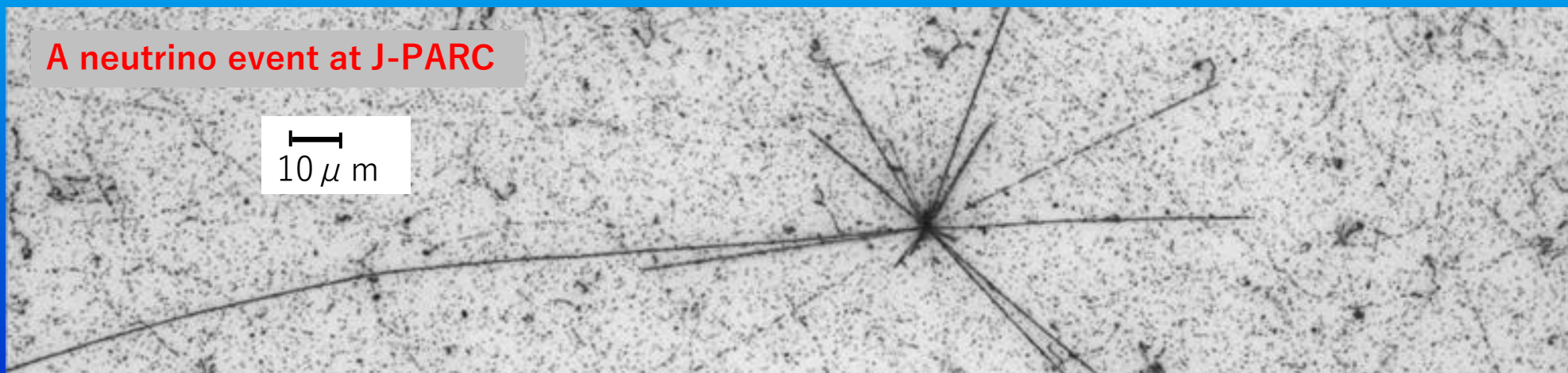


Neutrino interaction measurements in NINJA and Recent progress of Nuclear Emulsion technology

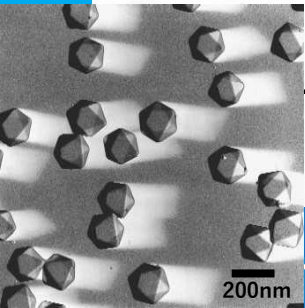
Tsutomu Fukuda (IAR/F-lab, Nagoya U./Kyoto Univ.)



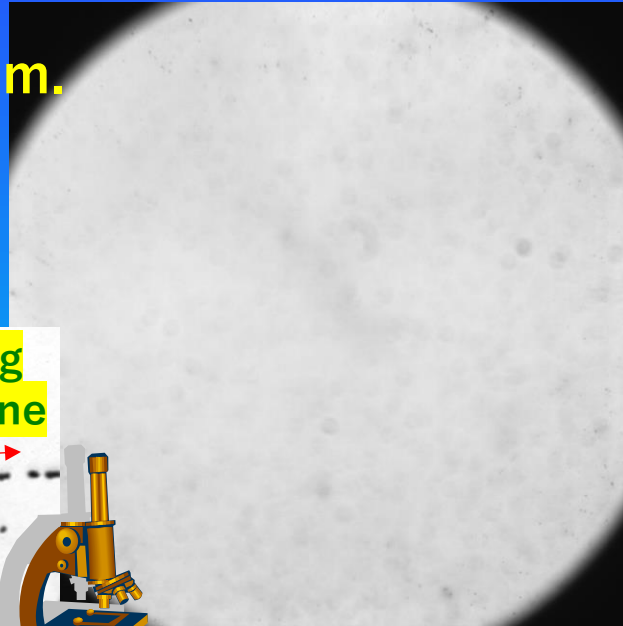
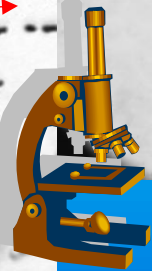
Nuclear emulsion and automatic readout system

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

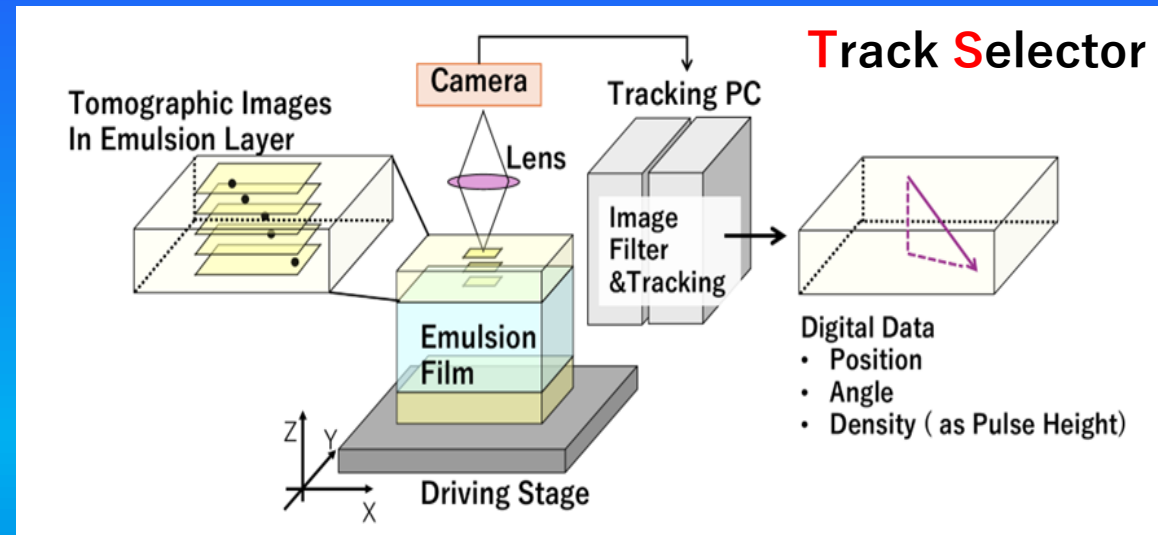
Recorded as silver grains along the particle passing through line



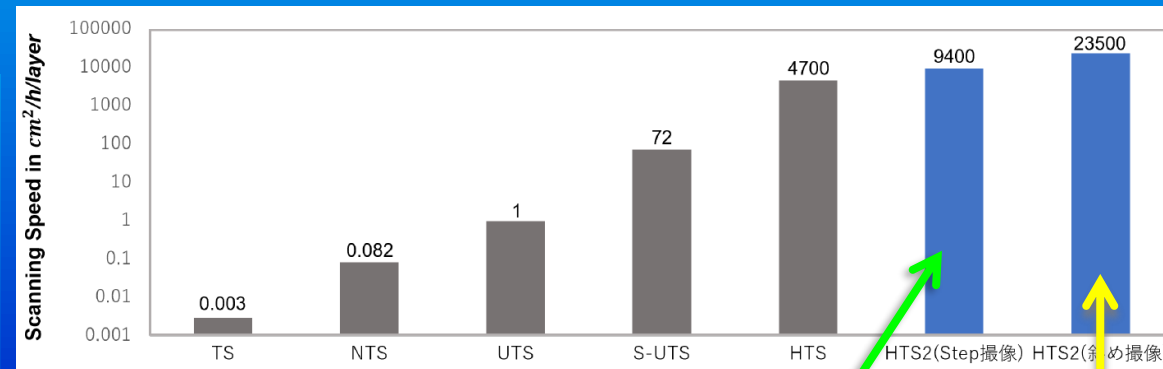
50 micron



Automatic track scanning system



Improvement of Scanning speed in 40 years



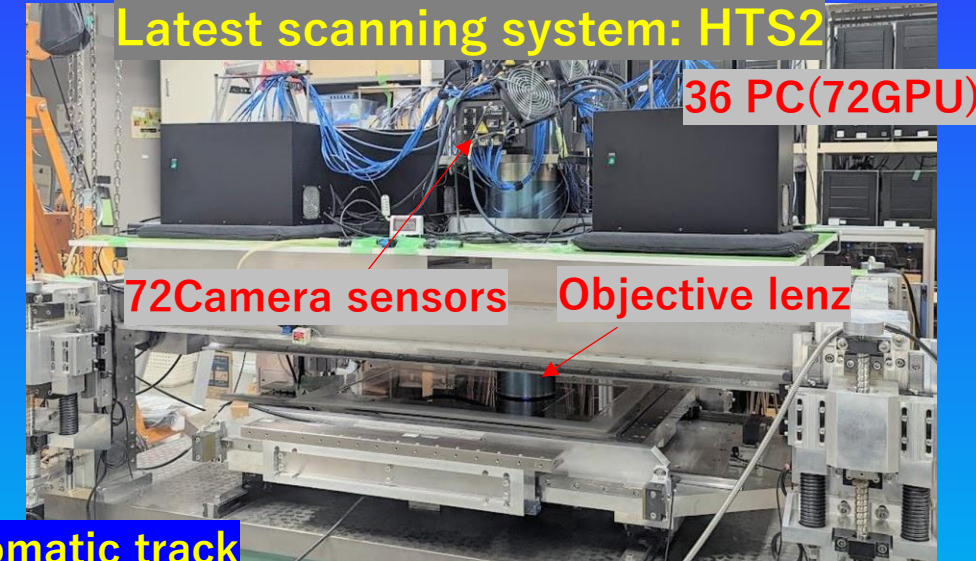
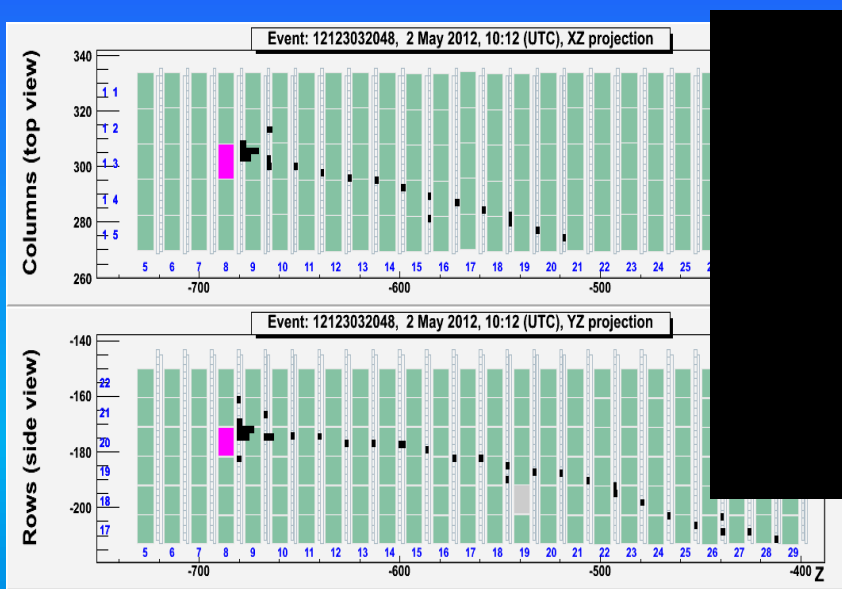
Current Speed Next step

