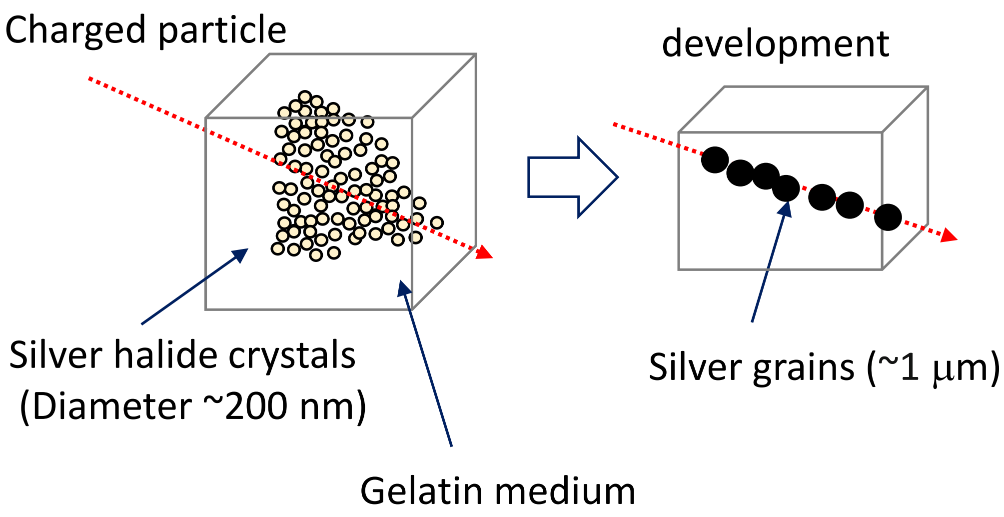
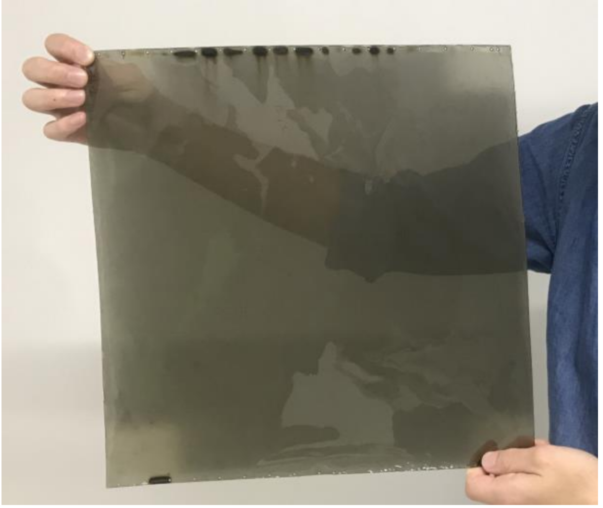
2023.11.28
加速器・ビーム物理の機械学習ワークショップ2023

Analysis of nuclear emulsion images for hypernuclear physics using machine learning

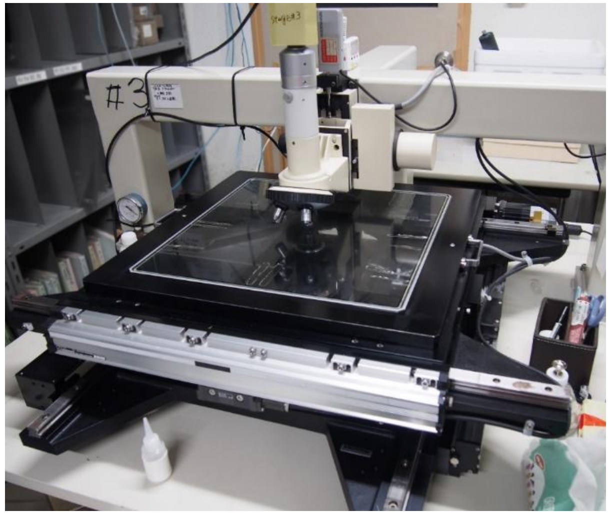
International Center for Synchrotron Radiation Innovation Smart, Tohoku University
Junya Yoshida

