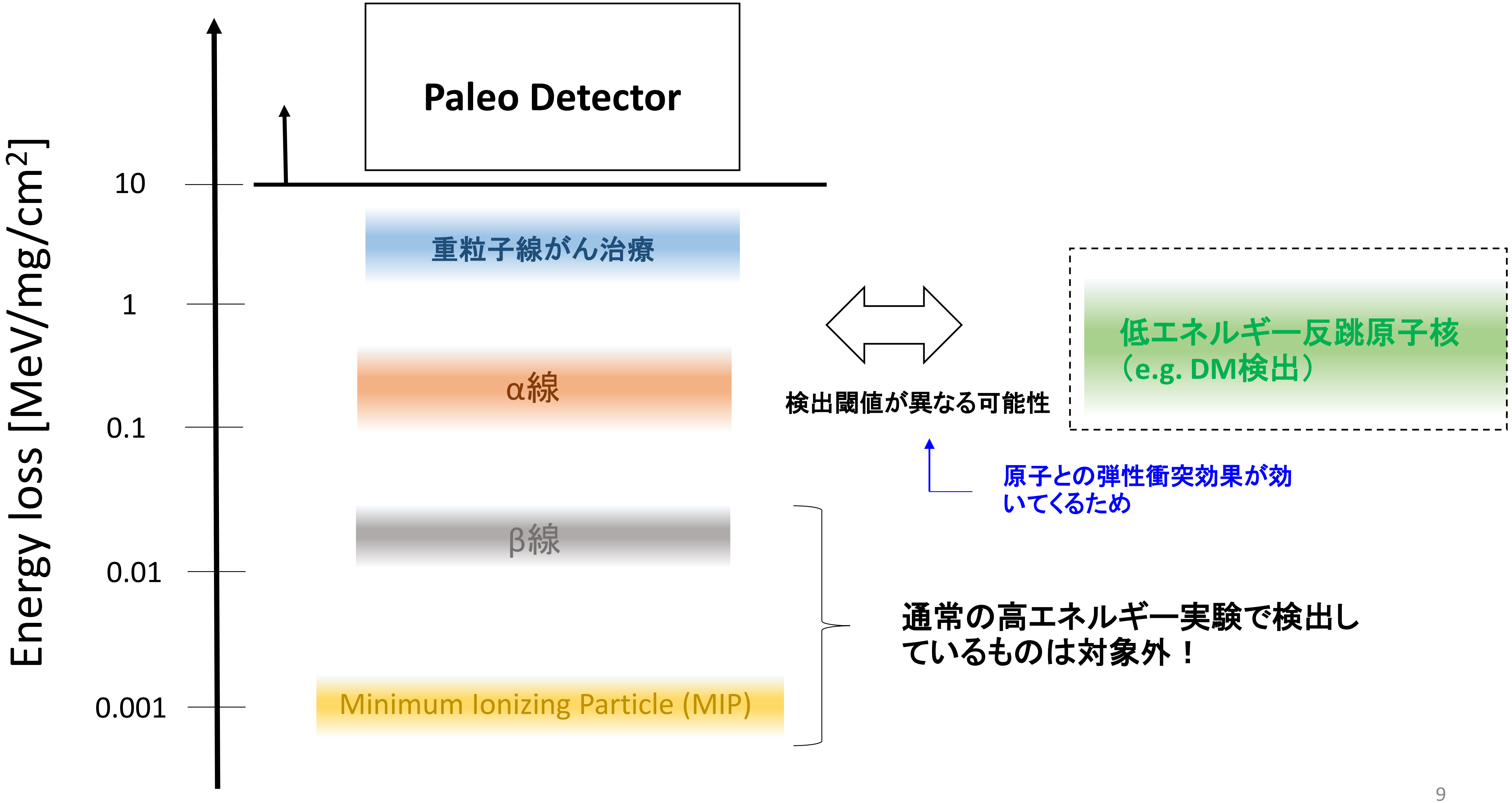
TABLE III. The ratio of the mechanical stress to the electrostatic stress in various materials.

	Material[q]	$R\,(\pm 50\%)$[a]	$R_h\,(\pm 50\%)$[a]	$E\,(10^{11}$ cgs)	Knoop hardness (10^{10} cgs)	Dielectric constant	Specific gravity	Composition
Mineral	Olivine	2.6	1.7	10.3[c]	7.0[i]	20[j]	3.32[i]	$MgFeSiO_4$
	Hypersthene	...	1.2	...	3.9[i]	32[j]	3.45[i]	$Mg_{1.5}Fe_{0.5}Si_2O_6$
	Laboradorite	1.9	1.2	6.7–8.3[c,d]	5.0[i]	20[j]	2.71[i]	$Na_2Ca_3Al_8Si_{12}O_{40}$
	Zircon	...	1.3	...	10.0[i]	12[l,h]	4.68[i]	$ZrSiO_4$
	Phosphate glass	...	0.4	...	2.8[j]	14[j]	3.1[j]	$63P_2O_5{:}11UO_2{:}8Al_2O_3{:}9Ag_2O{:}9K_2O$
	Soda lime glass	1.0	0.4	7.0–7.8[e,c]	3.2[e]	9[j]	2.49[e]	$67SiO_2{:}14Na_2O{:}14CaO{:}5Al_2O_3$
	Tektite glass	0.7	0.3	7.0[e,c]	3.4[j]	6.4[m]	2.43[p]	$74SiO_2{:}12Al_2O_3{:}4FeO$+others[p]
	Orthoclase	...	0.4	...	5.0[i]	4.8[j]	2.57[i]	$KAlSi_3O_8$
	Quartz	0.5	0.5	7.9–10.2[c]	8.0[i]	4.7[c]	2.65[i]	SiO_2
	Phlogopite mica	...	0.06	...	0.90[i]	5–7[c,n]	2.86[i]	$KMg_2Al_2Si_3O_{10}(OH)_2$
	Muscovite mica	...	0.03	...	0.45[i]	5.7–8.7[c,n]	2.93[i]	$KAl_3Si_3O_{10}(OH)_2$
Polymer	Polyethylene terephthalate (Mylar)	0.02	...	0.45[f]	...	3–6[f]	1.35[f]	$C_{19}H_{16}O_7$
	Bisphenol-A polycarbonate (Lexan)	0.007	0.008	0.22[g]	0.25[k]	3.1[g]	1.20[g]	$C_{16}H_{14}O_3$
	HBpaIT polyester	0.013[b]	0.014[b]	...	...	4[o]	1.4[o]	$C_{17}H_9O_2$
	Cellulose acetate butyrate	0.009	0.009	0.04–0.24[f,h]	0.20[k]	3.2–6.4[h]	1.22[f]	$C_{20}H_{32}O_5$
	Cellulose nitrate	0.02	0.02	0.1–0.3[f,h]	0.25[k]	6–8[f,h]	1.33[r]	$C_6H_8O_9N_2$

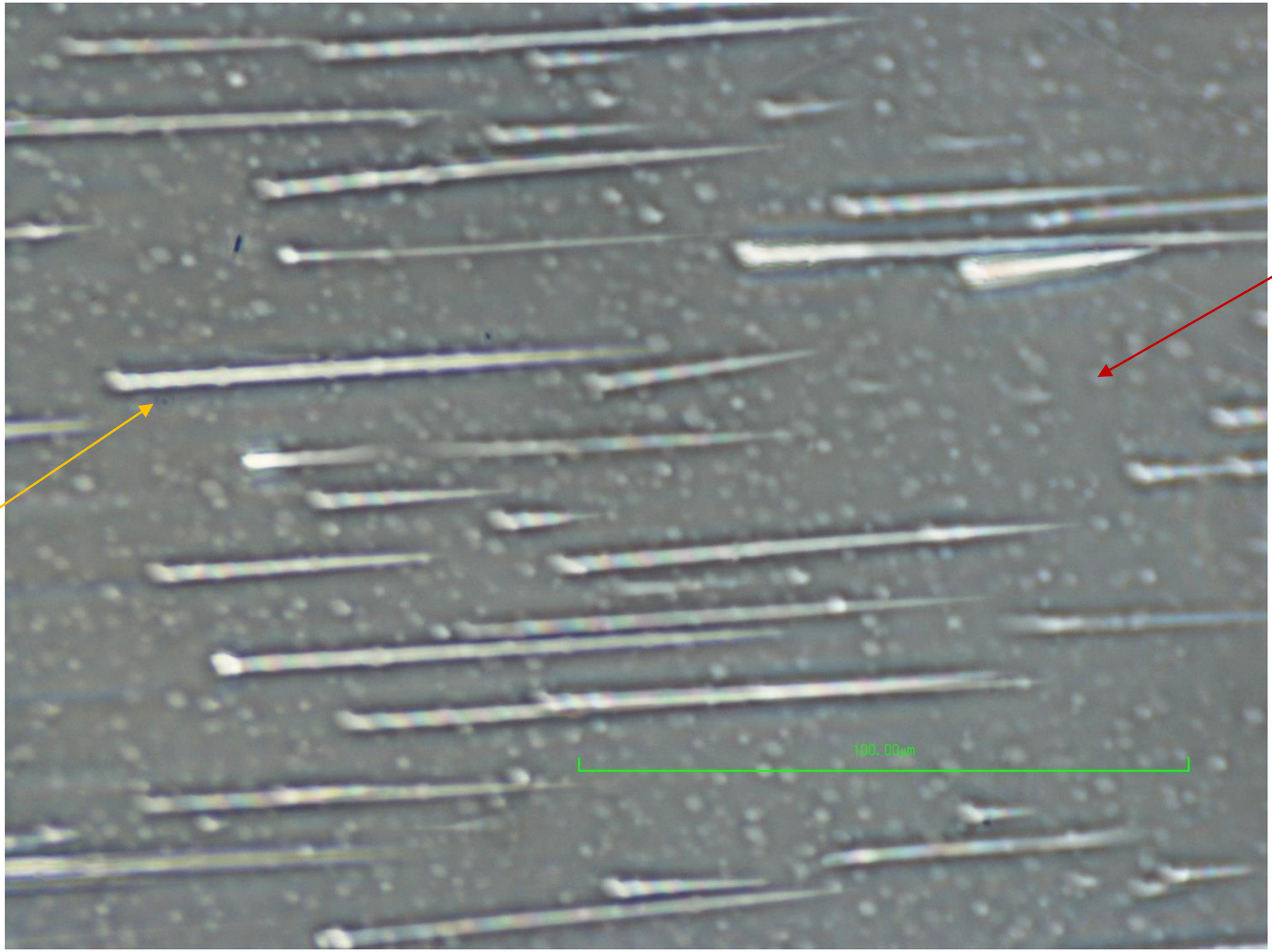
[a] Unit charge assumed on adjacent ions.

R.L. Fleischer *et al.*, J. Appl. Phys. 36, 3645 (1965)

高速度粒子 (β>~10^{-2})　　低速度粒子 (β<~10^{-3})



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



α-recoil track due to ^{238}U

Fe ion track

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

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Phys.Dark Univ. 41 (2023) 101245

Mineral Detection of Neutrinos and Dark Matter

Jan 8 – 11, 2024
US/Eastern timezone

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Timetable

Mon 08/01 | Tue 09/01 | Wed 10/01 | Thu 11/01 | All days

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10:00
Welcome *Sebastian Baum et al.* 10:05 - 10:15
Mineral Detectors for Dark Matter - overview *Patrick Stengel*
11:00
Coff
Pale
12:00
Lun

2023, 2024と2度開催

2025年は日本開催
@海洋研究開発機構
(JAMSTEC)

For Neutrino Detection

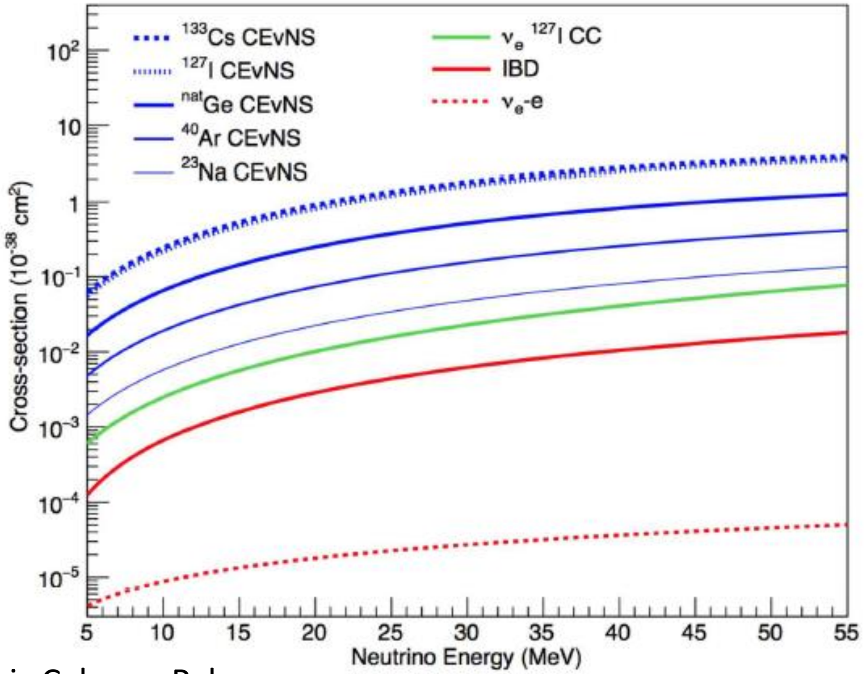
Neutrino coherent scattering

Neutrino coherent scattering is predicted in the standard model.

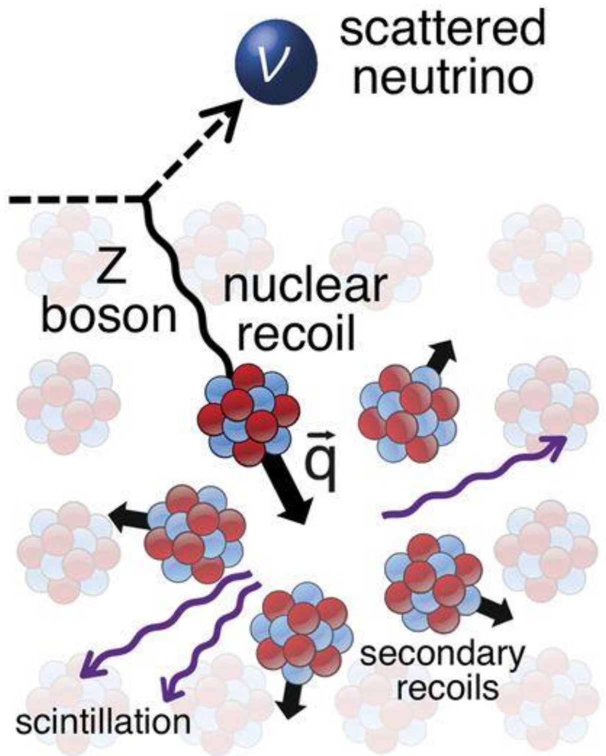
$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi^2}(N - (1 - 4\sin^2\theta_W)Z)^2 m_N(1 - \frac{m_N E_r}{2E_\nu^2})\pi r^2 F^2(E_r)$$

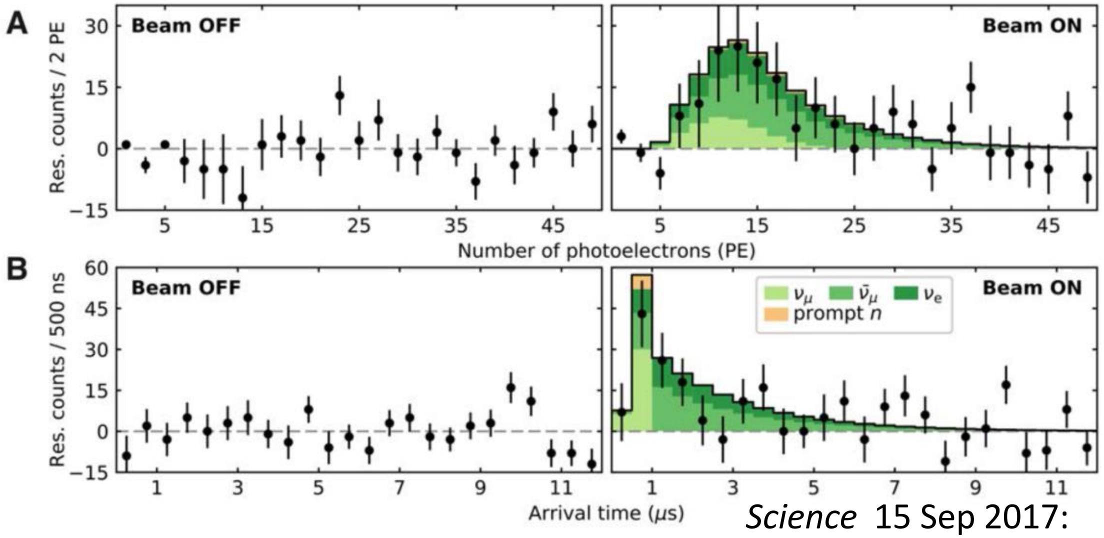
$\propto N^2$ N: number of neutrons

Cross section



Belkis Cabrera-Palmer,
Applied Antineutrino Physics 2018

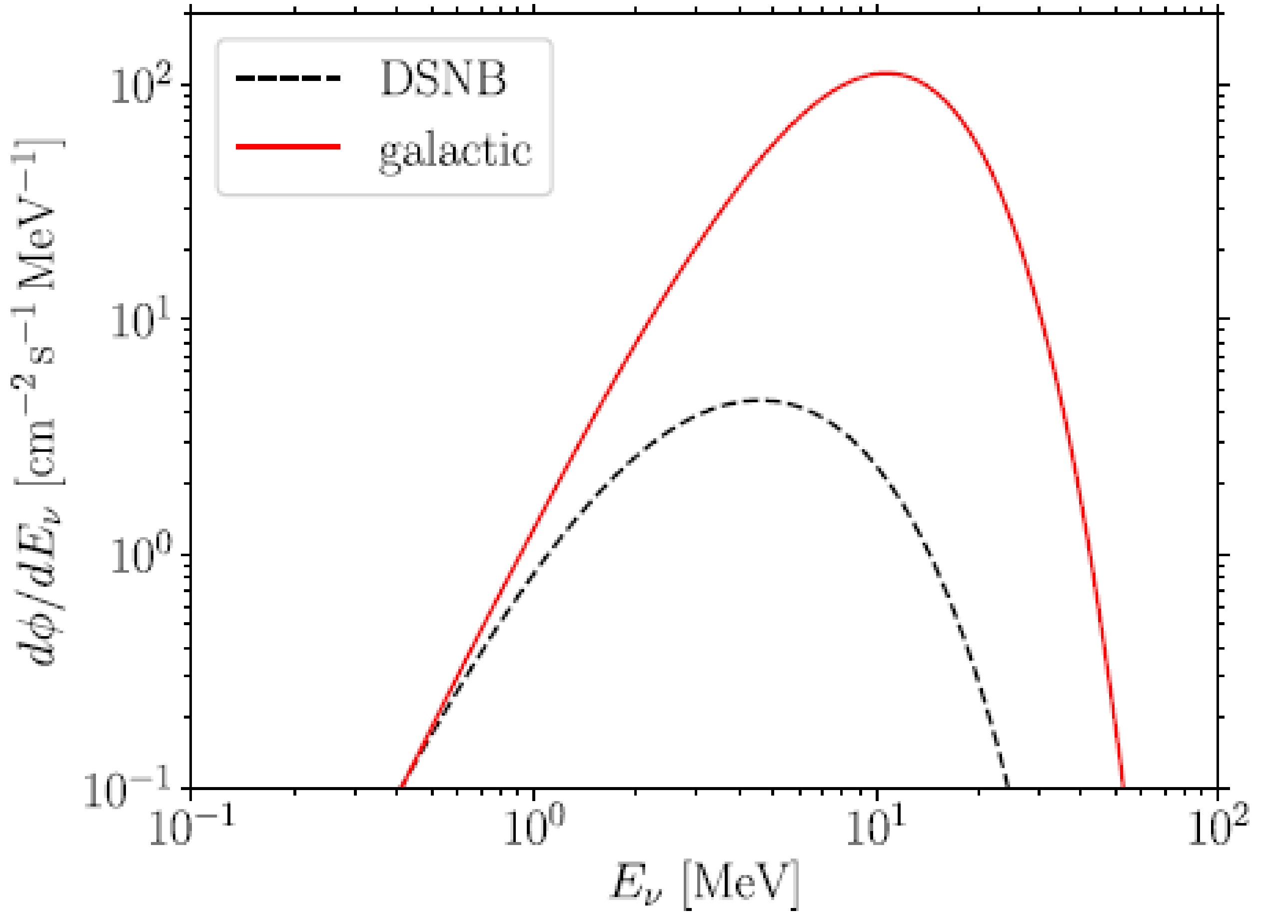




Observation of COHERENT detector @Oak Ridge National Laboratory

Science 15 Sep 2017:
Vol. 357, Issue 6356, pp. 1123-1126

Neutrino Flux from Galactic Core Collapse(CC) Super Novae



Galactic Core Collapse Super Novae rate : 2.3 × 10^{-2} yr^{-1}

S. Baum *et al.,* Phys. Rev. D. 101, 103017(2020)

- **Diffused SN Background(DSNB)**

→ flux input from J.F. Beacom (2010)

- **Galactic CC SN**

$$\left(\frac{d\phi}{dE_\nu}\right)^{gal} = \dot{N}^{gal}_{CC}\frac{dn}{dE_\nu}\int_0^\infty dR_E \frac{f(R_E)}{4\pi R_E{}^2},$$

TABLE I. Parameters of the neutrino spectra, Eq. (1), for electron neutrinos, antielectron neutrinos, and $\nu_x \equiv \{\nu_\mu, \nu_{\bar{\mu}}, \nu_\tau, \nu_{\bar{\tau}}\}$ used in our numerical calculations [75].

