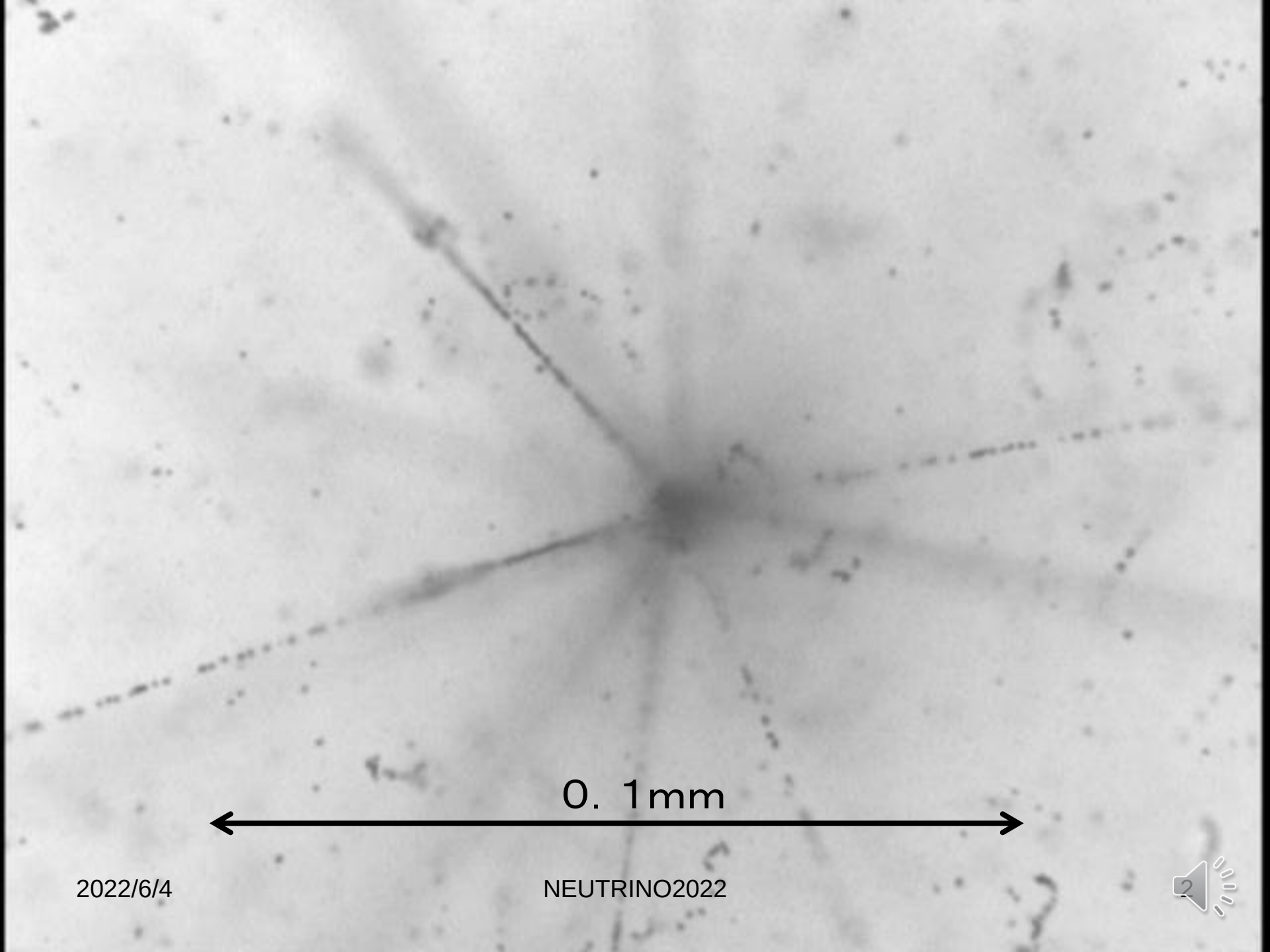
# Overview on emulsion detector technique

Toshiyuki NAKANO
Emulsion readout system

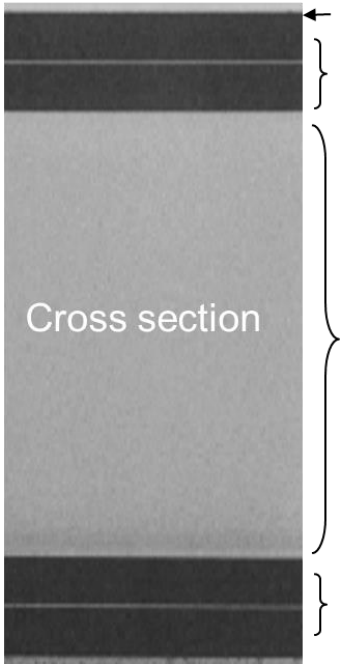
Hiroki ROKUJO
Emulsion film production

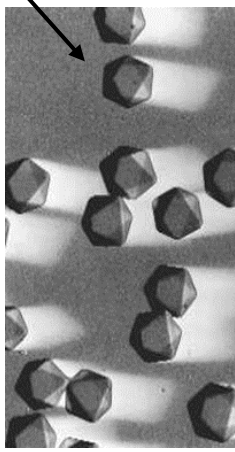
Nagoya Univ.

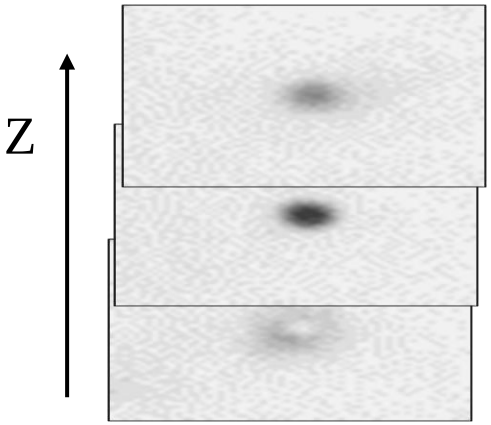

0．1mm

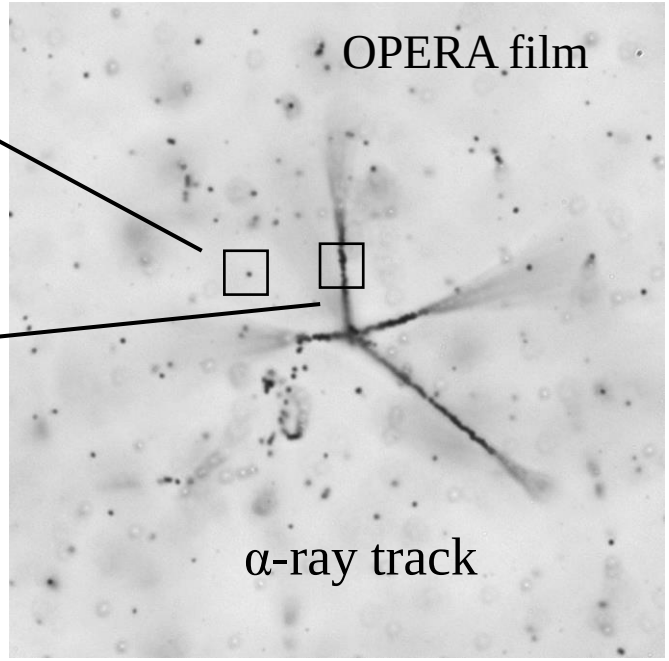
# Nuclear emulsion

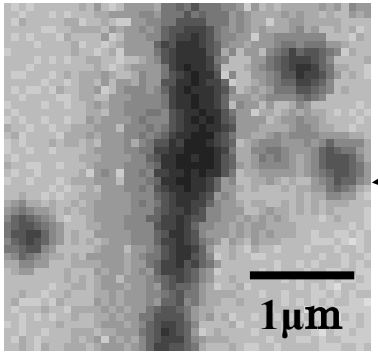
- 3D tracking detector
- Thickness of the emulsion layer >50μm
- Microscope depth of field ~3μm
- Size of the silver grain ~0.3μm
- Optical resolution which is required <0.5μm



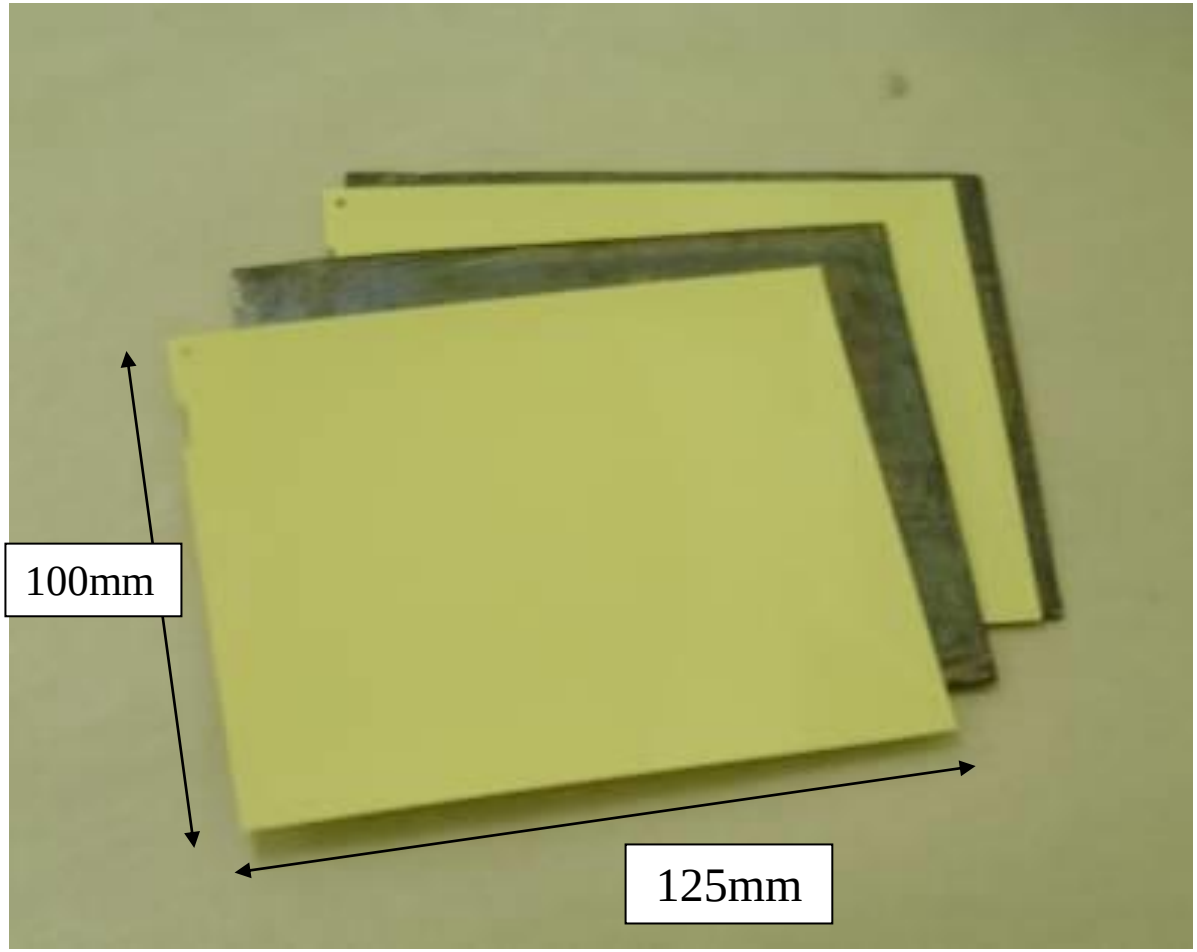



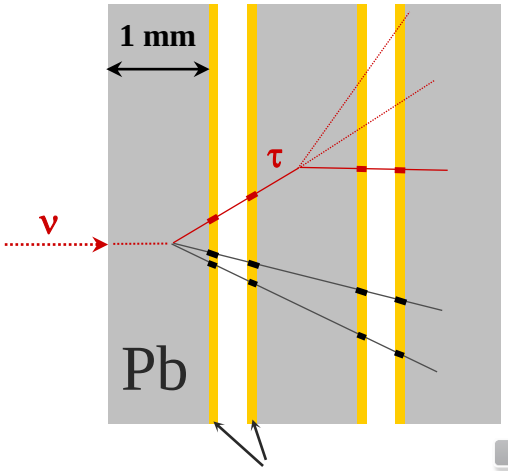

Stacked image res. 0.27μm

# Nuclear Emulsion Film




**Emulsion Cloud Chamber**

**56 lead plates + 57 films**



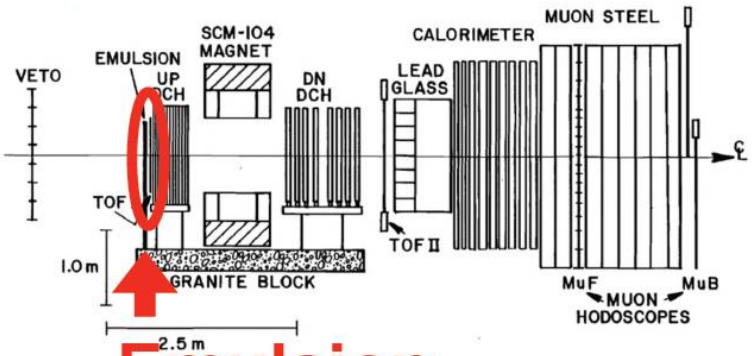

**Nuclear Emulsion Films**

1979-

## Fermilab E531

Neutrino Charm Production

$\nu_\mu \rightarrow \nu_\tau$ Oscillation Search



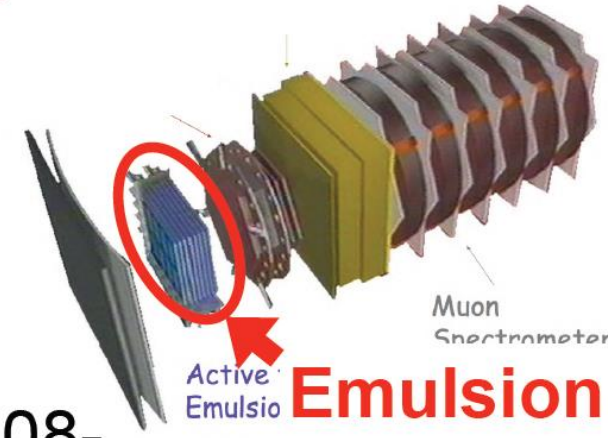

Emulsion

1994-

## CERN WA95 CHORUS

CERN Hybrid Oscillation Research Apparatus

$\nu_\mu \rightarrow \nu_\tau$ Oscillation Search

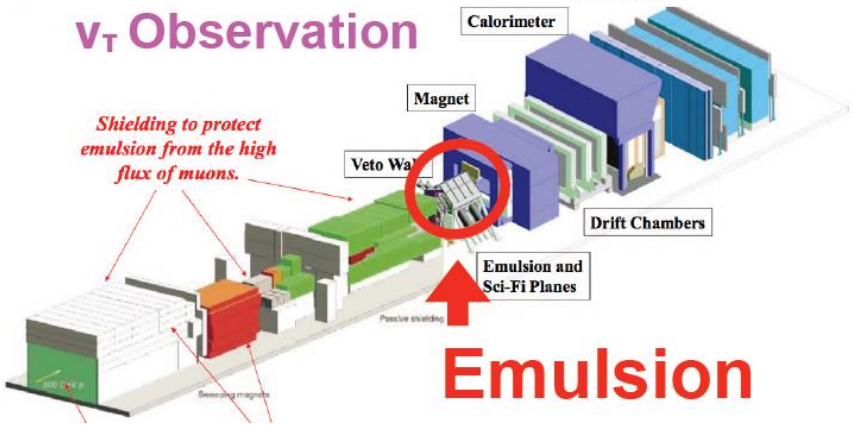



1997-

## Fermilab E872 DONUT

Direct Observation of Nu Tau

$\nu_\tau$ Observation




Emulsion

2008-

## CERN CNGS1 OPERA

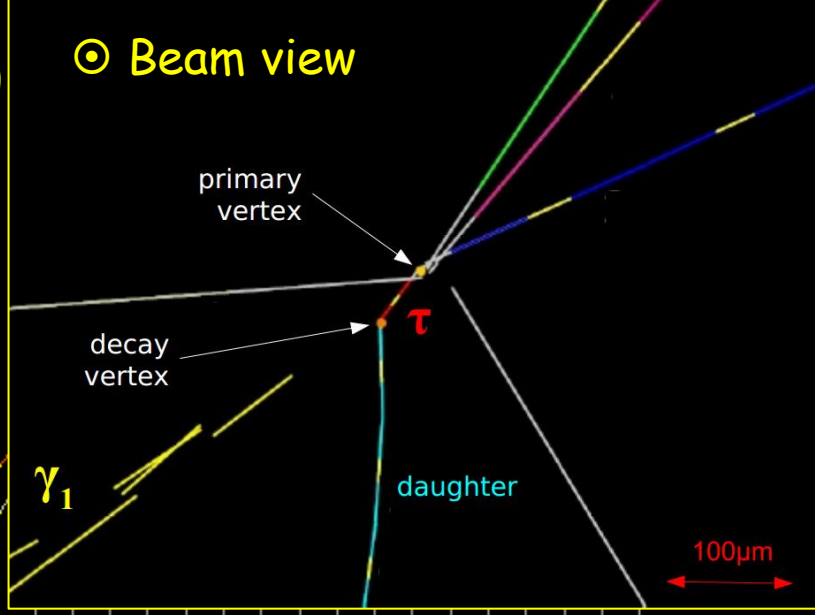
Oscillation Project with Emulsion Tracking Apparatus

$\nu_\mu \rightarrow \nu_\tau$ Appearance Search

Emulsion

# 1st $\nu_\tau$ candidate ($\tau \to h$) (2010)

Phys. Lett. B691 (1010) 138







$\tau \to \rho \nu_\tau$ **candidate**

$\rho \to \pi\text{-}\pi^0$ $(\pi^0 \to \gamma\gamma)$

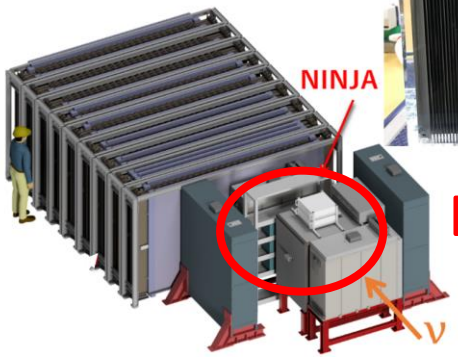
$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV

