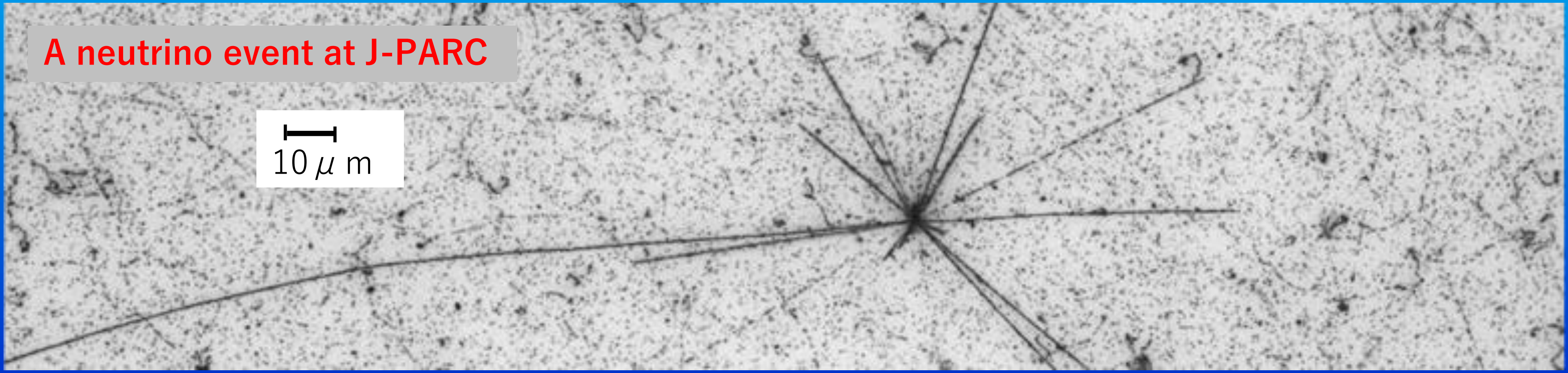
NINJA experiment and novel neutrino activities using nuclear emulsion

Tsutomu Fukuda (IAR/F-lab, Nagoya U.)

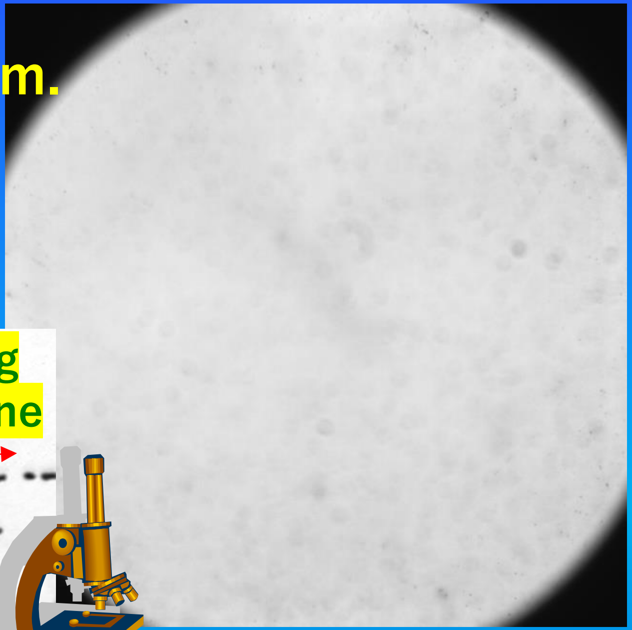


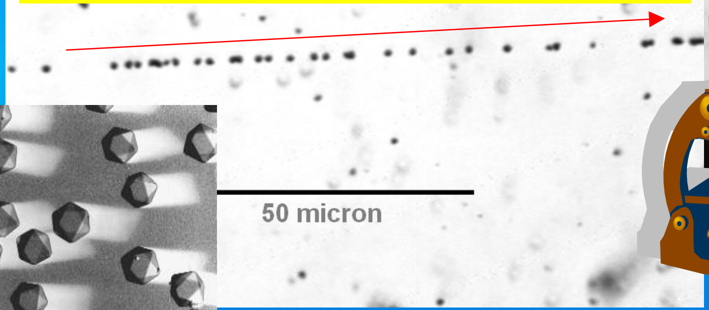
tfukuda@flab.phys.nagoya-u.ac.jp

6th KMI symposium, 5th Mar. 2025

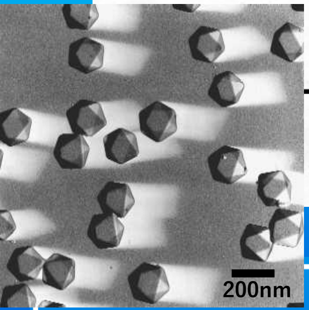
Nuclear emulsion and automatic readout system

- Nuclear Emulsion is a special **photographic film.**
- Signal is amplified by **chemical process.**



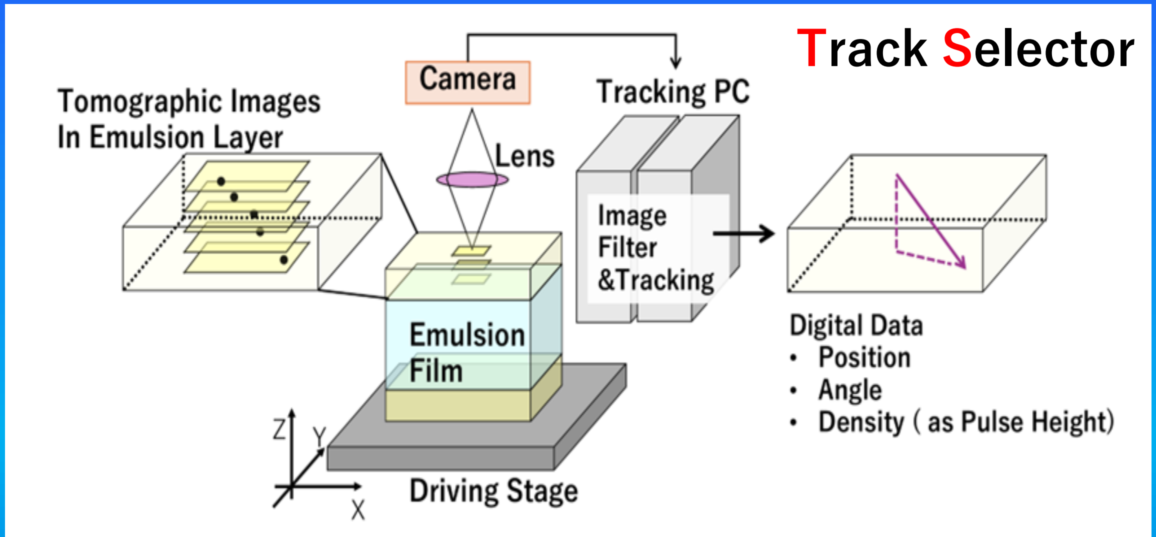


Recorded as silver grains along the particle passing through line

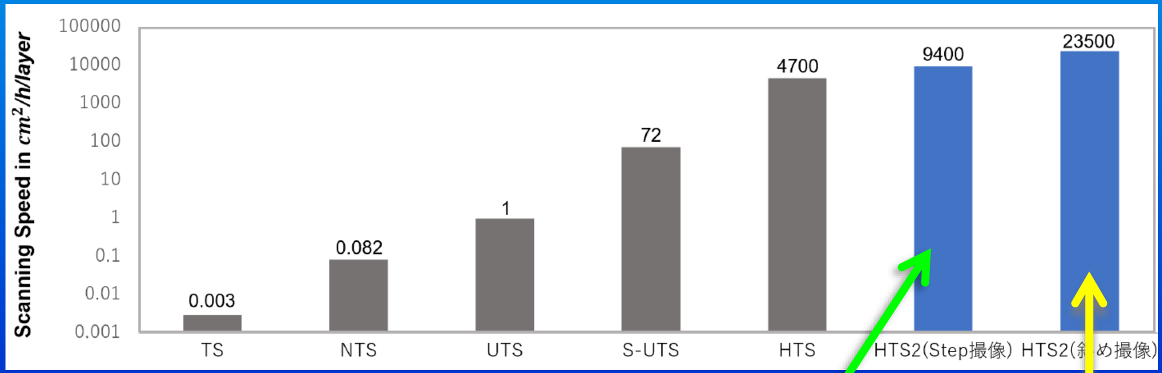


	Merit	Image detection
Film camera	**High resolution**	Sliver halide (Photochemical reaction)
Digital camera	Real time	CCD, CMOS (Photoelectric conversion)

Automatic track scanning system



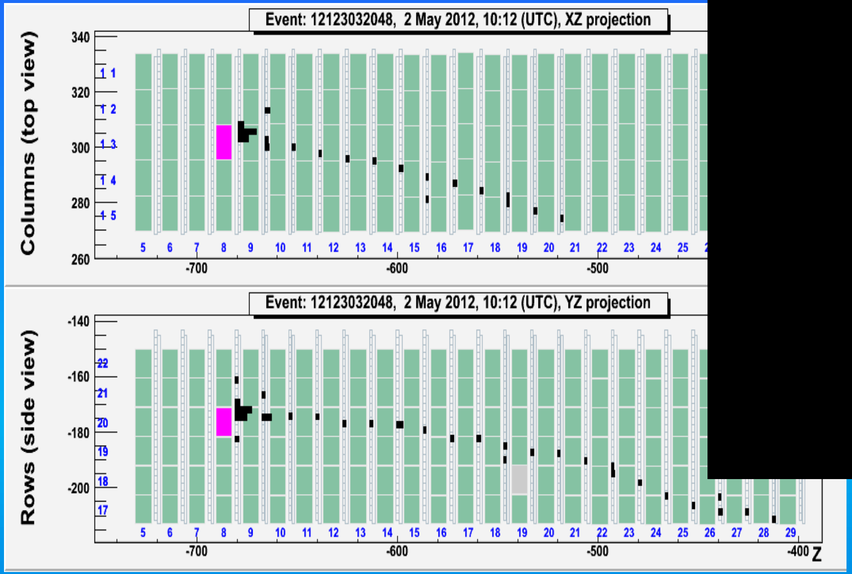
Improvement of Scanning speed in 40 years



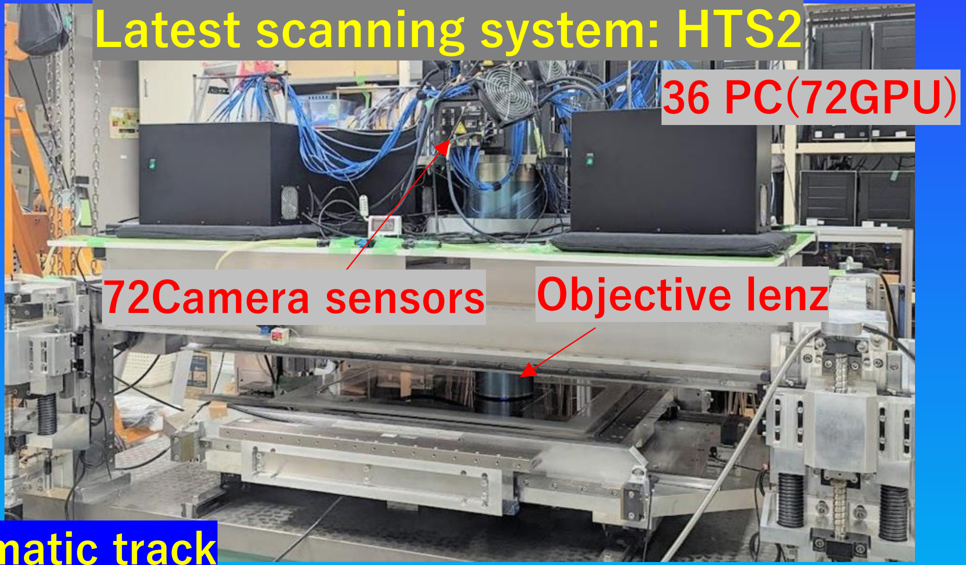
Current Speed Next step

Neutrino experiments with nuclear emulsion

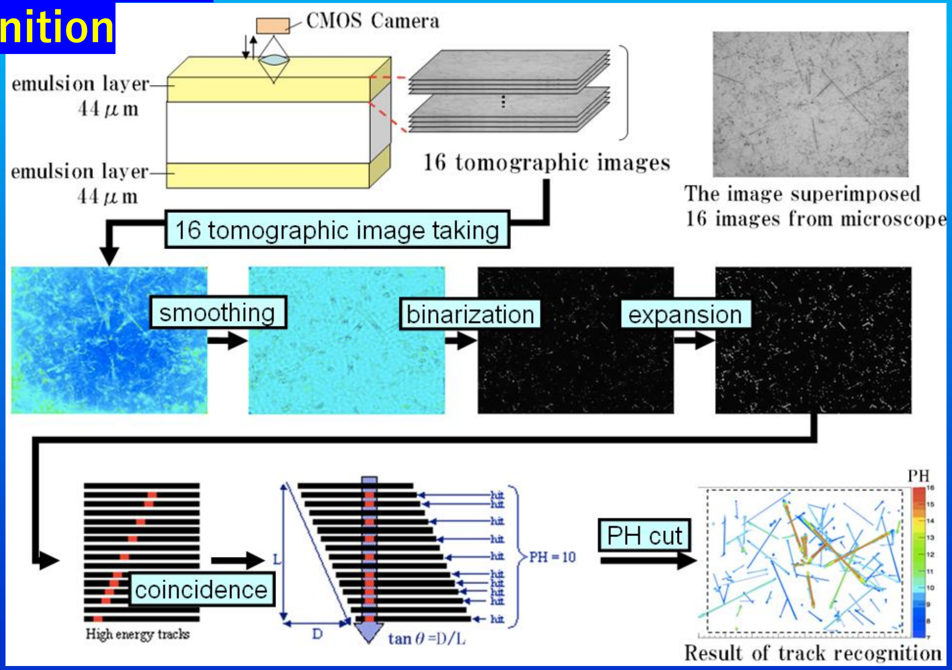
- Accelerator based experiments
  → Emulsion-Counter Hybrid analysis