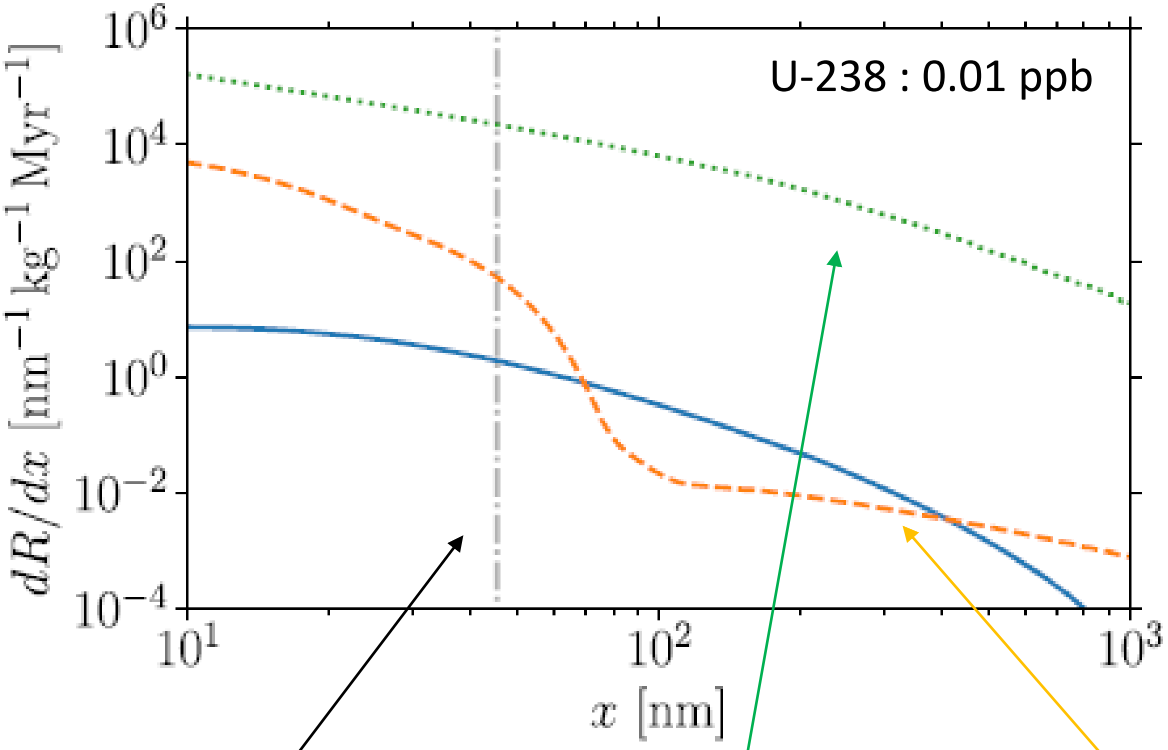
ν	E_ν^{tot} (erg)	$\langle E_\nu \rangle$ (MeV)	α
ν_e	6×10^{52}	13.3	3.0
$\nu_{\bar{e}}$	4.3×10^{52}	14.6	3.3
ν_x	2×10^{52}	15	3

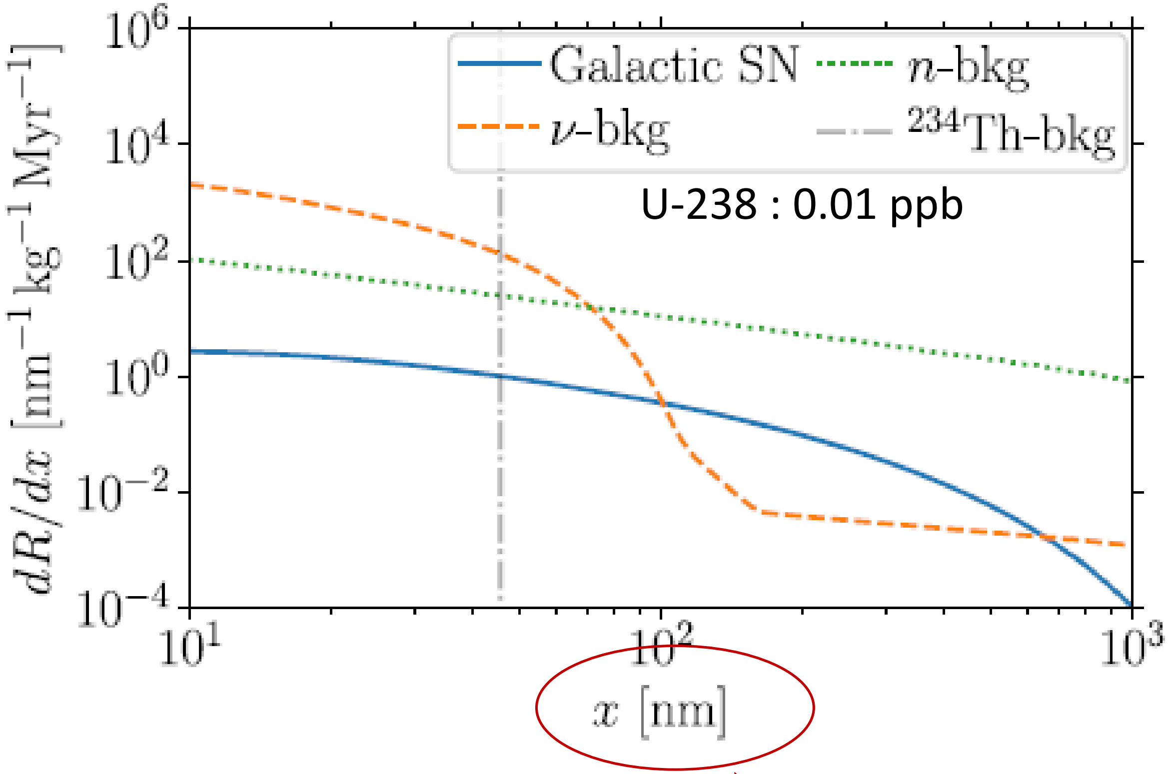
⇨

原子核のコヒーレント散乱
反跳エネルギー: 10～100keV

Halite(岩塩） [NaCl]

Epsomite (瀉利塩) [$Mg(SO_4)$・$7(H_2O)$]





$^{238}U \rightarrow$ ^{234}Th + α

72 keV

Neutron background

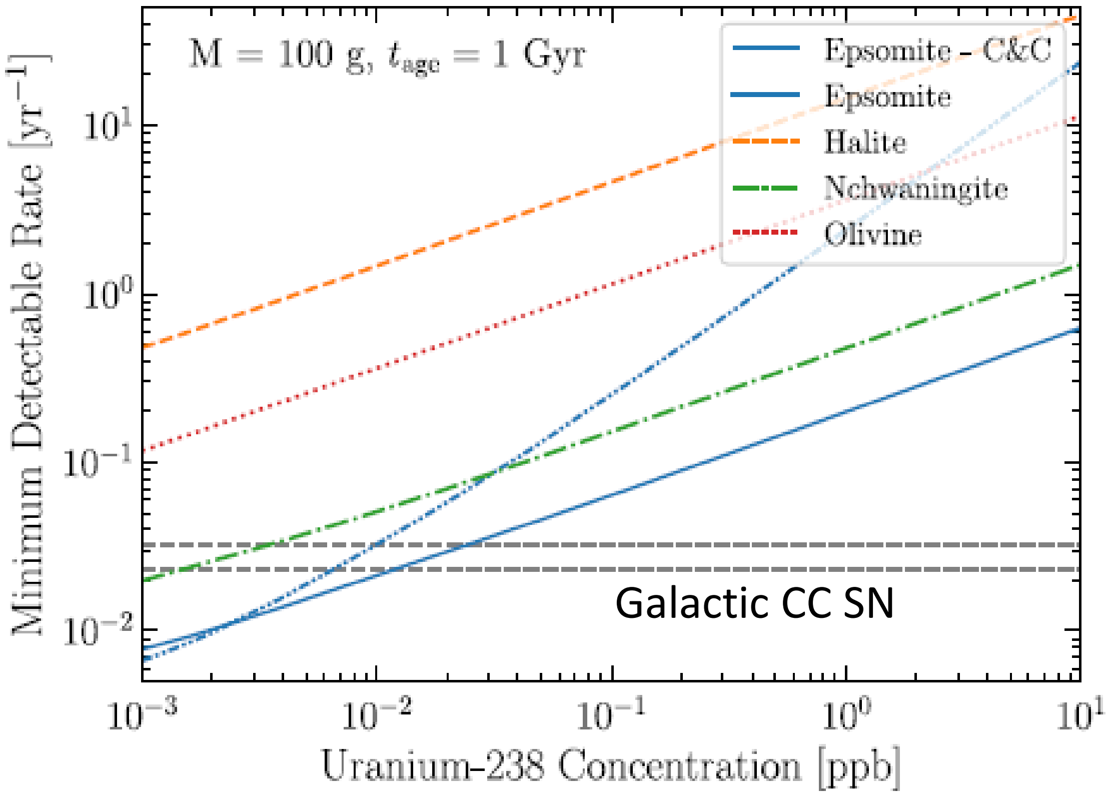
- Spontaneous fission
- (α, n) reaction

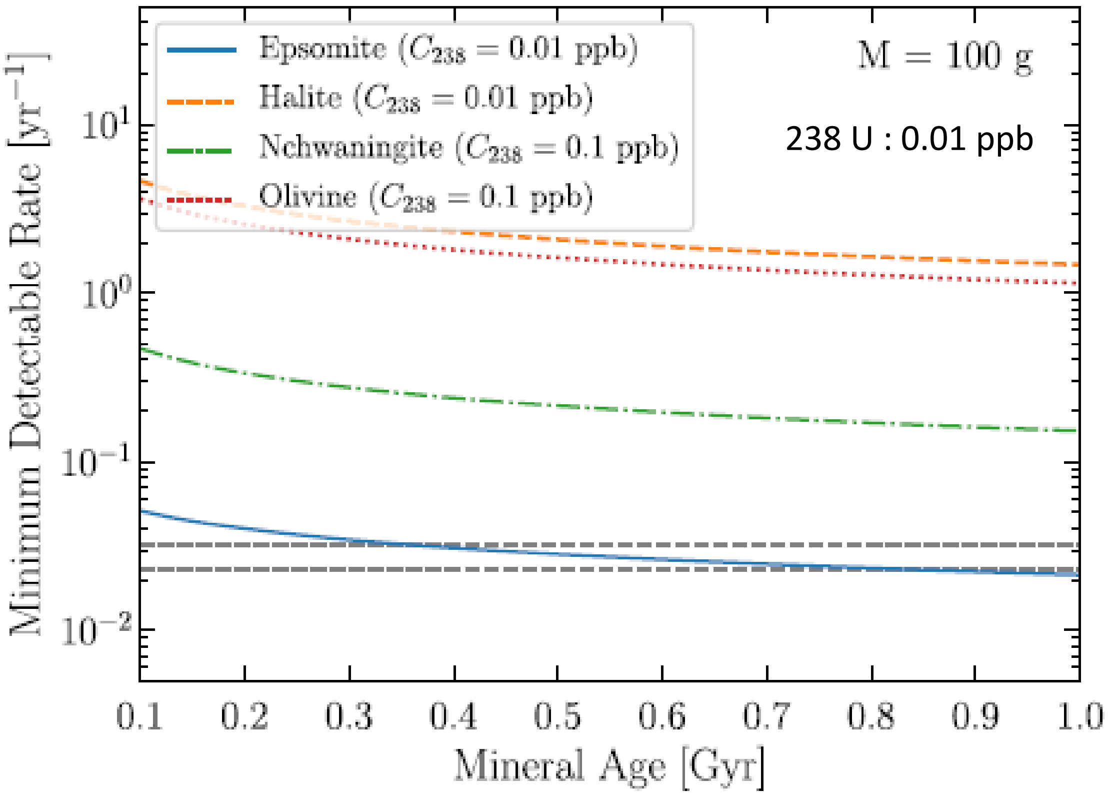
ν background

- Solar neutrino (< 20 MeV)
- Diffused SN ν (DSNB) (20 MeV < E < 30 MeV)
- Atomospheric ν (E > 30 MeV)

飛跡長 ∝ 反跳エネルギー

Galactic CC SN rate in the mineral





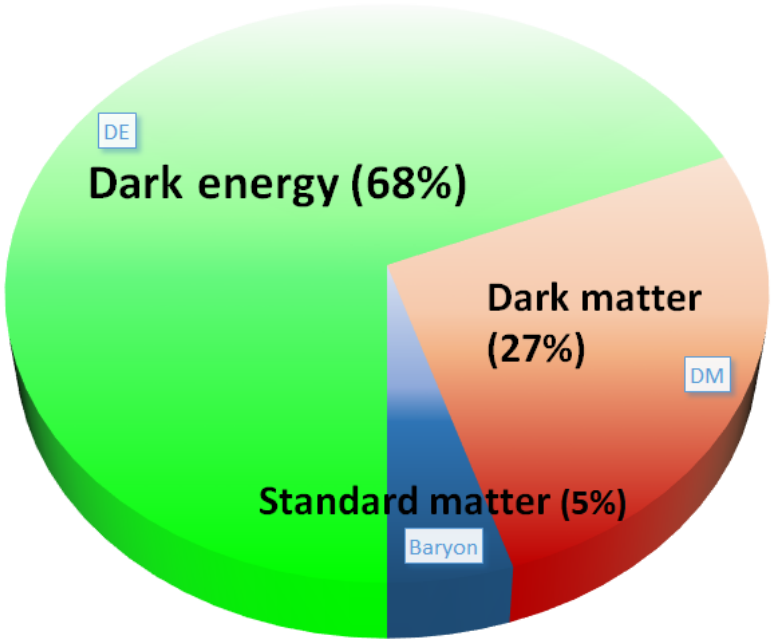

Episomite[$Mg(SO_4)\cdot 7(H_2O)$]


Halite[NaCl]


Nchwaningite [$Mn_2^{2+}SiO_3(OH)_2\cdot H_2O$]

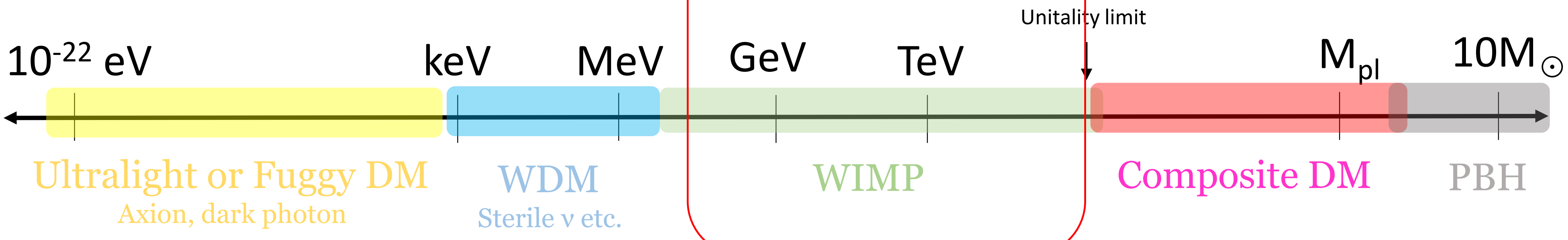

Olivine [$Mg_{1.6}Fe^{2+}_{0.4}SiO_4$]

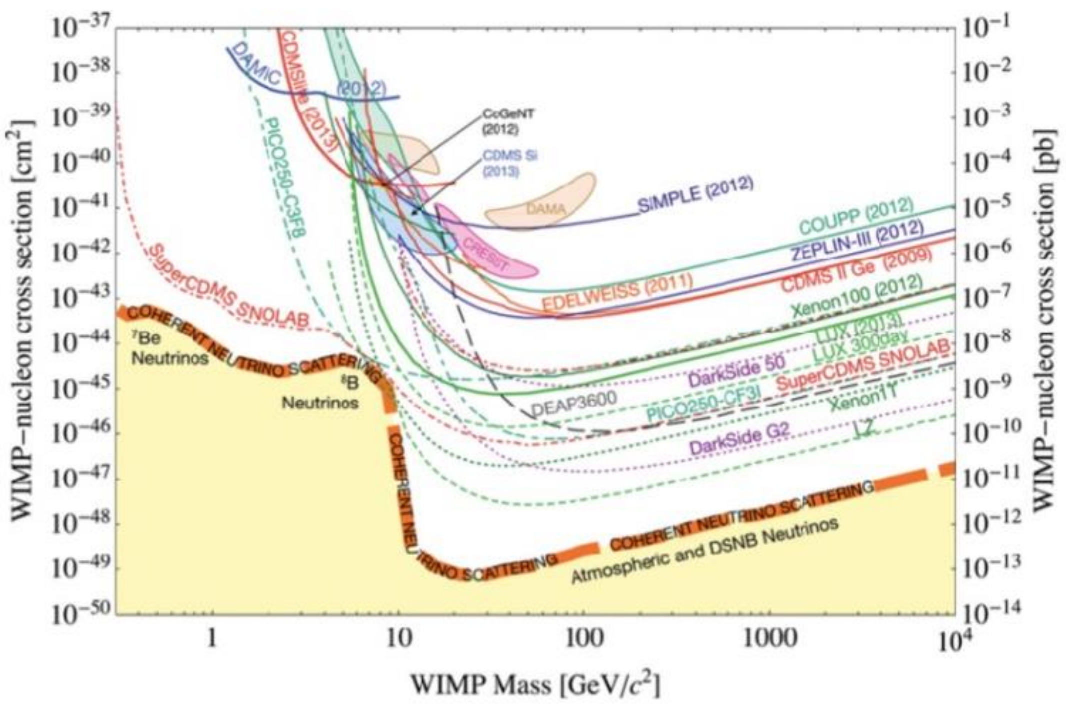
For Dark Matter Detection



Planck 2013 results

Dark Matter mass scale





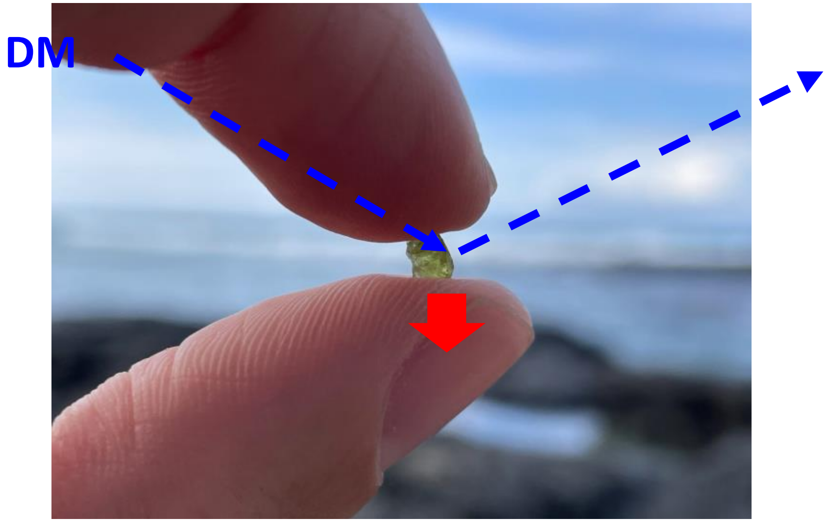
Number of signal $N = R\,[/kg/year] \times M\,[kg] \times T\,[year]$

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

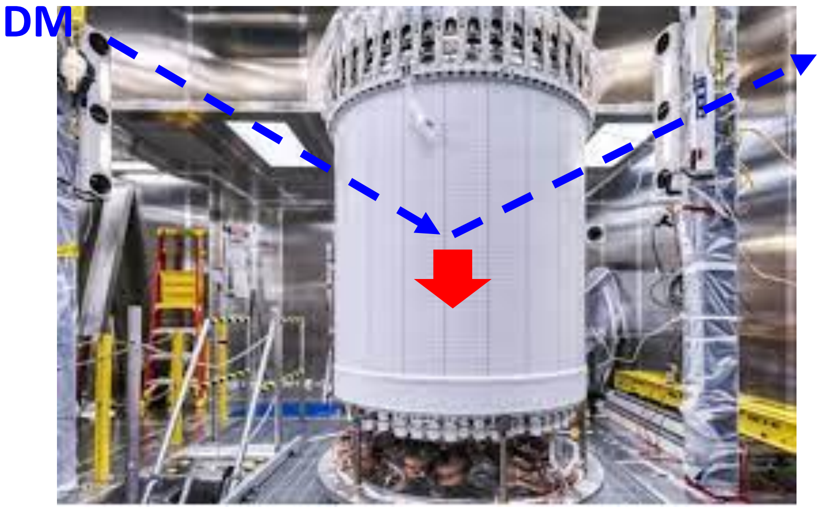
DM-nuclei cross section (unknown parameter)