$m(\pi\text{-}\gamma\gamma) = 640^{+125}_{-80}{}^{+100}_{-90}$ MeV

$Br(\tau \to \rho \nu_\tau) \sim 25\%$

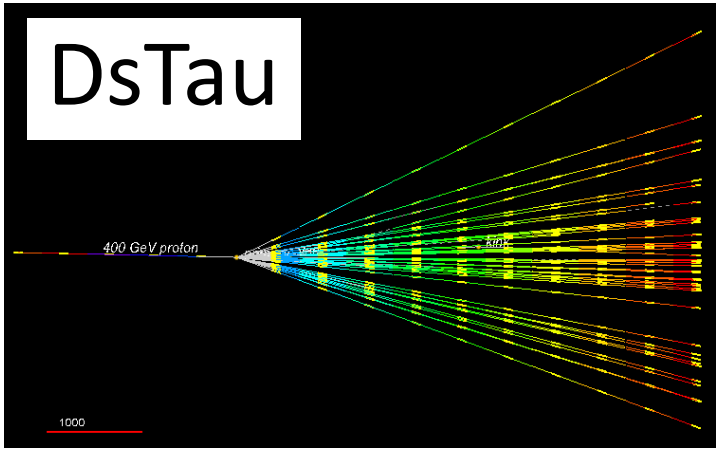
# Coming experiments

NINJA

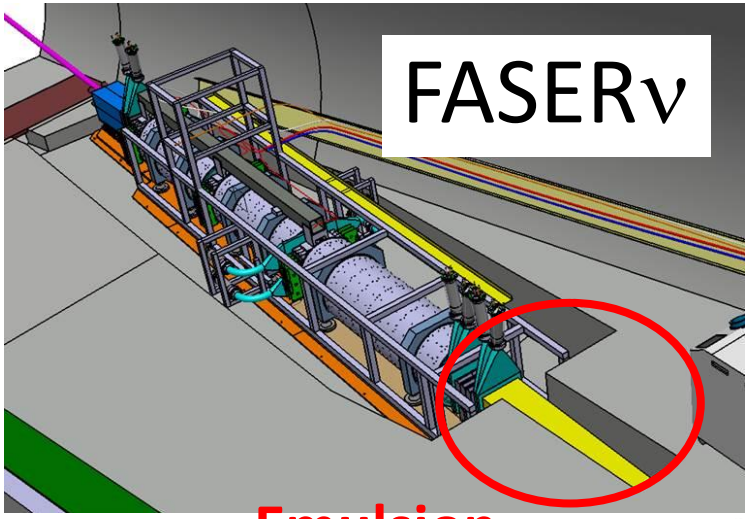



Emulsion

DsTau

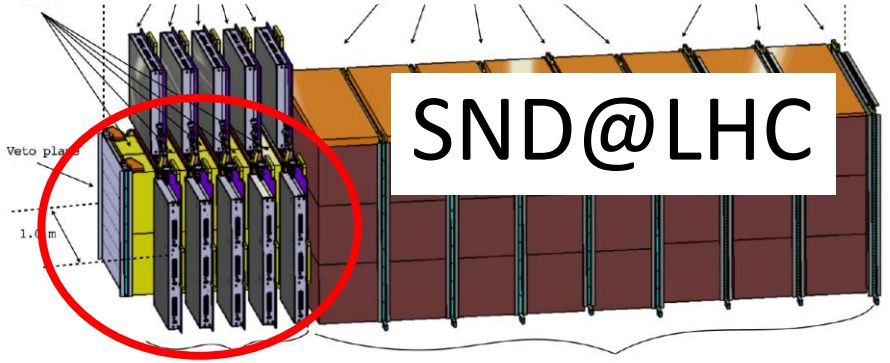



FASERν

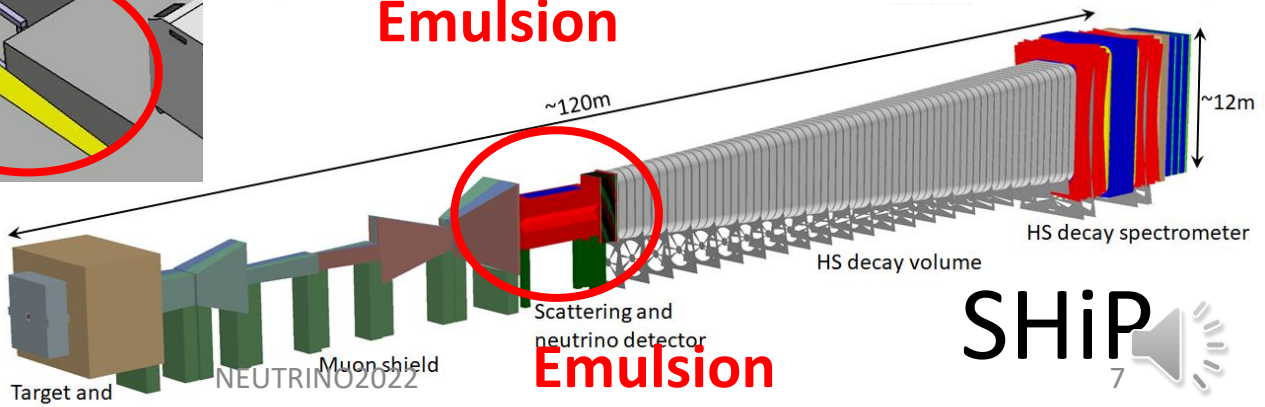


Emulsion

SND@LHC




Emulsion

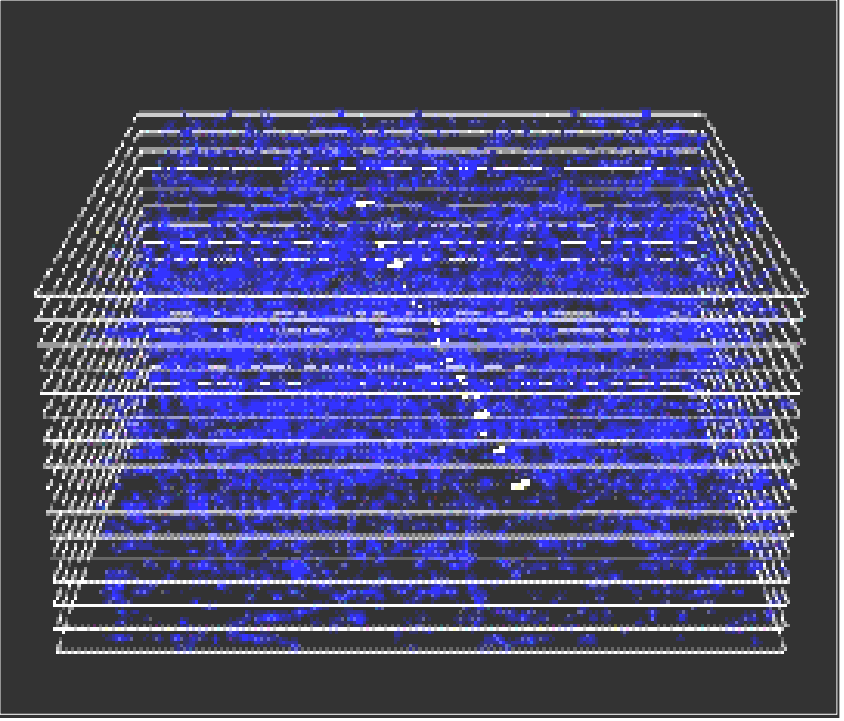


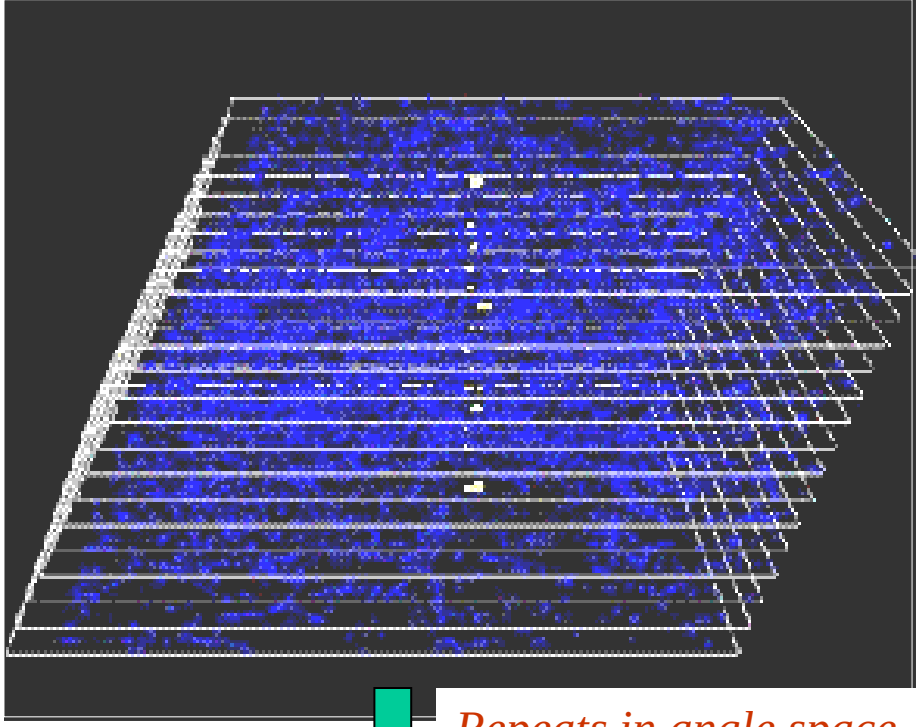

Emulsion

SHiP

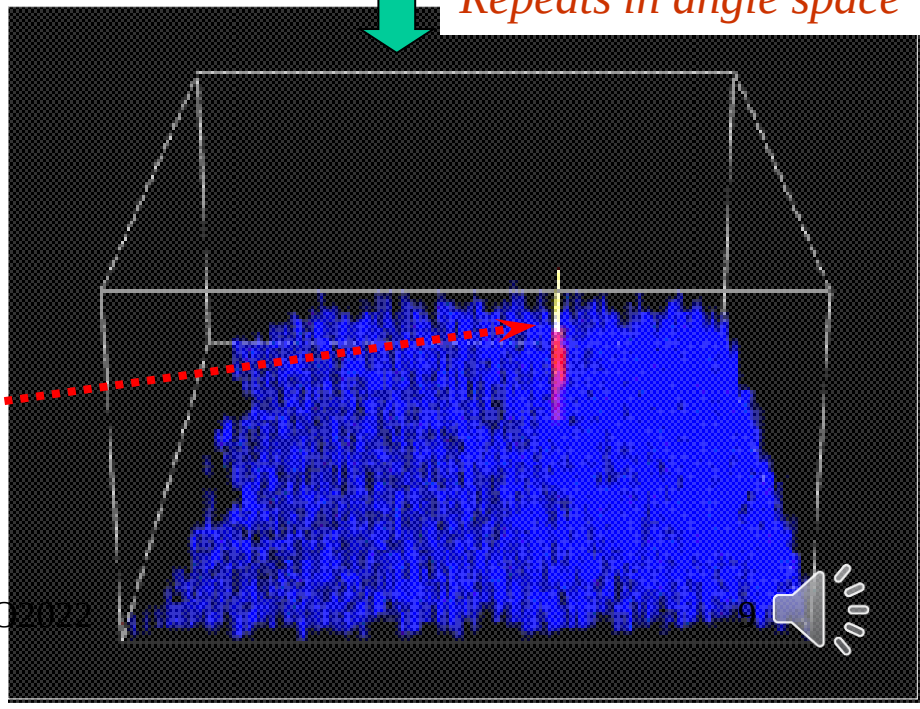
# Emulsion scanning system







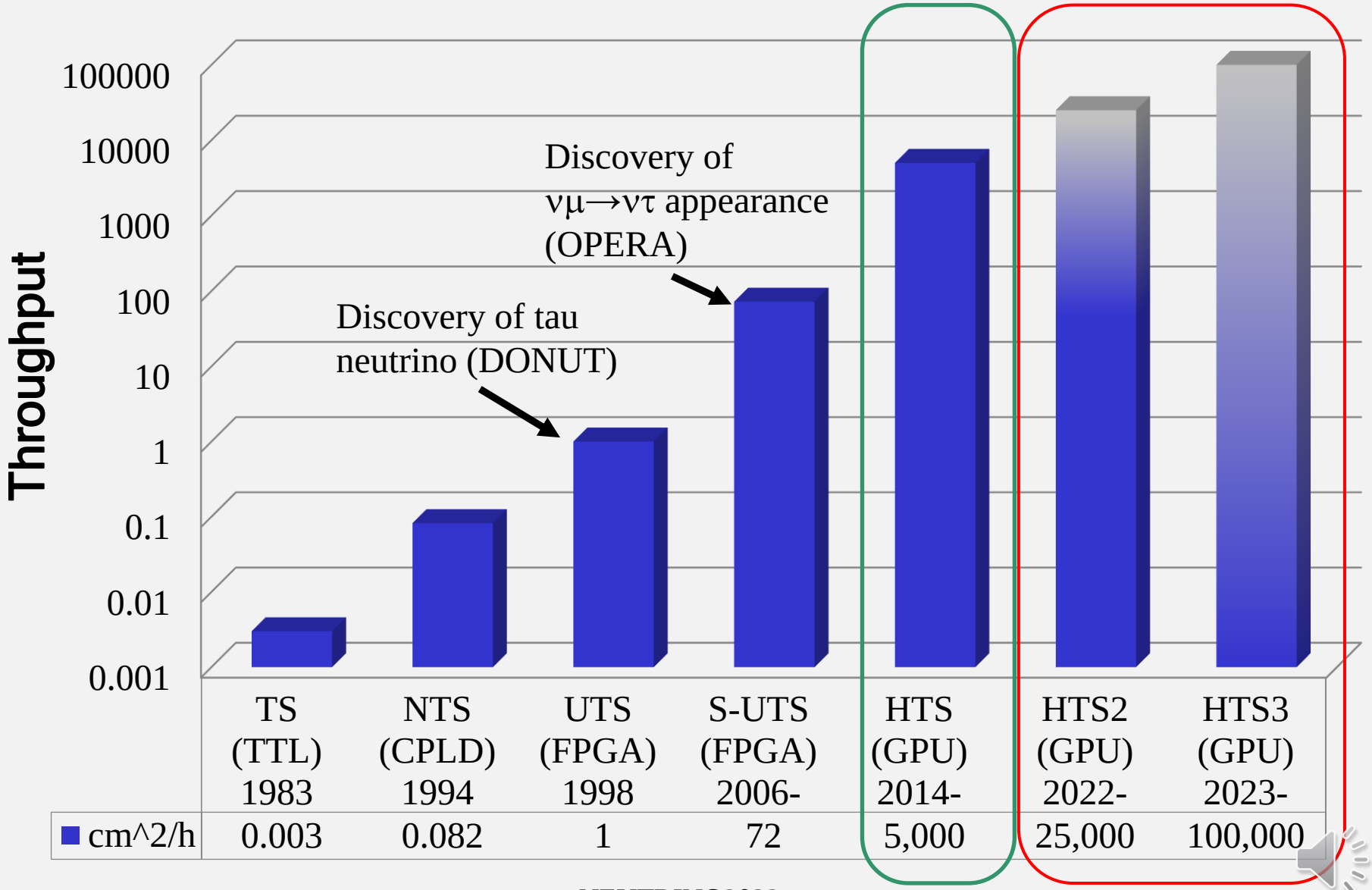
*Repeats in angle space*



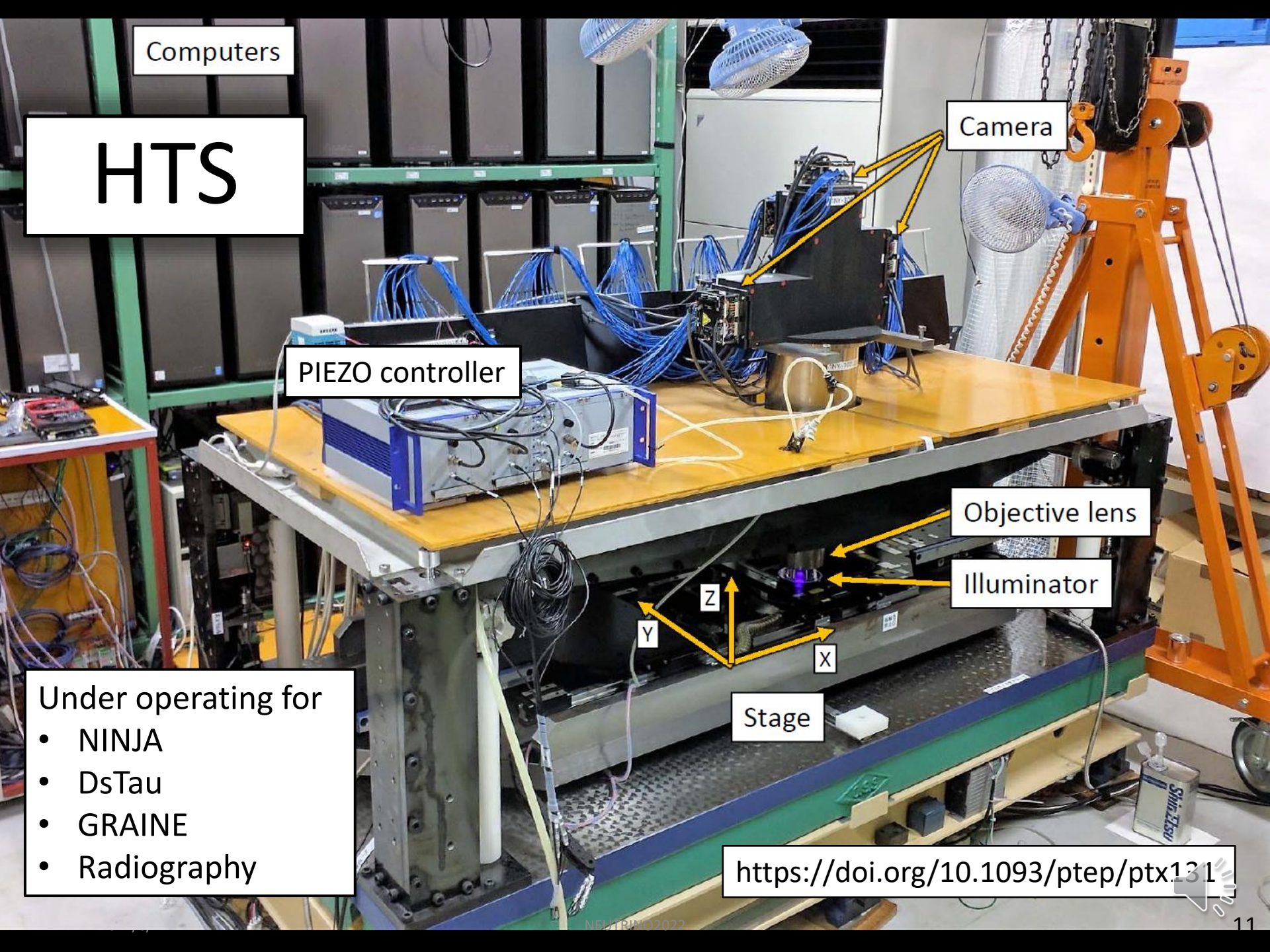
- Take 16 tomographic images by microscope optics.
- Shift images to aim at specific angle tracks
- Sum up 16 images to examine coincidence.
- Find signal of tracks.

***Invented by K.Niwa in 1974***

# Emulsion Readout History and Roadmap

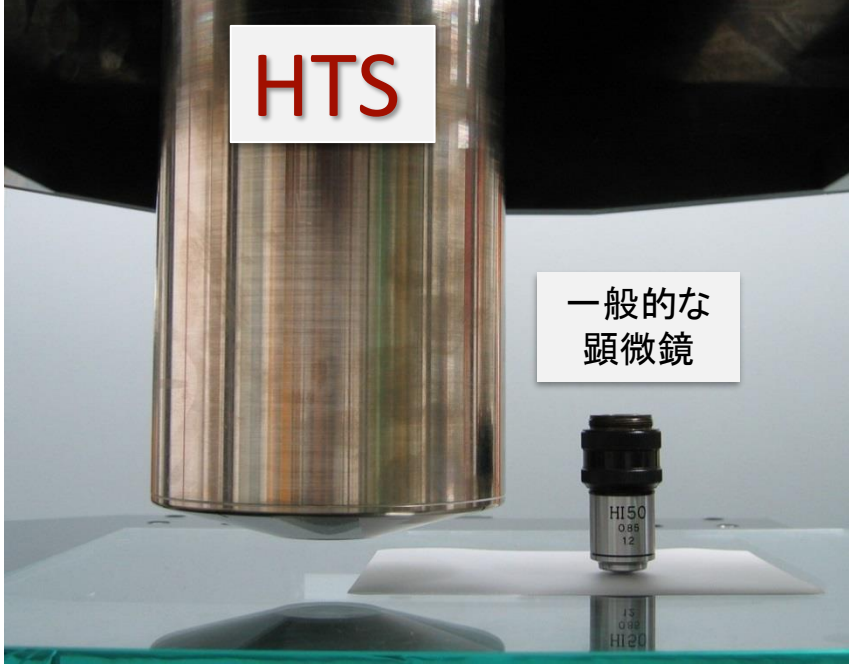



| | TS (TTL) 1983 | NTS (CPLD) 1994 | UTS (FPGA) 1998 | S-UTS (FPGA) 2006- | HTS (GPU) 2014- | HTS2 (GPU) 2022- | HTS3 (GPU) 2023- |
|---|---|---|---|---|---|---|---|
| cm^2/h | 0.003 | 0.082 | 1 | 72 | 5,000 | 25,000 | 100,000 |


Computers
HTS
Camera
PIEZO controller
Objective lens
Illuminator
Z
Y
X
Stage
Under operating for
• NINJA
• DsTau
• GRAINE
• Radiography
https://doi.org/10.1093/ptep/ptx131

# HTS concept

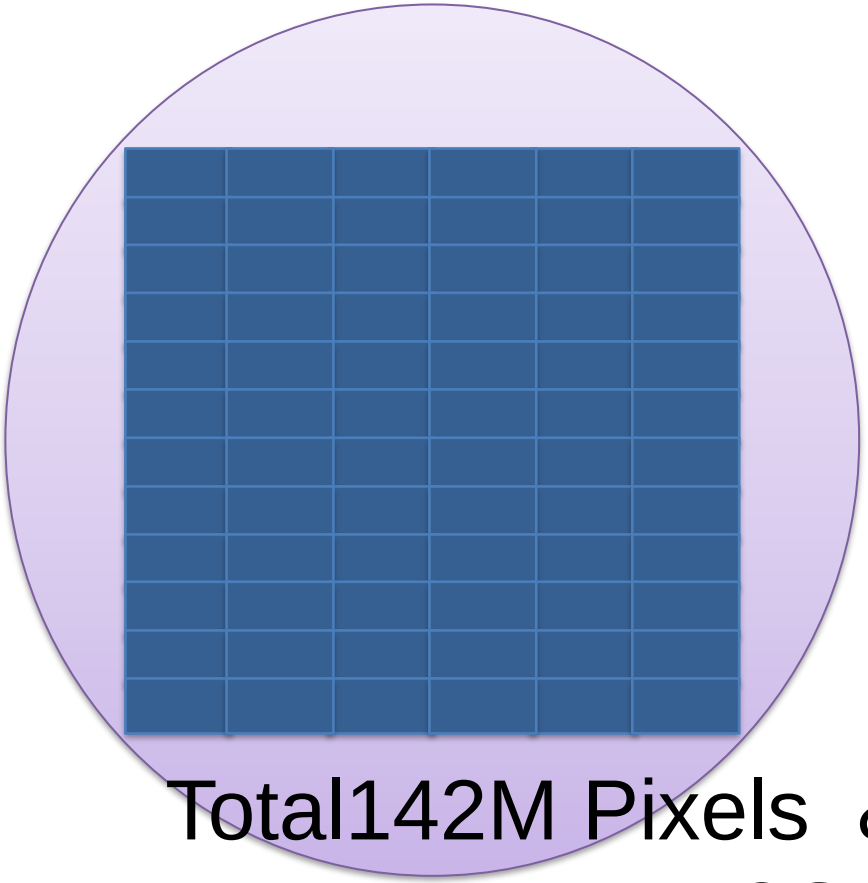
- Very large field of view
  5 x 5 $mm^2$ (x600 cf. SUTS)
- Quick stage using the linear motors (good transfer characteristic) and counter stage.
- GPGPU based image processing
  <100ms @tanθ<1.6 (Geforece GTX680 *72)



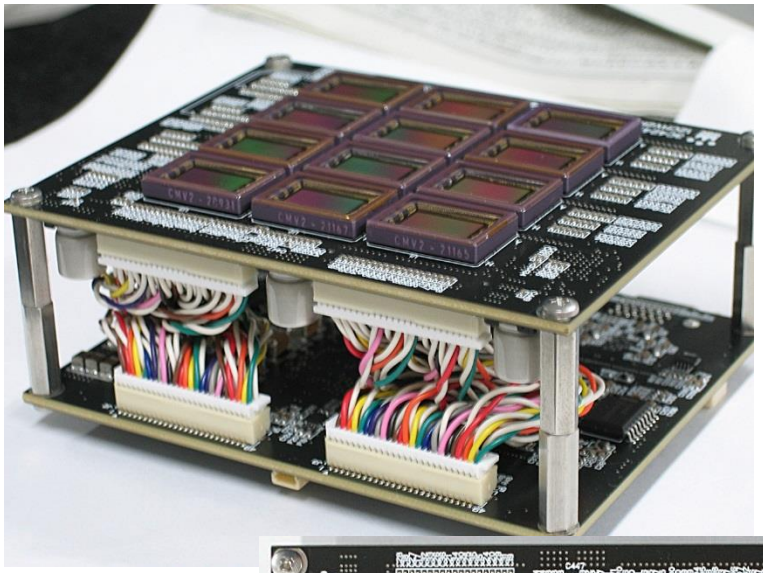

| | FOV | View Cycle | Scan speed |
|---|---|---|---|
| SUTS | 0.04$mm^2$ | 50Hz | 72$cm^2$/h |
| **HTS (running)** | **25$mm^2$** | **5Hz** | **4500$cm^2$/h** |
| **HTS2 (under commissioning.)** | 50$mm^2$ | 15Hz equiv. | 25000$cm^2$/h |

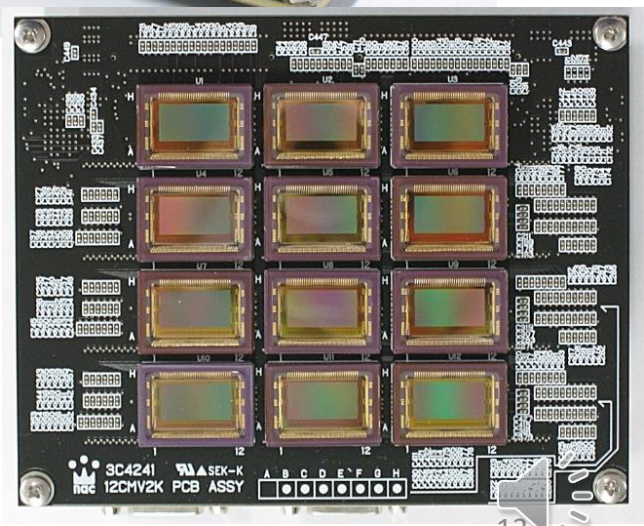
# Mosaic Imager

Divide FOV into 72 parts.
Need the sensor of 2M pixel and 300fps.