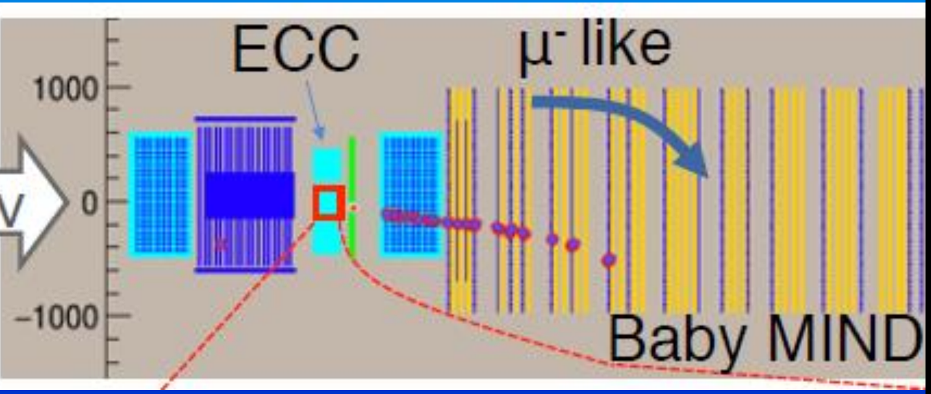
OPERA

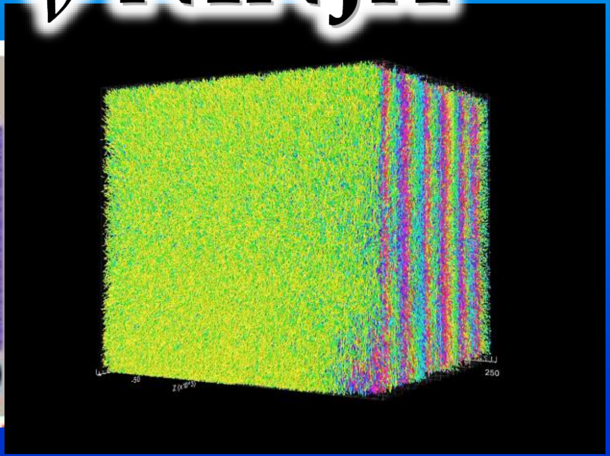


Automatic track recognition



NINJA

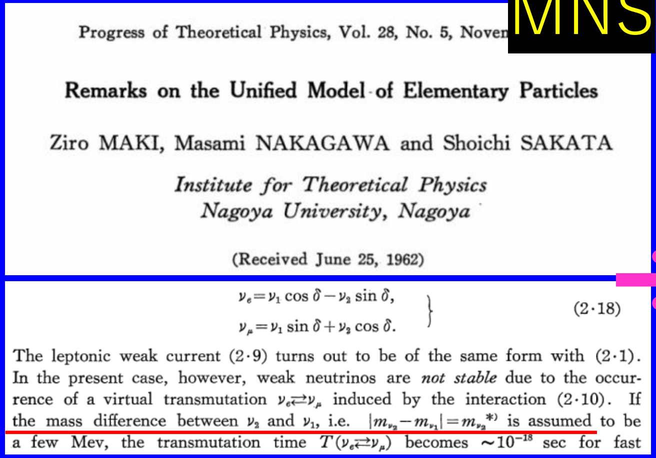




Neutrino oscillation

- First experimental result beyond the standard model in the particle physics

MNS



Progress of Theoretical Physics, Vol. 28, No. 5, Nover

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

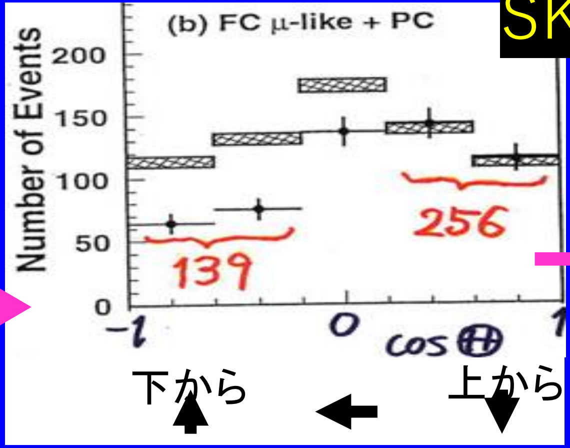
(Received June 25, 1962)

$$\nu_e = \nu_1 \cos\delta - \nu_2 \sin\delta, \quad \nu_\mu = \nu_1 \sin\delta + \nu_2 \cos\delta. \qquad (2\cdot18)$$

The leptonic weak current (2·9) turns out to be of the same form with (2·1). In the present case, however, weak neutrinos are *not stable* due to the occurrence of a virtual transmutation $\nu_e \rightleftarrows \nu_\mu$ induced by the interaction (2·10). If the mass difference between ν_2 and ν_1, i.e. $|m_{\nu_2} - m_{\nu_1}| = m_{\nu_2}{}^{*)}$ is assumed to be a few Mev, the transmutation time $T(\nu_e \rightleftarrows \nu_\mu)$ becomes $\sim 10^{-18}$ sec for fast

Theory (1962)

SK

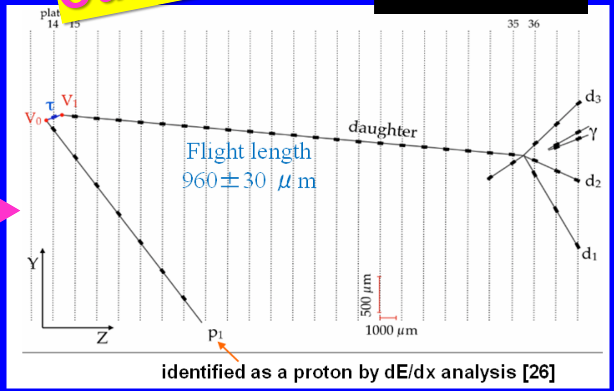


First experimental evidence (1998)

SNO,MACRO, K2K, KamLAND, MINOS, T2K, ANTARES, IceCube, …

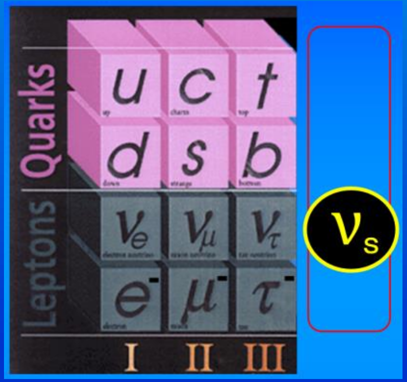
Our work

OPERA



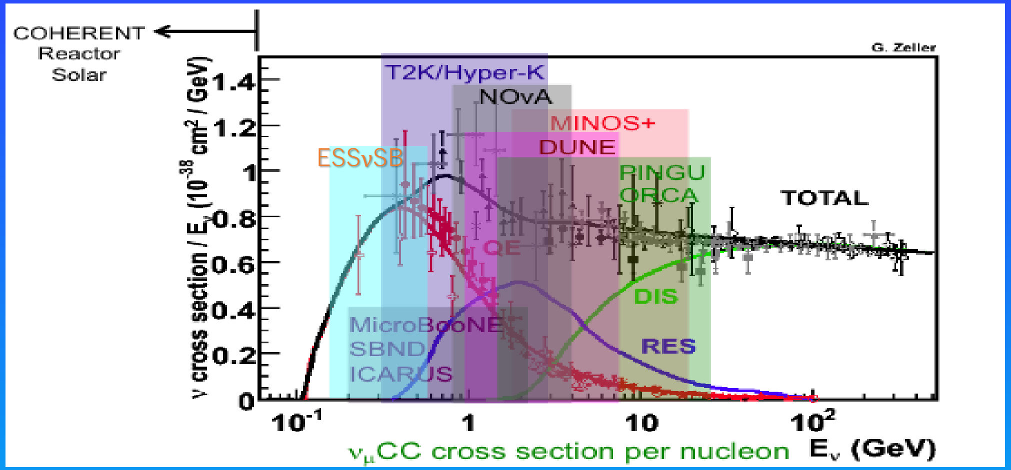
Final demonstration (2015)

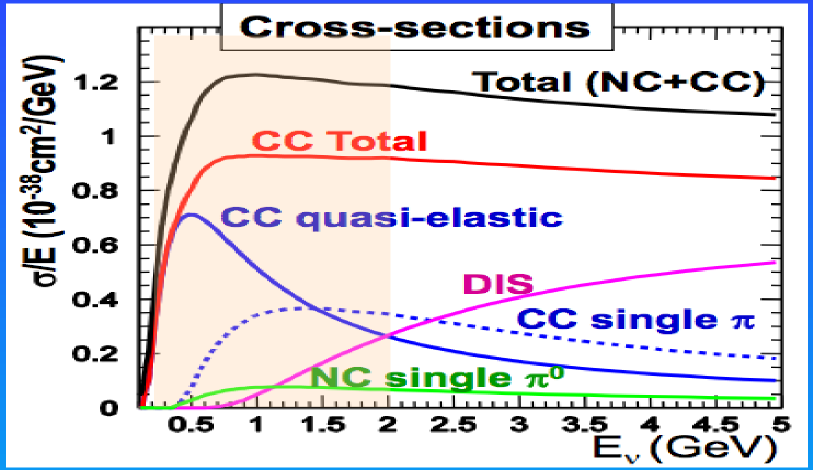
Precise measurement of neutrino oscillation
→ Open the door to new physics of the particle physics and the universe.



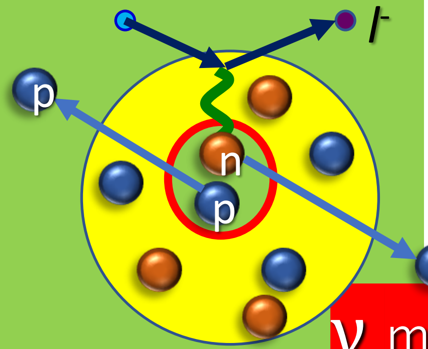
Sterile neutrino!?
→ fourth generation?
one of dark matter?

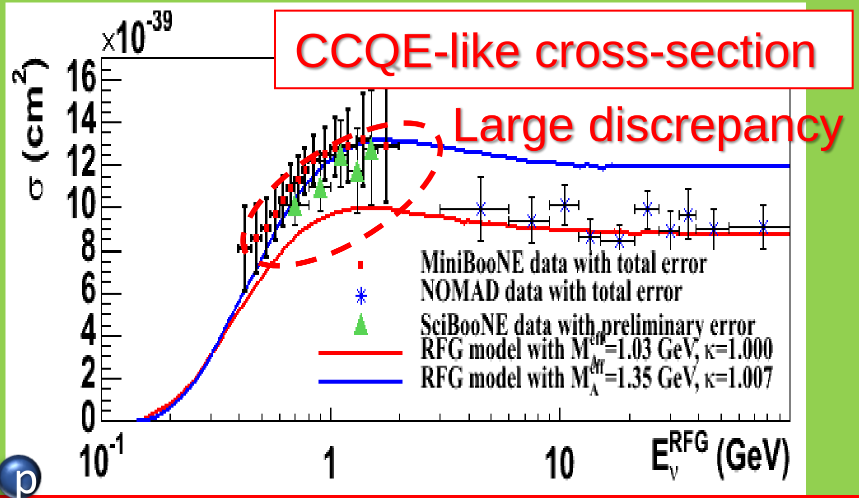
Neutrino physics on sub-multi GeV



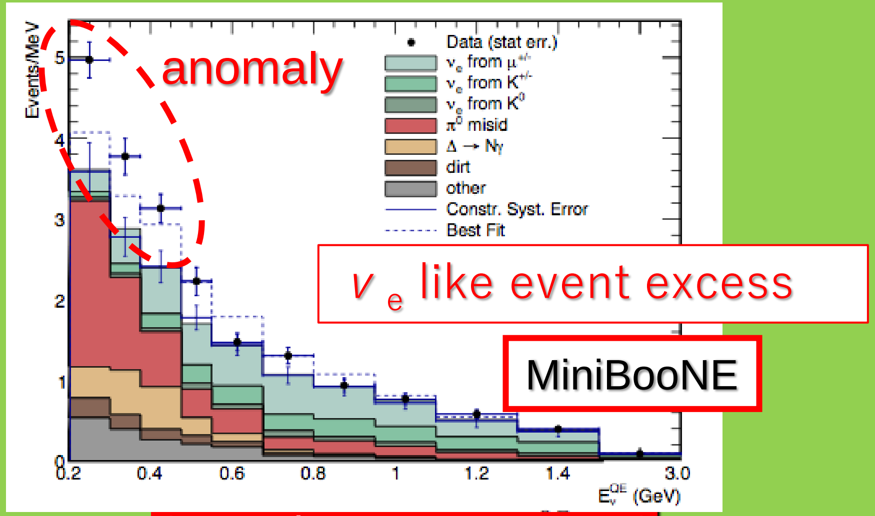


Most current and future neutrino oscillation experiments are implemented in this energy region





ν multi-nucleon (CC2p2h) interaction?