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

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

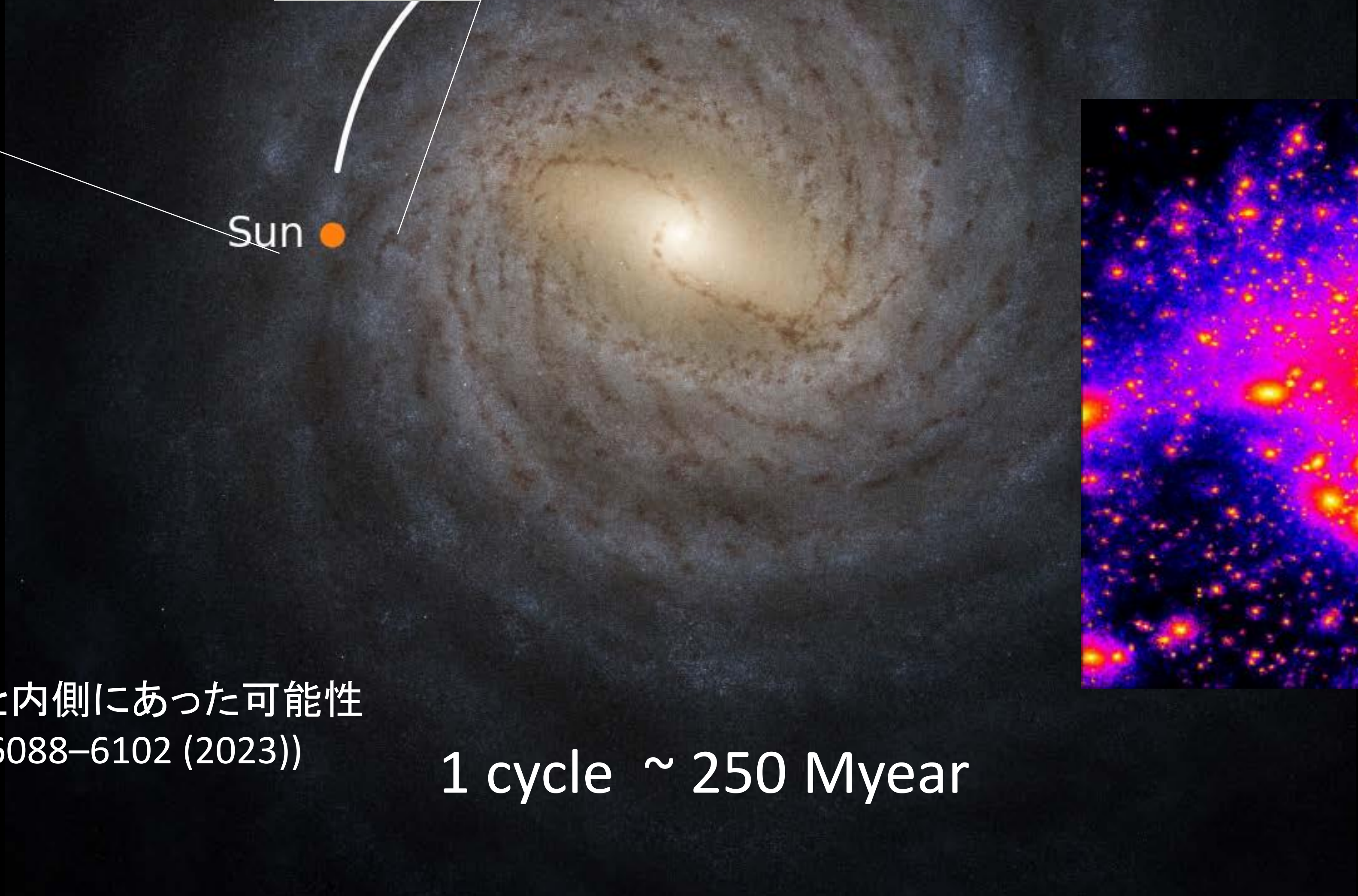


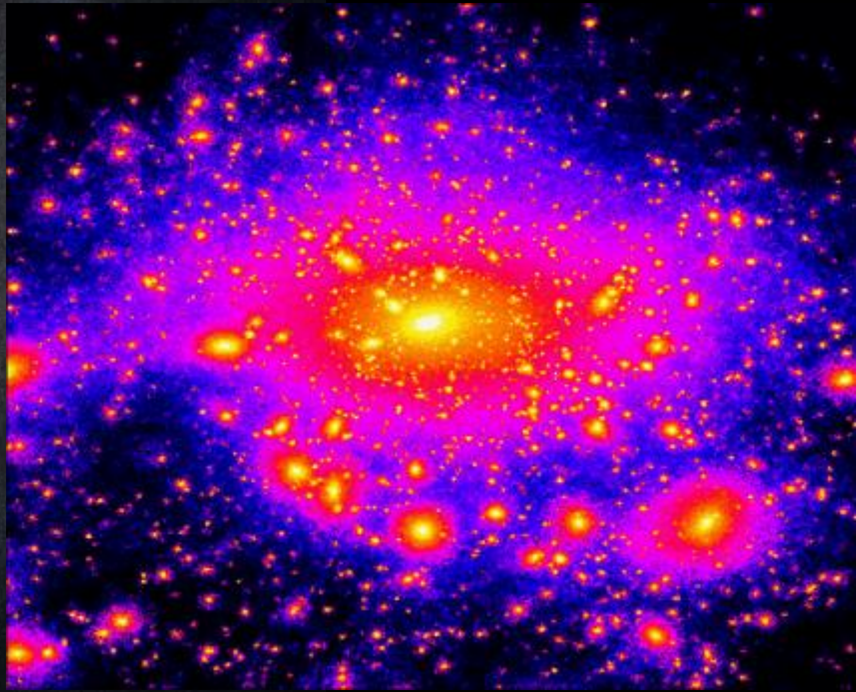
VS



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..

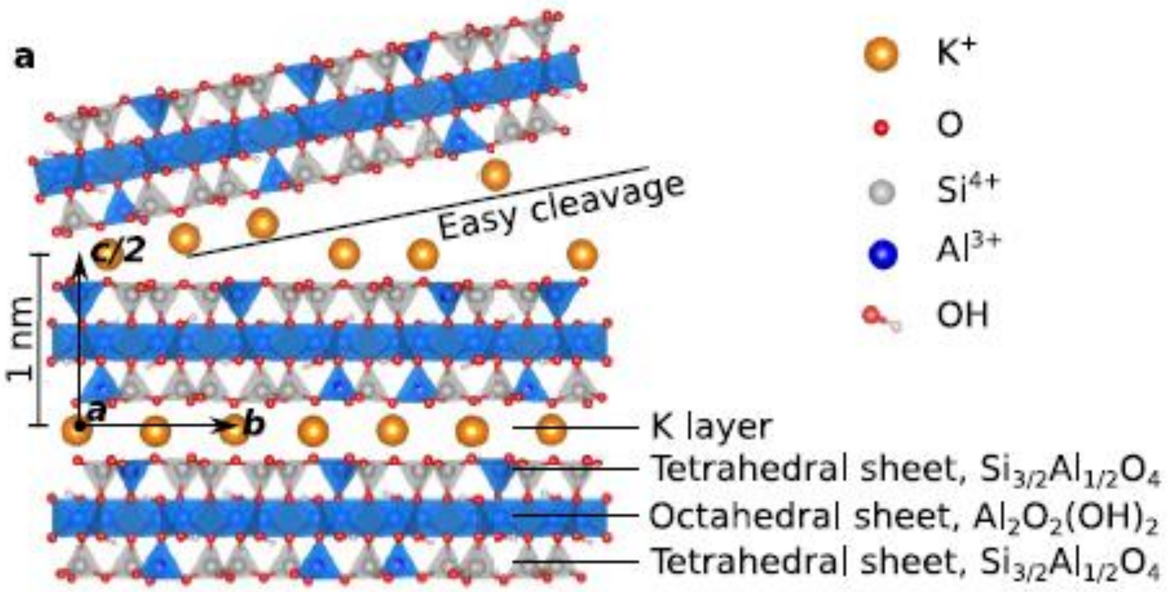




昔の太陽系は、もっと内側にあった可能性もある (MNRAS 526, 6088–6102 (2023))

1 cycle ~ 250 Myear

Muscovite Mica (白雲母)



Franceschi+ 2023

Formula	$KAl_2(AlSi_3O_{10})(OH)_2$
Cleavage	Perfect on {001}
Geological Setting	Common in many different rock types as a primary mineral

- Lower tracking threshold for energy deposition
- Low Uranium contamination (~ ppb)
- Thin layer and transparent

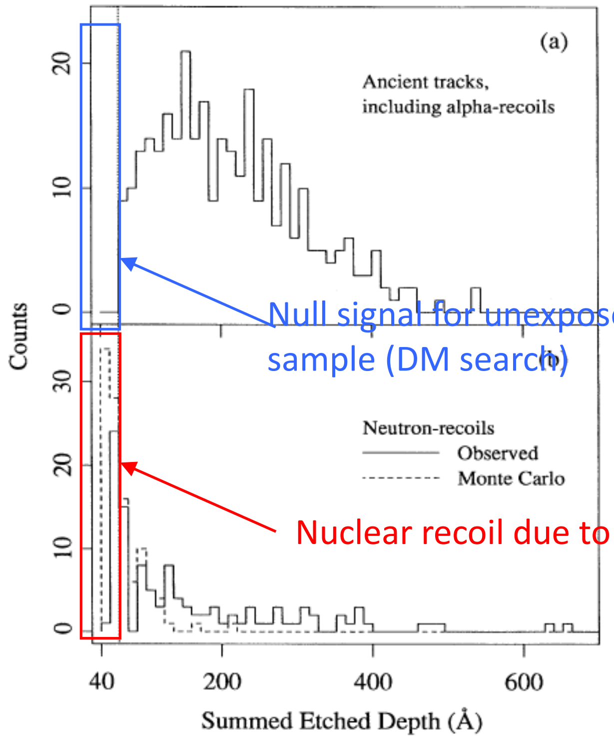
Previous research for WIMP search

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.

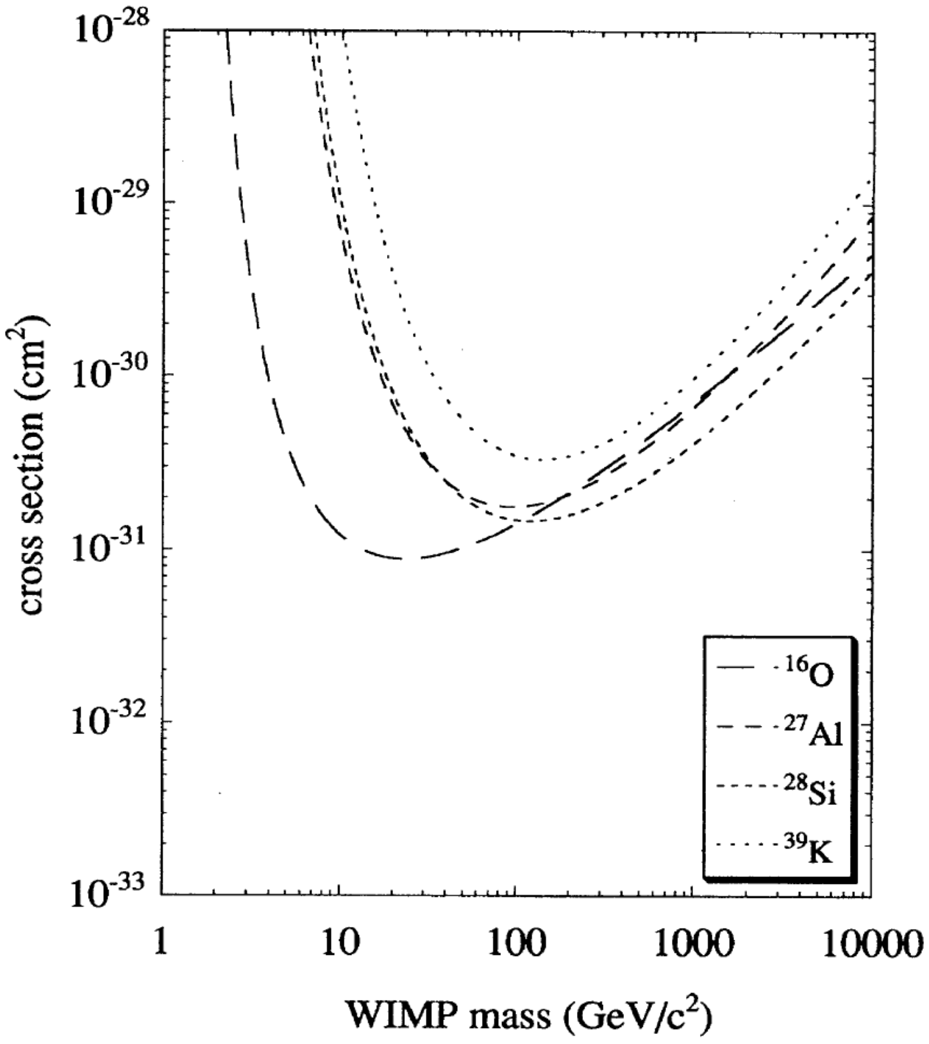


Scanning area : 80720 μm^2
=8×10^{-4} cm^2
(Probably ~ 10^{-9} g)

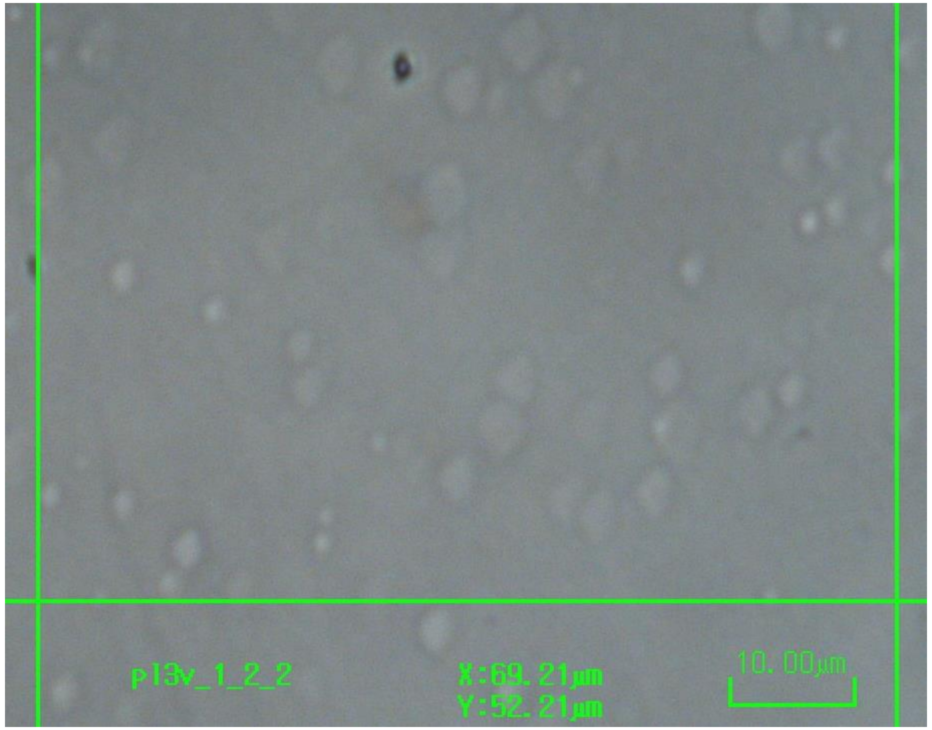
Exposure : 0.5 Gyear

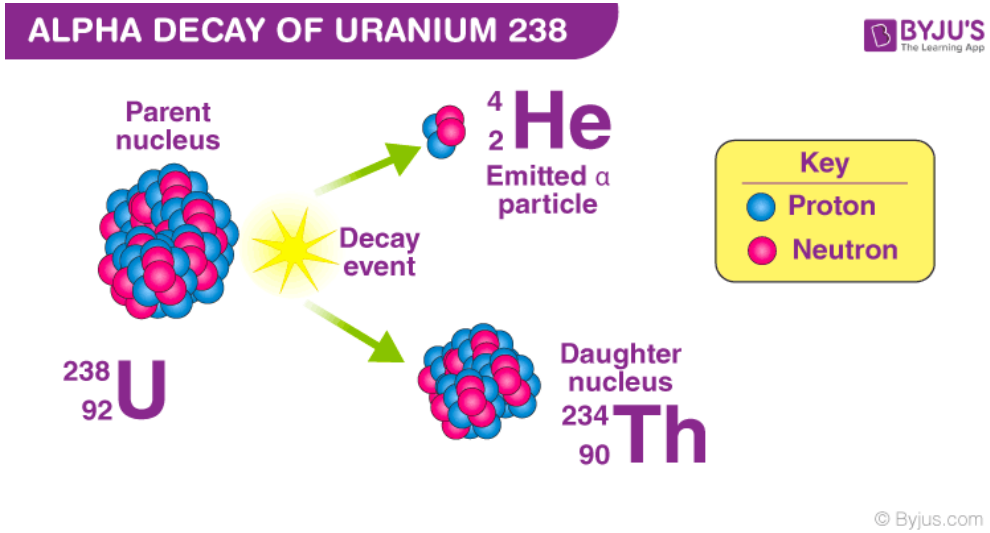
⇨ ~ 0.5 g・year exposure

Readout technique : AFM



α-recoil tracks





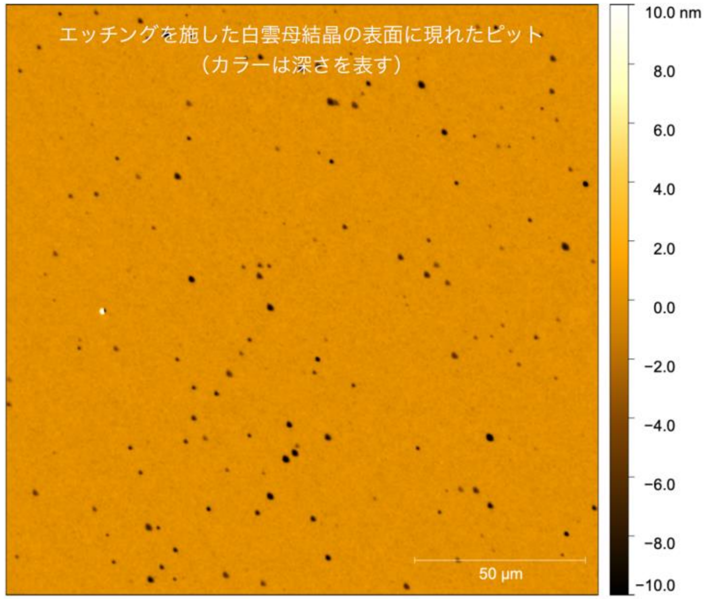
Electronic loss : ~ 1.4 MeV/mg/cm^2

Nuclear loss : ~ 12 MeV/mg/cm^2

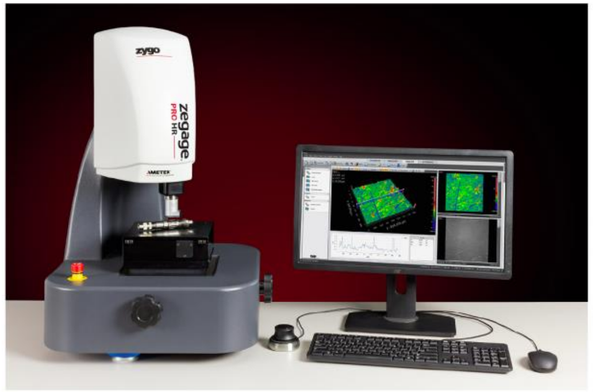
28nm nm

DMICA project

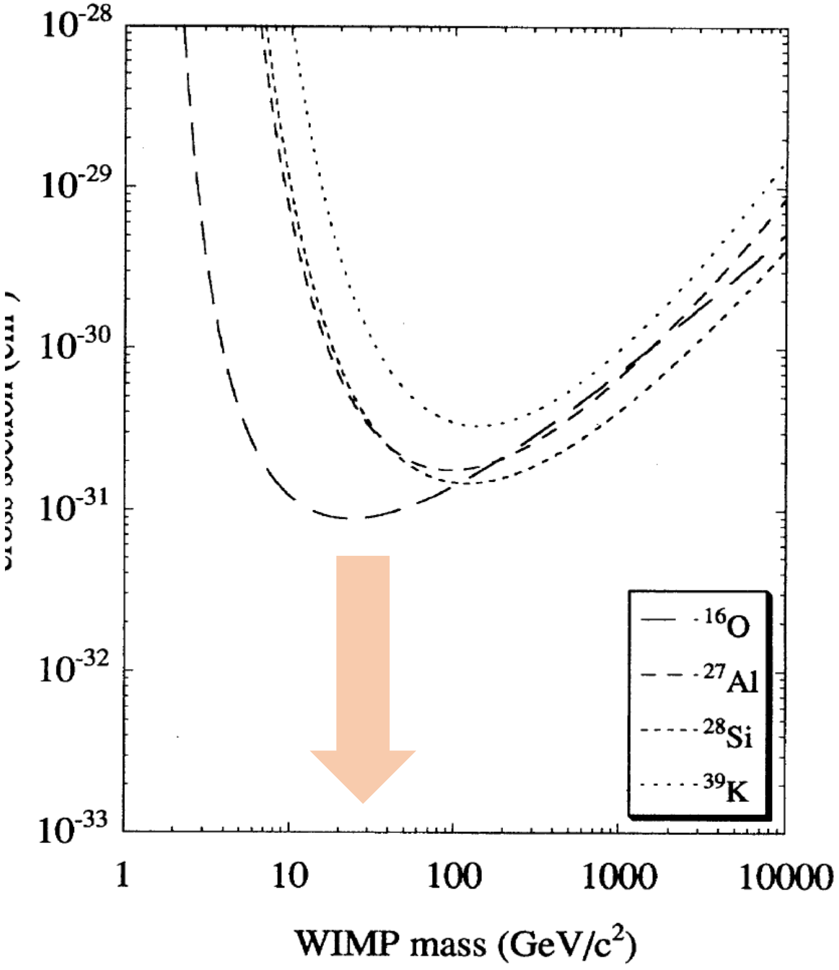
JAMSTEC 廣瀬さん +



劈開面から10nm程度の深さまでに存在したトラックがピットとして現れている



- DMICAではのべ400cm²の劈開面測定を目指す
  - 1視野（3e-4cm²）の測定に5秒かかる
  - 1試料（2cm²）の測定が1日（9.2時間）で完了する
  - “計算上”、200日でのべ400cm²の測定を達成