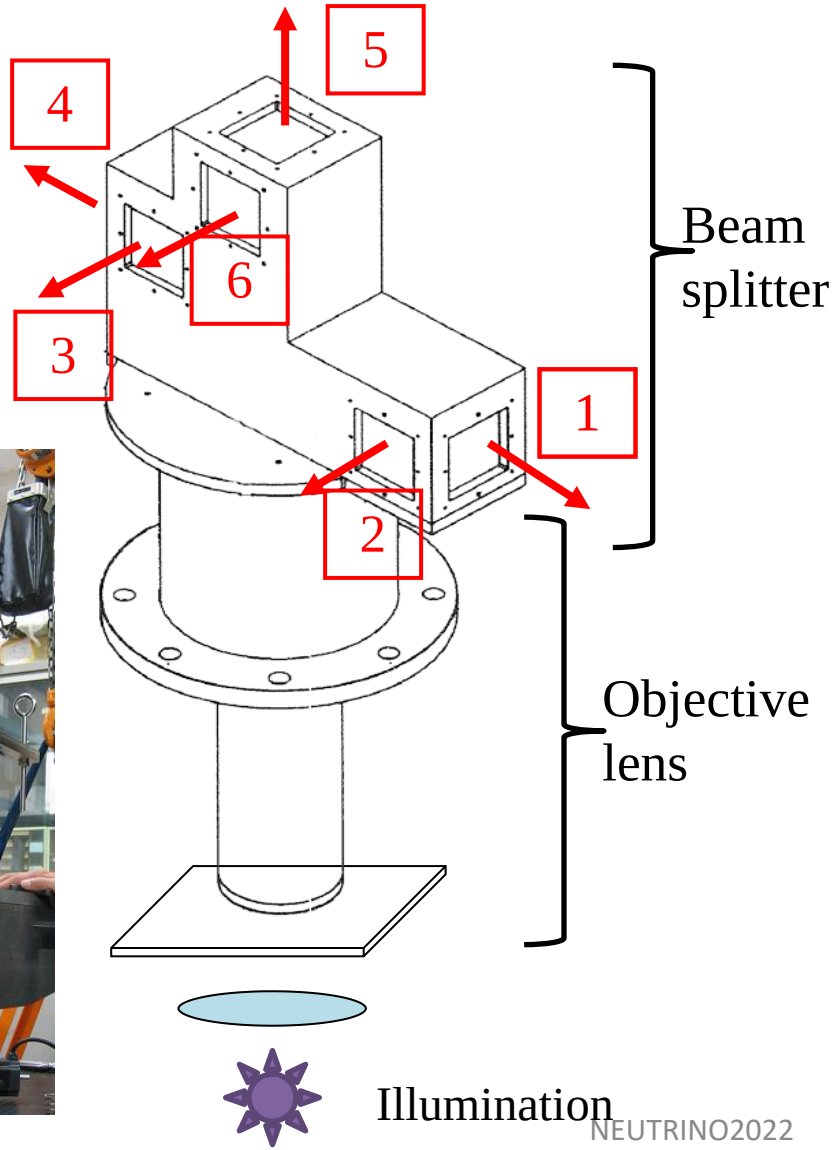
Specially ordered Mosaic Imager

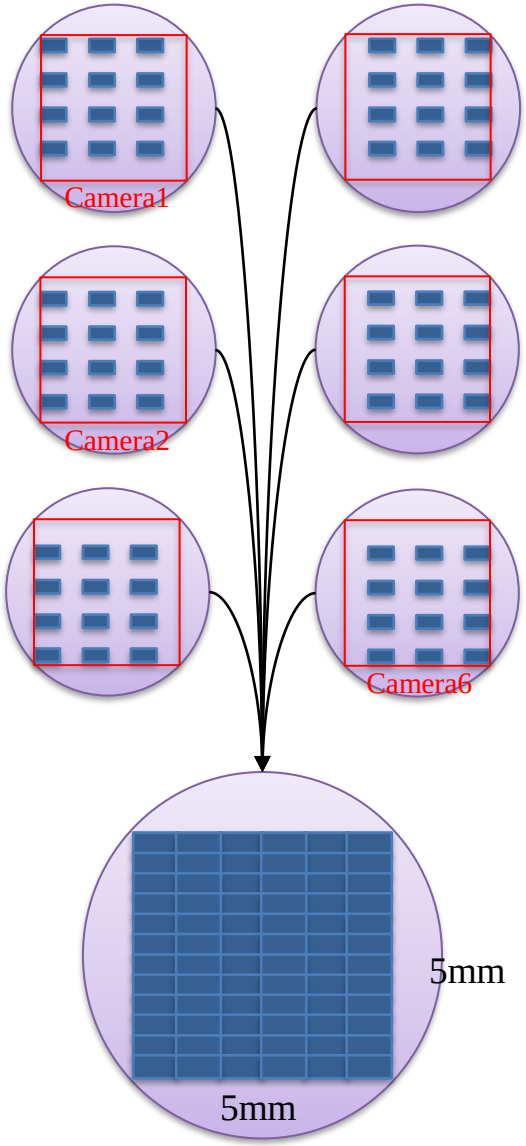





Total142M Pixels & 300fps
Data rate : 43GByte/s

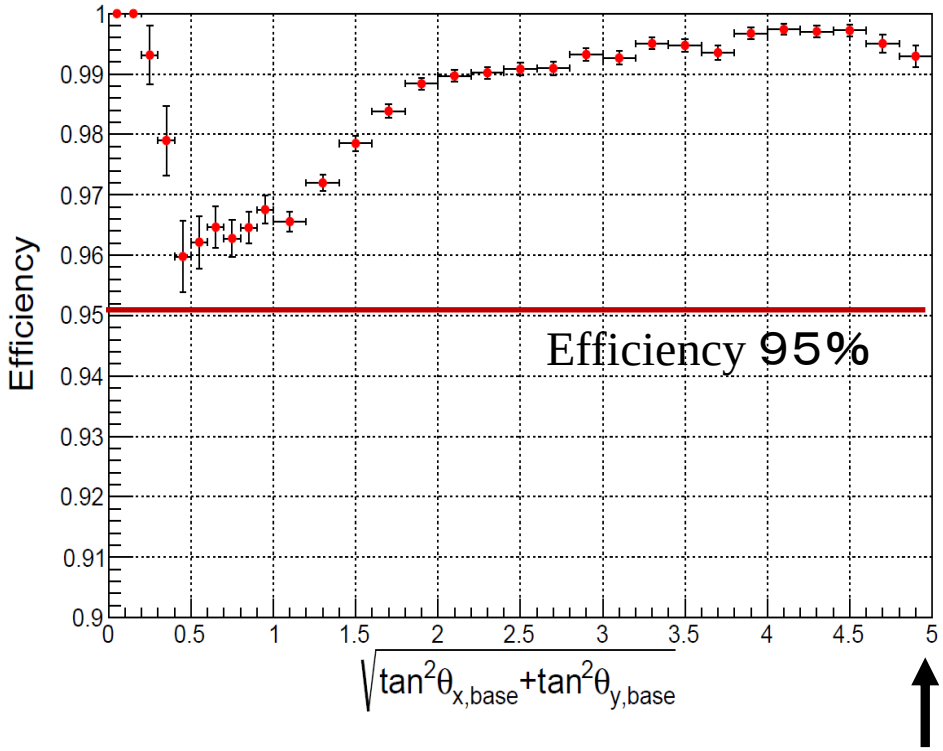
# Mosaic Imager with beam splitter

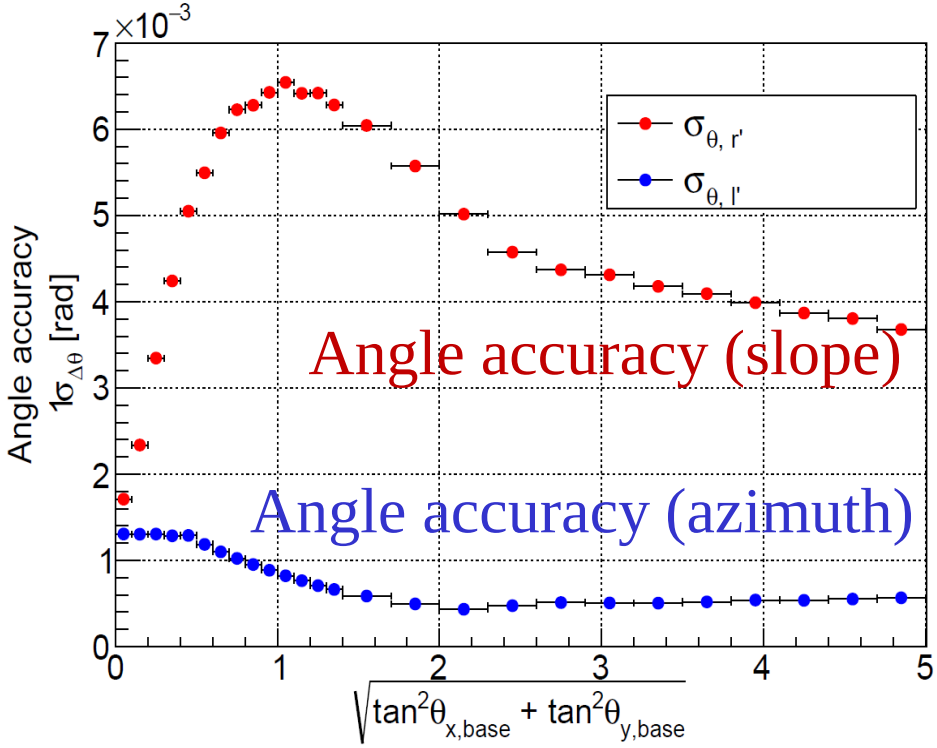


# Efficiency and Angle accuracy

arXiv:2112.02887 [physics.ins-det]
https://doi.org/10.1093/ptep/ptac076



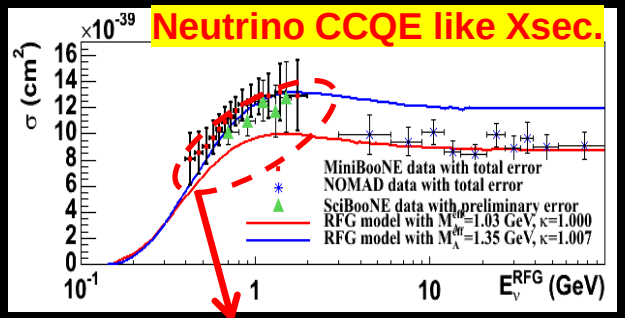

**80% of Solid angle**

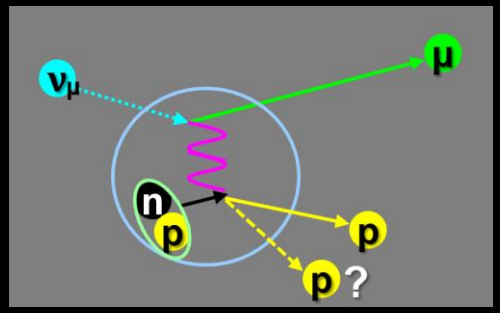
# NINJA experiment

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

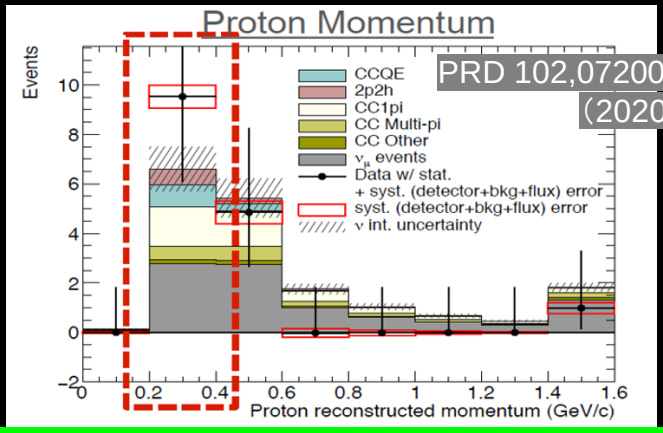
**Physics motivation**

1. Precise measurement of neutrino cross-sections
2. Sterile neutrino search

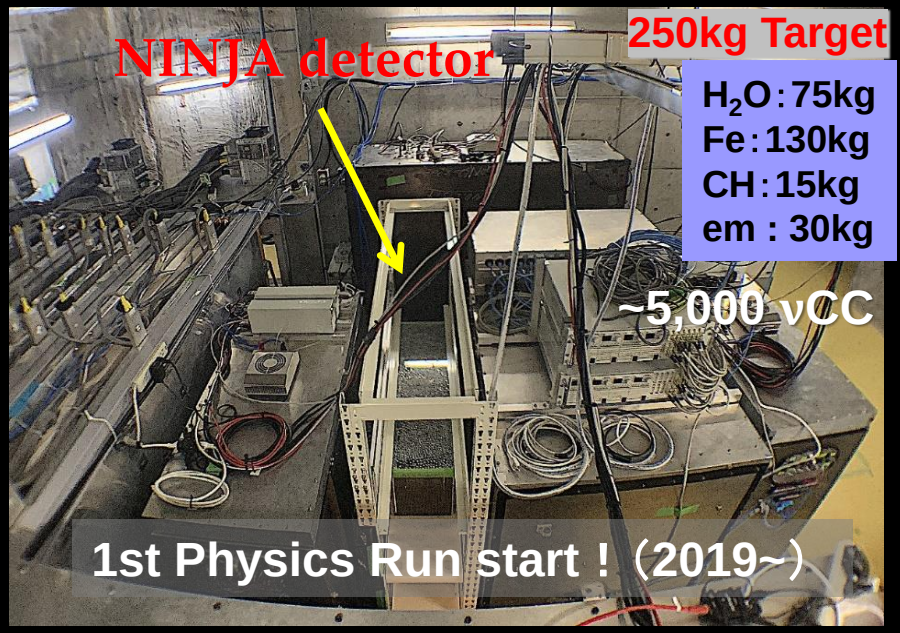


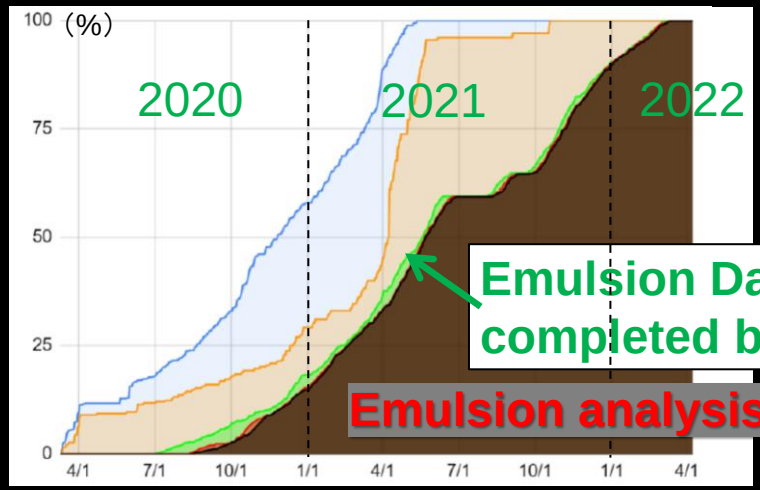




ν-multi nucleon interaction (MEC, 2p2h)??



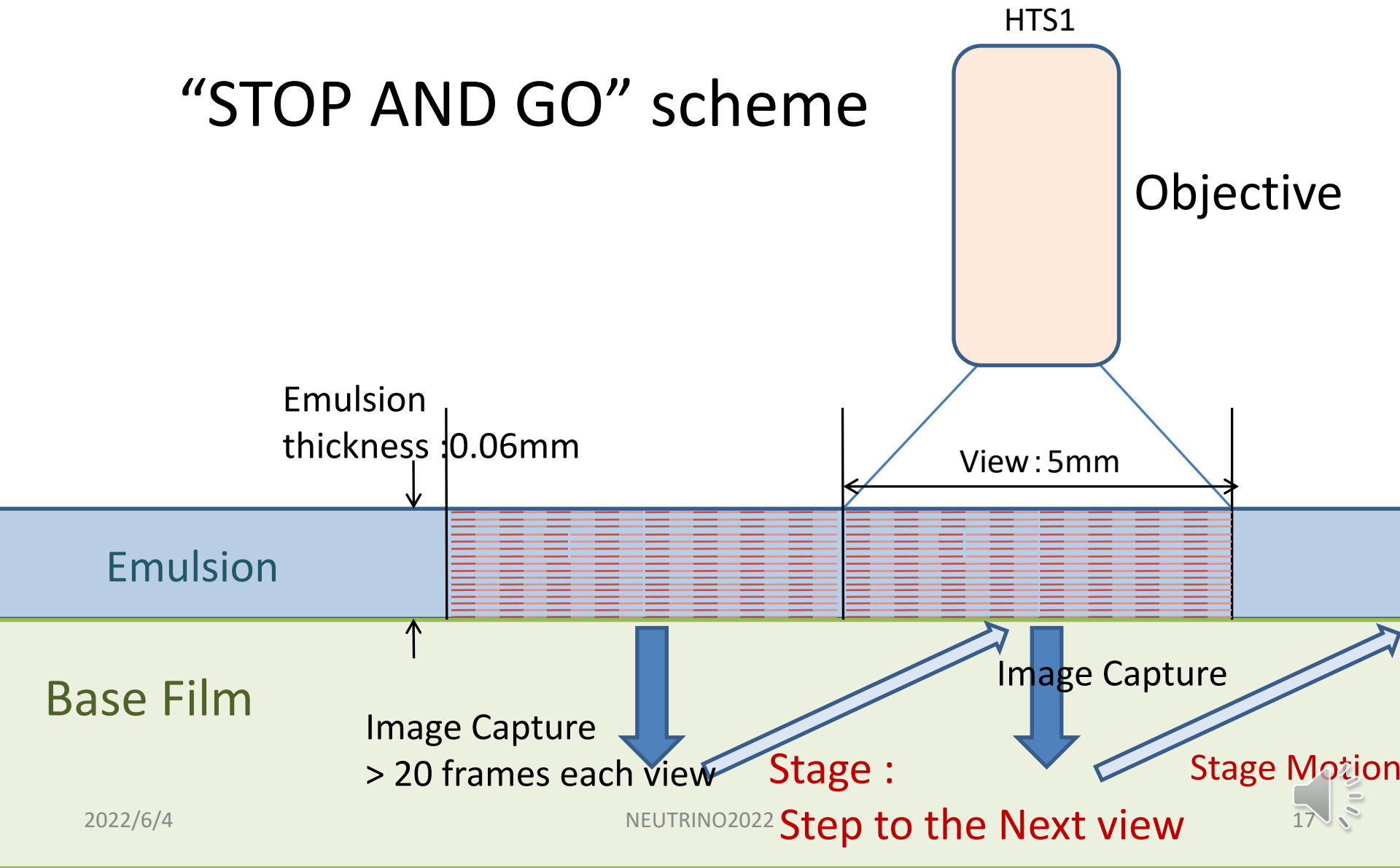

First measurement of slow protons in ν-water interactions



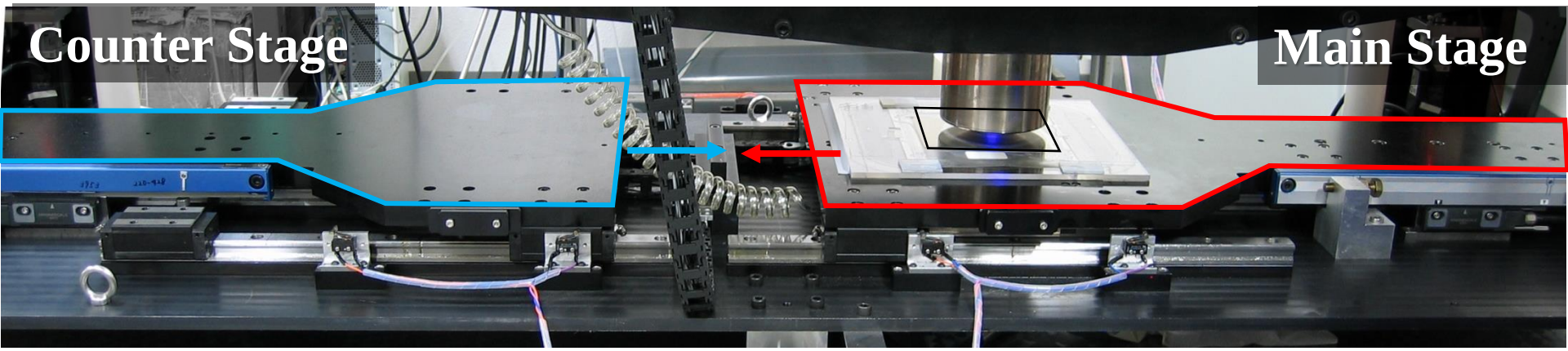



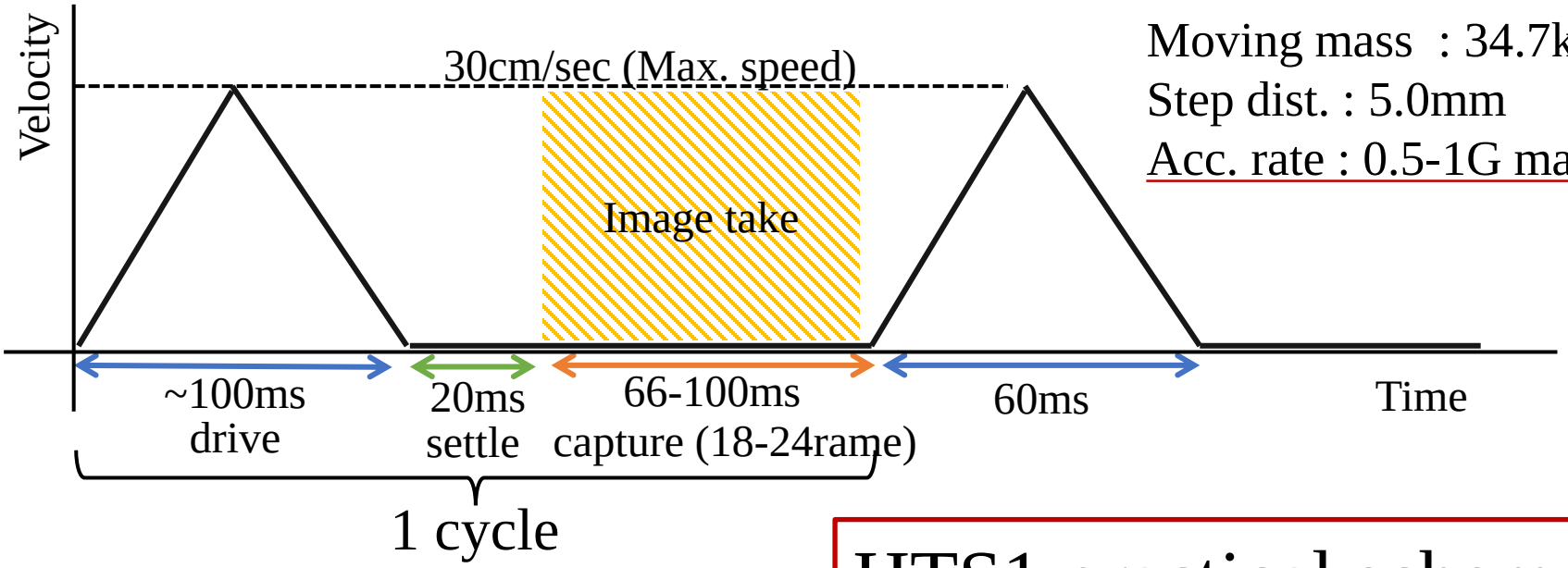

→ 2nd Physics Run : 500m² (4x)

# What is scan speed limit in HTS1



# Time chart of each cycle



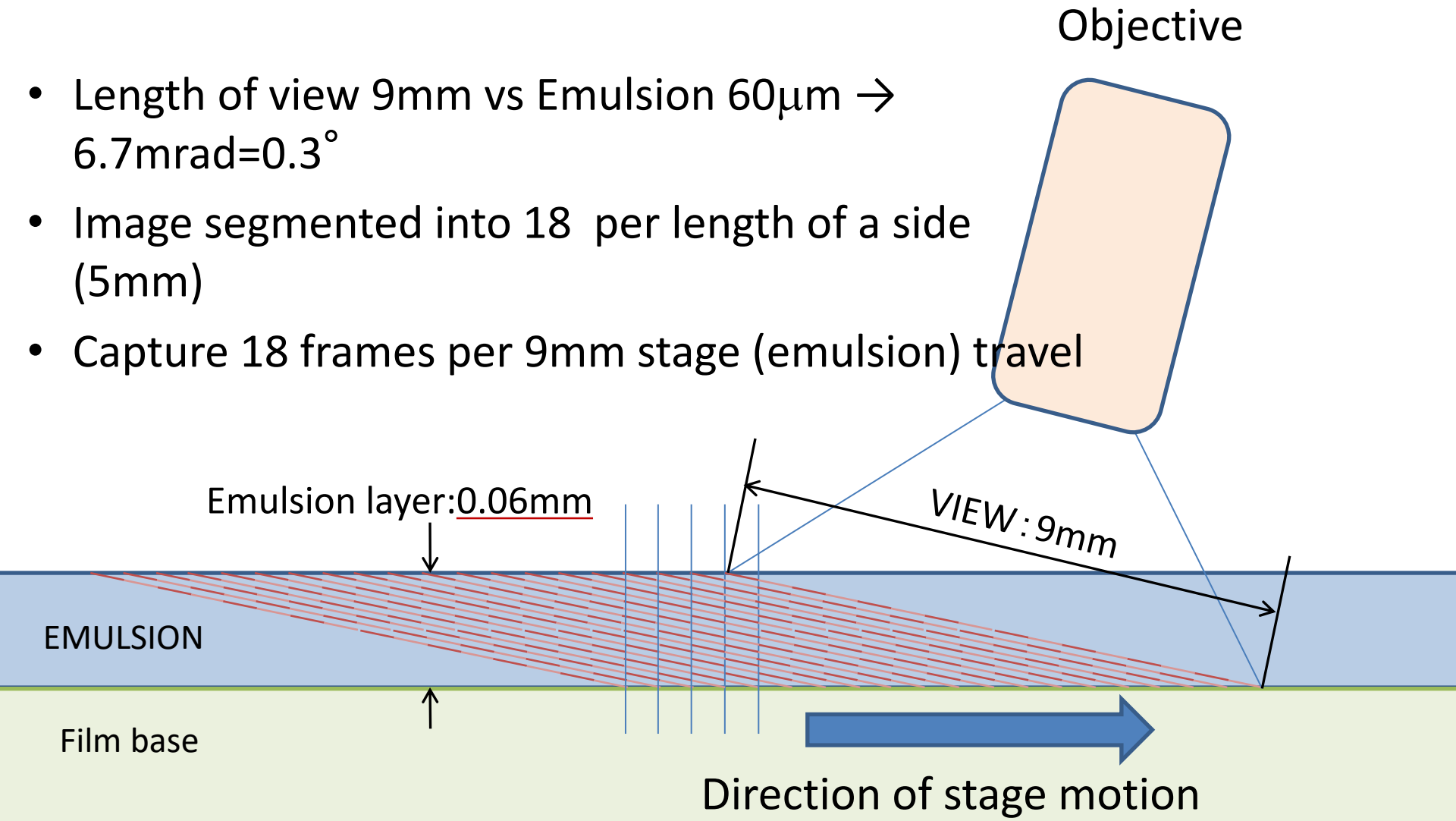




Moving mass : 34.7kg
Step dist. : 5.0mm
Acc. rate : 0.5-1G max.

