Status and discussion for underground experiment

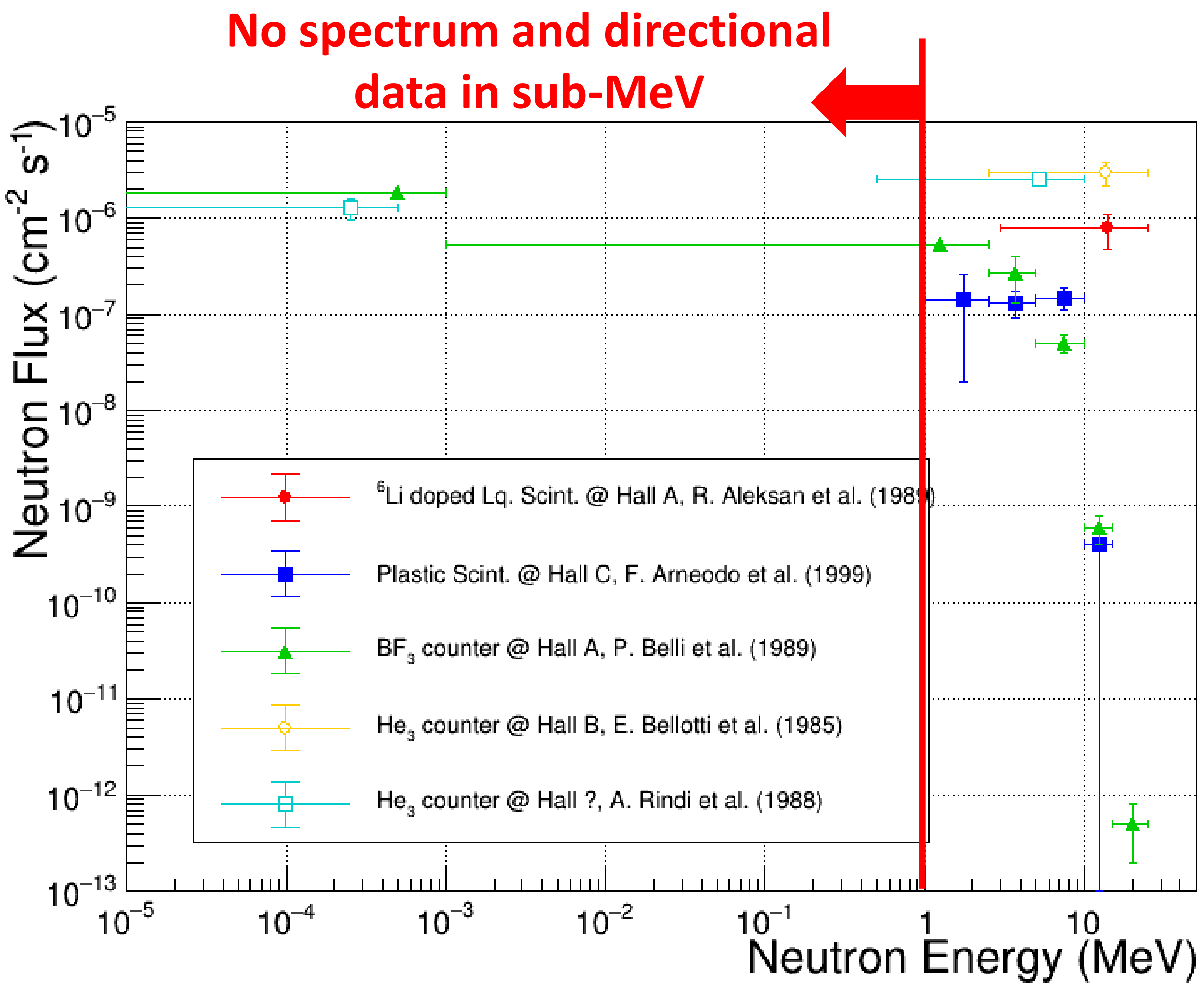
- Neutron measurement ⇒ Shiraishi's activities
- MeV dark matter search

Tatsuhiro NAKA

Toho University

2025.8.1 meeting @LNGS

Underground neutron measurement



H. Wulandari et al., Astropart. Phys. **22** (2004) 313.

- Most of the systems use moderator + thermal neutron capture
- The detectors themselves have no energy resolution
  → Uncertainty due to moderation materials
- Angular distribution is unknown
- Neutron flux varies with each measurement
  → Possibly affected by location or changes in moisture content in rocks during rainy/dry seasons

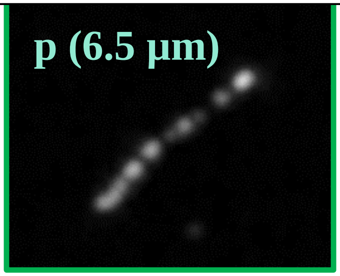
Neutron Detection Methods for Wide Energy Range