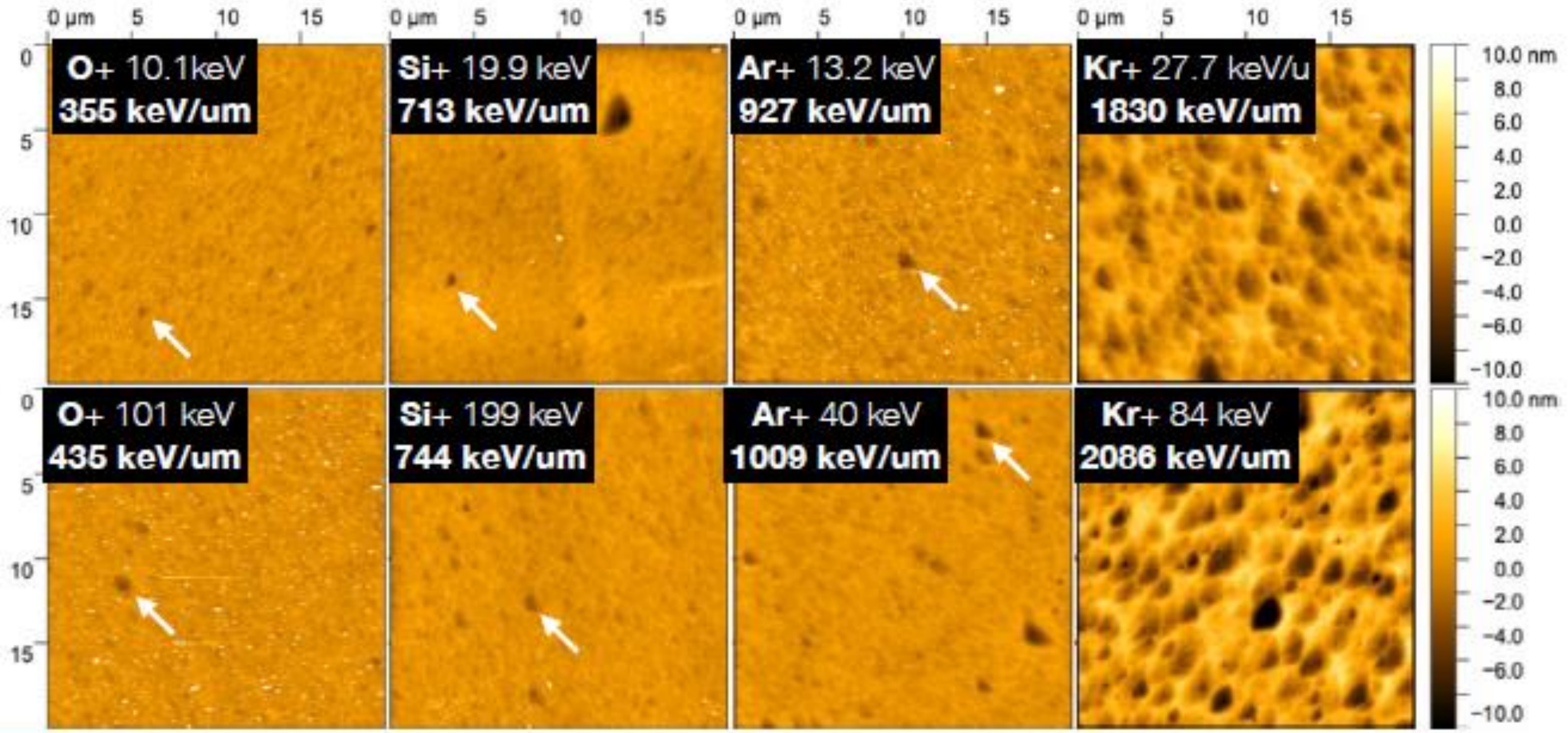


	survey area	sample age	exposure	readout
Snowden-Ifft	0.08 mm²	0.5 Gyr	1e-6 ton year	AFM
DMICA	**400 cm²**	**1 Gyr**	**1 ton year**	**3D optical profiler**

Larger stopping power results in higher pit formation efficiency

arXiv:2301.07118

AFM image
(原子間力顕微鏡)

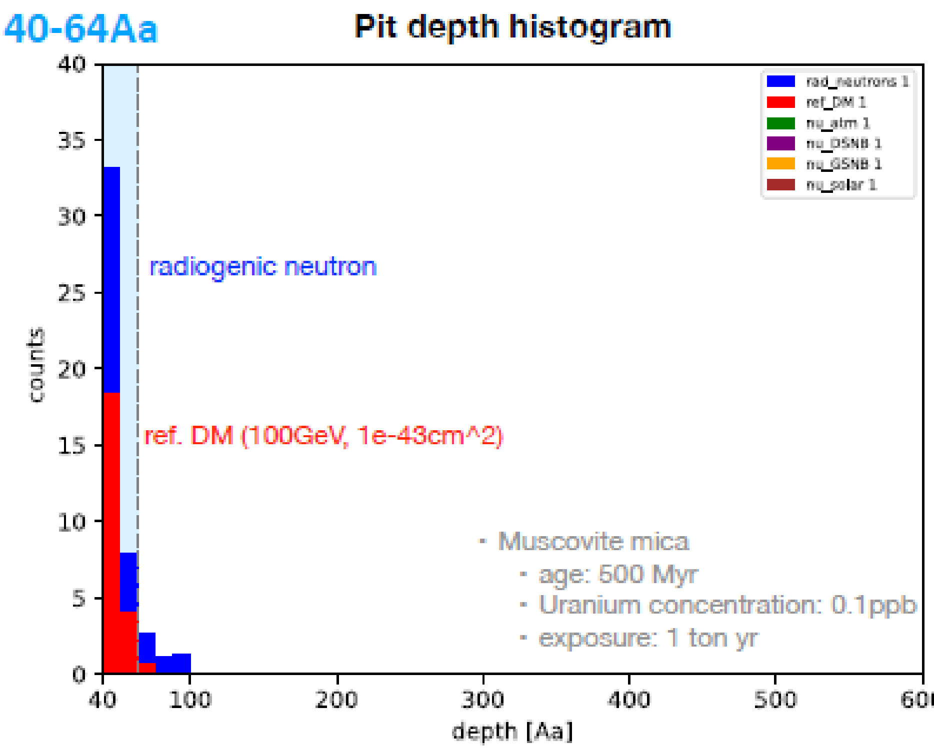


Irradiation dose is 80 ions per field of view (20umx20um).

proxy	DM scattering	alpha recoils
pit formation efficiency	several to 10 %	~ 100%

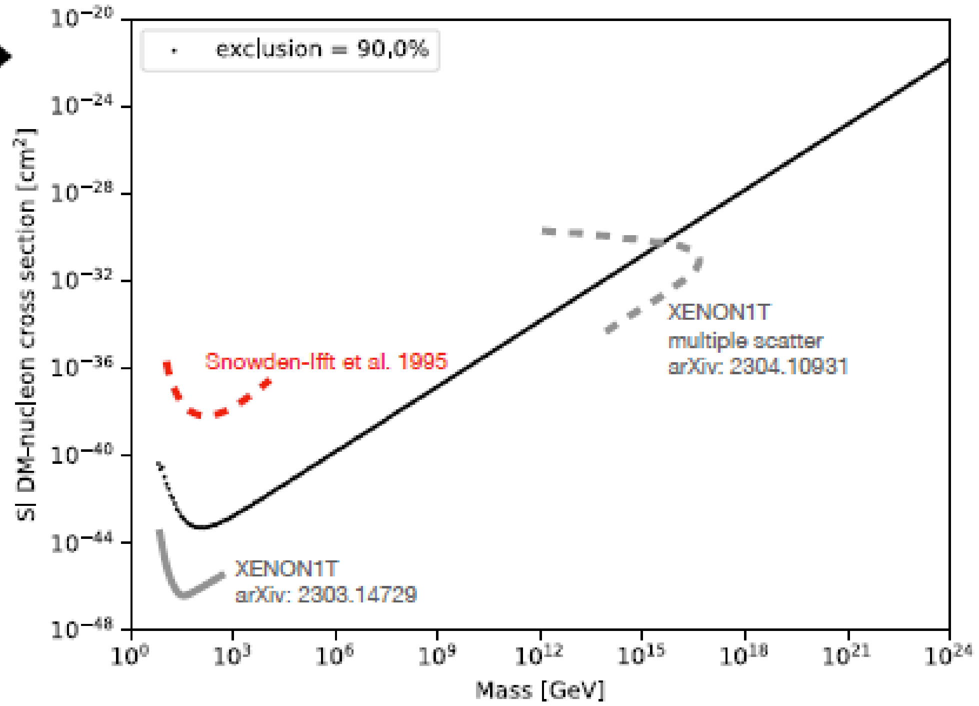
S. Hirose, slide of MDvDM'23

Sensitivity Curve derived for DMICA's target exposure of 1 ton year case



Likelihood ratio test
using paleoSens

Hirose et al. in prep

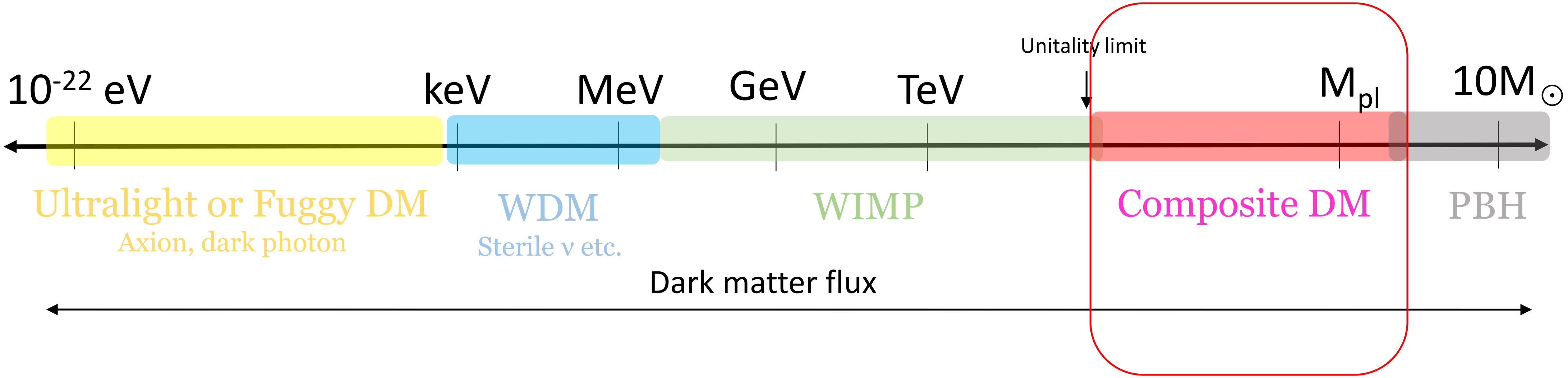


- High-mass end of the curve of DMICA could be significantly larger than that of the XENON1T experiment.

S. Hirose, slide of MDvDM'23

天の川一周分以上の情報の蓄積データの解析のため、質的に異なる検証

Dark Matter mass scale



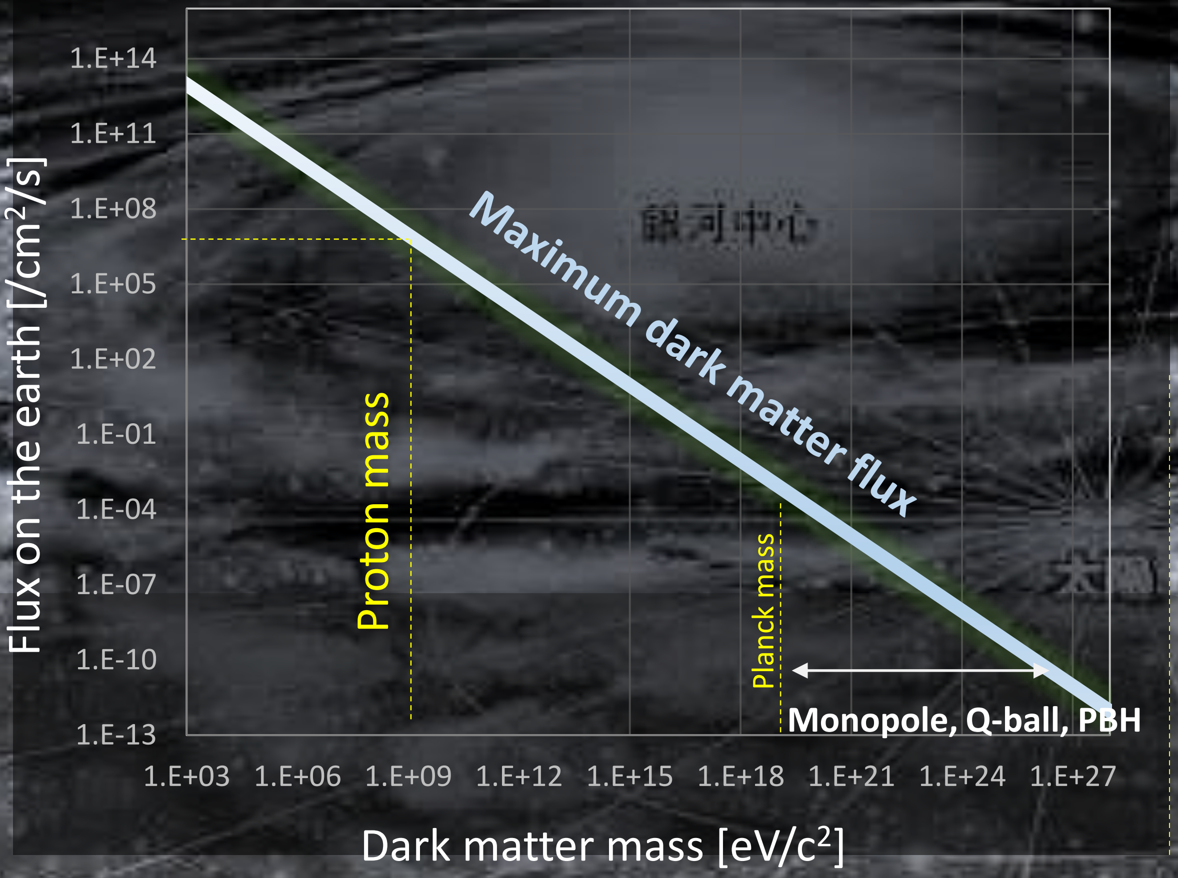
Candidate : Q-ball, quark nugget、Nuclearite, etc.
Mass scale : > 10^{20} GeV

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

➡ **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} /cm²/sec

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

⬇

Paleo detector with geoscience scale is powerful methodology!

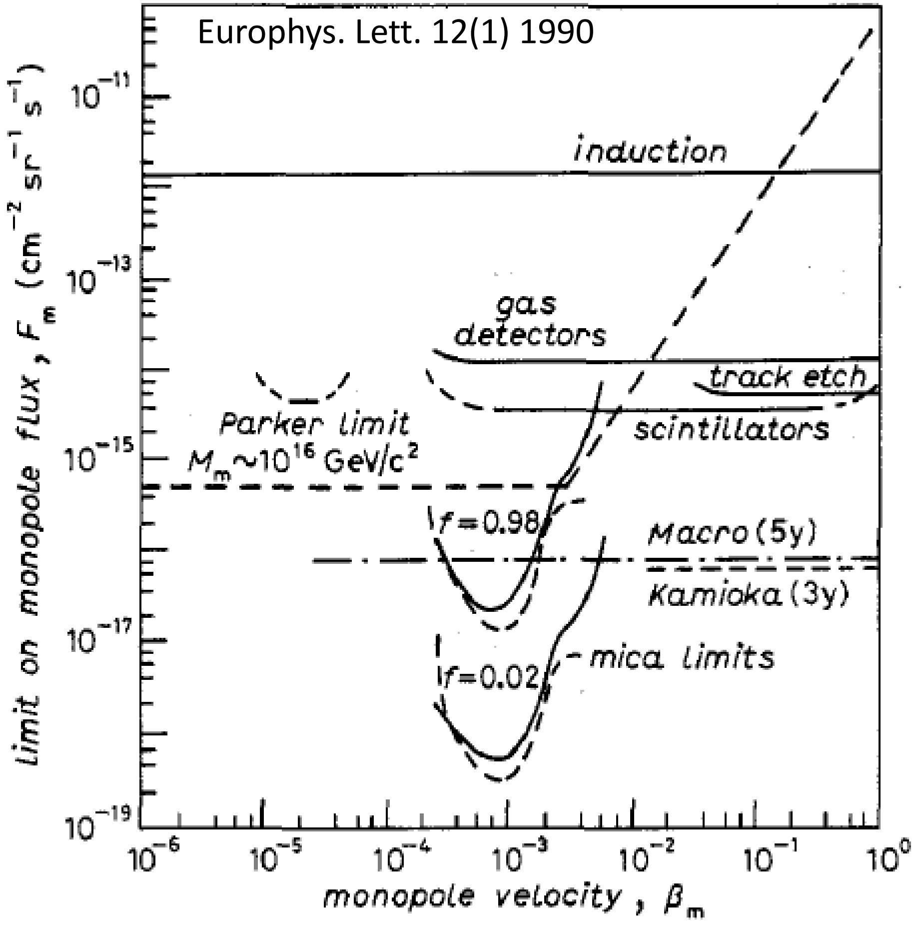
Monopole

PDG

Monopole Flux — Cosmic Ray Searches

"Caty" in the charge column indicates a search for monopole-catalyzed nucleon decay.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	*MASS* (GeV)	*CHG* (g)	*COMMENTS* ($\beta = v/c$)	*EVTS*	*DOCUMENT ID*		*TECN*
<1.5E−18		1	β >0.6	0	[1] ALBERT	17	ANTR
<2.5E−21		1	1E8< γ <1E13	0	[2] AAB	16	AUGE
<1.55E-18			β >0.51	0	[3] AARTSEN	16B	ICCB
<1E-17		Caty	1E-3< β <1E-2	0	[4] AARTSEN	14	ICCB
<3E-18		1	β >0.8	0	[5] ABBASI	13	ICCB
<1.3E-17		1	β >0.625	0	[6] ADRIAN-MAR..	12A	ANTR
<6E-28	<1E17	Caty	1E-5< β <0.04	0	[7] UENO	12	SKAM
<1E-19		**1**	**γ >1E10**	0	[8] DETRIXHE	11	ANIT
<3.8E-17		1	β >0.76	0	[5] ABBASI	10A	ICCB
<1.3E−15	1E4<M<5E13	1	β >0.05	0	[9] BALESTRA	08	PLAS
<2.E−13			4.E−4 < β <1	0	TSUKAMOTO	87	CNTR
<5.E−14		1	all β	1	[19] CAPLIN	86	INDU
<5.E−12		1		0	CROMAR	86	INDU
<1.E−13		1	7.E−4 < β	0	HARA	86	CNTR
<7.E−11		1	all β	0	INCANDELA	86	INDU
<1.E−18			4.E−4 < β <1.E−3	0	[18] PRICE	86	MICA
<5.E−12		1		0	BERMON	85	INDU
<6.E−12		1		0	CAPLIN	85	INDU
<6.E−10		1		0	EBISU	85	INDU



Mica was utilized for monopole search assumed M-Al bound condition

Q-ball

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

Q-ball solution and Affleck-Dine(A-D) mechanism

- Q-ball solution (Coleman, 1985)

Scalar field ϕ with U(1) symmetry

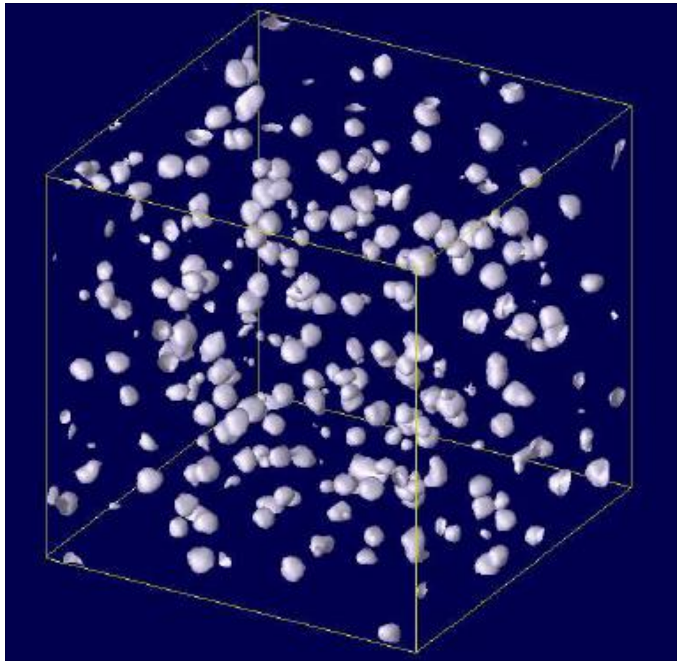
$$Q = \frac{1}{2i}\int d^3x(\phi^*\dot{\phi} - \dot{\phi^*}\phi)$$