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

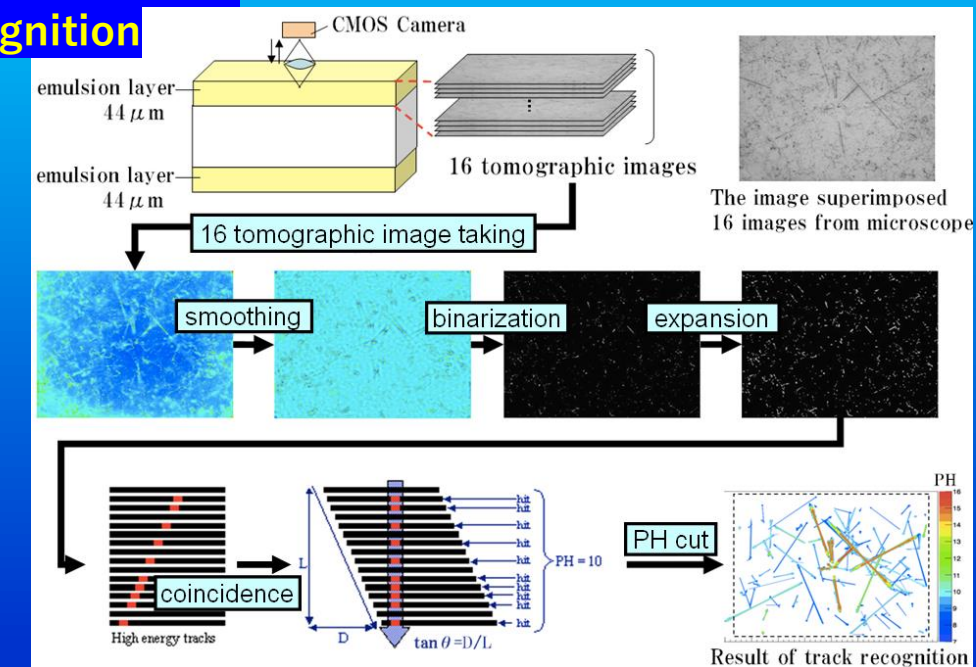
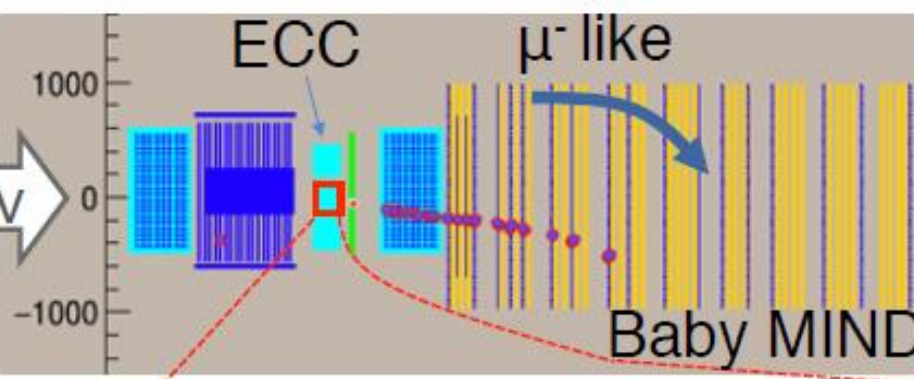
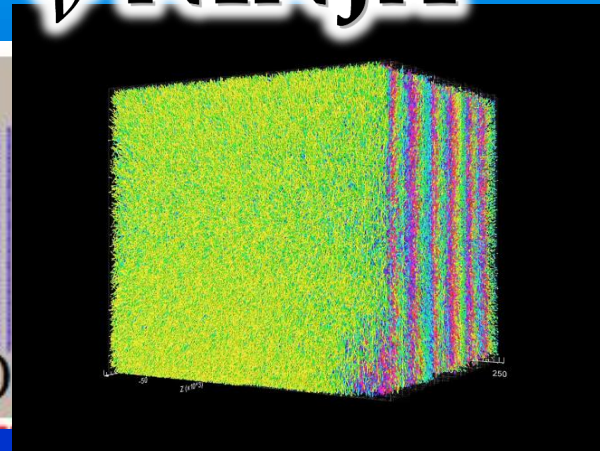
Neutrino experiments with nuclear emulsion

3

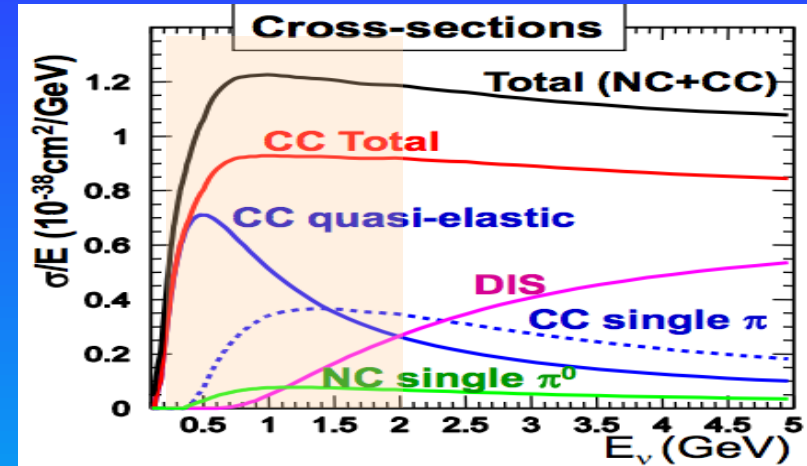
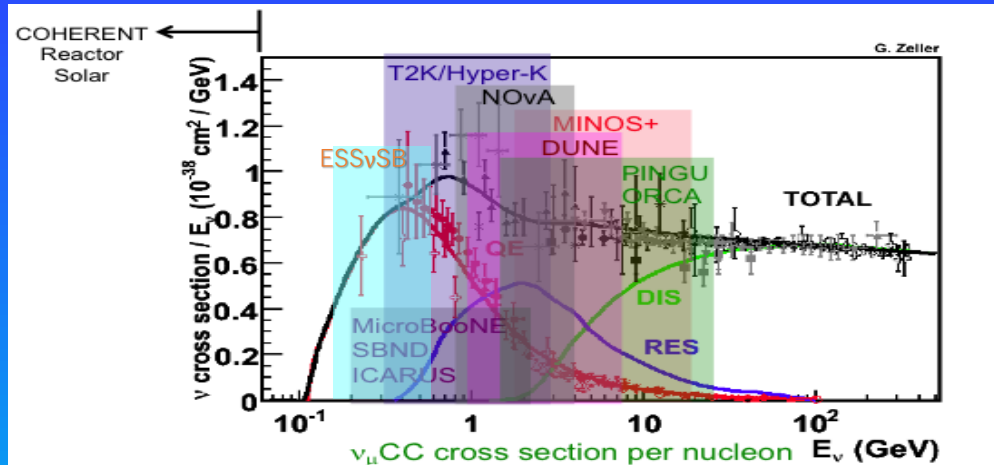
- Accelerator based experiments
→ Emulsion-Counter Hybrid analysis



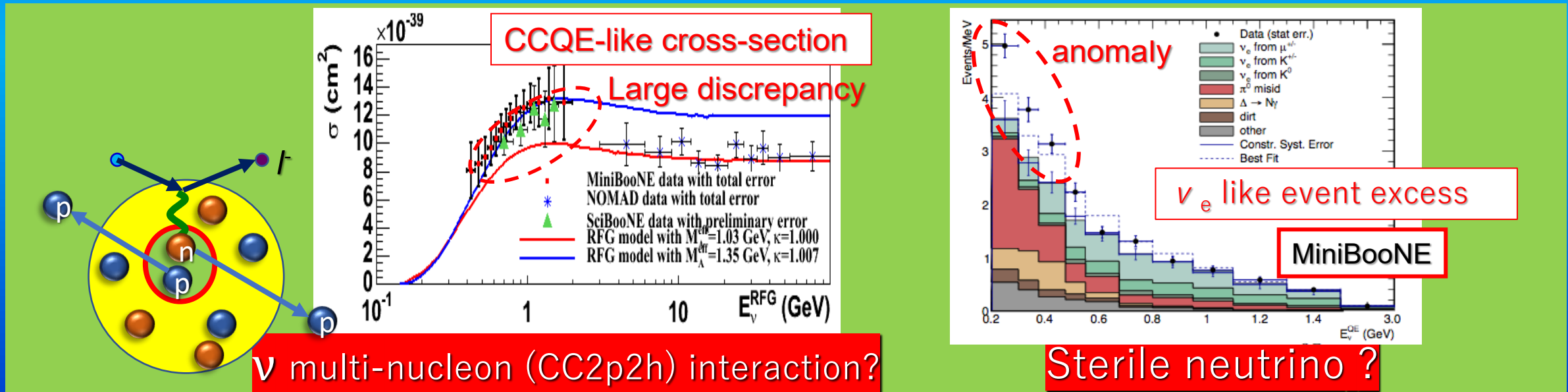
NINJA



Neutrino physics on sub-multi GeV



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



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

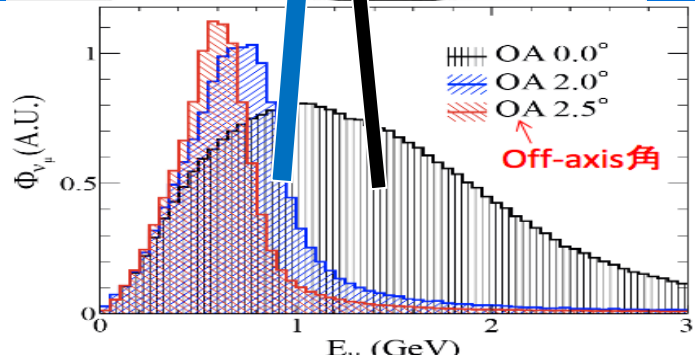
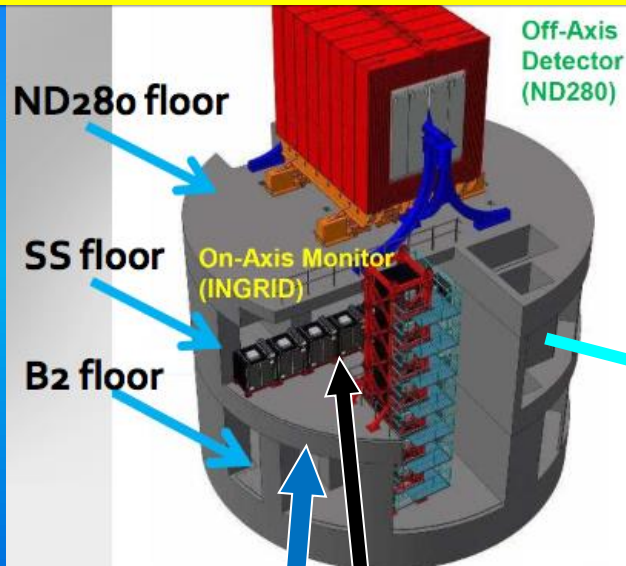
Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