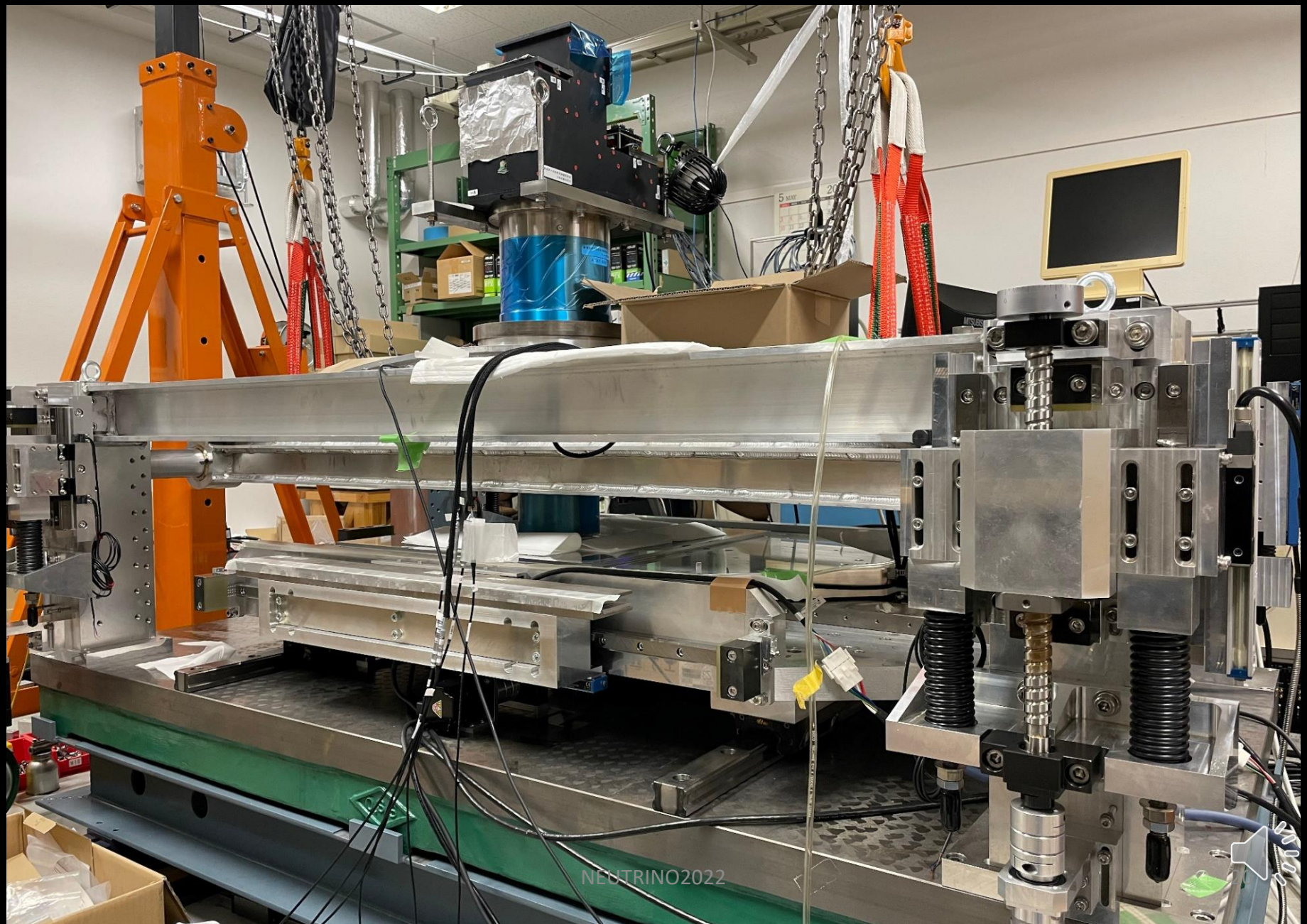
HTS1 practical scheme

# Continuous image capturing

- Length of view 9mm vs Emulsion 60μm → 6.7mrad=0.3°
- Image segmented into 18 per length of a side (5mm)
- Capture 18 frames per 9mm stage (emulsion) travel



# HTS2



# Summary of readout system

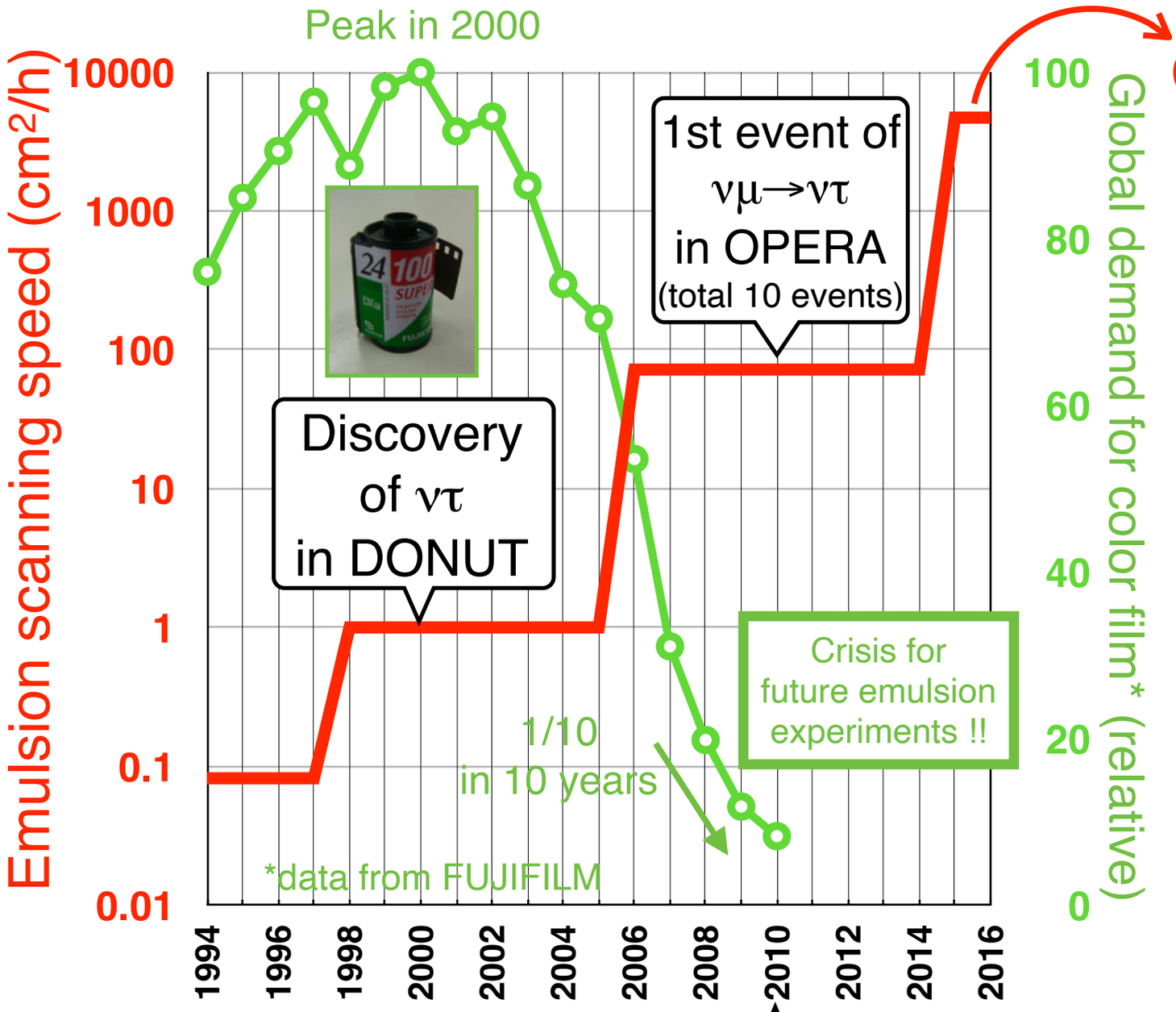
- The feature of Nuclear Emulsion
  - True 3D tracking detector
  - Intrinsic acceptance is 4-pi
  - dE/dx, momentum by MCS, shower detection
- Data quality by high speed scanning system
  - Angle accuracy : ~1mrad in azimuth, 2-6mrad in slope
  - Detection efficiency > 95%
  - Scanning Speed : 10,000 $m^2$/y will be coming soon

# Nuclear Emulsion Detector
# Recent technologies

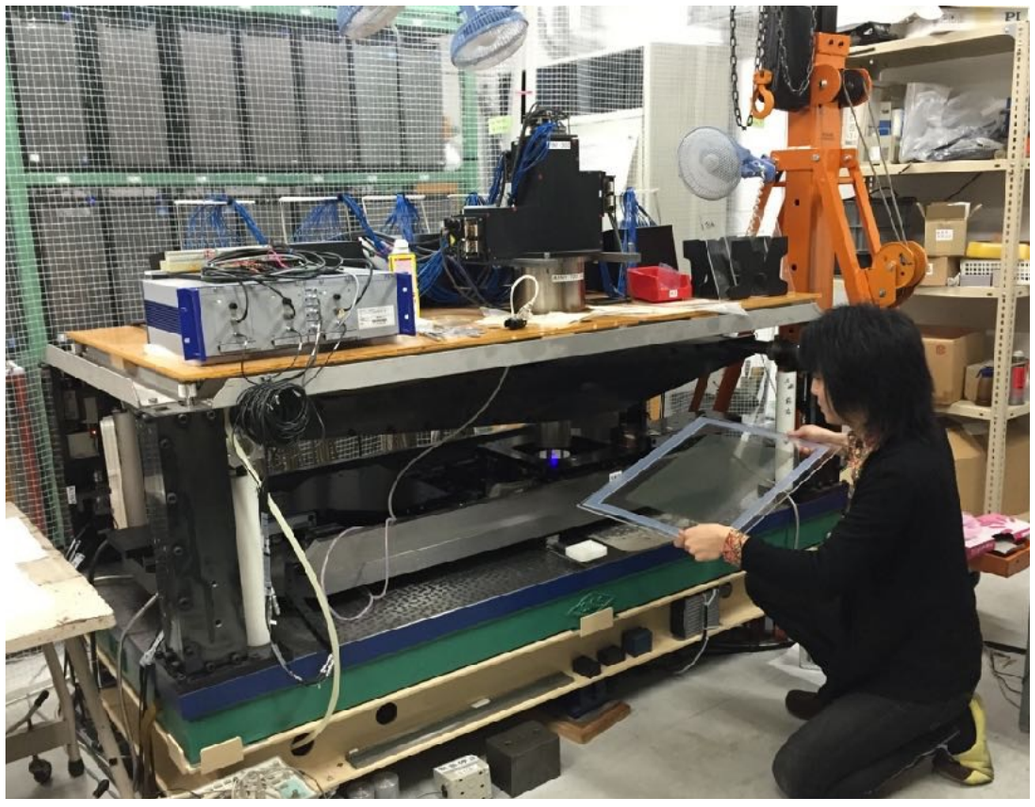

## Hiroki ROKUJO
## (Nagoya Univ.)


1. Birth of Nagoya-made Nuclear Emulsion
2. Large-scale Emulsion Production Facility

# Evolution of Emulsion Scanning Speed
## and Decline of Photographic Film Industry




Current system "HTS" 5000 cm²/h



→New system "HTS-II" (developing) will be 25000 cm²/h (x5 faster)

Presented by Nakano

We started the development and supply of Nuclear Emulsion itself in our laboratory (2010–)

# Introduction of Emulsion Gel Production System

名古屋大学 NAGOYA UNIVERSITY

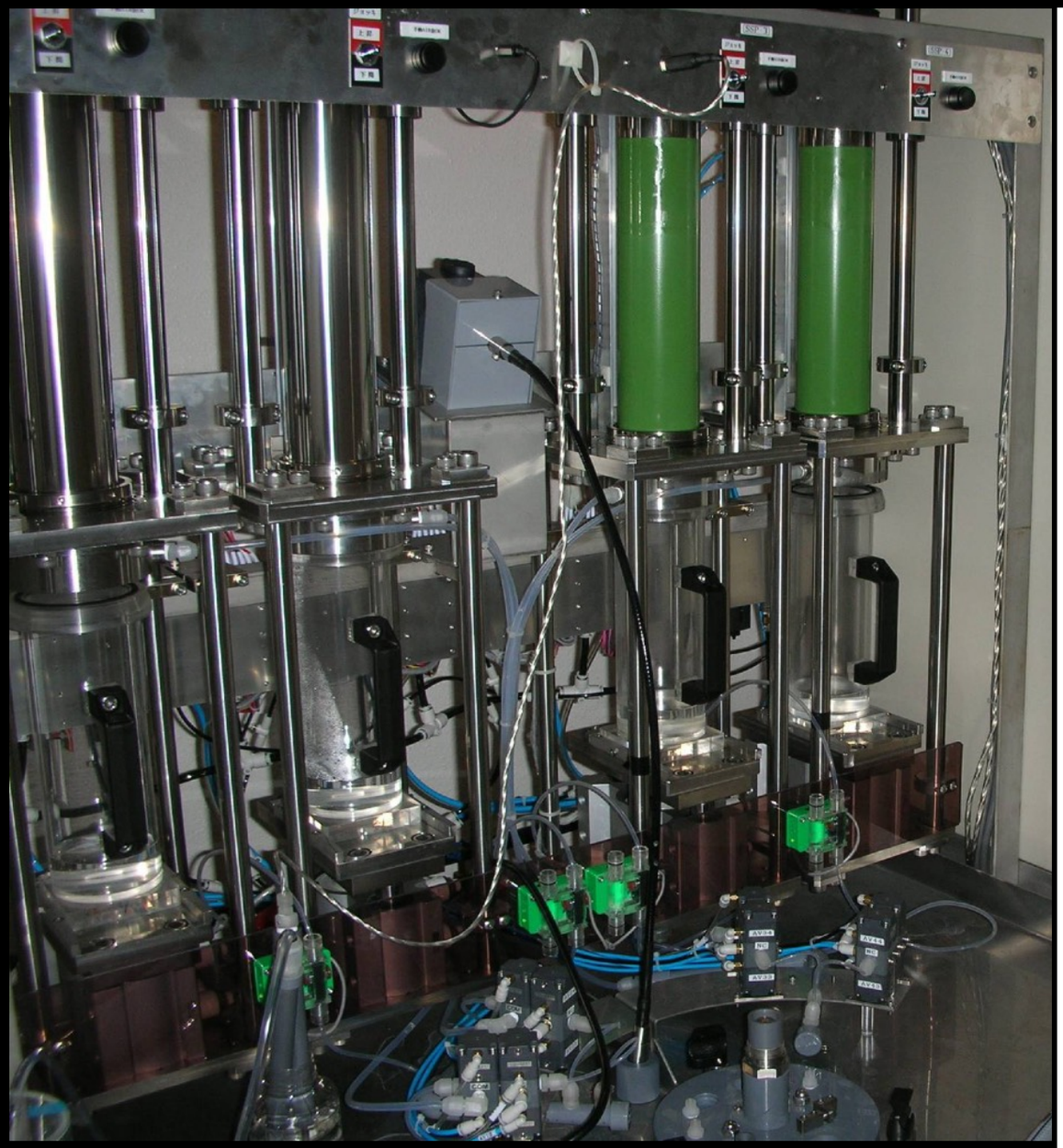
in cooperation with former members of Fuji Film