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

Q-ball = field configuration minimizing E with Q constant

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

- 空間的なスカラー場のゆらぎ
- Q-ball の生成



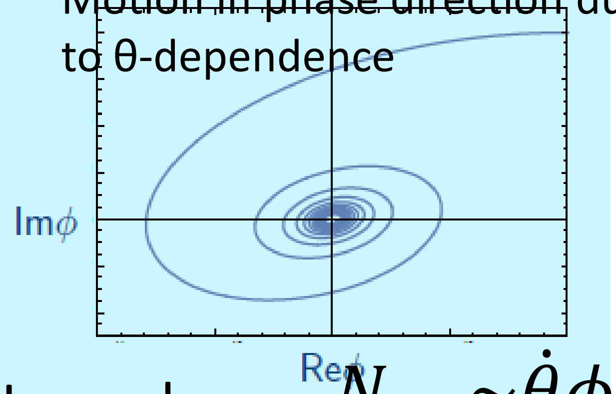
Hiramatsu, Kawasaki, Takahashi (2010)

- A-D mechanism

- MSSM scalar field

- SUSY breaking and inflation

Motion in phase direction due to θ-dependence



Generation of B and L number $N_{B,L} \sim \dot{\theta}\phi^2$

初期宇宙におけるBaryon数（Lepton数）生成機構

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) < ϕ²

Gage-mediation type — new type

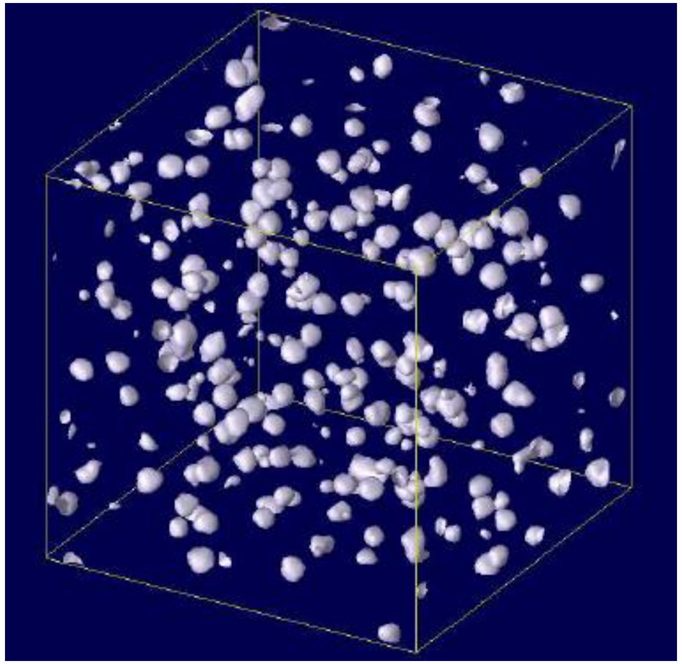
Q-ball is always formed

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

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)

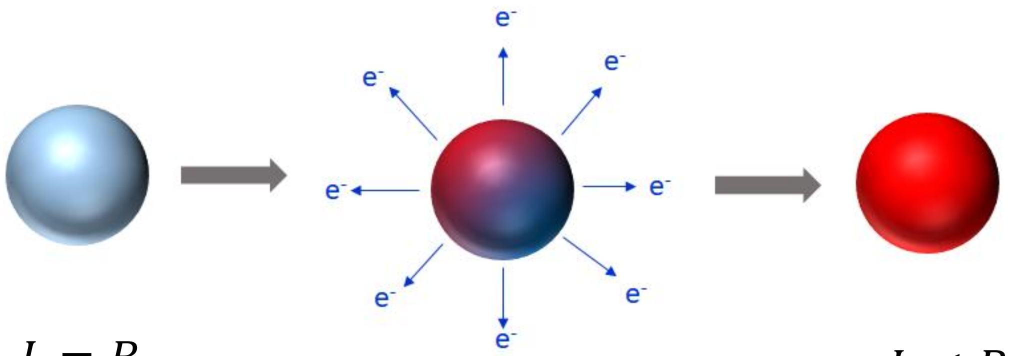
Q-ball can be the Dark Matter because there is no lighter particle with baryon number than proton.

Stable "charged" Q-ball

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

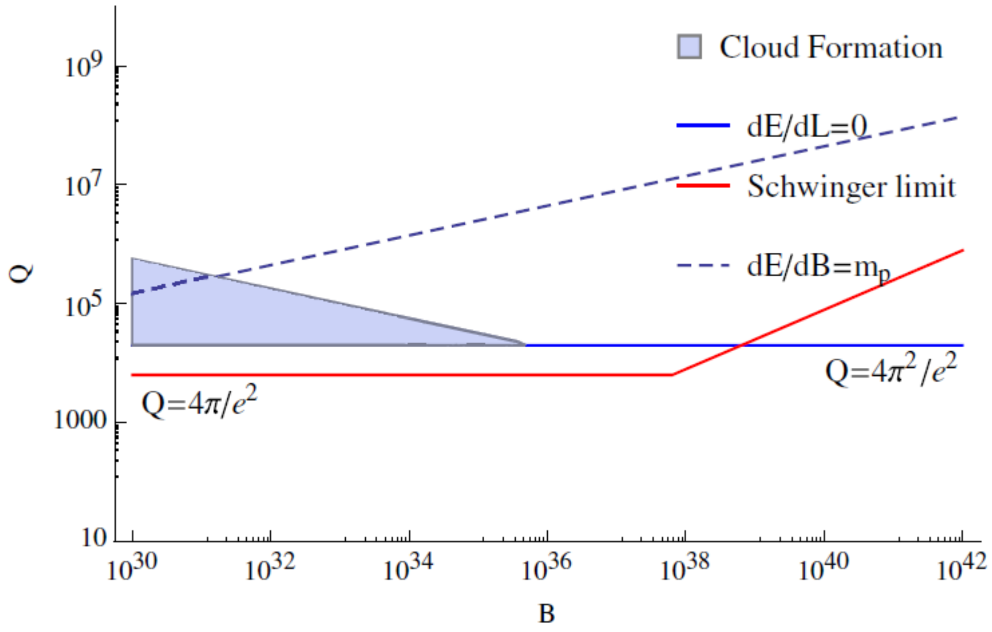
J.P. Hong, M. Kawasaki , PRD, 95, 123532 (2017)

- 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



$L = B$
$Q_e = B - L = 0$

$L < B$
$Q_e = B - L > 0$

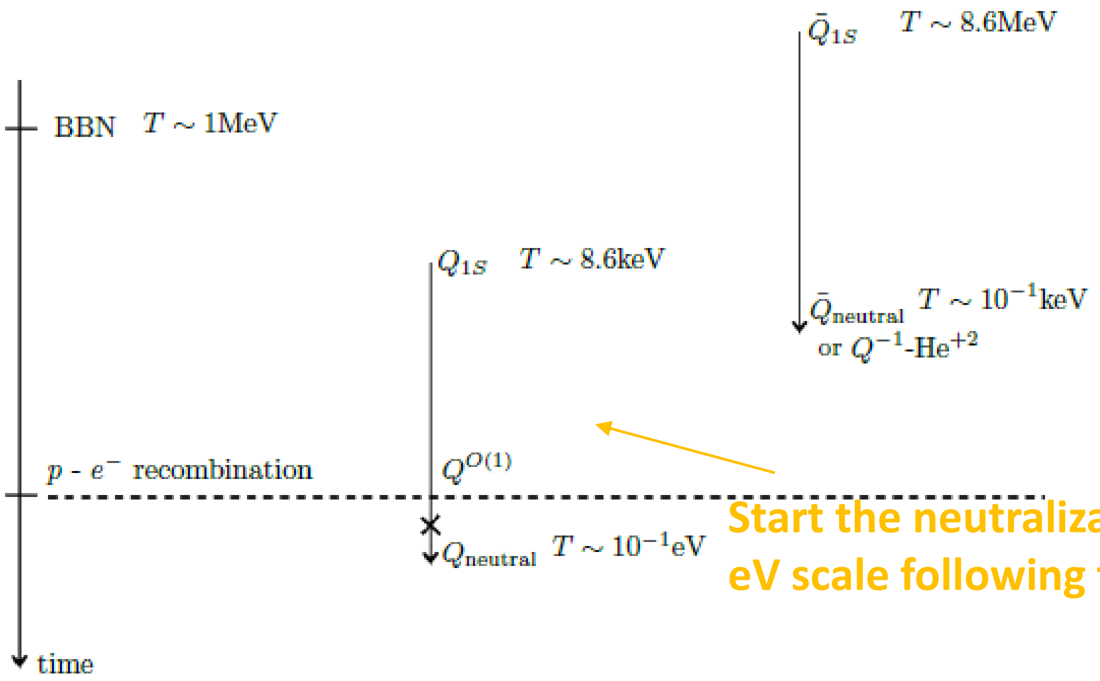


Stable charged Q-ball condition

- **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**

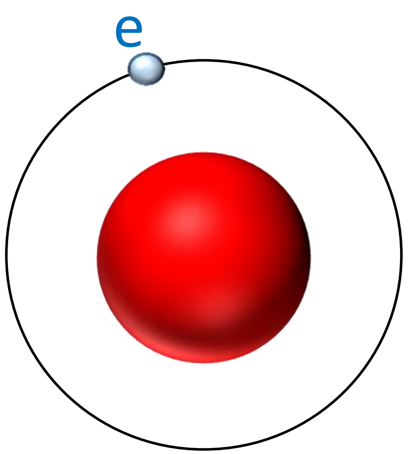
Condition of “charged” Q-ball dark matter

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

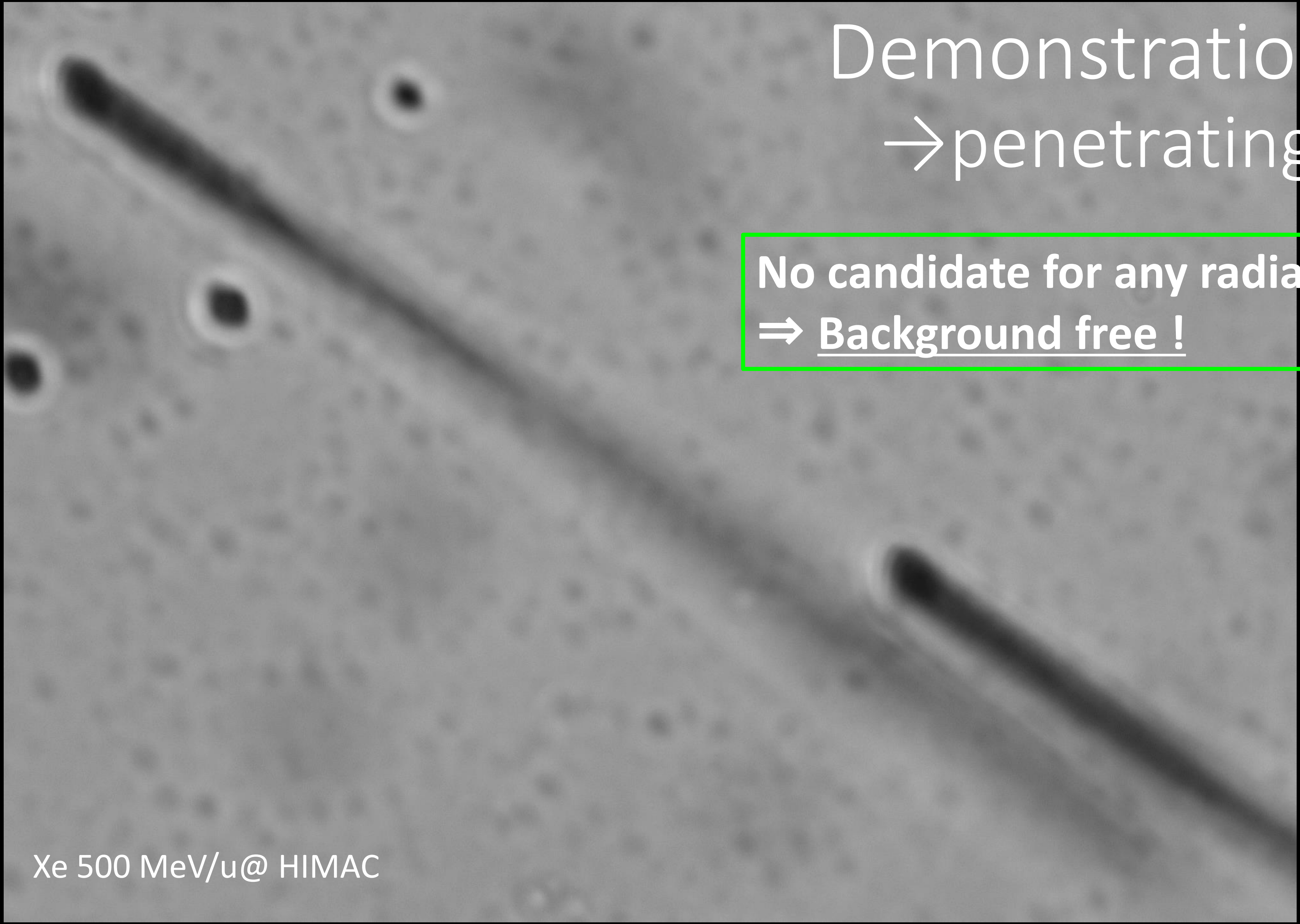
$Q_e = \alpha^{-1} \sim 137$

+O(1) ionlike

β : 10^{-3}

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

Demonstration
→penetrating long track



No candidate for any radiation on the earth
⇒ <u>Background free !</u>

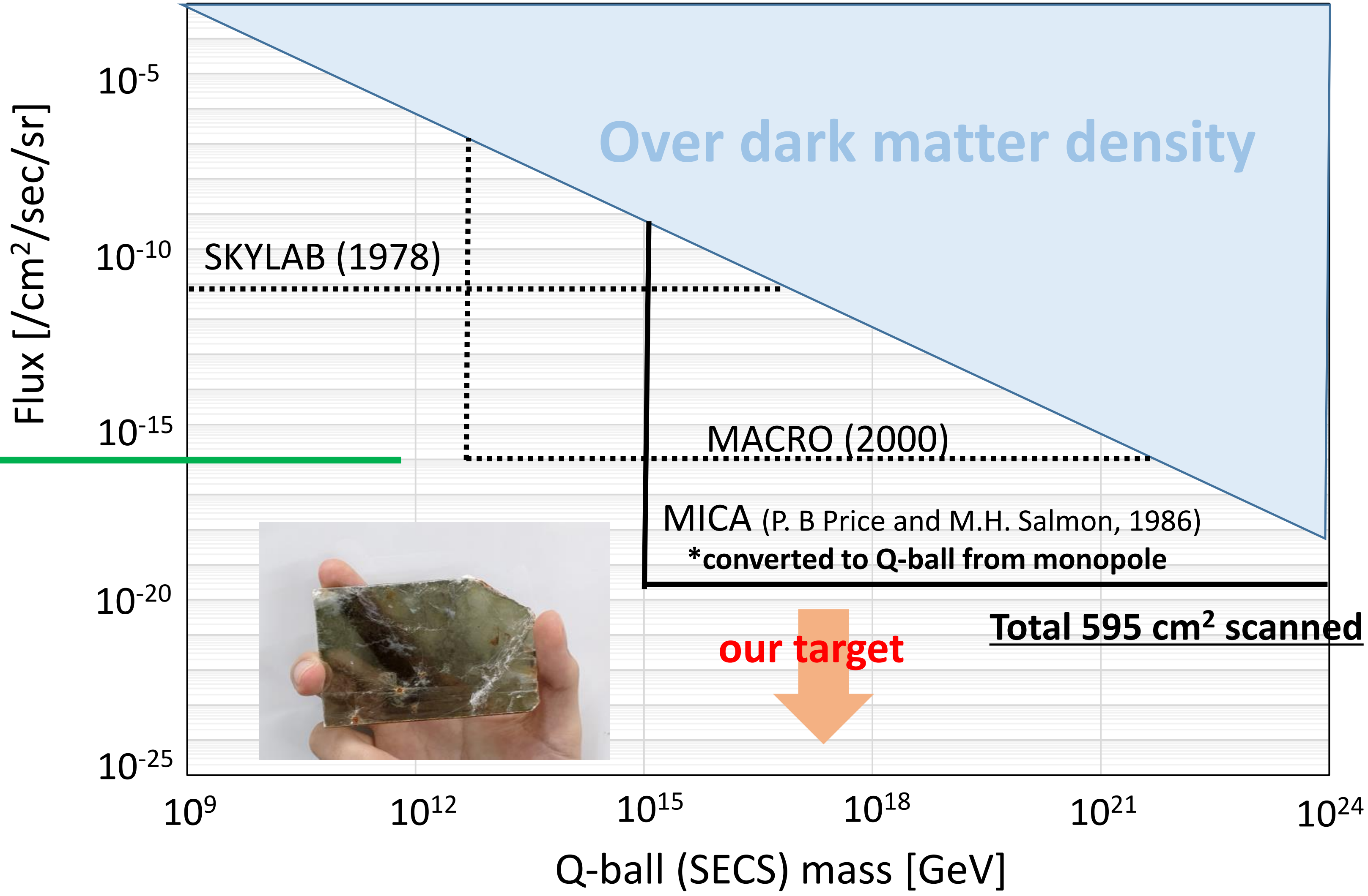
Expected achievement for Q-ball search with the mica + current cutting-edge technologies

MACRO experiment [1989-2000]

CR-39 (plastic damage detectors)

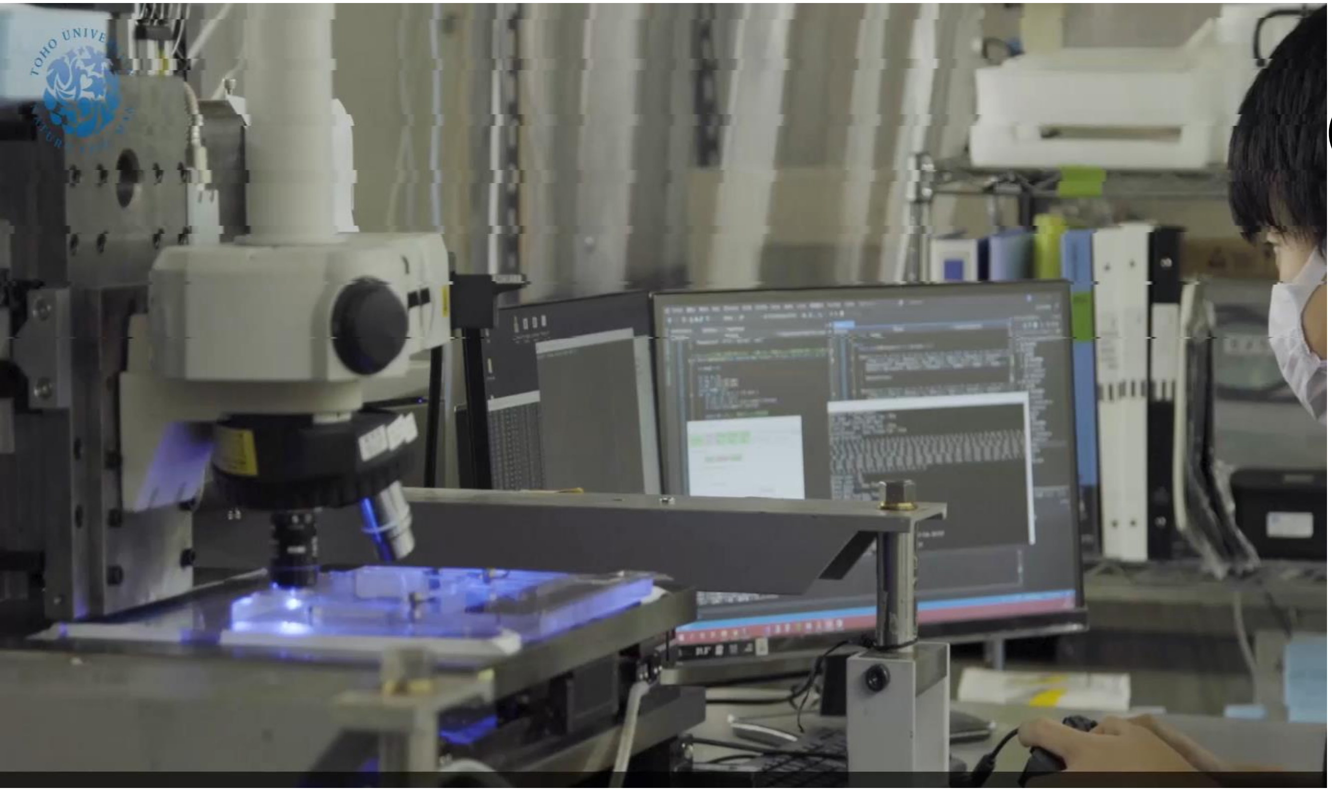
Observed area : O(10 x 10) m^2

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

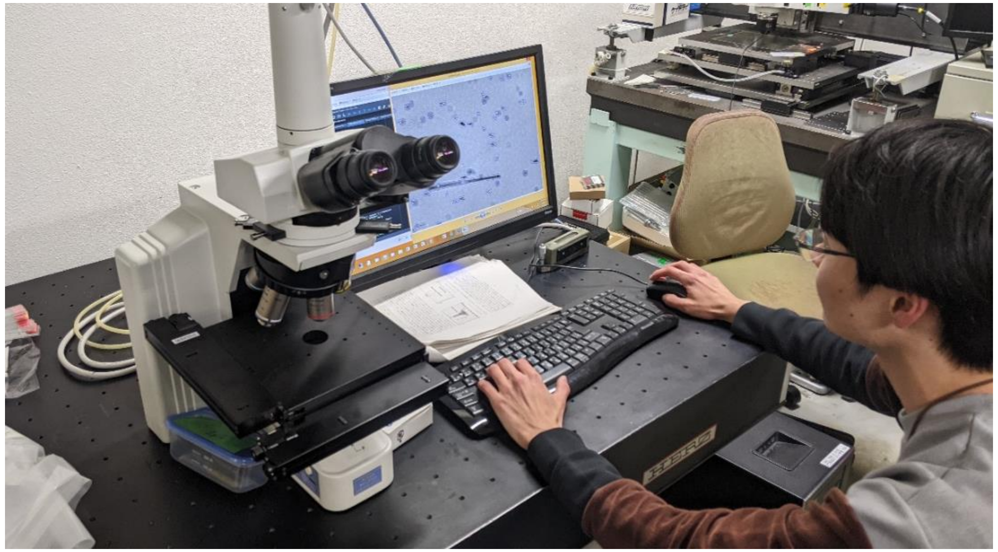
Current system : ~20h /100 cm^2
(optimized for nano-metric tracking with nuclear emulsion)