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

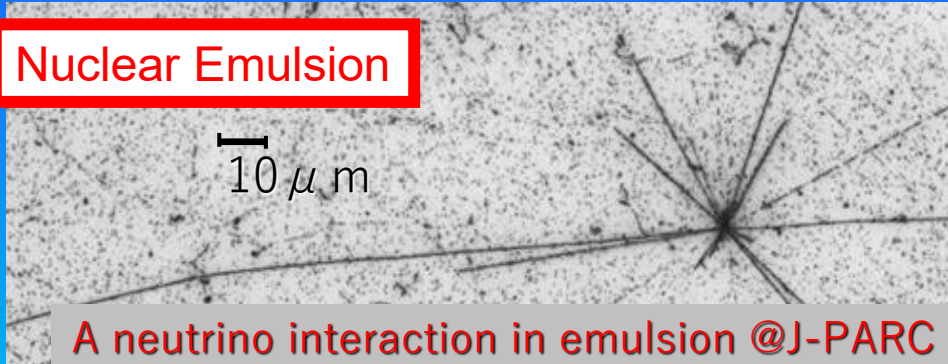


3 countries,
13 institutes

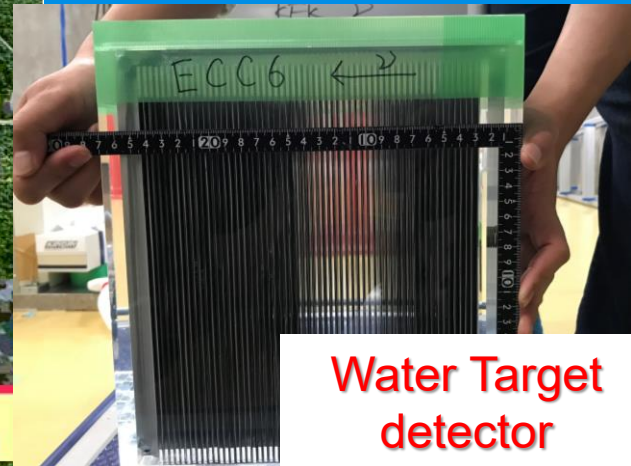
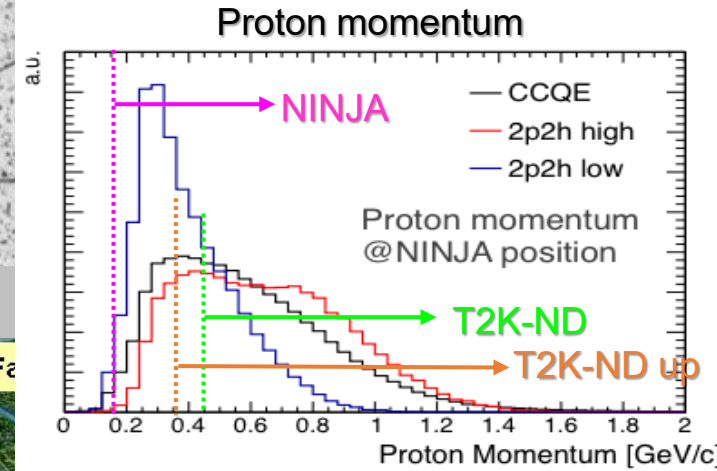
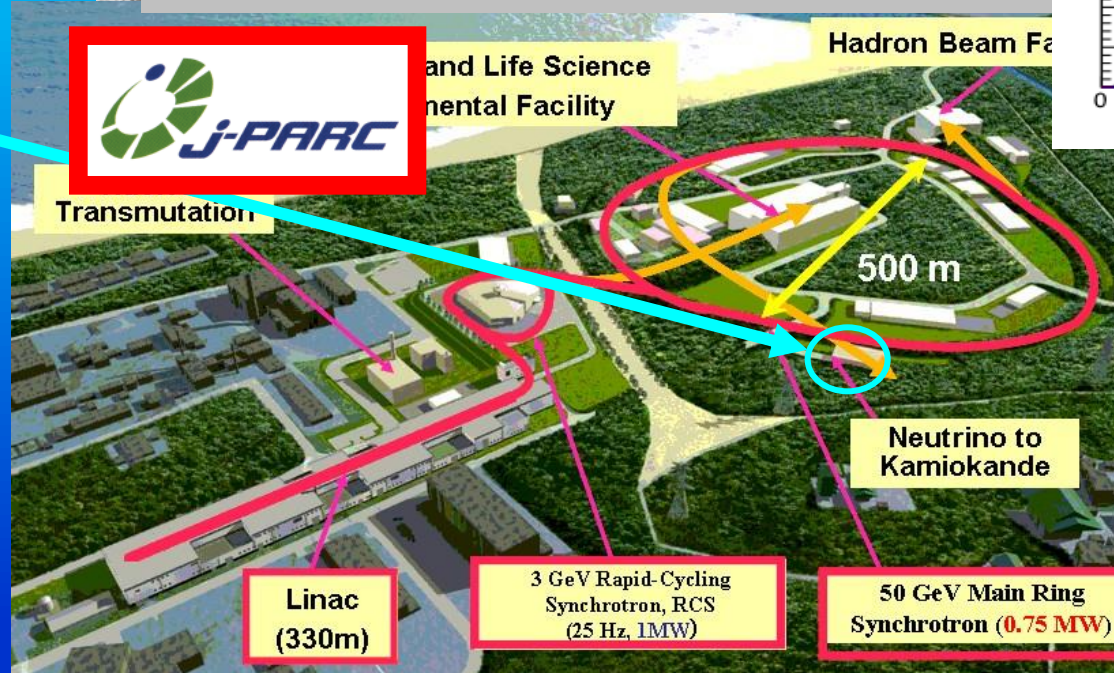
J-PARC Neutrino monitor building



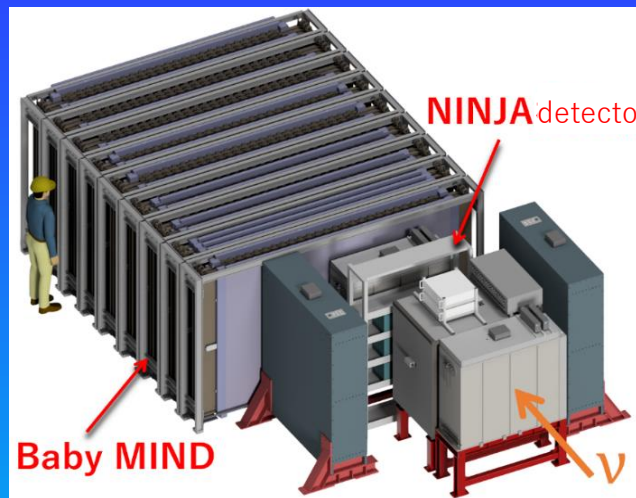
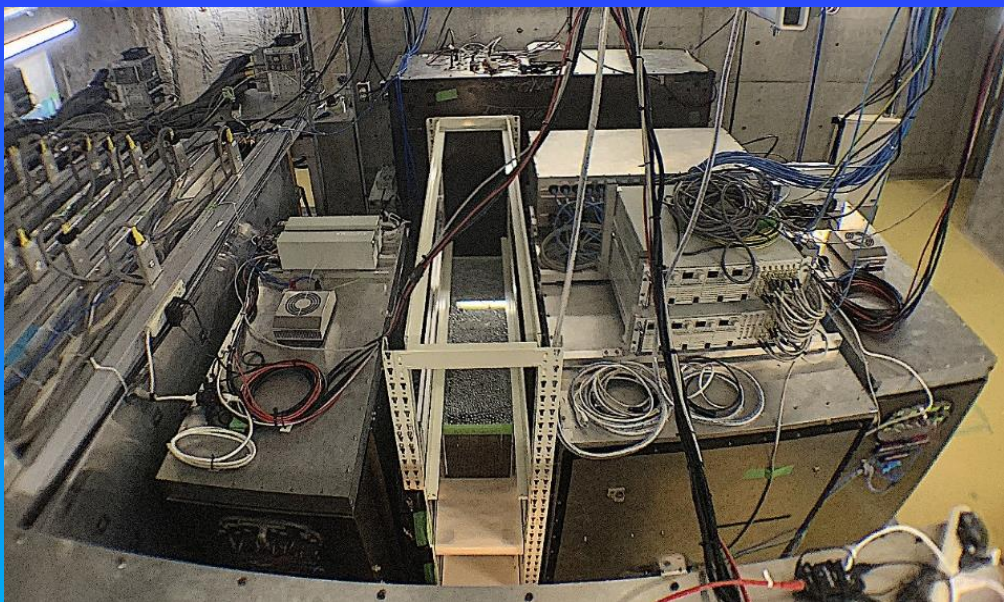
Nuclear Emulsion