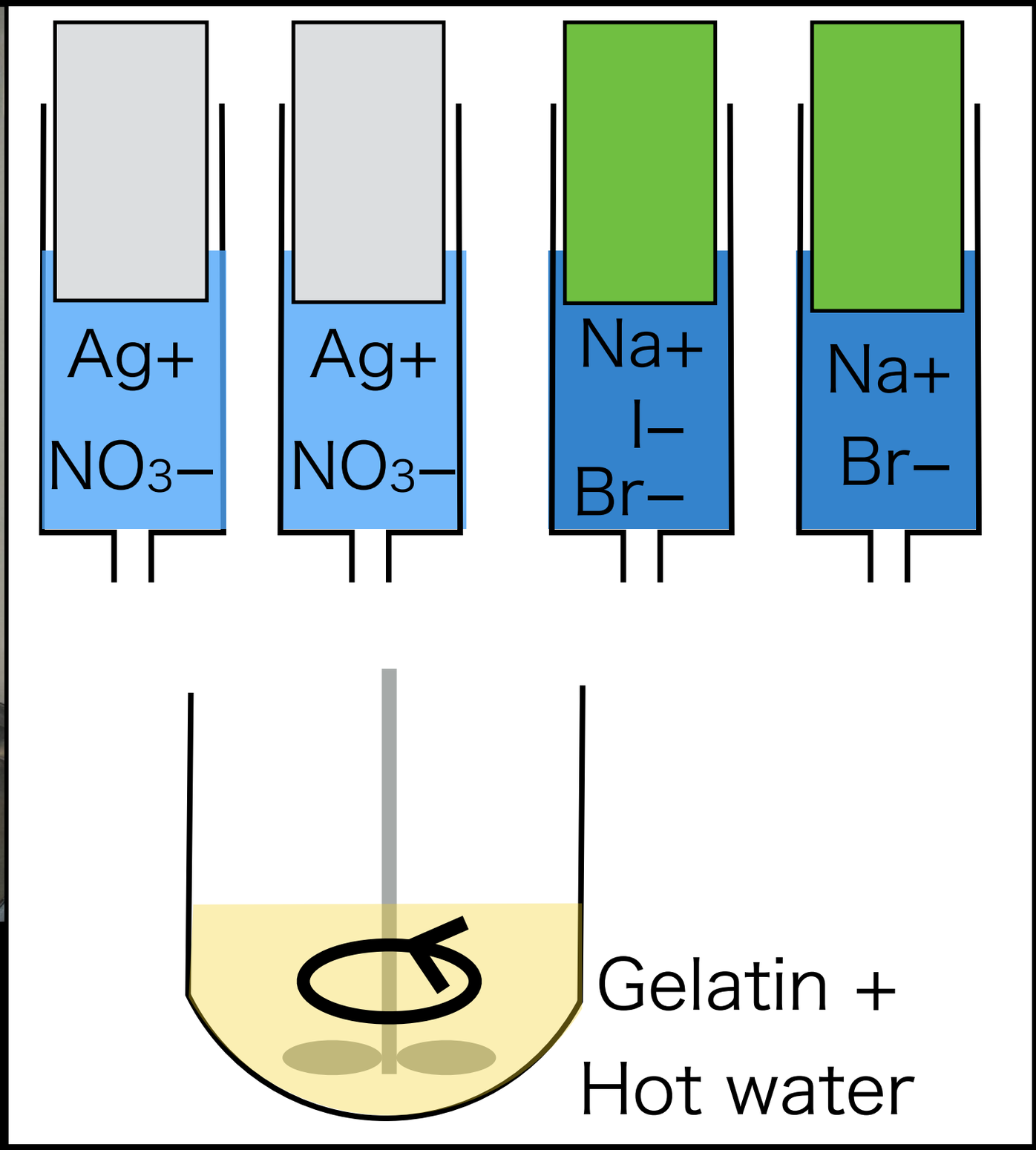

**Developing self-produced nuclear emulsion that satisfies our own research requirement.**

# Introduction of Emulsion Gel Production System

名古屋大学 NAGOYA UNIVERSITY

in cooperation with former members of Fuji Film

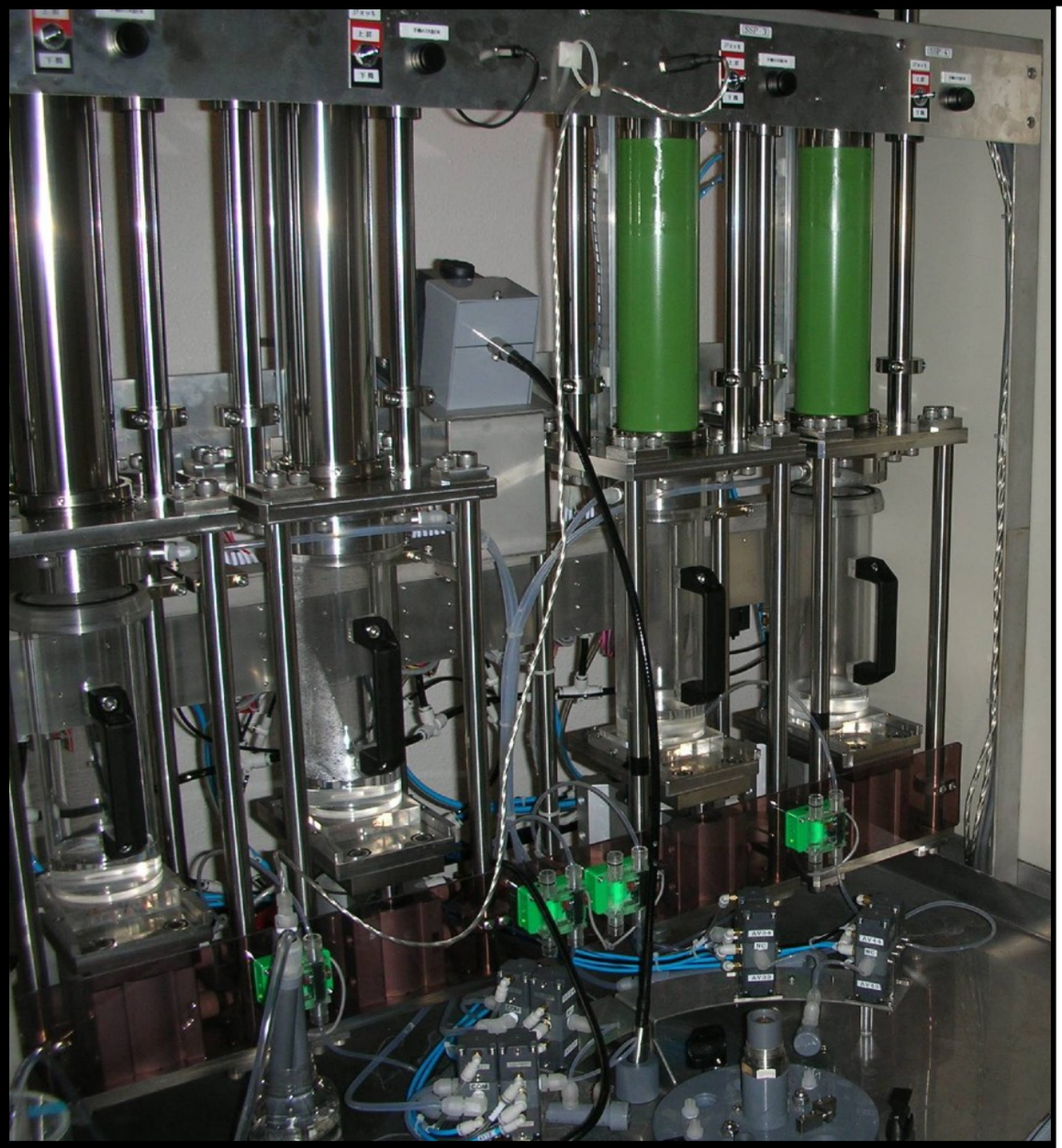


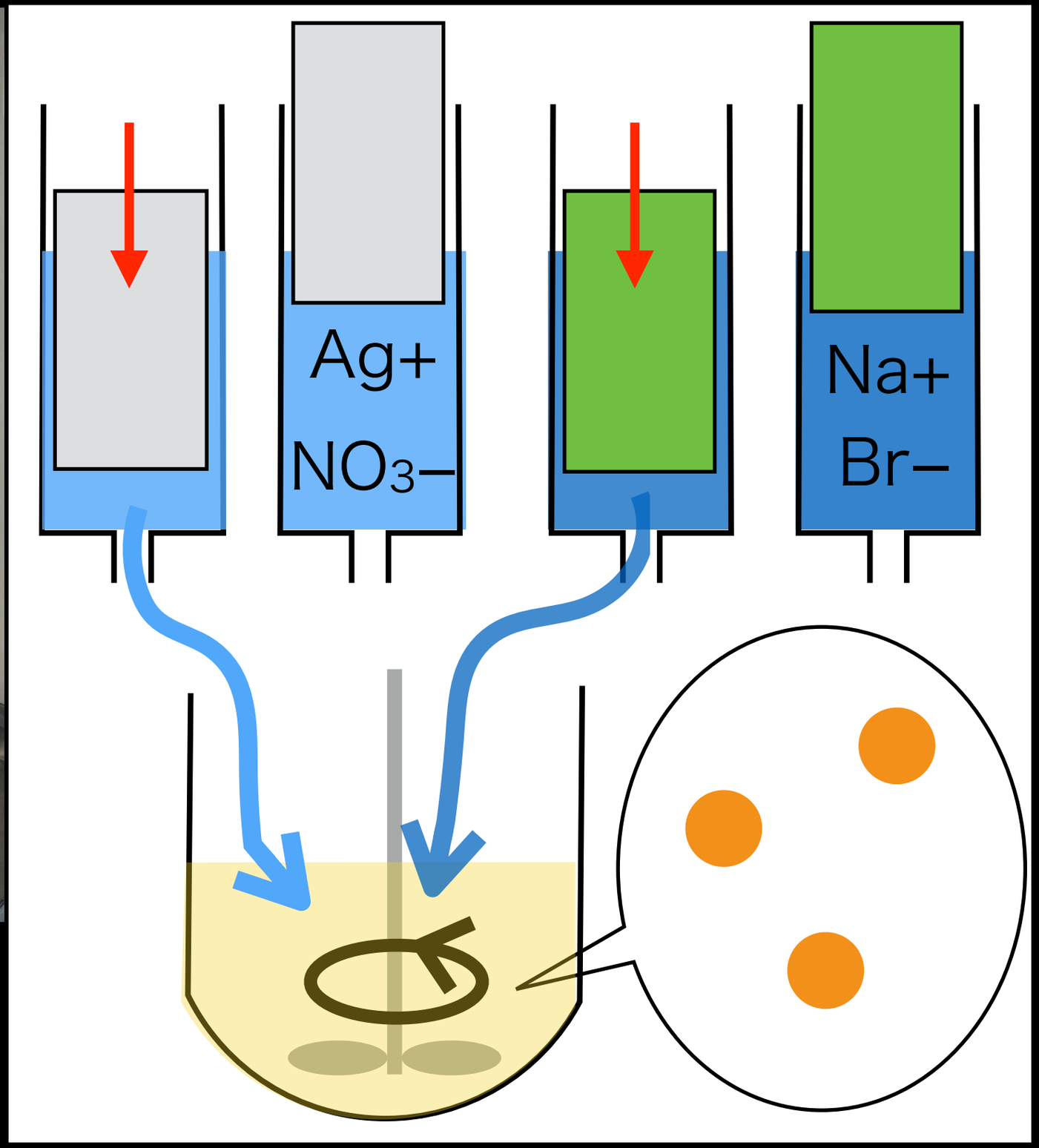


# Introduction of Emulsion Gel Production System

名古屋大学 NAGOYA UNIVERSITY

in cooperation with former members of Fuji Film





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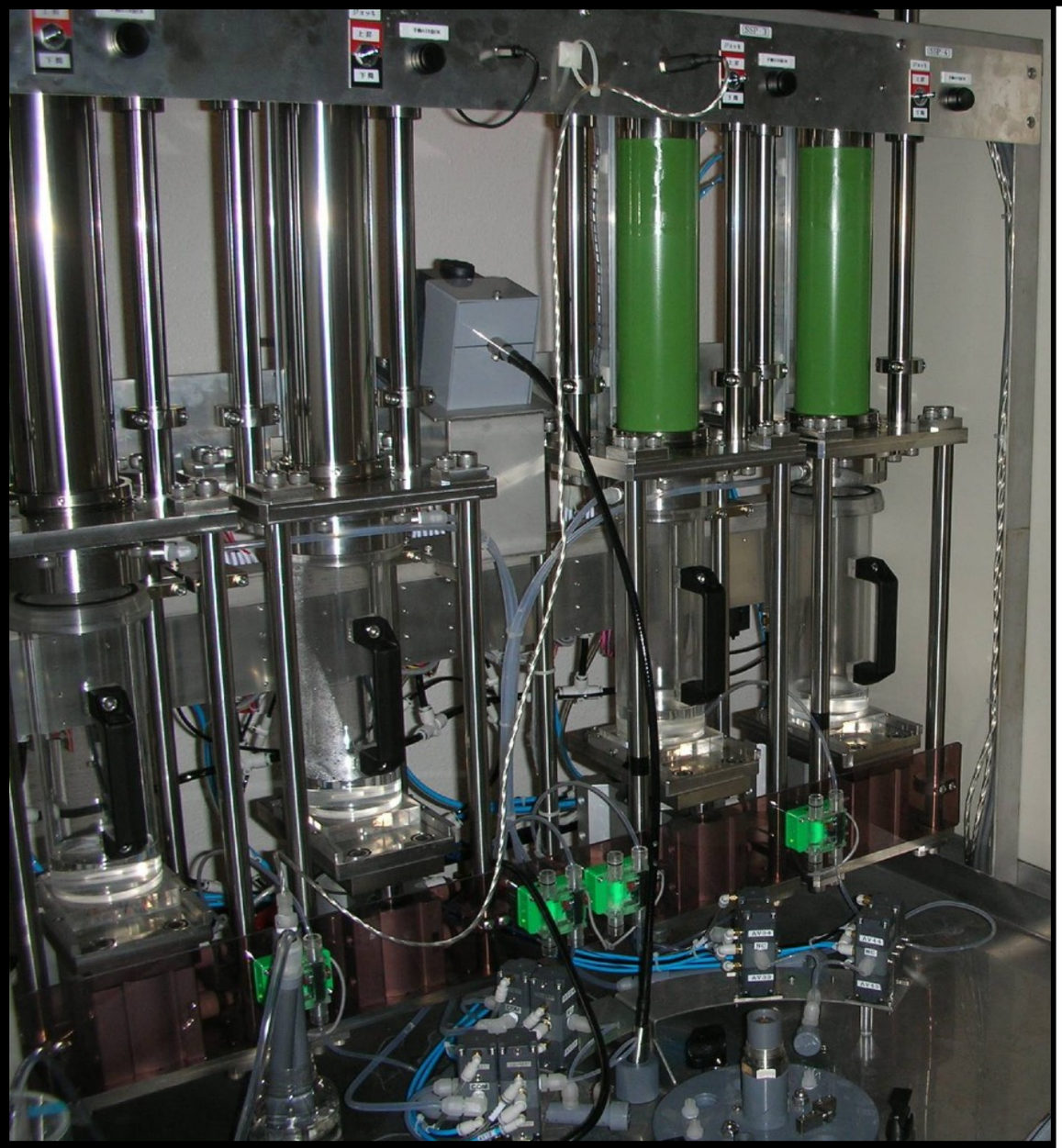
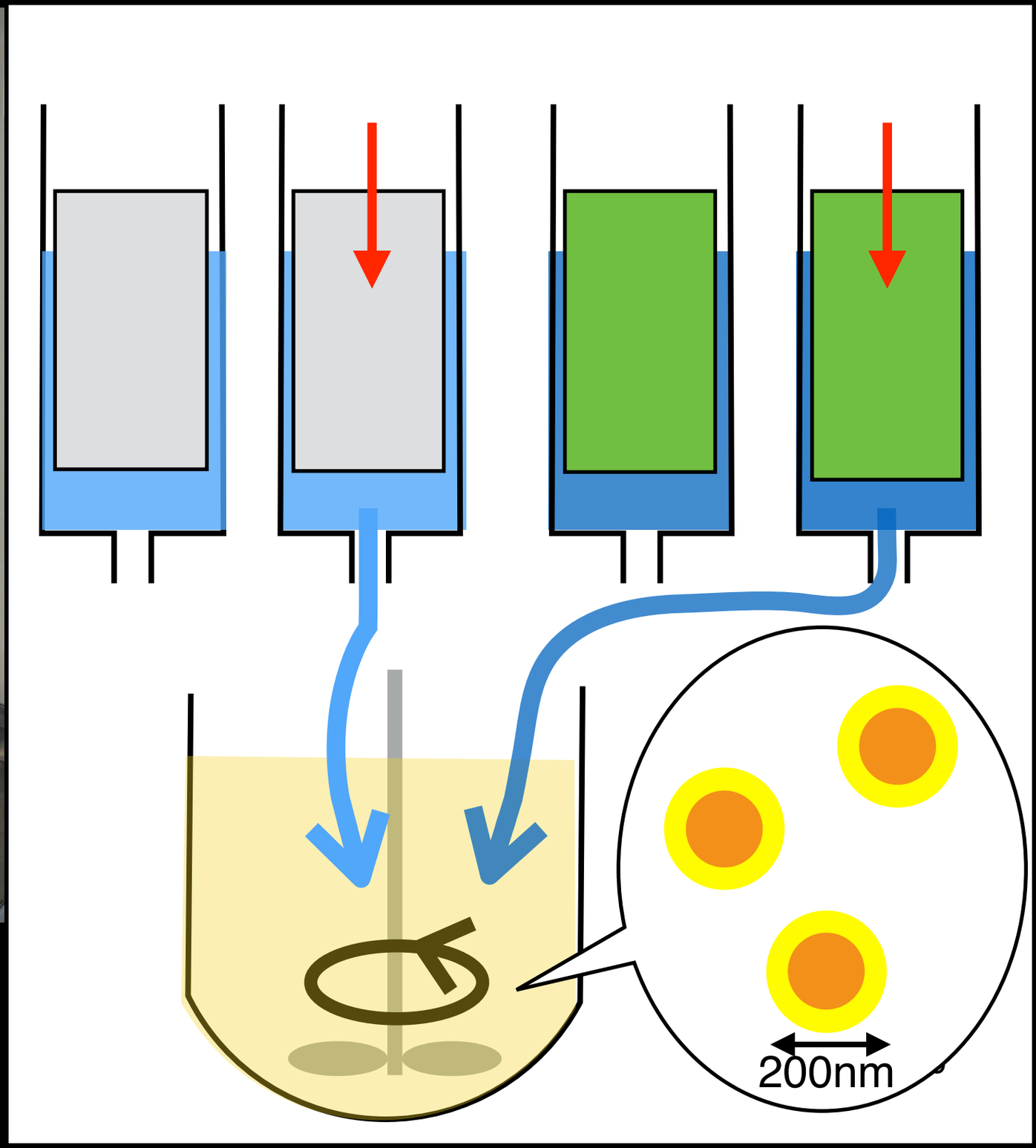
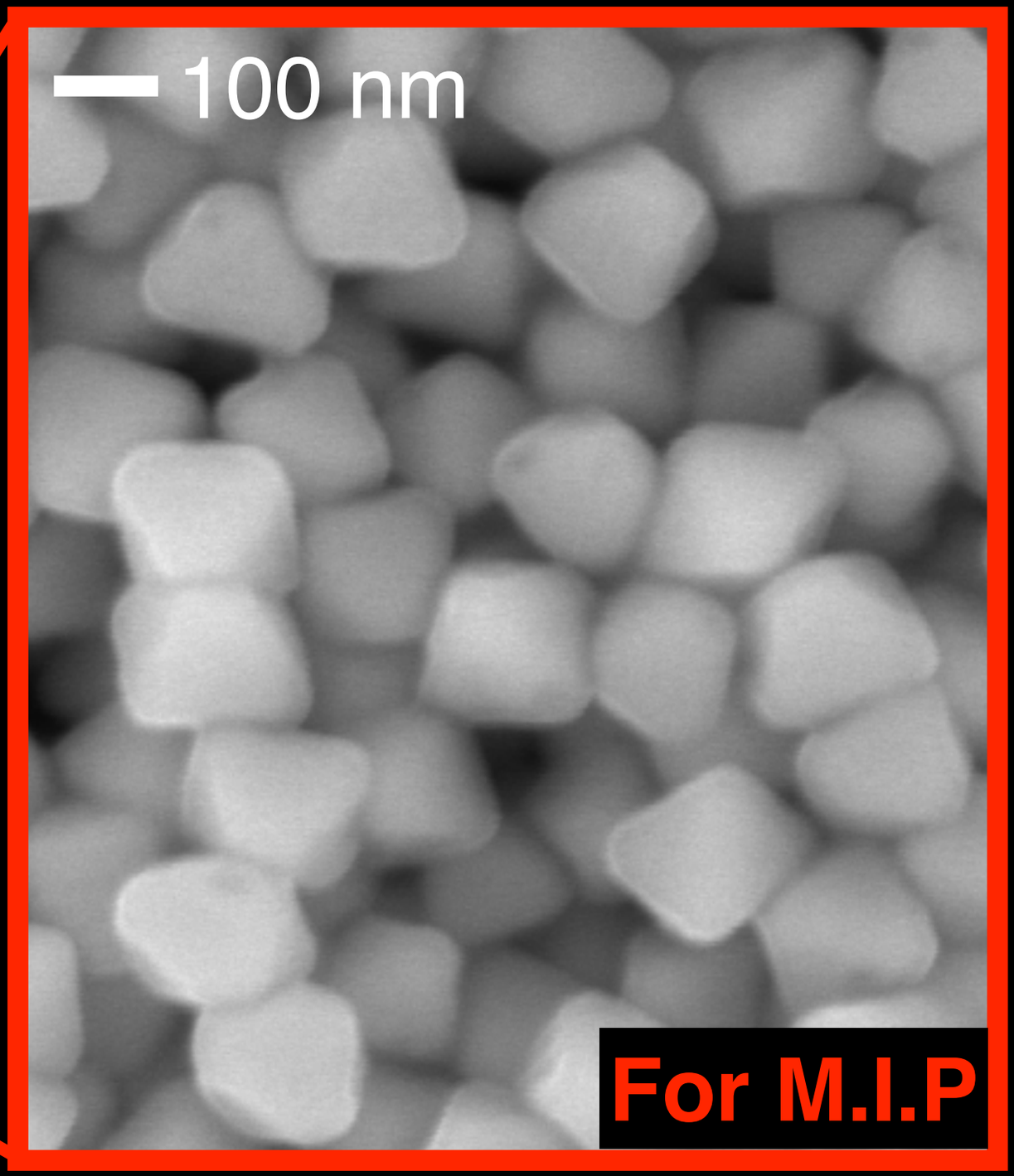


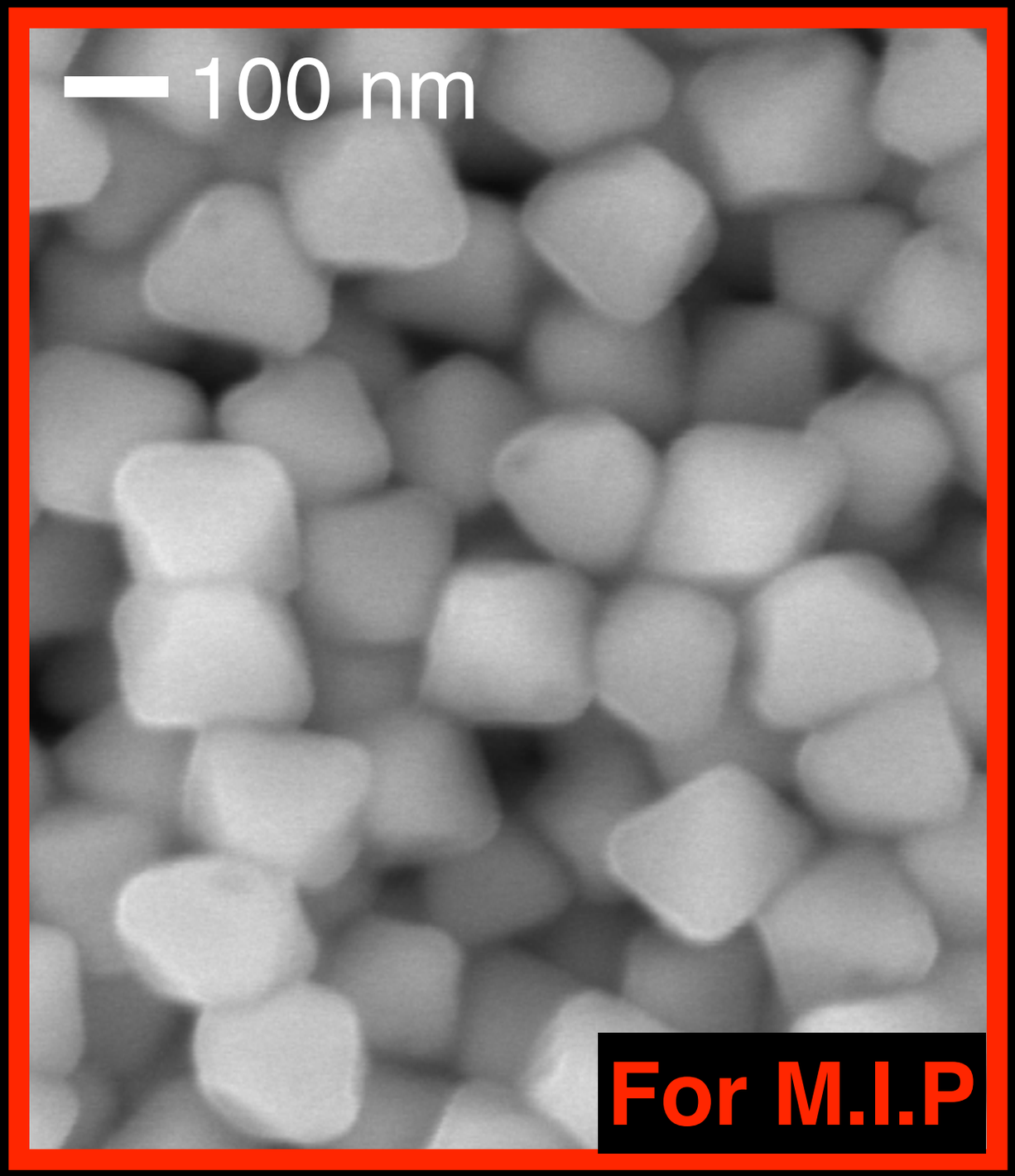


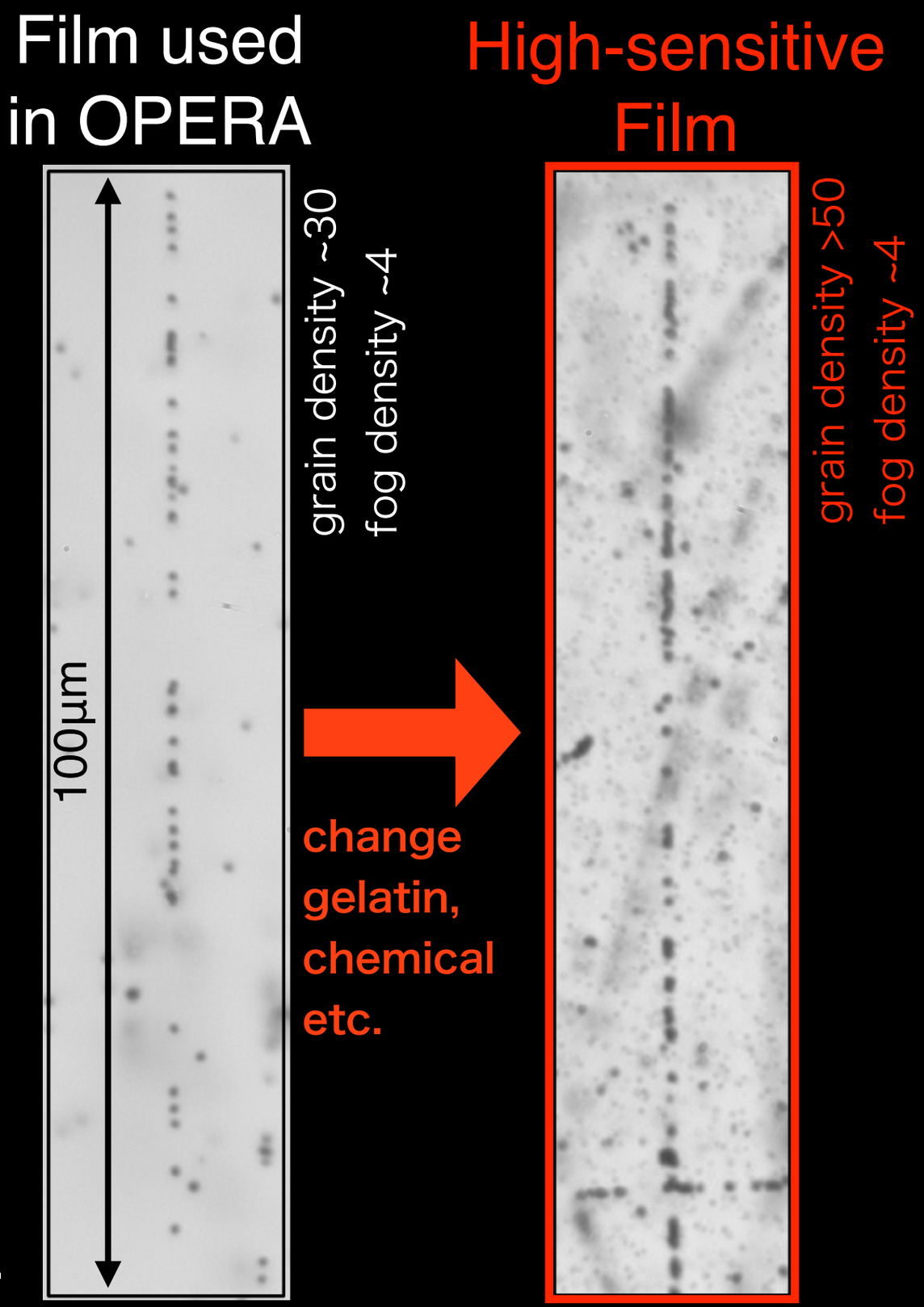



Each AgBr crystal in gelatin
functions as 3-D position censors.

Intrinsic resolution: ~ 50 nm

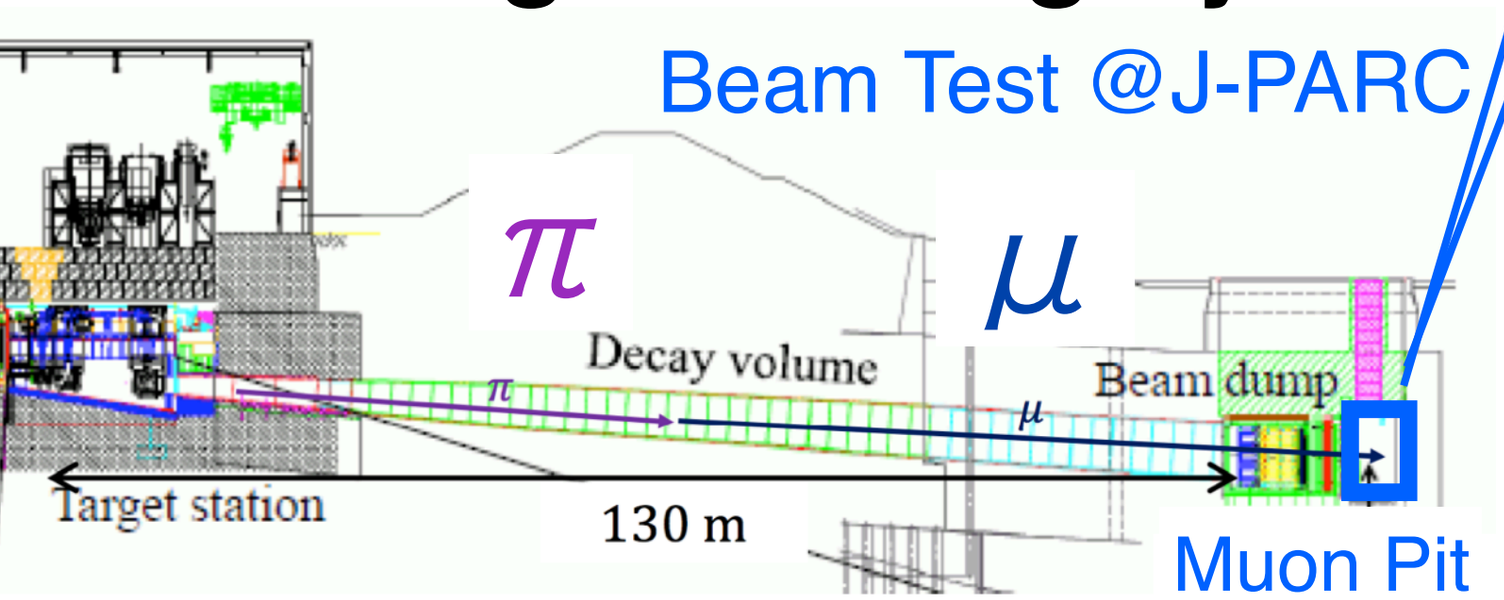
# Self-produced nuclear emulsion
## —High sensitive—

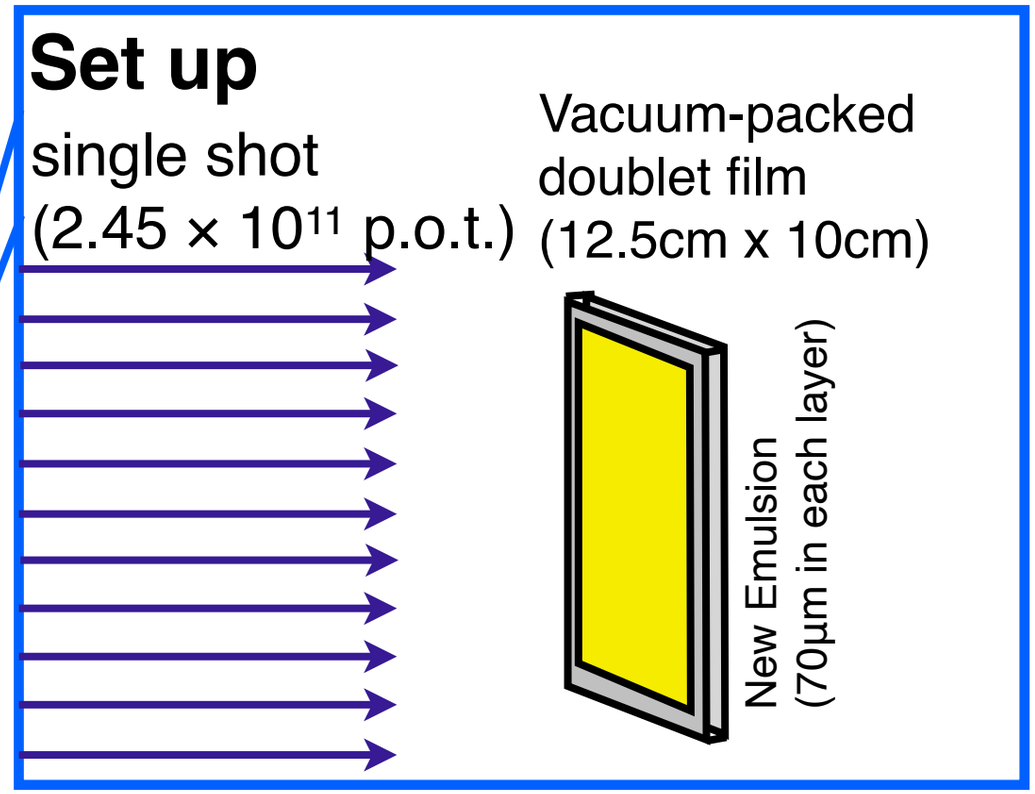



N. Naganawa et al.

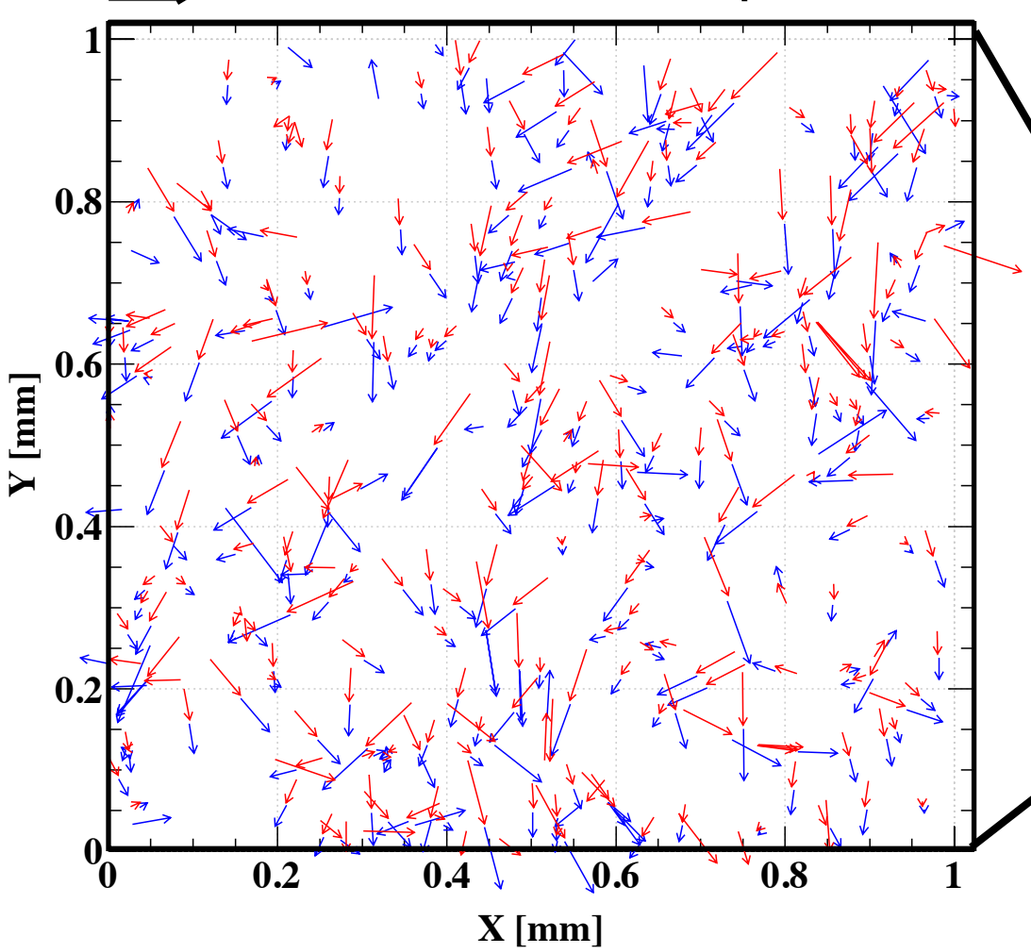
# Nagoya Emulsion Film & Data using Scanning System