Photographic emulsion sheet for visualizing charged particle tracks

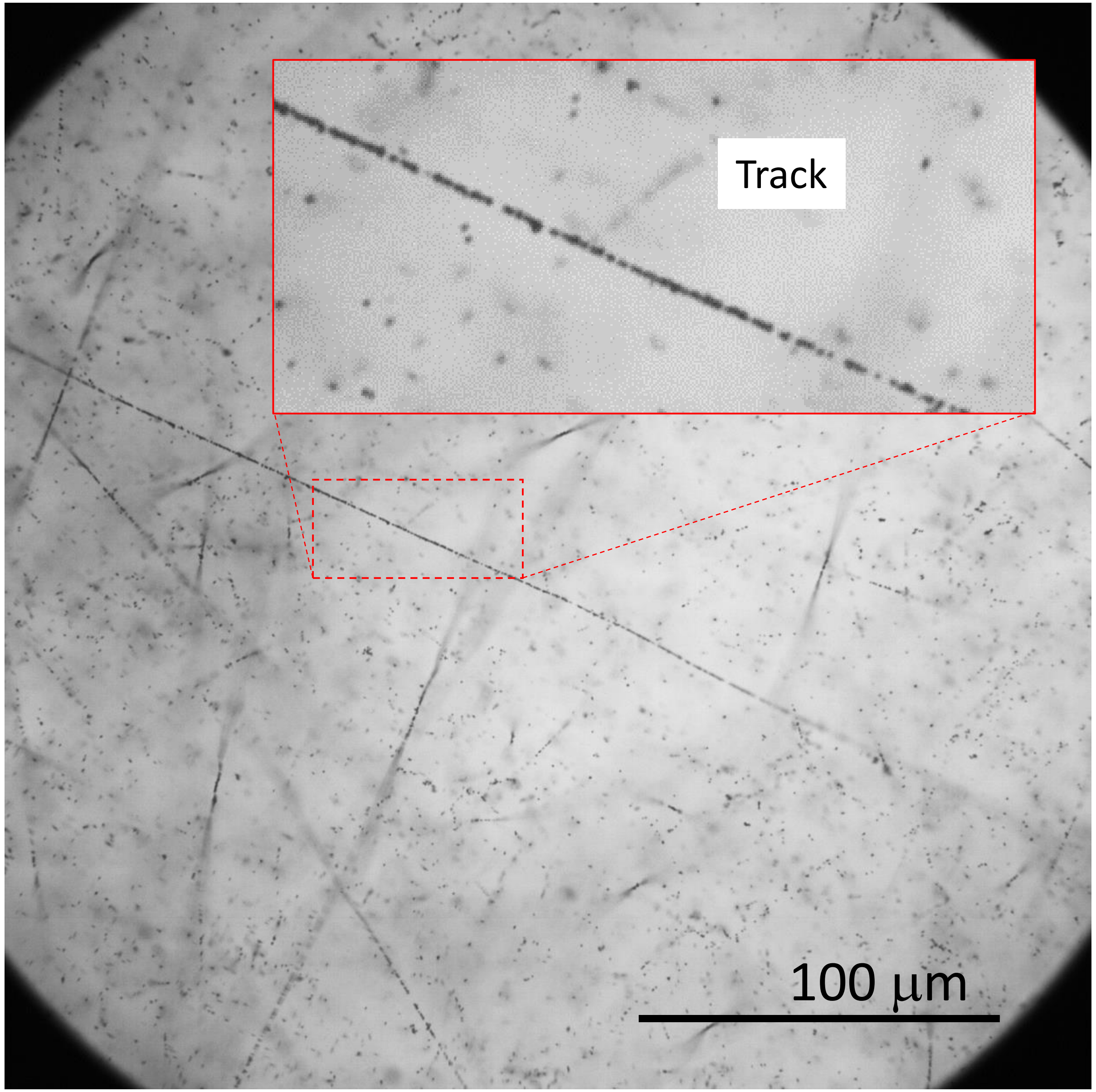




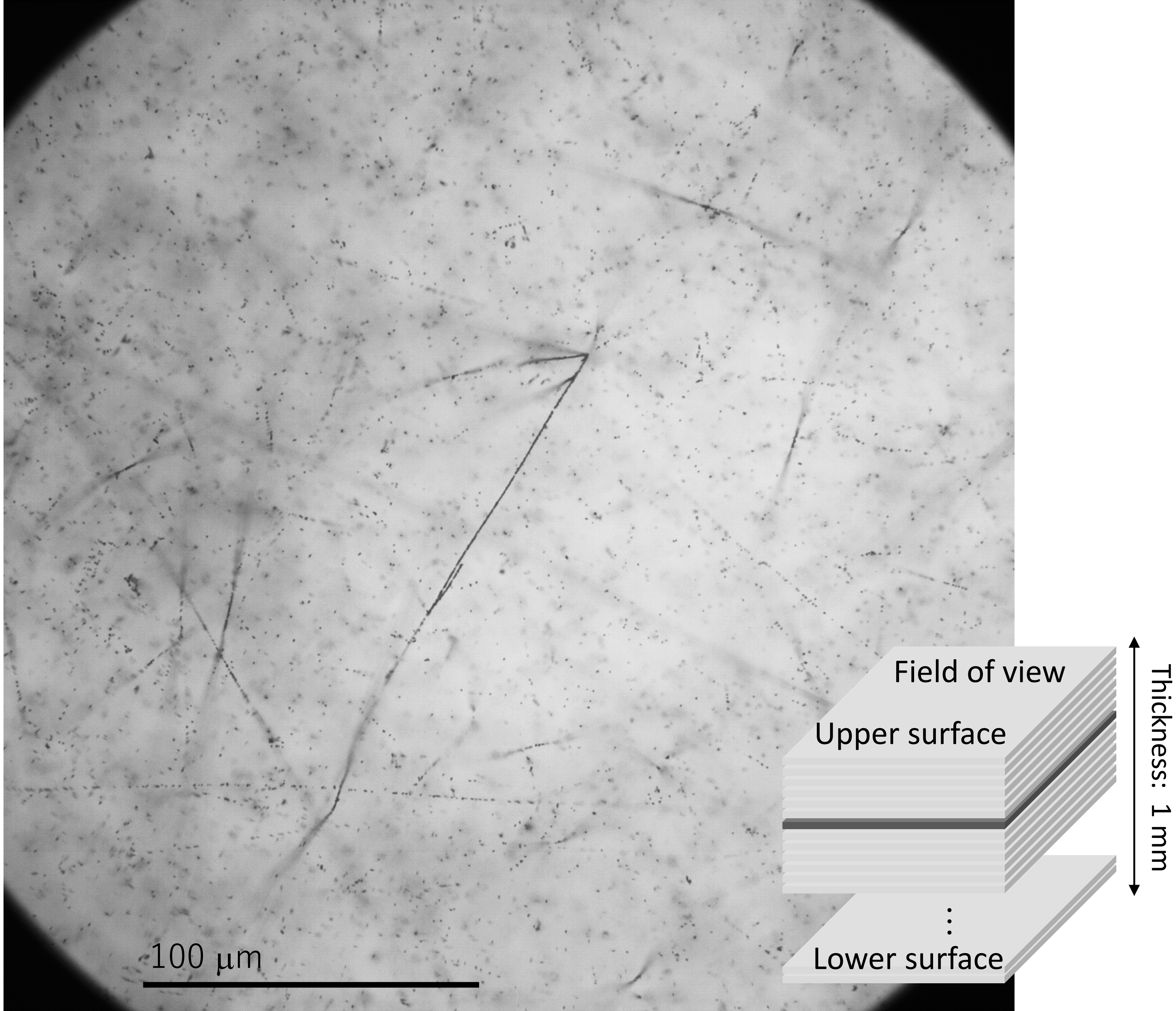
Developed emulsion sheet

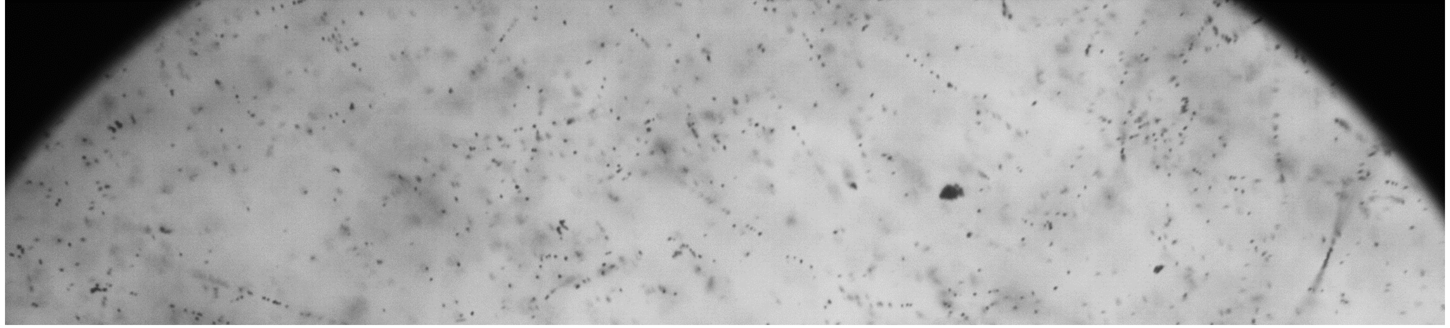


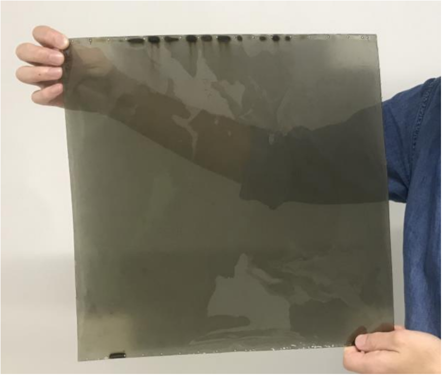
Optical microscope



Micrograph

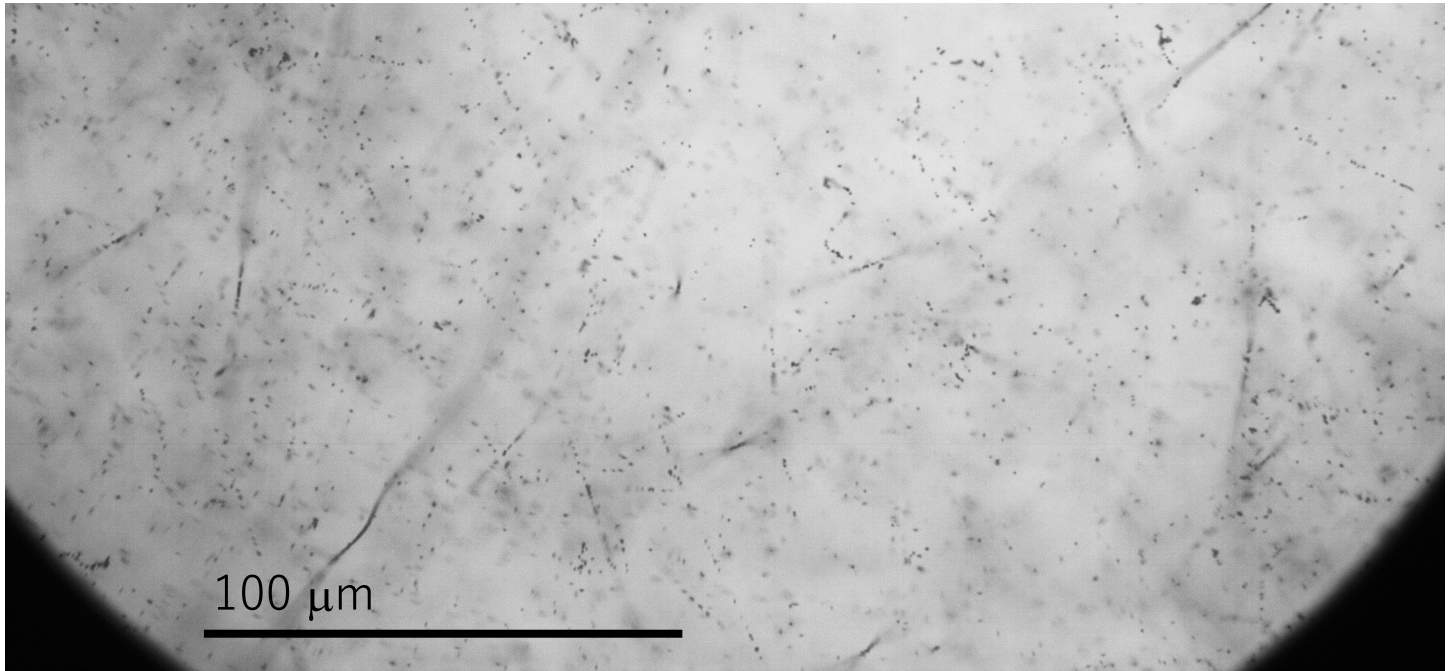

100 μm
Field of view
Upper surface
Lower surface
Thickness: 1 mm





Datasize of emulsion sheet:

1 sheet	=	~100 TB
10^3 sheets	=	~100 PB



My research experience

2006-2008 Graduate student at Nagoya-U

Imaging the interior of volcanoes using cosmic ray muons

2008-2013 Ph. D. student at Nagoya-U

OPERA experiment aiming to detect neutrino oscillations

2013-2017 Postdoc researcher at Gifu-U

2017-2020 Postdoctoral Fellow at Advanced Science Research Center, JAEA

2020-2022 Tohoku-U, RIKEN High energy nuclear physics lab.

Hypernuclear physics

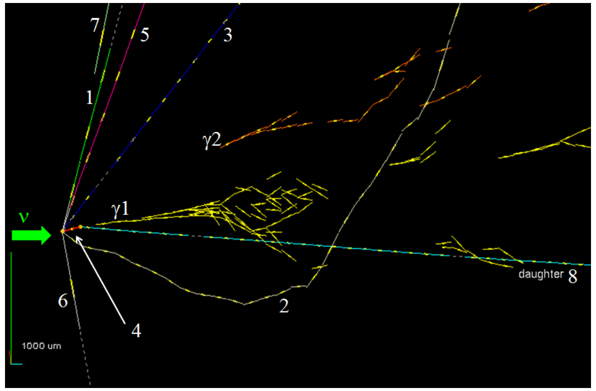
2020-2022 RIKEN High energy nuclear physics lab.

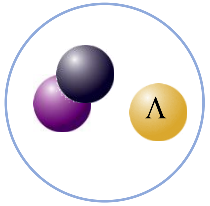
Machine learning for hypernuclear physics, neutron imaging

2022 May- International Center for Synchrotron Radiation Innovation Smart, Tohoku-U

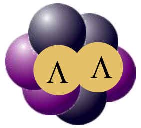
Synchrotron radiation science

Phys. Lett. B 691 (2010) 138.

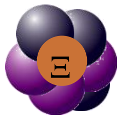




Hypertriton ($^{3}_{\Lambda}H$)



Double Λ hypernucleus



Ξ hypernucleus

Hypernucleus, normal nucleus + hyperon

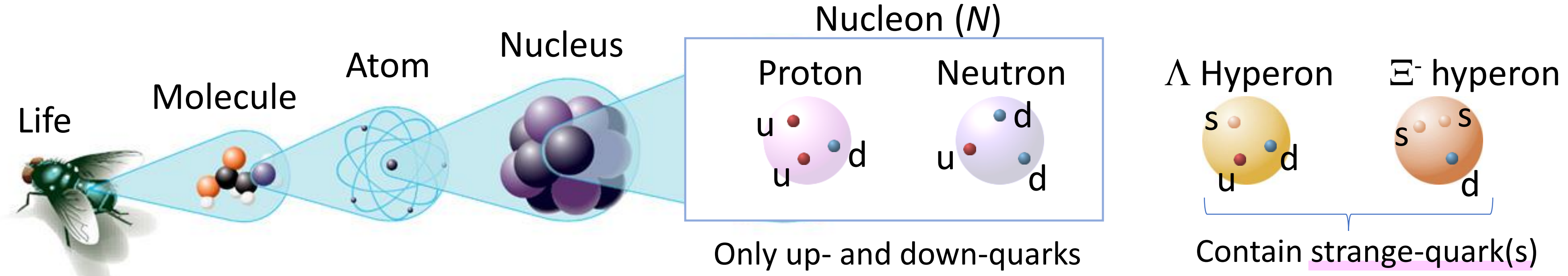
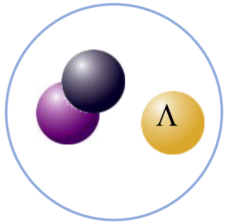


Image: The Nobel Prize in Physics 2008

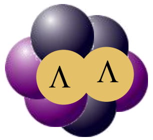
- Important for understanding generalized nuclear forces
- Strange quark: unstable on the earth (lifetime: ~ 10^{-10} sec)
- Hyperons are generated by accelerator experiments

Single Λ hypernucleus

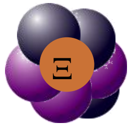


Hypertriton ($^{3}_{\Lambda}$H)