Neutron Energy

meV (thermal neutron) — 100 keV (~ 1 µm) — Sub-GeV –

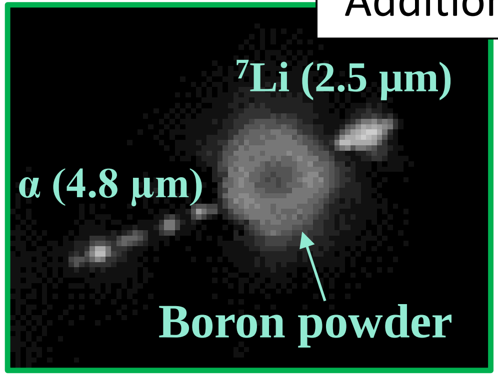
Neutron Capture

Self-contained target

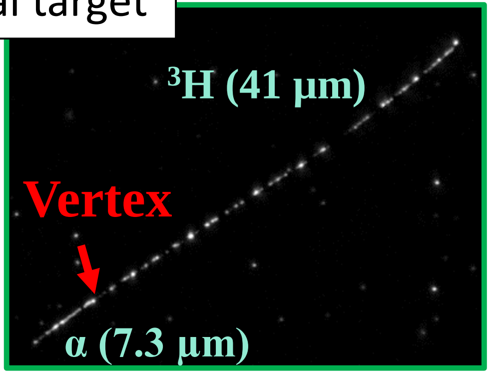


n + ^{14}N → p + ^{14}C + 0.62 MeV
2 barn @ 26meV

Additional target

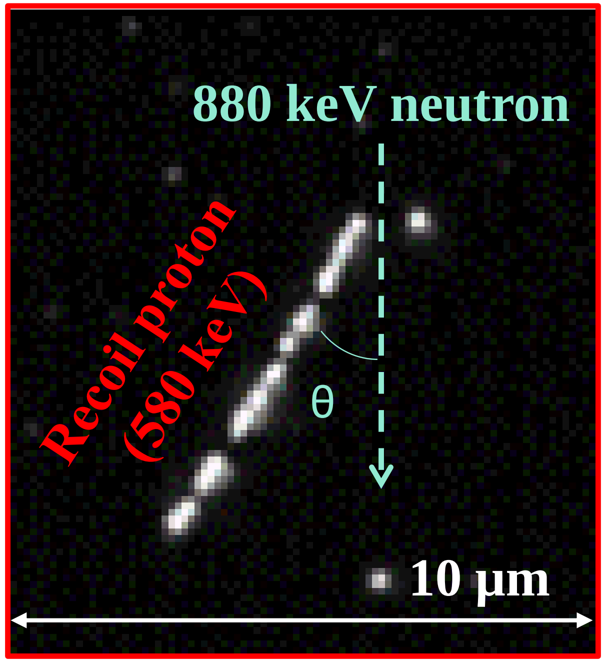


n + ^{10}B → α + ^{7}Li + 2.31 MeV
4000 barn @ 26meV

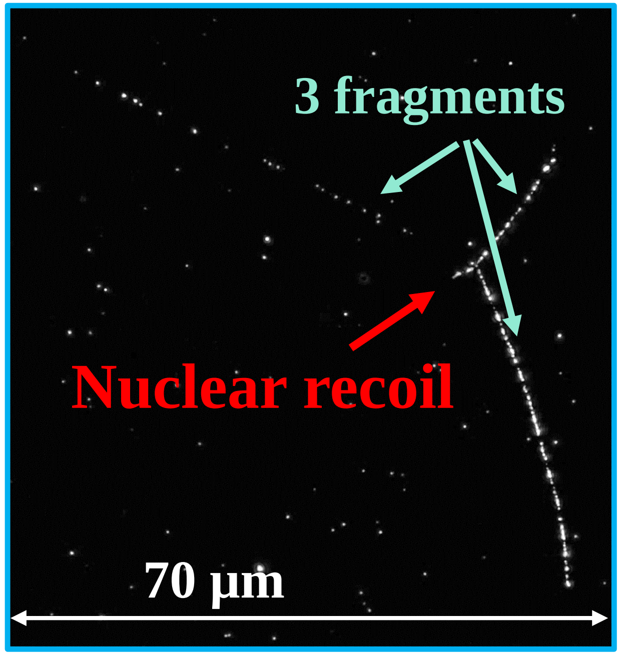


n + ^{6}Li → α + ^{3}H + 4.78 MeV
950 barn @ 26meV

Proton Elastic Scattering

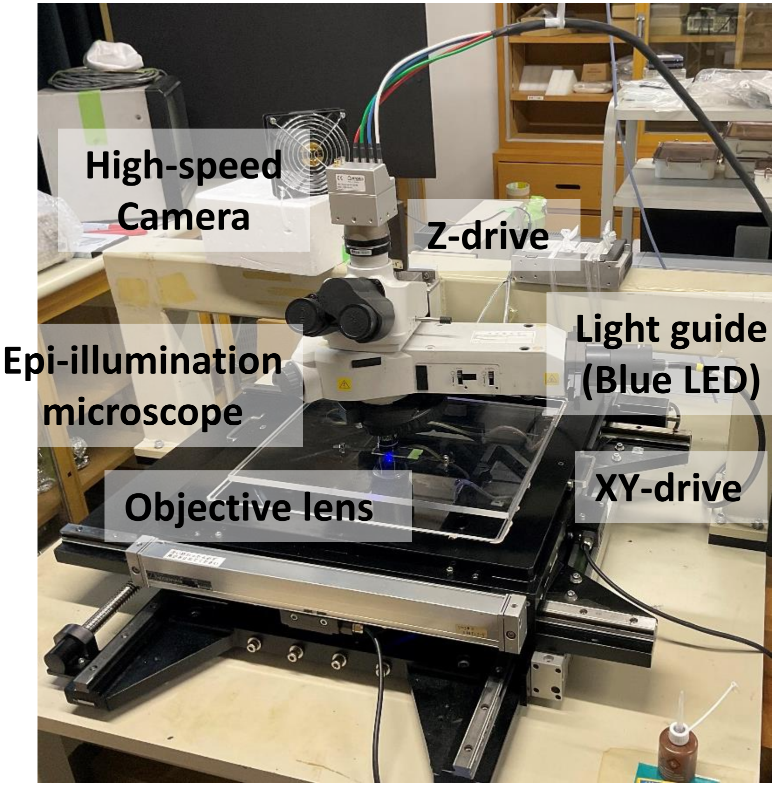


Deep Inelastic Scattering

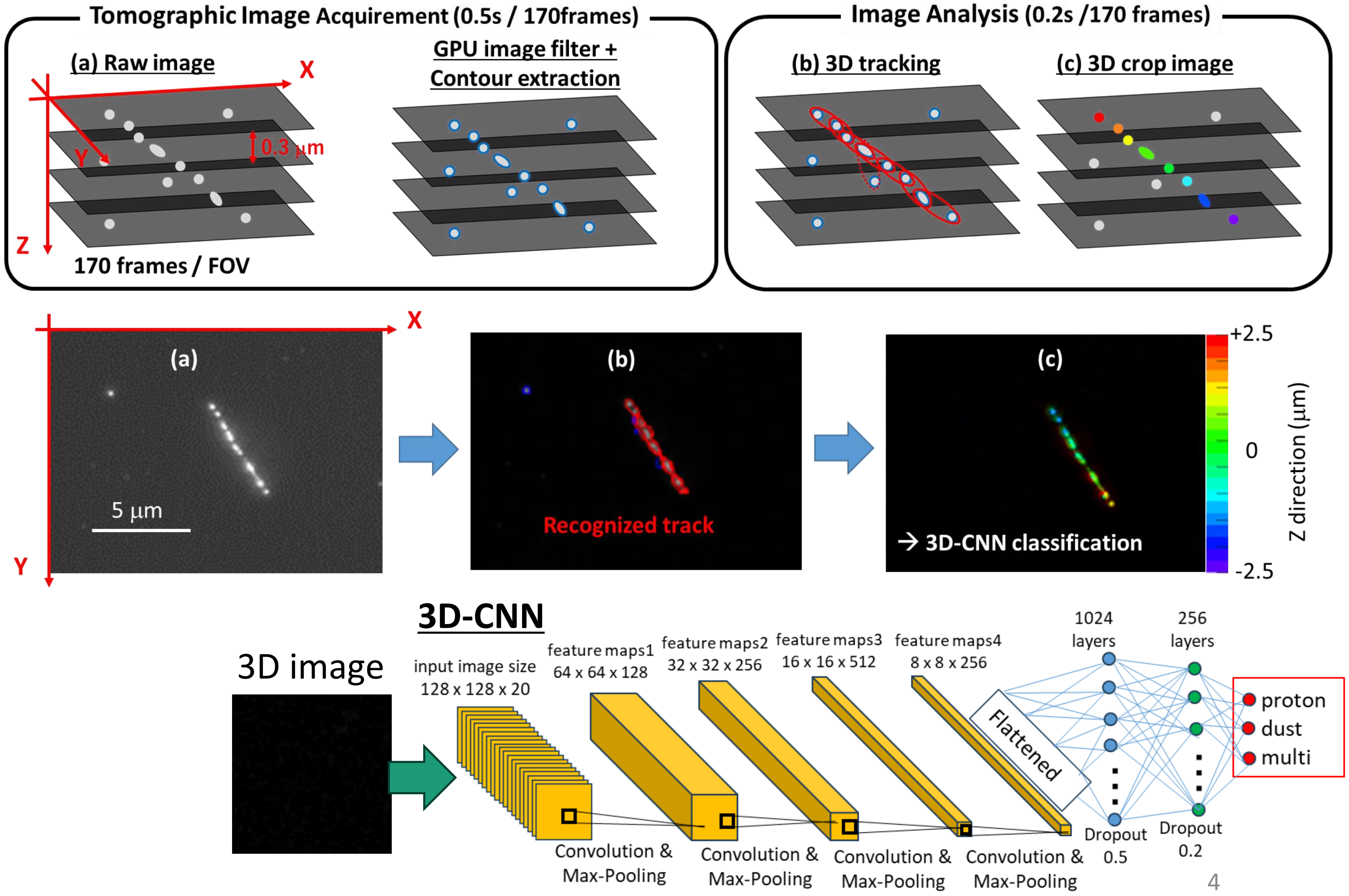


Chain analysis for ~ µm scale tracks

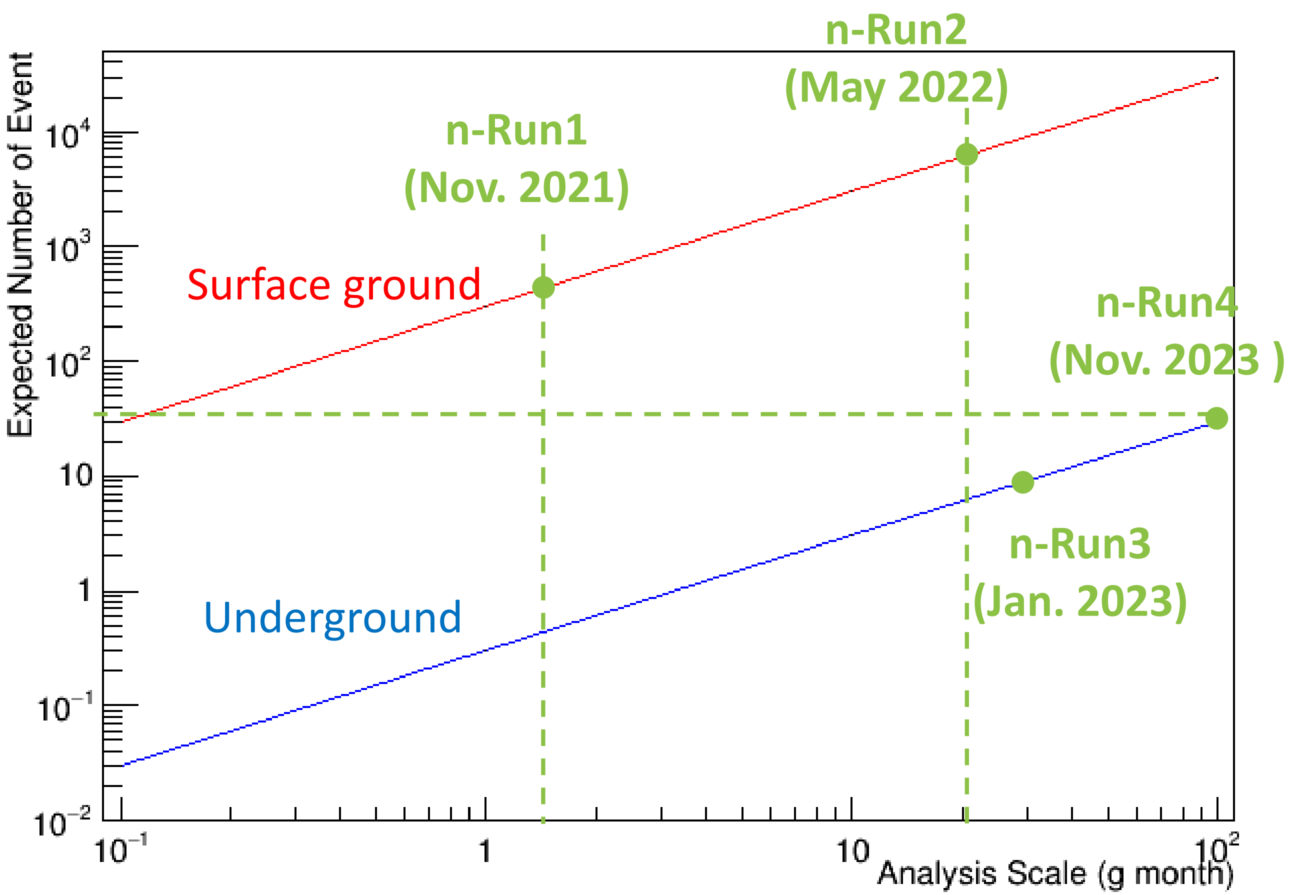
PTS2.2 at Kanagawa University



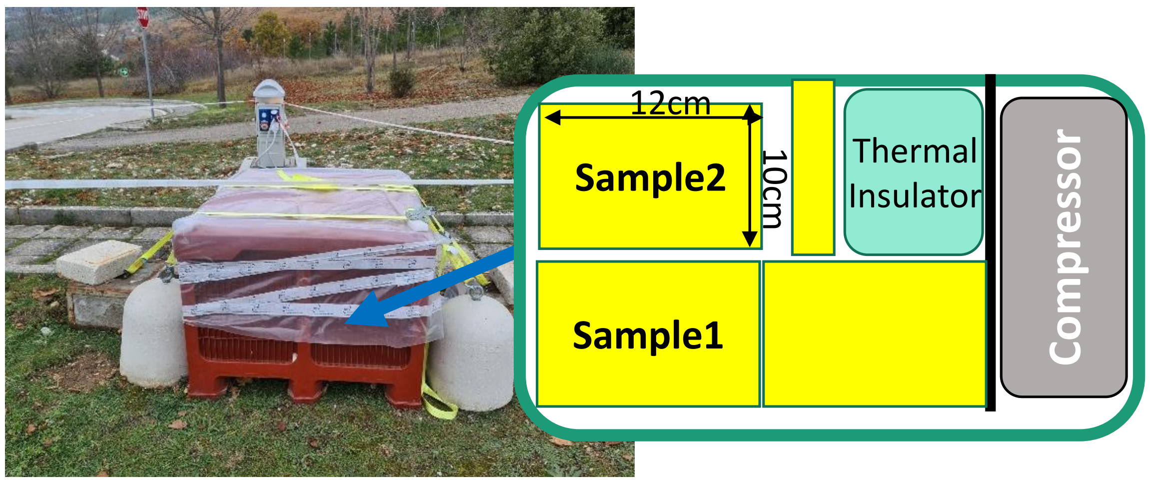
1.1 kg/year @ 1µm threshold



Environmental Neutron Measurement by NIT @ LNGS



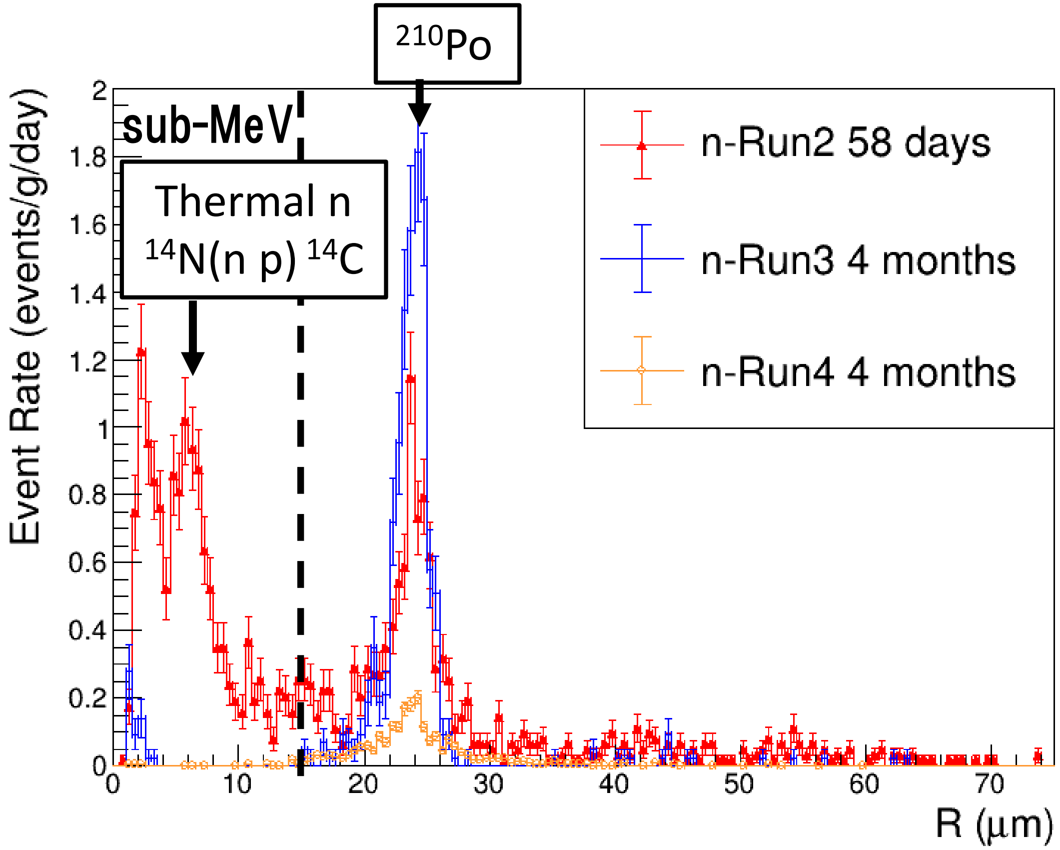
n-Run1 @ LNGS surface ground lab.



✓ **Without shielding!**

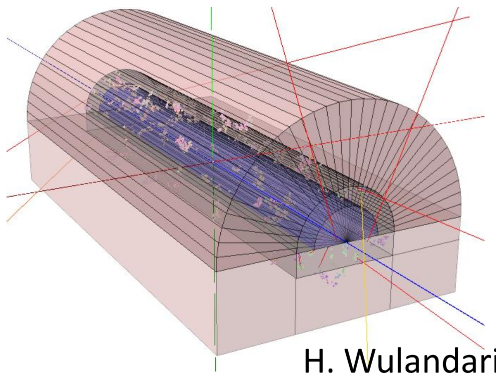
because of no sensitivity to muon and gamma

Underground neutron measurement



Neutron around sub-MeV region started to see without background.

MC Simulation using NeuCBOT, PHITS, and GEANT4

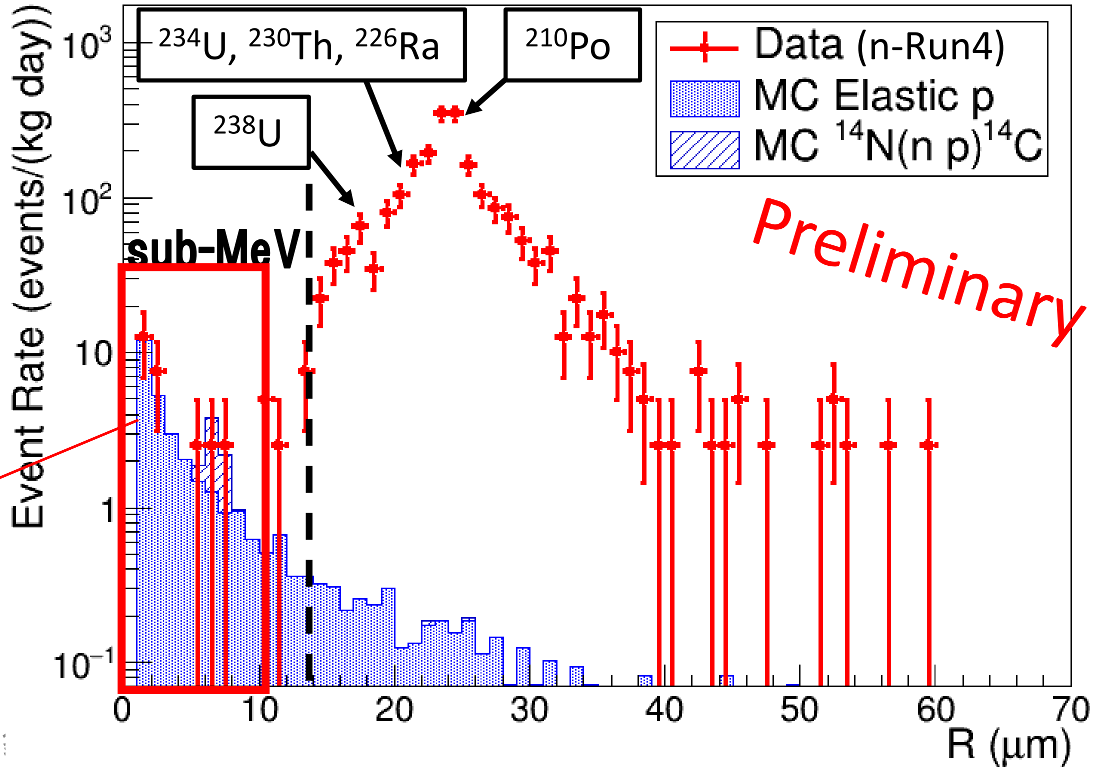


Taken into account the (α, n) reaction due to U･Th chain in the rock

※assuming 8% water content in the rock

H. Wulandari et al., Astropart. Phys., 22, 313-322 (2004)

n-Run4 0.52 kg*day analysys



Next approach

nRun4 : 1kg･day exposure ⇒ expected number of event around 10 events or less

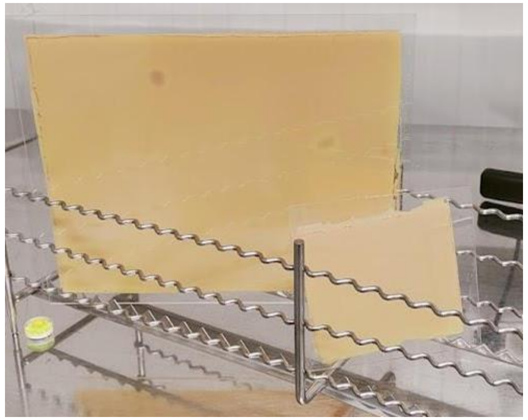
First result of flux

nRun5 ~ : > 10kg･day exposure ⇒ expected number of event : order of 10

Energy spectrum, angular distribution

To be updated the handling properties

Will be reported by Asada

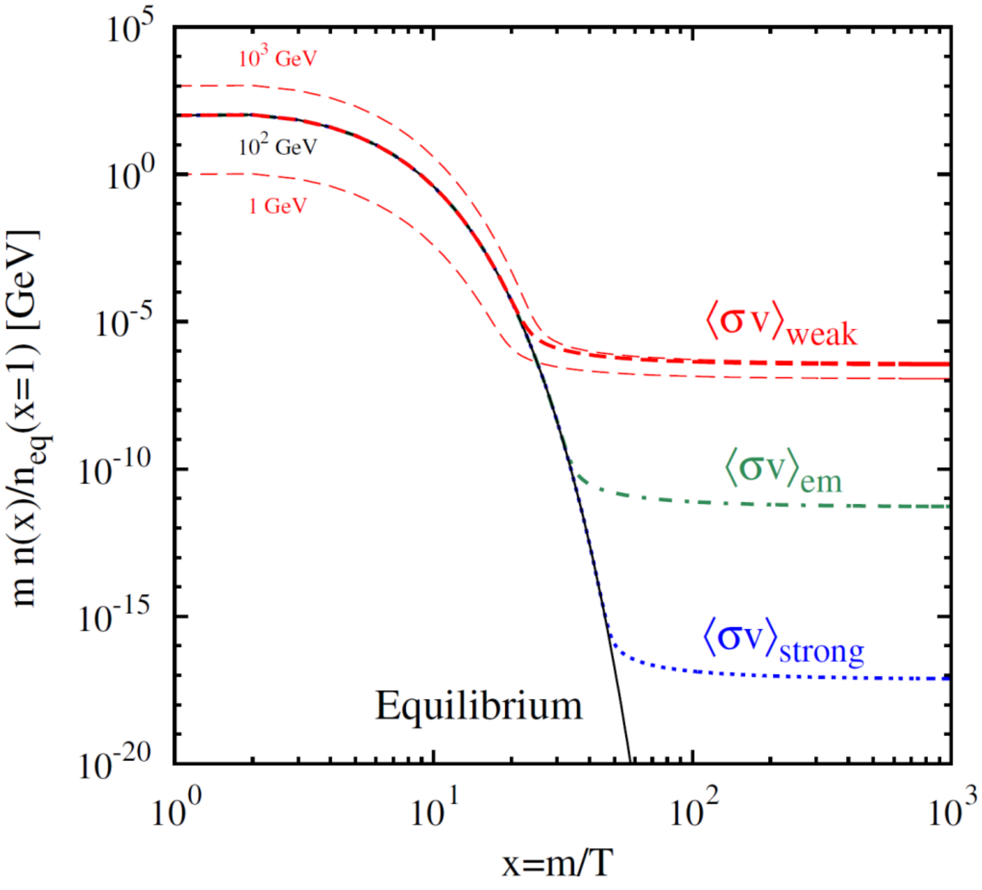


Application of neutron measurement

- Dark matter study using proton recoil ⇒ MeV scale dark matter search
- Directional measurement with the telescope (galactic center)

Light WIMP search with NEWSdm

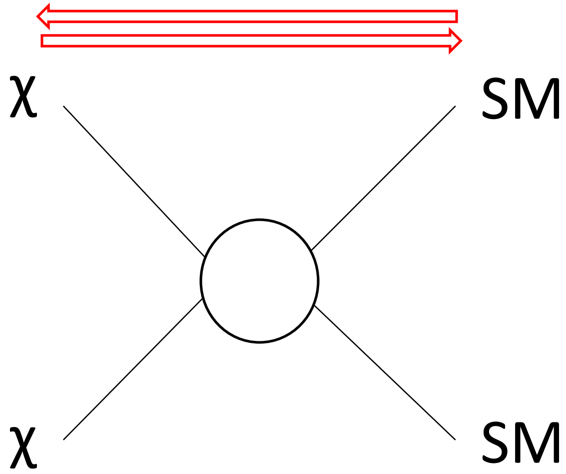
WIMP scenario



Phys. Rev. D 86, 023506(2012)

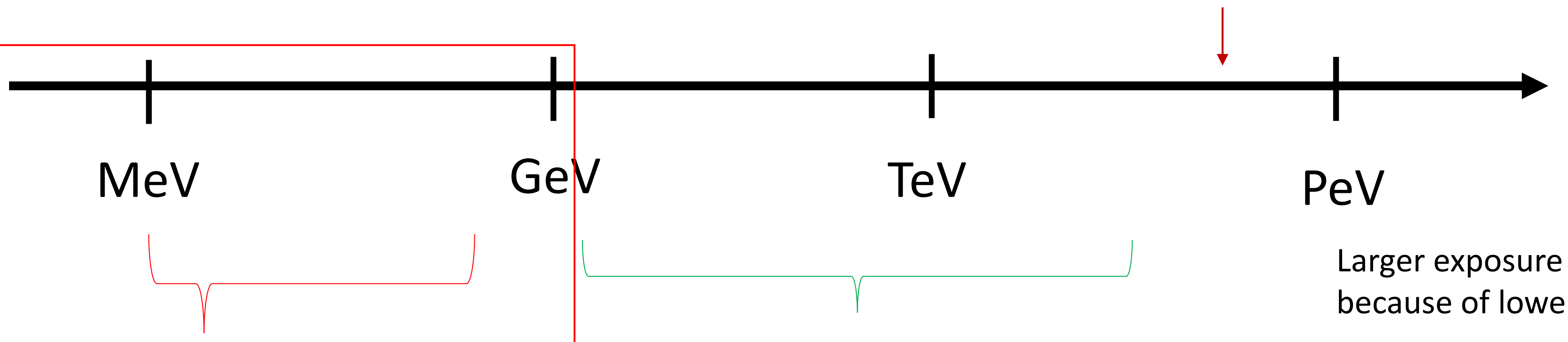
Dark matter abundance is explained by thermal relic process, i.e., decoupling from thermal equilibrium

$$\Omega_{DM} \sim \frac{2 \times 10^{-26}\ cm^3/s}{\langle \sigma v \rangle}$$



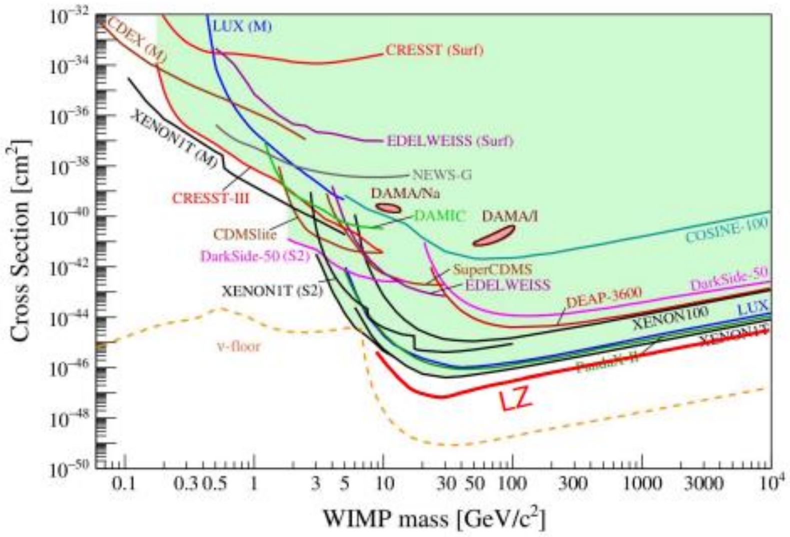
Weak scale cross section with SM particles