Sterile neutrino ?

A better understanding of ν-nucleus interactions is important for the precise measurement of ν oscillations.

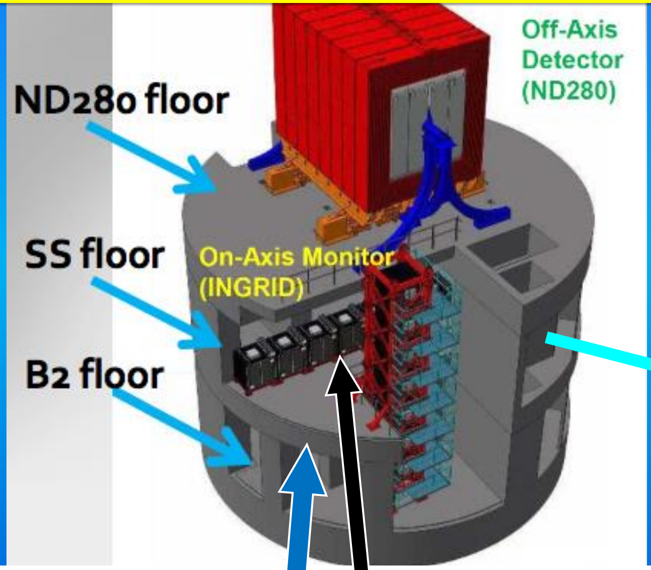
NINJA Experiment

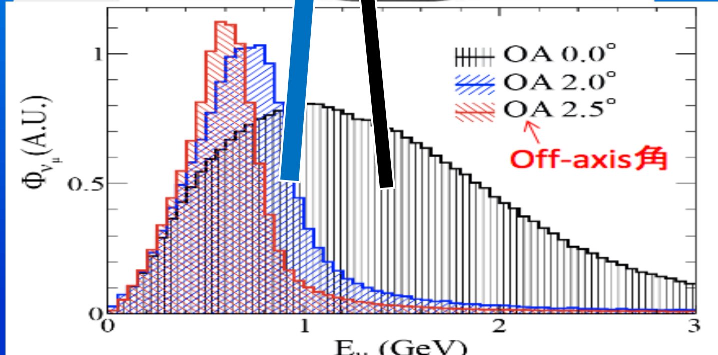
Neutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator

- Precise measurement of ν_μ-nucleus CC cross-sections in Sub-Multi GeV region
- Electron neutrino cross-section measurement, Sterile neutrino search

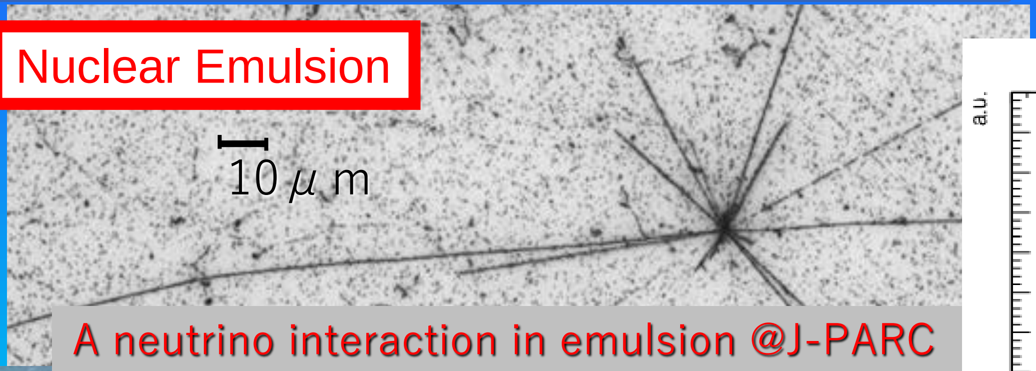
3 countries, 13 institutes

J-PARC Neutrino monitor building

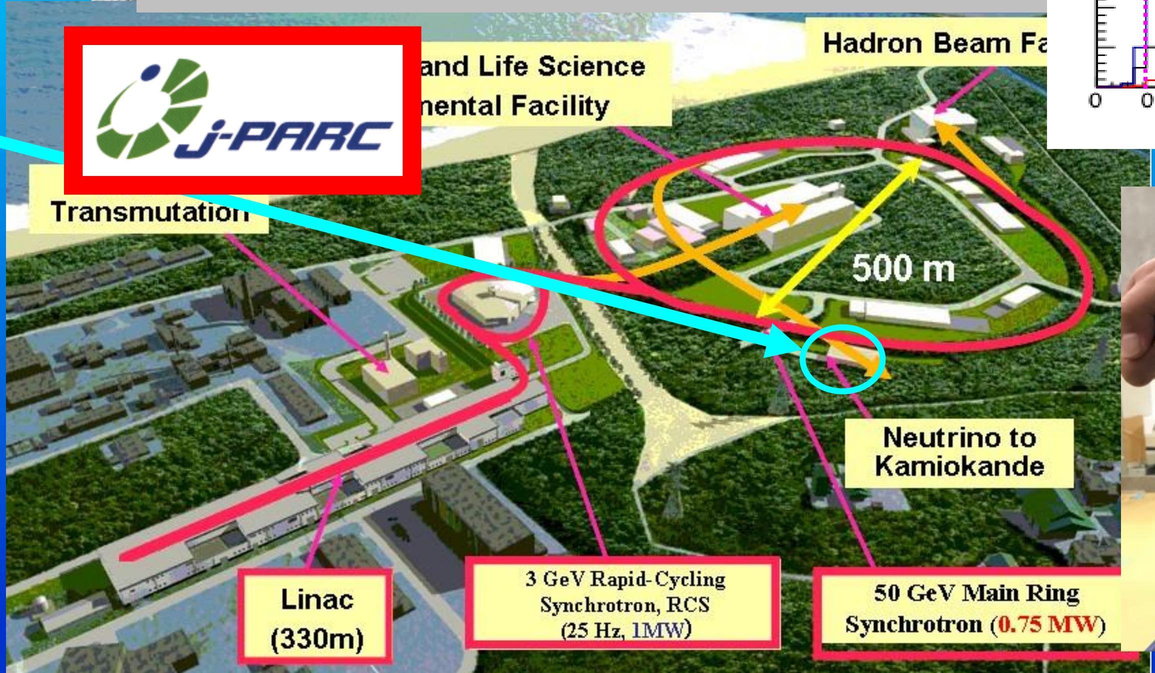


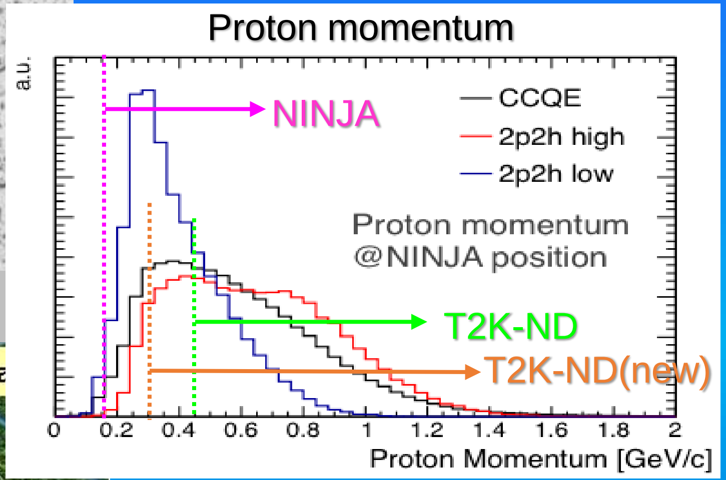


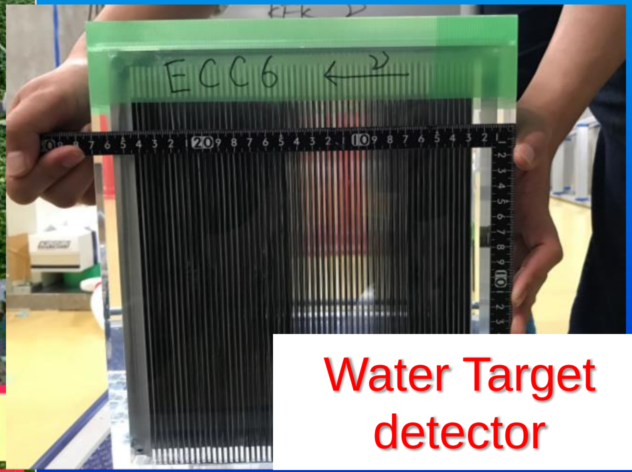
Nuclear Emulsion



A neutrino interaction in emulsion @J-PARC

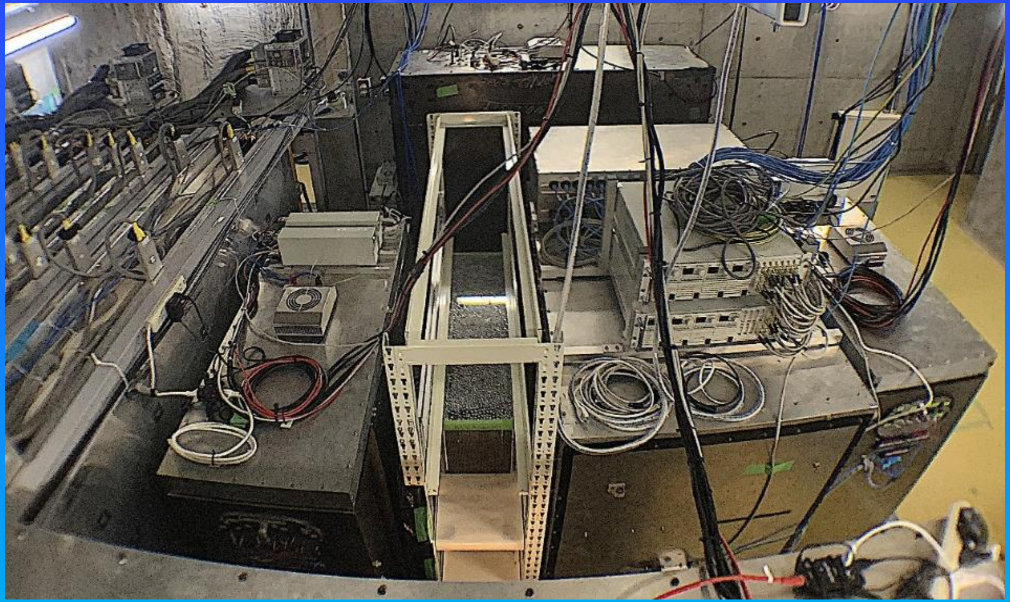


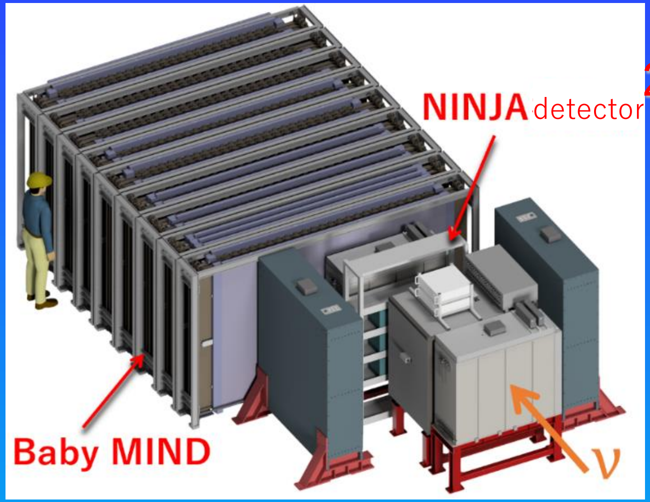




Water Target detector

NINJA Physics Run (E71)