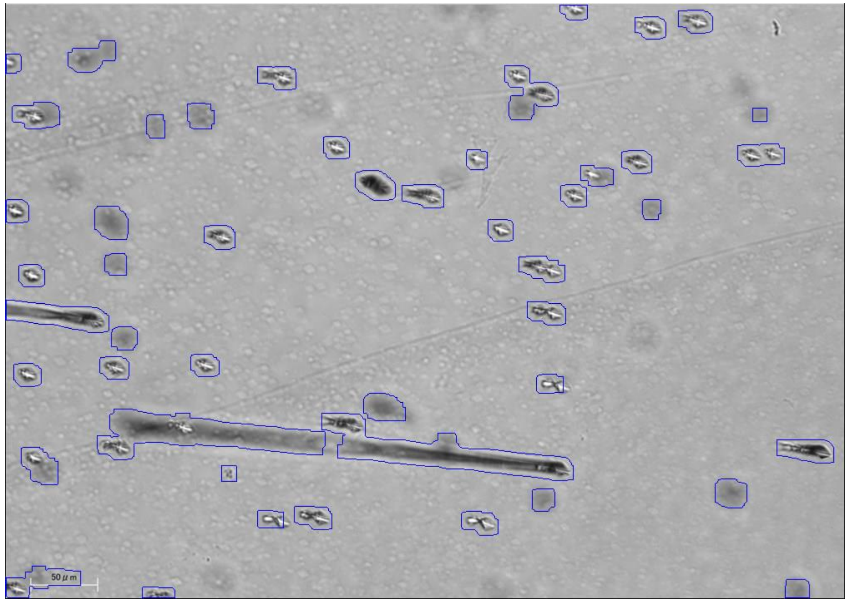
Optimization : 1h /100 cm^2 (for Paleo detector)

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

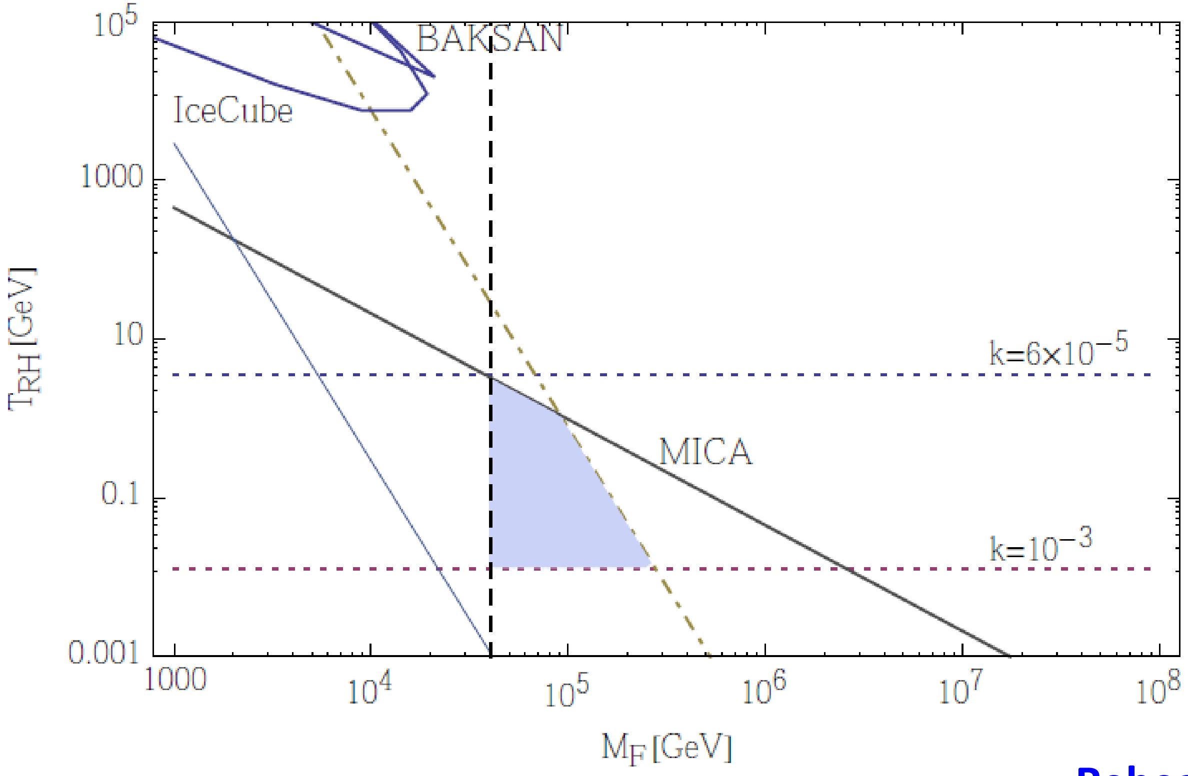
- Optimal image processing is investigating
- Deep learning will be installed for more efficient event selection

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

Expectation for searching the astroparticle physics parameter space

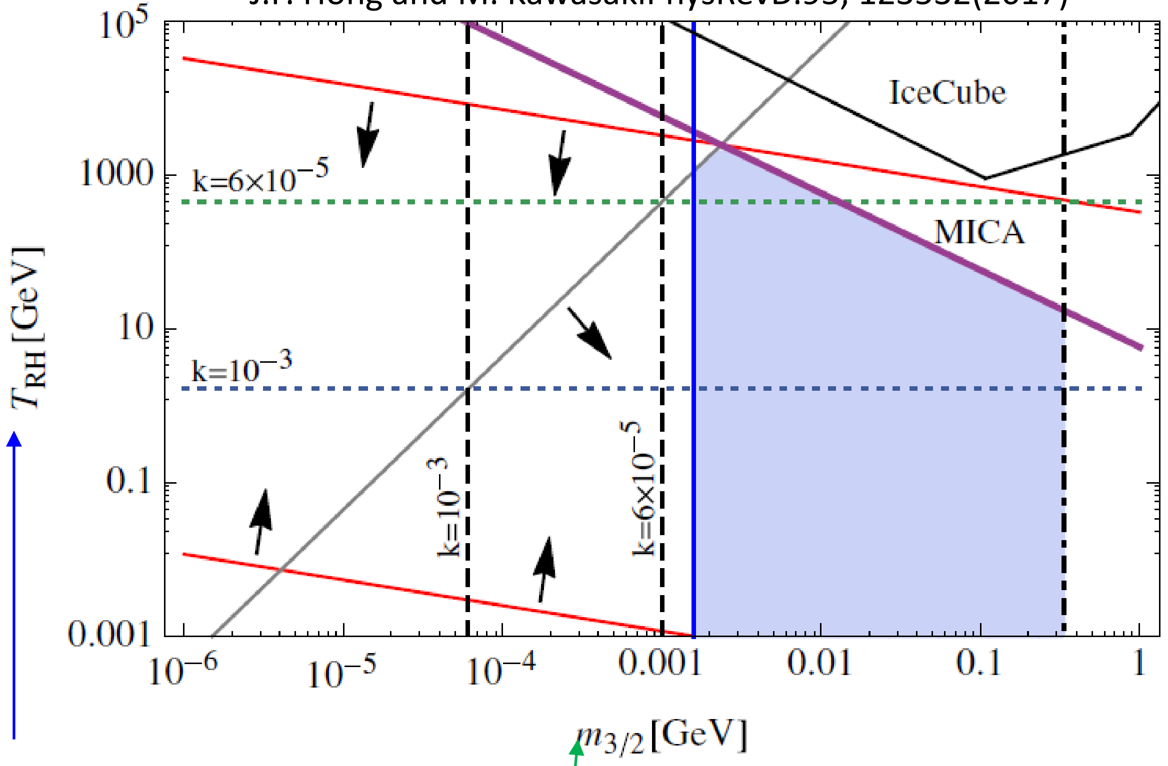
Gage mediated Q-ball

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



New type Q-ball

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



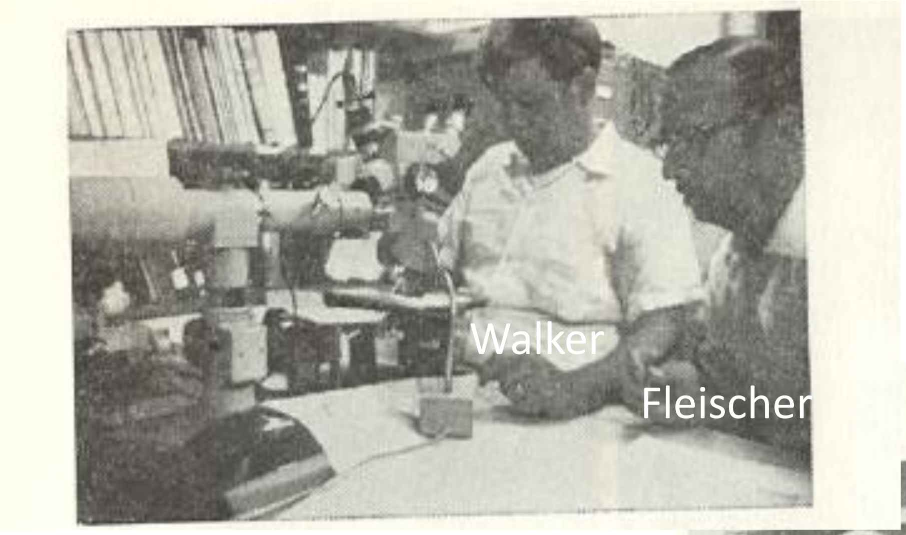
Reheating temperature

Gravitino mass

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

For Cosmic-ray (especially, Ultra-heavy ion)

歴史：Apollo sample



アポロ11号の月試料のトラック観察

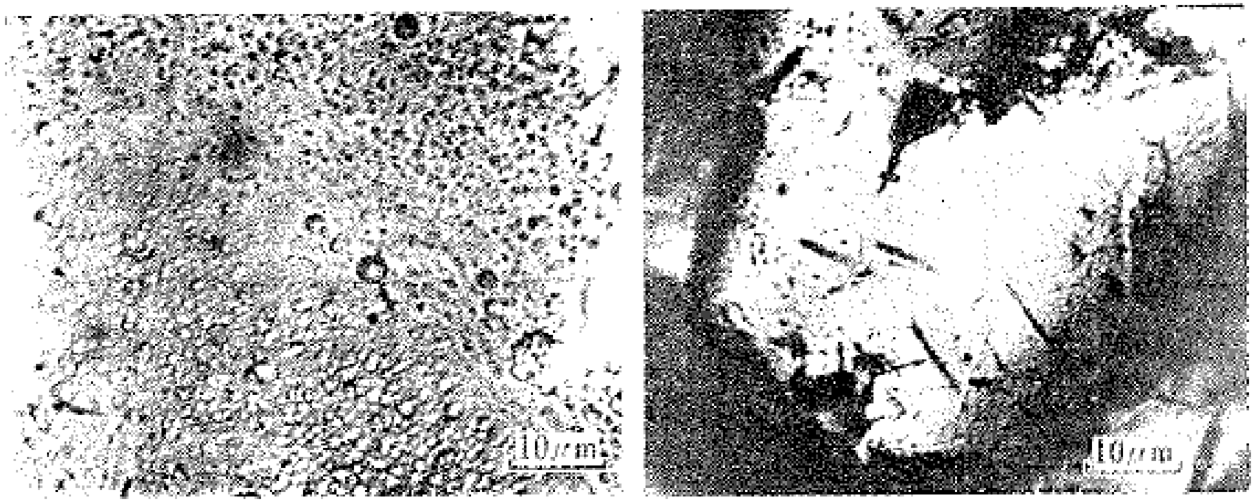


図 95　月試料のトラック　(a) 試料 10005；小ガラス球中の破砕反跳トラック　(b) 試料 10017；小さな輝石粒中の宇宙線トラック（ある方向で長い），多くの浅い短いトラックは破砕反跳による [R. L. Fleischer *et al.*: *Geochim. Cosmochim. Acta Suppl.* 1 3, 2103 (1970)]

1960年代から80年代くらいに積極的に研究

「粒子トラックとその応用」（阪上正信　著）より

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

Apolo12 サンプル
ピジョン輝石 [$(Mg,Fe,Ca)_2Si_2O_6$]

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

<u>少なくとも1mm程度のトラックを1 event 観測</u>

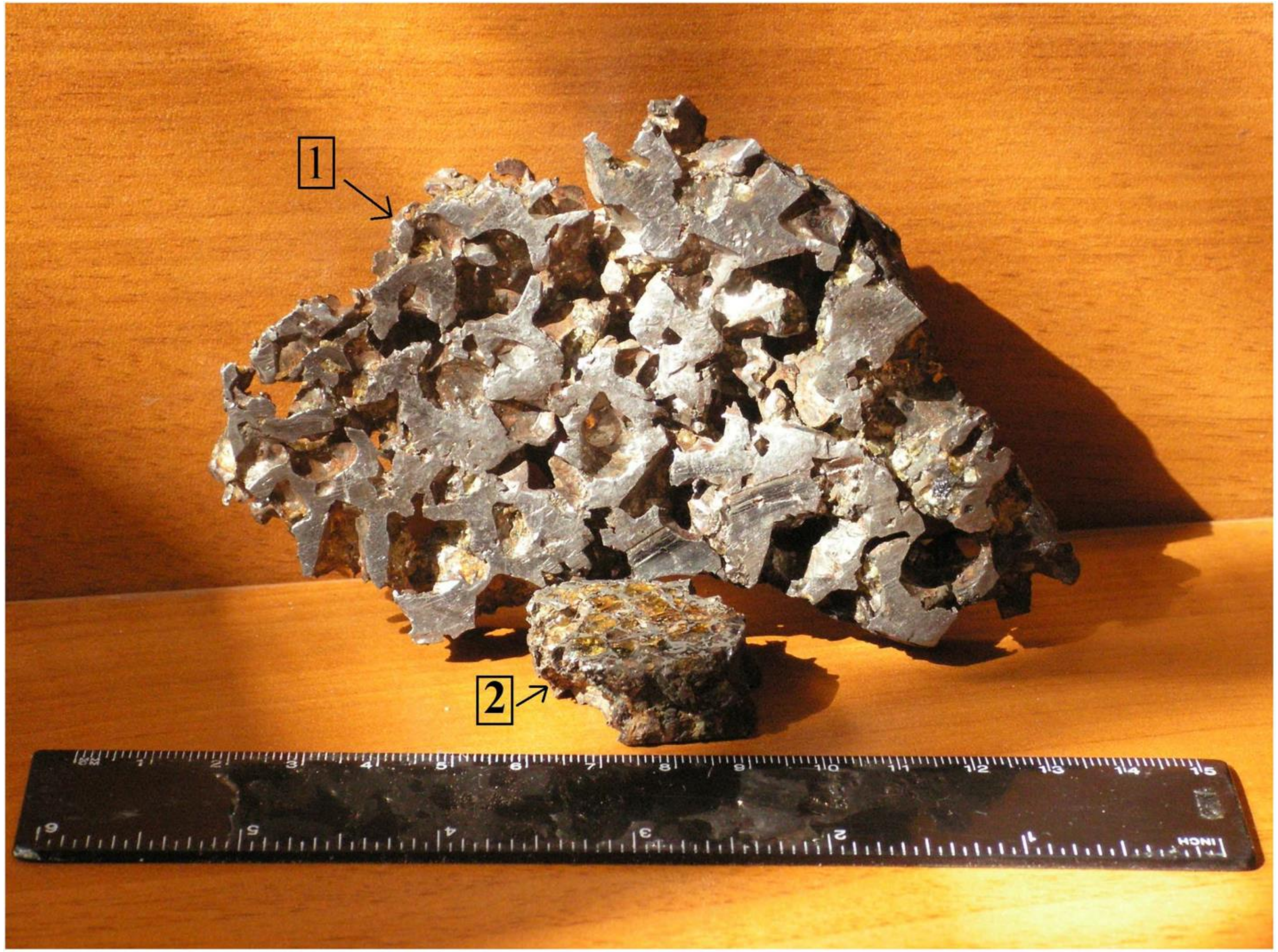
重元素の場合 : Z > 80～90
→ 入射エネルギー > 100 MeV/u

⟺

モノポール解釈 (Q-ballでも良い)
線幅が一様である→ エネルギー損失の変化が小さい（ように見える）

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

OLIMPIYA experiment @Russia



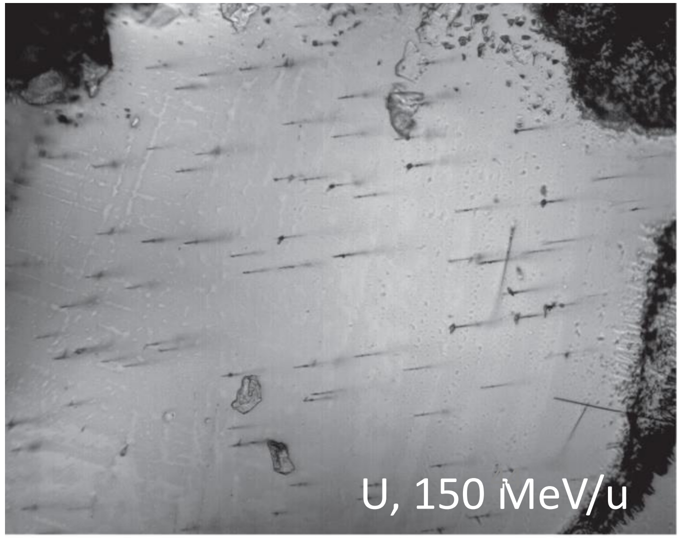
ApJ, 829:120 (2016)

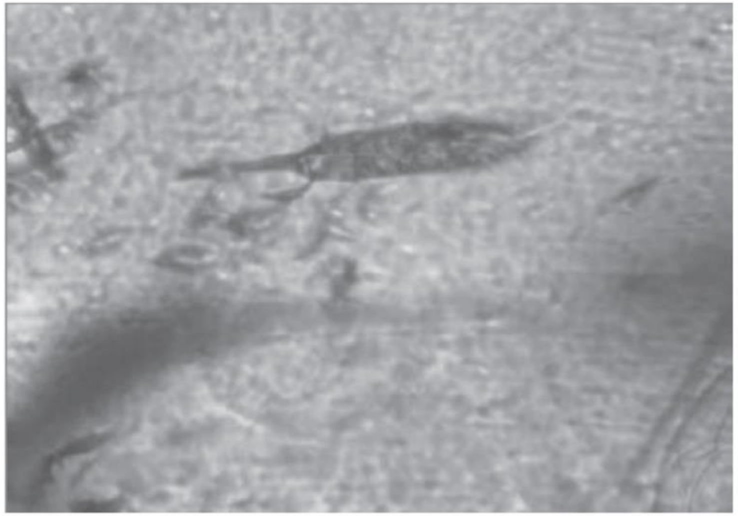
<u>パラサイト隕石</u>

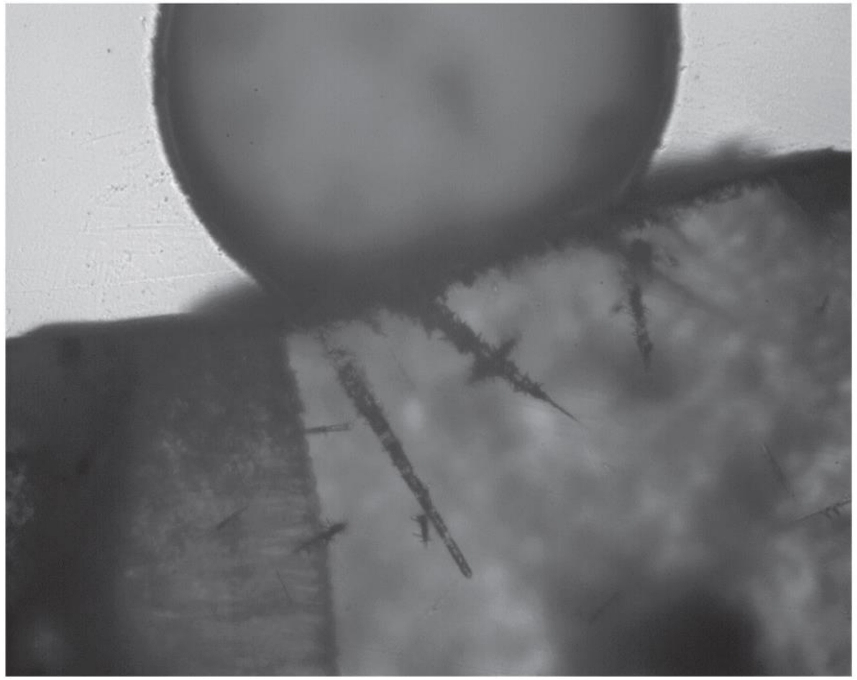
鉄とカンラン石でできた隕石

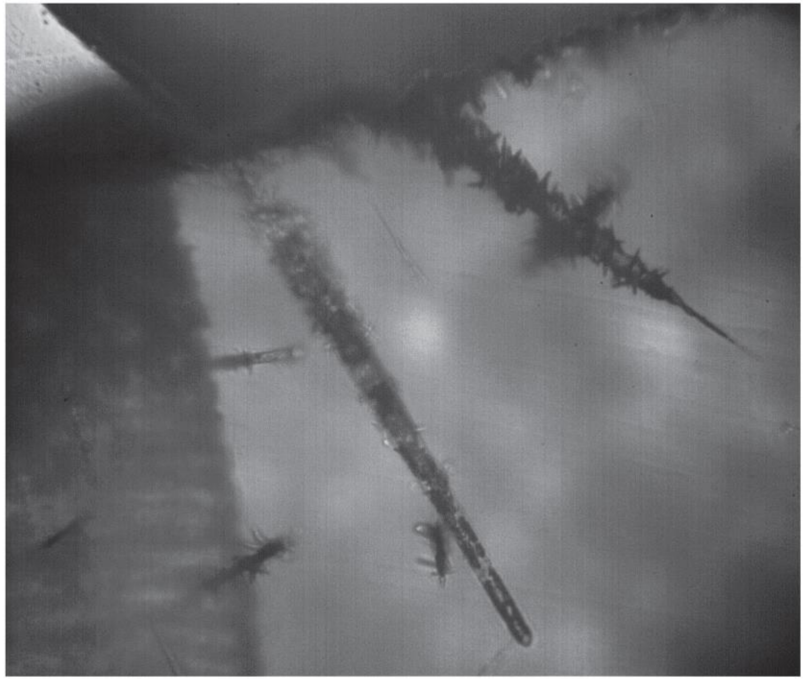
カンラン石を取り出し、エッチング処理によってトラック分析

Olivine [$Mg_{1.6}Fe^{2+}_{0.4}SiO_4$]