A neutrino interaction in emulsion @J-PARC



Water Target
detector

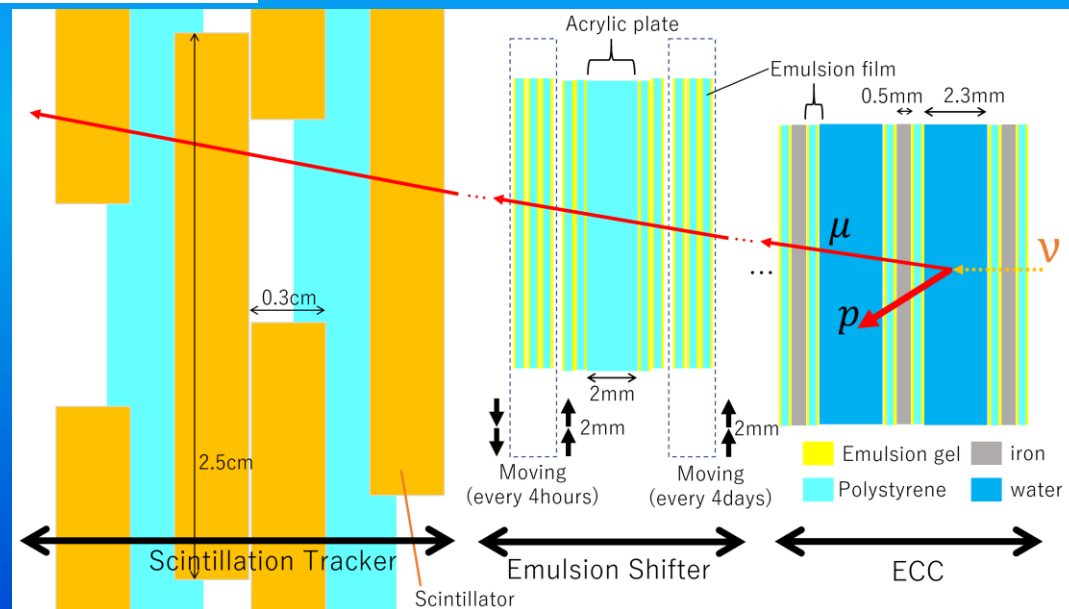
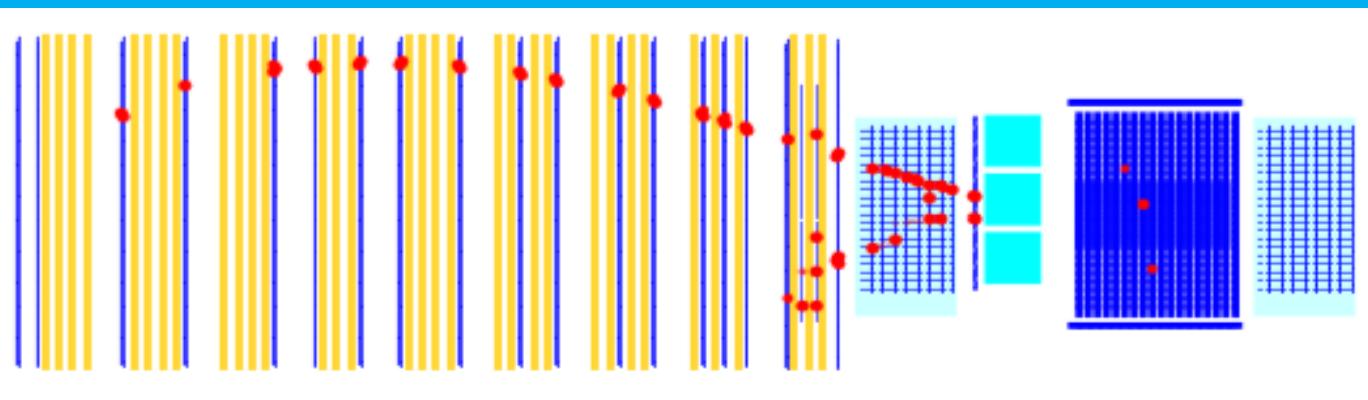
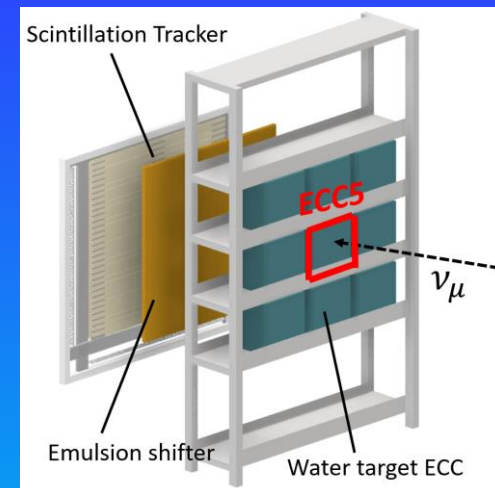


250kg Target

H₂O: 75kg
Fe: 130kg
CH: 15kg
em : 30kg

Film 130m²

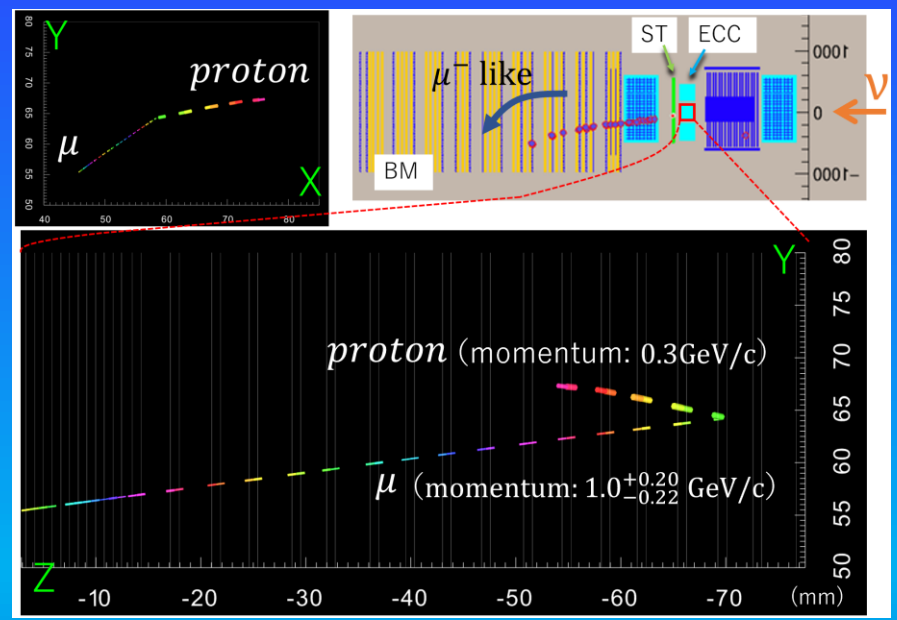
5,000 events



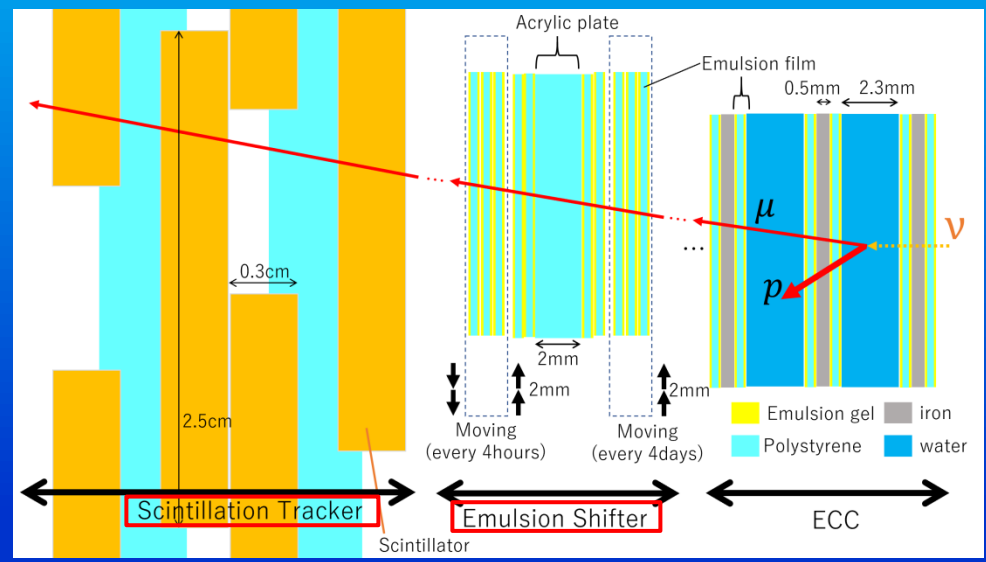
E71a: 2019 Nov. – 2020 Feb.
E71b: 2023 Nov. – 2024 Feb.
E71c: 2025 Nov. – 2026 Mar.