Mass scale for WIMP scenario



Larger exposure is needed because of lower flux

Main target for current experiment

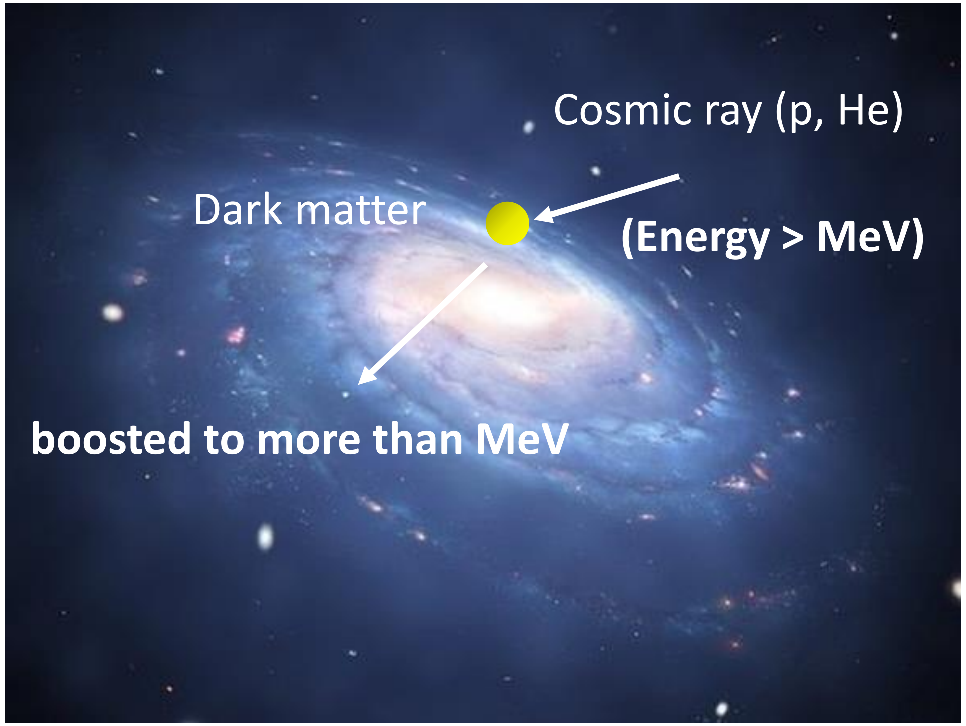


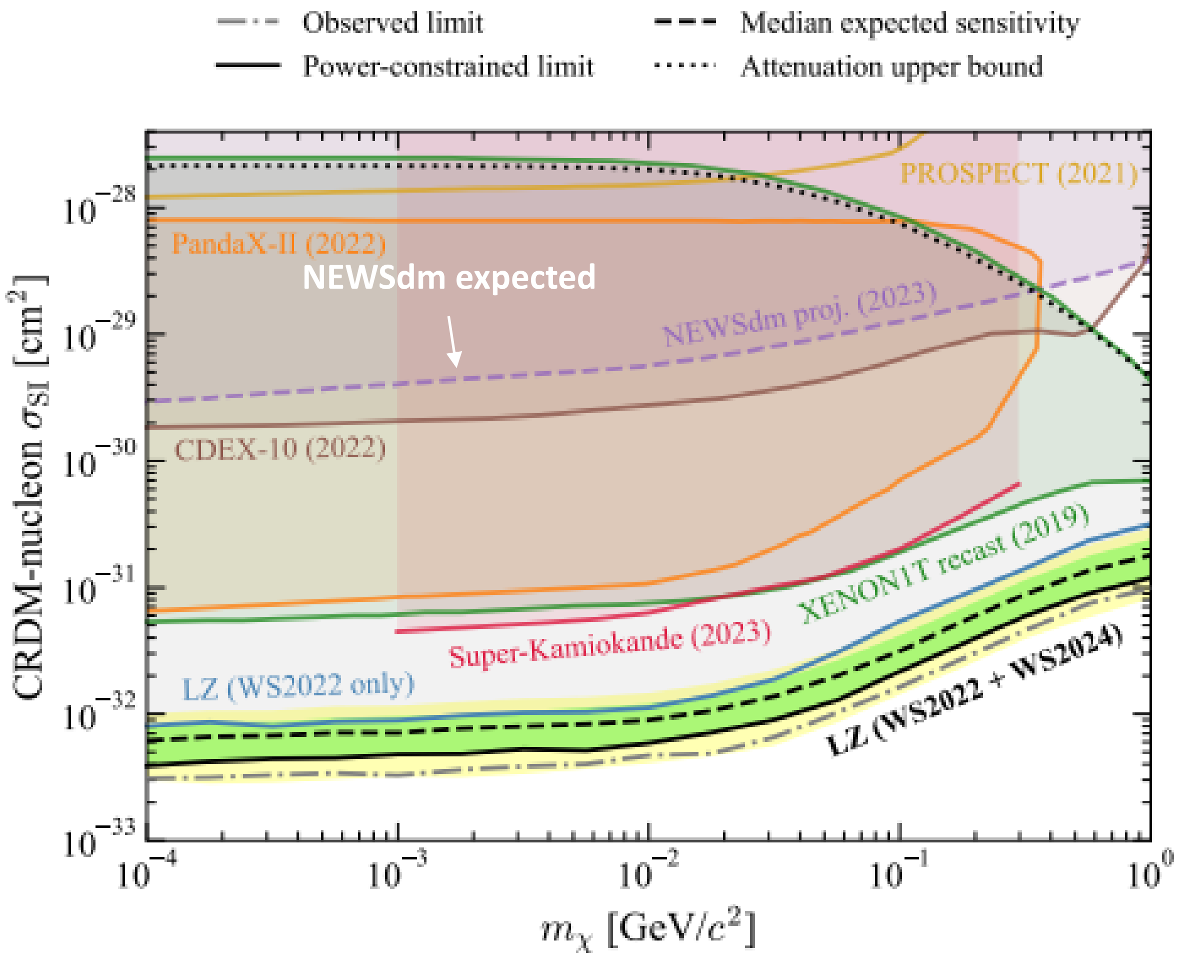
- MeV scale WIMP (light WIMP) is also allowed for thermal relic scenario, but it's still blue ocean.
- Simple direct detection methodology is very difficult to detect the signal because energy threshold for current detector is not enough.

Currently, there are no clear indication.
Only DAMA/LIBRA insists the signal with annual modulation, but it's not inconsistent with any other experiments.

Boosted DM scenario

Cosmic-ray boosted dark matter

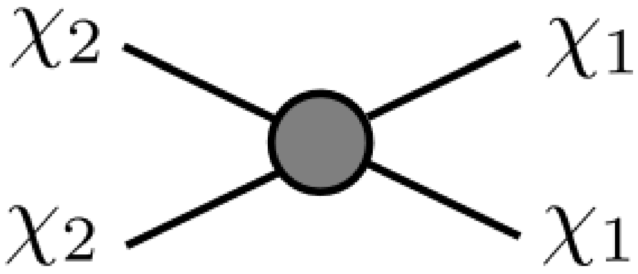




Physical Review Letters 134, 241801 (2025)

- Boosted energy is expected to distribute higher energy to GeV scale.
- Directionality is interesting, but currently another detector has more advantage for sensitivity

■ Multi-component dark matter scenario

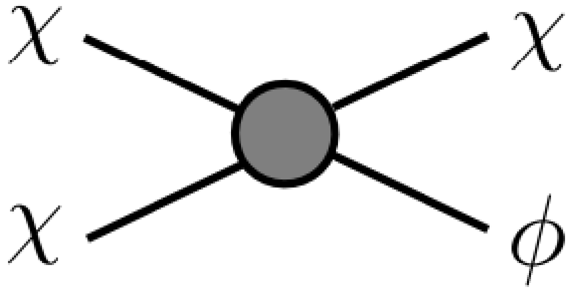


$M_{\chi_2} > M_{\chi_1}$ Here, χ_2 is main component of DM halo

$$T_{\chi_1} = M_{\chi_2} - M_{\chi_1}$$

χ_1 is boosted depending on the mass difference

■ Semi-annihilation scenario

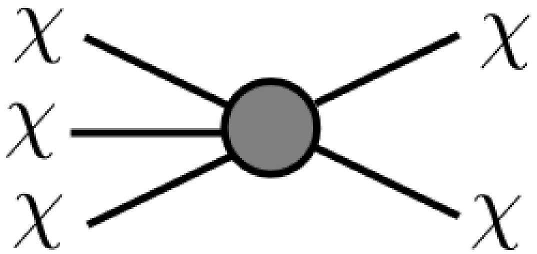


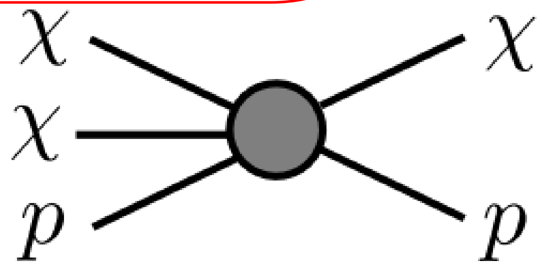
ϕ is light SM particle (e.g., neutrino)

$$T_\chi = \frac{1}{4} M_\chi c^2$$

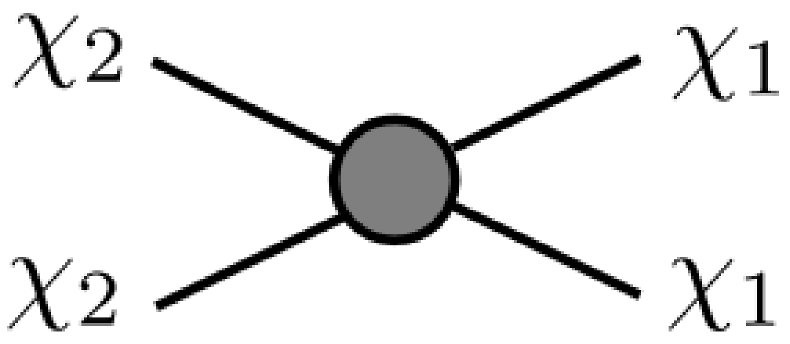
χ *has the kinetic energy depending on the mass*