Double strangeness hypernuclei



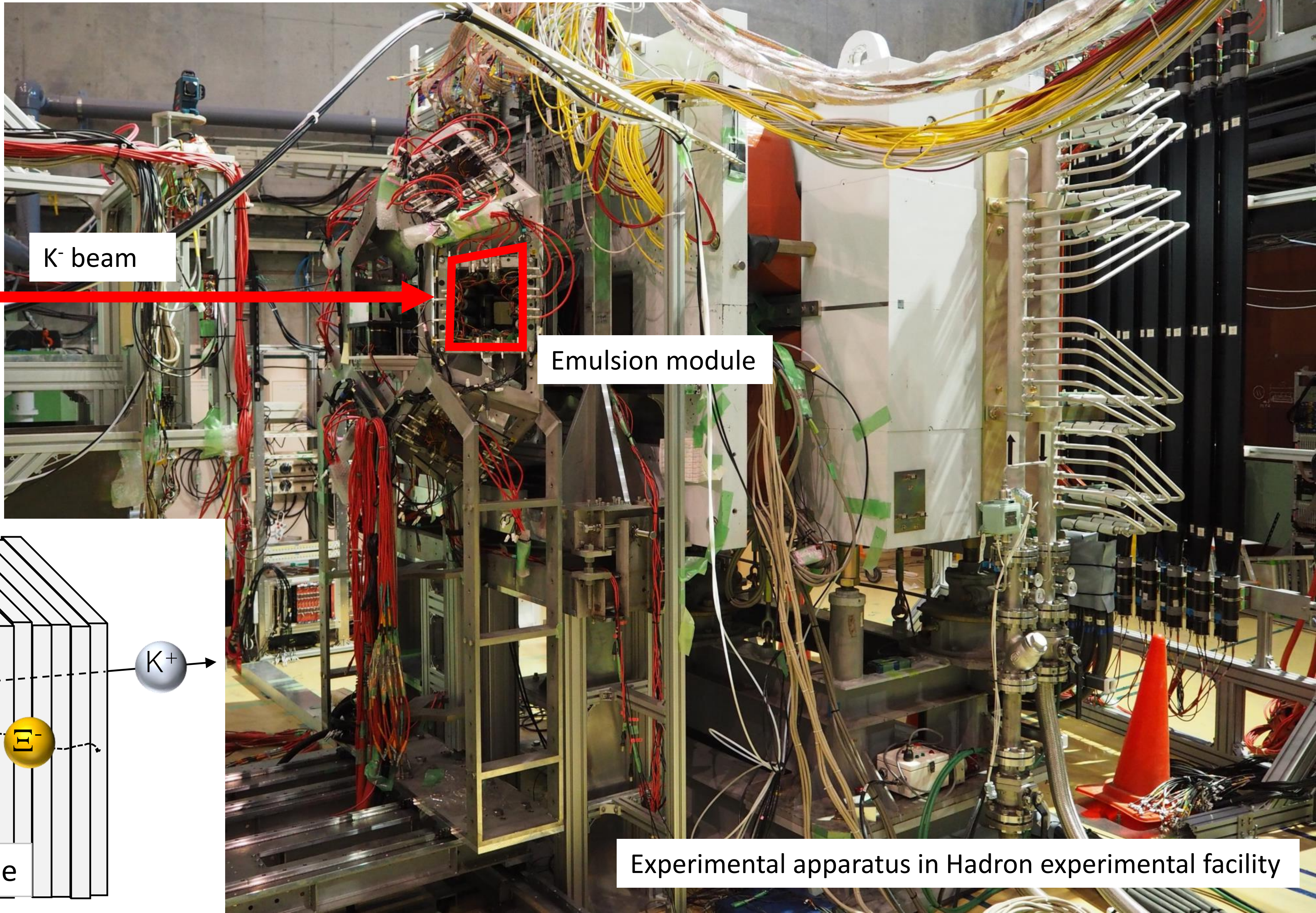
Double Λ hypernucleus

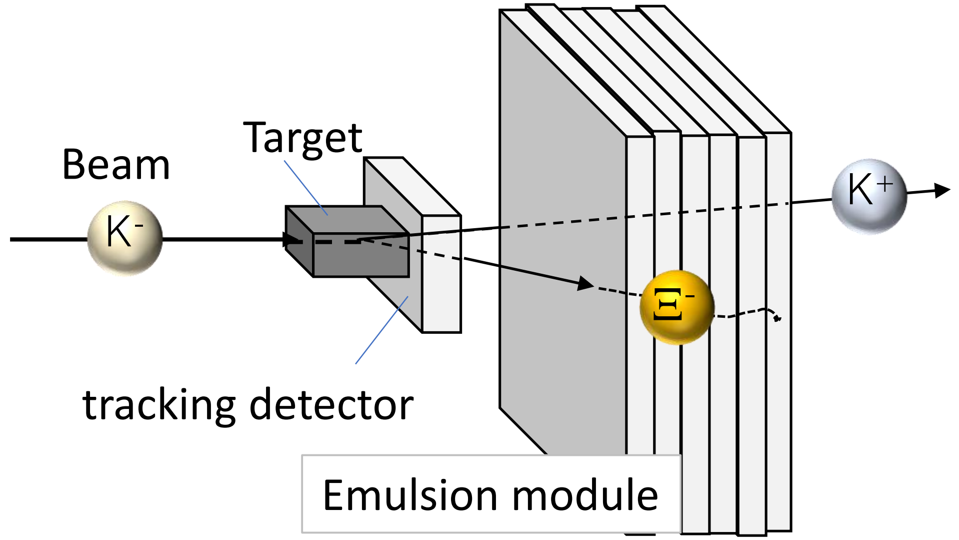


Ξ hypernucleus

- Information on the interaction from its binding energy with normal nucleus
- Emulsion sheet is a suitable detector to detect their production and decay at rest

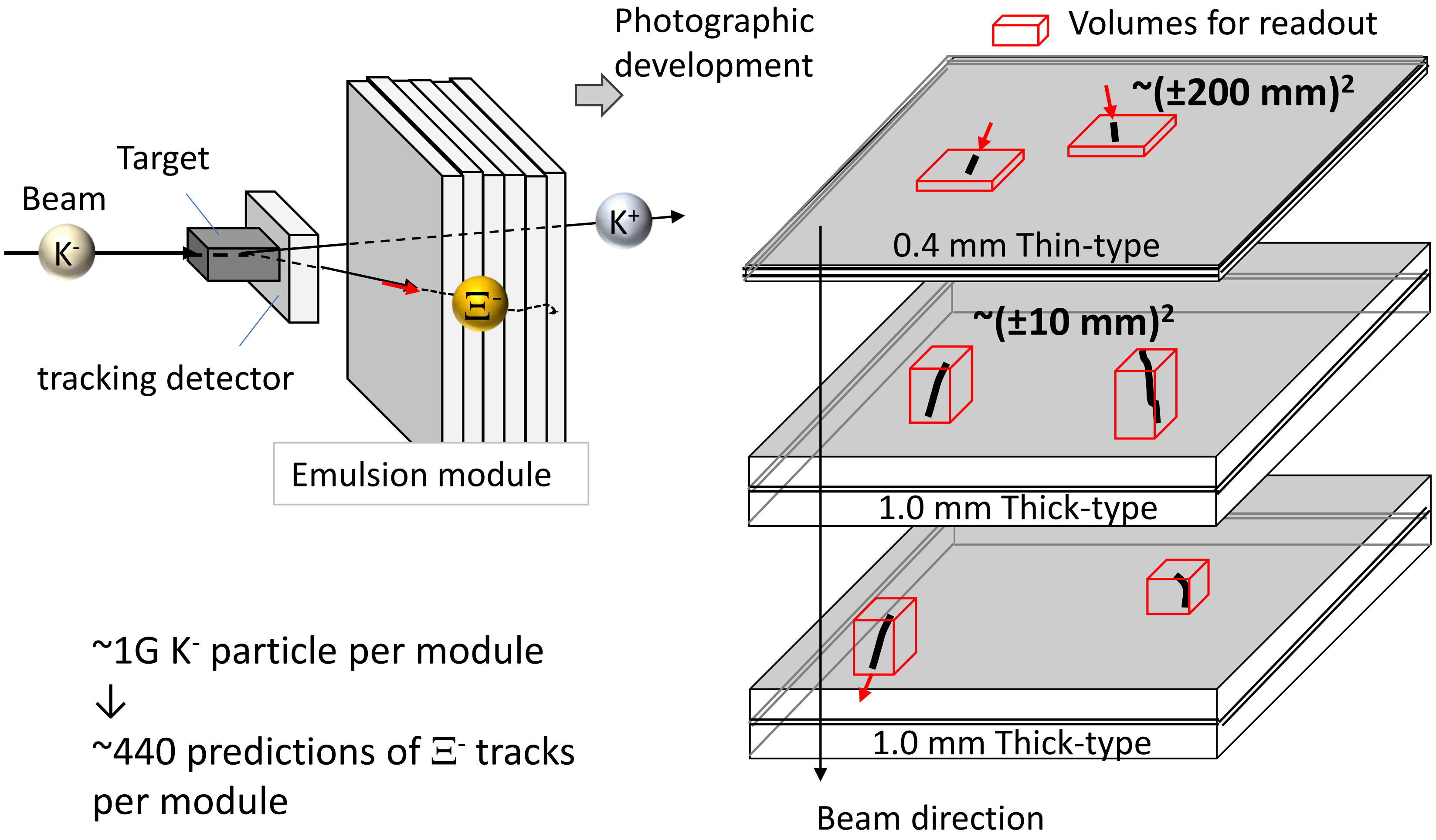
J-PARC E07, a hybrid emulsion experiment to investigate double hypernuclei

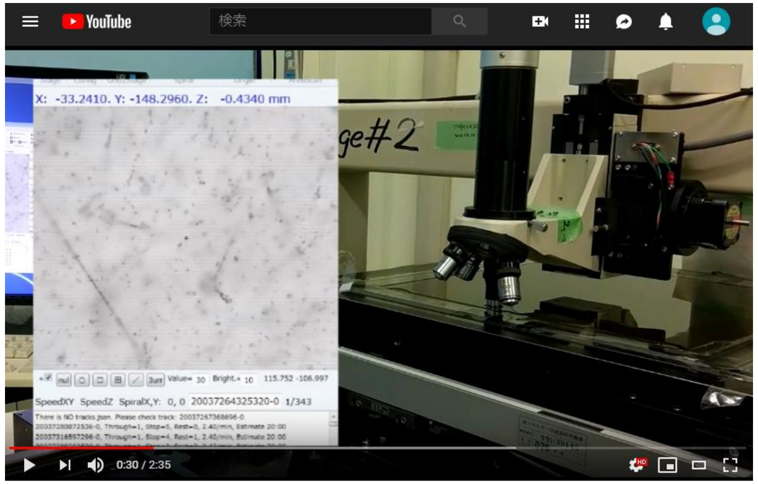




Automated track following

M.K.Soe , ..., J. Yoshida et al., N.I.M. A 848 (2017) 66





Automated Track Following
https://youtu.be/3fiWI5tDx2U

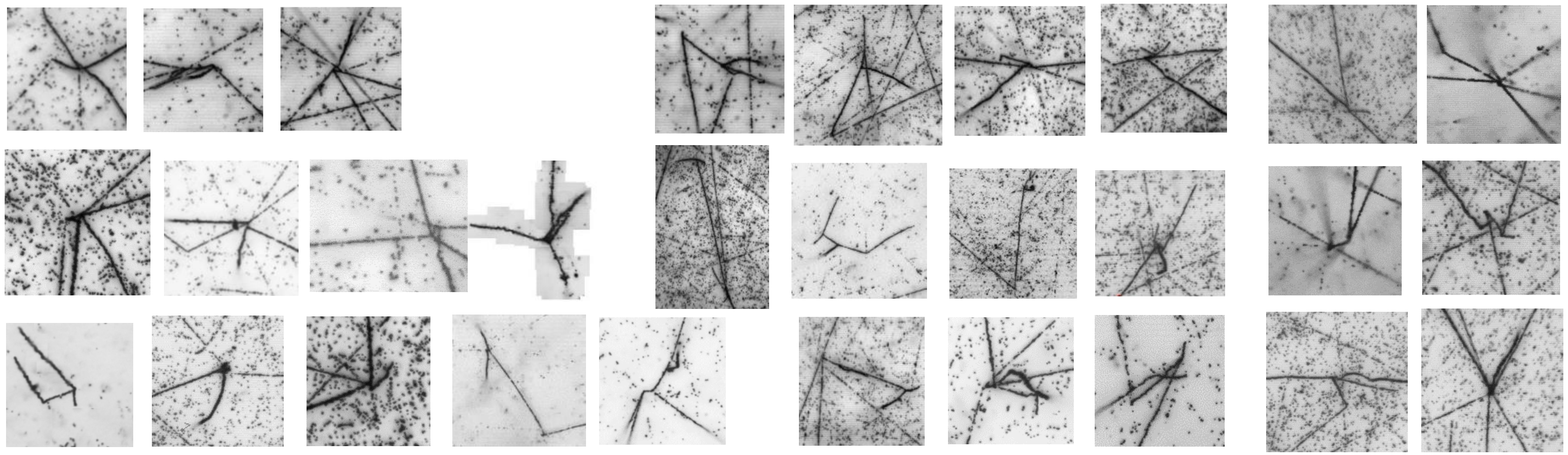
~1G K^- particle per module
↓
~440 predictions of Ξ^- tracks per module

x 118 modules

In the 1998 experiment:
~5k tracks for ~7 years.
J-PARC E07:
~40k tracks for **~2 years**.