Total POT: 10²¹

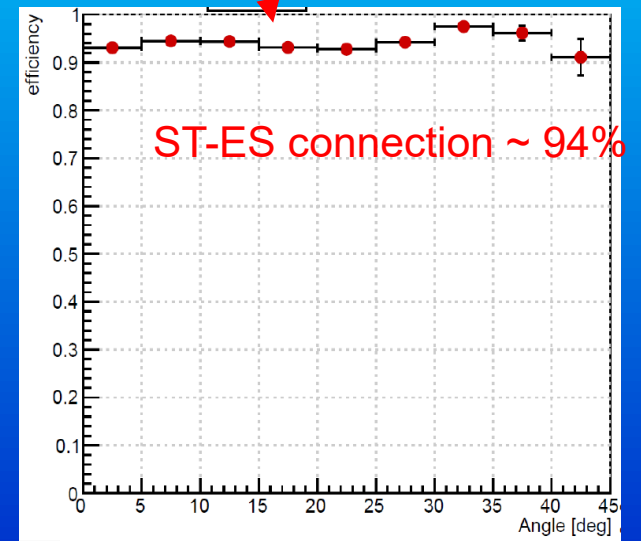
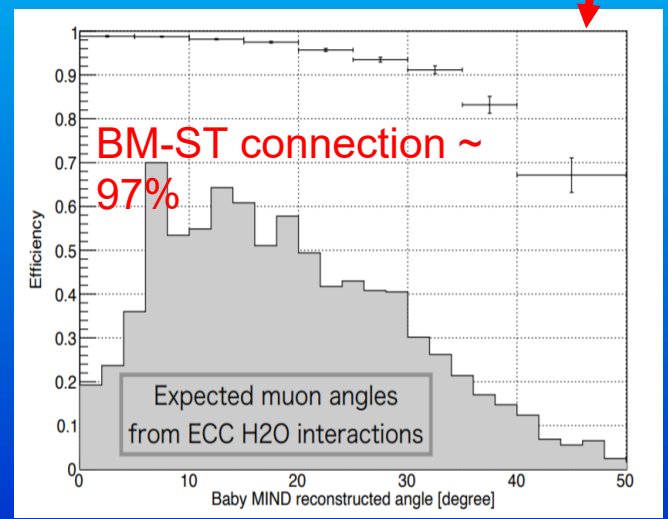
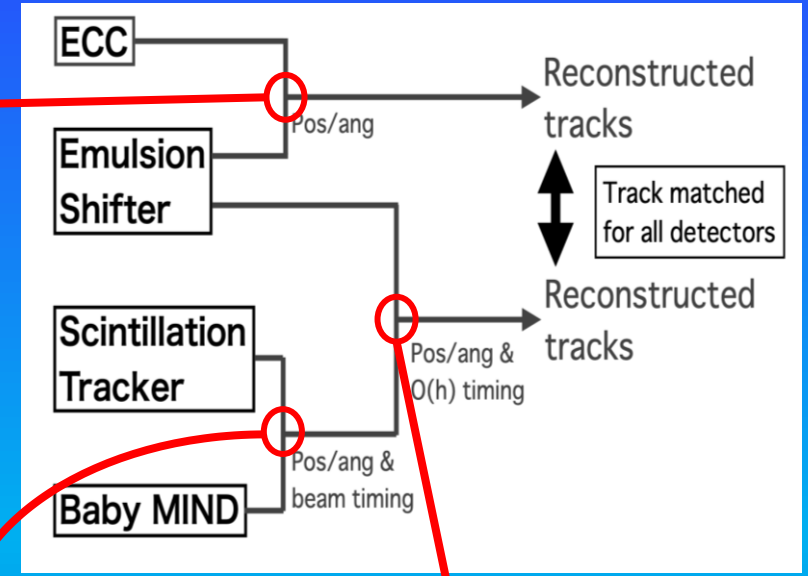
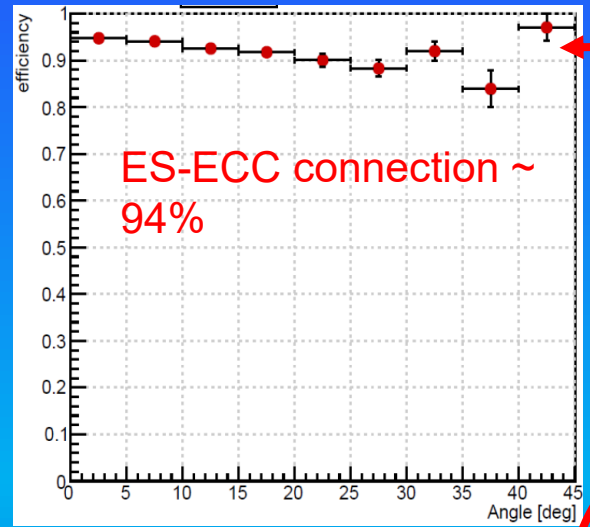
	Scintillation Tracker	Emulsion Shifter	Water ECC
Time resolution	10 nsec level	4 hour	--- (100 day)
Position resolution	2.1 mm	1 μm level	1 μm level



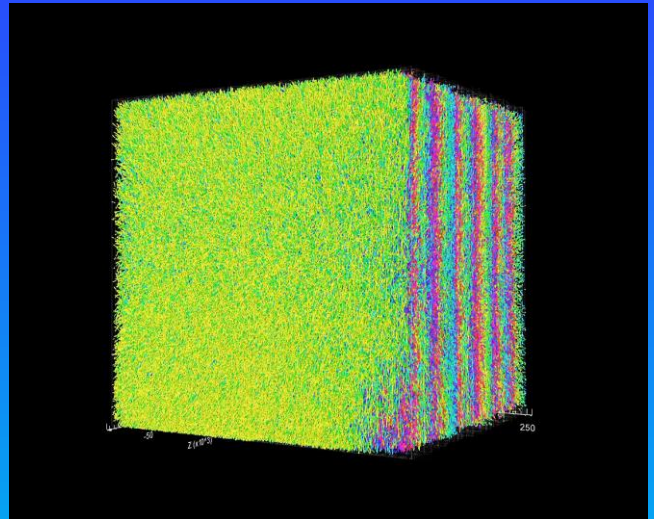
Connected muon tracks between ECC-BM with ES and ST



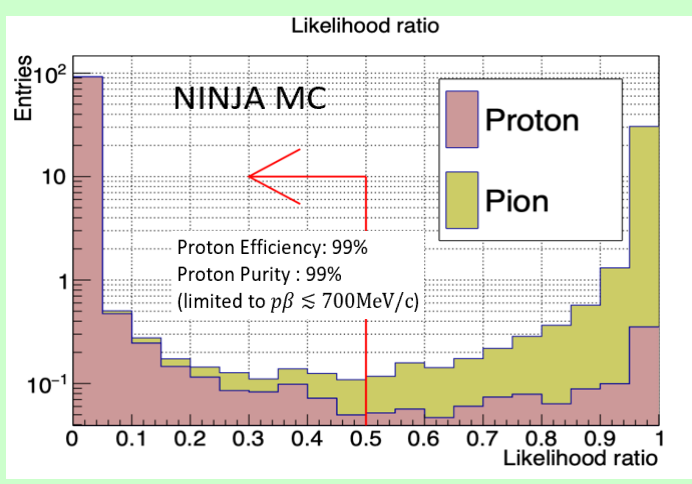
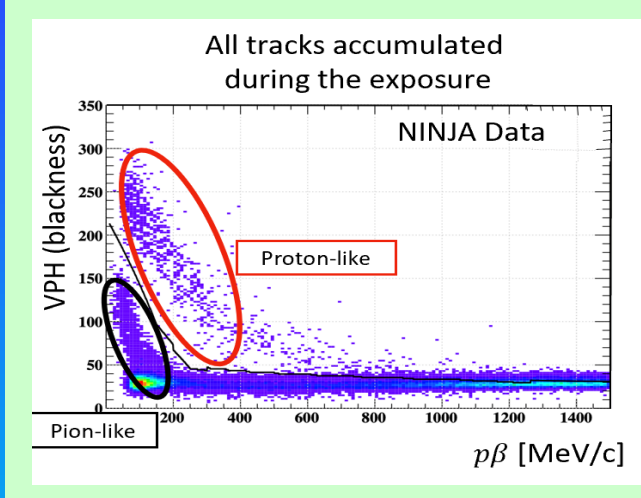
Track matching
estimated by sand-muon



Status of Analysis

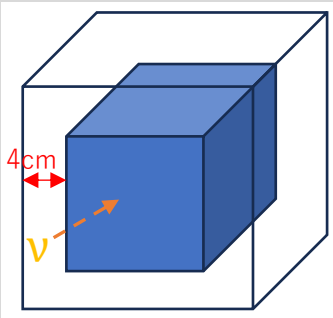


PID

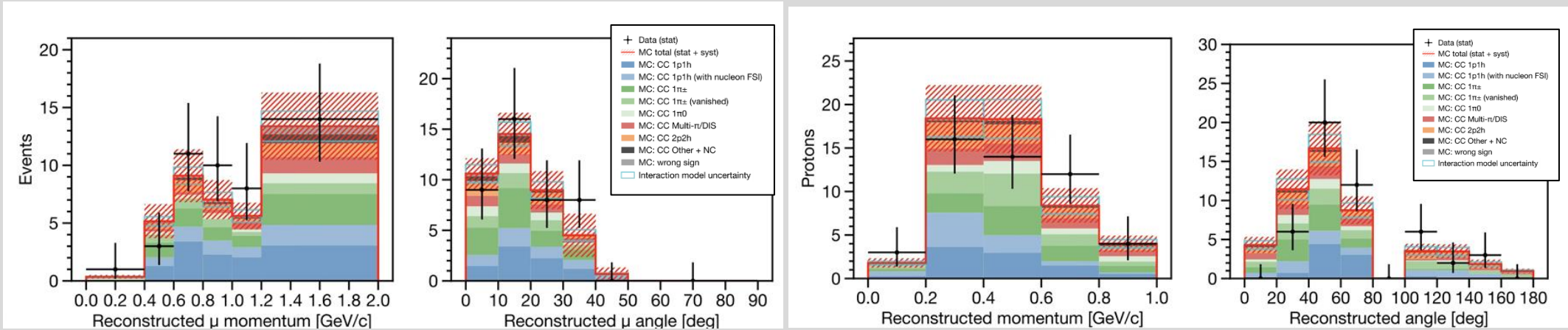


Neutrino events in the central area (4cm inside from the edge) of the ECCs where partner search is reliable.

First results for muon and proton kinematic distributions of neutrino-water CC interactions



FV:central area



See arXiv:2608.16063

Status of Analysis

Other measurements: iron target data

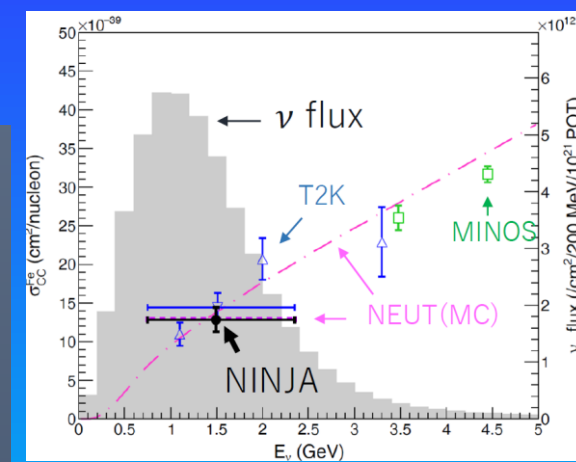
Iron int.: 183 events

Flux averaged CC inclusive cross section:

	Result $\times 10^{-38}$ (cm ² /nucleon)	MC $\times 10^{-38}$	T2K(INGRID) $\times 10^{-38}$
σ_{CC}^{Fe}	$1.28 \pm 0.11(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$	1.30	$1.444 \pm 0.002(\text{stat.})^{+0.189}_{-0.157}(\text{syst.})$
$\sigma_{CC \text{ phase space}}^{Fe}$	$0.84 \pm 0.07(\text{stat.})^{+0.07}_{-0.06}(\text{syst.})$	0.87	$0.859 \pm 0.003(\text{stat.})^{+0.12}_{-0.10}(\text{syst.})$