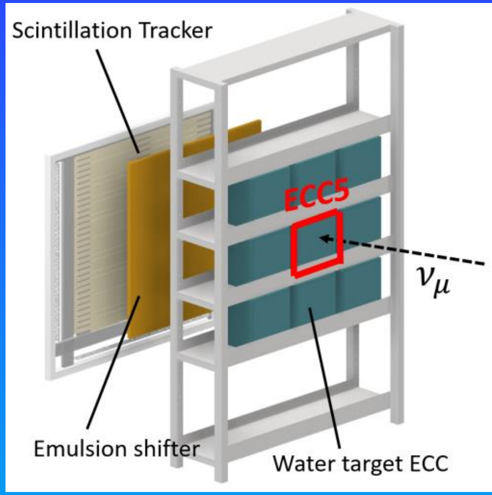


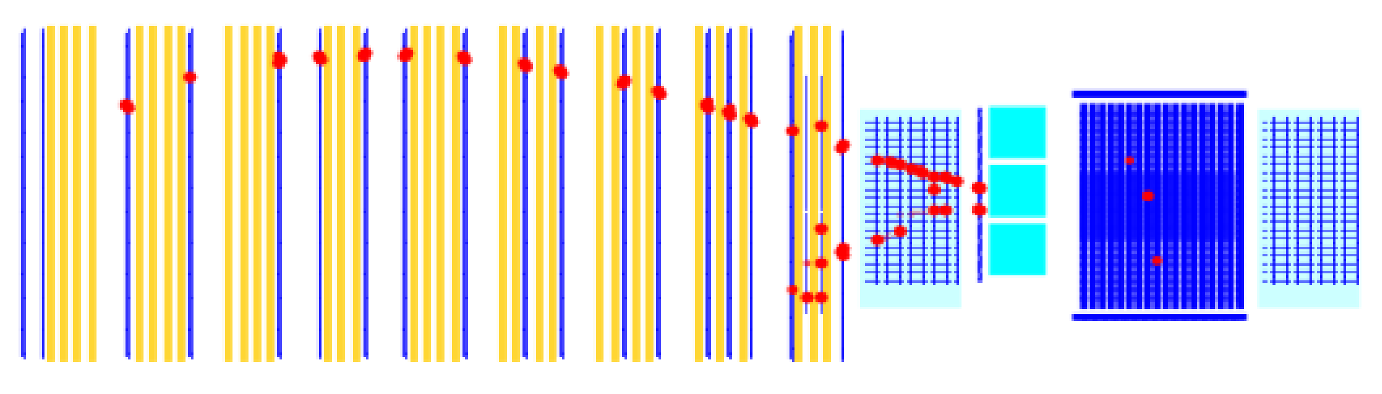
250kg Target

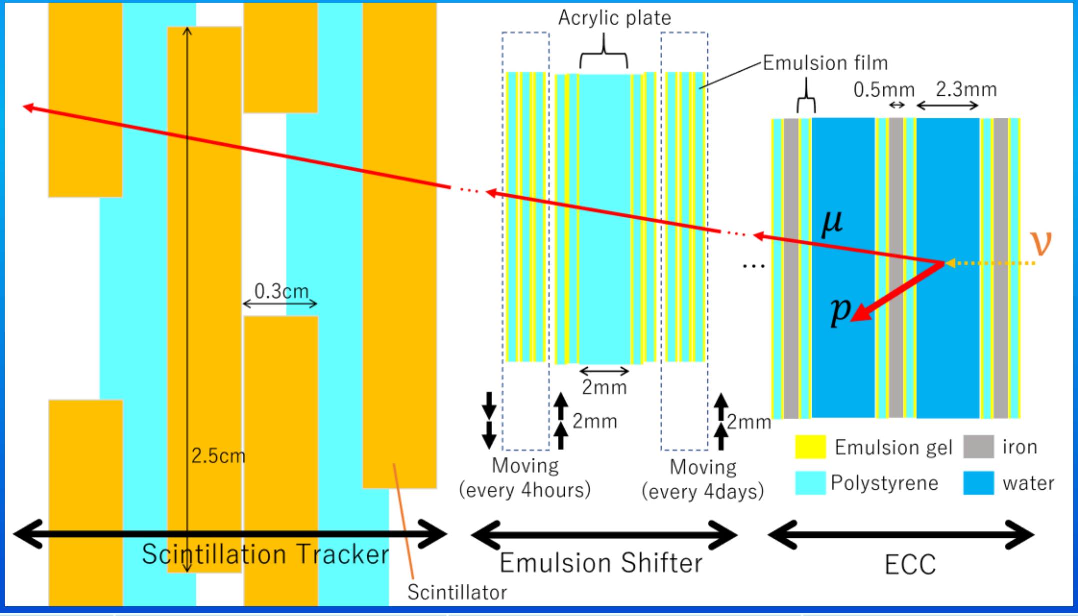
H_2O : 75kg
Fe : 130kg
CH : 15kg
em : 30kg

Film 130m^2

5,000 events







E71a : 2019 Nov. – 2020 Feb.
E71b : 2023 Nov. – 2024 Feb.
E71c : 2025 Nov. – (plan)

Total POT: 10^{21}

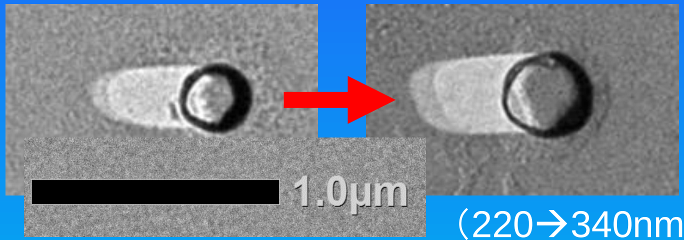
	Scintillation Tracker	Emulsion Shifter	Water ECC
Time resolution	10 nsec level	4 hour	--- (100 day)
Position resolution	2.1 mm	1 μm level	1 μm level

NINJA

Latest Physics Run(E71b)

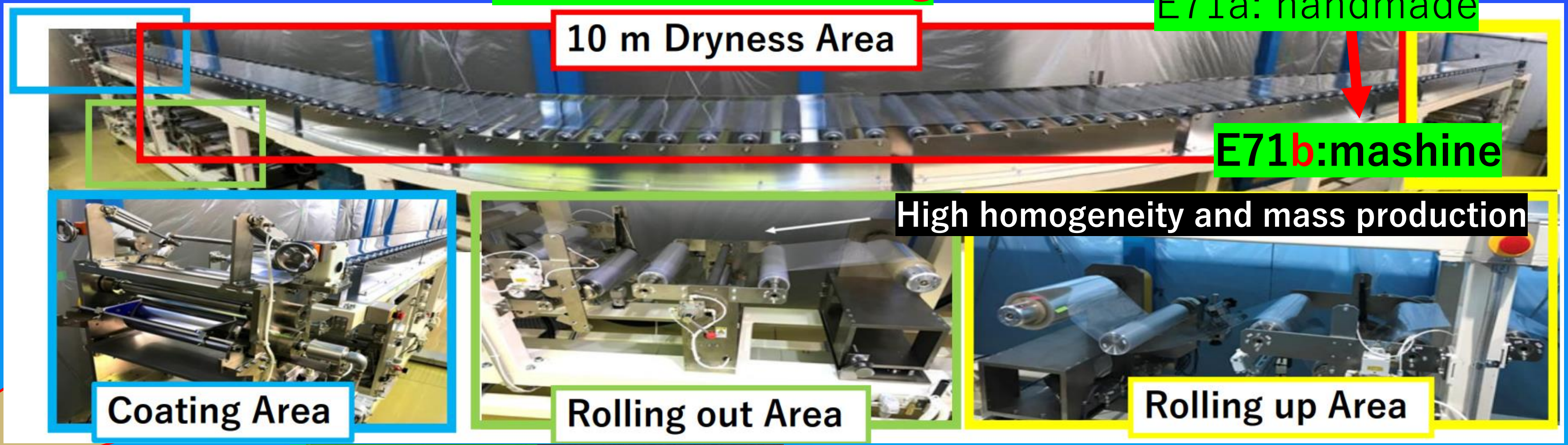
Emulsion films production

Refreshable large crystal emulsion

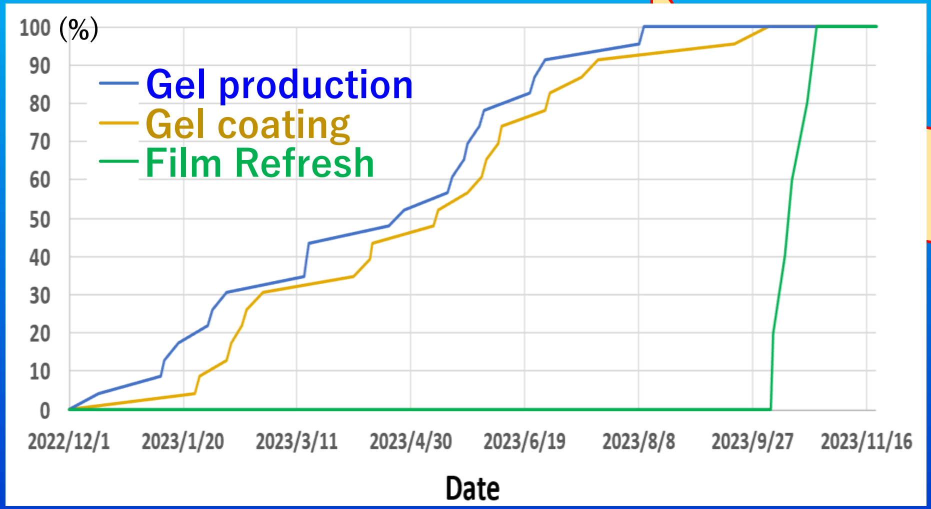


(220→340nm)

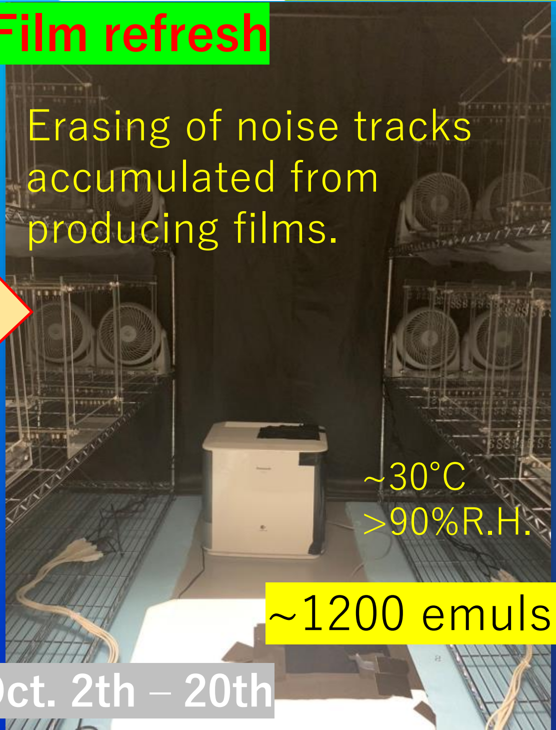
Emulsion film coating



Film preparation



Film refresh



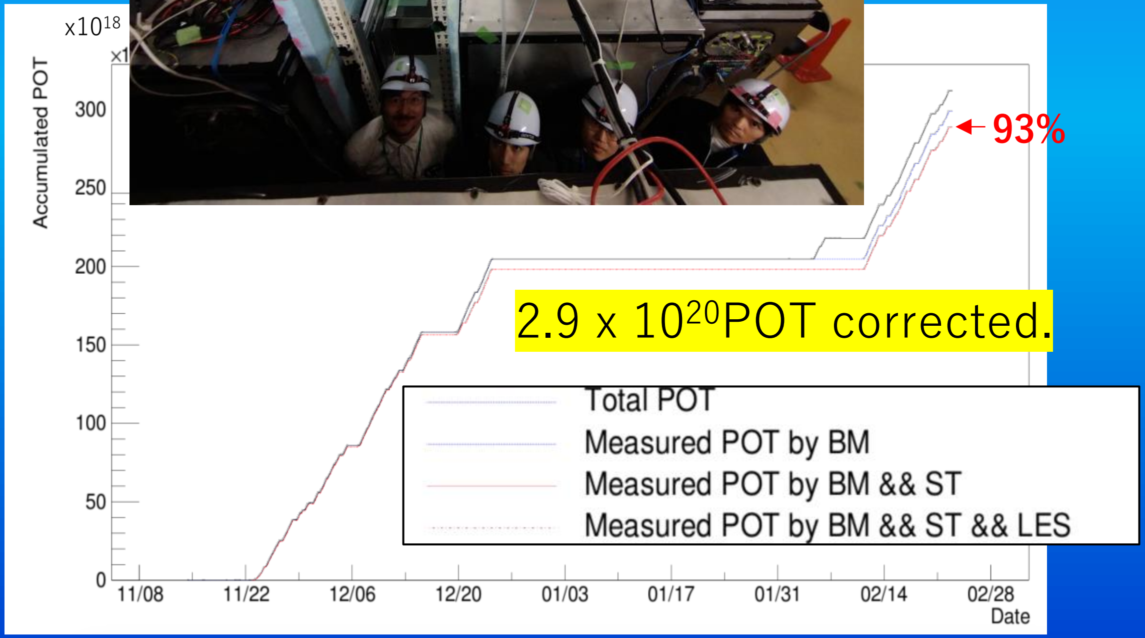
Production of Water ECCs

NINJA

Latest Physics Run(E71b)

We successfully conducted our second physics run! (2023-2024)

Neutrino beam exposure (Nov.→Feb.)