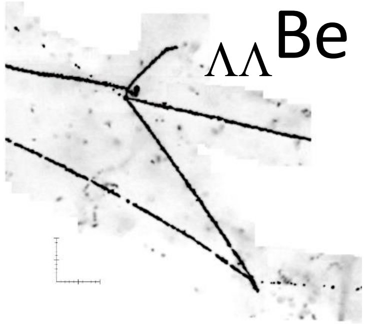
Detected double strangeness events

14 events in the former experiments
33 events in J-PARC E07



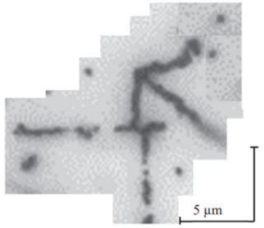
Double Λ hypernuclear events

$_{\Lambda\Lambda}$Be



H. Ekawa, et al.,
Prog. Theor. Exp. Phys.
2019, 021D02 (2019)

$_{\Lambda\Lambda}{}^{8}$Li or $_{\Lambda\Lambda}{}^{10}$Be

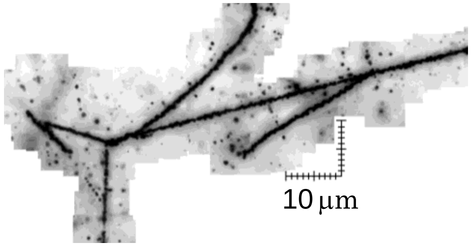


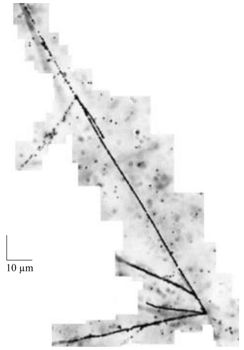
Nyaw, A. N. L. et al.,
Bull. Soc. Photogr. Imag. Japan
30, 22– 25 (2020)

Ξ hypernuclear events

$_{\Xi}{}^{15}$C

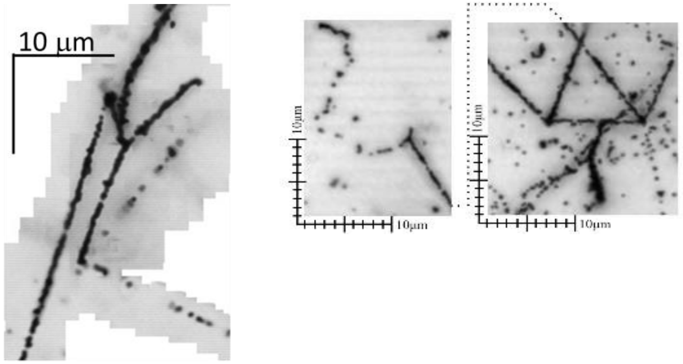
K. Nakazawa, et al.,
Prog. Theor. Exp. Phys.
2015, 033D02 (2015)





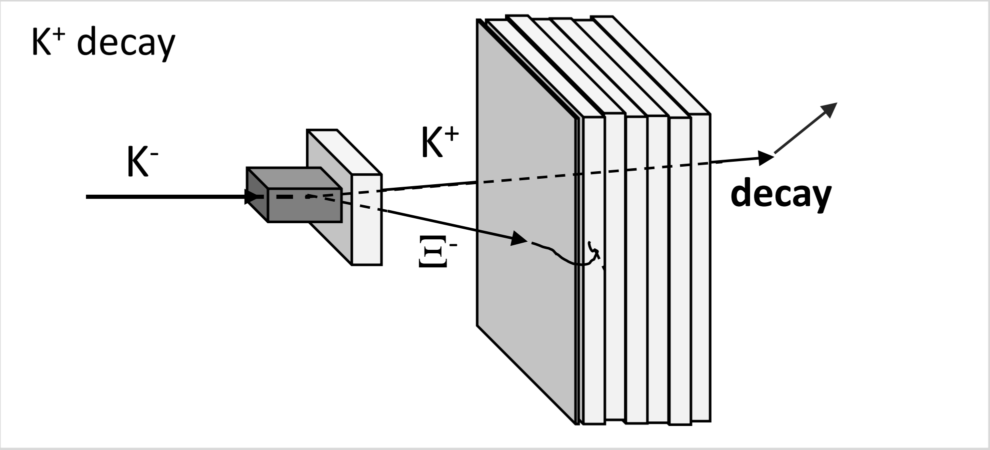
S. H. Hayakawa, et al.,
Phys. Rev. Let., 126, 062501 (2021)

M. Yoshimoto, et al.,
Prog. Theor. Exp. Phys. 2021, 073D02 (2021)

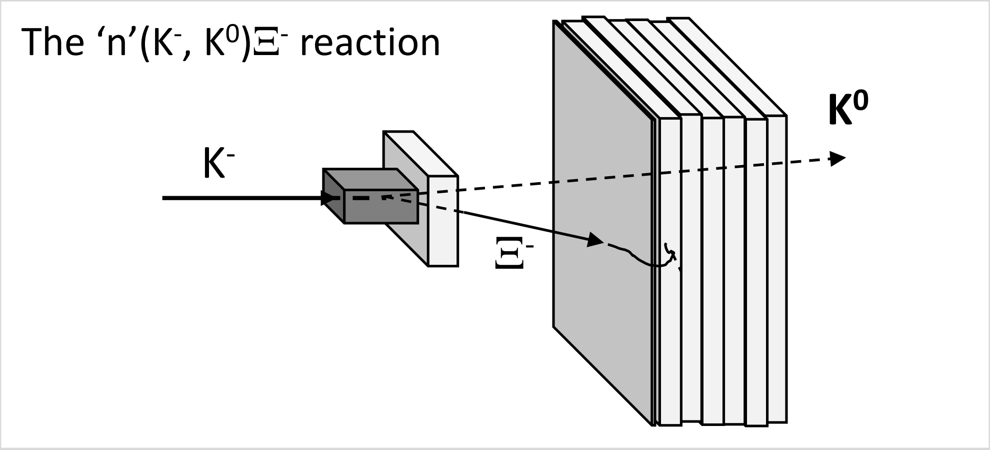


Overall scanning method

Detectable events by the hybrid method are estimated to be ~10% of all.

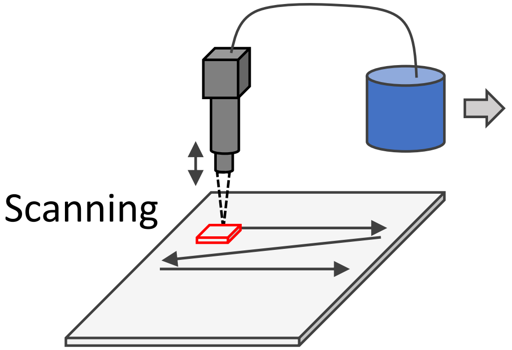


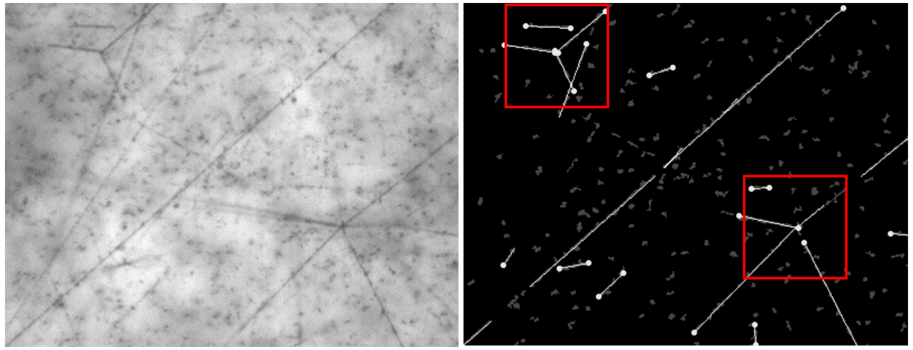
Detection efficiency: ~30%



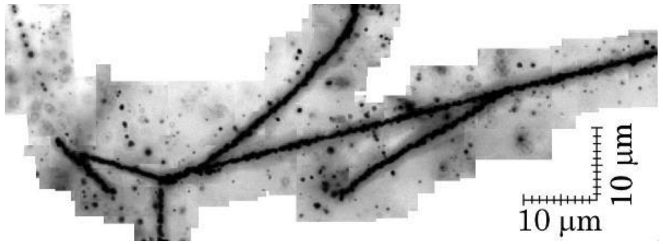
Twice the probability of (K^-,K^+) reaction

- Single Λ hypernuclear events (~10^6 / sheet)
- Even if they are not triggered, they are certainly recorded in the emulsion sheets
- Exhaustive search using image recognition
- Development began around 2010.





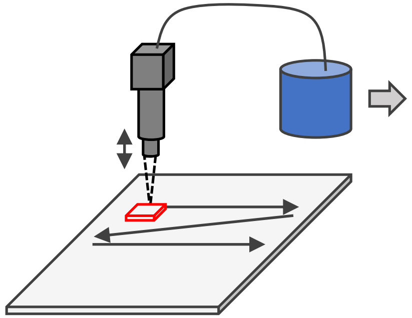
Ξ^- + ^{14}N → $^{15}_{\Xi}C$ → $^{10}_{\Lambda}Be$ + $^{5}_{\Lambda}He$

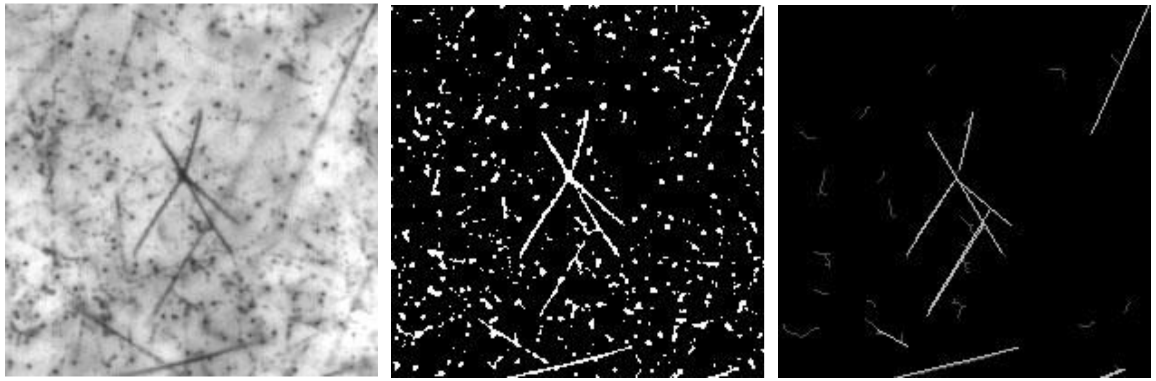


The first observation of the Ξ hypernucleus

Vertex Picker, Image processing for vertex-like shape detection

J. Yoshida, et al., N.I.M A, 847 (2017) 86-92



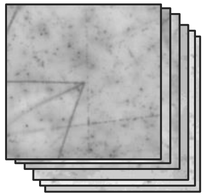


- Line segment detection
- Vertexes where line segment endpoints are concentrated.

- Image processing parameters were set to detect found double hypernuclear events.