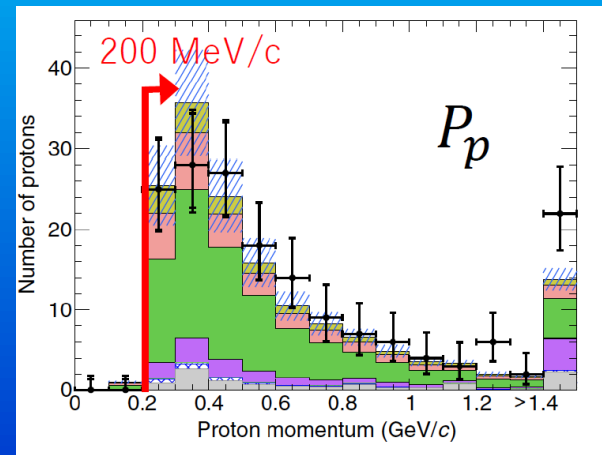
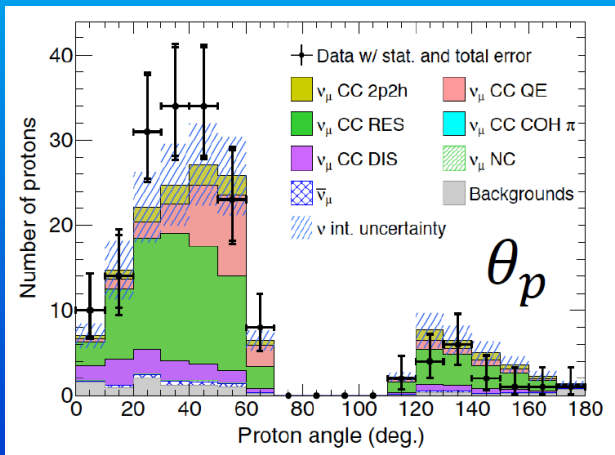
[H. Oshima et al., PTEP 2021, 033C01 \(2021\).](#)

[H. Oshima et al., PRD 106, 032016 \(2022\).](#)

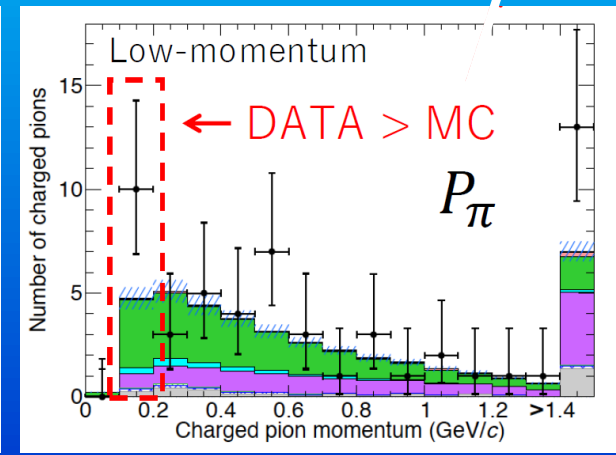
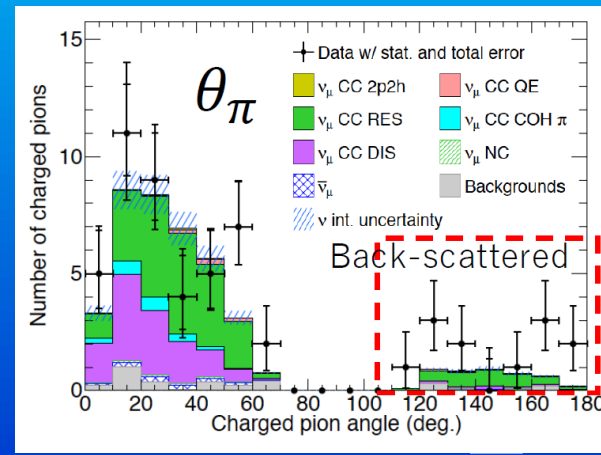


Phase space: $\theta_\mu < 45^\circ, P_\mu > 400 \text{ MeV}/c$

Proton kinematics

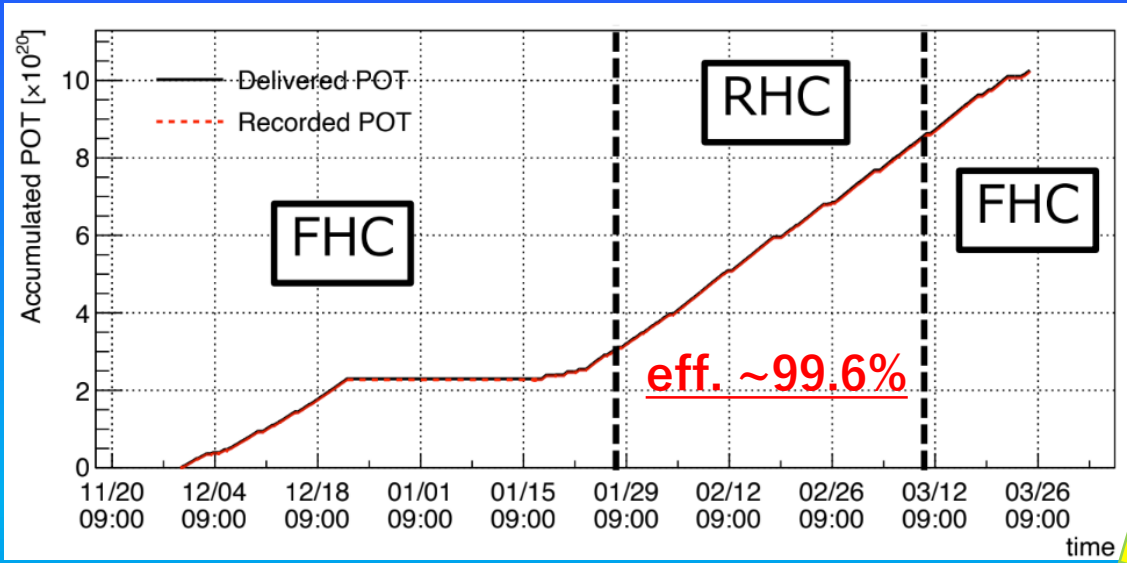


Charged Pion kinematics



NINJA Latest exposure

Beam exposure(2025 Nov. – 2026 Mar.)



Period	Mode	Delivered POT
2025/11/29~12/22, 2026/1/16~1/28, 2026/3/11~3/25	FHC	4.74×10^{20}
2026/1/28~2026/3/11	RHC($\bar{\nu}$)	5.52×10^{20}
Total		10.26×10^{20}

Total 1.24×10^{21} POT in FHC
(E71 requested: 1.0×10^{21} POT)

First RHC-mode data
during the physics run



Film development(2026 Apr. – Jun.)

of films



Future prospects

All data of E71

FHC	Period	POT
1 st :E71a	2019-2020	4.8×10^{20}
2 nd :E71b	2023-2024	2.9×10^{20}
3 rd :E71c	2025-2026	4.7×10^{20}

RHC ($\bar{\nu}$)	Period	POT
3 rd :E71c	2025-2026	5.5×10^{20}

• Recent publication

- First inclusive ν -H₂O CC results (arXiv:2608.16063)
- Sterile neutrino search (arXiv:2606.30135)

• Planned data releases include:

- Inclusive measurements
- Exclusive measurements
(0π CC, multi- π CC, 2p CC, and other channels)
- Anti-neutrino measurements
- Electron neutrino measurements



All films are expected to be scanned by the end of 2027.

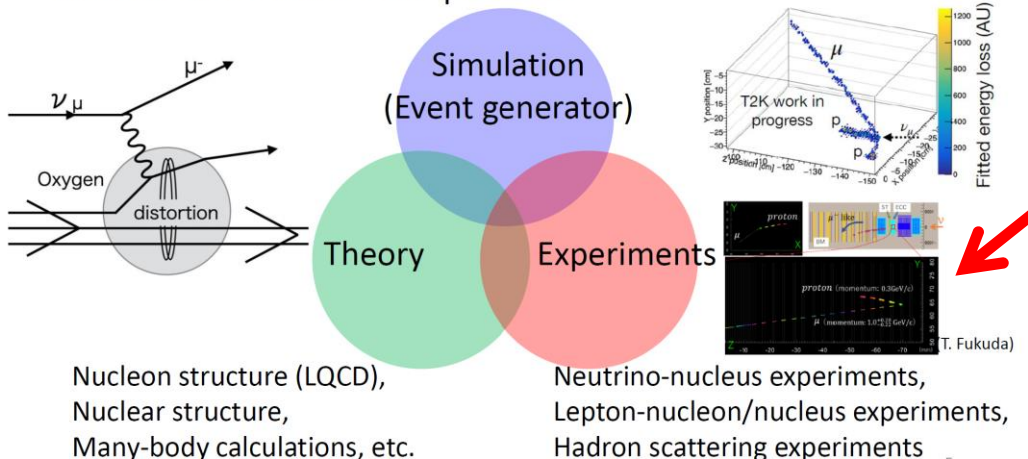
Current data release: about 2% of the total dataset
Goal: Release 20% ($10\times$ increase) over the next 6 months
Target: Increase the data release to 50% by JFY2027

JSPS Core-to-Core Program (JFY2026-2030)

Establishment of an International Research Hub for Promoting Theoretical and Experimental Research Using Neutrino-Nucleus Interactions

International research center for neutrino-nucleus interactions

- Improving our understanding of neutrino–nucleus interactions requires broad knowledge of theoretical and experimental particle and nuclear physics.
- We need a framework that brings together experts from Japan and abroad to address this problem.