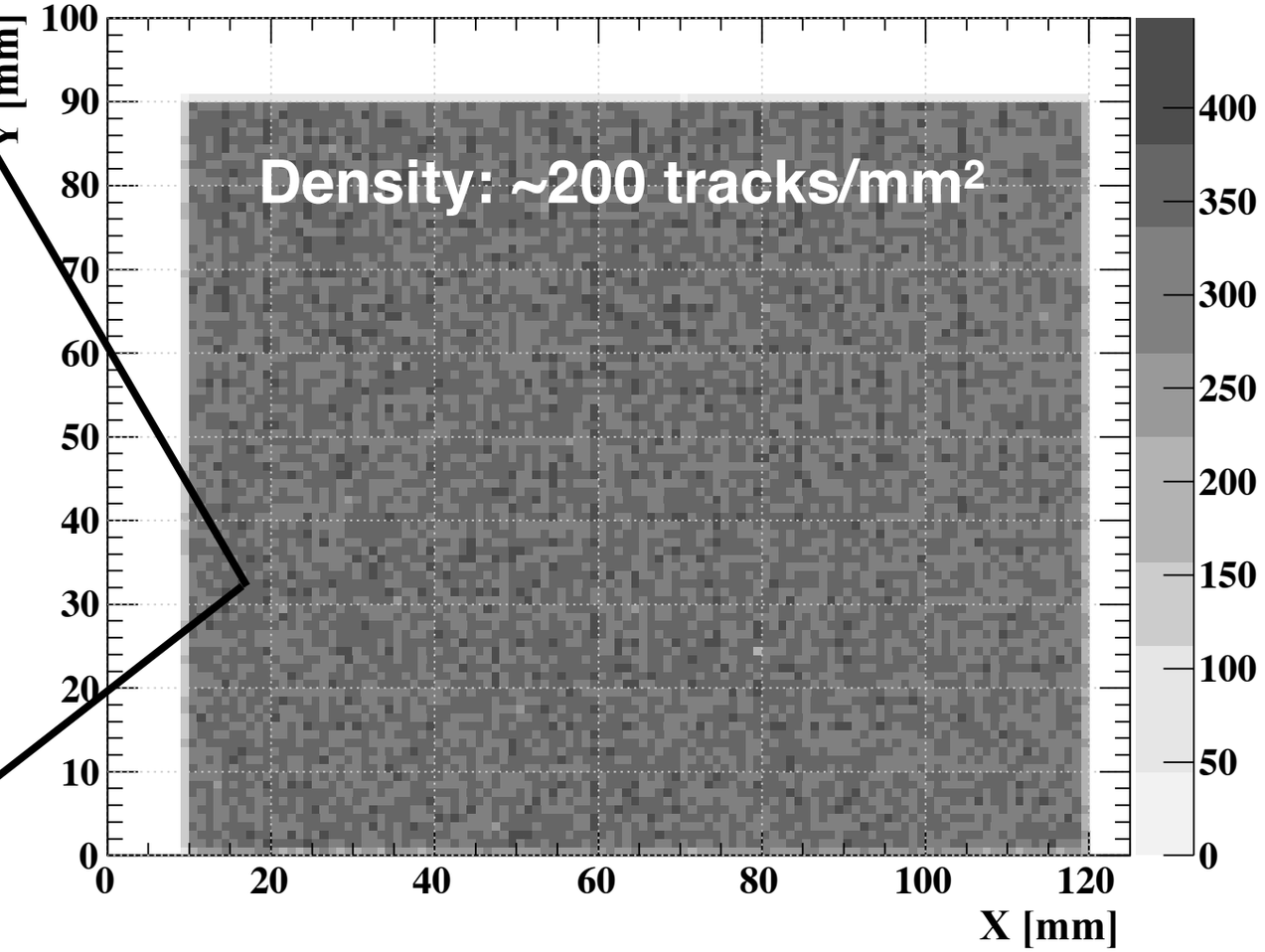




thanks to A.Ariga, T.Nakadaira

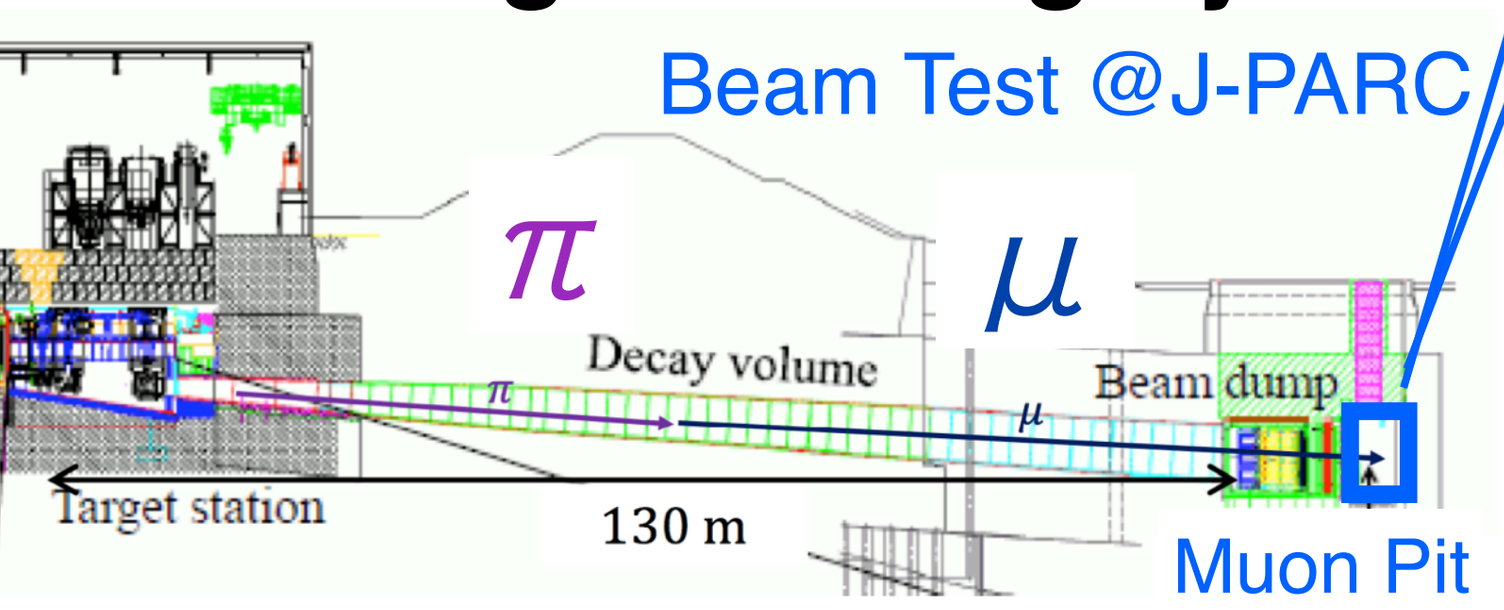
Track Vector Map




Position Distribution



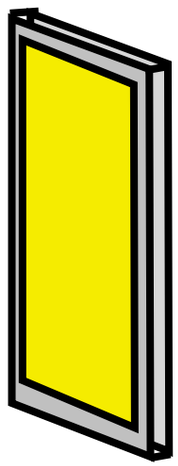
# Nagoya Emulsion Film & Data using Scanning System




## Set up

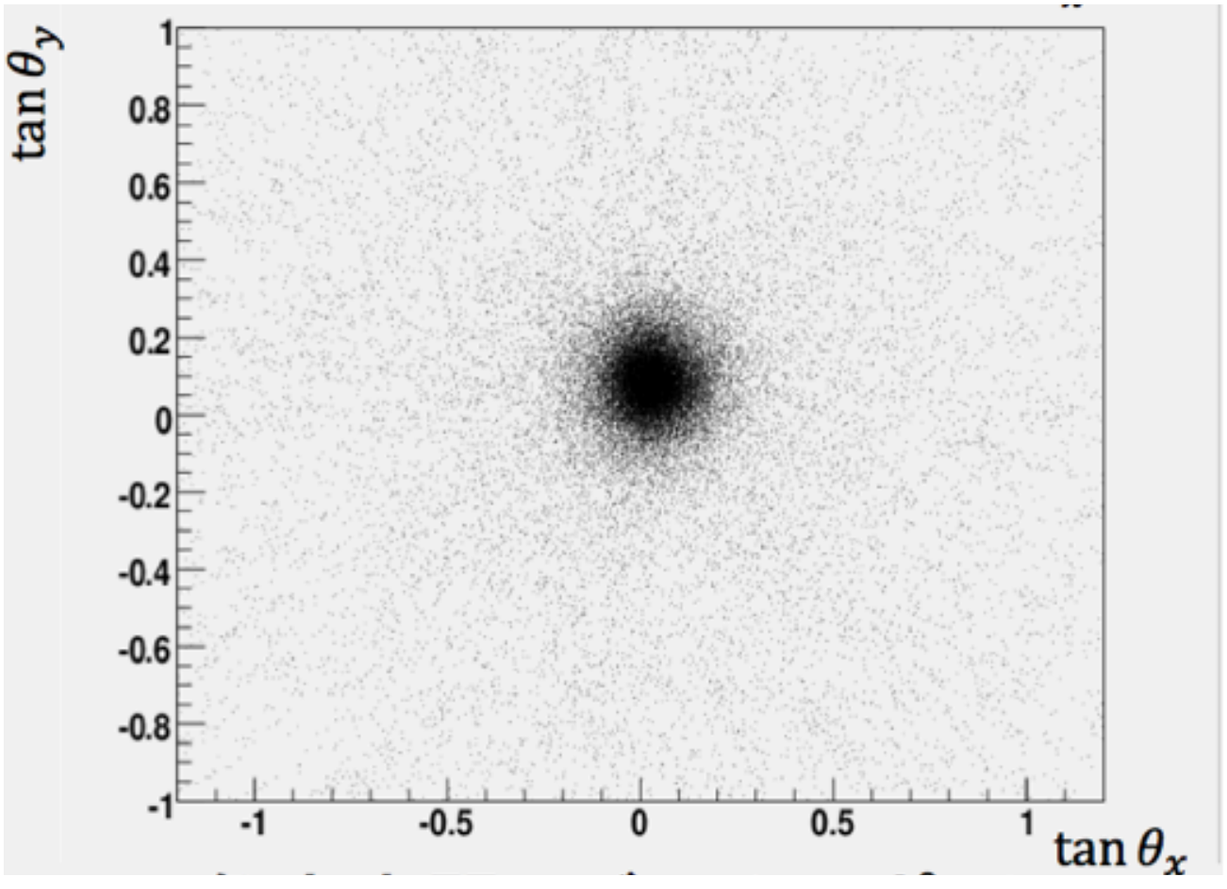
single shot
(2.45 × $10^{11}$ p.o.t.)

Vacuum-packed
doublet film
(12.5cm x 10cm)

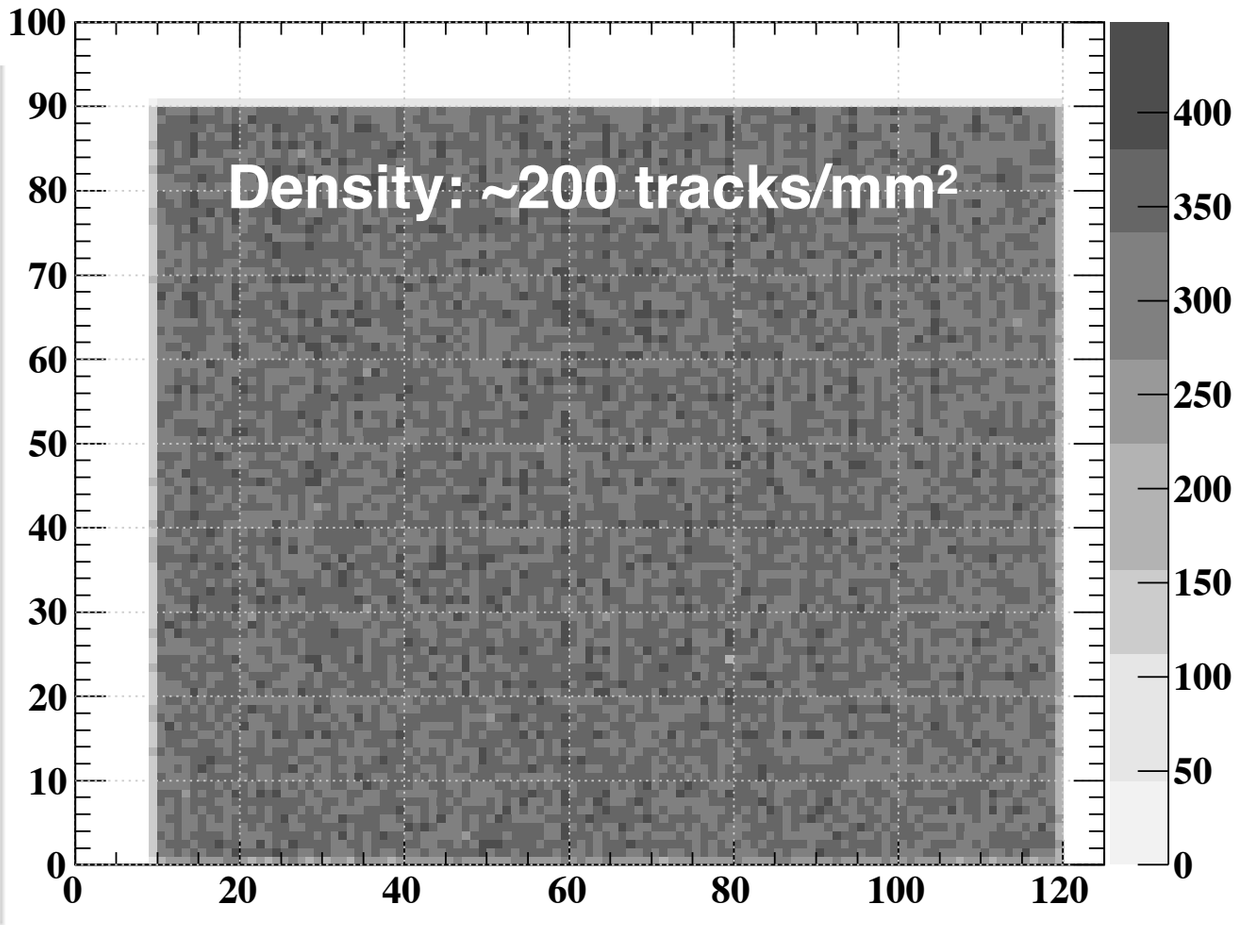



thanks to A.Ariga, T.Nakadaira

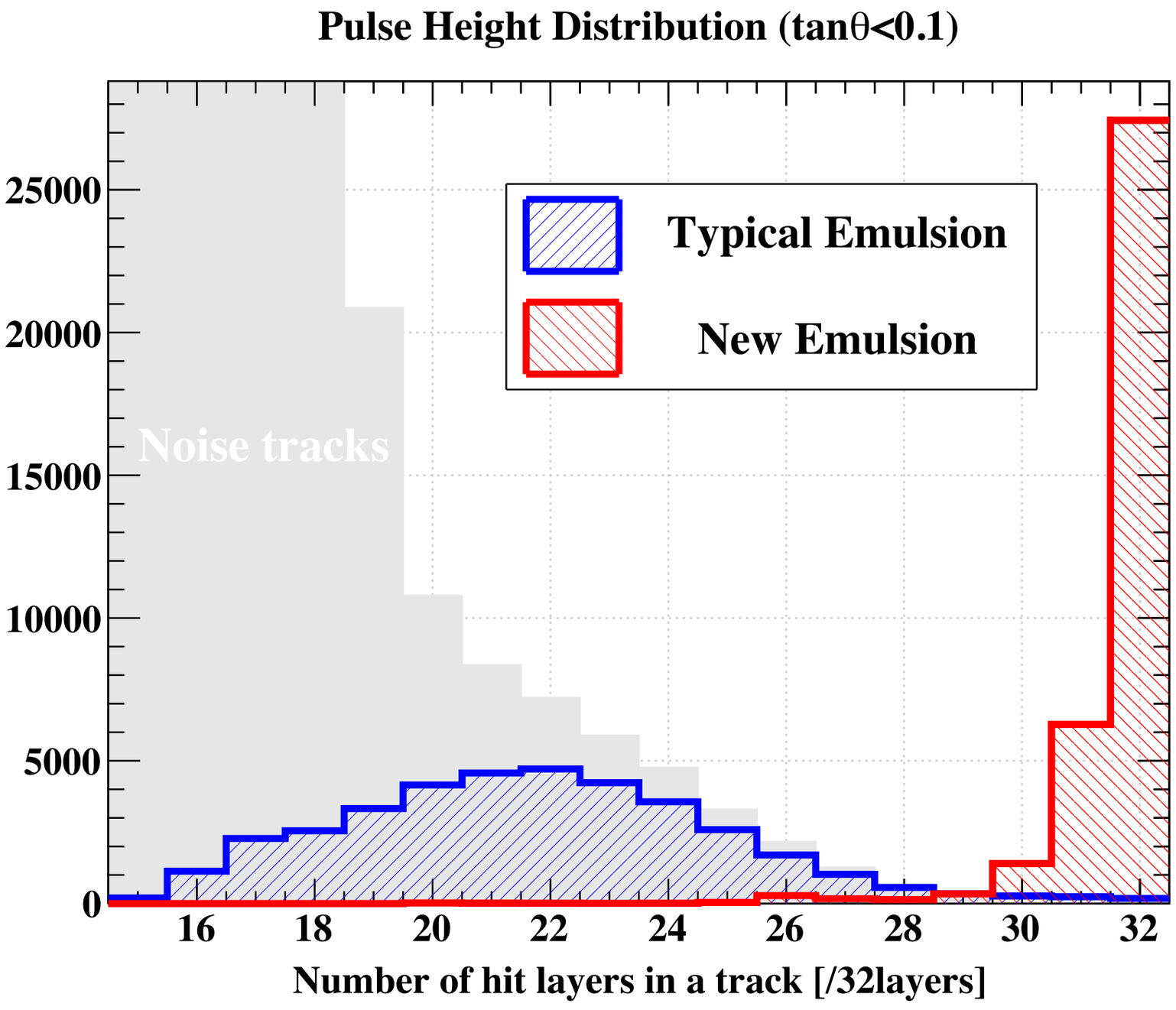
## Beam image (angular distribution)




## Position Distribution



# Nagoya Emulsion Film + Scanning System = High quality track data




- Track-finding Efficiency : 80%→97%
- Good separation from noise track →High S/N data

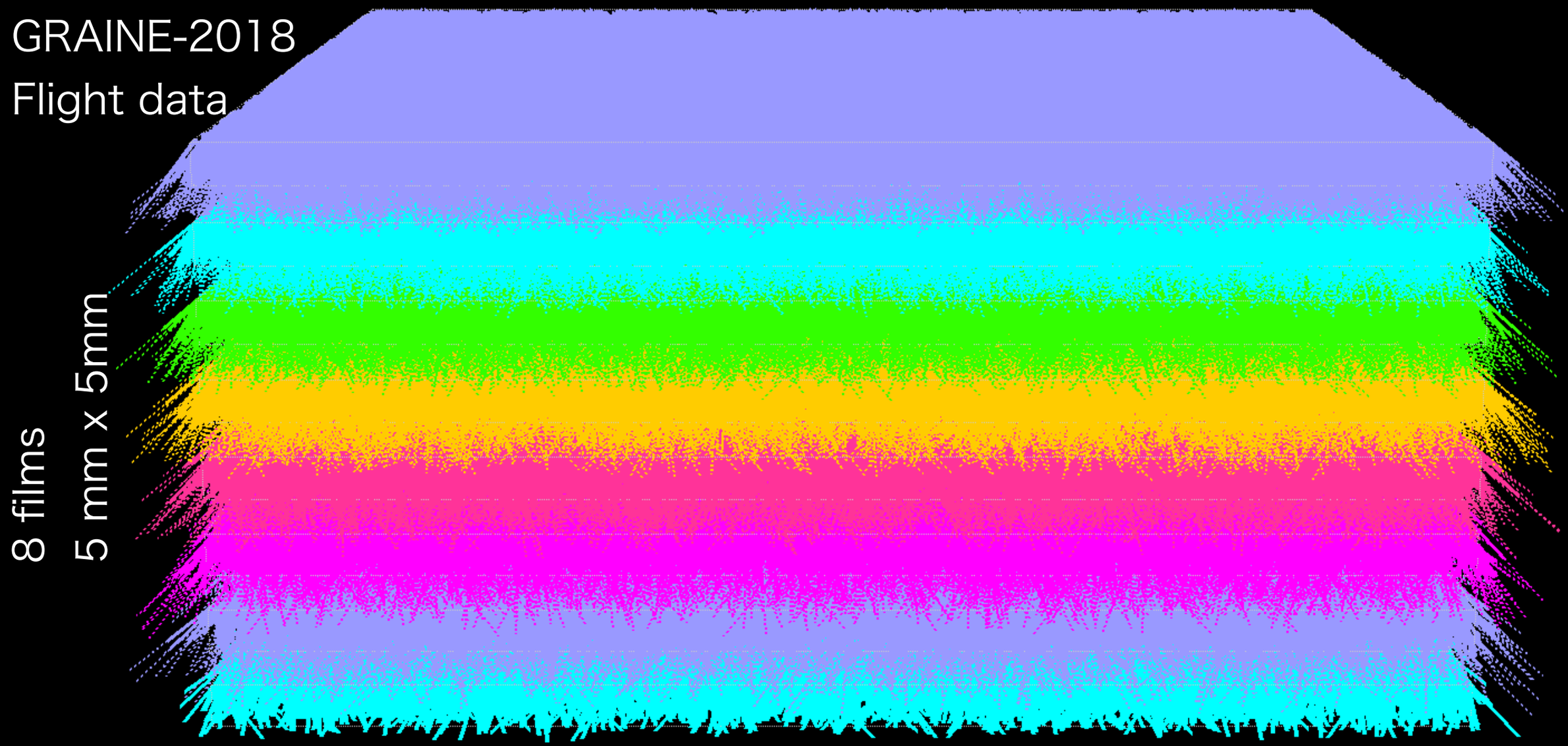
K. Ozaki *et al* 2015 *JINST* **10**

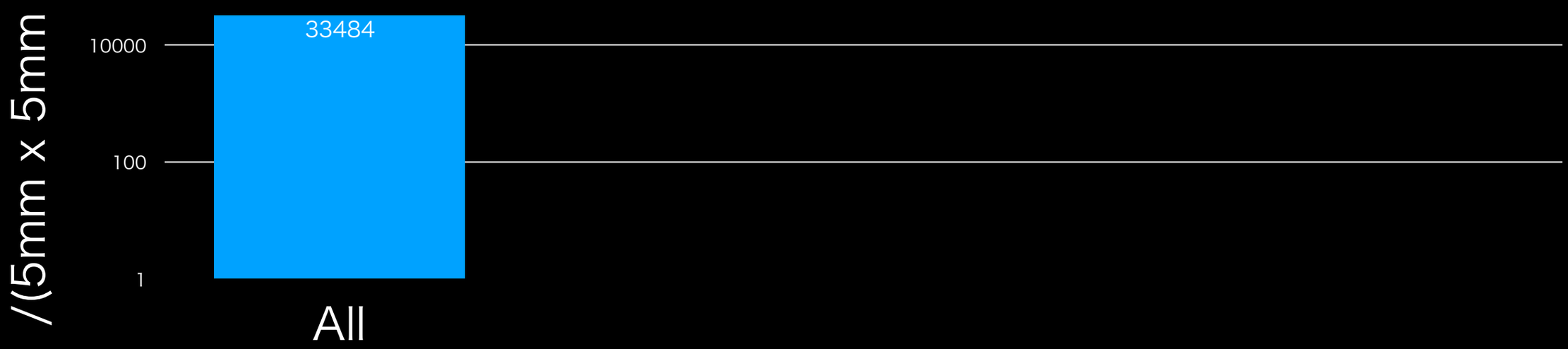
# $\gamma \rightarrow e^+e^-$ Event Selection