■ Another : SIMP scenario, Decaying DM ‥

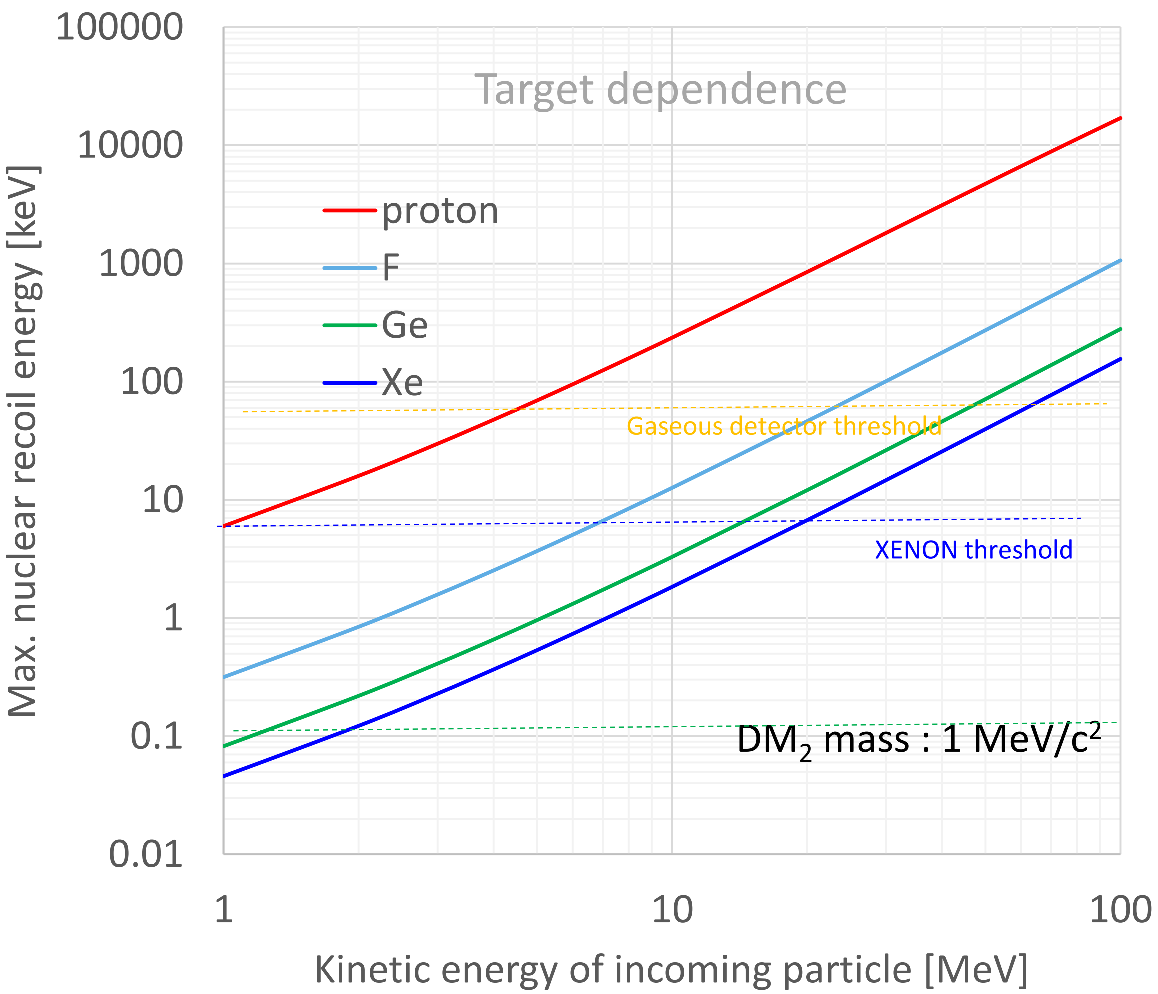


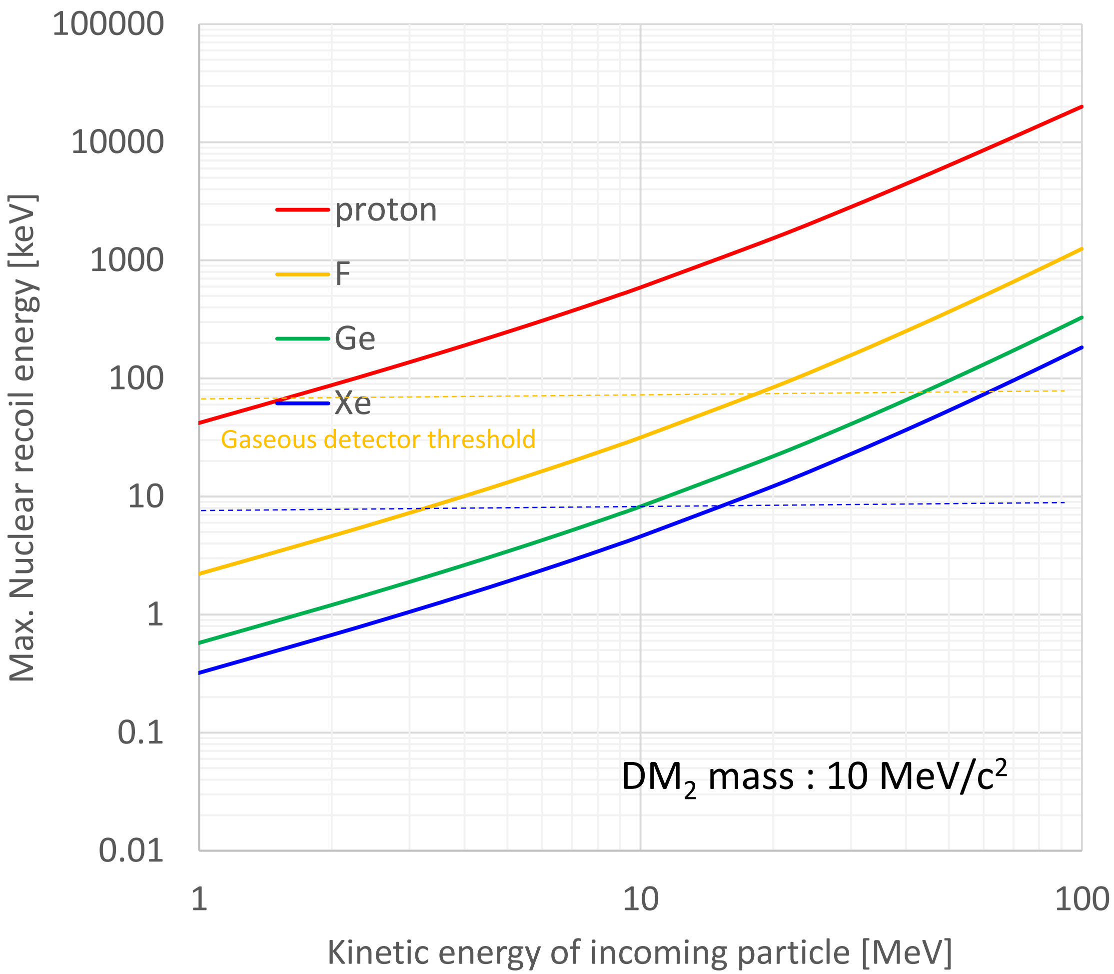


Discussion of sensitivity for the multi-component dark matter scenario

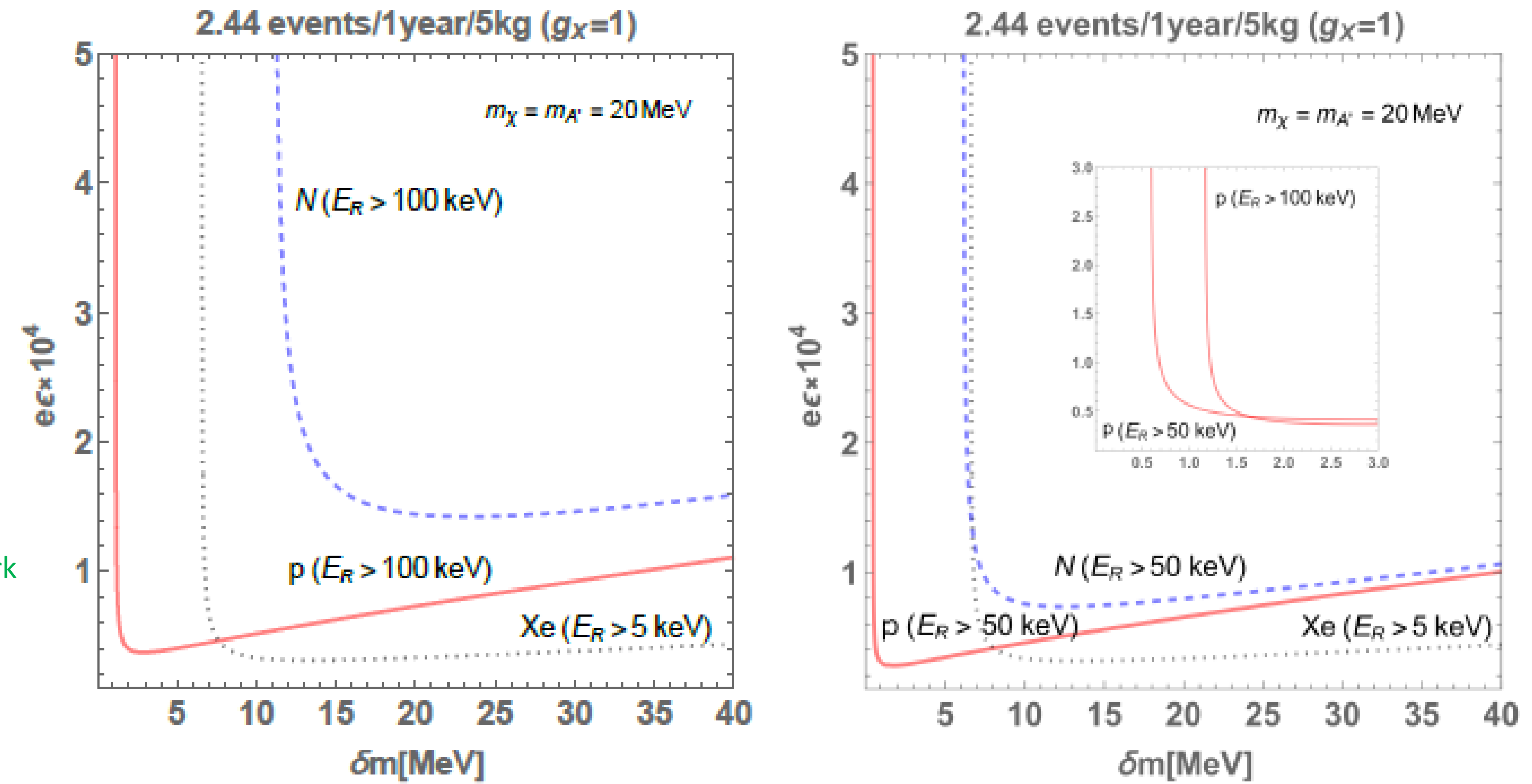


Recoil energy from coherent scattering kinematics





For the light WIMP with MeV mass scale, proton target has good advantage from momentum transfer.



Mixing parameter for the case of dark photon model

Lighter targets have advantage for MeV scale and degenerate case

Figure 2. Contours giving $N_{ev} = 2.3$ on $\{\delta m, e\epsilon\}$ plane where $m_\chi = m_{A'} = 20$ MeV. The threshold energy is 100 keV and 50 keV for p and N in the left and right figures, while that of Xe is taken to be 5 keV. In the right plot, we also show the behavior of the proton case with different threshold energy in small δm region.

$$\frac{d\sigma_{\chi N\to\chi N}}{d\Omega} = \frac{1}{(4\pi)^2}\frac{(\epsilon e)^2 g'^2}{(q^2-m_{A'}^2)^2}\frac{p'/p}{1+(E_\chi - pE'_\chi\cos\theta/p')/m_N} \times\left[G_E^2\frac{4E_\chi E'_\chi+q^2}{1-q^2/(4m_N^2)} + G_M^2\left((4E_\chi E'_\chi+q^2)\left(1-\frac{1}{1-q^2/(4m_N^2)}\right)+\frac{q^4}{2m_N^2}+\frac{q^2 m_\chi^2}{m_N^2}\right)\right] \qquad (3.6)$$

Formalism of sensitivity calculation

$$\frac{dN}{dT_r} = \sigma_{x-N} G_N^2(2m_N E_r) \frac{1}{T_r^{max}} \int dT_r \frac{d\Phi}{dT_r}$$
$$= \sigma_{x-N} G_N^2(2m_N E_r) \frac{1}{T_r^{max}} \Phi$$

- **Form factor**

$$G_N^2(Q^2) = \frac{1}{(1 + Q^2/\Lambda^2)^2}$$

$\Lambda_p \cong 770\ MeV$

$\Lambda_{He} \cong 410\ MeV$

* Helm form factor for heavier nuclei is assumed, but it's assumed 1 because of low momentum transfer

- **Flux from GC**

$$\Phi \sim 1.6\ cm^{-2} s^{-1} C_p \left(\frac{< \sigma v >}{5 \times 10^{-26}\ cm^3/s}\right)\left(\frac{5\ MeV/c^2}{M_1}\right)^2$$

https://arxiv.org/pdf/1405.7370.pdf

* NFW profile is inputted.

- **Maximum recoil energy**

$$T_r^{max} = \frac{(E_x - m_x)^2 + 2m_x(E_x - m_x)}{(E_x - m_x) + (m_x + m_N)^2/2m_N}$$

- **DM-nuclei cross section (coherent scattering)**

$$\sigma_{x-N} = \sigma_{x-n} A^2 \left(\frac{m_N(m_x + m_p)}{m_p(m_x + m_N)}\right)^2$$

* In this case, constant value is assumed, but it may have energy dependence for model of massive mediator such as dark photon model

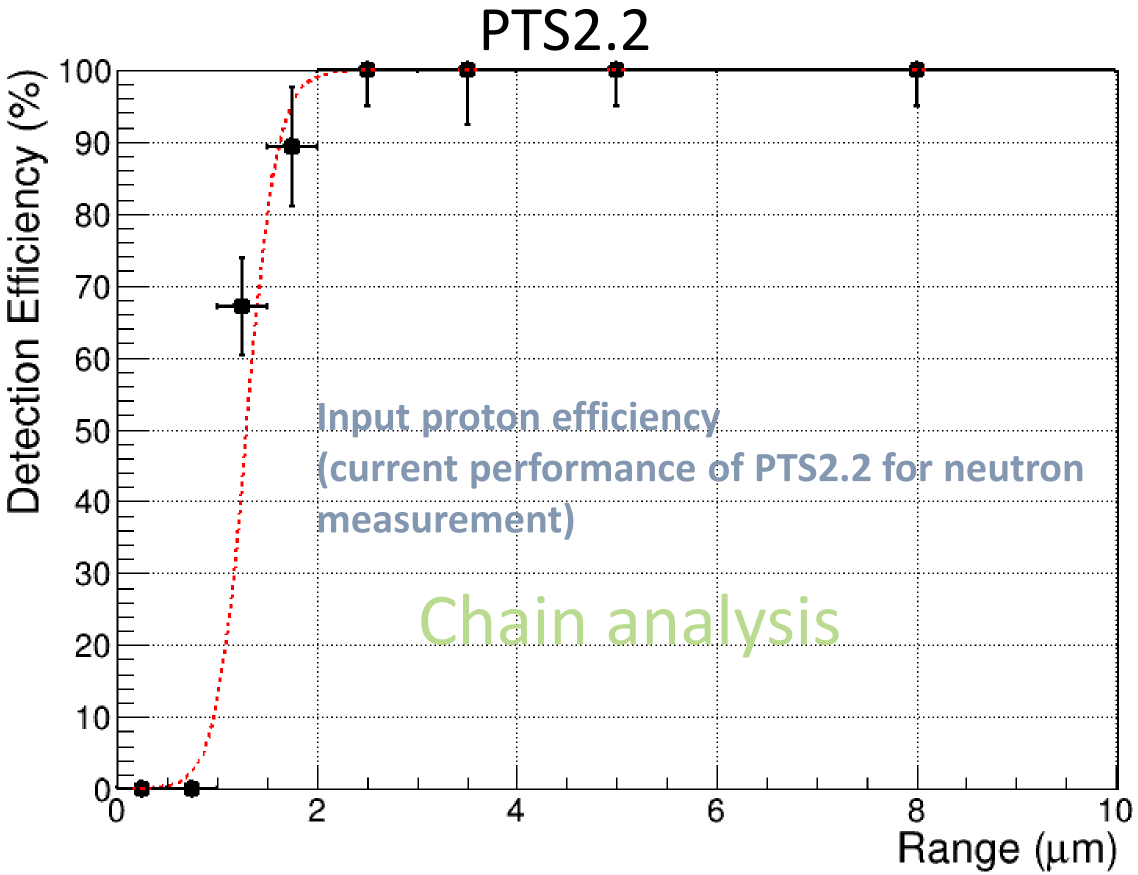
Density profile of DM in the MW

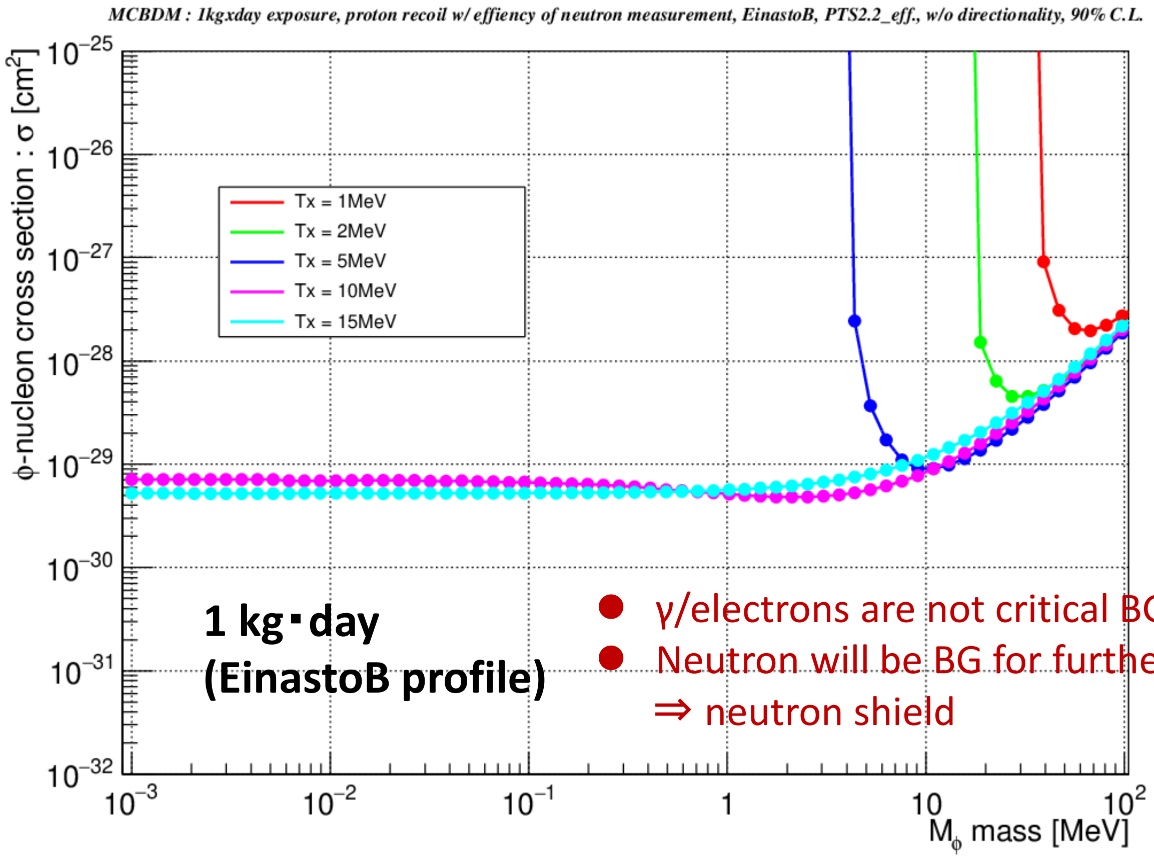
C_p 1 : NFW profile

3.76 : Einasto profile

From recent velocity curve measurement of the MW, Einasto profile is suggested

Sensitivity for the current neutron measurement performance w/o attenuation effect





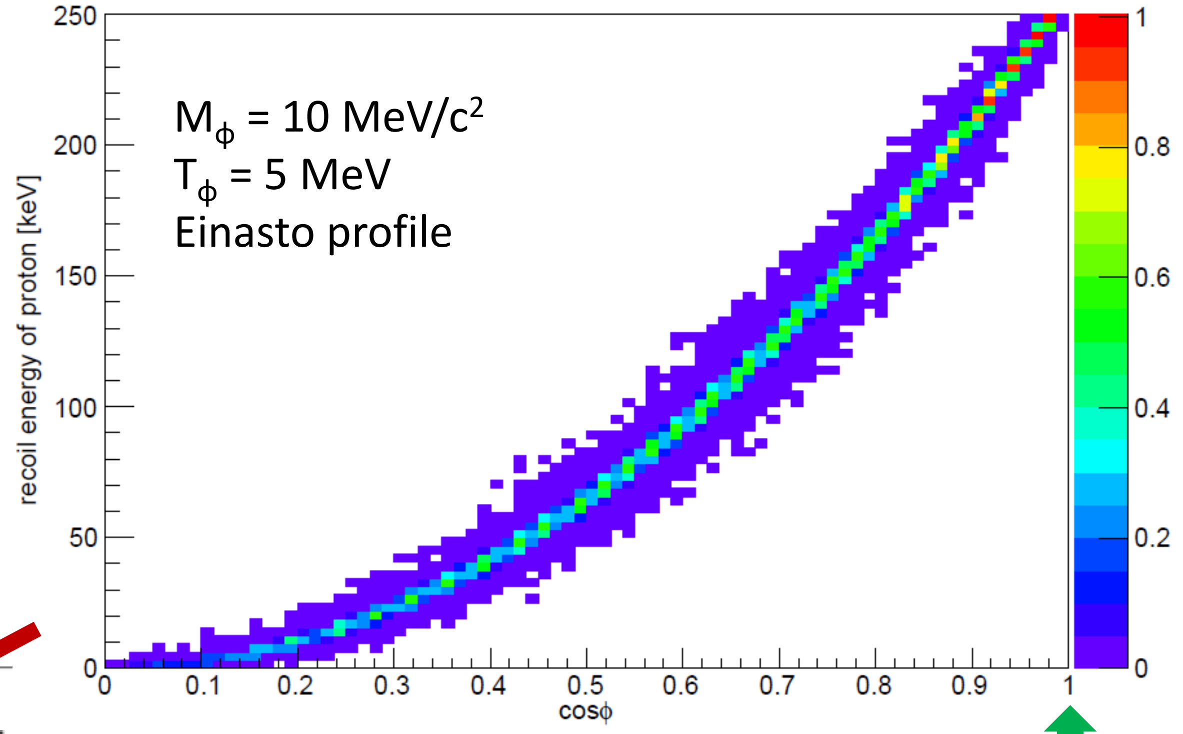
- γ/electrons are not critical BG
- Neutron will be BG for further scal
  ⇒ neutron shield

Currently, there are no limit for this parameter space by any other experiments.

Advantage of Tracking detector

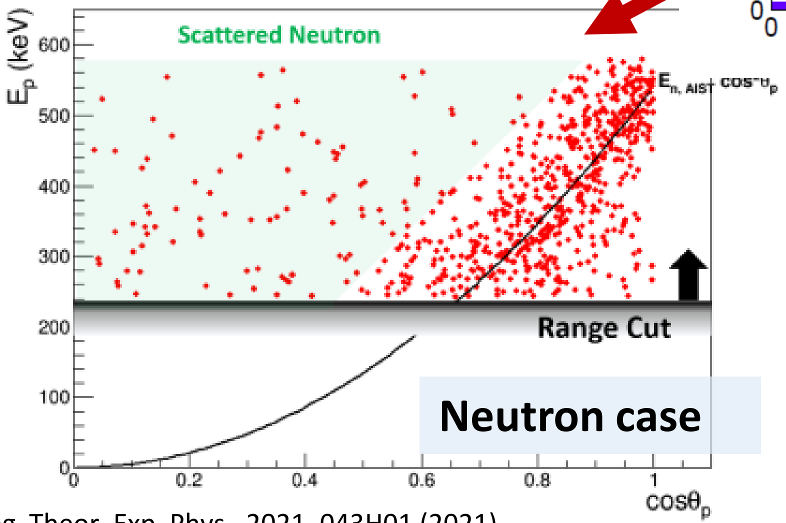
- Strong unique angular distribution from galactic center than standard WIMP search.
- For this selection condition, 3D reconstruction is possible by the chain analysis.
- For this approach, we will search the direction of the galactic center with the equatorial telescope.