- Used to detect alpha decay events as the 1st step
  - U, Th in gelatin
  - Calibration source for the correspondence between track length and kinetic energy

46948 images

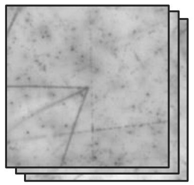


16.1cm² * 0.5mmThick

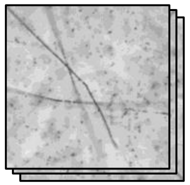
Eye check

alpha
255

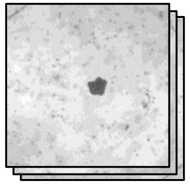
others
46693



Nuclear spallation



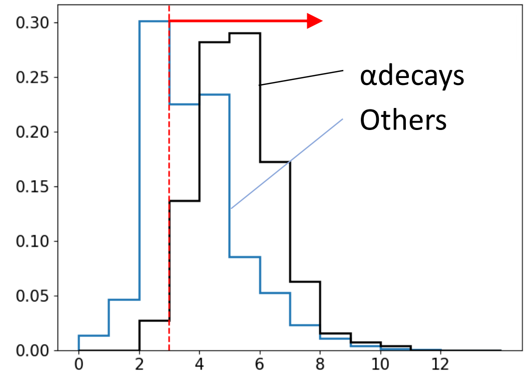
Cross



Dust like object

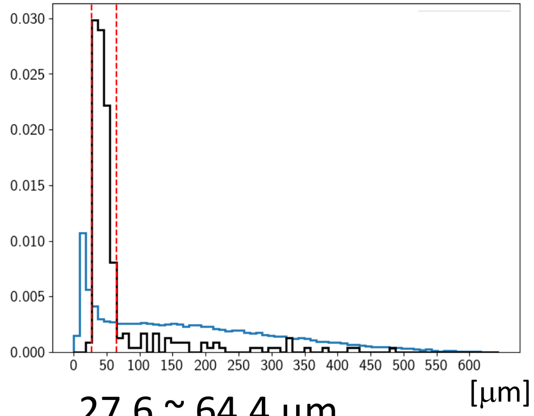
Performance of alpha decay selection using line information.

N_tracks that make up a vertex.



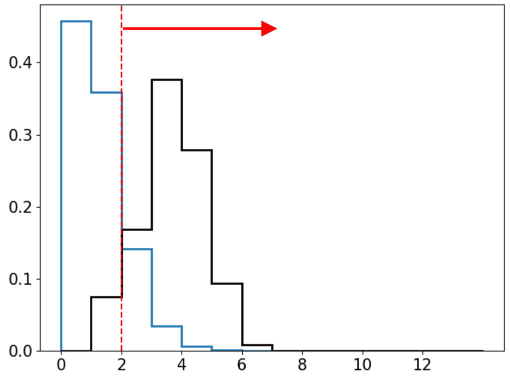
More than 3 tracks

Length of the longest track



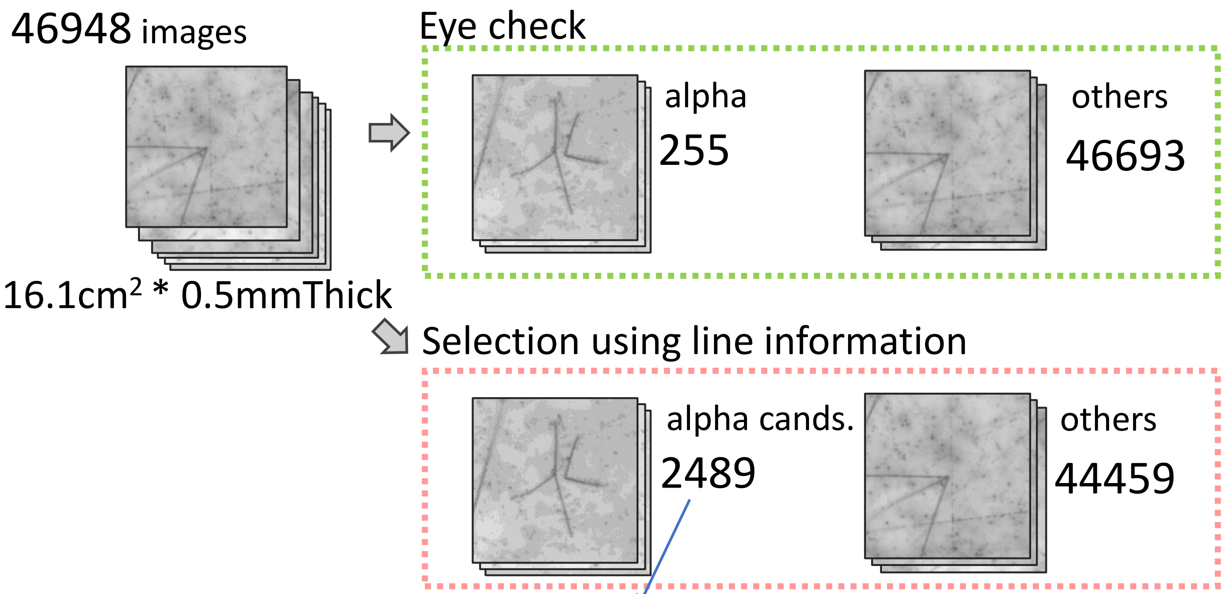
27.6 ~ 64.4 μm

N_tracks having typical length of alpha-tracks(18.4~46.0 μm)



More than 2

Developed by M. Yoshimoto



Precision (Purity): 0.081 ± 0.006 $= (201 \pm \sqrt{201}) / 2489$

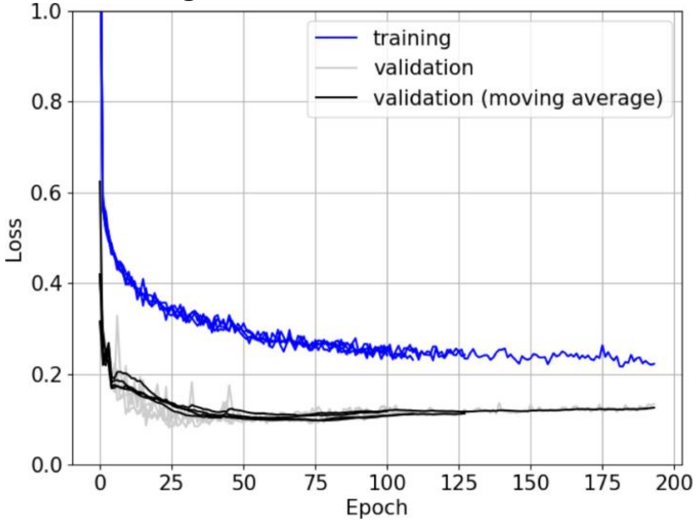
Recall (Efficiency): 0.788 ± 0.056 $= (201 \pm \sqrt{201}) / 255$

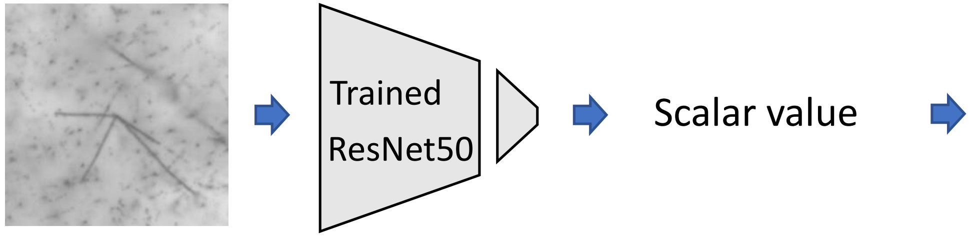
→ Development of a CNN-based image classifier.

Image classification using Convolutional Neural Network (CNN)

J. Yoshida, et al. Nucl. Inst. and Meth, A 989 (2021) 164930

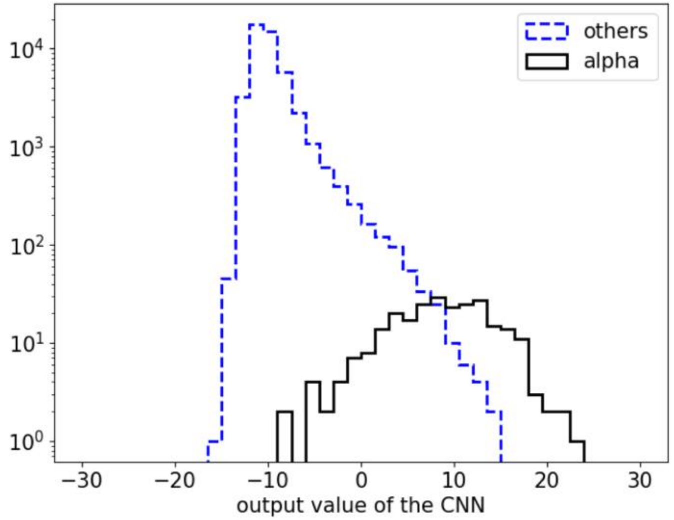
Learning curve for 4 trials





224*224 pix

Output scalar value



- Scalar values are calculated by the CNN for each image
- If the value exceeds a threshold value, it is considered a signal.

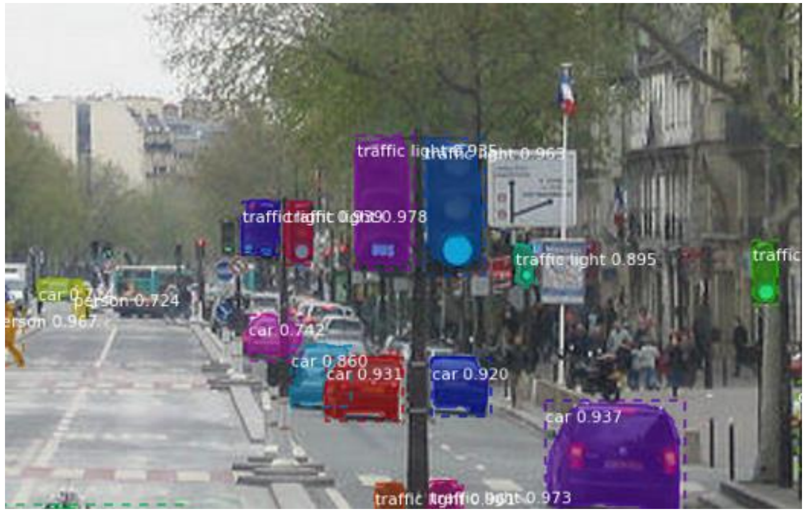
Comparison

	Precision (Purity)	Recall (Efficiency)	Number of Selected images
Conventional method	0.081 ± 0.006	0.788 ± 0.056	2489
CNN（Average of 4 trials）	0.547 ± 0.025	0.788	366 ± 18

6.8 ± 0.6 times smaller

Object detection using Region based CNN

Mask R-CNN https://arxiv.org/abs/1703.06870



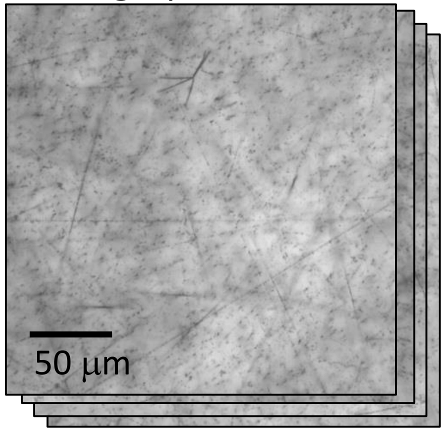
https://github.com/multimodallearning/pytorch-mask-rcnn

- Displaying frames and region where detected objects are located
- One can train dedicated models using 10^3 ~10^4 pairs of images and masks.

A Pedestrian dataset by Pennsylvania and Fudan Univ.