# Balloon-borne Emulsion Chamber Data

H.Rokujo et al.,
PTEP 2018, 063H01

GRAINE-2018
Flight data



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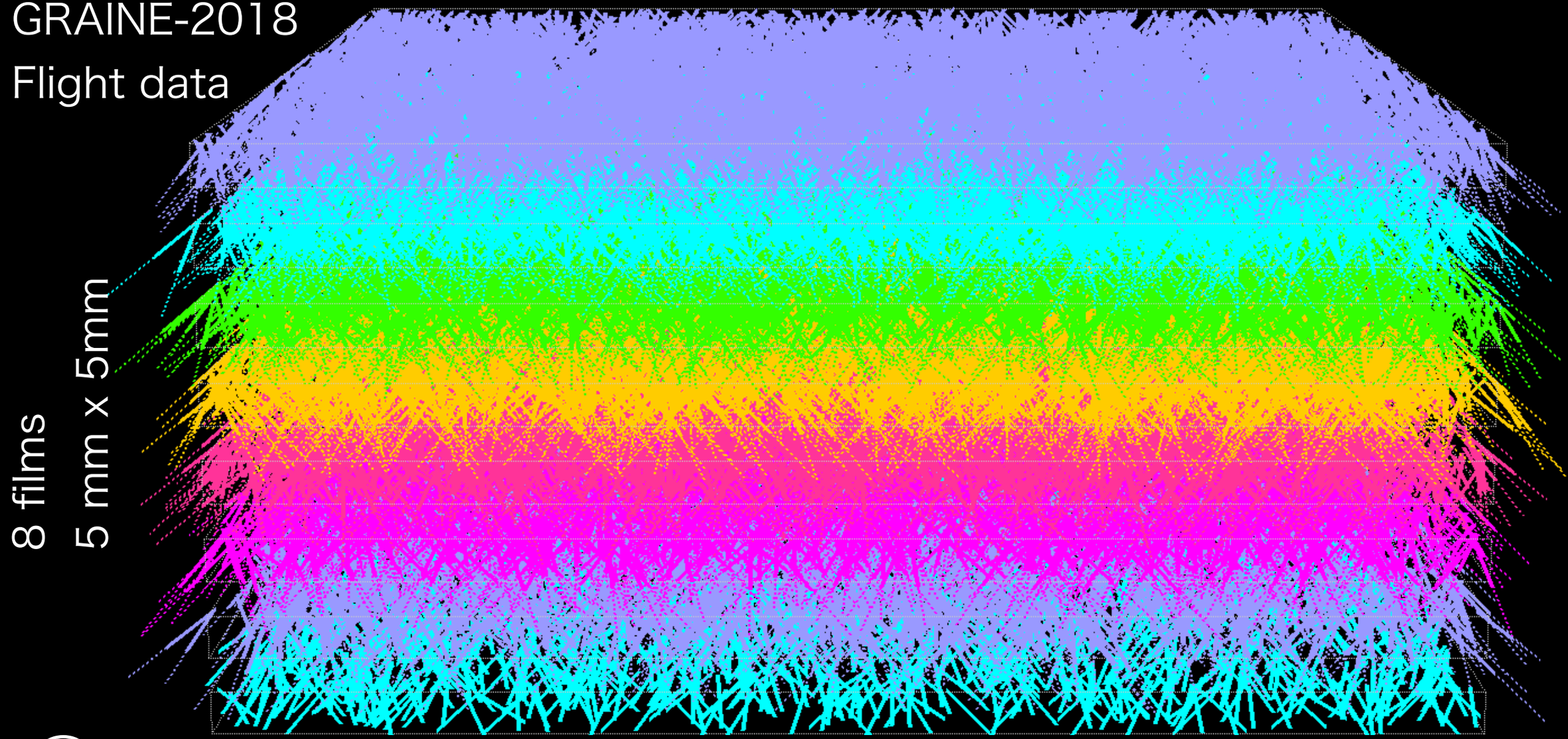


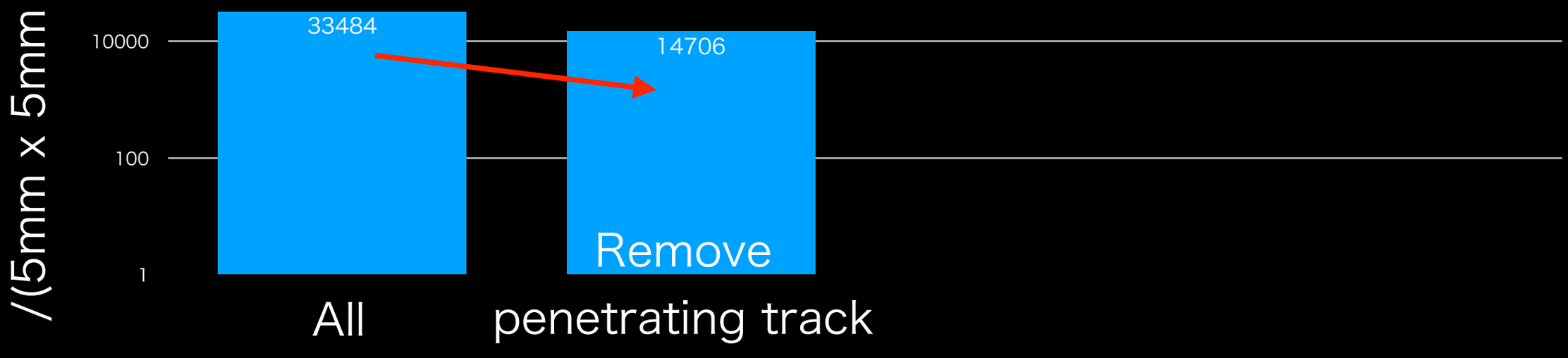

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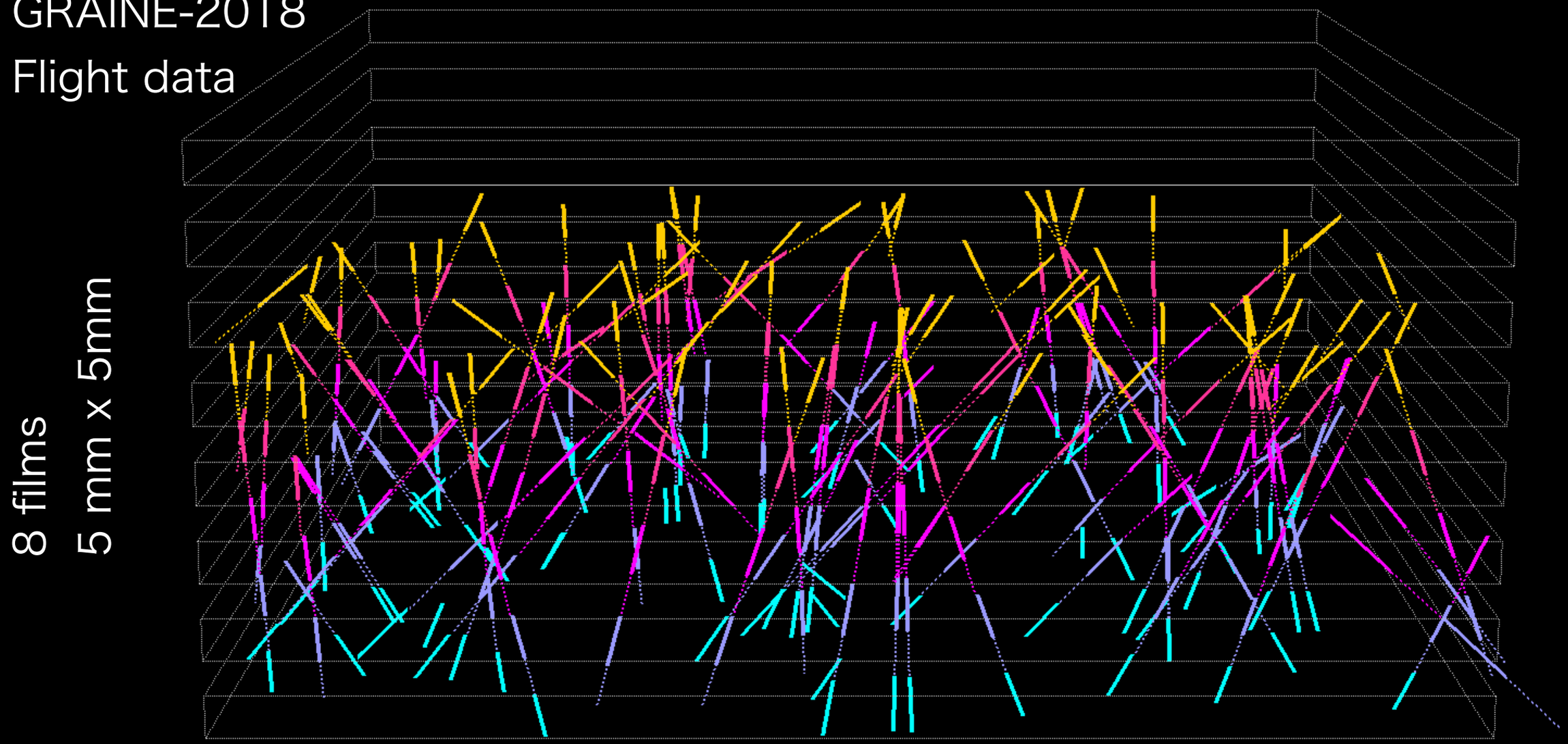
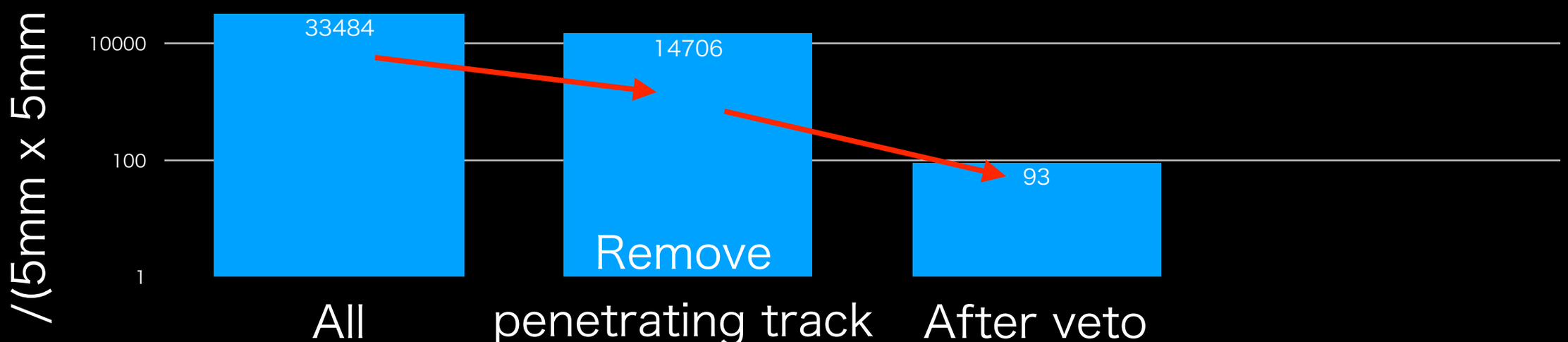
PTEP 2018, 063H01

GRAINE-2018
Flight data



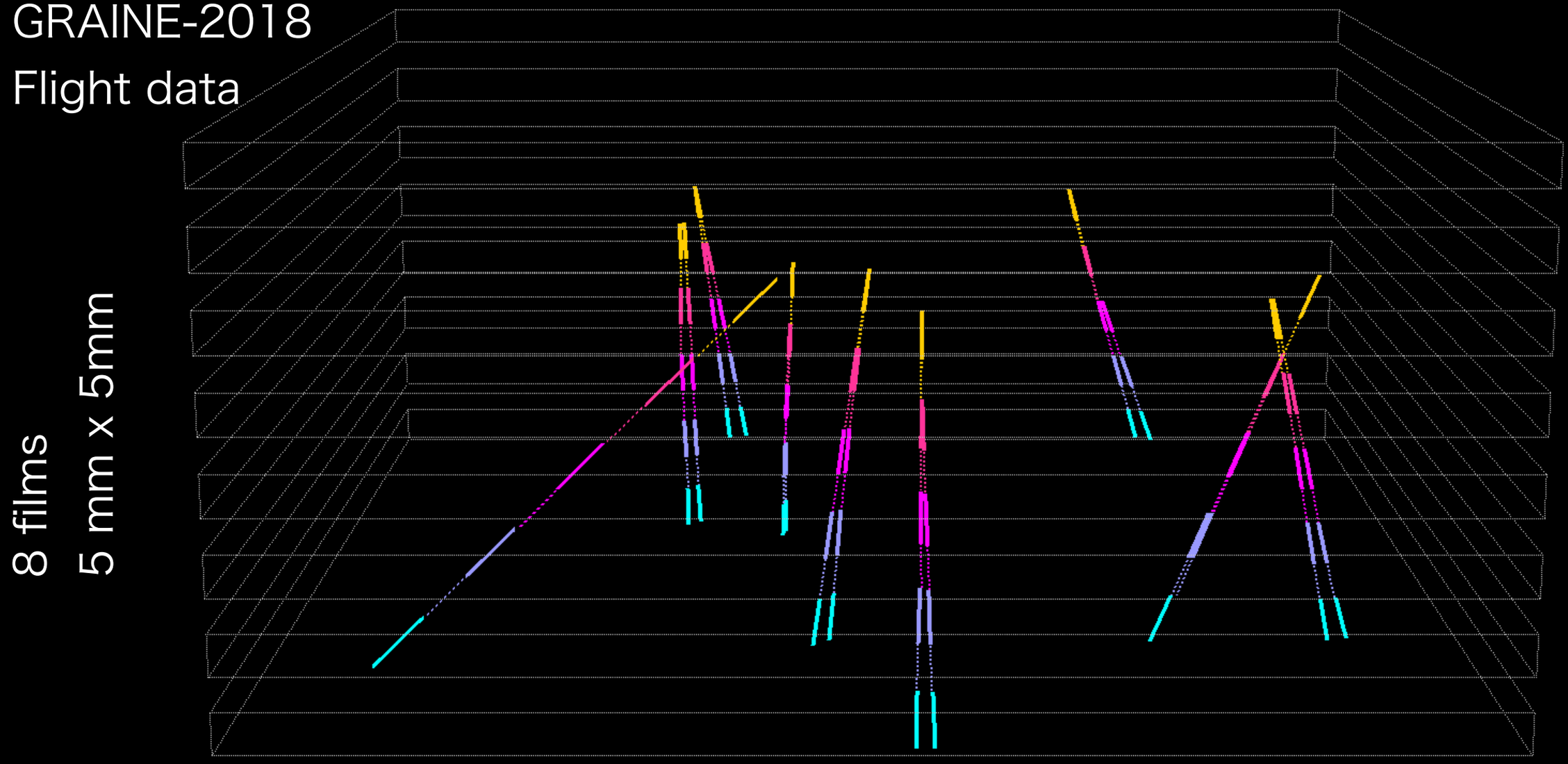
# $\gamma \rightarrow e^+e^-$ Event Selection

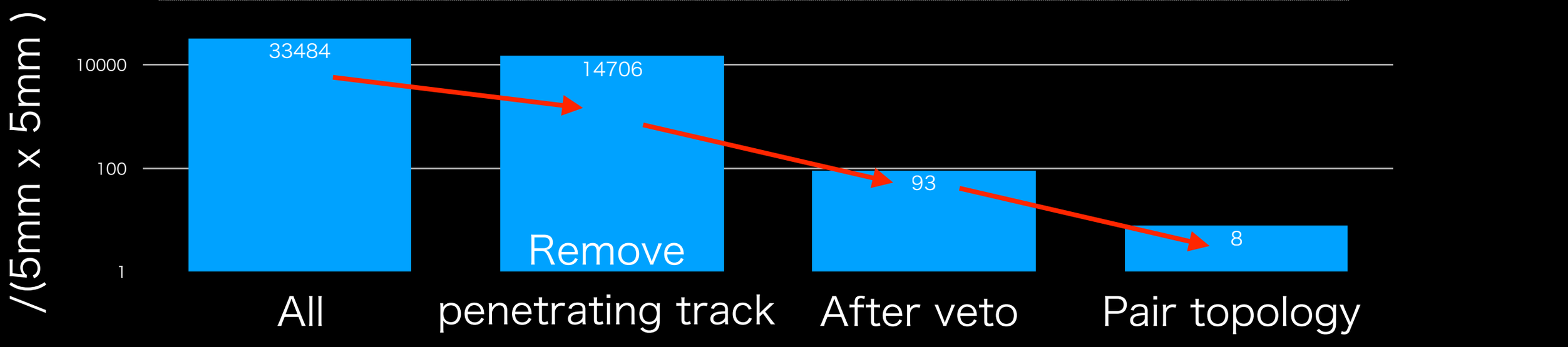
# Balloon-borne Emulsion Chamber Data

H.Rokujo et al.,
PTEP 2018, 063H01

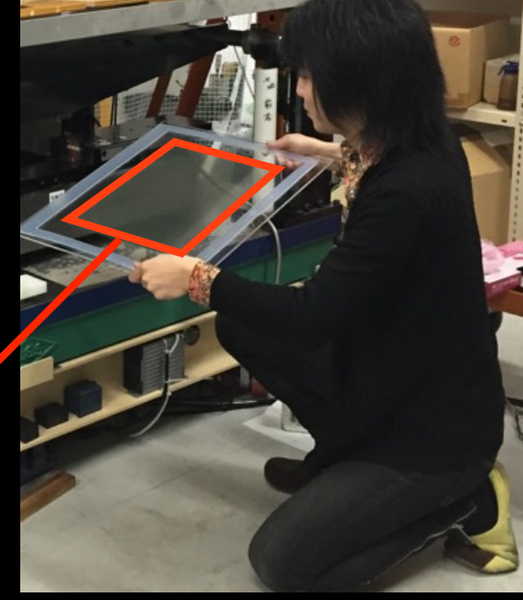
GRAINE-2018

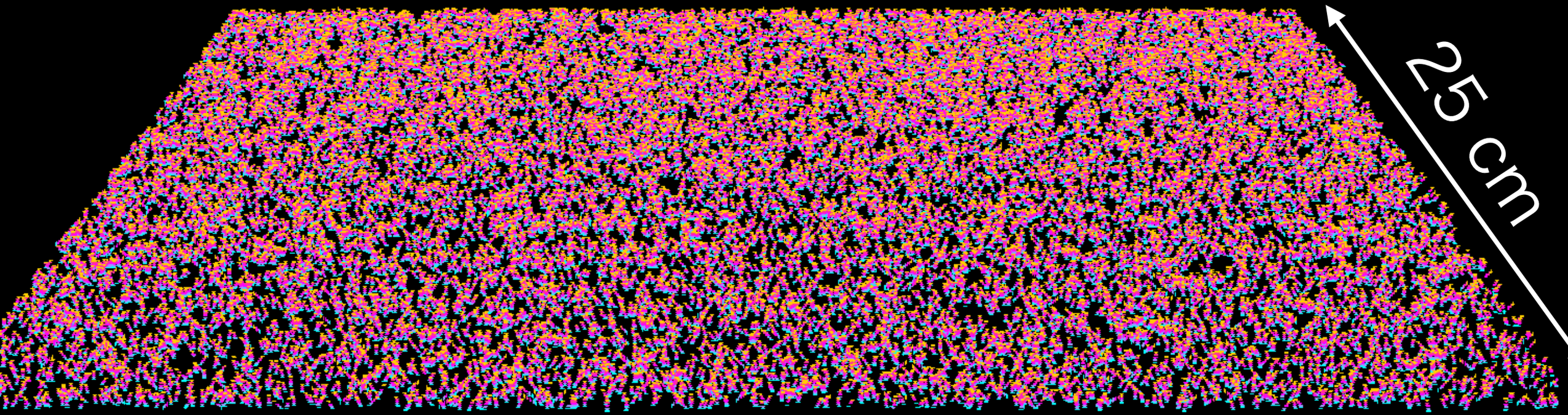
Flight data



H.Rokujo et al.,
PTEP 2018, 063H01






High efficiency and high SN ratio data set
→Systematic analysis and large-area emulsion experiments.

# Ongoing Emulsion Projects

Particle Phys.

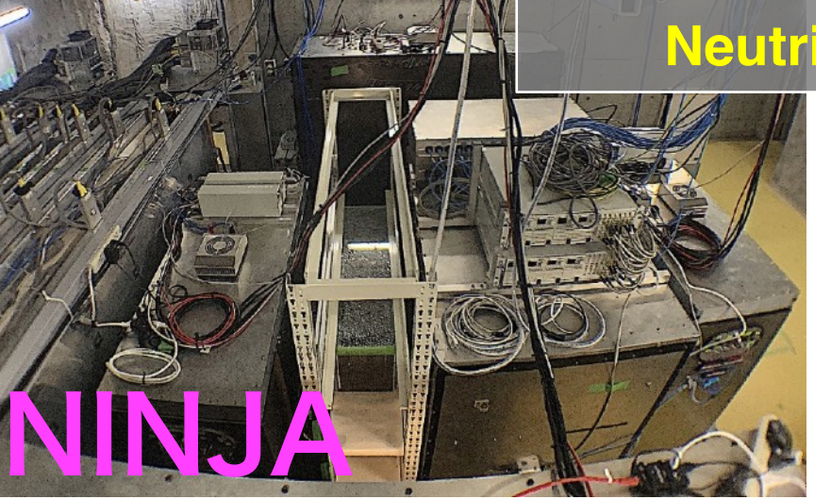
Nuclear Phys.