Chain 3D case



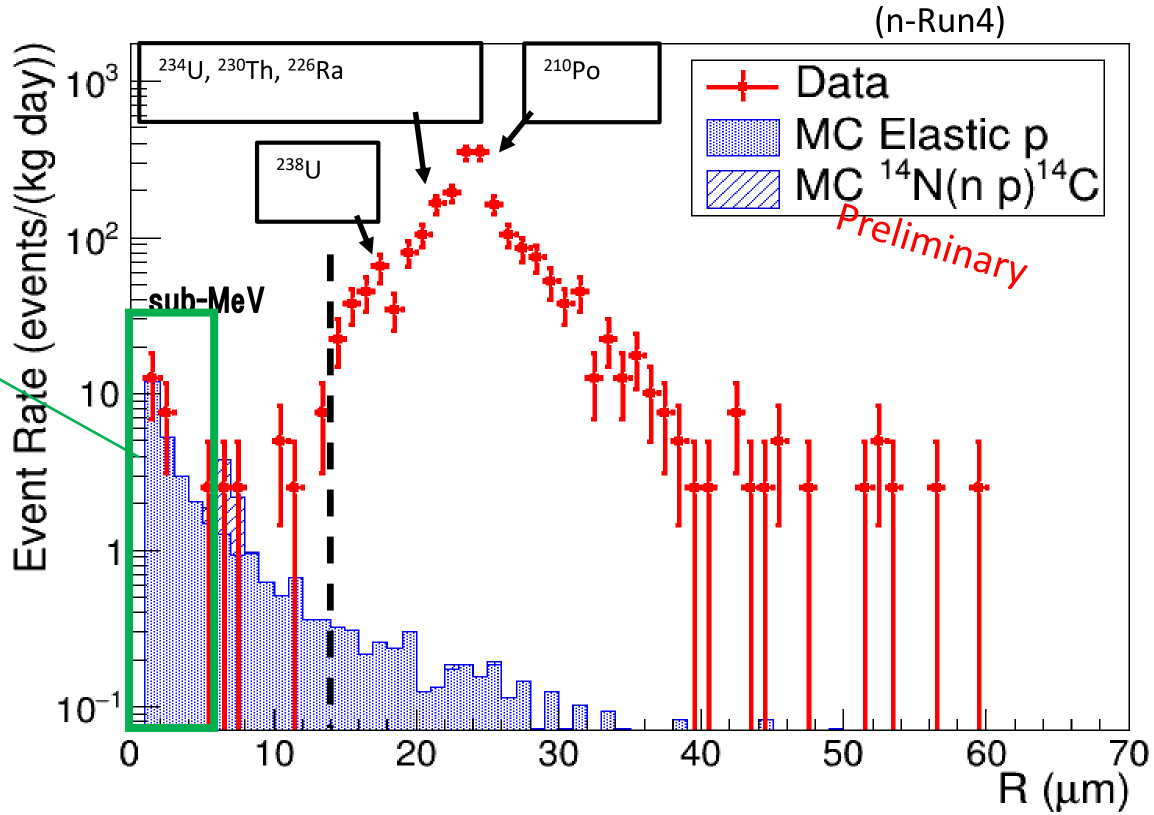
Galactic center

Same behavior have been demonstrated by neutron measurement due to nuclear fission reaction.
(reported by Shiraishi in past meeting)



T. Shiraishi et al., Prog. Theor. Exp. Phys., 2021, 043H01 (2021)

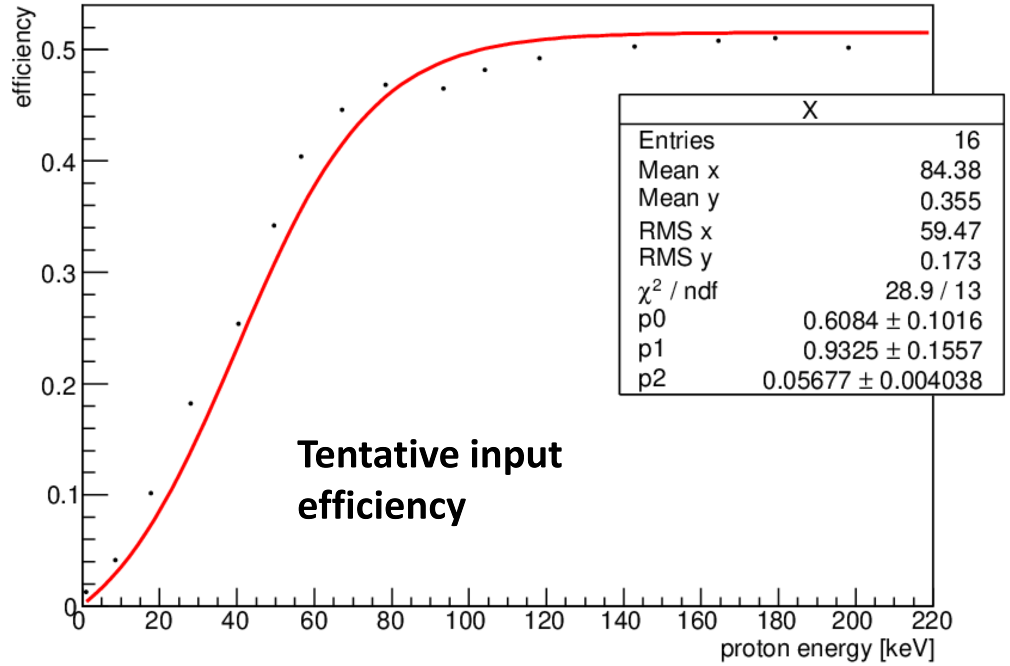
- Signal region for this dark matter search
- Currently, main BG will be neutron
  ⇒ it will be easy rejected by the shield
- Current neutron run have not used the telescope. ⇒ mount the telescope and analysis to the direction of galactic center

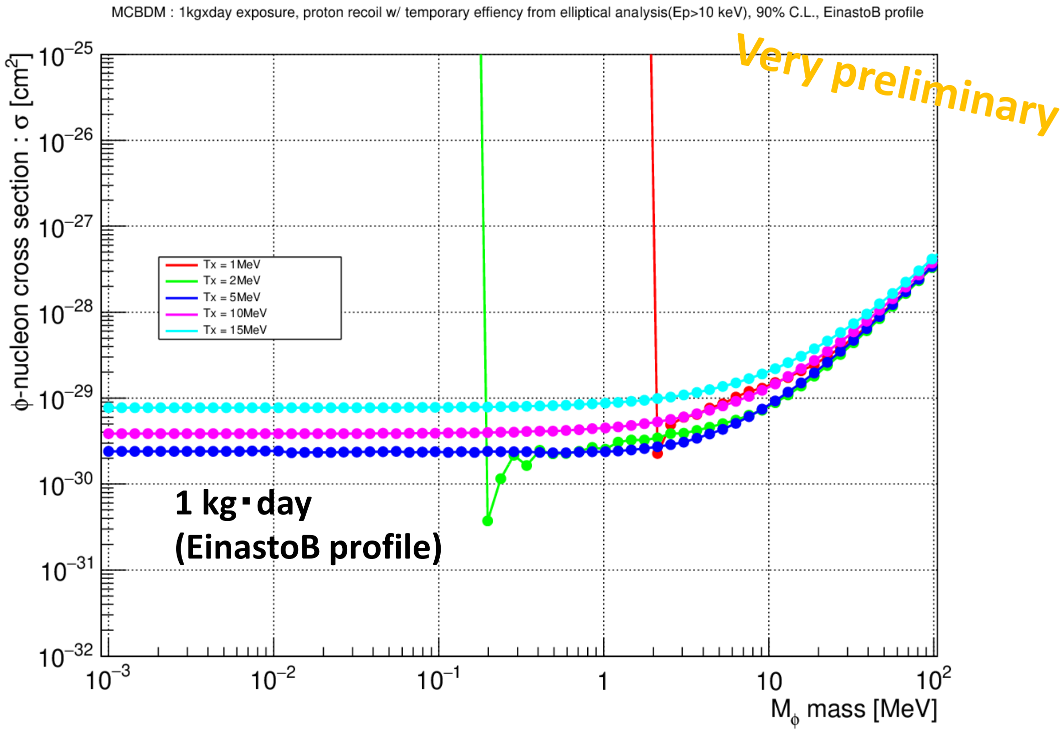


In this time, first demonstration was carried out in the underground .

Possibility for the elliptical selection (lower energy threshold)

- Current chain analysis threshold has around 100 keV of proton corresponding to 1 μm length.
- For shorter length (lower energy proton) selection, elliptical shape selection will work.





It has good sensitivity for degenerate mass scenario between two-component dark matters.

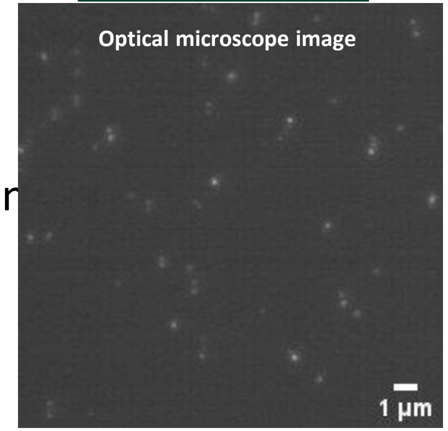
Technical update

Proton 60 keV

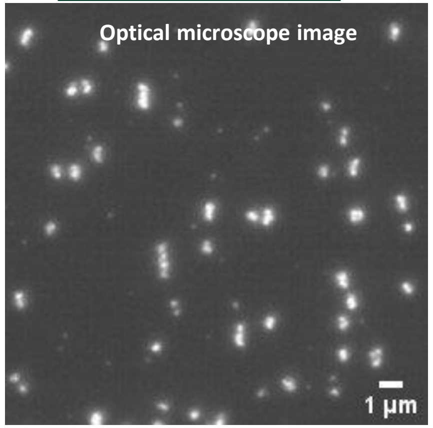
- **Updated of development treatment**

  MAA developer ⇒ GR-1 developer
  (already demonstrated in the GRAIN experimen

MAA



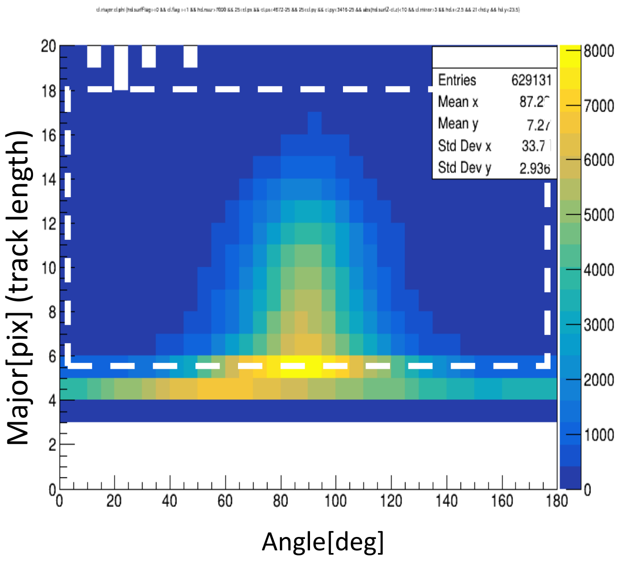
GR-1

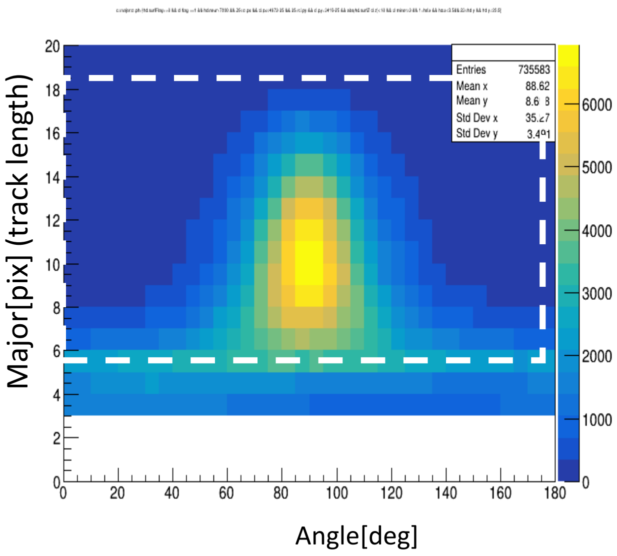


- ➢ **Higher brightness**
  ⇒ It has advantage for lower energy threshold, energy resolution, fading etc.

- ➢ **Stable : keep for long-time**
  ⇒ easier handling for larger scale treatment

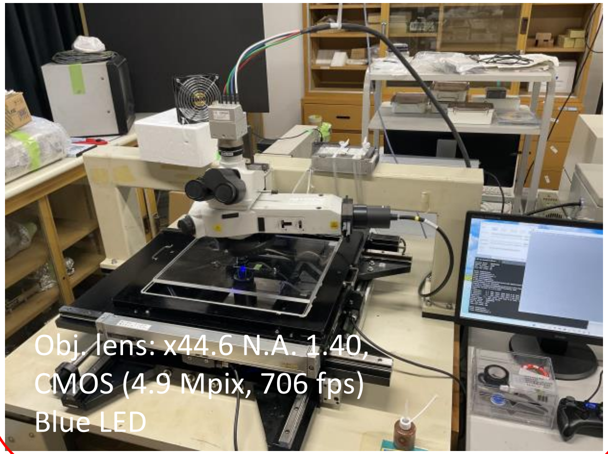
- ➢ **Easy sensitivity tuning**
  ⇒ optimization depending on each motivation





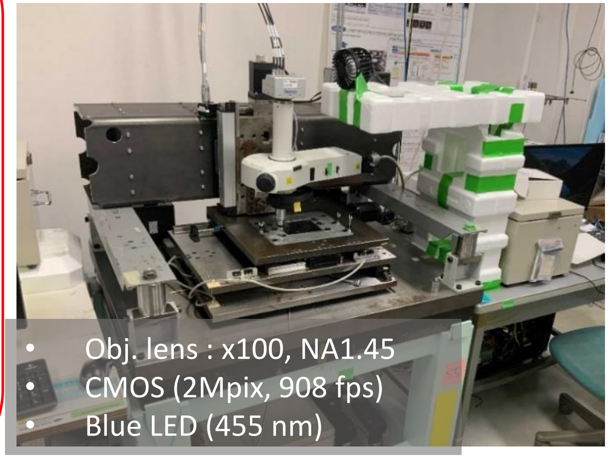
Optical microscope system in Japan

PTS-2’ @ Kanagawa U.



- Obj. lens: x44.6 N.A. 1.40,
- CMOS (4.9 Mpix, 706 fps)
- Blue LED

PTS-3 @ Nagoya



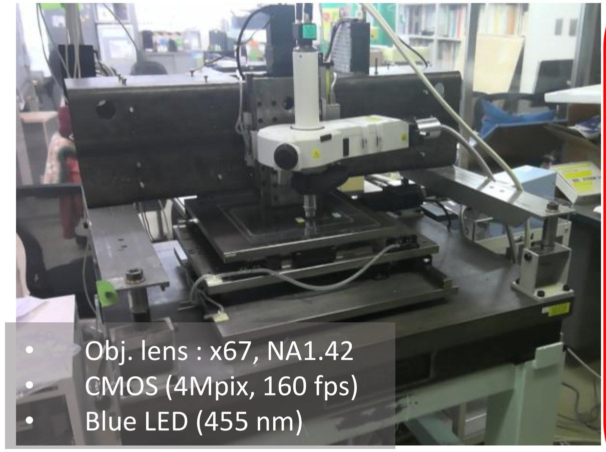
- Obj. lens : x100, NA1.45
- CMOS (2Mpix, 908 fps)
- Blue LED (455 nm)

Proton analysis (neutron, MeV-scale DM search)
⇒ **1.4/kg/y/machine**

+ **PTS-5 started to demonstrate**

Target speed : > ~2kg/year scale
(> 100 kg･day)

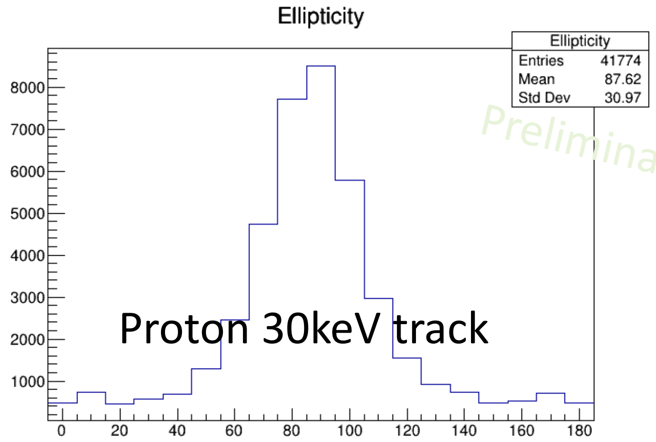
PTS-4 @ Toho



- Obj. lens : x67, NA1.42
- CMOS (4Mpix, 160 fps)
- Blue LED (455 nm)

PTS-5 @ Nagoya

Just started the track readout

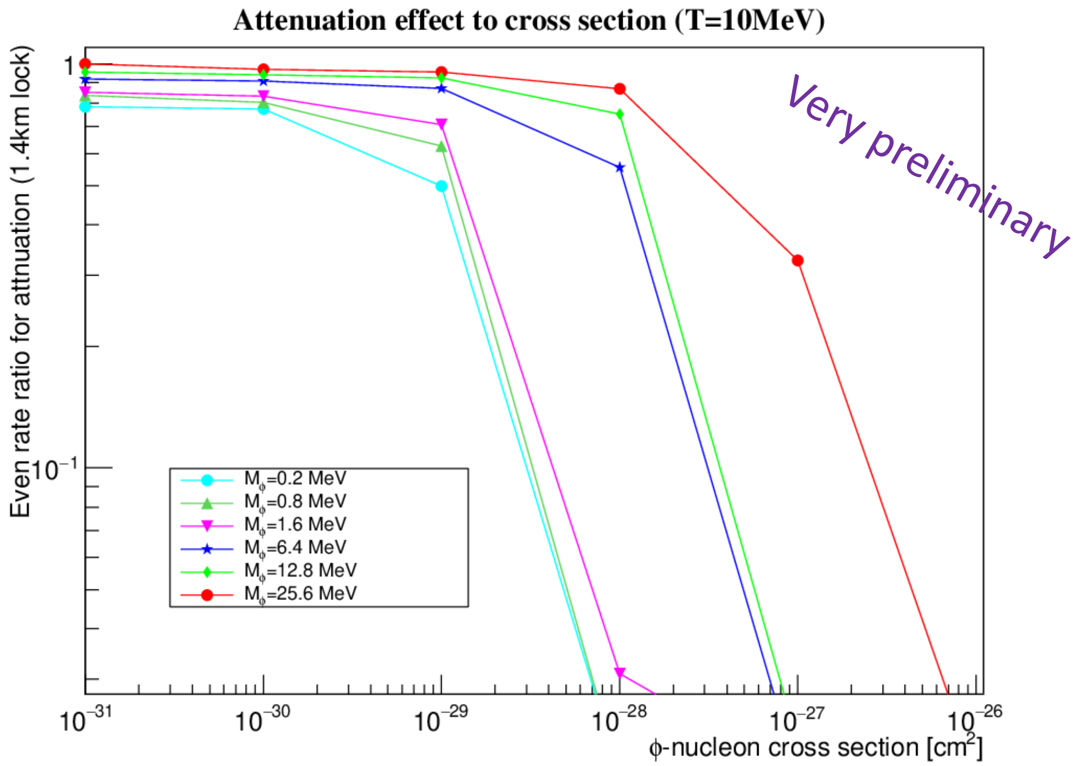


Install the chain analysis system is ongoing

Estimation of Attenuation effect

- Attenuation in the rock will be shift the energy and flux
- Finally, we estimate the sensitivity taking into account the attenuation effect
- Also, observed time of the galactic center in the northern hemisphere is limited, so future it's interested in the observation on the southern hemisphere.