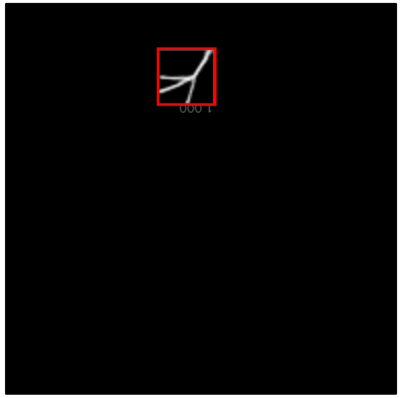
Our strategy

Micrograph



Trained Mask R-CNN

Object detection



How to collect training data for rare events?

➔ Using

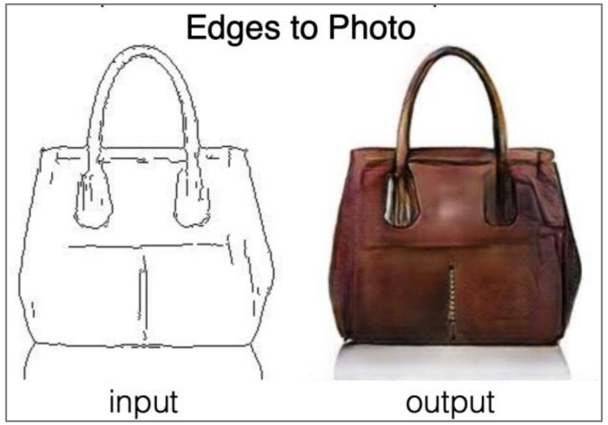
- Machine learning (Style Transfer)
- Physics simulation (GEANT4)

to generate training data without any actual example.

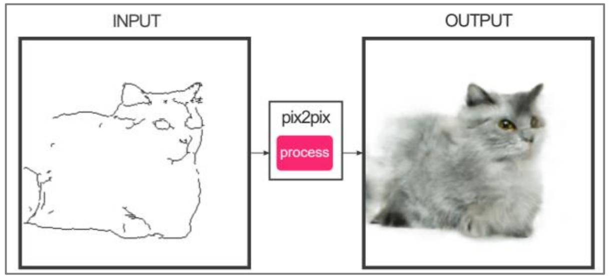
Synthesized images: from line to simulated images using Image Translation as an optical simulator.

Pix2Pix

https://arxiv.org/abs/1611.07004

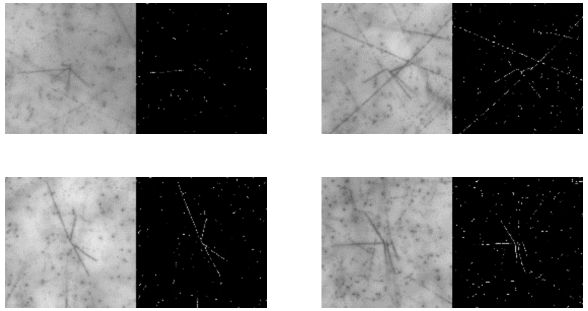


https://affinelayer.com/pixsrv/index.html



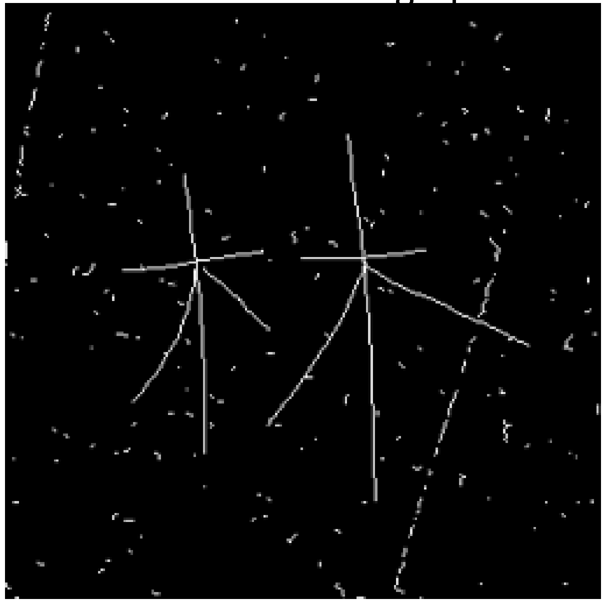
- Inverse transformation of Edge detection
- Recover the colors of the original image from the line drawing

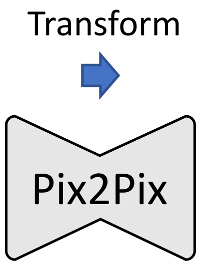
Training using our data



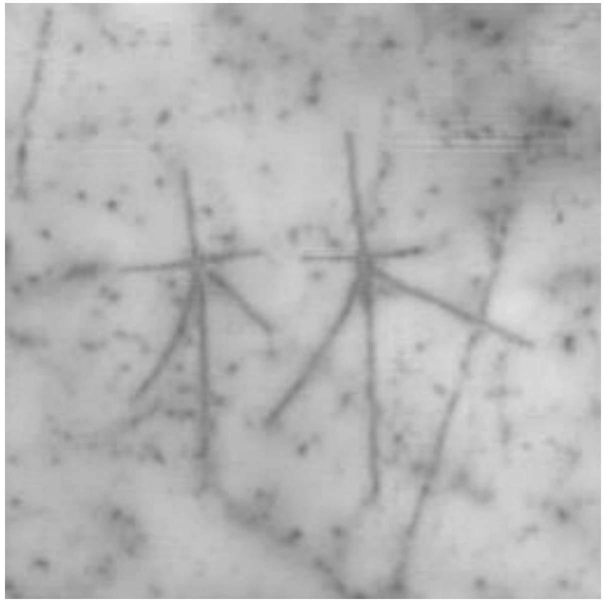
Pairs of ~10^4 real images and binarized images were used to train the inverse transformation.

Artificial lines on binarized actual micrograph



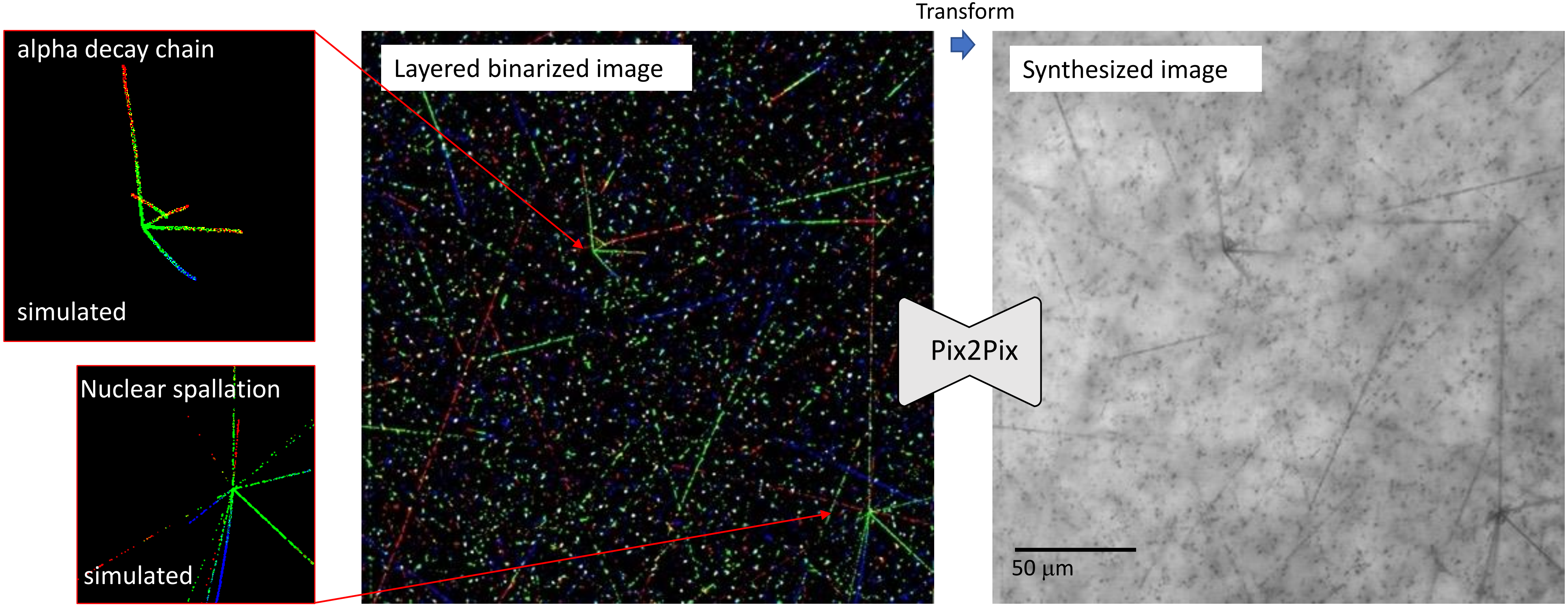


Synthesized image



Synthesized images: from line to simulated images using Image Translation as an optical simulator.

A. Kasagi et.al, N.I.M. A 1056 (2023) 168663

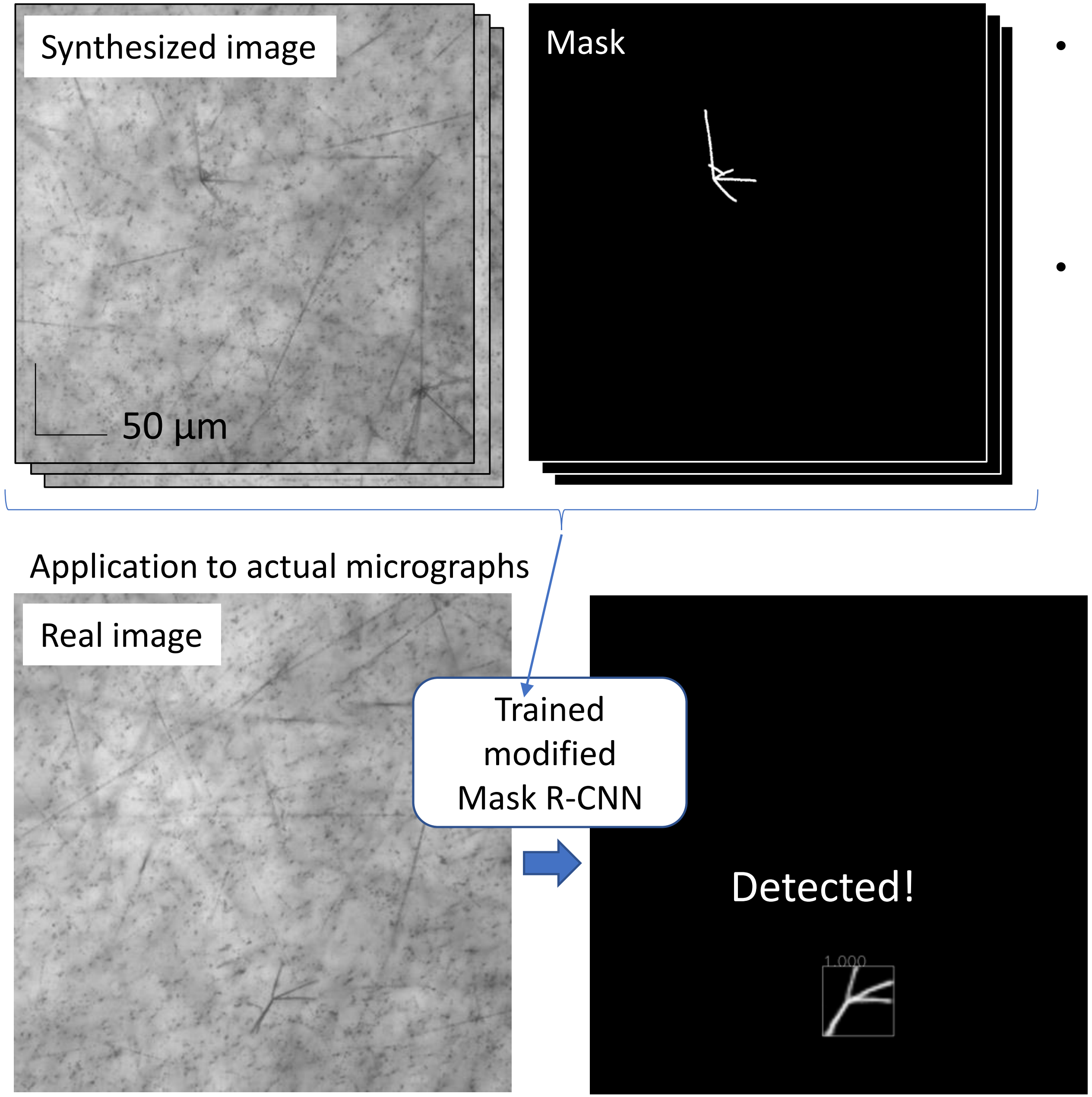


Line drawings of tracks using GEANT4

RGB channels for focused and adjacent depth layers

Application for alpha decay search

A. Kasagi et.al, N.I.M. A 1056 (2023) 168663



- Training a modified Mask R-CNN
    - 30k pairs of simulated image and mask are used.
    - Masks are created without manual annotation works.
- Mask R-CNN
    - Implemented by PyTorch
    - Backbone: ResNet50
    - Modified for our purposes