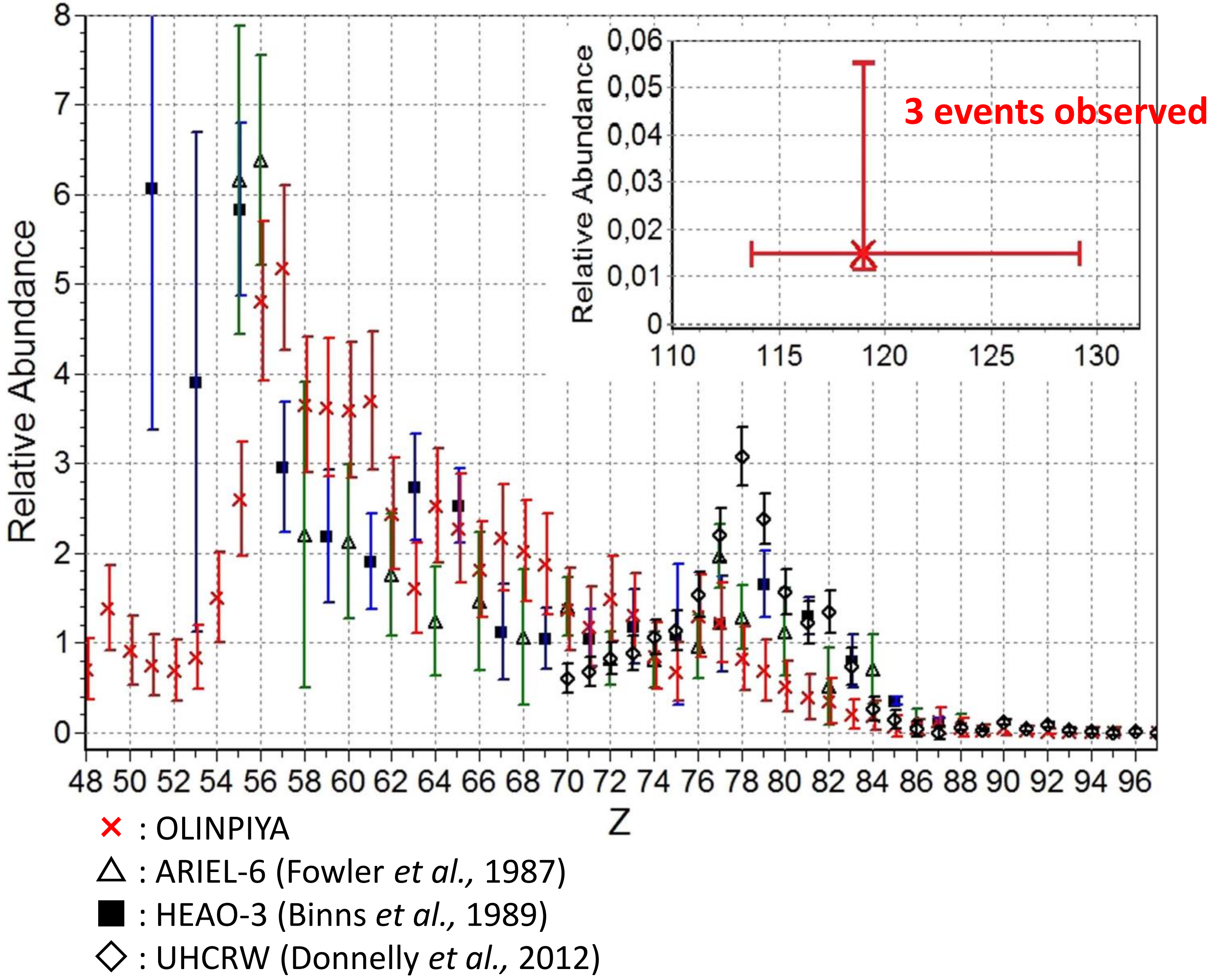






飛跡ごとのエッチングの進み具合(エッチング速度)からZを同定することができる

Nuclear charge spectrum from track analysis



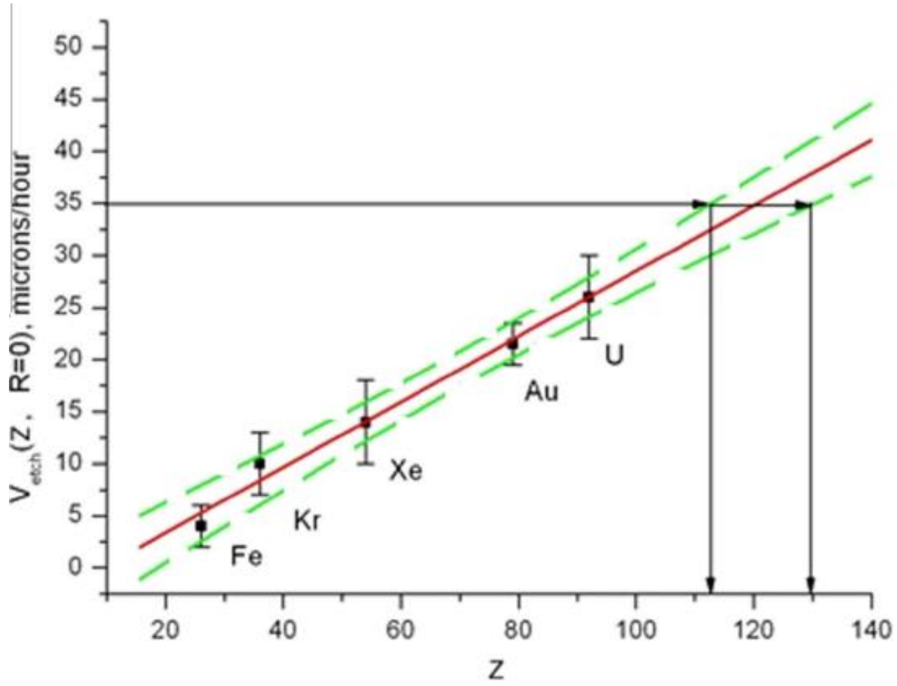
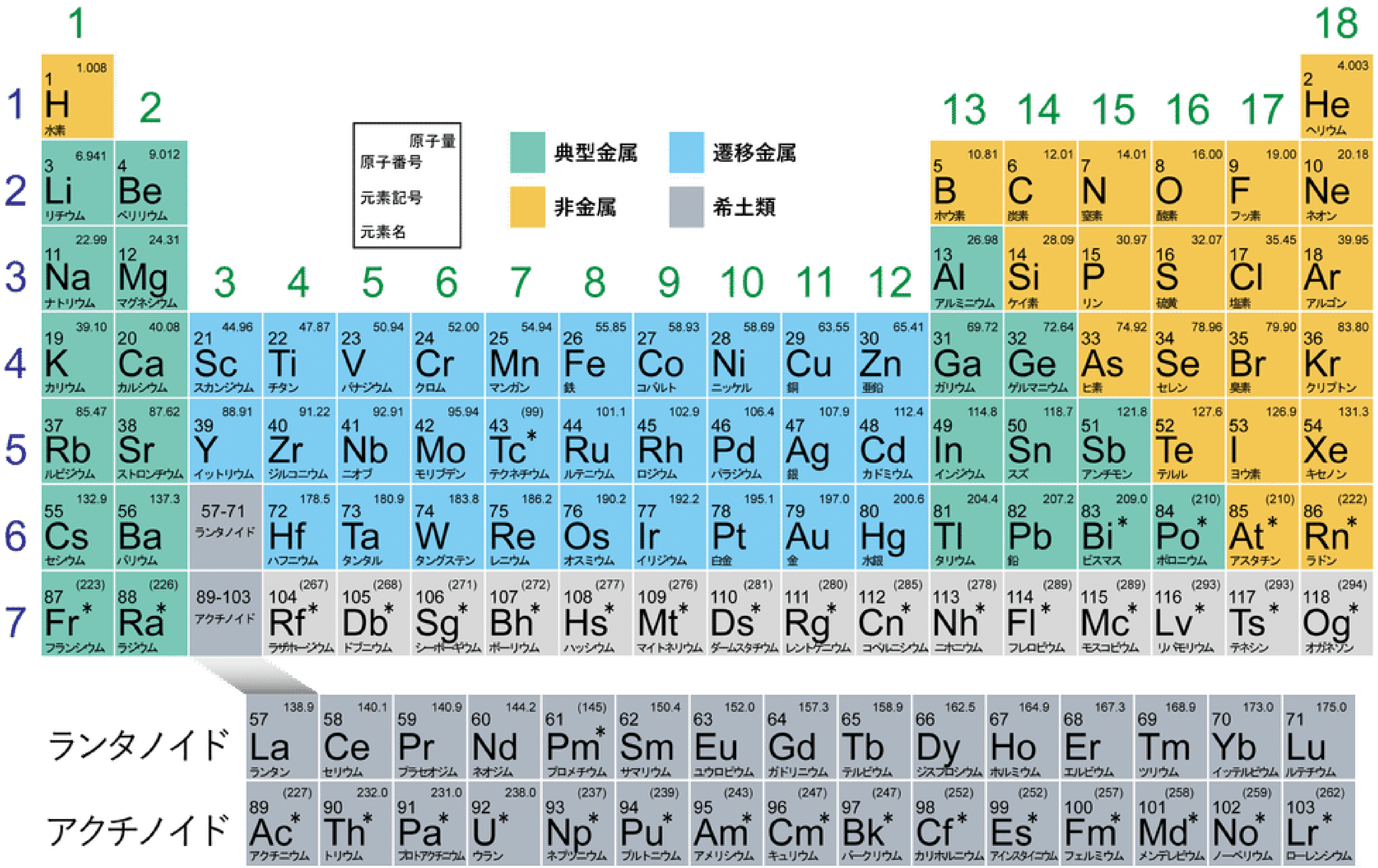
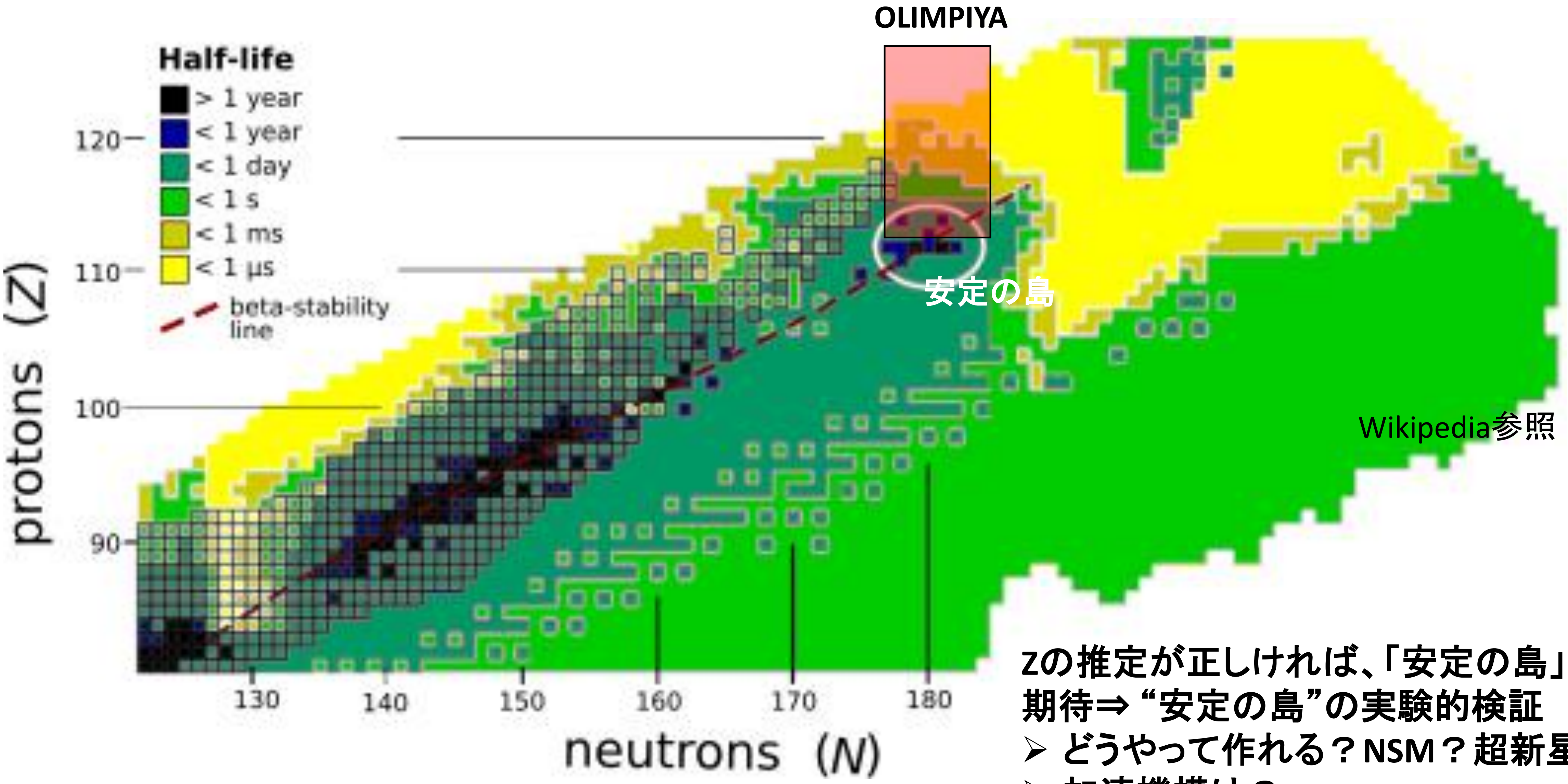


Table 2
Registered Events of Heavy and Superheavy Nuclei in Various Experiments

	Z Interval	Ariel 6 (1)	*HEAO-3* (2)	UHCRE (3)	OLYMPIYA
1	$Z \geqslant 50$	412	362	—	10283
2	$50 \leqslant Z \leqslant 58$	240	204	—	5612
3	$60 \leqslant Z \leqslant 68$	84	34	—	2814
4	$Z \geqslant 70$	88	62	2567	1233
5	$70 \leqslant Z \leqslant 73$	29	10	—	715
6	$74 \leqslant Z \leqslant 80$	29	42	—	449
7	$81 \leqslant Z \leqslant 86$	27	10	—	59
8	$88 \leqslant Z \leqslant 103$	3	0	35	9
9	$Z \geqslant 92$	2	0	—	4



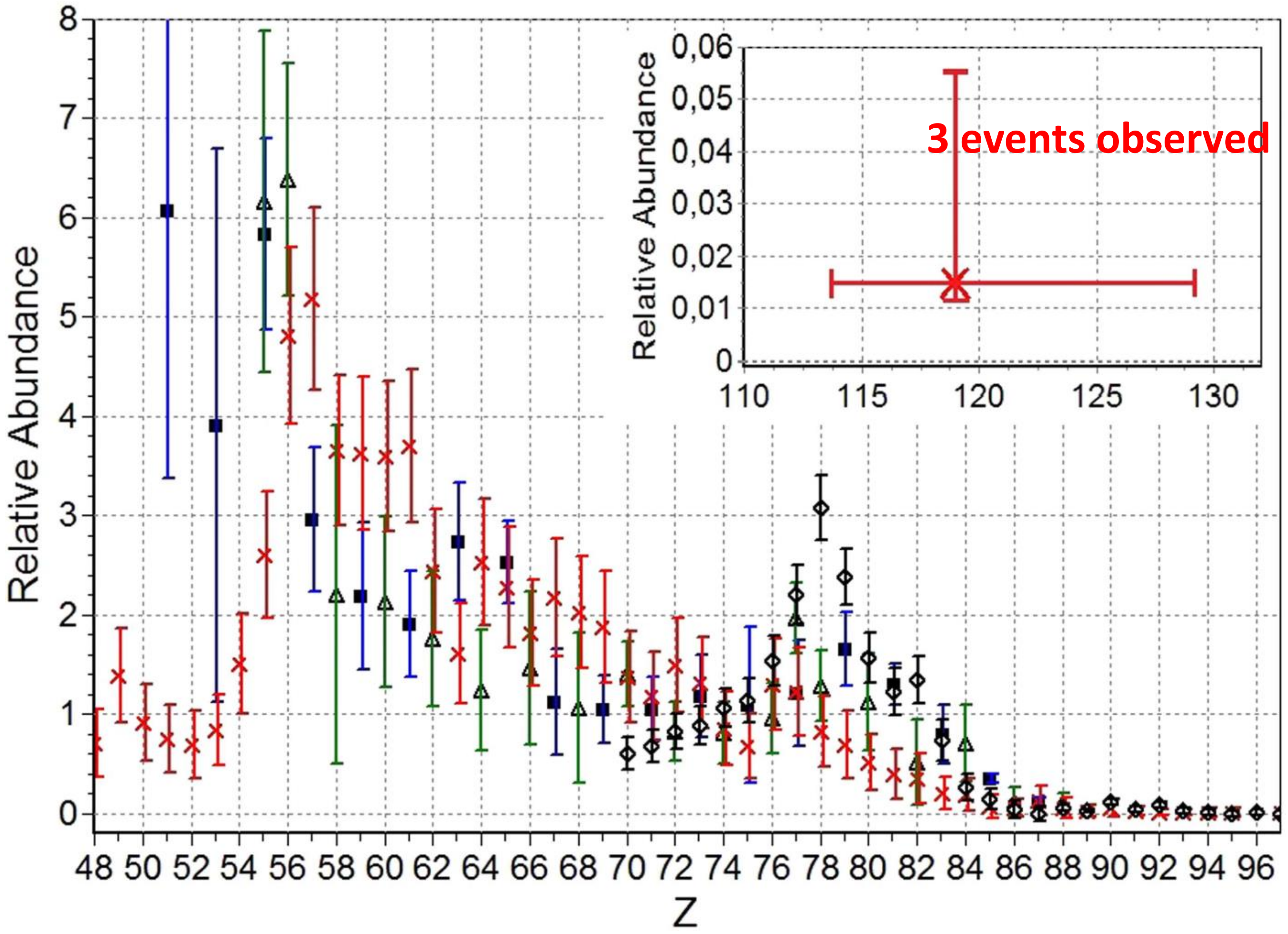
原子量として日本化学会原子量小委員会が作成した4桁の原子量を採用した。
安定同位体が存在しない元素には元素記号の右肩に*を付す。
天然で特定の同位体組成を示さない元素については、最もよく知られた質量数を括弧内に示す。



Zの推定が正しければ、「安定の島」にあると期待⇒“安定の島”の実験的検証

- **どうやって作れる？NSM？超新星？**
- **加速機構は？**

Nuclear charge spectrum from track analysis



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

■ UHCRW (ApJ, 747:40, 2012)

Detector : LDEFに搭載したsolid track detector (polycarbonate)

Exposure : 170 m^2sryear (5.8 year)

■ Ariel 6 (ApJ, 314-739-746, 1987)

Detector : Spherical gas scintillator + Cherenkov detector

Exposure : 1.7 m^2sryear

■ HEAO-3 (ApJ, 346: 997-1009, 1989)

Detector : Ionization chamber + cherenkov detector
Exposure : 6 m^2sryear

OLIMPIYA case
Analyzed area : (probably) > 10 mm^2
Exposure time : Gyear scale
> 10^4 m^2sryear