Simulation study is ongoing.



Refer from arXiv:2410.17727v3

Model dependent scenario

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An IOP and SISSA journal

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Directional direct detection of MeV scale boosted dark matter in two component dark matter scenario via dark photon interaction

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Abstract: This study explores a two-component dark matter model in which one component, heavier dark matter, annihilates into a lighter dark matter. The lighter dark matter is expected to generate detectable signals in detectors due to its enhanced momentum, enabling direct detection even for MeV-scale dark matter. We investigate the effectiveness of directional direct detections, especially the nuclear emulsion detector NEWSdm, in verifying these boosted dark matter particles through nuclear recoil. In particular, we focus on light nuclei, such as protons and carbon, as suitable targets for this detection method due to their high sensitivity to MeV-scale dark matter. By modeling the interactions mediated by a dark photon in a hidden $U(1)_D$ gauge symmetry framework, we calculate the expected dark matter flux and scattering rates for various detector configurations. Our results show that nuclear emulsions have the potential to yield distinct, direction-sensitive dark matter signals from the Galactic center, providing a new way to probe low-mass dark matter parameter spaces that evade conventional detection methods.

Keywords: dark matter theory, dark matter experiments, dark matter detectors

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JCAP04(2025)030

Formalism

U(1) hidden gage mediated (i.e., dark photon) interaction

$$\psi\bar{\psi} \to A' \to \chi\bar{\chi},$$
$$\chi\bar{\chi} \to A'A',$$

The relevant Lagrangian for new fermions χ and ψ is

$$\mathcal{L}_{\rm DM} = \bar{\chi}(i\not{D} - m_\chi)\chi + \bar{\psi}(i\not{D} - m_\psi)\psi,$$

where $D_\mu\chi(\psi) = (\partial_\mu + iQ_{\chi(\psi)}g_D A'_\mu)\chi(\psi)$ is the covariant derivative. In the following, we write the DM-A' interaction in eq. (2.3) as

$$A'_\mu(g_\chi\bar{\chi}\gamma^\mu\chi + g_\psi\bar{\psi}\gamma^\mu\psi), \tag{2.4}$$

Angular deifferential cross section

$$\frac{d\sigma_{\chi N\to\chi N}}{d\Omega} = \frac{1}{(4\pi)^2}\frac{(\epsilon e)^2 g'^2}{(q^2 - m_{A'}^2)^2}\frac{p'/p}{1+(E_\chi - pE'_\chi\cos\theta/p')/m_N} \times\left[G_E^2\frac{4E_\chi E'_\chi + q^2}{1-q^2/(4m_N^2)} + G_M^2\left((4E_\chi E'_\chi + q^2)\left(1-\frac{1}{1-q^2/(4m_N^2)}\right) + \frac{q^4}{2m_N^2} + \frac{q^2 m_\chi^2}{m_N^2}\right)\right] \tag{3.6}$$

Recoil energy for each target nuclei

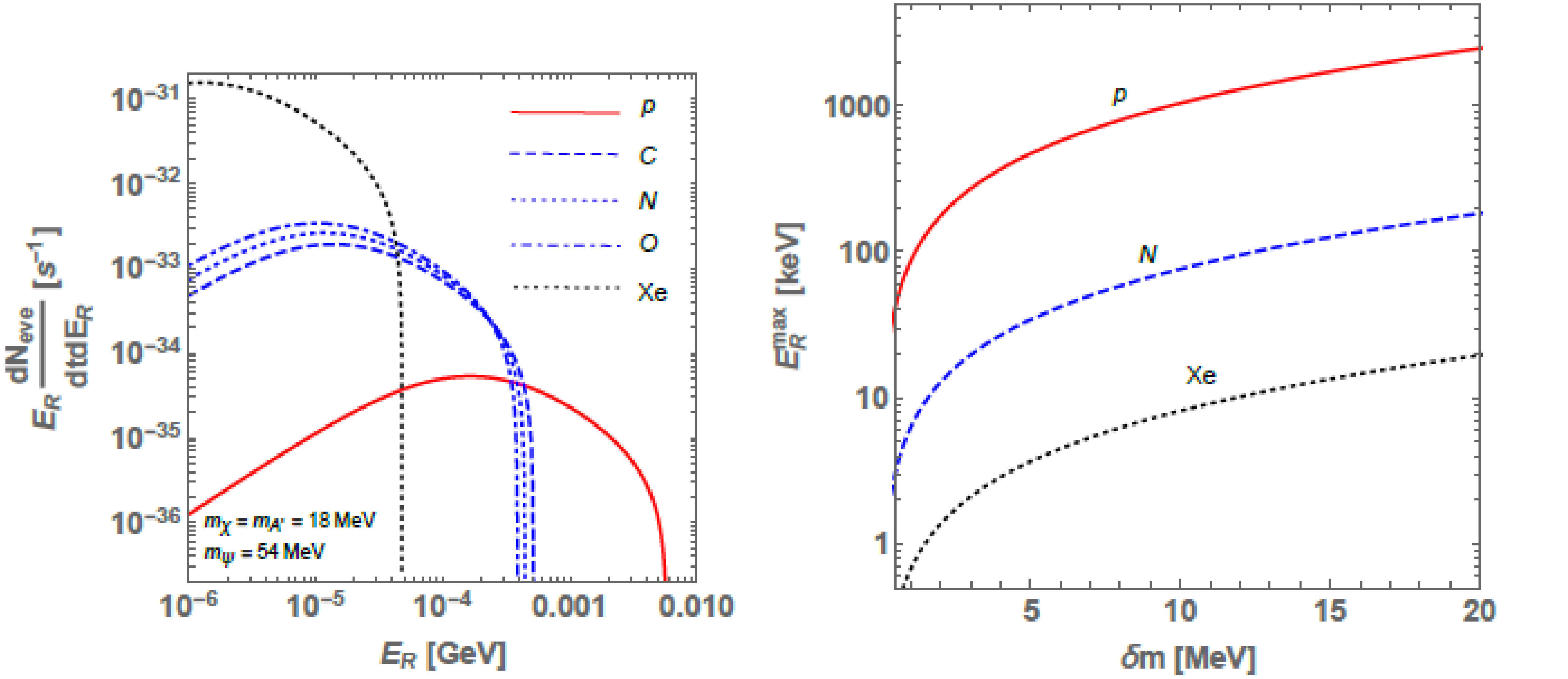
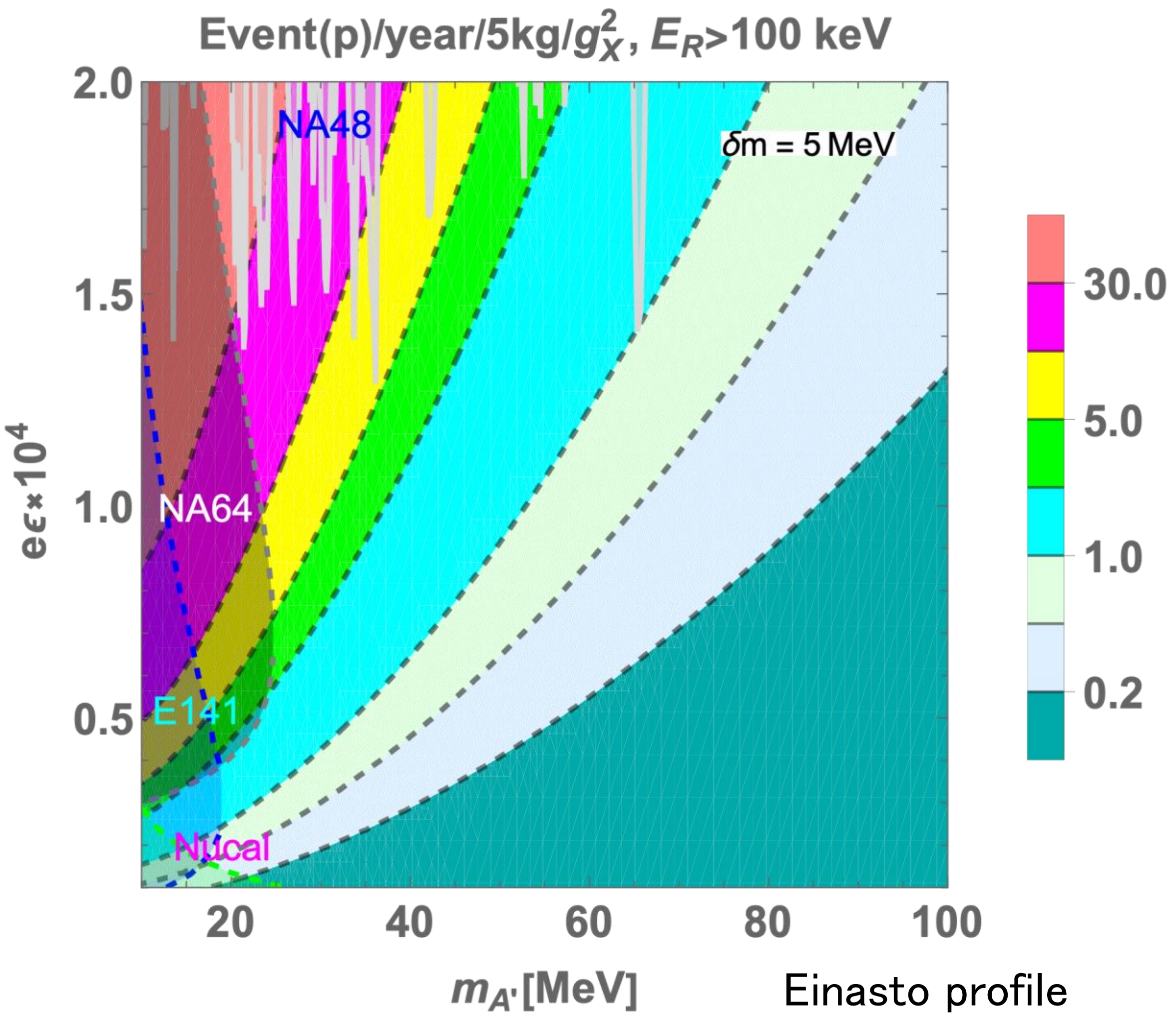


Figure 1. Left: the function associated to the event rate $E_R \frac{dN_{eve}}{dE_R dt}$ as functions of E_R for each nucleus where we adopt $m_\chi = m_{A'} = 18\,\text{MeV}$, $m_\psi = 3m_\chi$, $g_X = 1$ and $e\epsilon = 2 \times 10^{-4}$ as a reference point. Right: maximal recoil energy for each nucleus as a function of δm where we adopt $m_\chi = m_{A'} = 20\,\text{MeV}$.

Lighter targets have advantage for MeV scale and degenerate case

Case of Degenerating DM Masses



Einasto profile

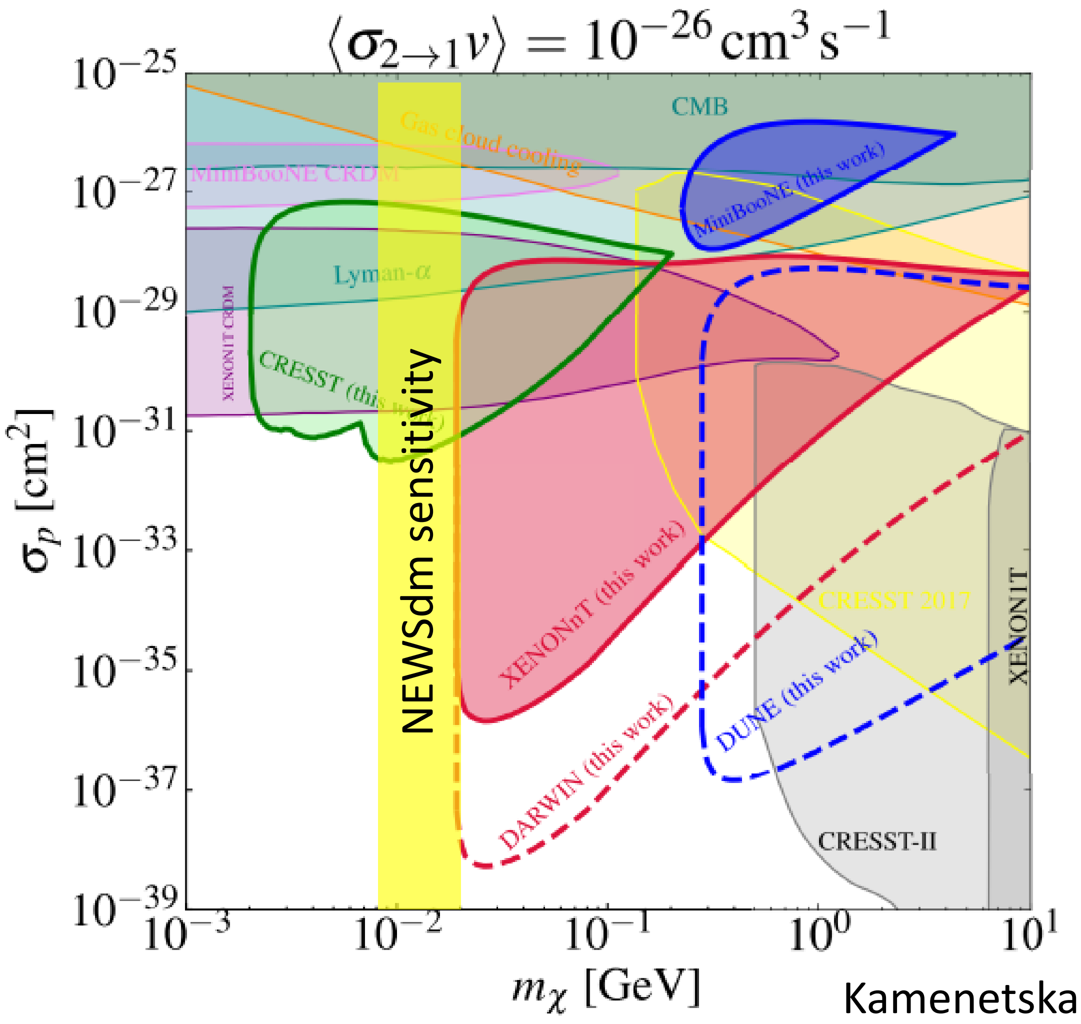
- $m_\psi \simeq m_\chi$

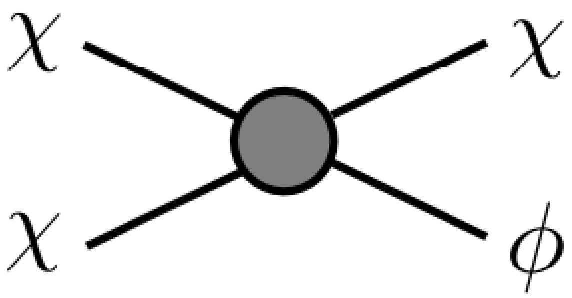
  ⇨ Boost of χ is too tiny to scatter targets in detector

- Then the lightest target p can be a hopeful target. We can expect ~ 30 events at most.

$$m_\chi = m_{A'}, m_\psi - m_\chi = 5\text{MeV}$$

Semi-annihilation process





Detail sensitivity is now on simulating, but for this model is also, NEWSdm should be possible to search new parameter space

Kamenetskaia, Fujiwara et al. PLB (2025)

Conclusion

- Recently, MeV scale dark matter have been actively discussed phenomenologically.
- New light dark matter is possible to be searched unique parameter space using NIT technologies and applied the neutron measurement
- Proton recoil tracks around 1 μm are capability of 3D angular reconstruction, energy reconstruction without electron BG.
- ⇒already demonstrated by neutron measurement
- Galactic center is target to search for boosted process with annihilation.
- This search is ongoing in LNGS underground with telescope

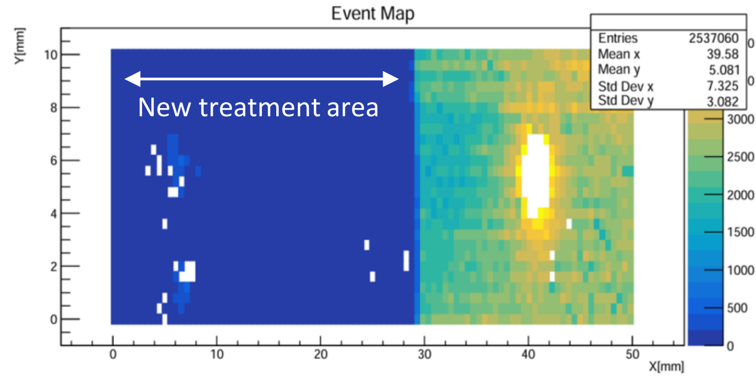
Technical updated

✓ Developer is changing to GR-1 development from MAA development

✓ Additional PTS system started to operate.