Astro-particle

Applications

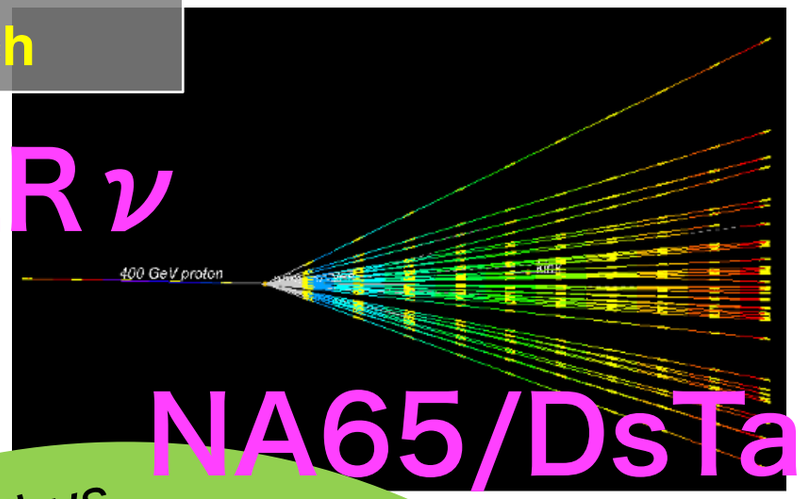
Education

## Neutrino research



NINJA

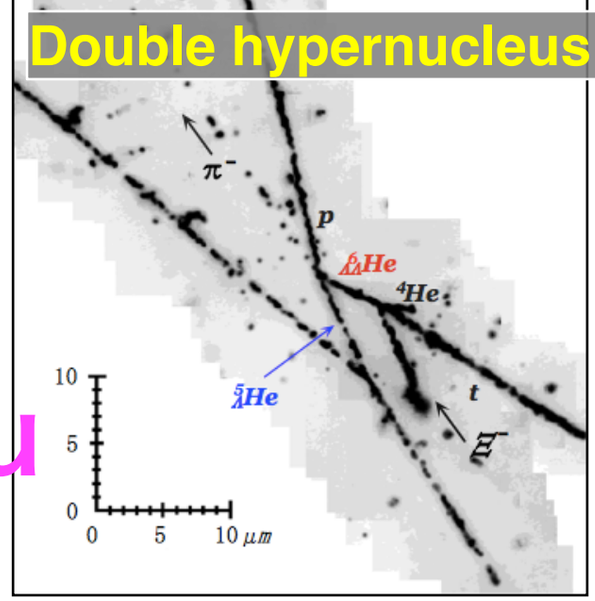
FASER$\nu$



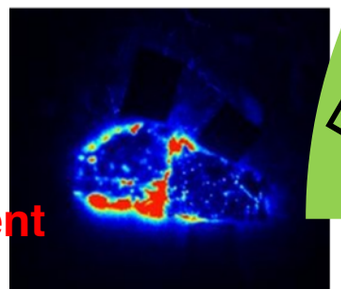

SND

NA65/DsTau

## Double hypernucleus

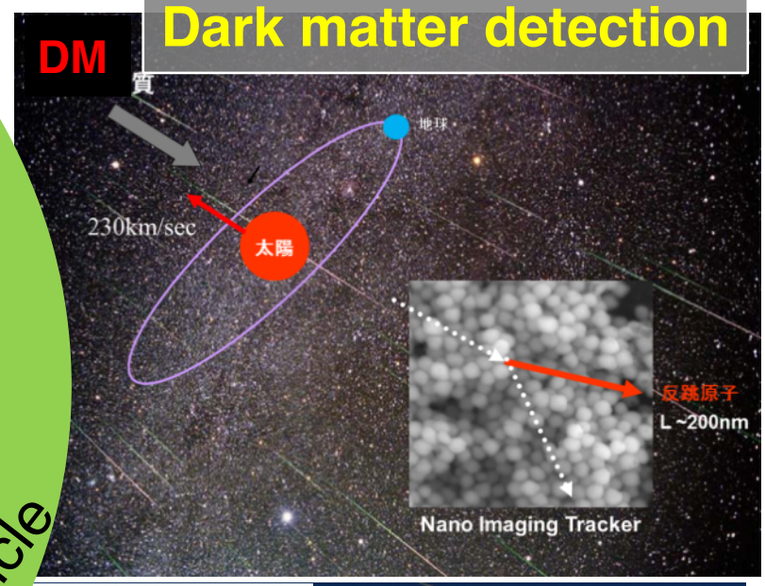



## Radiation education



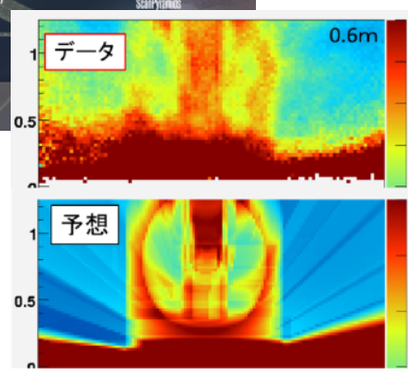
Radiation measurement from rocks

## Dark matter detection



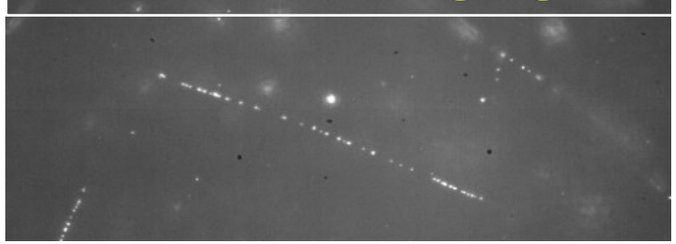

## Cosmic-ray imaging

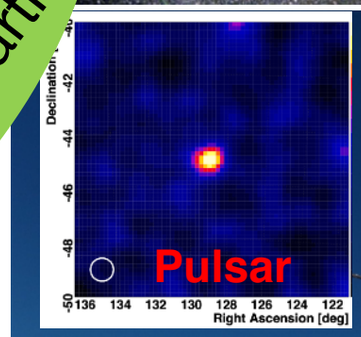

Pyramids




Reactor

## Neutron imaging






## Cosmic gamma-ray imaging

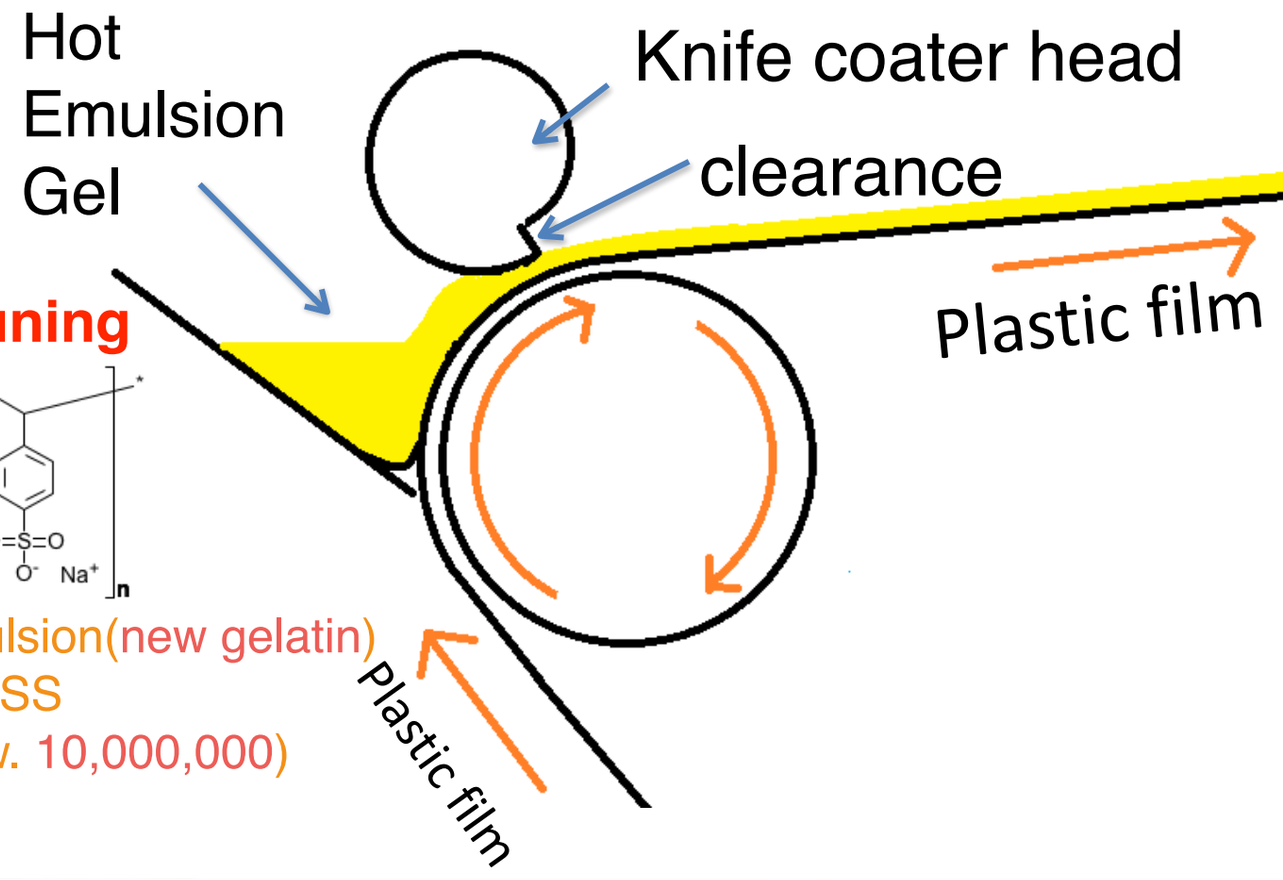
# Upgrade of Film Production




In 2018, We started construction of a new facility that can supply films with 10 times larger capacity.

# Development of Automatic Coat Method

## - Knife Coater Method-




**Viscosity Tuning**




Emulsion(new gelatin)
+PSSS
(m.w. 10,000,000)

# We designed facility based on results of tests

**“Roll-to-Roll Coater”**

**2021 May.-**

# Roll-to-roll emulsion film coating facility started practical operation

**(Real production in the dark)**

Drying

Coating

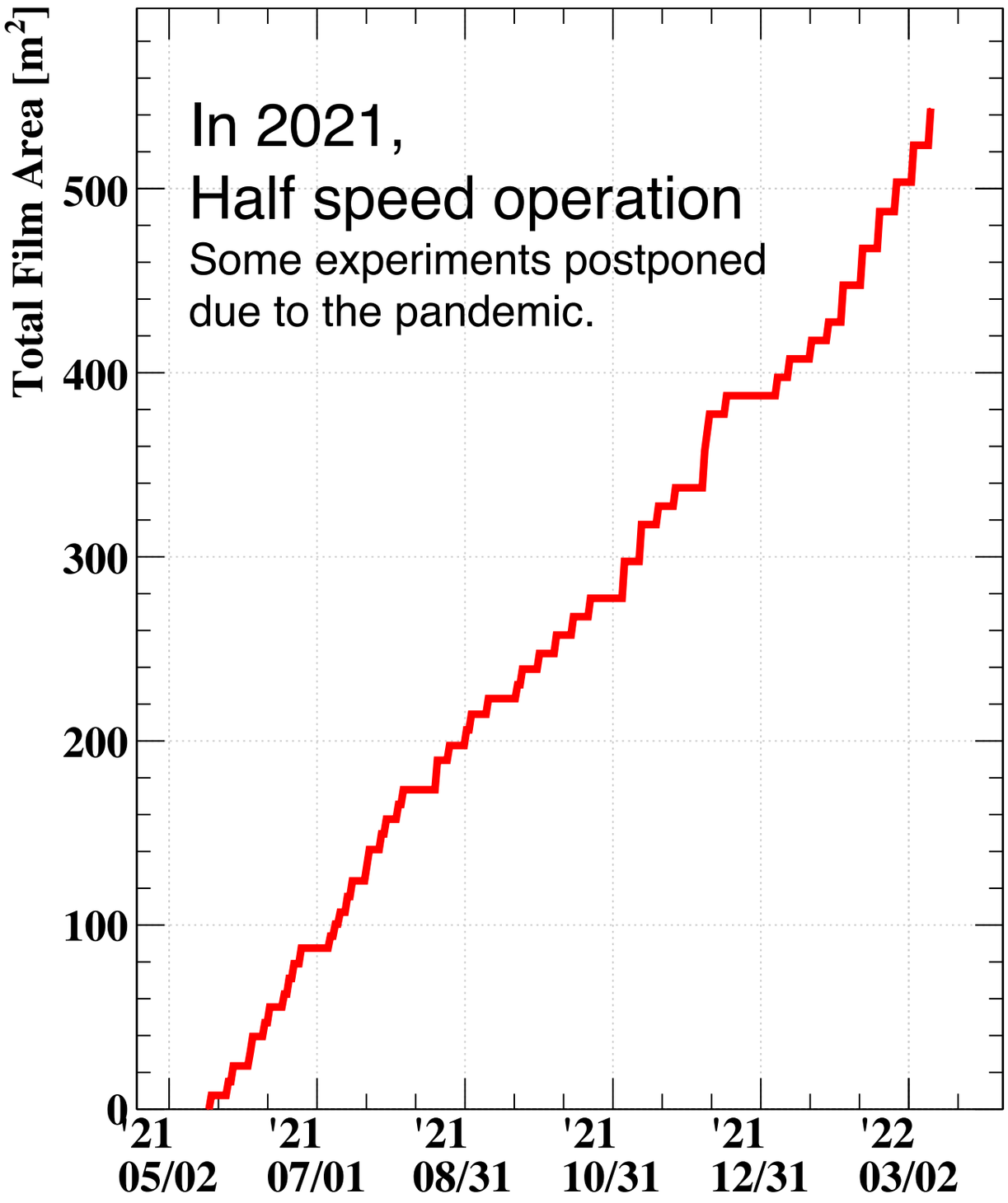
Winding

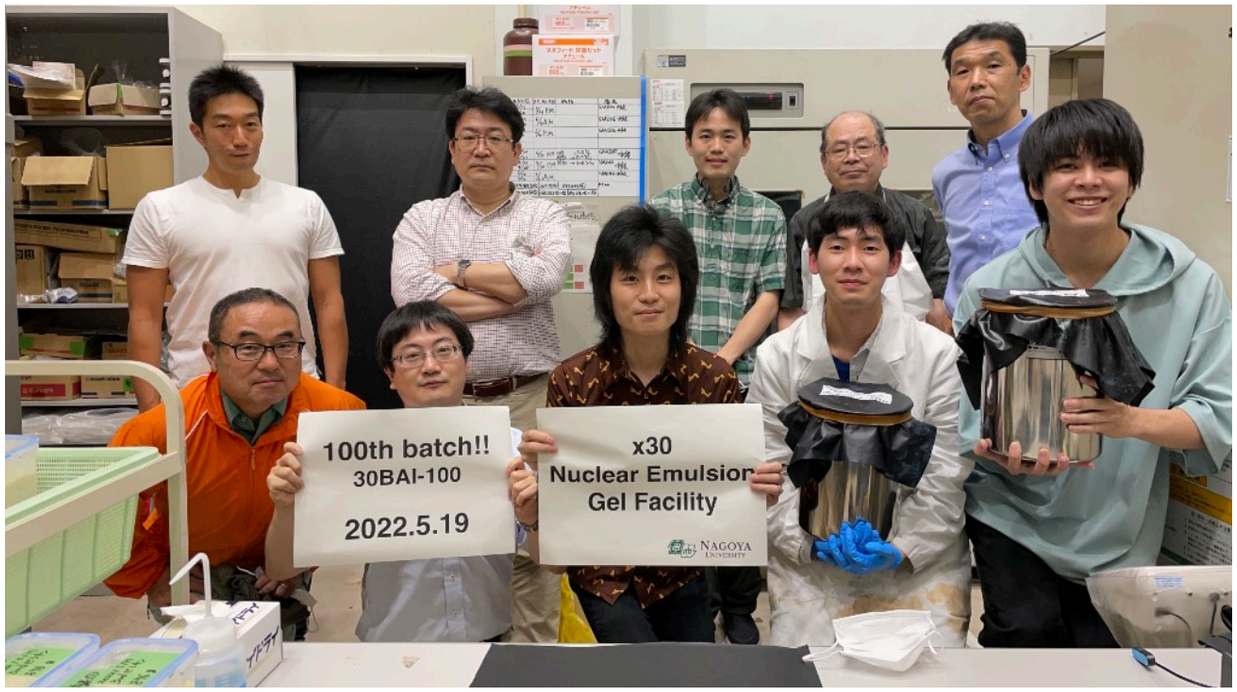
Melting

**achieved production speed of ~8 m²/day**

Double-sided emulsion film after two processes

# Started Mass Production in the new facility




celebration for the 100th batch in the new facility

Started supply for
- DsTau (2021&2022 run)
- FASER-nu (2022 run)
- SND (2022 run)
- GRAINE R&D
- Proton radiography R&D

In June 2022,
Full speed operation for
- GRAINE (Balloon experiment)
- NINJA (2023run)
- …etc.

# Summary

## - Part of Emulsion Development and Production-

- **Developing nuclear emulsion consistently from gel production to scanning**
  - Nuclear emulsion suitable for each experiment.
  - Immediately put into practice the necessary development and ambitious ideas.
  - Expansion of applications.

- **High-speed and high-quality scan data**
  - Full-scale data analysis of large-area nuclear emulsion

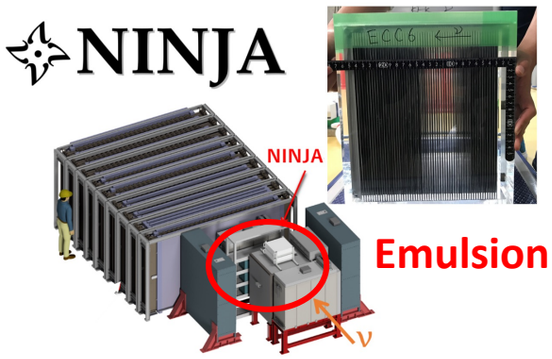
- **Upgrade of Film Production Facility**
  - Large-scale gel production & Roll-to-roll film production facility
  - Started supply to ongoing neutrino experiments

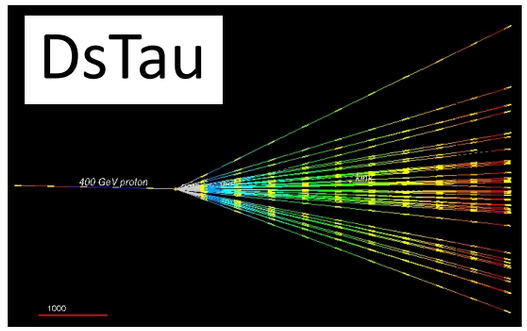
- **Emulsion Experiments enter to the next stage! Stay tuned for results.**

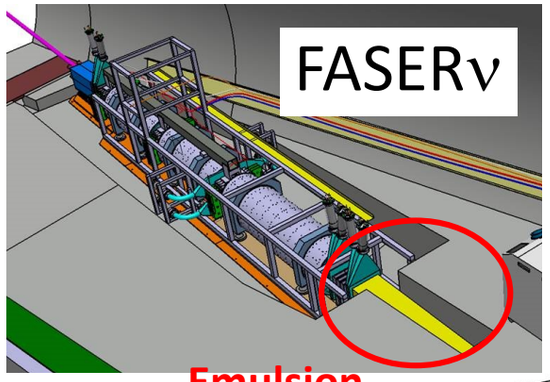
# Emulsion technology

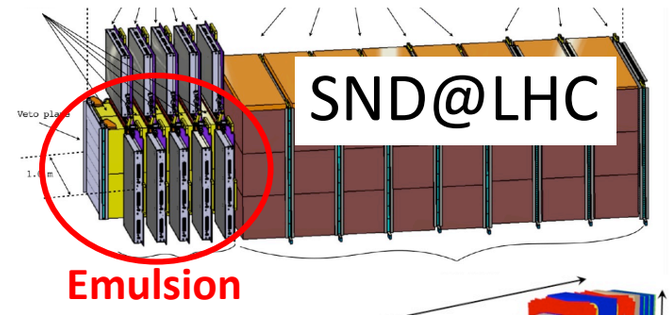
- Contributing in neutrino physics such as observations of $\nu\tau$ & $\nu\tau$ appearance in oscillations.
- Further contributions through **coming experiments.**

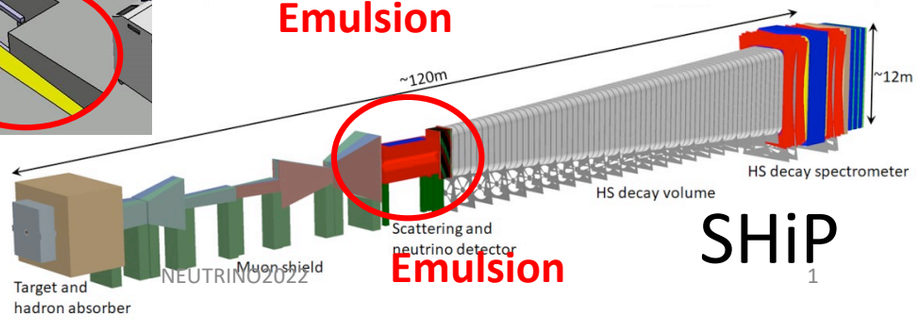
## Coming experiments



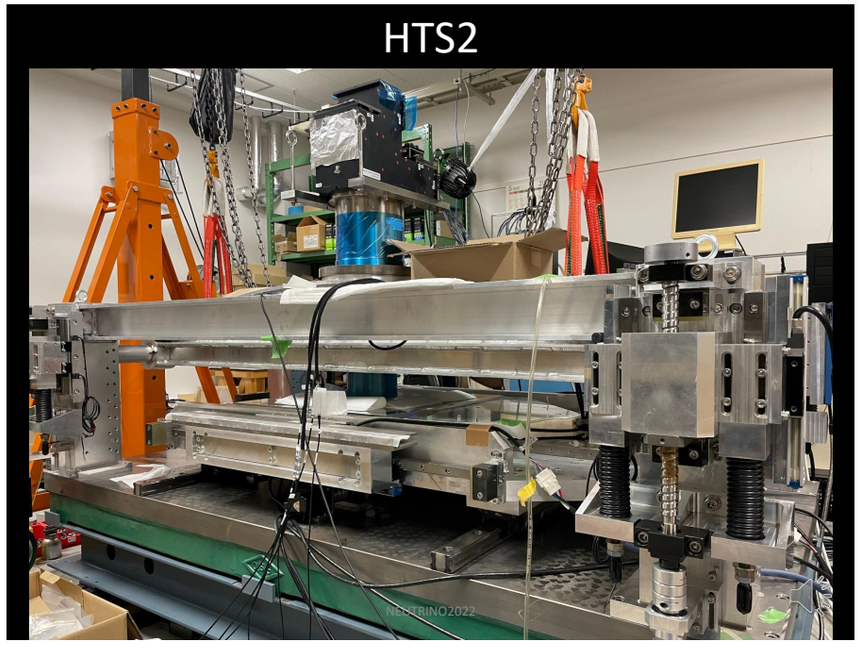



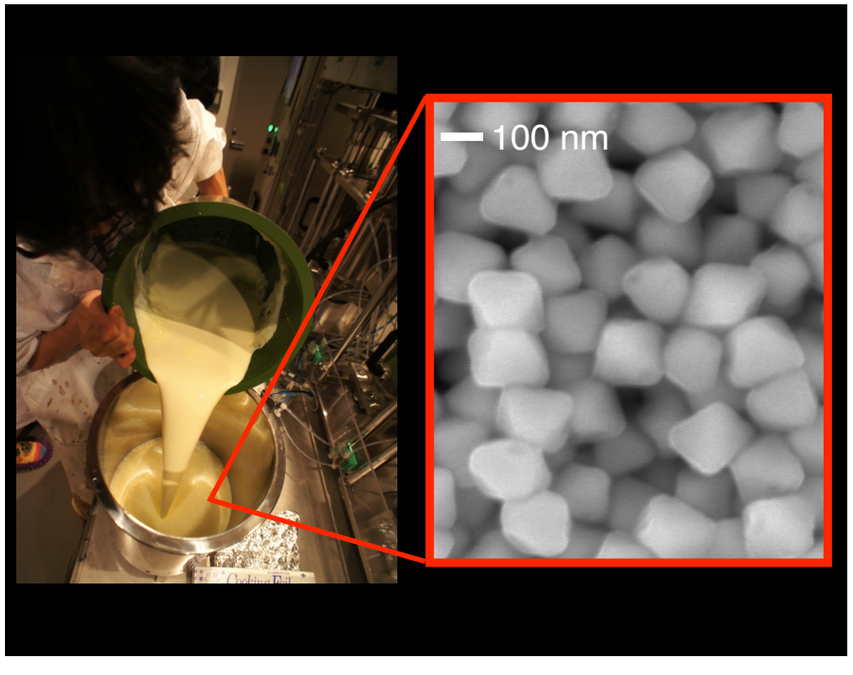



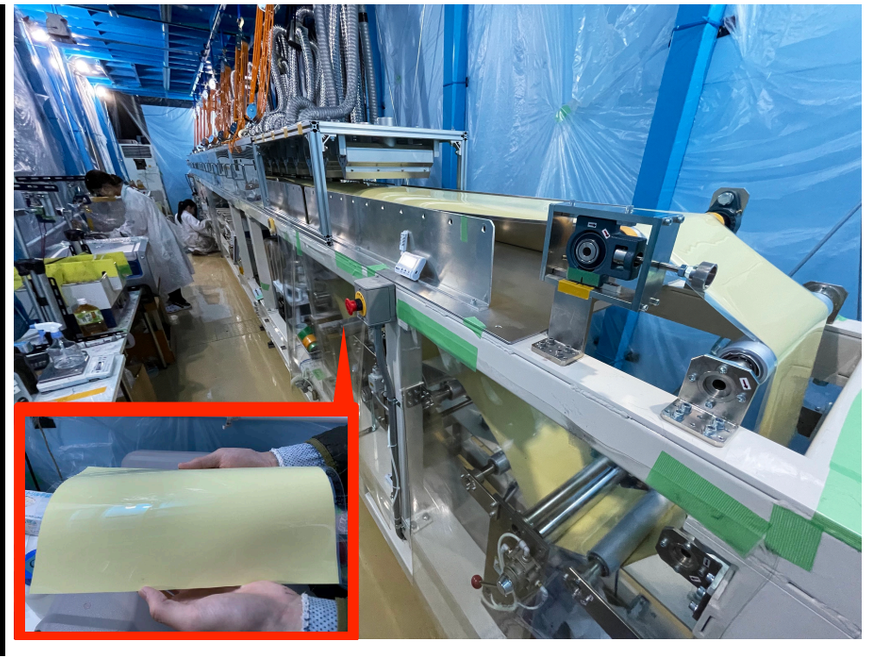





- We welcome your interesting ideas using nuclear emulsion!