Neutrino-nucleus scattering experiments

J-PARC

T2K-ND280+

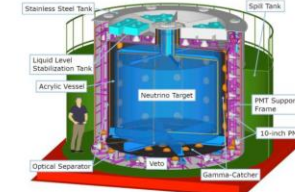
(upgraded near detectors)

Ninja



JSNS² and JSNS²-II

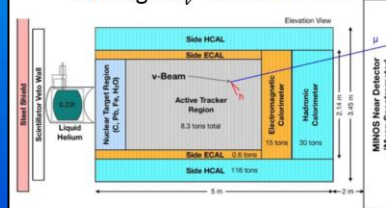
(Sterile neutrino search experiment)



FermiLab

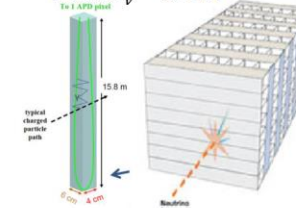
MINERvA

Various target nuclei
Average $E_\nu = 3.5$ or 6 GeV



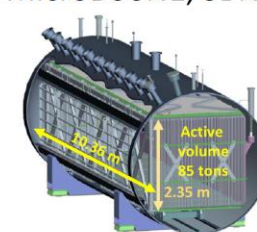
NOvA ND

Scintillator detector
Peak $E_\nu \sim 2$ GeV



Liquid Argon TPCs

MicroBooNE, SBND



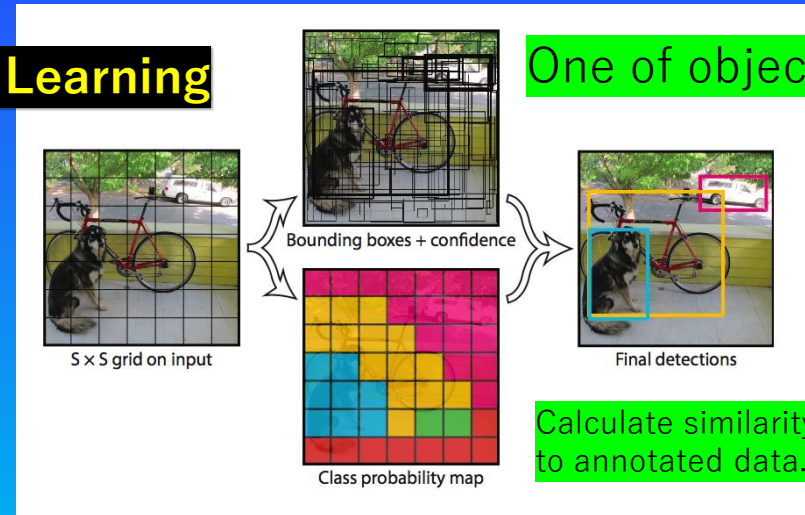
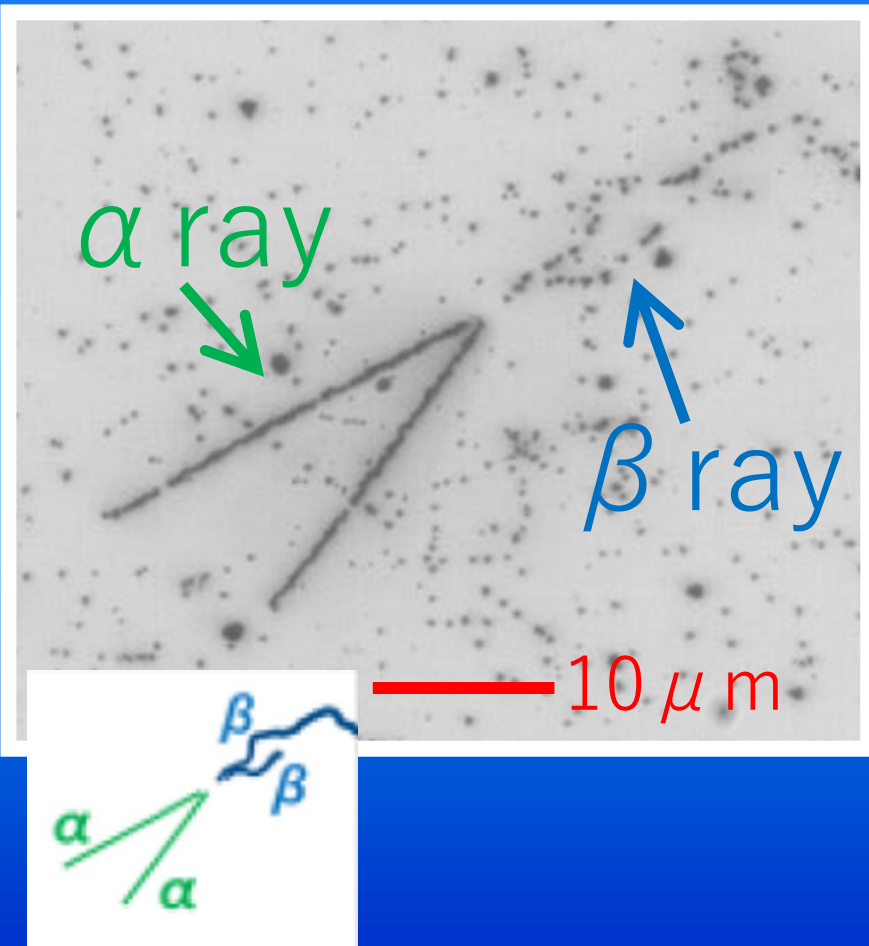
- Kick-off workshop was held on June 5th. (<https://www-kam2.icrr.u-tokyo.ac.jp/event/22/>)
- NINJA is one of the core research activities within this program.

Novel neutrino activities using nuclear emulsion

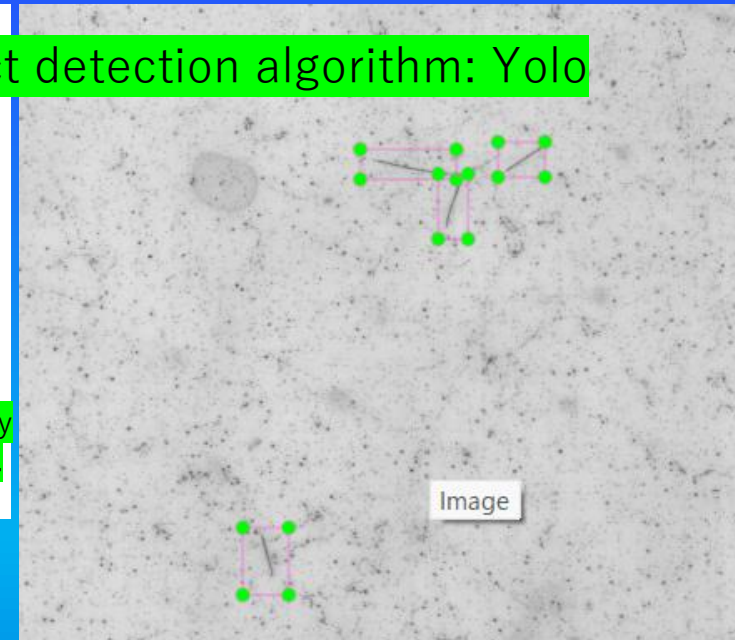
- Other Short Topics -

Application of α and β particles

α track detection by Machine Learning

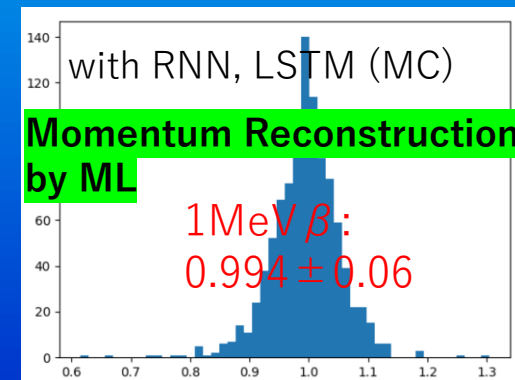
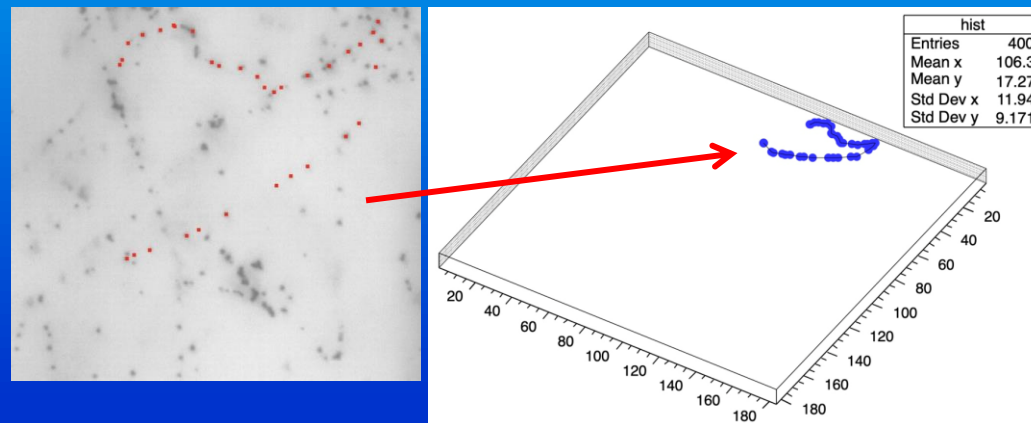


One of object detection algorithm: Yolo



β track detection

Automatic recognition of curved tracks



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

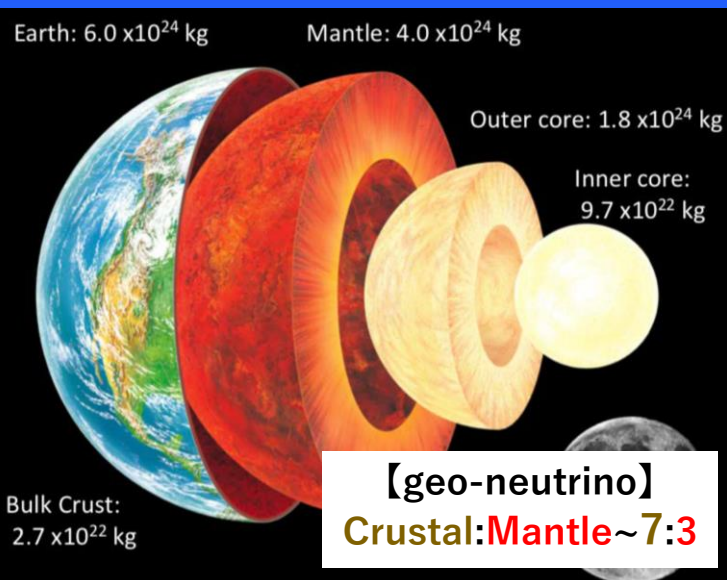
**Plate movement
Volcanic activity**

**First detection of geo-neutrinos
by KamLAND (2005)**

Current situation

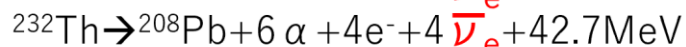
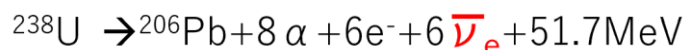
20 years of observations, statistical accuracy has improved, reaching a level where geoscientific insights can be obtained

$$v_{\text{geo}} (\text{Mantle}) = v_{\text{geo}} (\text{KamLAND}) - v_{\text{geo}} (\text{Crustal})$$