✓ **New fog reduction method** for lower energy threshold include standard WIMP search has been proposed, and studying the method.

⇒ demonstrated the principle of that, now on searching the optimum condition

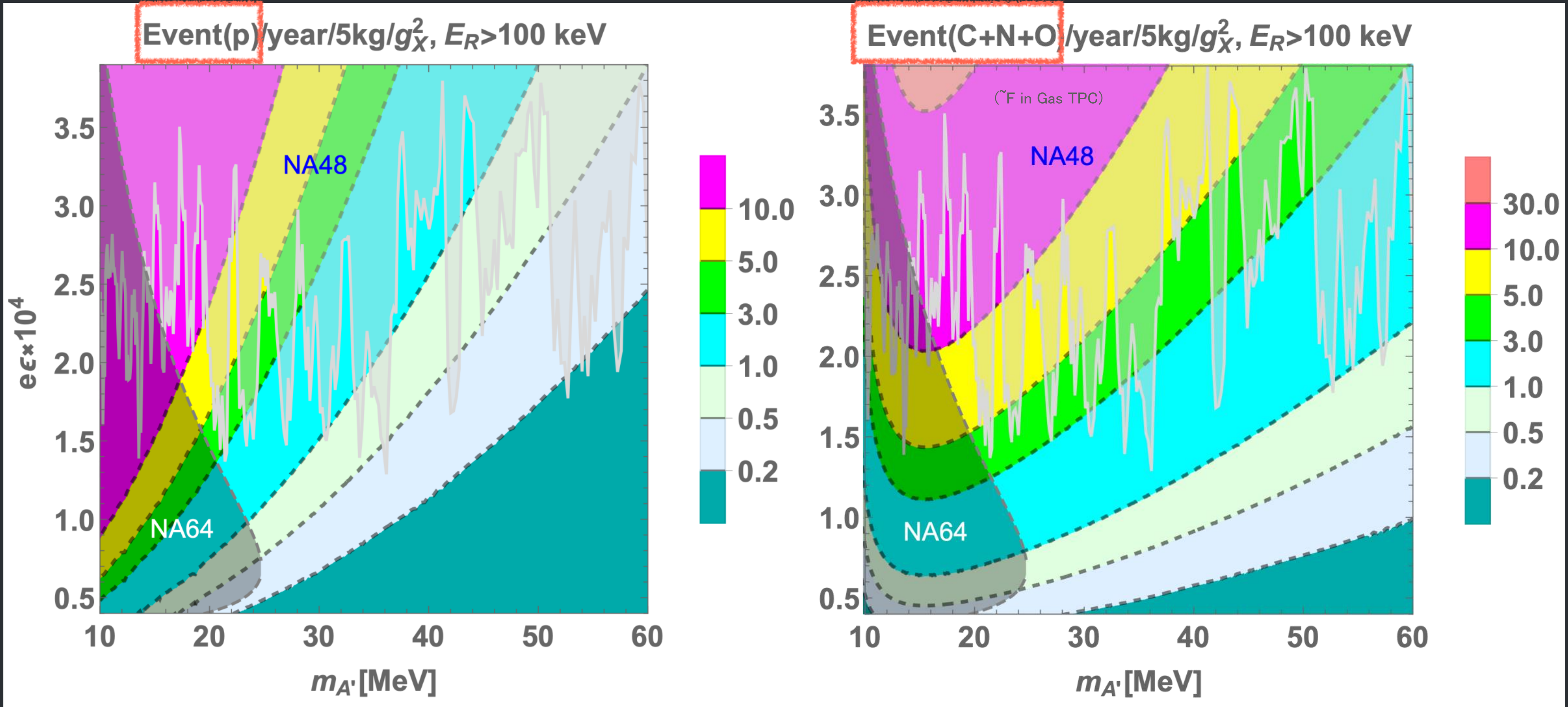


Back up

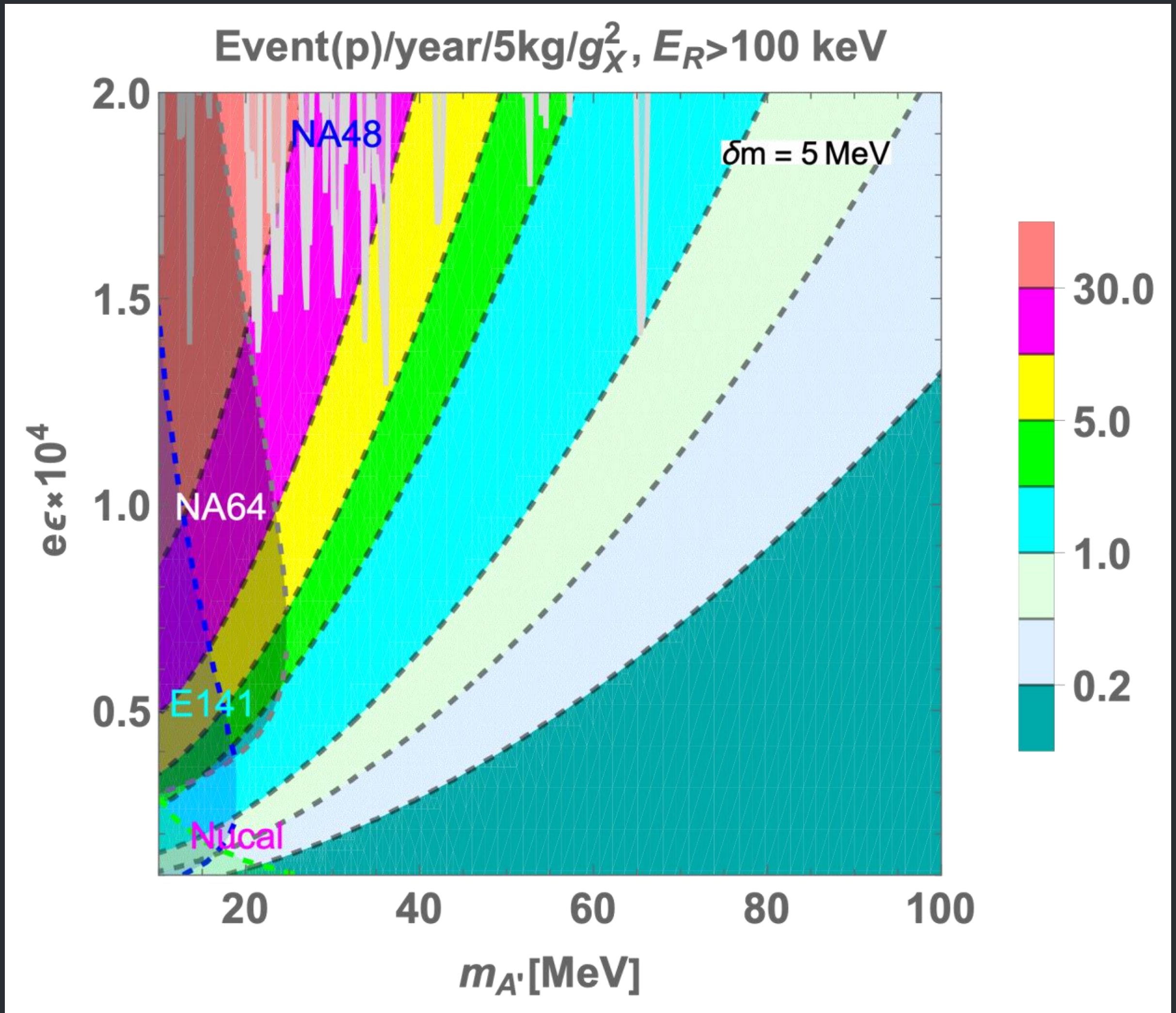
Event number

Einasto profile

$m_\chi = m_{A'}, m_\psi = 3m$



Case of Degenerating DM Masses



- $m_\psi \simeq m_\chi$

  ⇨ Boost of χ is too tiny to scatter targets in detector

- Then the lightest target p can be a hopeful target. We can expect ~ 30 events at most.

Einasto profile

$m_\chi = m_{A'}, m_\psi - m_\chi = 5\text{MeV}$

Density profile of DM

- Navarro–Frenk–White (NFW) profile

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/r_0)(1+r/r_0)^2}$$

J. Navarro, C. Frenk, S. White Astrophys. J. 490(1997)

- Einasto profile

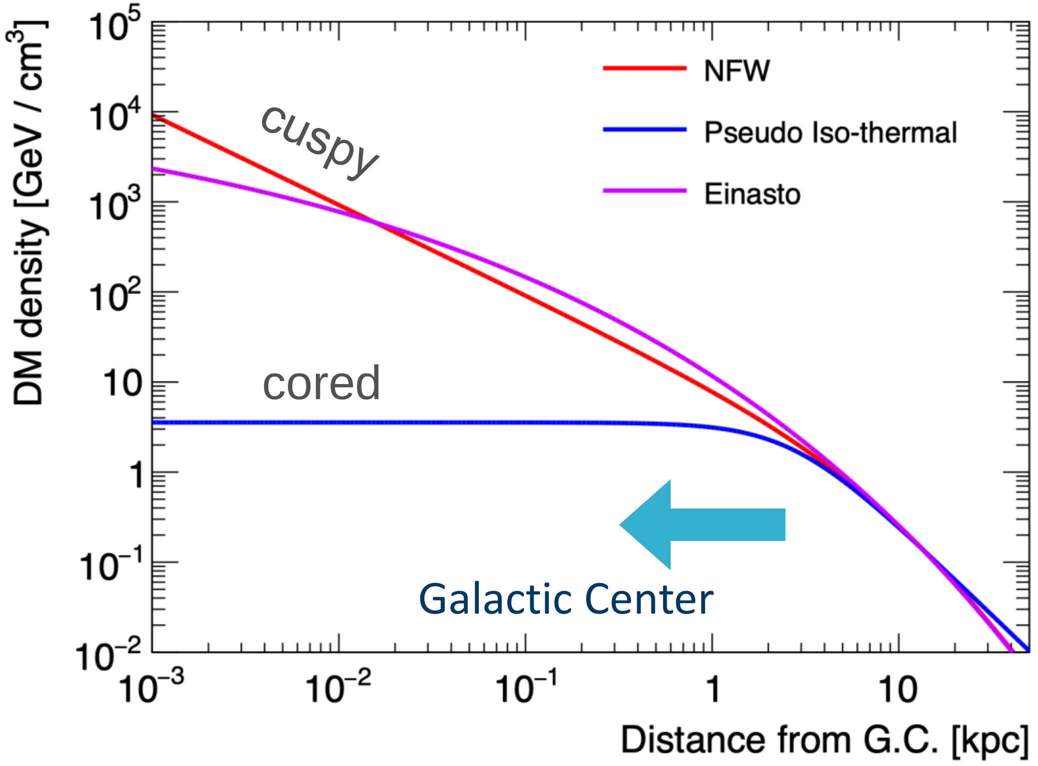
$$\rho_{Ein}(r) = \rho_0 \exp[2\alpha(1-(r/r_0)^{1/\alpha})]$$

J. Navarro et al. curves. Mon. Not. Roy. Astron. So 349 (2004)

- Pseudo-isothermal profile

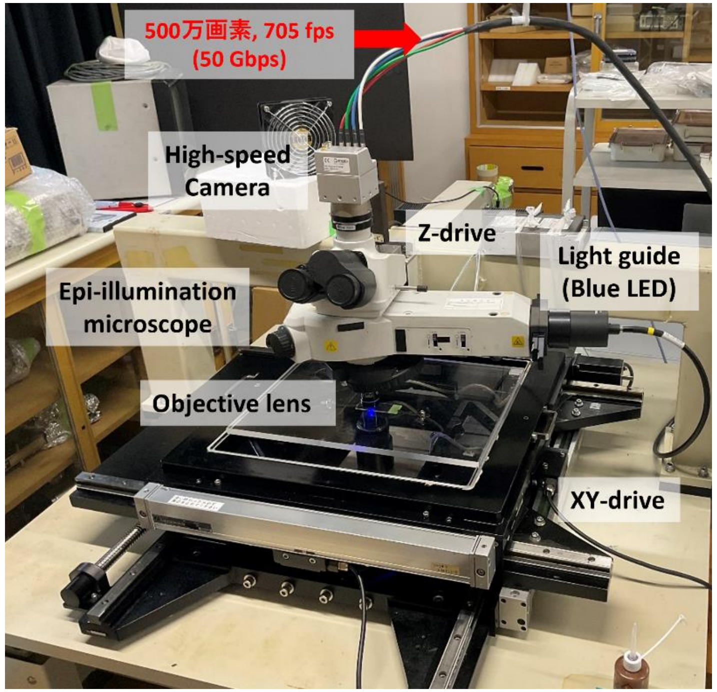
$$\rho_{Iso}(r) = \frac{\rho_0}{1+(r/r_0)^2}$$

R. Jimenez, L. Verde, S. Pen, Mon. Not. Roy. Astron. So 339 (2003)



Upgrade of scanning system for neutron measurement

PTS2.21@Kanagawa Univ.

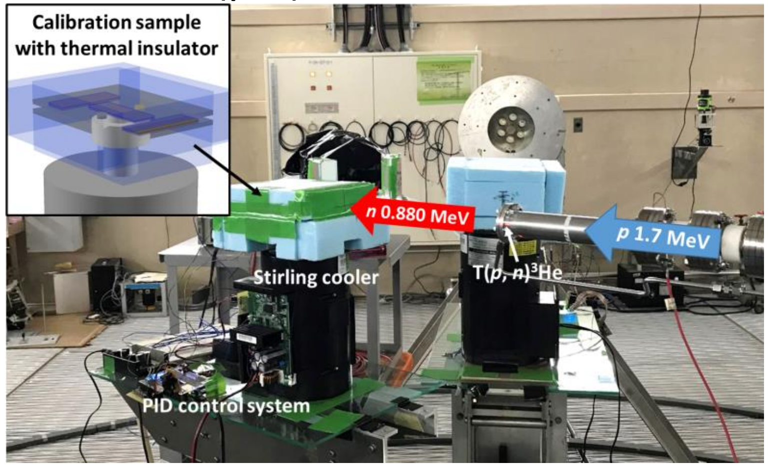


			Now	Future plan
	PTS4 (2022) [1]	**PTS2.1 (2024)**	**PTS2.2 (2025)**	**PTS2.3 (2026?)**
対物レンズ	N.A. 1.42, 66.8x	N.A. 1.40, 44.6x		
カメラ通信規格	CXP-6 x 4ch 25 Gbps	CXP-12 x 4ch 50 Gbps		QSFP28 -100GigE 100 Gbps
画素数	2304 x 1720	4672 x 3416	2560 x 1920	4608 x 2176
XYピッチ （ピクセル精度）	0.105 µm	0.087 µm	0.112 µm	0.101 µm
Zピッチ	0.30 µm			
FOV	241 µm x 180 µm	410 µm x 300 µm	287 µm x 215 µm	465 µm x 220 µm
フレームレート	500 fps	300 fps	705 fps	1000 fps
GPU	RTX 2080Ti	RTX 4070Ti SUPER	RTX 4080 SUPER	RTX 5080 SUPER?
解析速度 (kg/year)	**0.25**	**1.0**	**1.3**	2.5?