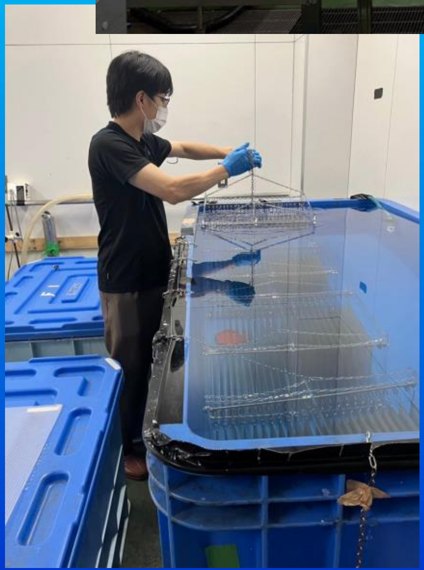
← 93%

2.9×10^{20} POT corrected.

Nov. 2023 Feb. 2024

93% of neutrino beam exposure are effective.

Development of emulsion films @Gifu Univ.

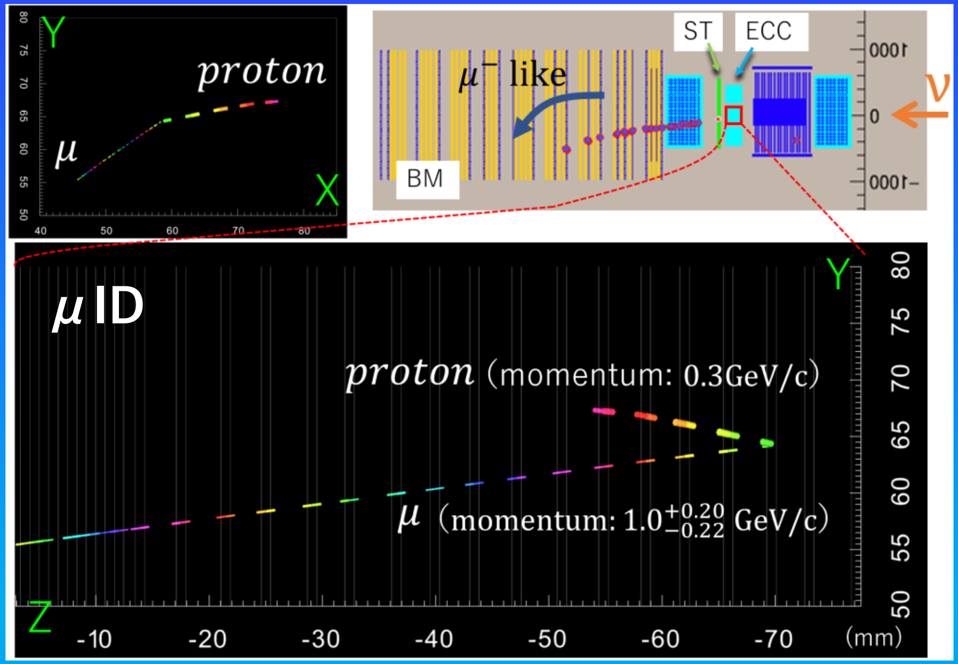


Completed without a single mistake!

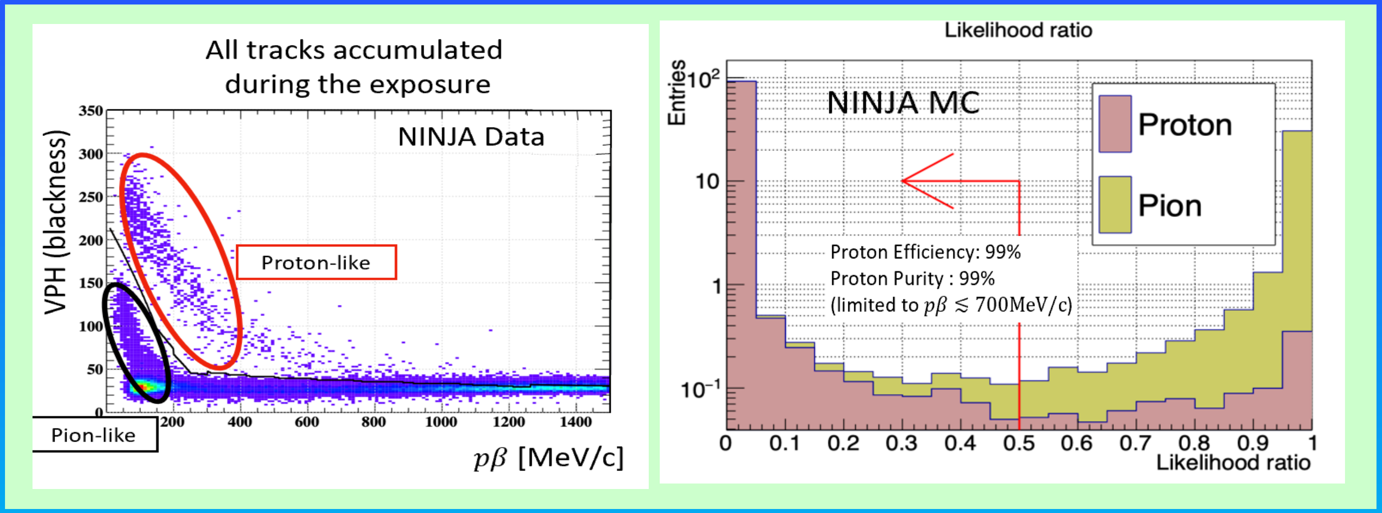
Mar. 2024 Apr. 2024

→ Emulsion scanning in progress

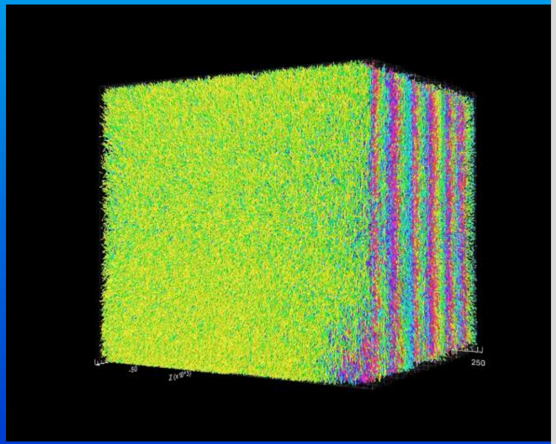
E71 Neutrino event analysis

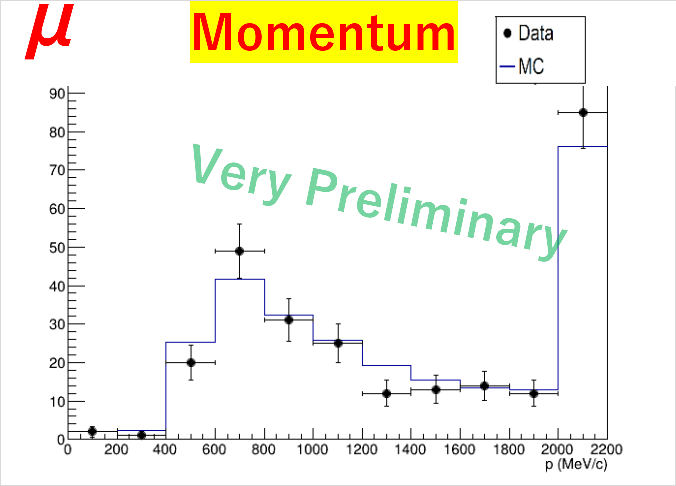


PID

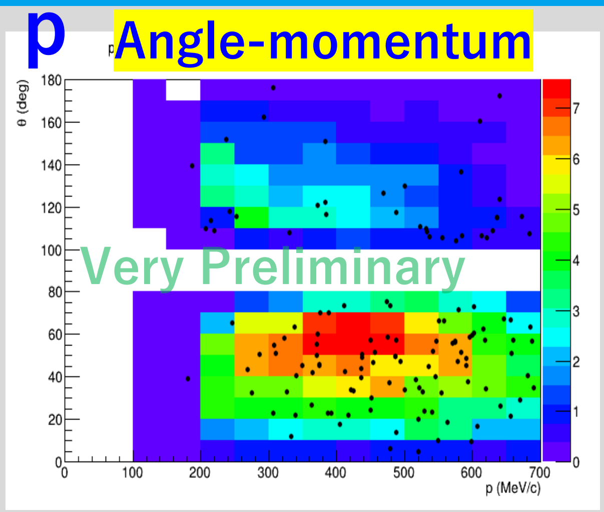


Detailed analysis is in progress → 1st Publication in 2025

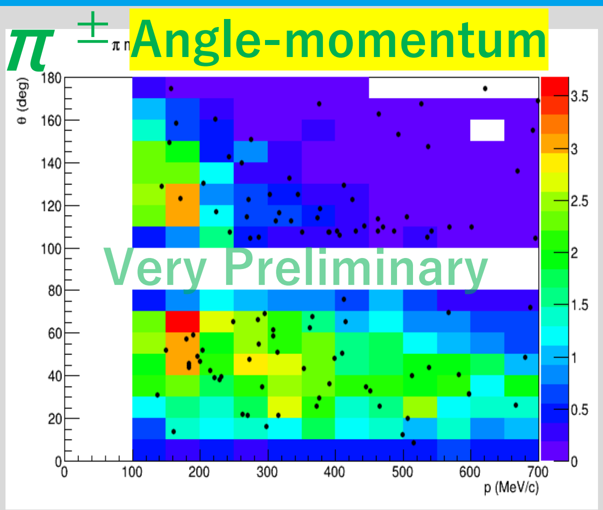




Normalized by # of events



Normalized by # of events

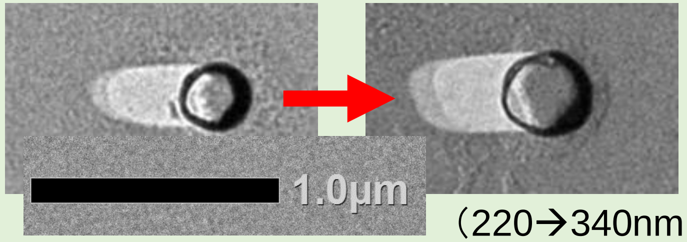


Normalized by # of events

Technical improvements

Emulsion gel

①：Refreshable large crystal emulsion

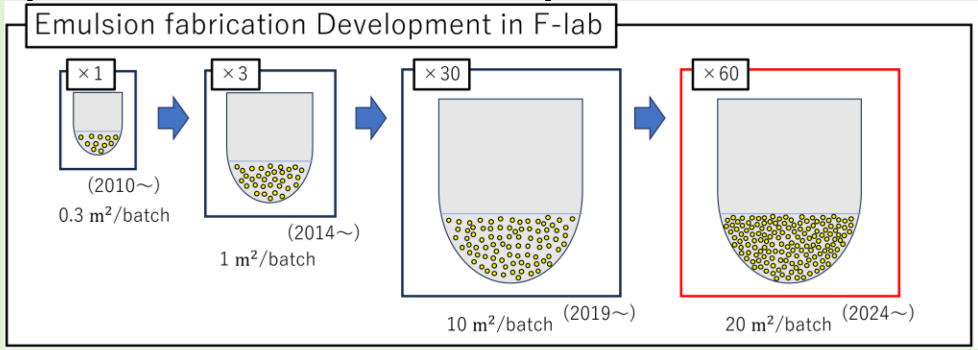


Enough sensitivity
Good noise rejection

(220→340nm)

Doped with chemicals (5MBT) to improve noise delete performance.

②：Development of recipes that enable emulsion production at twice the speed.