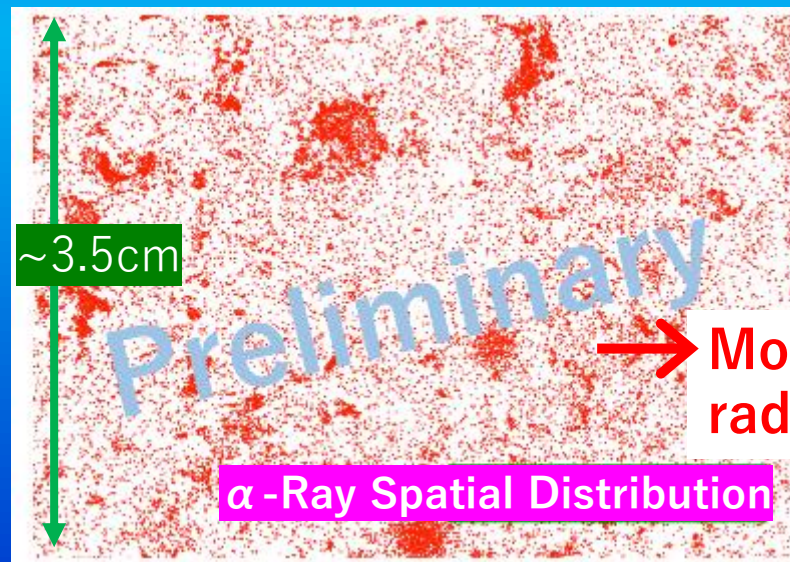


Geo-neutrino

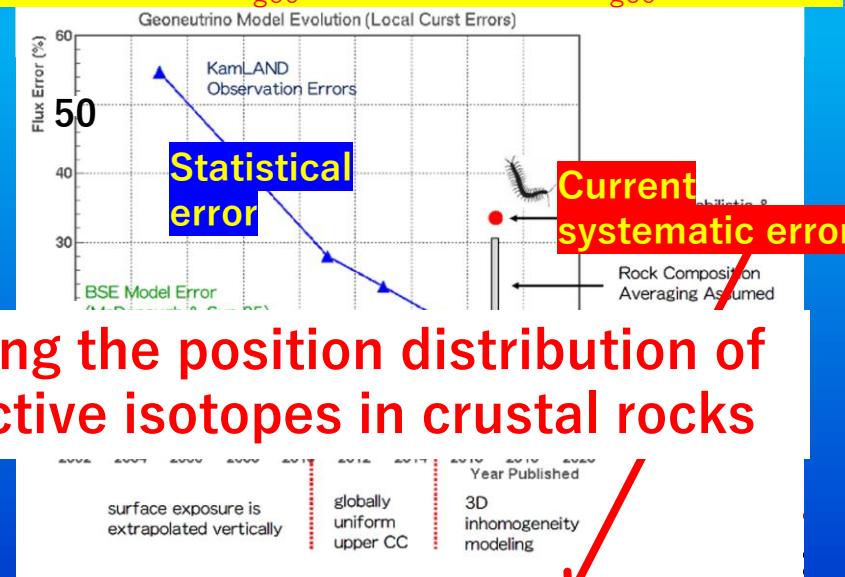
Anti-electron neutrinos from the decay of radioactive isotopes in the earth ($\bar{\nu}_e$). mainly,



α decay β decay **Earth's heat source**



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



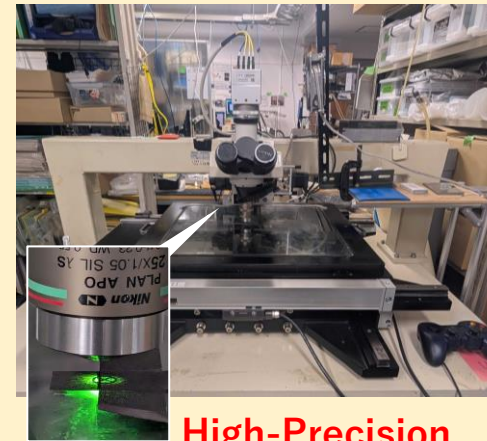
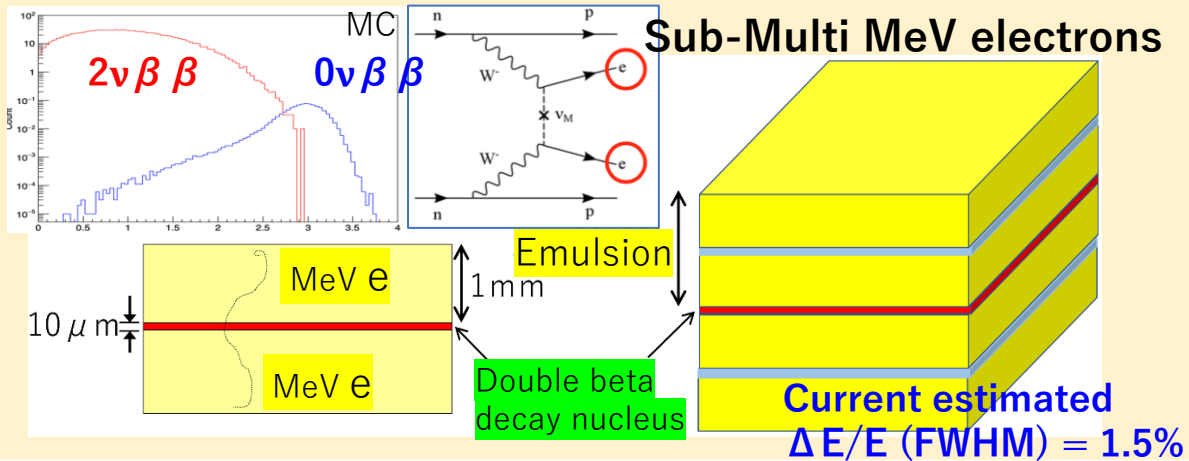
Dominant uncertainty is crustal neutrino flux models

Application of β tracking in emulsion

Emulsion for $0\nu\beta\beta$

challenge to
Normal Ordering
(meV scale)

- Excellent BKG reduction
- Good scalability



High-Precision
Microscopy System

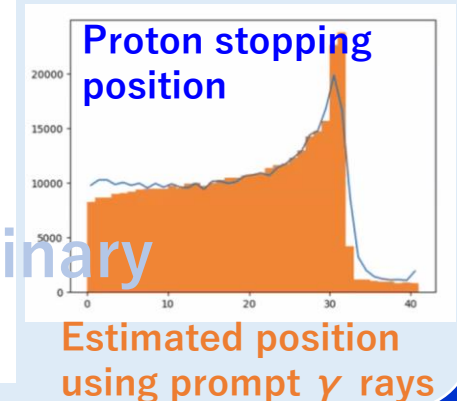
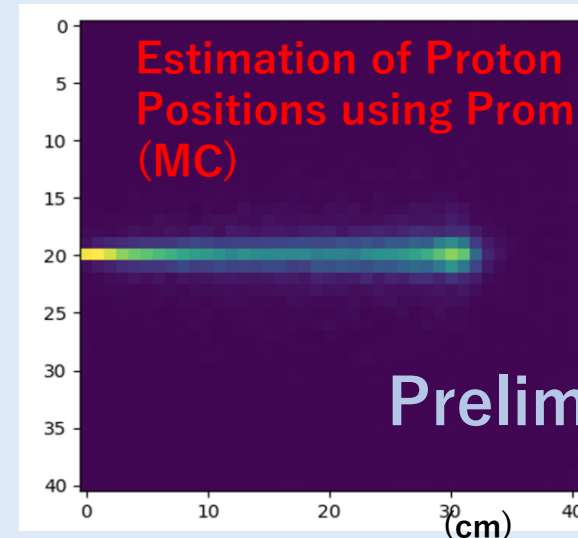
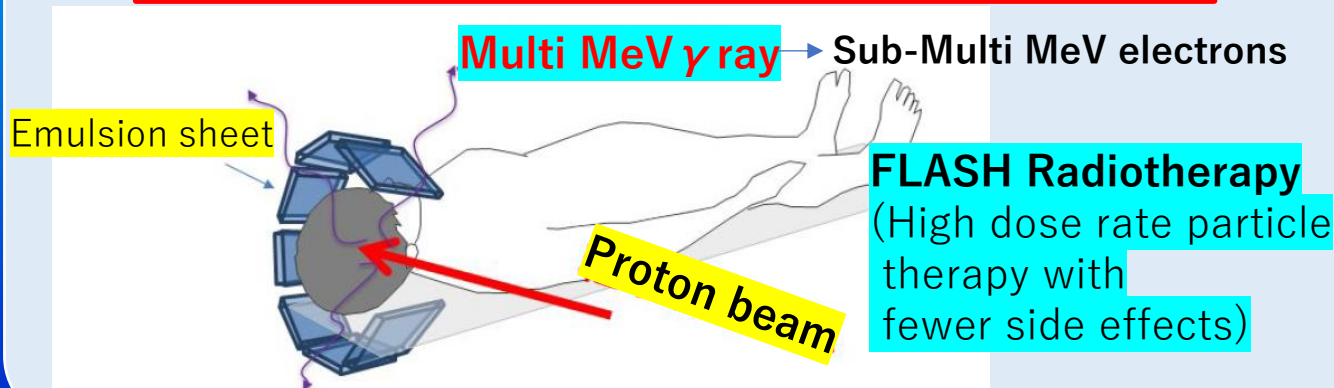


High-Speed Dryer for
Thick Nuclear Emulsion

Medical application

→ Radiation Cancer Therapy

- In-treatment monitoring • Improved pre-simulation



Summary

- 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
- With the 3rd data-taking campaign, the originally requested beam exposure of 1.0×10^{21} POT in FHC mode was achieved.
In addition, 0.5×10^{21} POT of RHC data were successfully collected.
- The first physics paper from the physics run has been submitted. We aim to publicly release a dataset of about 5,000 neutrino–water CC events within the next few years.
- 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
 - Neutrino less double beta decay search
 - Medical application (FLASH Radiation Cancer Therapy)

Back up