宇宙史の記録を保持。本質的に異なるデータ

Detectable Energy for Olivine

Mean free path in the space : 1/(~10^{-24} cm^2 ×6.5×10^{-3} atom/cm^3)

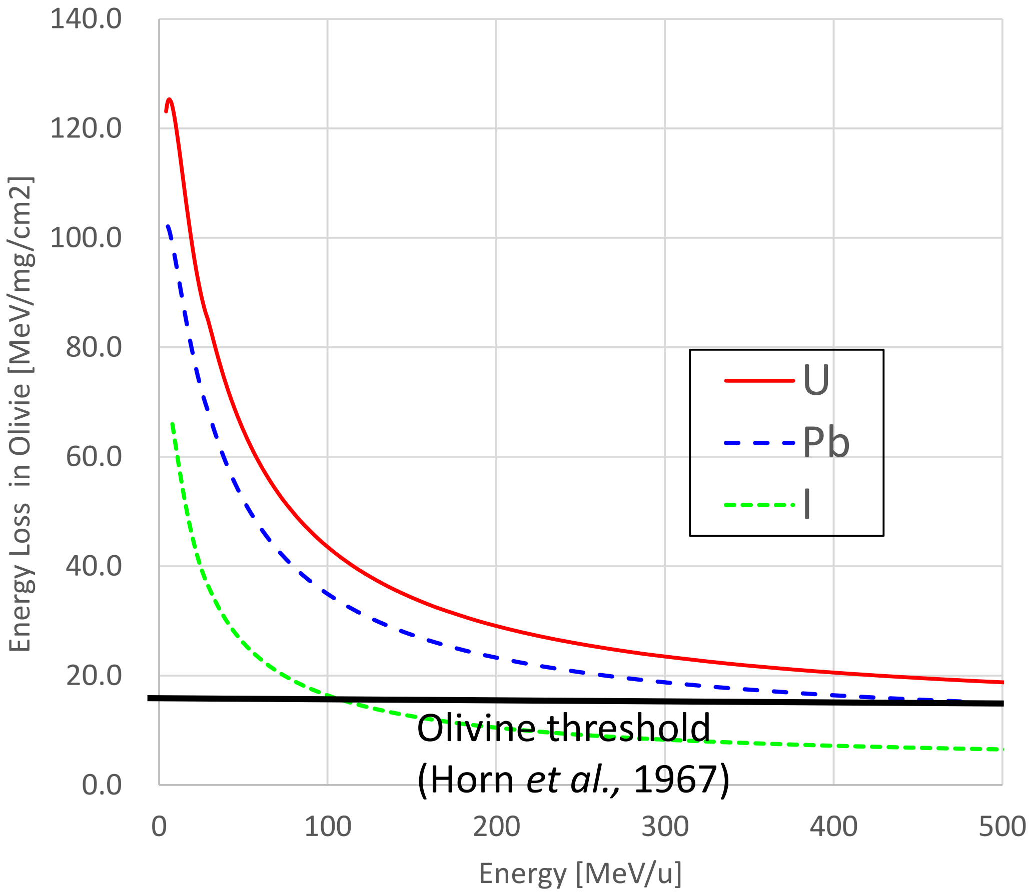
Hot ionized gas density

= ~10^{28} cm ~ 100 MPc

連星中性子合体: 銀河系内で100万年に10-20回程度(?)
超新星 : 銀河内で100年に1-2回 (?)

Incident ion energy is expected to have
<u>O(10-100) MeV/u</u> for heavy nuclei such as U, Pb･･.

超重元素生成＋加速メカニズムにおける重要な情報

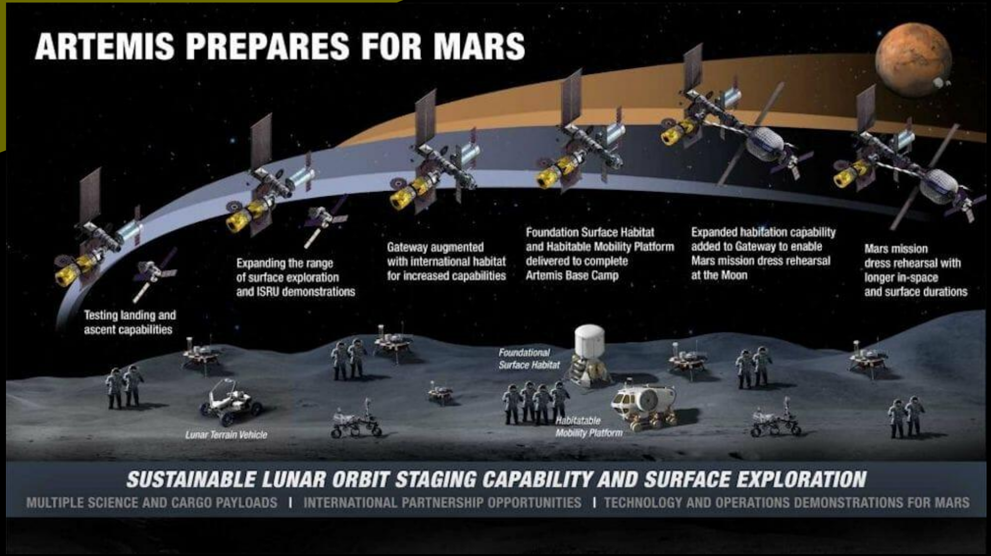


月面探査プロジェクト


SLIM
©JAXA/タカラトミー/ソニーグループ㈱/同志社大学


https://humans-in-space.jaxa.jp/future/


Wikipedia より


ARTEMIS PREPARES FOR MARS
Testing landing and ascent capabilities
Expanding the range of surface exploration and ISRU demonstrations
Gateway augmented with international habitat for increased capabilities
Foundation Surface Habitat and Habitable Mobility Platform delivered to complete Artemis Base Camp
Expanded habitation capability added to Gateway to enable Mars mission dress rehearsal at the Moon
Mars mission dress rehearsal with longer in-space and surface durations
Foundational Surface Habitat
Lunar Terrain Vehicle
Habitable Mobility Platform
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION
MULTIPLE SCIENCE AND CARGO PAYLOADS | INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

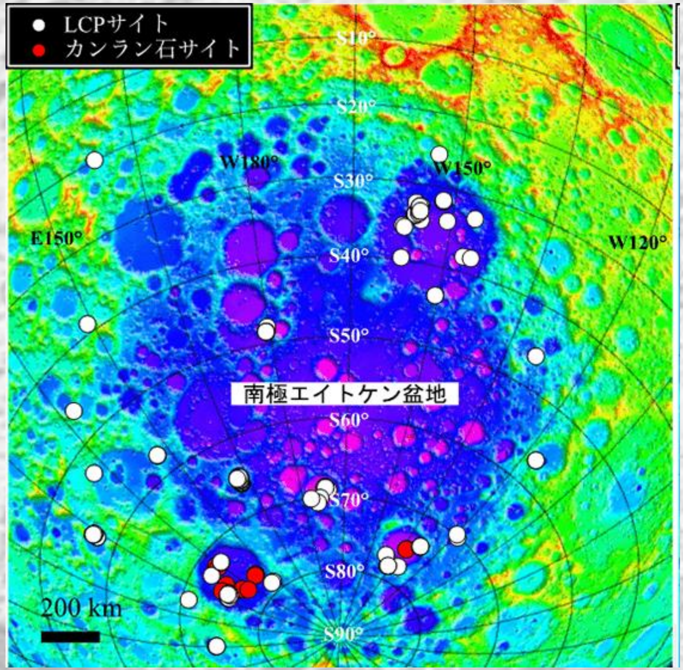
月面の鉱物･レゴリス

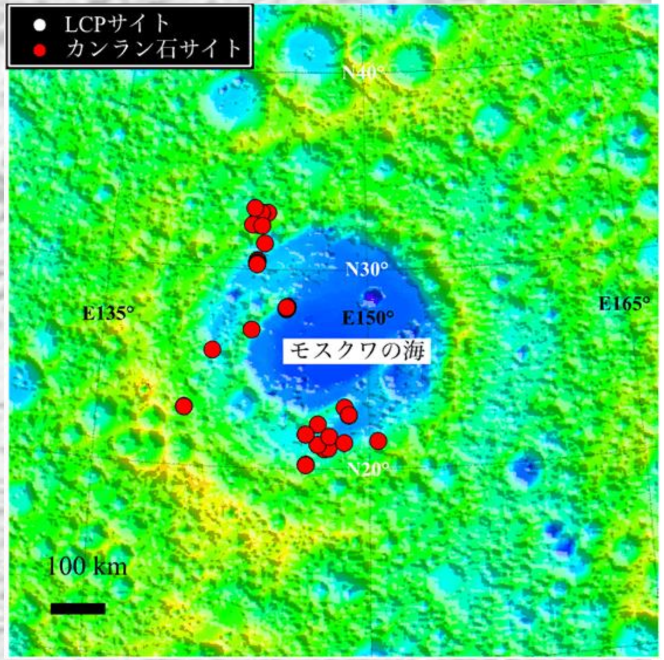
輝石(Pyroxene, $(Mg,Fe,Ca)_2Si_2O_6$)

かんらん石(Olivine, Mg_2SO_4)

斜長石（Plagioclase, $NaAlSi_3O_8$)

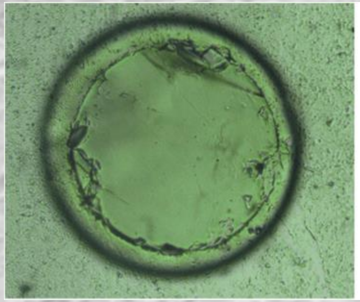
イルメナイト(Ilmenite, $FeTiO_3$)

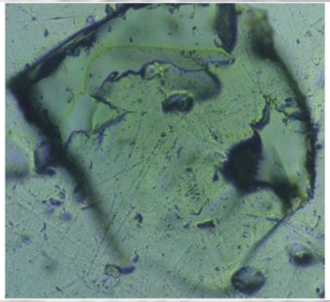




「かぐや」スペクトルデータより
https://www.isas.jaxa.jp/home/research-portal/gateway/2023/0608/

インパクトガラス



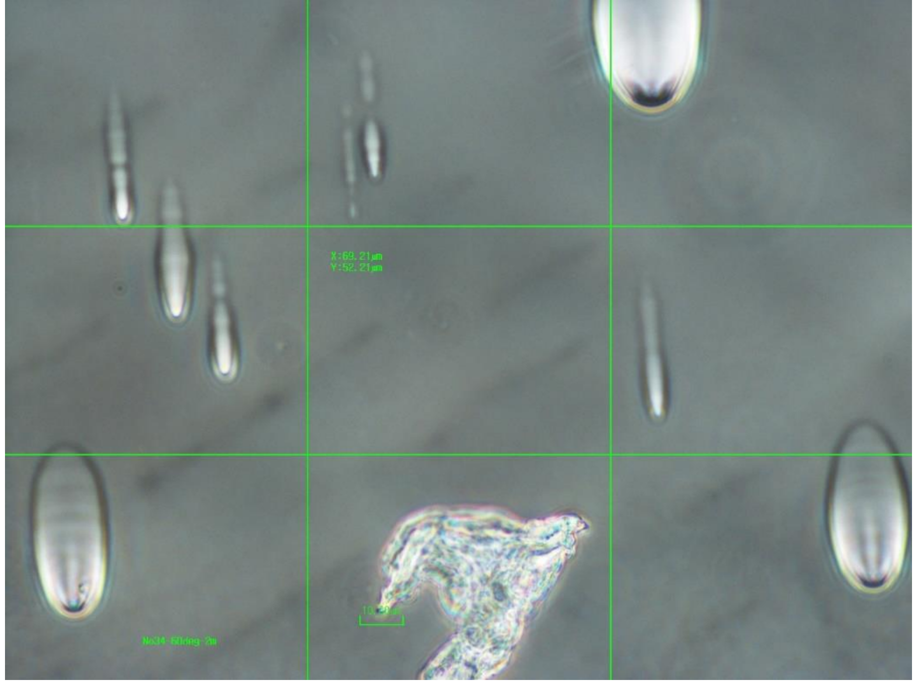


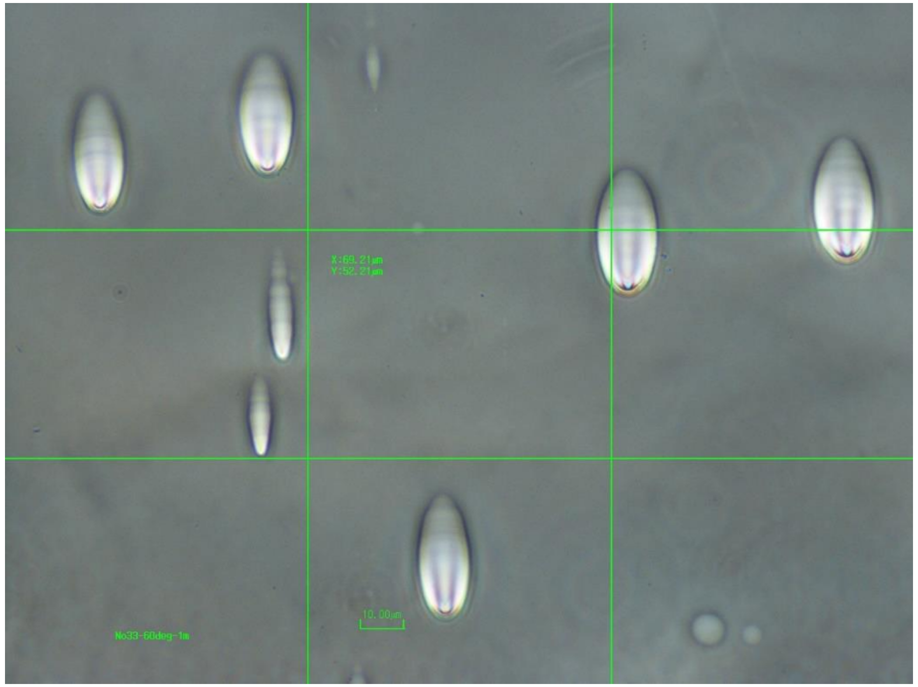
AGU, Volume 124, Issue 11

人工ガラス

硬度の面から、インパクトガラスと同等
と考えてよい

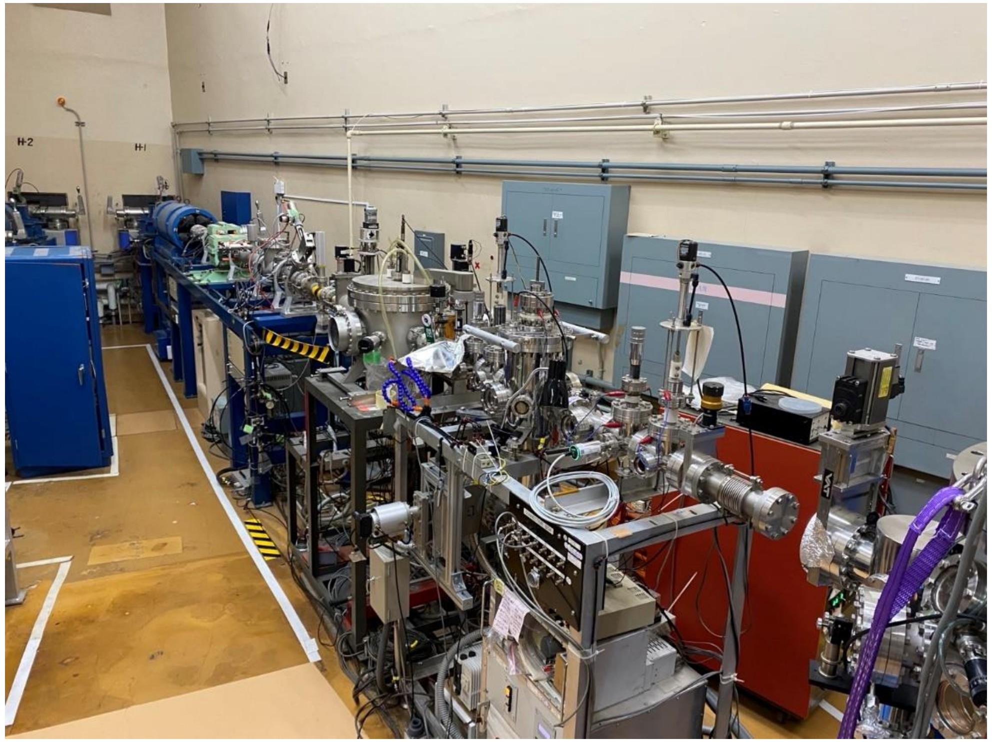
Xe ion [38 GeV (275 MeV/u)]
@ HIMAC, QST (量子科学技術研究開発機構）

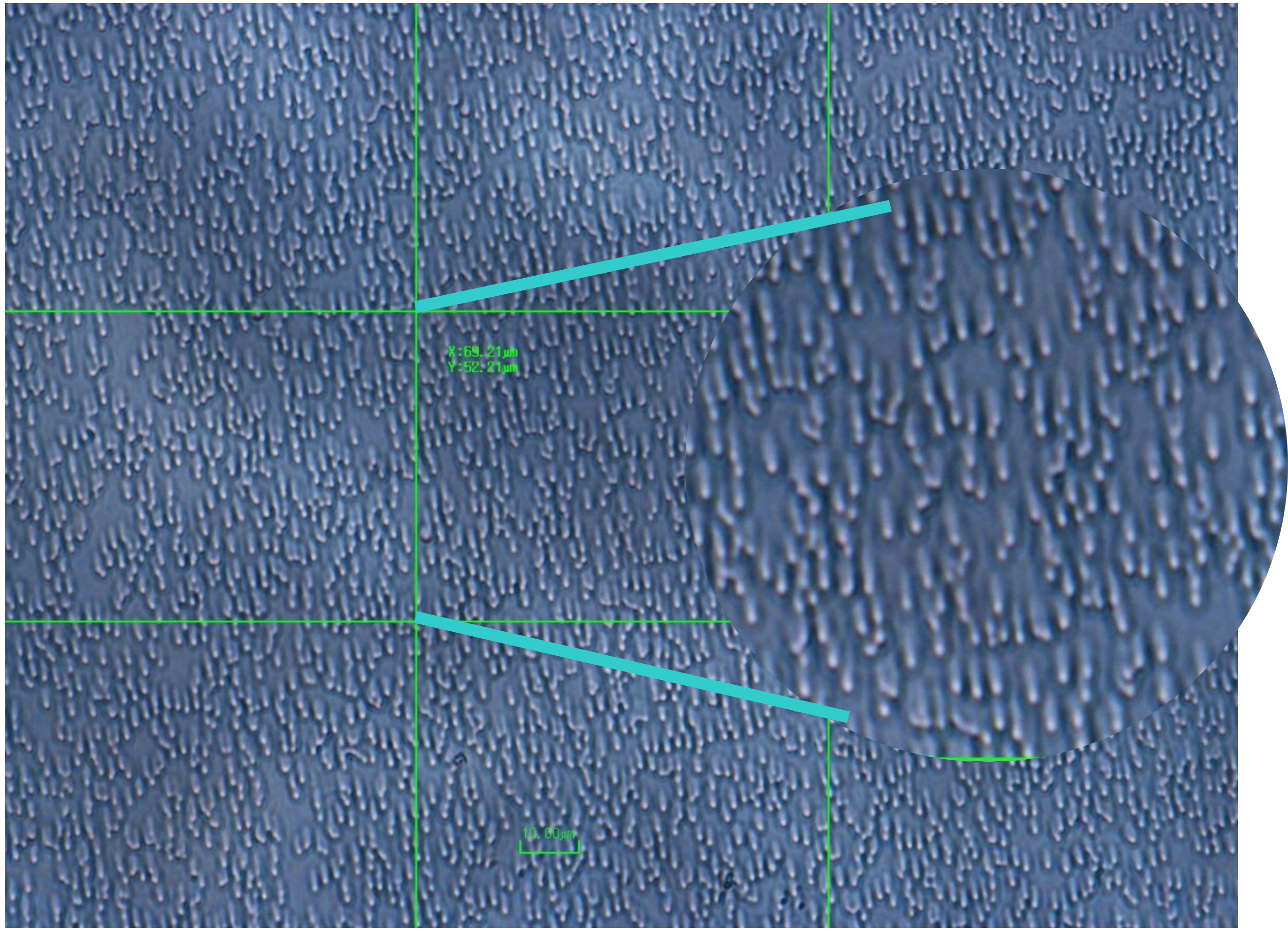




原子力研究開発機構・タンデム加速器

Ion 核種 : ^{6+}Fe
エネルギー : 70 MeV





飛跡形成閾値 > 30-35 MeV/mg/cm²であることを確認

Conclusion

Paleo Detector with ancient mineral

Direct detection of Cosmic ray for Geological time scale

✓ **Neutrino**

→ 過去の超新星ニュートリノの情報 ：コヒーレント散乱による原子核反跳

✓ **Dark Matter**

→ WIMP探索 : 原子核反跳の深さ分布によるイベント識別

→ 超重暗黒物質（e.g., Q-ball, quark nugget, monopole ）

➡ **白雲母中のlong track +光学顕微鏡システムによる探索感度の劇的向上**

✓ **Cosmic ray**

→ 超重元素（e.g., 超ウラン元素）の生成と加速

➡ **・月面試料**
・小惑星・隕石試料

すでに興味深いトラックを検出
⇒ 要検証＋さらなる感度向上が必須

数億年以上に渡る宇宙線の記録媒体を探る