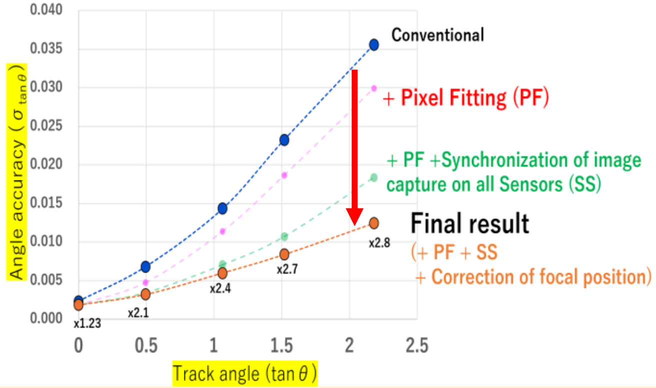


Initial performance of sensitivity and noise level is good.
→ Long-term characteristic are currently testing.

Scanning technique in HTS2

①：High speed and good angle accuracy

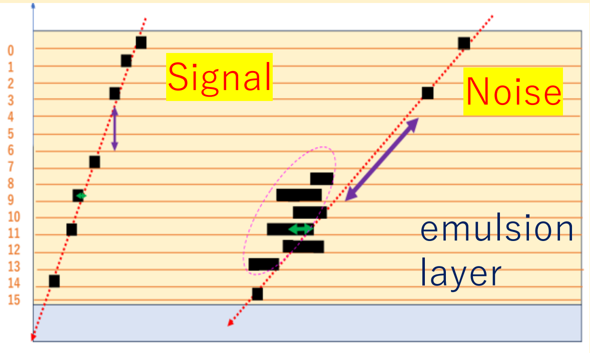
# of sensors	period	Task
1/72	2022 Dec. ~	Stage moving, Sensor response, etc.
24/72	2024 Jan. ~	Multi sensor test
72/72	2024 Apr. ~	Full sensor test Angle accuracy
72/72	2024 Sep. ~	Operation start

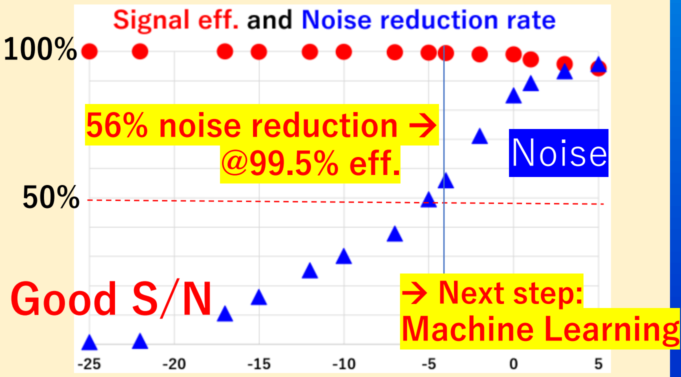


②：New Track Ranking（Fine S/N tracking）

Image analysis → 3 new selection parameters

[i]grain fitting [ii]# of grains around tracks [iii]maximum gap of grains

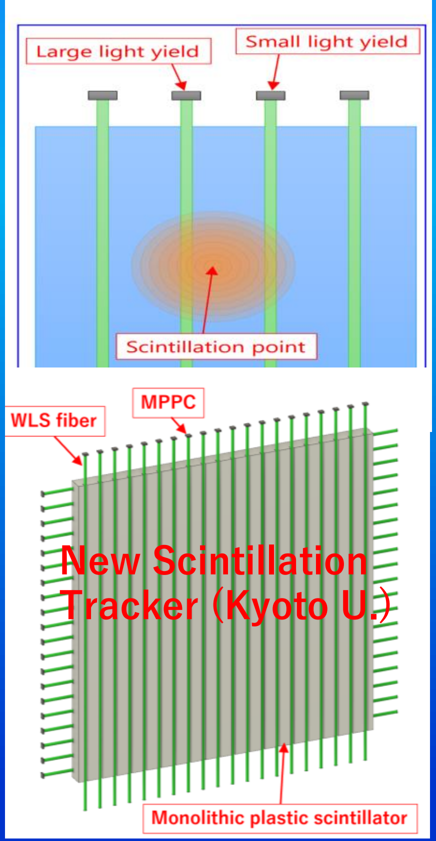




Future prospects

E71c

	Period	POT
1st :E71a	2019-2020	4.8×10^{20}
2nd :E71b	2023-2024	2.9×10^{20}
3rd :E71**c**	2025 fall-	**> 2.3×10^{20}**



Letter of Intent:
Precise measurement of neutrino interactions and sterile neutrino search with nuclear emulsion detector at J-PARC

S. Aoki[a], D. Barčot[b], T. Fukuda[c,*], M. Ghosh[b], S. Han[d], T. Hayakawa[c], Y. Hayasaka[c], Y. Hayato[e], L. Halić[b], Y. Hirobe[c], H. Inamoto[c], G. Iwamoto[c], S. Ito[f], C. Jesús-Valls[g], A. Kasumi[c], T. Katori[h], T. Kawahara[c], T. Kawanago[c], T. Kikawa[d], B. Kliček[b], H. Kobayashi[c], R. Komatani[c], M. Komatsu[c], T. Matsuo[c], S. Mikado[i], A. Minamino[f], Y. Morimoto[c], K. Morishima[c], Y. Nakamura[c], T. Nakano[c], T. Nakaya[d], N. Naganawa[c], T. V. Ngoc[d], S. Ogawa[j], H. Oshima[e], N. Otani[d], H. Rokujo[c], O. Sato[c], T. Sato[k], H. Shibuya[l], K. Sugimura[c], L. Suzui[c], A. Suzuki[a], M. Suzuki[f], I. Usuda[c], S. Yamamoto[c], M. Yoshimoto[m],
(The NINJA Collaboration)

December 9, 2024

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[d]Kyoto University, Kyoto 606-8502, Japan
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[g]Kavli IPMU (WPI), The University of Tokyo, Kashiwa 277-8583, Japan
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[m]RIKEN, Wako 351-0198, Japan

Abstract

The **NINJA** experiment stands for **N**eutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator. It aims to conduct precise measurements of neutrino interactions in the Sub-Multi GeV energy range and to search for sterile neutrinos using an emulsion-counter hybrid detector with nuclear emulsion as the main detector and neutrino beams produced by the J-PARC accelerator. Thus far, the NINJA experiment has conducted proof-of-principle tests, test runs, and physics runs, using nuclear emulsion detectors with water and iron targets to measure neutrino interactions. We are now discussing the physics goals for the next decade and the means to achieve them.

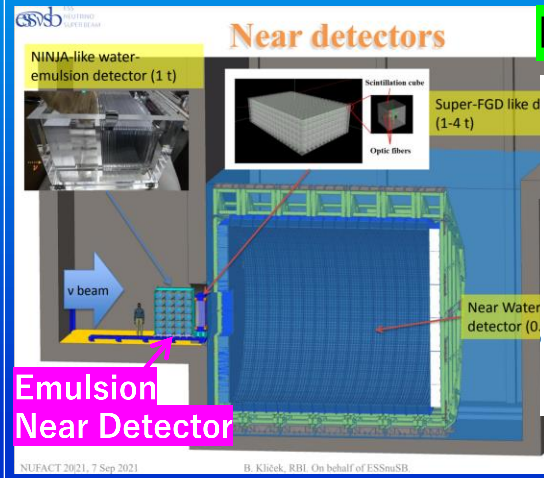
This Letter of Intent (LOI) details several proposed objectives based on the results of previous experiments. These include: 1. Precision measurements of neutrino interactions using water-target nuclear emulsion detectors to provide crucial inputs for long-baseline neutrino oscillation experiments such as T2K, HK and ESSνSB, which uses large water Cherenkov detectors. 2. Measurements of neutrino-nucleon interactions using heavy water-target nuclear emulsion detectors, establishing a foundation for calculating all neutrino interactions. 3. Exploration of sterile neutrinos through high-statistics experiments using heavy targets, such as lead. This LOI presents these objectives in detail and outlines how they can be accomplished.

Keywords: NINJA, neutrino, cross-section, sterile neutrino, nuclear emulsion

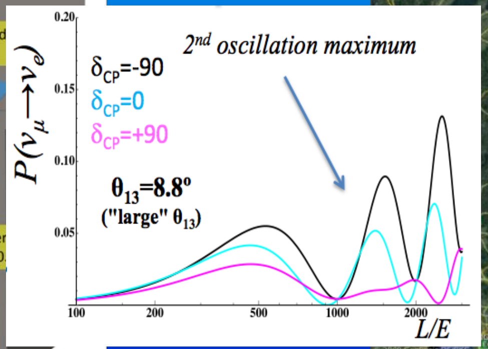
Submitted last Dec.

LOI for next NINJA physics

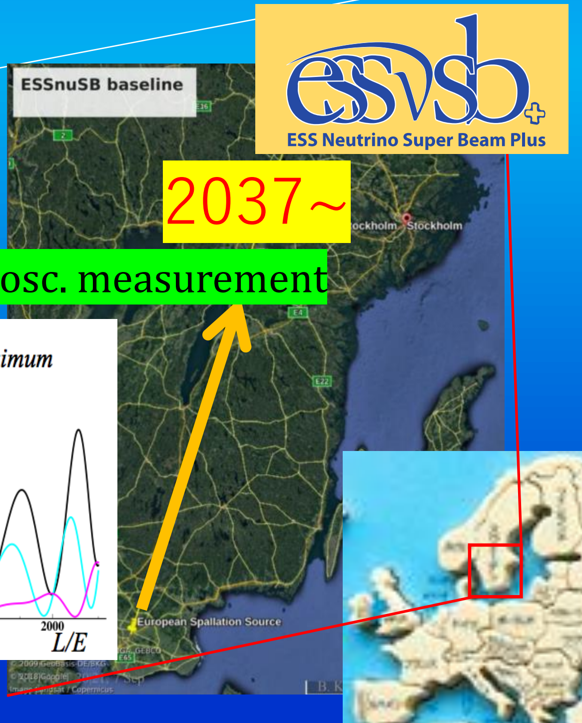
- Water target Run →HK, ESSνSB
- Heavy water target Run →Neutrino-nucleon interactions
- Lead/Iron target Run →ν_e Xsec./Sterile ν search



Post HK/DUNE: ν osc. measurement



2037~



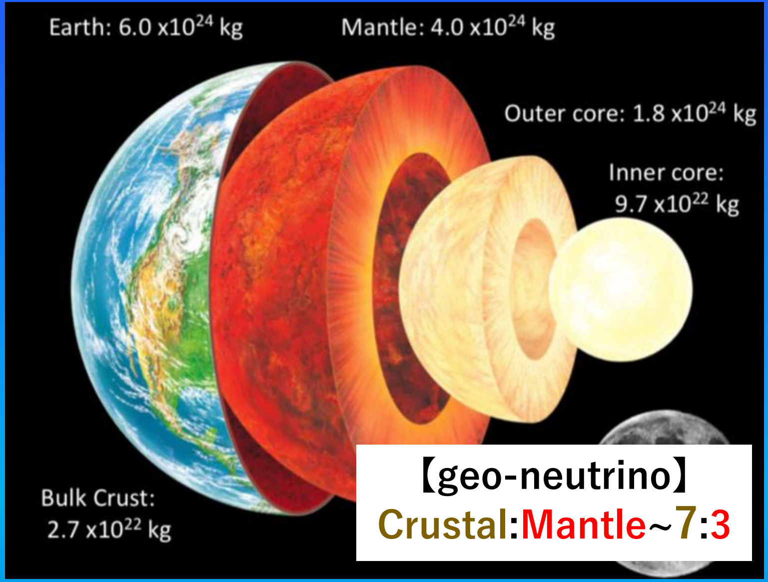
Novel neutrino activities using nuclear emulsion

Toward precise measurements of geo-neutrino

Geo-neutrino from Mantle is important information for the earth science to understand the driving force of mantle convection

that causes

Plate movement
Volcanic activity



Geo-neutrino

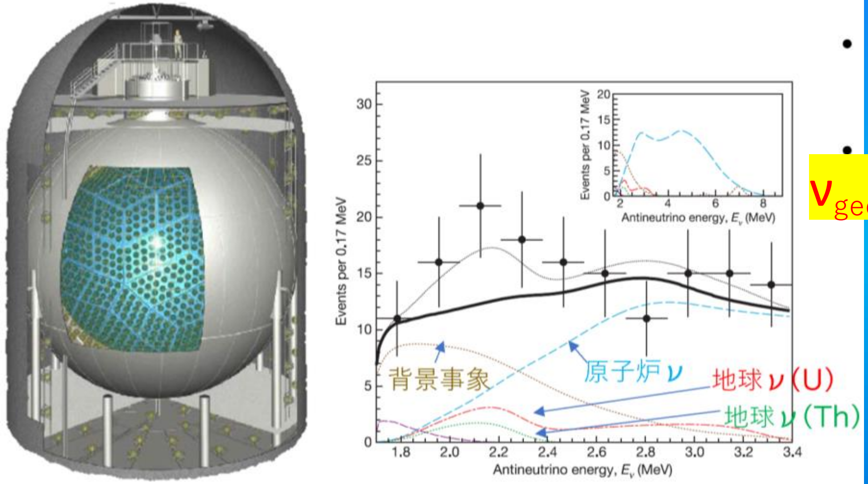
Anti-electron neutrinos from the decay of radioactive isotopes in the earth ($\overline{\nu}_e$). mainly,