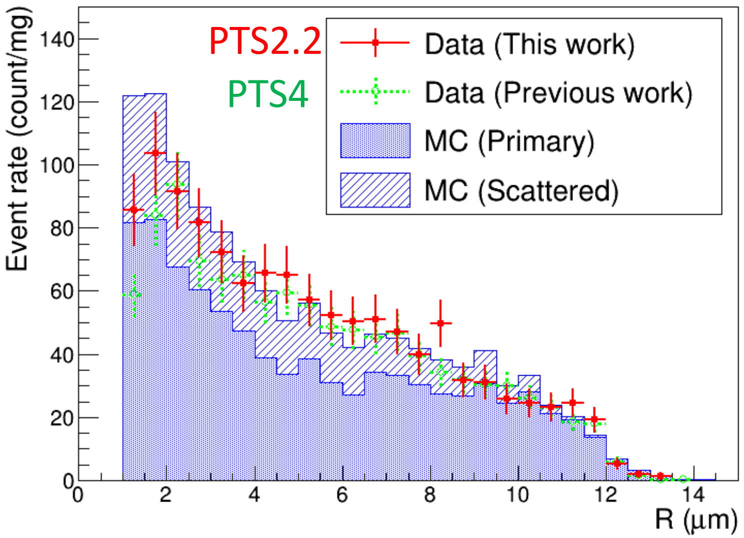
1) T. Shiraishi *et al.*, Phys. Rev. C **107**, 014608 (2023)

Proton detection calibration using 880keV neutron

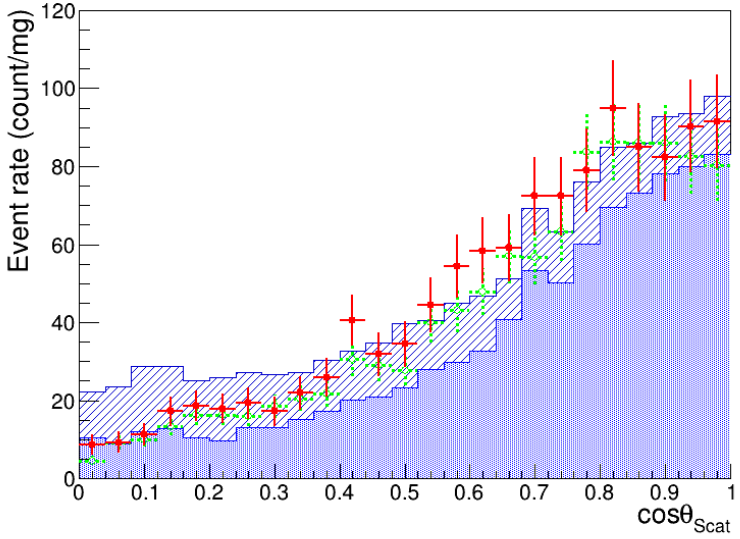
880 keV mono neutron
(T(p n)^{3}He reaction)



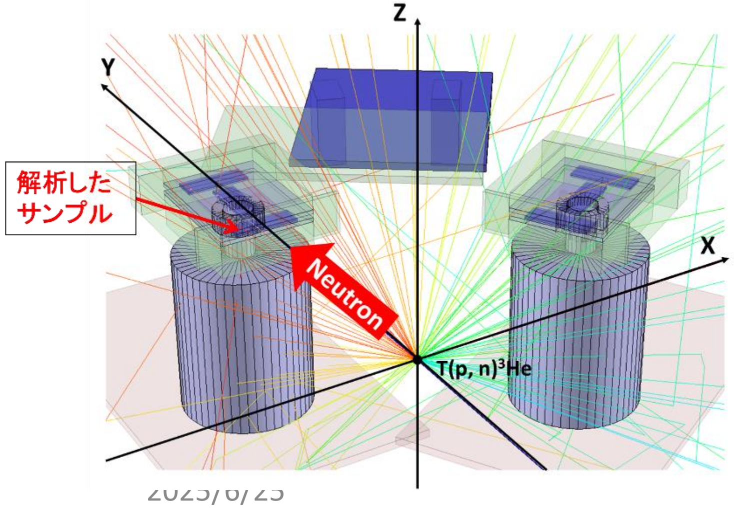
Length



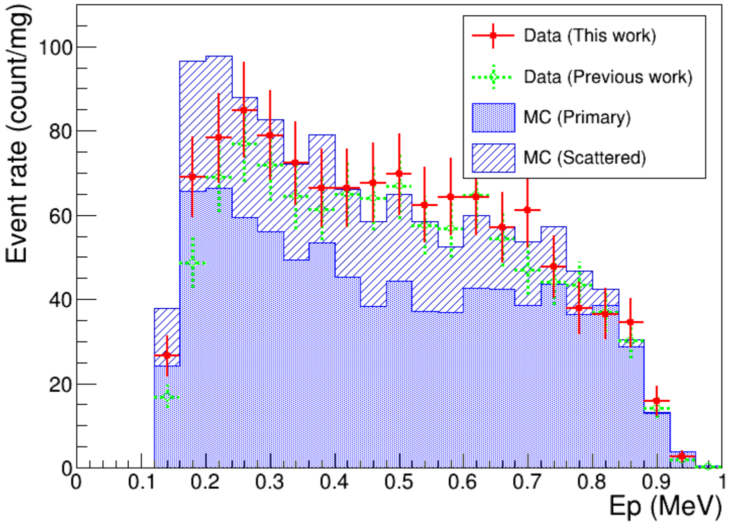
Sactter angle



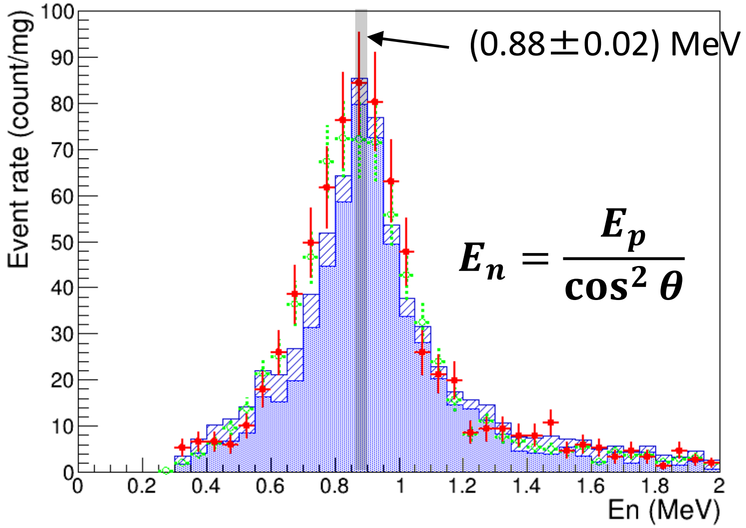
Geant4 simulation



Proton energy

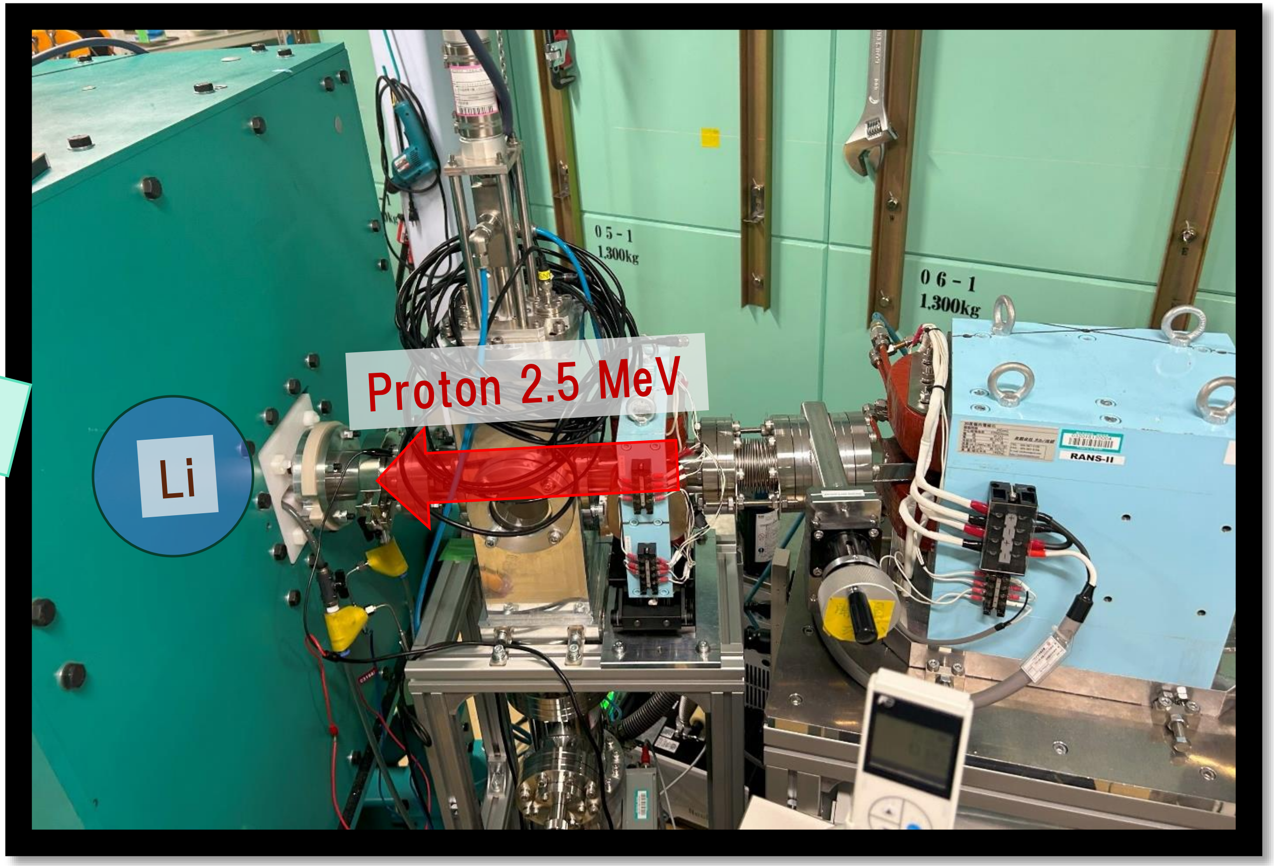


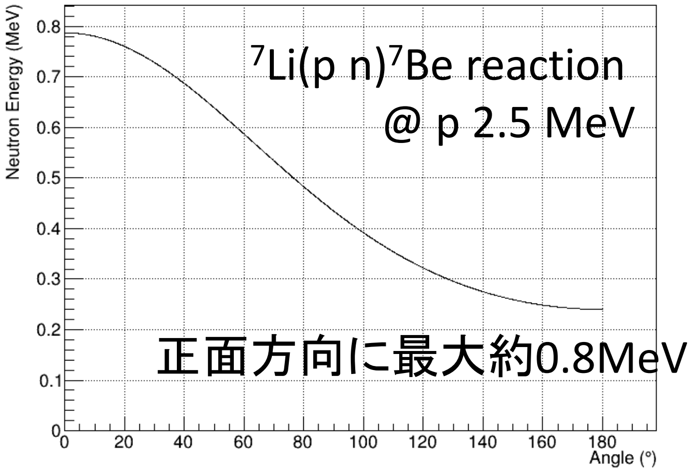
Reconstructed neutron energy



2025/3/25～

RIKEN RANS-Ⅱ : thermal neutron calibaration





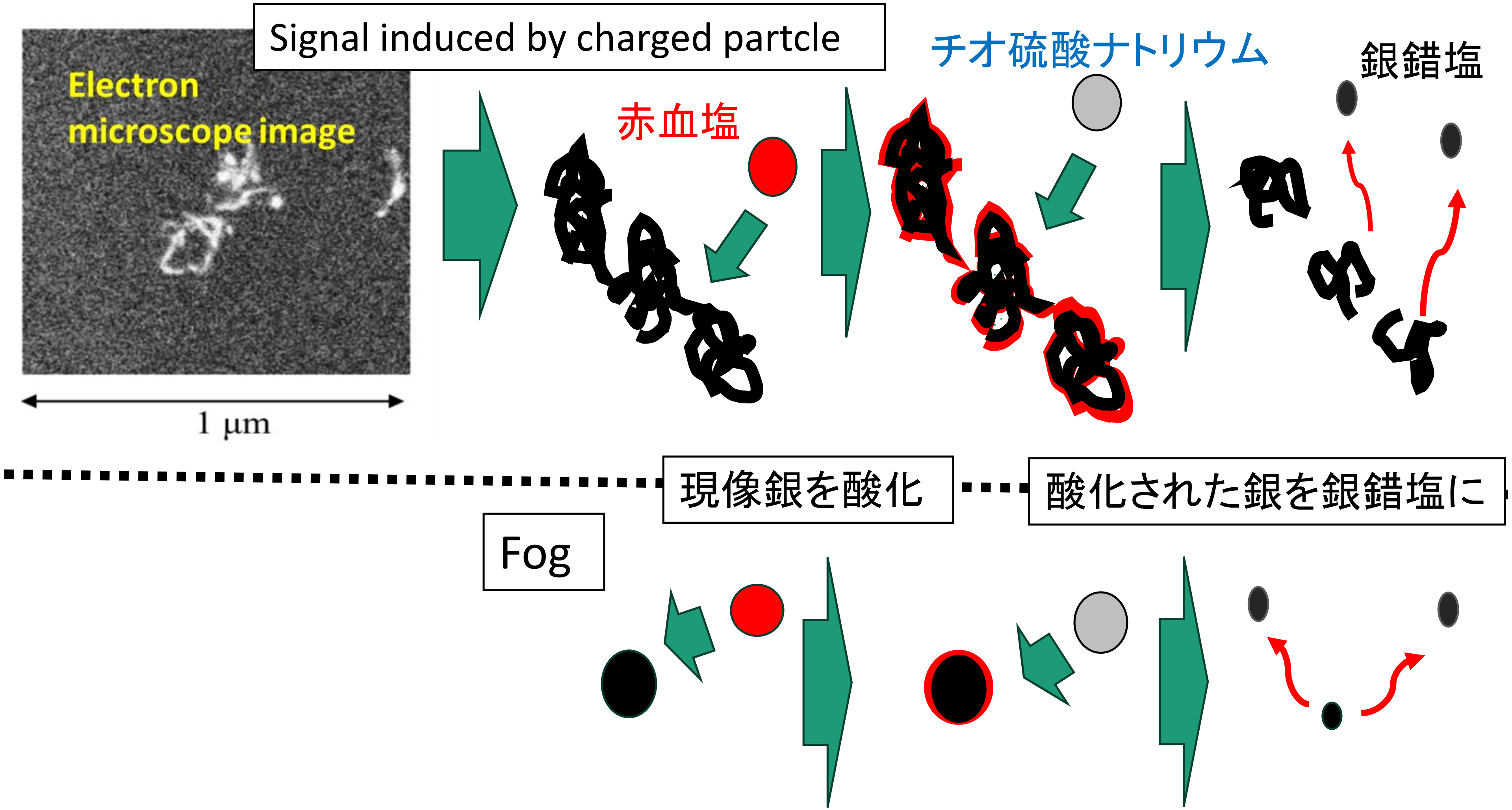
^{7}Li(p n)^{7}Be reaction
@ p 2.5 MeV

正面方向に最大約0.8MeV

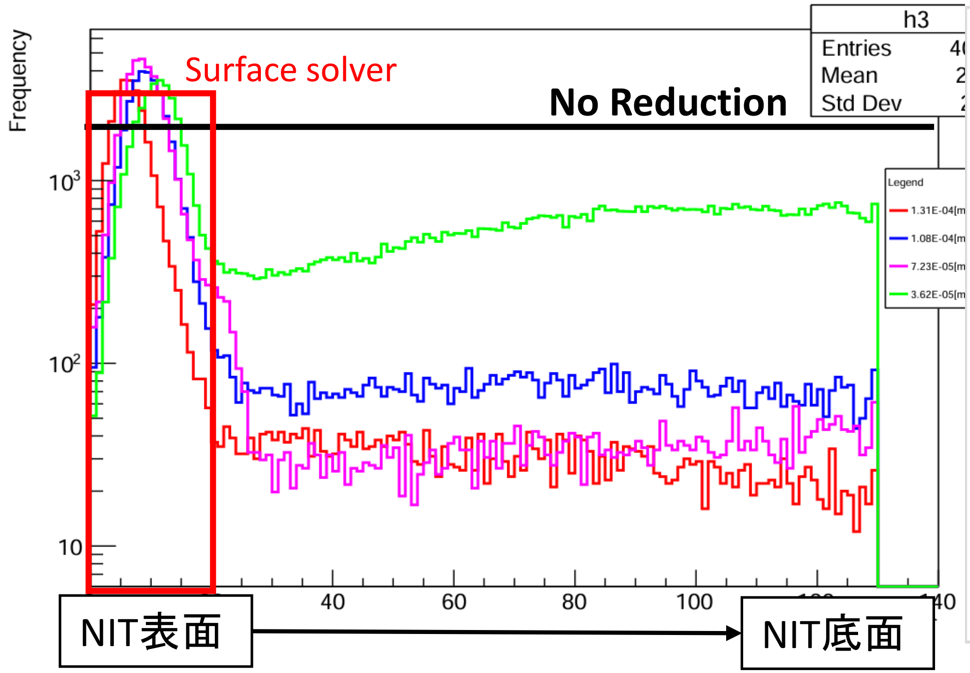
BG erasing method using oxidation process

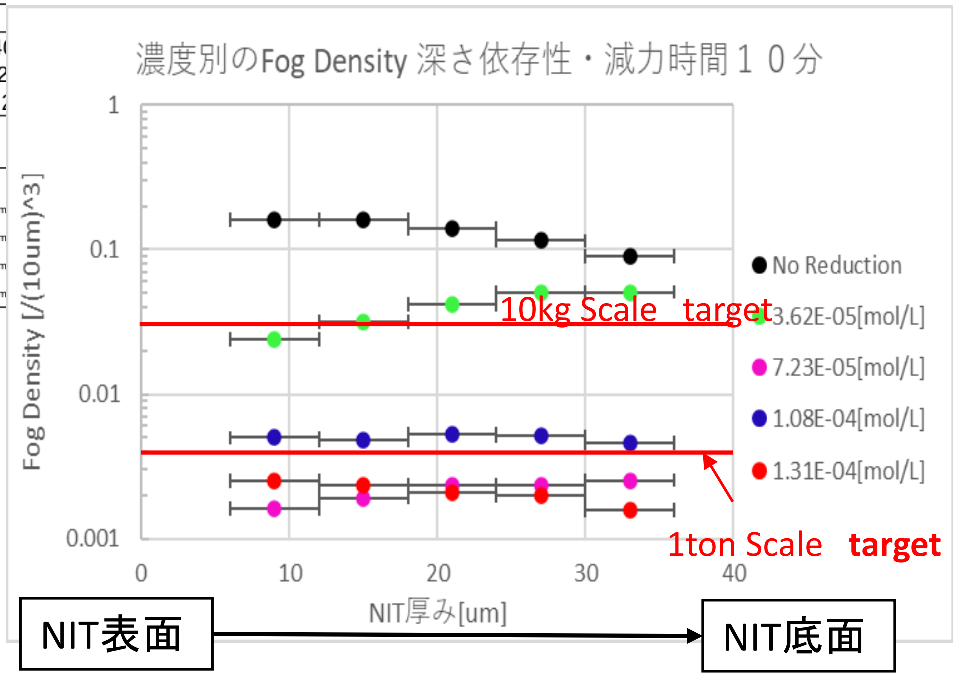
Reaction

$$4Ag + 4K_3Fe(CN)_6 + 6Na_2S_2O_3 \rightarrow 2Ag_2S_2O_3 \cdot 2Na_2S_2O_3 + 3K_4Fe(CN)_6 + Na_4Fe(CN)_6$$



Performance fog reduction





濃度

① $3.62 \times 10^{-5} [mol/L]$
② $7.23 \times 10^{-5} [mol/L]$
③ $1.08 \times 10^{-4} [mol/L]$
④ $1.31 \times 10^{-4} [mol/L]$