Performance

$$\text{Efficiency} = \frac{(\text{Number of detected } \alpha\text{\_decay event})}{(\text{Number of } \alpha\text{\_decay events in test dataset})}$$

$$\text{Purity} = \frac{(\text{Number of detected } \alpha\text{\_decay event})}{(\text{Number of detected candidates})}$$

Using eye search

	Efficiency [%]	Purity [%]
VertexPicker+CNN	$40.8^{+5.6}_{-5.5}$	$8.9^{+1.1}_{-1.2}$
Mask R-CNN	$80.3^{+4.2}_{-4.8}$	$17.3^{+0.9}_{-1.0}$

In operation for physics research; hypertriton search

NUCLEAR WALLET CARDS 2011

Appendix–IV Observed Λ Hypernuclides†

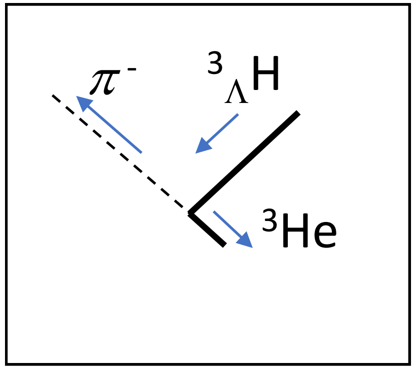
El	A	J(g.s.)	B_Λ(g.s.)	Excited states (MeV)
H	3	1/2+	0.13 *5*	
	4	0+	2.04 *4*	1.05 *4* 1+
He	4	0+	2.39 *3*	1.15 *4* 1+
	5	1/2+	3.12 *2*	
	6		4.18 *10*	
	8		7.16 *70*	

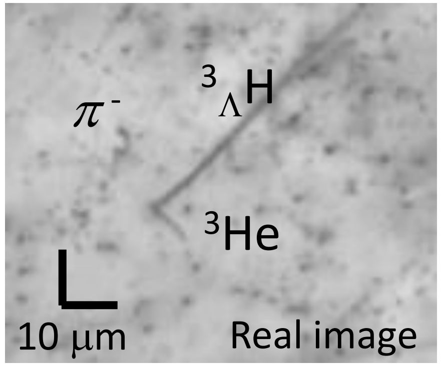
0.13 ± 0.05 MeV, measured in the 1970s

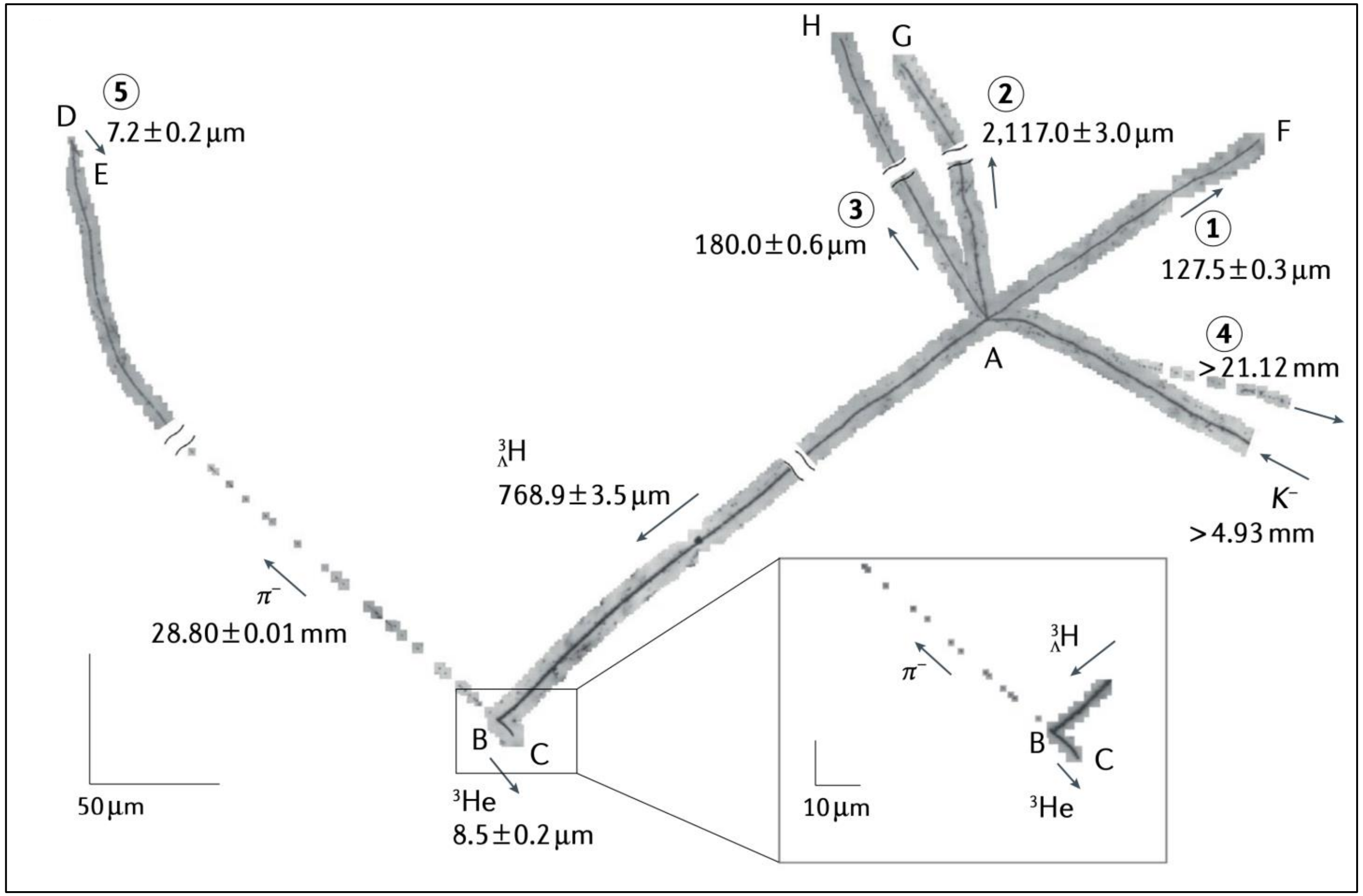
Remeasuring using modern techniques

E. Liu, …, J. Yoshida et al., Eur. Phys. J. A (2021) 57:327

A decay event at rest







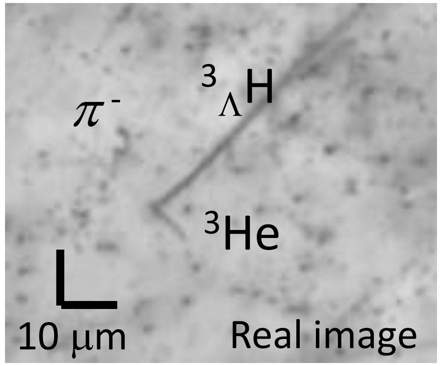
The 1st hypertriton event detected in an emulsion sheet of J-PARC E07 using ML

"New direction of hypernuclear physics"
T.R Saito et.al., Nature Reviews Physics
https://doi.org/10.1038/s42254-021-00371-w

Personal impression

Why does it work?

- Effective usage
  - Event search
  - Alpha decay and decay event of hypertriton
  - Image processing for micrograph of emulsion sheet

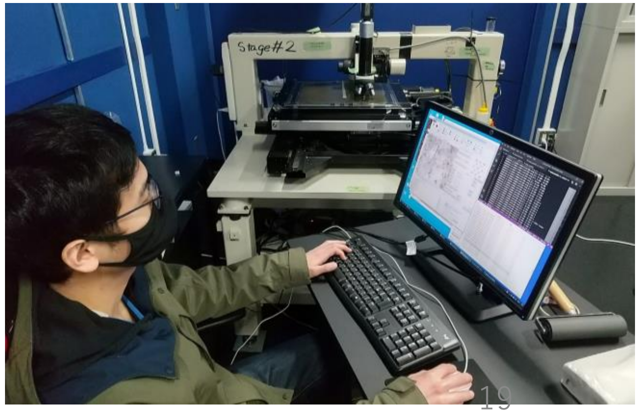


- Collaboration with experts of machine learning
  - RIKEN, Rikkyo-U

- Timing and public understanding of machine learning
  - Google bought Deepmind for $650m (Jan. 2014)
  - AlexNet on Caffe
  - Chainer (Jul. 2015), TensorFlow (Nov. 2015), PyTorch (Oct. 2016)
  - AlphaGo vs Lee Sedol (Mar. 2016)

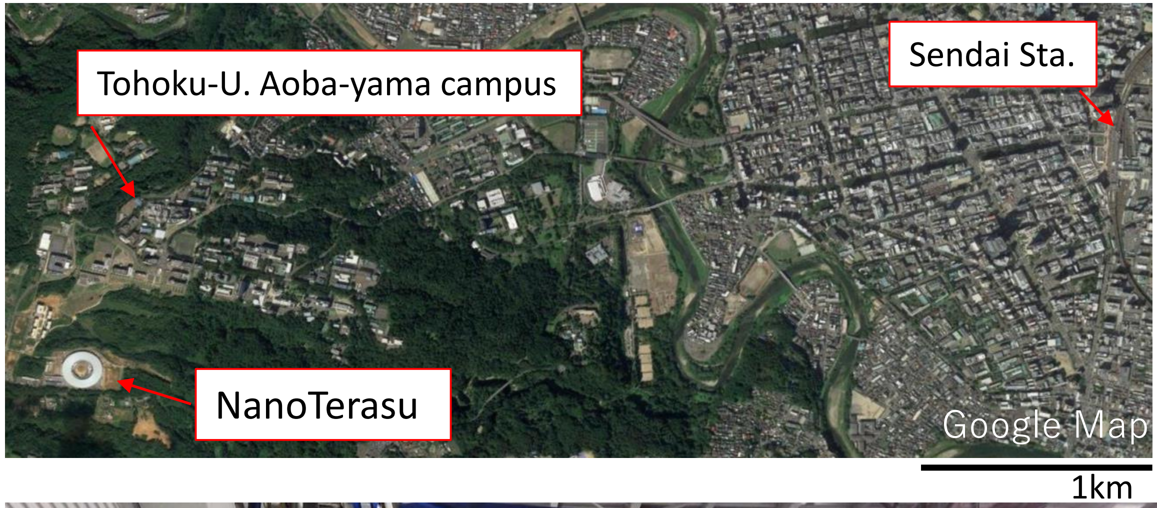
Development issues

- Reduction of increased eye-check work
- Other decay modes of hypertriton
- Searching for double strangeness hypernuclei