$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6e^- + 6\overline{\nu}_e + 51.7MeV$

$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\overline{\nu}_e + 42.7MeV$

α decay β decay Earth's heat source

First detection of geo-neutrinos by KamLAND (2005)

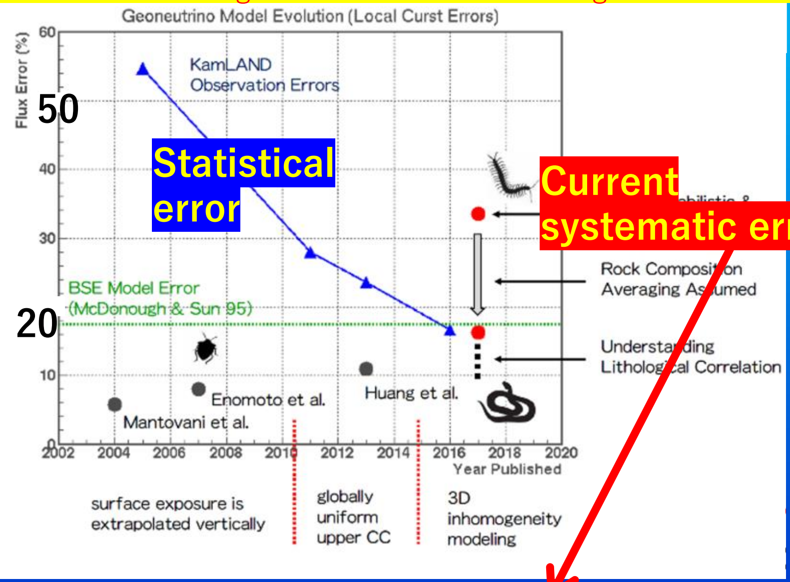


KamLAND collab. T. Araki et al., Nature 436, 499-503 (2005).

Current situation

20 years of observations, statistical accuracy has improved, reaching a level where geoscientific insights can be obtained.

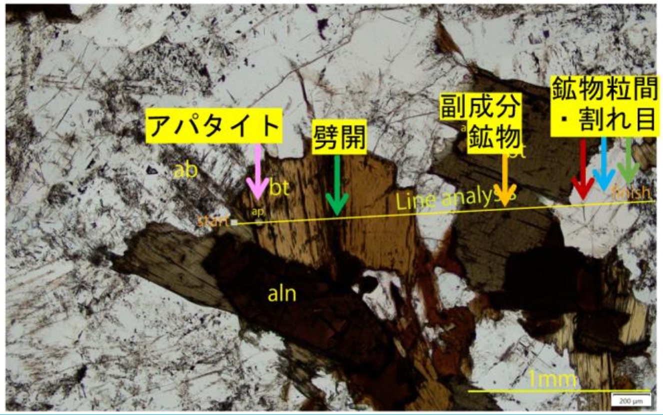
ν_{geo} (Mantle) = ν_{geo} (KamLAND) – ν_{geo} (Crustal)

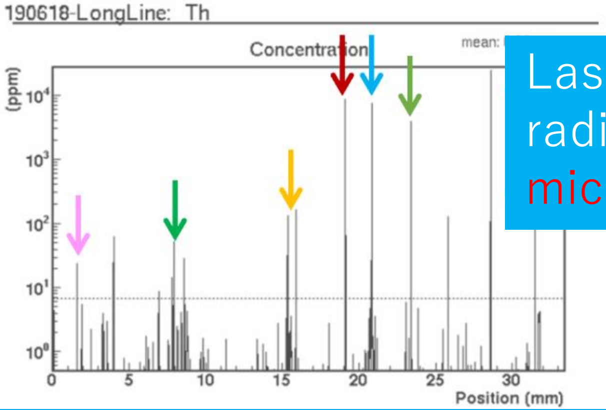


Dominant uncertainty is crustal neutrino flux models

Measurement of the position distribution of radioactive isotopes in crustal rock using nuclear emulsion

Main uncertainty: Where are radioactive isotopes concentrated?
In minerals? In accessory micro-minerals? Between mineral grains?





Laser measurements suggest the possibility that radioactive isotopes are concentrated in accessory micro-minerals or between mineral grains.

A large number of various crustal rocks measurement using nuclear emulsion!

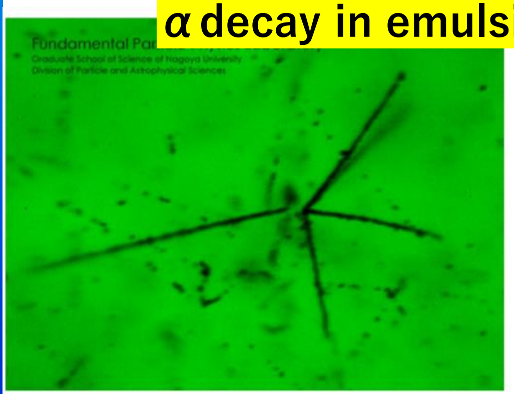
→ **Modeling the position distribution of radioactive isotopes in crustal rocks**

$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6e^- + 6\overline{\nu}_e + 51.7MeV$

$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\overline{\nu}_e + 42.7MeV$

α decay   β decay

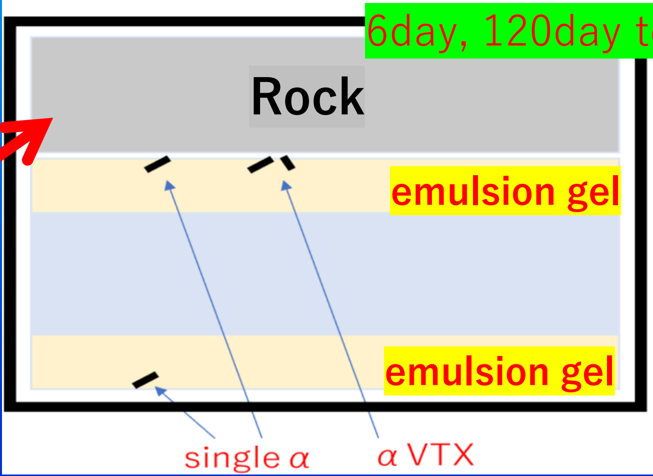
α decay in emulsion



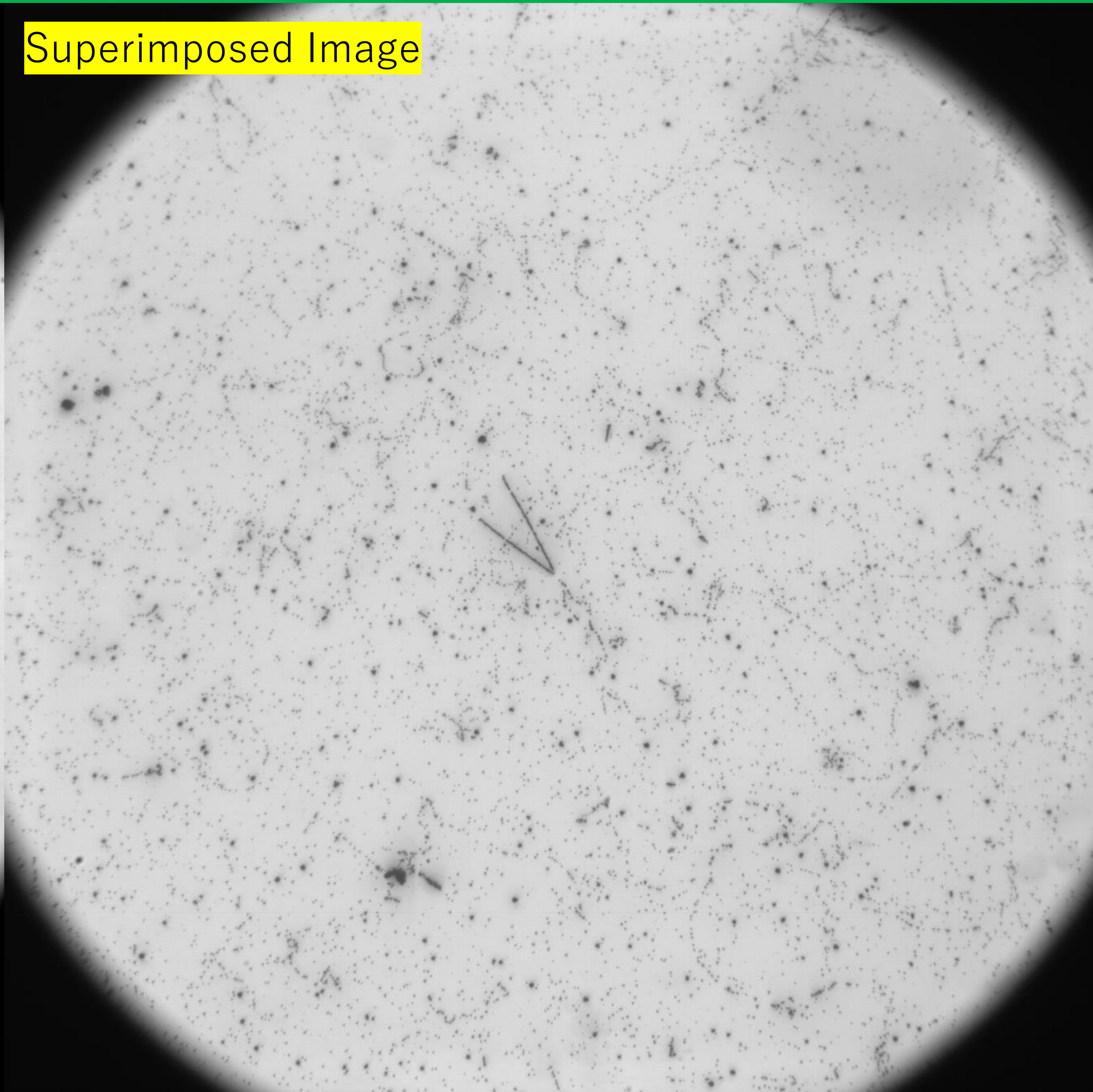
Various of Crustal rocks (Granite)

How long can measurements be made with emulsion?

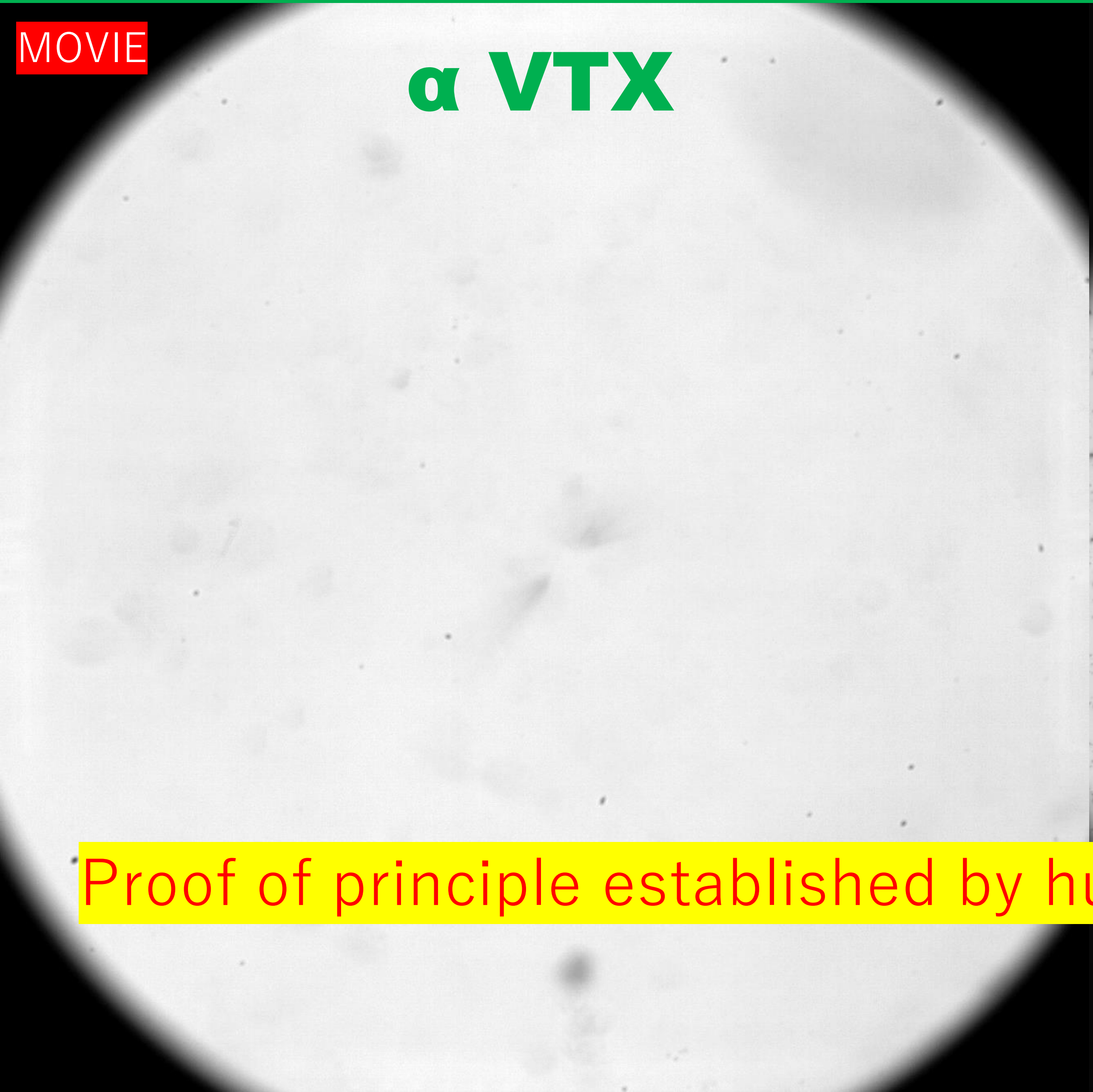
6day, 120day test



Proof-of-principle test (6days)

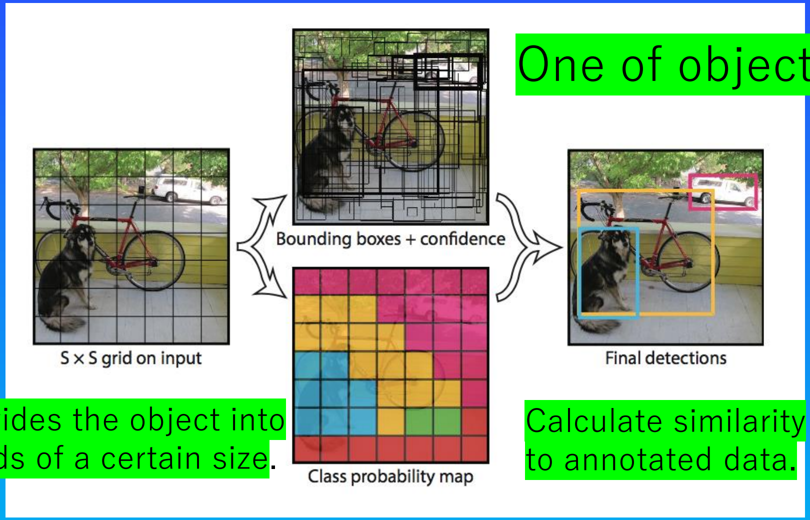


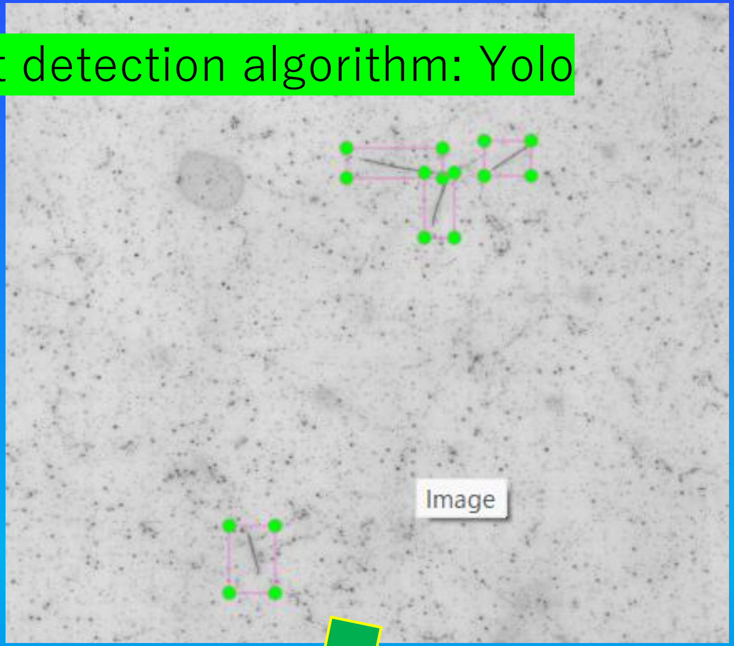
Proof-of-principle test (6days)



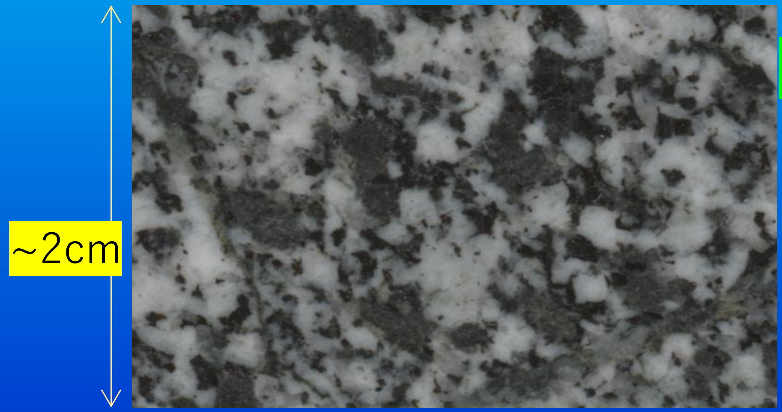
Proof of principle established by human eyes→ 120days observation

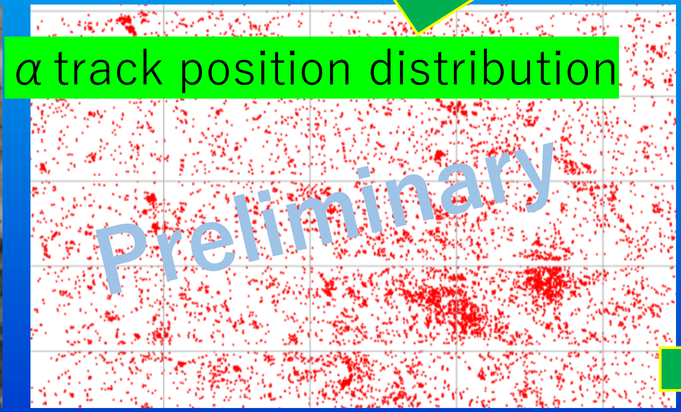
Large area analysis → α track detection by Machine Learning





● 120days sample measurement





→ α track detection eff., S/N ・Comparison with mineral distribution

Earth science using emulsion

Research on mantle rocks appeared on the earth's surface by eruptions, etc., as well as on the earth's crust.
→ Earth formation and evolution

Analysis of lunar and meteorite rocks.
→ Moon/star formation and evolution

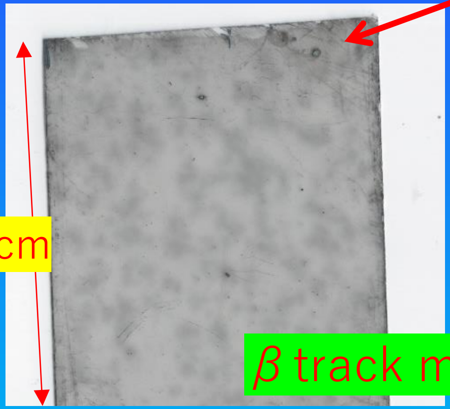
Half-life-time measurements based on α-ray measurements
→ Use for Radiometric dating

Interdisciplinary research with experts in petrology, geochemistry, seismology and absolute dating is initiated!

β track measurement in emulsion

Earth science

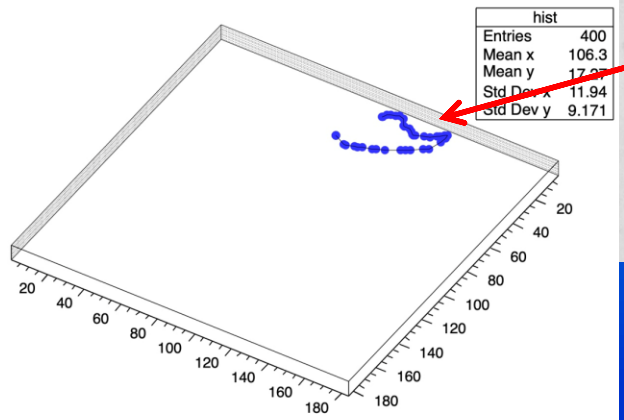
One of 120days sample

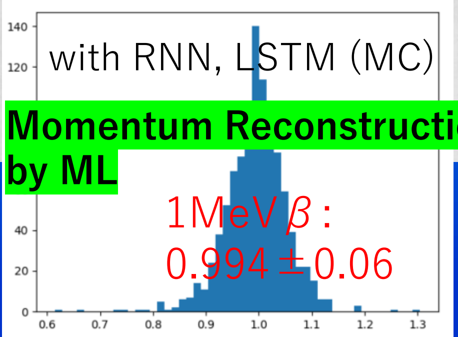


speckled pattern
→ β ray (by eye check)
β track only area
(From potassium(K)?)

β track measurement is also important!

β track detection
Automatic recognition of curved tracks



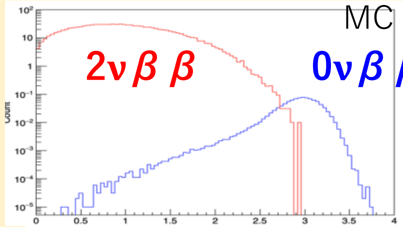


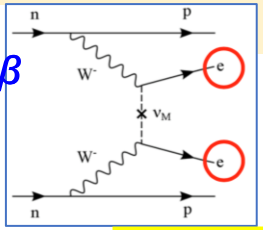
Momentum Reconstruction by ML

Emulsion for 0νββ

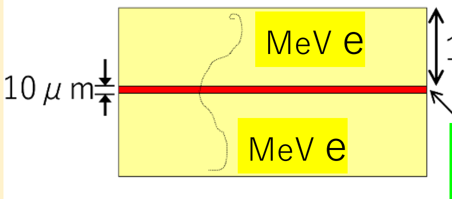
challenge to Normal Ordering (meV scale)

- Excellent BKG reduction
- Good scalability



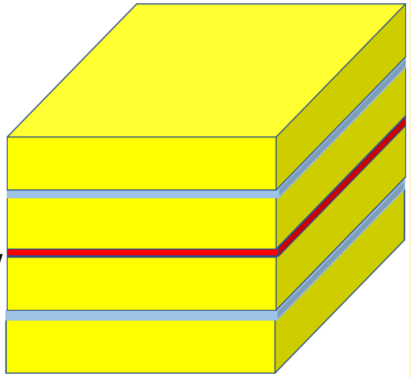


Sub-Multi MeV electrons



Emulsion

Double beta decay nucleus

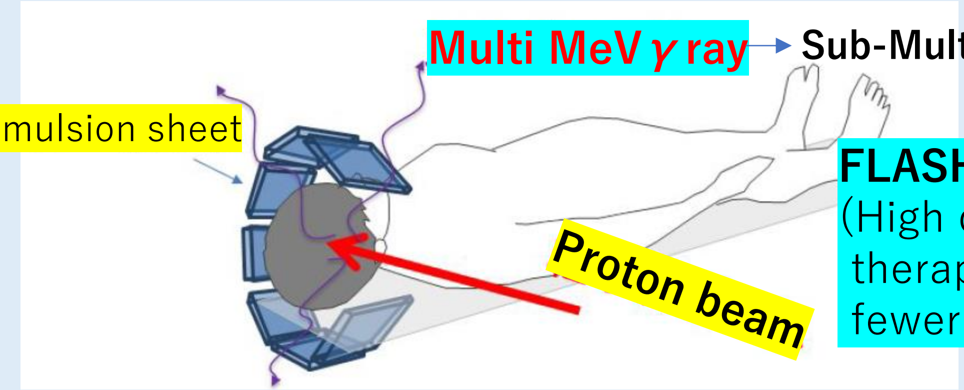


Medical application → Radiation Cancer Therapy

- In-treatment monitoring
- Improved pre-simulation

Multi MeV γ ray → **Sub-Multi MeV electrons**

Emulsion sheet



FLASH Radiotherapy
(High dose rate particle therapy with fewer side effects)

Summary

- The study of neutrino oscillations is the key to pioneering the next new physics.
- We are promoting the NINJA experiment, an accelerator based neutrino experiment using nuclear emulsion for precise measurements of neutrino oscillations. → Deepening neutrino-nucleus interaction study

  Long-baseline neutrino oscillation experiments and sterile neutrino searches.
- 2nd Physics Run The neutrino beam exposure in the 2nd physics run was successful and the analysis is now being diligently promoted. The aim is to publish the first physics paper this year.
- We also are developing α and β track analysis method in emulsion using ML.
  → Earth science, not only geo-neutrino but also Star formation and evolution
  → Radiometric dating science
  → Neutrino less double beta decay search
  → Medical application (FLASH Radiation Cancer Therapy)

Back up