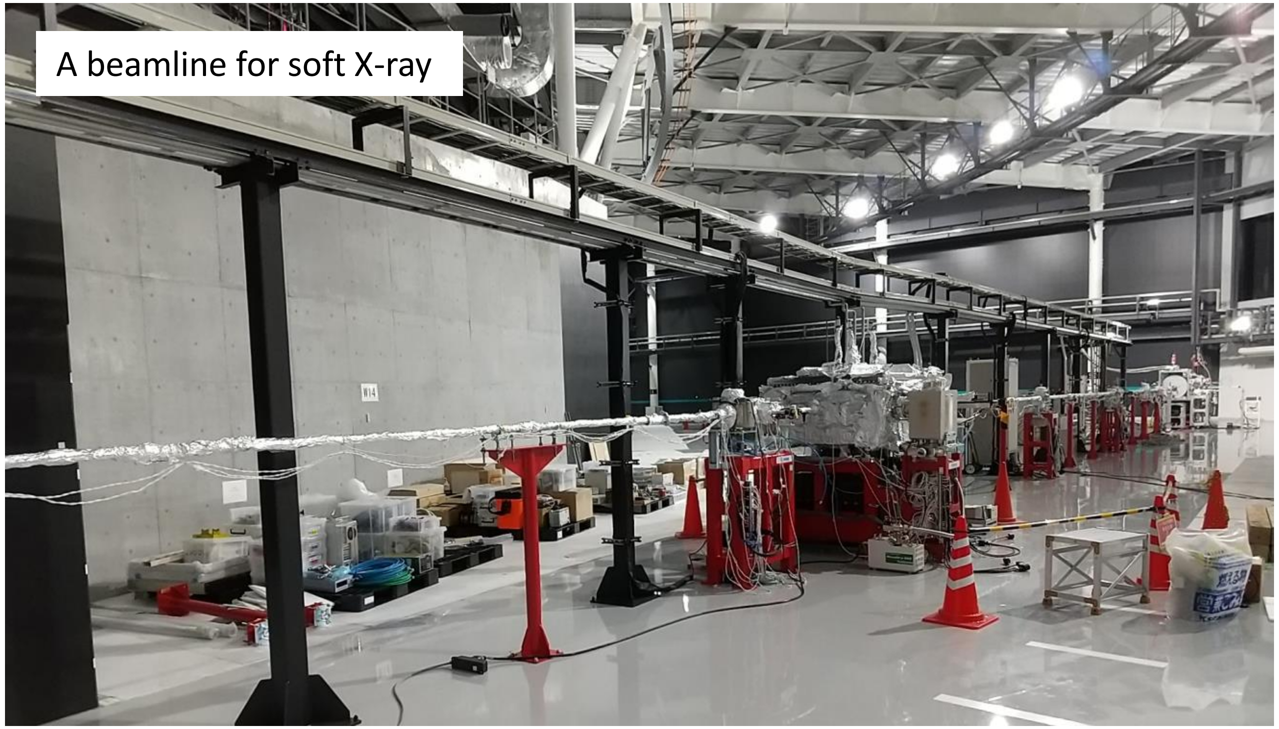


My current work: construction of a new synchrotron radiation facility, NanoTerasu

This facility is being set up for operation in April 2024.

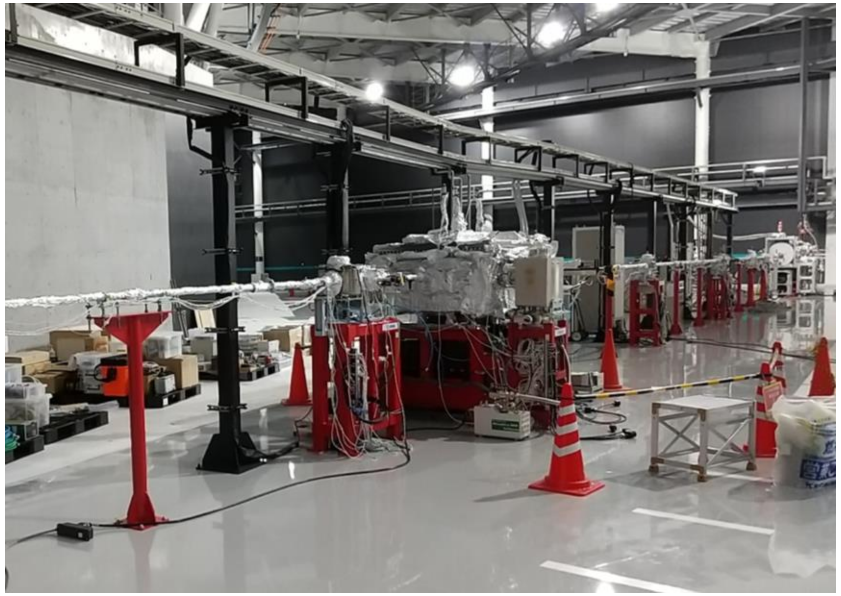


https://www.sris.tohoku.ac.jp/



My recent interest

X-ray Optics



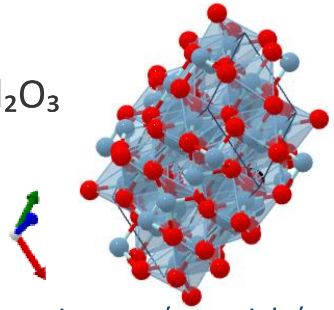
- Stabilization and tuning
- Nano-focusing
- Advanced measurement system

Accelerator Science

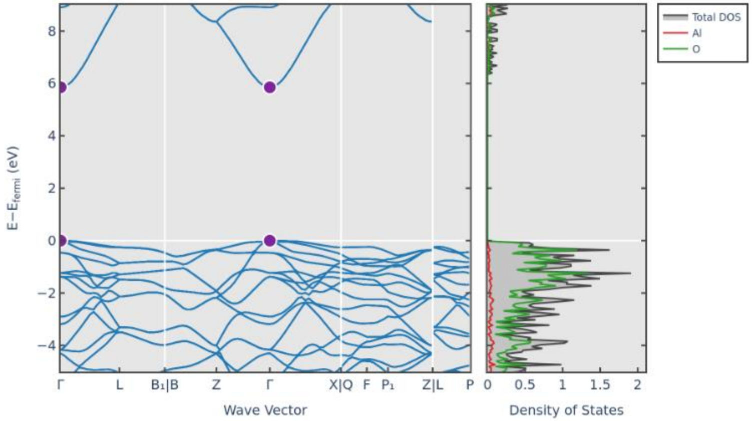
- Beam stabilization and tuning

Material science

Al_2O_3



https://next-gen.materialsproject.org/materials/mp-1143



- New material search
- Scintillator, tracking detector

A. Muneem, J. Yoshida, et al.,
Radiation Meas. 158 (2022) 106863

Summary

- Implemented deep learning-based image processing for event detection in nuclear emulsion sheets.

- Trained an object detector using training data generated through simulations and Image translation.

- Currently applied in physics analysis for:
    - Searching for alpha decay events used in calibration.
    - Measuring the binding energy of a Lambda particle in Hypertriton.
    - Searching for double-strangeness hypernuclear events.

- The author is currently involved in the launch of a synchrotron radiation facility while learning optical system control, accelerator science, and material science.

- Exploring applications of machine learning.
- Intending to develop measurement systems that support data-driven science.

- I would like to collaborate with you accelerator scientists.

E07 Collaboration (Author list of PTEP 2019, 021D02)

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Collaboration on machine learning for nuclear physics

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[10]GSI Helmholtz Centre for Heavy Ion Research
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[12]Graduate School of Artificial Intelligence and Science, Rikkyo University
[13]RIKEN Nishina Center for Accelerator-Based Science, RIKEN

一般向けの資料

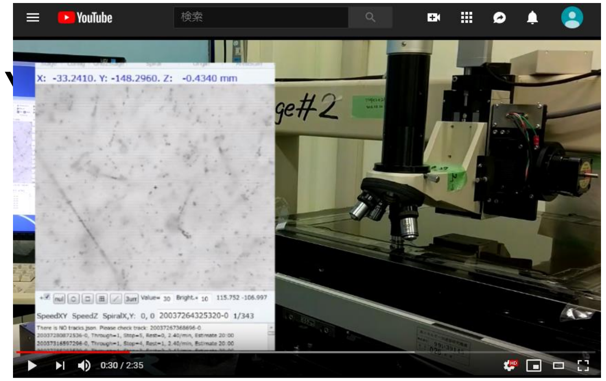
プレスリリース

ハイパー核の束縛エネルギー精密測定へ (2021.09.14)
－ハイパートライトンパズルの解明に向けて－

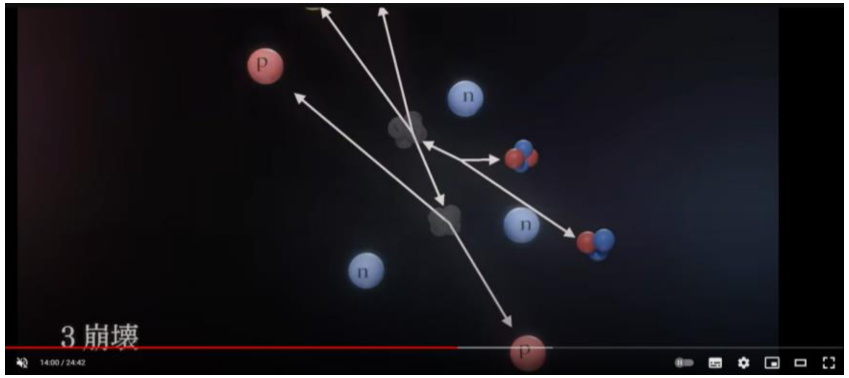
「グザイ核」の内部構造、ついに観測成功 (2021.07.26)
原子核の成り立ちや中性子星の構造の理解に新たな知見

稀少な超原子核「グザイ核」の質量を初めて決定 (2021.03.02)
原子核の成り立ちや中性子星の構造を理解する新たな知見

新種の超原子核（二重ラムダ核）を発見 (2019.02.26)
－中性子星の内部構造の謎に迫る－「美濃イベント」と命名



Automated Track Following
https://youtu.be/3fiWI5tDx2U



国立科学博物館　企画展「加速器」
https://youtu.be/iI4iUwqf7dQ?t=670

朝日新聞岐阜版

中性子星 解明に光
岐大シニア教授ら 新種の「ハイパー核」発見

ブラックホールの撮影成功が世界的な話題になっている天文学の世界で、ブラックホールと共に謎の多い存在の一つである「中性子星」。岐阜大学の仲沢和馬シニア教授（実験物理学）らのグループが、中性子星に存在すると考えられる粒子を含んだ新種の「ハイパー核」を発見した。将来的に、現在はほとんど分かっていない中性子星の内部構造の解明につながる可能性があるという。

「宇宙の謎に近づきたい」

ハイパー核の痕跡を調べる学生

ハイパー核の痕跡